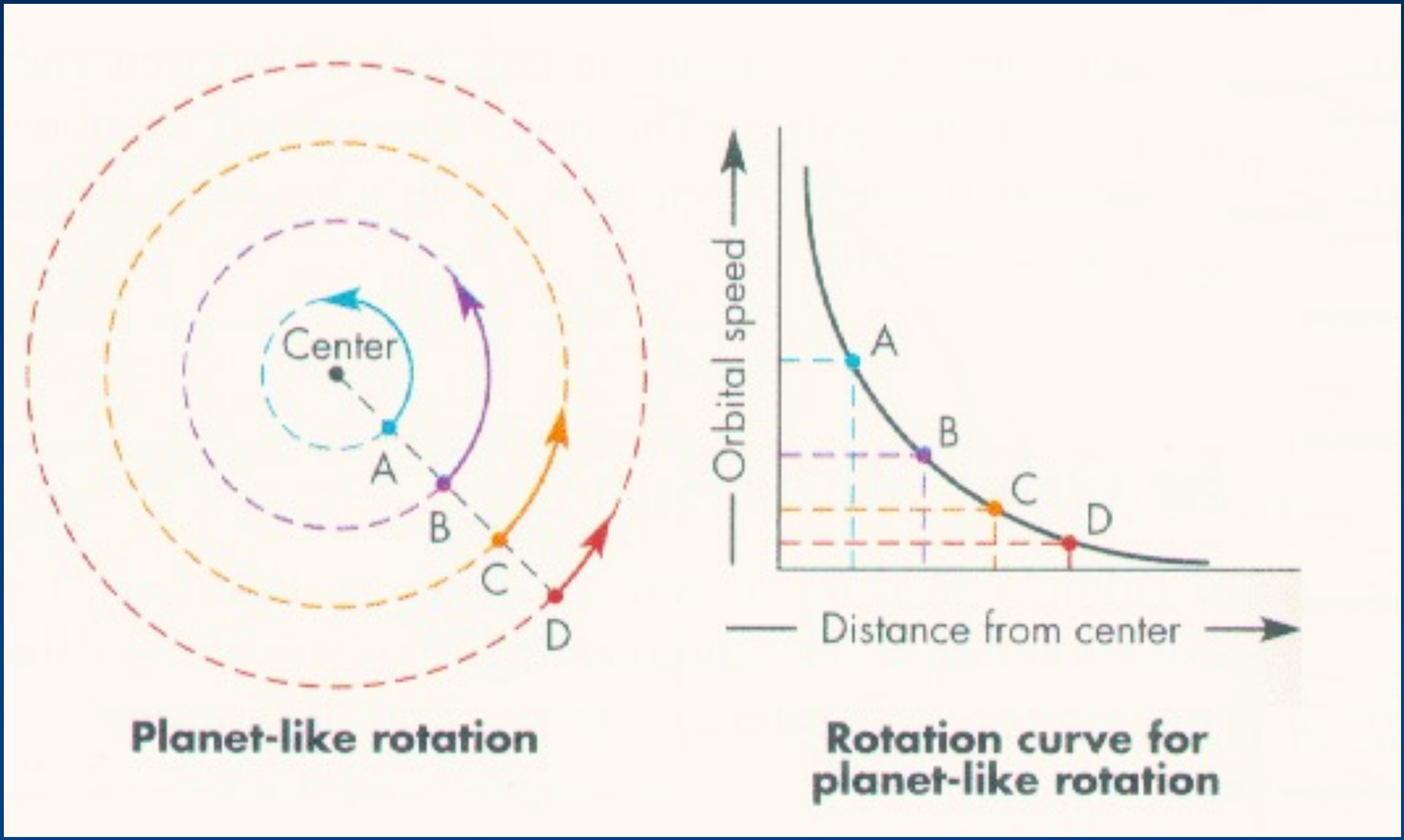
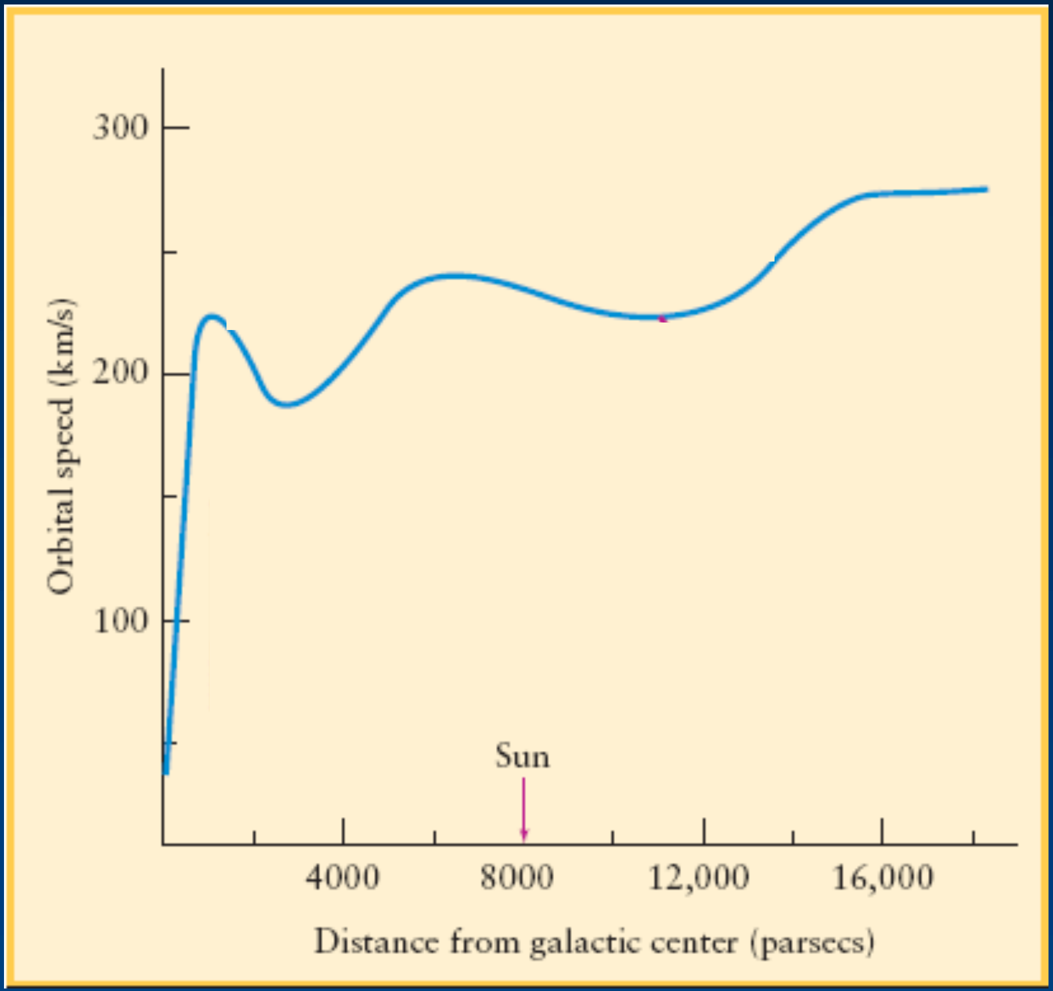
Keplerian rotation curves

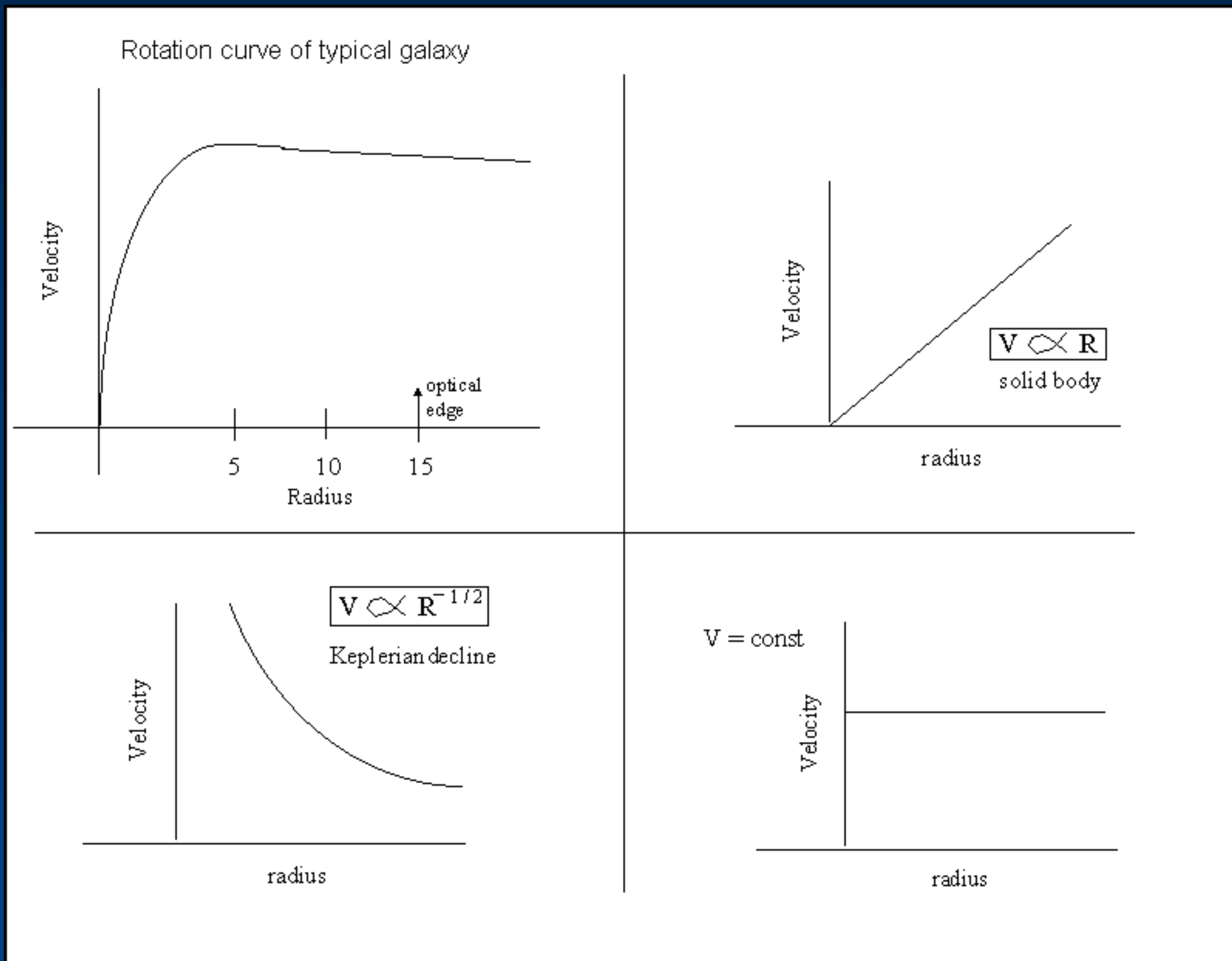
- When the system is dominated by the central mass: $v \propto r^{-1/2}$



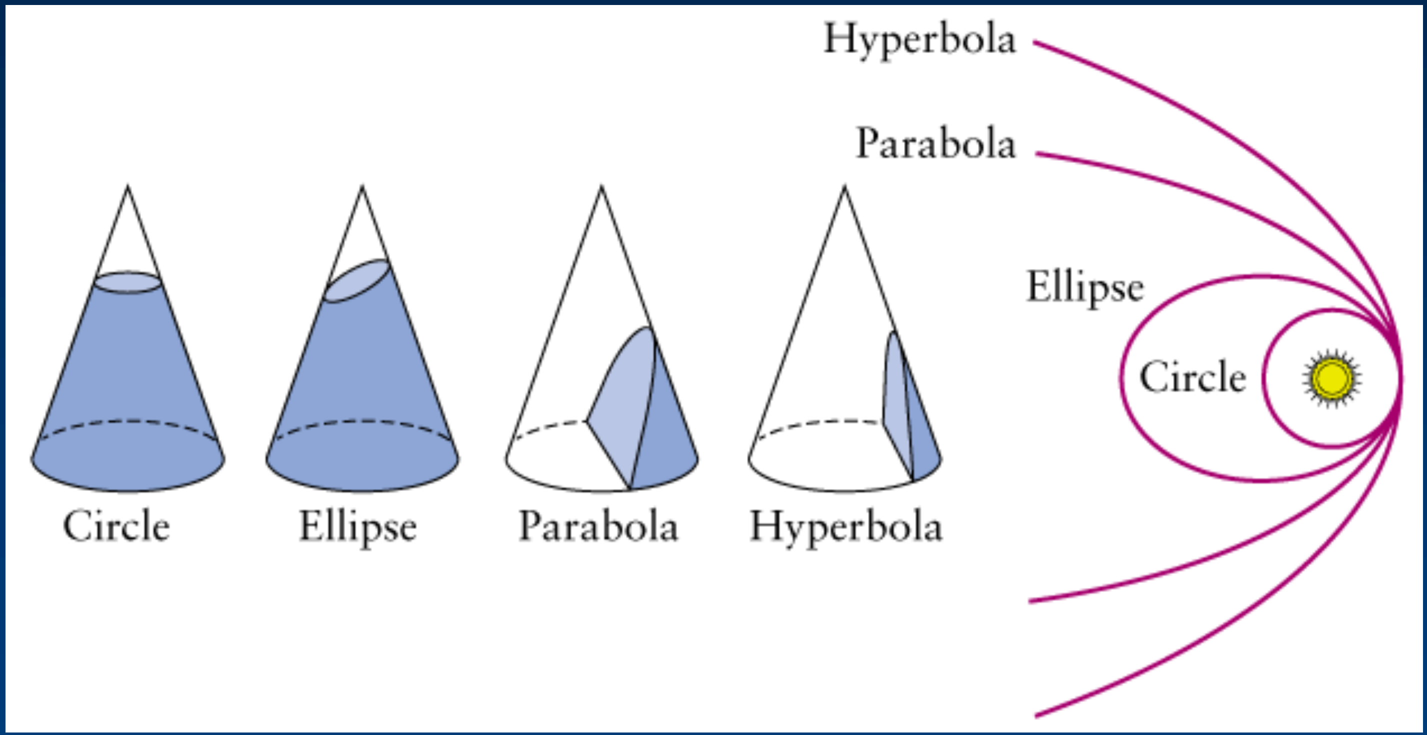
Milky Way also rotates. But rotation curve not Keplerian, but nearly “flat”. Milky Way mass is not dominated by a central mass



Rotation Curves



What if injection velocity isn't the circular velocity?
In general, orbits are conic sections (Newton).

