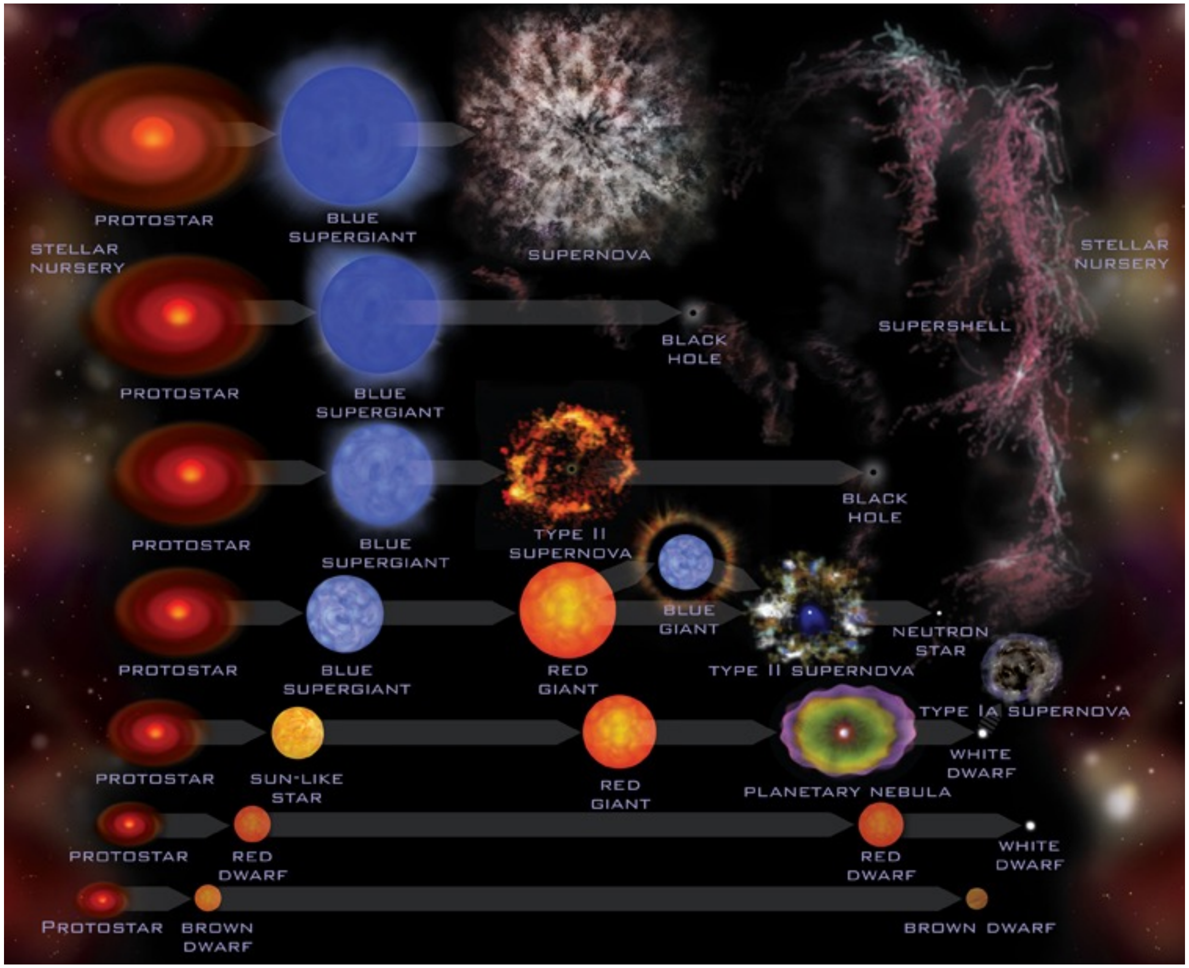
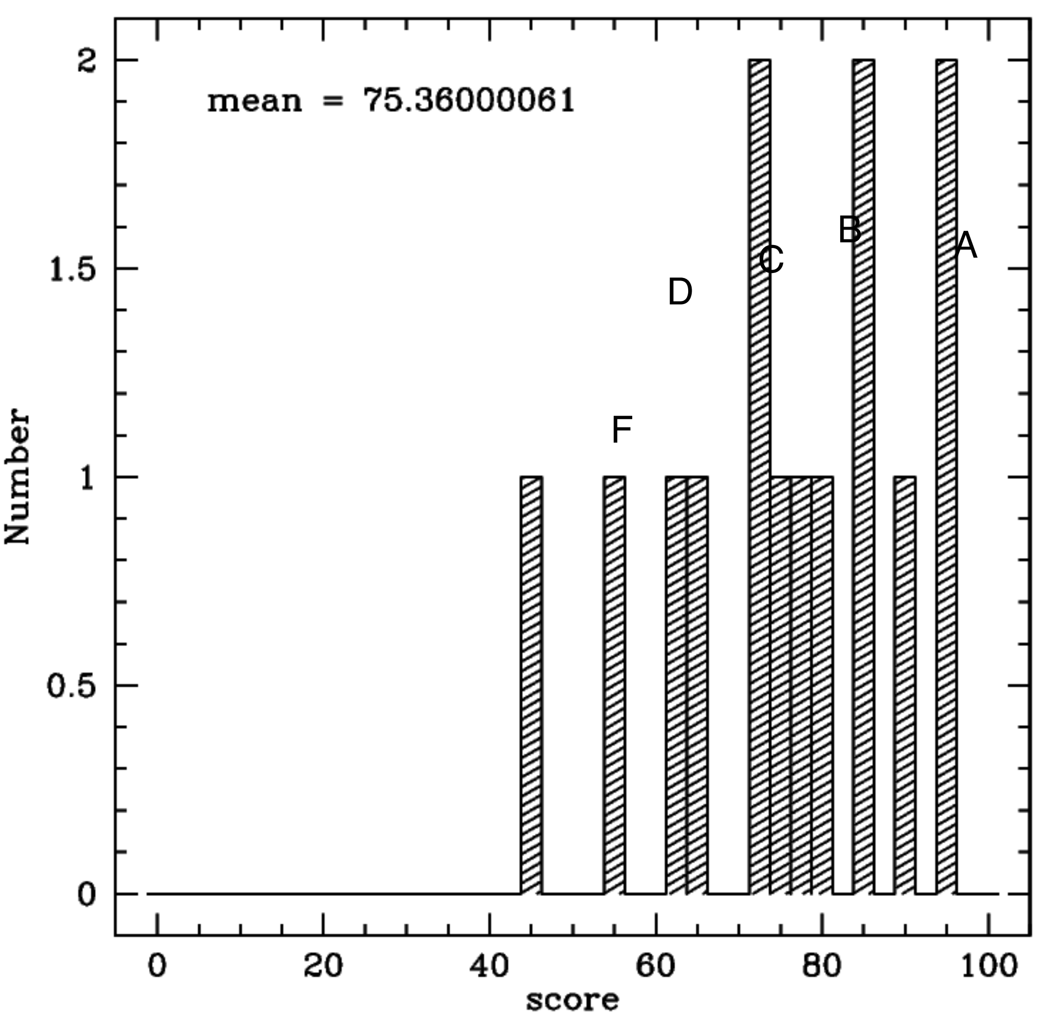
Astronomy 421



Lecture 20: Stellar Evolution II

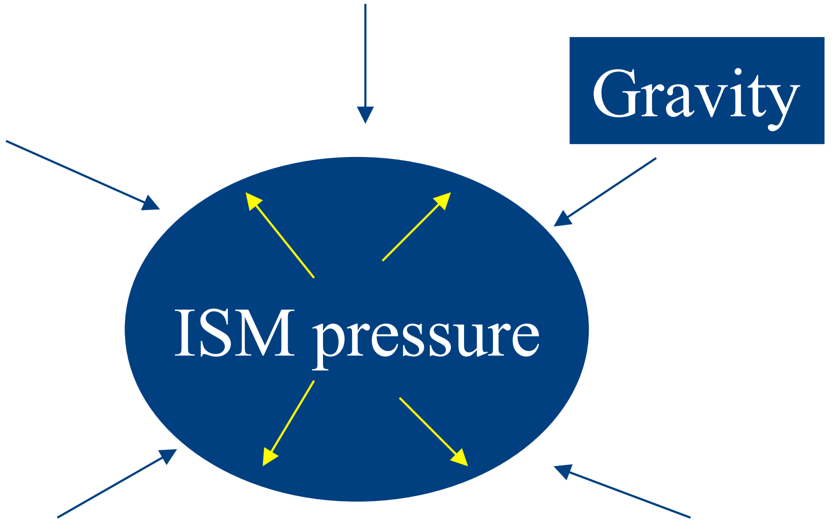
Test #2 Results

90 – 100: A
80 – 89: B
70 – 79: C
60 – 69: D
< 60 : F



Stars with Cloud collapse

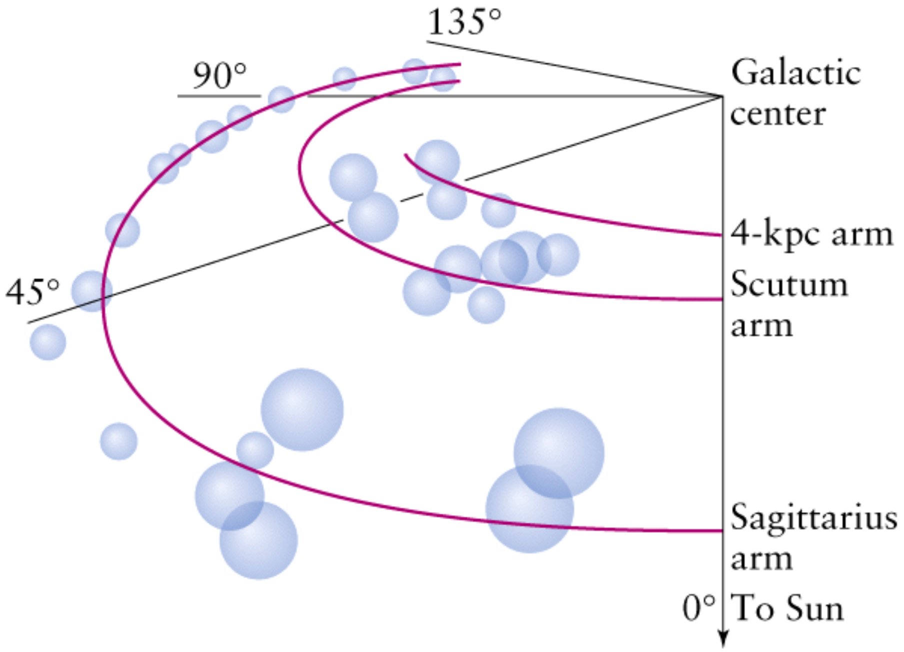
- Desired result: a star, with n~10^{24} cm^{-3}
- Resources: the interstellar medium (ISM), with n~10^5 - 10^7 cm^{-3} (dense molecular clouds)
- Recall: a cloud withstands gravitation by its internal pressure

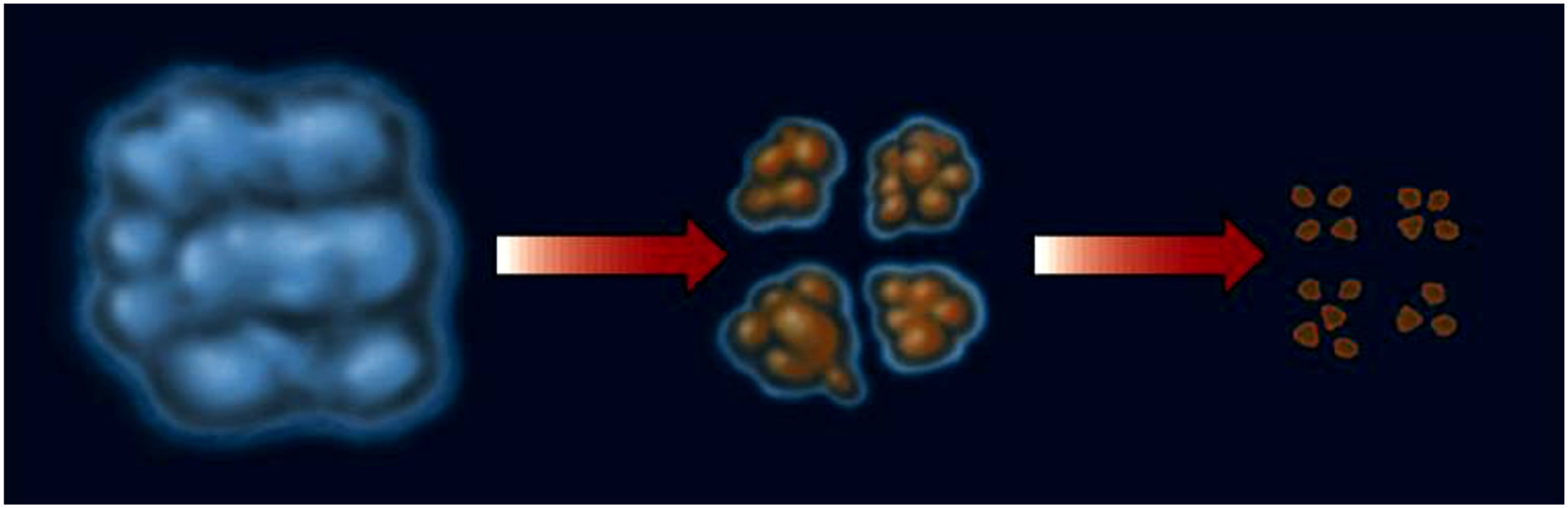

Gravity

ISM pressure

- Internal pressure sources: gas pressure from internal heat, radiation pressure, plus pressure from embedded magnetic fields

