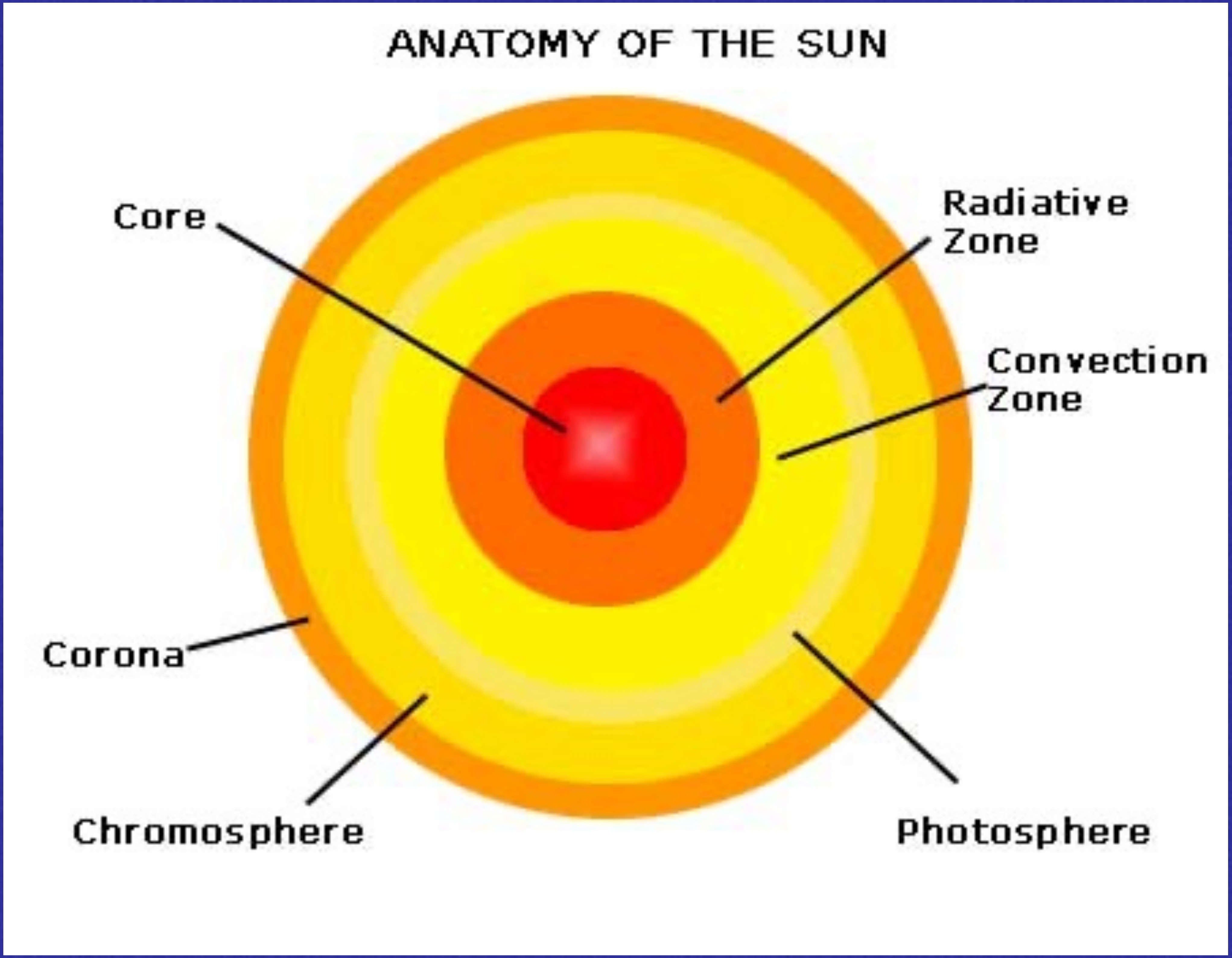
Announcements

Homework 2 is due next Thursday (Feb. 4)

Other than my office hours, homework help is also available Fridays 12-1pm (Ismael Mireles); https://physics.unm.edu/pandaweb/undergraduate/tutoring.php

Overall structure



The Sun's atmosphere

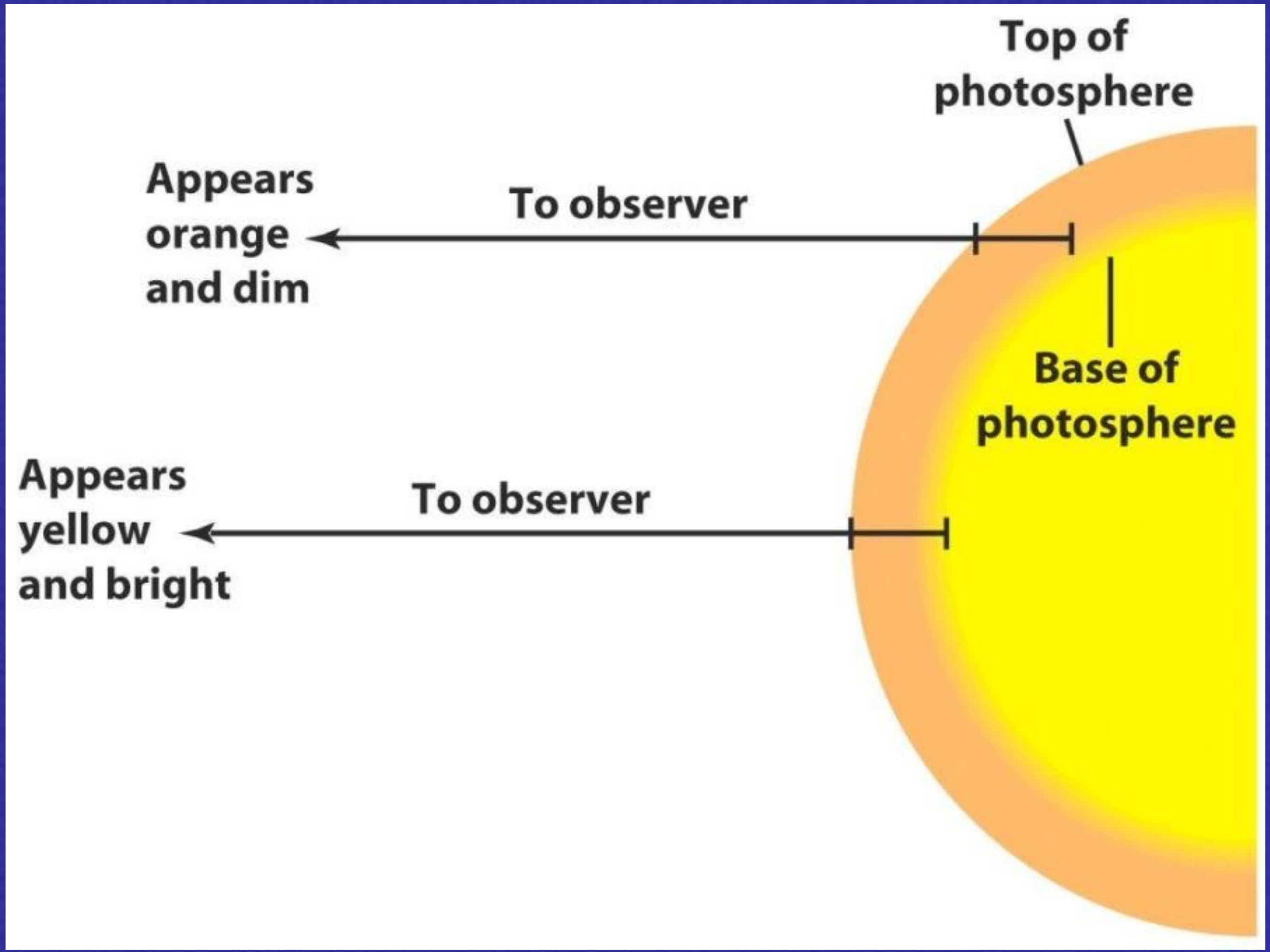
- Photosphere: yellowish color. The part we see, T=5800 K.
- The Sun is a giant sphere or gas - so it doesn't have a well defined surface
- Talking about the surface: we mean the photosphere
- The point where atmosphere becomes completely opaque is the photosphere (defines diameter of the Sun)

Limb darkening

- Outer portions of photosphere being cooler
- Photons travel about the same path length

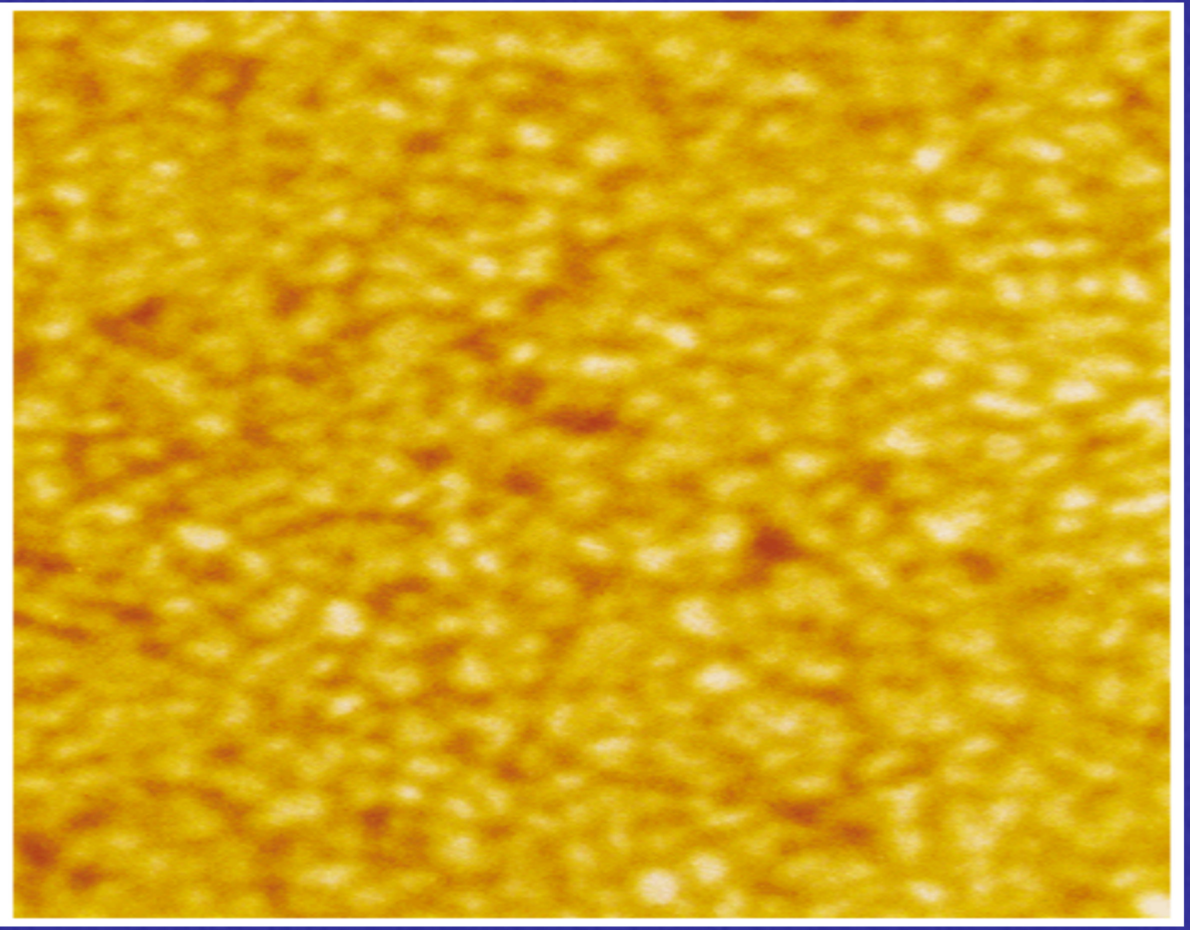
Dimmer light comes from higher, relatively cool layer within the photosphere

