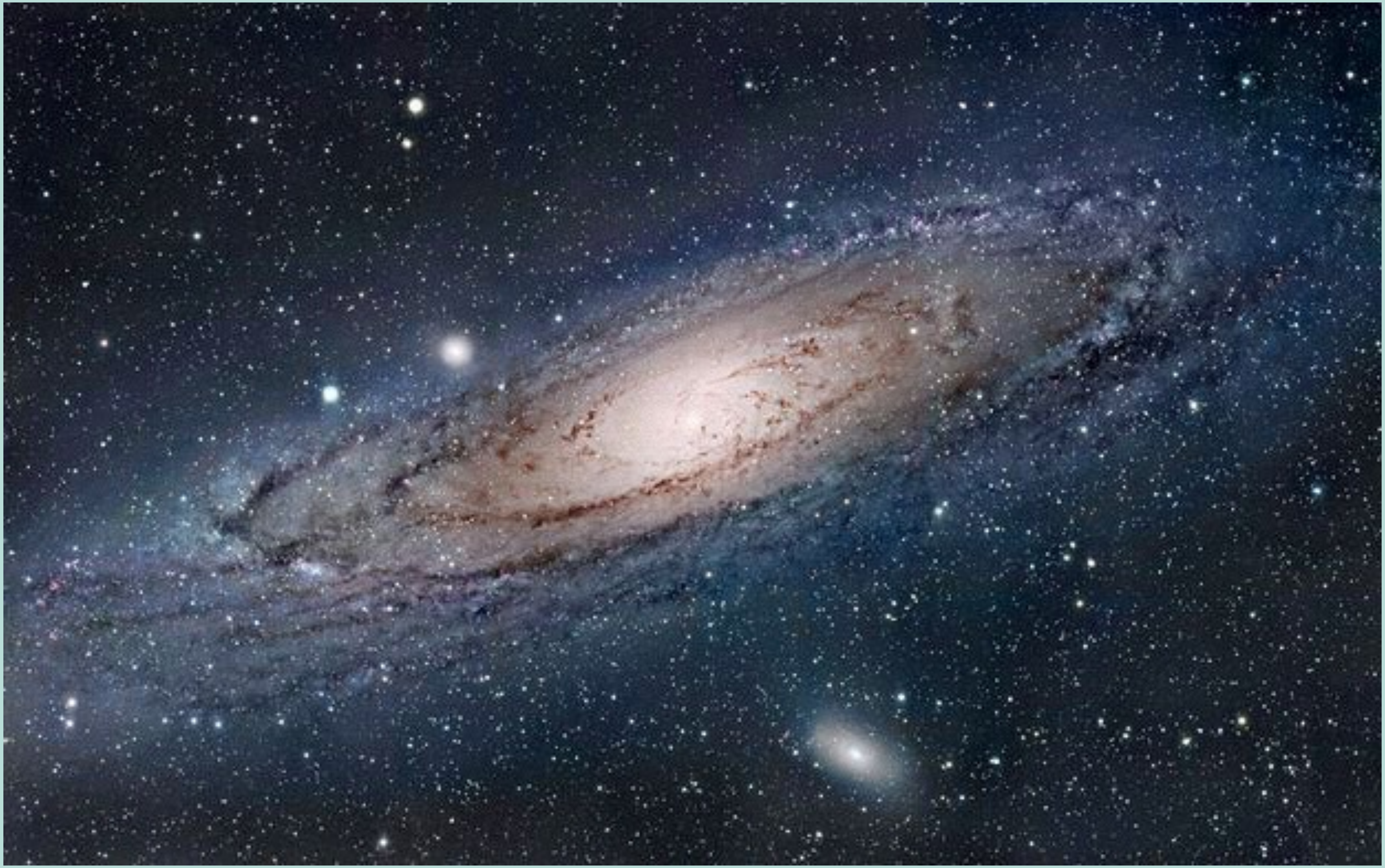
UCOR-125:

Astronomy

with your host:

Coop

Lecture 15: Stars

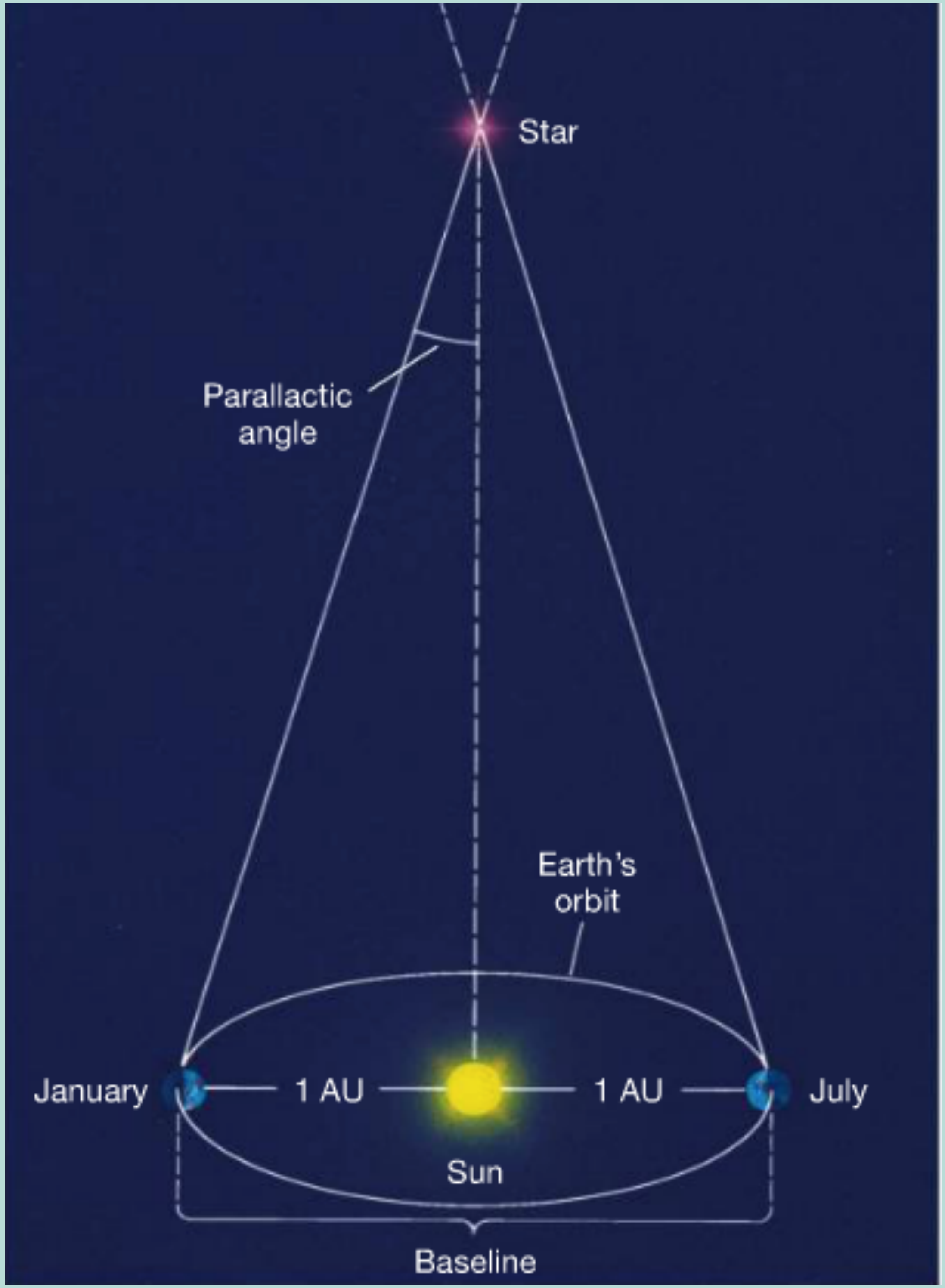


Milky Way

M ~ 3 e 12 M_sun

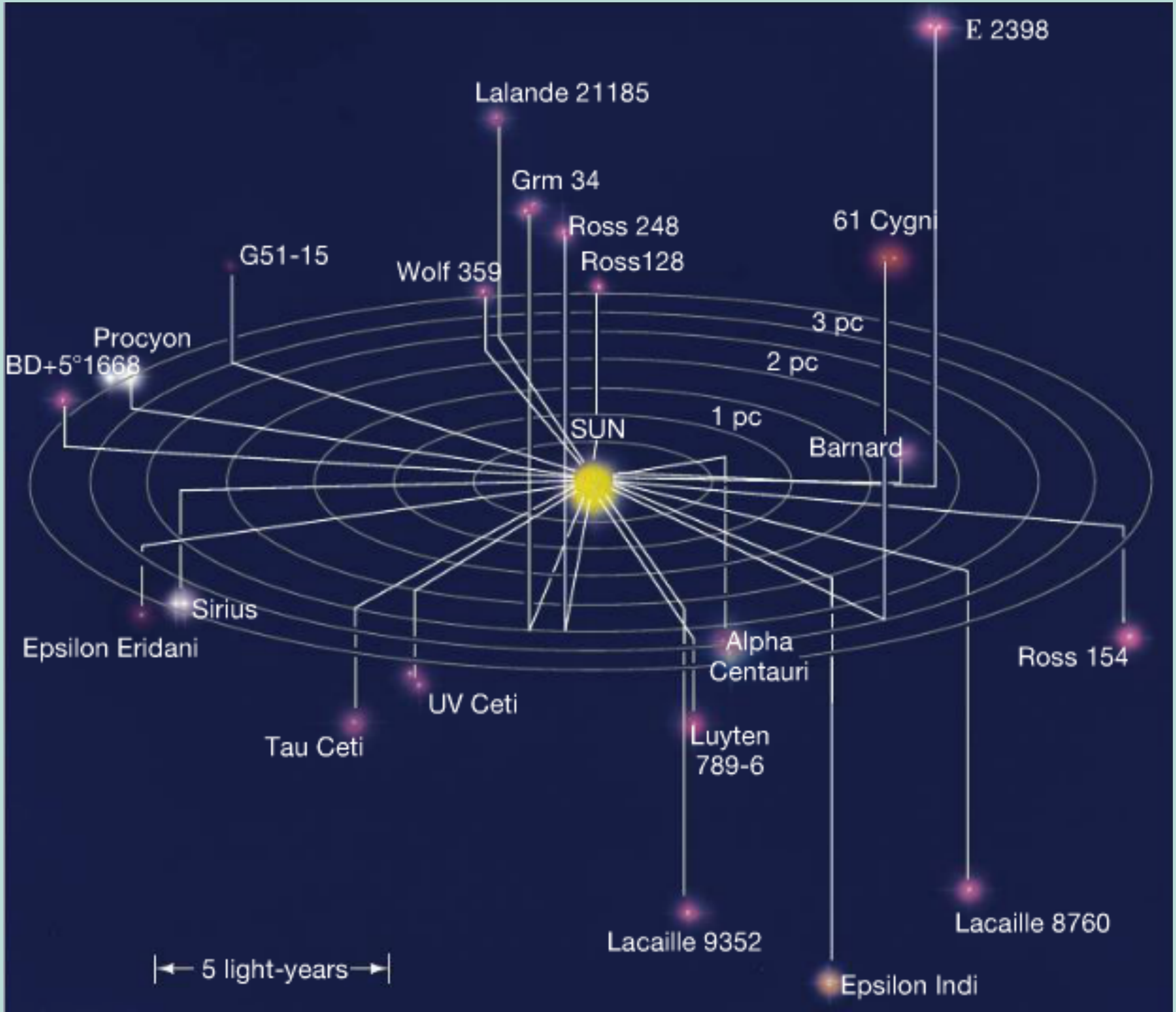
R ~ 5 e 4 lty, 15 kpc

Good Ol' Parallax



$$\text{distance} = \frac{1}{\text{parallax}}$$

Our Stellar Neighborhood

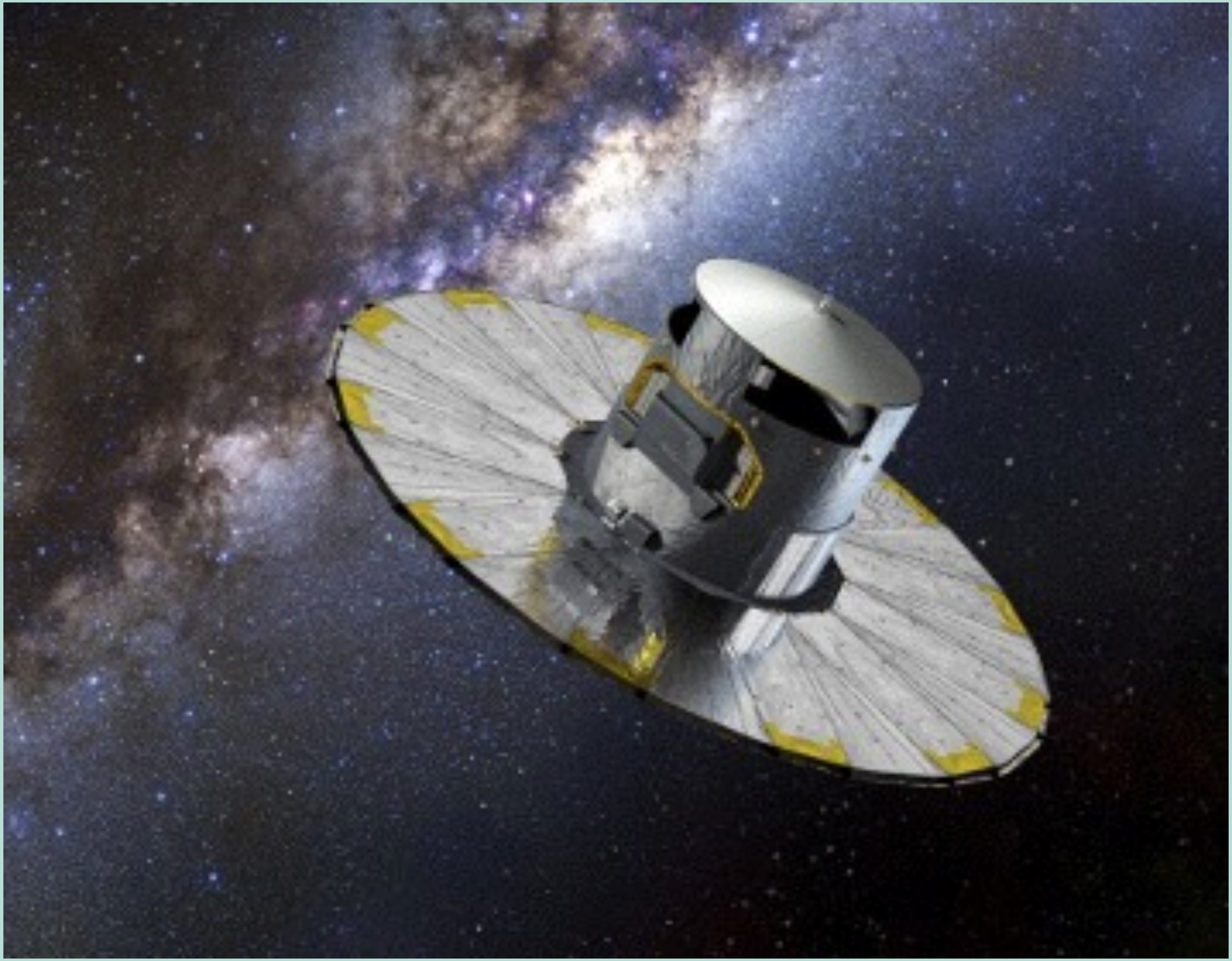


- Proxima Centauri, part of the Alpha Centauri Complex is 1.3 pc away (4.3 light years)

- Pearson Loves Analogies: Earth is a grain of sand, the sun is a marble 1m away, Proxima is a marble 270 kilometers away

- Recall, seeing disks are about an arc second, so 1 parsec is the limit without advanced technology

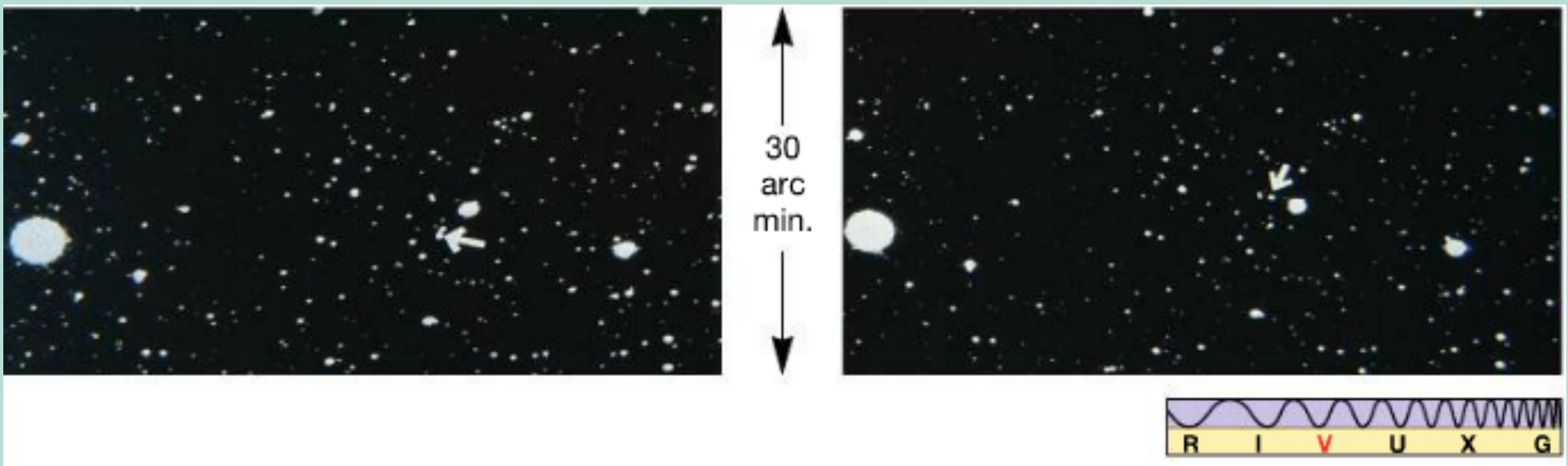
GAIA (In Progress)



- Will map ~1% of the Milky Way

Stellar Motion

Barnard's Star

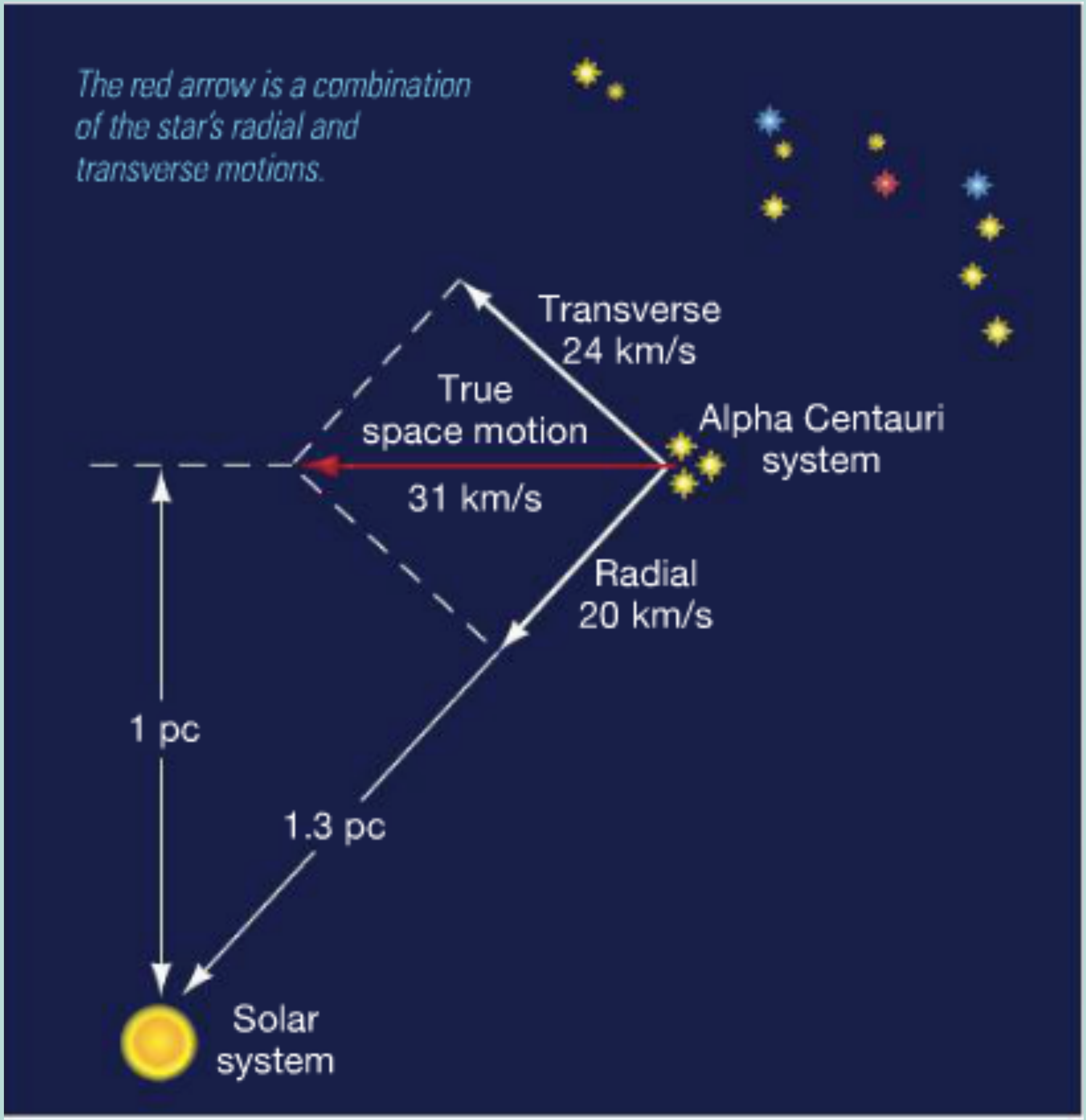


- Proper motion observed over 22 year period

- At 1.8 pc, this 10.4'' angle the star sweeps out per year amounts to 89 km/s

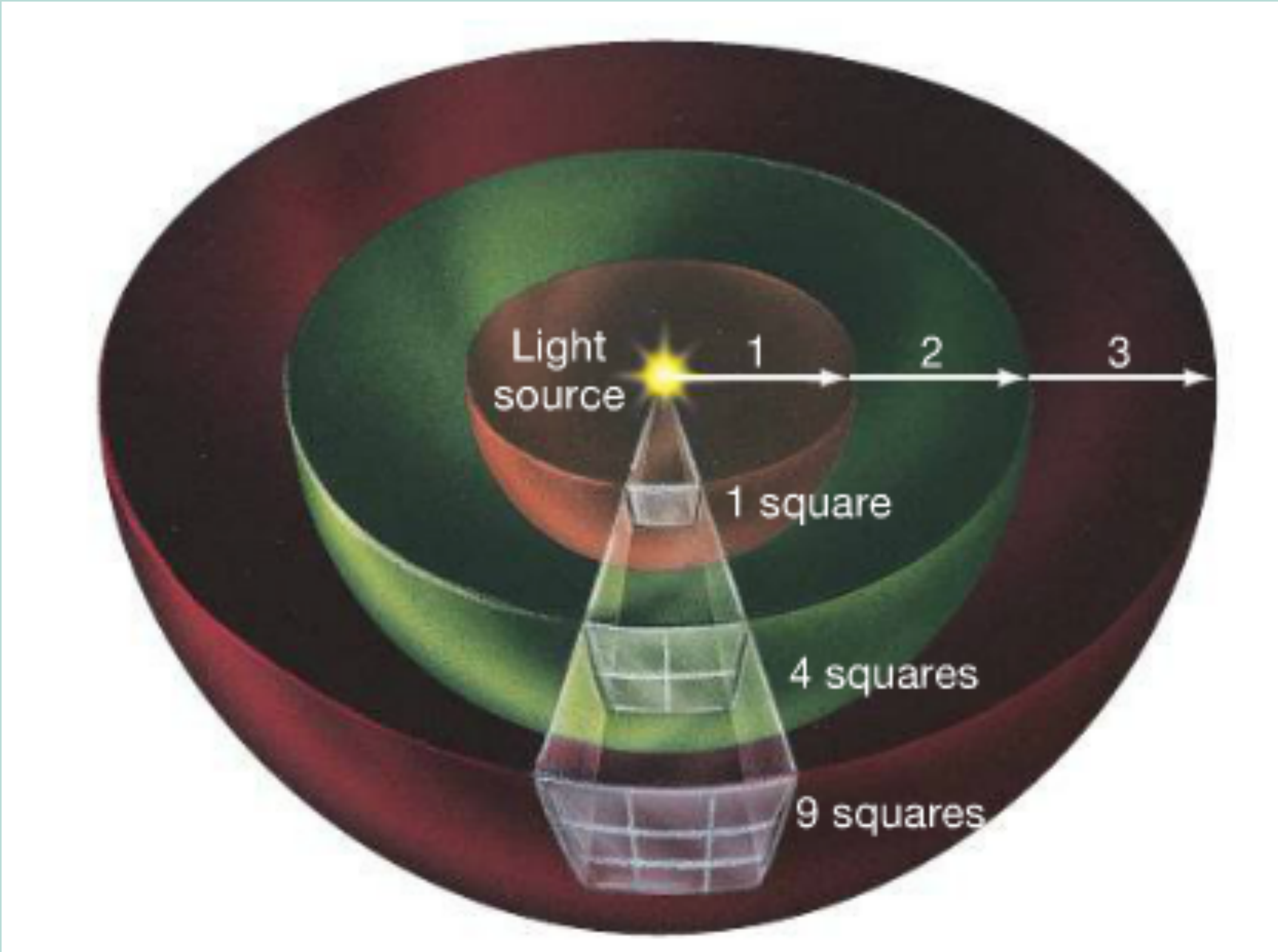
- This is the transverse velocity, radial velocity can be determined using the Doppler effect