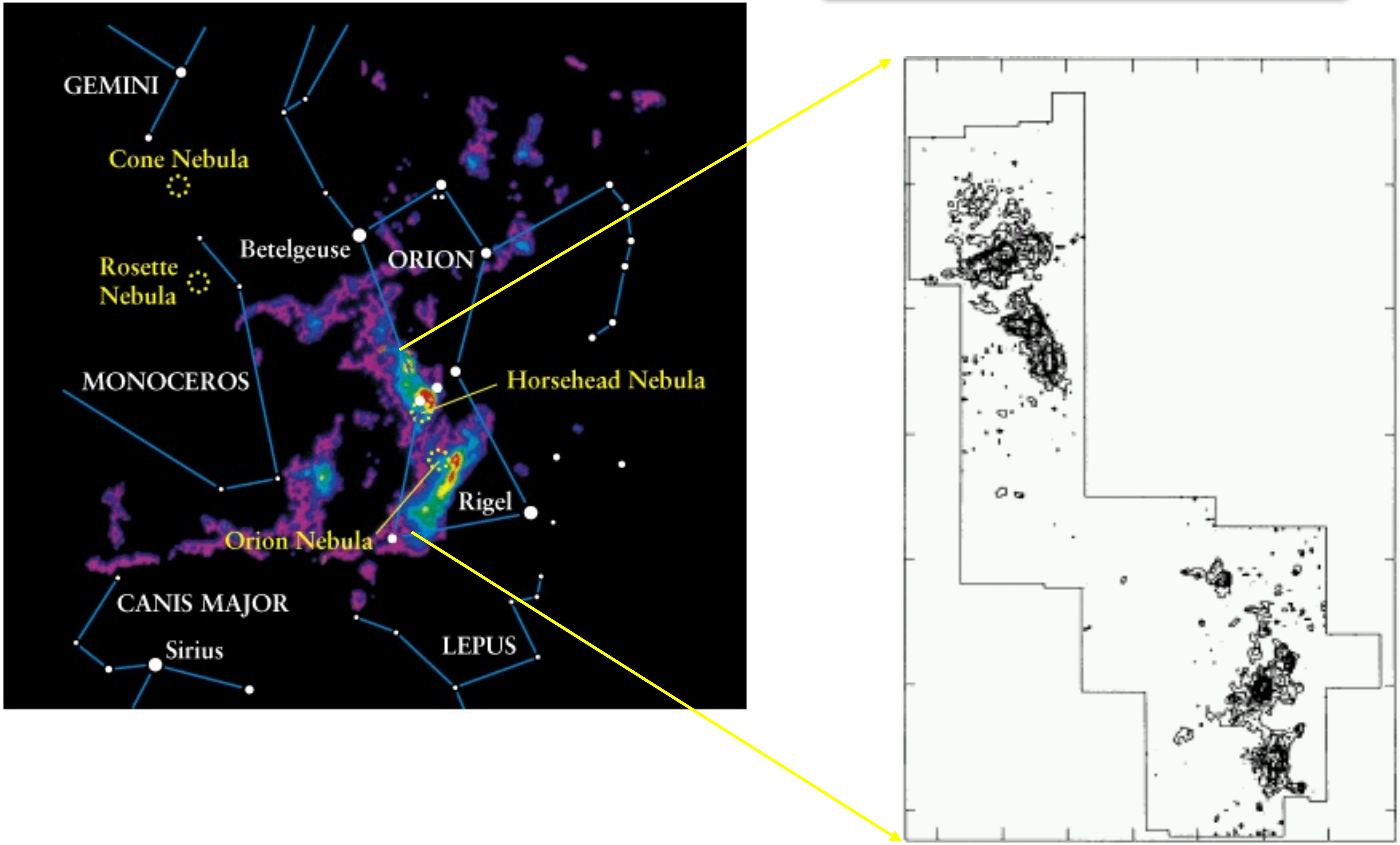
- A collapse (gravity>internal pressure) can be triggered by
  - Collisions with other clouds (cloud-cloud collisions)
  - Shocks from supernovas
  - Passage through a spiral arm in the Galaxy (density enhancement)



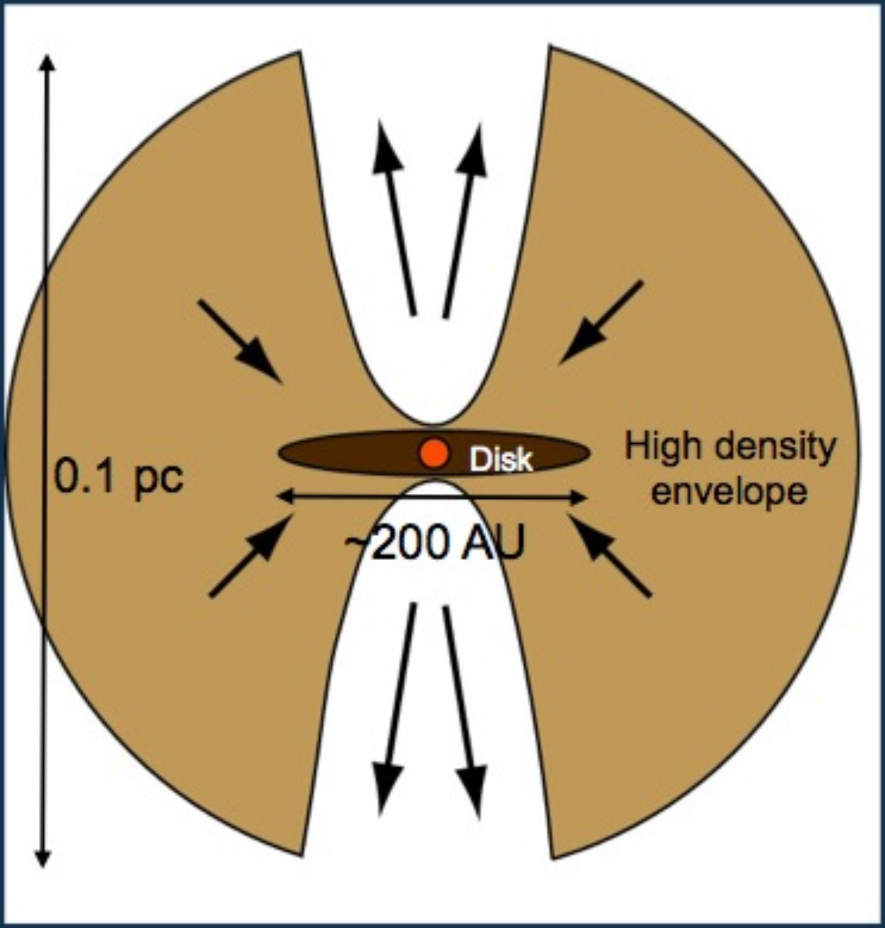


- Clouds are inhomogeneous - clumpy.
- Clumps start to collapse, densest clumps collapses first and fastest => fragmentation.
- 100s to 1000s of fragments may exist in one collapsing molecular cloud.

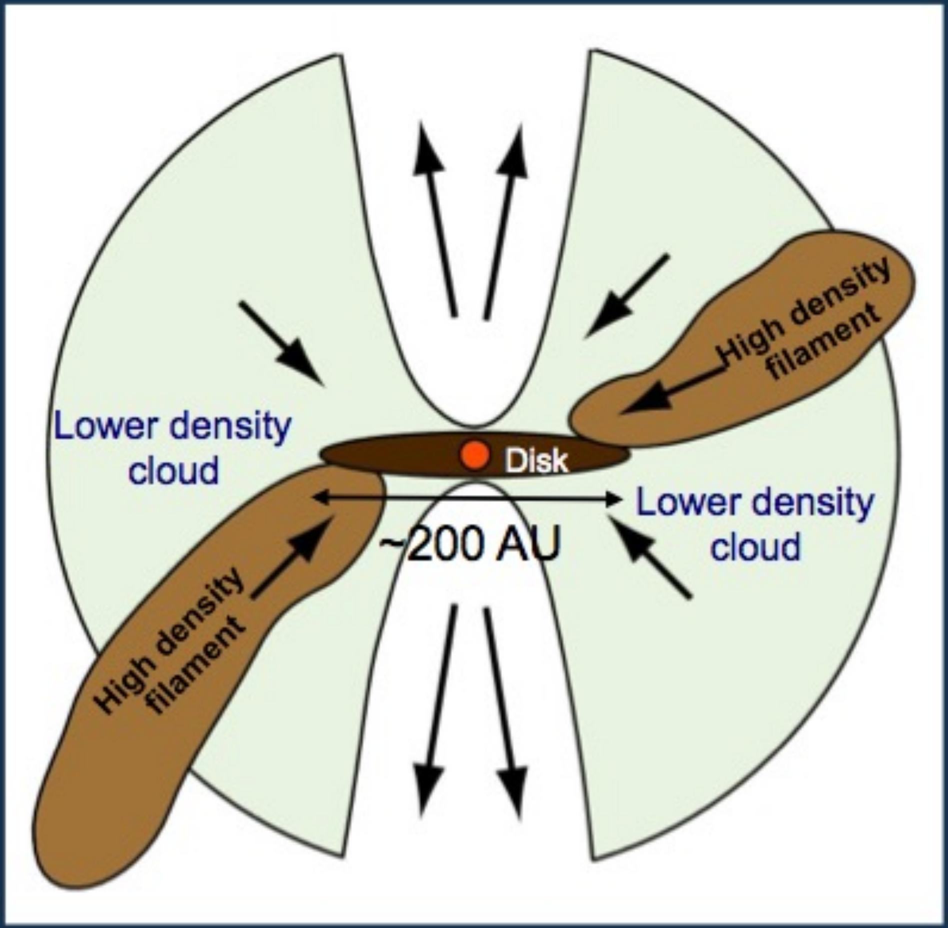
Fragments in Orion MC, about 1000 times denser than average gas in cloud.



revised picture of infall:



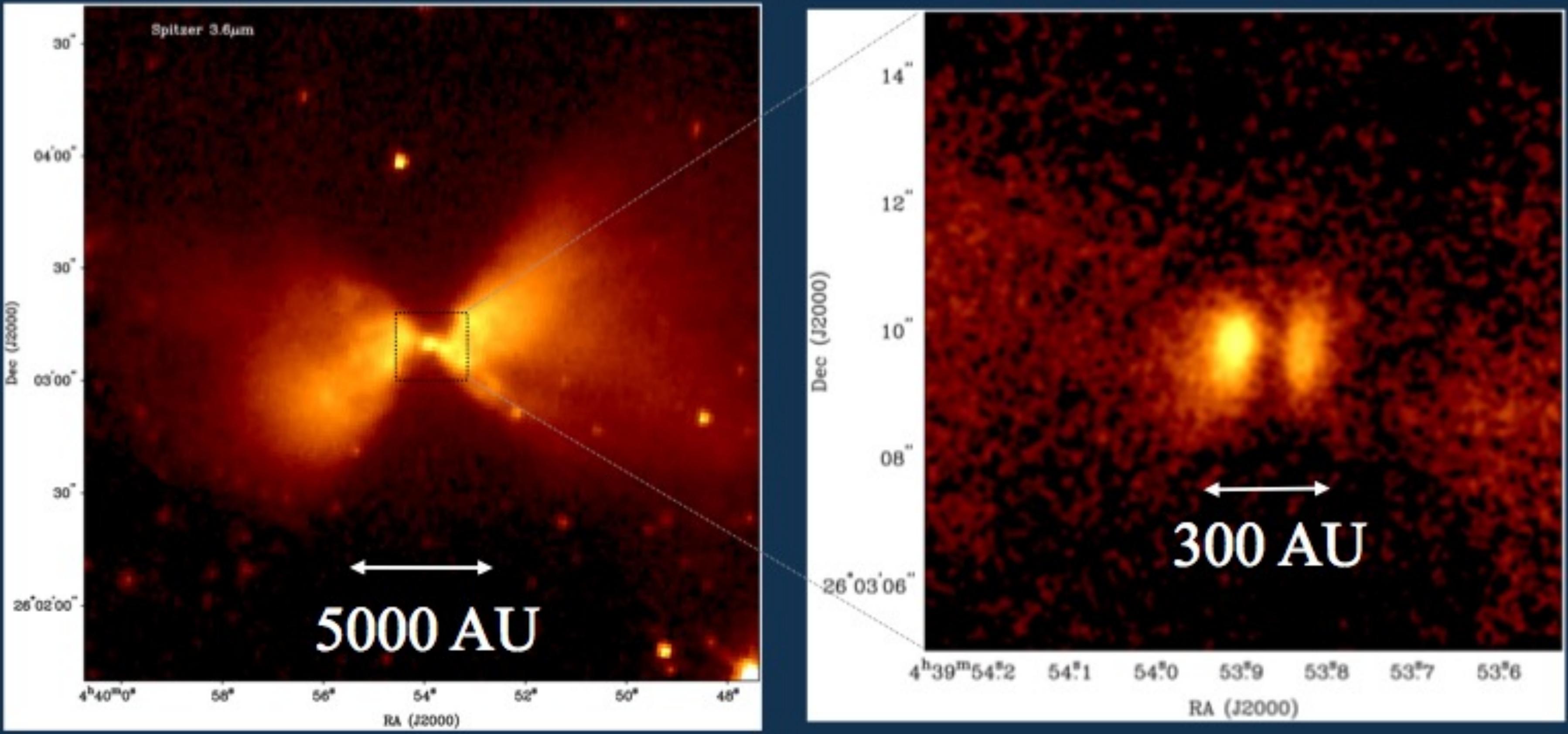
Idealized collapse



More Typical?