Bright light comes from low-lying, hot layer within the photosphere

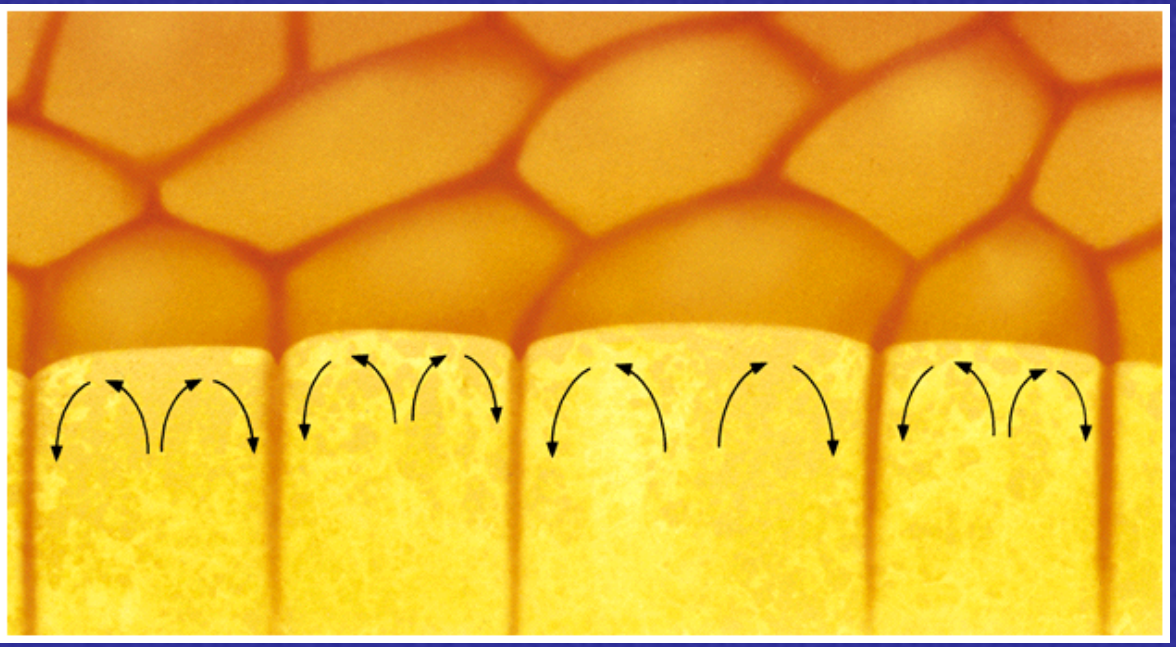


Granulation

- Photosphere is lowest of 3 atmospheric layers
- Granulation due to convection

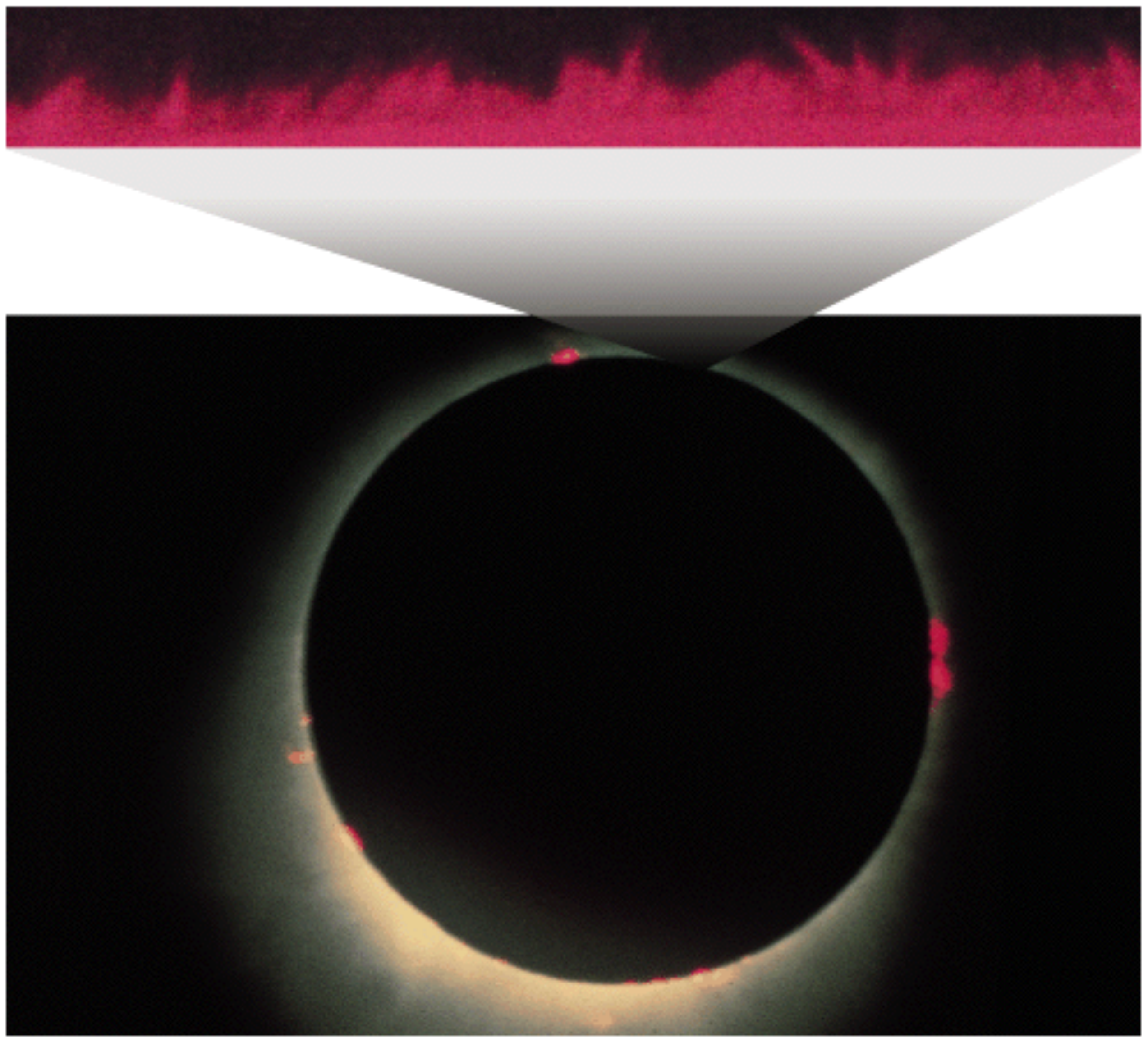


This picture shows blobs ~1000 km across

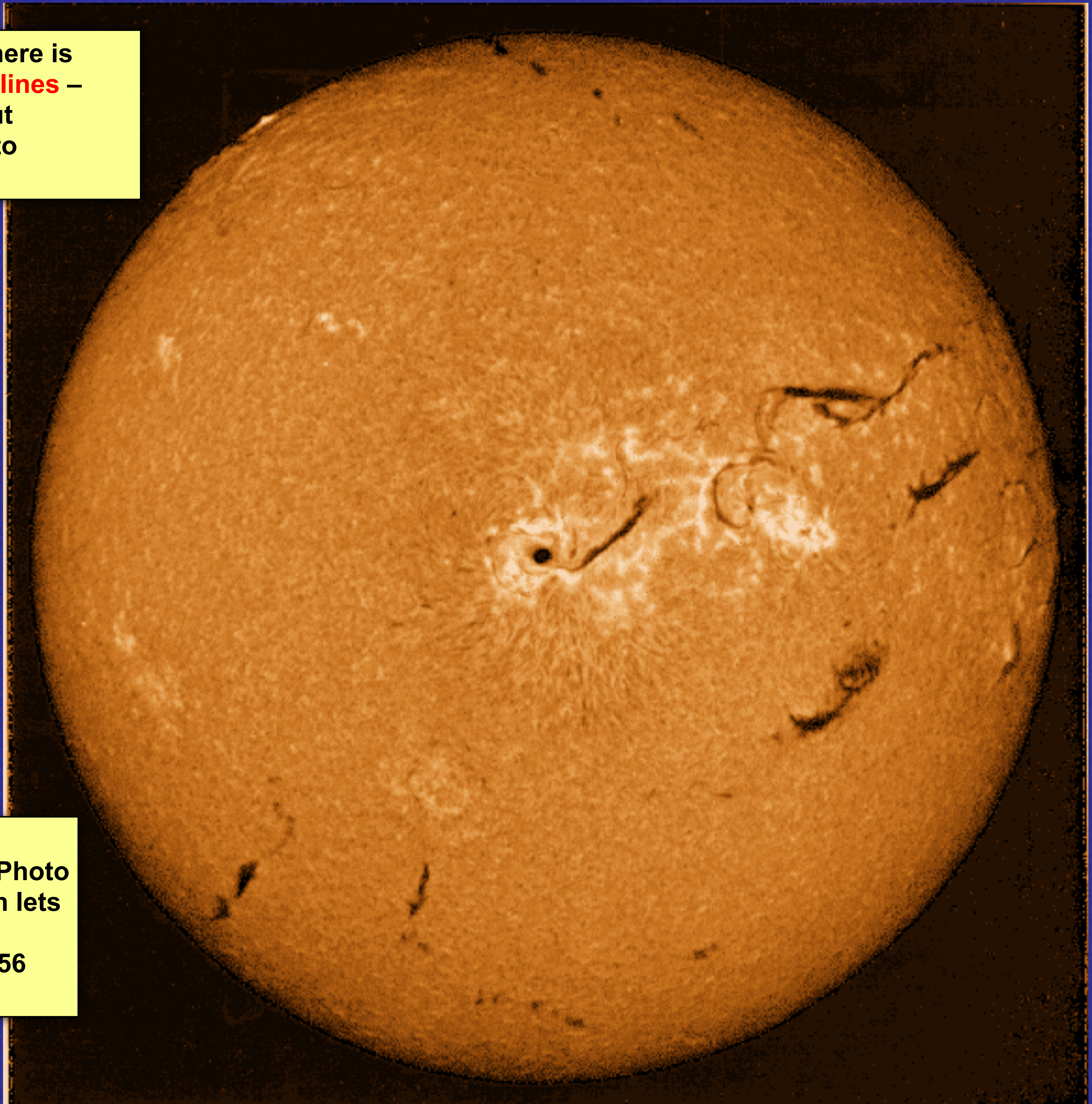


Chromosphere

- Middle layer, characterized by Hα emission: red color.
- The gas is very rarefied (10^{-4} density of photosphere).
- Also featured are gas plumes jutting upward.



Spectrum of chromosphere is dominated by emission lines – what does this say about temperature compared to photosphere?



H alpha image showing chromospheric activity. Photo taken through filter which lets through only light of wavelength of H-alpha (656 nm).

Corona

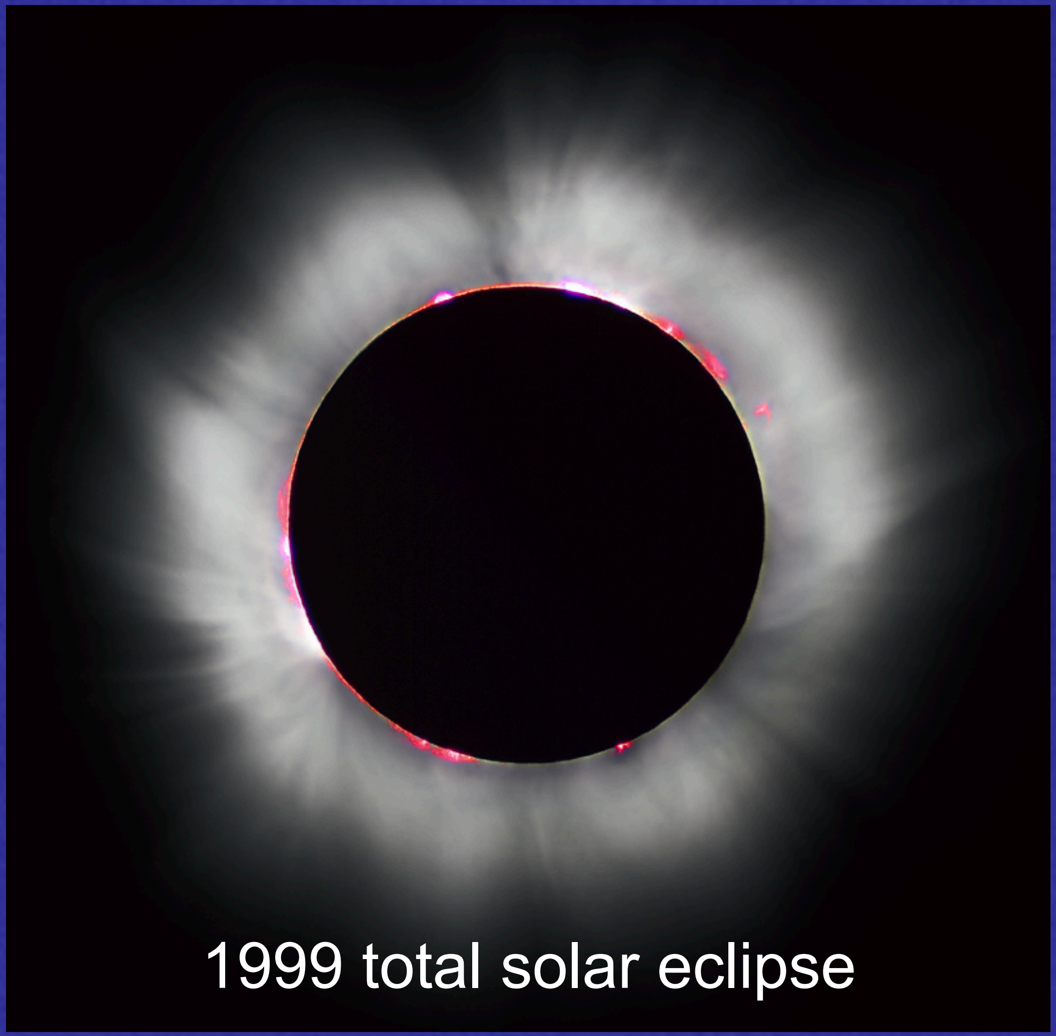
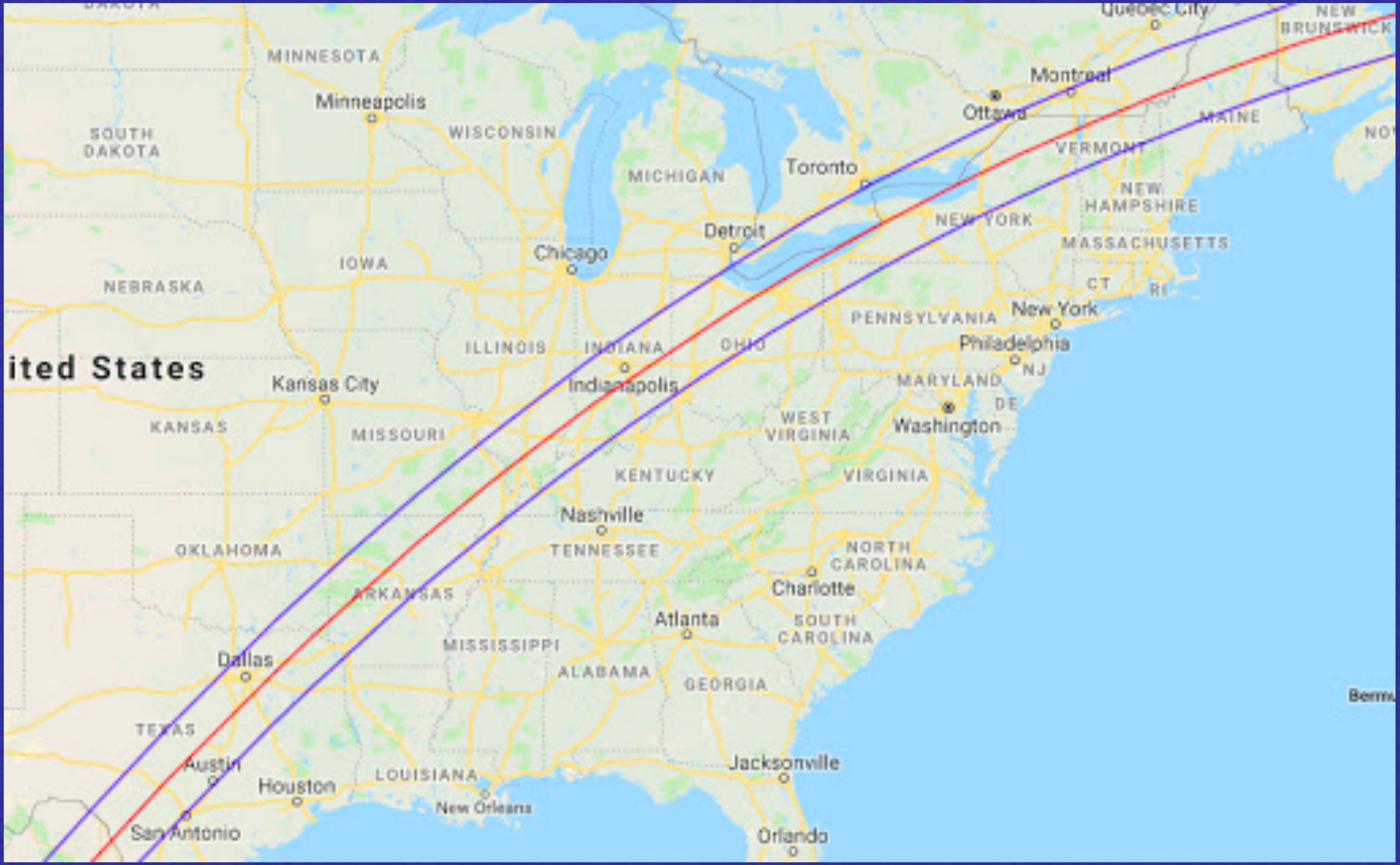