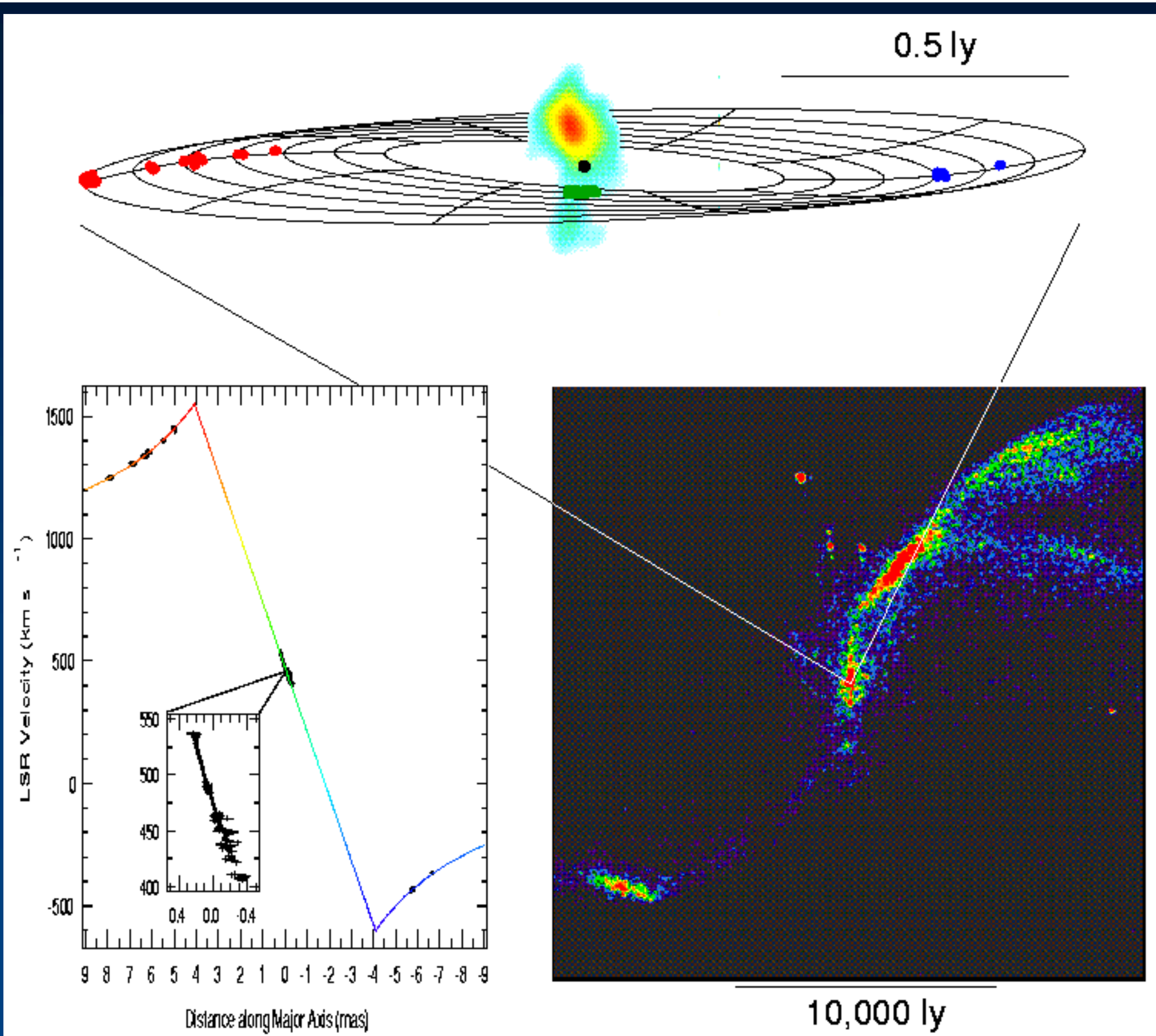


Ellipses and circles are *closed* orbits, hyperbolic and parabolic orbits are *open*. Objects on these orbits do not return – some comets do this!

General rules of orbits

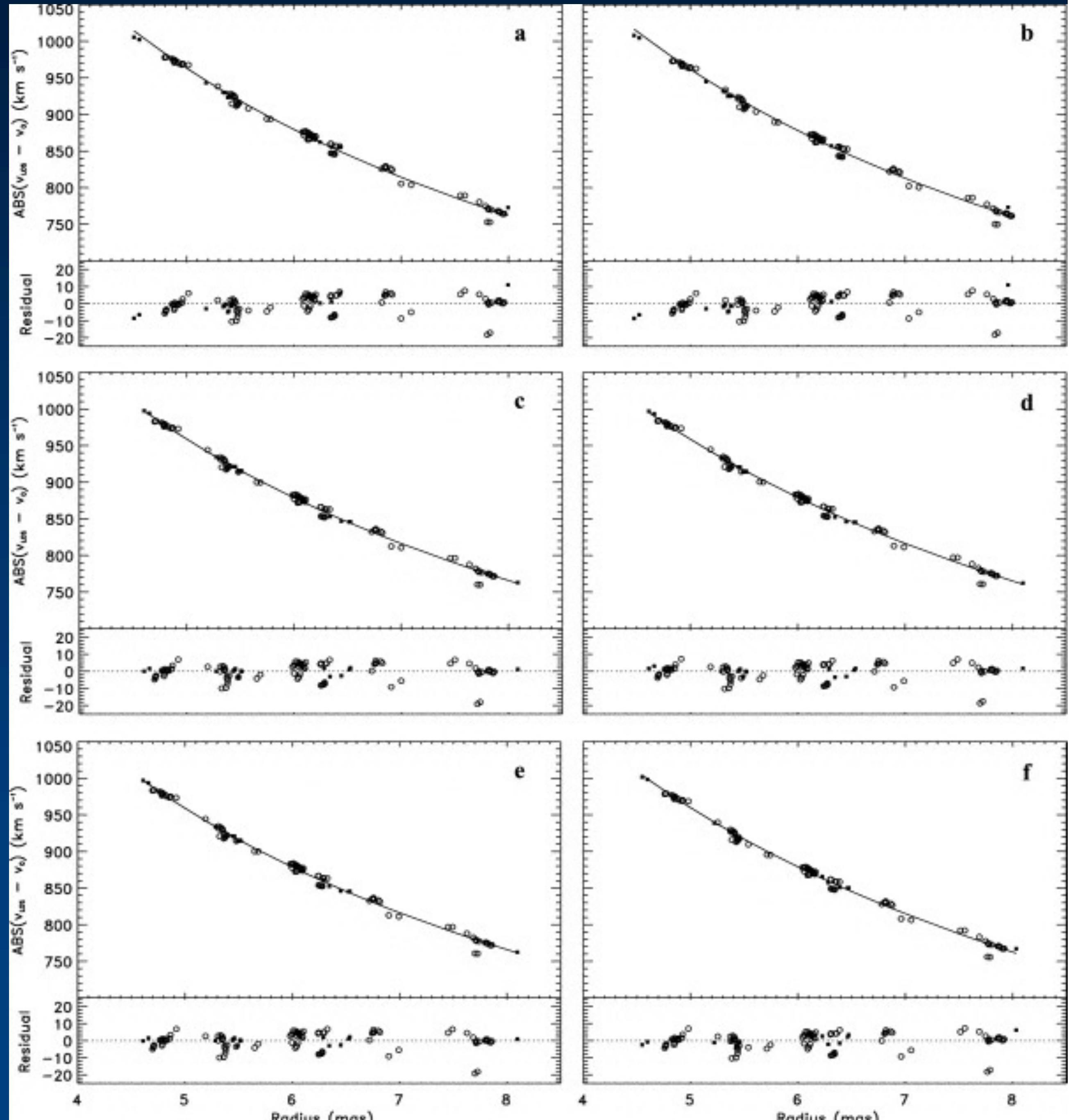
Orbit shape	System energy
Parabolic	Zero
Elliptical/circular	Negative
Hyperbolic	Positive

- Negative energy orbits are “bound”, positive energy orbits are “unbound”.
- What orbit is the most bound (minimum energy)?

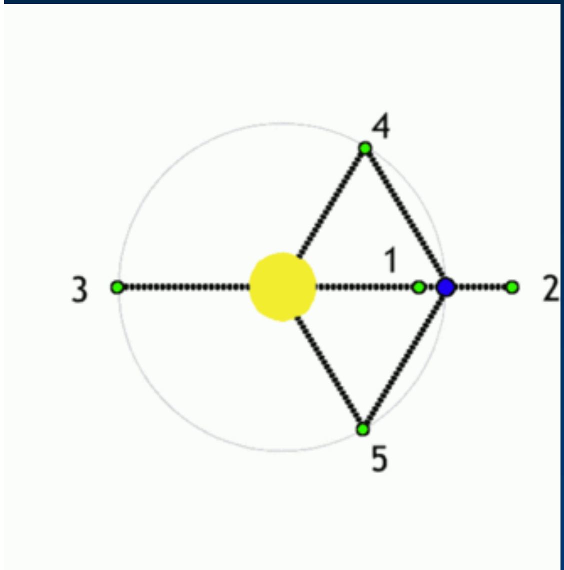


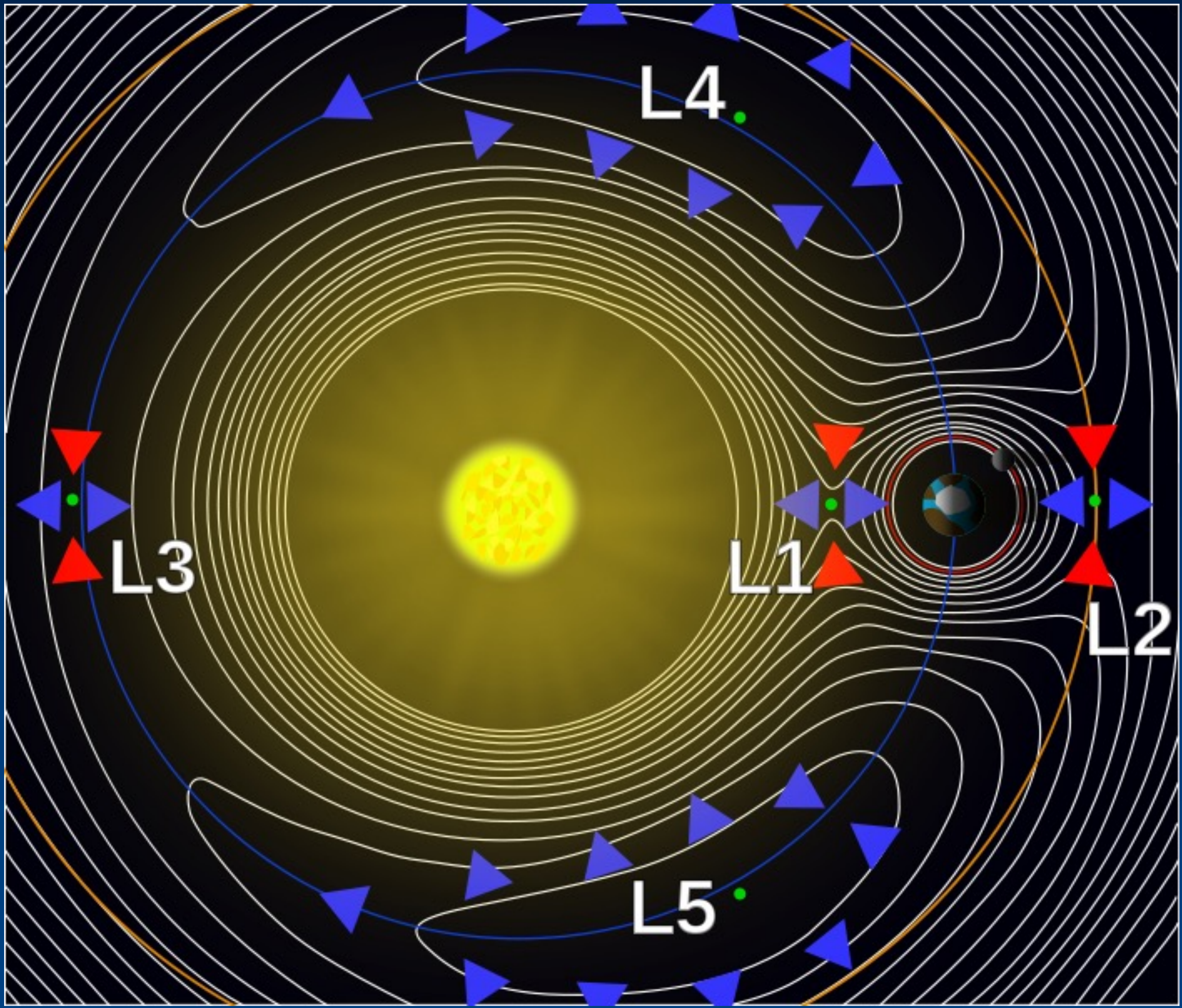
0.5 ly
LSR Velocity (km s⁻¹)
1500
1000
500
0
-500
550
500
450
400
0.4
0.0
-0.4
9 8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8 -9
Distance along Major Axis (mas)
10,000 ly

NGC4258 fits



Lagrange Points





The Nature of Light I:

Electromagnetic Waves
Spectra
Kirchoff's Laws
Temperature
Blackbody radiation

Electromagnetic Radiation

(How we get most of our information about the cosmos)

Examples of electromagnetic radiation:

- Light
- Infrared
- Ultraviolet
- Microwaves
- AM radio
- FM radio
- TV signals
- Cell phone signals
- X-rays

What is light?