Proper Stellar Motion

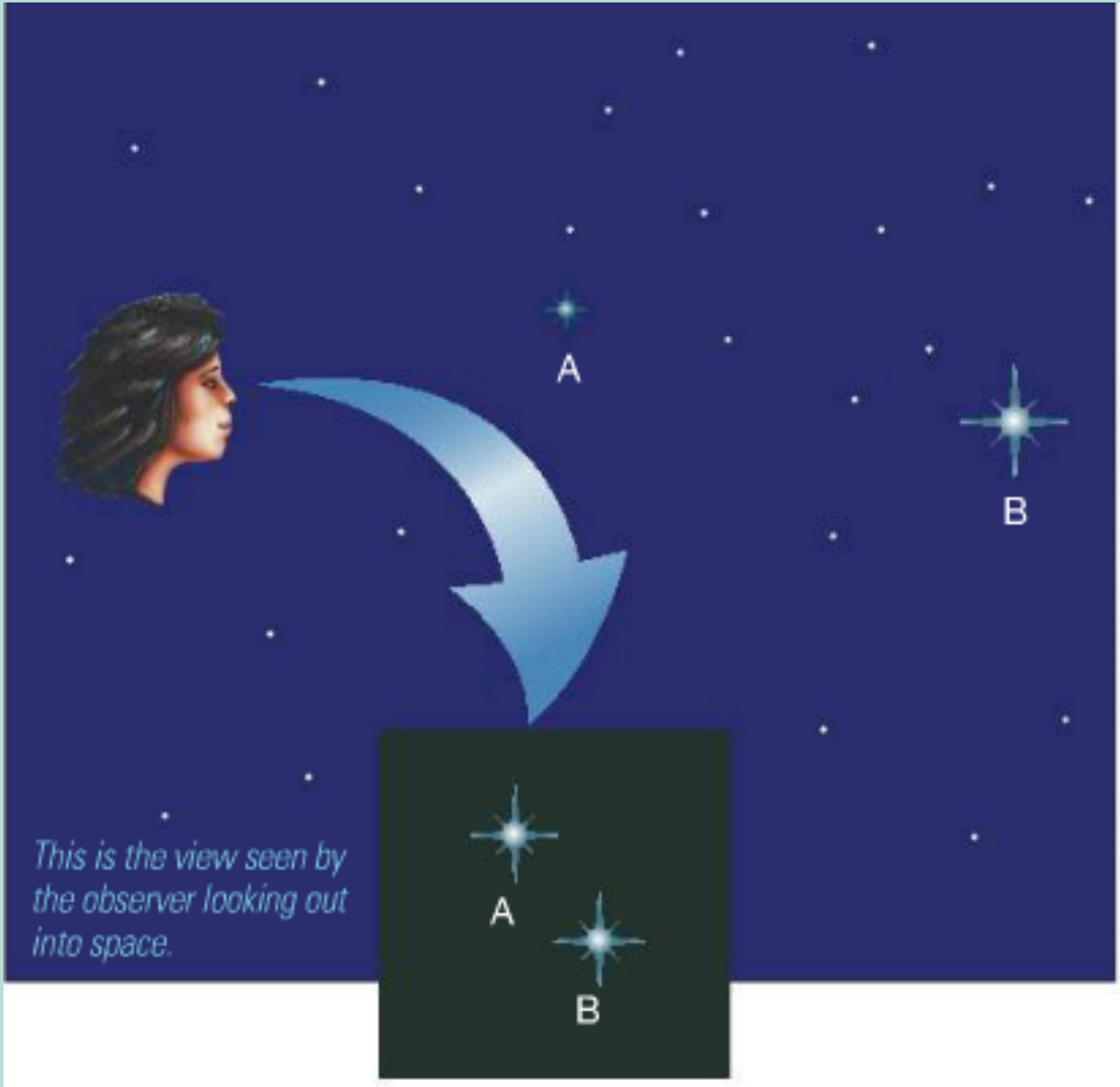


Luminosity

Yet Another “1 over r squared” Law



“Degeneracy”



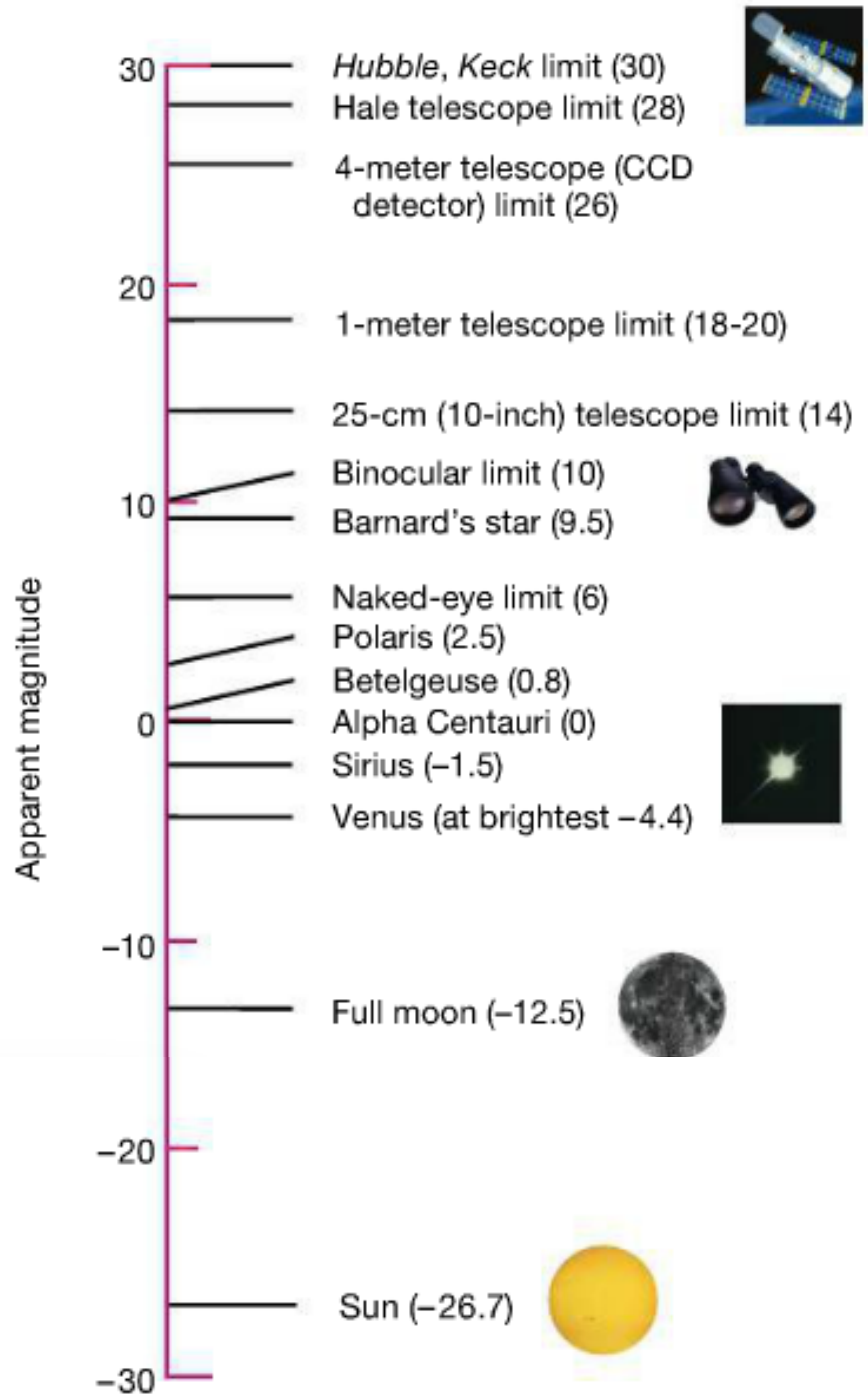
A
B
This is the view seen by the observer looking out into space.
A
B

- Apparent brightness (energy flux, what we measure) is luminosity over distance squared

- This is what the Greeks had to work with. Hipparchus rated the stars on a 1 to 6 brightness scale (1 being the brightest)

- Now we know that 1 is about 100 times brighter (in terms of true energy flux) than 6, with each number being roughly 2.5 times brighter than the last.

- Another example of our senses being ‘Logarithmic’

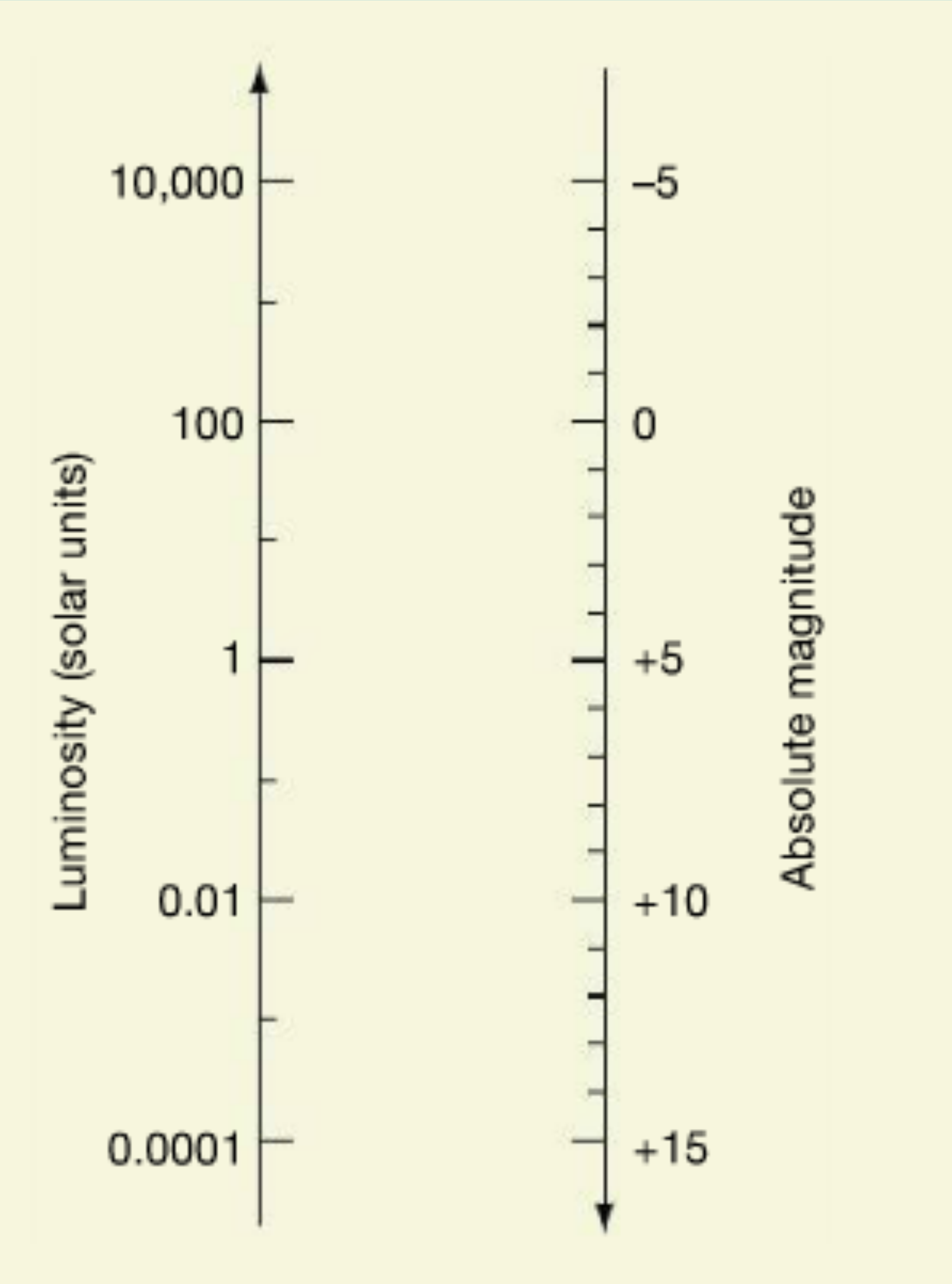


Brighter objects have smaller apparent magnitudes.

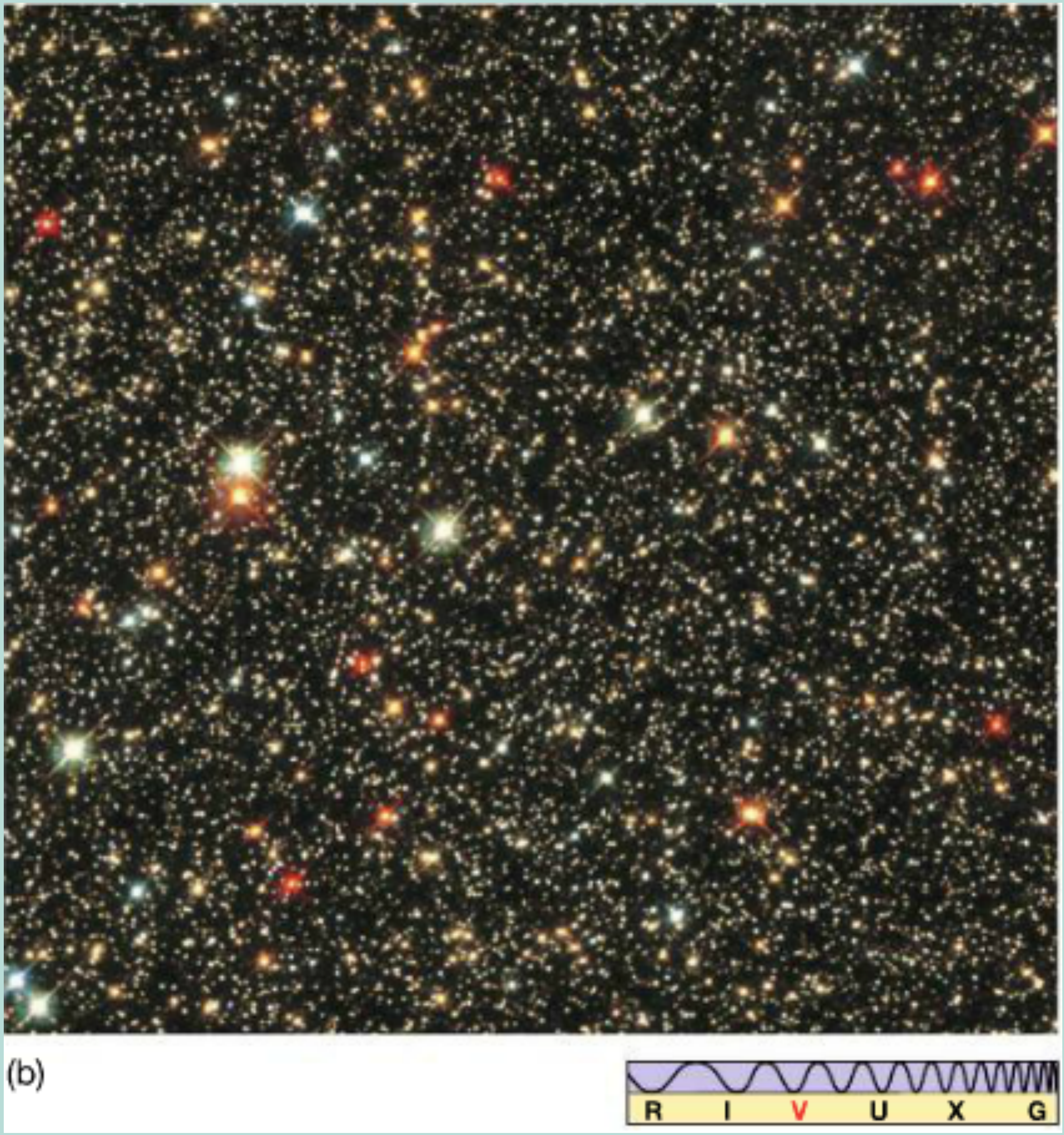
Absolute Magnitude

- Absolute magnitude is the apparent magnitude of an object placed at 10pc away
- If you took a 100pc star and put it at 10pc, it's brightness would go up by 10^2 = 100, thus it's 'apparent magnitude' would go *down* by a factor of 5 (recall, 2.5^5 = 100). Thus it's absolute magnitude would be less than it's apparent magnitude by 5.
- Confusing I know….

Logarithmic Relationship

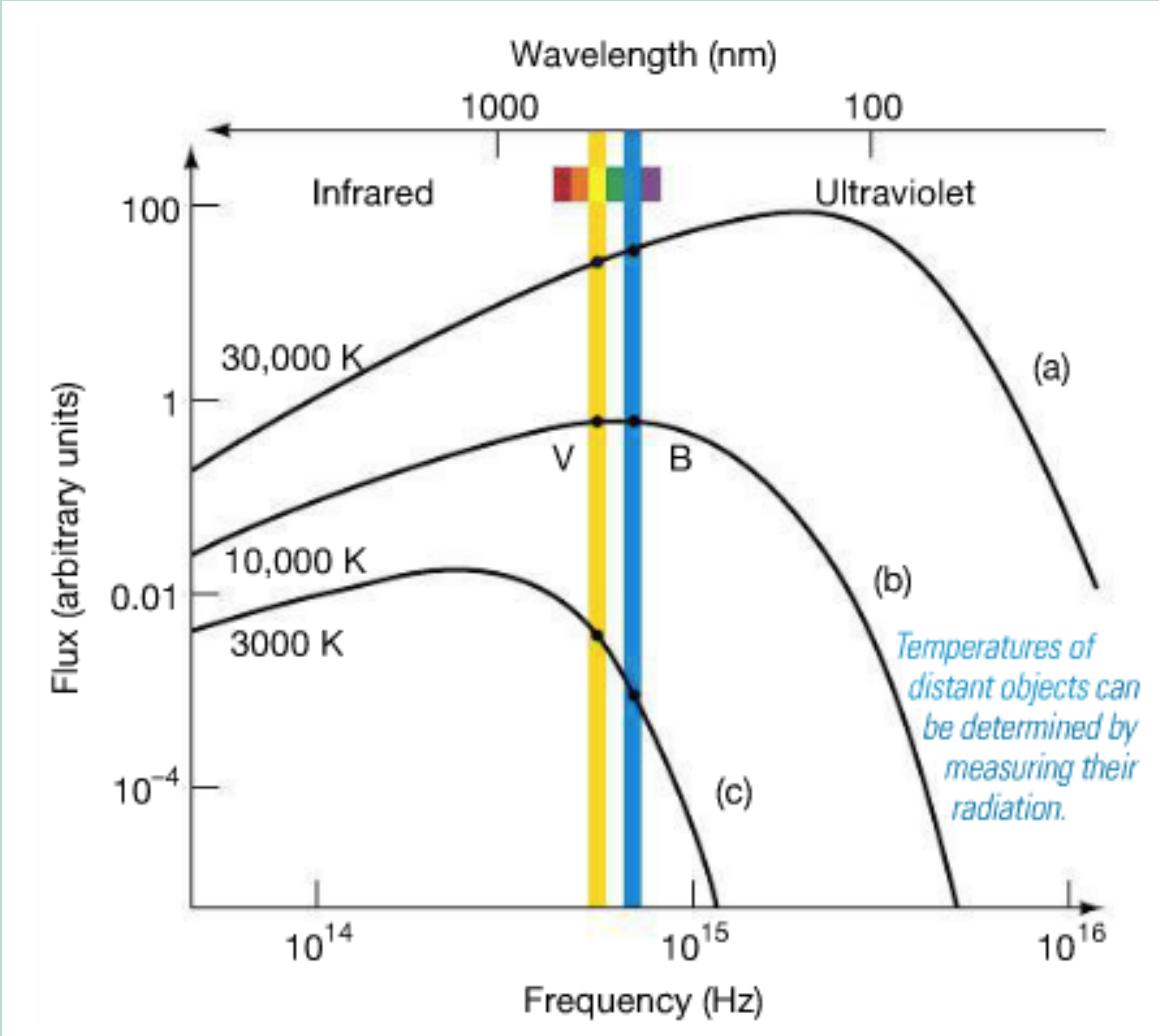


Dense heart of the Milky Way (2' across)



Zoomed out X100 (20 degrees)

- Notice the colors

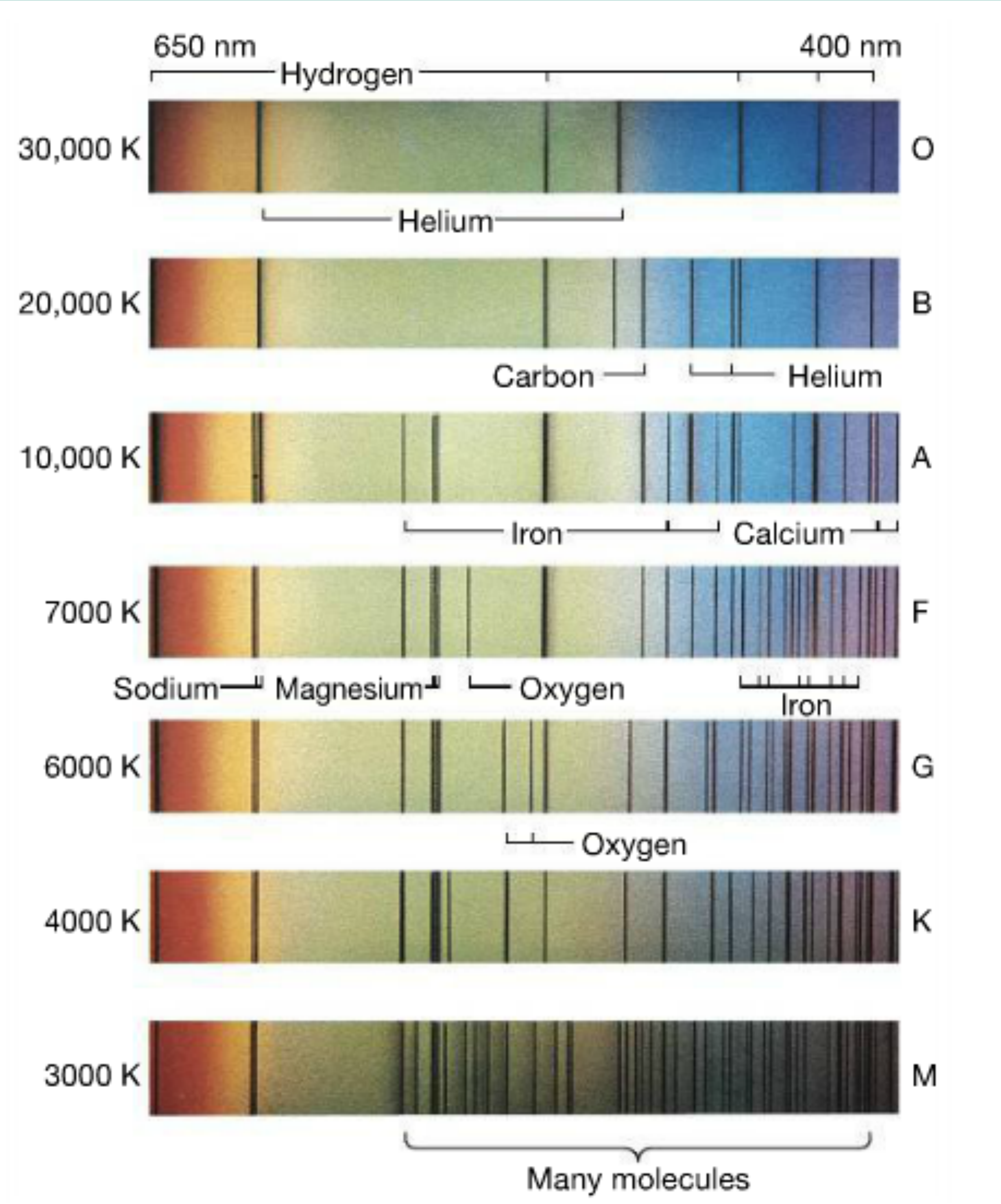


Just 2 points!

TABLE 17.1 Stellar Colors and Temperatures

Surface Temperature (K)	Color	Familiar Examples
30,000	Blue-violet	Mintaka (δ Orionis)
20,000	Blue	Rigel
10,000	White	Vega, Sirius
7000	Yellow-white	Canopus
6000	Yellow	Sun, Alpha Centauri
4000	Orange	Arcturus, Aldebaran
3000	Red	Betelgeuse, Barnard's star

Spectral Classification



- It turns out, this isn’t a ‘composition’ fingerprint as much as a ‘temperature’ fingerprint.

- Temperatures above 25000K have strong ionized Helium lines and multiply ionized heavier elements. These ionization energies are only available at these enormous temperatures

- Hydrogen lines in these hot stars are actually weak, even though the star is almost entirely hydrogen because hydrogen atoms don’t stay in tact at these temperatures (think ‘radiation zone’ in the sun)

- In intermediate temperature ranges (~10,000K) Hydrogen lines are strong. Lines from loosely bound atoms like calcium and titanium are common, but strongly bound atoms like helium and nitrogen are uncommon.