L1527 Spitzer 3.6 micron

Gemini 3.8 micron

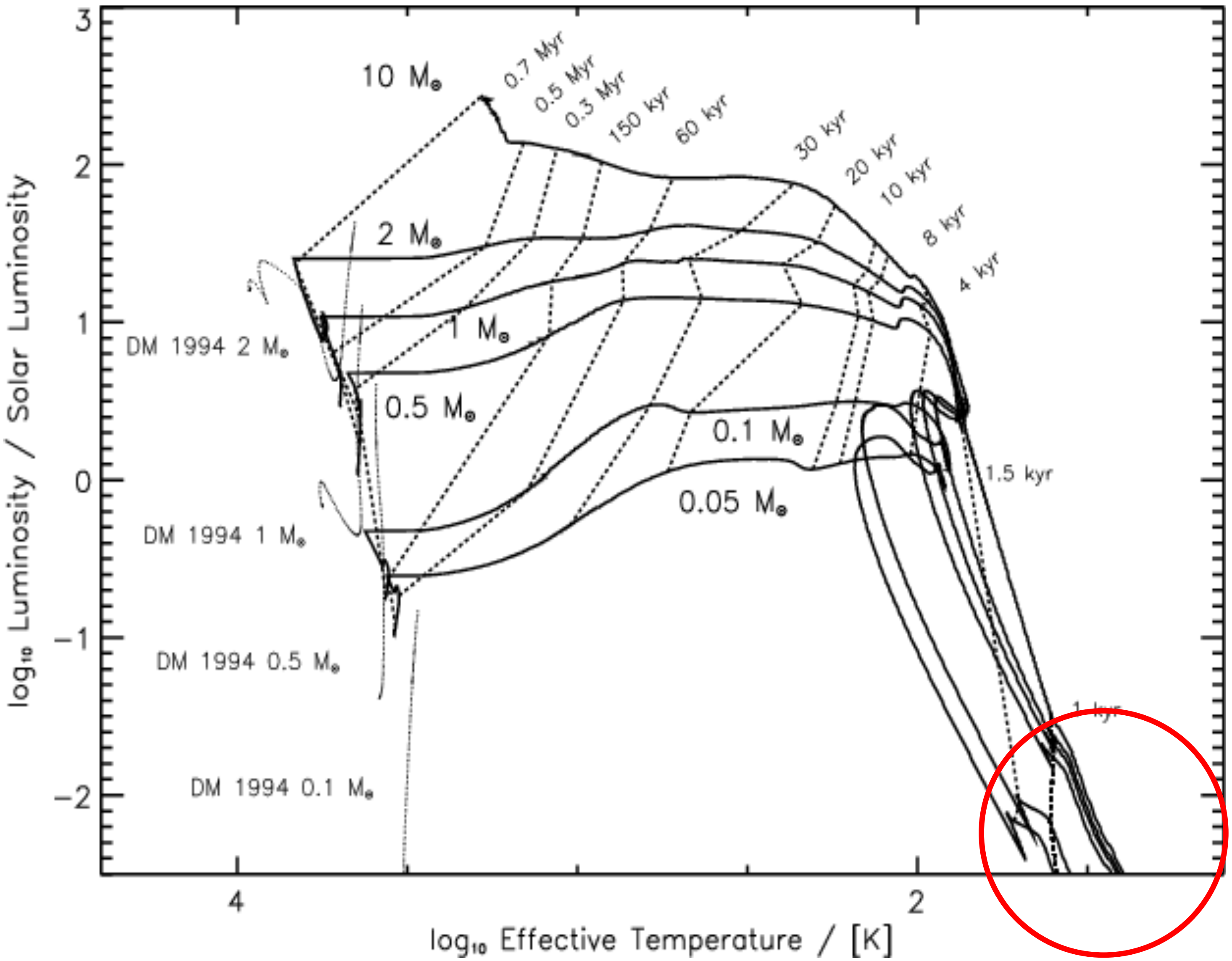


Recap: protostars (skip Ch. 12 on star formation)

- Depending on the Jean's mass, a cloud collapse is initiated. (2K < U)
- The timescale of this initial collapse is determined by the free-fall timescale.

$$t_{ff} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0} \right)^{1/2}$$

- Central regions become denser and eventually optically thick: we have a core that will radiate as a blackbody -> we can now plot it on an HR diagram.
- This is a quasi-static protostar (radius central region about 5AU, so much larger than e.g., the Sun).

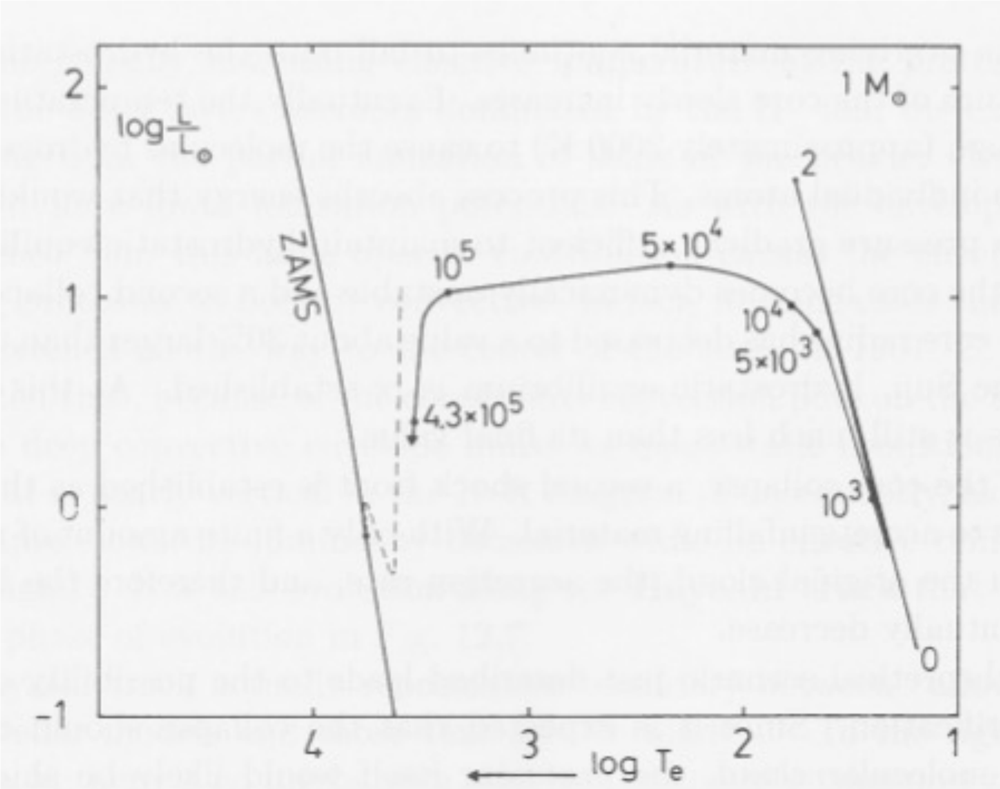


10 M⊙
0.7 Myr
0.5 Myr
0.3 Myr
150 kyr
60 kyr
30 kyr
20 kyr
10 kyr
8 kyr
4 kyr
2 M⊙
1 M⊙
0.5 M⊙
0.1 M⊙
0.05 M⊙
1.5 kyr
1 kyr
DM 1994 2 M⊙
DM 1994 1 M⊙
DM 1994 0.5 M⊙
DM 1994 0.1 M⊙
3
2
1
0
−1
−2
4
2
log₁₀ Luminosity / Solar Luminosity
log₁₀ Effective Temperature / [K]

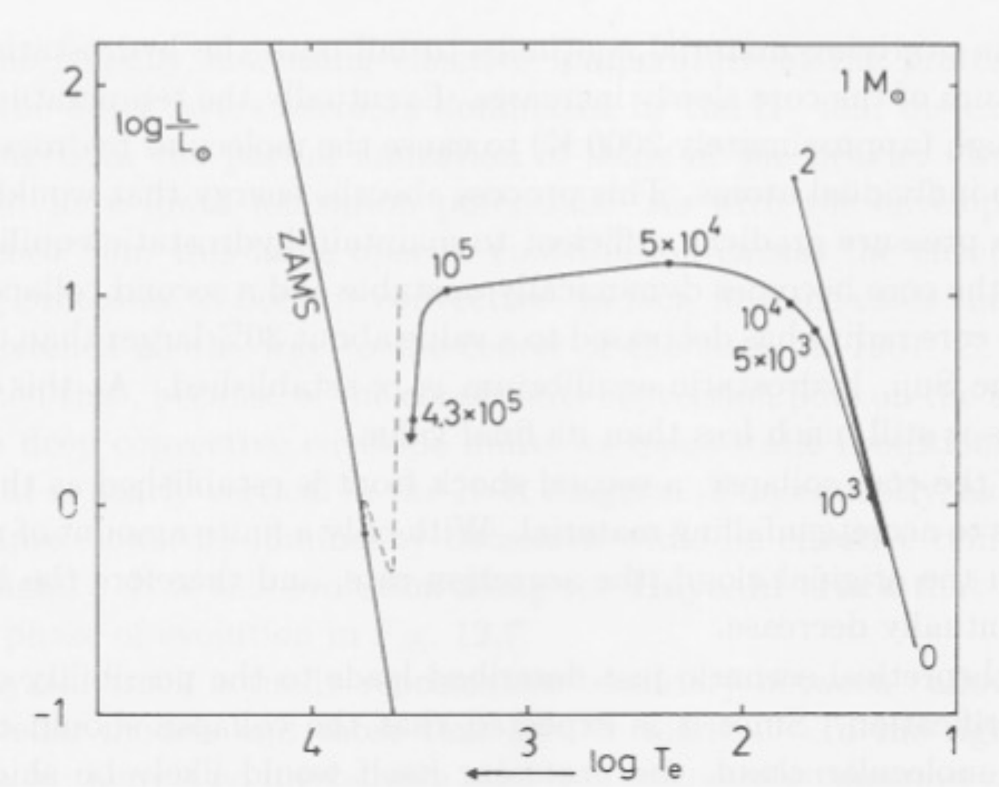
- As the core accretes material from the envelope, the outer collapse will continue. T_{eff}, R and thus L will increase.

- The core is almost hydrostatic (stopped collapsing) and the material meeting the core will develop a shock wave. Here kinetic energy will be lost, released mostly as heat. Thus, L is kept at a high level.

- When the surface temperature reaches T_{eff} ~1000 K dust will evaporate and so the opacity drops.
  - We can see deeper in the core so R basically drops.
  - BUT, energy is still being created at a high rate close to the core where temperature is higher, so L is conserved at this stage => T_{eff} increases.



