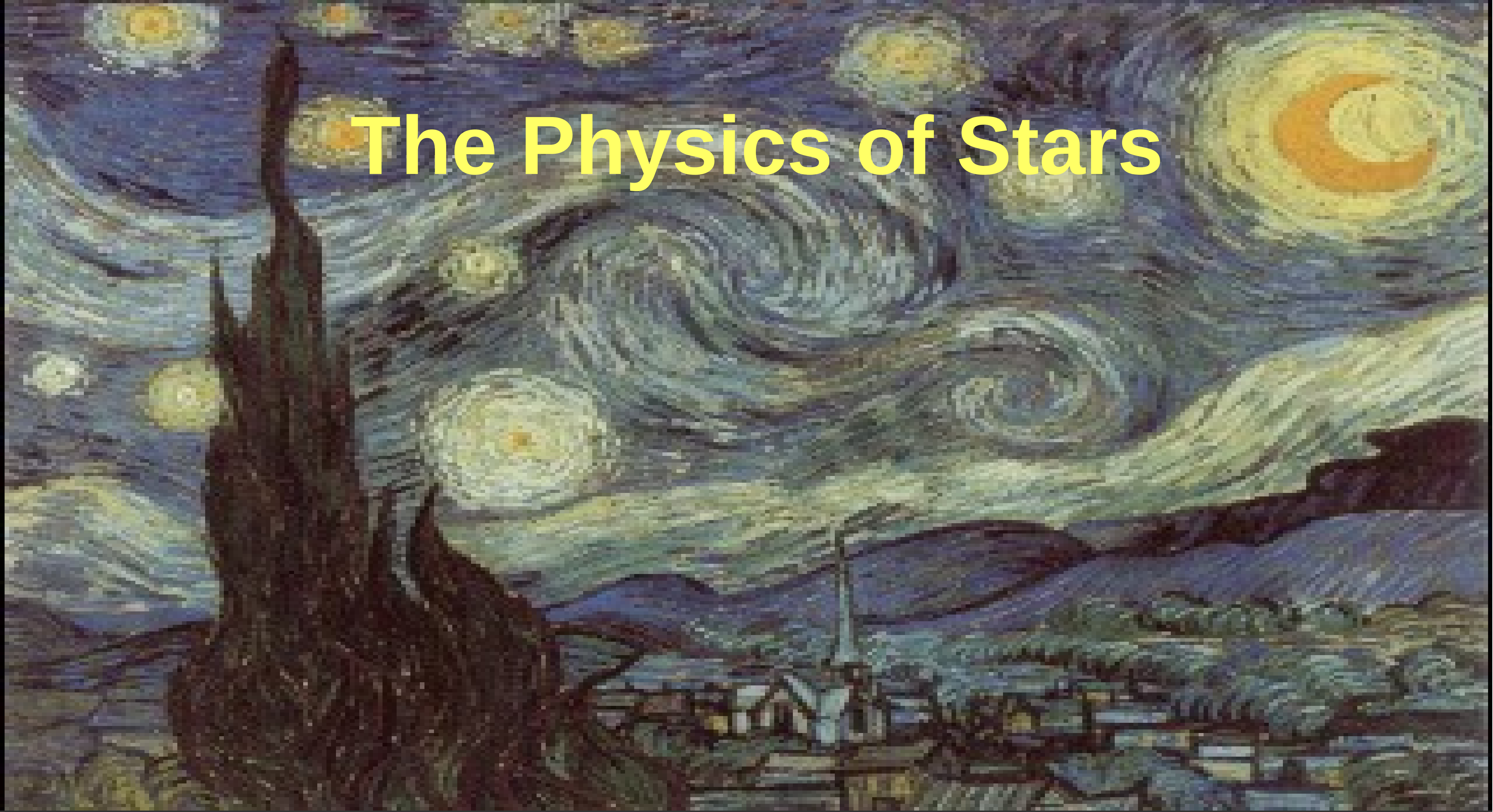
The Physics of Stars



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So, What are Stars?

Pumbaa: Timon, ever wonder what those sparkly dots are up there?

Timon: Pumbaa, I don't wonder; I know.

Pumbaa: Oh. what are they?

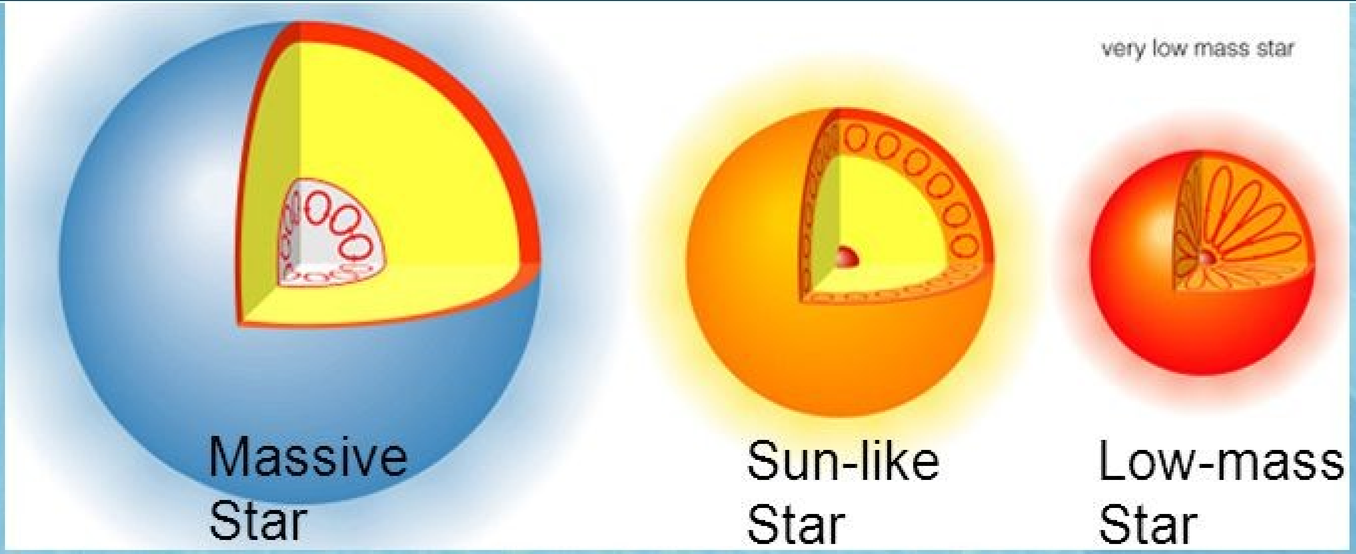
Timon: They're fireflies that got stuck up in that bluish-black thing.

Pumbaa: Oh, gee. I always thought they were balls of gas burning billions of miles away.

Timon: Pumbaa, with you, everything's gas.

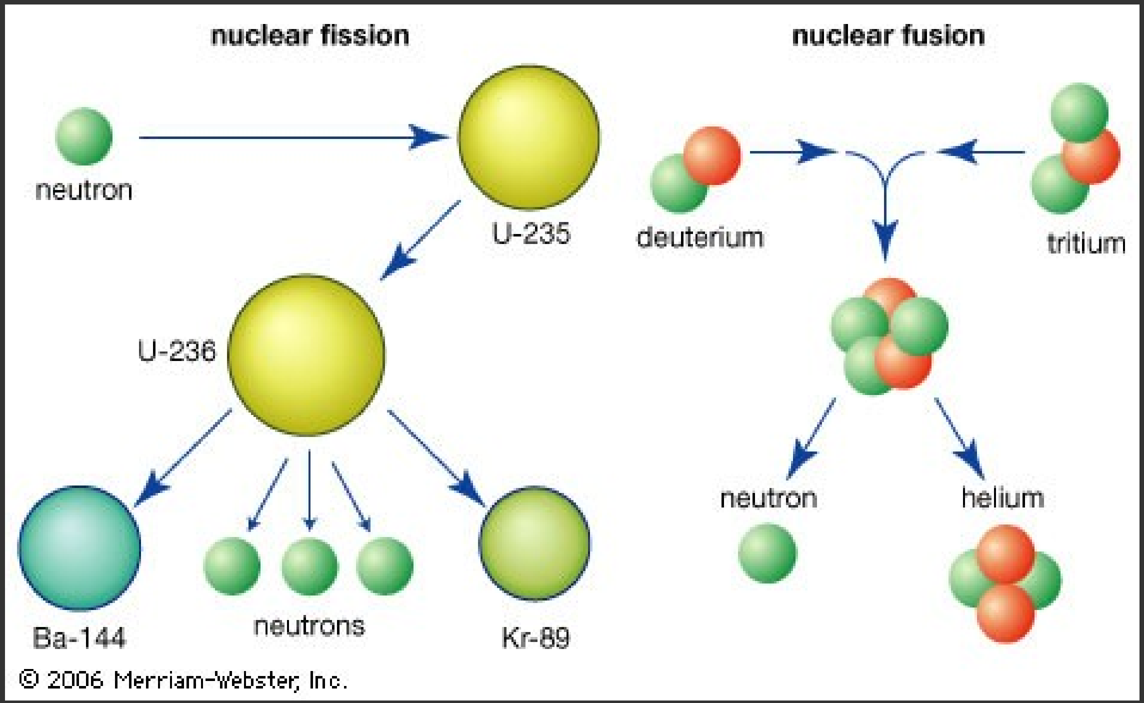
-The Lion King

A star is a big ball of gas, with fusion going on at its center, held together by gravity!



There are variations between stars, but by and large they're really pretty simple things.

A star is a nuclear reactor...



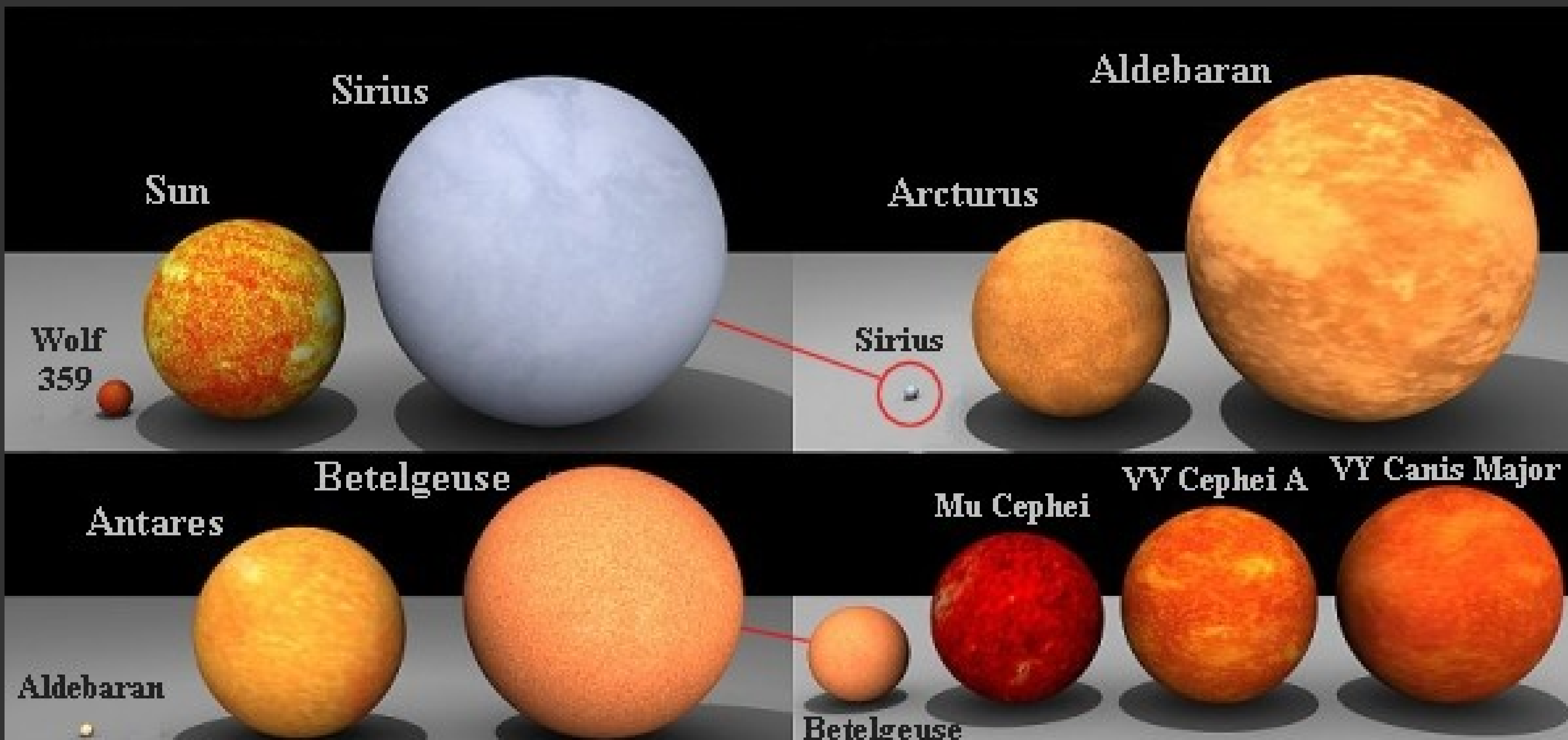
$$Binding\ Energy = mass\ defect \times c^2$$

What properties of the stars do you notice?

- **Difference in brightness of stars.**
- **Difference in the Colors of the stars.**

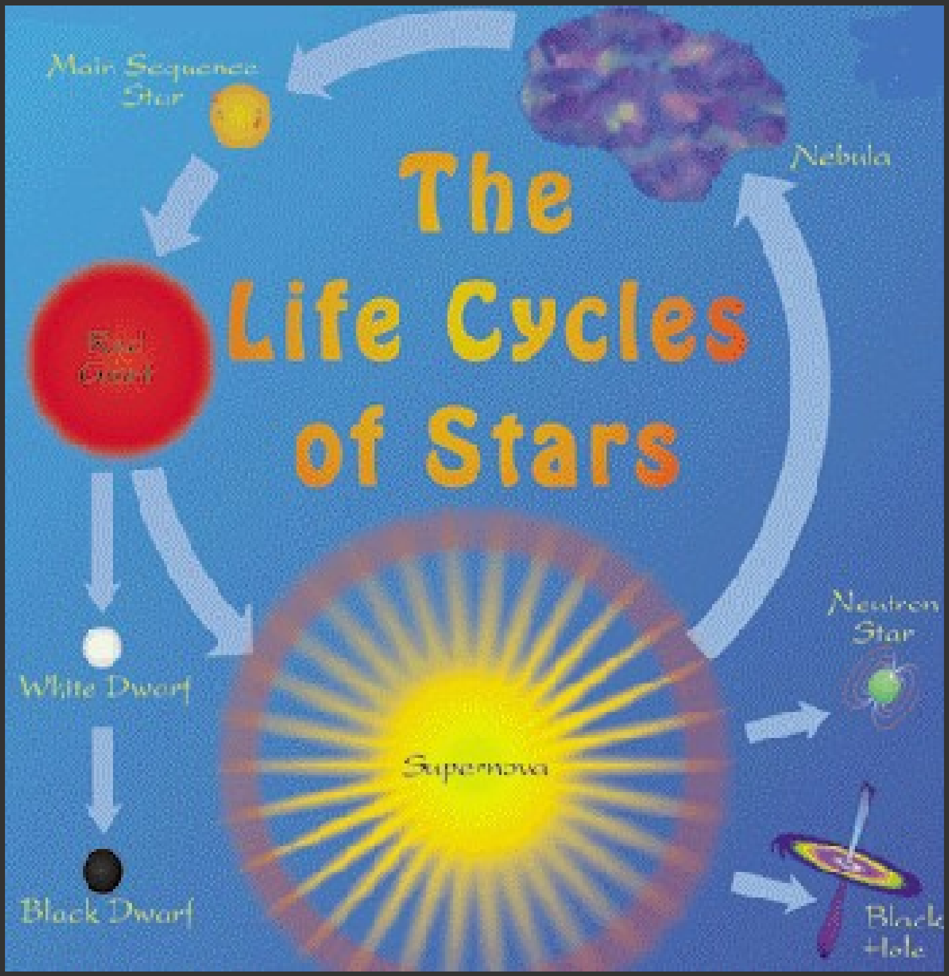
Brightness ≡ Luminosity

Sizes and Colours of Stars



Color of Stars

Understanding the stars



Russell-Voigt Theorem

- Mass
- Chemical composition

Hertzsprung-Russell Diagram

- Luminosity
- Temperature

Outline

- What is the HR diagram?
  - Absolute brightness (Luminosity)
  - Temperature (Spectral class)
- Where are most stars in the HR?
- What happens when stars evolve over time on the HR?
- What does an HR diagram of a star cluster tell us?

The basic problem...

When we try to understand the life of a star, we face a harder problem than a mosquito trying to understand a human life.

The basic problem...

- Human life = 3,000 mosquito lives (80*365/10) (male 10 days, female 42-56 days)
- Stellar life = 100,000,000 human lives
- We cannot sit back and watch; we need a different approach
- We use the laws of physics and a few observable quantities to understand the lives of stars

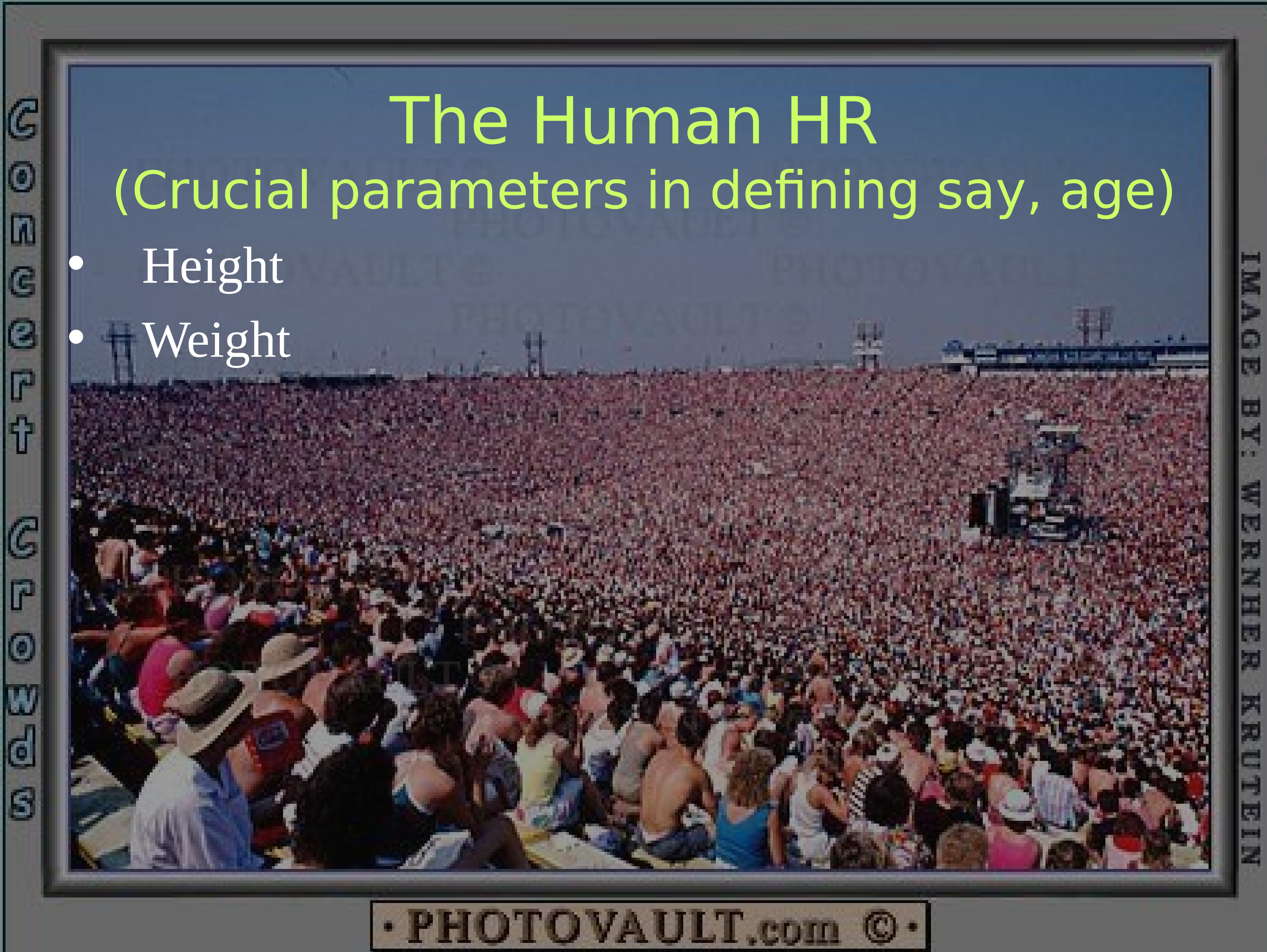
The basic problem…

Let’s say the mosquito takes the foll approach:

- The mosquito observes properties for each person: ***color of hair***, ***height, weight, age, etc of the person***.
- But what are the major properties that define the human lifecycle?
- What do we notice in people when we want to assess, say their age?

The Human HR
(Crucial parameters in defining say, age)

- Height
- Weight



HR for Human Beings

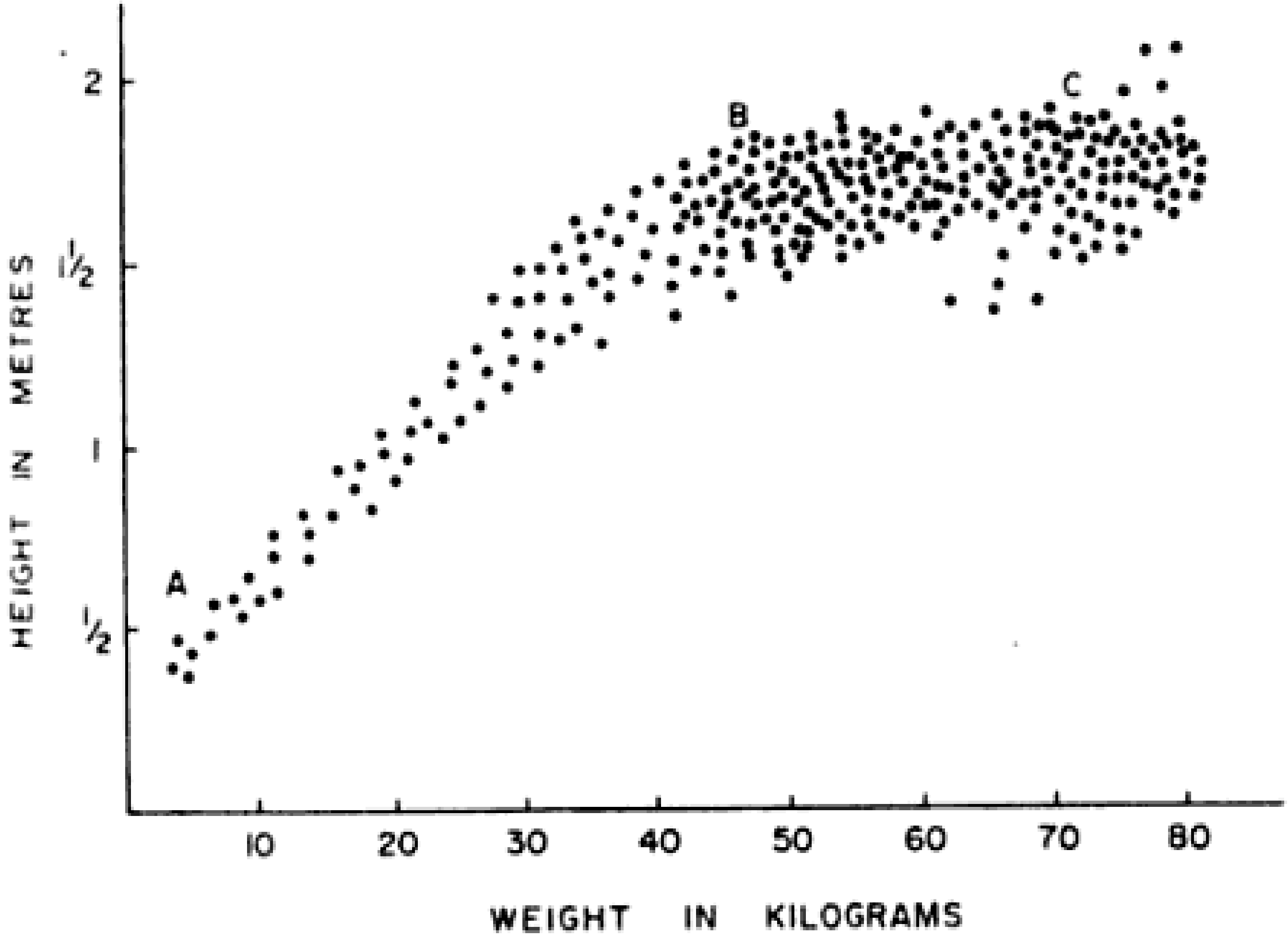


Figure 1.1. A schematic plot of height against weight of a group of human beings.

The important parameters for stars....

Russell-Vogt Theorem

Mass

Chemical composition

Hertzsprung-Russell Diagram

Luminosity

Temperature

The HR diagram

- The tool we use to study stars is called the Hertzsprung-Russell diagram.
- It plots two observable quantities: the absolute brightness of a star and the temperature of a star.
- Combined with some laws of physics, the HR diagram provides a way to understand how stars evolve with time.

Intensity and Magnitude

(the magnitude system is a logarithmic expression of intensity or flux)

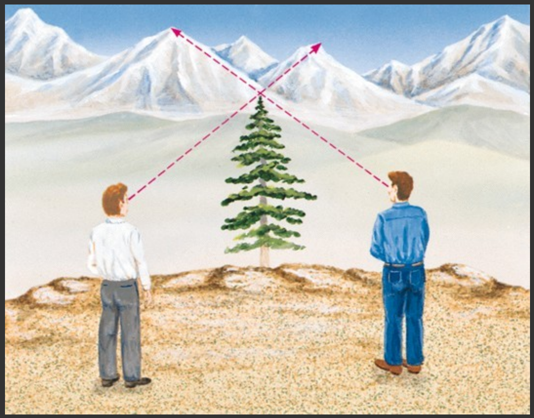
Five magnitudes corresponds to 100 factors of intensity. Thus, each magnitude corresponds to 2.5 factors of intensity.

