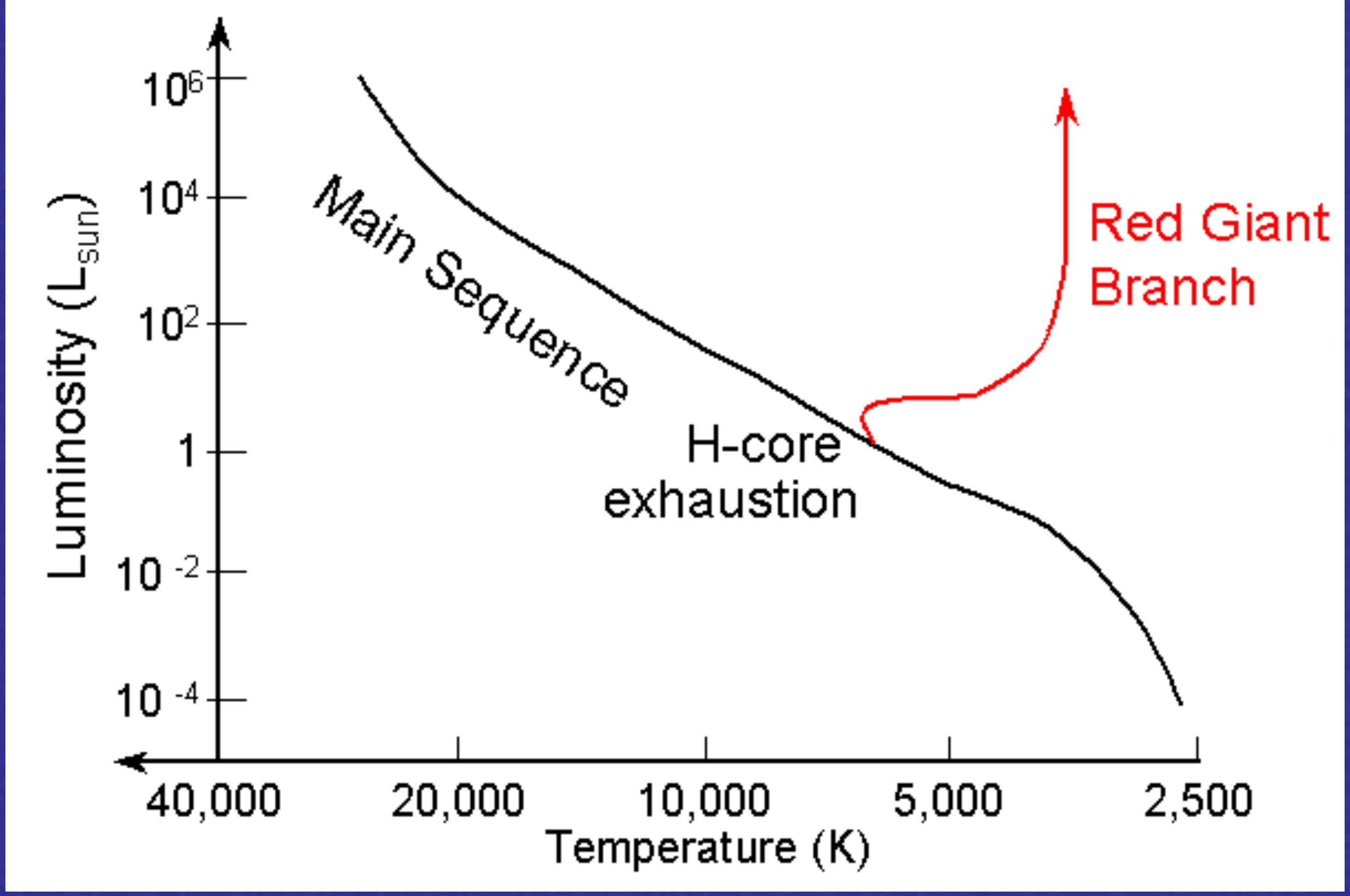
Announcements

Homework 4 is due on Tuesday (Feb. 23) by start of class

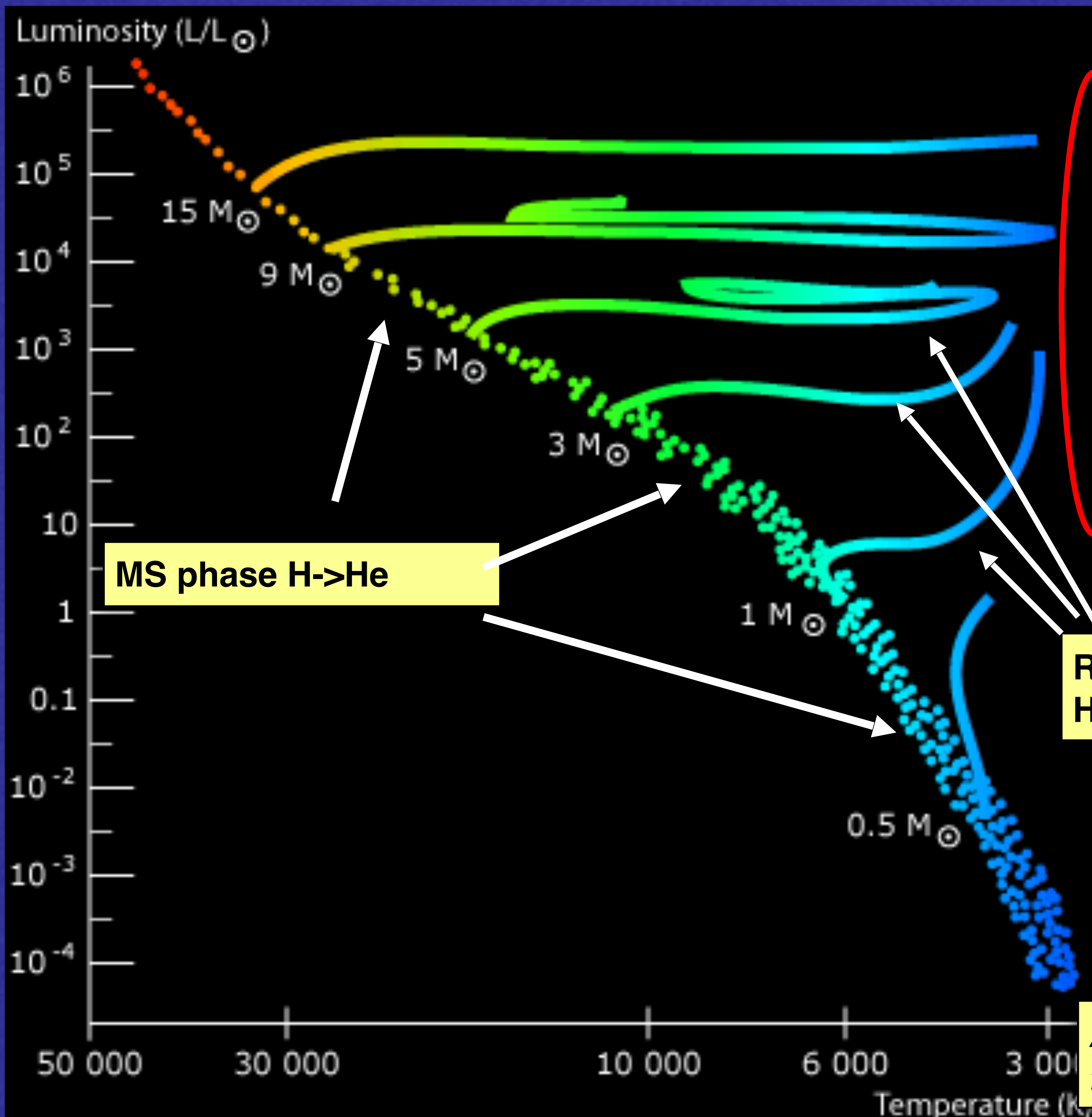
Post-main sequence evolution

- Core hydrogen exhaustion => inert He core, contracting and heating.
- Pushes outer layers outwards => expansion, and cooling (to the right in H-R diagram)



- Shell H fusion starts => luminosity increase (upwards in H-R diagram)
- Helium fusion starts (the triple alpha process, producing C and O) => the core expands and cools

Stellar evolution so far



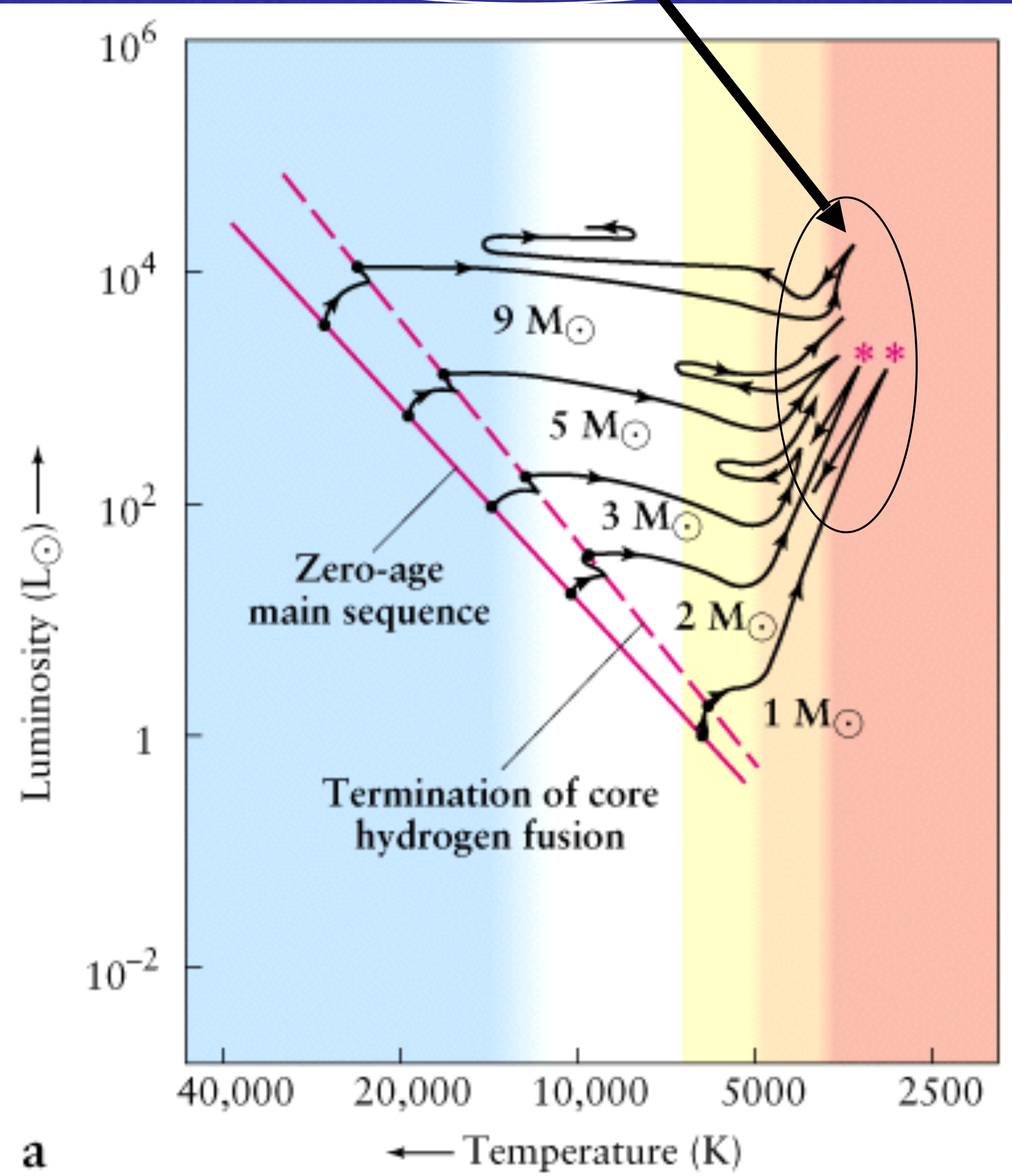
Different energy sources during different stages in the star's evolution

Protostar phase (KH contraction)

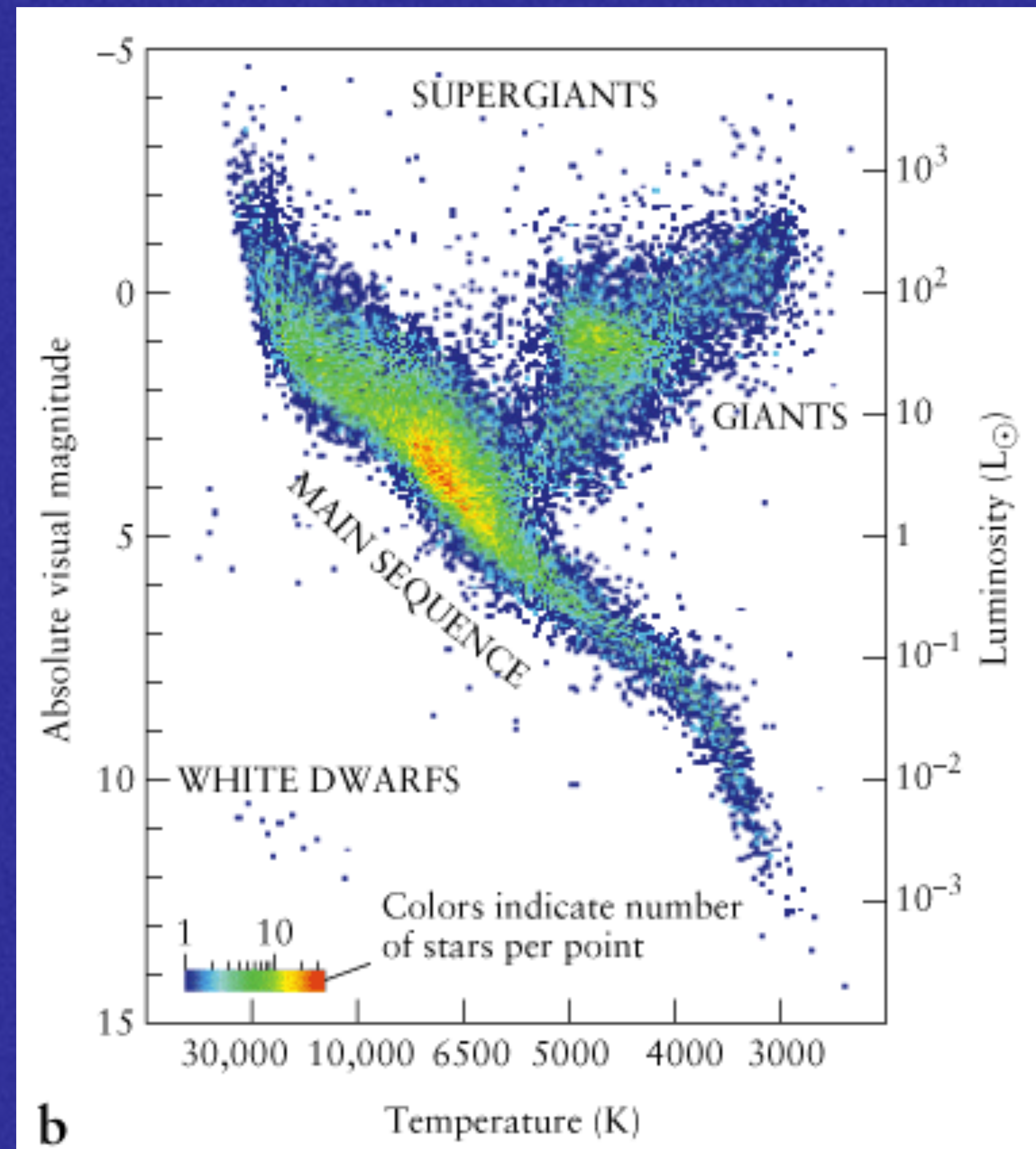
RGB phase (shell H->He)

And remember: more massive stars evolve faster during all stages

Helium ignition
occurs here



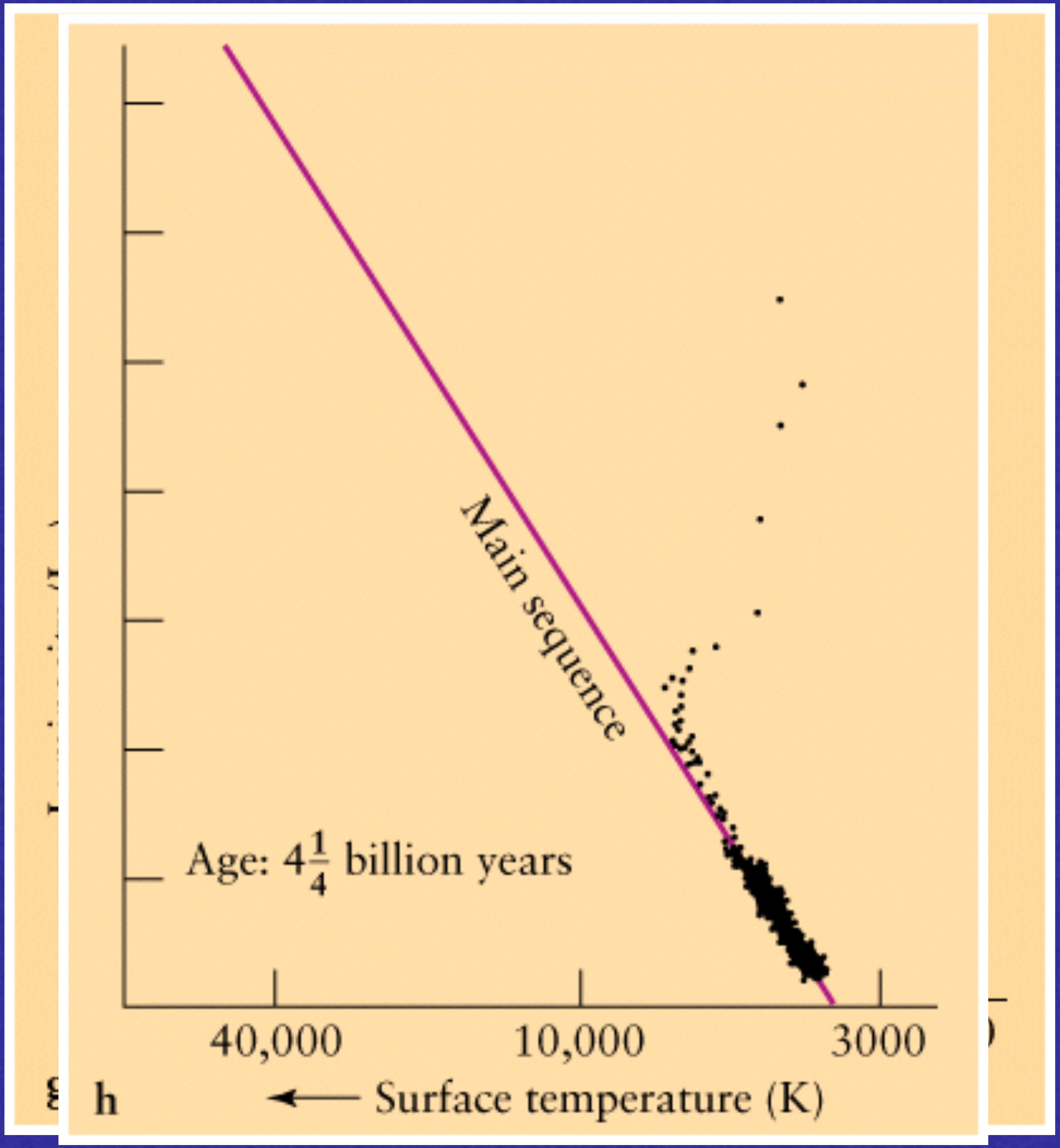
H-R diagram for 21,000 stars from Hipparcos. Note that ages are not homogeneous as in H-R diagrams of clusters.



- These are theories, and we cannot see deep down into stars. How can we test whether these models are viable?

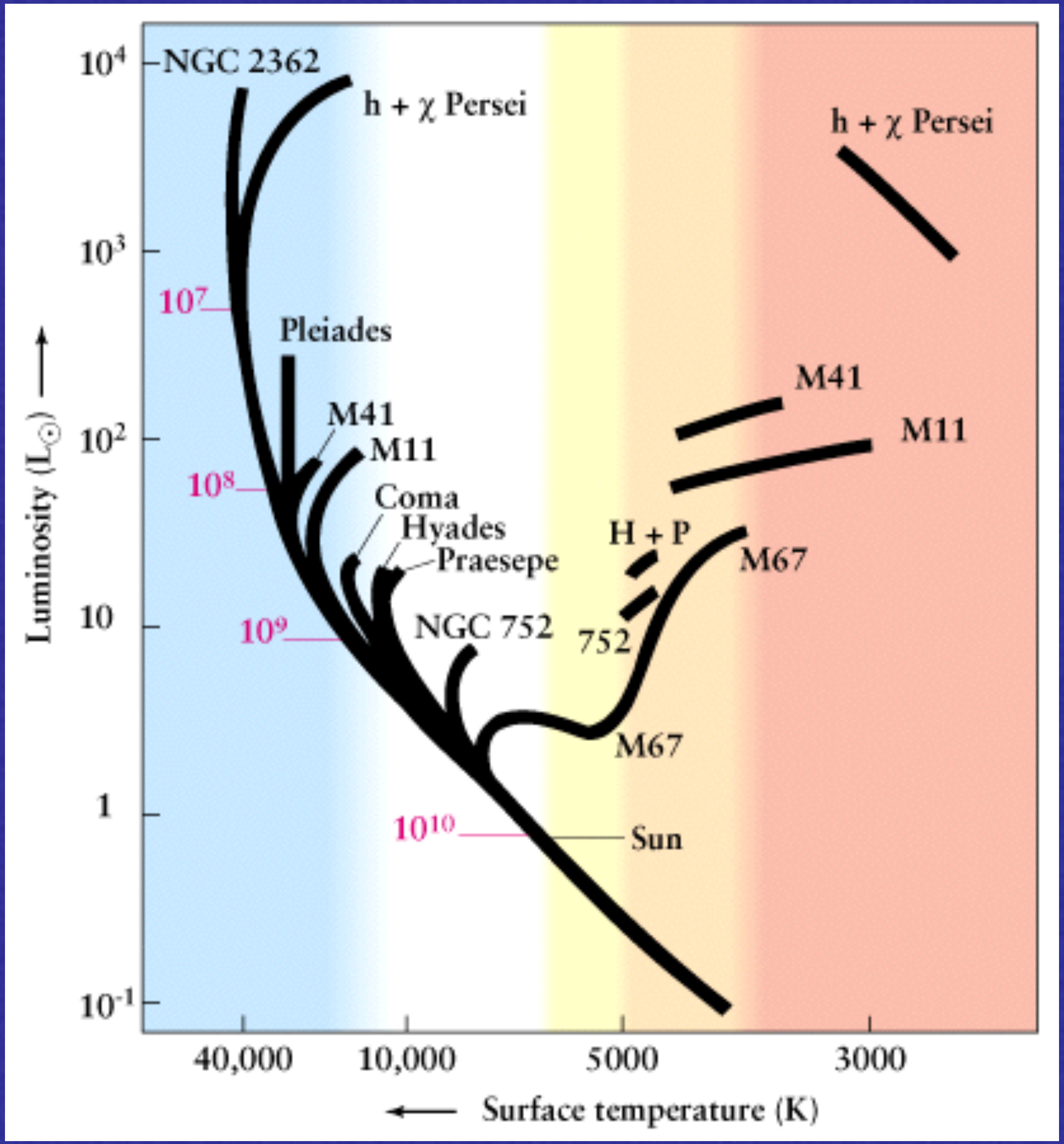
- Answer: compare theoretical “evolutionary tracks” on the H-R diagram with real stars.

Theoretical tracks:



Comparison of theory and observations

- The H-R diagrams of open clusters show that the turnoff point is the key to determining age.