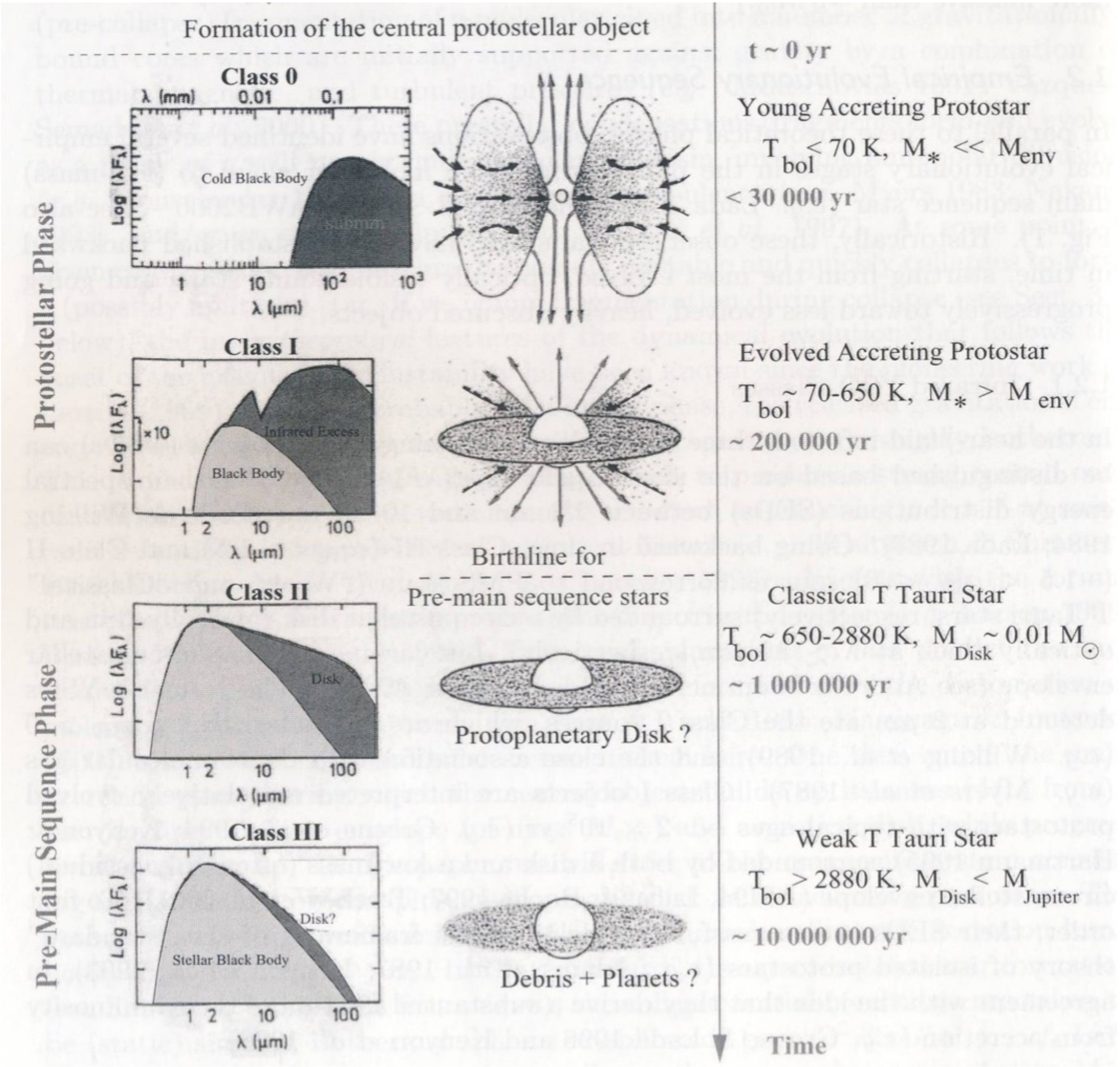
- At 2000 K, the molecular hydrogen dissociates.
  - That takes some energy that previously was used for heating.
  - Pressure drops, so core will start to collapse again.
  - New shock wave established when $R_{core} \sim 30\%$ larger than the Sun's *R.*
  - Less and less mass being accreted, deuterium burn-out, so *L* must drop.



Classification Young Stellar Objects (YSOs)

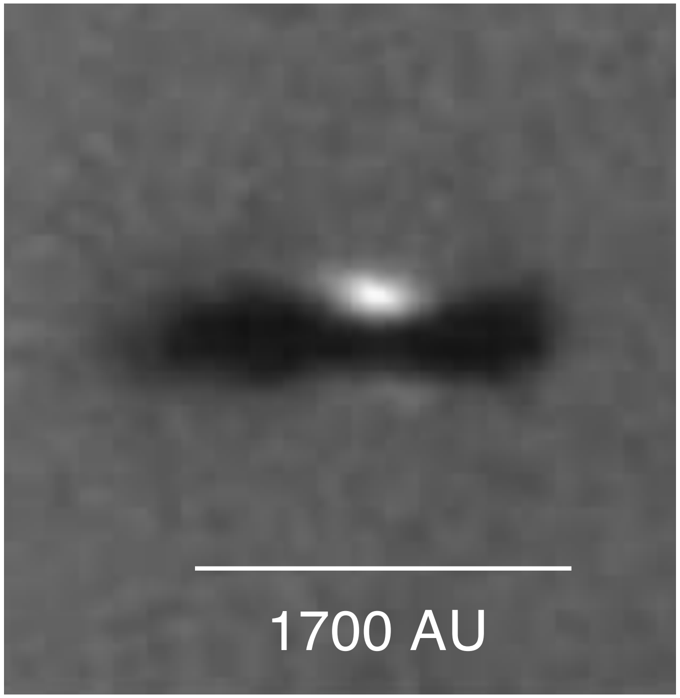
Young stars are classified as

- Class 0: protostellar concentration begins accreting from a molecular cloud
- Class I: protostellar core embedded in the infalling envelope. *L* is mainly from accretion. Timescale = free fall ~10^5 yrs.
- Class II: The envelope is still falling onto the star and its disk. The star is visible in the IR, and in the optical/UV from the hot disk. Examples are classical T Tauri stars. Timescale = gravitational release = KH ~10^6 yrs.
- Class III: The disk has also been accreted, so there is no additional UV and IR excess from disk. Examples are weak lined T Tauri stars. Timescale = gravitational release = KH ~ 10^6-10^7 yrs.


Formation of the central protostellar object
t ~ 0 yr
Protostellar Phase
Class 0
λ (mm)
0.01
0.1
1
Log (λF$_\lambda$)
Cold Black Body
submm
1
10
10^2
10^3
λ (μm)
Young Accreting Protostar
$T_{bol} < 70$ K, $M_* << M_{env}$
< 30 000 yr
Class I
×10
Infrared Excess
Black Body
1 2
10
100
λ (μm)
Evolved Accreting Protostar
$T_{bol} \sim 70$-650 K, $M_* > M_{env}$
~ 200 000 yr
Birthline for
Pre-main sequence stars
Pre-Main Sequence Phase
Class II
Disk
1 2
10
100
λ (μm)
Classical T Tauri Star
$T_{bol} \sim 650$-2880 K, $M_{Disk} \sim 0.01\ M_\odot$
~ 1 000 000 yr
Protoplanetary Disk ?
Class III
Disk?
Stellar Black Body
1 2
10
100
λ (μm)
Weak T Tauri Star
$T_{bol} > 2880$ K, $M_{Disk} < M_{Jupiter}$
~ 10 000 000 yr
Debris + Planets ?
Time

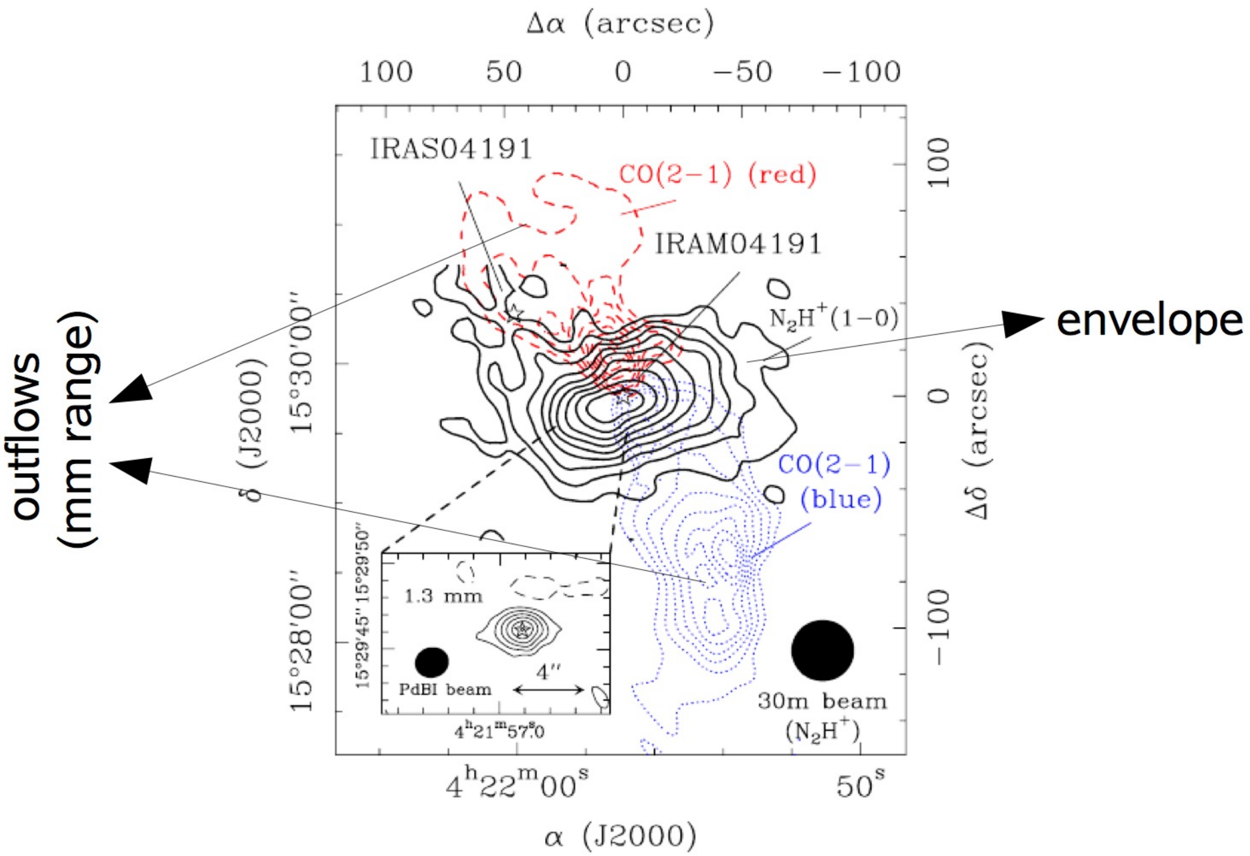
Protostars

Beta Pictoris in Orion



HST Image

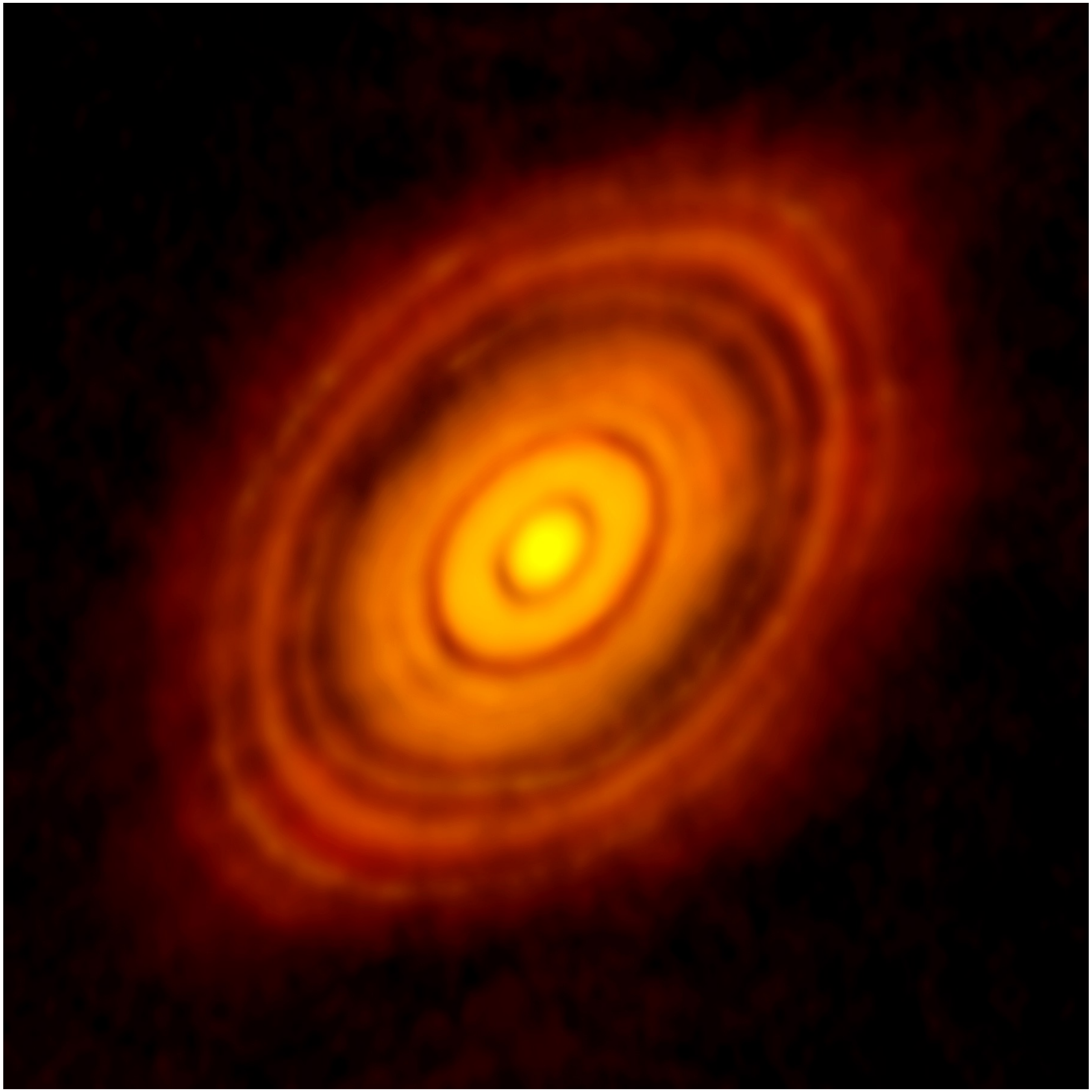
IRAS 04191 envelope + molecular outflow



outflows (mm range)