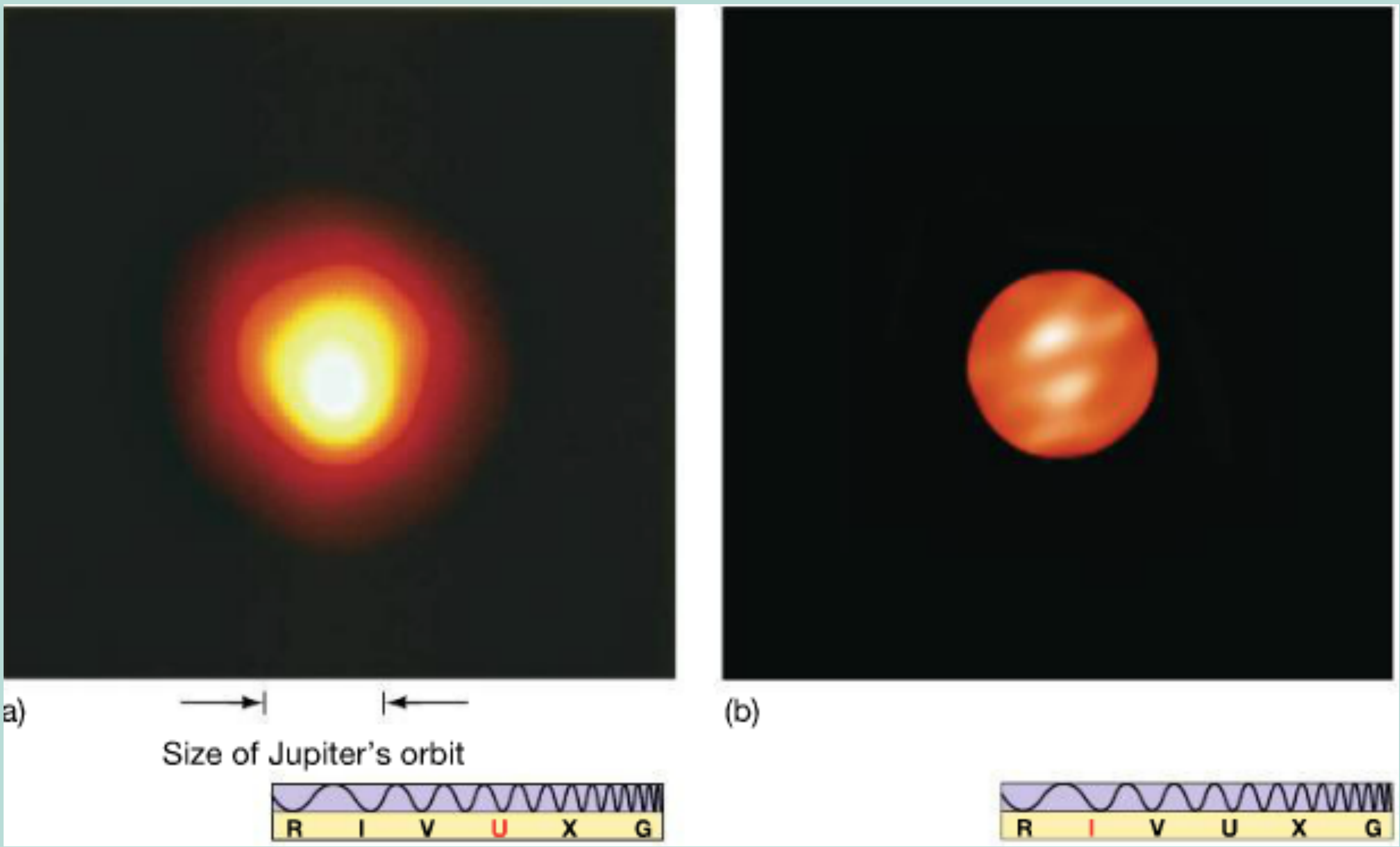
- In cool stars (~4000K) hydrogen lines are weak again because they're hard to excite. Intense spectral lines are from atoms easy to ionize and even molecular lines!

- We can use these properties to classify stars. At first people used hydrogen line intensity alphabetical order, A,B,C,D… Now we use surface temperature yielding:

TABLE 17.2 Stellar Spectral Classes

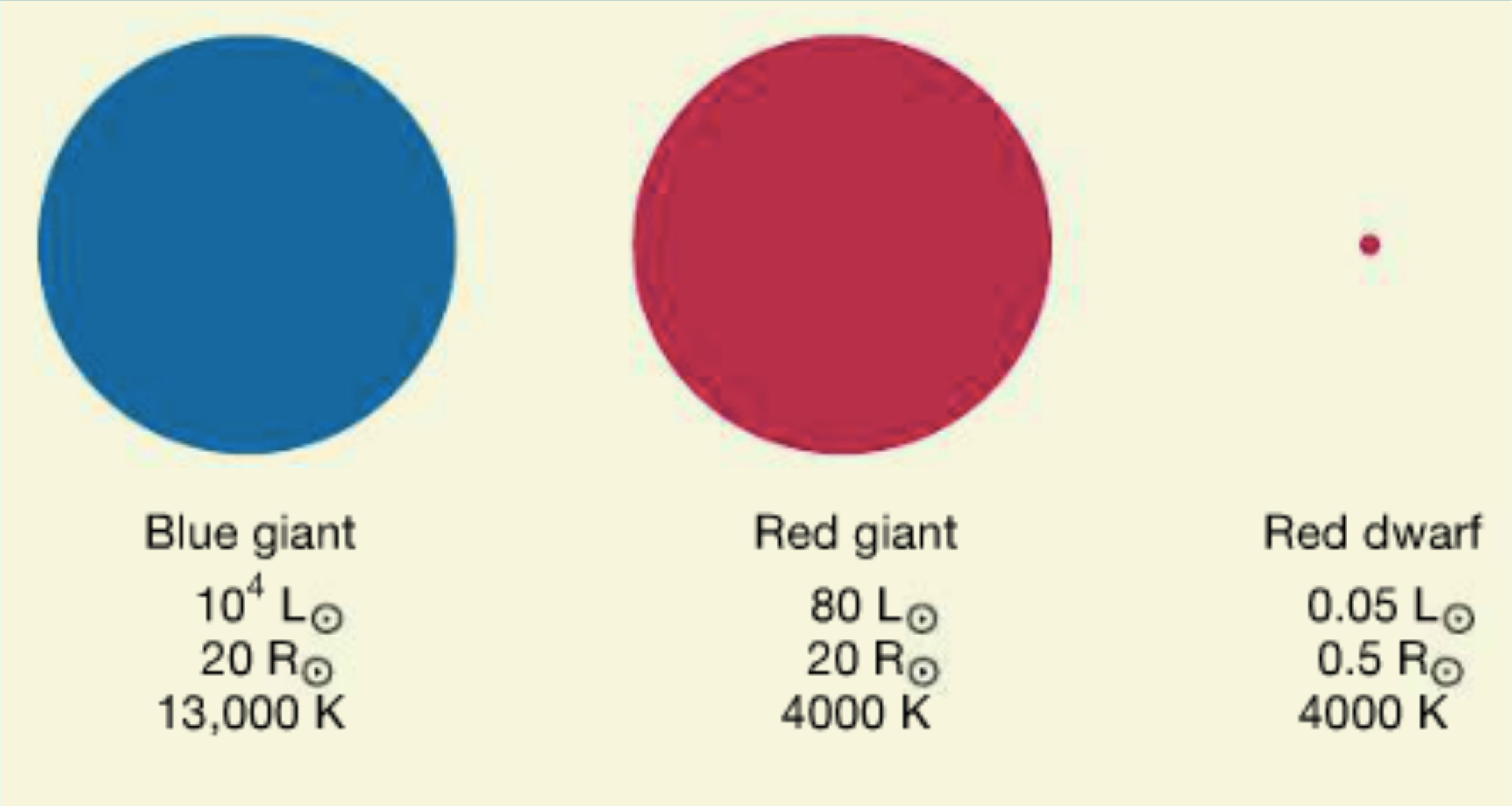
Spectral Class	Surface Temperature (K)	Noteworthy Absorption Lines	Familiar Examples
O	30,000	Ionized helium strong; multiply ionized heavy elements; hydrogen faint	Mintaka (O9)
B	20,000	Neutral helium moderate; singly ionized heavy elements; hydrogen moderate	Rigel (B8)
A	10,000	Neutral helium very faint; singly ionized heavy elements; hydrogen strong	Vega (A0), Sirius (A1)
F	7000	Singly ionized heavy elements; neutral metals; hydrogen moderate	Canopus (F0)
G	6000	Singly ionized heavy elements; neutral metals; hydrogen relatively faint	Sun (G2), Alpha Centauri (G2)
K	4000	Singly ionized heavy elements; neutral metals strong; hydrogen faint	Arcturus (K2), Aldebaran (K5)
M	3000	Neutral atoms strong; molecules moderate; hydrogen very faint	Betelgeuse (M2), Barnard's star (M5)

Stelar Size (direct measurement)



Betelgeuse: @ 130 pc, .045'' therefore 630 R_sun

Size Luminosity Temperature



$$L = 4\pi\sigma R^2 T^4$$

(All in 'solar' units)

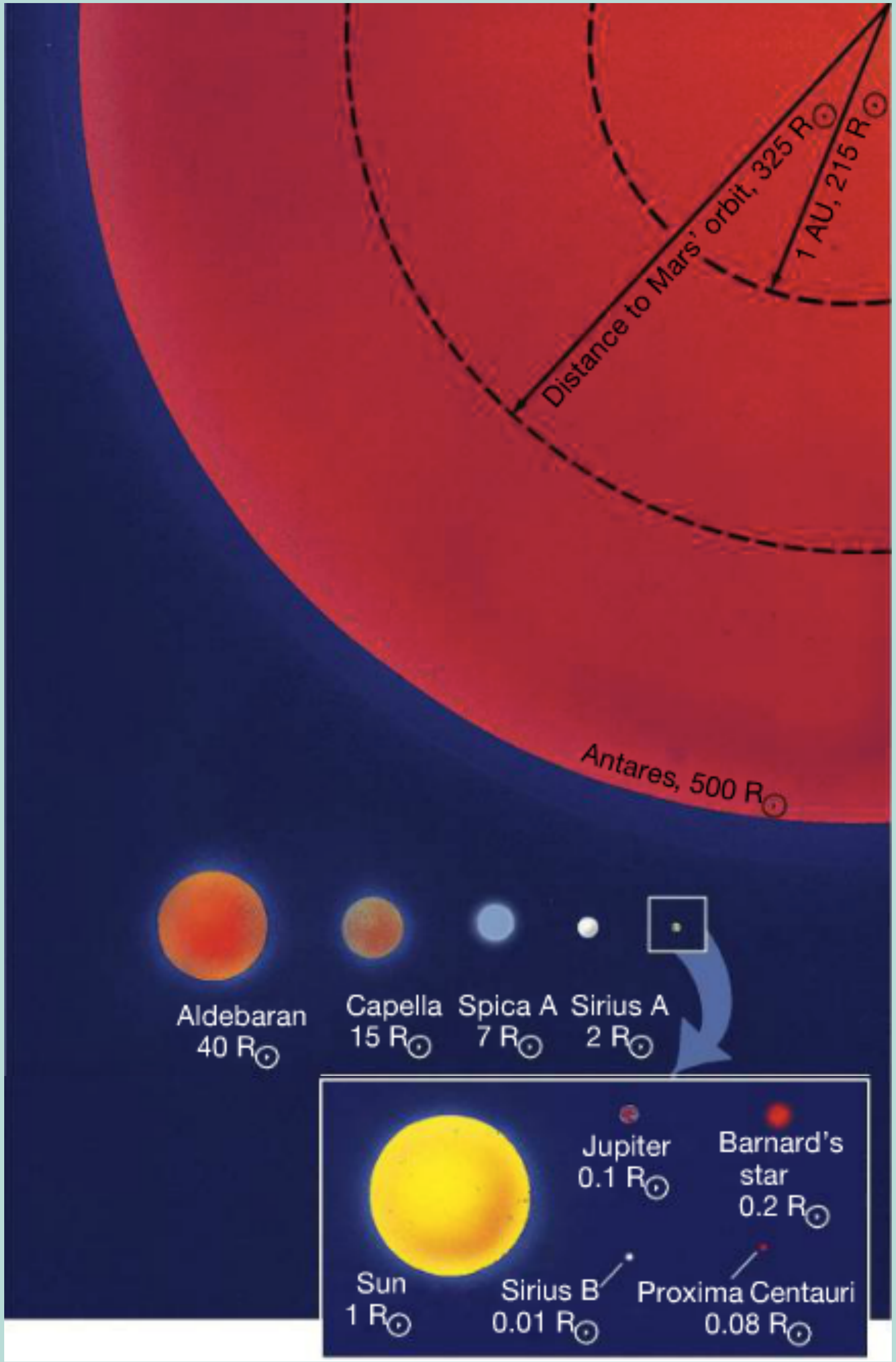
Star	Luminosity (L)	Temperature (T)	Radius (R)
Sirius B	0.025	4.7	0.007
Barnard's star	0.0045	0.56	0.2
Sun	1	1	1
Sirius A	23	2.1	1.9
Vega	55	1.6	2.8
Arcturus	160	0.78	21
Rigel	63,000	1.9	70
Betelgeuse	36,000	0.55	630

Notice Luminosity is not just 'visible' luminosity

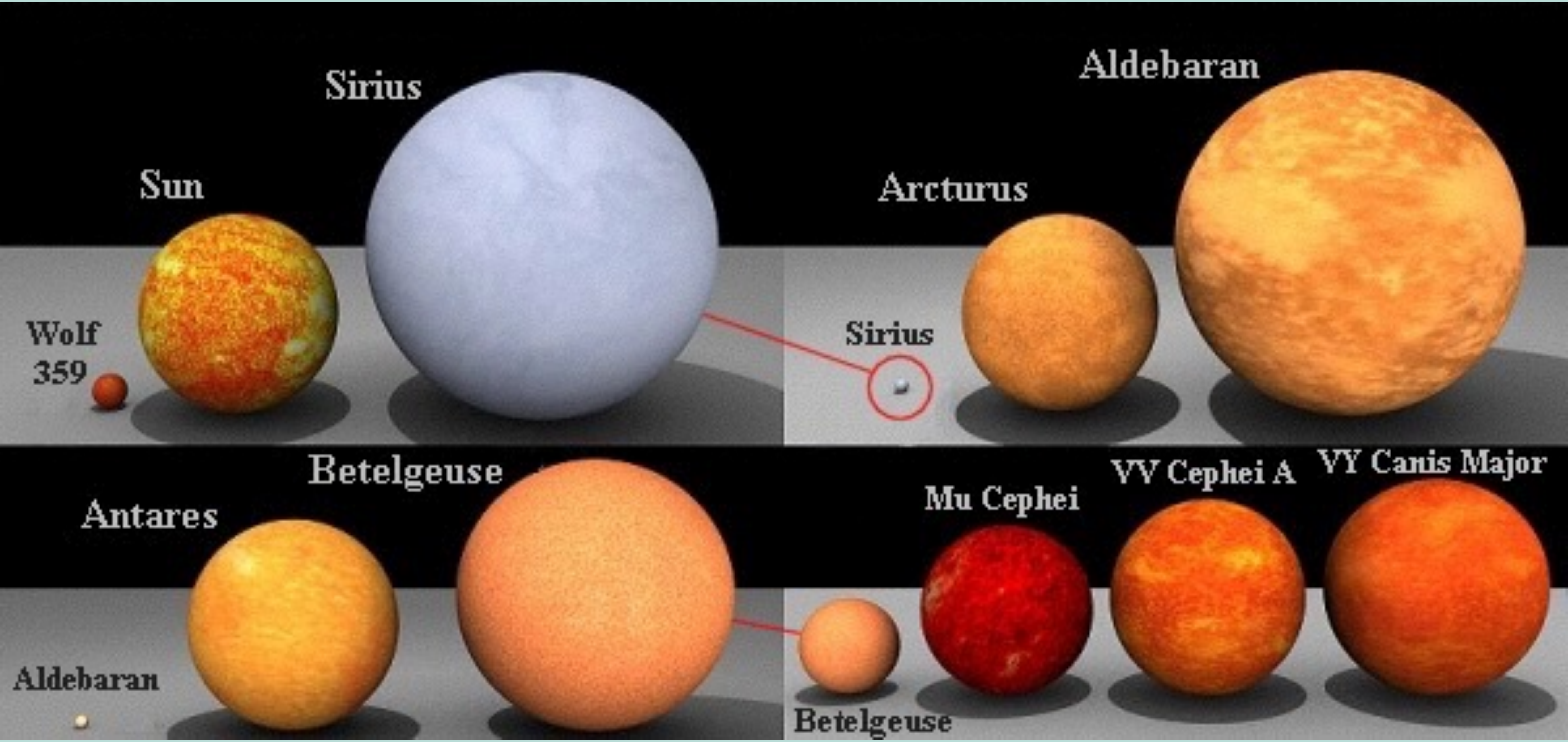
- “Giants” have between 10 and 100 times the radius of the sun

- 100 to 1000 are called “Super giants”

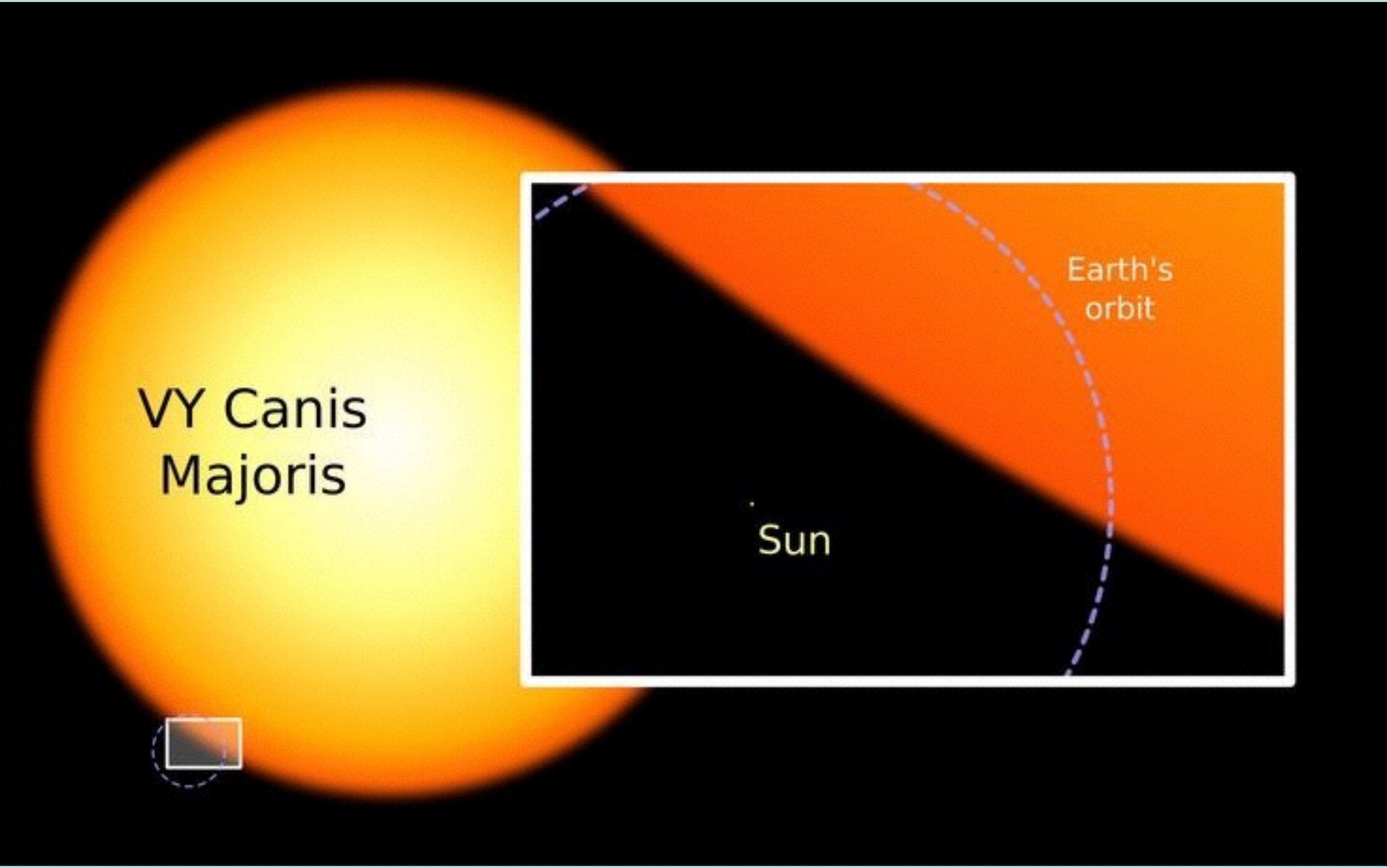
- Approximately 1 and smaller are called “Dwarves”



Distance to Mars' orbit, 325 $R_\odot$
1 AU, 215 $R_\odot$
Antares, 500 $R_\odot$
Aldebaran
40 $R_\odot$
Capella
15 $R_\odot$
Spica A
7 $R_\odot$
Sirius A
2 $R_\odot$
Sun
1 $R_\odot$
Jupiter
0.1 $R_\odot$
Barnard's star
0.2 $R_\odot$
Sirius B
0.01 $R_\odot$
Proxima Centauri
0.08 $R_\odot$

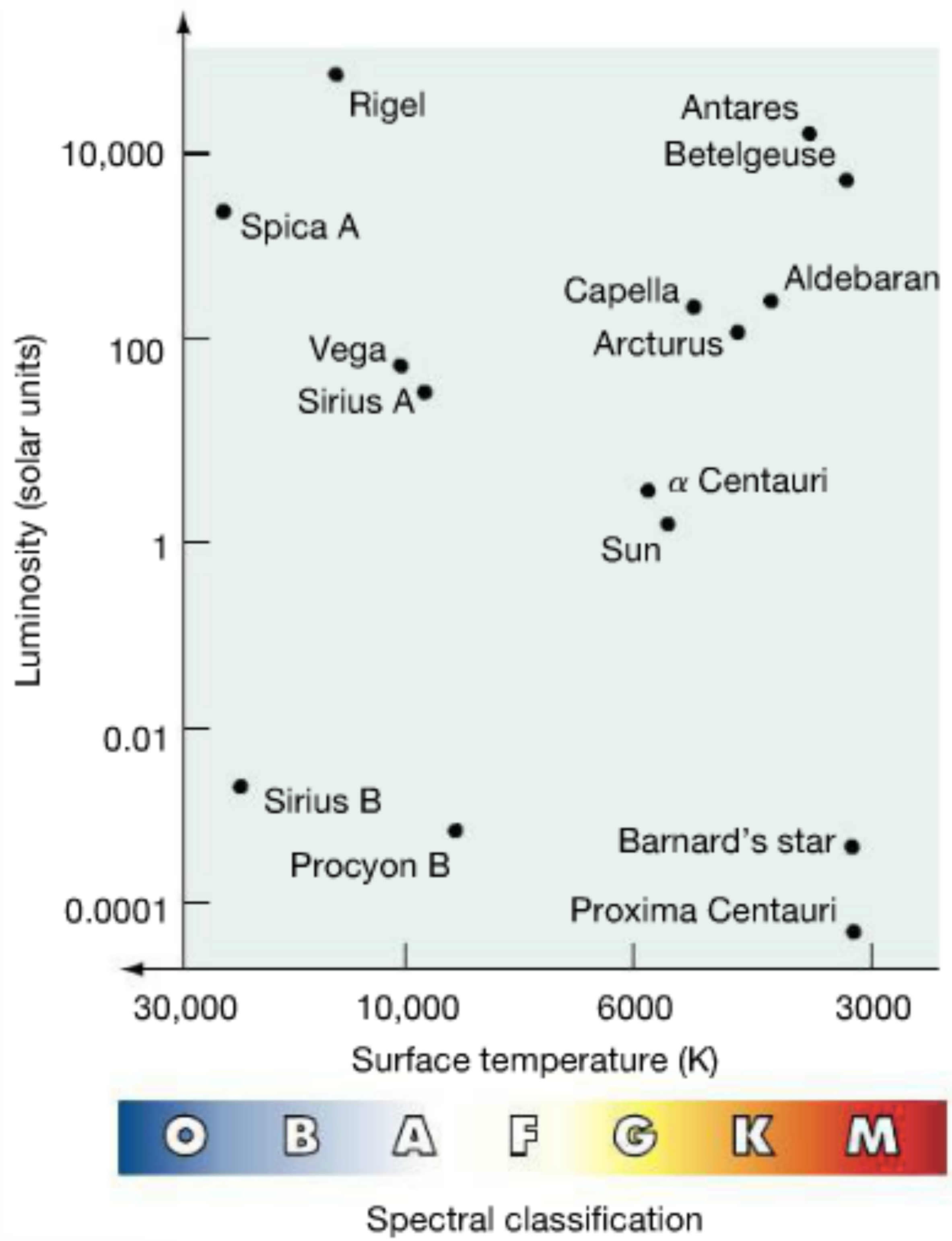


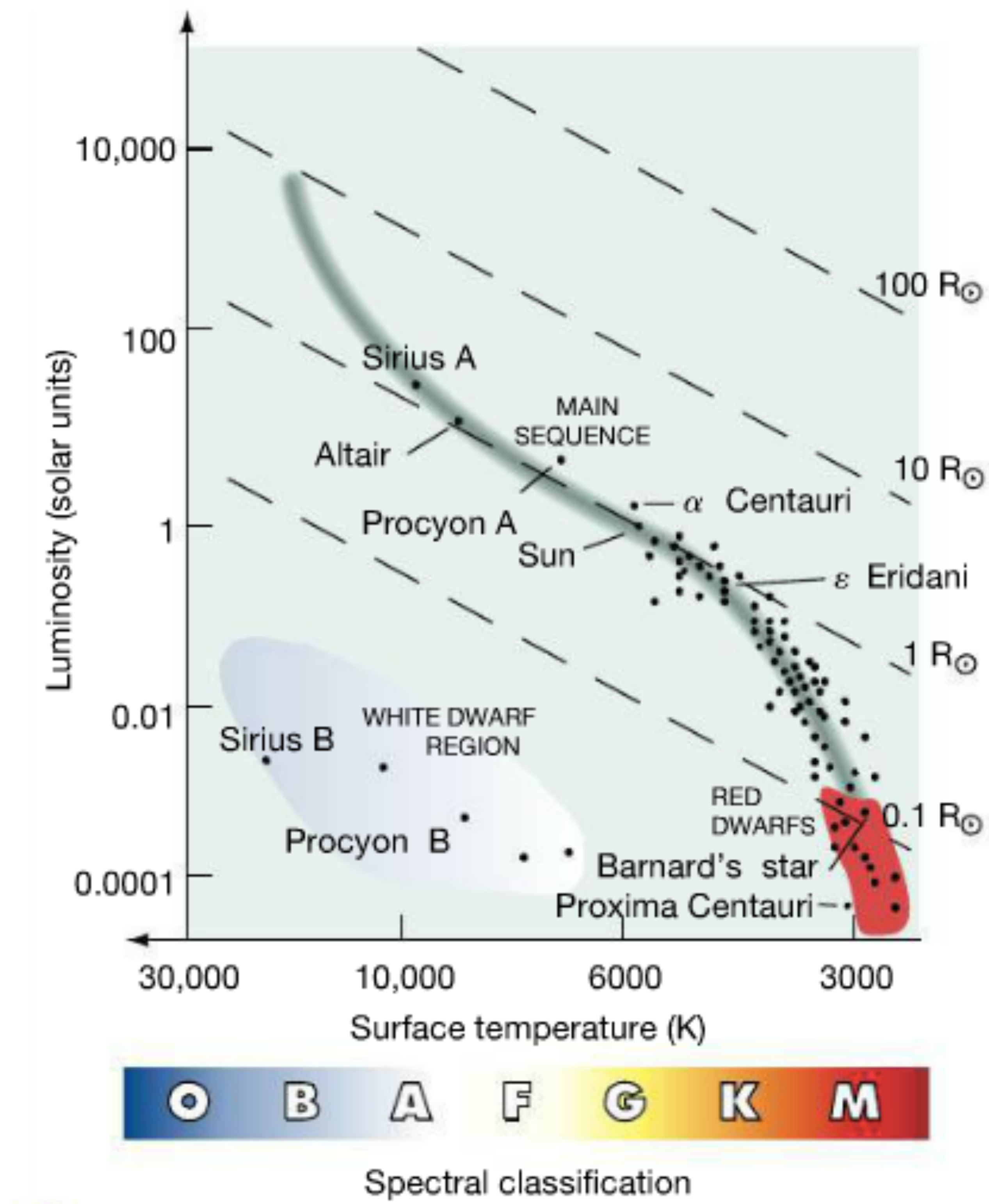
Sirius
Aldebaran
Sun
Arcturus
Wolf 359
Sirius
Betelgeuse
Antares
Mu Cephei
VV Cephei A
VY Canis Major
Aldebaran
Betelgeuse