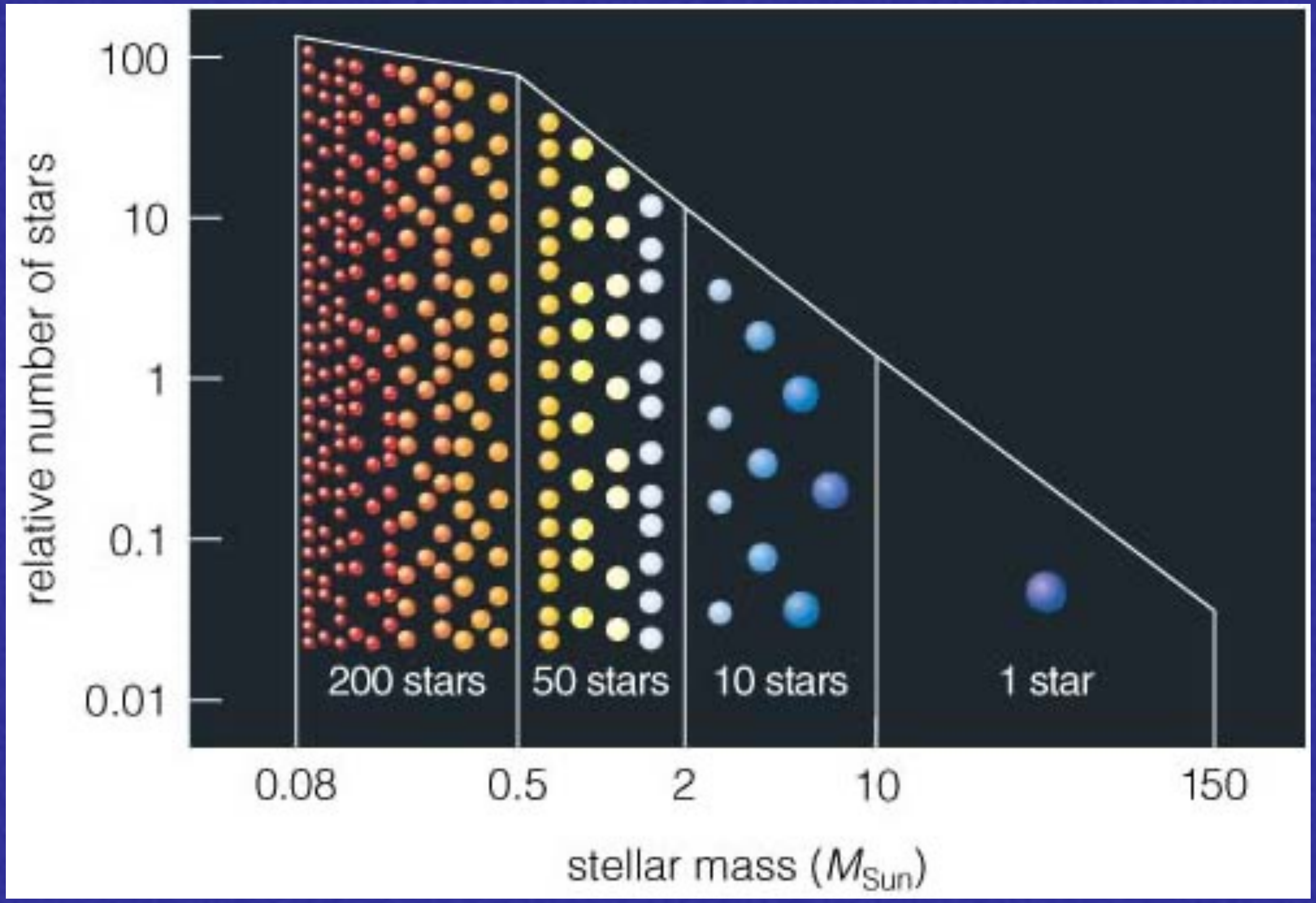


Star clusters

- Groups of stars moving together through space

- All stars in a cluster
  - Are at the same distance (easy to compare e.g. luminosities)
  - Have the same age
  - Have the same chemical composition
  - Have a wide range of stellar masses

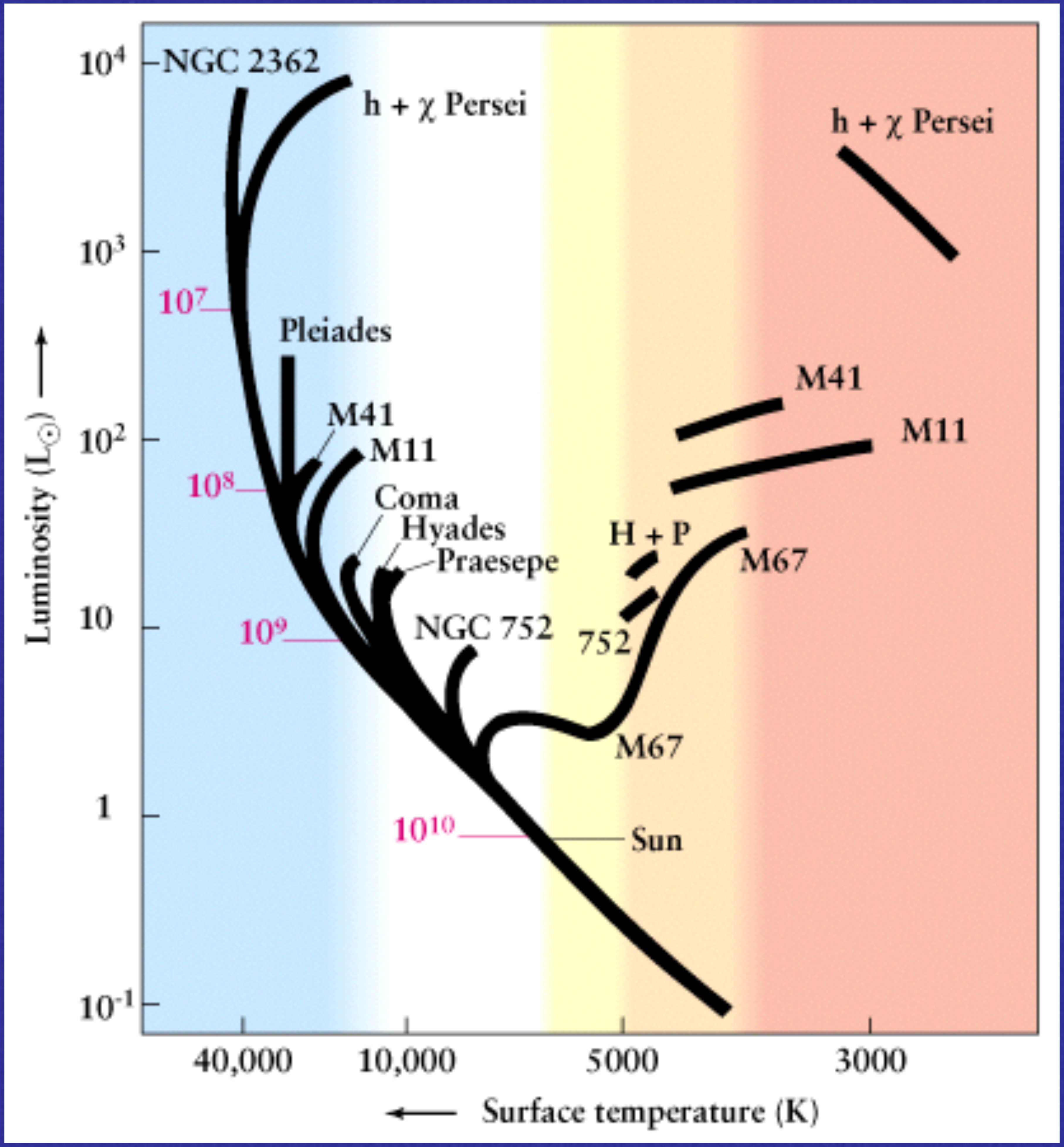
- A cluster provides a snapshot of what stars of different masses look like, at the same age and with the same composition



Open clusters

- Open clusters (galactic clusters) contain 10^2 to 10^4 stars, not centrally concentrated.
- The clusters are confined to plane of the galaxy.
- Stars are young, and often have lots of metals (recall a “metal” is any element beyond hydrogen and helium).

M1:1 the “Wild Duck” open cluster in Scutum.


NGC 2362
h + χ Persei
h + χ Persei
Pleiades
M41
M11
Coma
Hyades
Praesepe
NGC 752
H + P
752
M67
M67
M41
M11
Sun
10^4
10^3
10^2
10
1
10^-1
10^7
10^8
10^9
10^10
Luminosity (L☉)
40,000
10,000
5000
3000
Surface temperature (K)

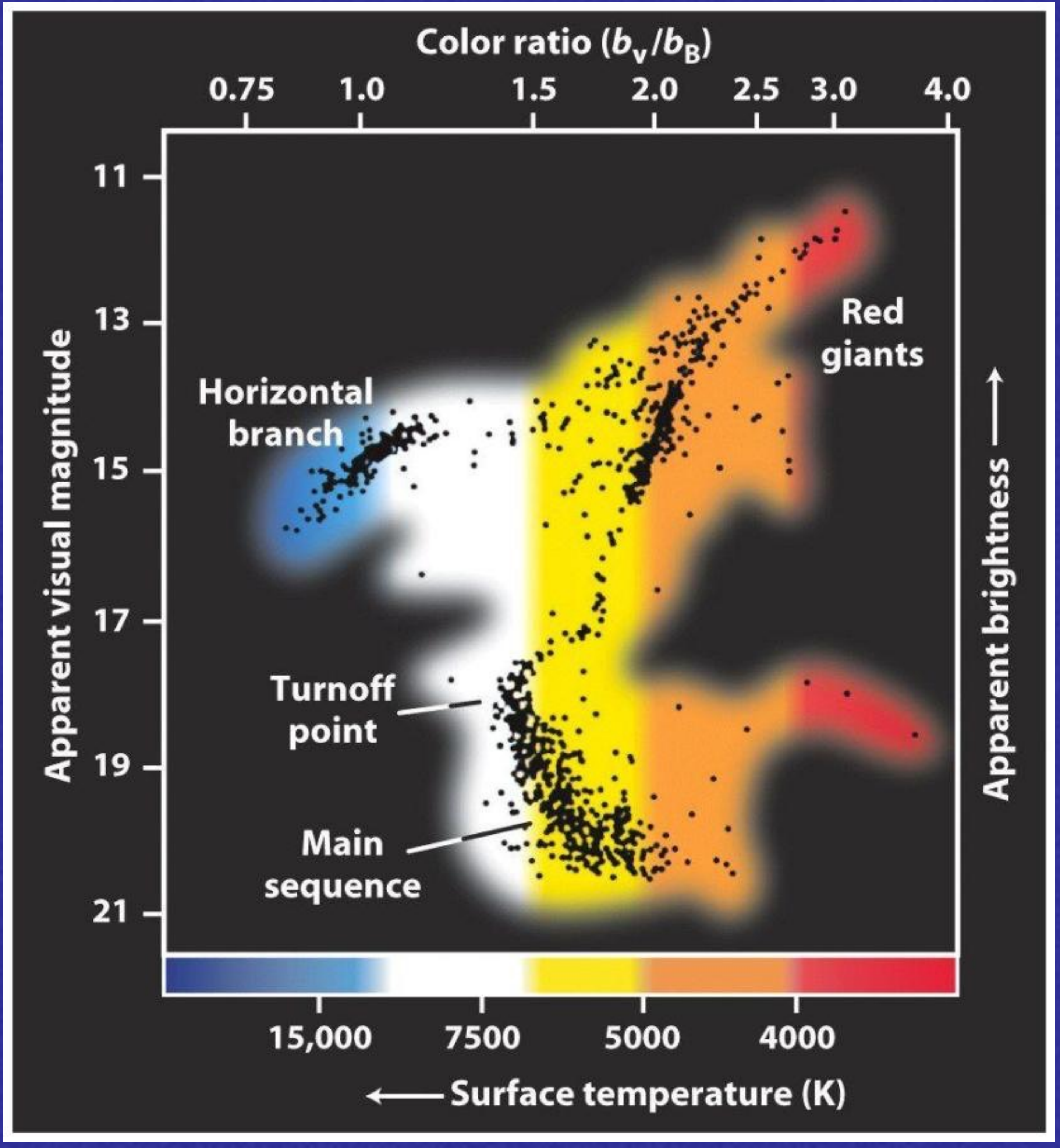
Globular clusters

- Globular clusters contain 10^5 to 10^6 stars, centrally concentrated.
- Found in the halo of the galaxy.
- The stars are old with low metallicity.
- Provide an important, lower limit to the age of the Universe.

M10

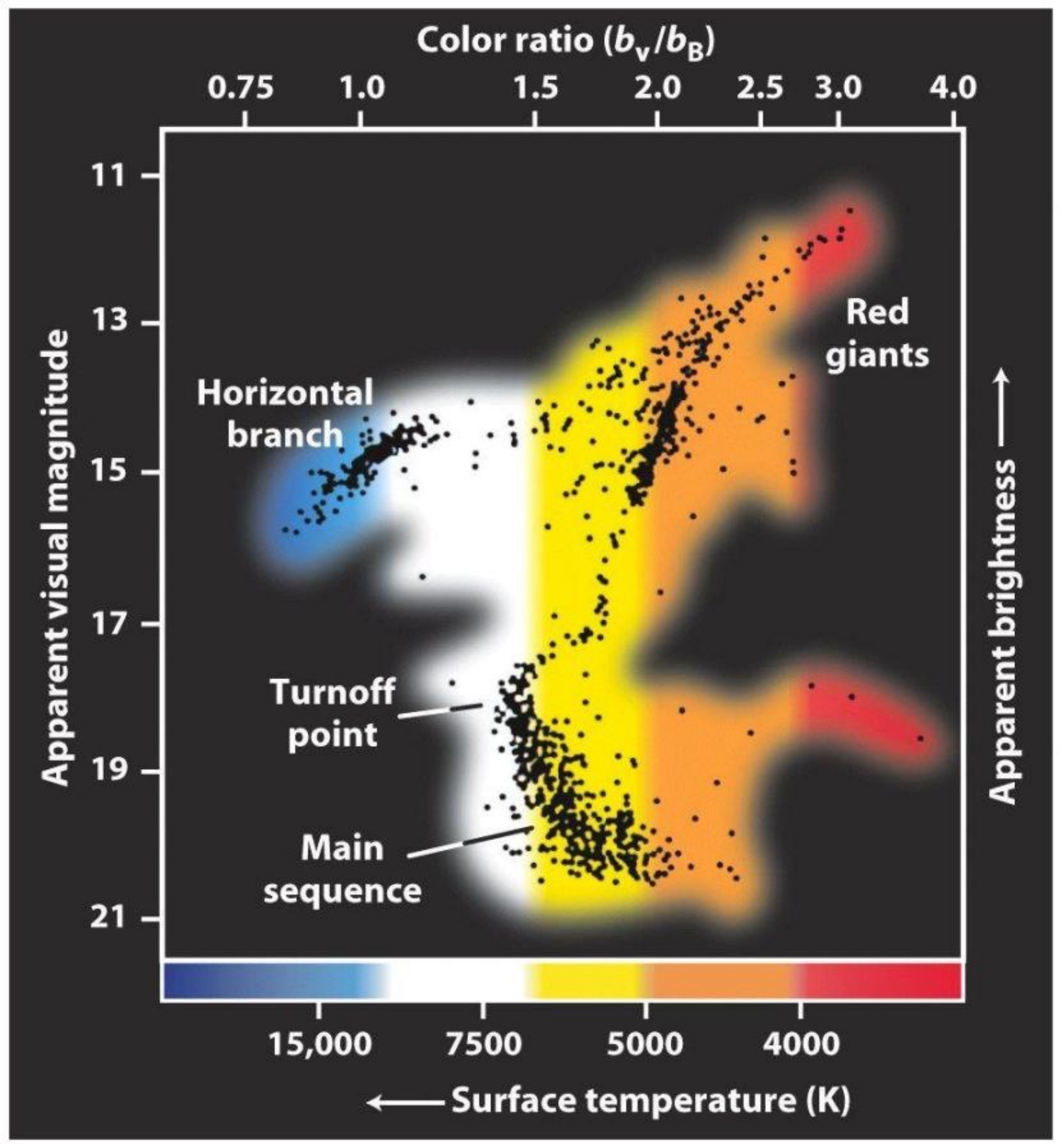
M80

- Typical globular cluster H-R diagram. Note low turnoff point, and many red giants.

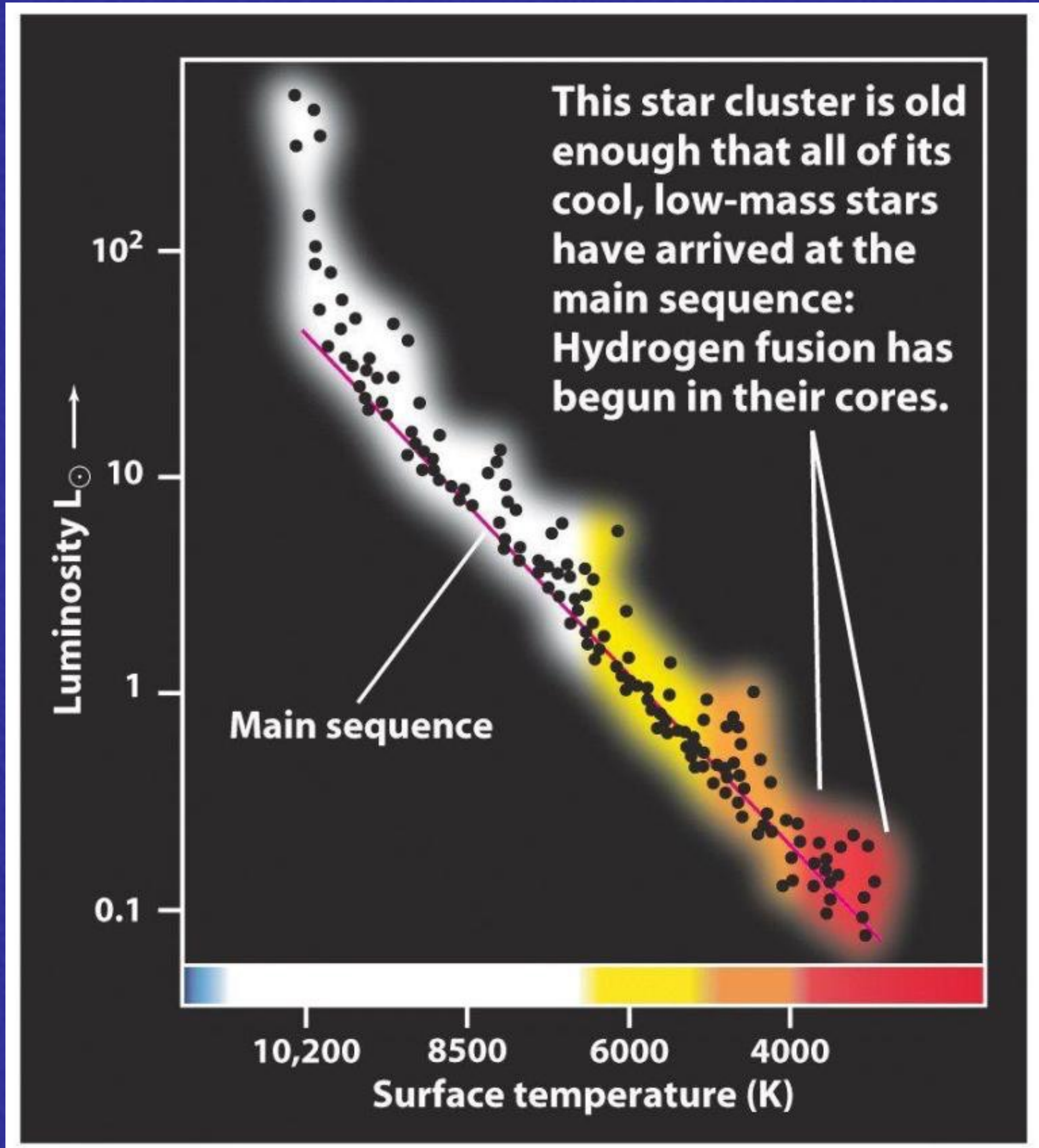


Compare to open cluster HR diagram

Globular cluster

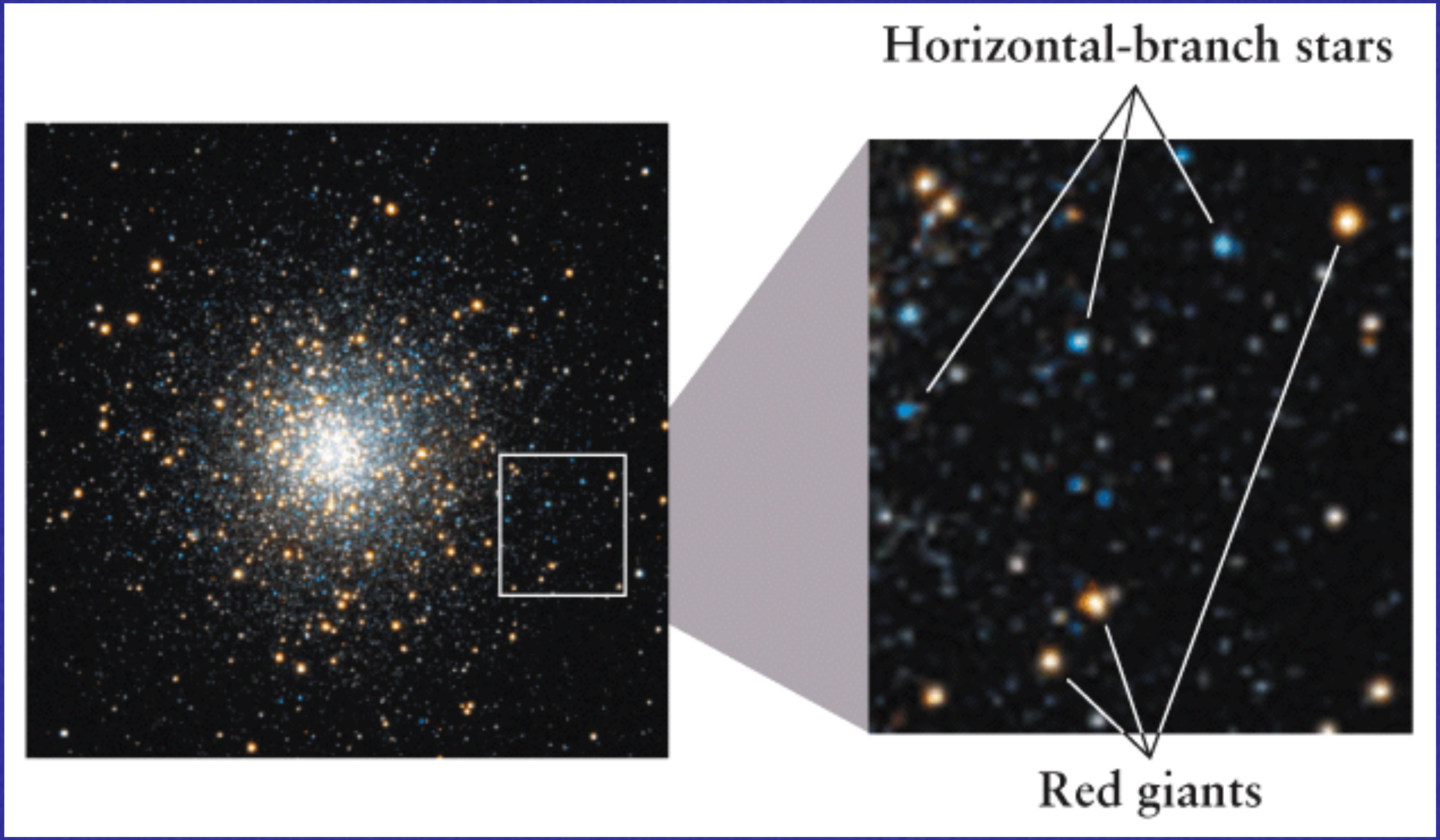


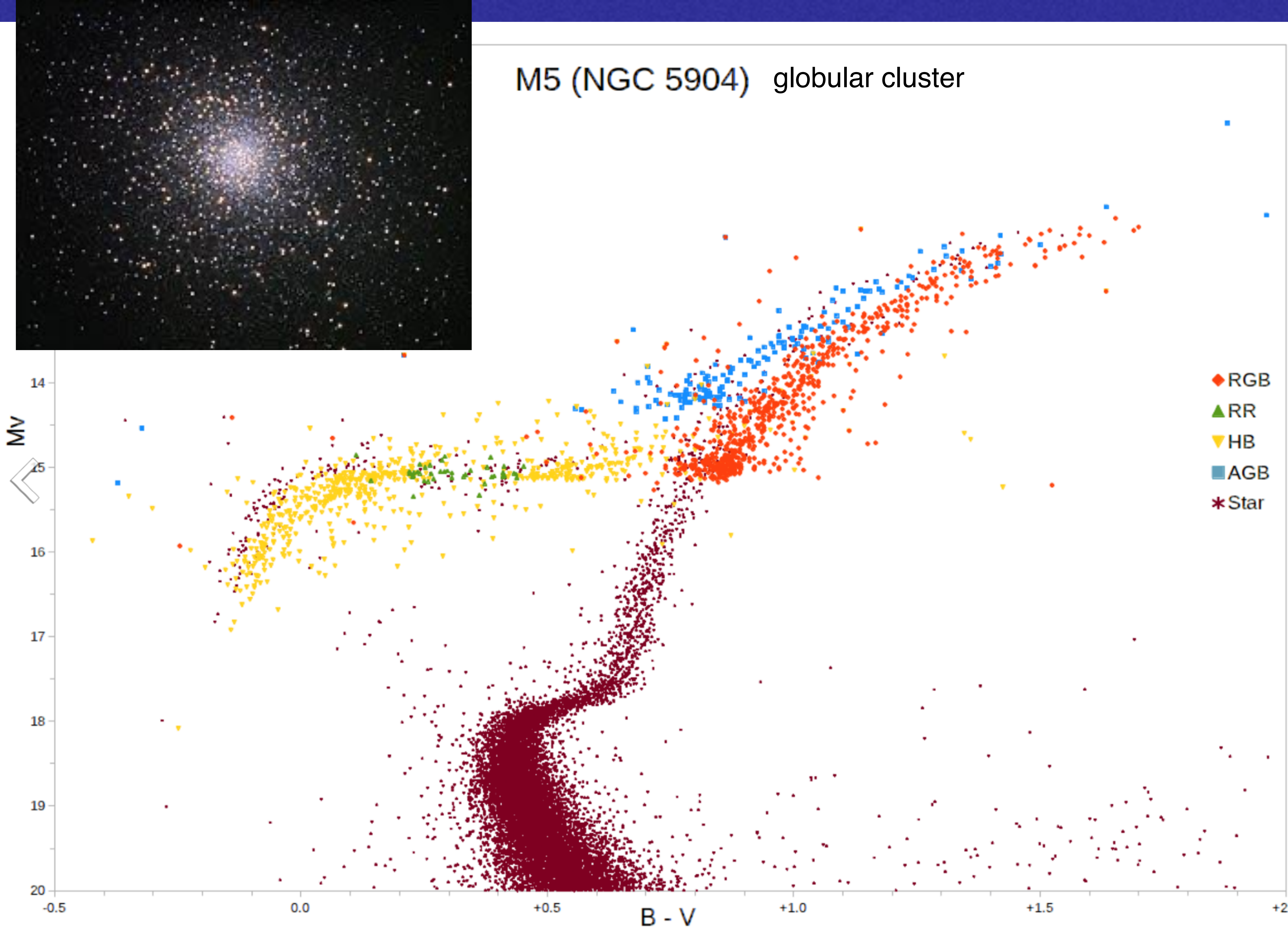
Open cluster



An H-R diagram of the stars in the Pleiades

M10 again: note that some stars are blue: these are not young stars, they are stars from an even later stage on the evolutionary sequence.