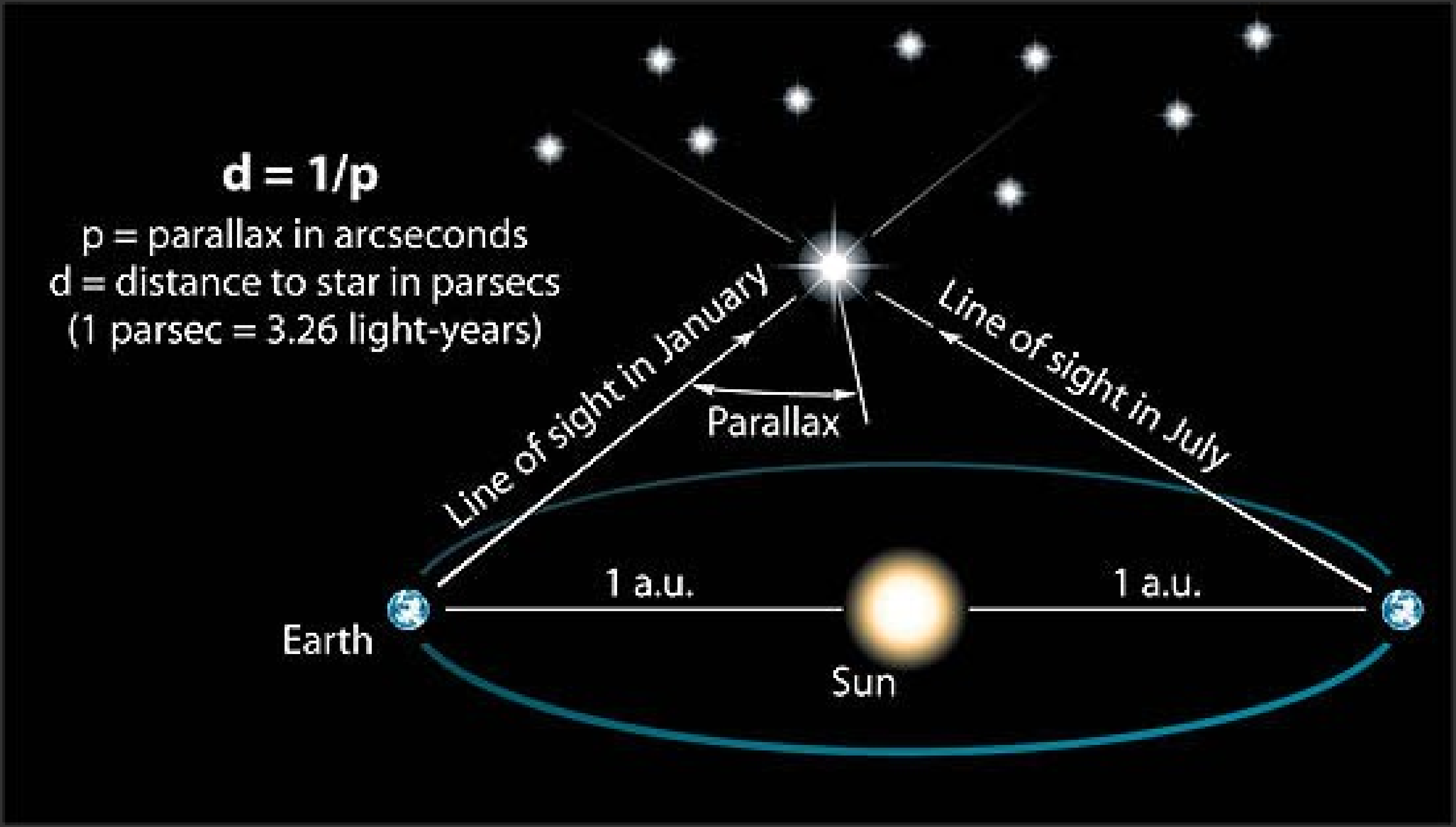
$$(100)^{\frac{1}{5}} = 2.512$$

Thus, we can compare the intensities (fluxes) of stars and A and B by forming a ratio and calculate their magnitude difference.

$$\frac{I_A}{I_B} = (2.512)^{(m_B - m_A)}$$

Parallax





d = 1/p
p = parallax in arcseconds
d = distance to star in parsecs
(1 parsec = 3.26 light-years)
Line of sight in January
Line of sight in July
Parallax
1 a.u.
1 a.u.
Earth
Sun

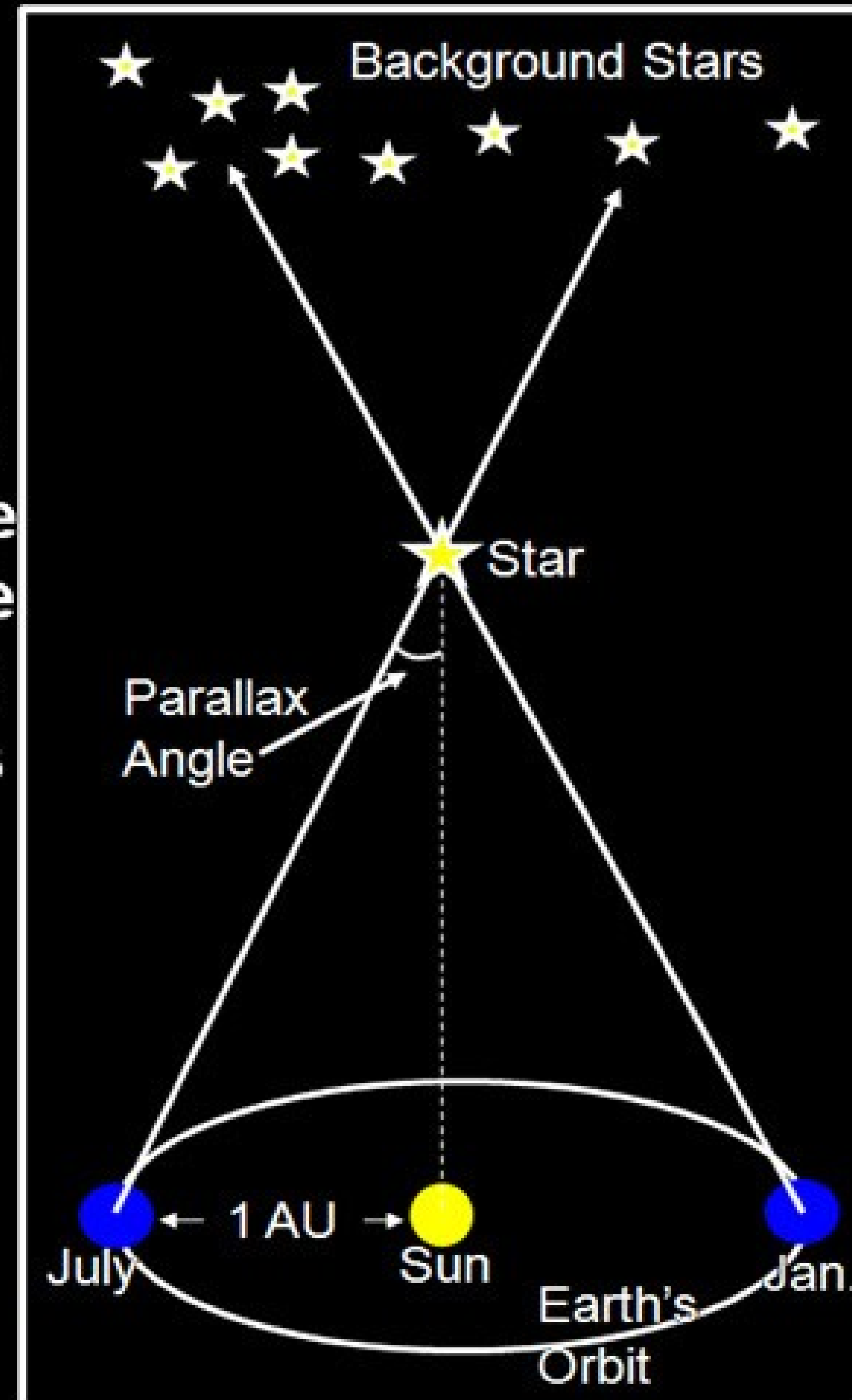
Parallax

(a method for obtaining the distance to nearby objects)

Parallax is the apparent change in position of nearby objects relative to more background objects as the observer changes position. As the earth revolves around the sun, the apparent positions of nearby stars change relative to background objects.

$$d = \frac{1}{\pi}$$ **or** $$\pi = \frac{1}{d}$$

Where d is the distance in parsecs and π is the parallax in arc seconds.



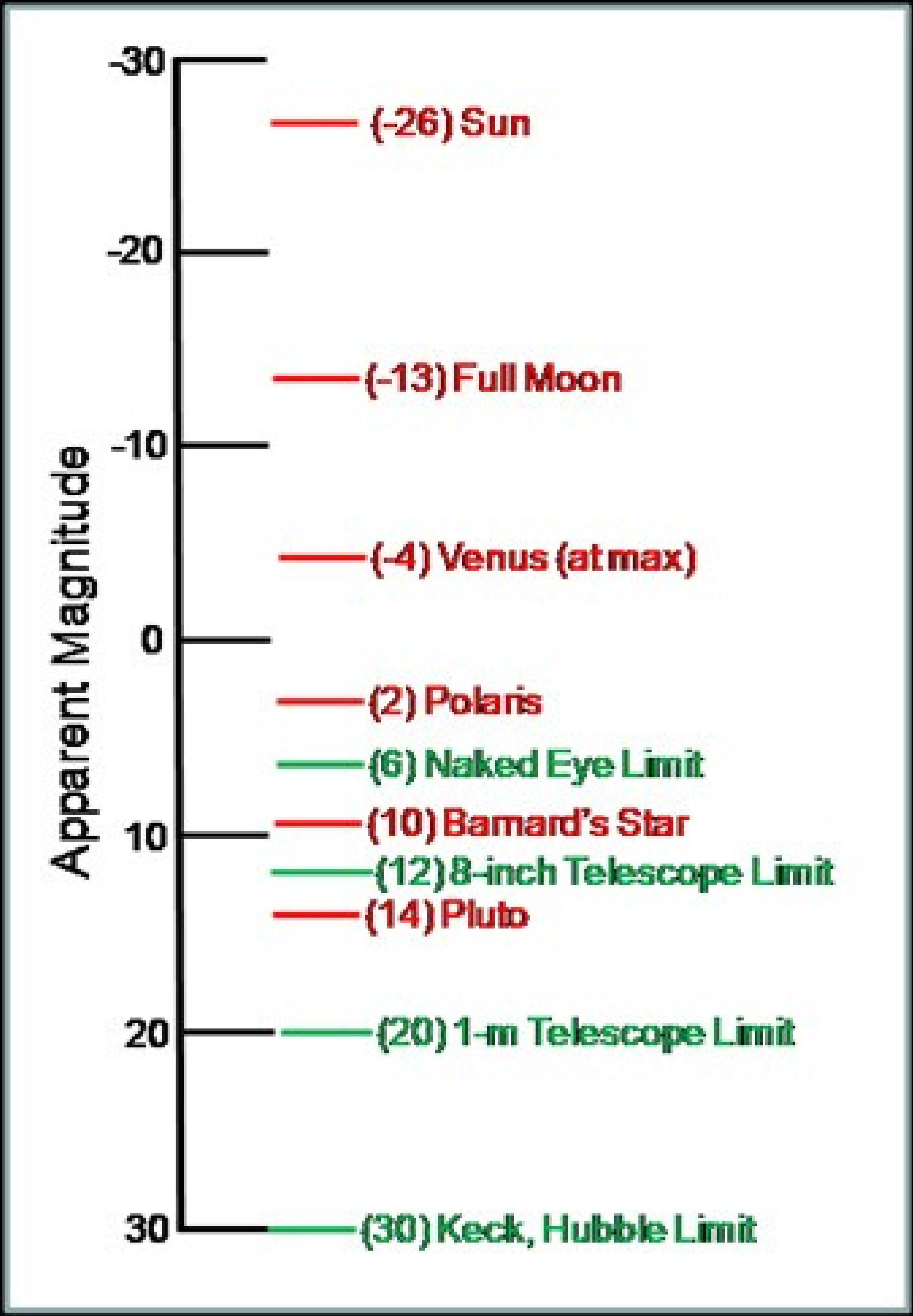
Apparent Magnitude

(useful for describing how bright objects appear from the Earth)

The original magnitude system of Hipparchus had:

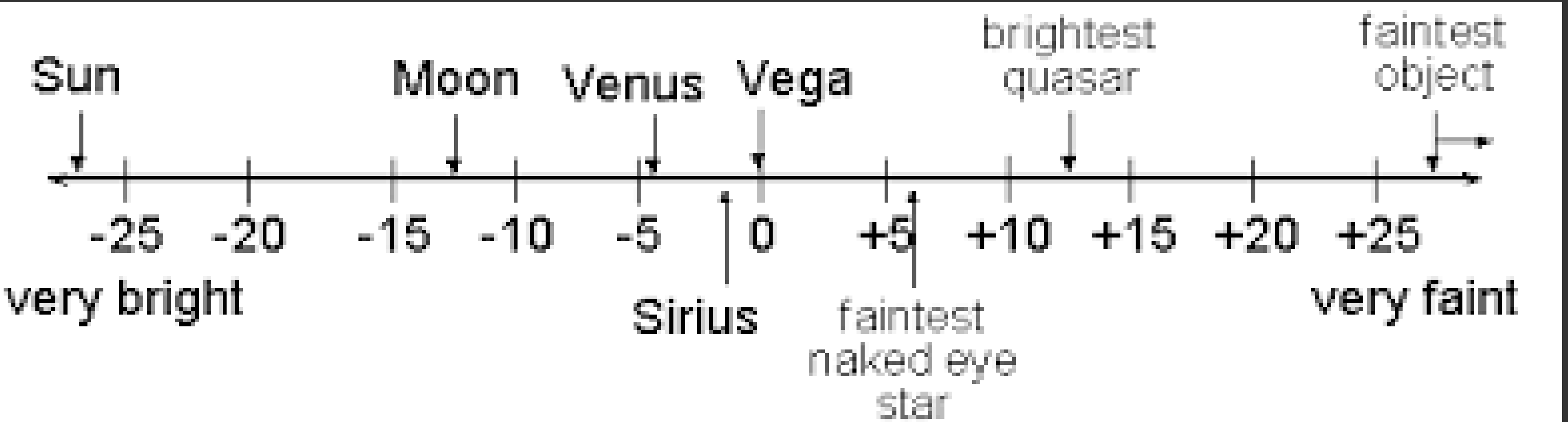
magnitude 1 – the brightest stars
magnitude 2 …
magnitude 3 …
magnitude 4 …
magnitude 5 …
magnitude 6 – the faintest stars

Today the magnitude system has been extended to include much fainter and brighter objects.



Magnitude scale (Apparent)

$$m_B - m_A = 2.5 \log \frac{\ell_A}{\ell_B}.$$



Apparent brightnesses of some objects in the magnitude system.

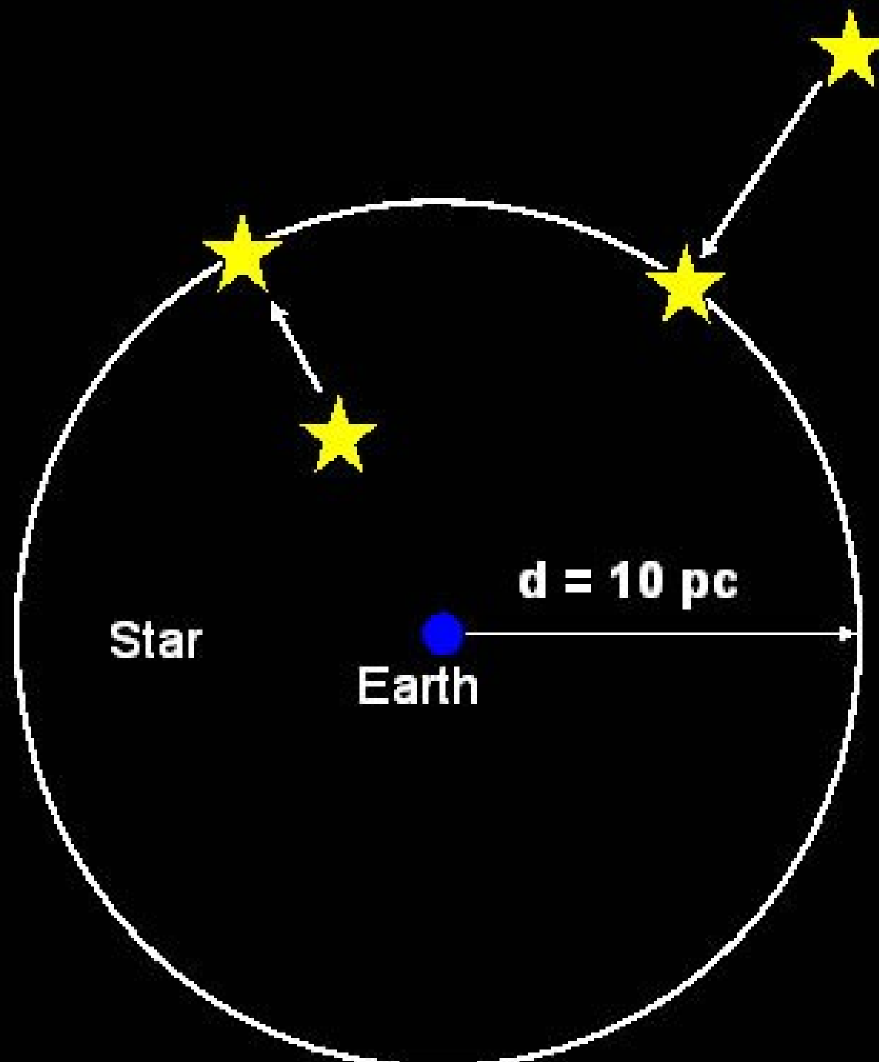
Absolute Magnitude

(useful for describing how intrinsically luminous objects are)

Absolute magnitude is described as the apparent magnitude an object would have at a distance of 10 parsecs.

Imagine moving all of the stars in the sky so that they reside on a sphere of radius 10 parsecs that is centered on the Earth. The apparent magnitude that these stars would have at that time is their absolute magnitude. Thus, it is a theoretical quantity.

Absolute magnitudes for stars ranges from about -8 for the most energetic stars to about 15 for the least energetic.

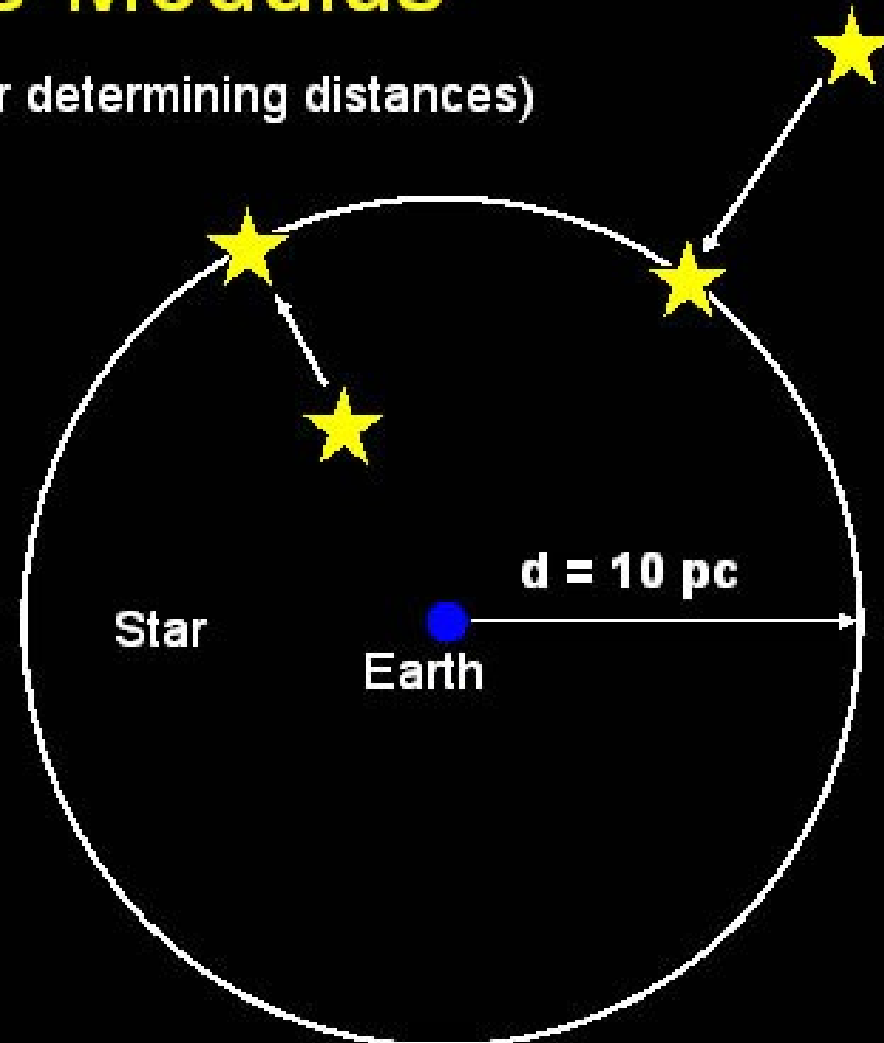


Distance Modulus

(a useful quantity for determining distances)

The distance modulus is the difference between apparent magnitude m and absolute magnitude M for an object.

$$m - M = -5 + 5\log_{10} d$$



m < M $\rightarrow$ d < 10 pc

m >M $\rightarrow$ d > 10 pc

$$d = (10\,pc) \times 10^{\frac{m-M}{5}}$$

Rule: A distance modulus of 5 corresponds to a distance of 100 pc

Stellar Velocities

1) **Radial Velocity (v_r)** is the component of velocity along the line of sight to the star. It is determined from Doppler shifts in spectral lines by:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v_r}{c}$$

- positive velocities imply separation is increasing; negative, decreasing

2) **Tangential velocity (v_t)** is the component of velocity perpendicular to the line of sight. It is calculated from:

$$v_t = 4.74 \mu d$$

Where μ is the proper motion in arc seconds/year and d is the distance in parsecs. Proper motion can be thought of as motion on the celestial sphere.

3) **Space velocity (v_s)** is a star's true velocity through space and is calculated from:

$$v_s = \sqrt{v_r^2 + v_t^2}$$

Luminosity

(the total energy that a star produces each second)

Luminosity depends on both the radius of a star and its surface temperature. It is the product of …

- Flux - the total energy produced each second by each square meter of a blackbody radiator. Given by the Stefan-Boltzmann Law in units of J/s-m^2 where temperatures in Kelvin.

$$f = \sigma T^4$$

- Area - the total surface area of the star (area of a sphere in m^2).

$$A = 4\pi R^2$$

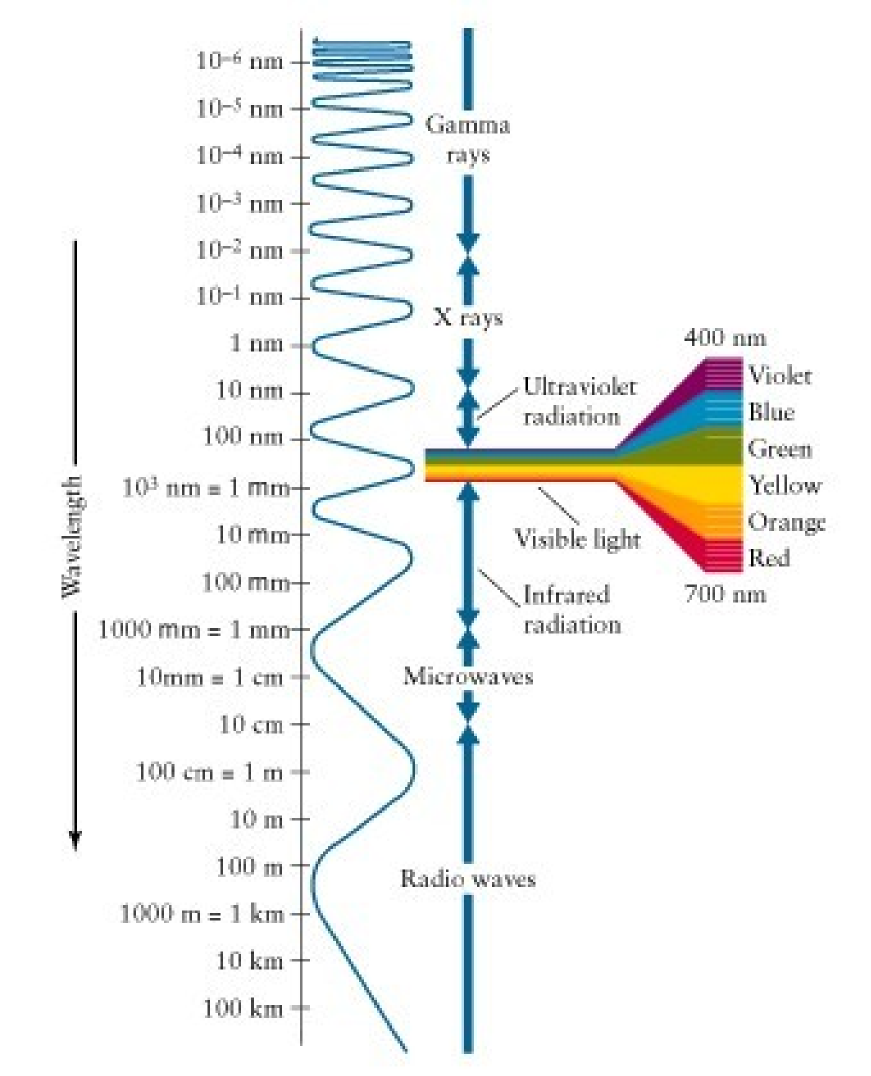
Thus, the Luminosity in units of J/s is given by:

