Light

Lecture 3, Oct. 8

Astronomy 102, Autumn 2009

Questions of the Day

I. What is light?

II. What are the wave/particle properties of light?

III. How do energy and wavelength vary along the electromagnetic spectrum?

IV. What makes light spectra interesting?

V. What are the properties of a thermal (blackbody) spectrum?

I. What is light?

- Light is a form of energy!

  (Light carries energy from the fire to your skin which is then transformed into heat)

- Light is comprised of electric & magnetic fields which carry the energy

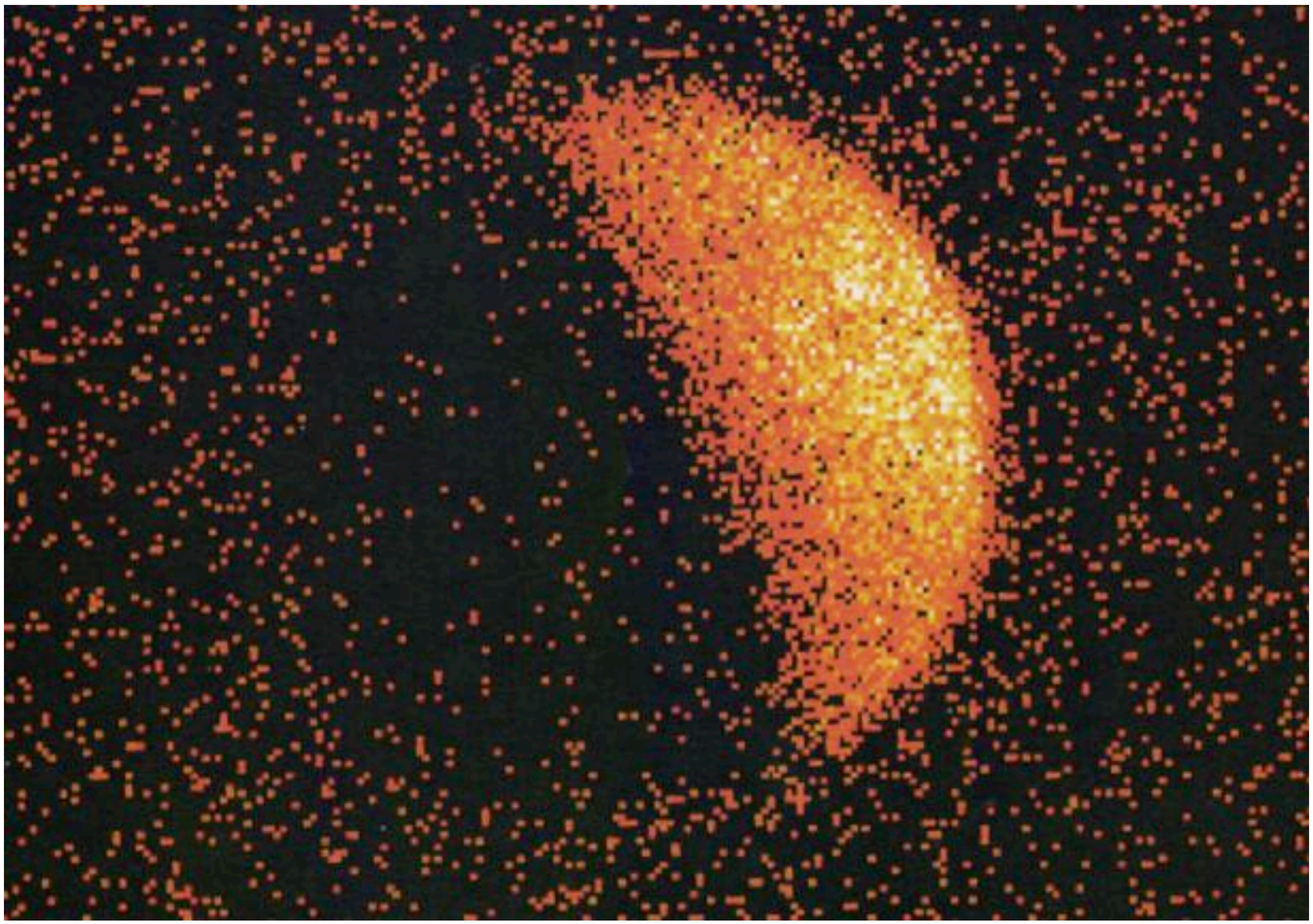
II. The Facts of Light:

A) Light acts like a massless particle: "photon"

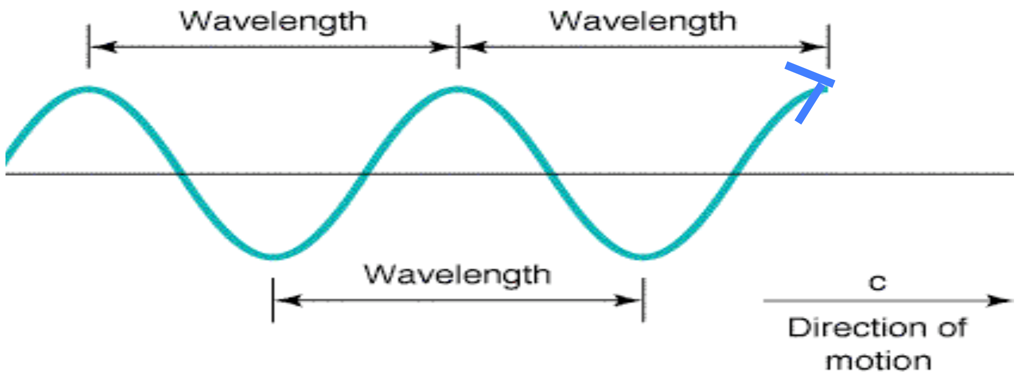
Photons:

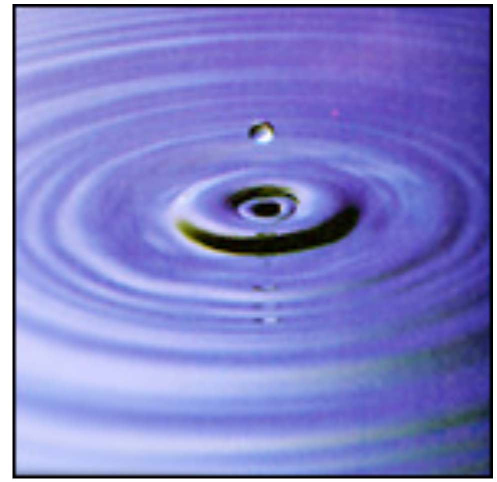
1. go in a *straight line* unless they are redirected or absorbed.
2. are discrete objects.
3. apply a force when they hit something.
4. can travel through empty space!

Proof that photons exist = X-ray images. This X-ray image of the moon shows individual photons detected:



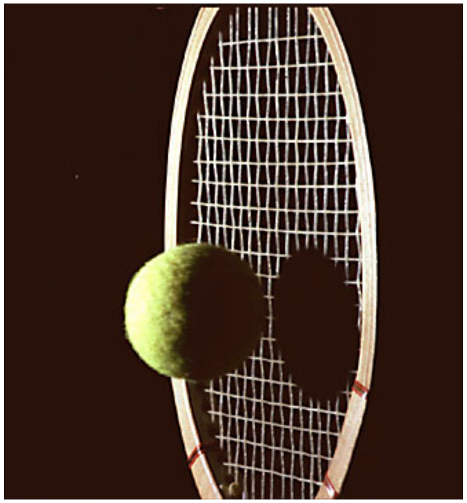
B) Light also acts like a wave.