M5 (NGC 5904) globular cluster
Mv
14
15
16
17
18
19
20
-0.5
0.0
+0.5
+1.0
+1.5
+2.0
B - V
RGB
RR
HB
AGB
Star

Stellar populations

Two basic types of stars – a young class and an old class.

- *Population I* – young, in disk of galaxy, metal-rich, many in open clusters.
- *Population II* – old , avoid disk (in halo), metal-poor, many in globular clusters.

And a third yet to be observed.

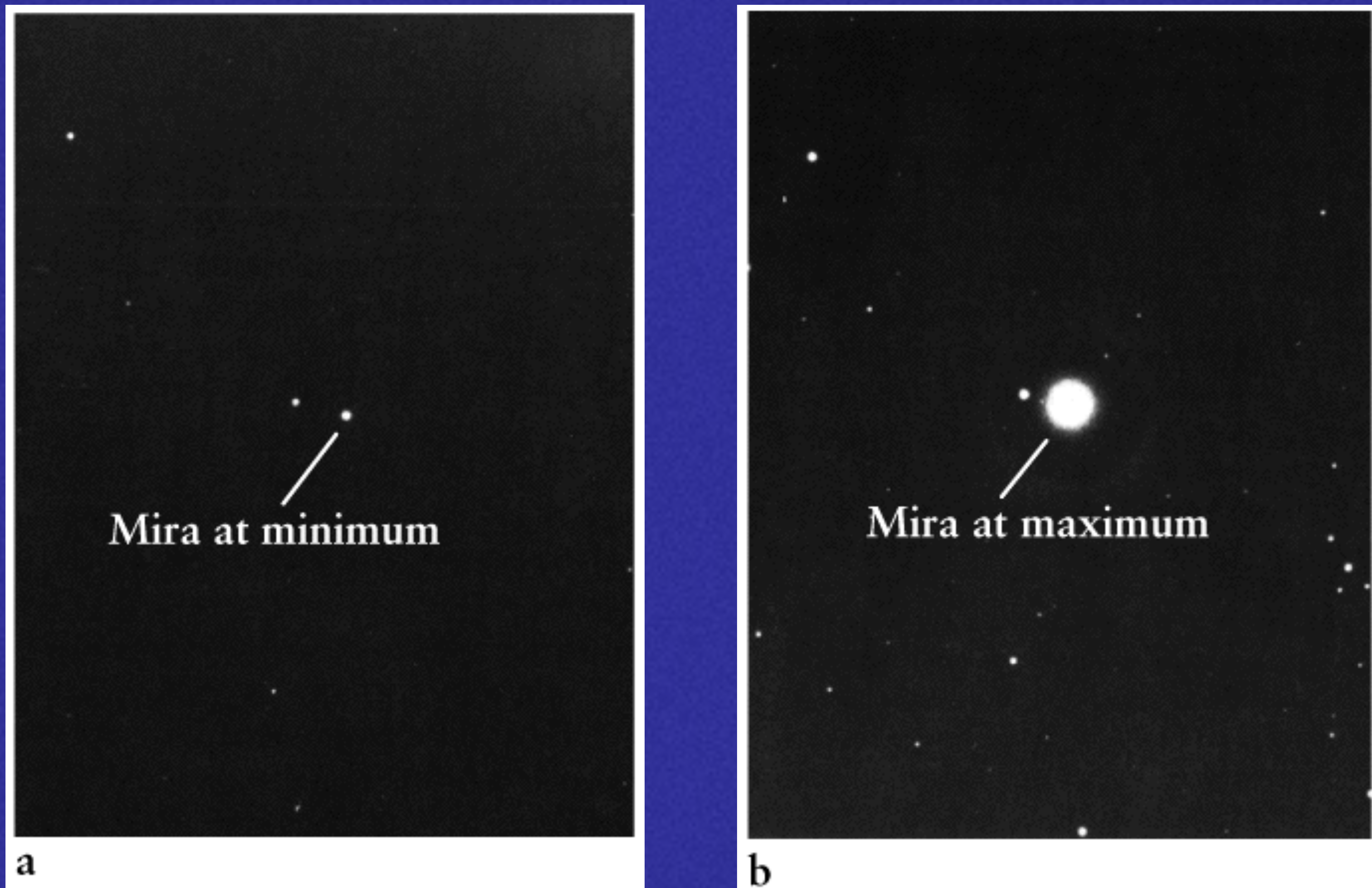
- *Population III* – oldest stars, composed entirely of primordial gas – hydrogen, helium and very small amounts of lithium and beryllium.

A has low metallicity,
B has high metallicity.

- Earlier stars formed out of “cleaner” gas (Pop II and III).
- Later generations formed out of gas which the first stars “polluted” with heavier elements they created (Pop I).

More on this when we discuss how the Milky Way galaxy formed…

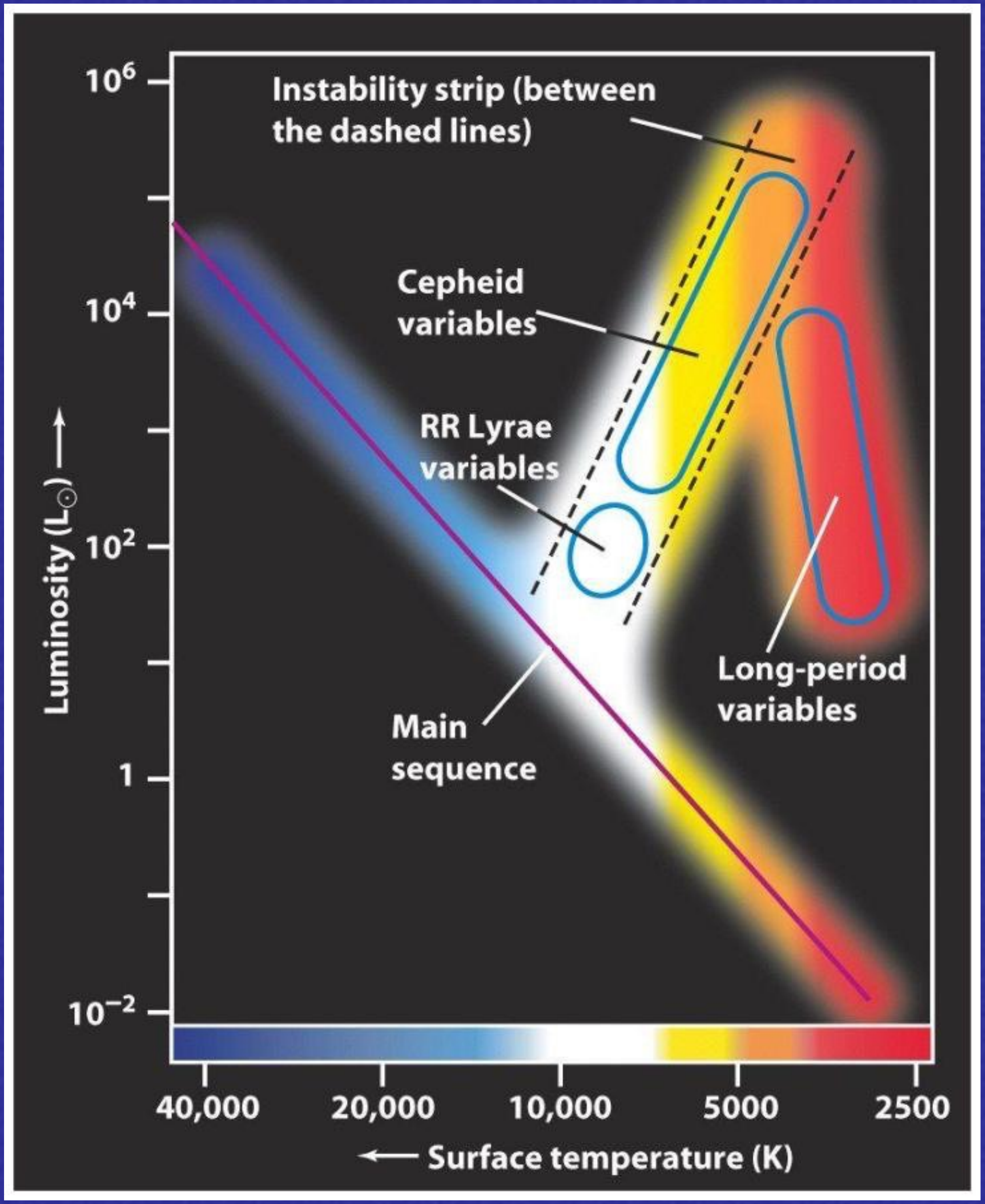
Variable stars



Some evolved stars vary in brightness. Mira variables are long period variables: red giants varying in brightness by a factor of ~100 over a timescale of months/years.

Intrinsic variability

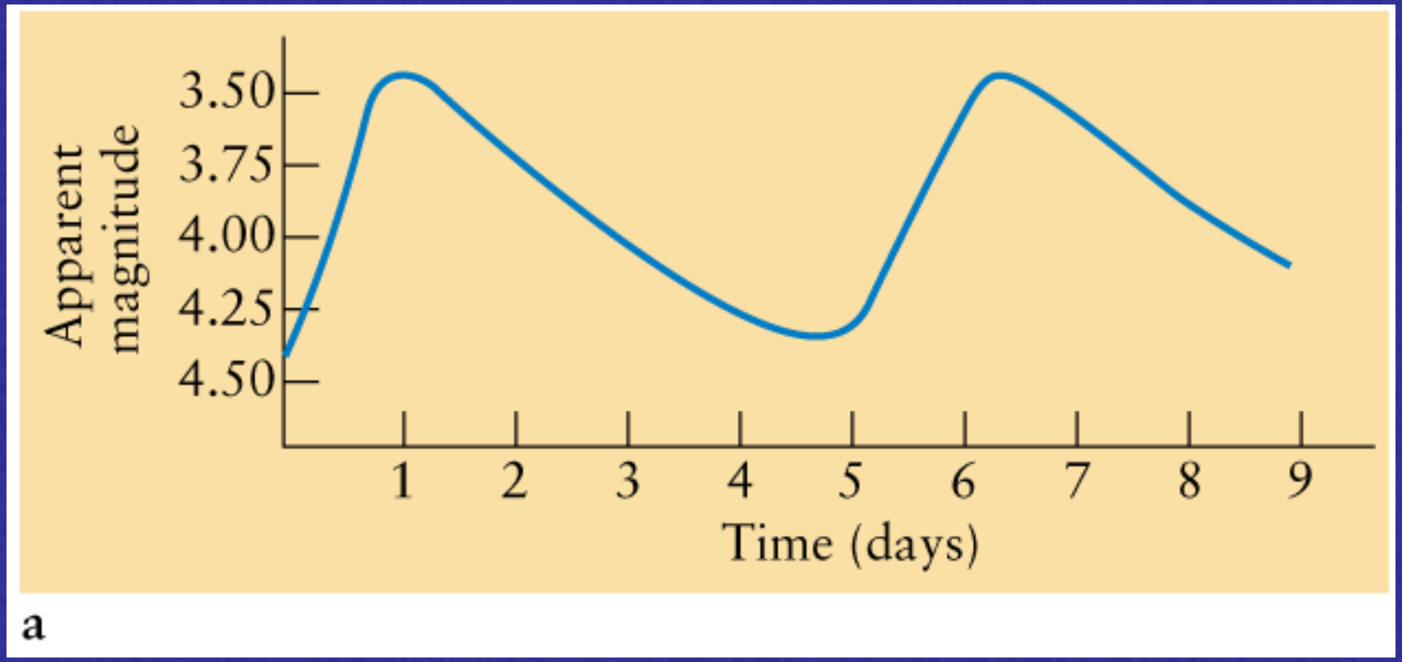
- Those that vary in brightness as a result of conditions within the star itself.
- Found in the *instability strip*. Any star within these portions of the H-R diagram will become unstable to pulsations.
- The different regions produce different kinds of observed phenomena.
- Stars may go through these stages several times during their lives.



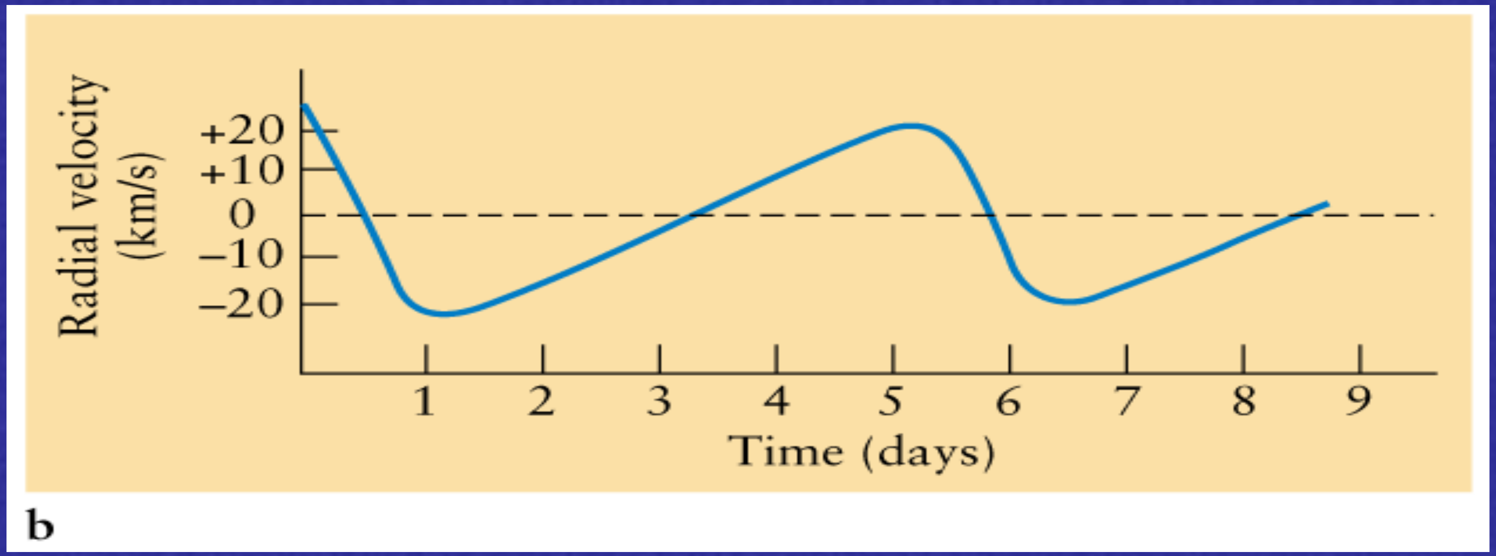
Cause of pulsations

- Stars are variable because they are unstable in one way or another: they lack hydrostatic equilibrium beneath surface.
- Miras are not well understood, but other, more periodically varying stars are better understood, like the Cepheids:
- The ionization zone of He lies at a distance from the center of the star, close to the surface.
- When He gas is ionized, it is opaque to radiation, thus effectively absorbing photons, trapping the heat.
- Radiation will push the surface layer outward, and cooling will begin.
- As the gas cools, it will recombine. Neutral He is transparent, ceasing the outward push and layers fall back as a result of gravity.
- Heating of those layers causes the process to repeat.

How to study variable stars

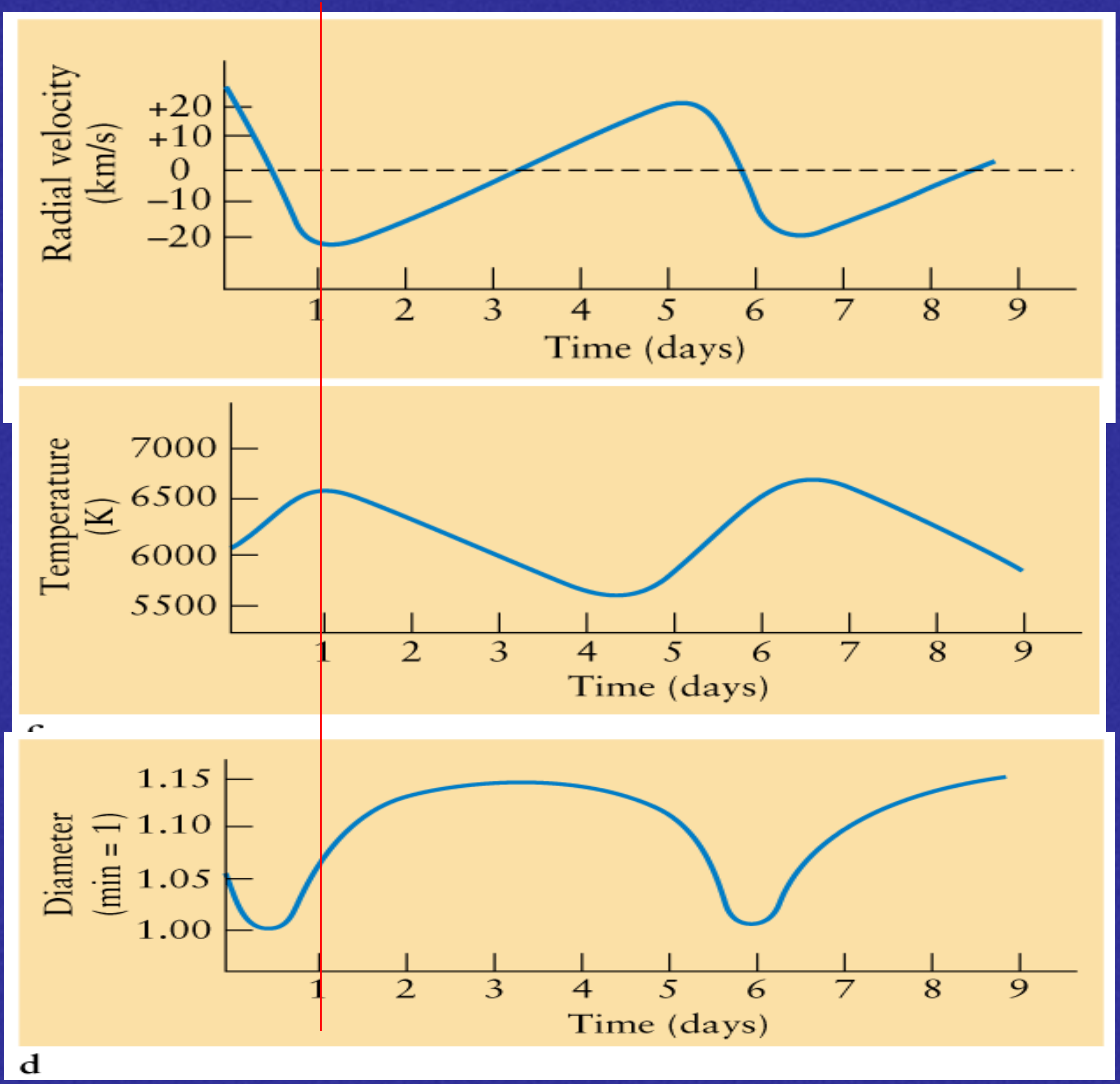


We use lightcurves, which show the brightness versus time for the star.



We can also look at the periodic change of other properties, such as the radial velocity, surface temperature, and size.

Max brightness



At max brightness, the star expands most rapidly. As it cools, the outer layers will start falling back onto the stars.

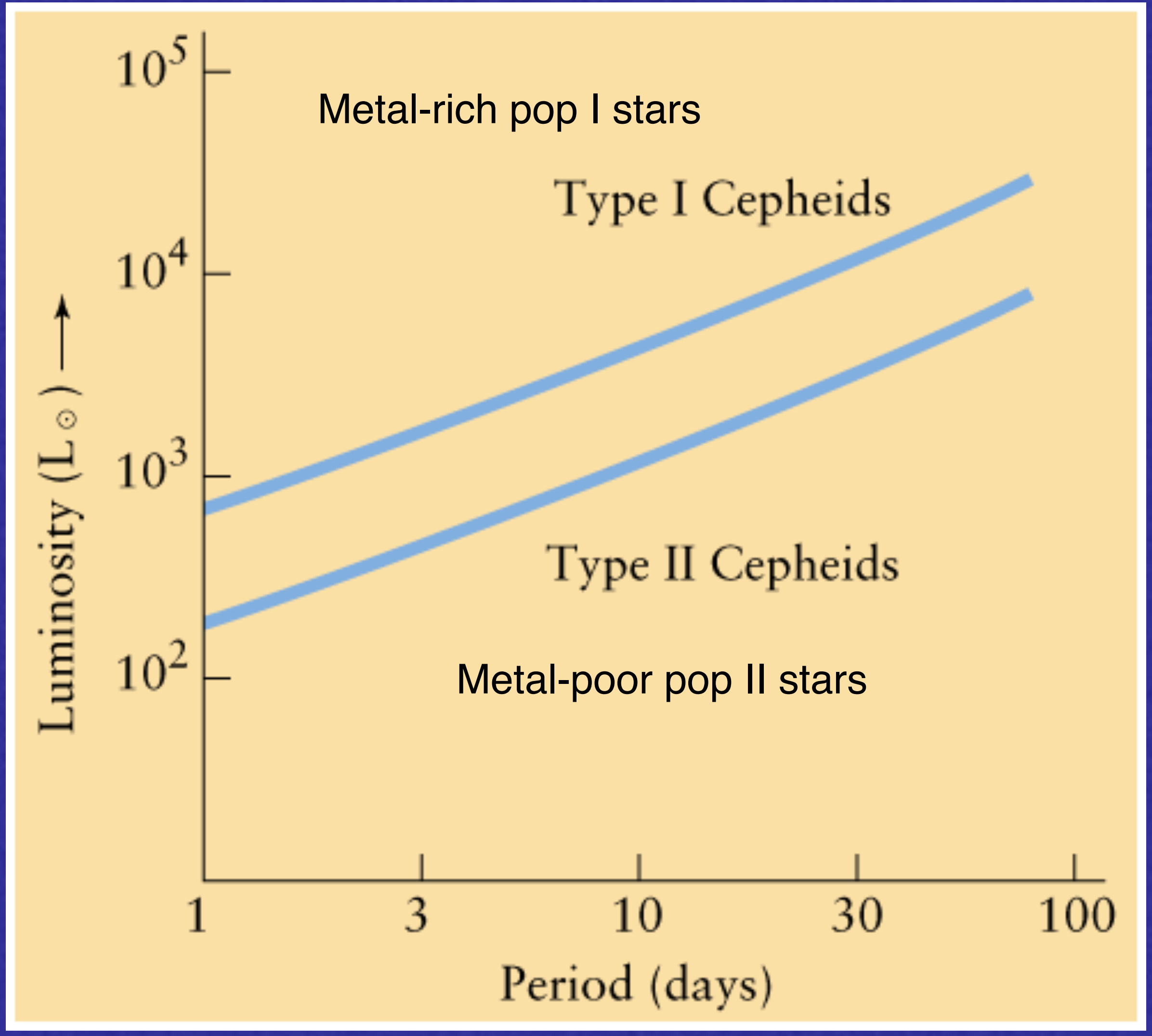
The surface temperature will vary with the brightness.

The star reaches its minimum size *before* maximum brightness, since it will take a little time to transport the radiation to the surface. A *time lag*.

Distance indicators

- Variable stars like Cepheids, and RR Lyrae stars can be used as distance indicators. How?
- The exhibit a relation between their period and their luminosity.

  => if we can measure the period of the star, then we know its luminosity (or absolute magnitude).