envelope

Proto Planetary Disks seen in the millimeter

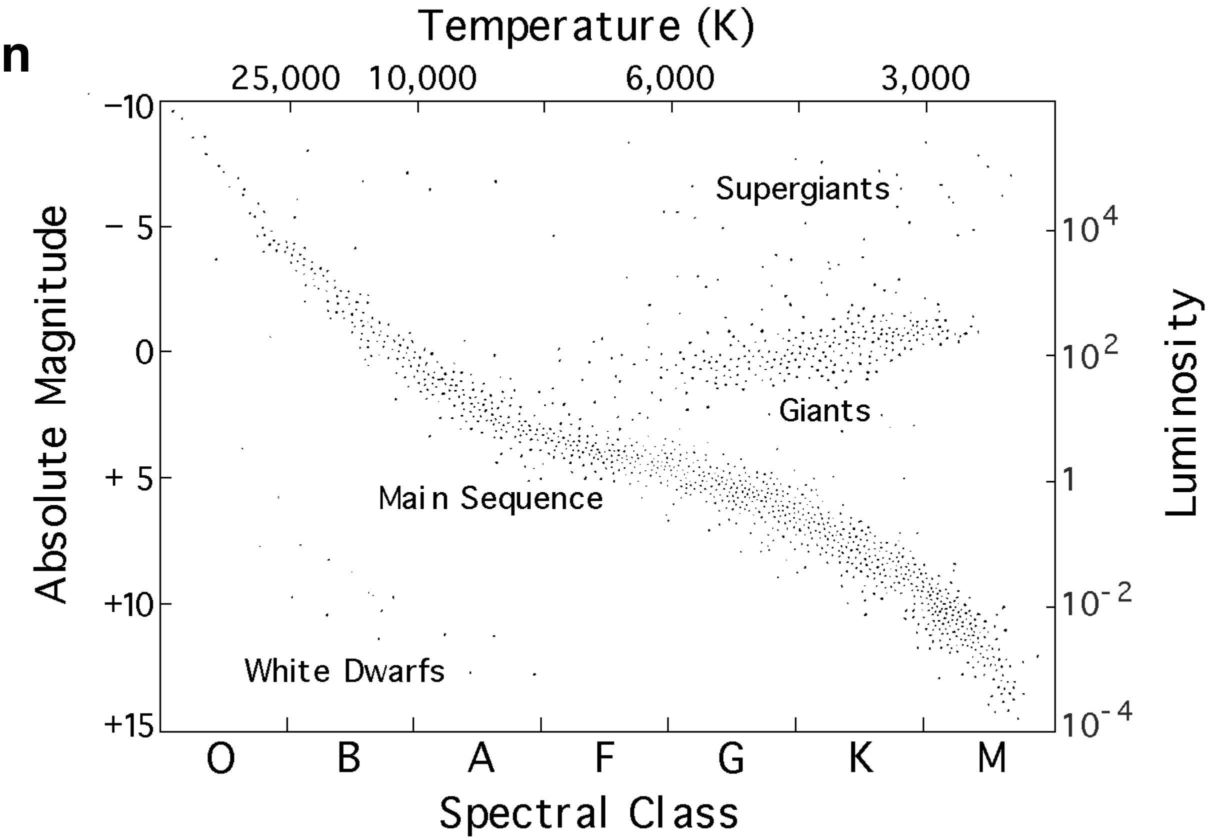


HL Tau
< 2 Myr old

Gaps swept out by
planets formation

Main sequence evolution

$$\boxed{P = \frac{\rho k T}{\mu m_H}}$$



Note width of MS. Why?

During MS H burns into He. After 50% of H has been used, the number of particles in core has decreased by a factor 0.73 (assuming original 10% He).

What are the implications?

$$P = \frac{\rho k T}{\mu m_H}$$

As H => He, μ increases in core.

$\Rightarrow$ *P* drops

$\Rightarrow$ core contracts

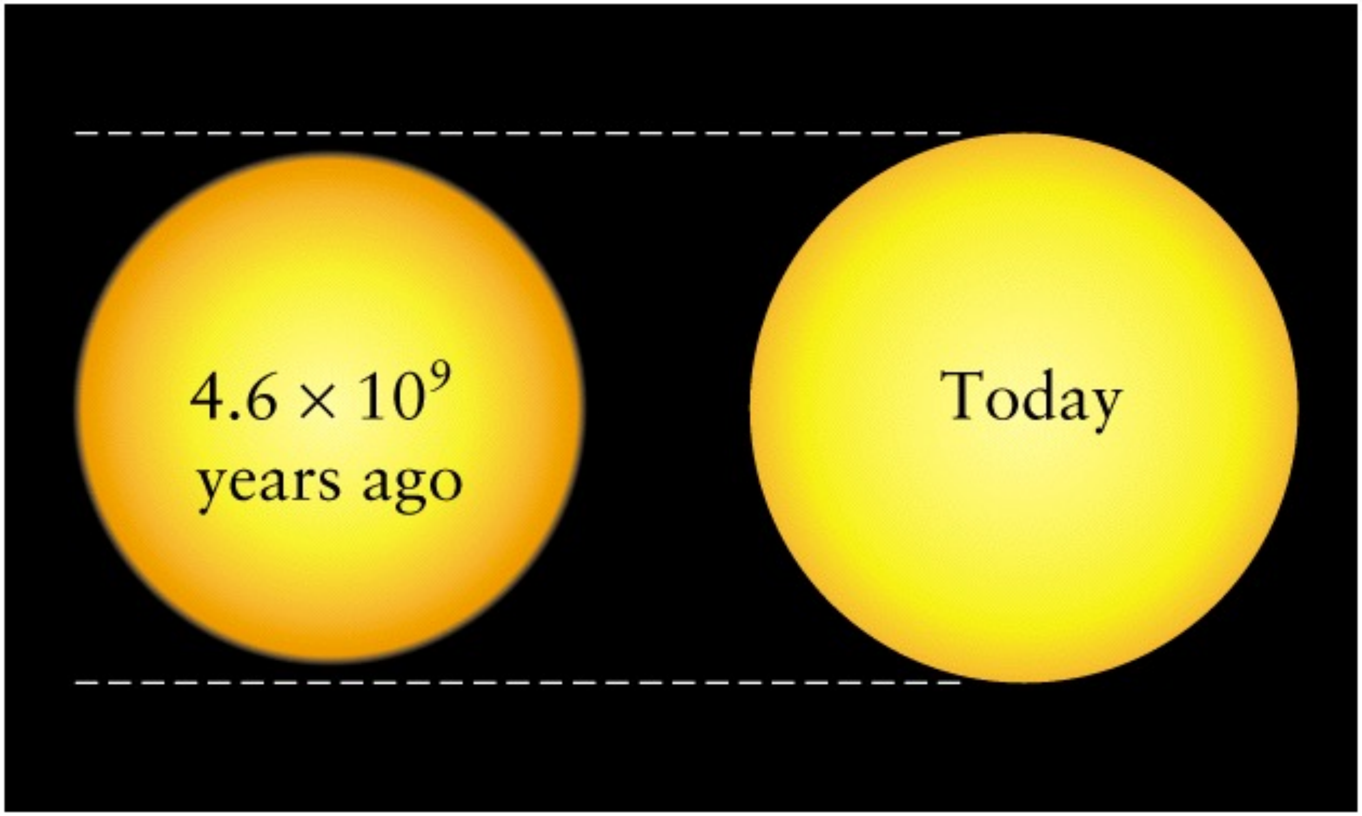
- According to Virial Theorem for a static star *E=U/2*.
- If gravitational collapse, *U* is being released, thus star must lose energy in process.
- Half of released P.E. goes into raising *T*, half goes into radiation

$\Rightarrow$ ρ, *T* rise => $\epsilon_{pp} \propto \rho X^2 T^4$ rises

$\Rightarrow$ *L* rise

Since the arrival on the MS, the Sun is 30% more luminous. Stars of a given mass, but different ages populate the MS with a width of ~ 0.5 dex.

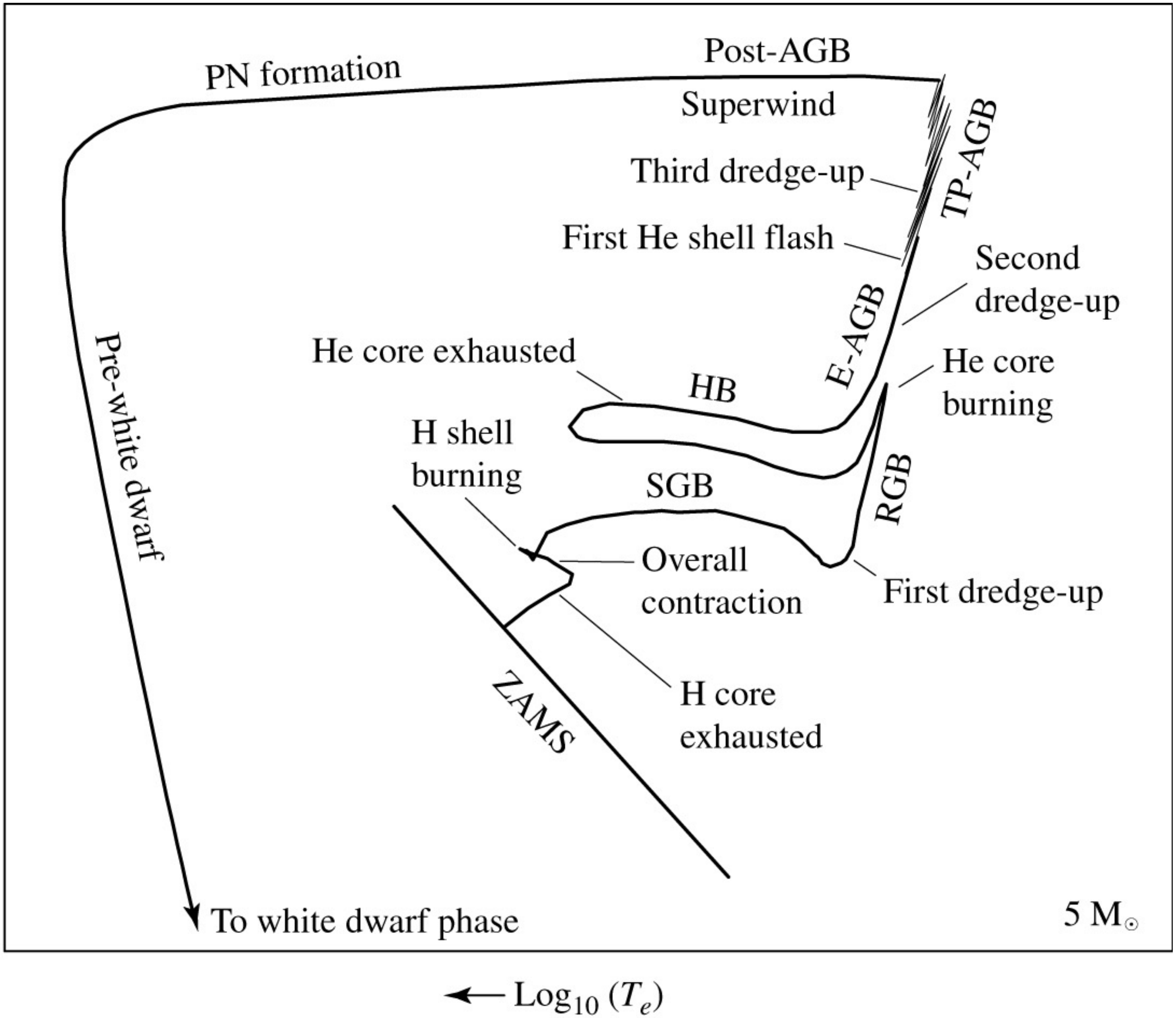
Thus, stars change a little during their MS lifetime.