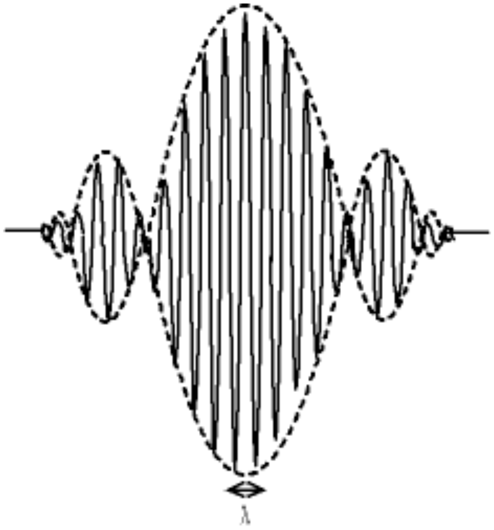


As light travels, there are high points and low points in the electric field and magnetic field which makes it behave like a wave.

So, light is a particle *AND* a wave!



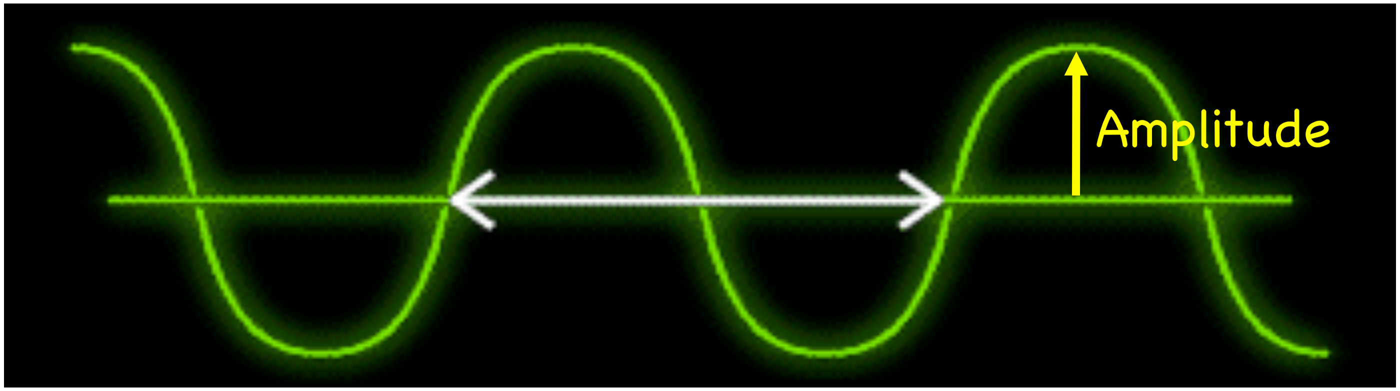
- Sometimes scientists talk about light as if it is a particle:
  - Speed
  - Energy
- But other times they talk about light as a wave.



  - Wavelength
  - Frequency

III. The Characteristics of light

A. Wavelength: The distance over which the wave pattern repeats itself.

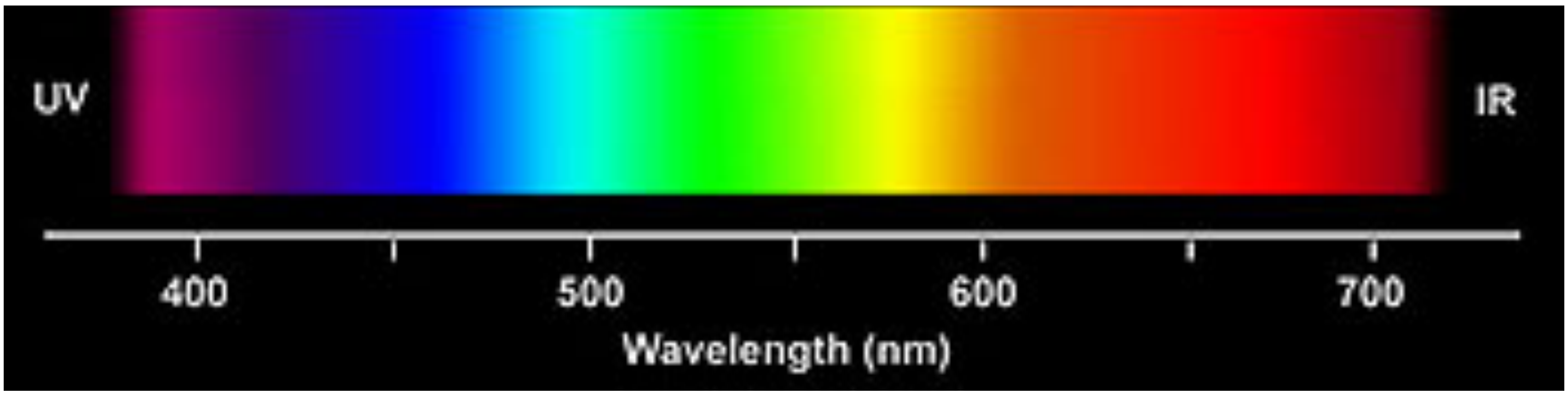


λ = "lambda" = the universal symbol for wavelength

Are we on the same λ?

Wavelength:

- The color of optical light depends upon its wavelength.

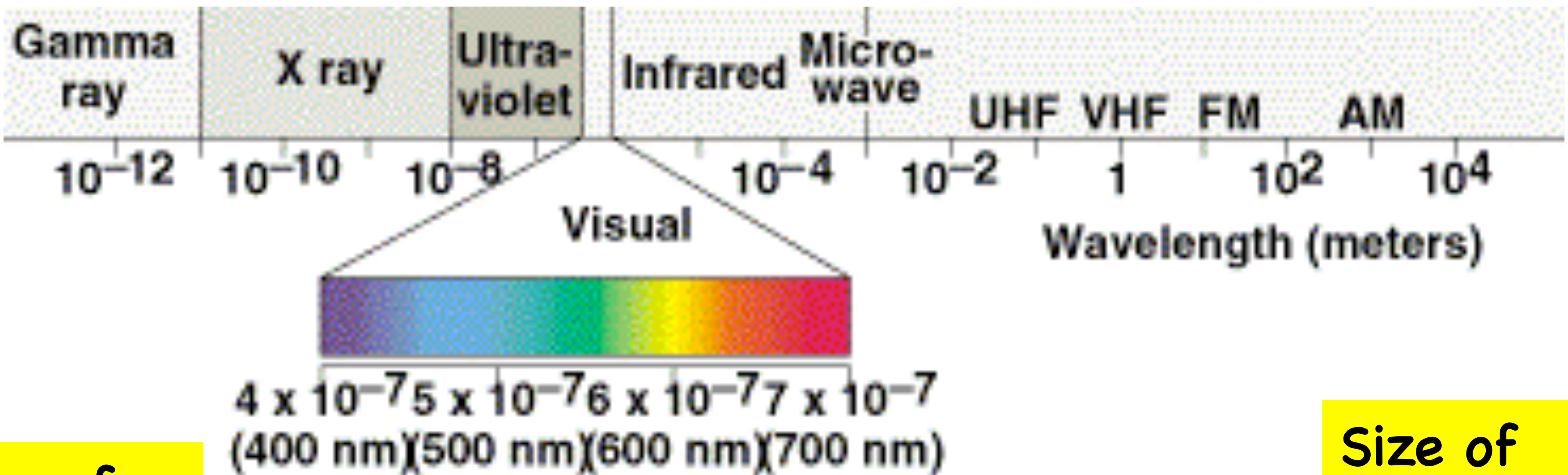


- Short wavelengths are Purple or Blue
- Long wavelengths are Red

Wavelength is measured in units of nm or "nanometers" (10^{-9} m)

Wavelength:

- We see with our eyes only a tiny fraction of the range of possible wavelengths

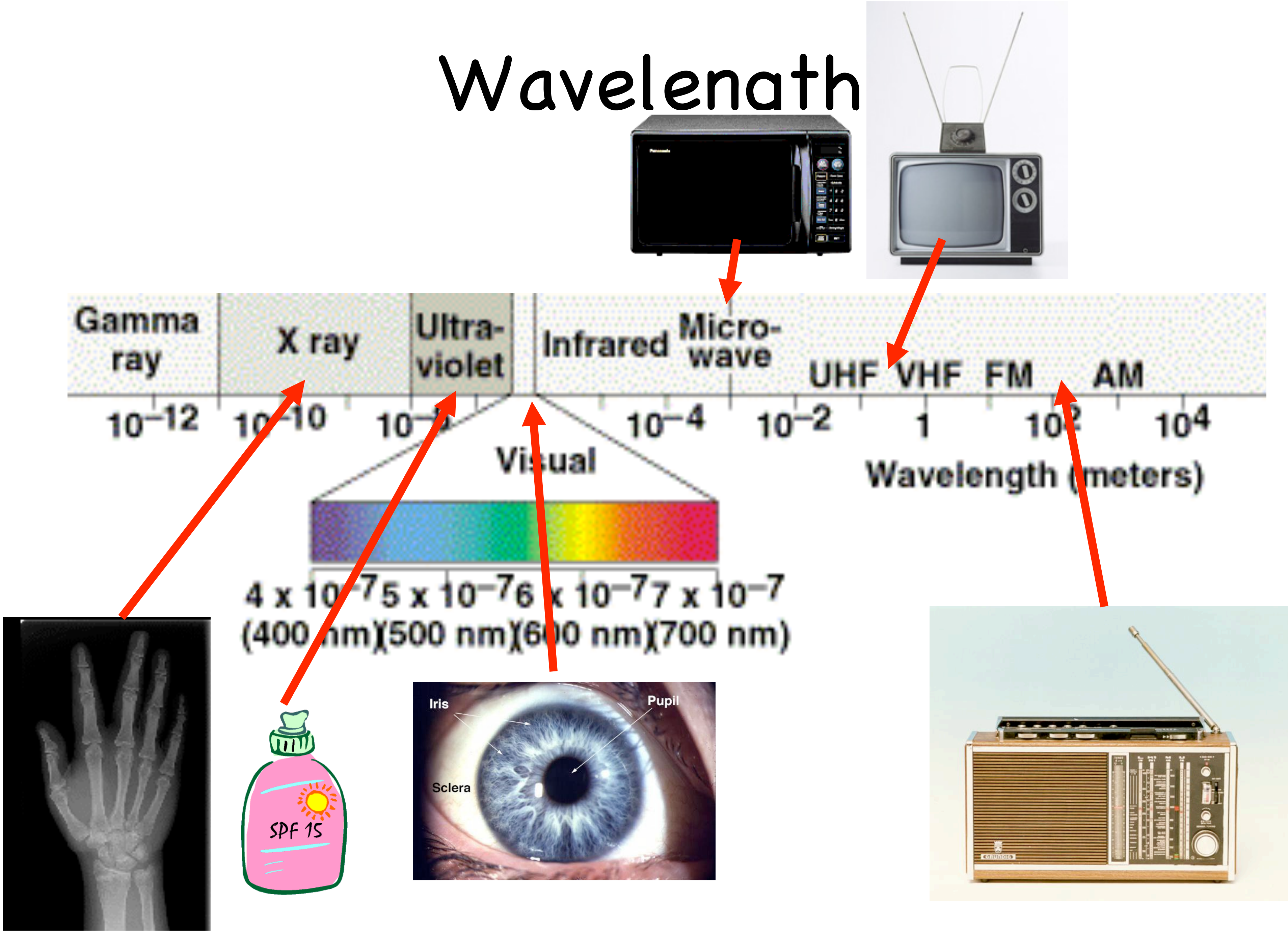


Size of atomic nucleus!

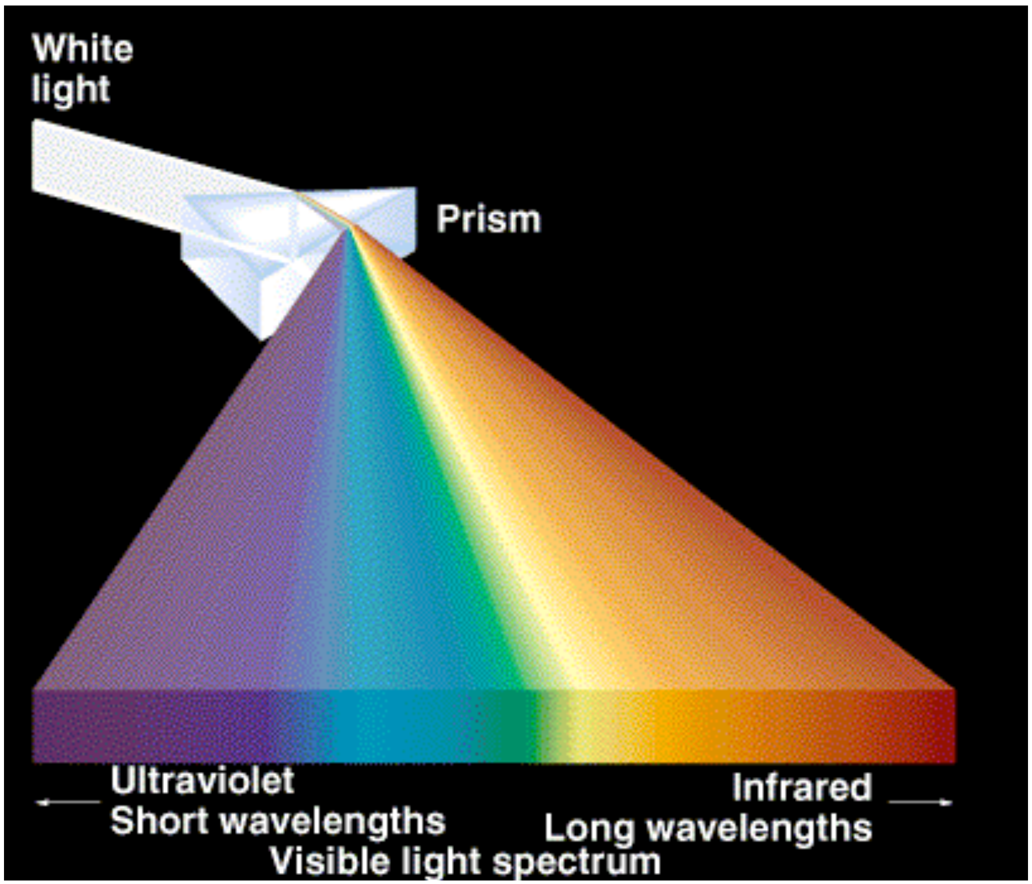
Size of Mt. Everest!

Note: each mark represents a *factor of ten* increase.