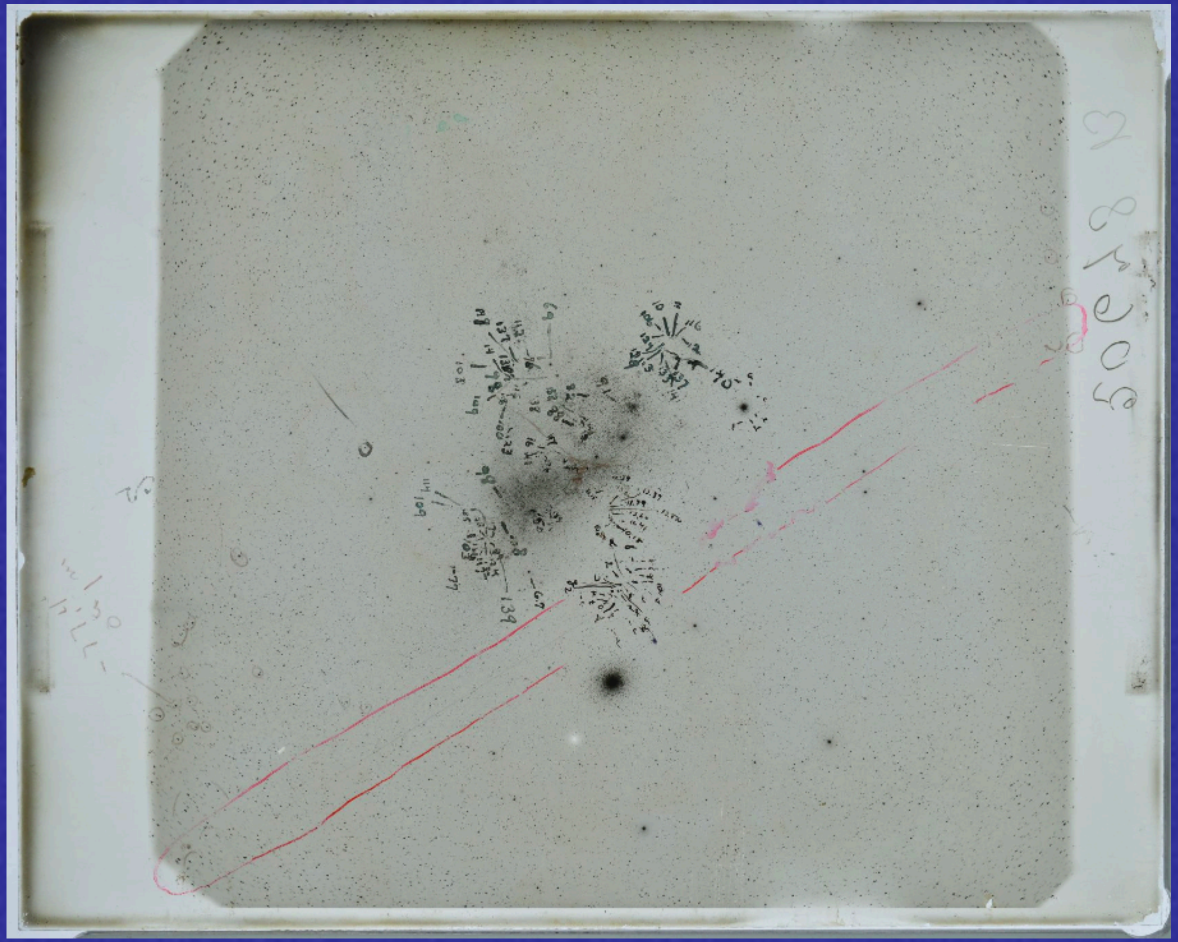


The period-luminosity (P/L) relationship for Cepheids

Type I and II Cepheids behave differently because they have different abundances of heavy elements in their atmospheres, affecting the opacity.

Cepheid PL relation: Henrietta Swan Leavitt

Worked as a “computer” at Harvard



- The P/L relationship **in visible** for RR Lyrae stars is trivial: all have M=+0.5.
- For Cepheids, the relation is fitted by:

$$M_{<V>} = -2.81 \log_{10} P_d - 1.43$$

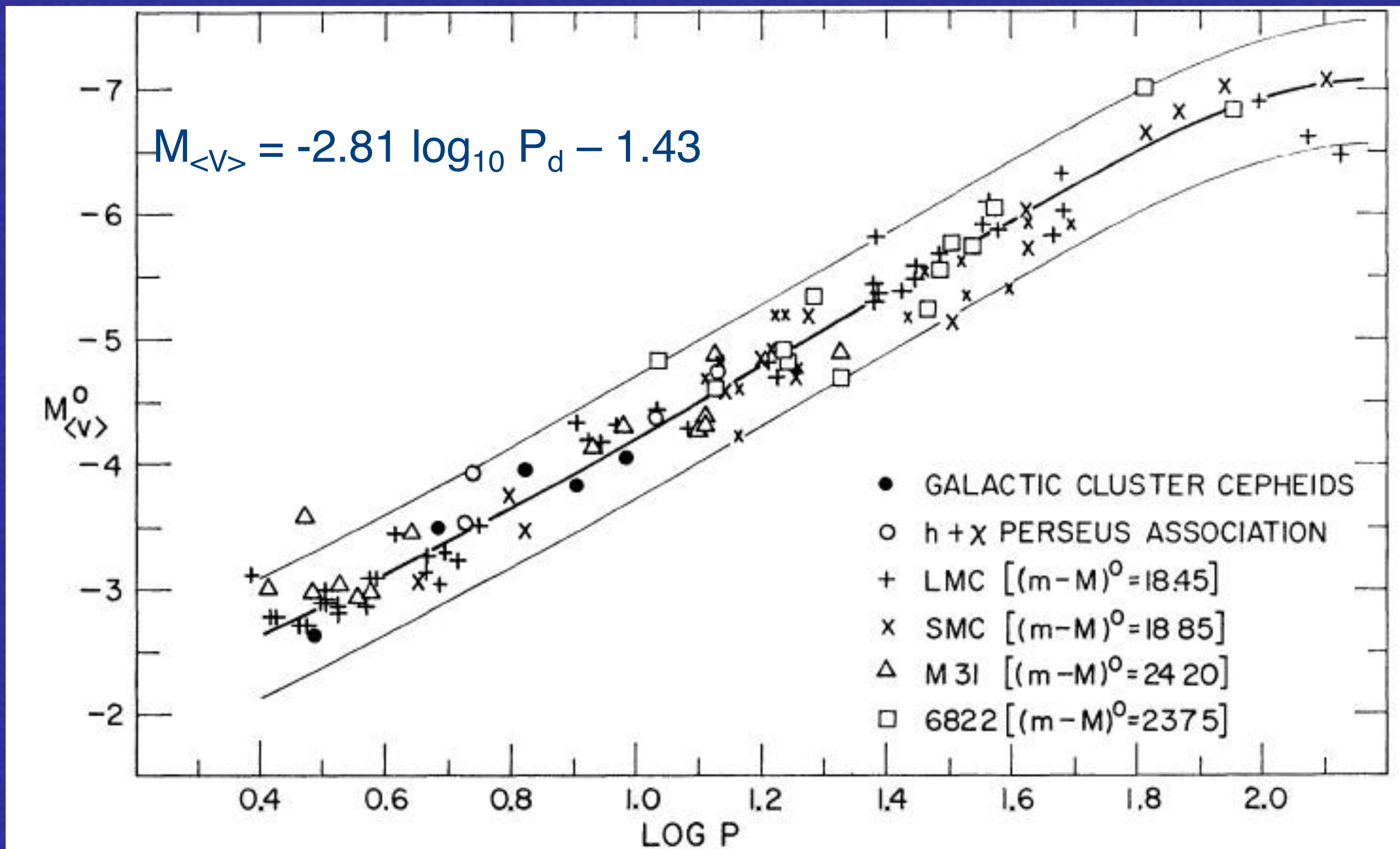
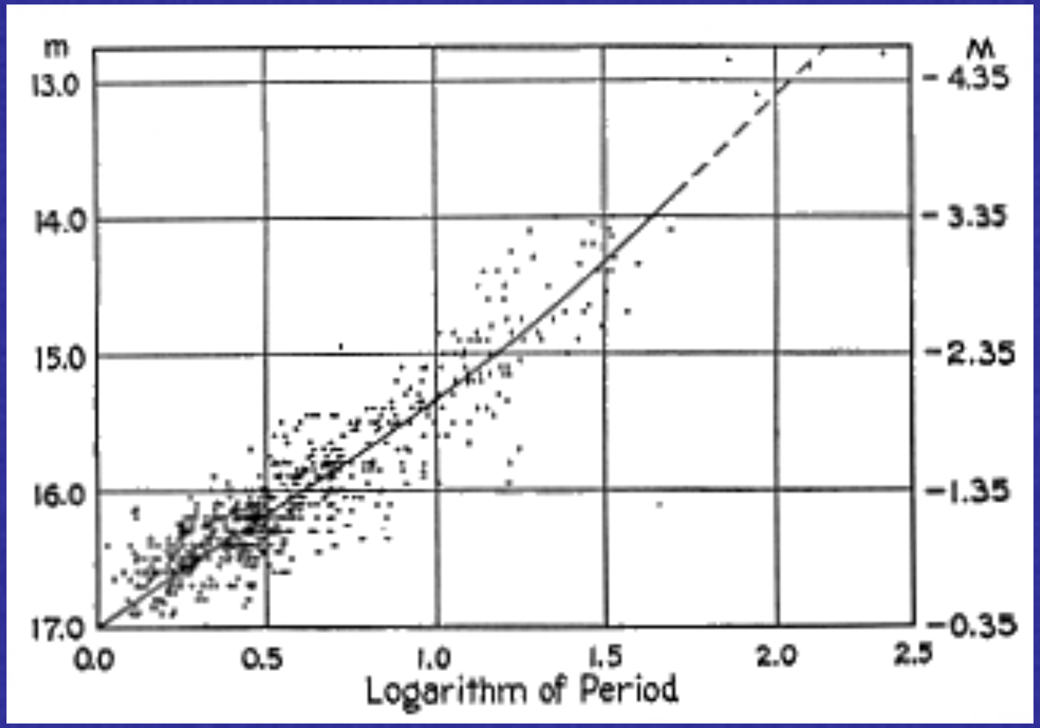


FIG. 1.—The composite period-luminosity relation at mean intensity in *B* and *V* wavelengths derived from the sources indicated at the lower right. The absolute calibration was made by using the nine Cepheids of the galactic system shown as open and filled circles. The photographic data from the SMC are plotted with smaller crosses than the Gascoigne and Kron photoelectric data.

- Knowing *L* or *M*, we can calculate the distance. Apparent magnitude (*m*) is always easy.

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

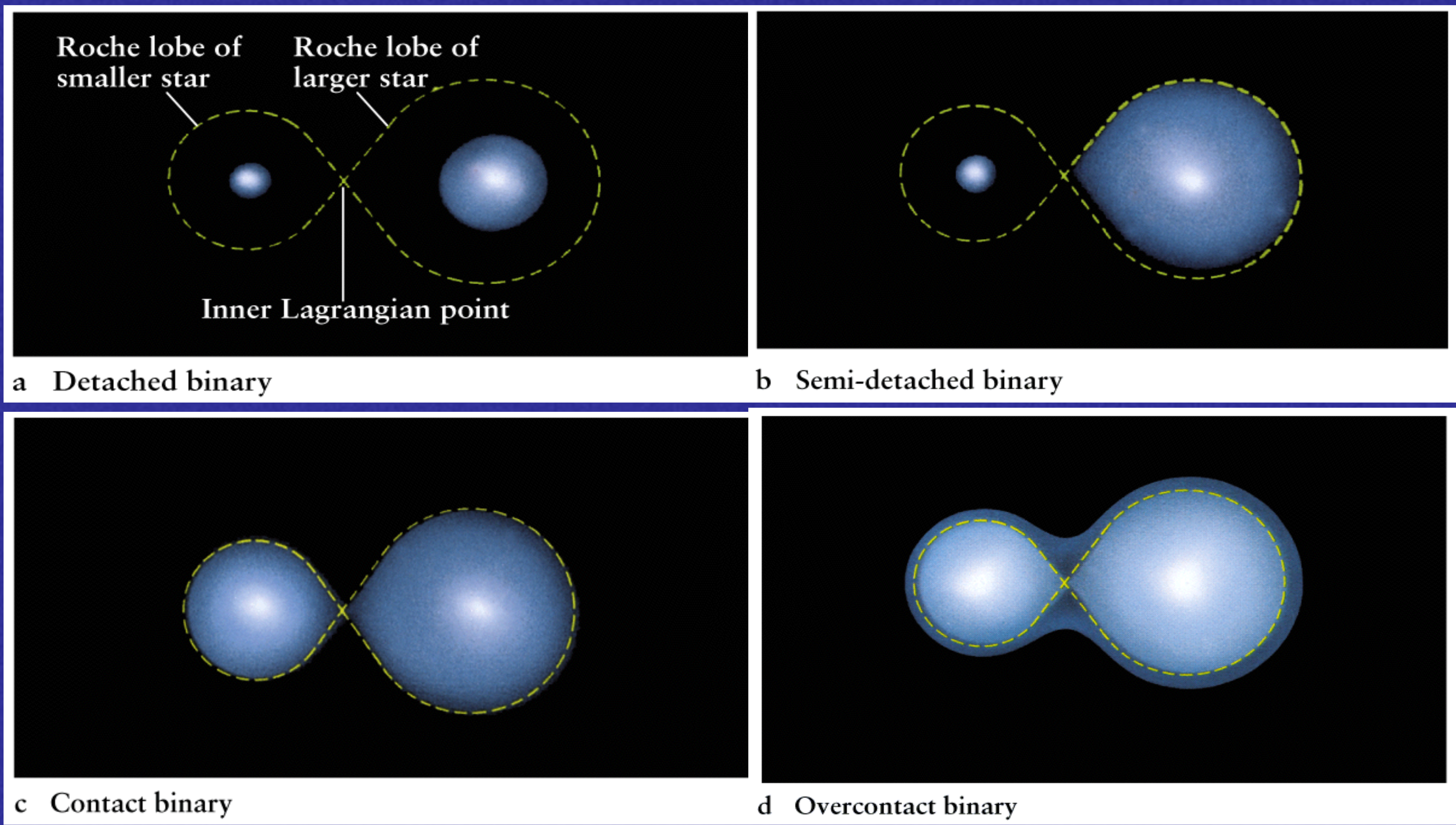
- Important relation: Cepheids and RR Lyrae stars are giant and thus very luminous. We can see them as individual stars in other galaxies.



Cepheids in the Small Magellanic Cloud

Mass transfer can affect stellar evolution

- Close binary systems - some binary systems are so close they are in contact.



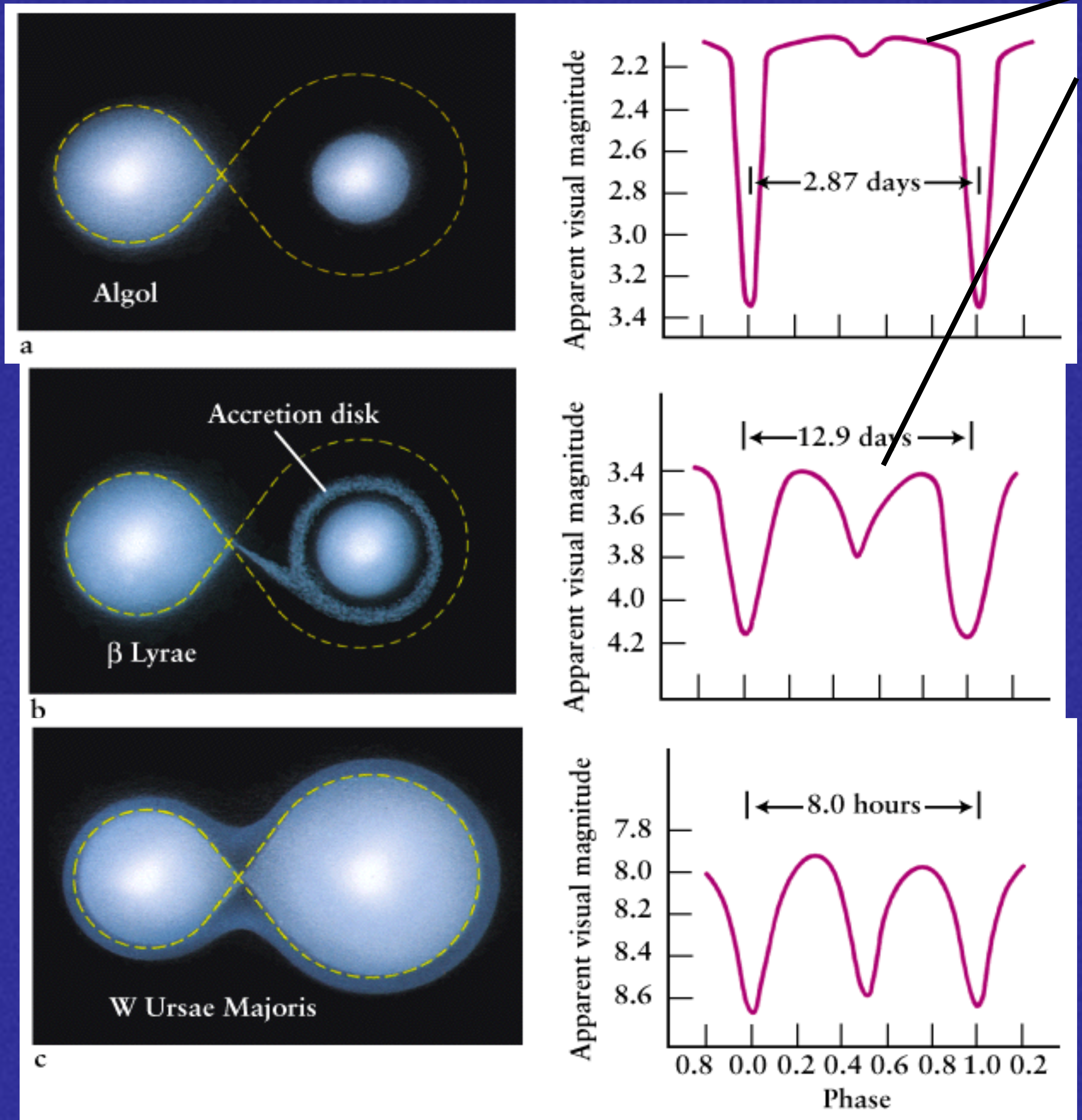
a Detached binary

b Semi-detached binary

c Contact binary

d Overcontact binary

Gas may flow from one star to another in close systems. This can alter the standard evolutionary pattern.



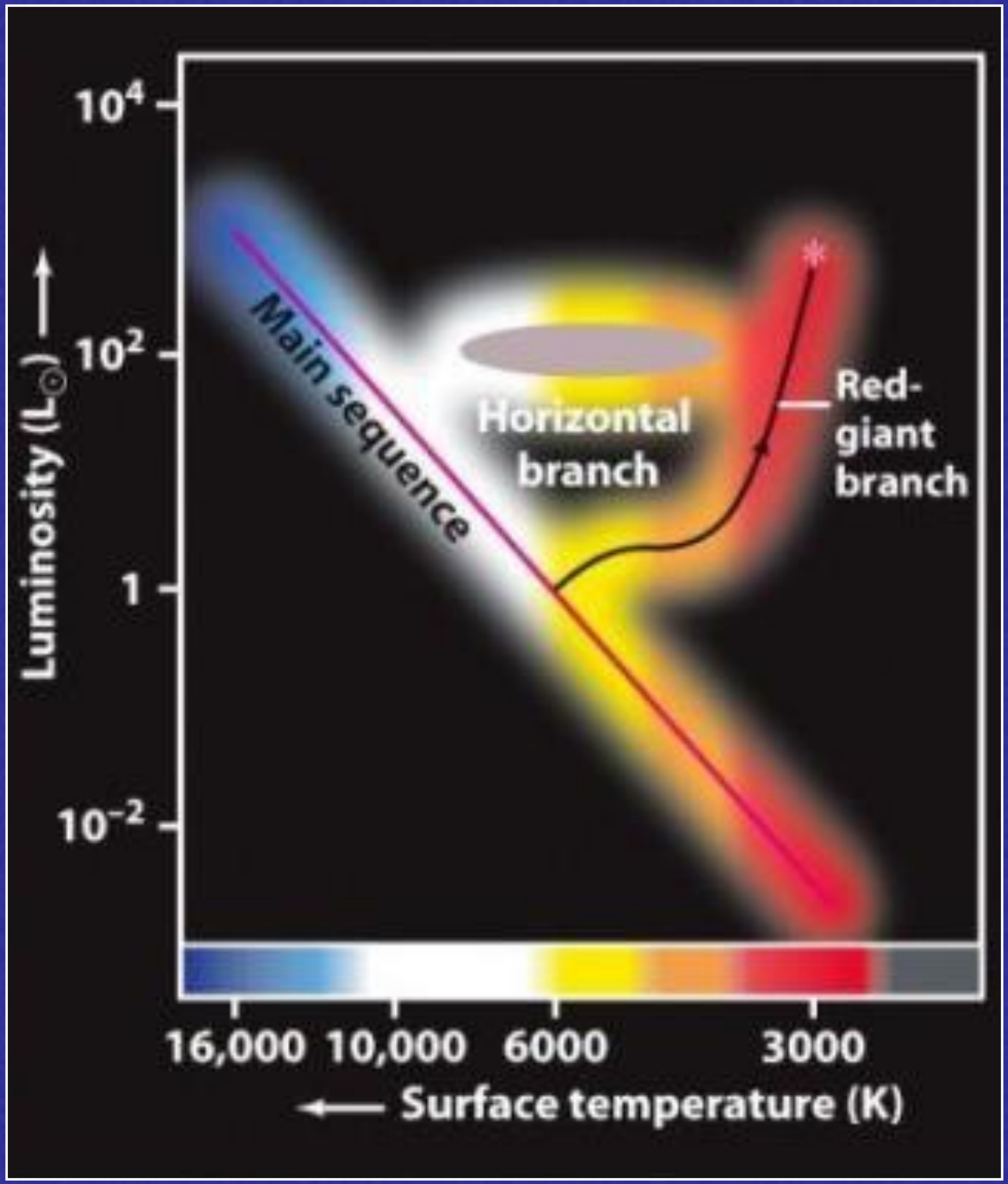
Small star eclipses large one

Death of a Low Mass Star

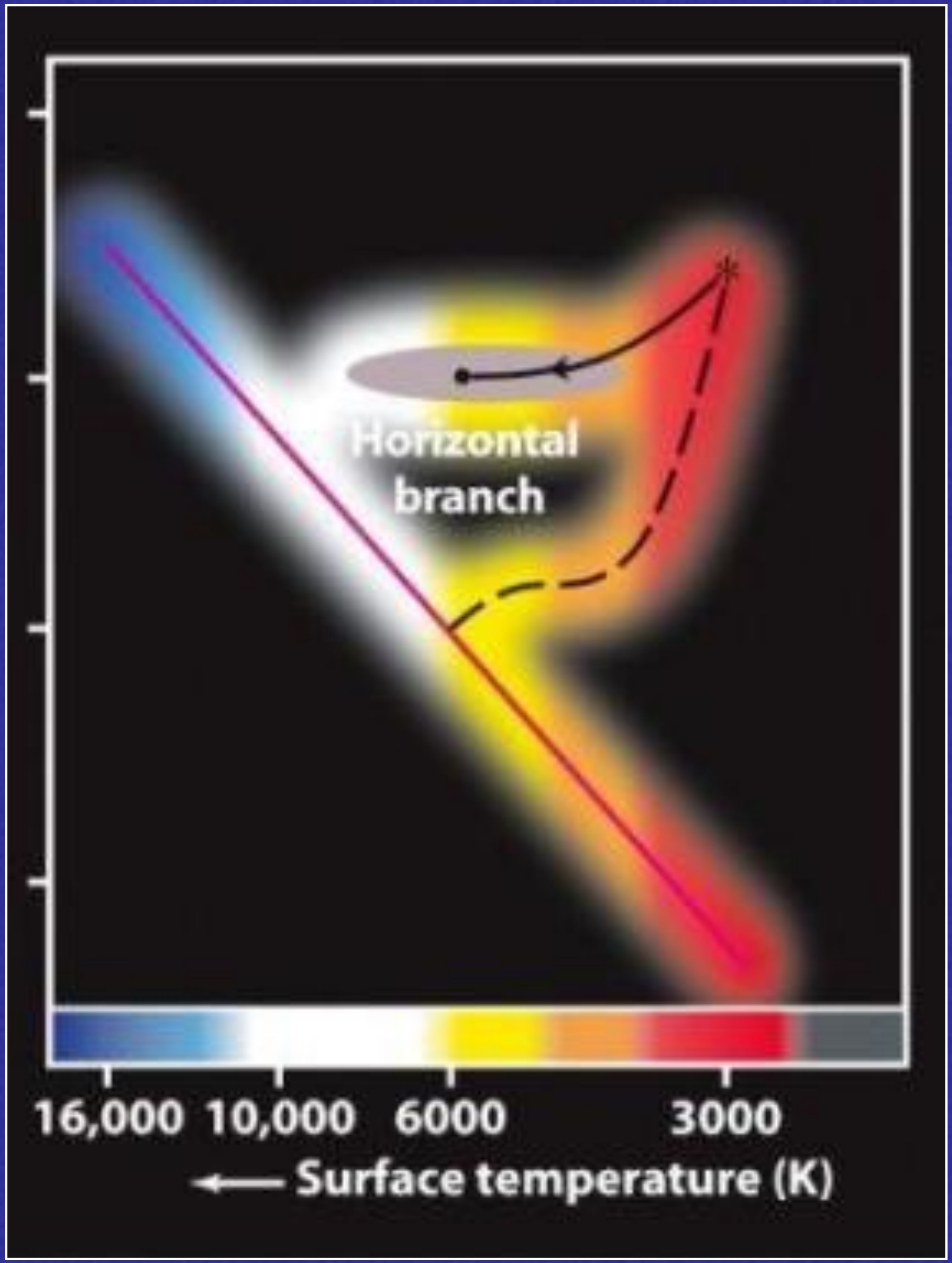
Low mass stars

- How stars live and die depends entirely on their masses
- when low-mass stars (< $4M_{\odot}$) evolve off the main sequence
- These stars have two, distinct red giant phases