- Light is *electromagnetic (EM) radiation*

- Light can be treated either as
  - waves
  - photons ("particles" of EM radiation)

- Both natures have to be considered to describe all essential properties of light
- We will start with wavelike properties

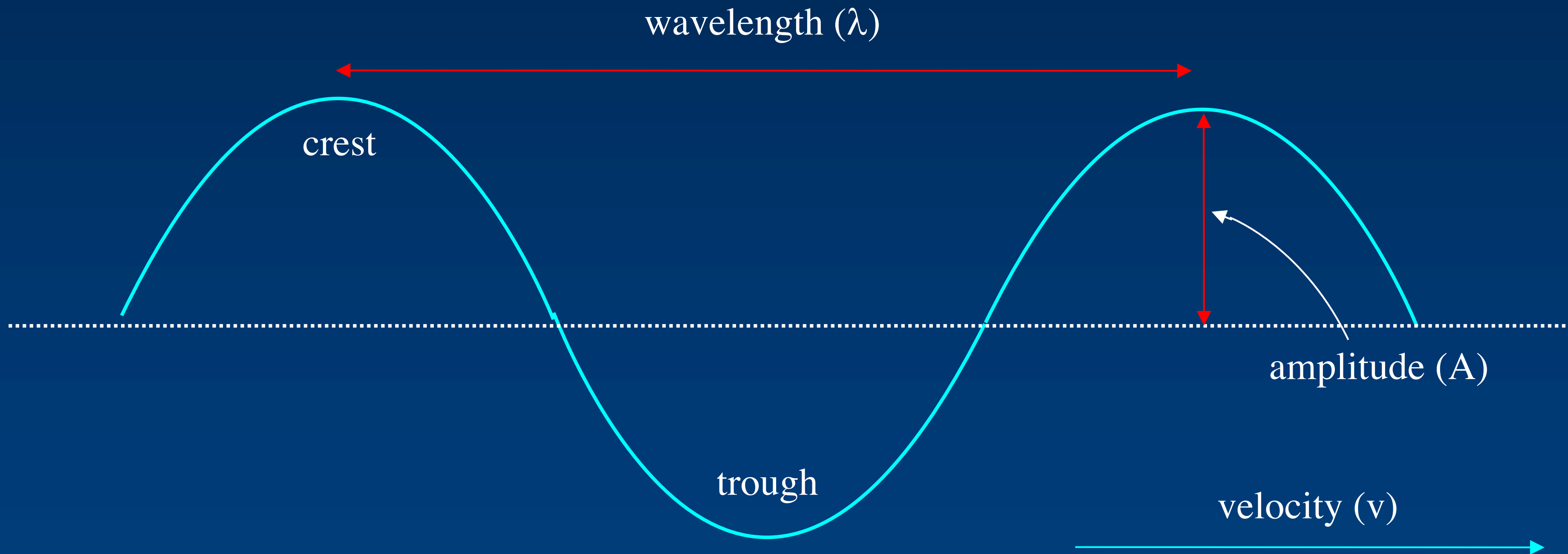
What is a wave?

- A wave is the transfer of energy from one point to another, without the transfer of material between the points

- A wave is manifested by a periodic change in the properties of a medium through which it travels

Radiation travels as waves.
Waves carry information and energy.

Properties of a wave



λ is a distance, so its units are m, cm, or mm, etc.

Period (T): time between crest (or trough) passages

Also, $v = \lambda \nu$

Frequency (ν): rate of passage of crests (or troughs), $\nu = \frac{1}{T}$
(units: Hertz or cycles/sec)

Demo: slinky waves

Radiation travels as Electromagnetic waves.

That is, waves of electric and magnetic fields traveling together.

Examples of objects with magnetic fields:

a magnet
the Earth
Clusters of galaxies

Examples of objects with electric fields:

Power lines, electric motors, …
Protons (+)
Electrons (-)

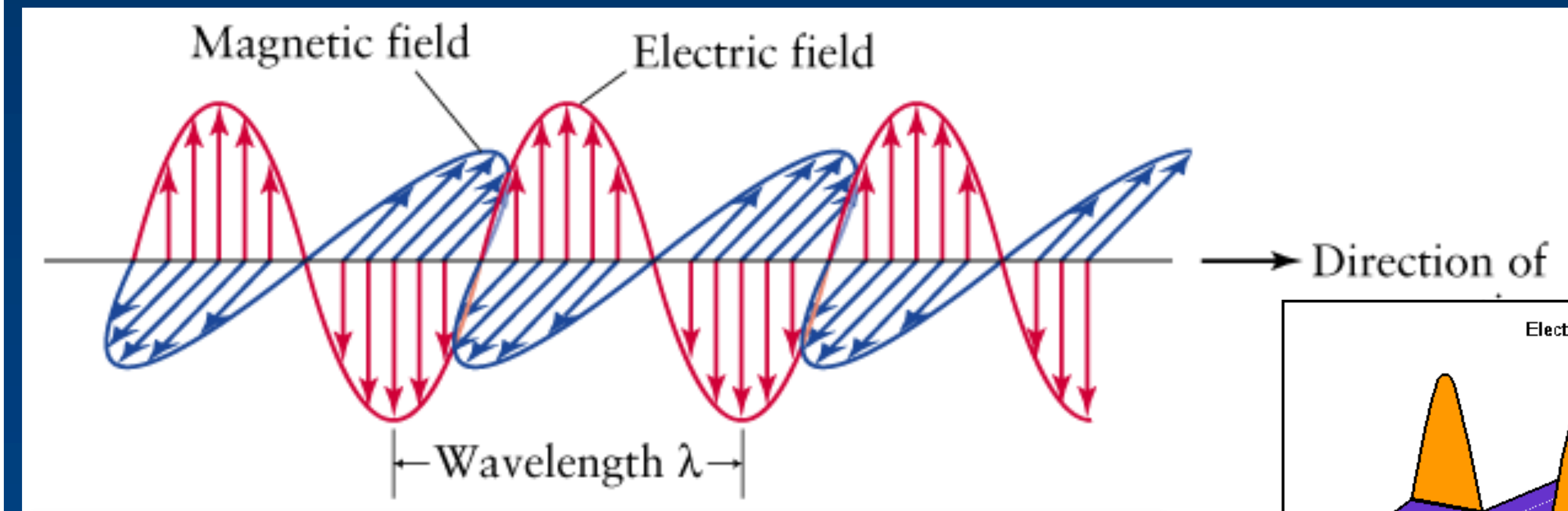
} "charged" particles that make up atoms.

Electromagnetic waves

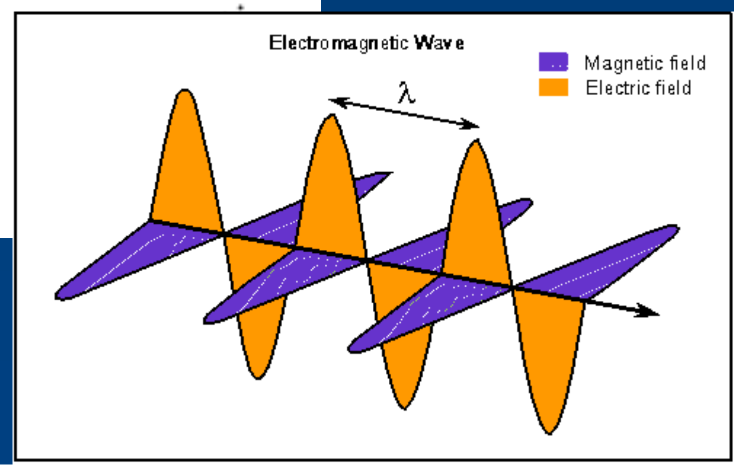
– EM waves: self propagating electric and magnetic fields (changes in strengths of E and M fields).

– Traveling (in vacuum) at the constant speed of light c, where $c = 3 \times 10^8$ m/s.

– $c = \nu\lambda$ and Energy $= h\nu$



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



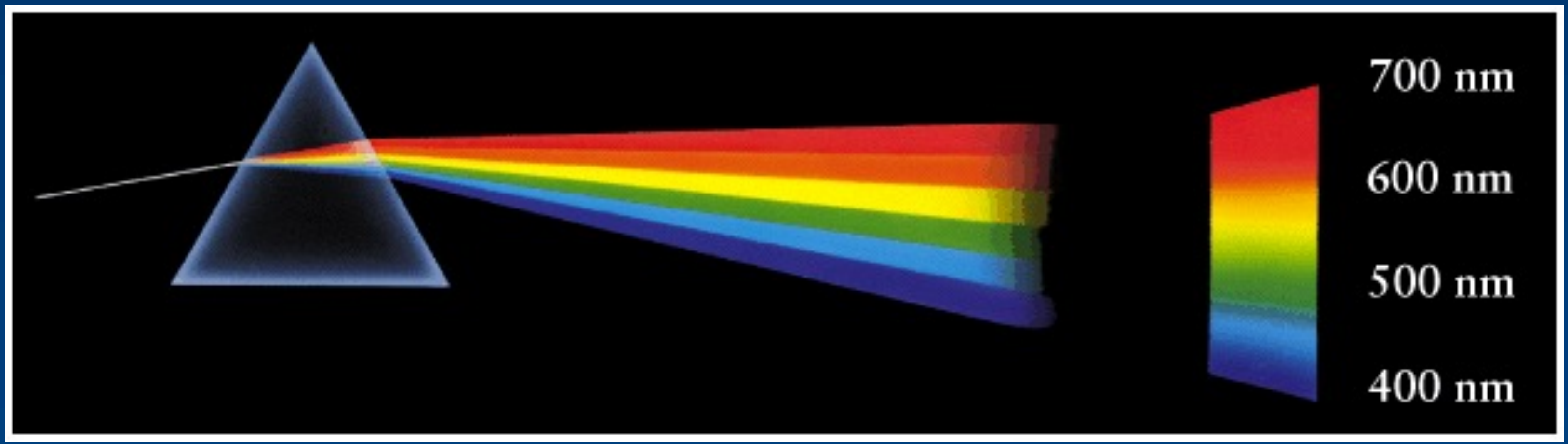
The human eye is sensitive to light with wavelength range:

$4{,}000\ \text{Å} < \lambda < 7{,}000\ \text{Å}$ where an Å is 10^{-10} m.

$= 400\ \text{nm} < \lambda < 700\ \text{nm}$ where 1 nm $=10^{-9}$ m.

[nm = nanometer,
Å = Ångström]

We see λ as color! From violet to red.



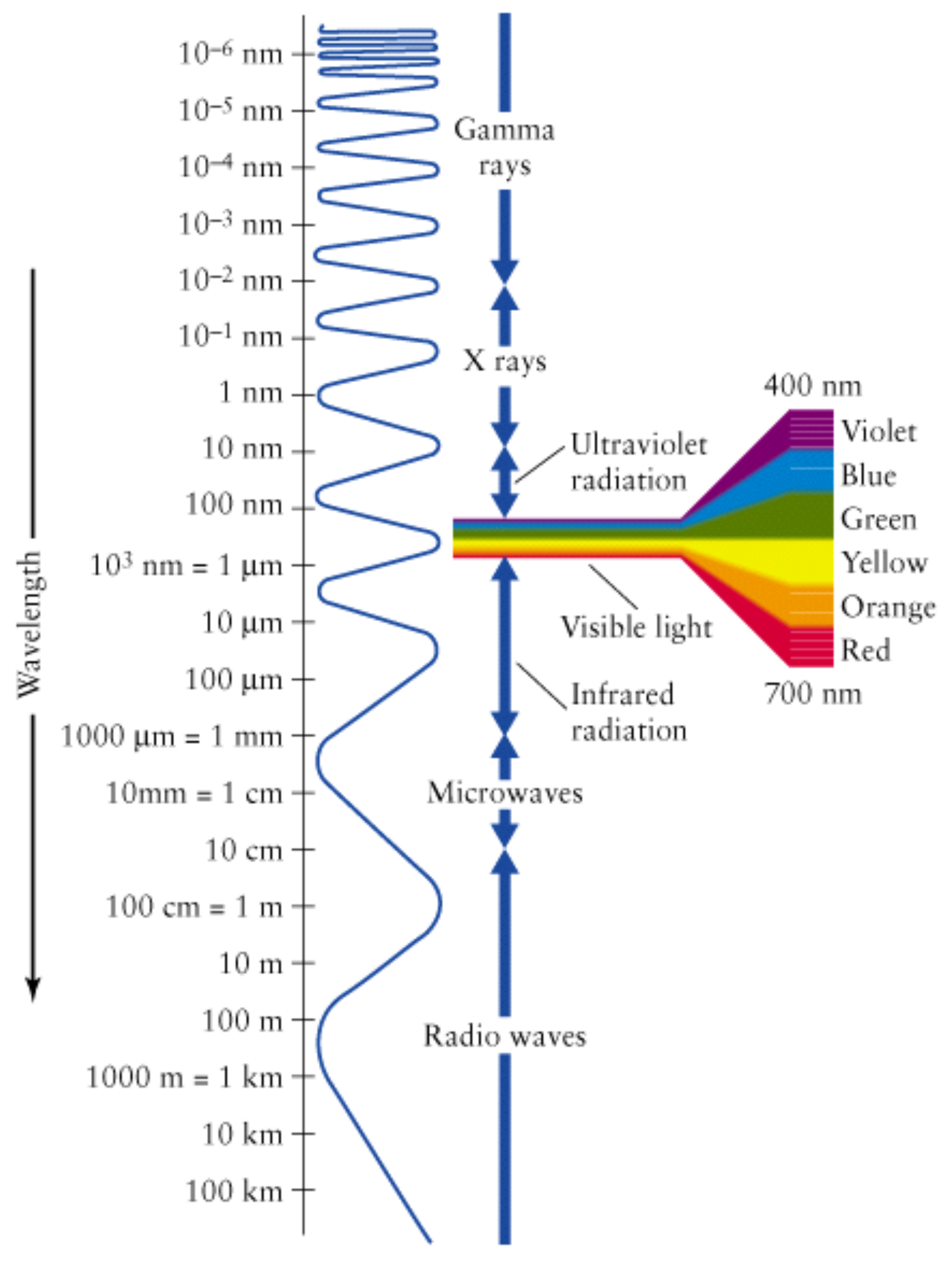
(This also demonstrates refraction: light bends when density of medium changes. Bending angle depends on wavelength.)

There's much more beyond the visible!