Image credit: Luc Viatour/Diliff

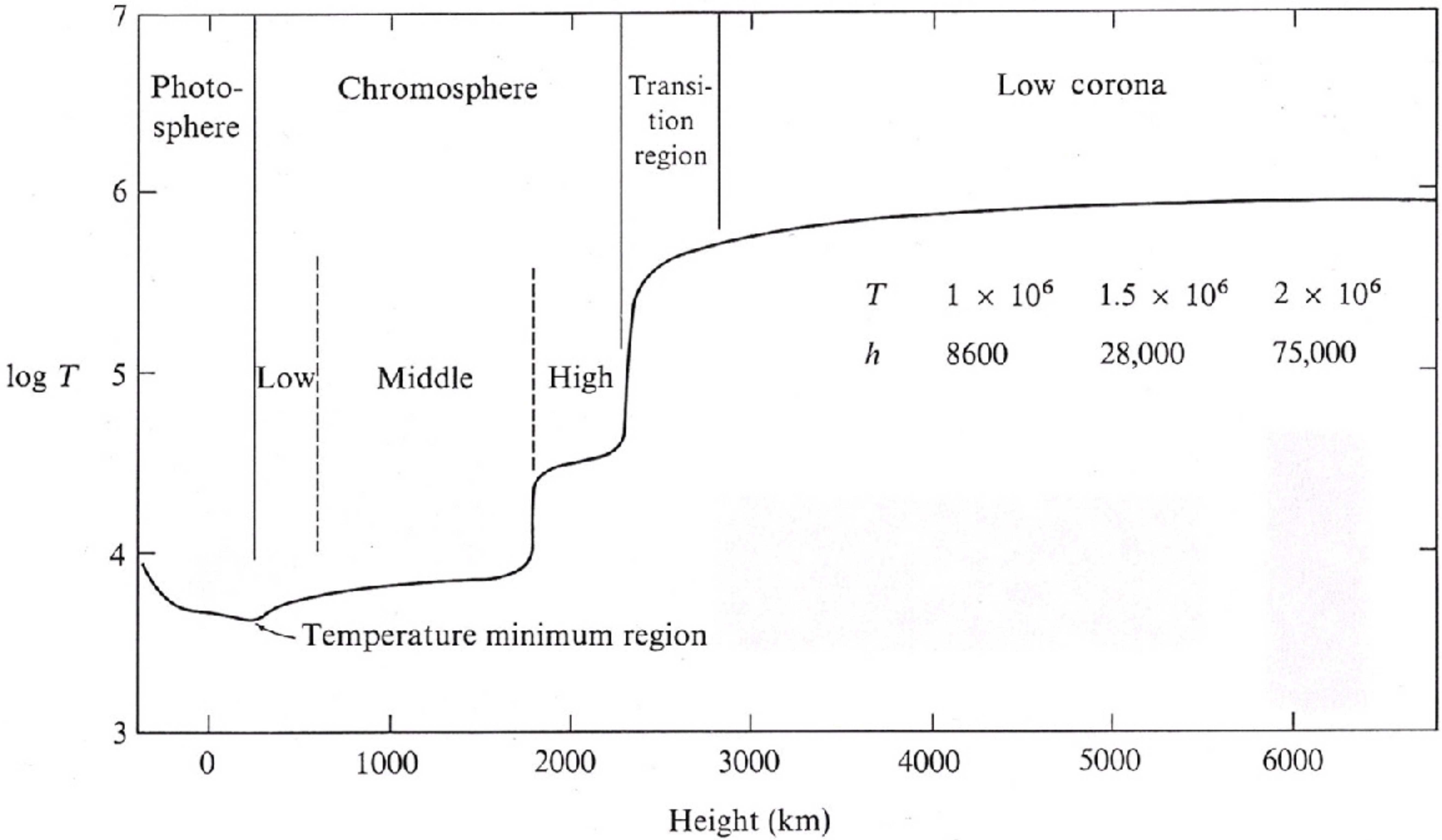
Ejects mass into space -> solar wind

Shapes of streamers vary on timescales as short as days!

Next total solar eclipse: April 8, 2024



Thermal Profile of the Sun




The nature of the stars

What are stars?

Are they all alike?
Is the Sun typical?

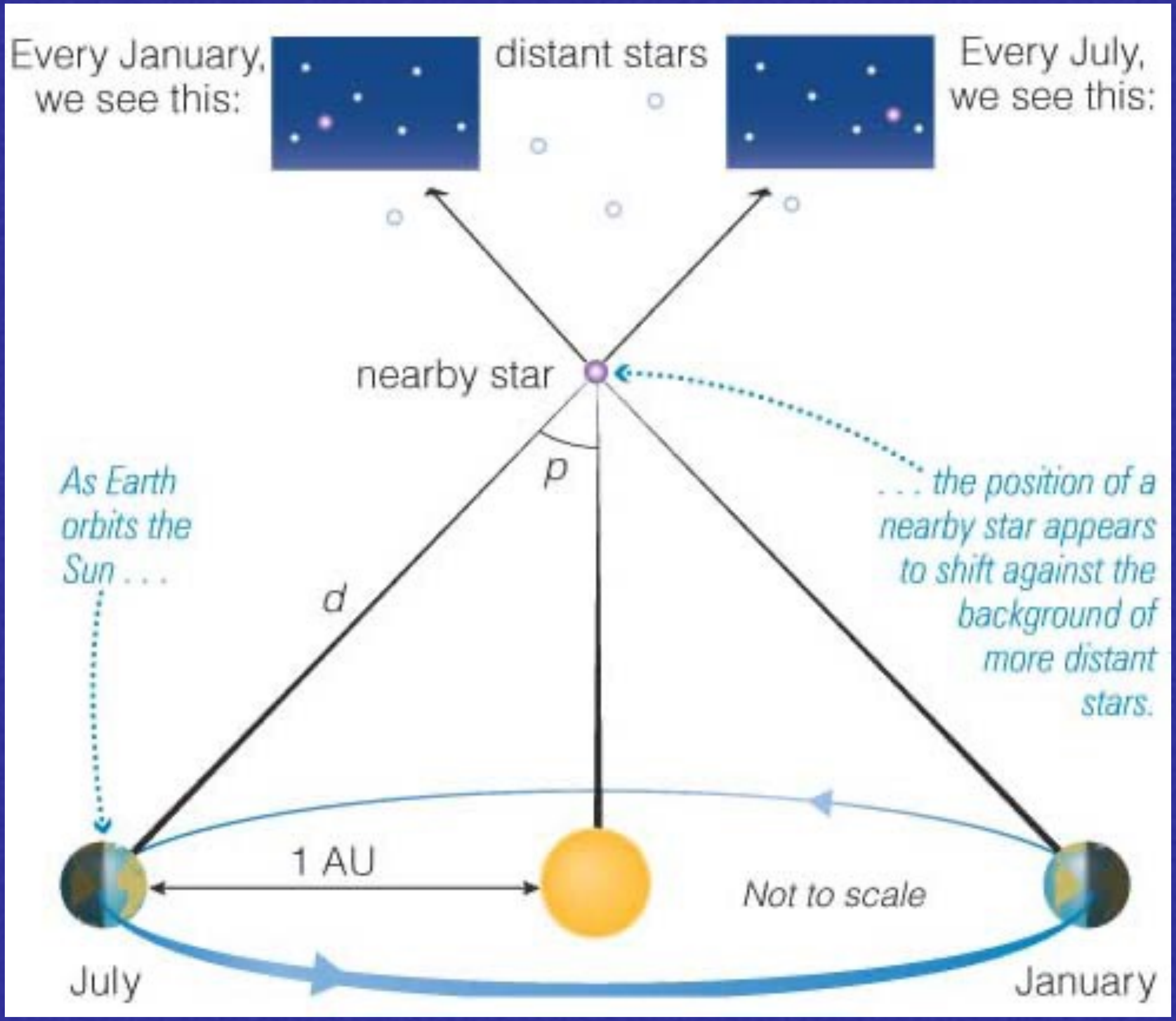
How can we describe/classify stars?

- Temperature
- Luminosity (total energy output)
- Mass (orbital motion)
- Physical sizes
- True motion in space

To estimate those parameters, we need to know the distance!

Two dimensions are easy – use photograph for angular position.
Distance not so easy, the only direct means is by parallax.

Parallax is the apparent angular shift of an object due to a change in an observer's point of view.



The parallax formula for distance

- $d = 1/p$ where p is the parallax angle and d is the distance in pc.
- Distance units: 1 pc = 3.26 ly = 3.09×10^{16} m = 206,265AU
- It took us until 1838 to measure stellar parallaxes since the stars are so far away => small parallax angles

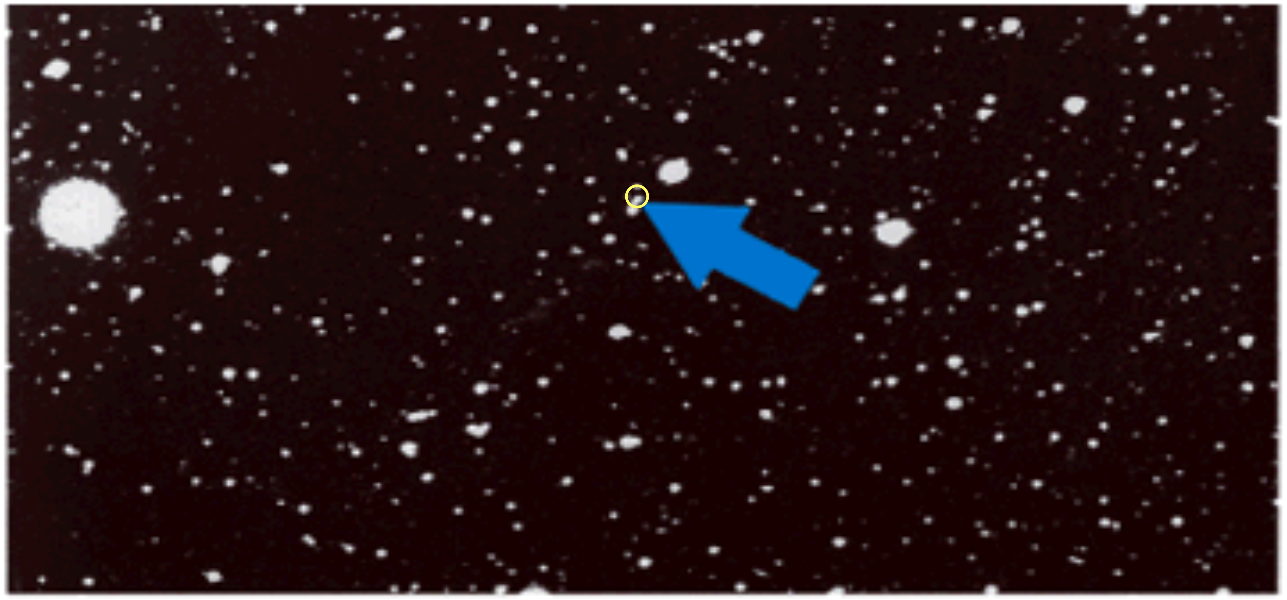
Limitations

- Until recently we only knew accurate (0.01") parallaxes for a few hundred stars (=> d~100pc)
- In the 1990's the ESA satellite Hipparchos measured over 100,000 parallaxes with an accuracy of 0.001"
- Gaia has measured over a billion stars to 2 kpc