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

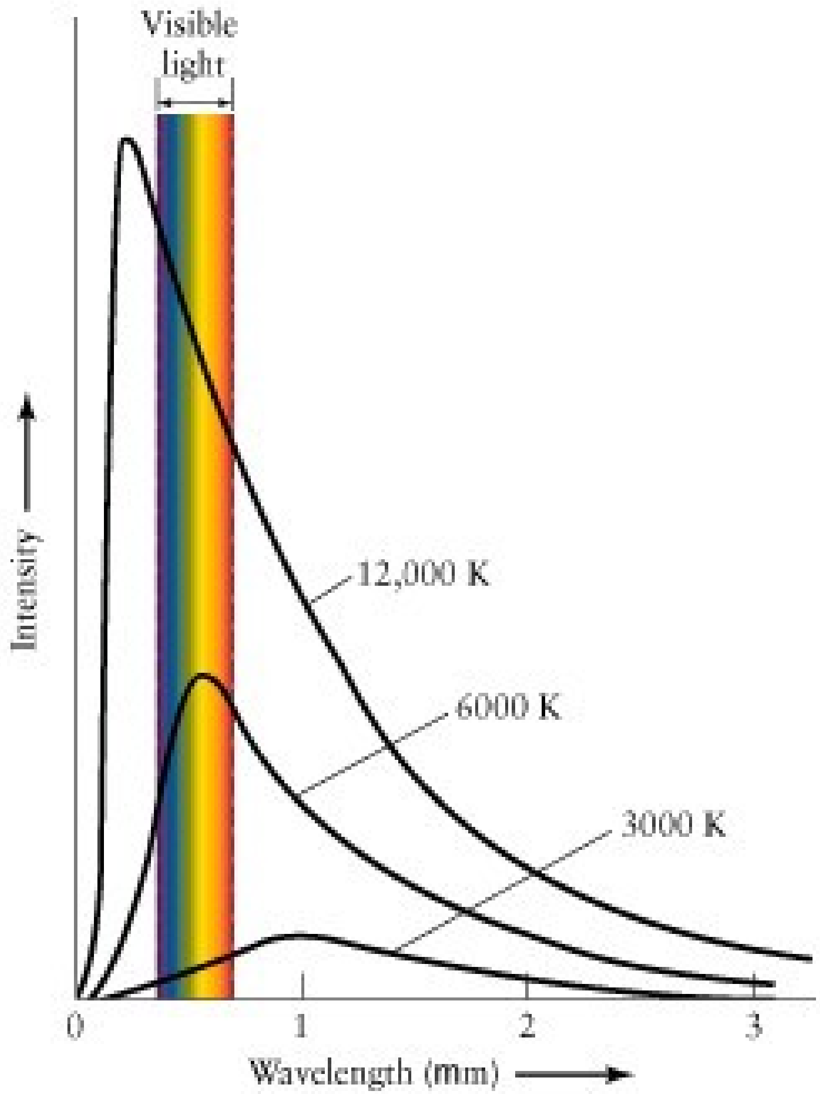
Temperature

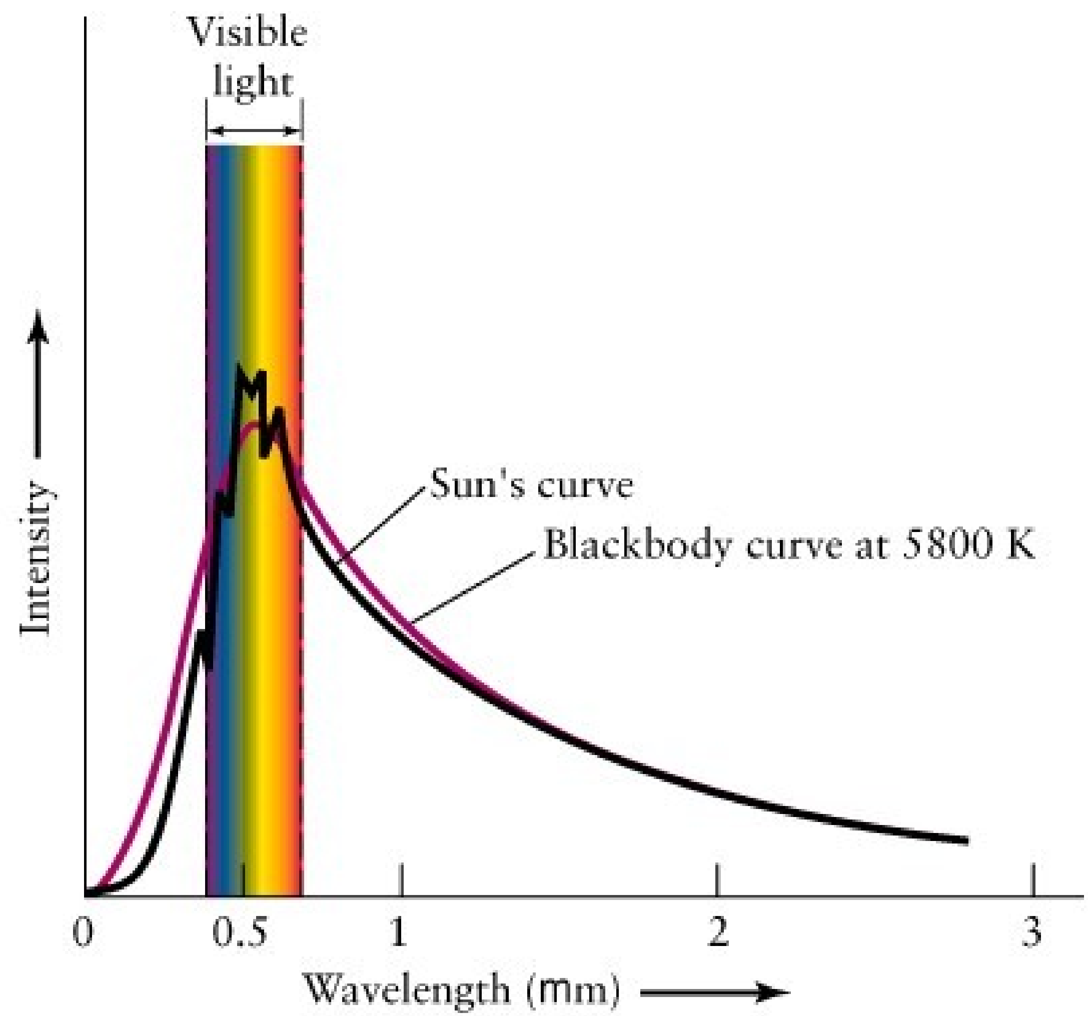
- To measure the temperature of a star we use must measure the spectrum of the star and then apply more physics
- We assume the star is a “black body radiator” and then we can compute the temperature from the spectral shape.

Temperature



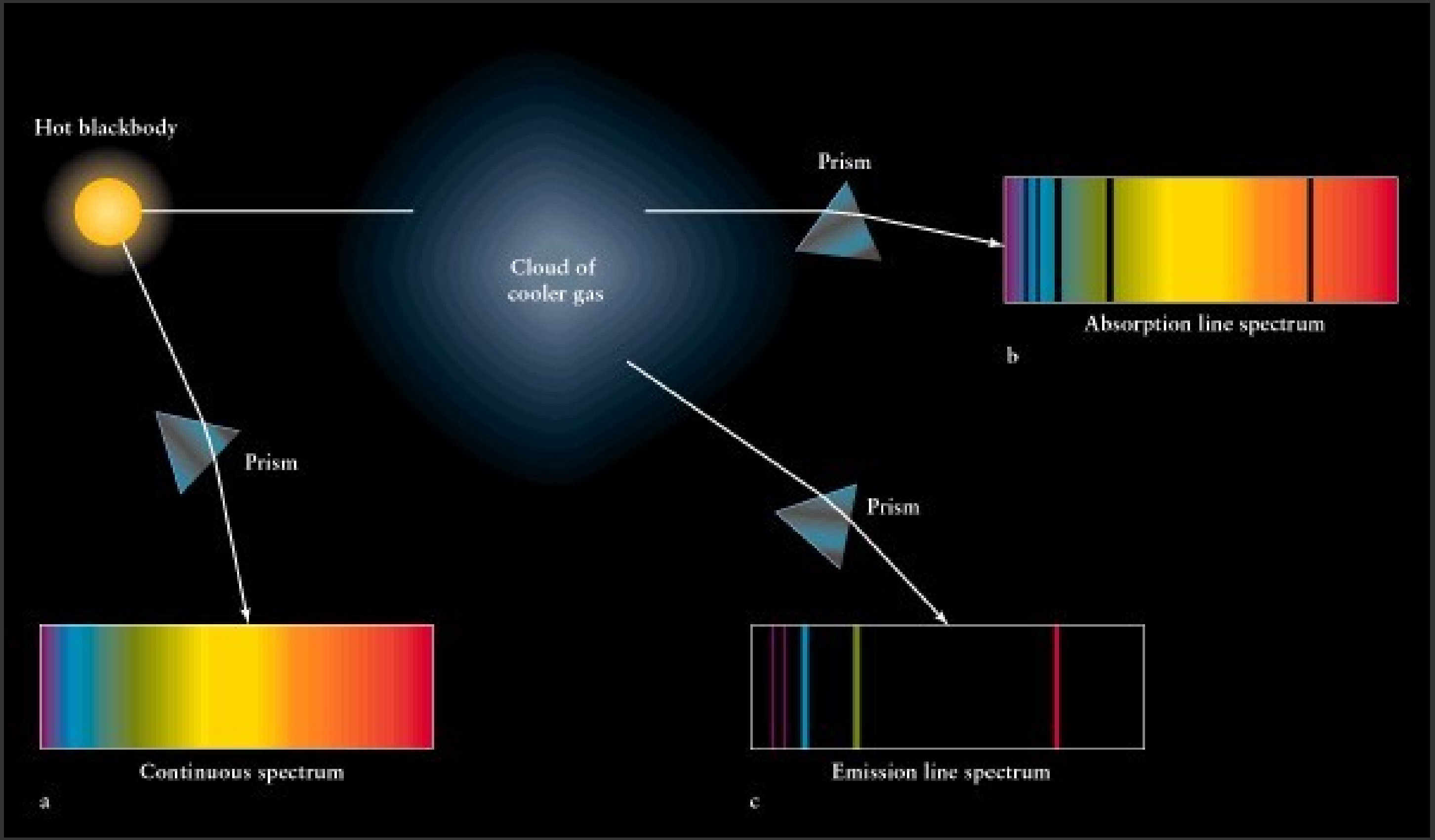
Temperature





Temperature

- Looking at individual spectral lines in a star's spectrum can also reveal the ***spectral class*** of the star; spectral class is closely related to the temperature of the star



Bolometric Magnitudes

The flux of any object varies with wavelength. To measure all the EMR from a body, we would have to observe at all wavelengths of EMR, from gamma rays to the longest radio waves.

Quantities integrated over all wavelengths (or at least over all wavelengths where the object emits significant radiation) are called bolometric quantities

The object must be observed with a number of different telescopes and detectors, satellite telescopes, etc

When we do multiwavelength astro, we are extrapolating/ interpolating bolometric mags!

Photometric systems

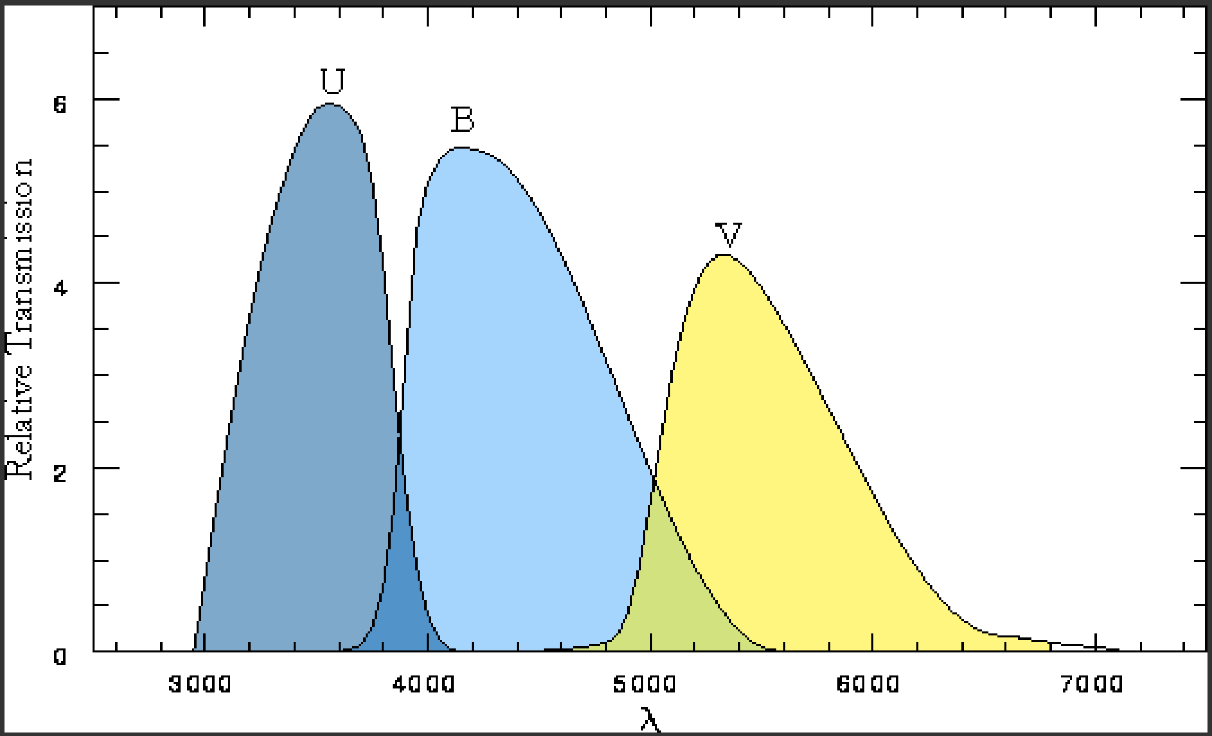
Three rough categories based on the size of the wavelength intervals transmitted by their filters.

Wide-band systems (such as the UBV system) have filter widths ~ 900 A

Intermediate-band filter widths ~ 200 A.

Narrow-band systems are used to isolate and measure a single spectral line and may have widths of 30 A or less.

UBV system



U for ultraviolet, B for blue, and V for visual.

The central wavelengths are : U - 3600 A; B - 4400 A, V -5500 A

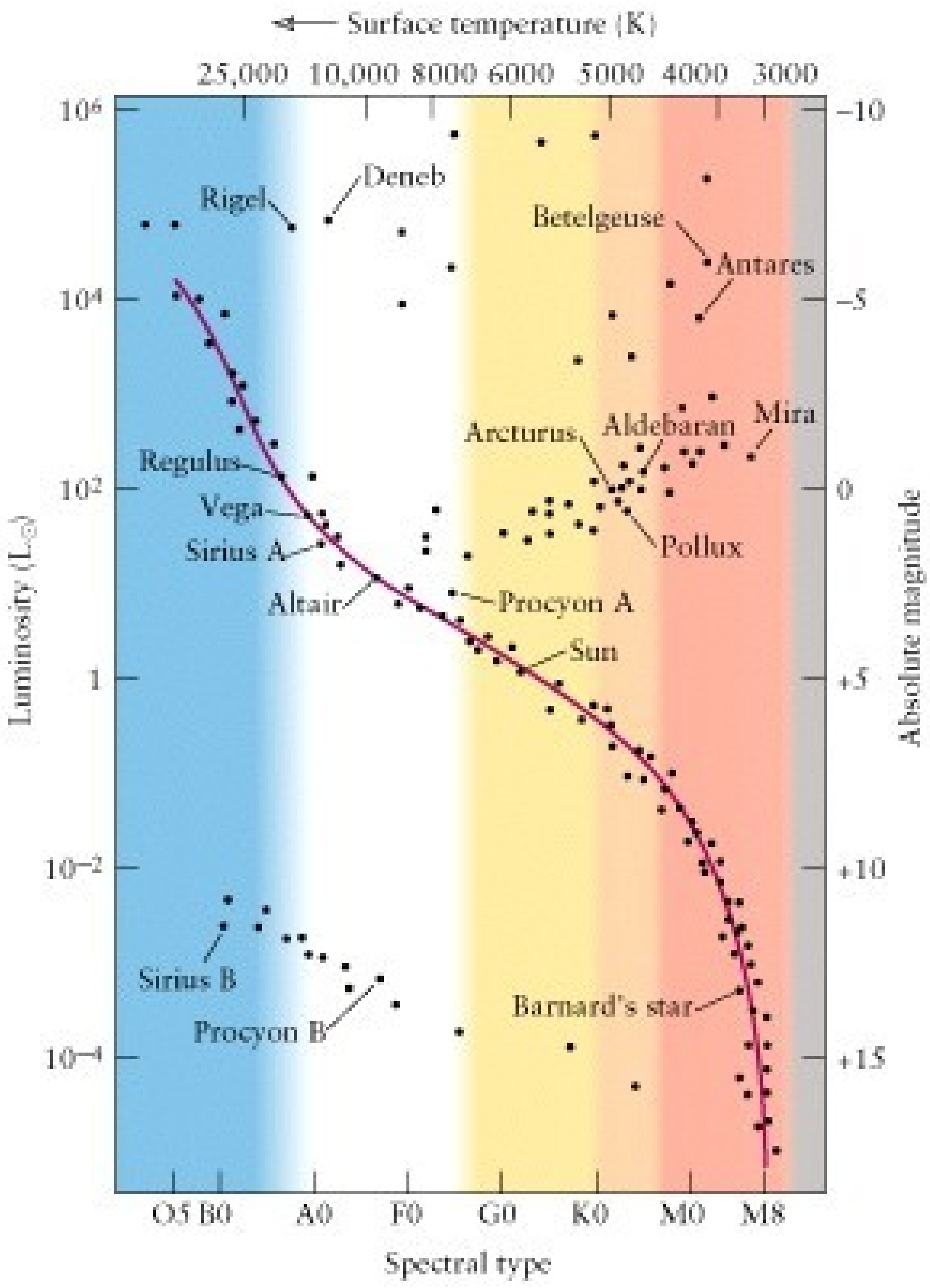
Width: 1000˚, B filter (3900 A - 4900 A)

Colors

$$B - V = m_B - m_V$$

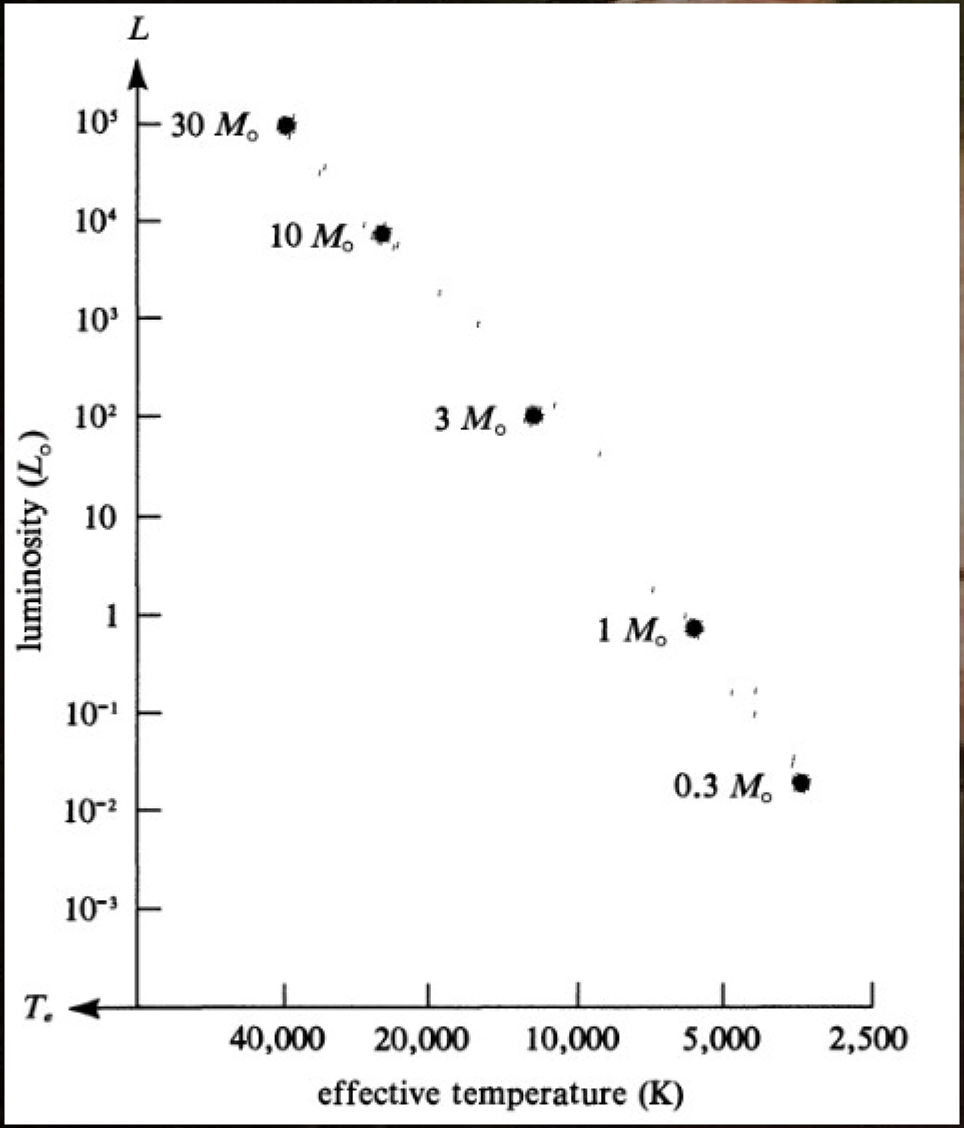
$$B - V = m_B - m_V = -2.5\log(f_B/f_V) + \text{constant}$$

B − V color of Vega is 0.00, “by definition”

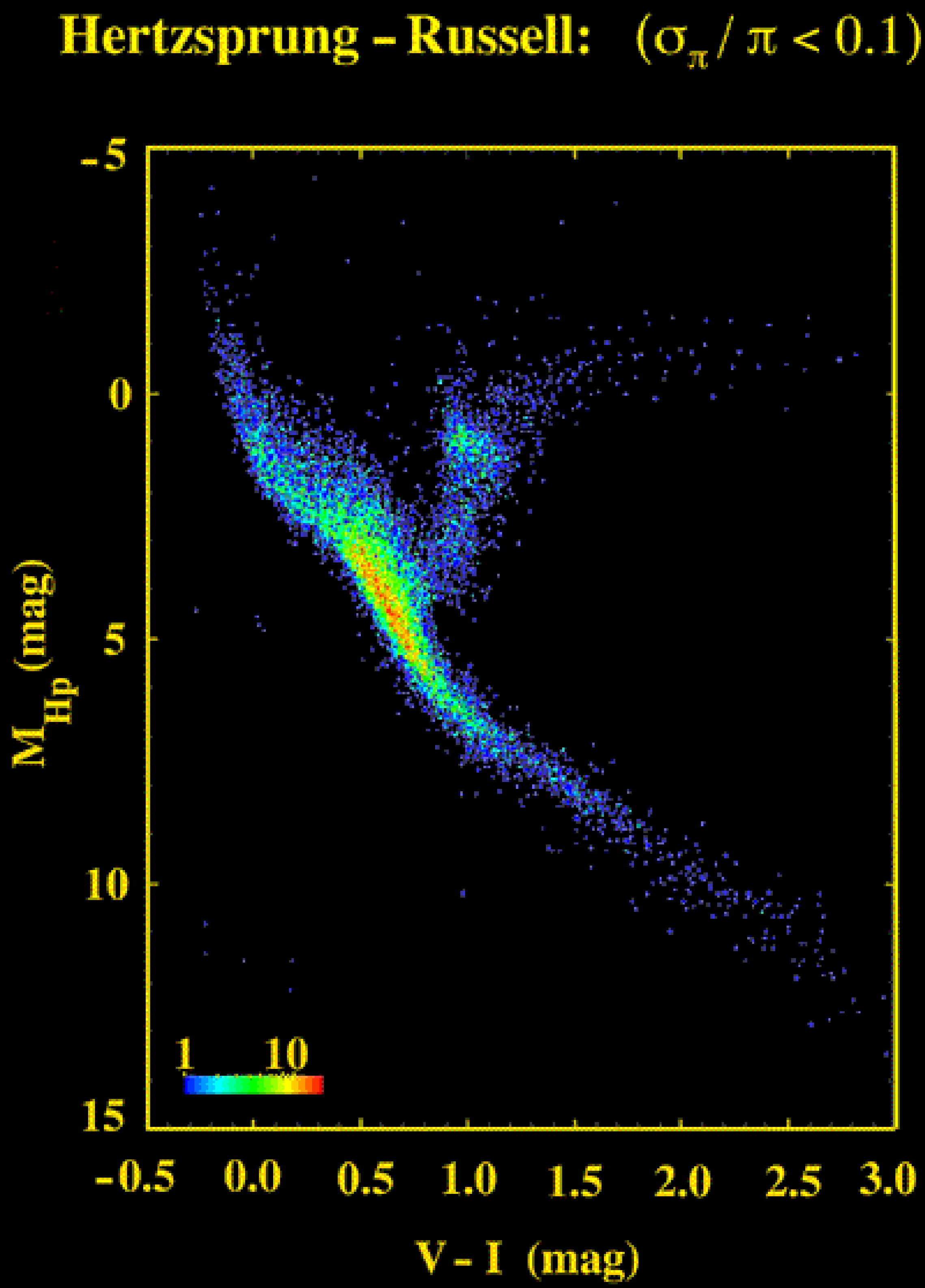


Surface temperature (K)
25,000
10,000
8000
6000
5000
4000
3000
Luminosity ($L_\odot$)
10^6
10^4
10^2
1
10^{-2}
10^{-4}
Absolute magnitude
−10
−5
0
+5
+10
+15
Rigel
Deneb
Betelgeuse
Antares
Mira
Aldebaran
Arcturus
Regulus
Vega
Sirius A
Altair
Procyon A
Pollux
Sun
Sirius B
Procyon B
Barnard's star
O5 B0
A0
F0
G0
K0
M0
M8
Spectral type