In order of increasing wavelength:

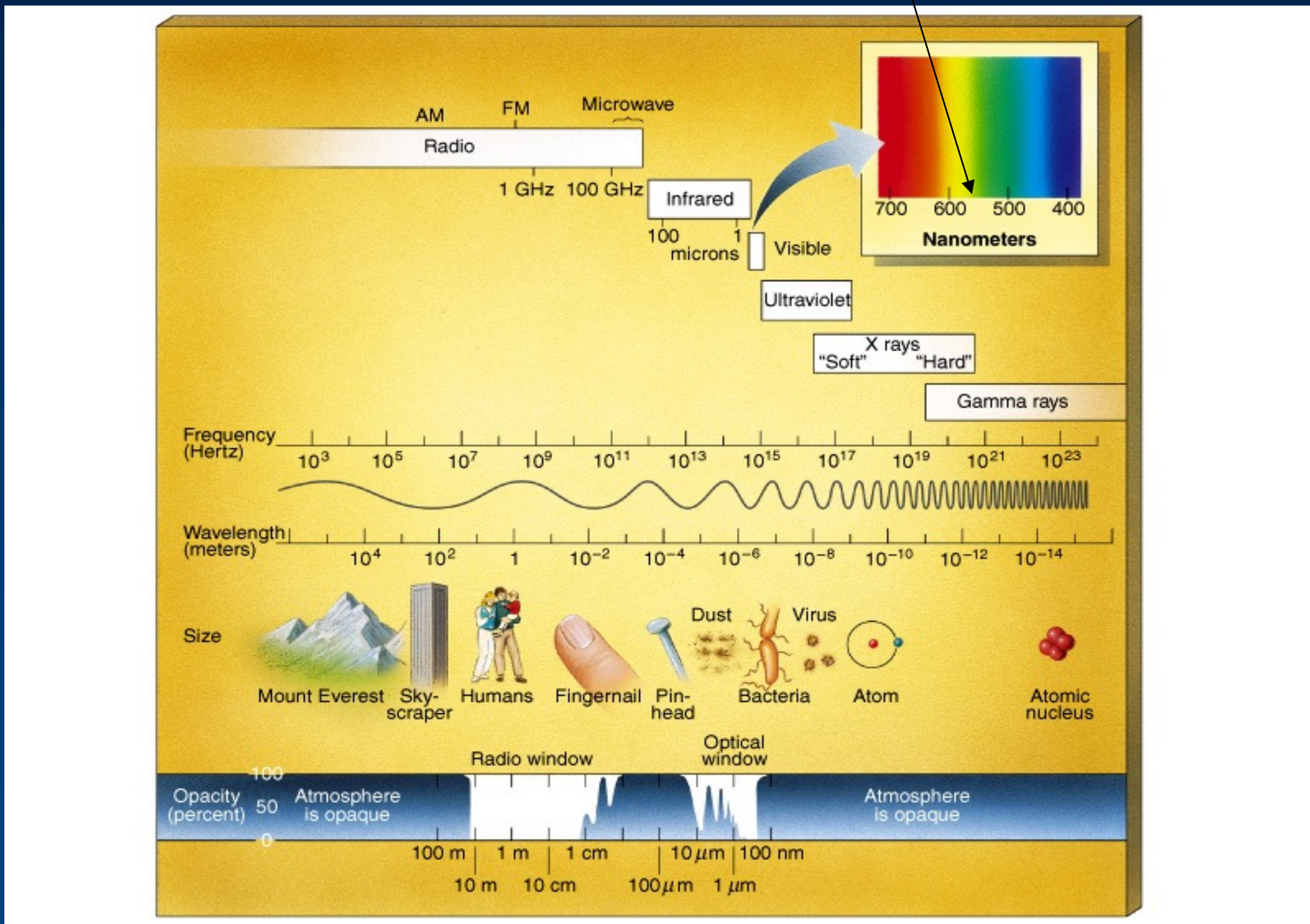
Gamma rays, X rays, Ultraviolet (UV), Visible, Infrared (IR), Microwaves, Radio.

Note use of nm, µm, mm, cm, m, km.



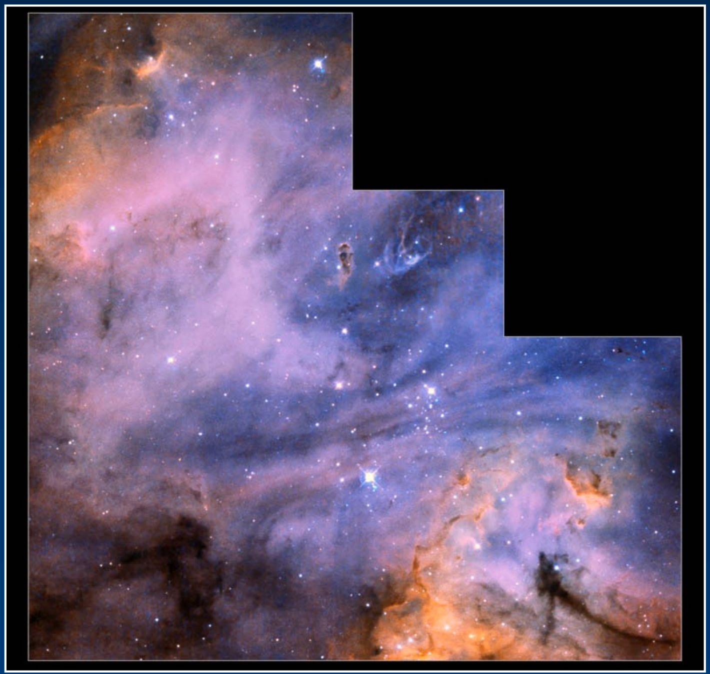
The Electromagnetic Spectrum

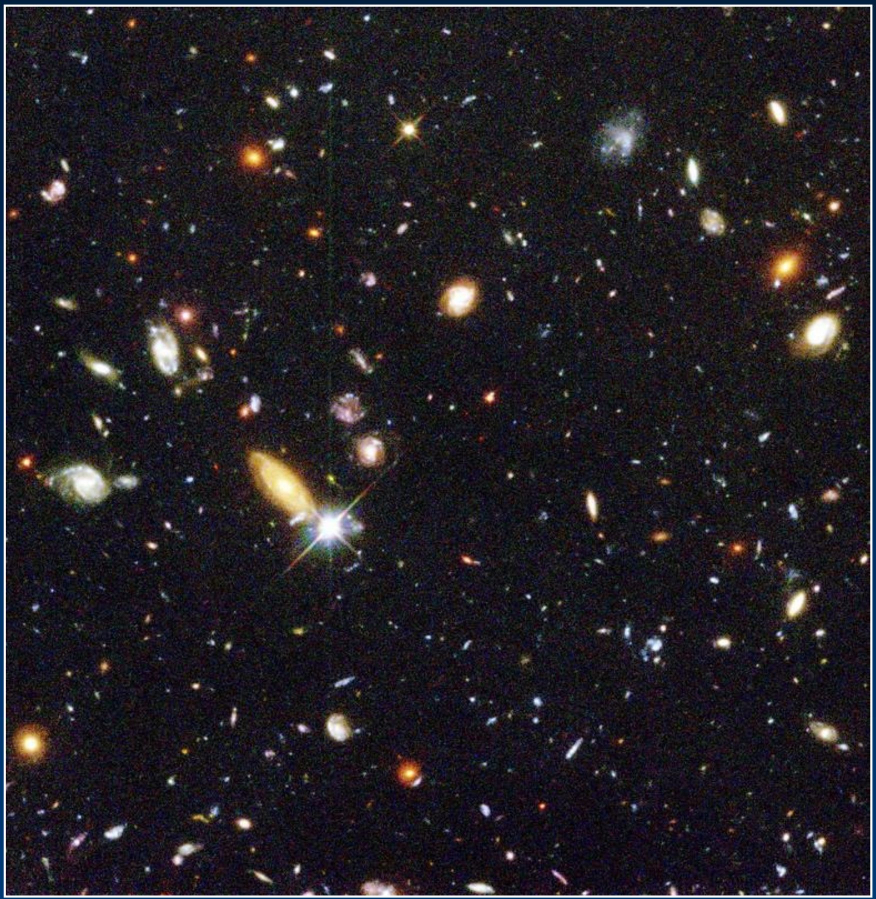
1 nm = 10^{-9} m , 1 Angstrom = 10^{-10} m

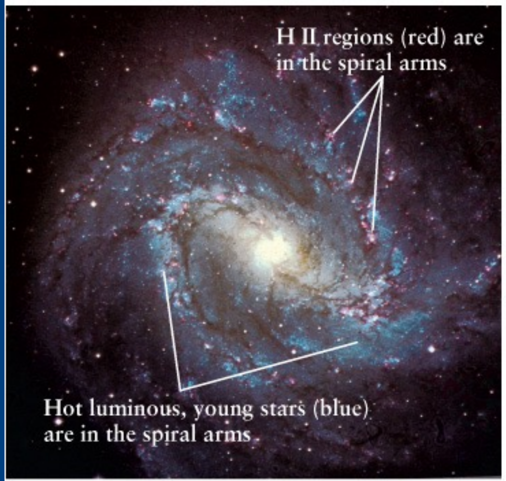


$$c = \lambda \nu$$

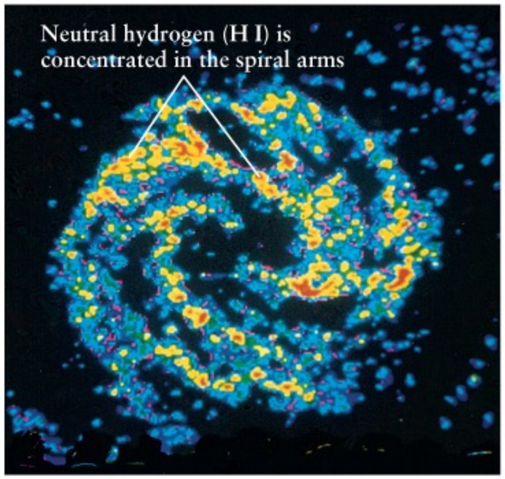
Different objects in the Universe give off EM radiation in different ways, depending on their physical condition.