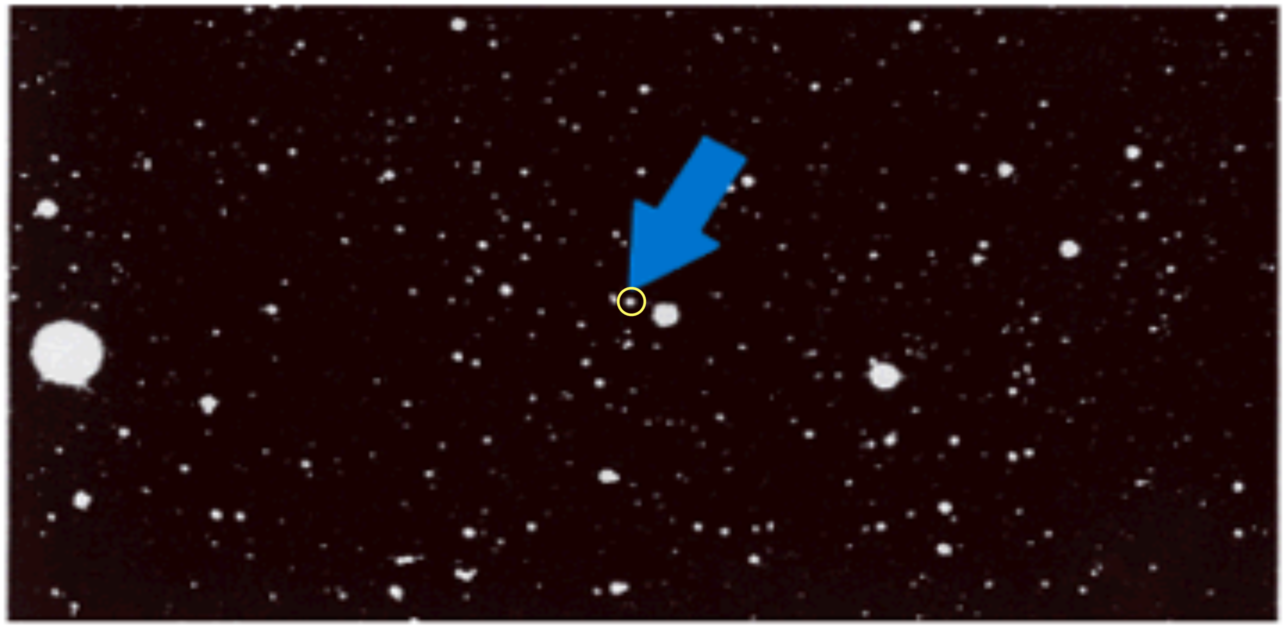
Gaia satellite

Proper motion

- Caused by physical movement of a star with respect to our Solar system
- This is in contrast to parallax which is an apparent motion of the star due to the motion of the Earth
- Proper motion is the angle a star moves per year (angular motion on the sky), and it is a linear drift
- The superposition of this linear drift and the elliptical motion from the parallax effect leads to a 'wavy' path on the sky



August 24, 1894



May 30, 1916

This star moved 4' over this time - a huge proper motion of 10″.9/yr.

Tangential velocity

$v_t = 4.74\,\mu d$, where μ is the proper motion [″/yr] and *d* is the distance [pc]; this choice of constants gives v_t in the units of km/s.

Dependent on distance

Radial velocity

Given by Doppler shift:

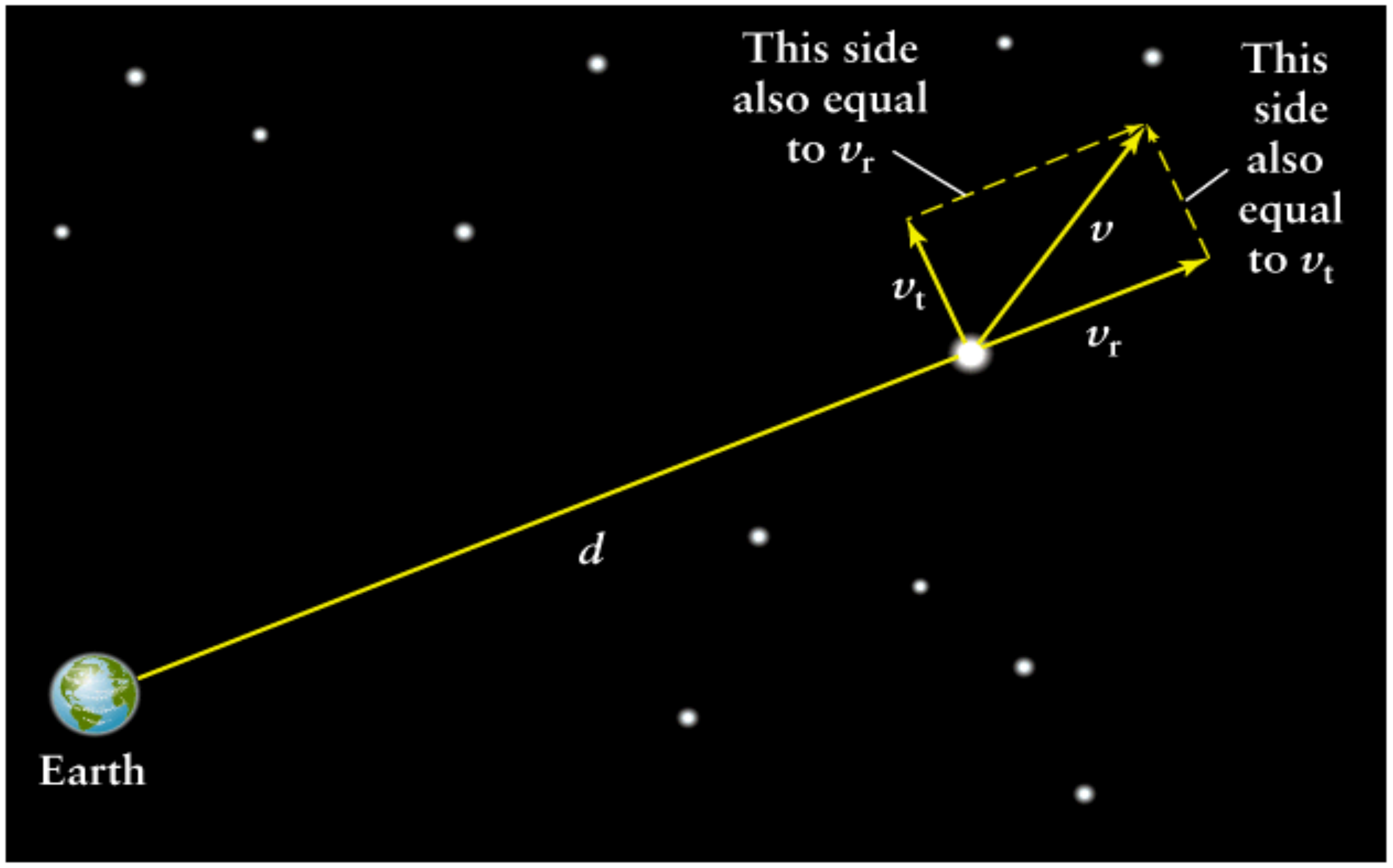
$v_r = [(\lambda_{observed} - \lambda_{emitted}) / \lambda_{emitted}]\, c$

Independent on distance

Space Velocity

Speed and direction of star. From Pythagorean theorem

$$V = \sqrt{V_t^2 + V_r^2} = \sqrt{(4.74\mu d)^2 + V_r^2}$$



Typical stellar space velocities are 20-100 km/s.

Three quantities need to be measured - distance is the most difficult one.

Why care about stellar motions?

- A tool to study structure of our Galaxy
  - Motion of the Sun (~ 20km/s)
  - Rotation of the Galactic Plane (local)
  - Odd phenomena/stars that might indicate special events
  - Past merger events

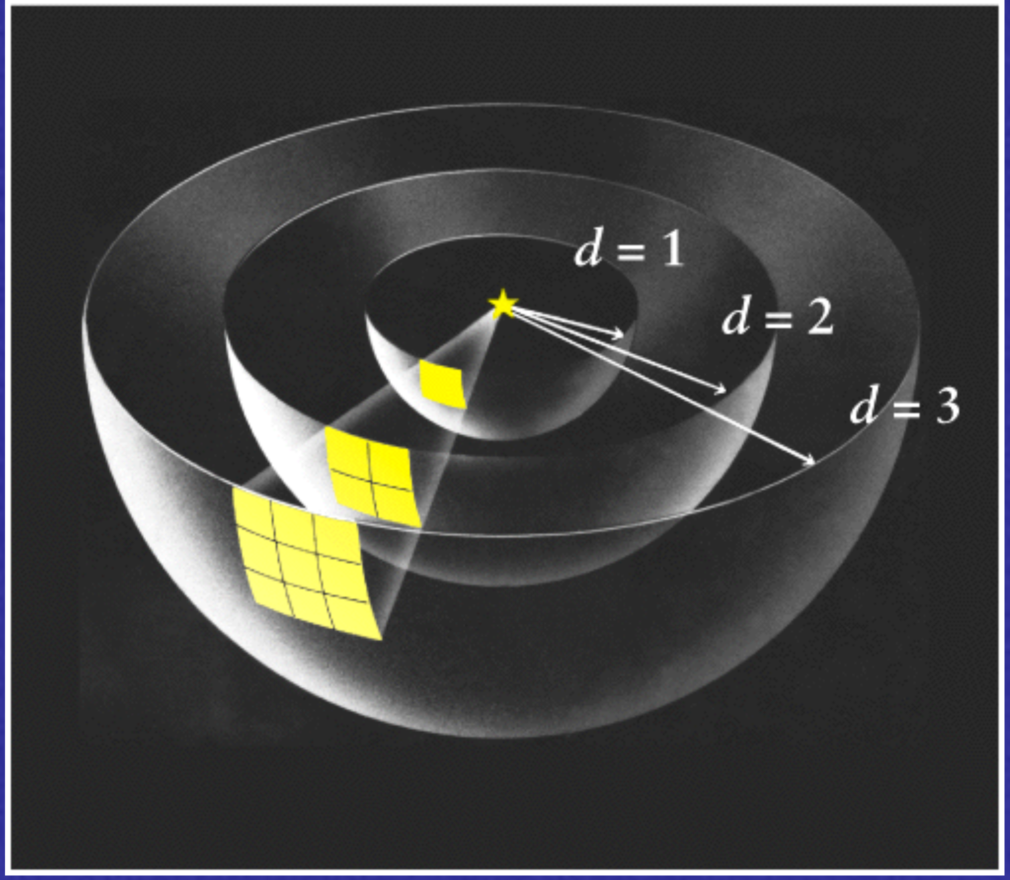
How bright is a star?

- Luminosity (*L*, intrinsic property): the total energy output, a physical property of the star. Doesn't depend on distance.

- Apparent brightness (*F*, or *b*): measures how bright a star appears to be on a distance. Does depend on distance!

- The brightness, or intensity, of light diminishes as the inverse square of the distance.

$$F = L/4\pi d^2$$



Same amount of radiation from a star must illuminate a bigger area as distance from star increases.The area increases as the square of the distance.

Apparent magnitudes

- Measurement of brightness of stars as they seem from Earth.
- Smaller magnitudes mean brighter stars and defined such that 5 magnitude differences implies a factor of 100 in brightness
- Magnitude difference related to brightness ratio:

$$m_2 - m_1 = 2.5\log\left(\frac{b_1}{b_2}\right)$$

- Also note: if $\frac{b_1}{b_2} = 100$, then $2.5\log\left(\frac{b_1}{b_2}\right) = 5$
- This is a logarithmic scale - no zero point is defined. Done by defining certain stars to have zero magnitude.

Apparent magnitude difference ($m_2 - m_1$)	Ratio of apparent brightness (b_1/b_2)
1	2.512
2	$(2.512)^2 = 6.31$
3	$(2.512)^3 = 15.85$
4	$(2.512)^4 = 39.82$
5	$(2.512)^5 = 100$
10	$(2.512)^{10} = 10^4$
15	$(2.512)^{15} = 10^6$
20	$(2.512)^{20} = 10^8$

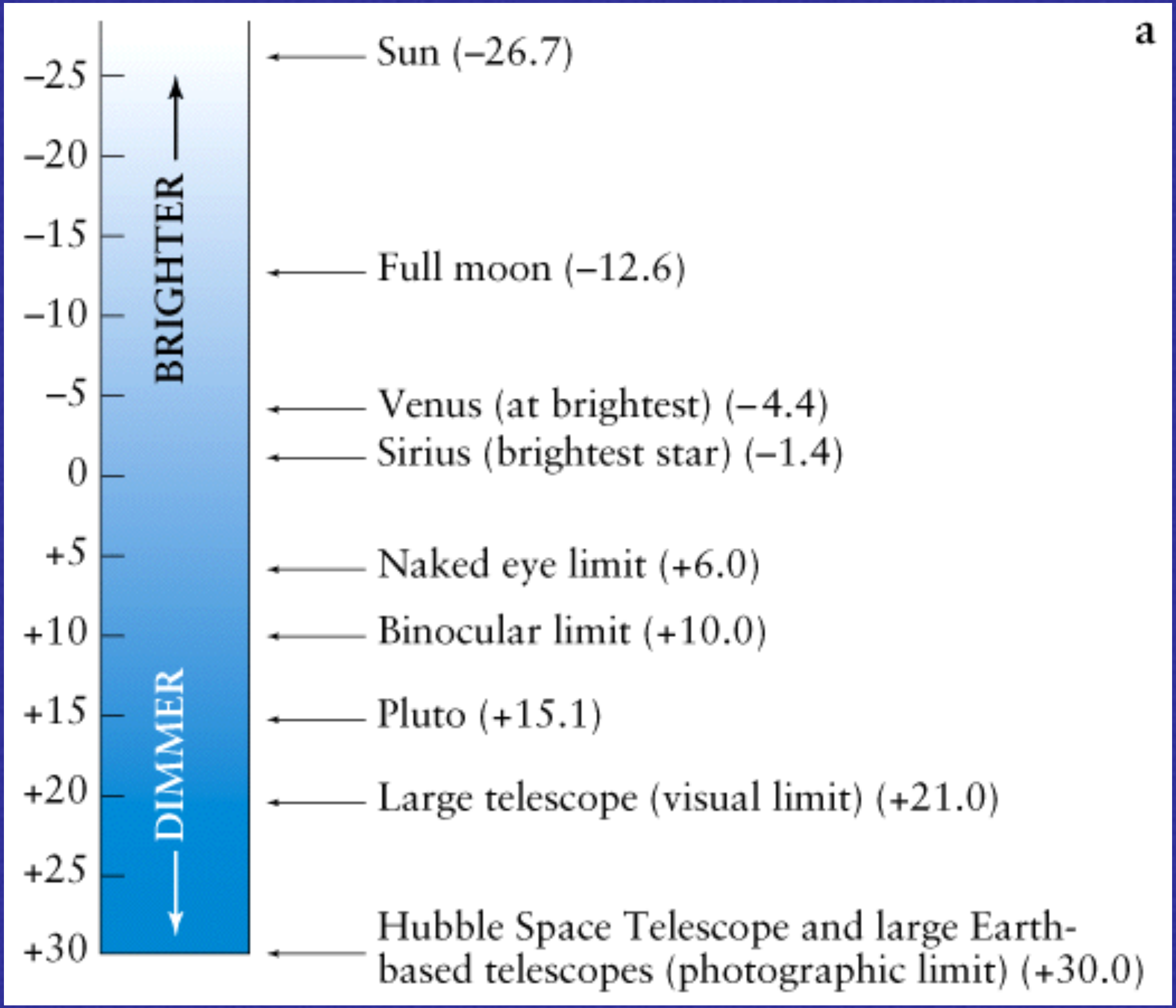
A simple equation relates the difference between two stars' apparent magnitudes to the ratio of their brightnesses:

Magnitude difference related to brightness ratio

$$m_2 - m_1 = 2.5 \log\left(\frac{b_1}{b_2}\right)$$

A factor of 2.512 difference in brightness per magnitude. Box 17-3.