The HR diagram

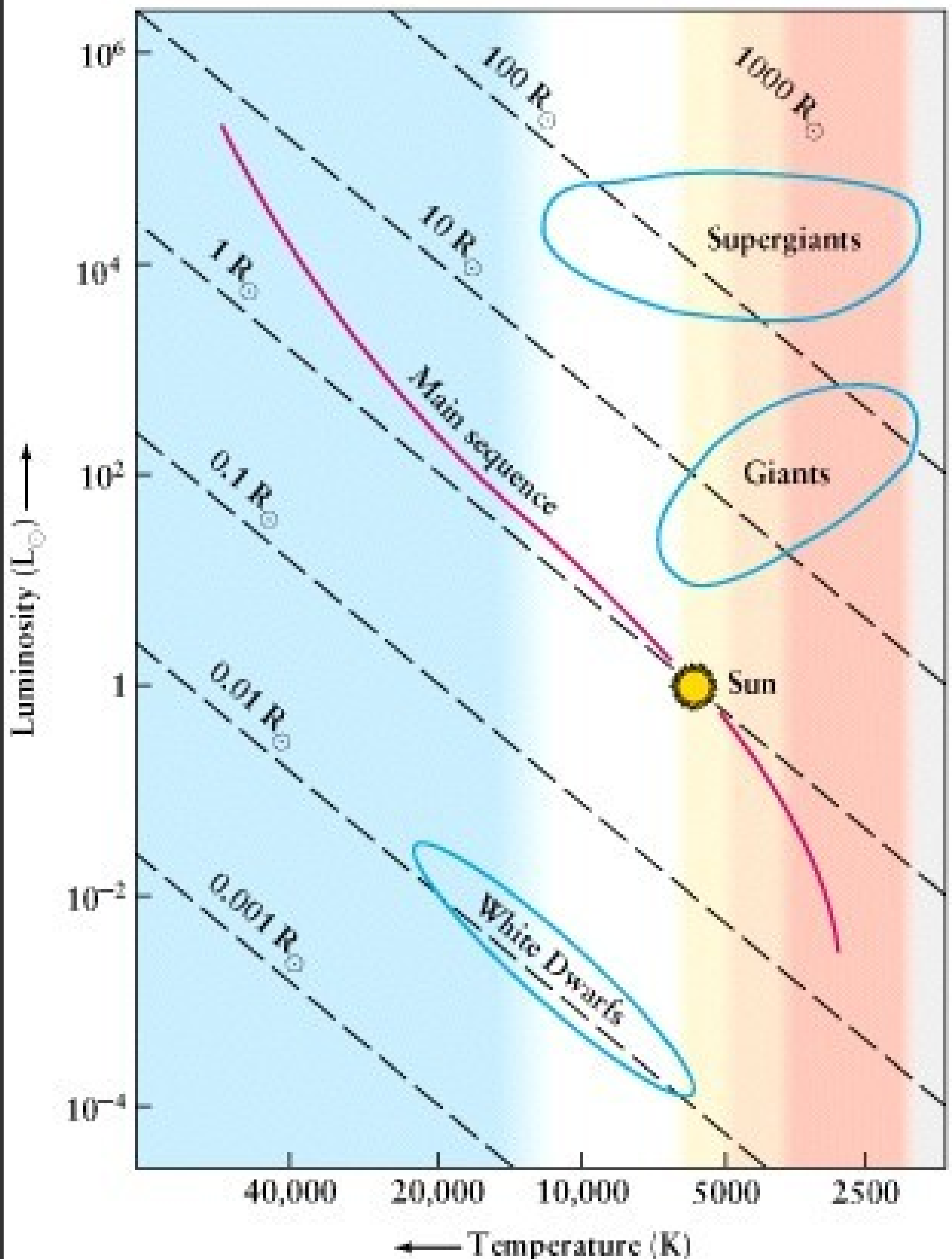


- Most stars lie along the "Main Sequence"
  - Simple relationship between temperature and luminosity
  - Stars spend most of their lives converting hydrogen to helium, and this is what occurs when the star is on the main sequence


Hertzsprung - Russell: $(\sigma_\pi / \pi < 0.1)$
-5
0
5
10
15
M_{Hp} (mag)
1
10
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
V - I (mag)

The HR diagram

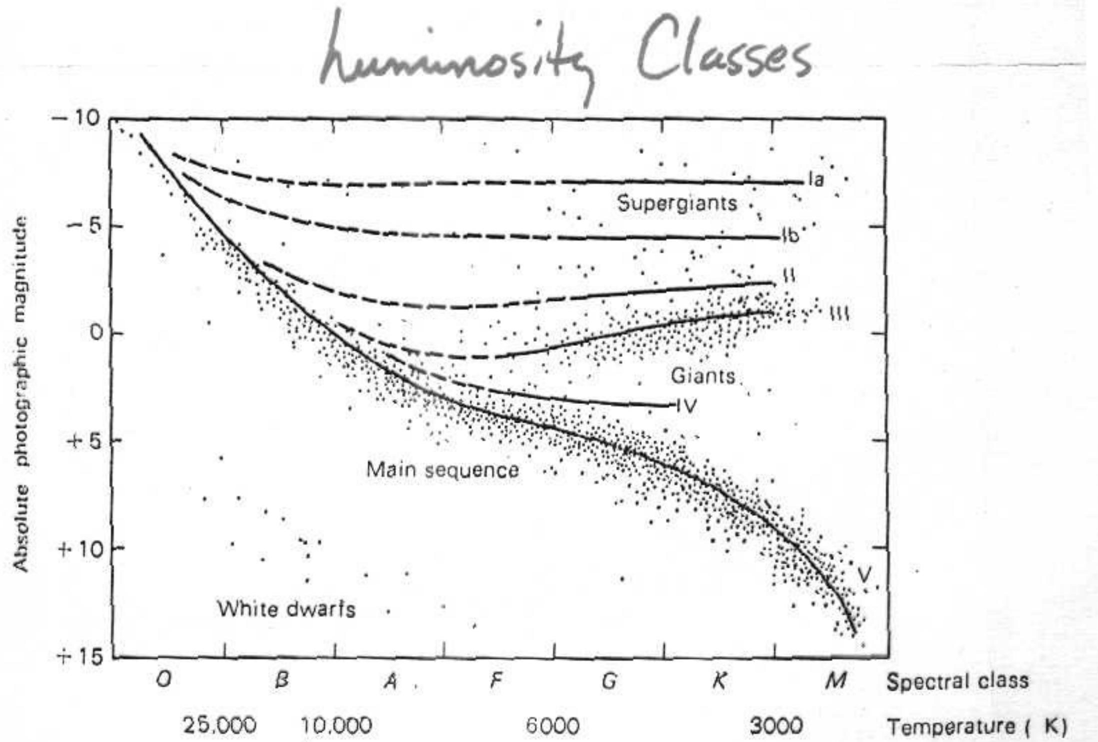
- The HR diagram can be used to determine other parameters of stars, like the radius
- A black-body radiator has a simple relationship between the absolute brightness (Luminosity) and the temperature $L = \sigma 4\pi R^2 T^4$, which defines lines of constant stellar radius on the HR diagram.

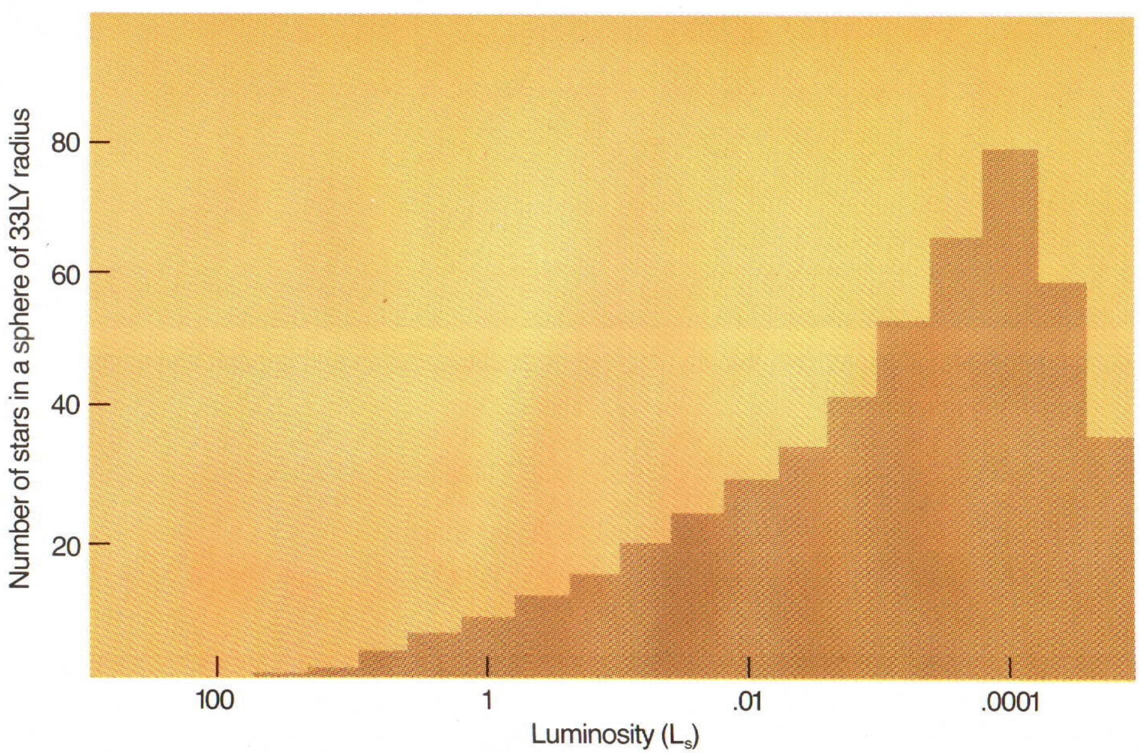


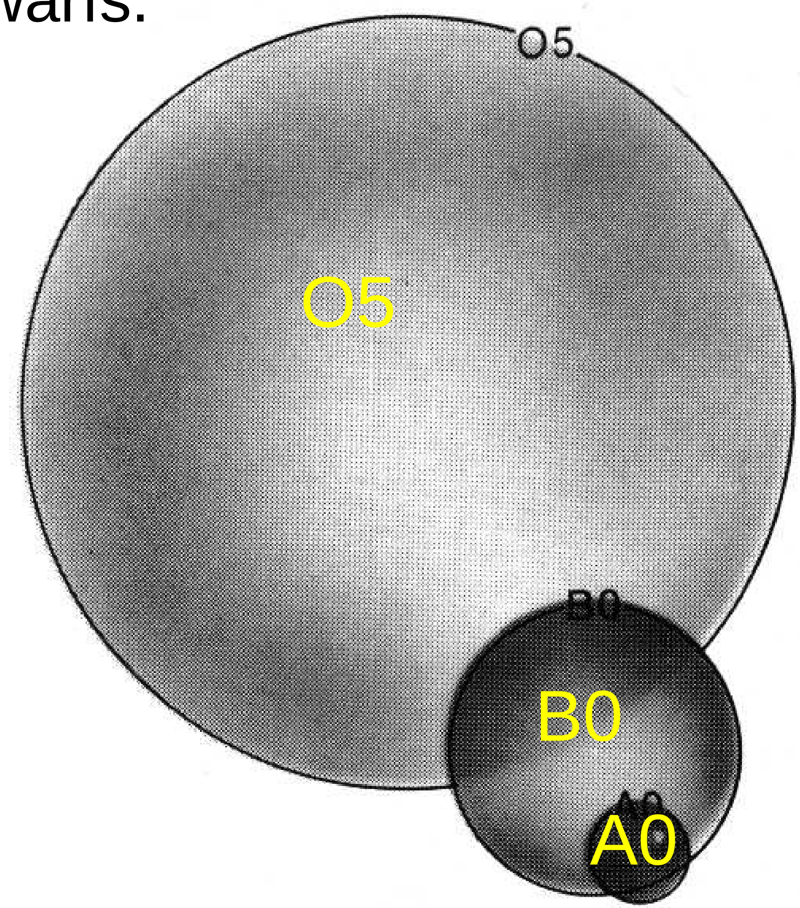
1000 R⊙
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
Supergiants
Giants
Main sequence
Sun
White Dwarfs
10^6
10^4
10^2
1
10^{-2}
10^{-4}
Luminosity (L⊙)
40,000
20,000
10,000
5000
2500
Temperature (K)

Size/Luminosity

Hot stars are very bright but very rare. They can affect the light, but not the mass of the Galaxy. Red giants are more common. Most common are red dwarfs.



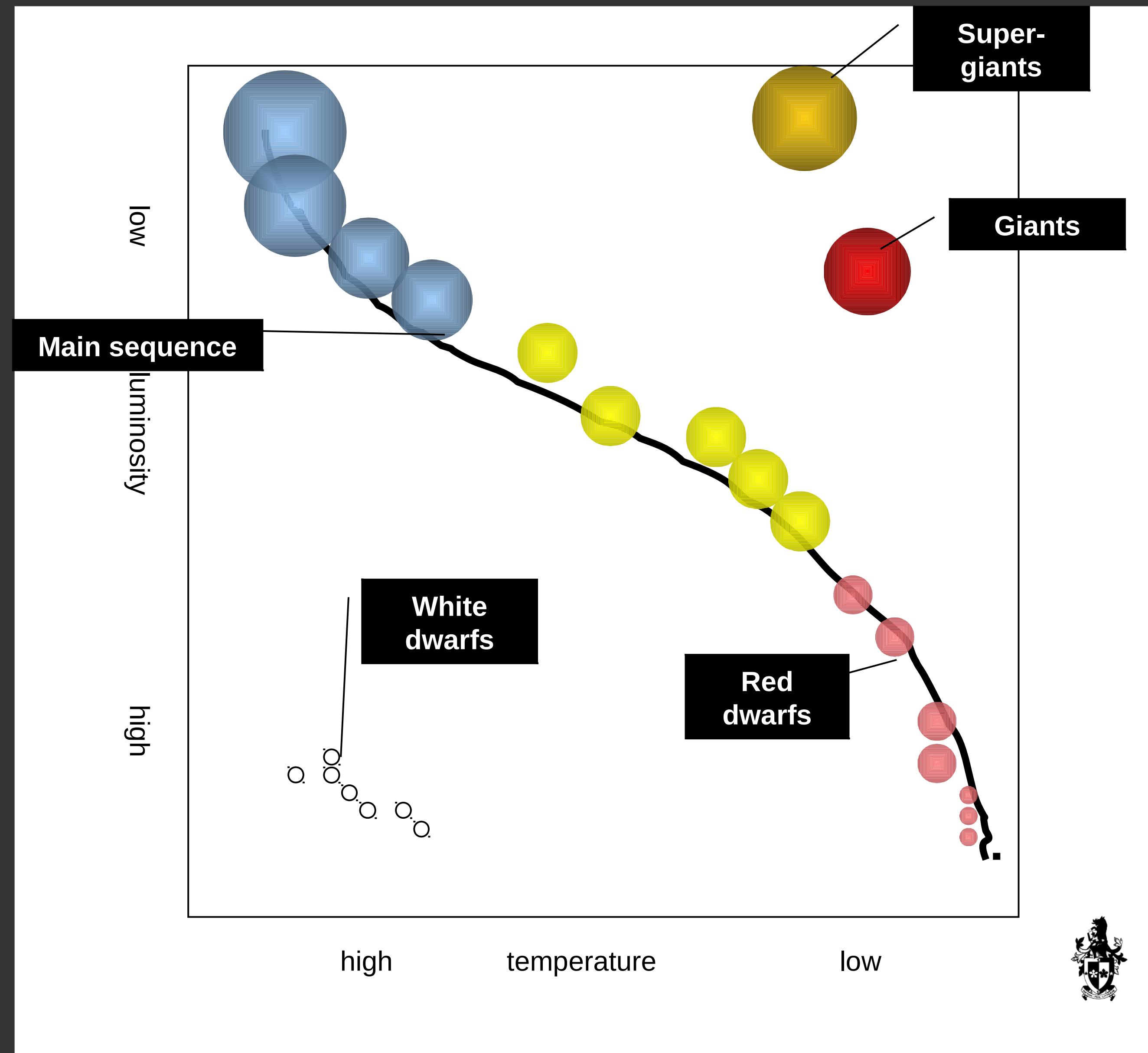




The HR diagram

- Stars in the upper right are very large and stars in the lower left are very small.
- This defines only the SIZE of the star and not the MASS, since the density of stars can be very different.
- So the branch of stars to the upper right of the MS are giant and supergiant stars.
- Temperature increases to the left, Luminosity increases upwards....

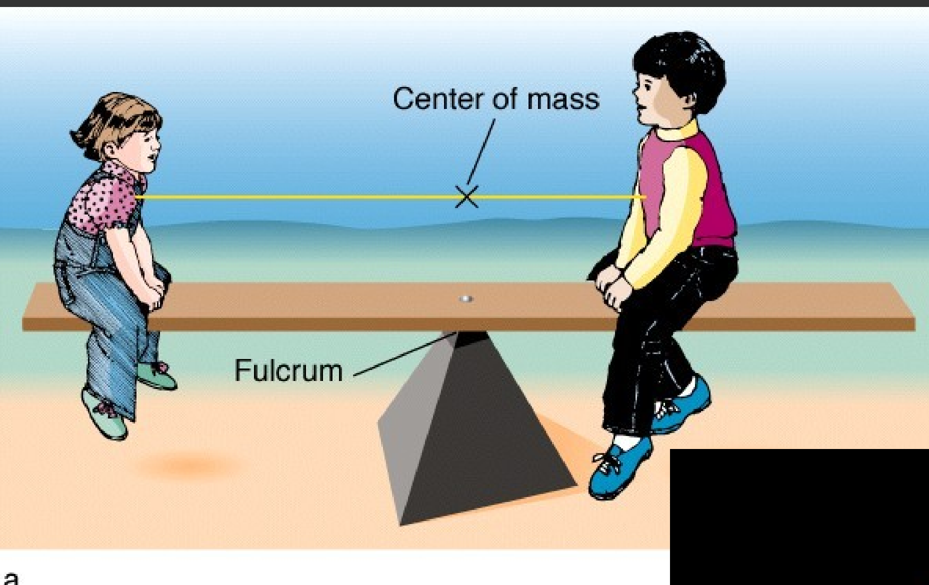
Families of stars

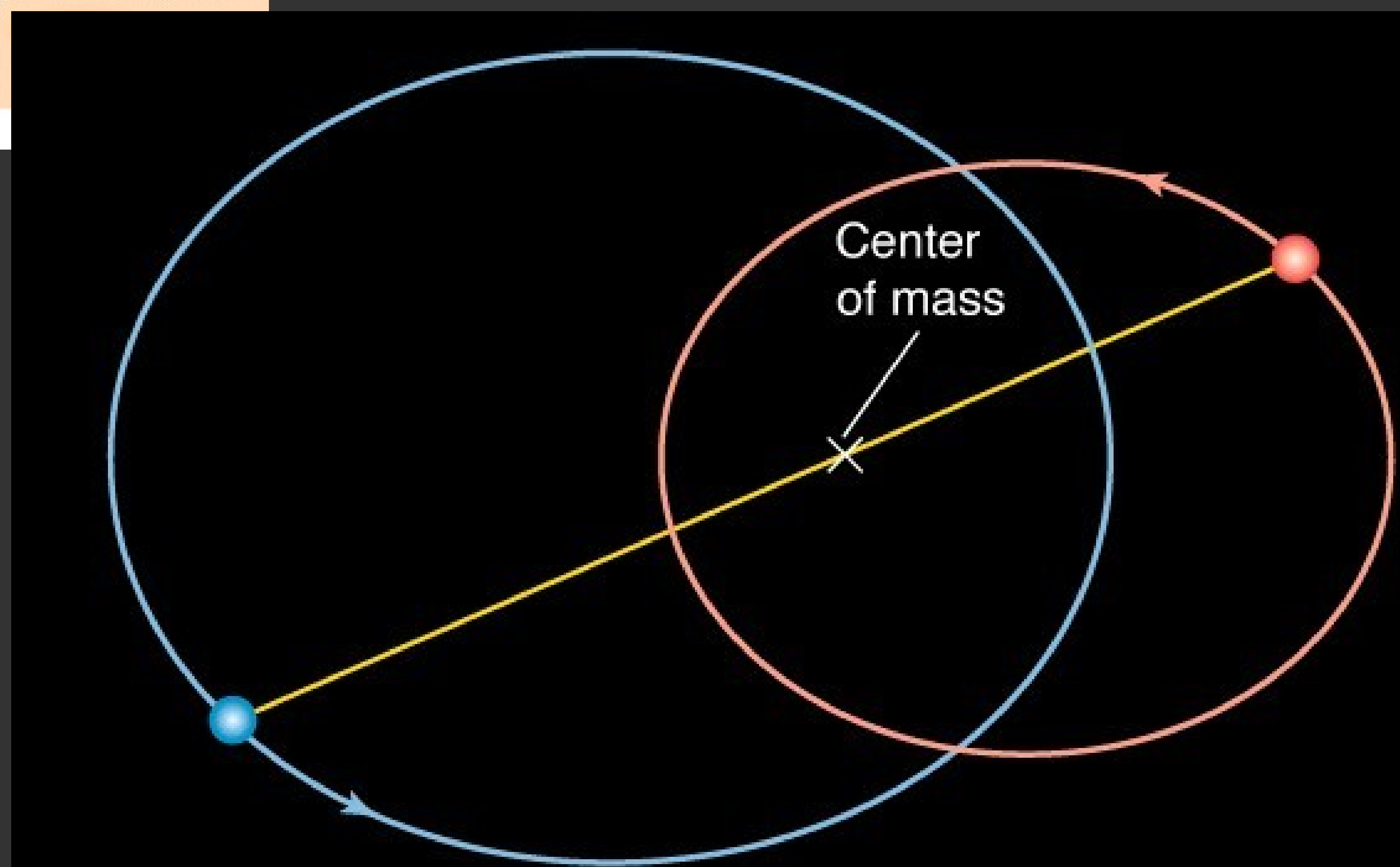


The HR diagram

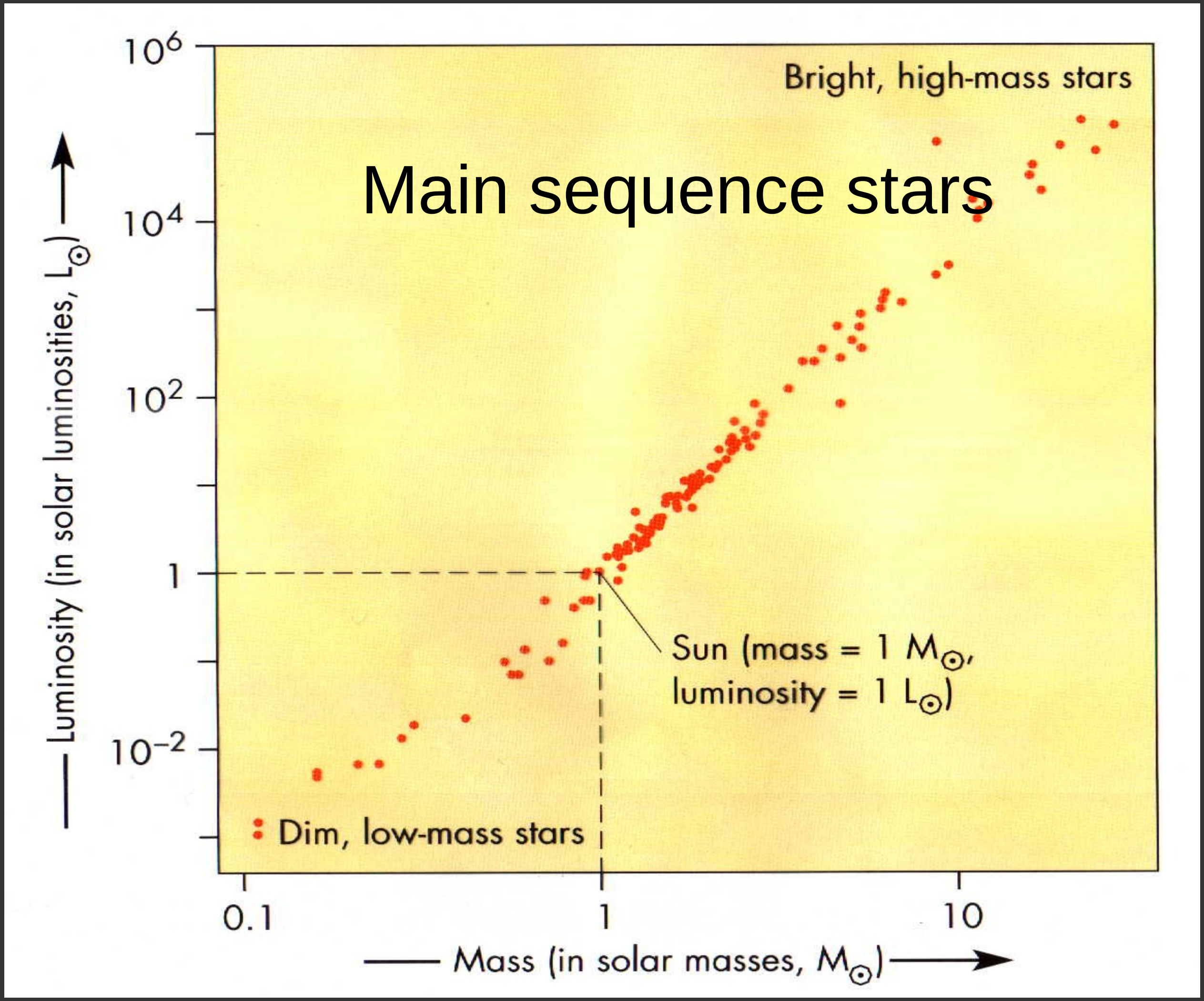
- It is very difficult to measure the mass of a star; it can only be done for binary stars.
- In a binary system, both objects move around the center of mass of the system, rather than one object “orbiting” the other object.