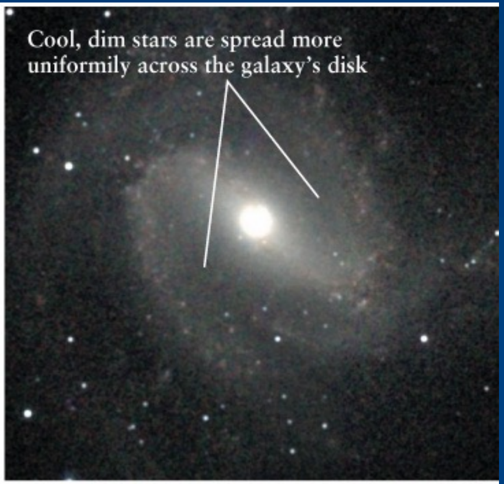




(a) Visible-light view of M83



(b) 21-cm radio view of M83



(c) Near-infrared view of M83

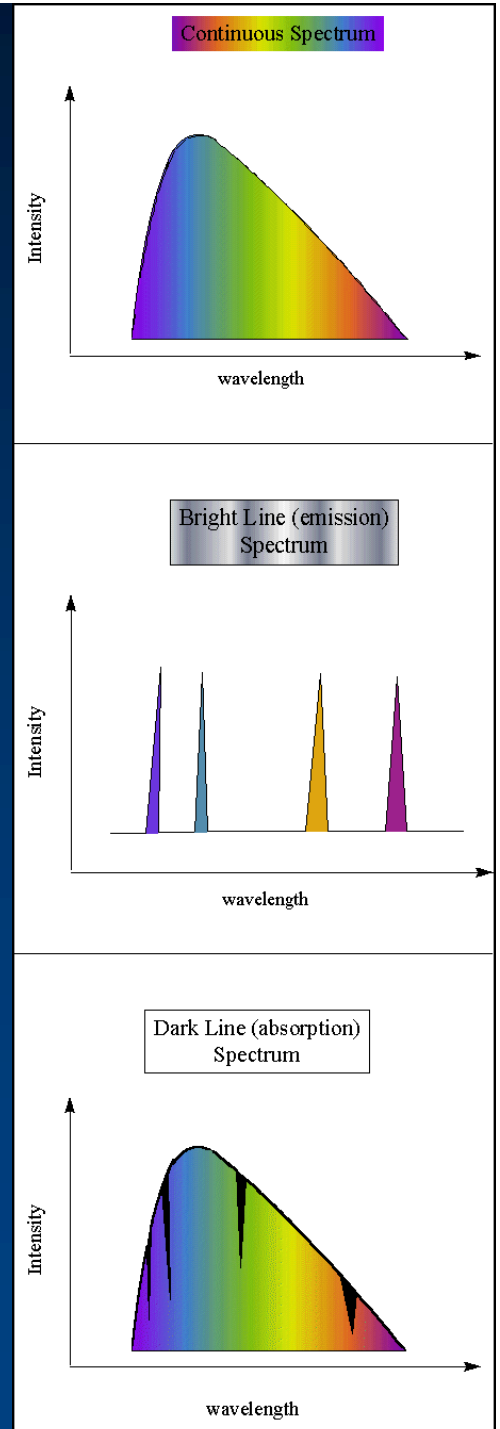
Kirchhoff's Laws

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

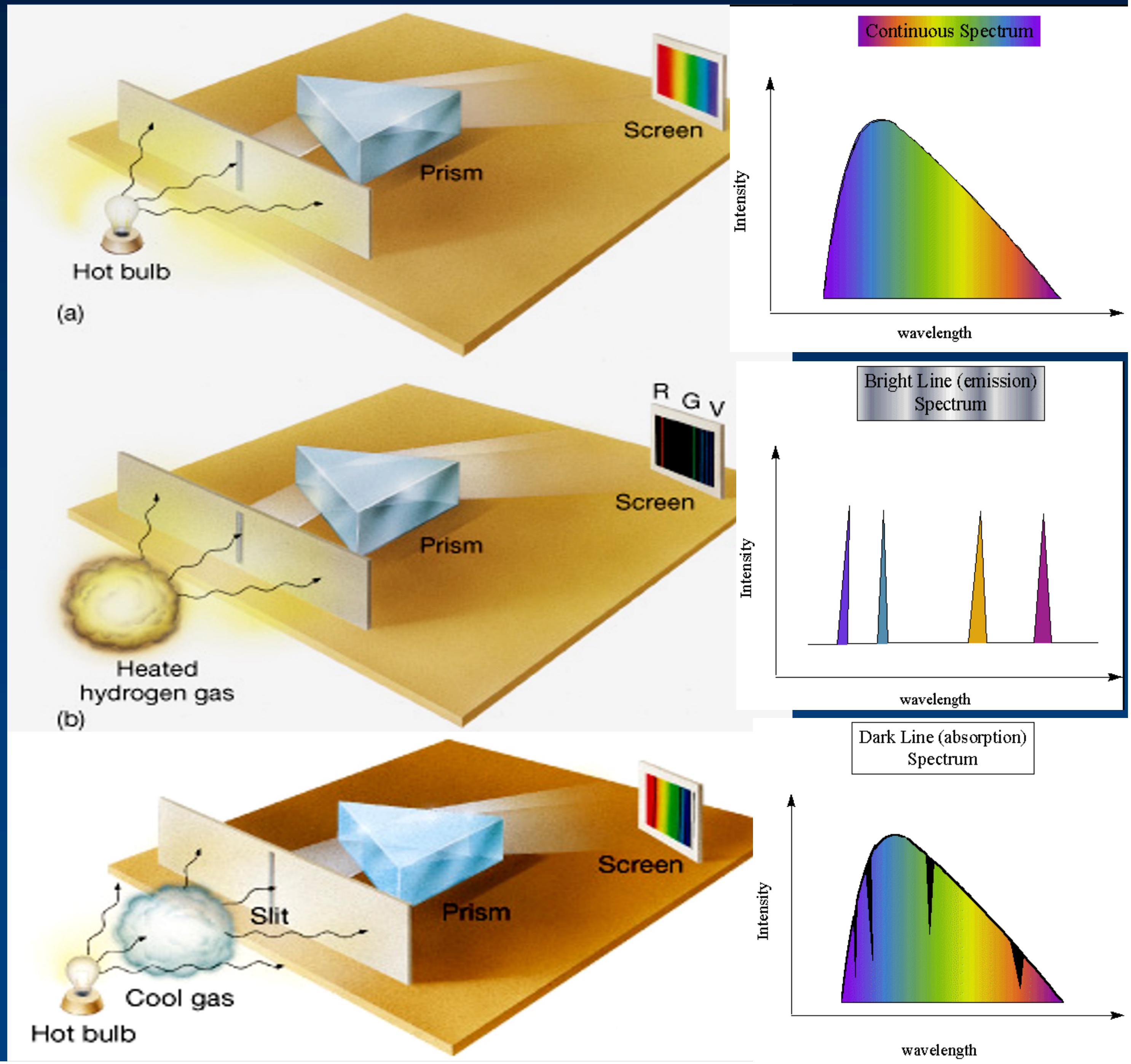
2. A hot, transparent gas produces an emission line spectrum.

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

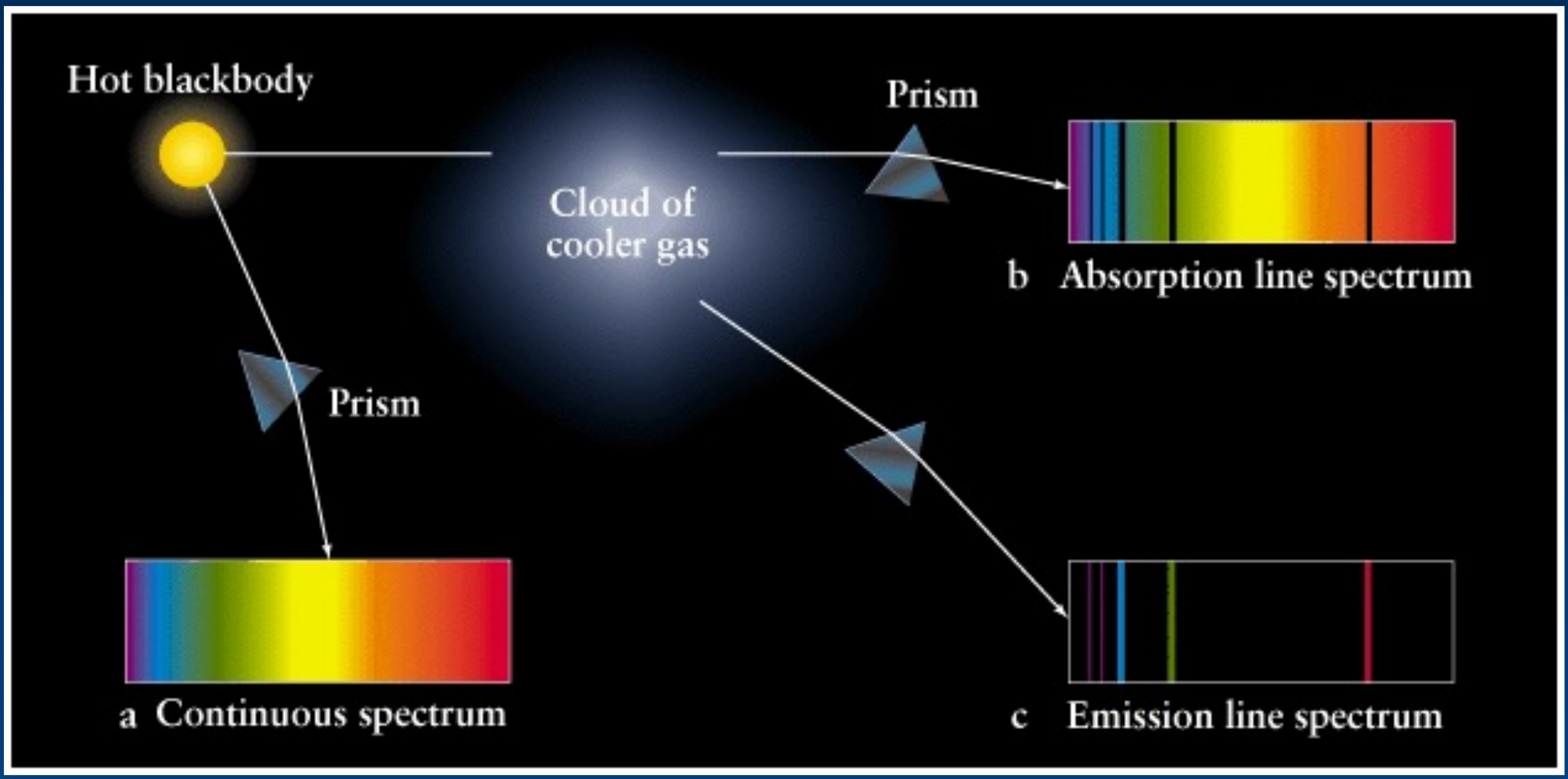
Empirical laws



Kirchhoff's Laws Illustrated

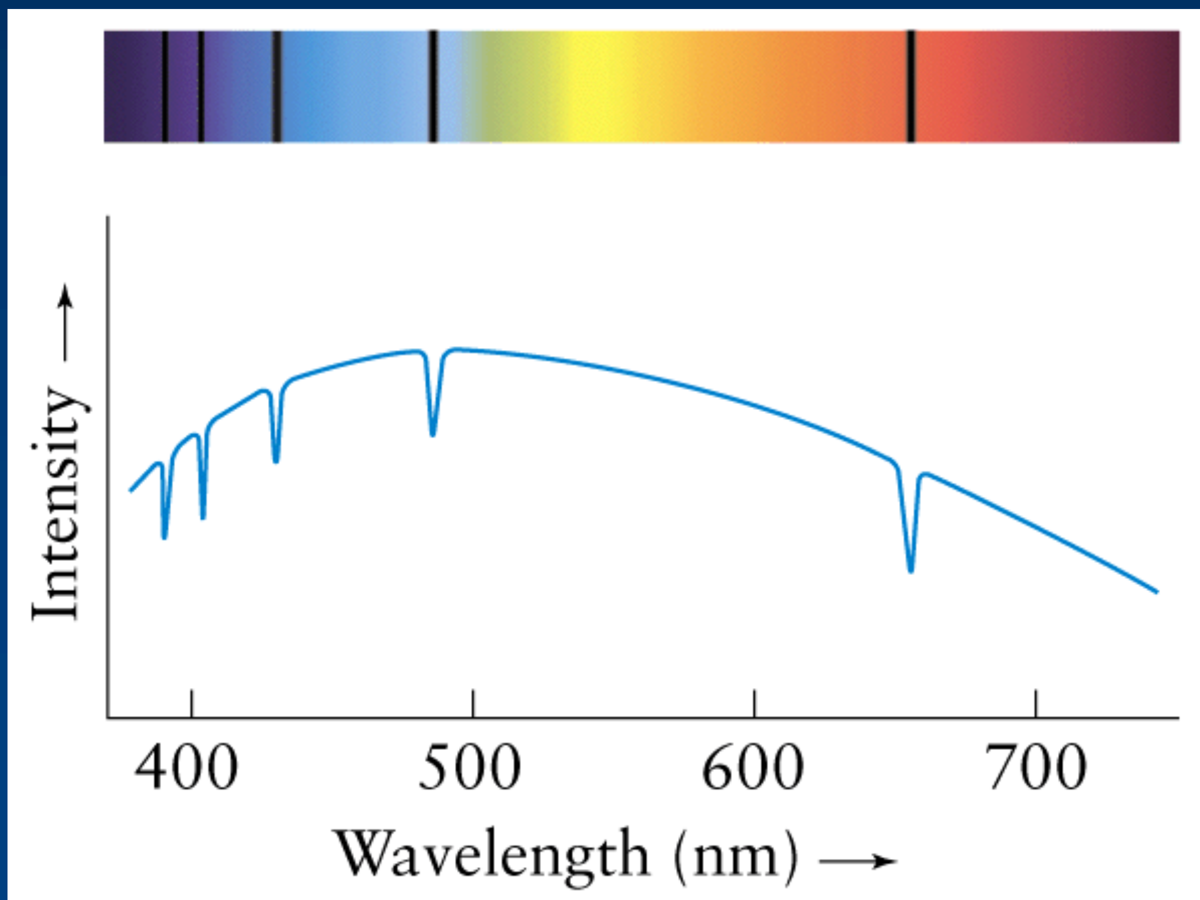


Kirchoff's Laws Illustrated – your book's version



Note: two ways to show a spectrum:

1)as an image
2)as a plot of intensity vs wavelength (or frequency)
3)Example:

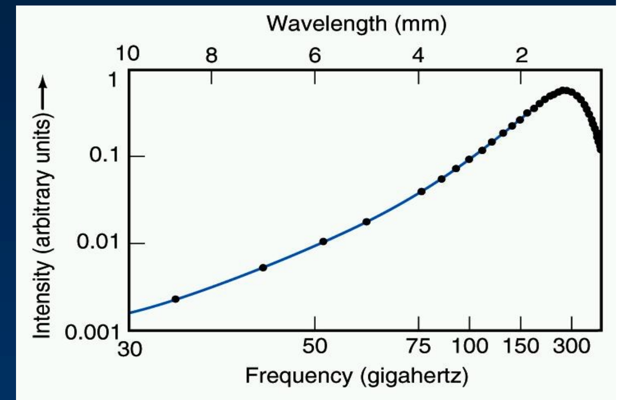


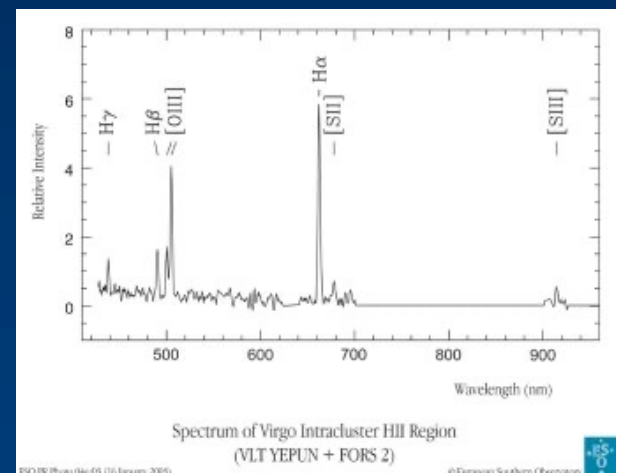
Astronomical and other examples:

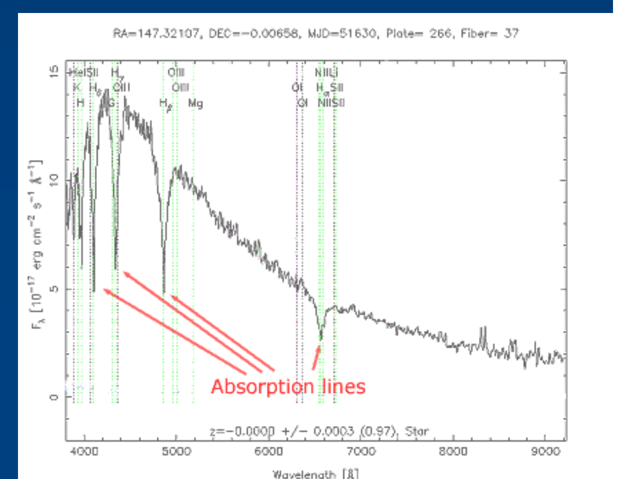
- Continuous: Incandescent lights, the Cosmic Microwave Background (CMB)

- Emission (bright) line: neon lights, hot interstellar gas -- HII regions, supernova remnants.

- Absorption (dark) line: stars (relatively cool atmospheres overlying hot interiors).