- The apparent magnitude scale - some examples:



Absolute magnitude

Caution:

Apparent magnitude is NOT power output! A star may have bright (small) apparent magnitude because it is close to us, or it might have a bright (small) magnitude because it produces a huge amount of light.

As scientists, we want a brightness scale that takes distance into account and measures the *total* energy output of the star.

Absolute magnitude:

Definition: the apparent magnitude a star would have if it were precisely 10 pc away from us

$$m - M = 5\log(d) - 5$$

m is apparent magnitude (measured)

d is distance (calculated from parallax)

M is absolute magnitude

Derivation

This comes from the definition of magnitude (a magnitude difference of 5 equals a factor 100 in brightness):

$$m_2 - m_1 = 2.5\log\left(\frac{F_2}{F_1}\right) \longrightarrow \frac{F_2}{F_1} = 100^{(m_1 - m_2)/5}$$

Now assume star 1 is at a distance *d* with an apparent magnitude $m_1 = m$, and star 2 is at the distance of 10 pc with apparent magnitude $m_2 = M$:

$$\frac{F_{10\,pc}}{F_d} = 100^{(m-M)/5}$$

Next we use the relation $F = L/4\pi d^2$ or, equivalently $b = L/4\pi d^2$

$$\frac{F_{10\,pc}}{F_d} = \frac{L}{4\pi(10\,\mathrm{pc})^2}\frac{4\pi d^2}{L} = \frac{d^2}{100\ \mathrm{pc}^2}$$

Thus,

$$\frac{d^2}{100\ \text{pc}^2} = 100^{(m-M)/5} \rightarrow d^2 = 100 \times 100^{(m-M)/5} = 100^{5/5} \times 100^{(m-M)/5} = 100^{(m-M+5)/5}$$

Taking the log of this then yields

$$2\log(d) = \frac{m-M+5}{5}\log(100) = \frac{m-M+5}{5}2$$

$$m - M + 5 = 5\log(d) \rightarrow m - M = 5\log(d) - 5$$

where *d* must be in units of parsecs.

The absolute magnitude is a more useful measure of a star's power output (Luminosity).

Examples:

M	Star
-5	Betelgeuse
-1.5	Sirius
+5	Sun
+10	Sirius B

- Since $L = 4\pi d^2 b$, we can compare any star's luminosity to the Sun's by a ratio:

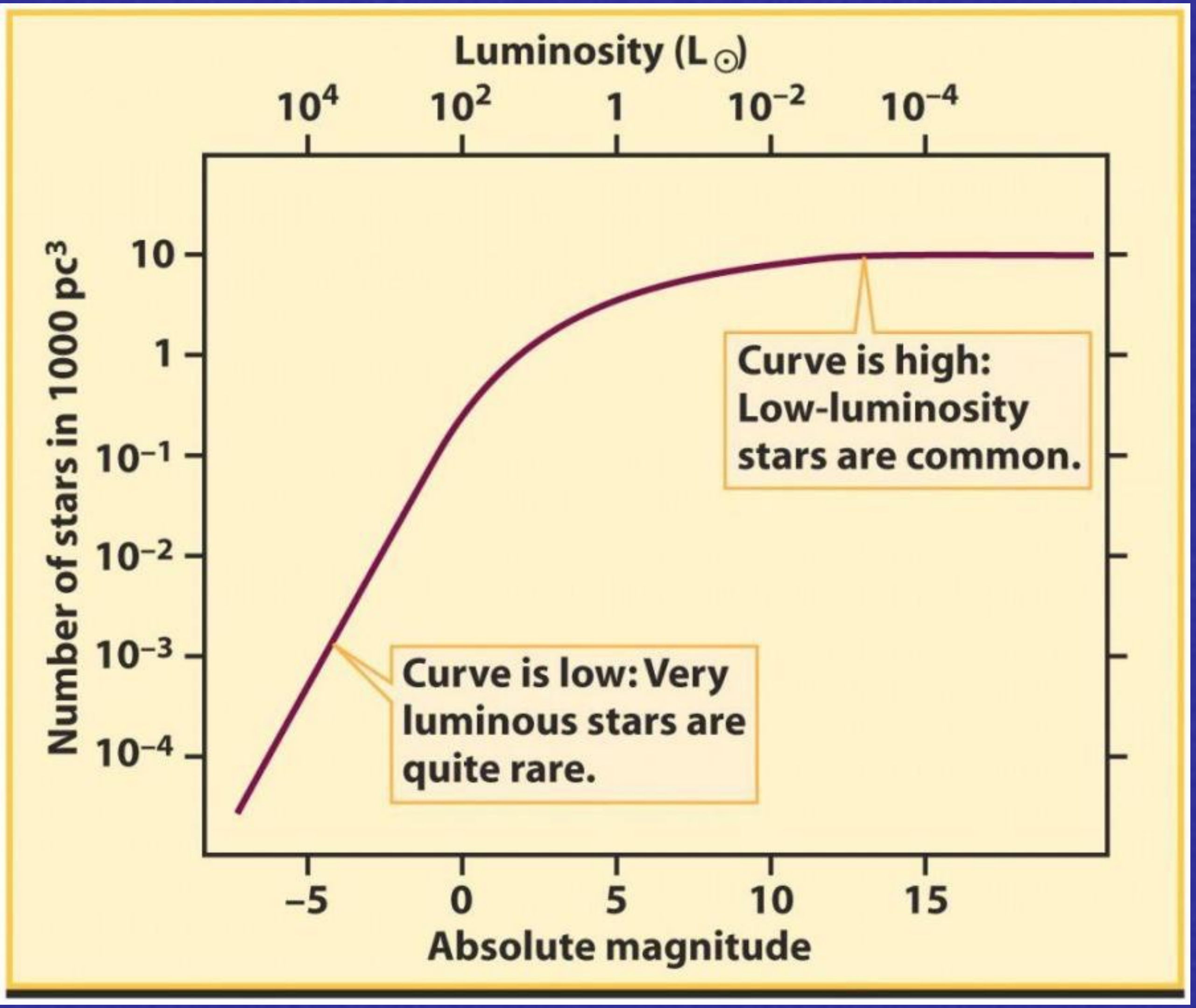
$$\frac{L_*}{L_{Sun}} = \frac{4\pi d_*^2 b_*}{4\pi d_{sun}^2 b_{Sun}} = \left(\frac{d_*}{d_{Sun}}\right)^2 \frac{b_*}{b_{Sun}}$$

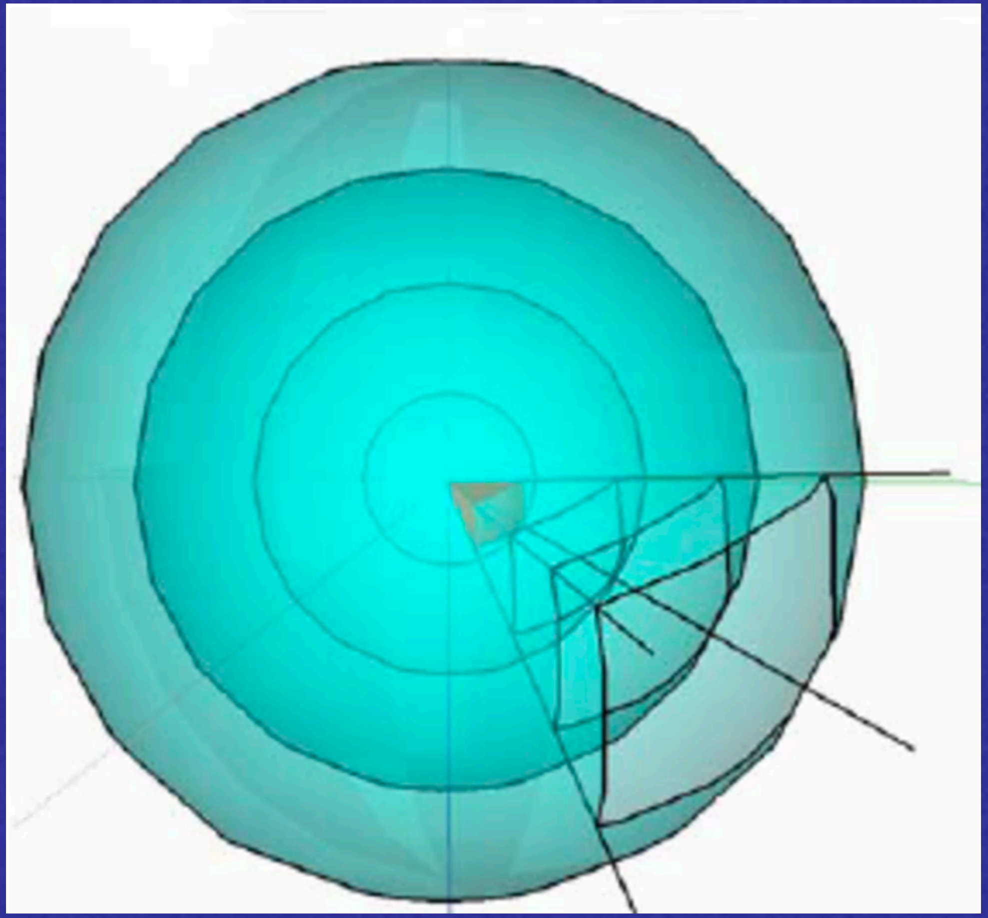
- Knowing relative distance and brightness, we know the star's relative luminosity. Finally, you can show that

$$M_{Sun} - M_* = 2.5 \log \frac{L_*}{L_{Sun}}$$

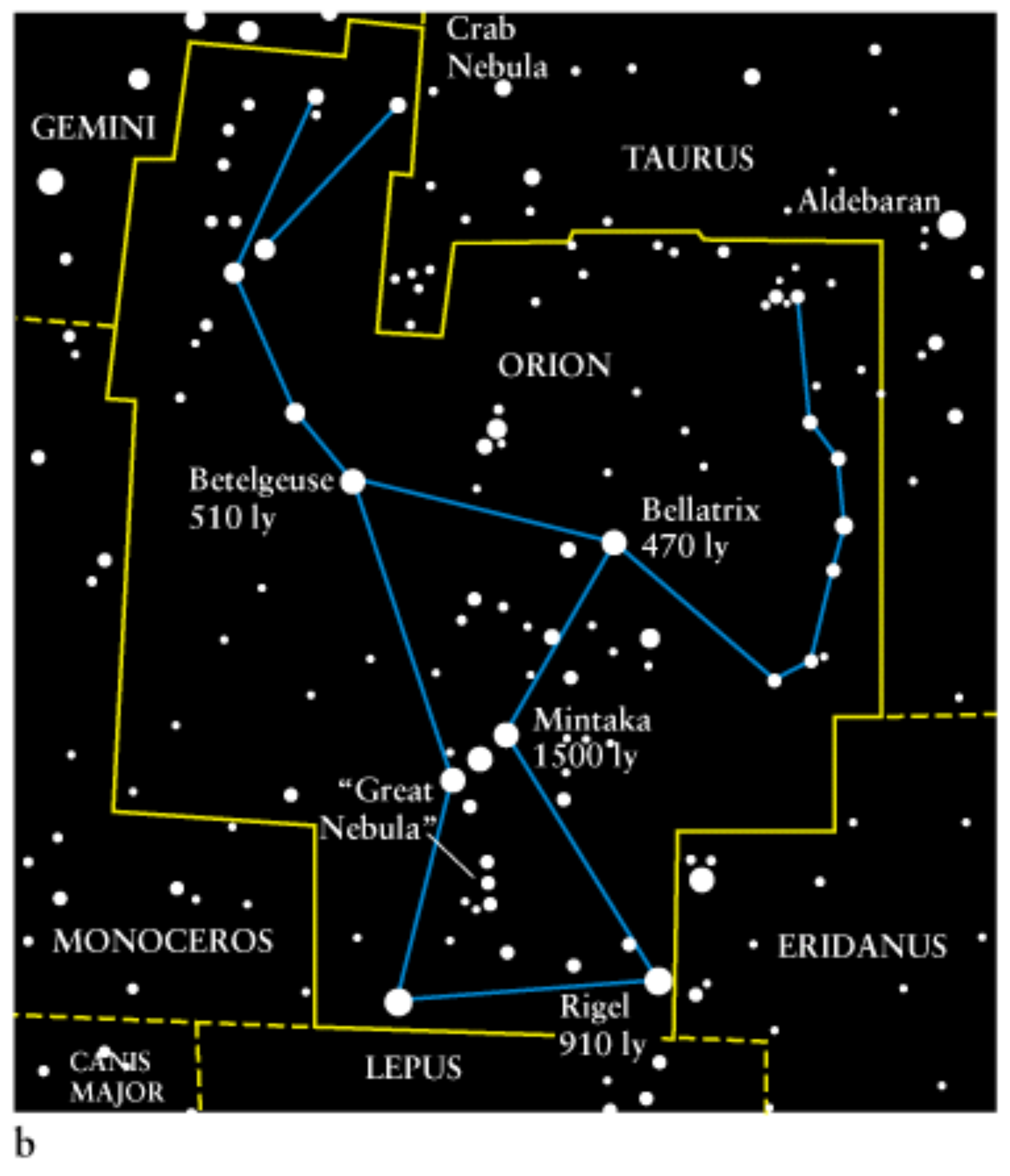
Luminosity function

- Describes the relative numbers of stars with different luminosities
- There are more faint stars than bright
- Note the enormous range in luminosity