The HR diagram



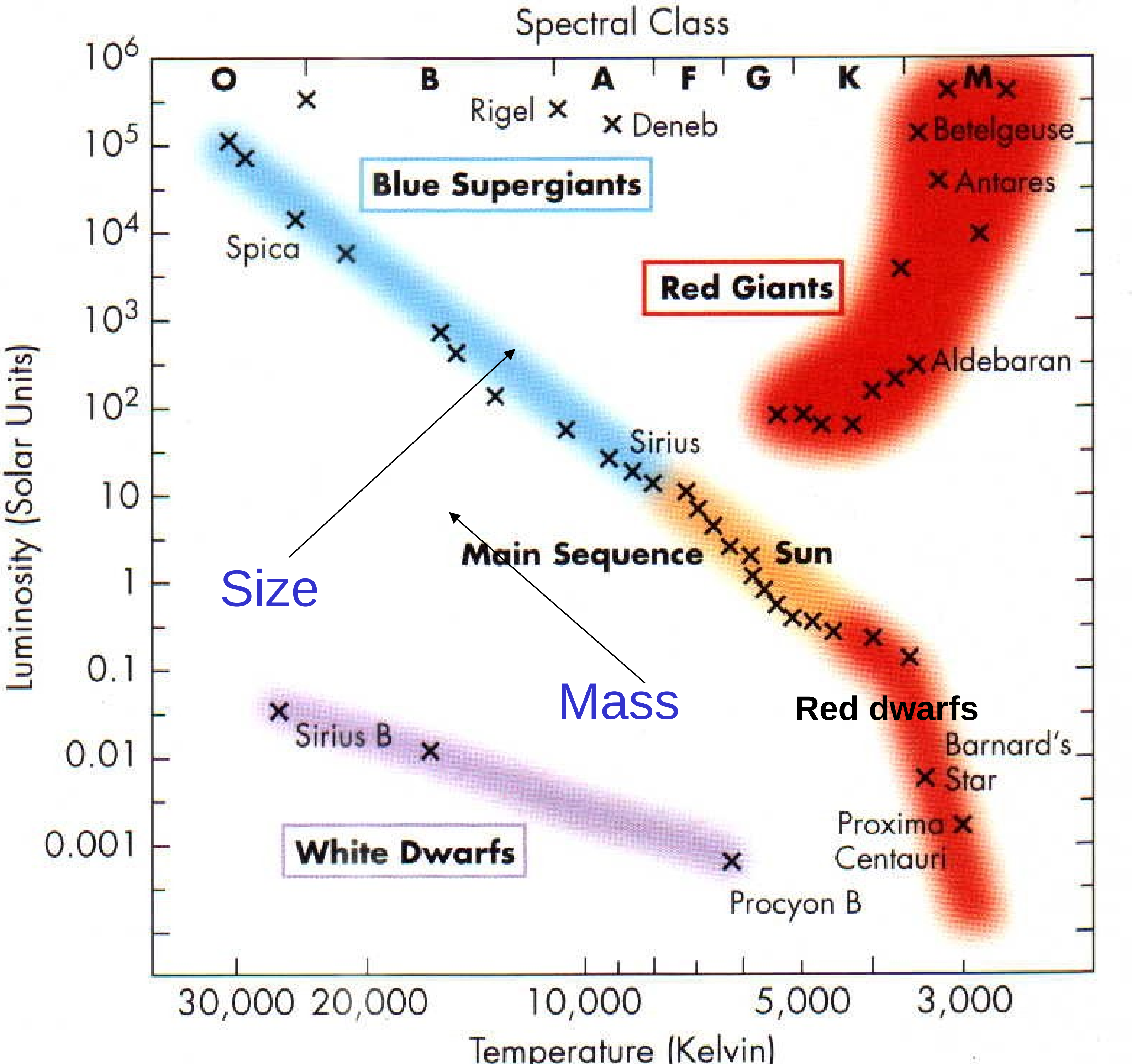


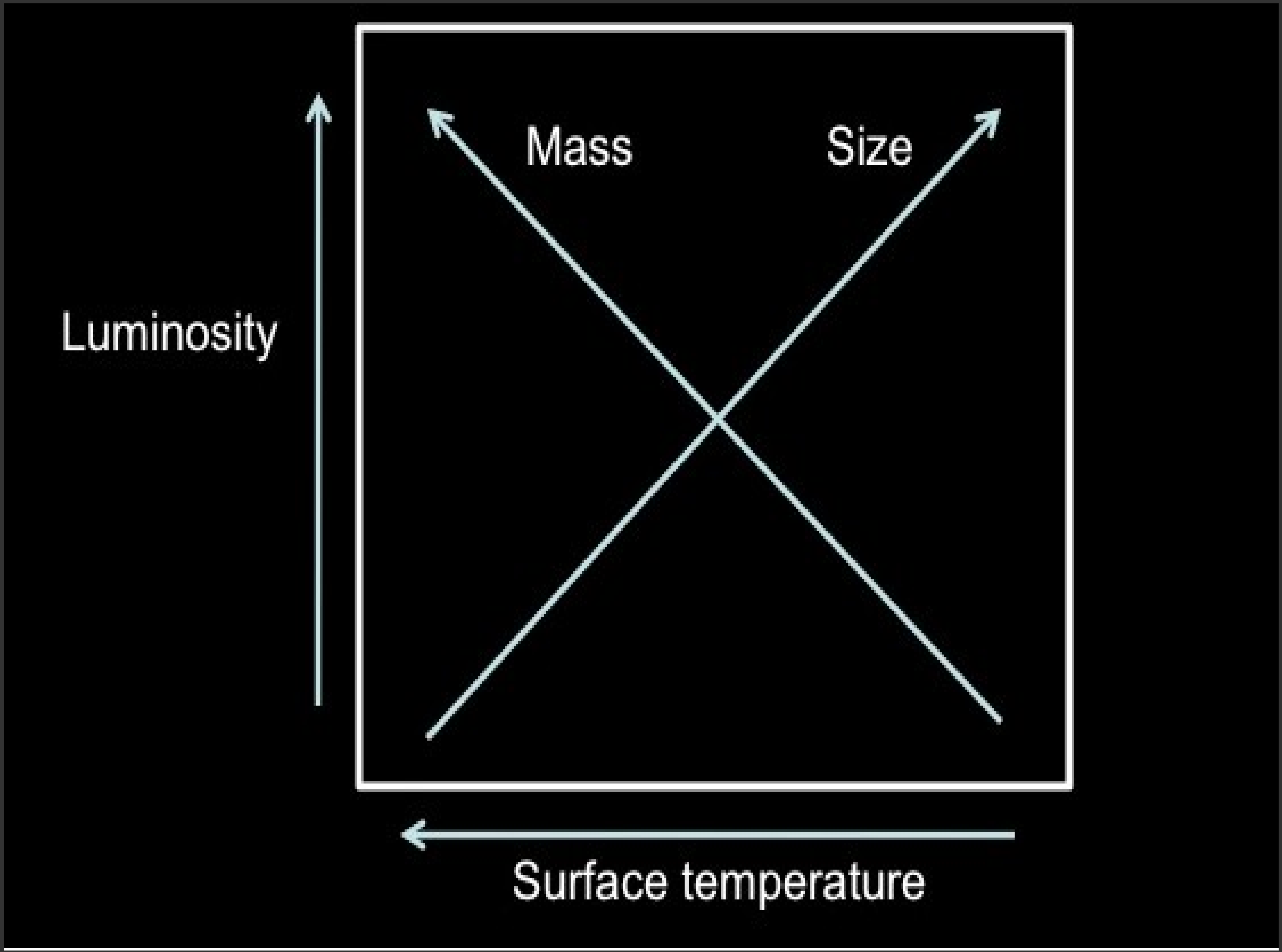
The Mass-Luminosity Diagram



The main sequence is a mass sequence!!

Basics of the HR diagram

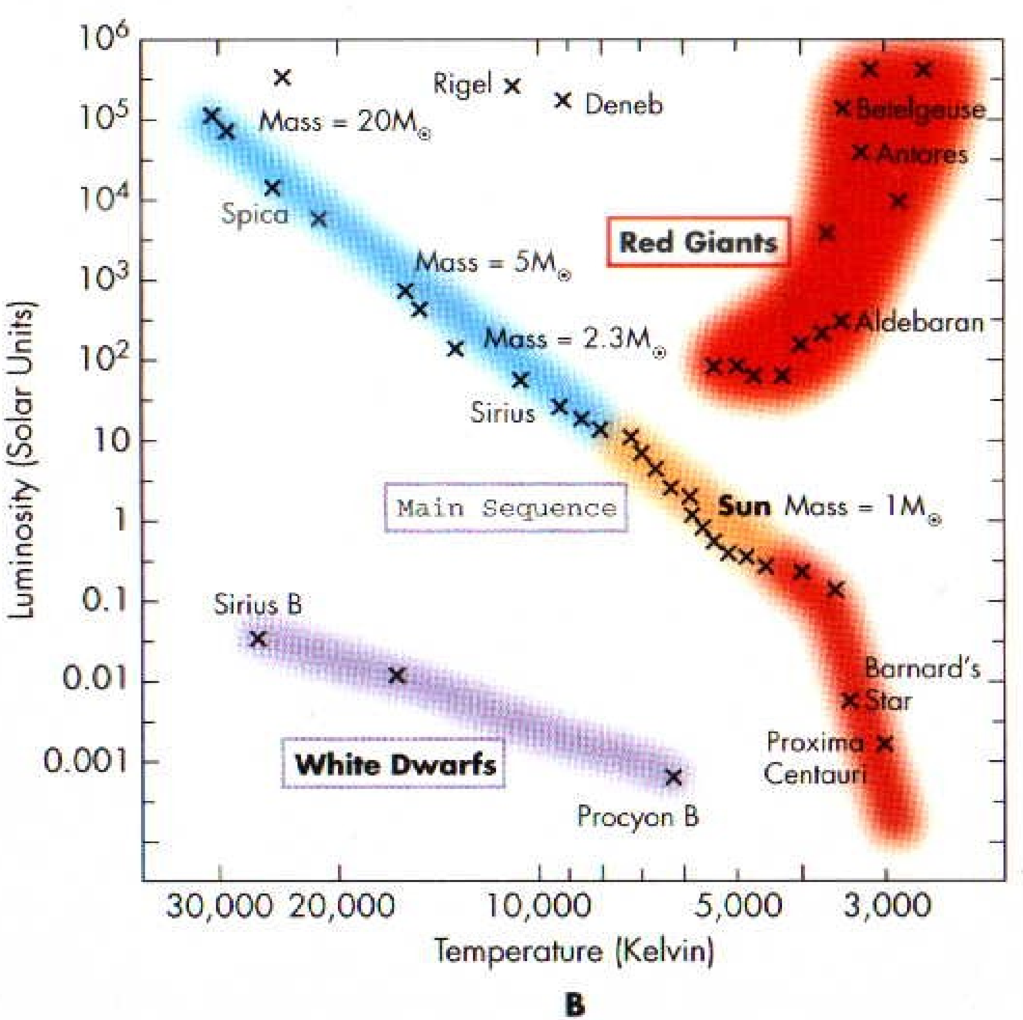



Mass
Size
Luminosity
Surface temperature

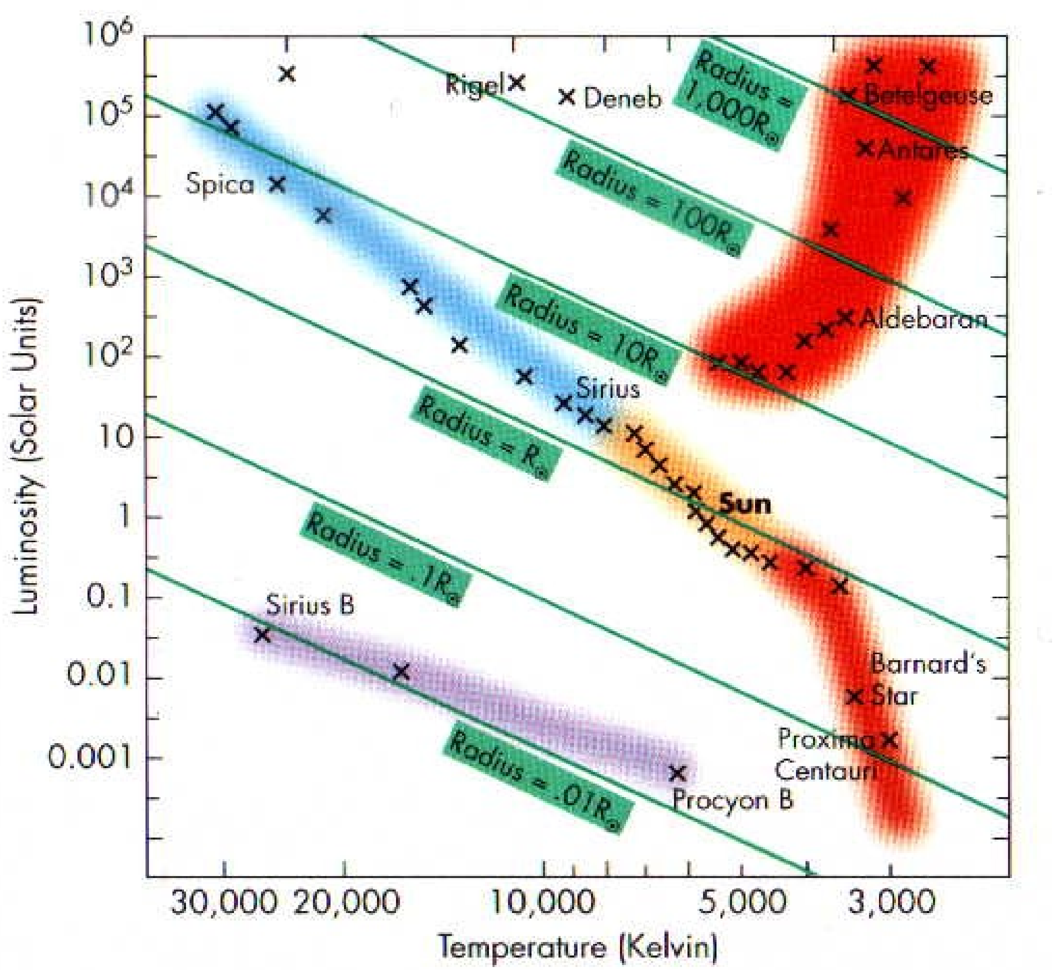
HR Diagram - Properties

Stars in different parts of the HR Diagram are in different phases of their life cycles. The Main Sequence is set by hydrogen fusion.

Masses on the Main Sequence



Stellar Sizes

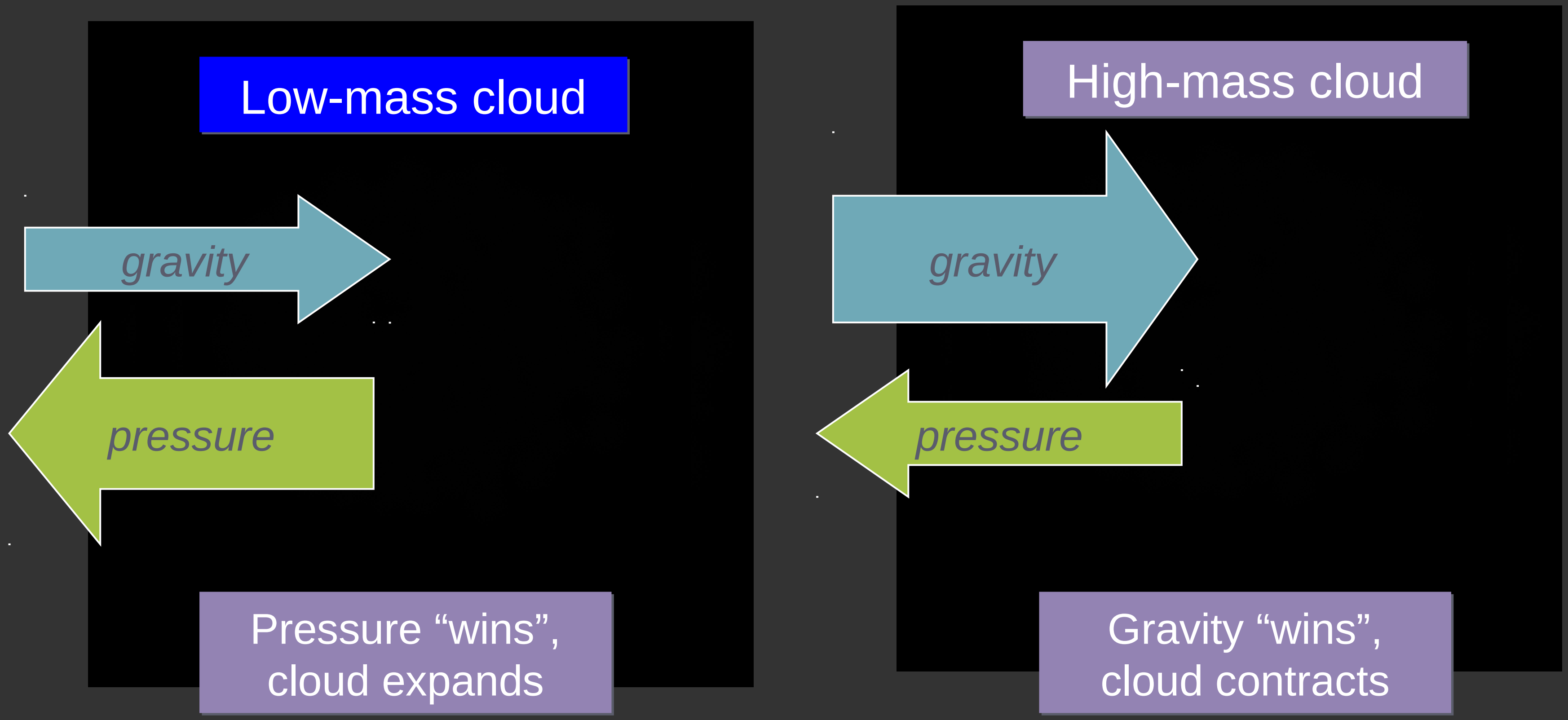


End of Part 1

Stars are born in clouds as these:

- Giant Molecular clouds
- Very thin, low-density cloud (10,000 atoms per cm^3)
- Very cold, T~10-20 K, so molecules can form --> molecular cloud
- Made mostly of H (75%) and He (23-25%) gas and a bit of heavier atoms (<2%).

If a nebula contains enough mass, it may begin to collapse because of gravity. Whether it succeeds in collapsing depends on the mass: pressure within the gas and dust opposes the collapse.



Jeans Mass

In gas clouds, the kinetic energy is due to the motions of the atoms which make up the cloud, so if there are N total atoms in the cloud the kinetic energy and the gravitational potential energy is given by

$$K = (N)(\frac{3}{2}kT) \qquad U = -\frac{3}{5}\frac{GM^2}{R}$$

So the virial theorem becomes

$$3NkT = \frac{3}{5}\frac{GM^2}{R}$$

if we want to have the cloud collapse, we have to have

$$3NkT < \frac{3}{5}\frac{GM^2}{R}$$

The number of particles is simply the mass of the cloud divided by the mass per particle:

Assuming the cloud has a constant density, the size of the cloud can be related to the mass and density by

$$N = M/m \qquad R = (\frac{3M}{4\pi\rho})^{1/3}$$

:

$$M_J = (\frac{5kT}{Gm})^{3/2}(\frac{3}{4\pi\rho})^{1/2}$$

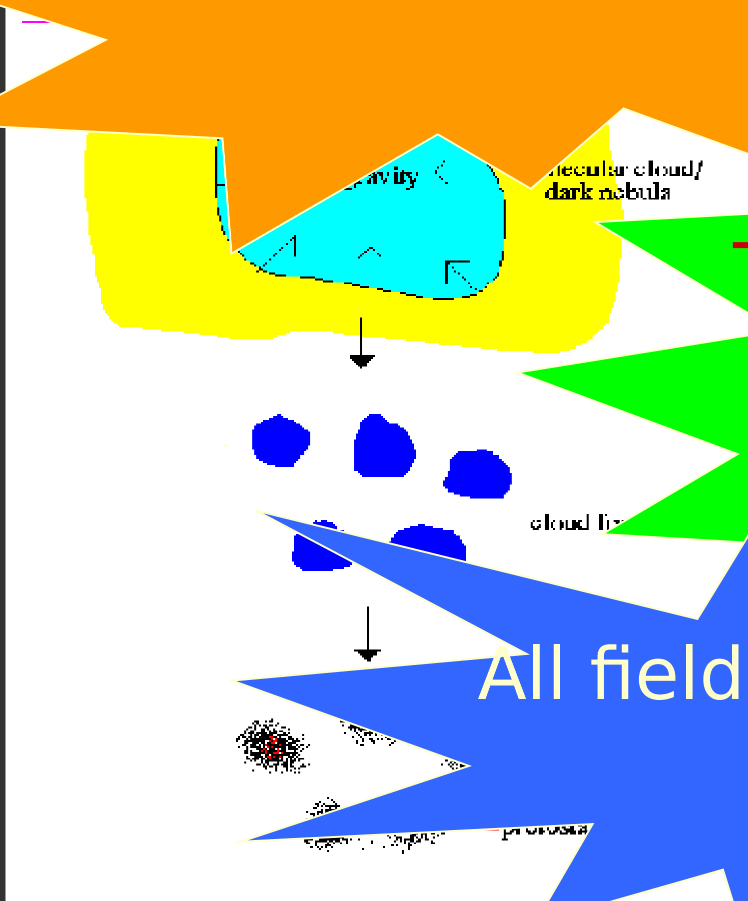
$$\text{if } \mathrm{M_{cloud}} > M_J \rightarrow \text{collapse!}$$

The cloud will collapse if its mass is bigger than the Jean's mass. This is called the Jean's criterion:

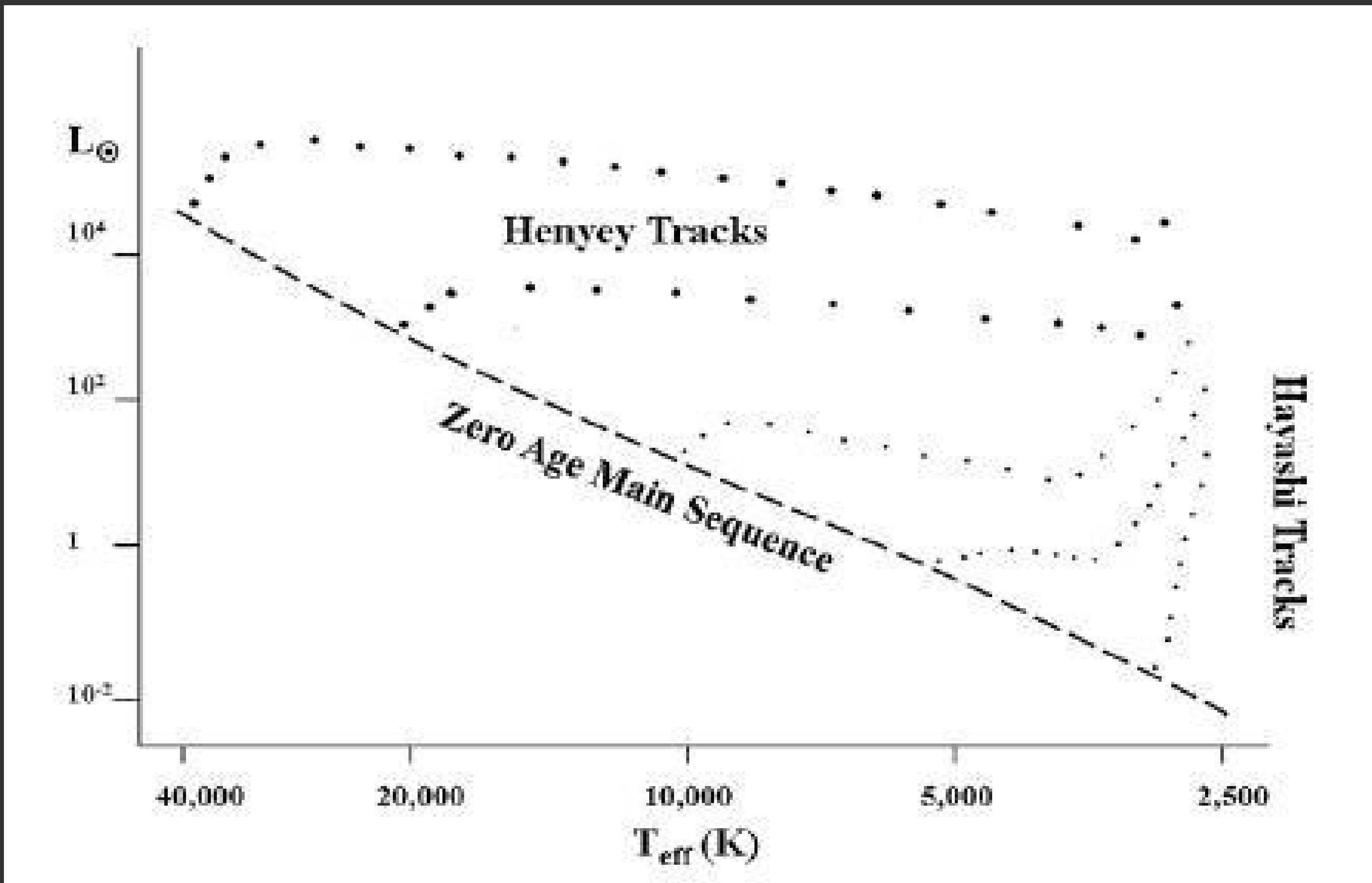
Stars are not born in isolation!