6.6 AU radius. 10 mg/m^3 density! (Earth: 5,500,000 mg/m^3)

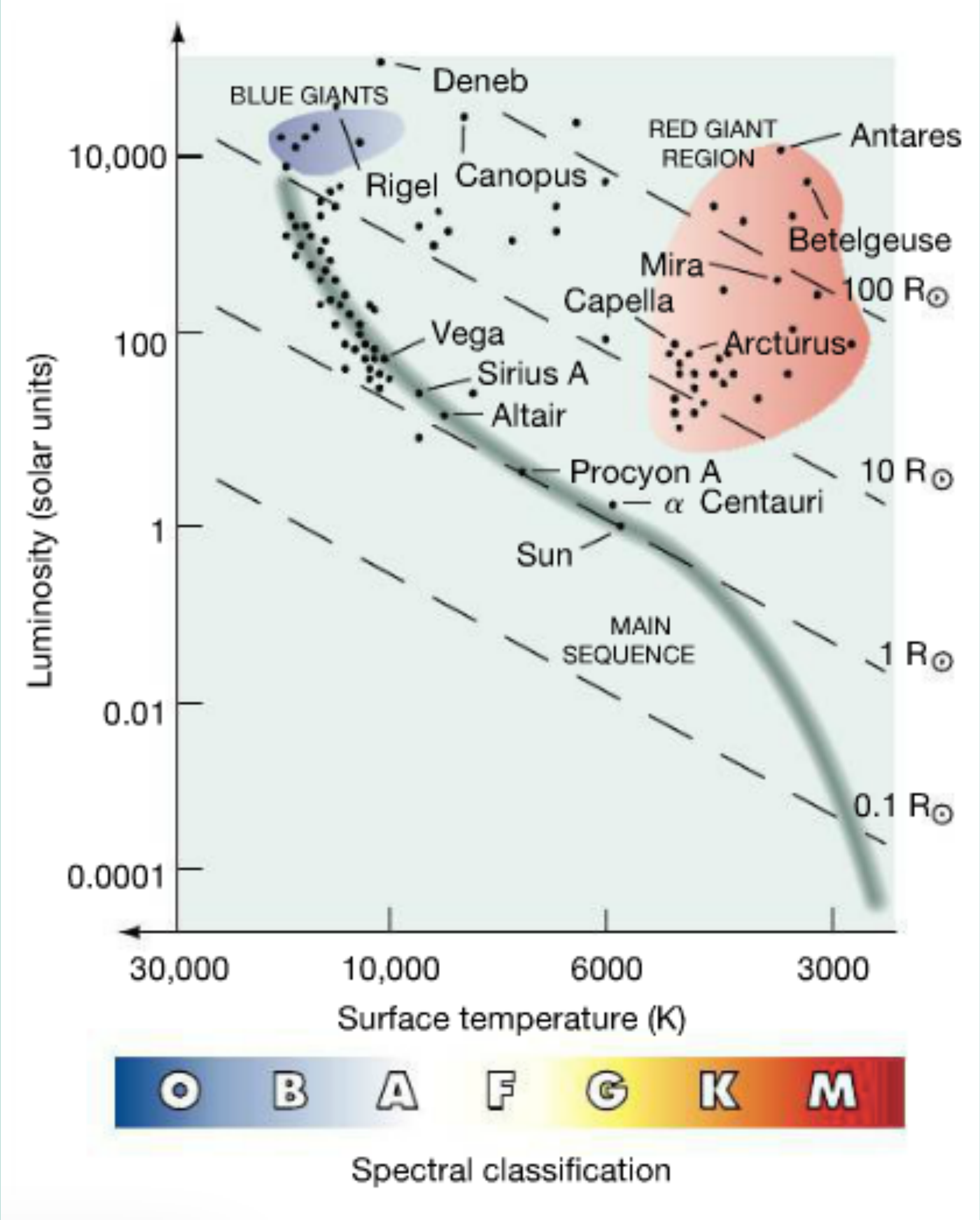
The Hertzsprung-Russell Diagram





Right diagram: ~5pc from the sun

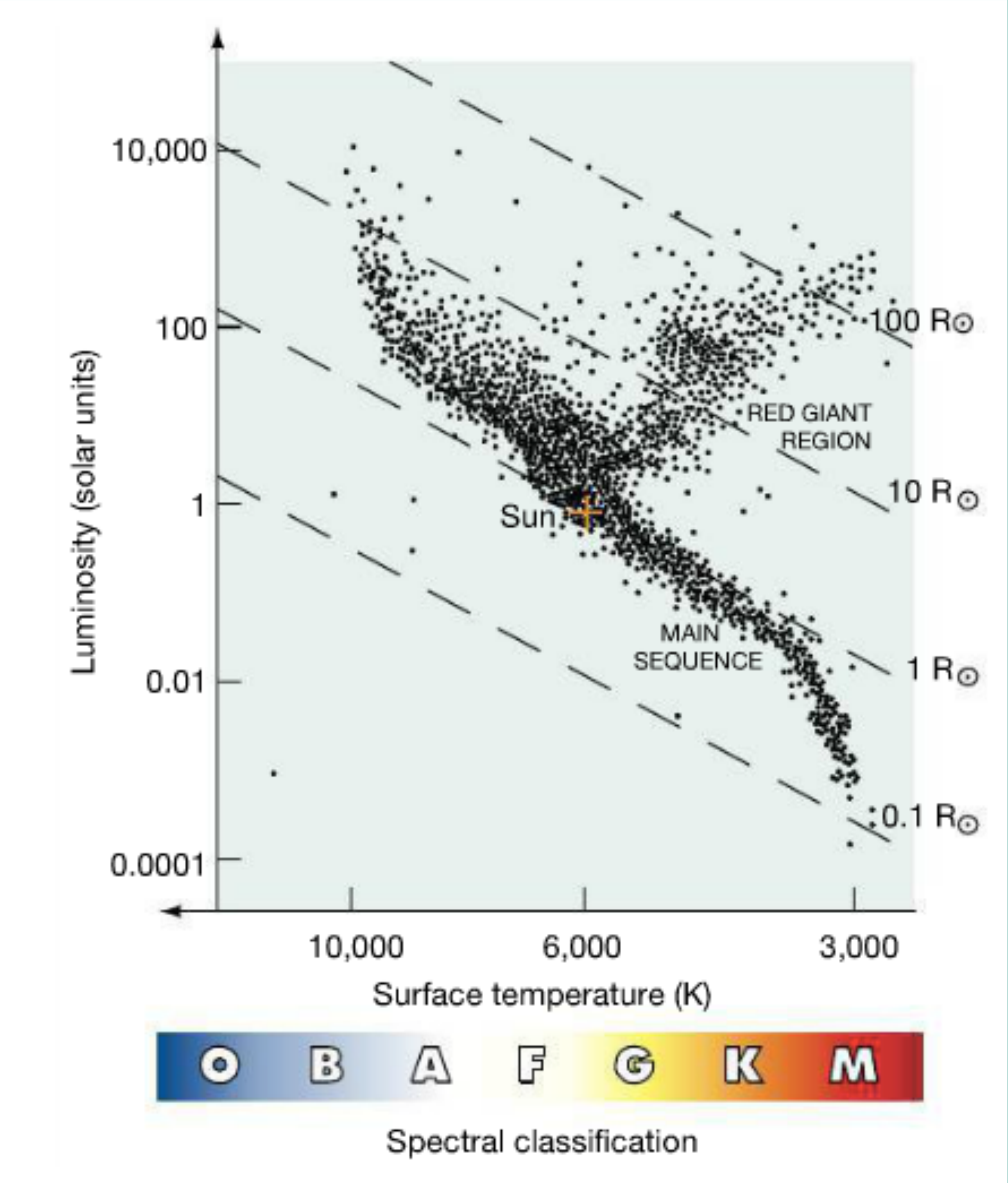
The brightest stars in the sky



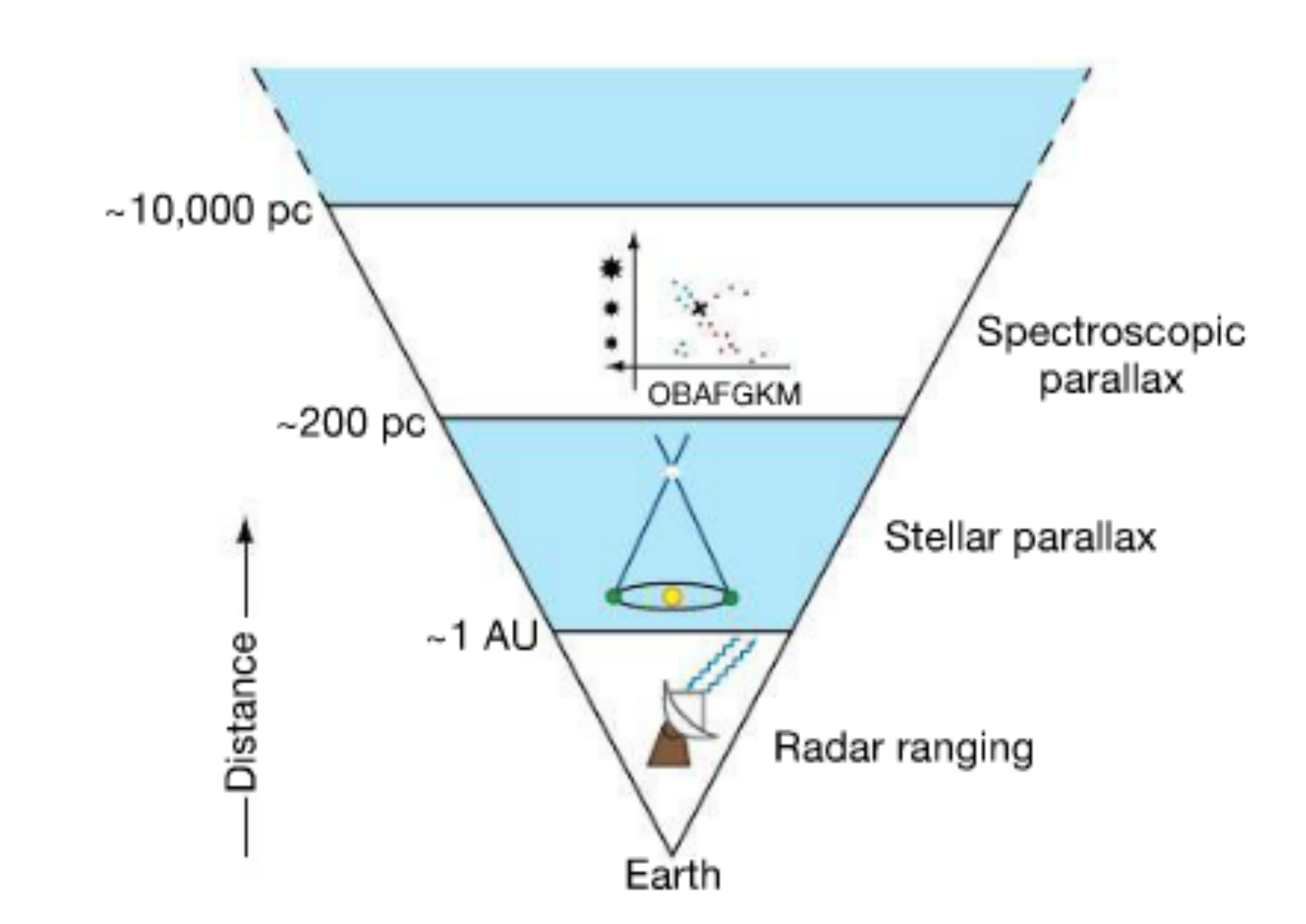
HIgh **P**recision **PAR**allax **CO**llecting **S**atellite

100k stars

Hipparcos H-R Diagram



Cosmic Distance Ladder



Spectroscopic Parallax

- Measure The stars apparent brightness and spectral type
- Use spectral type to estimate luminosity
- Use the inverse square law to determine the distance to the star
- All told, this gets you about 25% accuracy

Luminosity Class

- Red giants are way more luminous than K stars but have the same temperature and thus are in the same spectral class

- To distinguish these, we have luminosity class.

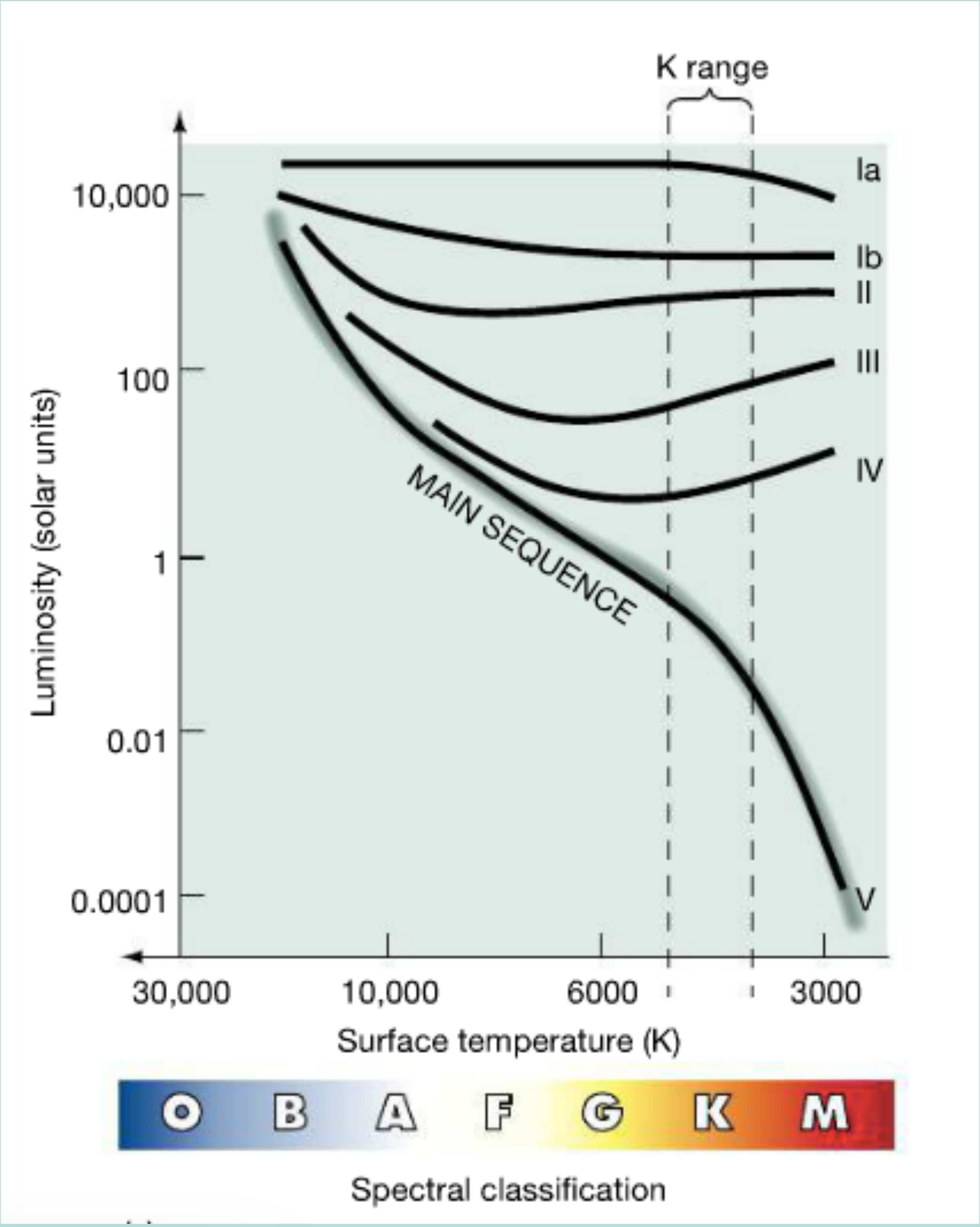
- Conveniently, density is very well correlated with luminosity (why?) which also determines the *width* of spectral lines.

- Thus spectral line width can be used to determine "luminosity class" (the OBAFGKM of the y-axis)

TABLE 17.3 Stellar Luminosity Classes

Class	Description
Ia	Bright supergiants
Ib	Supergiants
II	Bright giants
III	Giants
IV	Subgiants
V	Main-sequence stars and dwarfs

Luminosity Classes on the HR diagram



Spectral Line Width

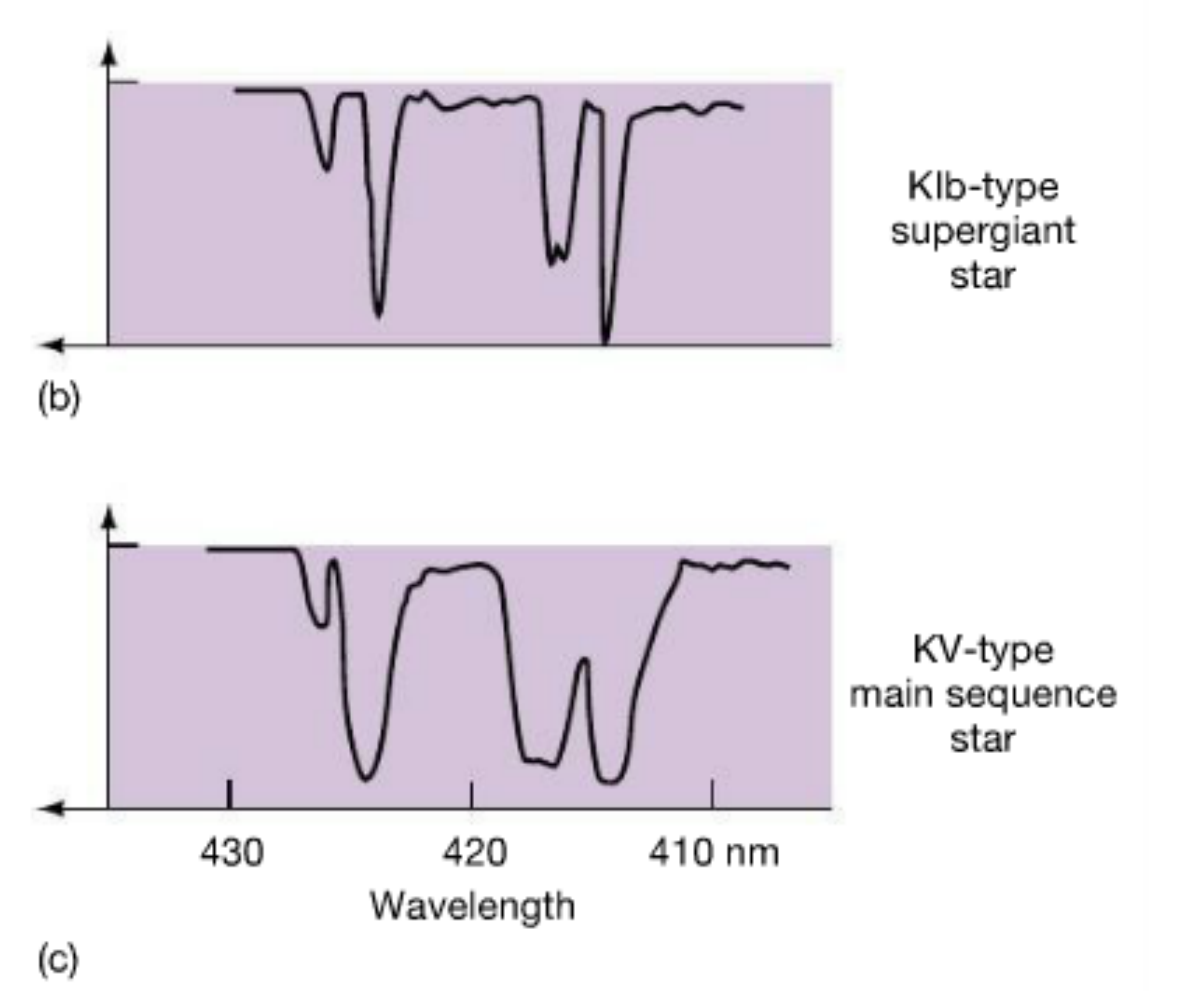
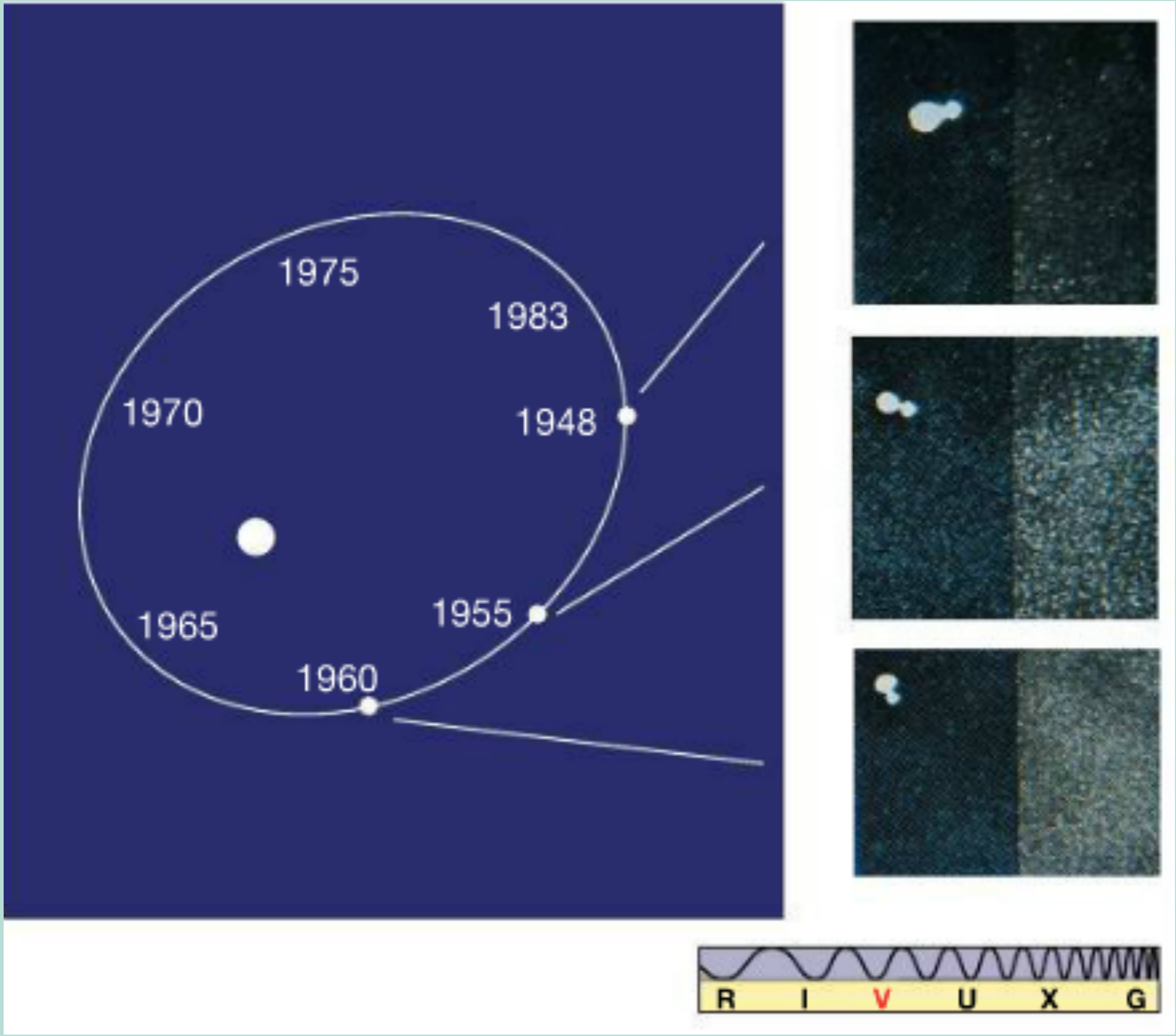