Luminosity change: ~0.7% every 100 Myr.

The Sun is 30-40% more luminous, has a 6% larger radius and is ~300 K hotter than it was as a ZAMS star.

Consider 5 $M_\odot$ stellar evolution



Stellar wind

Most likely a large radiation pressure at top of AGB phase drives mass loss. Particles can absorb photons and be accelerated to escape the gravitational potential well.

Observations of red giants and supergiants (more massive evolved stars) suggest mass loss rates of 10^{-9} - 10^{-4} $M_\odot$/yr (cf Sun 10^{-14} $M_\odot$/yr).

Two types of mass loss:

1) Stellar wind - described by a formula linking mass, radius, luminosity with a simple relation and a constant obtained from observations. Wind mass loss rates ~ 10^{-6} $M_\odot$/yr.

2) Superwind - stronger wind responsible for stellar ejecta observed in shell surrounding central star, Wind mass loss rates ~ 10^{-4} $M_\odot$/yr.

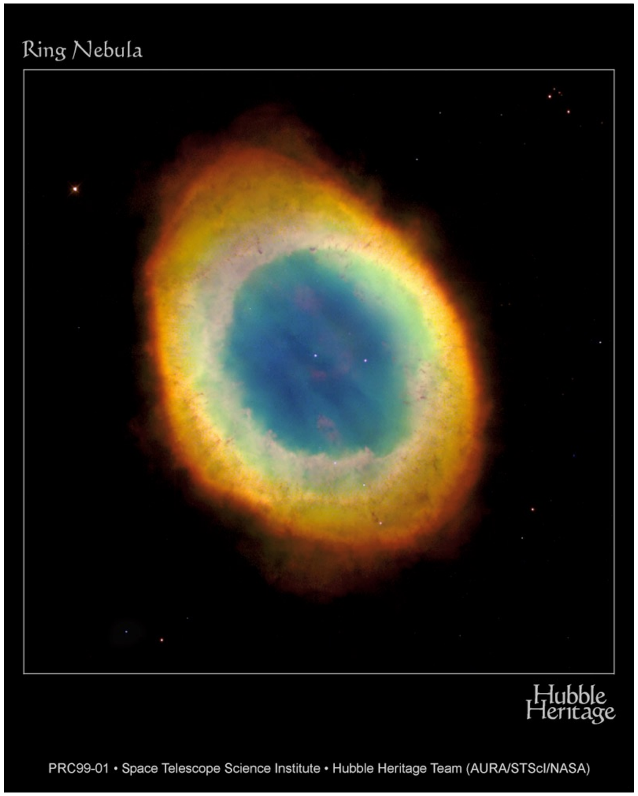
Do superwinds exist?

- agrees with high density in observed shells in stellar ejecta
- agrees with paucity of very bright stars on the AGB

Comes from # AGB stars expected compared to observed is > 10! A process must exist that prevent the stars from completing their motion up through the AGB while loosing mass only via stellar winds.

The superwind removes envelope mass before core has grown maximally.

The superwind causes envelope ejection. The cores evolve into C,O white dwarfs (WD). Core mass at top of AGB phase ~ $0.6M_\odot$ - consistent with masses of WDs.



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Some details due to circumstances and not completely obvious
from first principles.

Nevertheless, evolution driven by laws and concepts we have discussed, e.g.

- Blackbody radiation
- Fusion rate dependence on density, temperature
- Pressure vs. gravity
- Opacity, especially temperature dependence (lower with higher T)
- Gravitational contraction and Virial Theorem
- Convection

Post MS stellar evolution – intermediate mass stars $M < 8M_\odot$

Evolution into subgiant

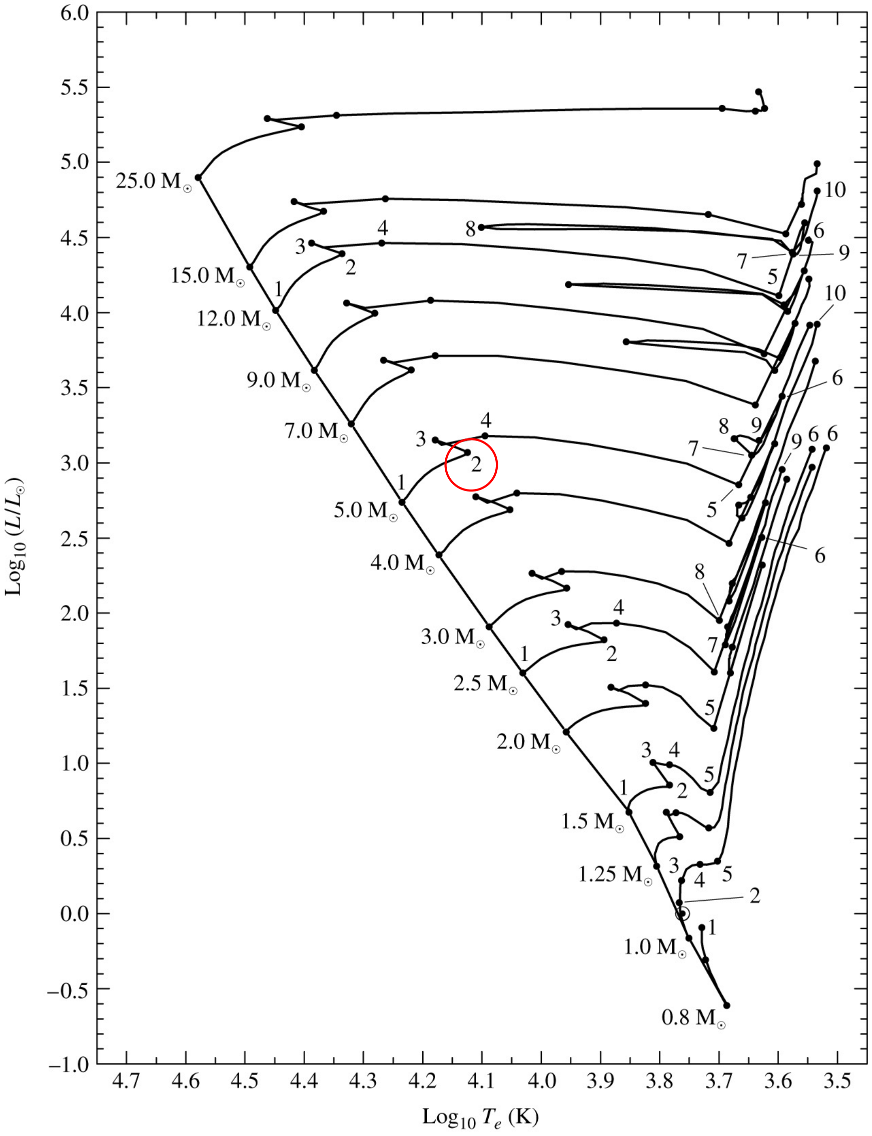
Focus mainly on $\sim 5M_\odot$ stars. Some of the details differ for $\sim 1M_\odot$ stars, please read. Total lifetime $\sim 10^8$ yr. Main sequence radius $\sim 3R_\odot$.

- Core H eventually exhausted. Core now He, fusion stops. But core can still support itself for now.

- The He core is isothermal, which can be seen from:

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\overline{\kappa}\rho}{T^3}\frac{L_r}{4\pi r^2} \qquad \text{so if } L_r = 0, \ \frac{dT}{dr} = 0$$

- Now at 2 in C+O Fig 13.
- Whole star contracts around “inert” He core on Kelvin-Helmholtz timescale (change in grav. PE of star divided by its luminosity). These changes *not* due to fusion but gravitational contraction at this point! Virial theorem applies: half of released gravitational PE goes into raising T_{eff}, half into radiation, so L rises.
- Reaches 3 in Fig 13.1.

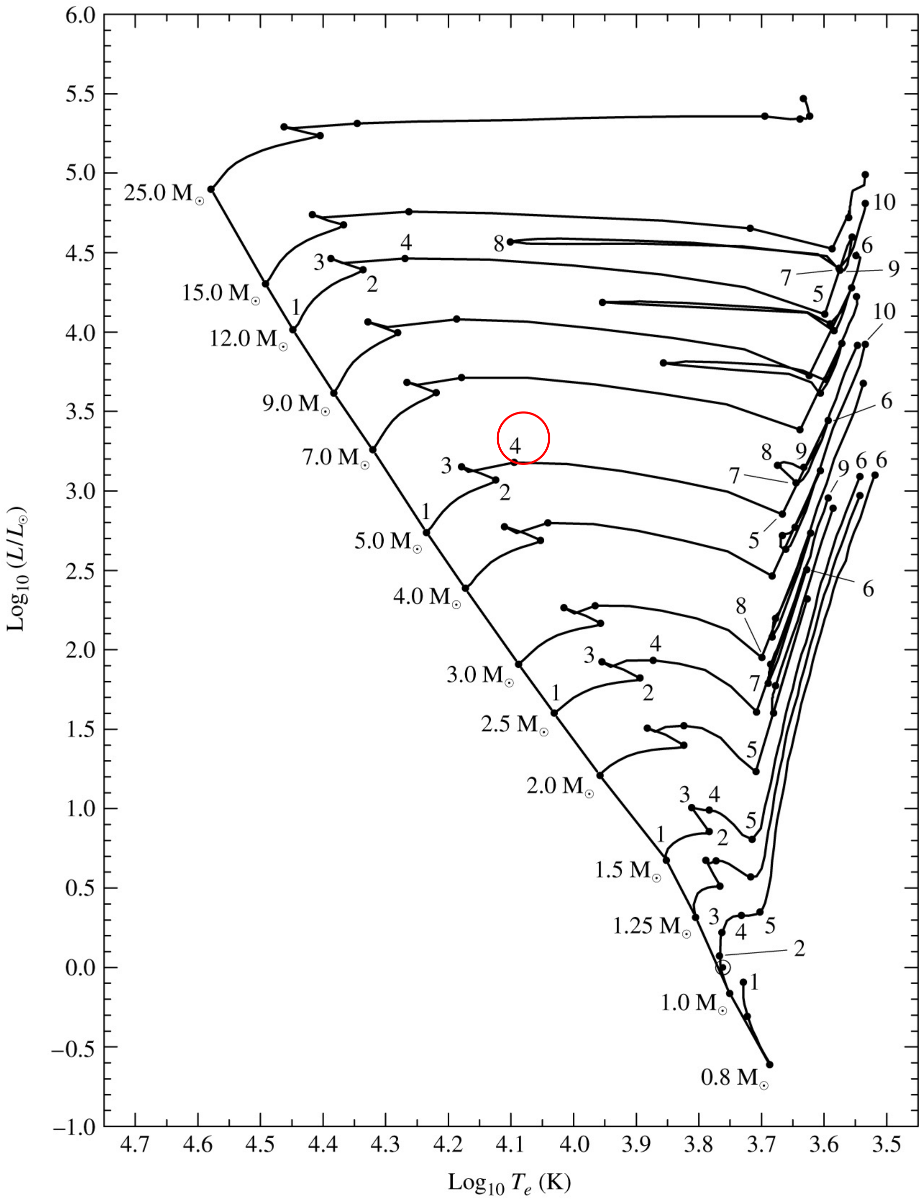


- Now region of envelope around inert core becomes hot enough for H to ignite – “shell H burning” phase starts. This is “mildly explosive”. Most energy into expanding star. R up, T_{eff} down.
- Reaches 4 in Fig 13.1.
- H shell burning dumps He onto core, increasing its mass

- An isothermal core can no longer support itself against envelope when:

$$\frac{M_{core}}{M_*} \gtrsim 0.08$$

(Schönberg-Chandrasekhar limit; skip derivation in 13.1)



- Core shrinks over ~ 10^6 yrs (Kelvin-Helmholtz timescale).