Wavelength


Gamma ray
X ray
Ultra-violet
Infrared
Micro-wave
UHF VHF FM AM
10^{-12} 10^{-10} 10^{-8} 10^{-4} 10^{-2} 1 10^{2} 10^{4}
Visual
Wavelength (meters)
4×10^{-7} 5×10^{-7} 6×10^{-7} 7×10^{-7}
(400 nm) (500 nm) (600 nm) (700 nm)
Iris
Pupil
Sclera
SPF 15

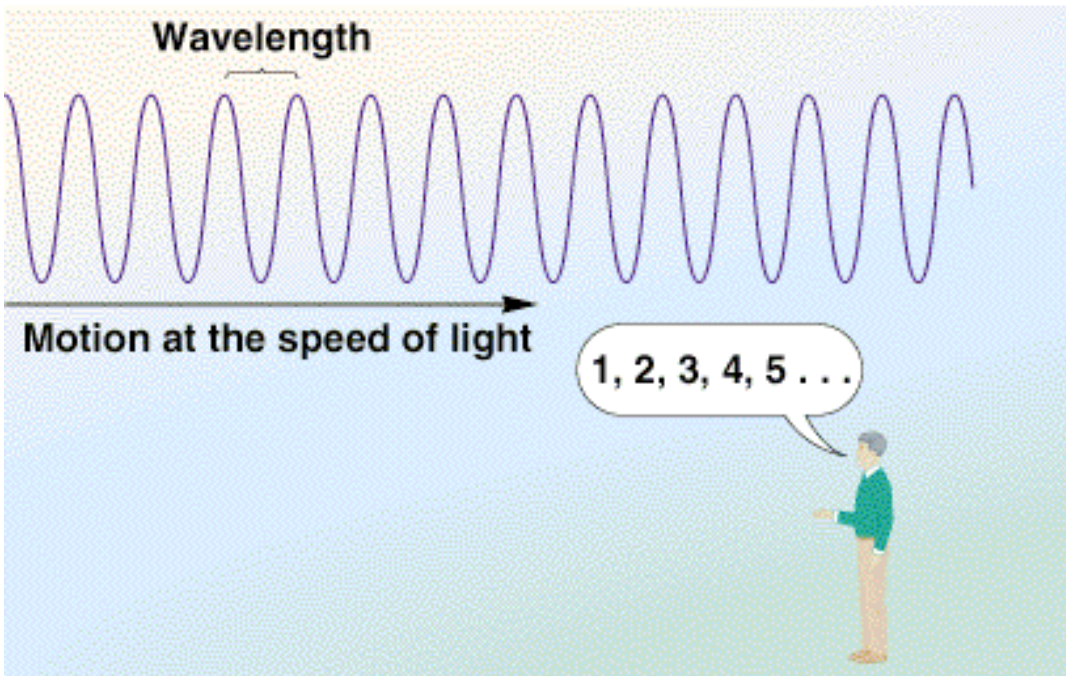
Wavelength:



- Natural light is comprised of many wavelengths of light
- We can distinguish the different wavelengths using a prism which creates a "spectrum".

B. Frequency =

the number of peaks (or troughs) that go by each second



- Frequency is measured in "Hertz", which has units of 1/second.
- One peak in one second is 1 Hertz, Two peaks in one second is 2 Hertz, and so on…

f is the symbol for frequency

C. Speed

- The speed of light is constant = 3×10^5 km/s
- The speed of light is related to its wavelength and frequency:

$$\text{speed} = c = \frac{\text{distance between peaks}}{\text{time between peaks}}$$

OR

$$c = \frac{\lambda}{(1/f)} = \lambda f$$

If you know the frequency, you can calculate the wavelength, or vice versa

Match the items from each column:

X-ray	500 nm	3×10^{8} Hz
Optical	1 m	6×10^{14} Hz
Radio	10 nm	3×10^{16} Hz

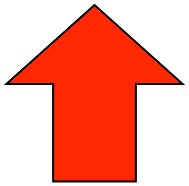
D. Energy

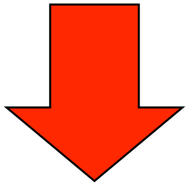
- The energy of a photon is determined by this formula:

$$E_{photon} = h \times f = \frac{hc}{\lambda}$$

h = 6.626 x 10^{-34} joule x s = Planck's constant

Energy is greater when.....

FREQUENCY 

WAVELENGTH 

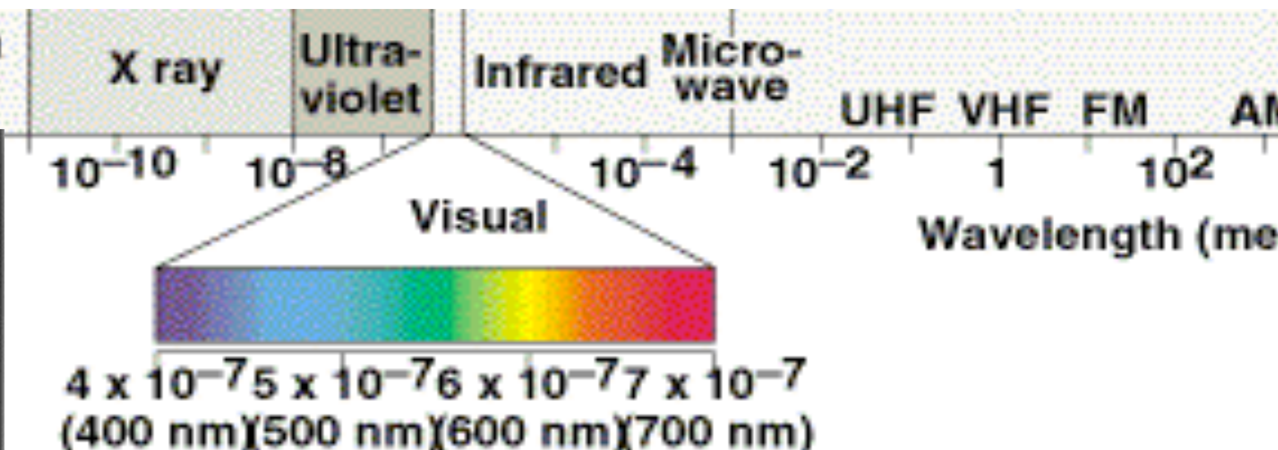
$$E_{photon} = h \times f = \frac{hc}{\lambda}$$

BLUE

- Short wavelength
- High frequency
- HIGH ENERGY

RED

- Long wavelength
- Low frequency
- LOW ENERGY

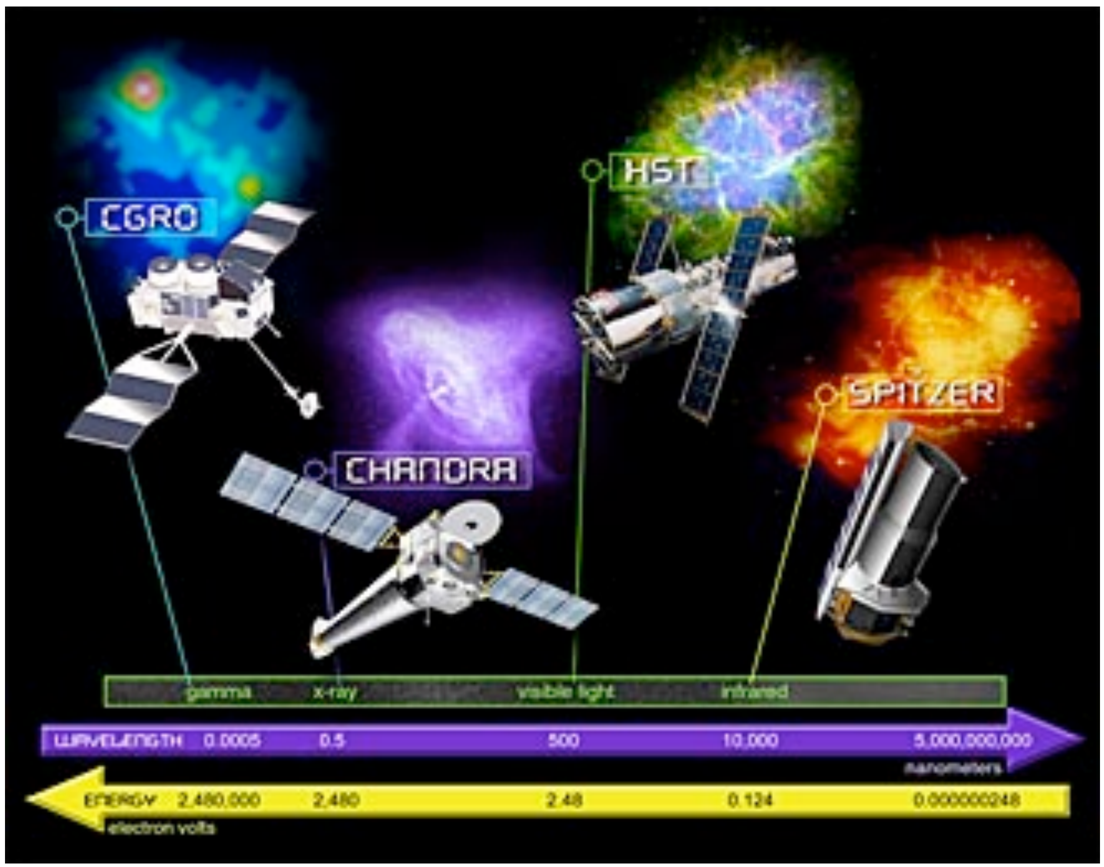


Dangerous - burns!