TABLE 17.4 Variation in Stellar Properties within a Spectral Class

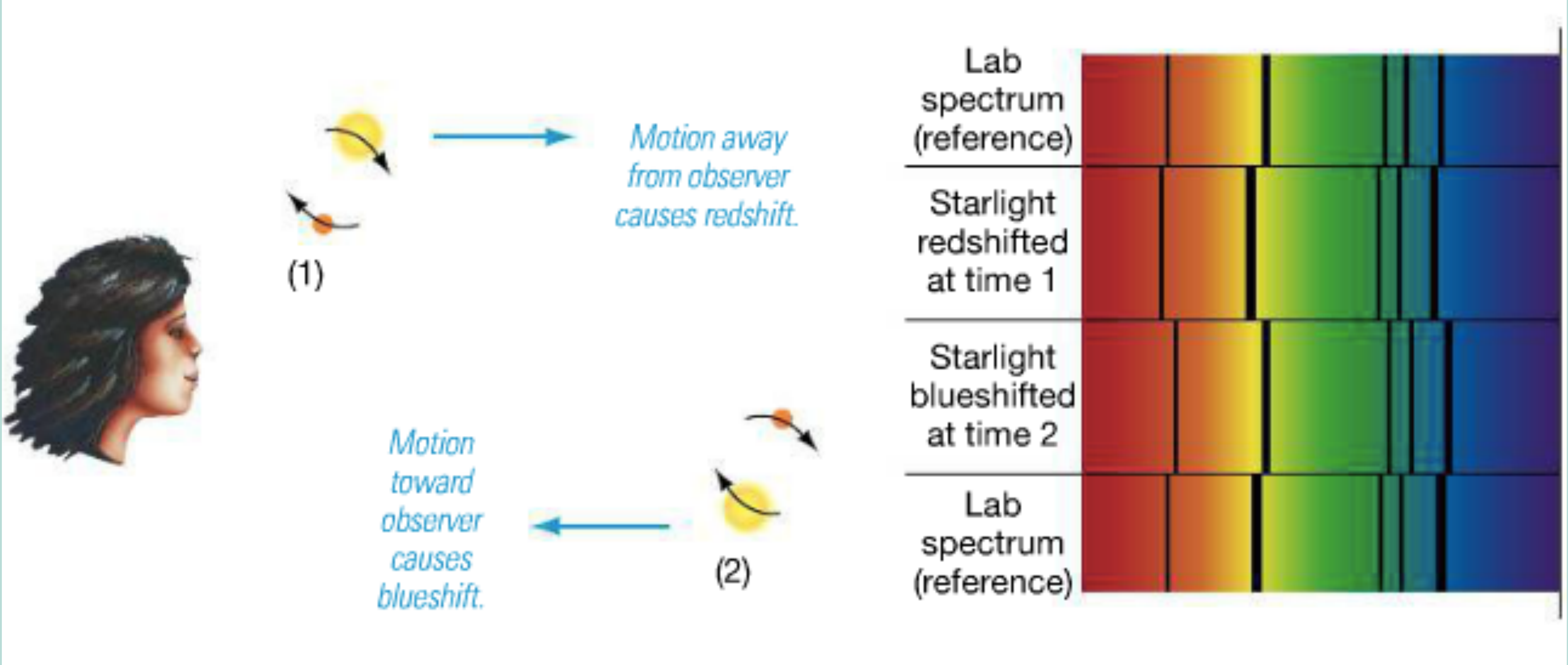
Surface Temperature (K)	Luminosity (solar luminosities)	Radius (solar radii)	Object	Example
4900	0.3	0.8	K2V main-sequence star	ϵ Eridani
4500	110	21	K2III red giant	Arcturus
4300	4000	140	K2Ib red supergiant	ϵ Pegasi

Stellar Mass



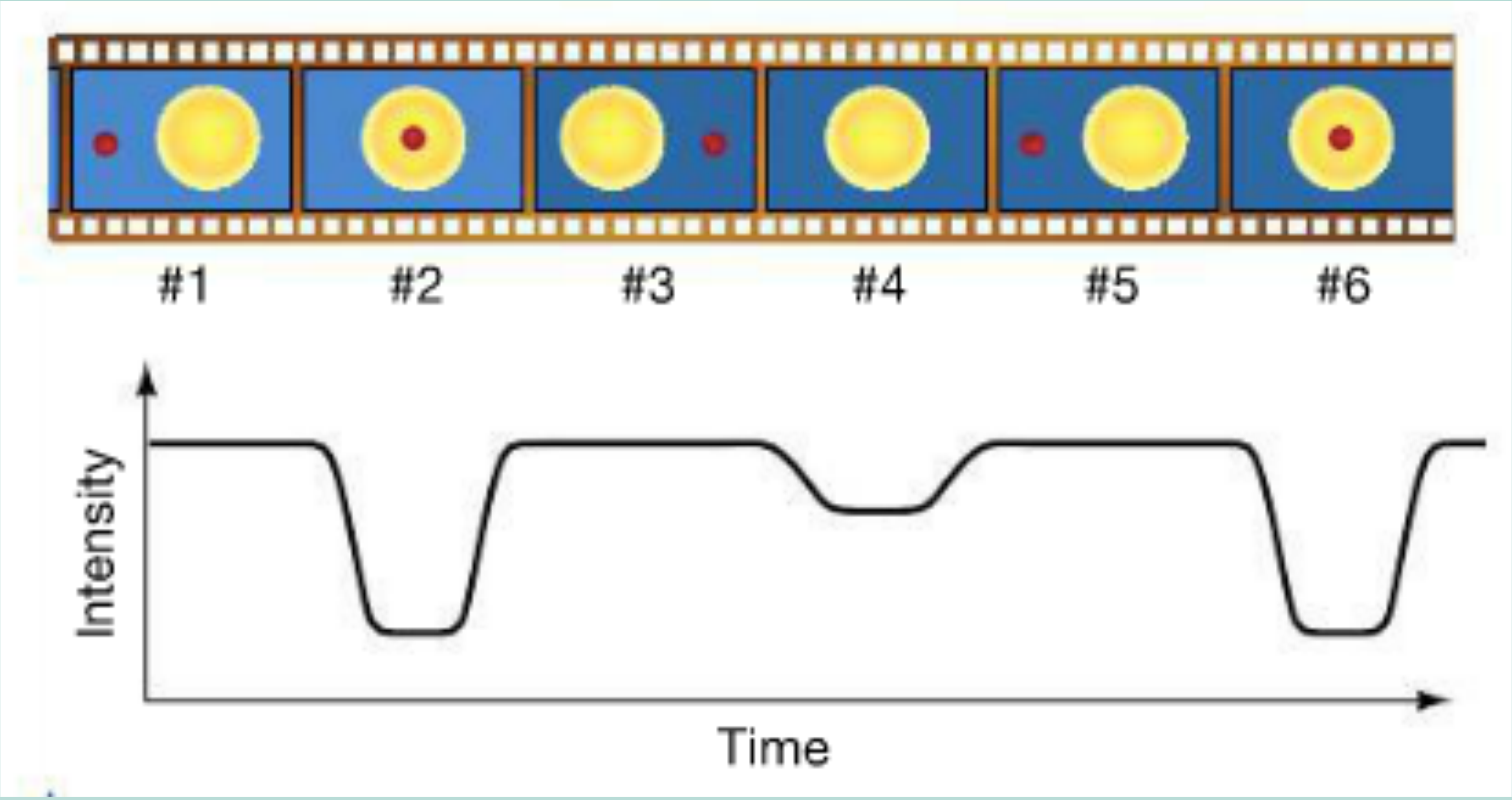
Kruger 60: Visual Binary

Determining mass with radial doppler shifting



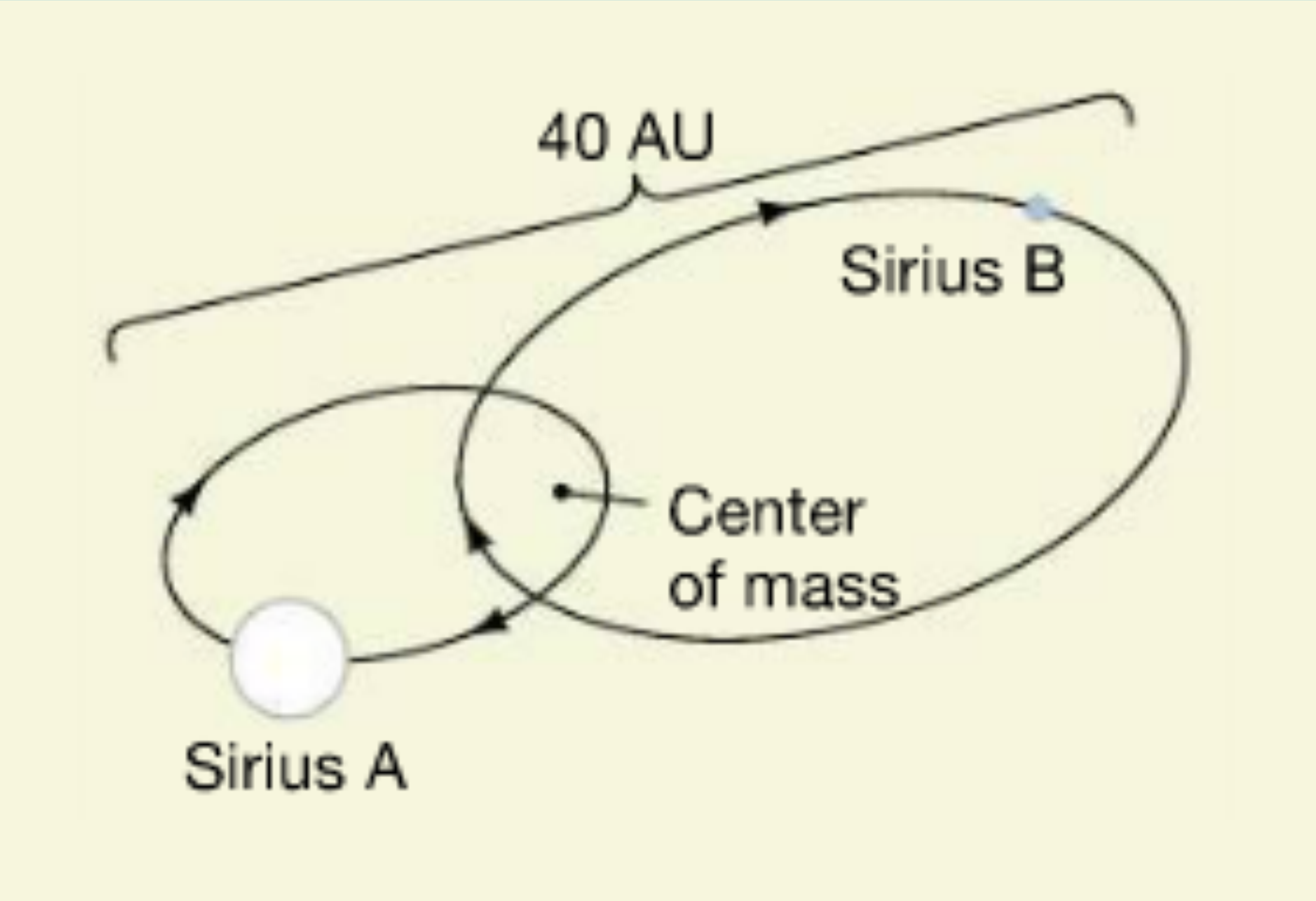
Spectroscopic Binary

Eclipsing Binaries



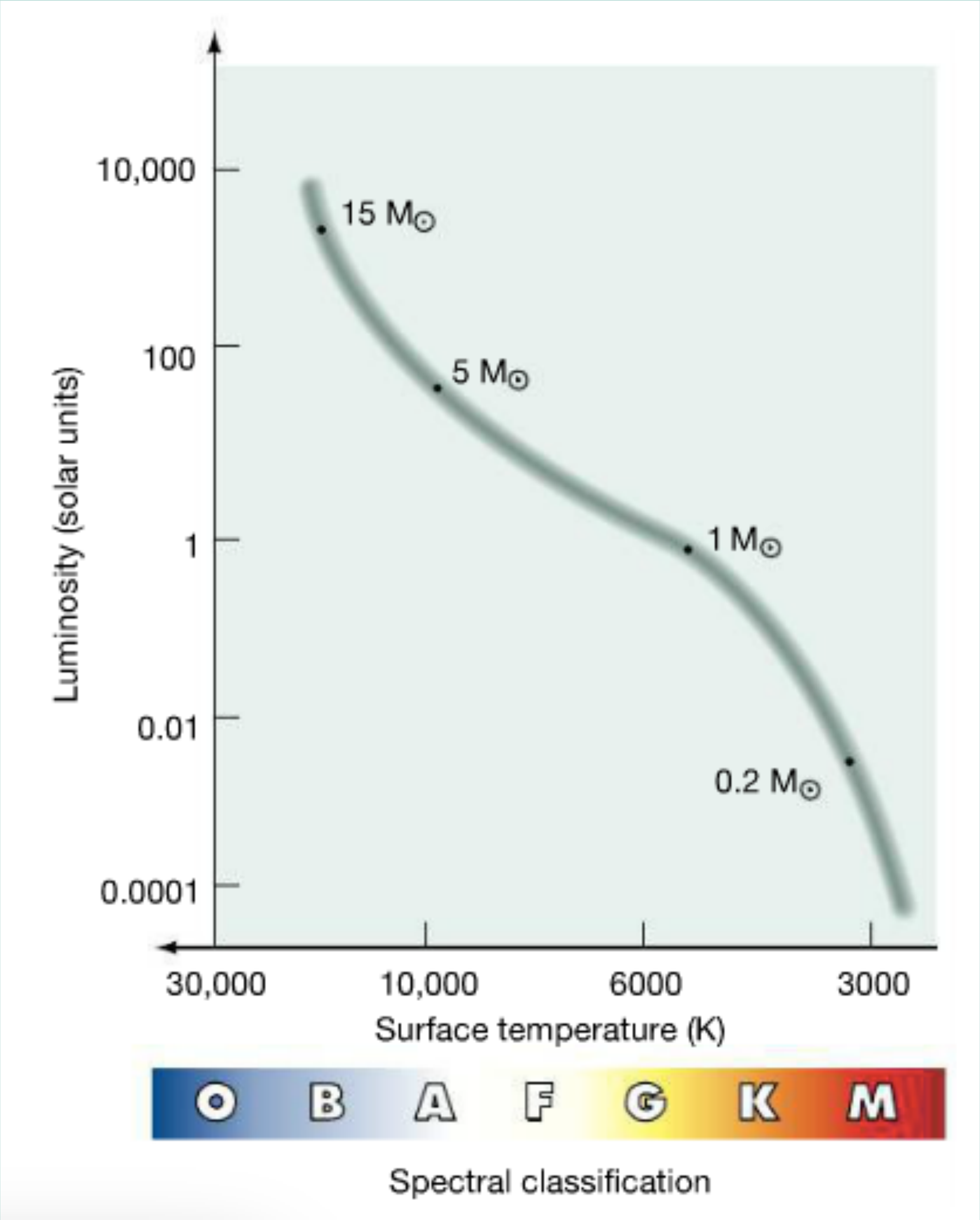
- From eclipsing binaries we can even learn radius!
- The amount of light that is eclipsed tells us (roughly) the ratio of the areas of the stars (radius squared)
- If we get orbital speeds from doppler shifting, then we get radius from width of the dip in the light curve

Sirius: textbook stellar binary

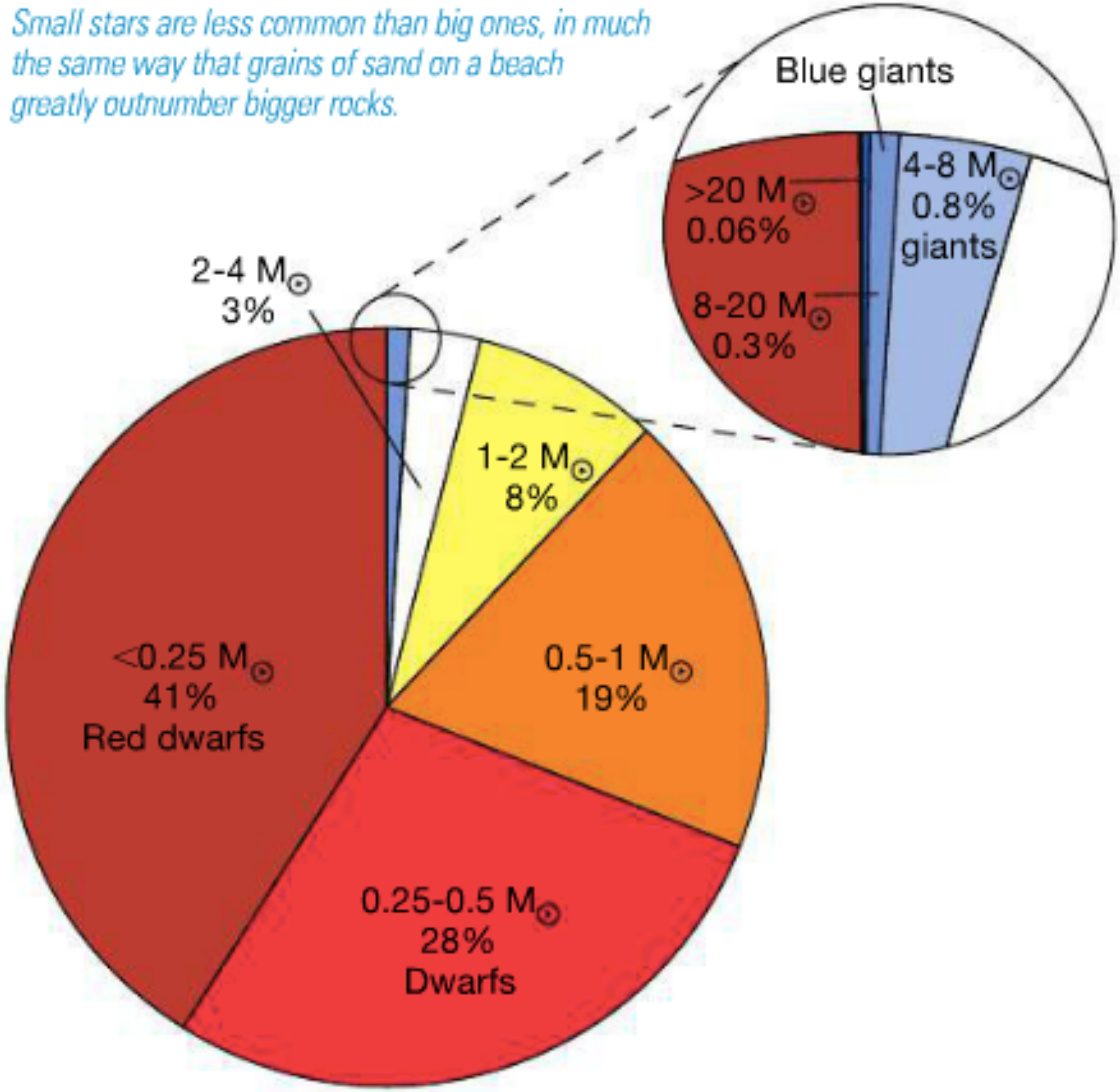


- The period of oscillation is 50 years
- Orbit is inclined 40 degrees
- Semi-major axis projected along line of sight is 20 AU (7.5'' at 2.7pc)
- Using Kepler's 3rd law we get the total mass is 3.2 M_sun
- Sirius A moves at half the speed of Sirius B relative to the center of mass
- Thus Sirius A has twice the mass so MA = 2.1 and MB = 1.1 solar masses

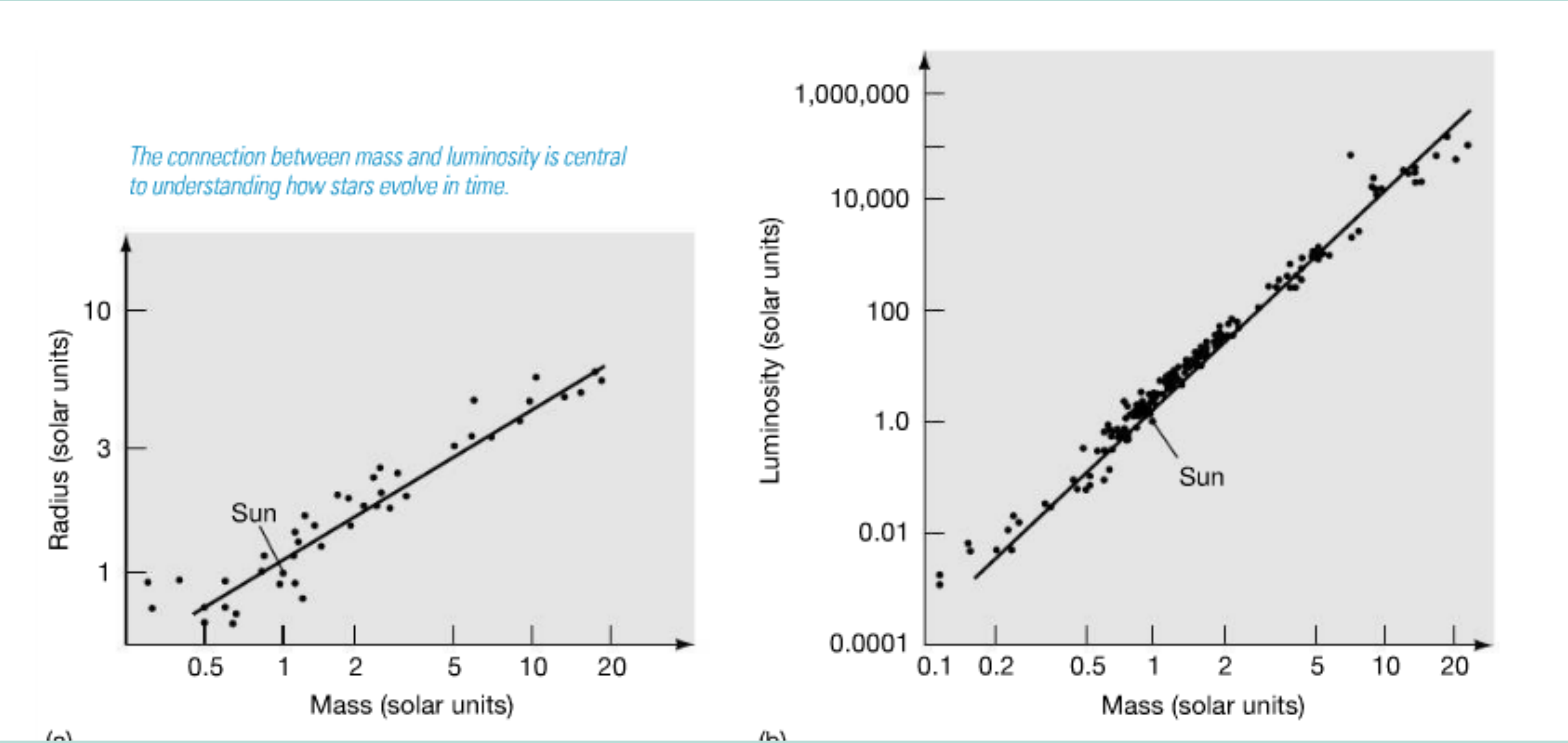
Mass determines Main-sequence location



Small stars are less common than big ones, in much the same way that grains of sand on a beach greatly outnumber bigger rocks.