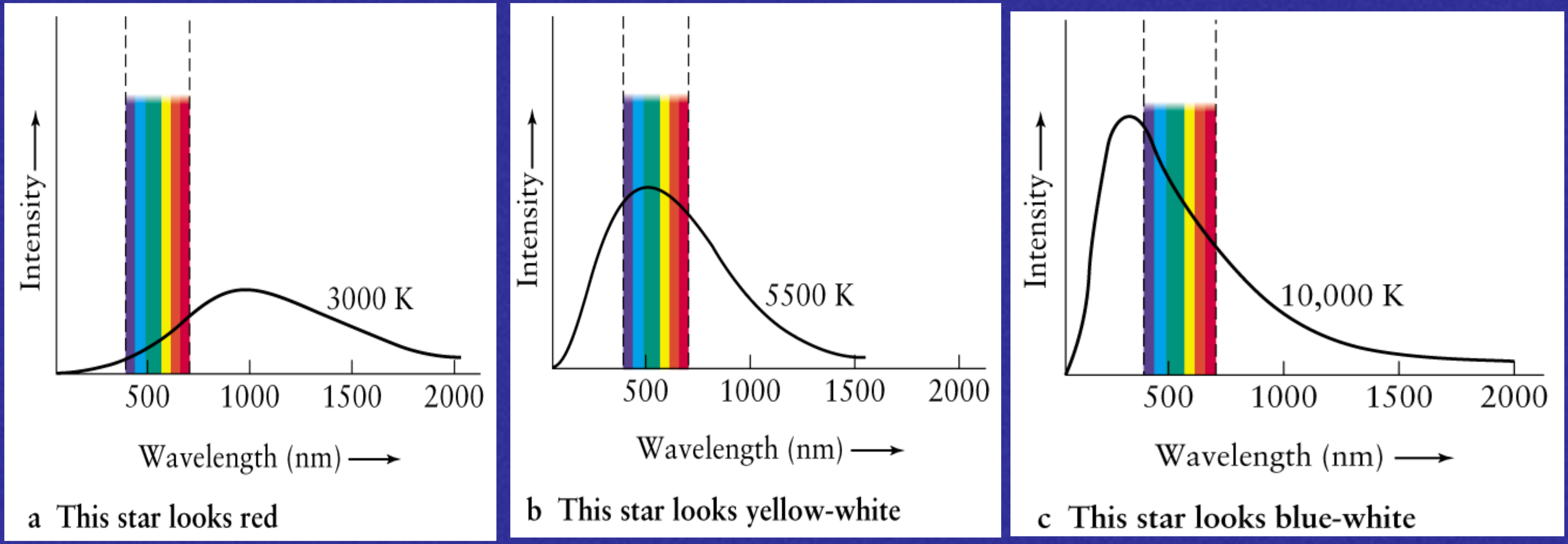
Are you seeing neighbor stars, or highly luminous (but distant) stars?



Recall that 1 pc is 3.26 ly. E.g. Betelgeuse is about 160 pc away.

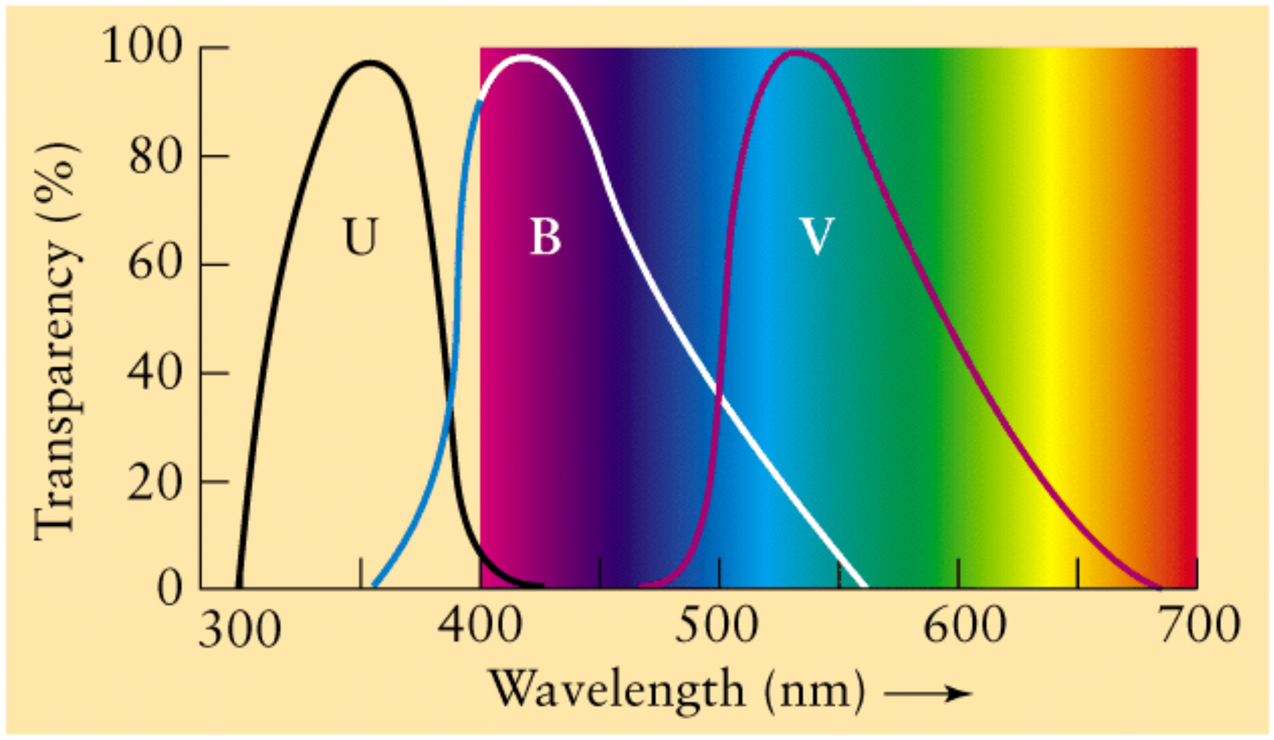
Colors of stars

- From Wien's law $\lambda_{max} = 0.0029/T$ we expect hotter objects to be bluer.



To measure colors

- A set of filters can be used to determine the colors of stars



The UBV system

- In fact, we don't need distances - apparent magnitudes in each filter works
- If a B magnitude is small, does that mean that the star is very blue?
  - Not necessarily, the V and R magnitudes might be even smaller. Then the star is brighter in redder filters.

To quantify color: color index

- Need brightness measurements through at least 2 filters to determine color
- Example: B-V color index

$$CI = B - V = 2.5\log\left(\frac{b_V}{b_B}\right) + const$$

- The constant is chosen so that a star at 10^4 K has a B-V = 0.0

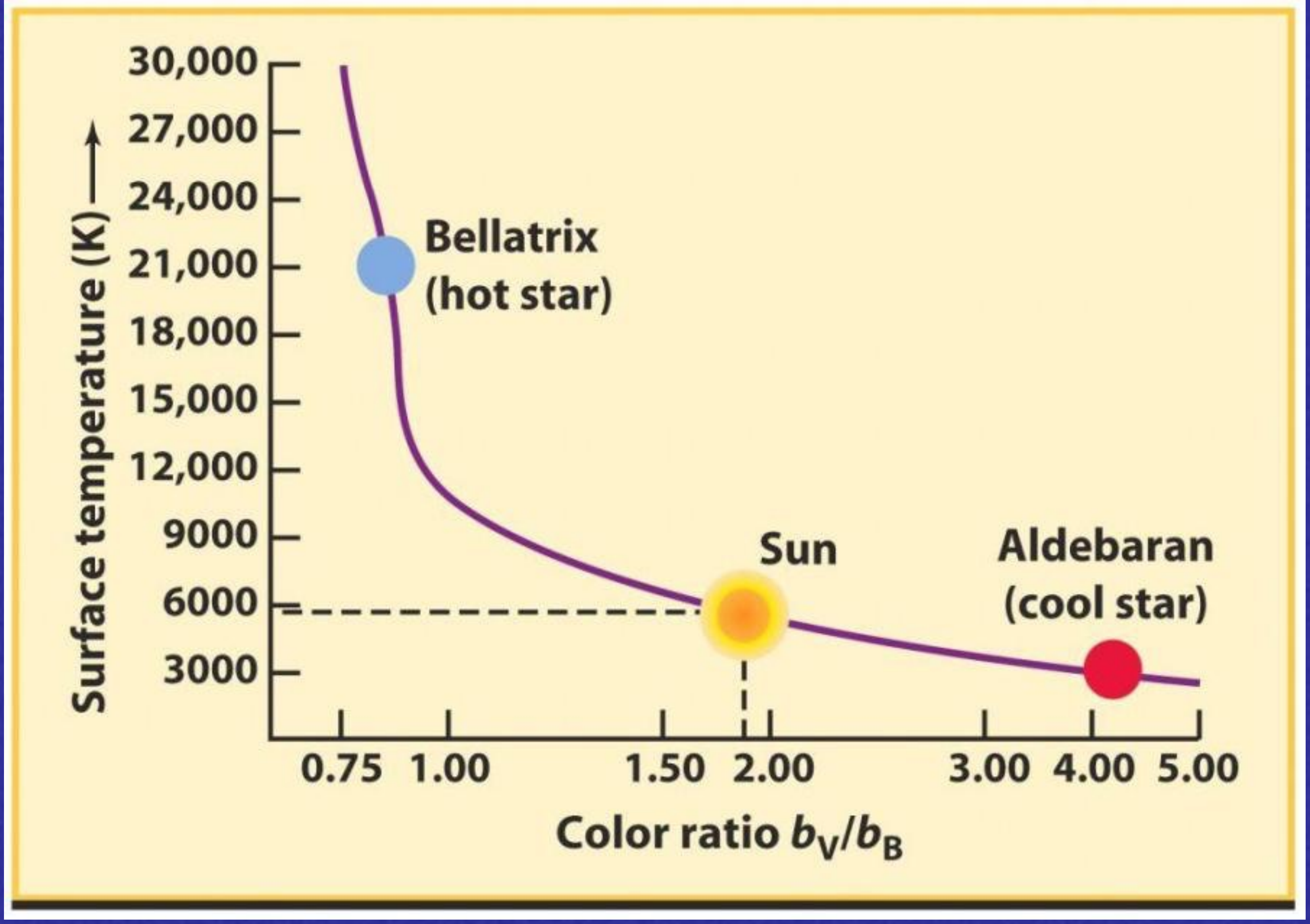
table 19-1 Colors of Selected Stars

Star	Surface temperature (K)	b_V/b_B	b_B/b_U	Apparent color
Bellatrix (γ Orionis)	21,500	0.81	0.45	Blue
Regulus (α Leonis)	12,000	0.90	0.72	Blue-white
Sirius (α Canis Majoris)	9400	1.00	0.96	Blue-white
Megrez (δ Ursae Majoris)	8630	1.07	1.07	White
Altair (α Aquilae)	7800	1.23	1.08	Yellow-white
Sun	5800	1.87	1.17	Yellow-white
Aldebaran (α Tauri)	4000	4.12	5.76	Orange
Betelgeuse (α Orionis)	3500	5.55	6.66	Red

Source: J.-C. Mermilliod, B. Hauck, and M. Mermilliod, University of Lausanne.

Temperature, color and color ratio

- The b_V/b_B color ratio is small for hot stars, and large for cool stars.