Mostly Harmless.

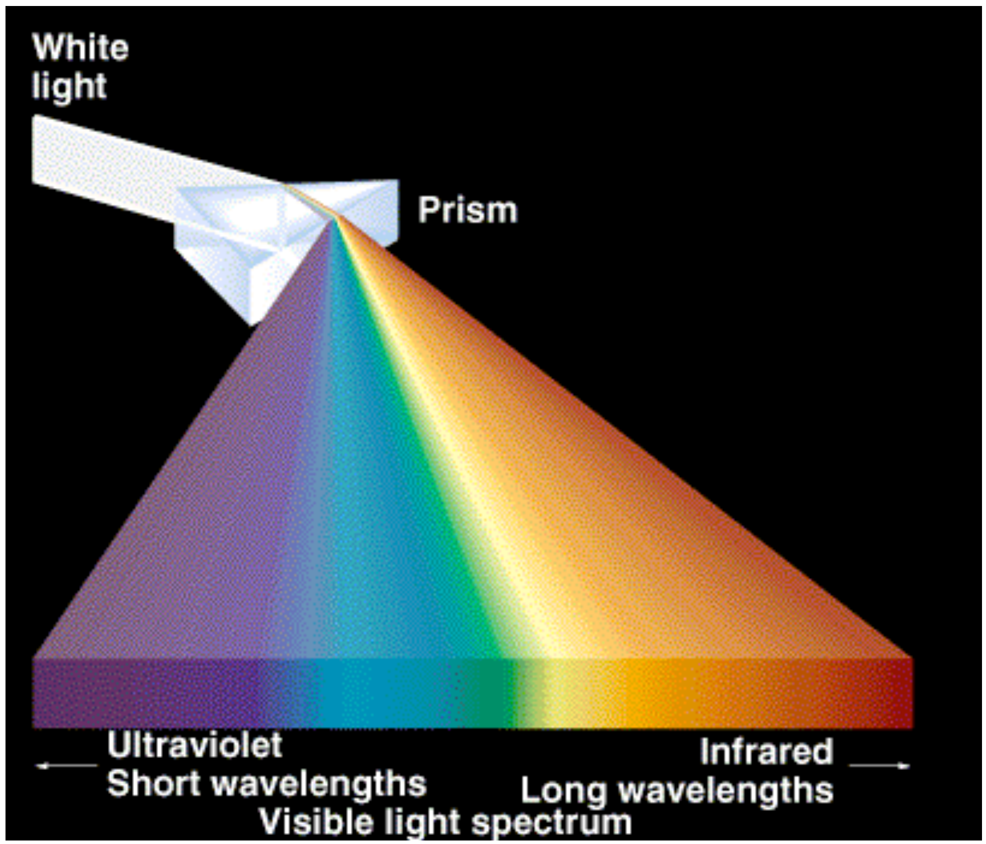
IV. Why are spectra interesting?

- Spectra give us the information we need to learn about our Universe's size, history, composition, movement, etc...



Without spectra we wouldn't know:

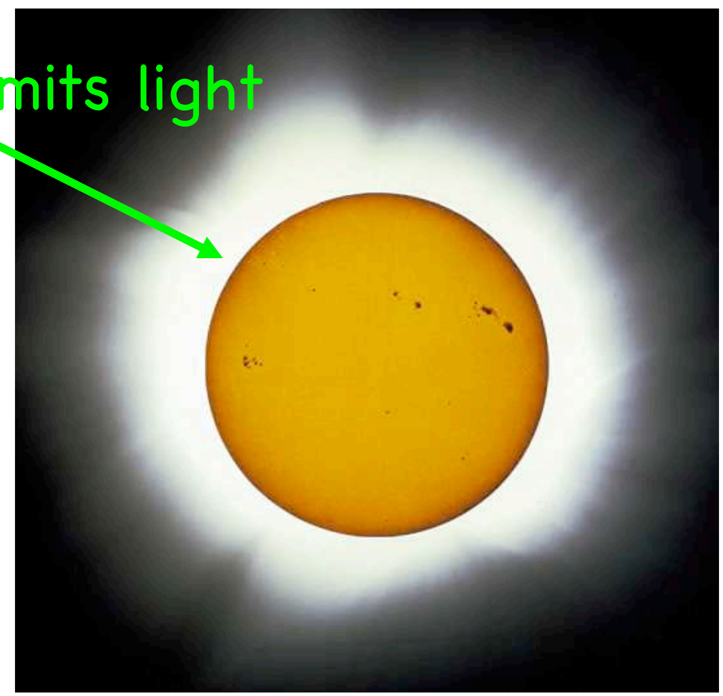
1) that the Universe is expanding from the Big Bang
2) about the existence of planets around other stars
3) the chemical composition of any star or galaxy
4) how much stars weigh



V. Thermal radiation spectrum:

All matter in the universe emits light due to the motion of atoms on the microscopic scale

Hot, so it emits light



Rules of thermal radiation:

a) If it's hotter, its BLUER.