They are always born in groups

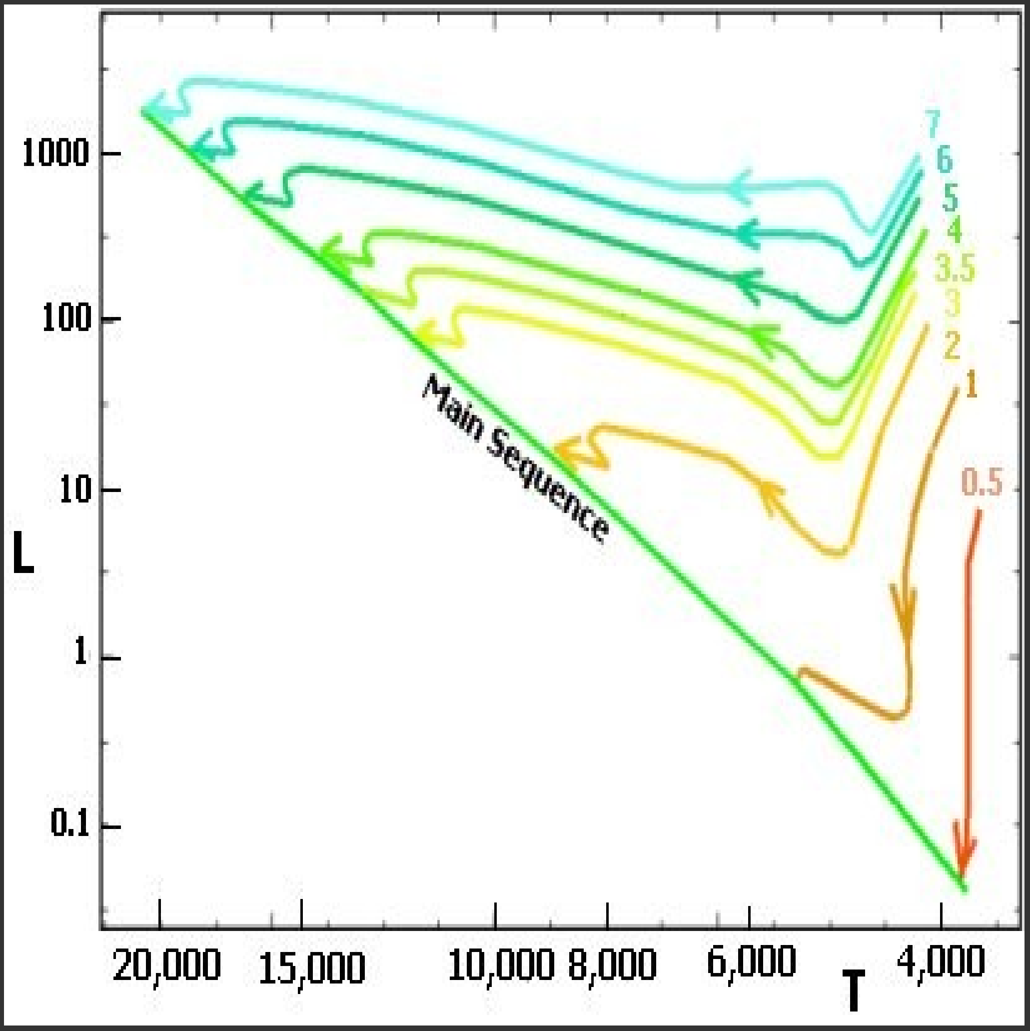
All field stars are from clusters



Hayashi, Henyey Tracks

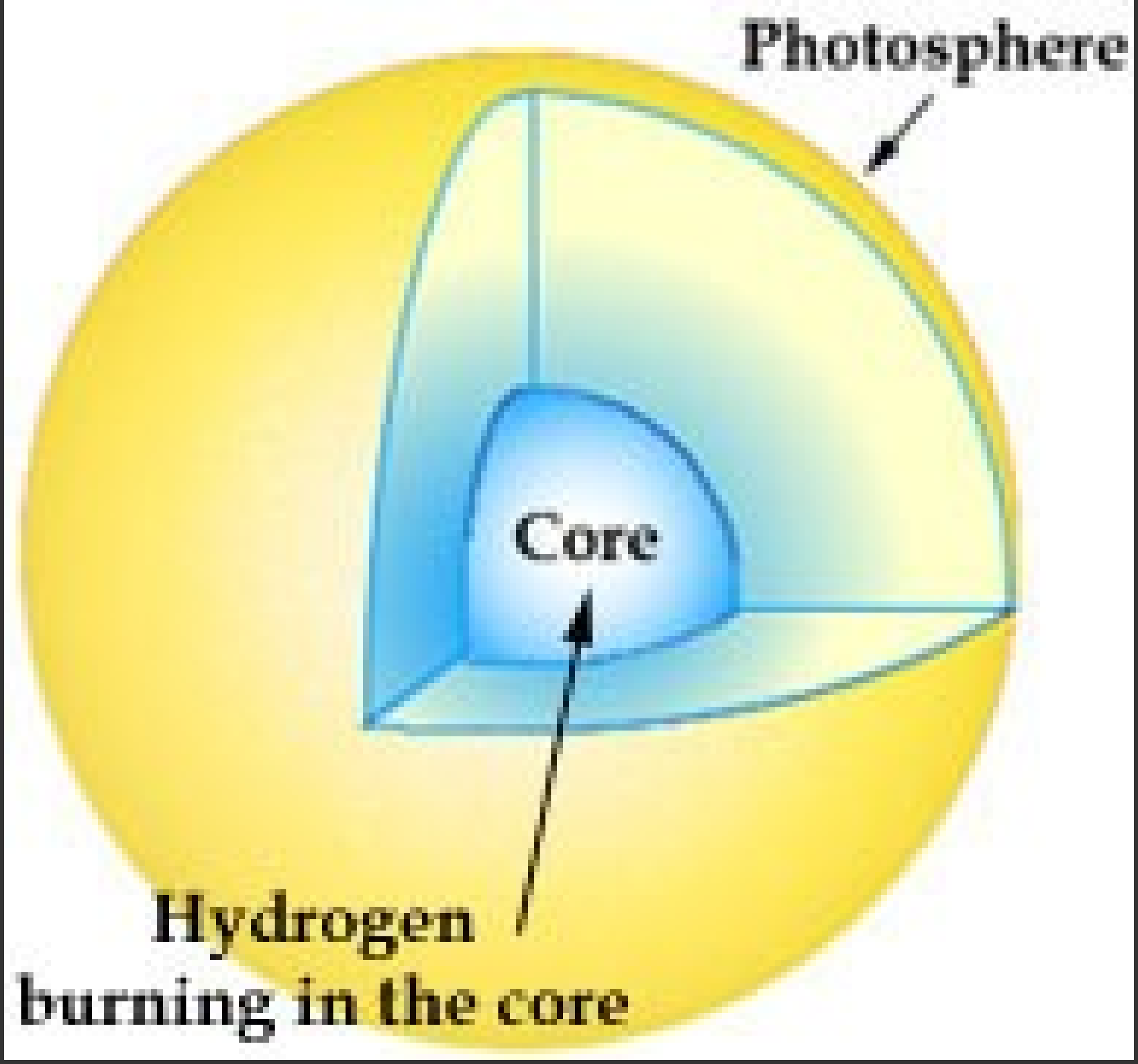


PMS Tracks



Stars with M<0.5 solar masses translates into a move along Hayashi tracks (almost vertically down, const T, convective) and later along Henyey tracks (almost horizontally to the left, towards the main sequence, const L, radiative)

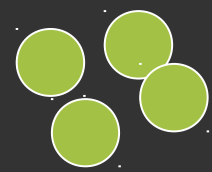
Throughout most of their life, stars convert hydrogen to helium...



Energy production

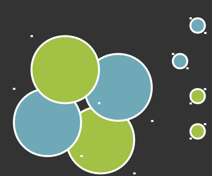
The proton-proton chain:

BEFORE:
four protons



Initial total mass = 6.693 x 10^{-27} kg

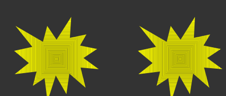
AFTER:
helium nucleus
plus two positrons
plus two neutrinos



Final total mass = 6.645 x 10^{-27} kg

Difference = 0.048 x 10^{-27} kg

… and two gamma rays



… and according to $E = mc^2$
this is equivalent to ...

Energy = 0.43 x 10^{-11} joules

… which is just the energy observed in the two gamma rays

Other important fusion reactions

Although in our Sun it is the proton-proton chain which dominates (91%), in other stars other reactions are very important. Here are the main ones:

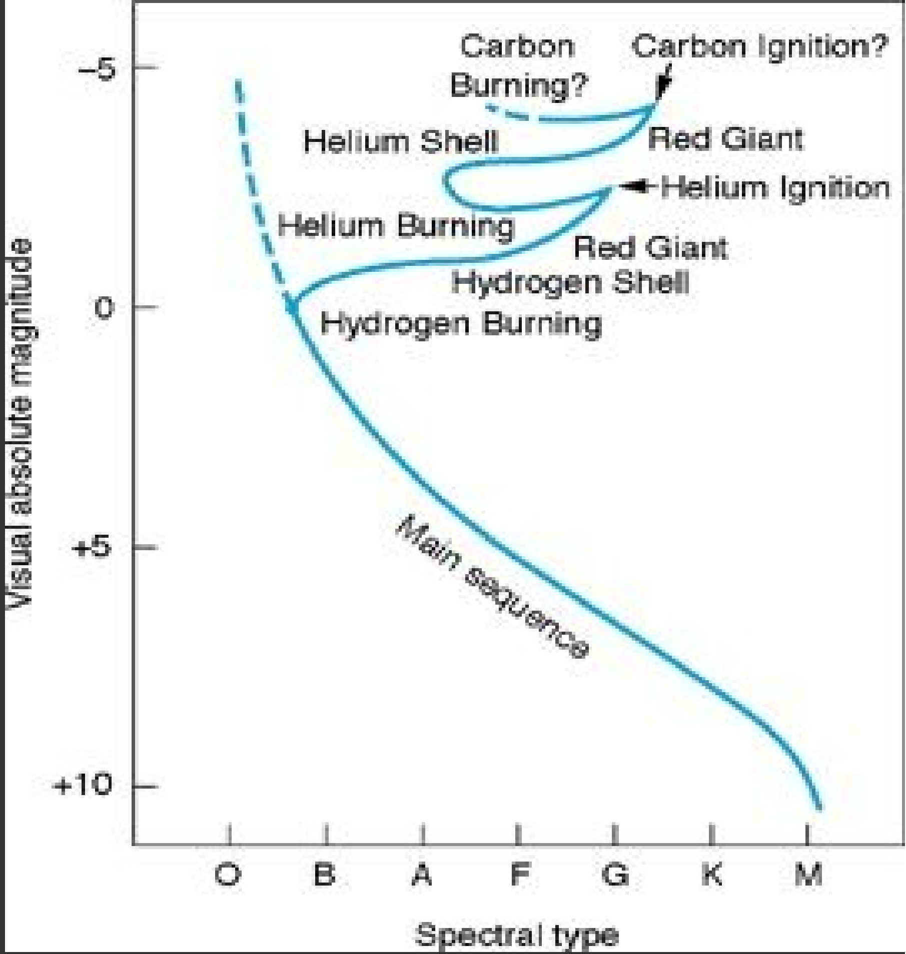
CNO cycle	***A complex series of reactions in which the transformation carbon - nitrogen - carbon - nitrogen - oxygen - nitrogen - carbon facilitates the conversion of four protons to one helium nucleus (plus energy)***
Helium "burning"	***Three helium nuclei fuse to create one carbon nucleus (plus energy). This is also called the "triple-alpha reaction".***
Carbon "burning"	***Carbon is fused to form heavy elements (plus energy): in particular, iron is the final product of much carbon burning.***

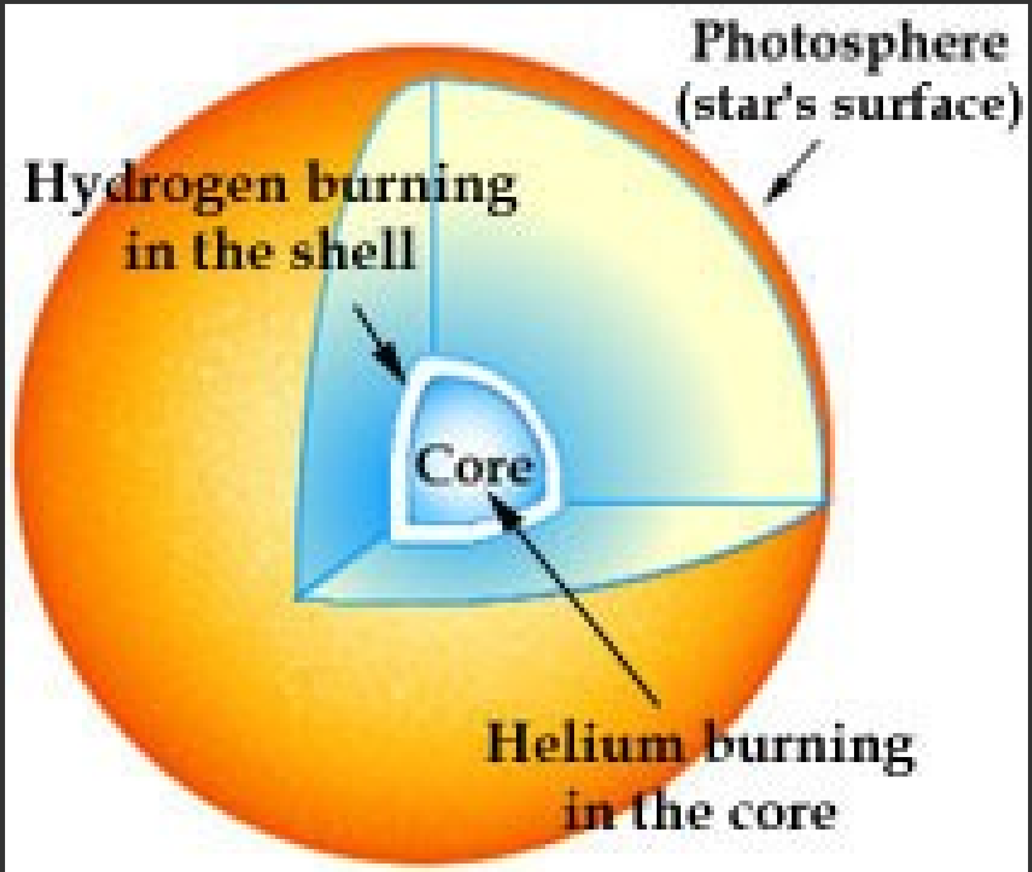
Mass is the key driving of stellar evolution

More massive stars evolve faster

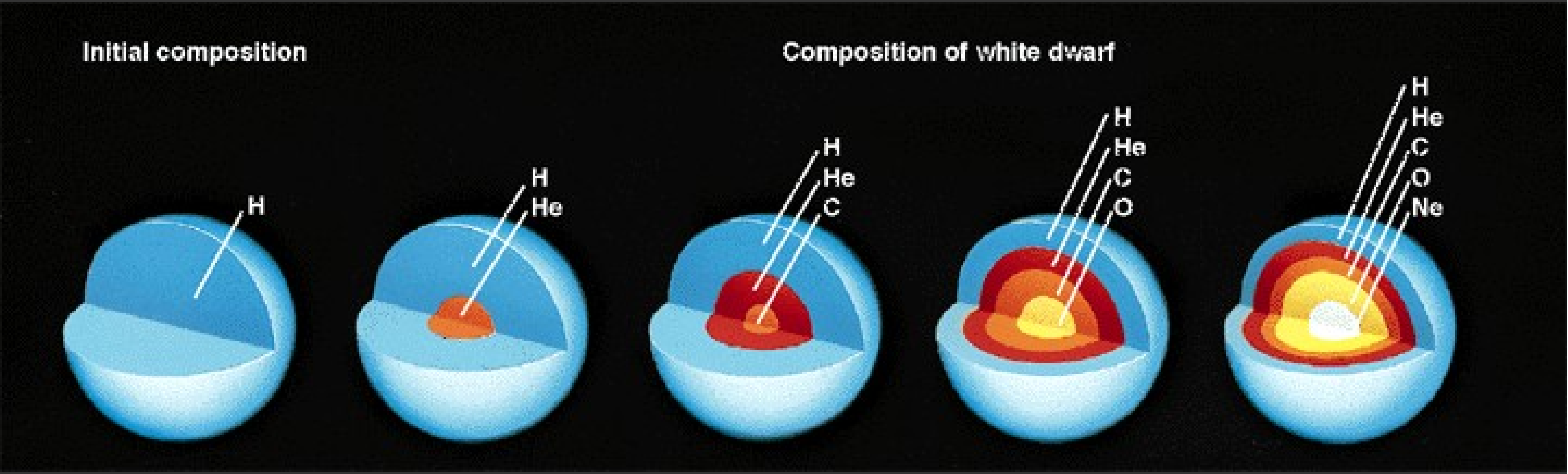
Stellar Mass	M-S Lifetime
$40M_\odot$	1×10^6 years
$15M_\odot$	12×10^6 years
$3M_\odot$	400×10^6 years
$1.5M_\odot$	3×10^9 years
$0.5M_\odot$	2×10^{12} years

As stars run out of hydrogen, they start "burning" helium:

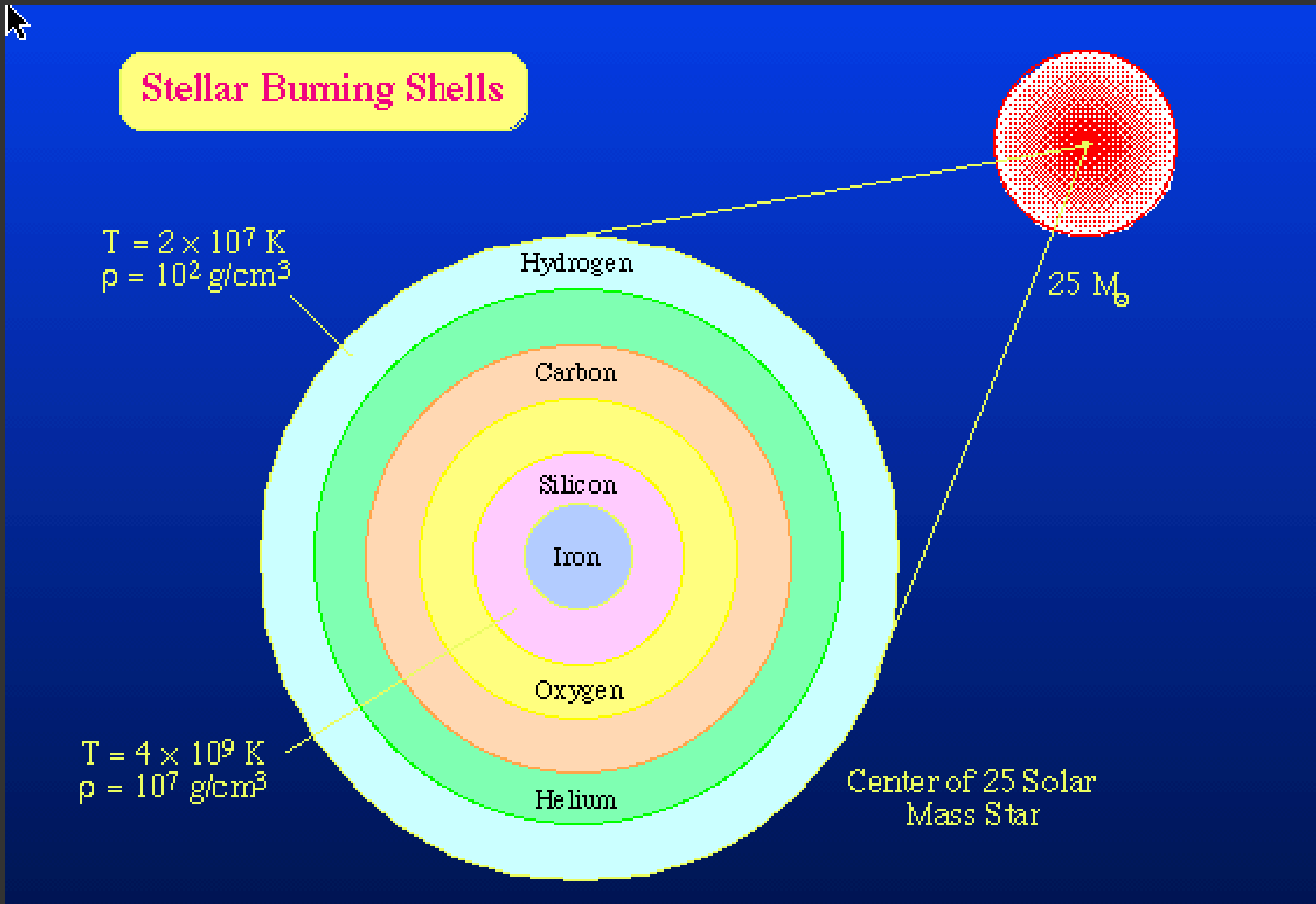




Later, the star may burn helium and other products



The star’s core can wind up looking like an onion



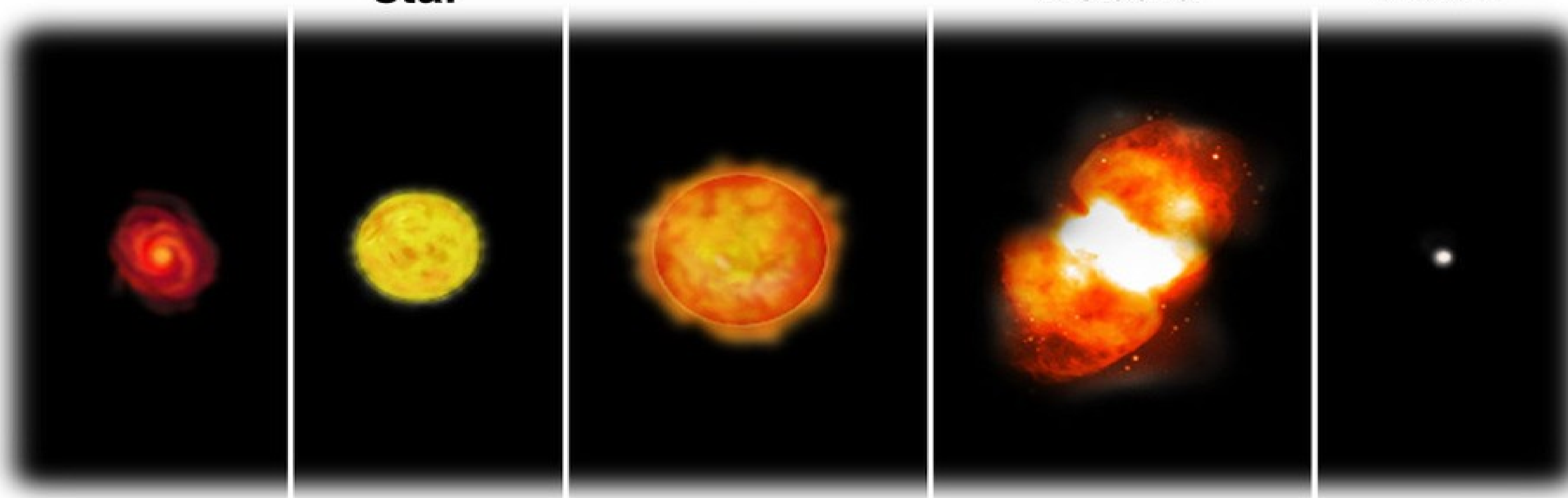
And then?

THE END

The fate of the Sun

About 4 billion years from now, the Sun will slowly fade and burn out.
The life cycle of stars, including the Sun:

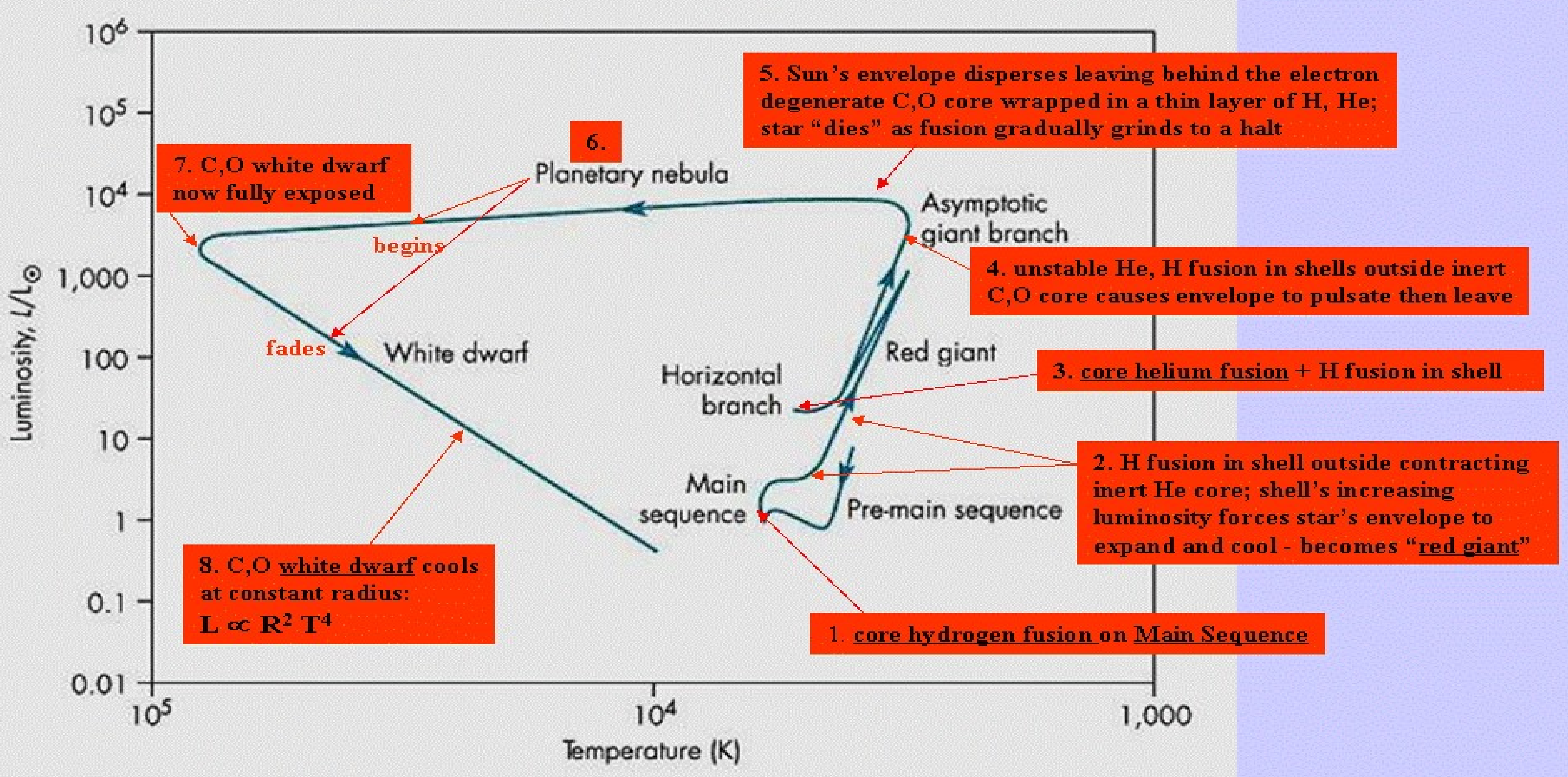
Protostar	Sun-like star	Red giant	Planetary nebula	White dwarf