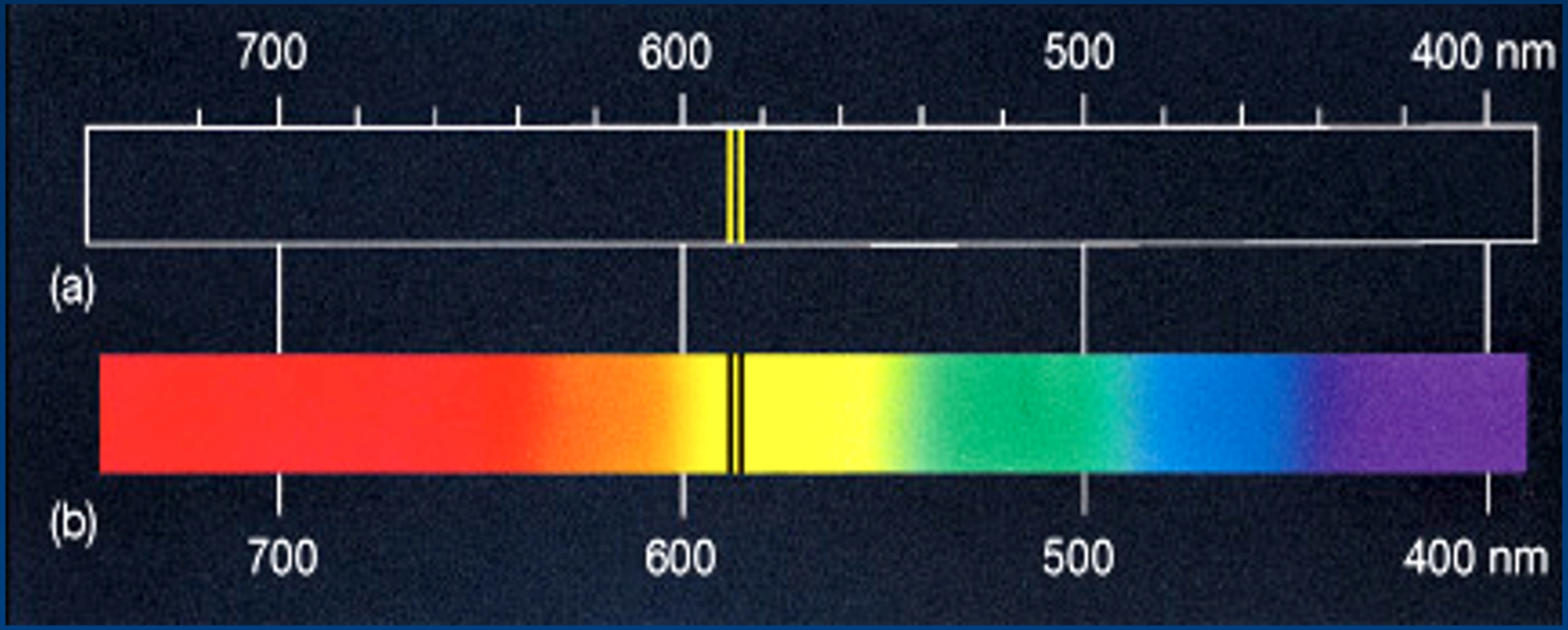






For a gas of a given element, absorption and emission lines occur at same wavelengths.

Sodium



Understood after development of quantum mechanics in early 1900's (we'll discuss this next lecture).

Temperature

- We have talked about “hot”, “cold” – to understand what produces these spectra, we need understanding of 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 higher average kinetic energy (faster speeds) per atom or molecule.

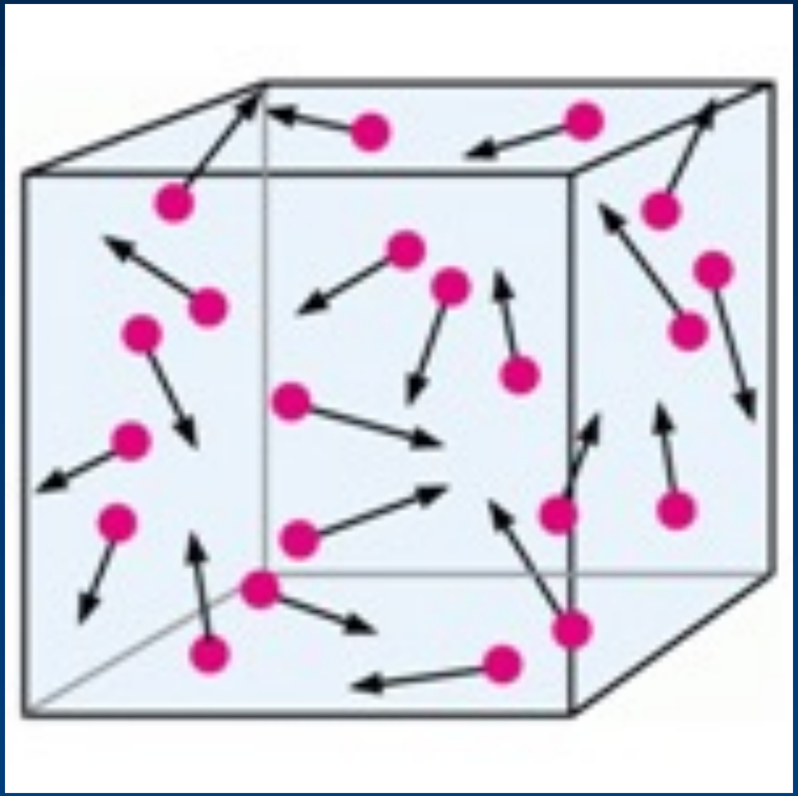
- At high temperatures atoms and molecules move quickly. They move more slowly at lower temperatures.
- If it gets cold enough, all motion will stop. How cold is that?

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

How does temperature relate to random motion? For an ideal gas, if particles have mass m and typical speed, v, then

$$v = \sqrt{\frac{3kT}{m}}$$



k is Boltzmann's constant, and has value 1.38 x 10^{-23} m^2 kg s^{-2} K^{-1}, (or Joules K^{-1}). We'll derive this in a later lecture.

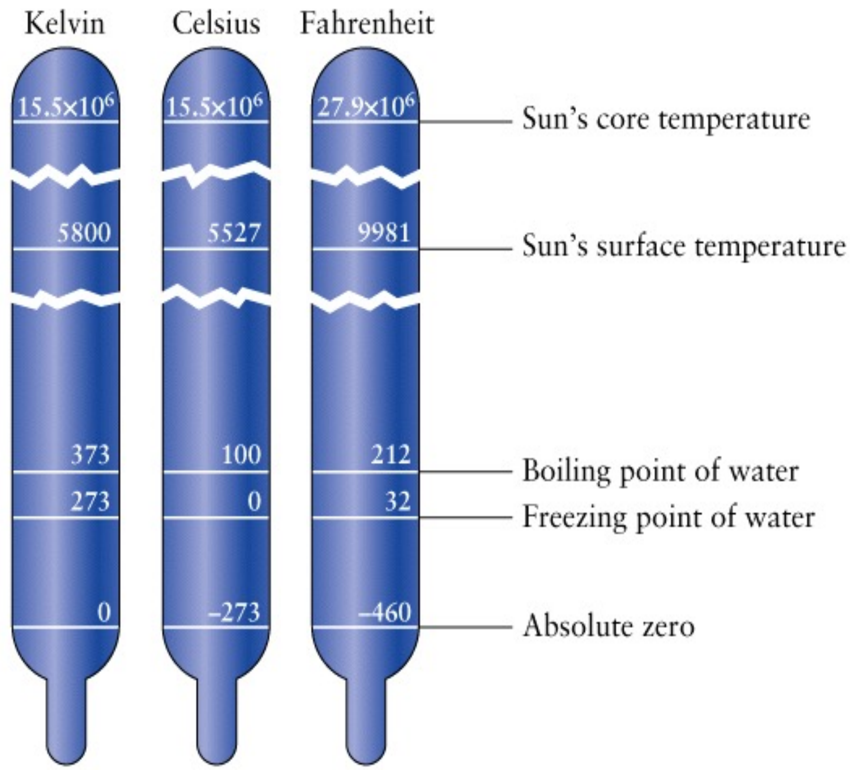
Temperature conversions

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

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

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

T_F = temperature in degrees Fahrenheit
T_C = temperature in degrees Celsius



Blackbody Radiation

- A blackbody is an object that absorbs all radiation, at all wavelengths: perfect absorber. No incident light is reflected
- As it absorbs radiation, it will heat up and radiate
- A blackbody will emit radiation at a broad range of wavelengths (continuous spectrum)

The spectrum of 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:

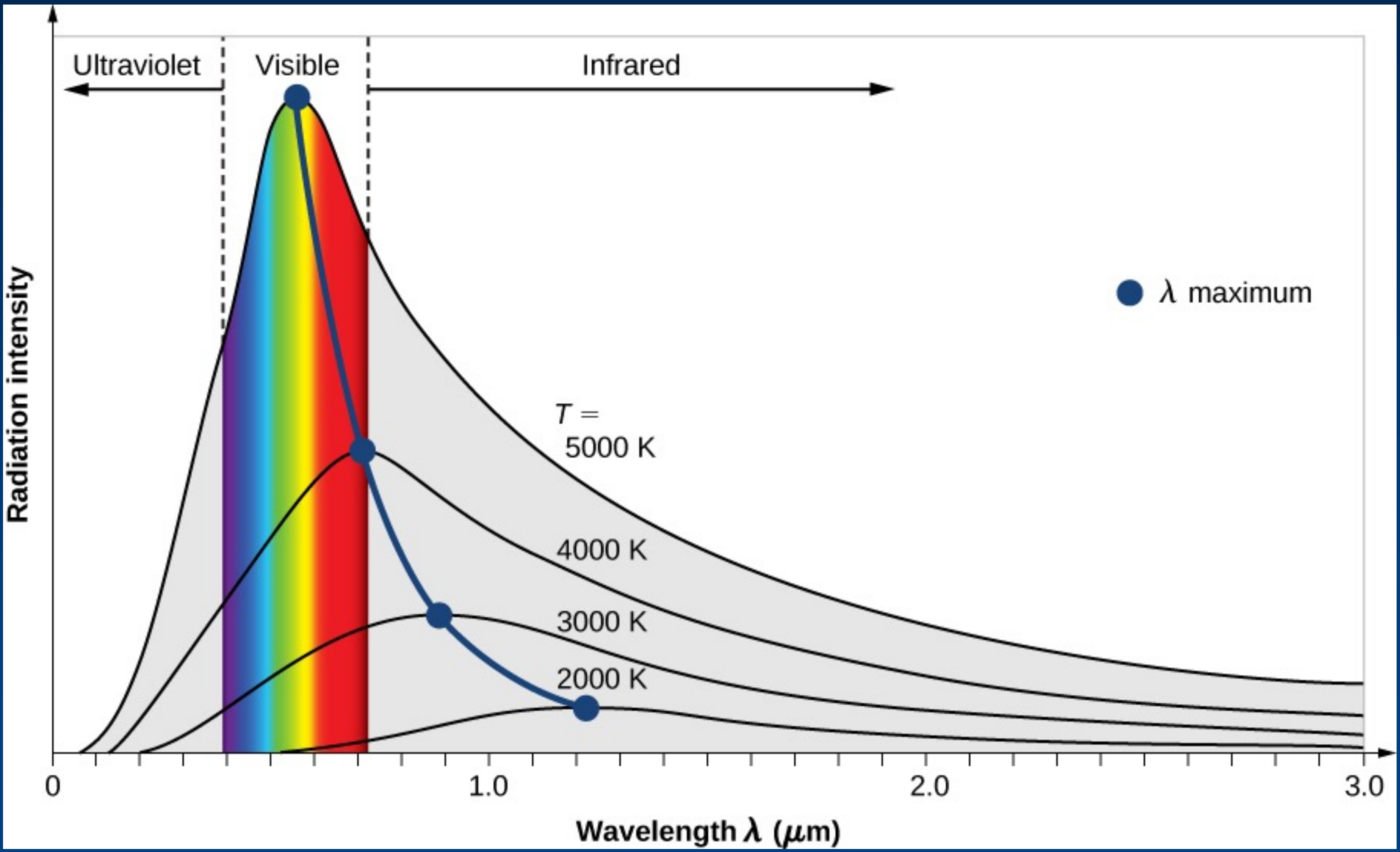
$$I_\nu = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{h\nu/kT}-1}\right] \quad \text{also} \quad I_\lambda = \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]$$

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

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

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

Example: 4 blackbody (Planck curves) for 4 different temperatures.



Wien's Law for a blackbody

- λ_{max} = 0.0029 (m K) / T
- λ_{max} is the wavelength of maximum emission of the object (in meters), and
- T is the temperature of the object (in Kelvins).

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

Hotter objects are bluer, cooler objects are redder. Worksheet #6

Example 1: How hot is the Sun?

Measure λ_{max} to be about 500 nm, so

T_{sun} = 0.0029 m K / λ_{max} = 0.0029 m K /5.0 x 10^{-7} m

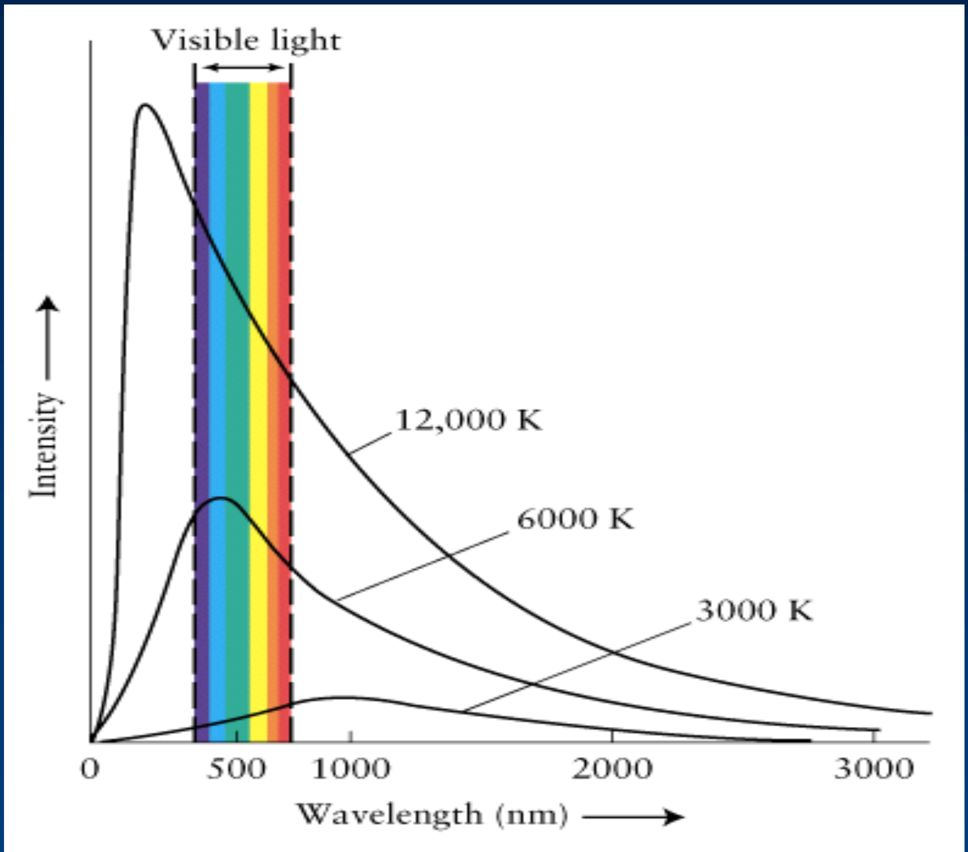
= 5800 K

Example 2: At what wavelength would the spectrum peak for a star which is 5800/2 = 2900 K?