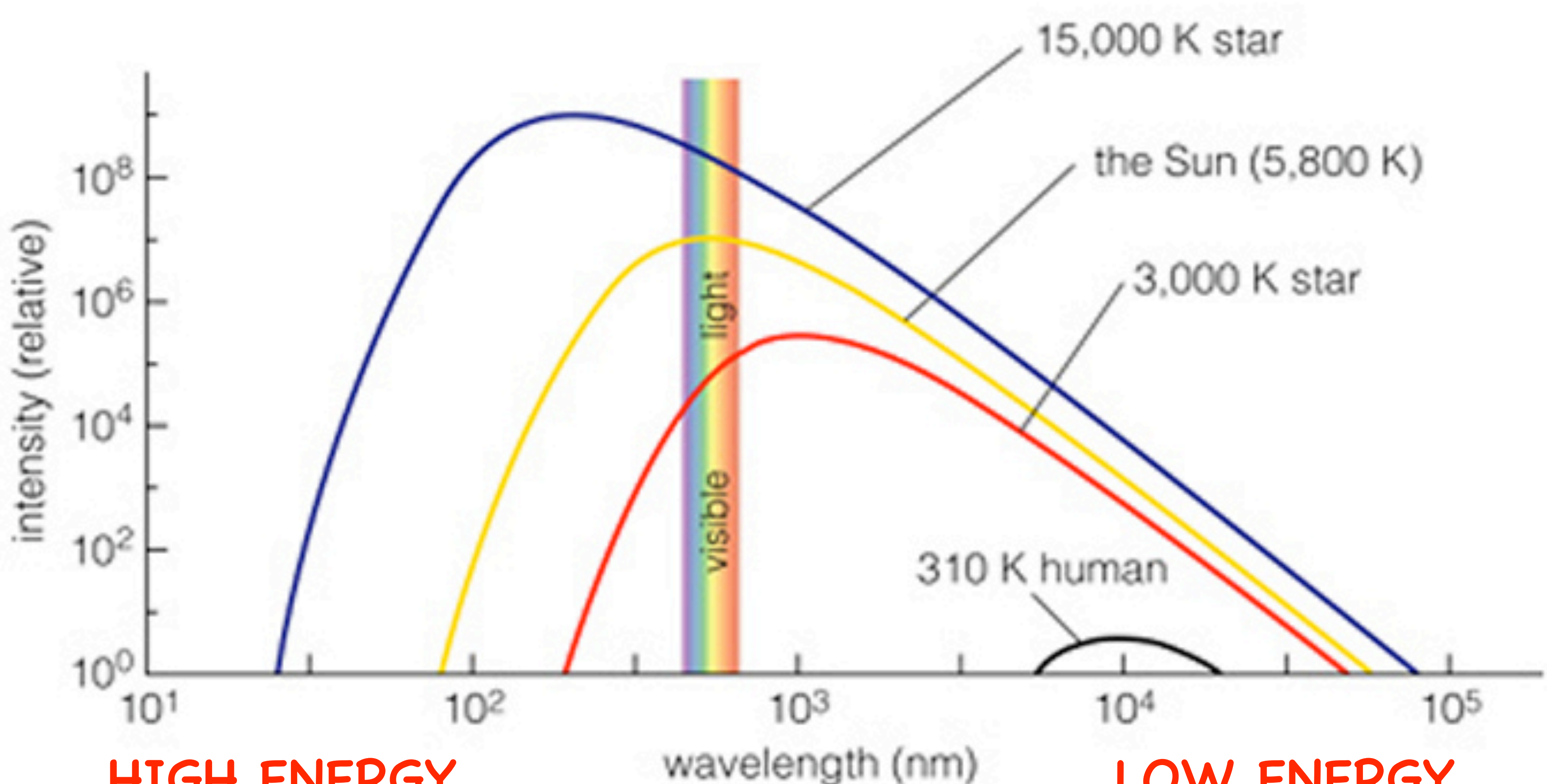
- More energy per particle = More energy per *photon* = bluer.
- Intensity peaks at: $$\lambda_{max} = \frac{0.0029m}{T(Kelvin)}$$

b) If its hotter, there's MORE light emitted per square meter at the surface at *every* wavelength

- Higher flux (power per square meter): $F=\sigma T^4$.
- $\sigma=5.67\times10^{-8}$ watts m^{-2} K^{-4}

Thermal radiation distribution:

- If its hotter, its BLUER.
- If its hotter, there's MORE of it →



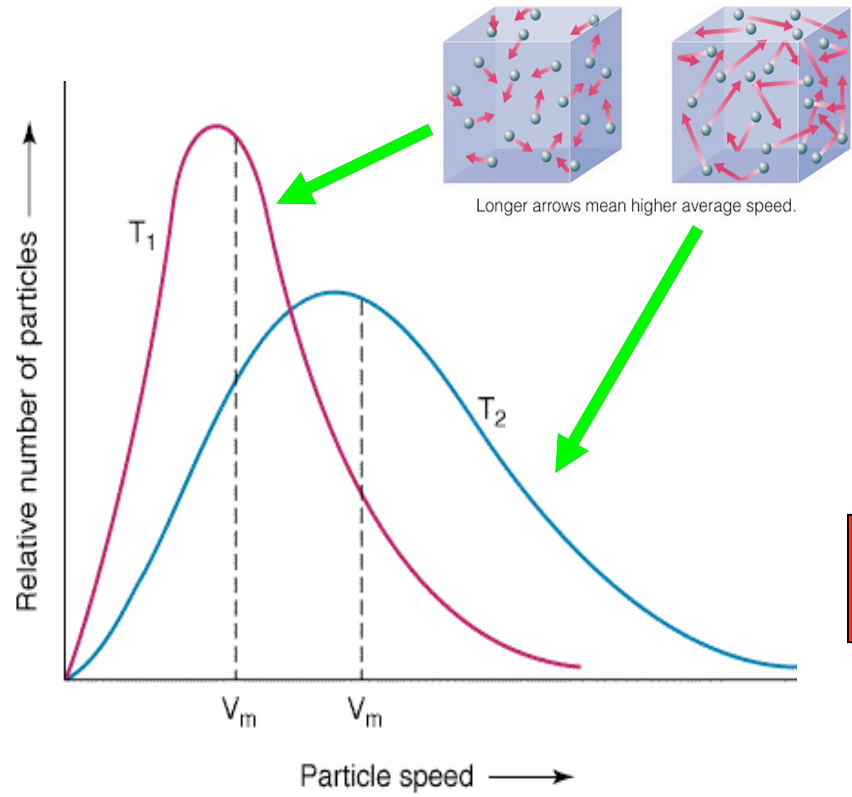
HIGH ENERGY

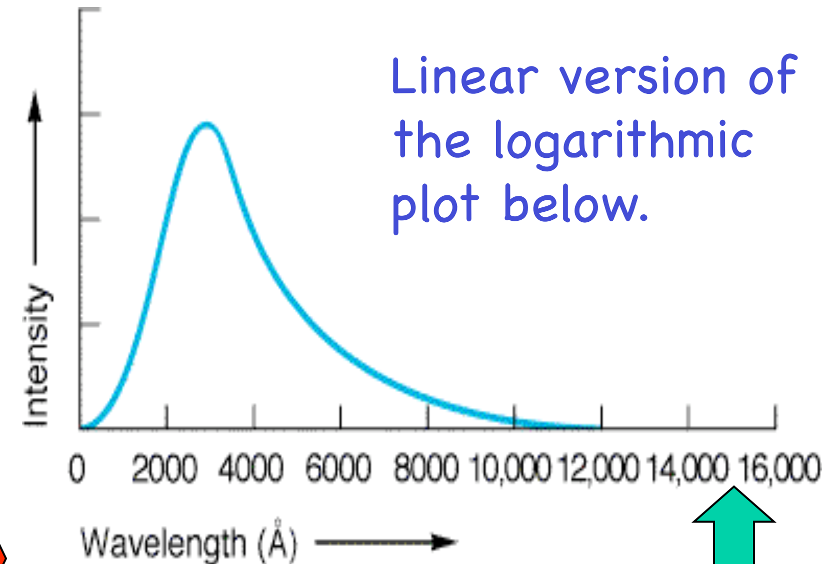
LOW ENERGY

(Log-log plot)

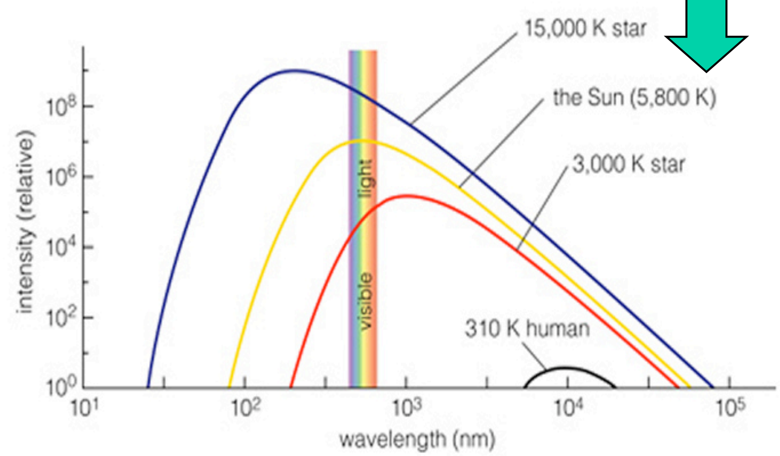
Thermal radiation distribution:

- This spectral shape is closely related to the distribution of particle velocities.





Linear version of the logarithmic plot below.