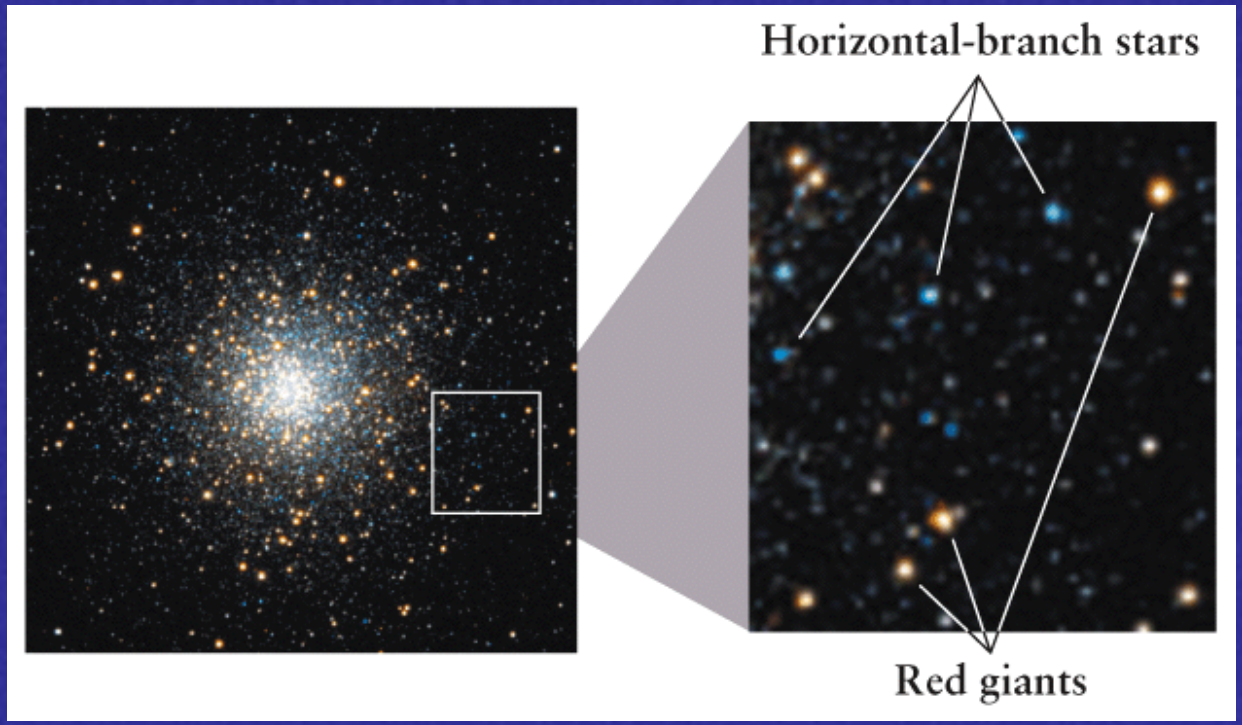
On the red giant branch



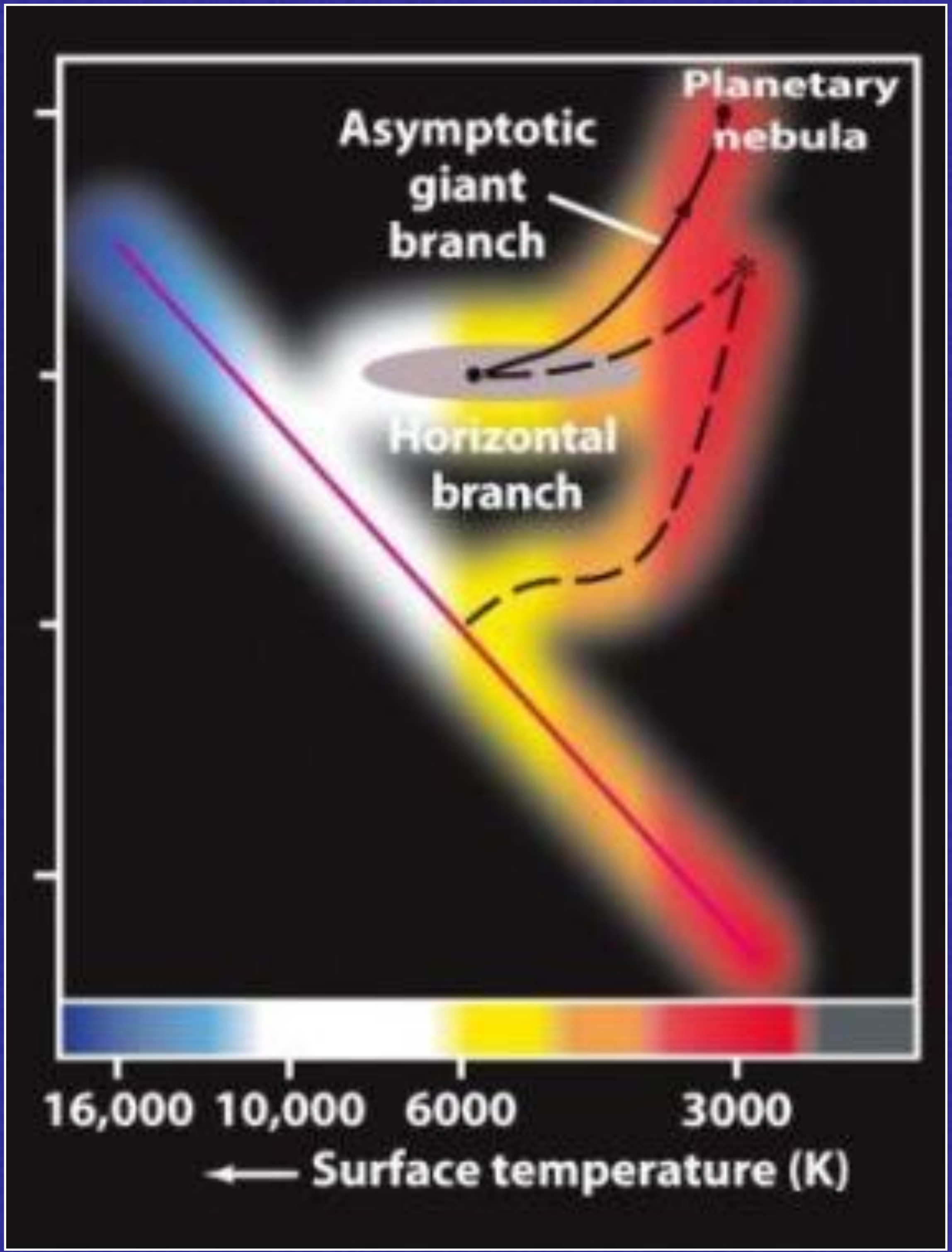
- Shell H burning continues after core H burning stops (core now filled with He).
- Outer layers expand and cool.
- As core contracts and heats, He burning starts with a flash (triple alpha process).
- The triple alpha process less efficient, can only last for about 10^8 yr.



- Core expands and cools when core He burning starts.
- H burning slower => lower luminosity. This means downwards in the H-R diagram.
- With less internal pressure, the outer layers shrink and heat up => to the left in the H-R diagram.
- Now the star is on the *horizontal branch.*

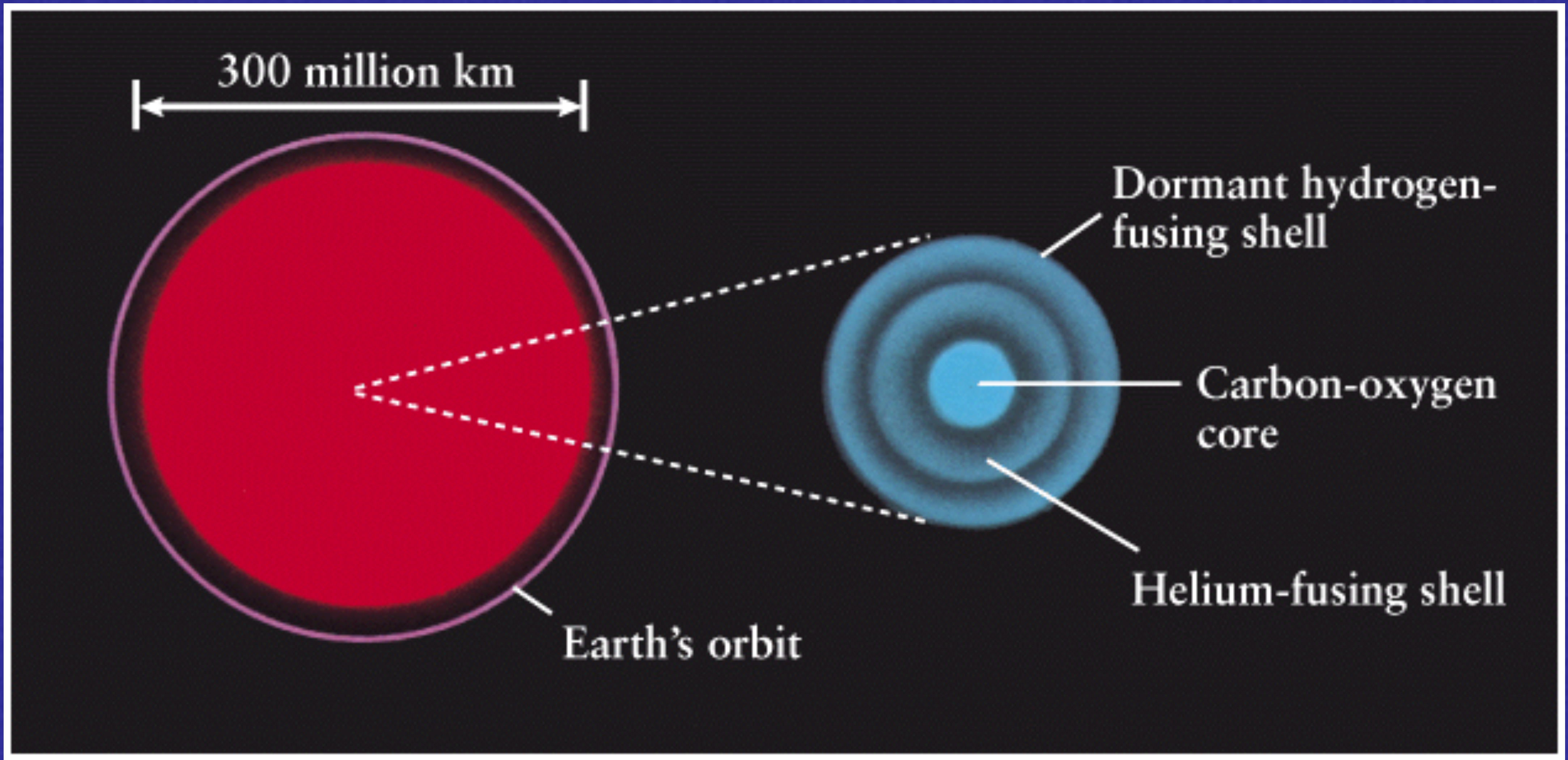


On the asymptotic giant branch



- After some time, the core will fill with C and O.
- Core He burning stops, core contracts => shell He burning
- Produces a lot of energy => outer layers expand and cool. Red giant again!
- This is an AGB (*asymptotic giant branch)* star.

An old, low-mass AGB star - the action is within a volume about the size of the Earth.

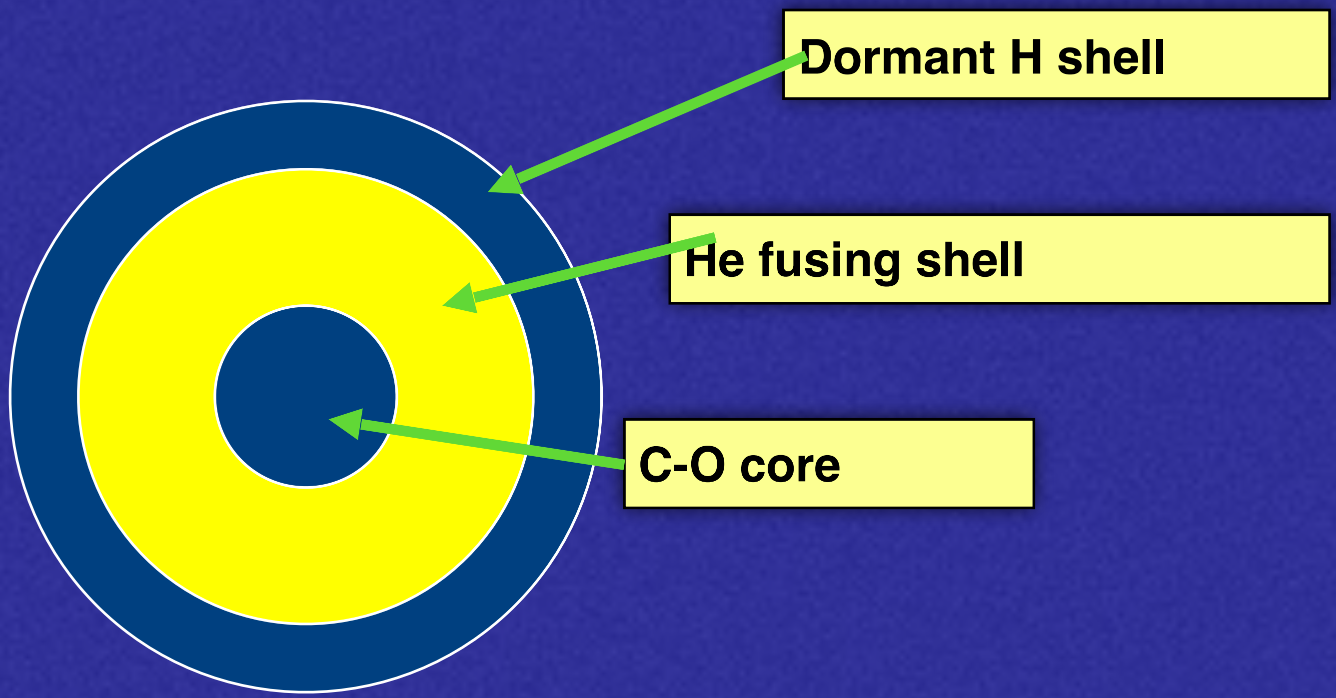


Mass loss

- Sun loses 4×10^9 kg/s (4 million tons/s) on MS
- Up to AGB, stars lose mass very slowly (e.g. via the solar wind).
- After AGB, mass loss is more extreme and stars are shedding their outer layers. Could reach 10^{-4} M_sun/year
- Produces *Planetary Nebulae* (PN), and PN central stars that cool to become *White Dwarfs*.

What is going on? Instabilities!

- He burning very temperature sensitive, triple-alpha fusion rate $\sim T^{40}$
- Small changes in T => large changes in fusion output
- Star experiences thermal pulses, destabilizing the outer envelope

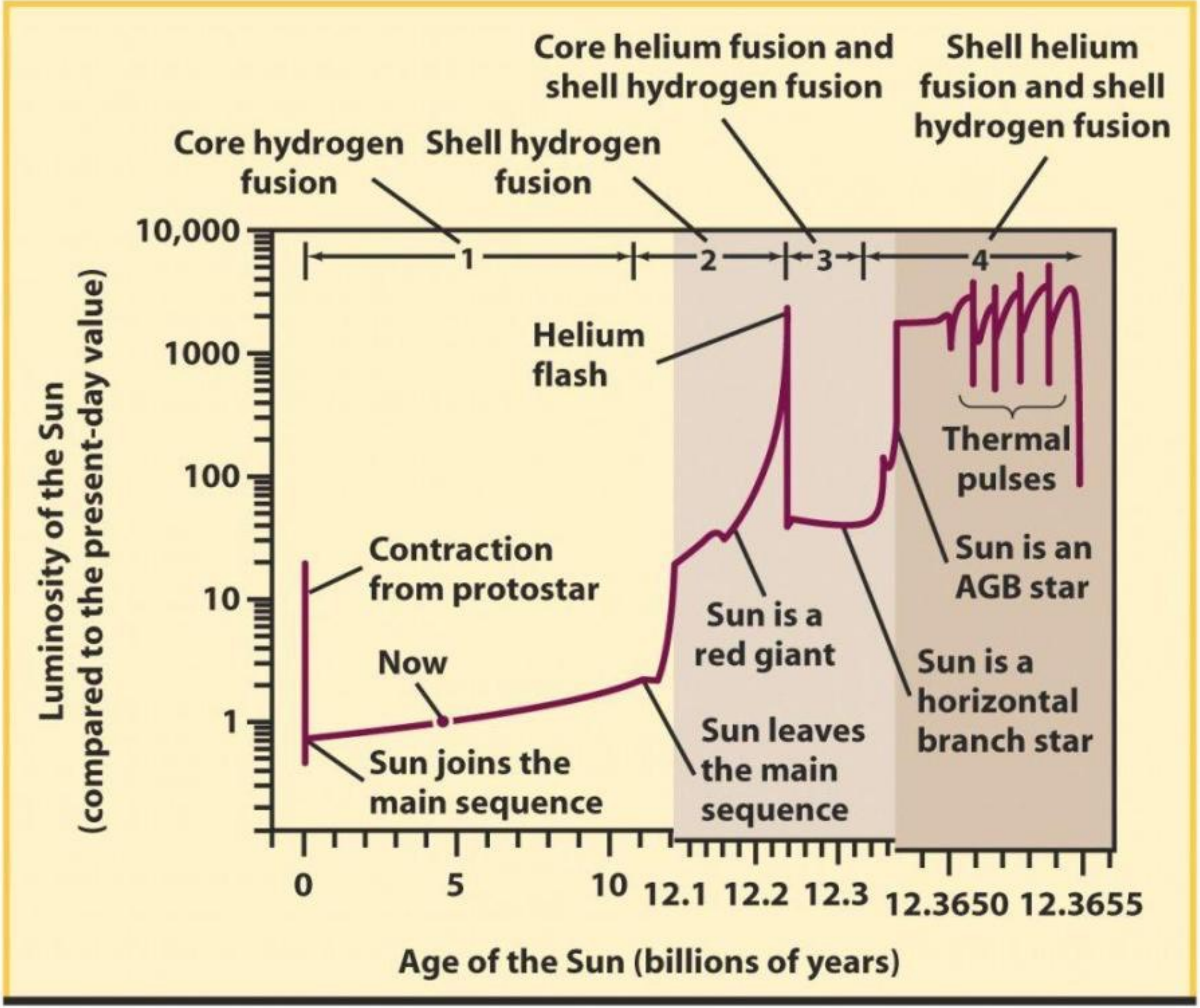


When He burning shell is depleted, the triple-alpha process stops and He shell starts contracting.

H shell also contracts, heats up => H fusion starts again

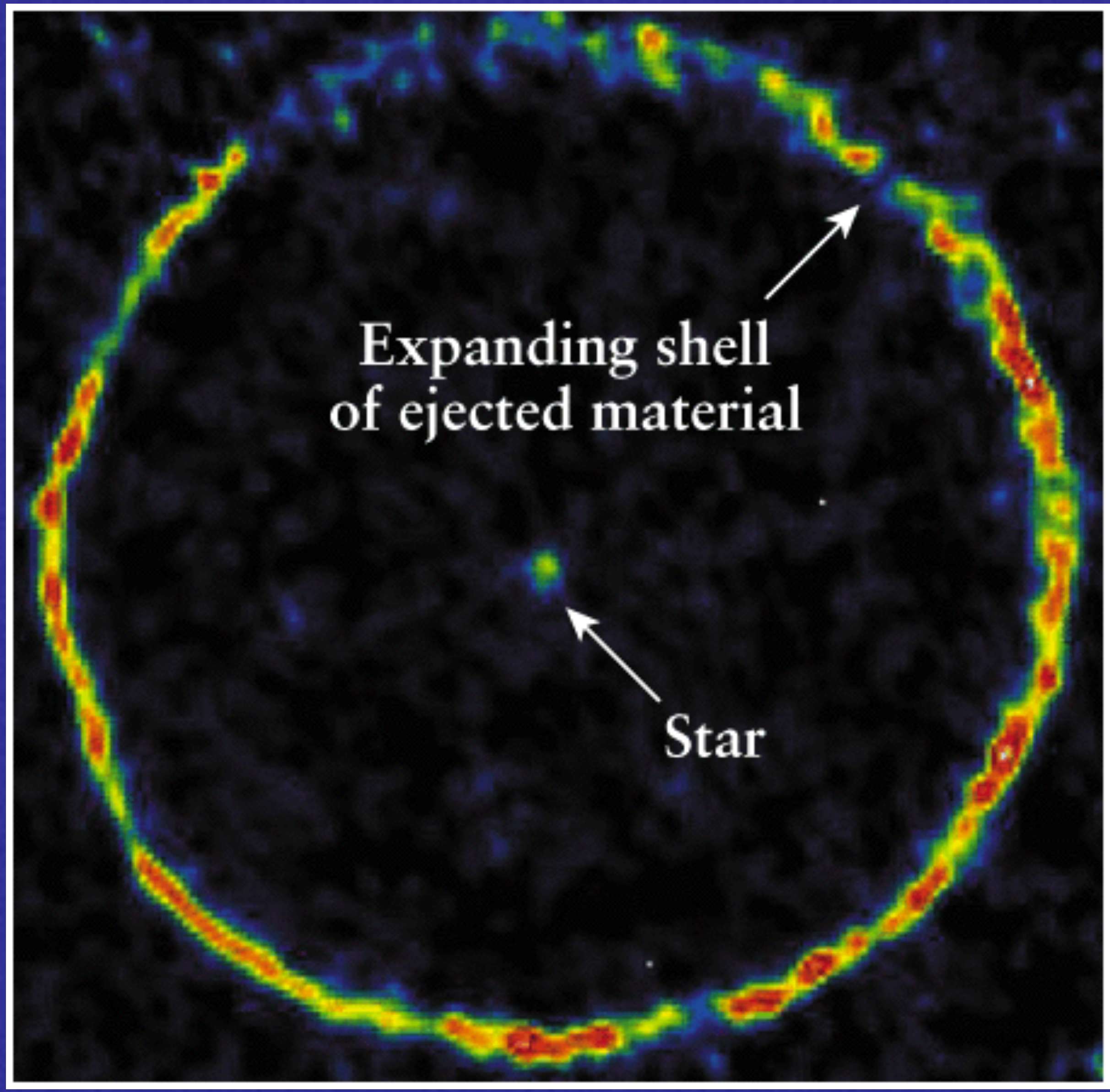
The p-p produced He replenishes the He shell, which will cause another He flash => pushes material outwards

Cools off H shell, which then becomes dormant again => cycle repeat


Core helium fusion and shell hydrogen fusion
Shell helium fusion and shell hydrogen fusion
Core hydrogen fusion
Shell hydrogen fusion
10,000
1000
100
10
1
1
2
3
4
Helium flash
Thermal pulses
Contraction from protostar
Sun is a red giant
Sun is an AGB star
Now
Sun is a horizontal branch star
Sun leaves the main sequence
Sun joins the main sequence
Luminosity of the Sun (compared to the present-day value)
0
5
10
12.1
12.2
12.3
12.3650
12.3655
Age of the Sun (billions of years)

Dredge-up

- Convection zone may extend down to core: convection brings enriched core material to surface.
- Produces objects like *carbon stars*.
- These stars are important sources for replenishing the ISM.



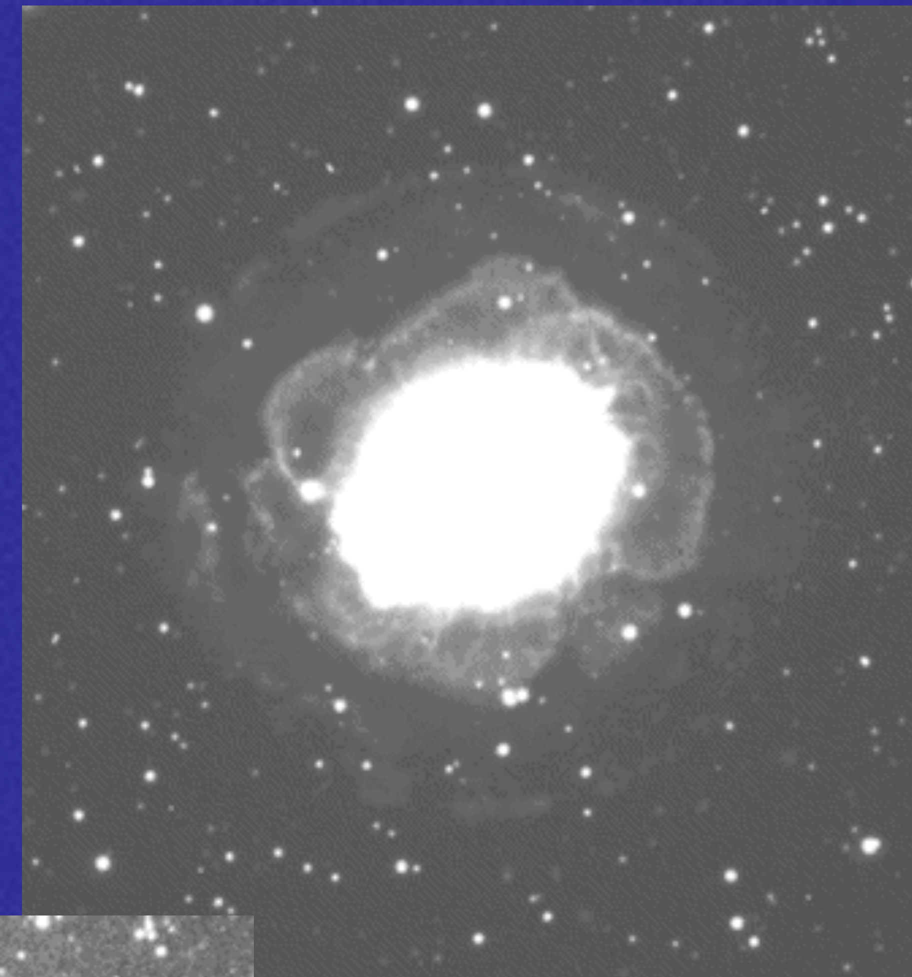
Molecular CO emission from shell surrounding the carbon star TT Cygni.