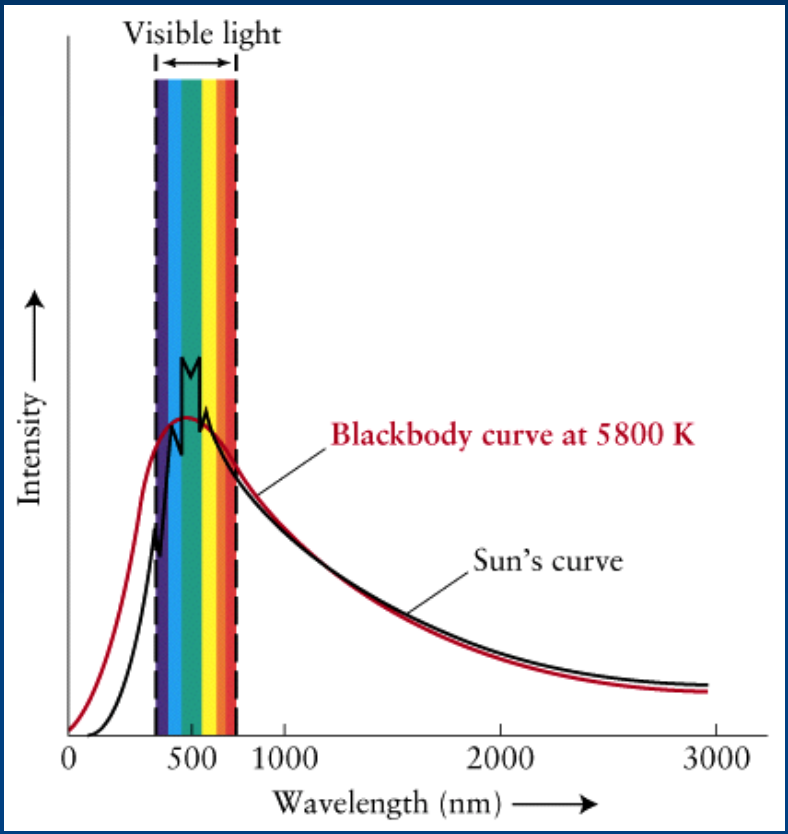
For a star with T= 5800 x 2 = 11,600 K?

What colors would these stars be?

Wavelengths of peaks of the curve illustrate Wien's Law.



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



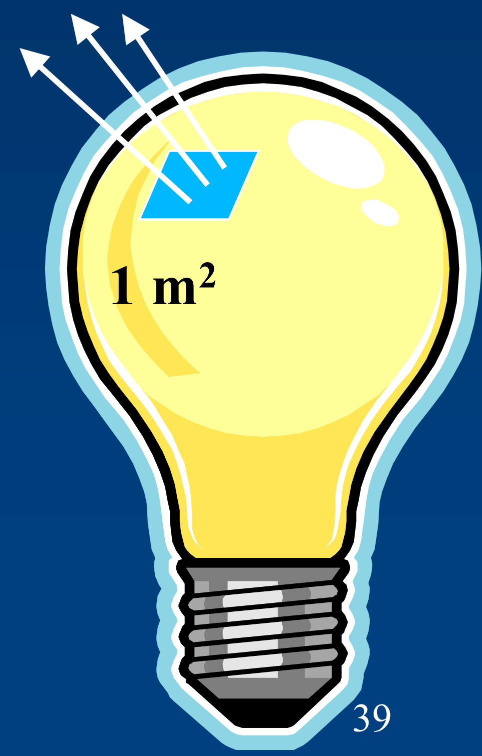
Betelgeuse
surface temp
3500 K

Rigel
surface temp
11,000 K

Stefan-Boltzmann Law for a blackbody

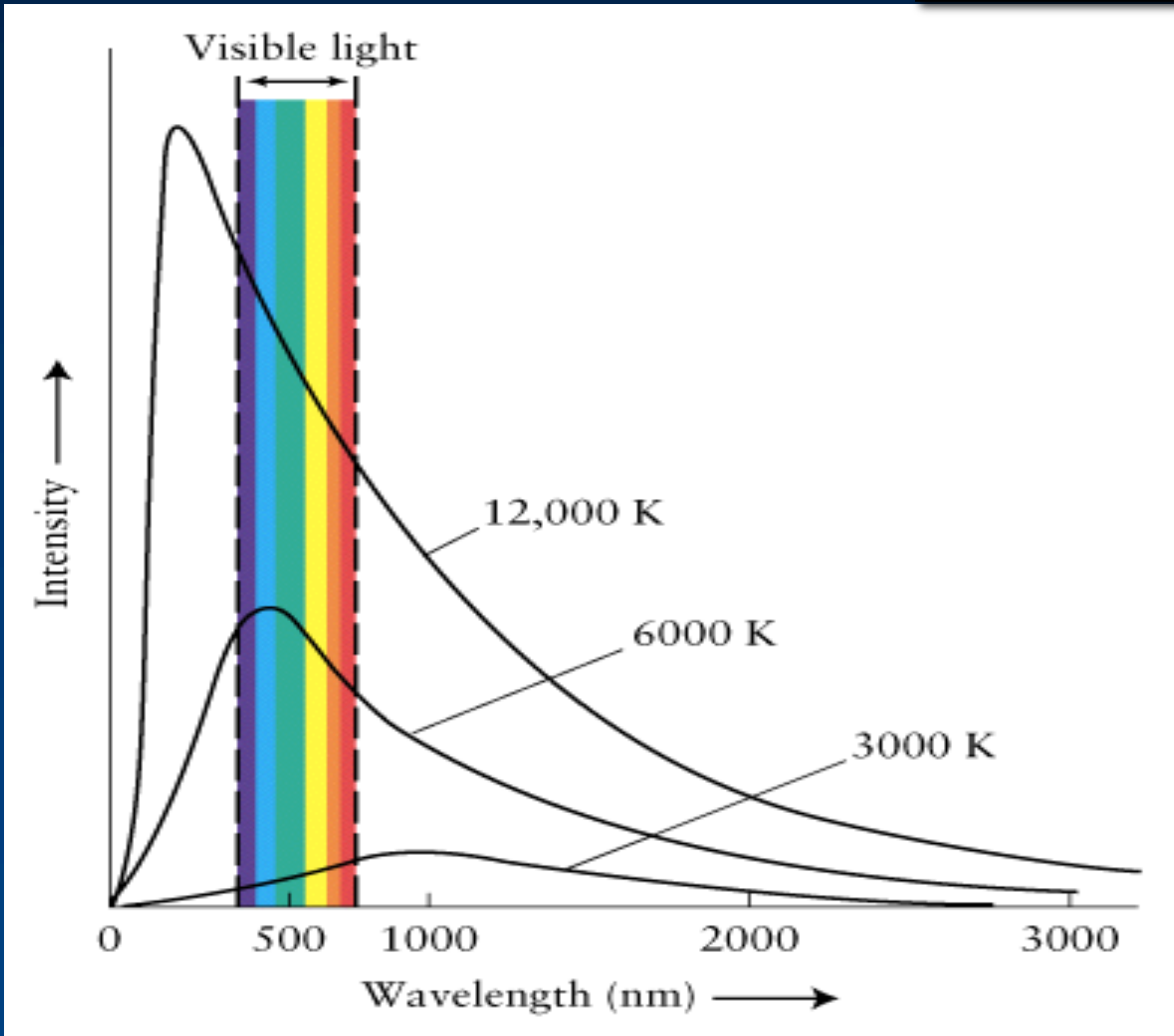
- $F = \sigma T^4$

- F is the <u>emergent flux</u>, in joules per square meter of surface per second ($J\ m^{-2}\ s^{-1}$, or $W\ m^{-2}$)
- 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

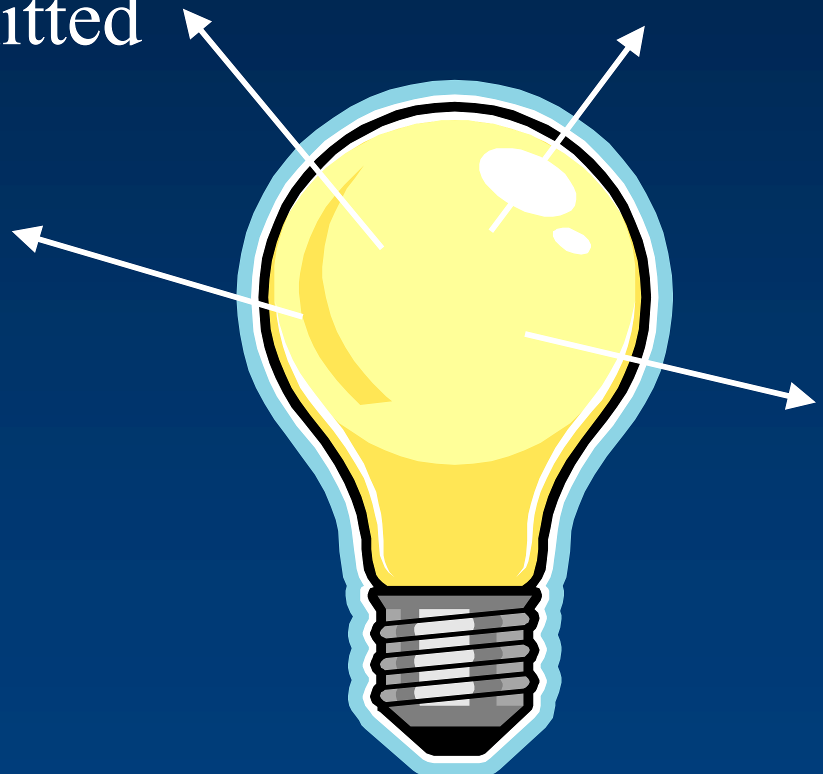


Example: If the temperature of the Sun were twice what it is now, how much more energy would the Sun produce every second?

(See box 5-2 for more examples.)

Luminosity and Blackbody Radiation

Luminosity is radiation energy emitted per second from entire surface:



$L = F_{emergent}$ x (surface area)

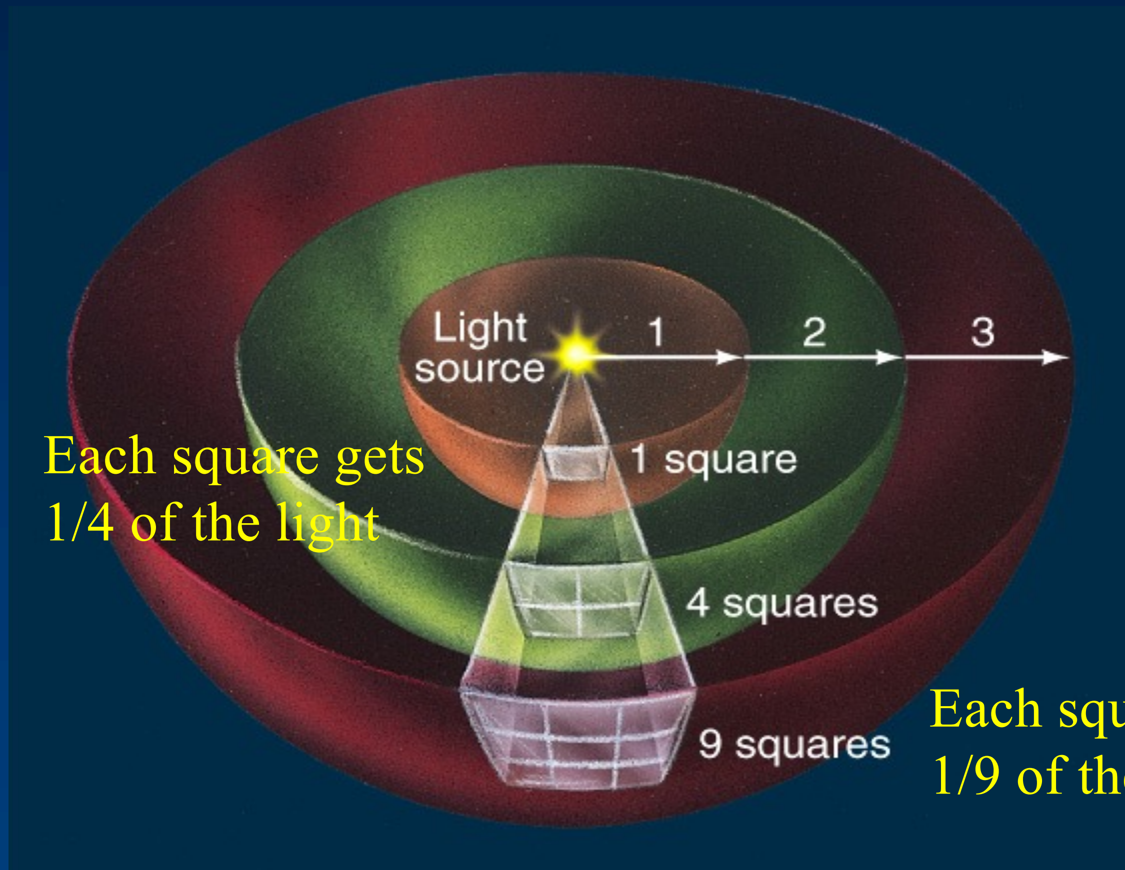
Units of L are Watts (W, or J/s)