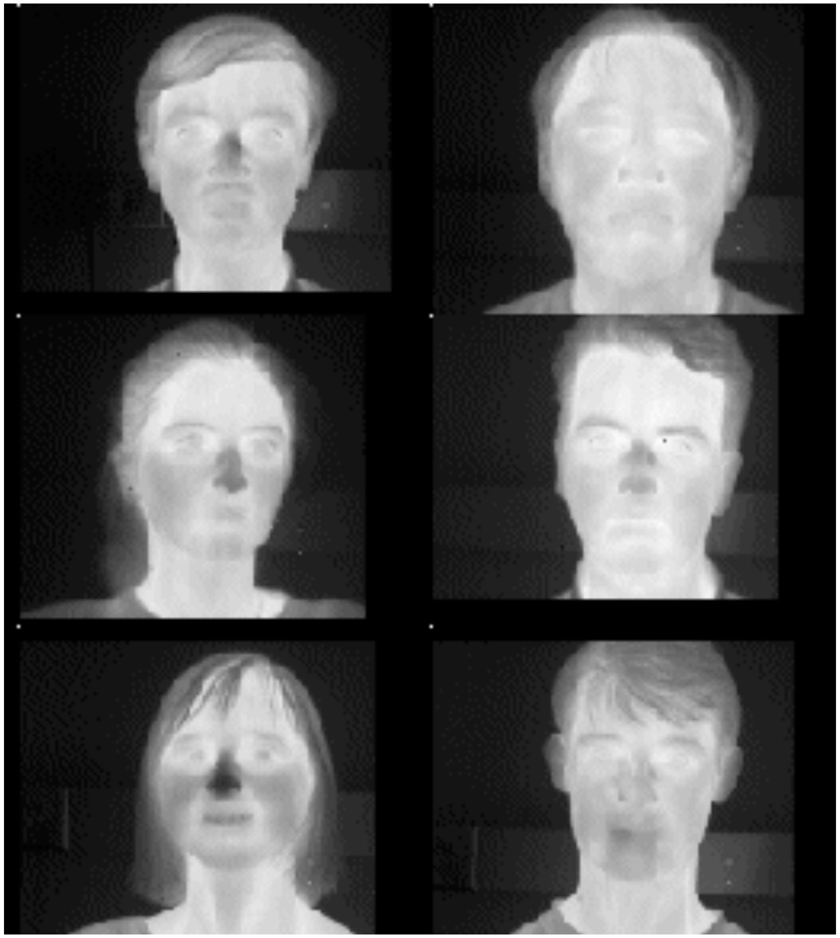
P.S. Note that the plots on the right have energy decreasing to the right, whereas the left hand plot is opposite

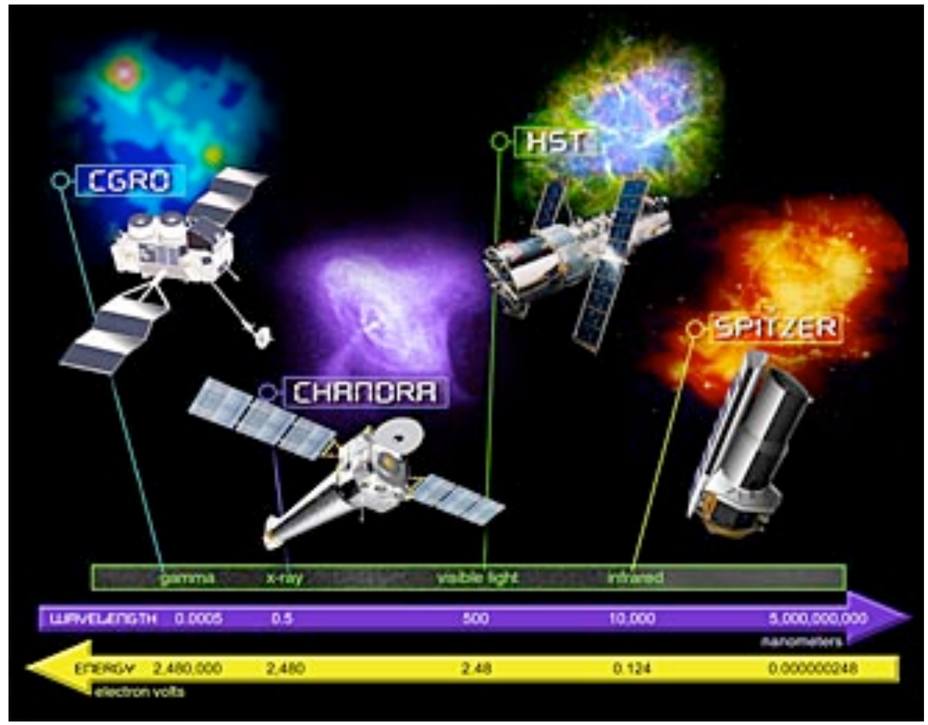
If humans have thermal radiation why don't we glow in the dark?

a) People do not emit any kind of light.
b) People only emit light that is invisible to our eyes.
c) People are too small to emit enough light for us to see.
d) People do not contain enough radioactive material.
e) People are not opaque enough to emit light.

Thermal radiation from people!

Humans emit light in the infrared.



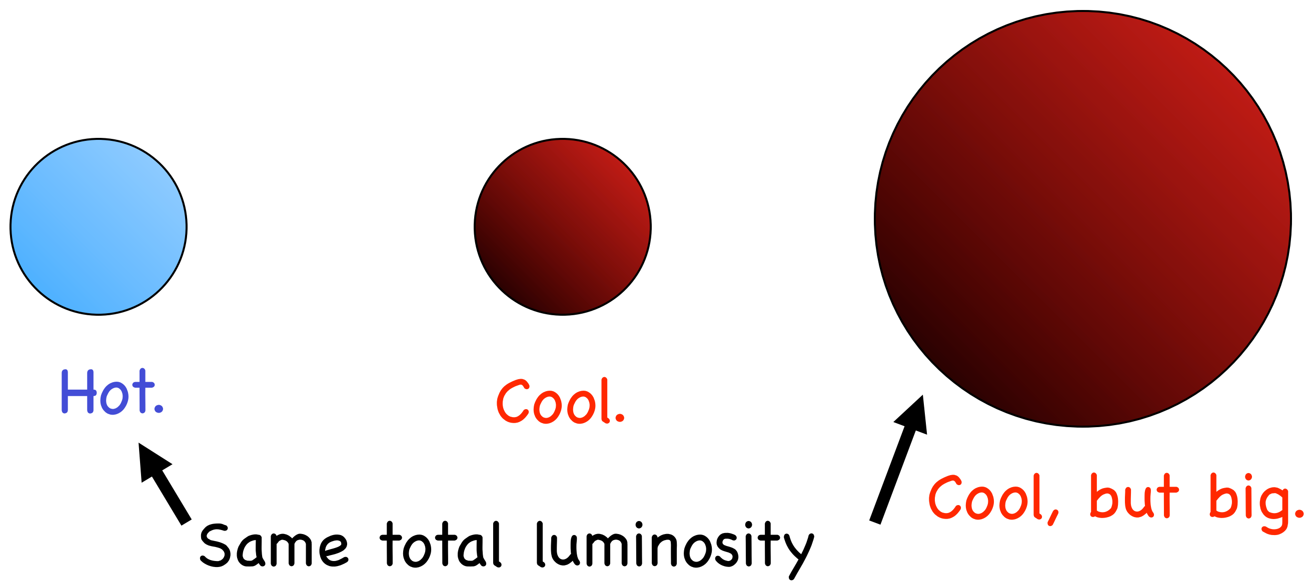


PS. You can only see other people when there is light to *reflect* off of them. We glow only in the infrared!