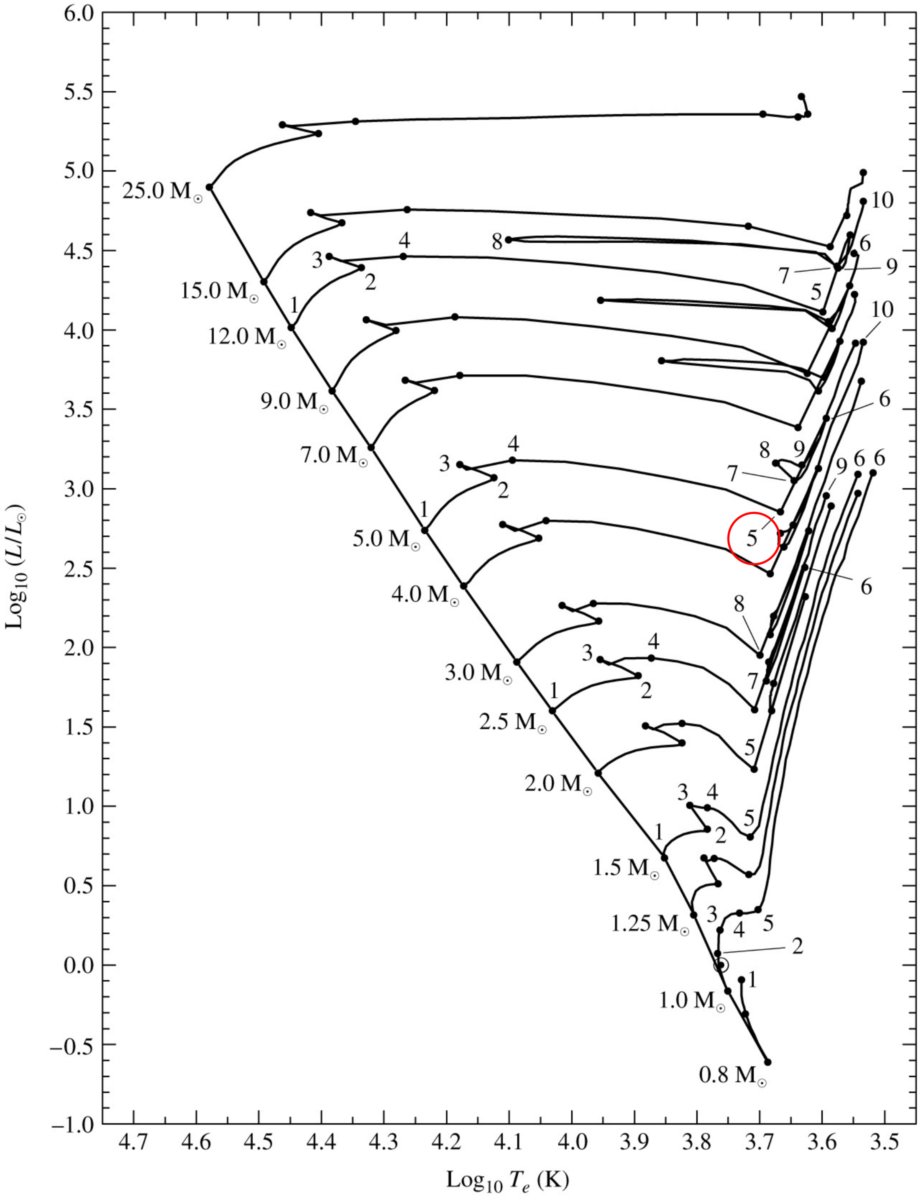
- ρ, T rise in shell. ϵ rises greatly. Most ϵ into expanding envelope. R rises, T_{eff} drops and L drops a little. Star now a Subgiant.

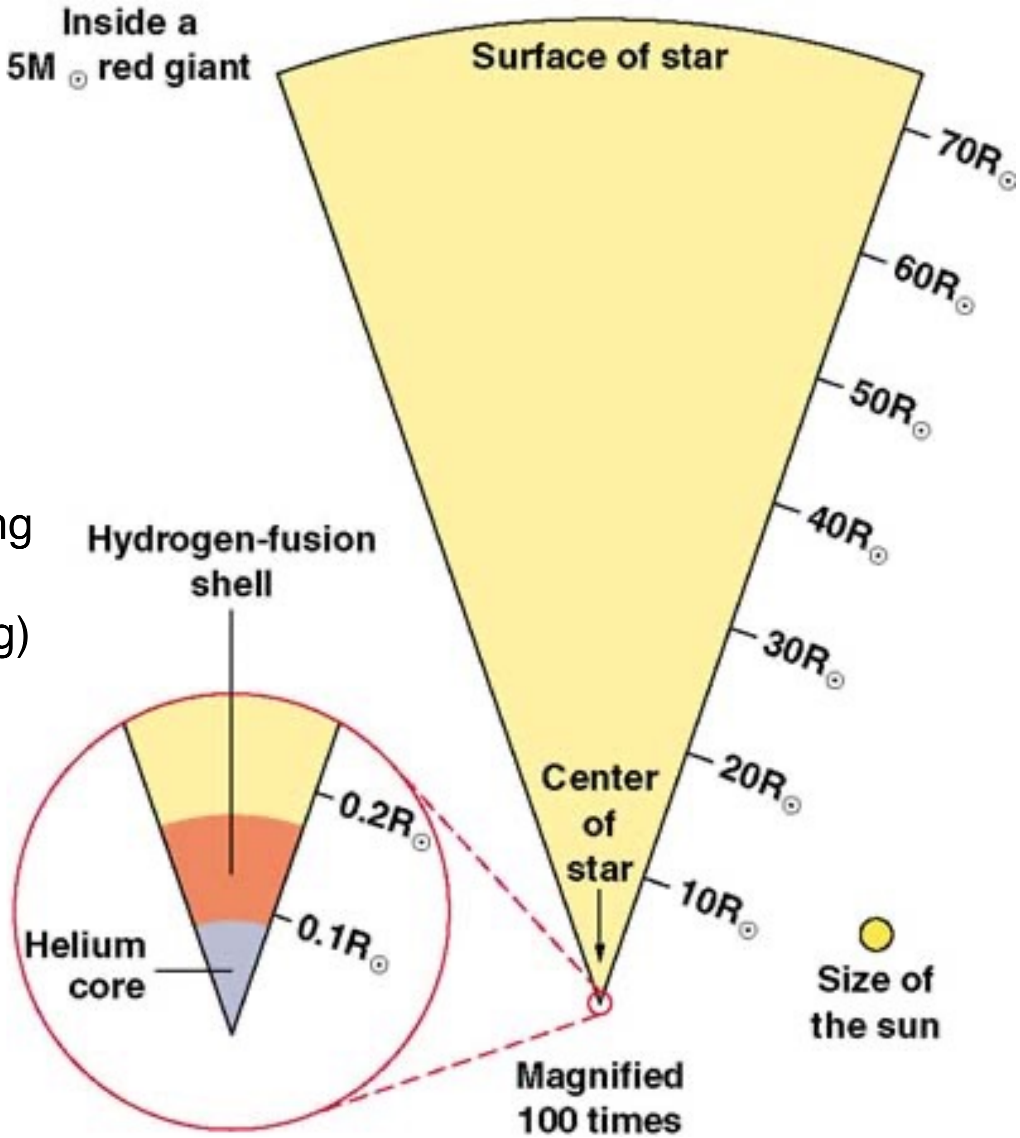
- 4 – 5 in Figure 13.1

- From 2 to 5 is about 3 x 10^6 yr for $5M_\odot$ star.

Red Giant

- Since T_{eff} drops, H$^-$ opacity rises, thus dT/dr rises, and convection zone moves deep into star.
- "Dredge-up" becomes possible for first time. Products of fusion reactions can be brought to surface, changing abundances in spectra.
- L starts to rise rapidly for two reasons. First, efficient energy transport by convection. Second (not properly explained in C+O) in cooling envelope e^-'s start to combine with metals, reducing supply for H$^-$ to form. Opacity drops, radiation can escape. Star moves nearly vertically in the HR diagram.
- 5 – 6 in Fig 13.1. Almost 10^6 yr.
- Strong mass loss through winds.





shell shrinking, getting
hotter and denser,
fusion rate increasing)

(core shrinking)

He flash, core He burning and the Horizontal Branch

- Core contraction until *T* reaches 10^8 K when He can ignite (He -> C, some C-> O).

- For $M < 1.8 M_\odot$, the He core will have contracted to a degree that it becomes a “degenerate” gas. $\rho \sim 10^8$ kg m^{-3}. Each electron confined to such a small volume that its momentum becomes very large by the Heisenberg Uncertainty Principle. For such a gas

$$P \propto \rho^{5/3}$$

P independent of *T* (due to e$^-$ pressure). Fusion raises *T*, but not *P.* So fusion does not stop core from contracting. Fusion rate therefore increases, etc. Runaway “He flash”.

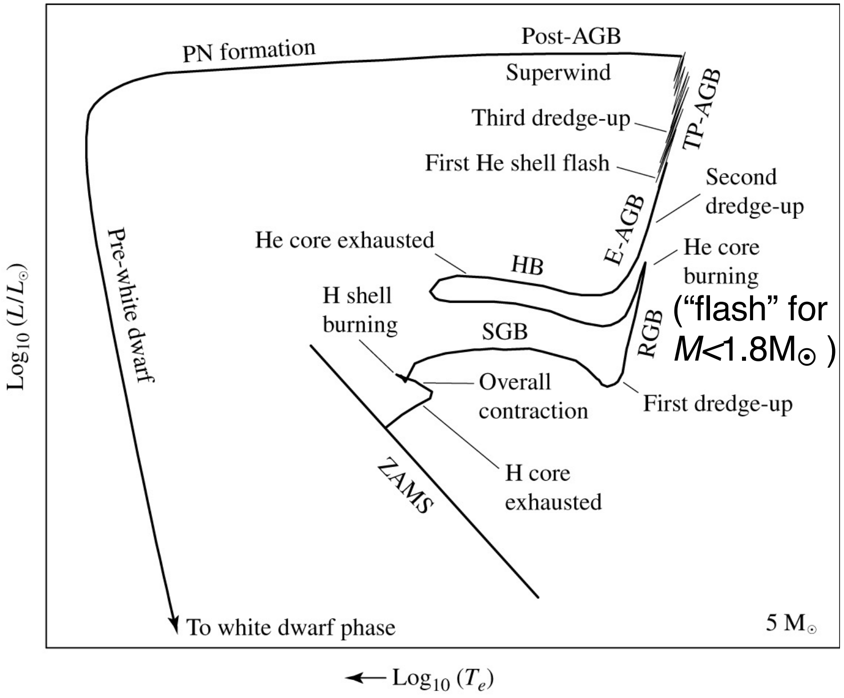
- But *condition* for degeneracy *does* depend on T. Eventually T high enough so that gas reverts back to ideal gas, now with very high ρ and T. Core re-expands in a few seconds. For $M > 1.8 M_\odot$, He fusion starts smoothly, and so does core re-expansion.

- Expanding core pushes H-burning shell outward.

- Shell H-> He burning actually dominates core fusion. But core expansion has dropped shell T and thus energy generation.
- => shell $T\downarrow$, $\rho\downarrow$, $L_{shell}\downarrow$
- *=>* $L_* \downarrow$, $R\downarrow$, $T_{eff}\uparrow$

- Enters the *Horizontal Branch*. On "blueward" part, $T_{eff}\uparrow$ means opacity drops. Even as fusion weakens, radiation can get out more easily, $L_* \uparrow$ slightly.

- On the "redward" horizontal branch, the core slowly shrinks again as μ increases. H shell fusion intensifies, so $R\uparrow$, $T_{eff}\downarrow$.



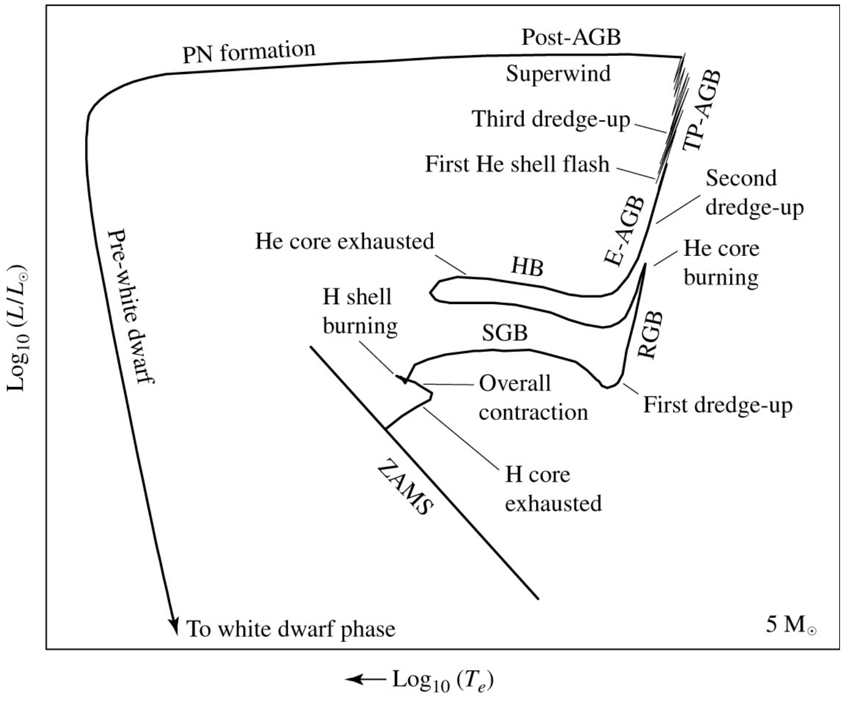
Asymptotic Giant Branch

- Core continues to shrink. T = 2 x 10^8 K, density 10^9 kg m^{-3}. Becomes degenerate. He shell forms around inert C,O core, and He fusion intensifies as core beneath it shrinks.
- Evolution similar to Red Giant phase.