Mass - Radius - Luminosity



Linear

Quartic

TABLE 17.5 Key Properties of Some Well-Known Main-Sequence Stars

Star	Spectral Type	Mass (*M*) (solar masses)	Central Temperature (10^6 K)	Luminosity (*L*) (solar luminosities)	Estimated Lifetime (*M/L*) (10^6 years)
Spica B*	B2V	6.8	25	800	90
Vega	A0V	2.6	21	50	500
Sirius A	A1V	2.1	20	22	1000
Alpha Centauri	G2V	1.1	17	1.6	7000
Sun	G2V	1.0	15	1.0	10,000
Proxima Centauri	M5V	0.1	0.6	0.00006	16,000,000

* *The "star" Spica is, in fact, a binary system comprising a B1III giant primary (Spica A) and a B2V main-sequence secondary (Spica B).*

- Note the mass luminosity correlation!

Stellar Lifetime

$$\text{stellar lifetime} \propto \frac{1}{(\text{stellar mass})^3}$$

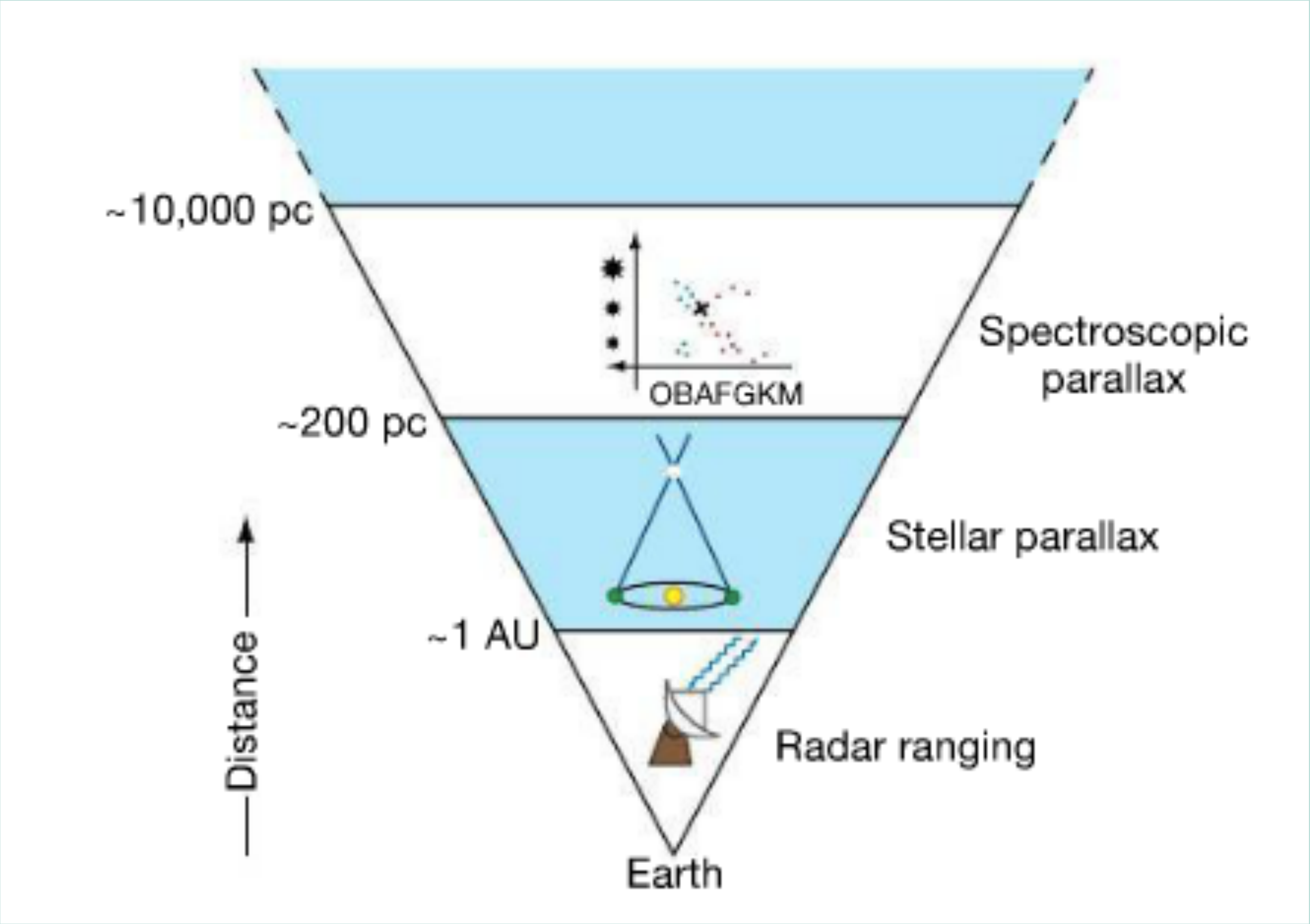
- O type stars with about 10 solar masses only last about 10 million years
- K and M type stars with 1/10 solar masses could shine for another trillion years!

Back to Cosmic Distances

- “Degeneracy”

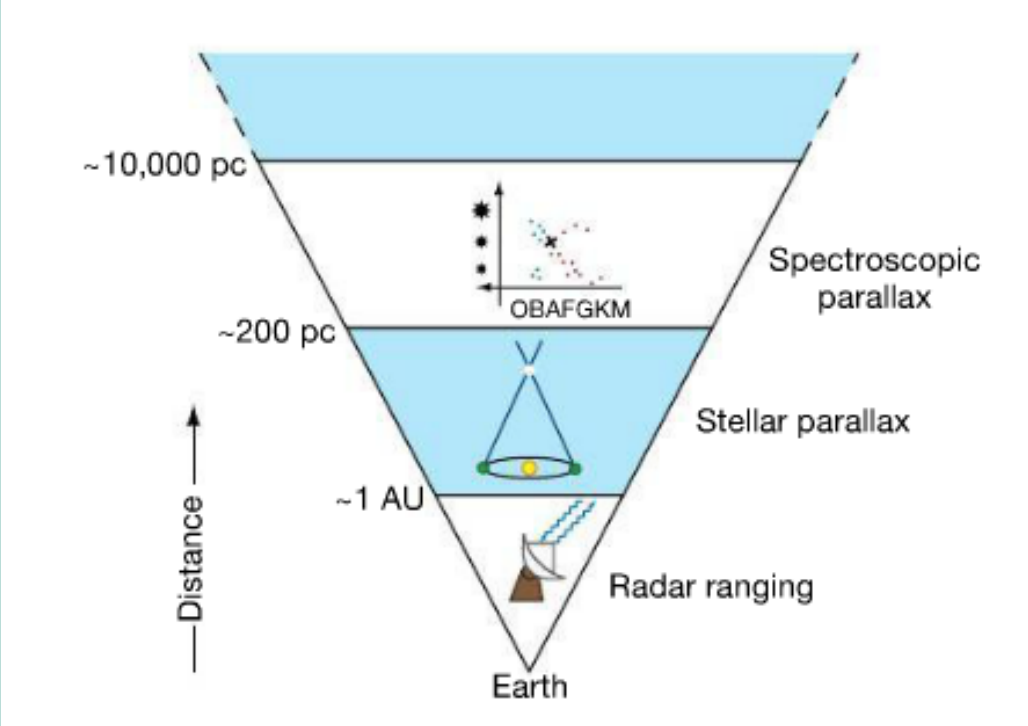
- So how do we “know” the 3D configuration of the universe without ever leaving home?

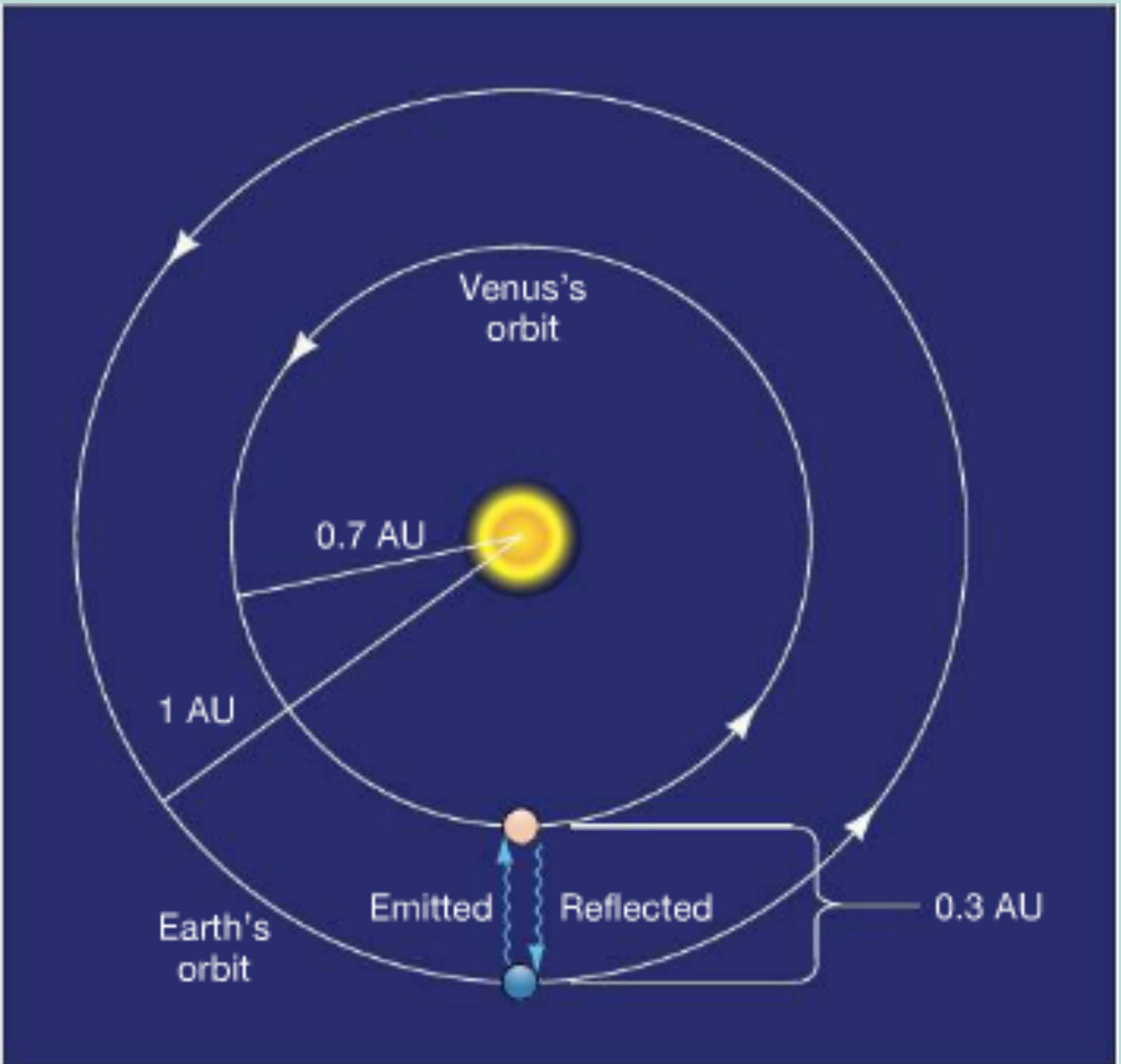
Radar Ranging, Stellar Parallax, Spectroscopic Parallax

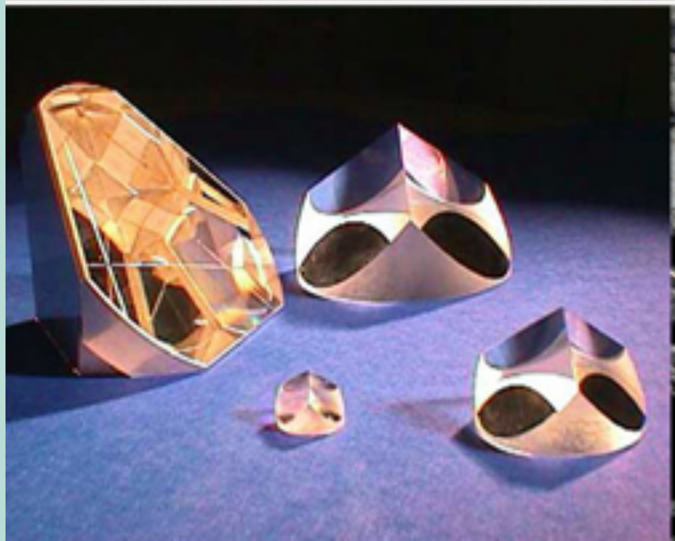


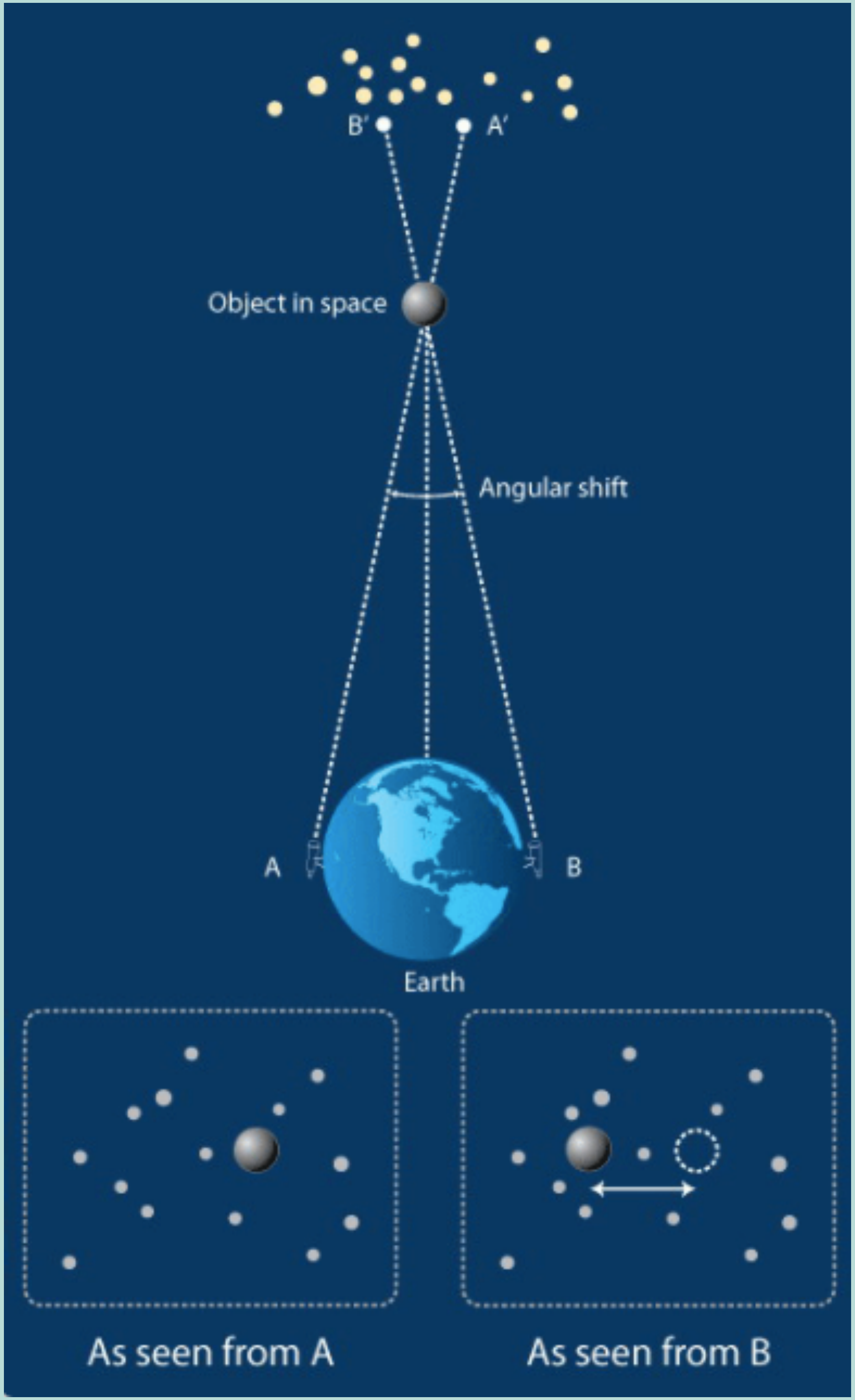
Radar Ranging

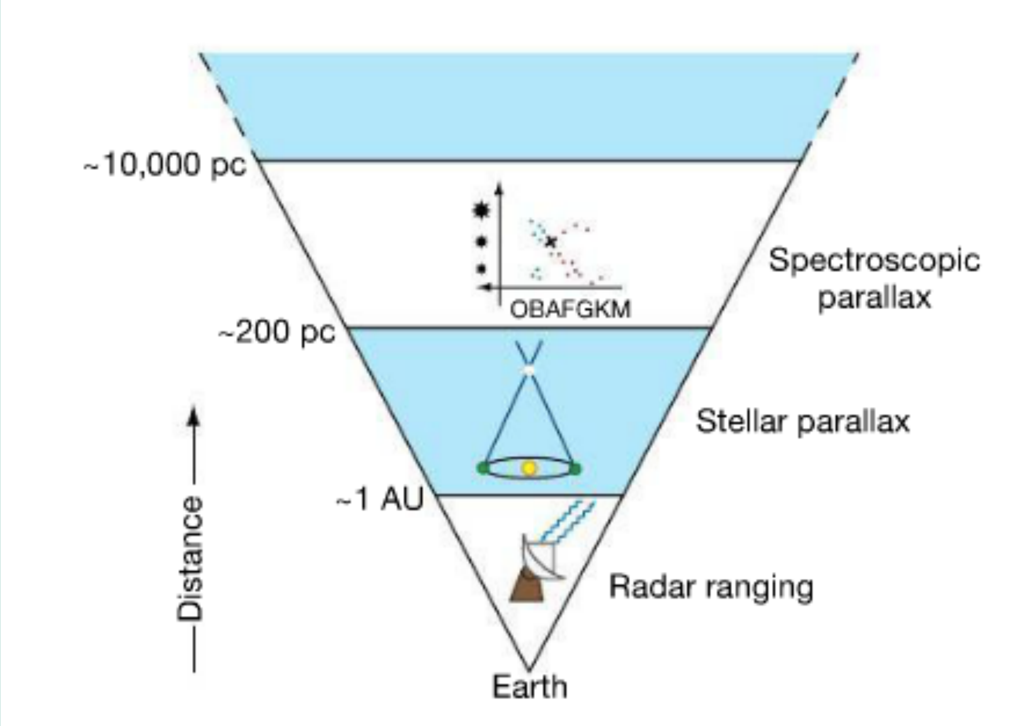
(seconds - minutes)









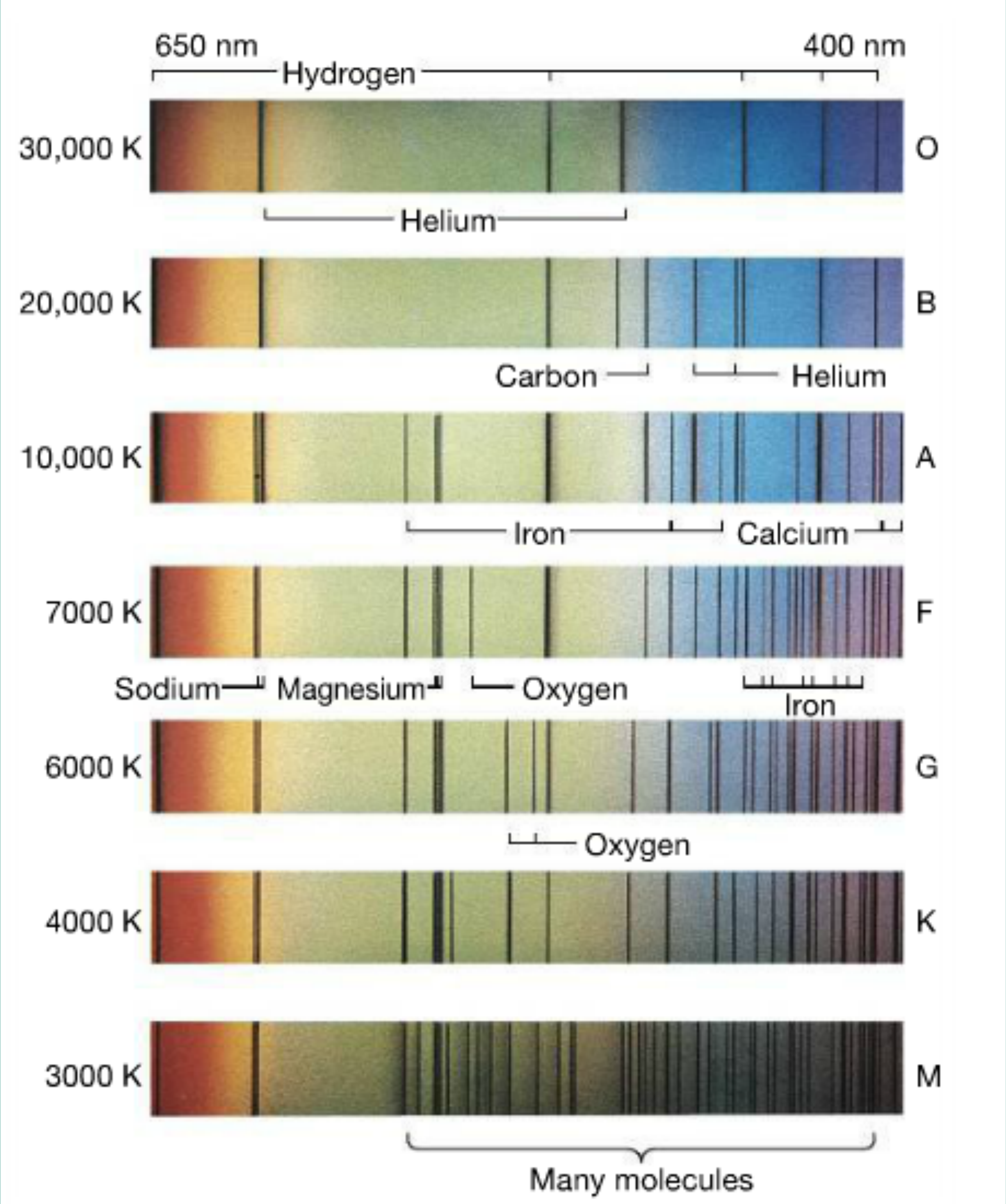


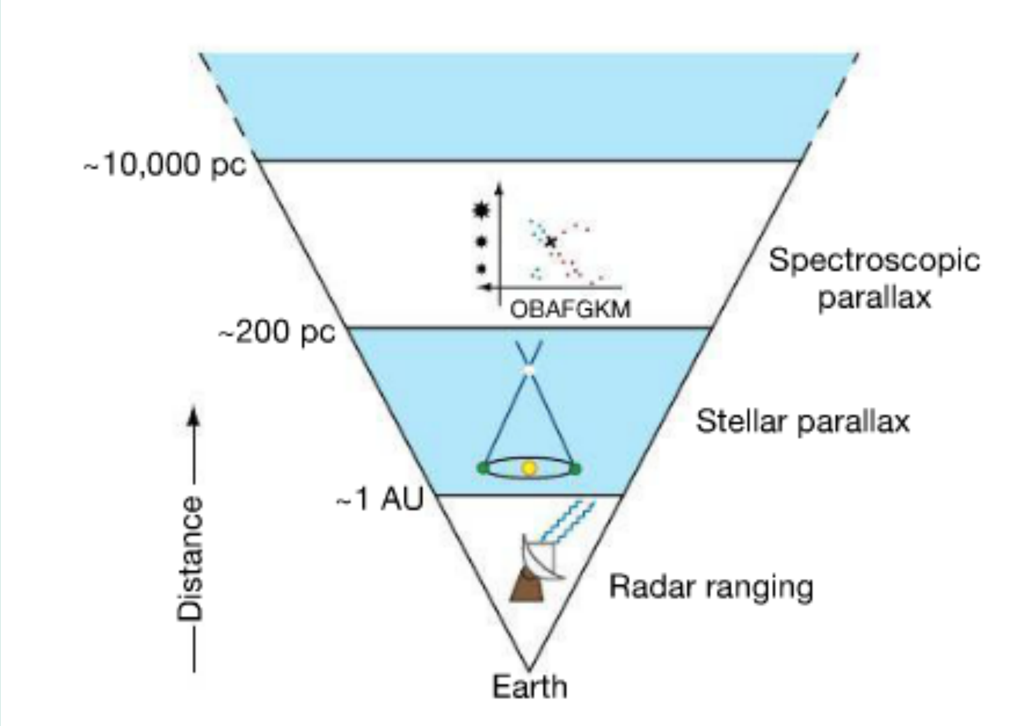
Parallax

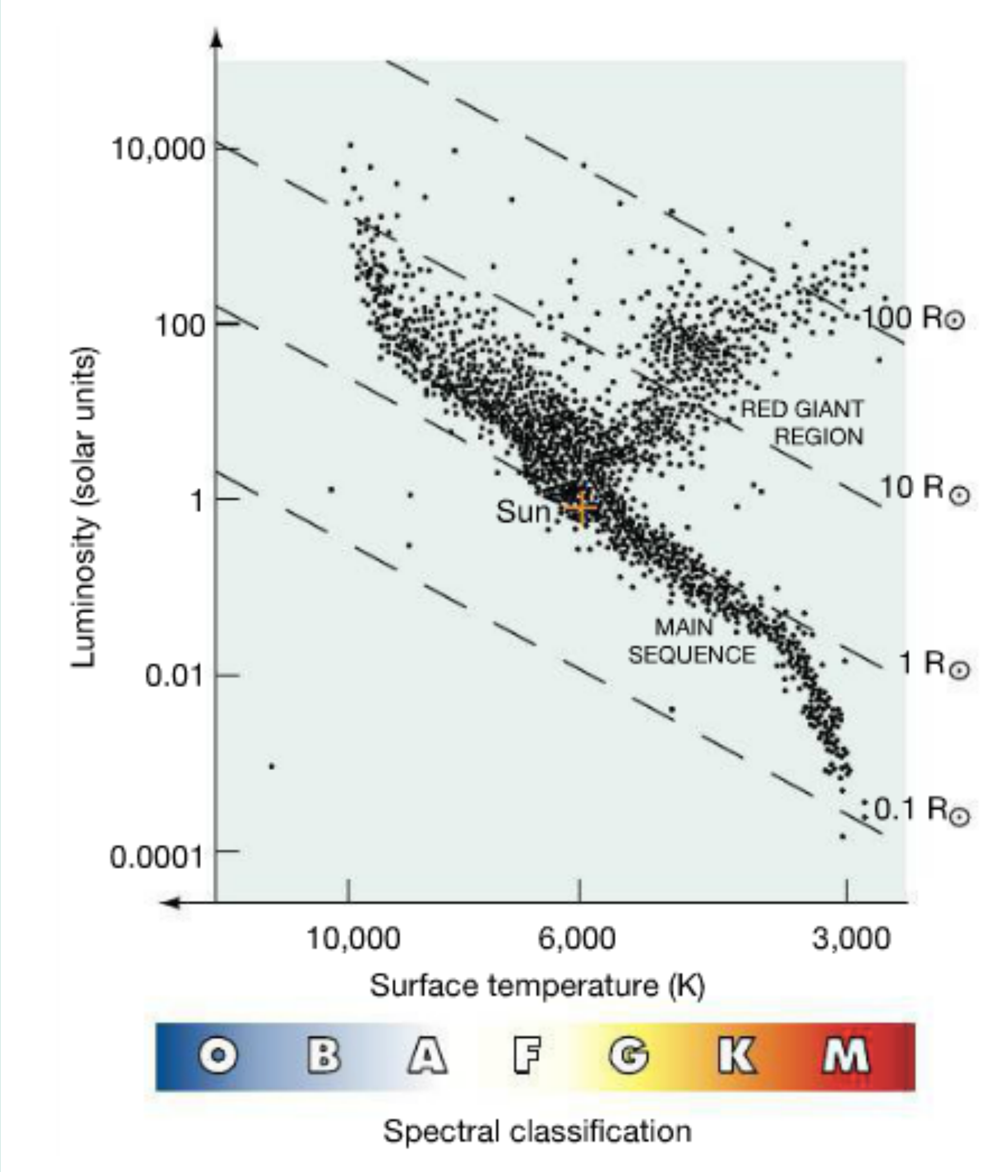
(centuries)