More rules of thermal radiation:

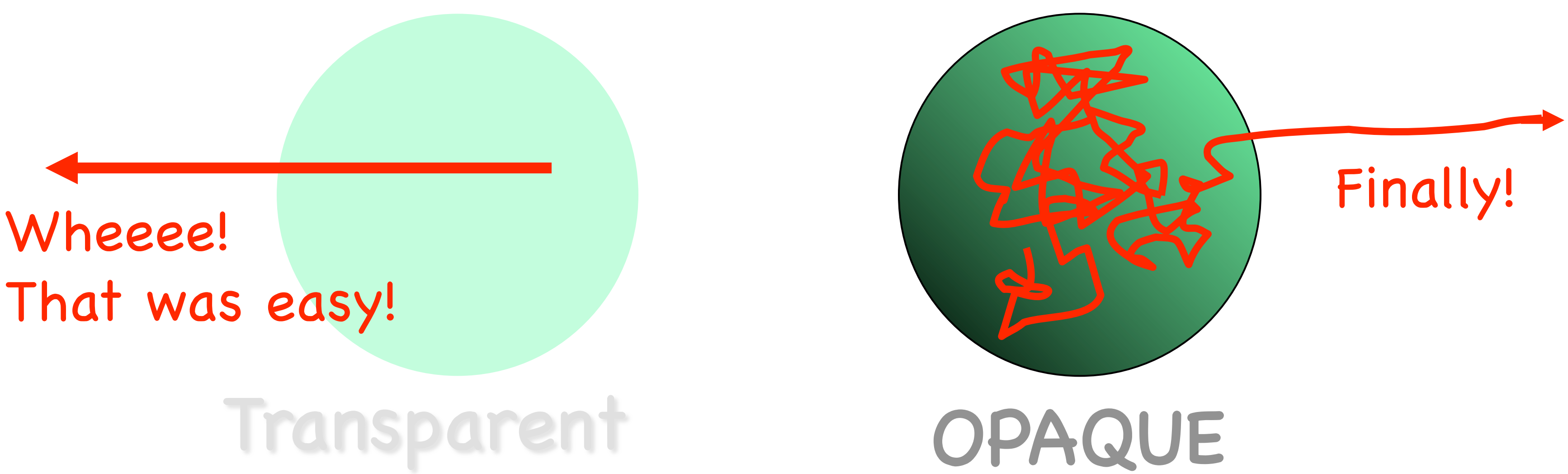
c) Cooler objects can sometimes emit more light overall (i.e. larger power released).

- Decreasing temperature means less light emitted per unit area. An object can compensate by being **BIGGER**.



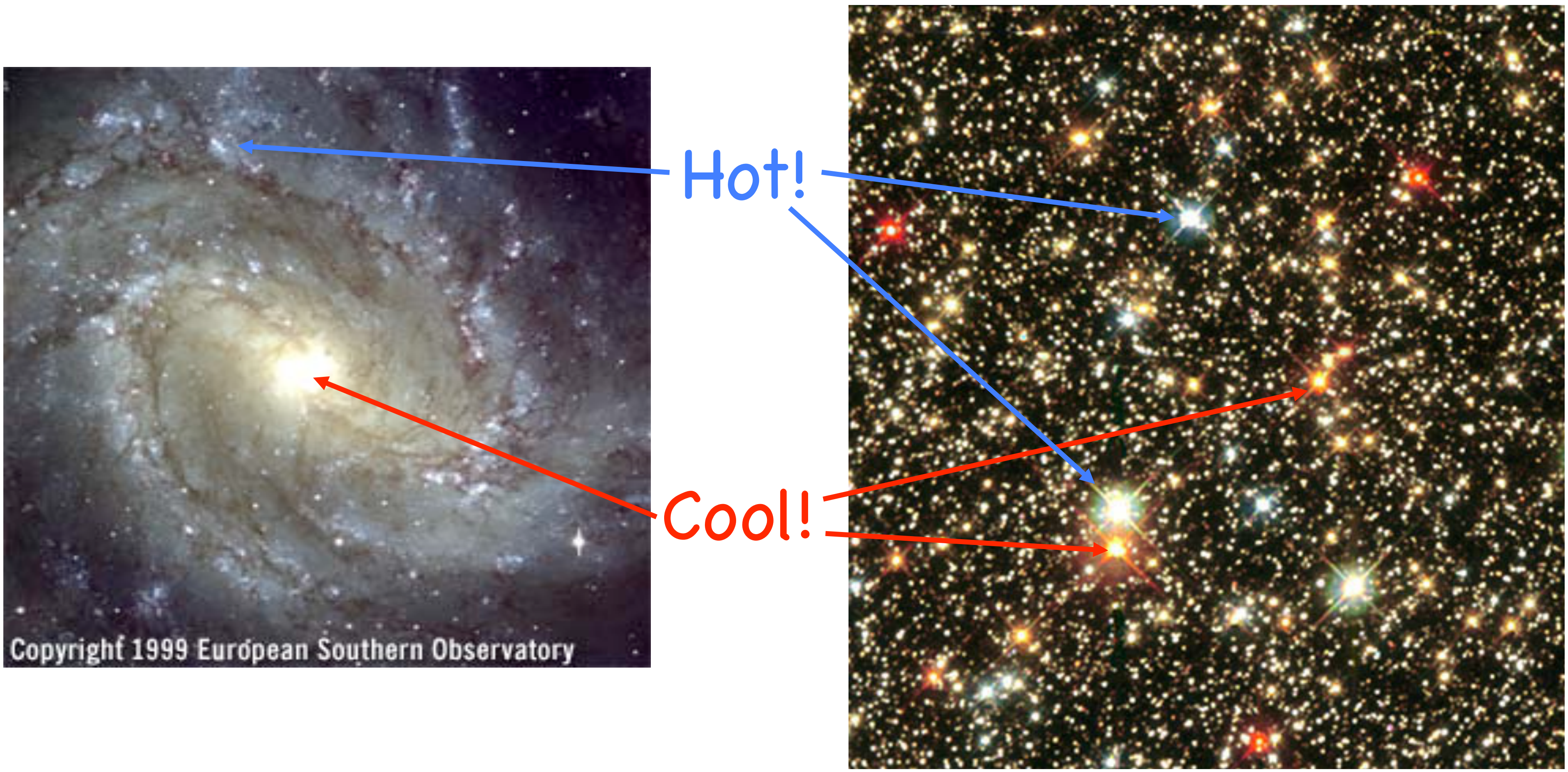
d) A thermal spectrum is emitted only if the object is OPAQUE.

- Thermal radiation is created by multiple interactions between photons and matter.
- If photons go sailing through the matter (i.e. transparent), no thermal emission.



Why thermal radiation matters for astronomy

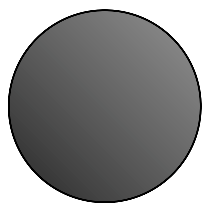
- You can tell a galaxy's or star's or temperature just by measuring its color!!!!

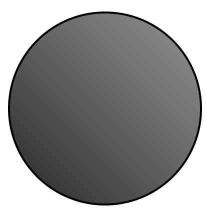


Which star will look bluest & peak at the shortest wavelength?

A.  $T = 5{,}000$ K $R = 1\ R_\odot$

B.  $T = 20{,}000$ K $R = 1\ R_\odot$

C.  $T = 5{,}000$ K $R = 10\ R_\odot$

D.  $T = 10{,}000$ K $R = 10\ R_\odot$

Recap:

- Light behaves like a particle & a wave
- The speed of light is constant
- The wavelength times frequency equals the speed: $c = \lambda f$

  λ = wavelength, f = frequency

  c = 3.00 x 10^8 m/s = speed of light
- The energy of light increases with frequency:

  $E = h \times f$ = photon energy
- Thermal (blackbody) radiation becomes bluer & brighter (per unit area) as the temperature increases