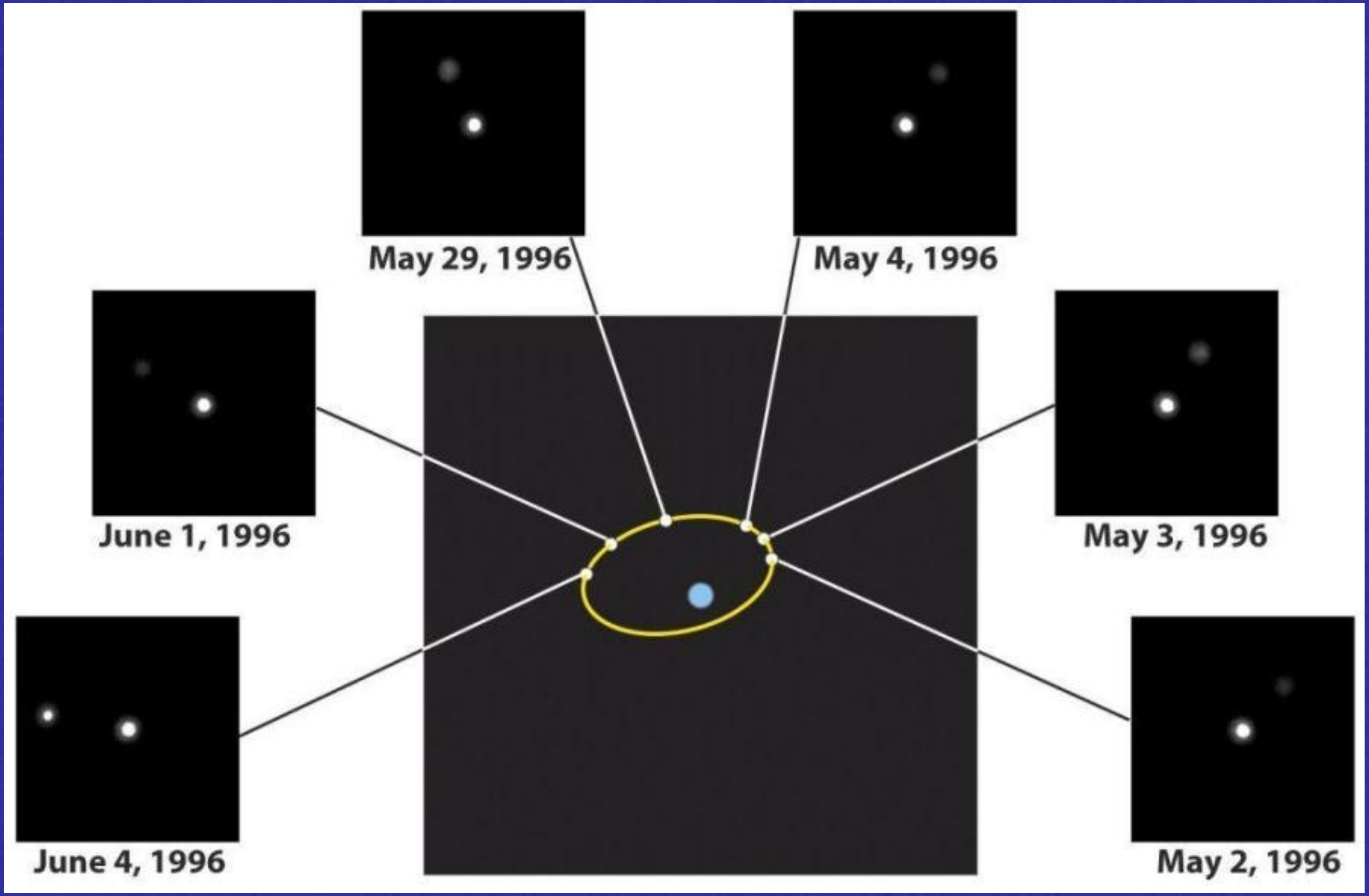


Binary stars

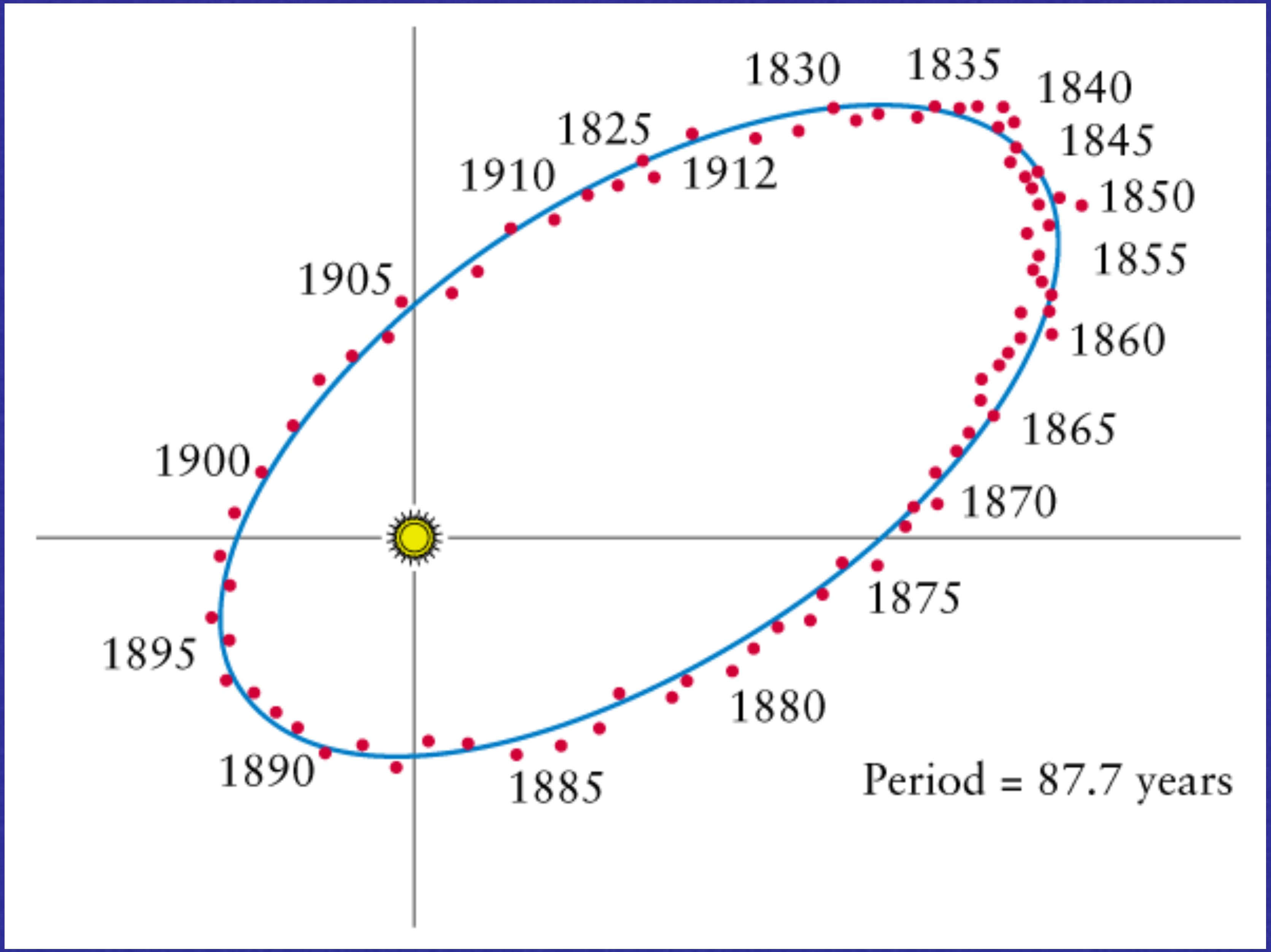
Tatooine

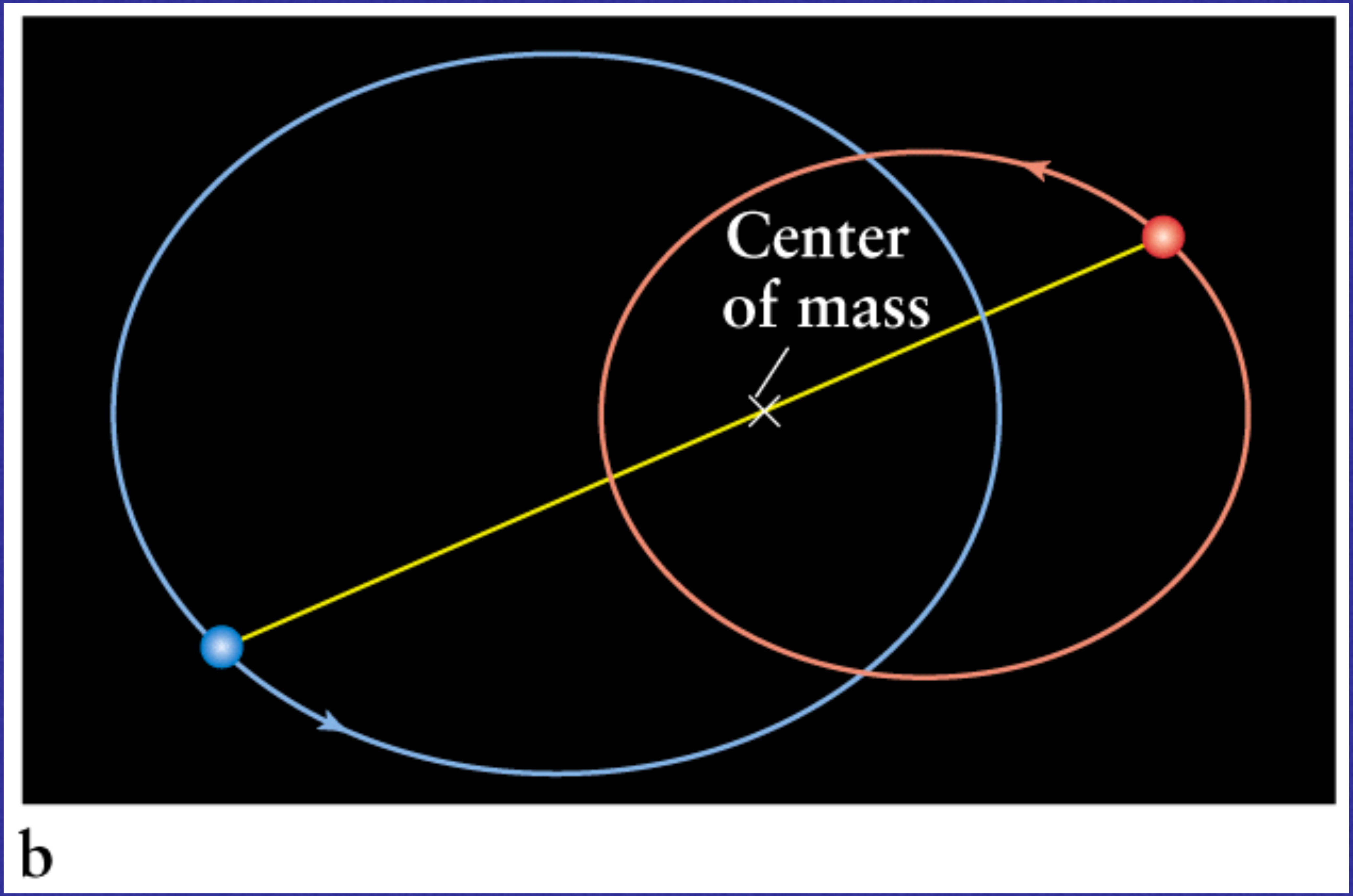
Binary stars

1. Visual binaries - can see both stars. Binaries (any type) always orbit around the mutual center of mass.



- Can plot orbit of either star around the other, treated as stationary.





$$a_1M_1=a_2M_2$$

where a = semimajor axis, M = mass

Recall semimajor axis = half of the long axis of ellipse

Visual binaries allow direct calculation of stellar masses. Use Kepler's third law:

$$M_1 + M_2 = \frac{a^3}{P^2}$$

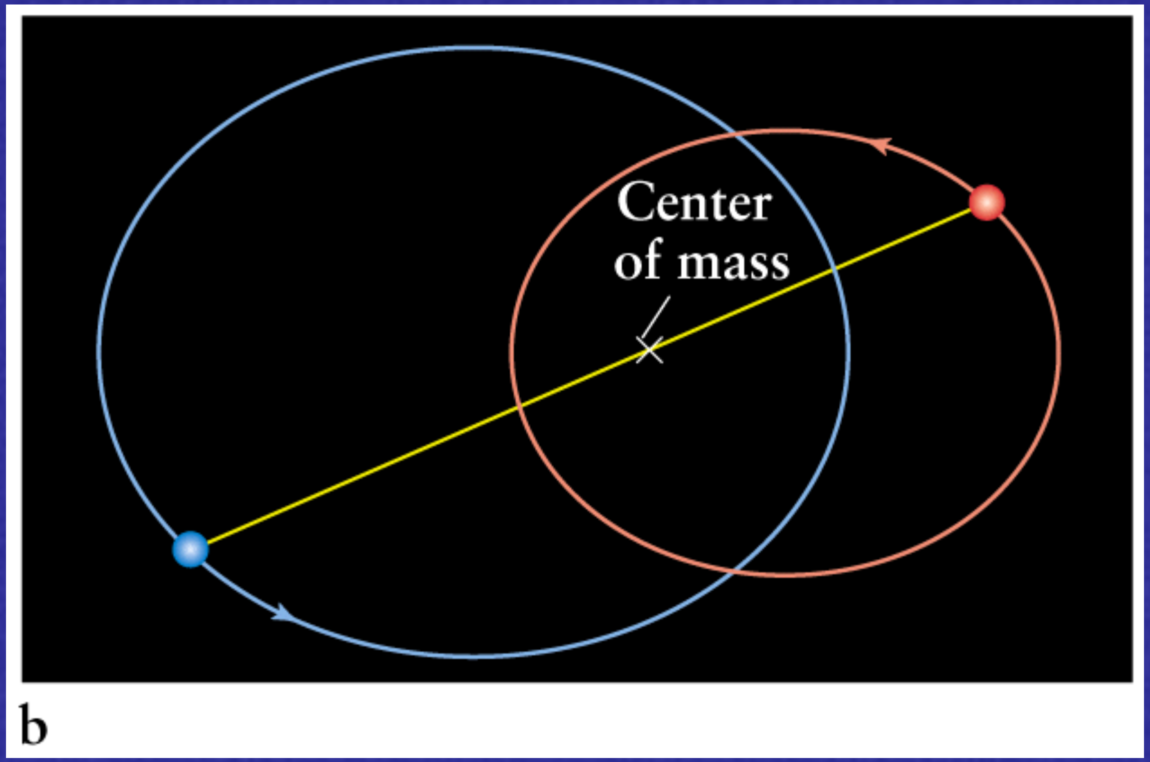
M_1, M_2 are masses of the two stars (in $M_\odot$)

a = semimajor axis of one star's orbit around the other (in units of Earth-Sun distance, AU)

P = orbital period (in years)