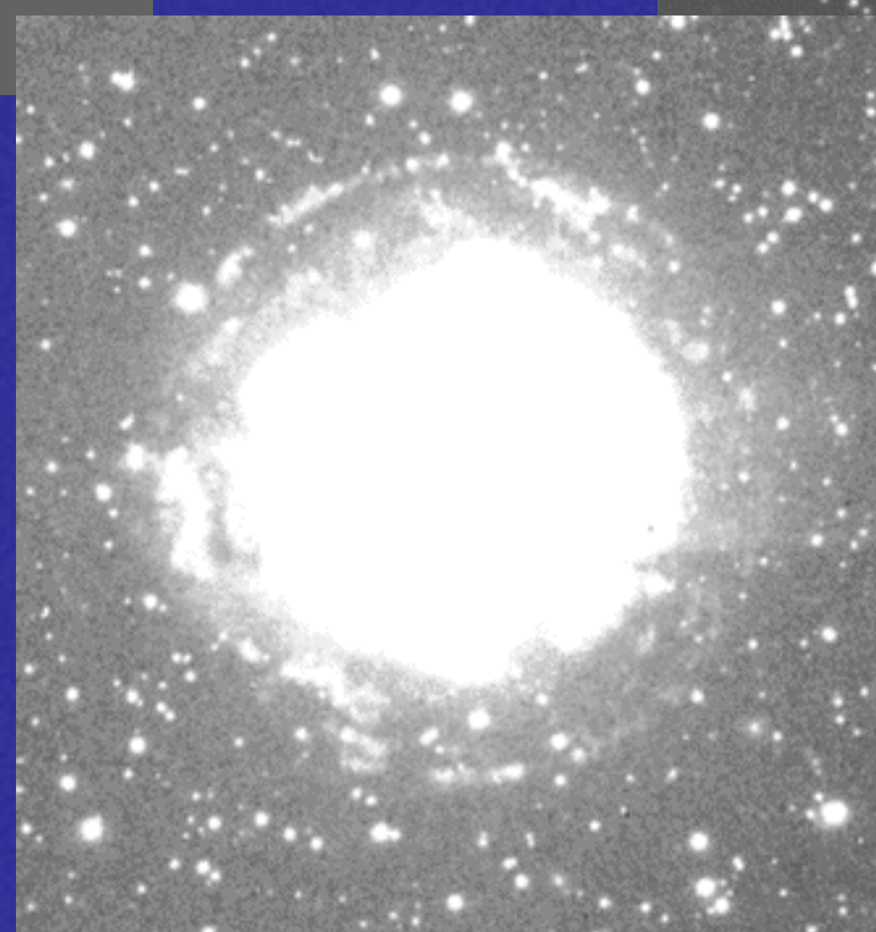
Core-envelope separation

- Rapid process (~10^5 yr), outer envelope gets ejected
- C-O core still contracts, but less weight of envelope results in a core that never gets hot enough for C to ignite (600M K)
- Core and envelope separate physically, expanding envelope forms a nebula around the C-O core (*planetary nebula*)

M57, the Ring Nebula. Located in Lyra.

The ring is really a shell - illustration of how one sees more and more with increased exposure times.





- **Why do planetary nebulae shine so brightly?**

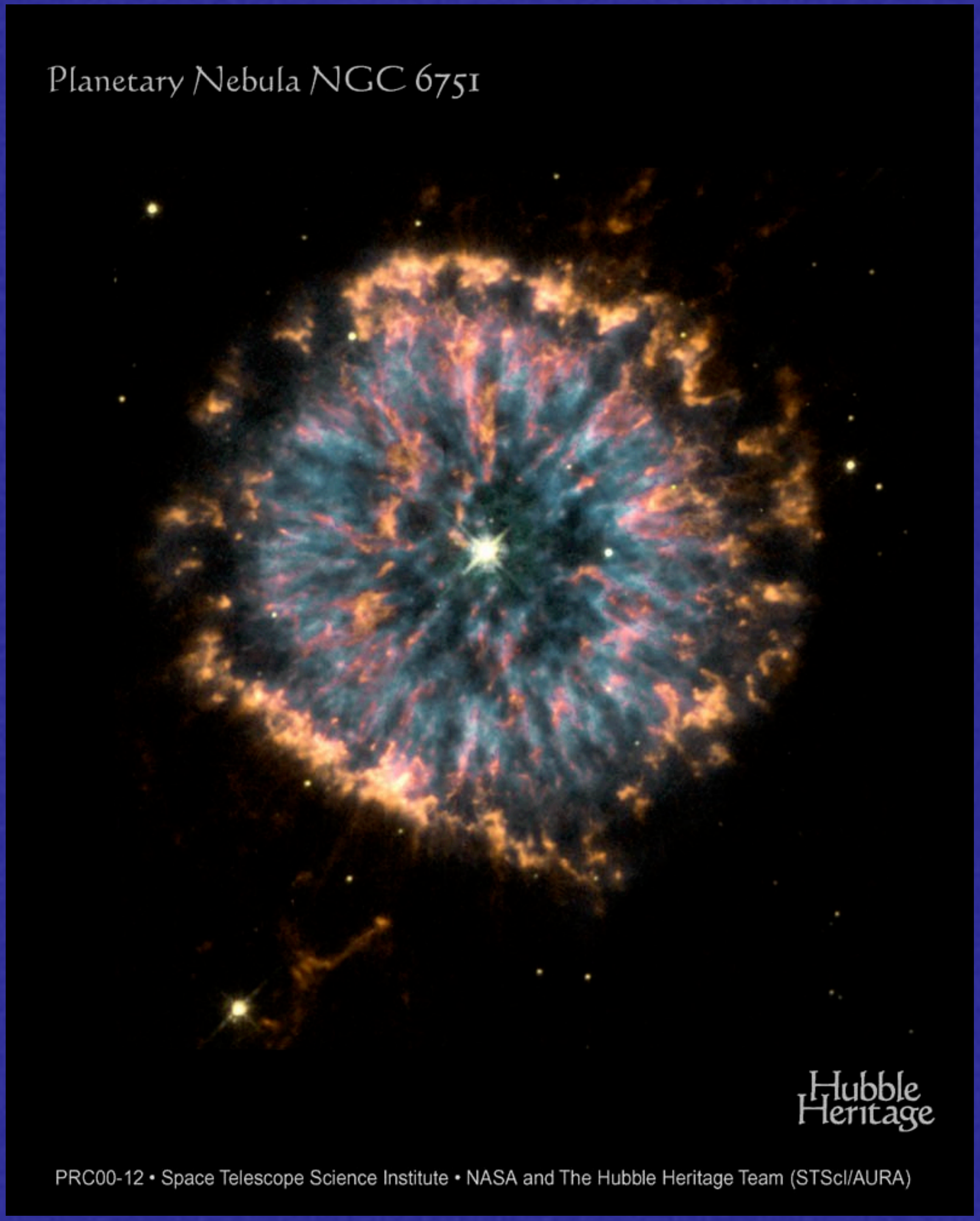
- Dying star ejects outer layers and exposes the hot core.

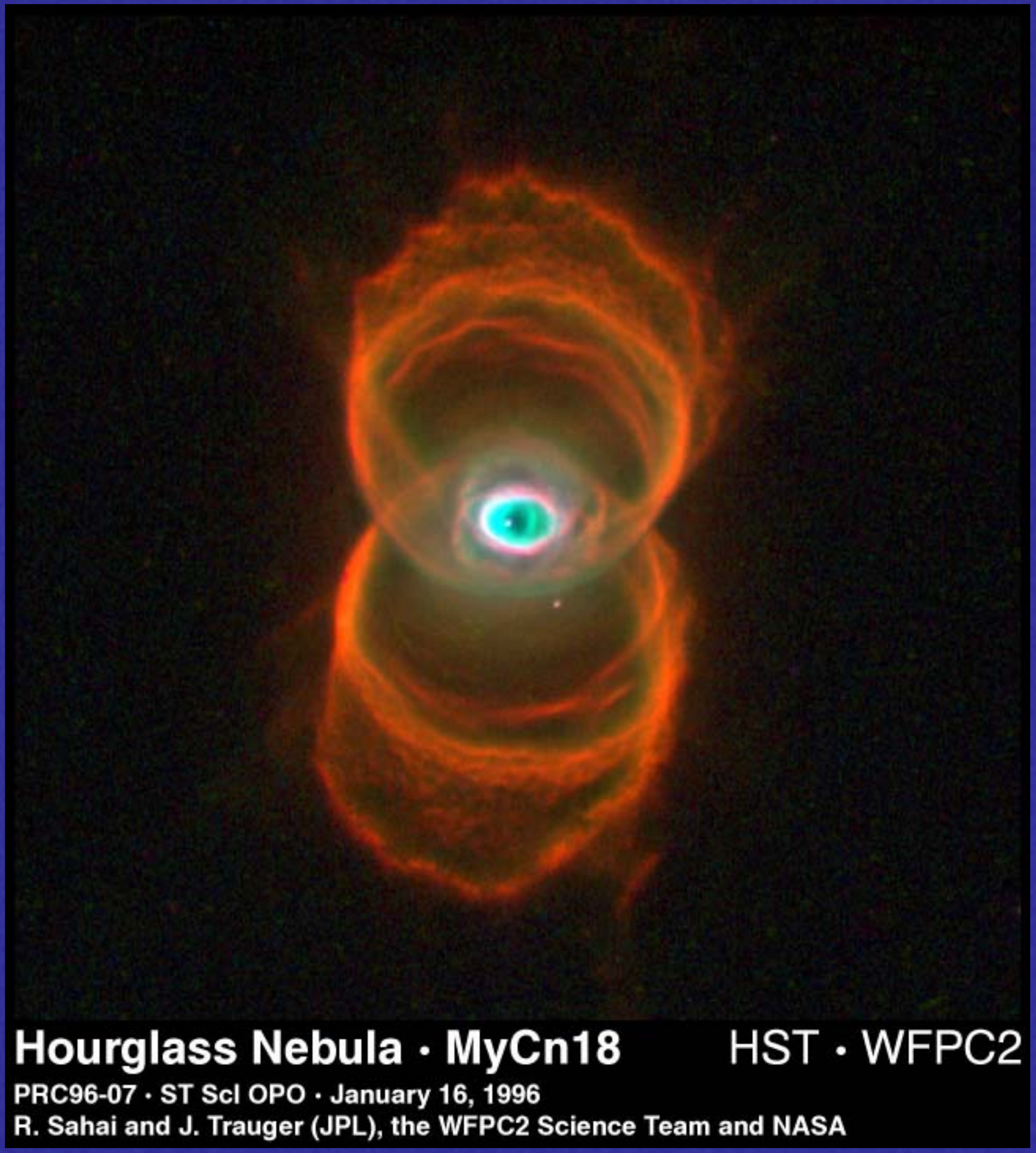
- The hot core emits UV radiation => excites and ionizes the surrounding low density gas

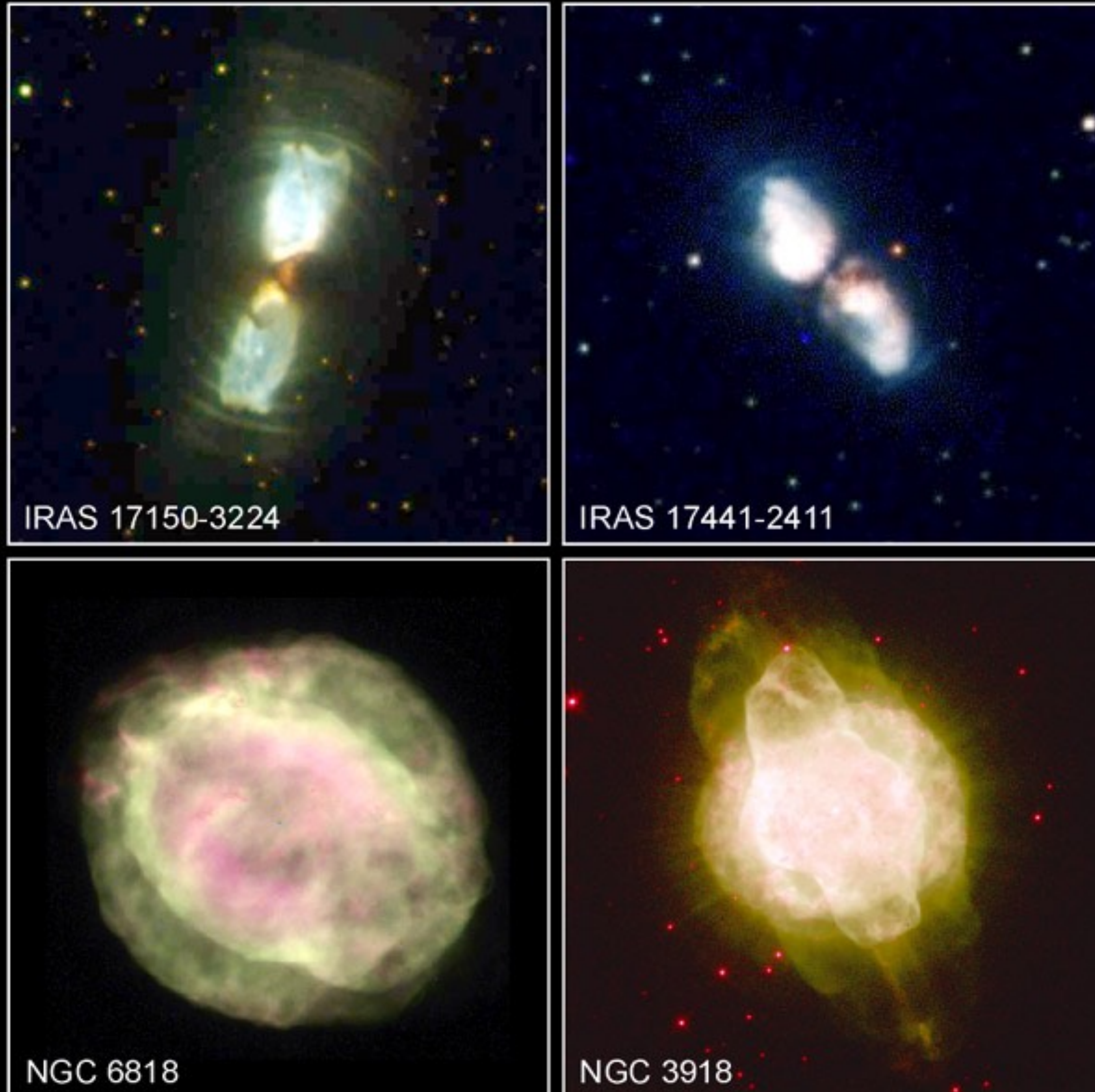
…what kind of spectrum would a planetary nebula show?

The Spirograph Nebula

Not all are spherical: bipolar shapes are common







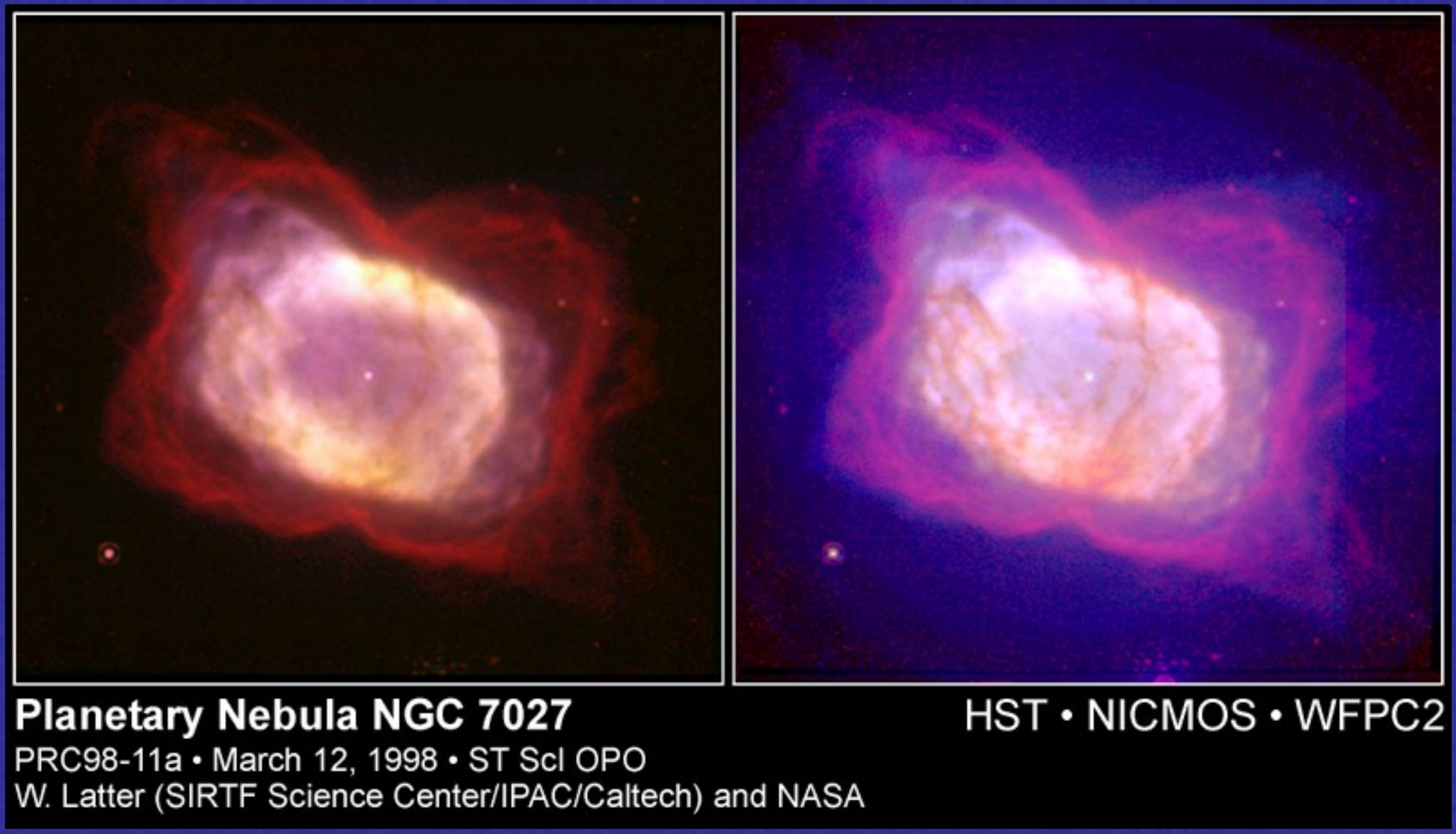
Planetary Nebulae

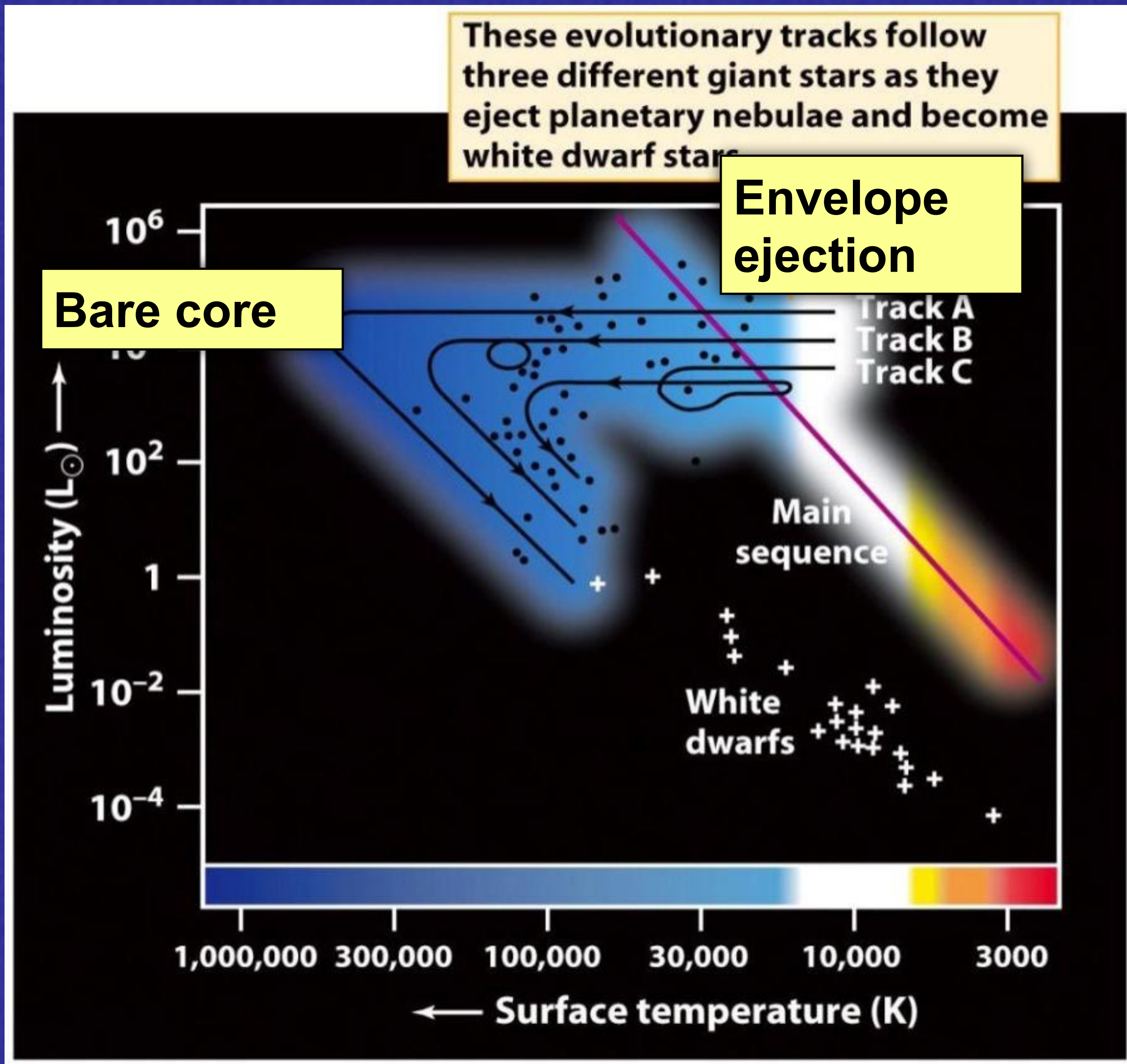
HST • WFPC2

PRC98-11b • ST ScI OPO • March 12, 1998
S. Kwok (University of Calgary),
R. Rubin (NASA Ames Research Center),
H. Bond (ST ScI) and NASA

What happens to the core?

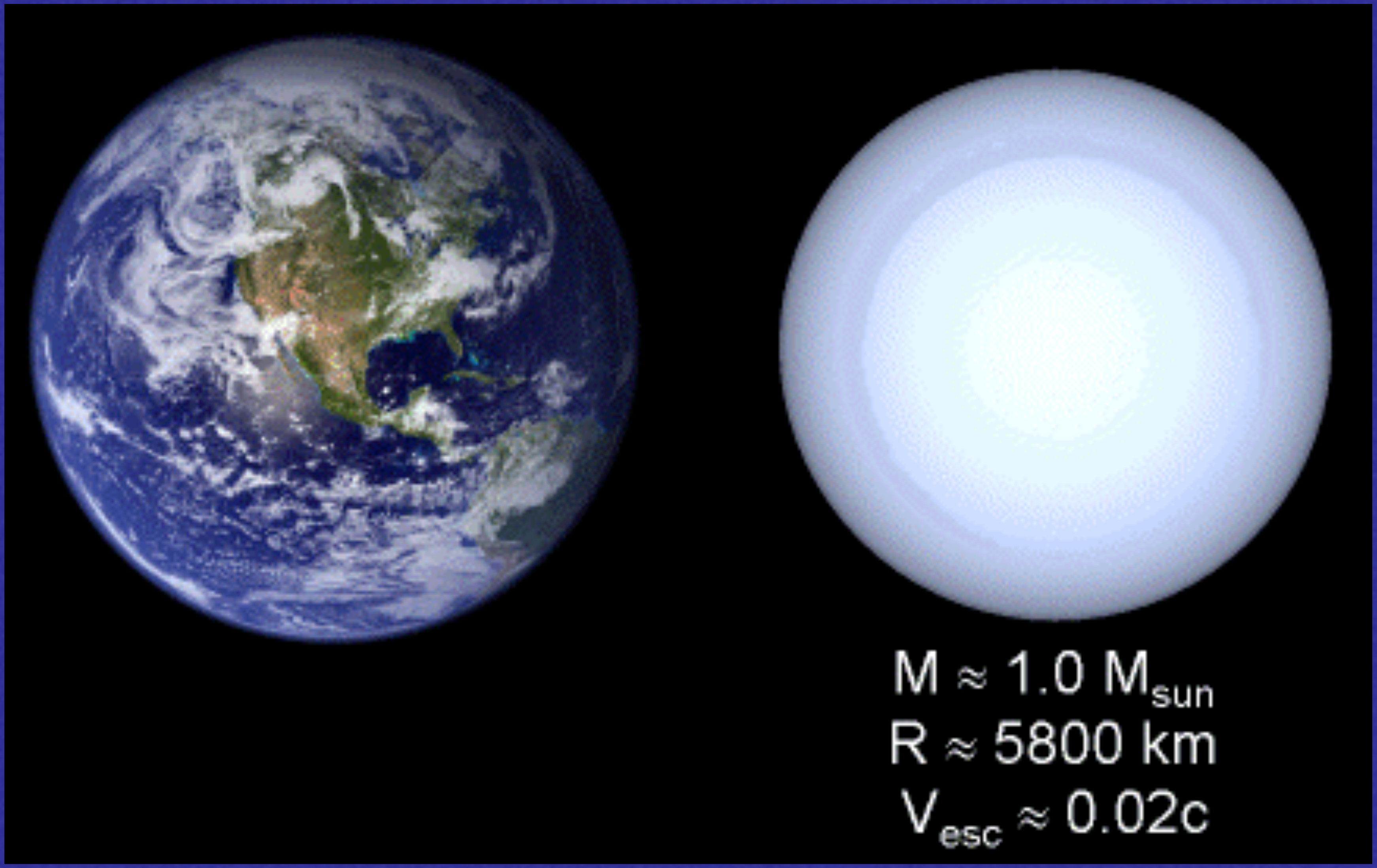
- For stars with original mass < $4M_{\odot}$, the central temperature never becomes hot enough for C or O to fuse.
- The central star of the PN is a *White Dwarf*. No more nuclear fusion processes occur.
- Shines because it is hot, and doesn't collapse because of pressure of degenerate matter.