For sphere (stars),

$L = 4\pi R^2 \times F_{emergent}$

For spherical blackbody (stars, approx.): $L = 4\pi R^2 \sigma T^4$

The "Inverse-Square" Law for Radiation



Each square gets 1/4 of the light

Each square gets 1/9 of the light

<u>Incident</u> flux ($F_{incident}$), or <u>apparent</u> brightness (b) is amount of radiation received in a unit area at distance r from source

$$F_{incident} = \frac{L}{4\pi r^2}$$

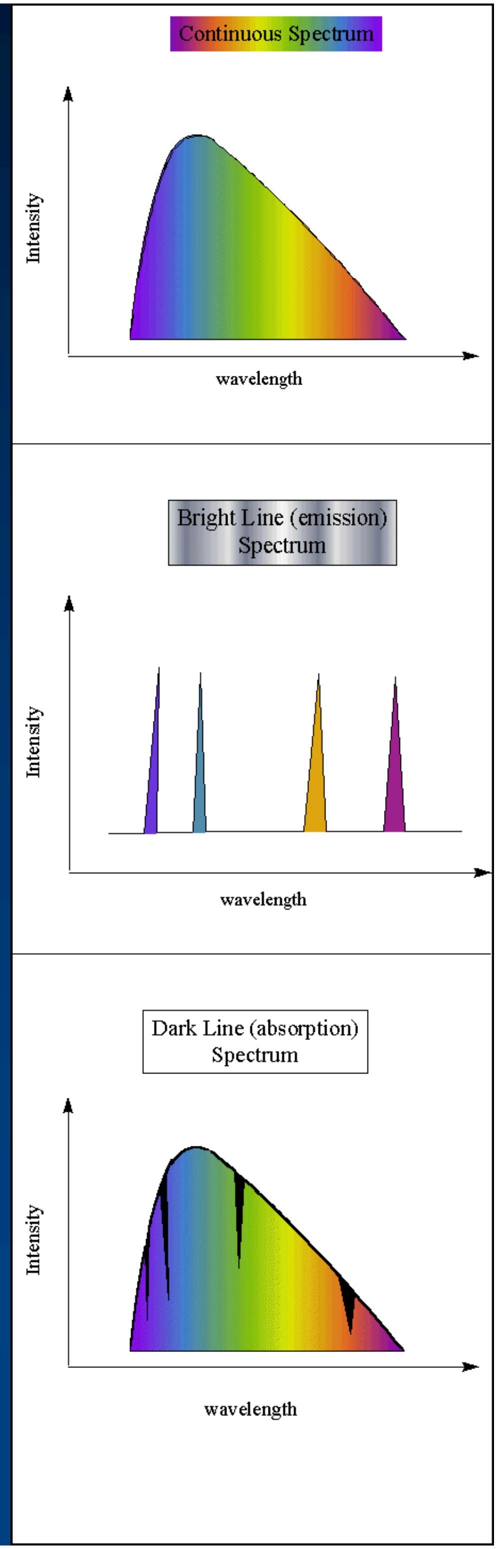
Kirchhoff' s Laws

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

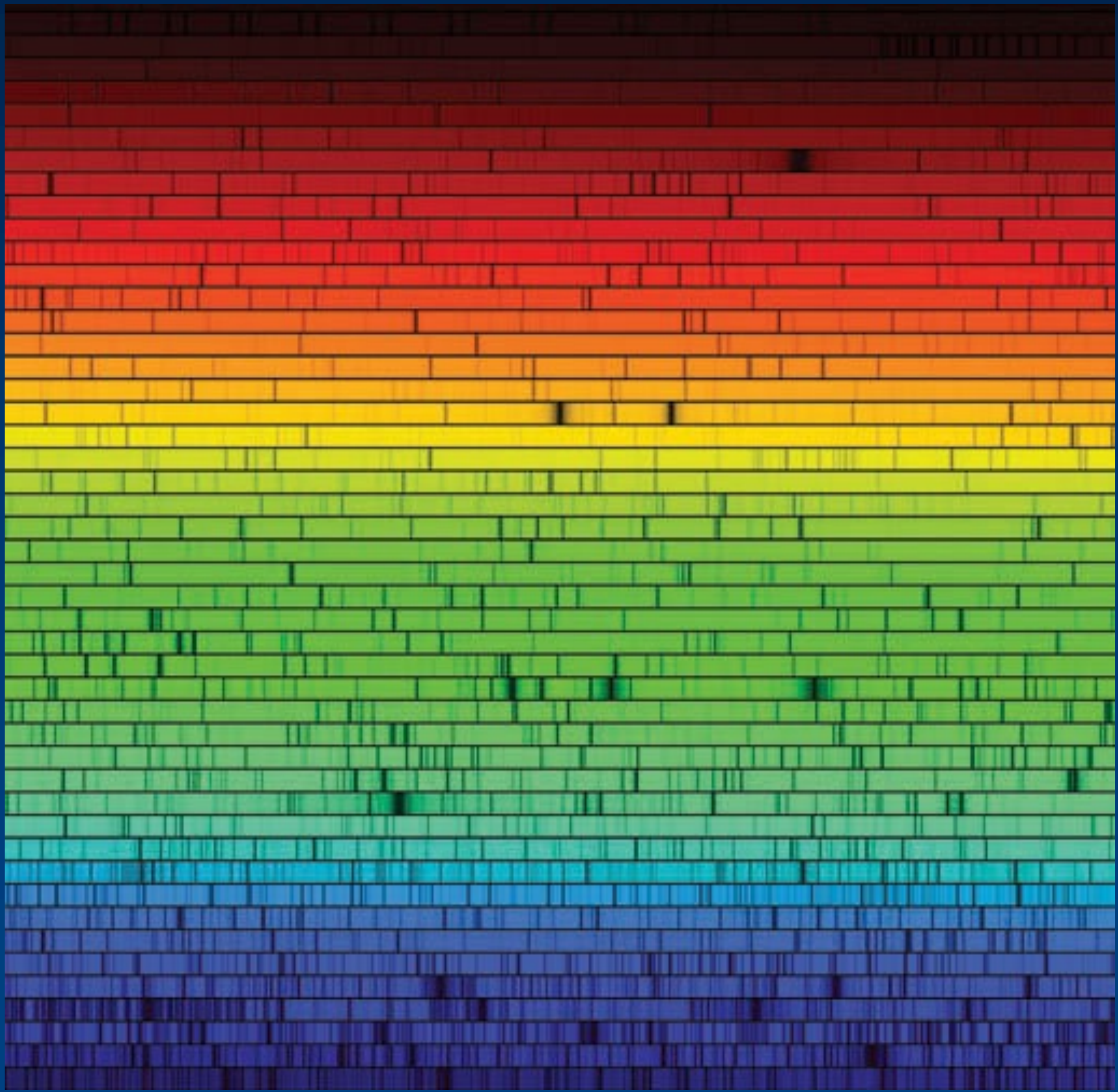
   Explained

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

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



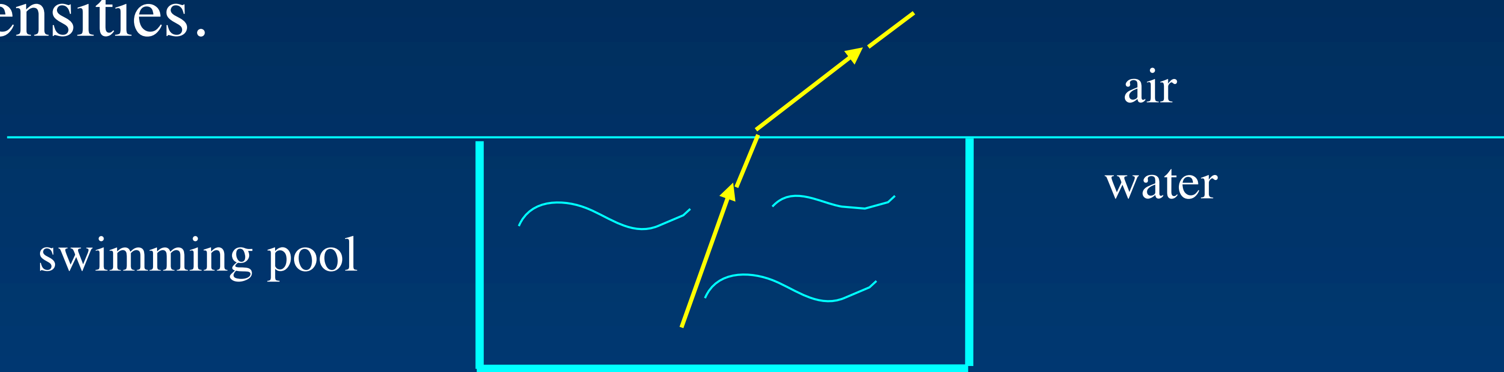
Spectrum of the Sun – what kind of spectrum is this?

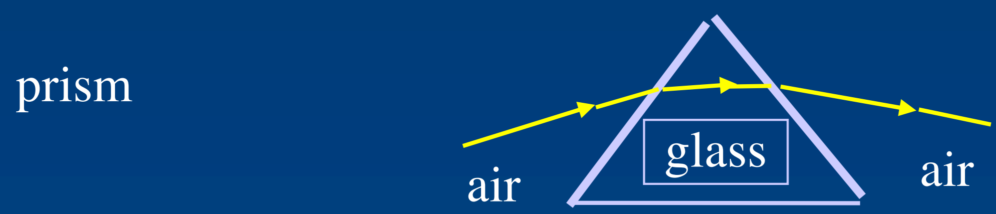


Things that waves do

1. Refraction

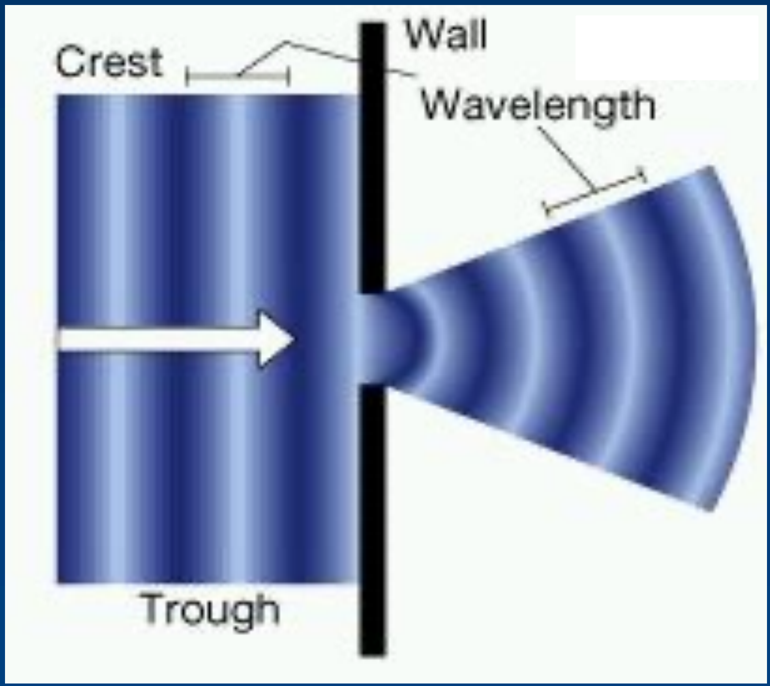
Waves bend when they pass through material of different densities.



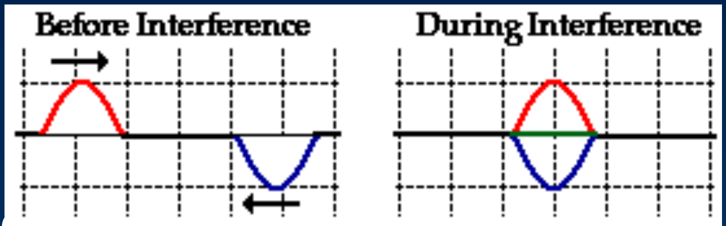


2. Diffraction

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

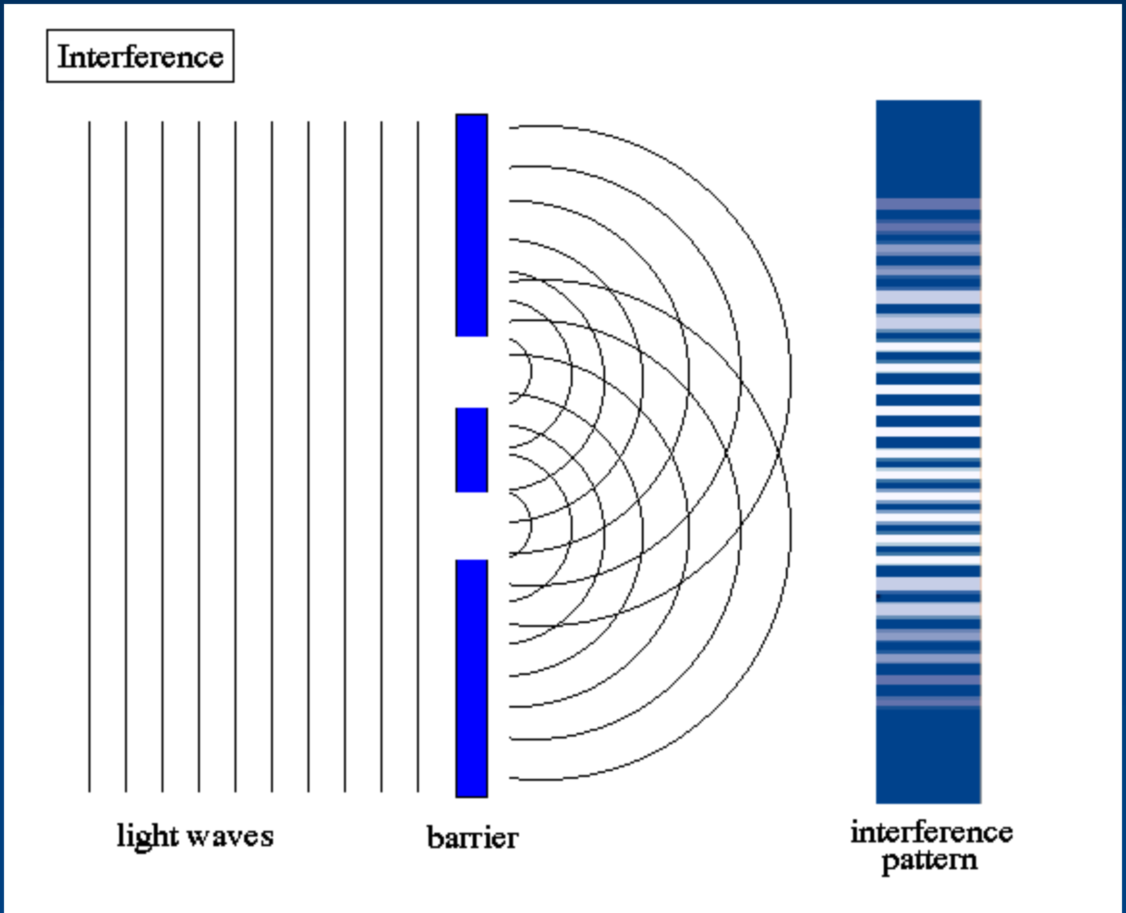


3. Interference



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)