(millenia)

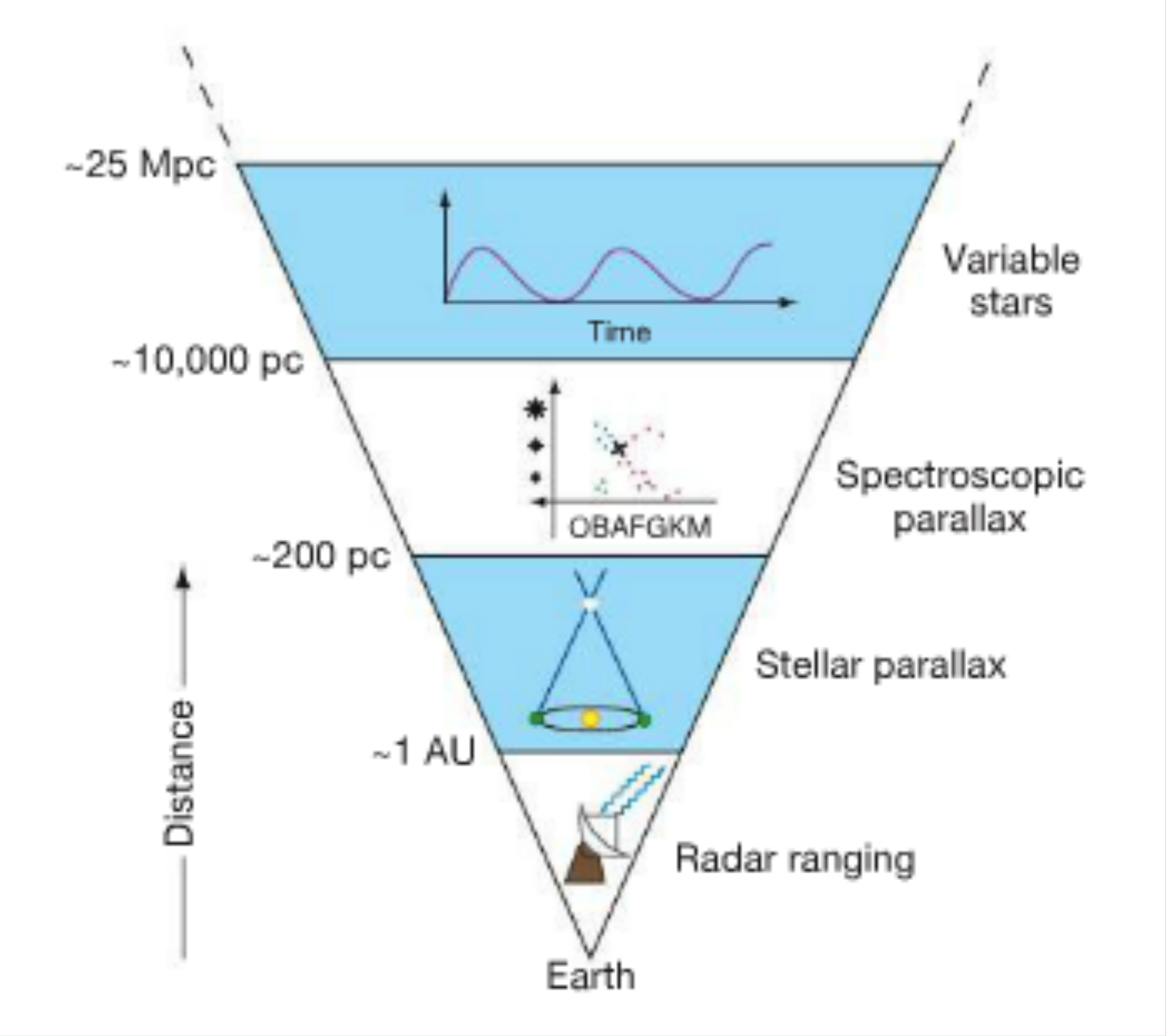
Spectroscopic Parallax



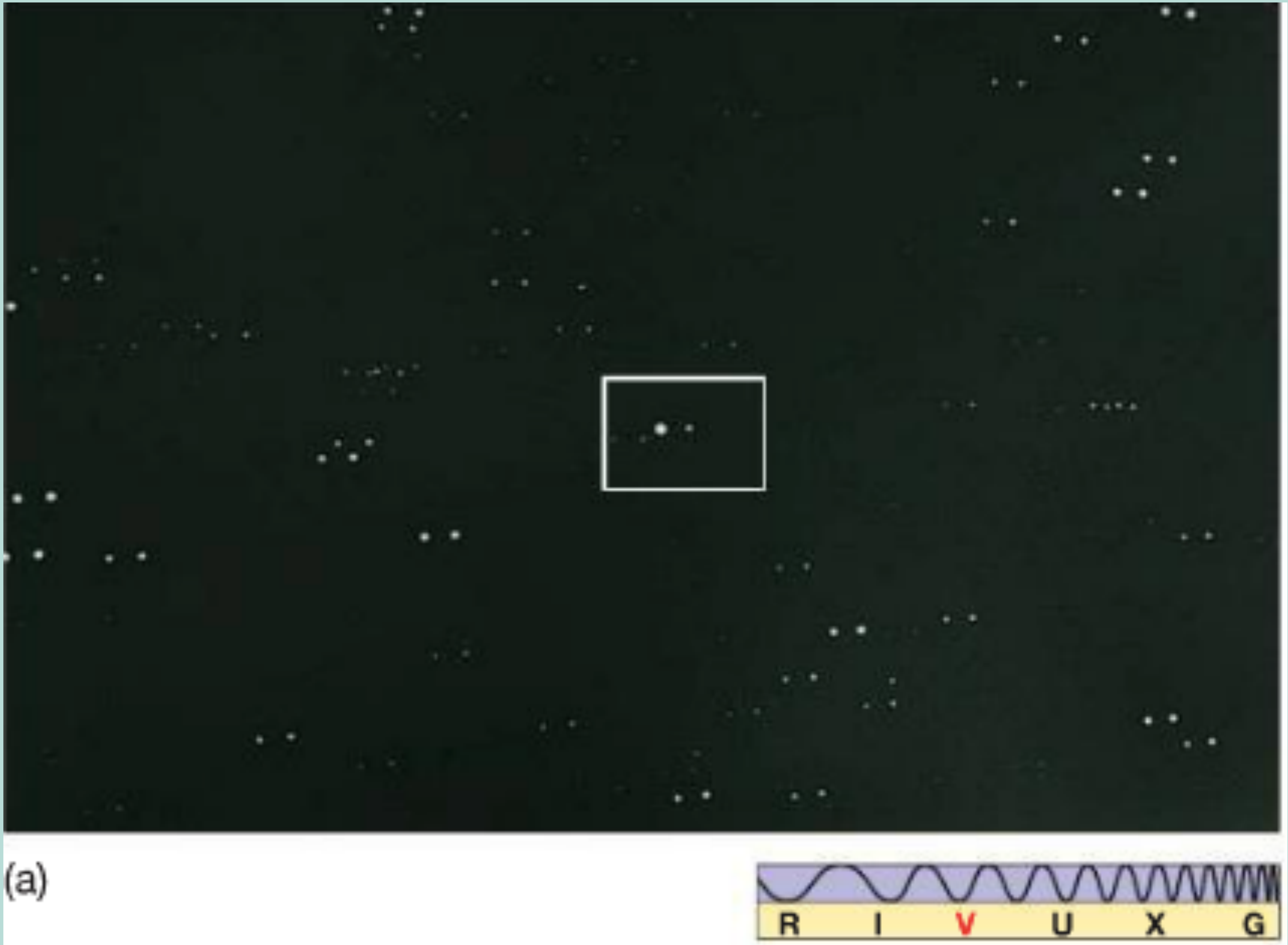




Variable Stars (megadecades)

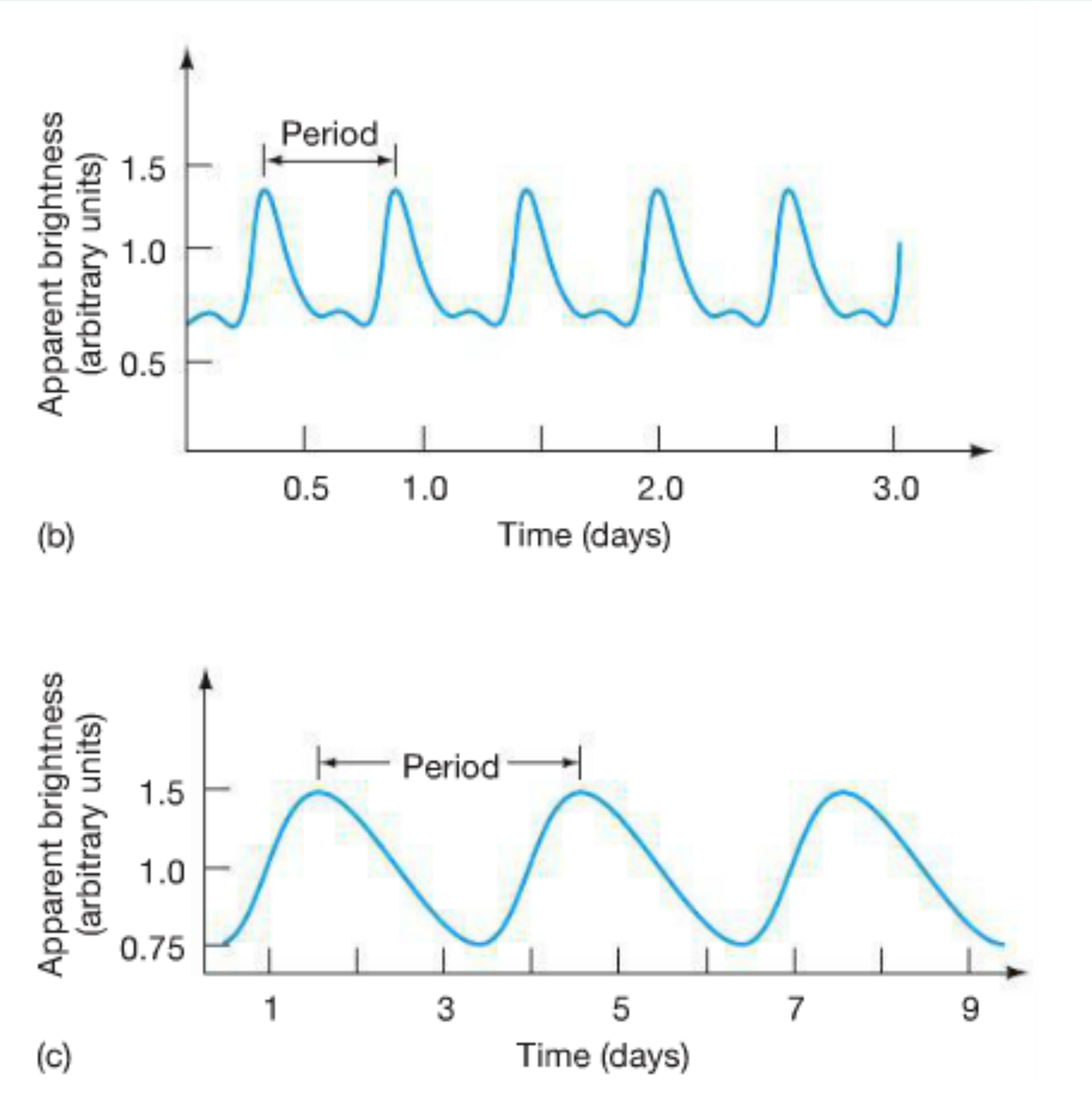


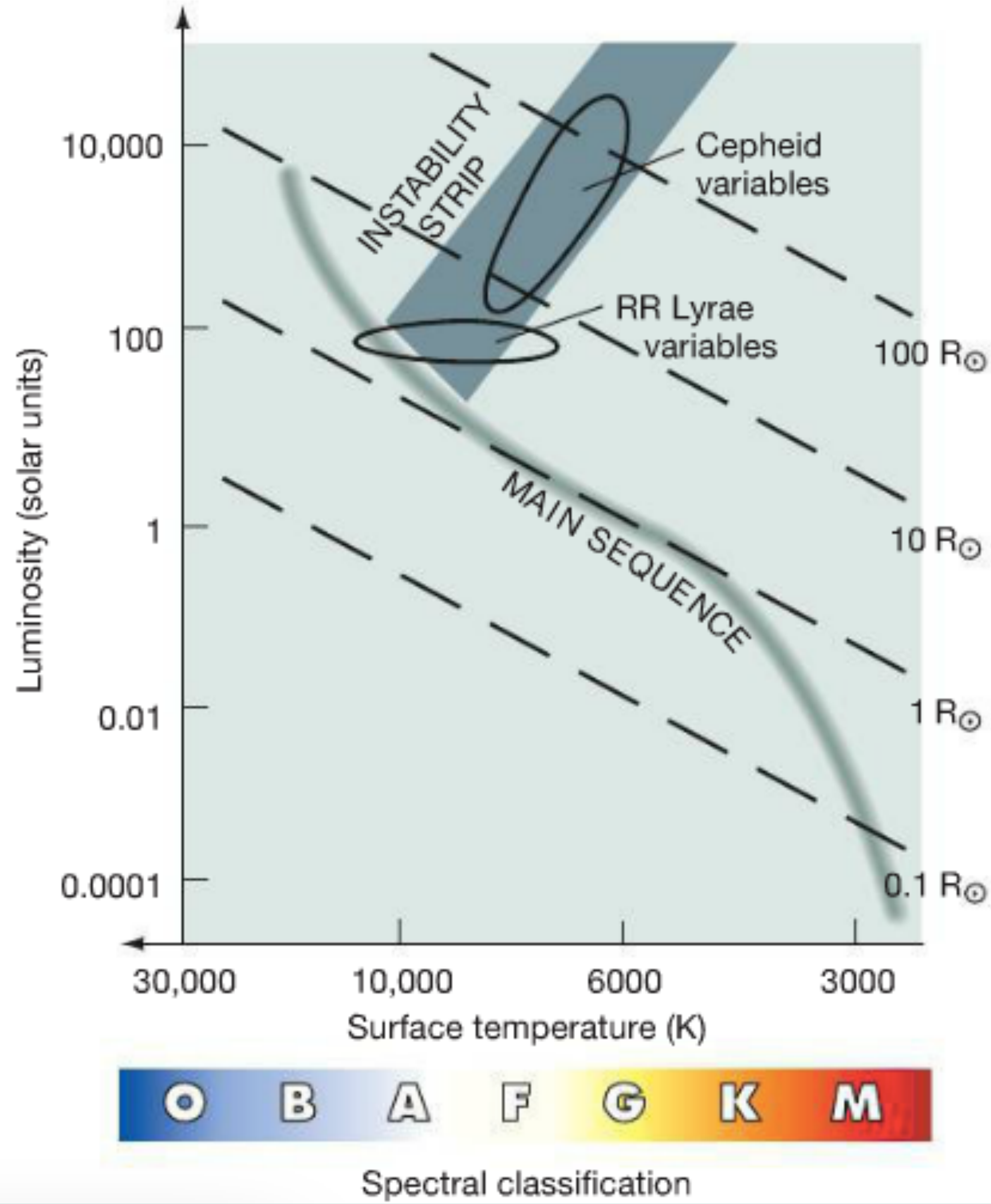
WW Cygni (cepheid variable)



(a)

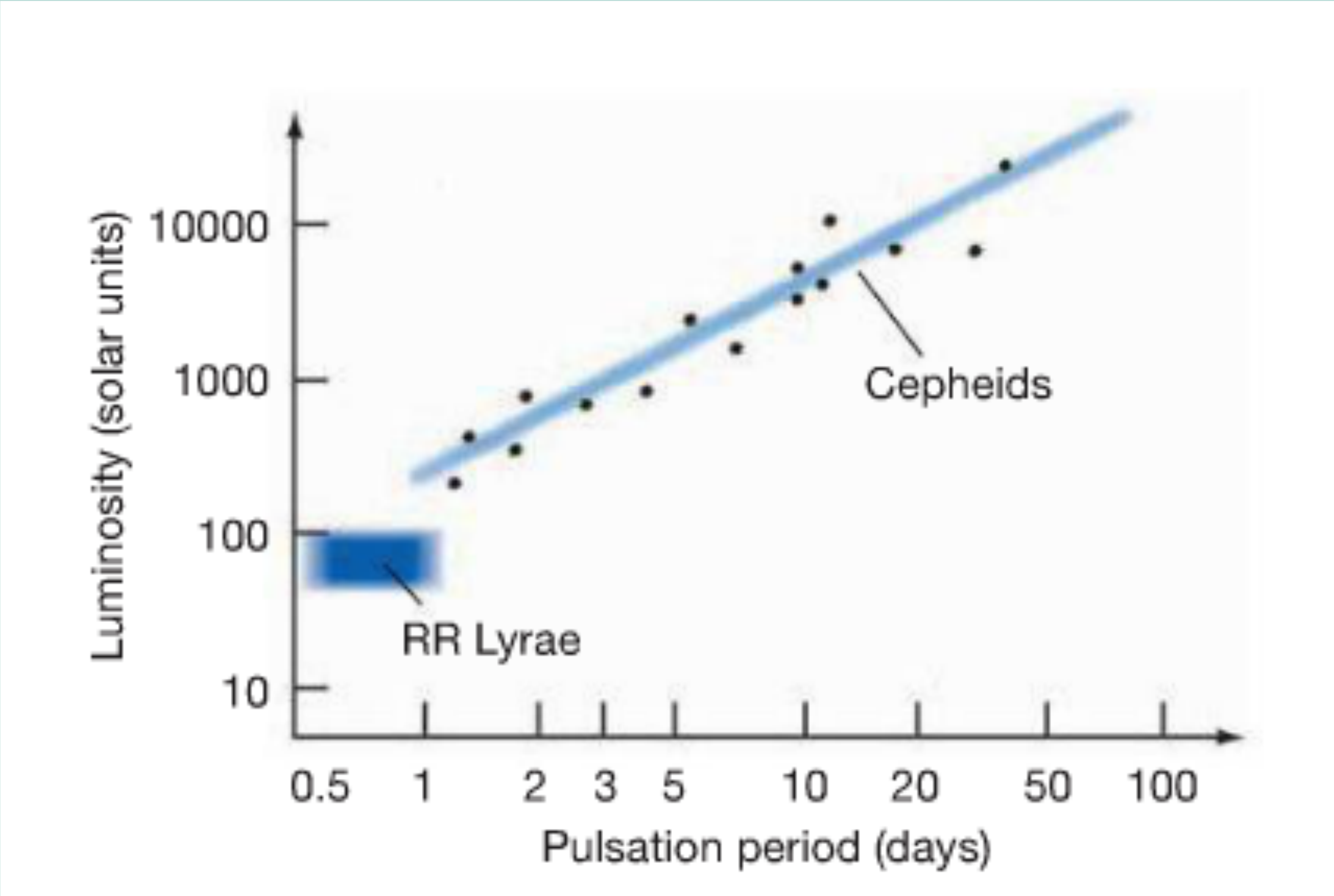
Light curve


Period
Apparent brightness (arbitrary units)
1.5
1.0
0.5
0.5
1.0
2.0
3.0
(b)
Time (days)
Period
Apparent brightness (arbitrary units)
1.5
1.0
0.75
1
3
5
7
9
(c)
Time (days)