Evolutionary track	Mass ($M_\odot$): Giant star	Ejected nebula	White dwarf
A	3.0	1.8	1.2
B	1.5	0.7	0.8
C	0.8	0.2	0.6

- Core contracts until degenerate (P independent of T)
- Then P grows fast, halting contraction (when $R \sim R_{earth}$)
- => Bare core = white dwarf

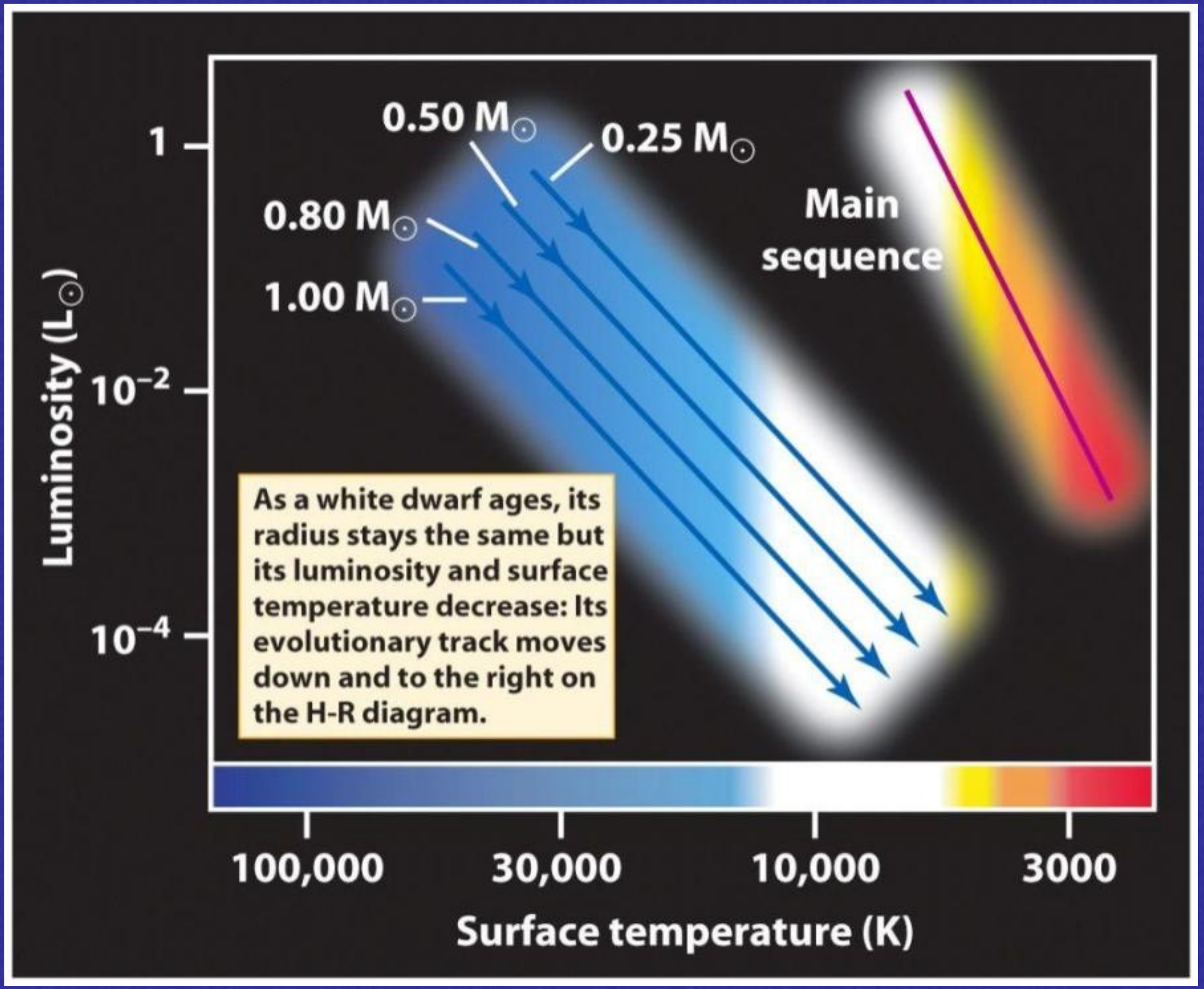


White dwarfs are of the size of the Earth, with the mass of the Sun. Much denser than anything ever made on Earth.

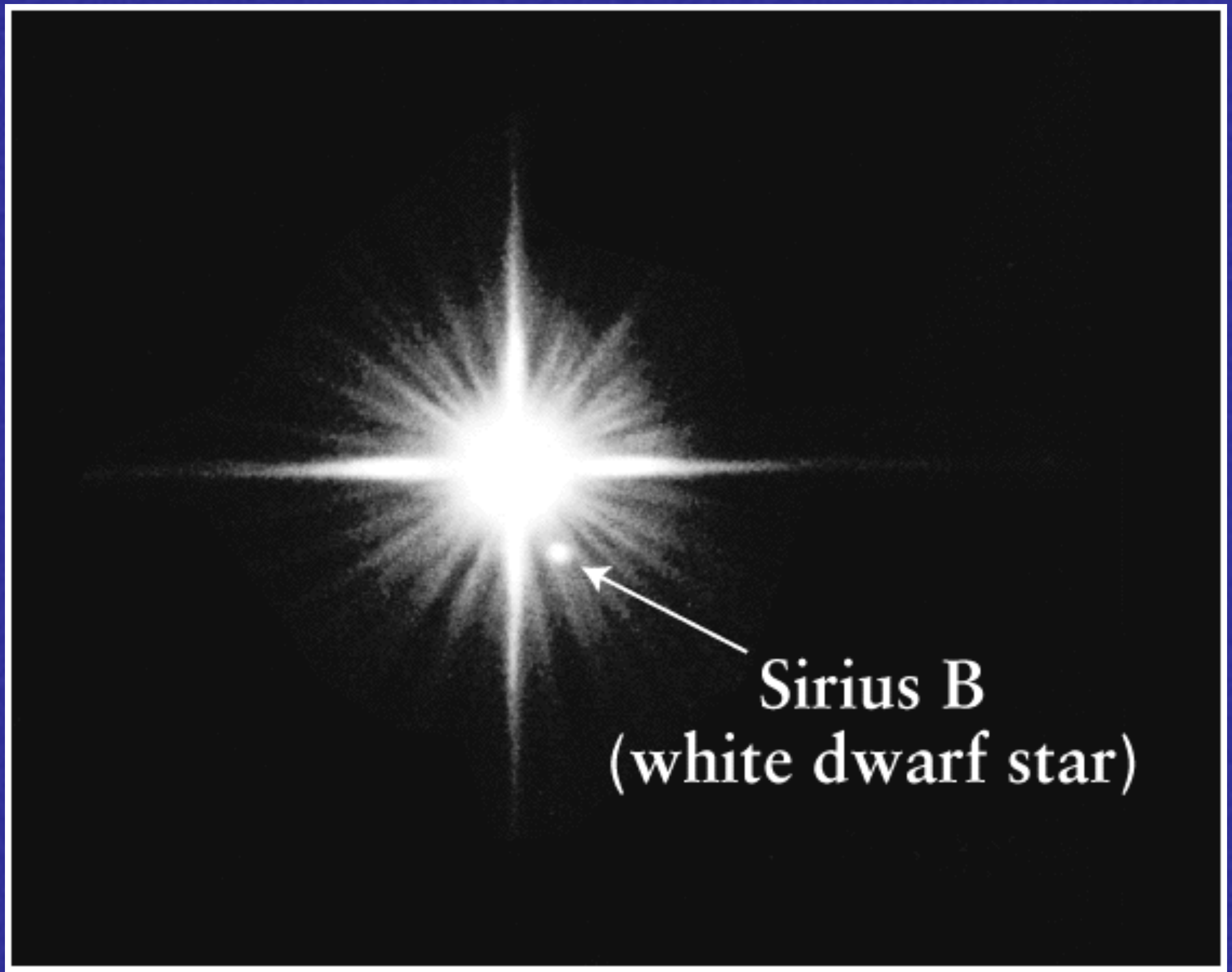
Density ~ 1.9 billion times the density of water

Made of C and O with possibly a thin atmosphere of H.

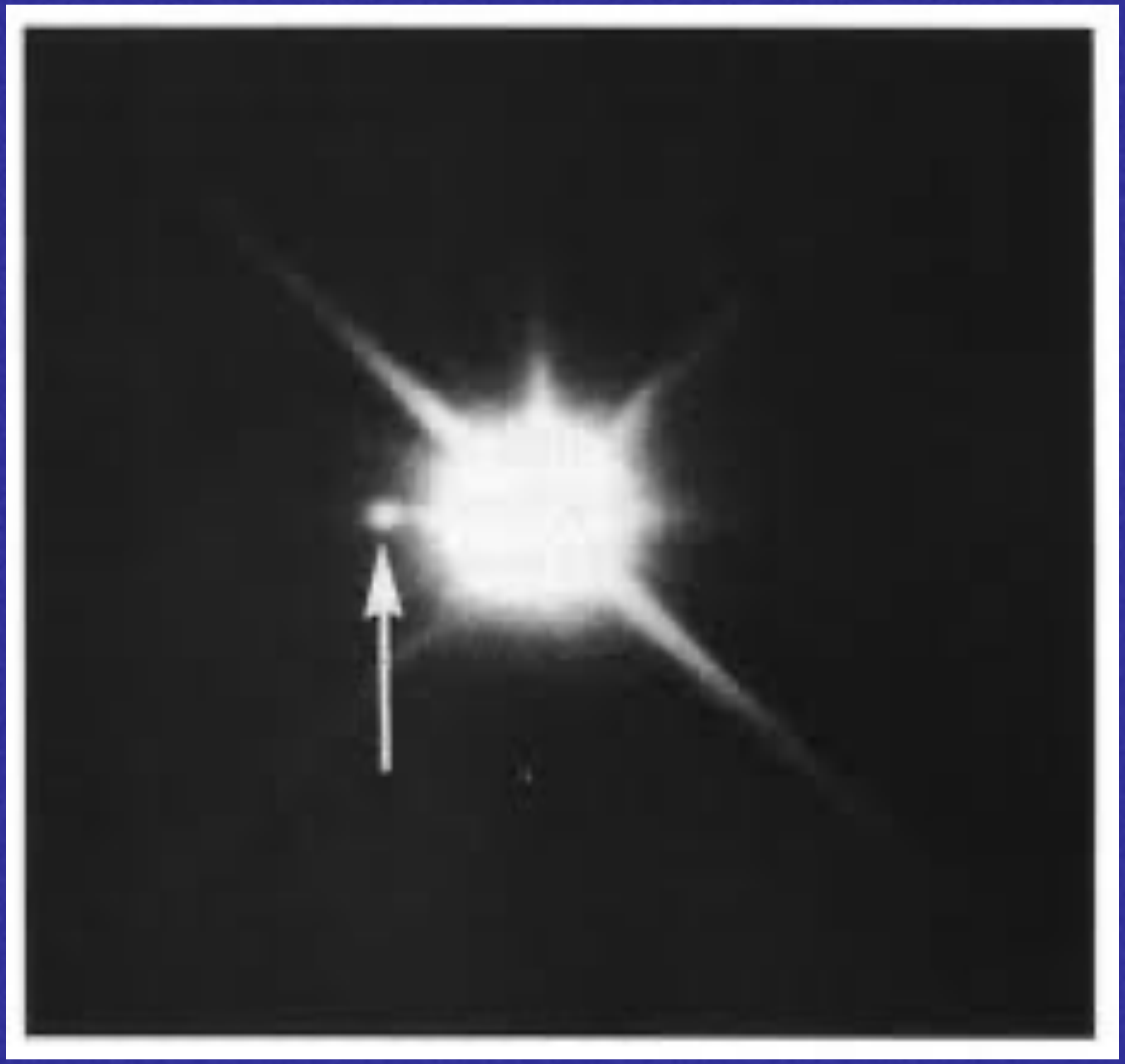
- Where are white dwarf stars on the H-R diagram as they cool? Follow "Cooling Curves":

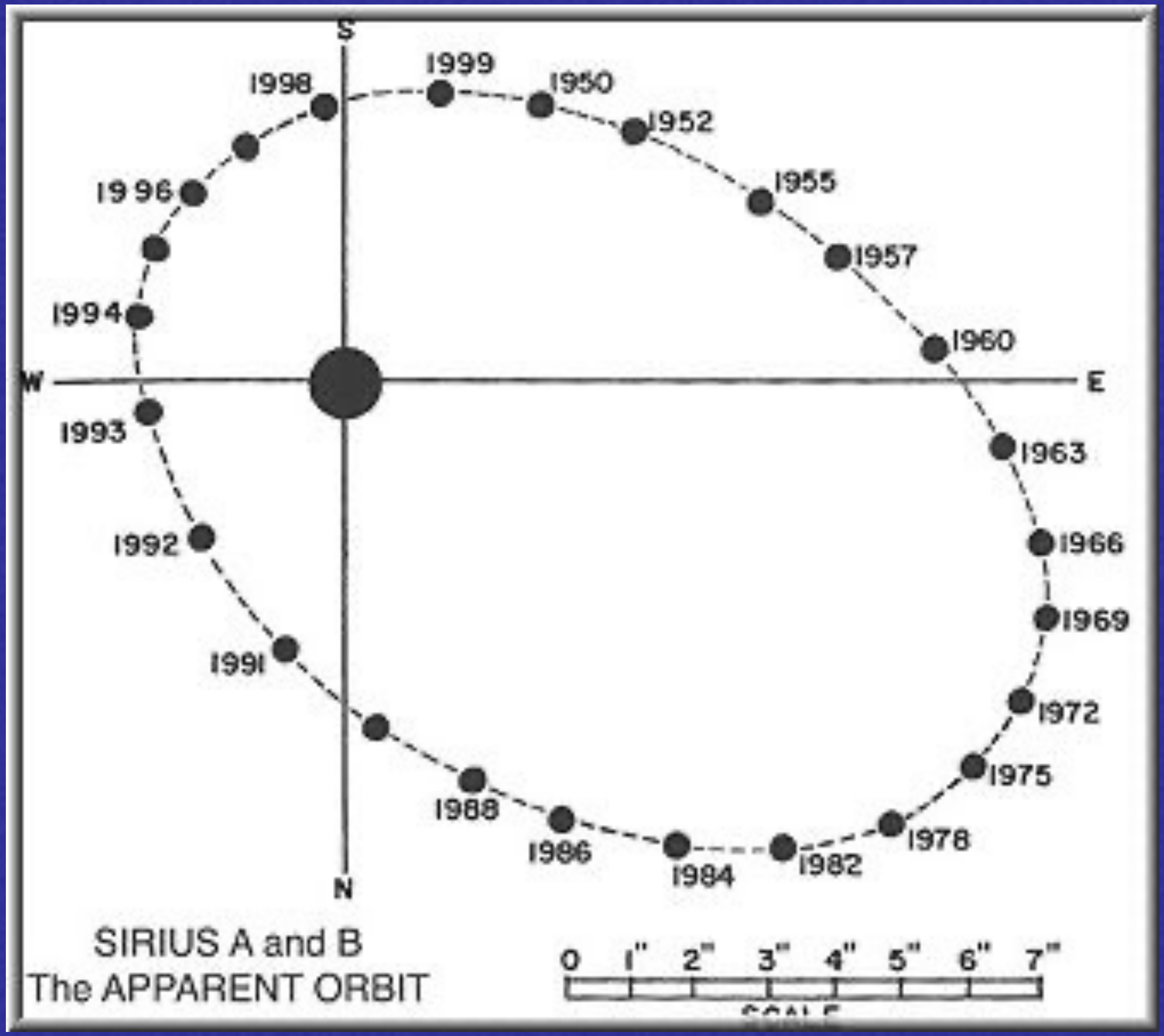


We can see some white dwarfs directly (with telescopes). For example, Sirius has a WD companion Sirius B. You can easily see this from the campus observatory.

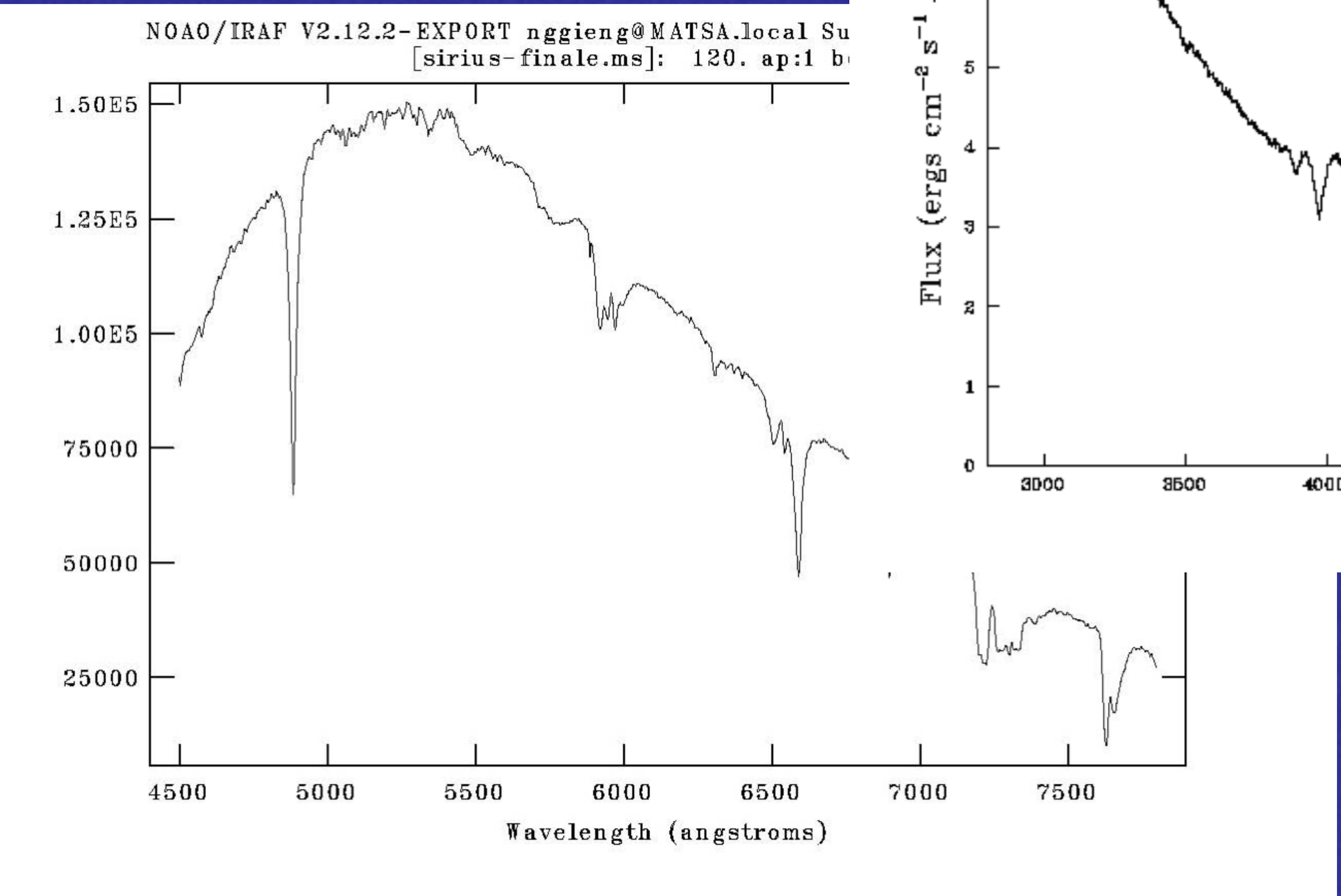


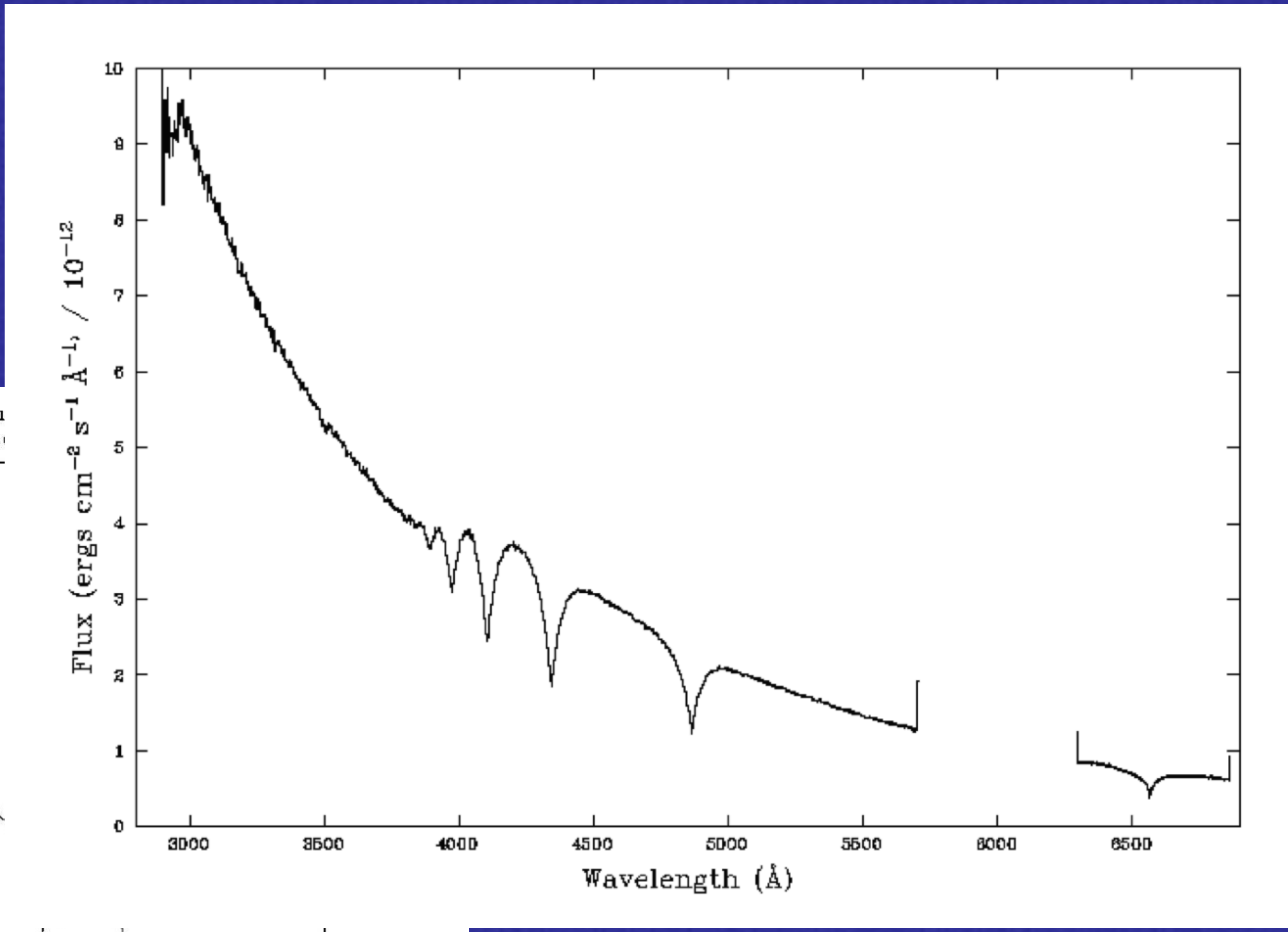
Discovery of Sirius B aka "the pup"