Protostar	Sun-like star	Red giant	Planetary nebula	White dwarf
Region of condensing matter	**Stage Sun is at now**	Outer layers expand, cool and shine less brightly	Gaseous shell that moves around diminishing core	Inner core; star cools, dims

Source: McClatchy Washington Bureau
Graphic: Lee Hulting, Judy Treible

the evolution of our Sun

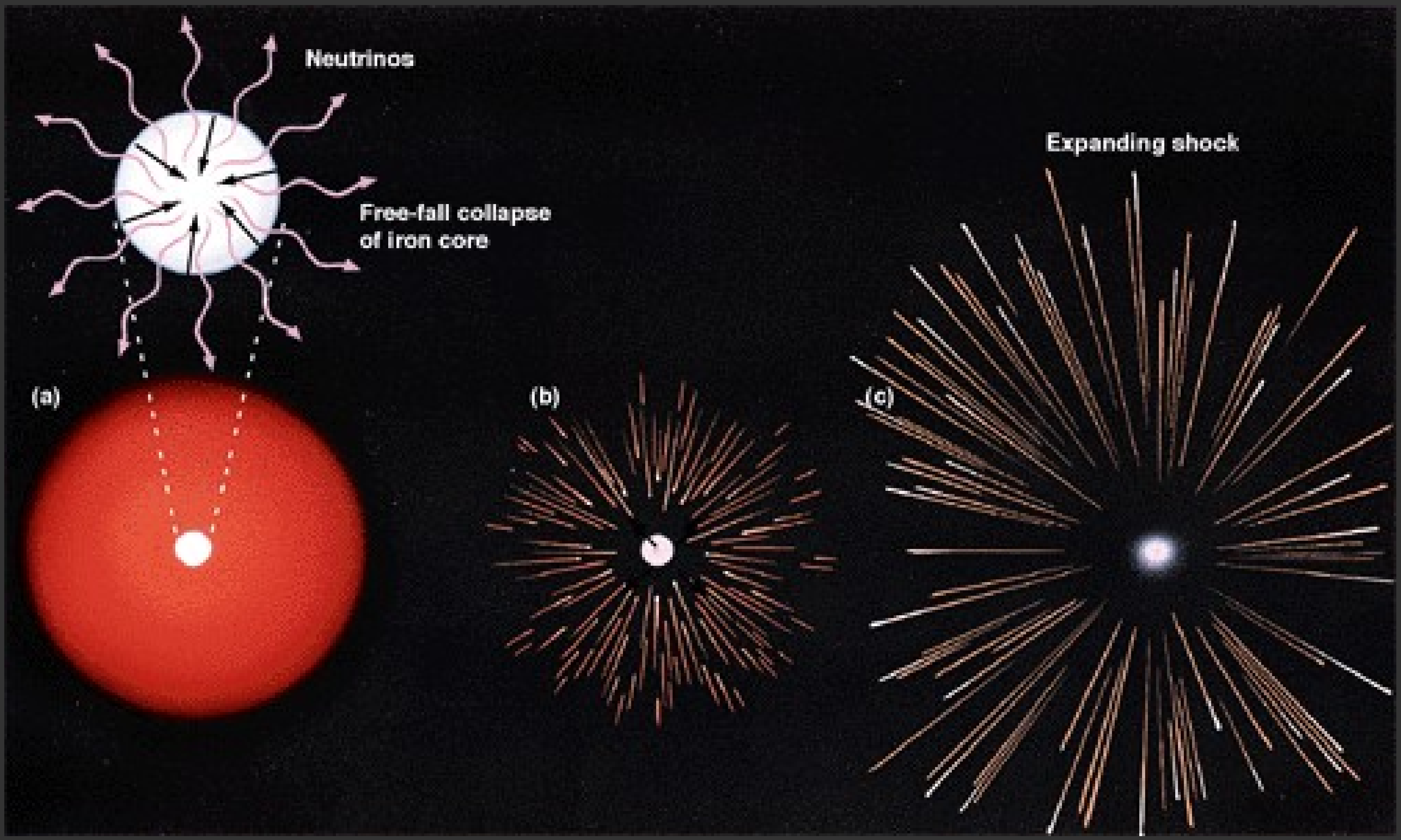


Planetary Nebula

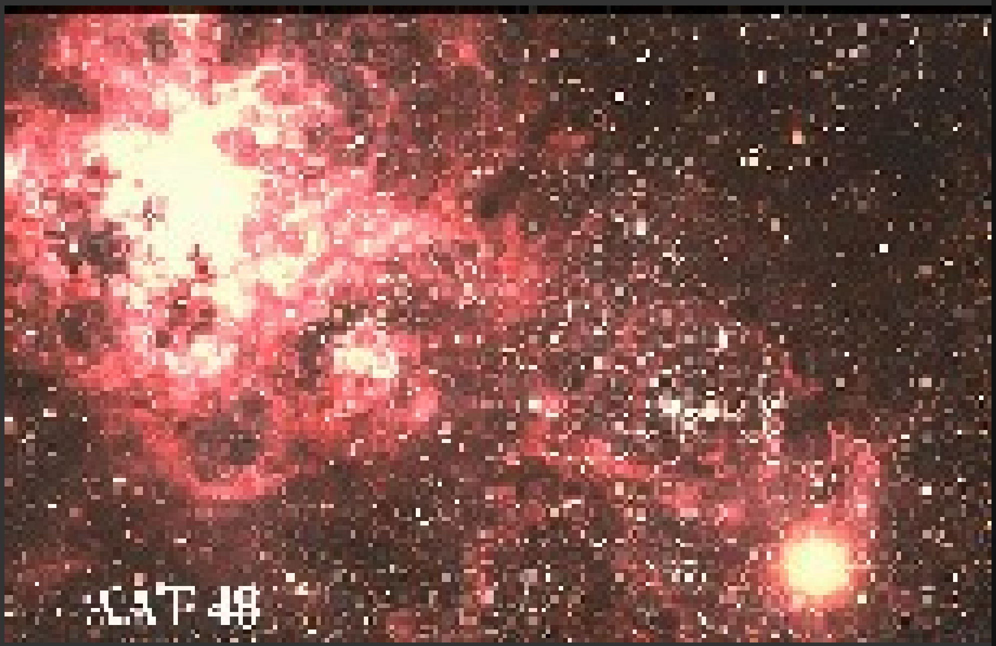
Outer atmosphere of stars is ejected and the surrounding could of gas is called a planetary nebula

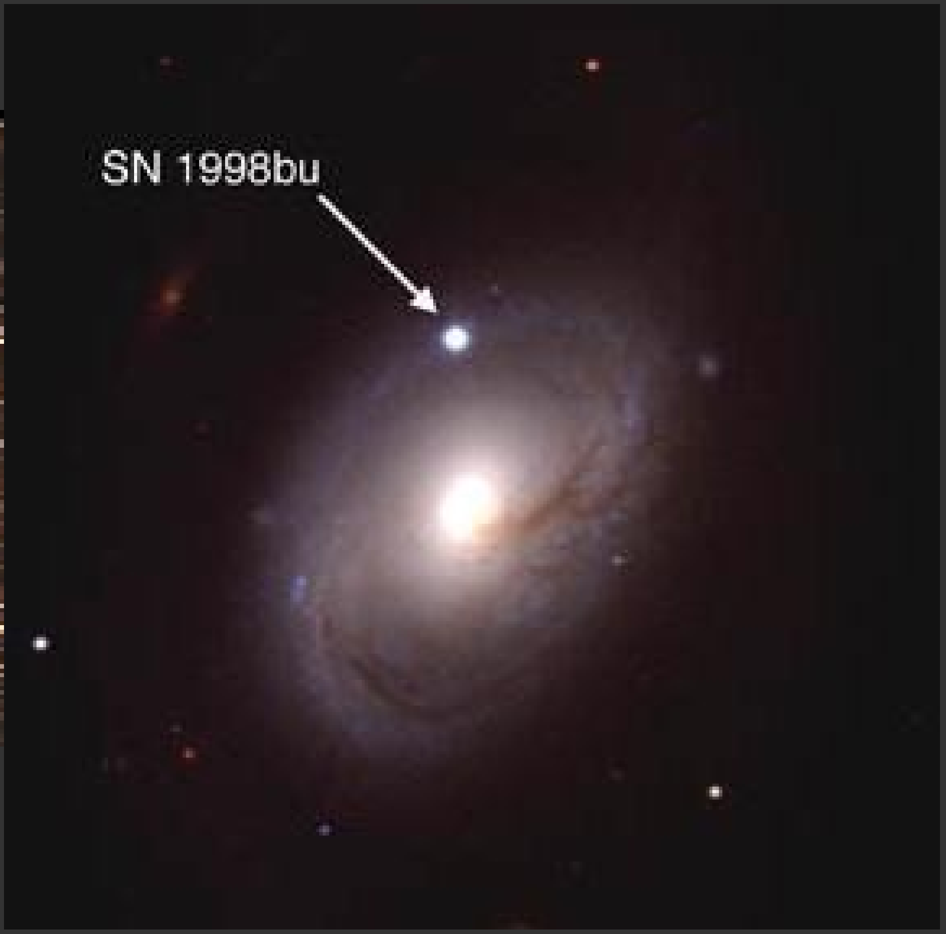
- has nothing to do with planet formation

For the heaviest stars, those with iron cores, death can come as a supernova

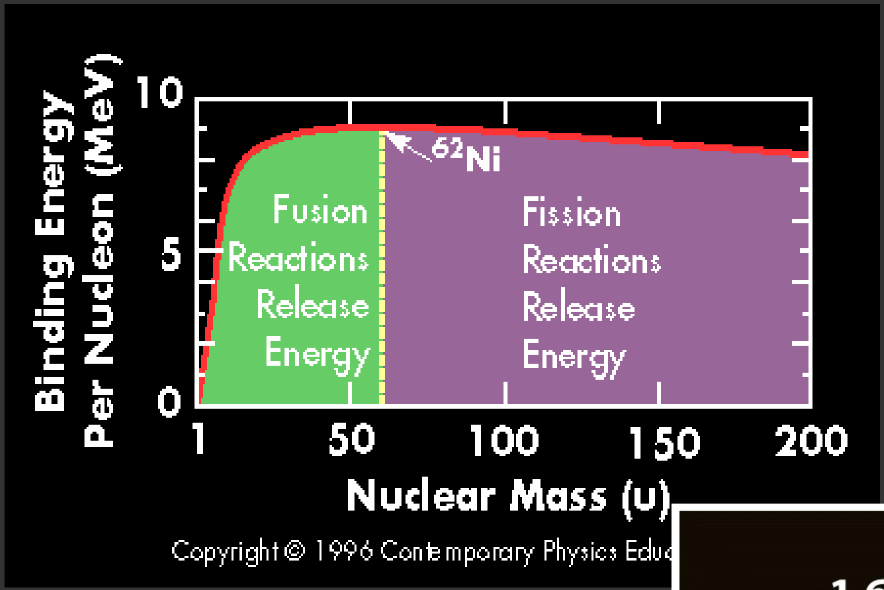


Supernovae are rare, but they can be as bright as a whole galaxy





U are Star stuff!!!



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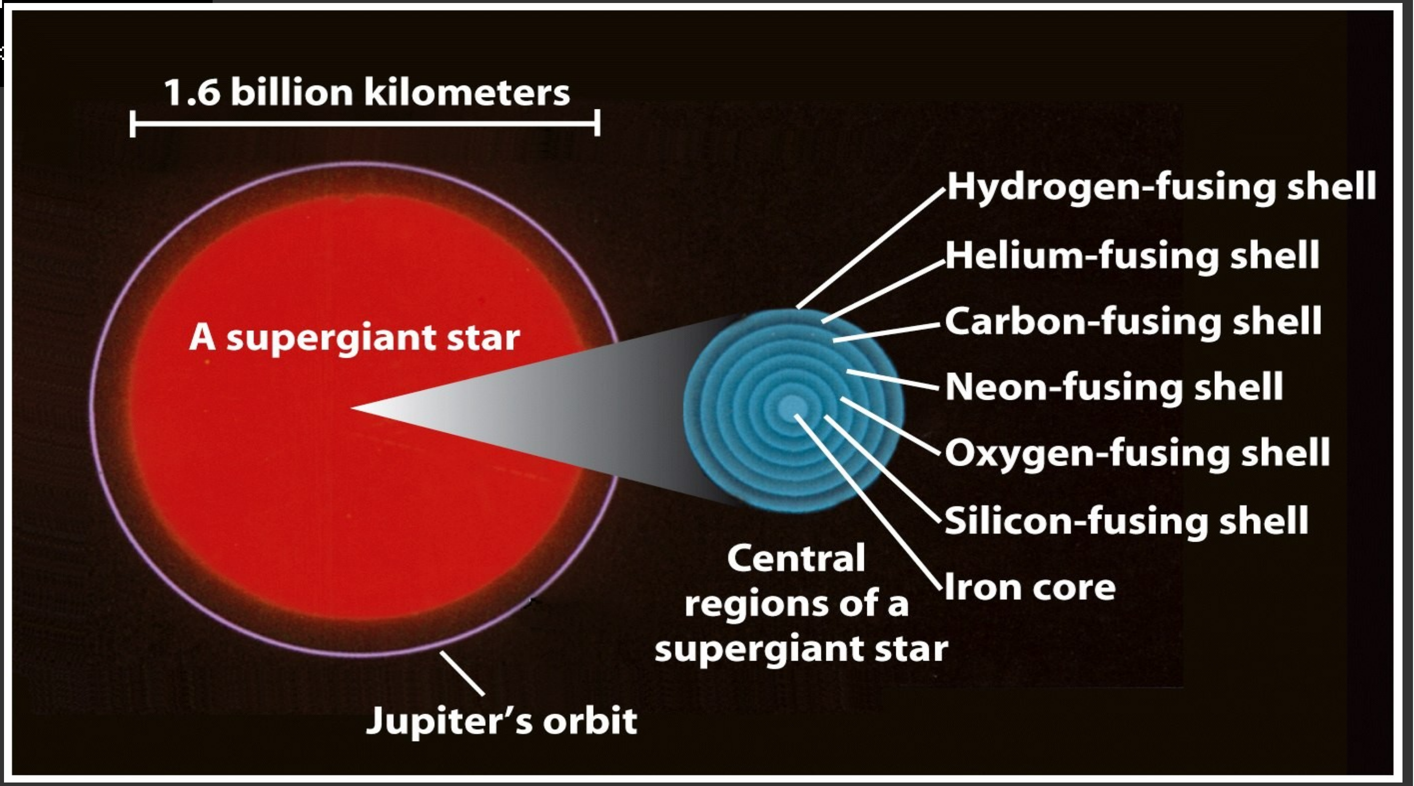
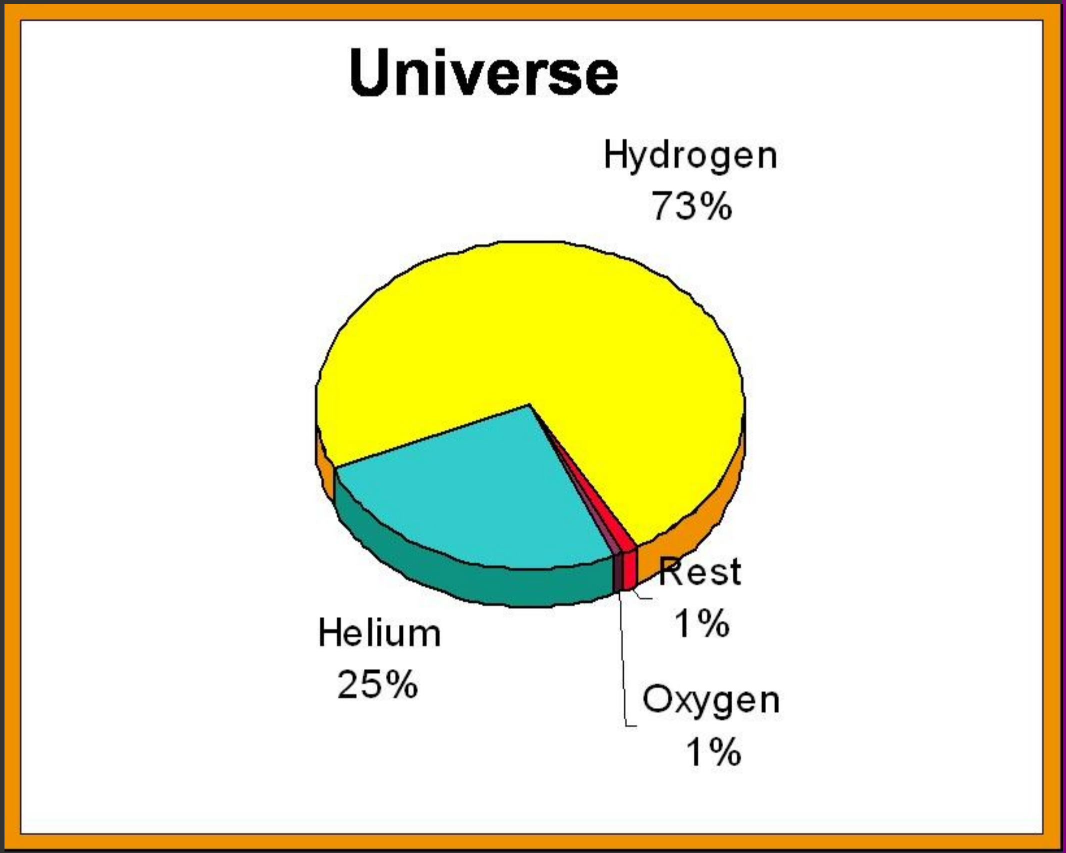
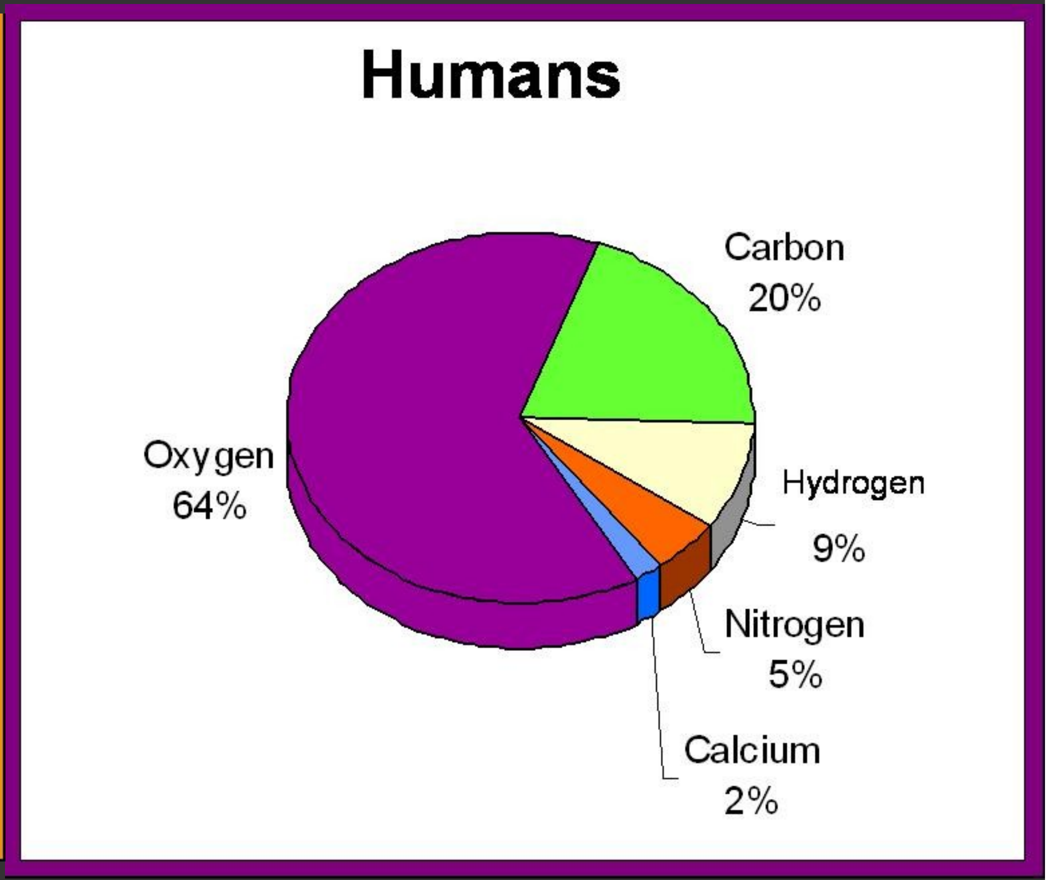
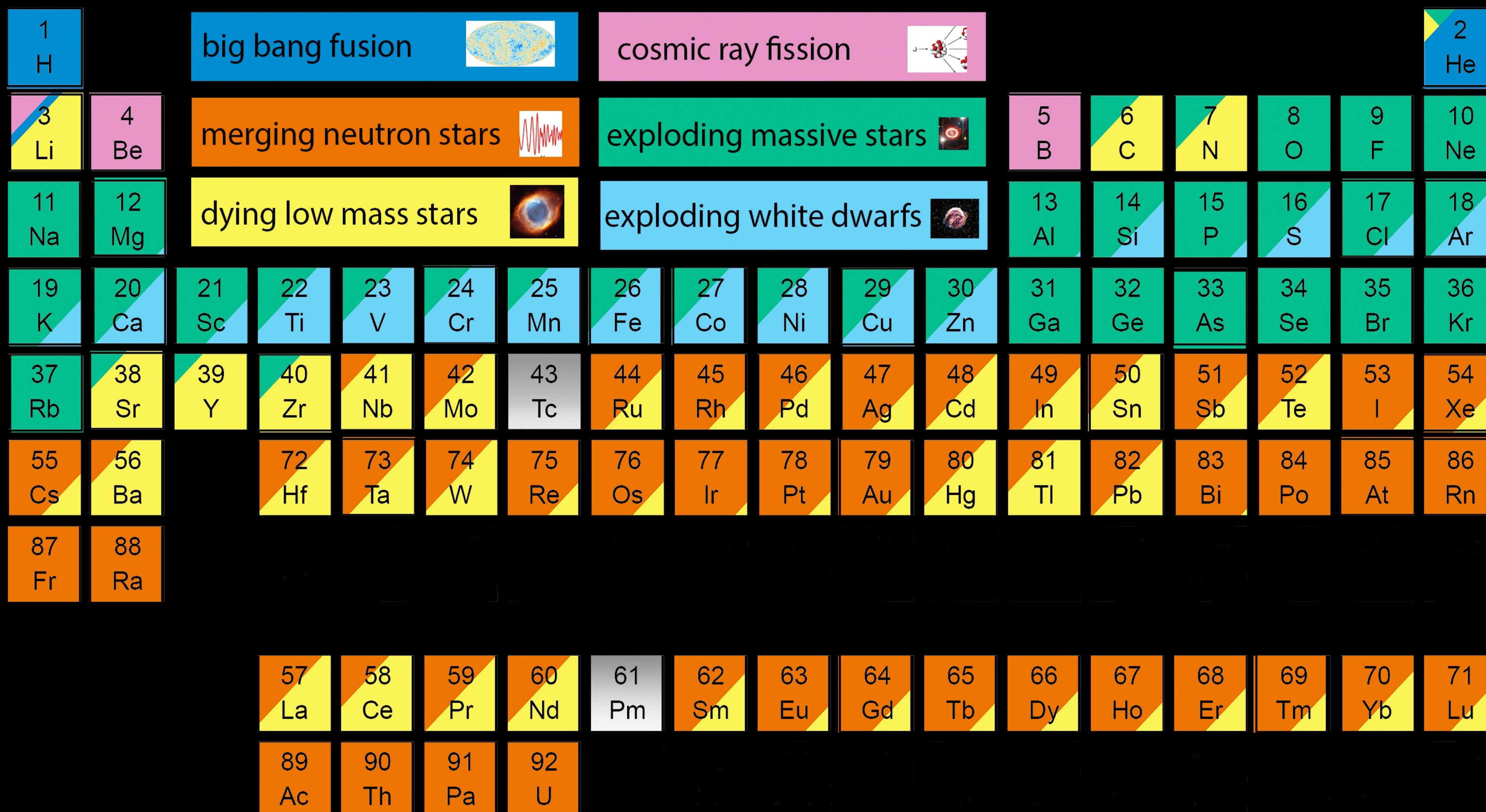


We are made of stardust!