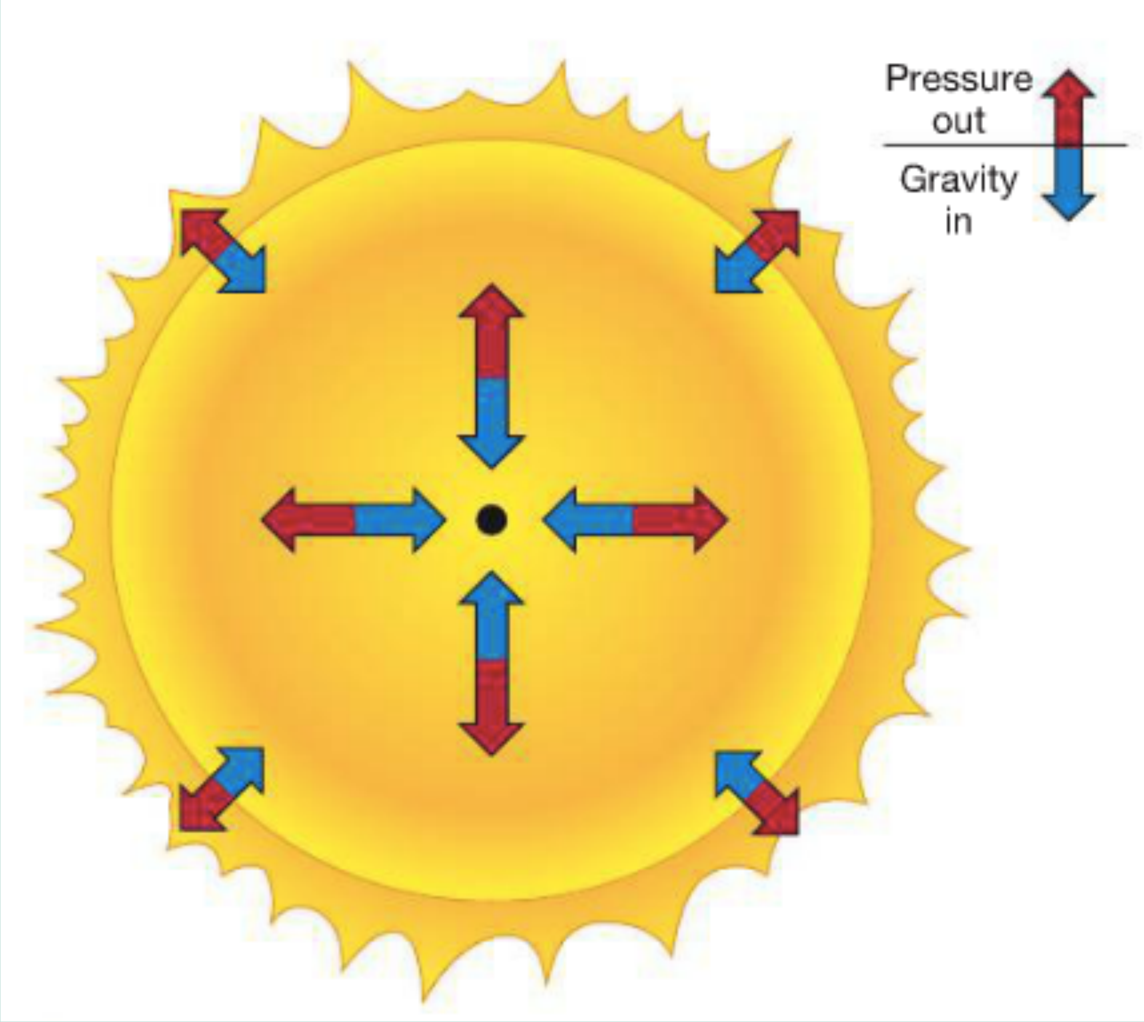


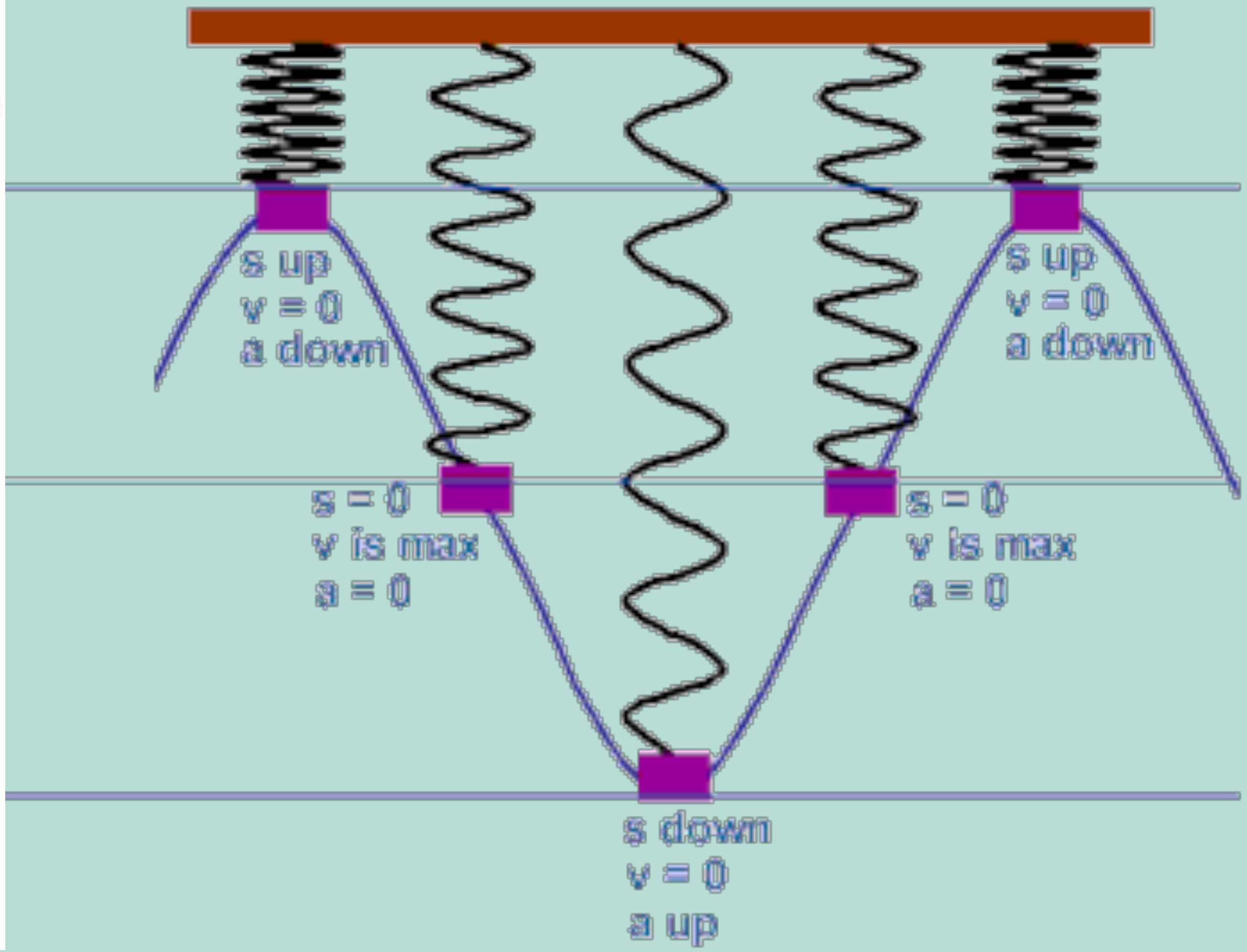
Luminosity (solar units)
10,000
100
1
0.01
0.0001
INSTABILITY STRIP
Cepheid variables
RR Lyrae variables
MAIN SEQUENCE
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
30,000
10,000
6000
3000
Surface temperature (K)
O
B
A
F
G
K
M
Spectral classification

Luminosity vs Period



But why do these stars pulsate?





Think equilibrium!

Variable Stars

- Recall from hydrostatic equilibrium, gravity is fighting against radiation pressure from the explosive fusion reactions
- This leads to an elastic situation, where if you squish a star, the radiation pressure will push it out to it's original state, and if you expand a star, the gravity will squish it back to its original state.
- This is because pressure is inversely proportional to volume (so 1/r^3) and gravity is proportional to distance to the center of mass (1/r^2), so as the star expands, both pressure and gravity drop, but pressure drops faster so gravity squishes it again.

Variable Stars

- One would think this oscillation would dampen over time (just like when you stop pumping on the swings), not continue at a constant rate (like someone is pushing you on the swings)
- Helium is responsible for driving the expansion and contraction and thus cooling and heating of variable stars.
- Doubly ionized helium is more opaque than singly ionized helium, so when its hot and helium is ionized, the radiation pressure builds up and the star expands and cools

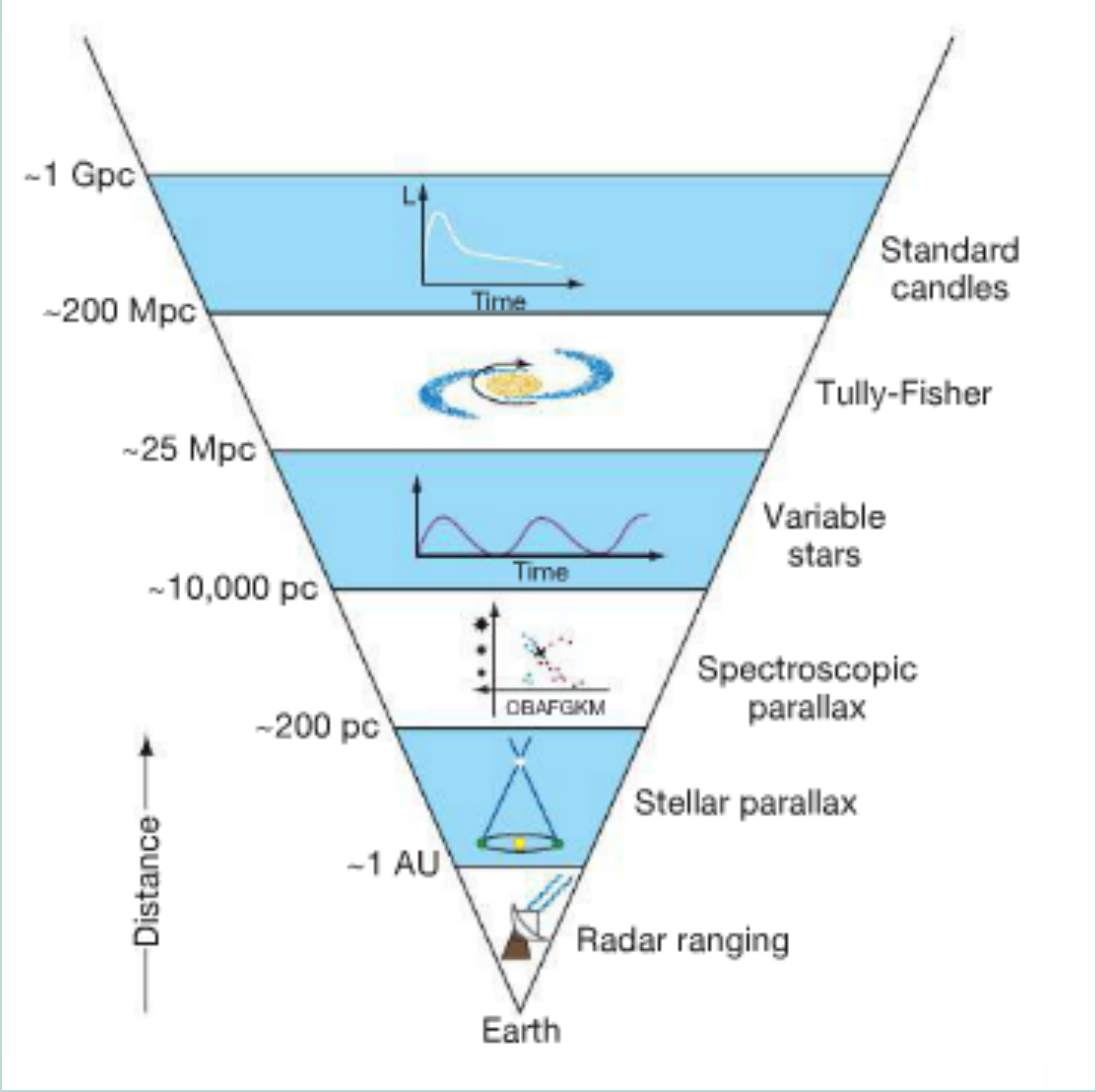
Variable Stars

- But when it cools, Helium becomes un-ionized as it captures electrons, then becomes more transparent, releases this pressure and gravity wins and begins to crush the star, heating it up, repeating the cycle.

- Luminosity goes like R^2 but goes like T^4 so it’s small but hot, its very luminous, and when it’s large and cool it’s not very luminous (careful! This is the opposite of what wikipedia says!)

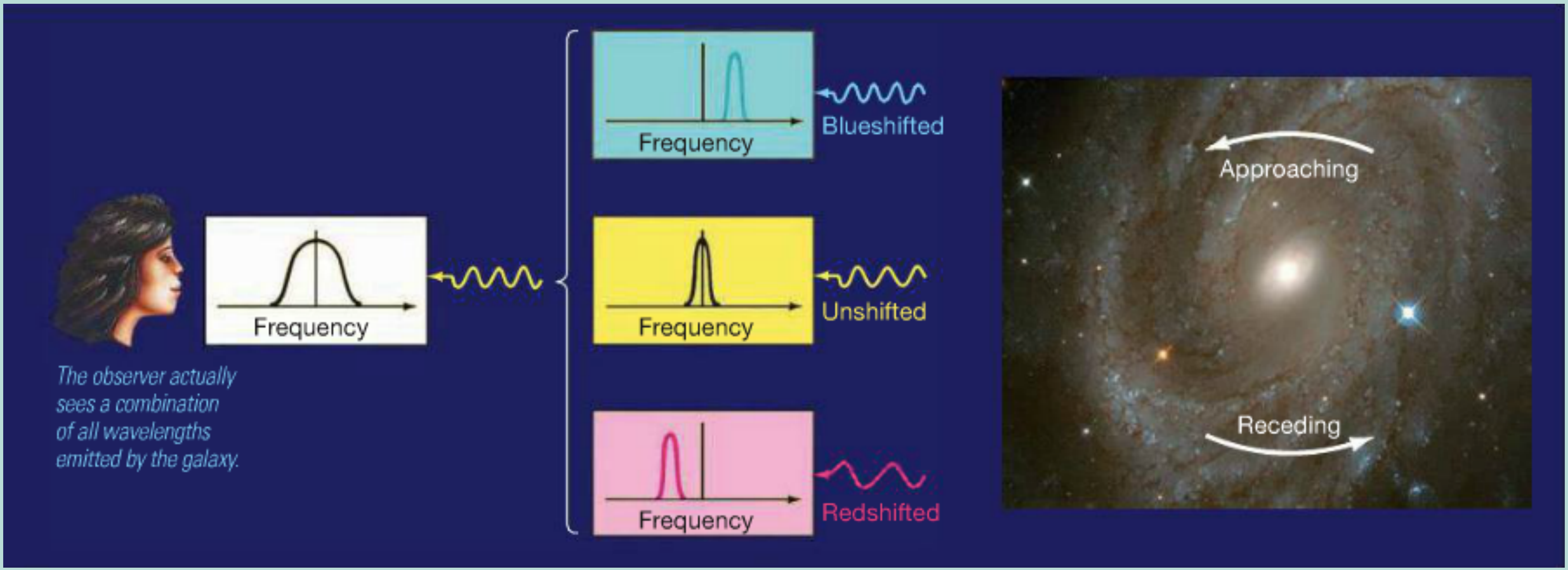
- Thus the cycle repeats and we can see this in the light curves of variable stars.

Tully-Fisher, Supernovae (megacenturies)



Tully-Fisher

- Tully and Fisher found an incredibly tight correlation between the rational speed of a galaxy and its luminosity
- This shouldn't be surprising, think Newton's Laws! (more stars, more bright, more stars, more mass, more mass, more centripetal force, more centripetal force, more rotational speed)
- We measure rotational speed with line broadening! Which line is subtle, we should pick one that is usually pretty sharp and not subject to being obscured by dust in our own galaxy: 21cm radio line



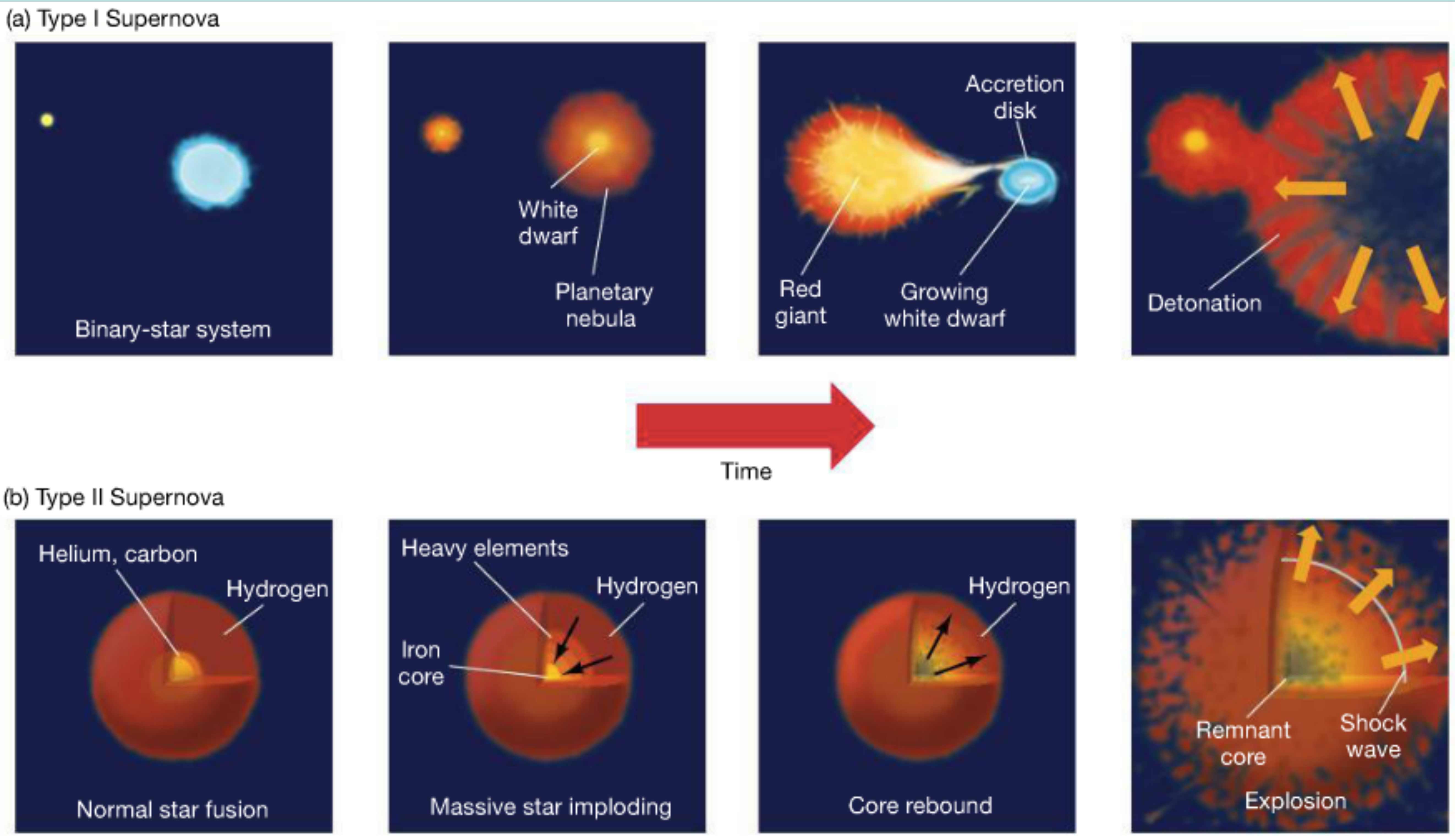
Frequency
Blueshifted
Frequency
Unshifted
Frequency
Redshifted
Frequency
The observer actually sees a combination of all wavelengths emitted by the galaxy.
Approaching
Receding

Supernovae

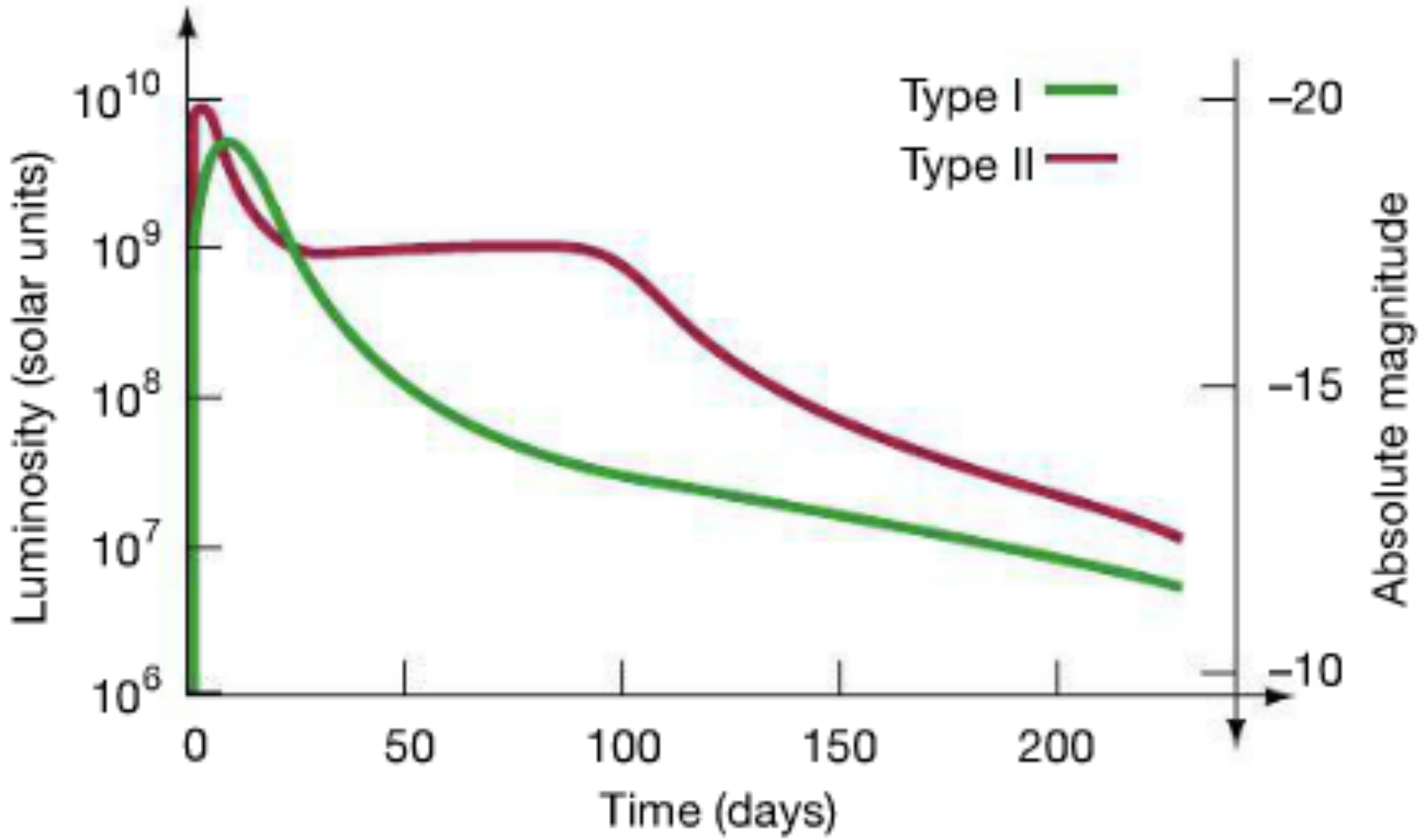
- Type I supernovae all have about the same luminosity because their mechanism is very straightforward and well understood (carbon fusion from ignited white dwarves)

- Thus they provide a “standard candle” for far away galaxies. When we see a specific light curve, we know it was a type I supernova, so we know its luminosity and then by measuring its apparent brightness, we know its distance.

- This allowed us to measure the cosmological constant!

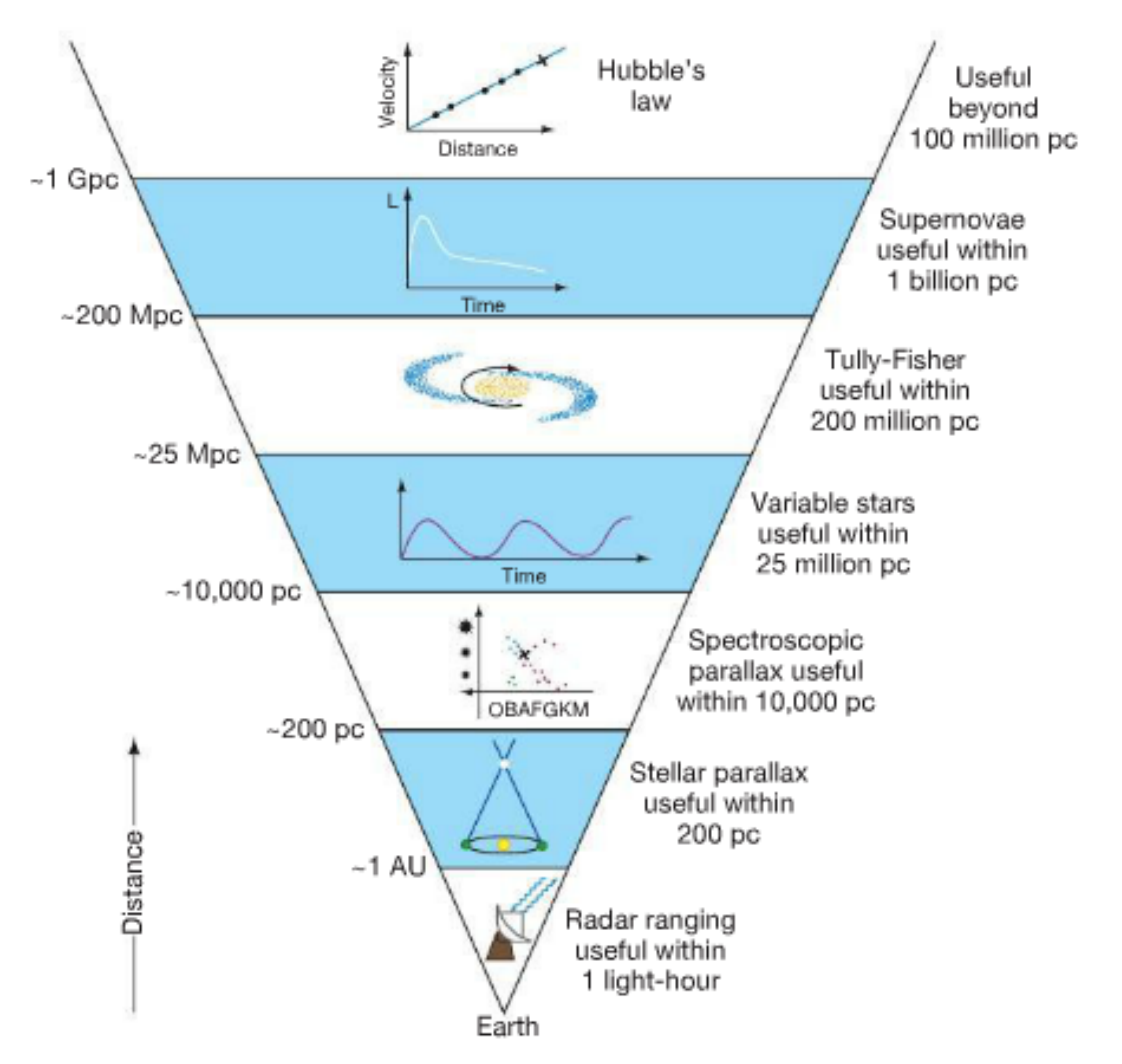


(a) Type I Supernova
Binary-star system
White dwarf
Planetary nebula
Accretion disk
Red giant
Growing white dwarf
Detonation
Time
(b) Type II Supernova
Helium, carbon
Hydrogen
Normal star fusion
Heavy elements
Hydrogen
Iron core
Massive star imploding
Hydrogen
Core rebound
Remnant core
Shock wave
Explosion



Type I
Type II
Luminosity (solar units)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
0
50
100
150
200
Time (days)
Absolute magnitude
−20
−15
−10

aeons.



…behold

Hubble's Law

$$v = H_0 r$$

H = 70 km/s/Mpc

Hubble's Law

- This is only true for *very* far away things in the universe

- Note the velocity just keeps on growing linearly with distance! Eventually it reaches the speed of light!

- This distance, when $v = c$ is the edge of the "observable universe". So the size of the observable universe is $c/H_0 \sim 14$ billion years.