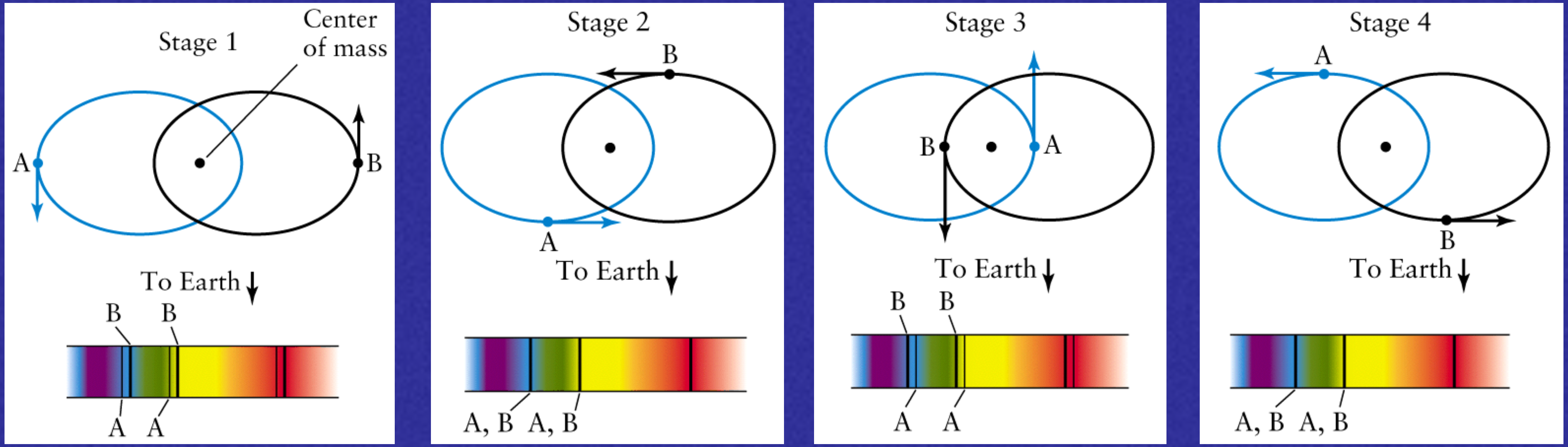
- Gives the sum of the masses, not individual masses. Need another equation: Use fact that the more massive star will be closer to center of mass:

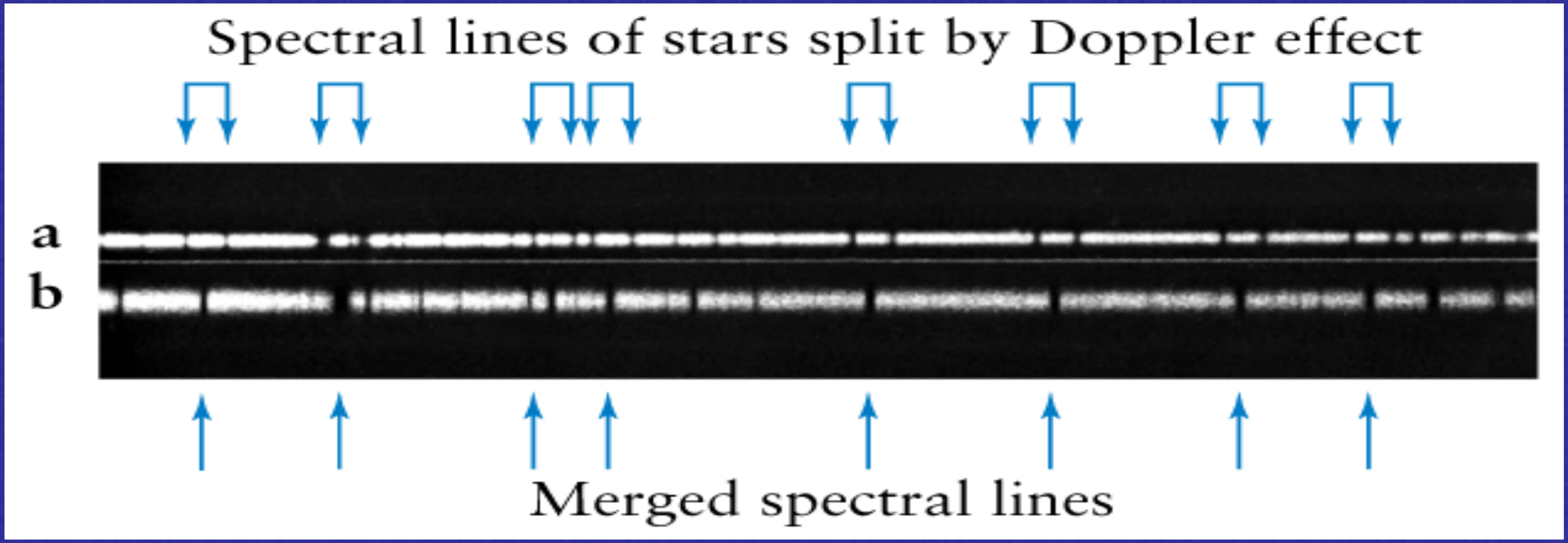
$$\frac{a_2}{a_1} = \frac{M_1}{M_2}$$



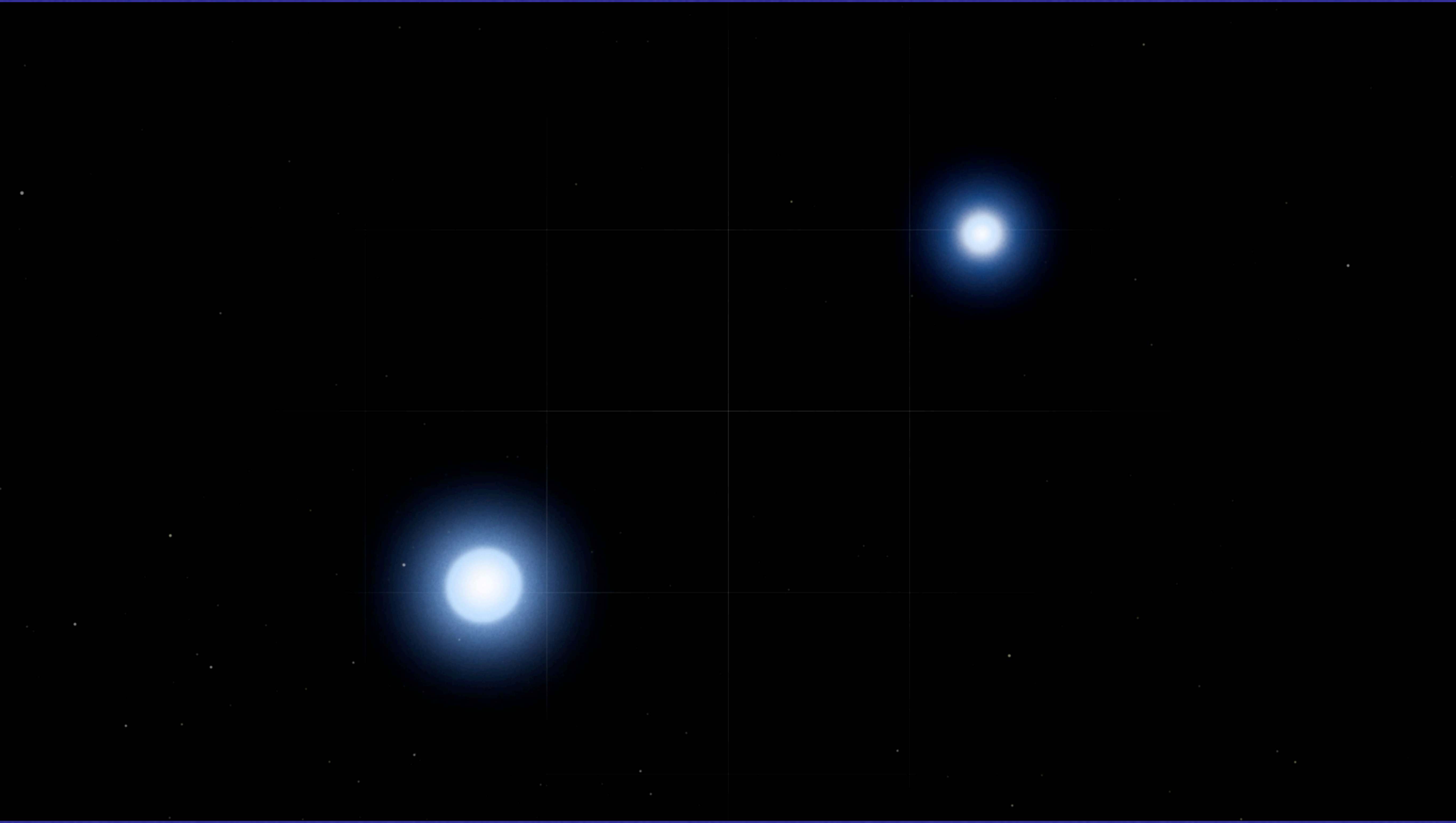
- Two equations in two unknowns => can solve for individual masses.

2. Spectroscopic binaries - even if you can't see both stars, might infer binary from spectrum

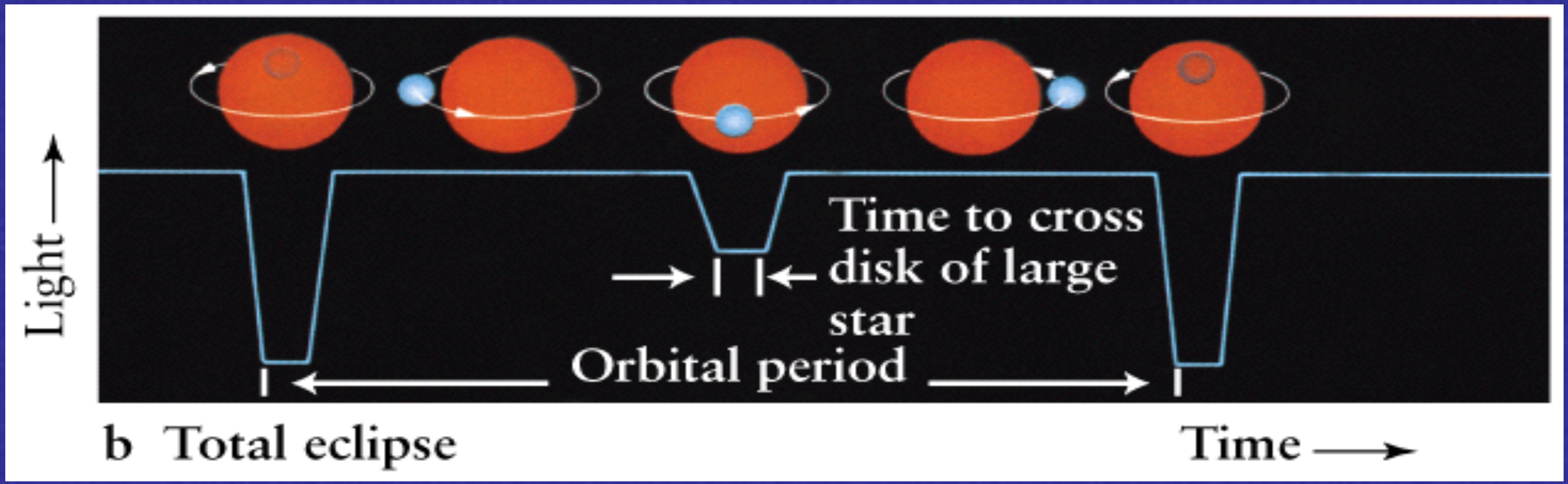


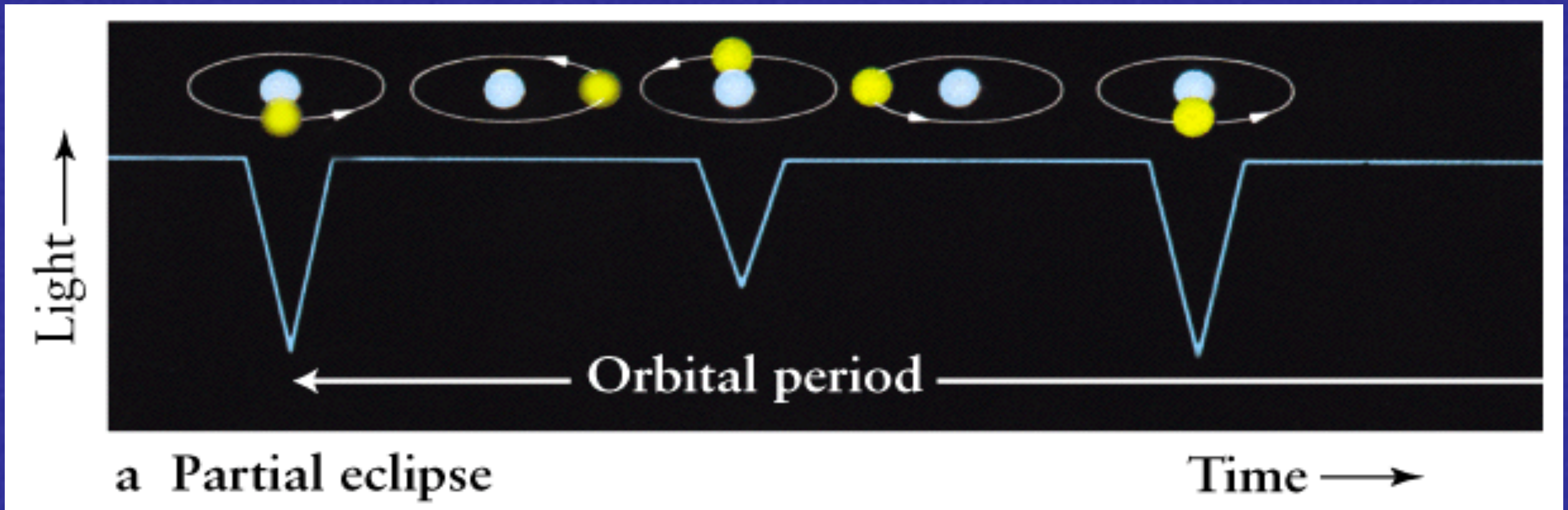


3. Eclipsing binaries - stars periodically eclipse each other.



3. Eclipsing binaries - stars periodically eclipse each other. Can tell it's binary from "light curve" - plot of brightness vs. time.





4. Astrometric binaries - one star can be seen, the other can't. The unseen companion makes the visible star "wiggle" on the sky.