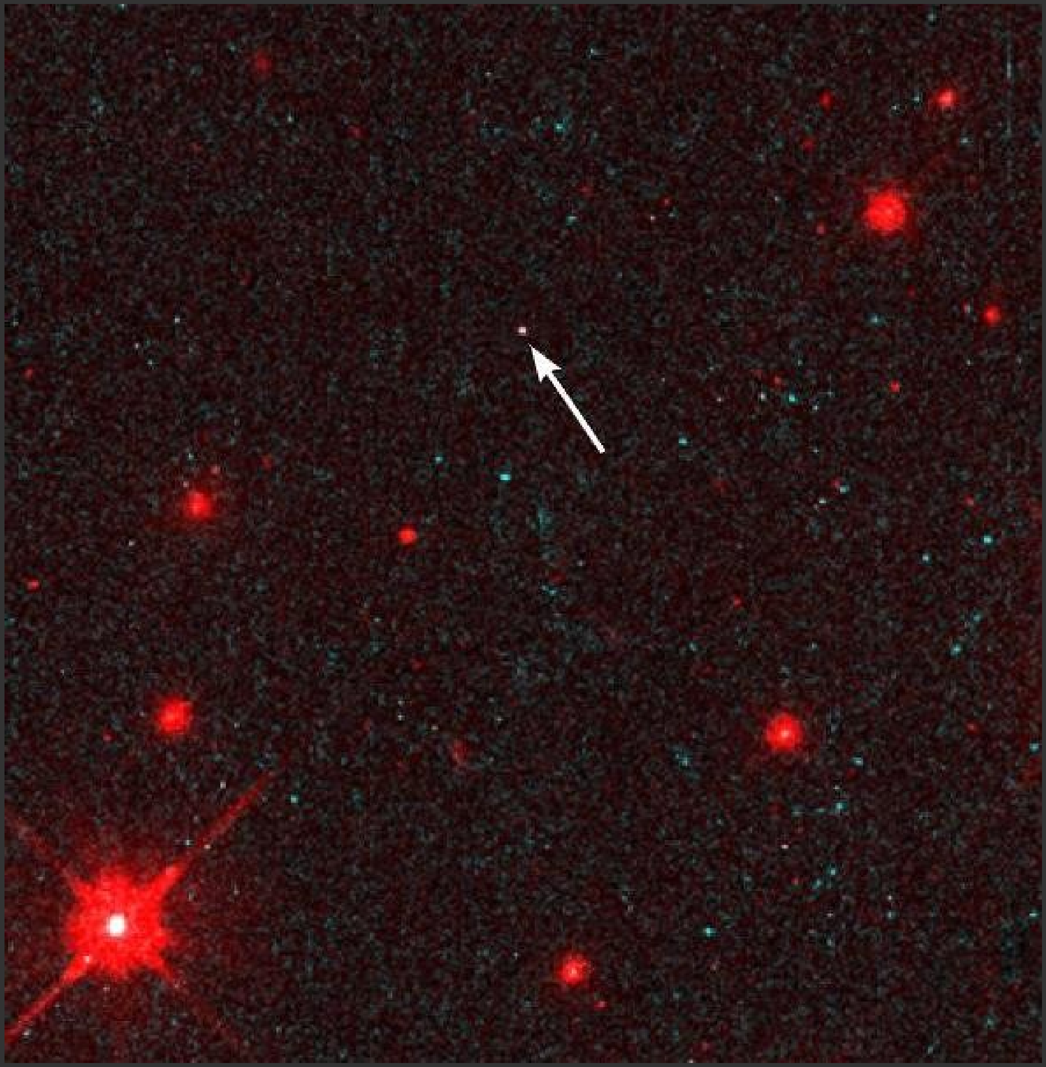
The Origin of the Solar System Elements



Astronomical Image Credits:
ESA/NASA/AASNova

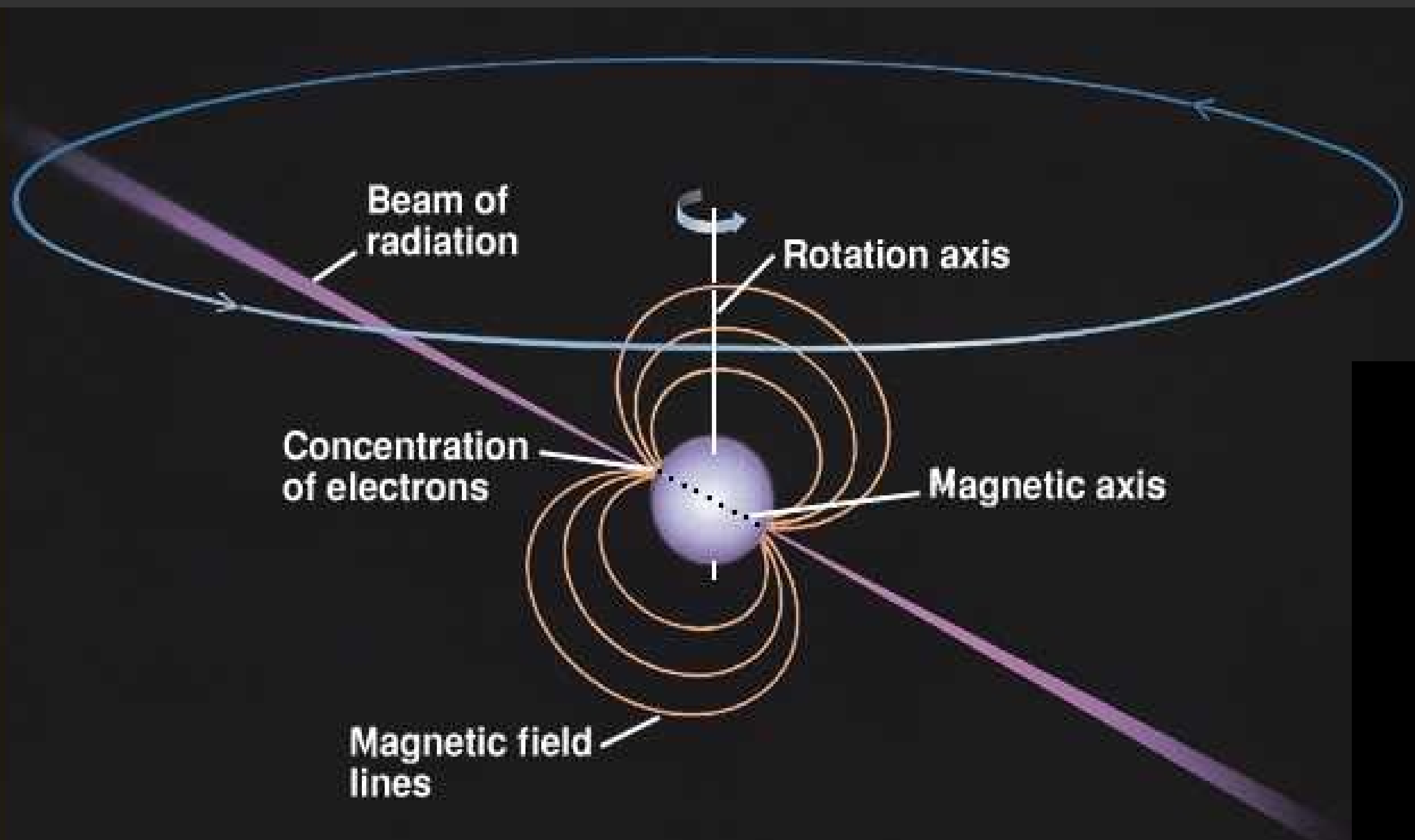
Graphic created by Jennifer Johnson

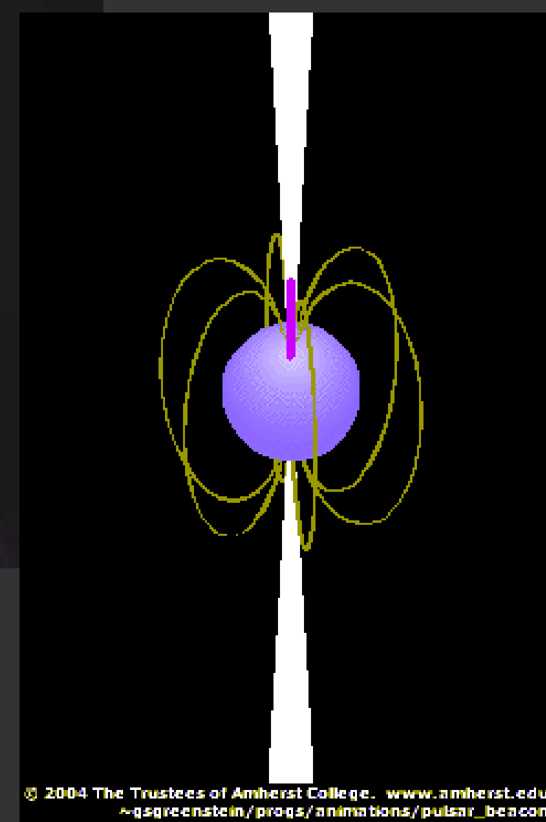
The core that remains might become a neutron star (or pulsar)



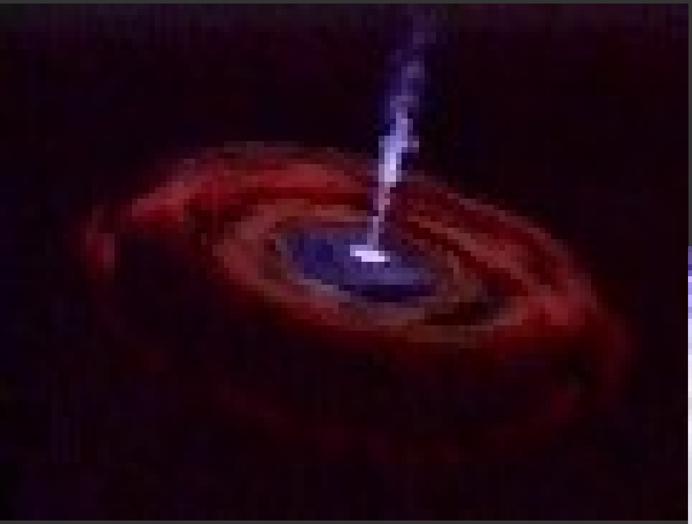
- The magnetic field collapses also, creating a very high energy density electric dynamo
- field energizes and beam out charged particle
  - "lighthouse" model

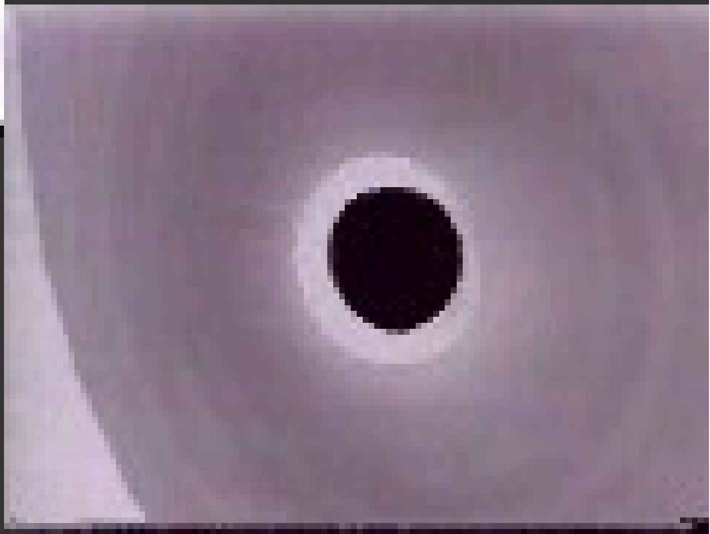
Rotating neutron stars are called pulsars



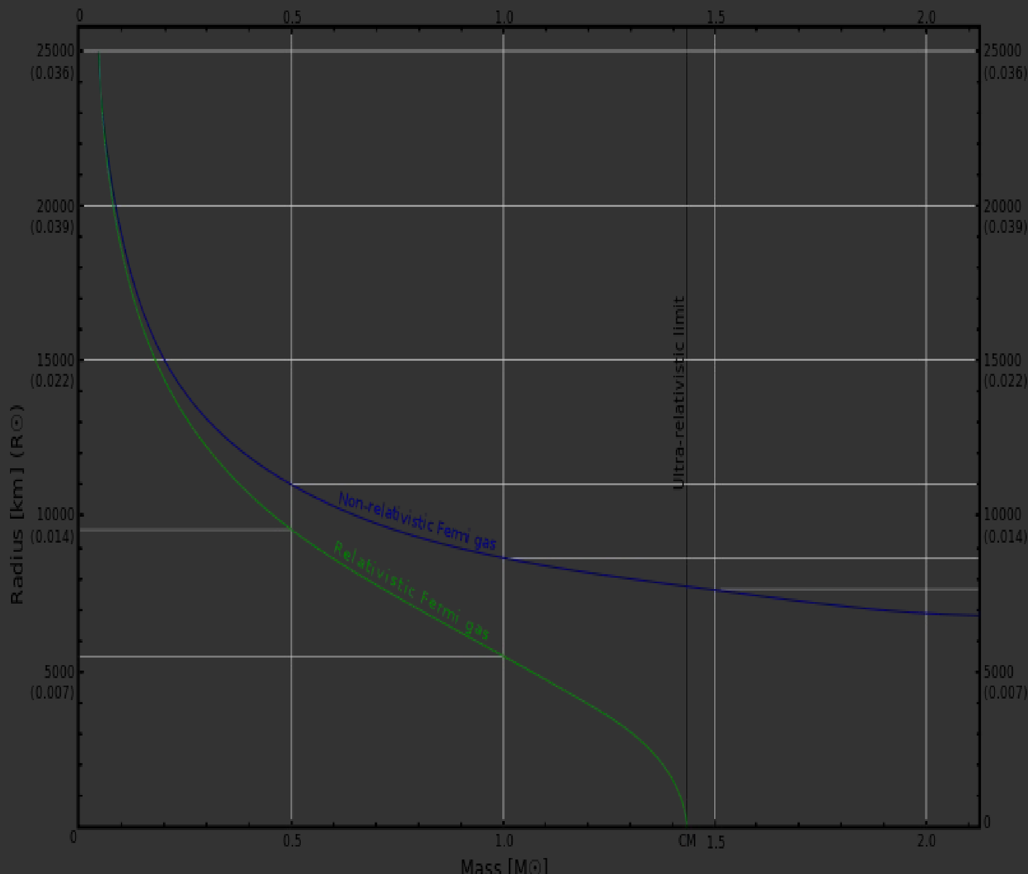


Very large stars can have their cores wind up as black holes





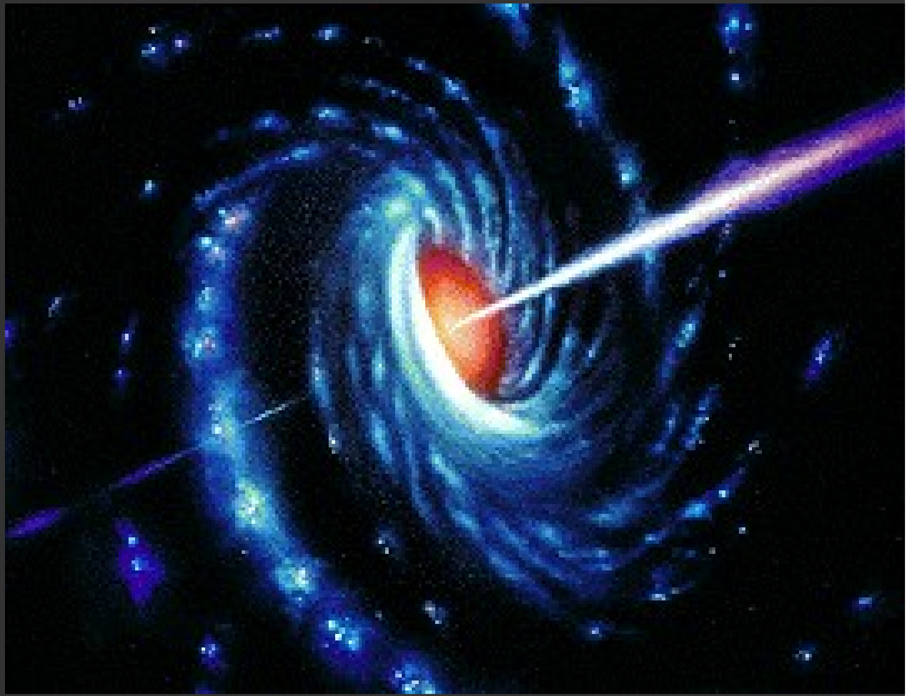
Chandrasekhar limit

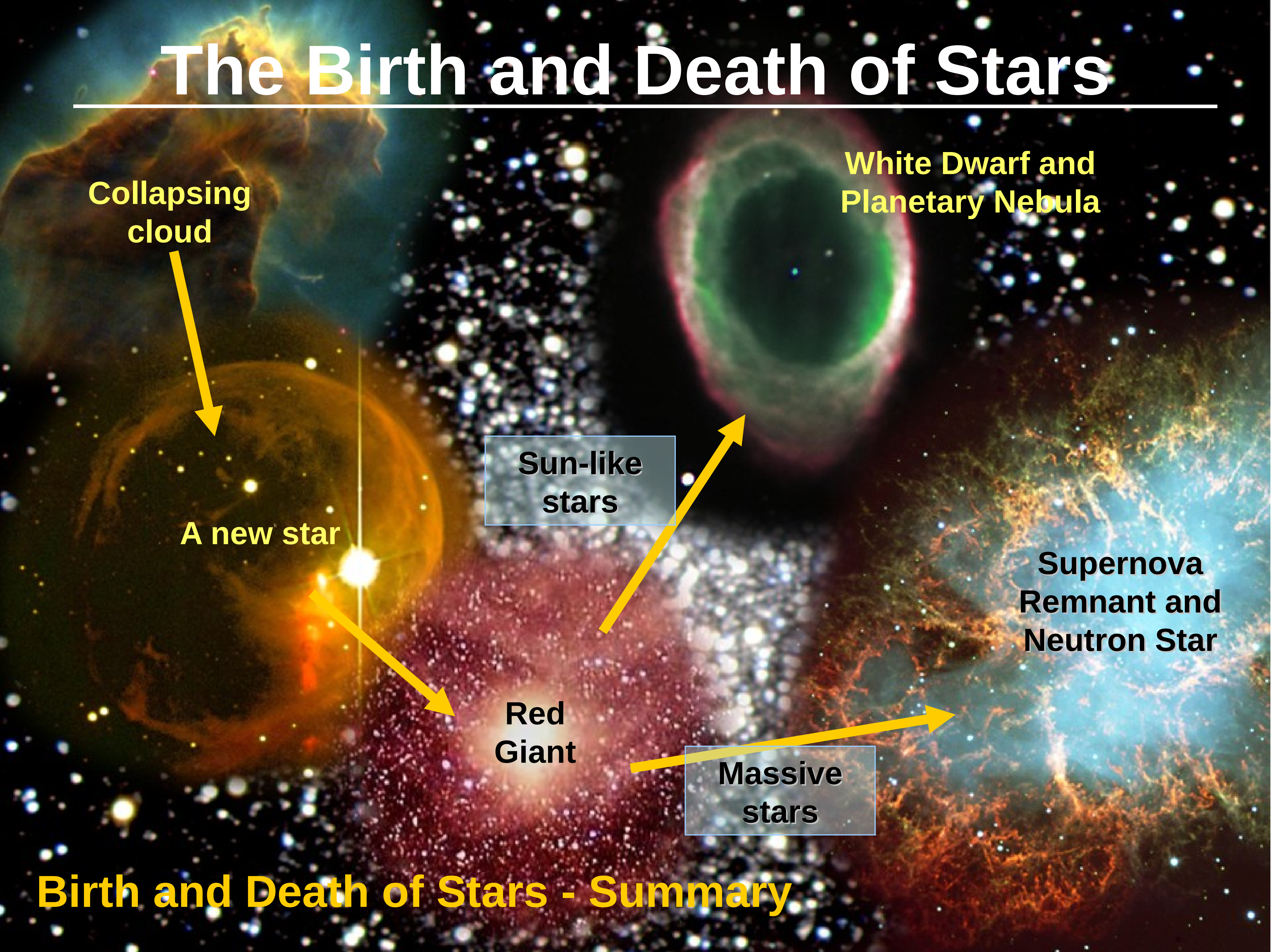


The maximum mass of a stable white dwarf star

The electron degeneracy pressure in the star's core is insufficient to balance the star's own gravitational self-attraction. Consequently, white dwarfs with masses greater than the limit undergo further gravitational collapse, evolving into a different type of stellar remnant, such as a neutron star or black hole.

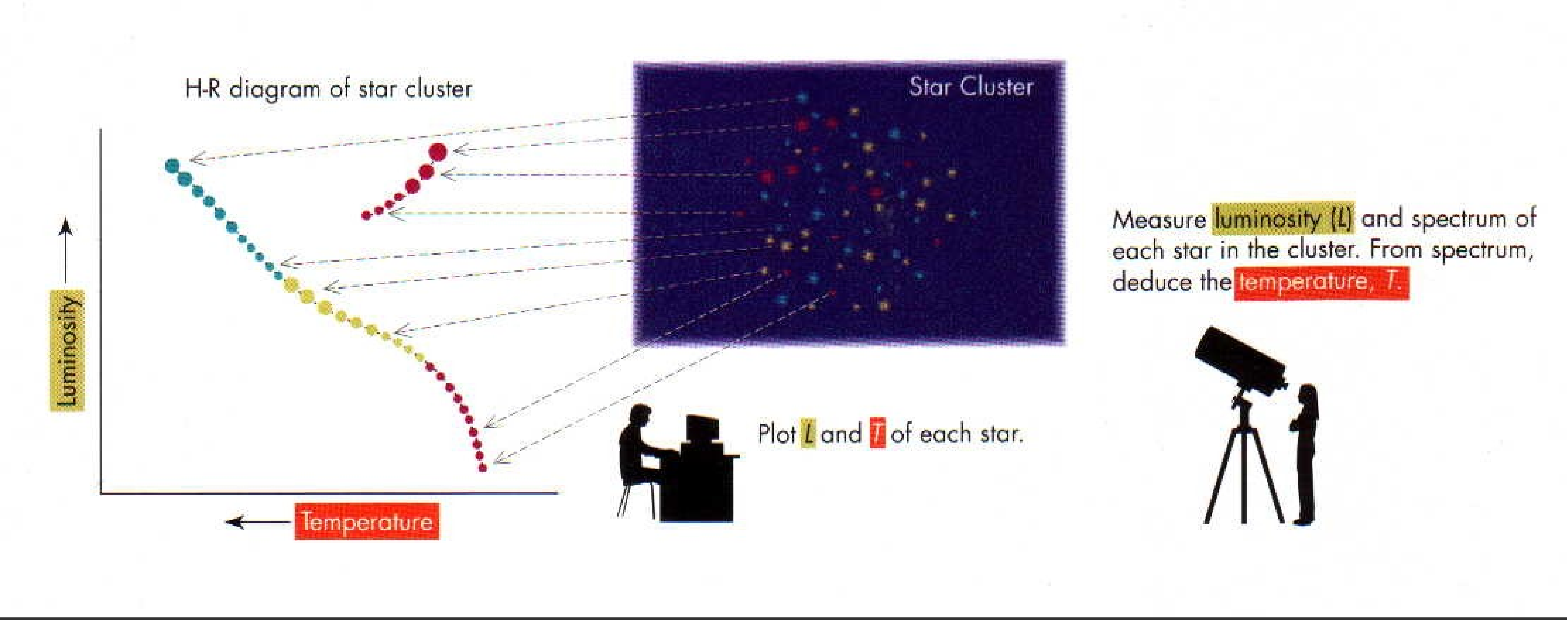
It’s believed that some, perhaps most, galaxies have a supermassive black hole at their centers



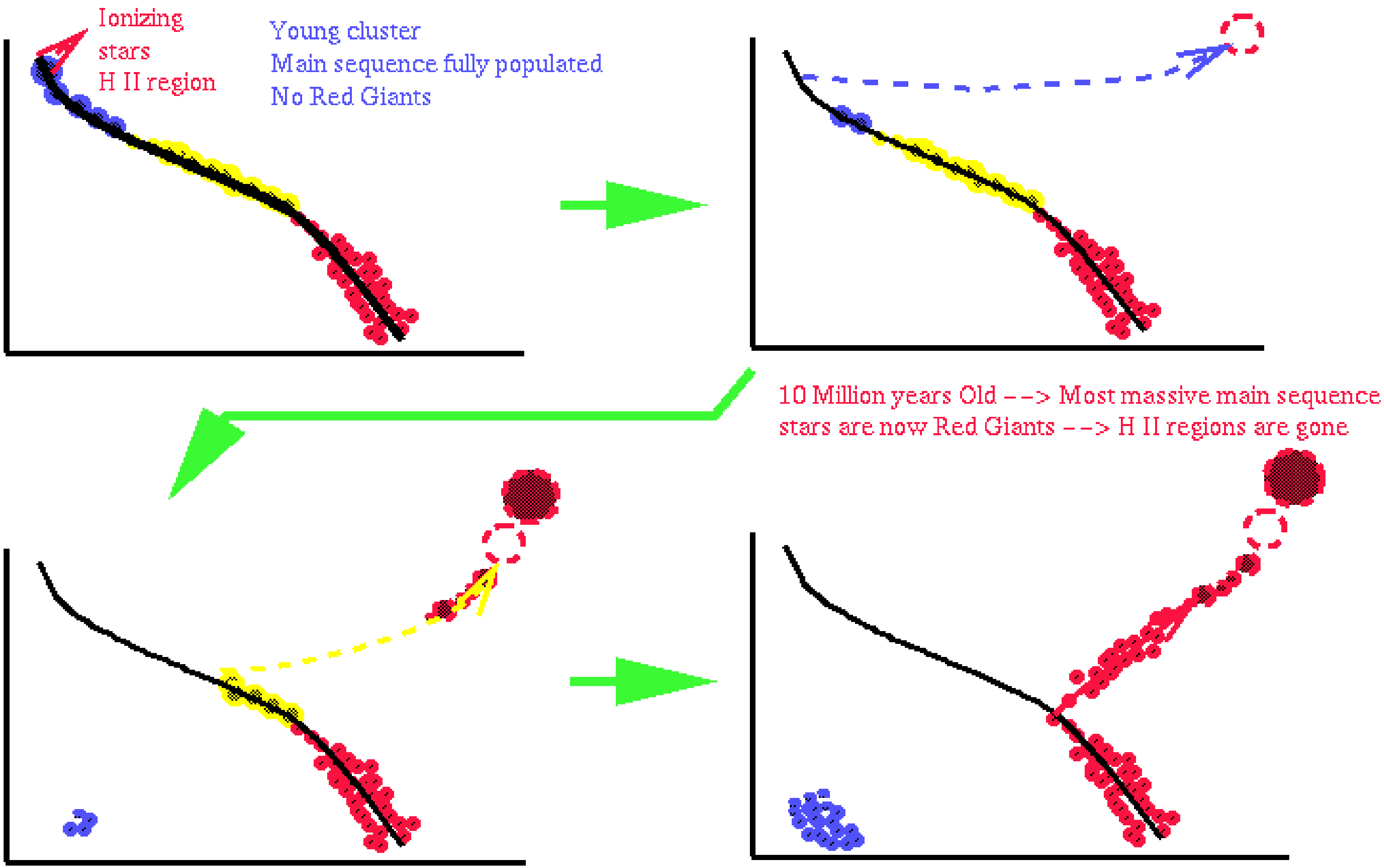

The Birth and Death of Stars
Collapsing cloud
White Dwarf and Planetary Nebula
Sun-like stars
A new star
Supernova Remnant and Neutron Star
Red Giant
Massive stars
Birth and Death of Stars - Summary

The H-R Diagram of a star cluster

Works best for a cluster, where you know the stars are all at the same distance, born from the same cloud, same chemical composition and of the same age....differ only in mass.



Evolution off the Main Sequence



1 Billion years old --> more stars on the giant branch; some white dwarfs now. Upper main sequence gone above 2 solar masses

T = 10 billion years old --> just red stars left; lots of white dwarfs; no stars more massive than one solar mass left on the main sequence

And for Galaxies?

Thank You