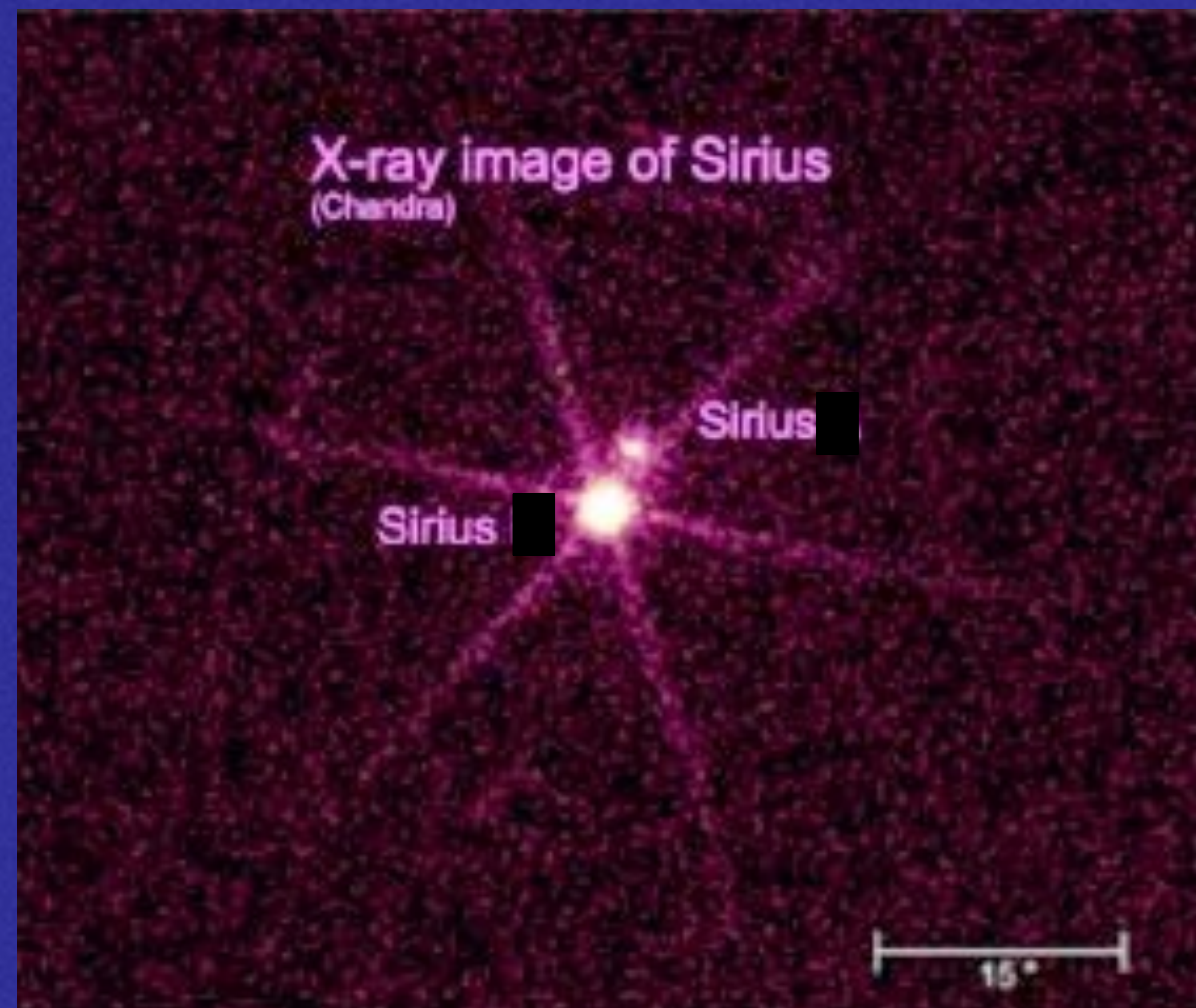


Spectrum of Sirius B and A

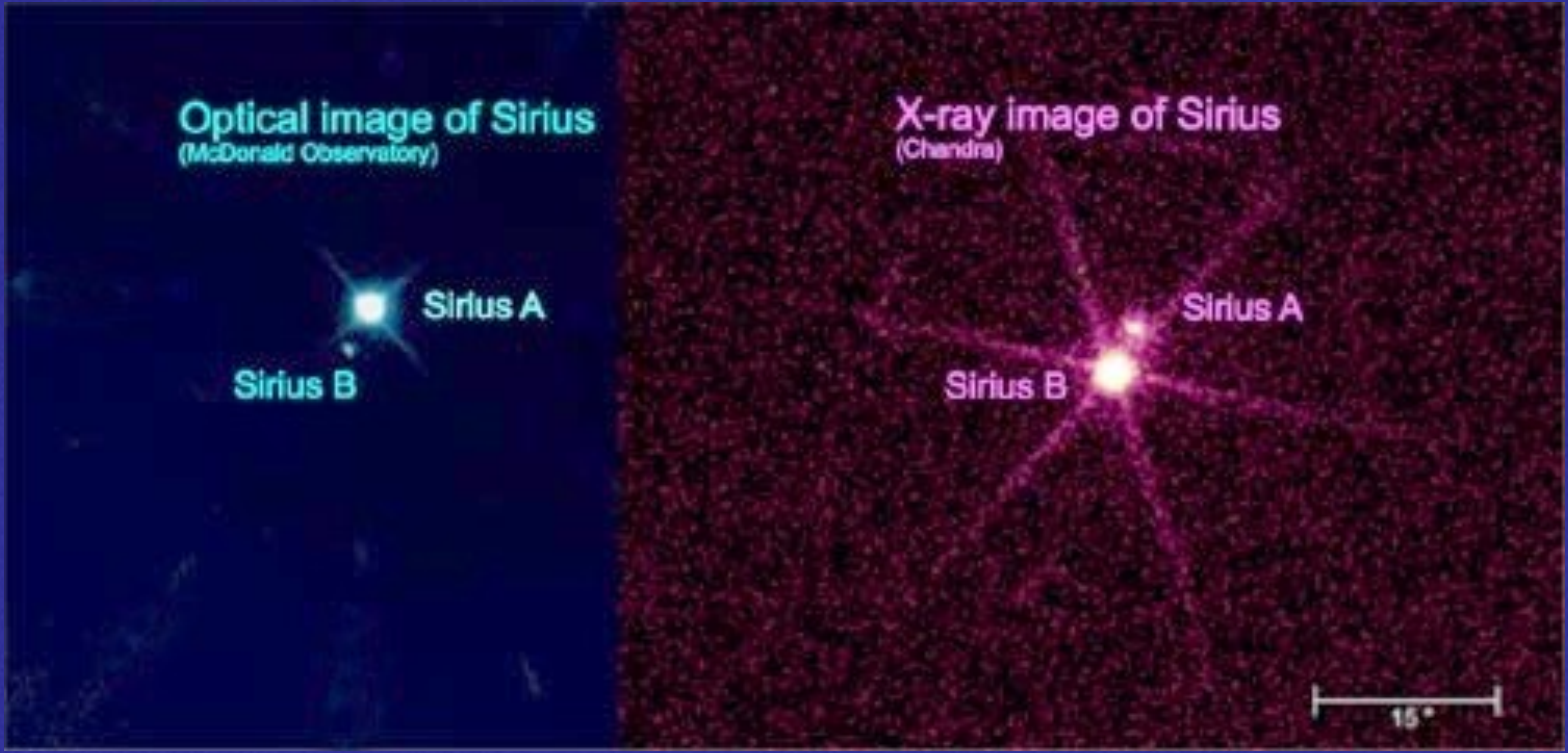




X-ray image of Sirius B aka “the pup”

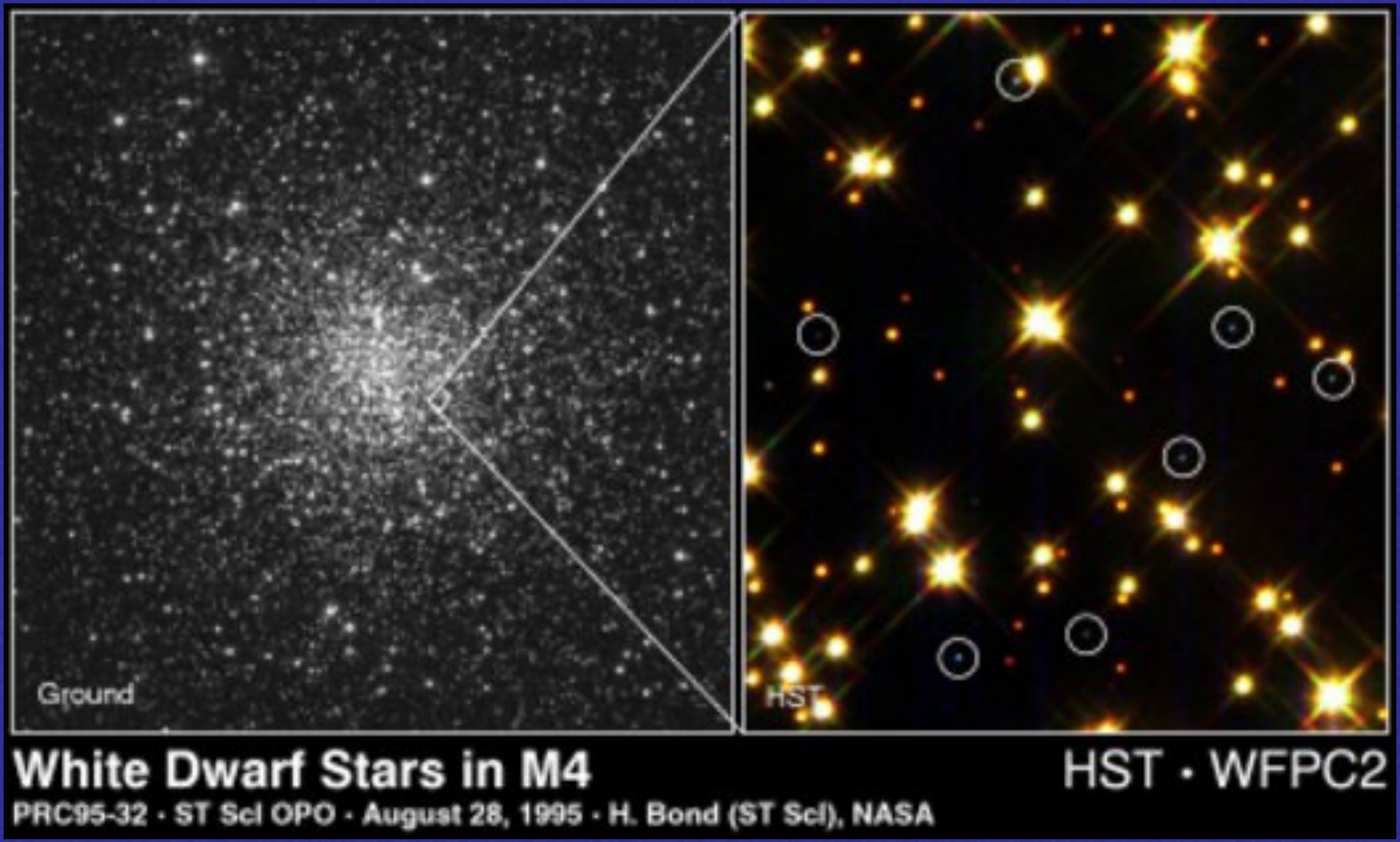


Discovery of Sirius B aka "the pup"



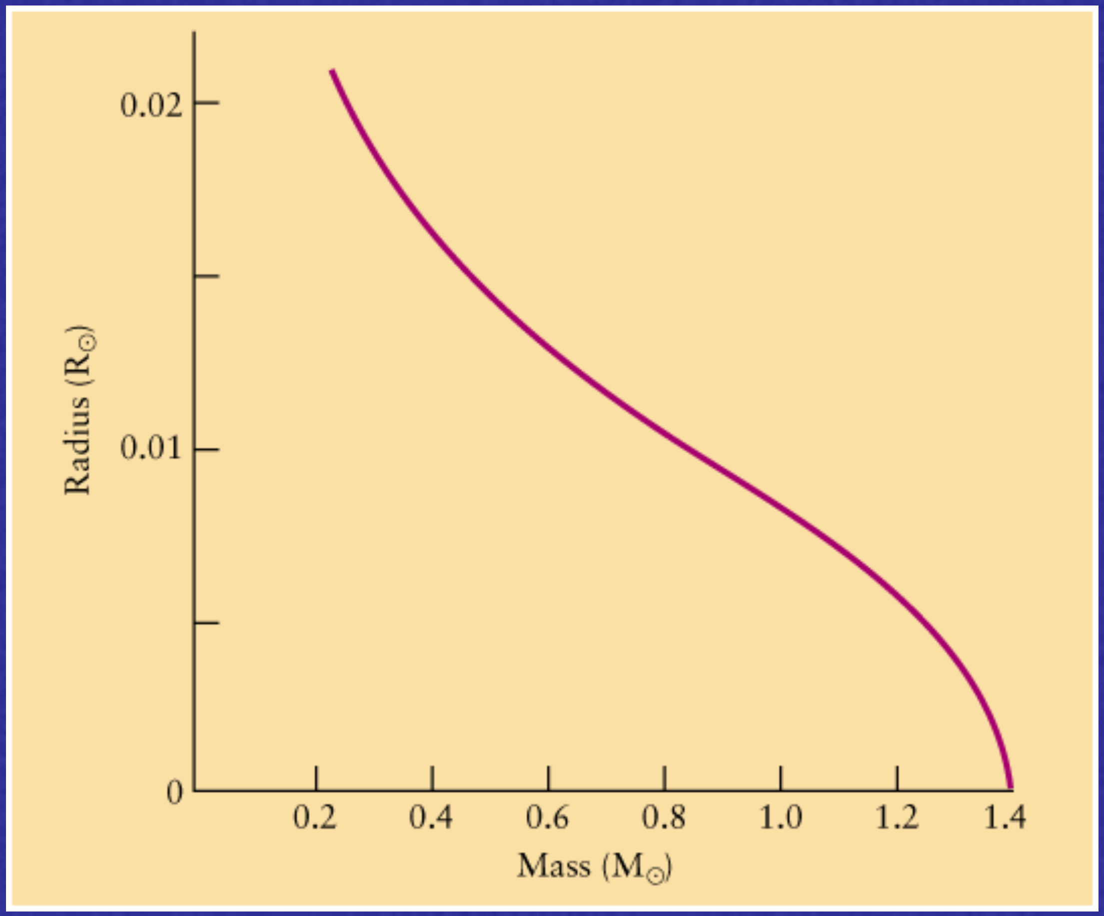
M4, a globular cluster. A stellar graveyard!

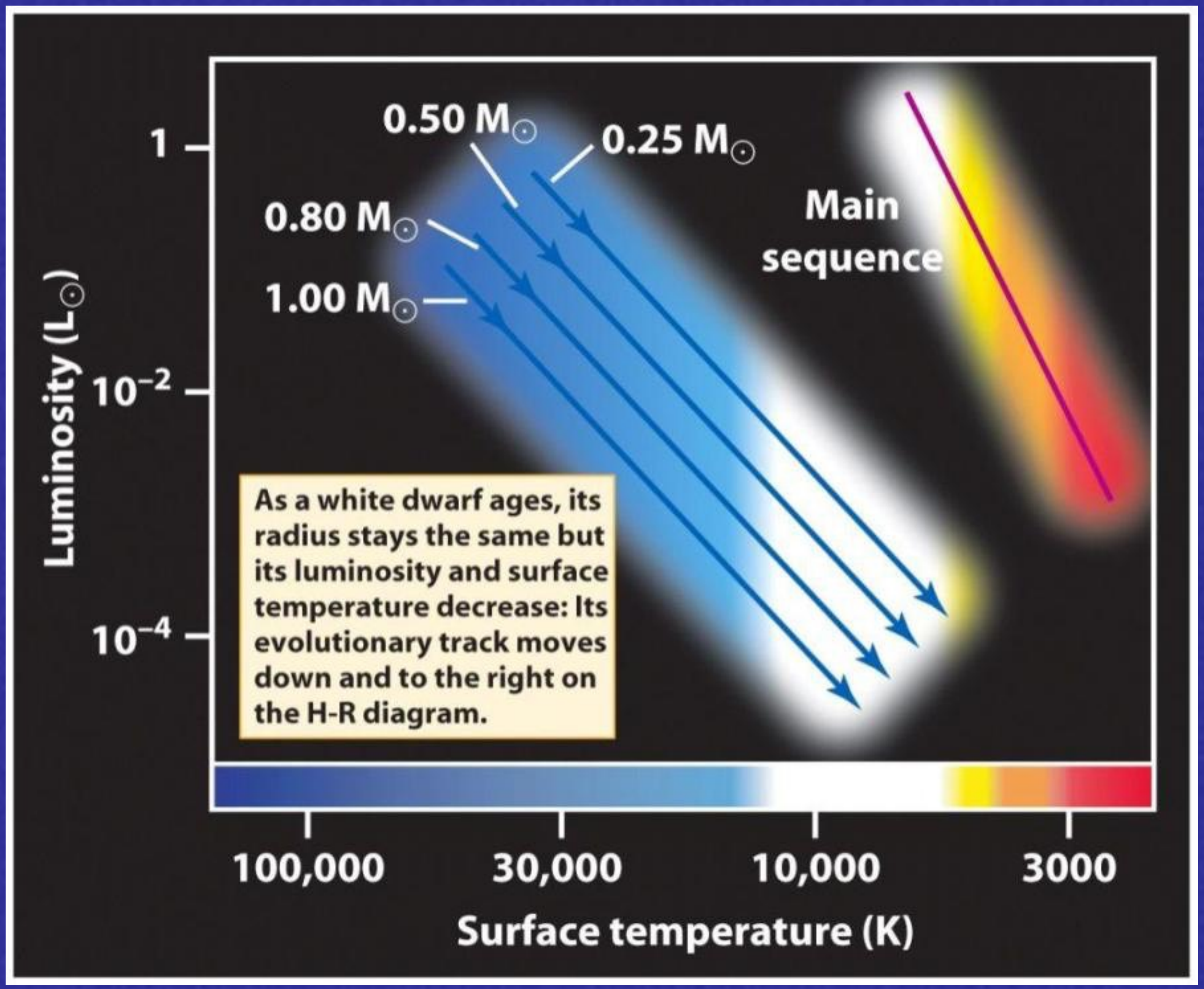
WD represents endpoint of stellar evolution for solar- mass stars.



Mass-radius relation

- Totally different from that for main sequence stars.
- The greater the mass, the smaller the white dwarf.
- This is why more massive WDs are fainter at a given *T*.





Types of white dwarf stars

Core:

- Carbon/Oxygen
- Helium
- Oxygen/Neon/Magnesium

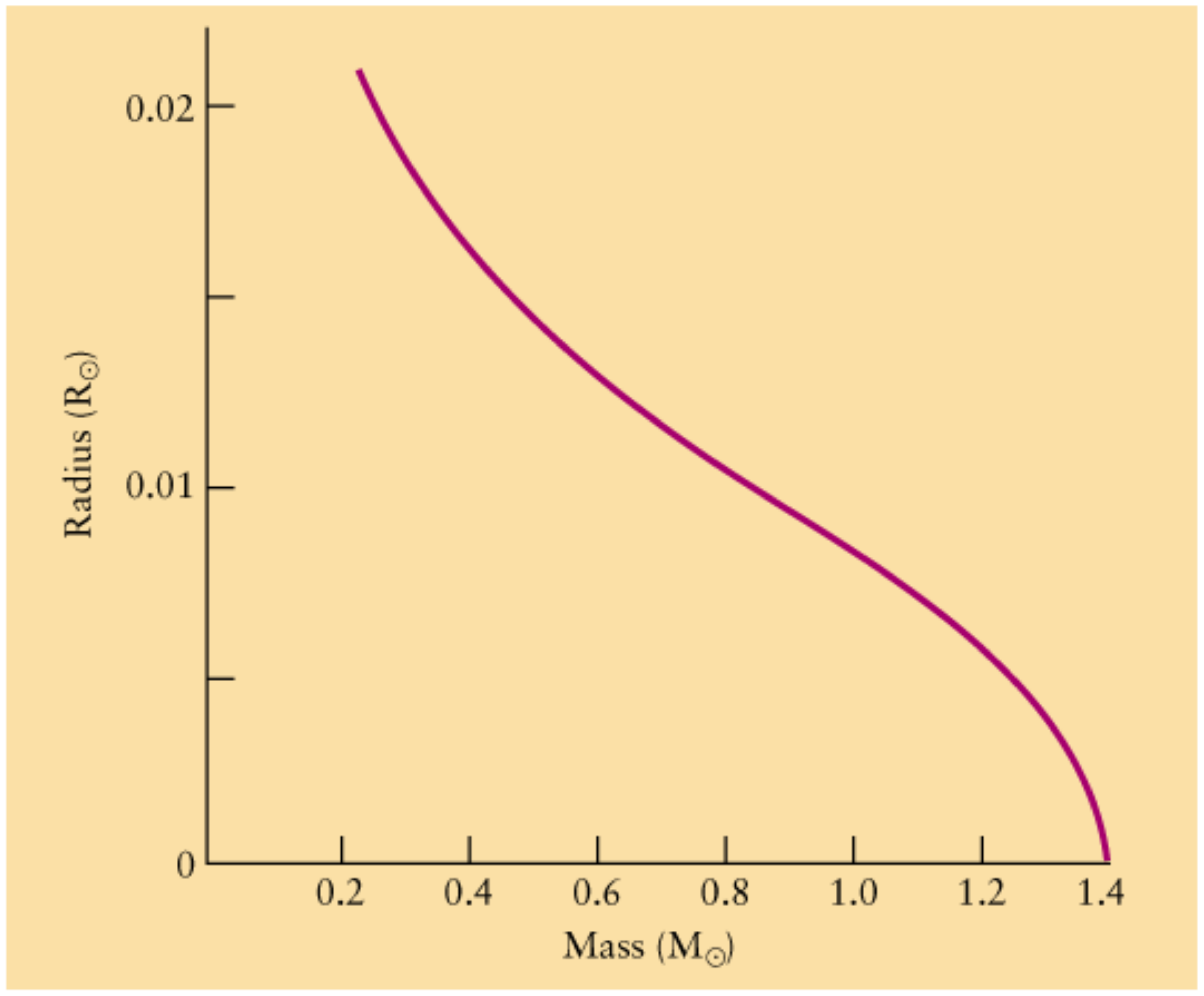
Atmosphere

- Hydrogen rich
- Helium rich
- Metal lines

Temperatures 3000 – 50,000 K

Note the catastrophe at M=1.4 solar masses!

What happens to density as R-> 0?



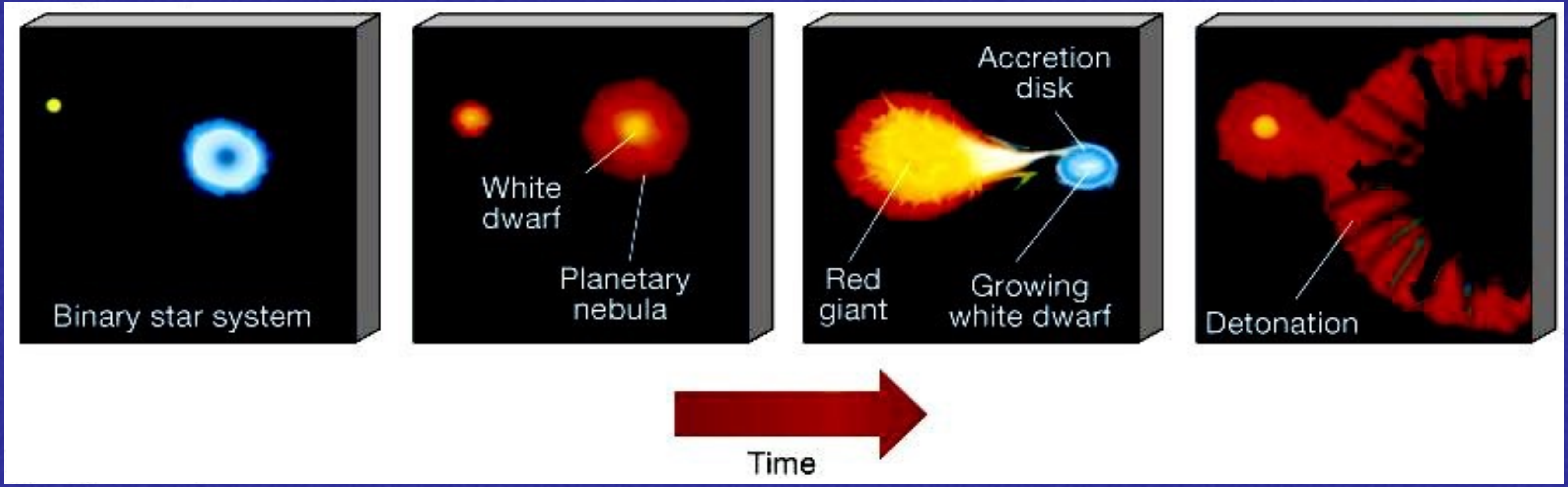
Chandrasekhar limit

- WD starts with C and O ions floating in sea of degenerate electrons
- As the WD cools, C and O form a lattice structure (solid, like a diamond), held up by degeneracy pressure
- Larger masses put more strain on structure. Beyond 1.4 $M_{\odot}$ (*Chandrasekhar limit*) structure collapses.

What does the star become?

Type Ia supernovae

If enough mass dumped onto WD by binary companion to push it over Chandrasekhar limit, starts collapsing until hot enough for C,O fusion. Proceeds rapidly through WD, explosion, no remnant.



Problem, not enough of these systems

New idea: white-dwarf white dwarf merger (the double degenerate)