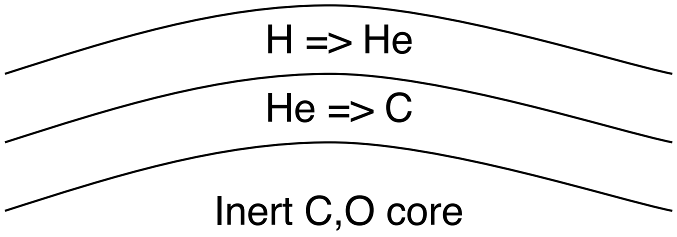
- High *L* in He shell eventually causes *R, L* of star to increase, and H shell pushed out and nearly turns off. This is Early AGB. Star becomes convective again – second phase of dredge-up.

- Eventually, He shell starts to run out of fuel and contracts, as does H shell around it, so that H shell reignites. Now H shell dominates energy production.

- Track in HR diagram approaches RG branch => "*asymptotic*"



He shell flashes - thermal pulses



H => He

He => C

Inert C,O core

Due to fusion from H shell, He shell builds up, compresses, heats up, becomes slightly degenerate.

⇒ When hot enough, He shell flash.

H shell expands, cools, turns off. He fusion ends, H shell contracts.

⇒ H fusion again.

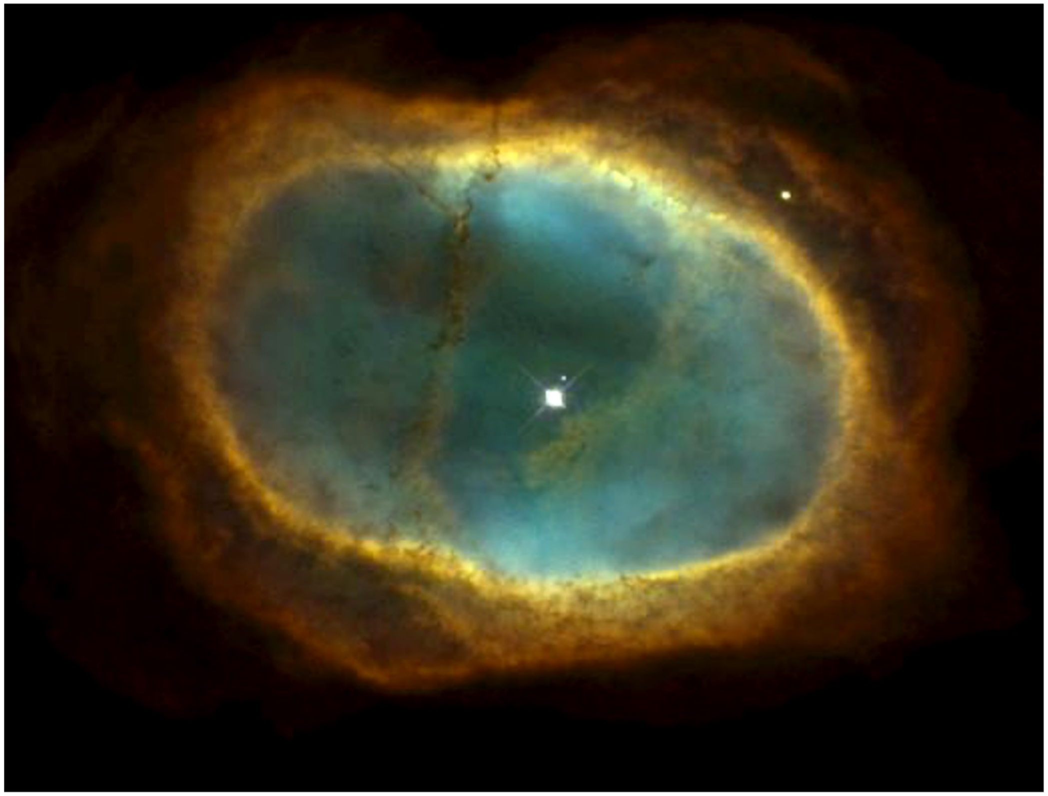
Whole process repeats. Each flash more violent, envelope pulsates, *L* rises and falls. Period 1000's of years for $5M_\odot$ star, slower for lower masses.

This is "Thermal-Pulse AGB" phase. Strong winds again. Convection and dredge-up again, especially of C produced in He shell -> "Carbon stars".

Planetary nebulae

High mass loss rates during this phase, up to 10^{-4} $M_\odot$ yr^{-1}. Eventually, rest of envelope expelled at speeds 10-30 km/s after a few 100 years it will be visible as a “planetary nebula” (PN). PN lasts for ~10^5 yrears

Inert, degenerate C,O core (with residual layer of H, He) remains, a *white dwarf* (WD), Earth size. *M* ~ few 10ths $M_\odot$. Cools over billions of years. Degenerate.



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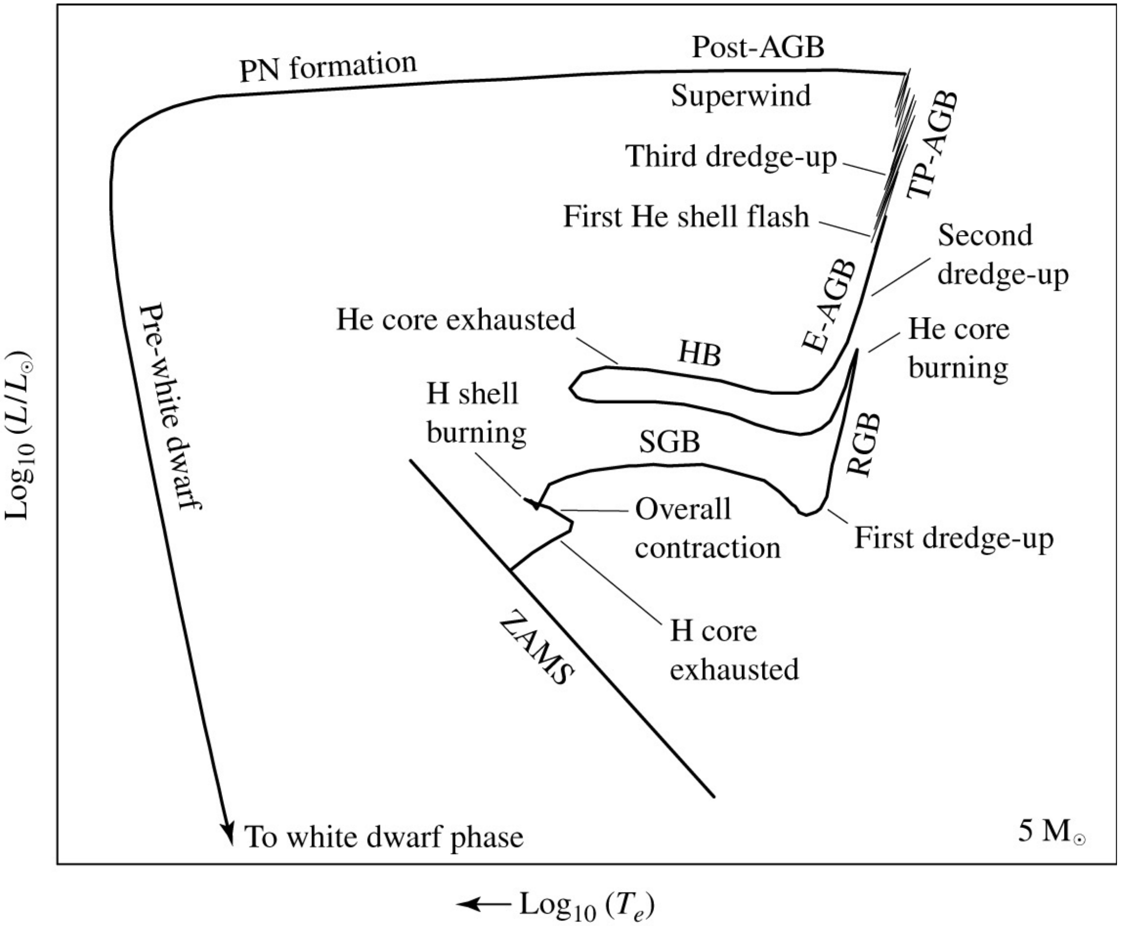
Summary of 5 $M_\odot$ evolution

Typical timescales:

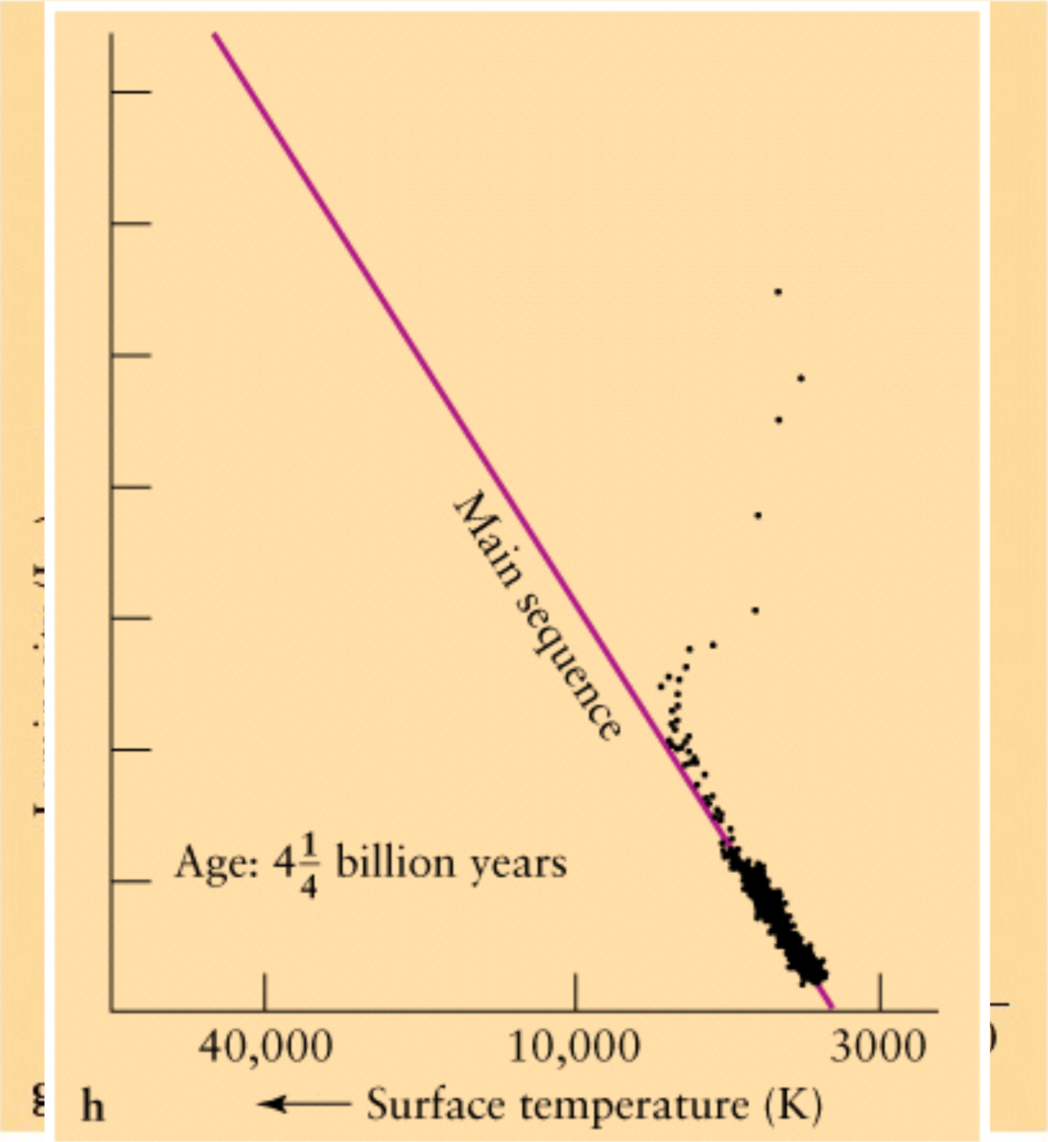
MS	9×10^7 yrs
Subgiant	3×10^6
Red Giant Branch	5×10^5
Horizontal Branch	1×10^7
AGB evolution	1×10^6
PN	1×10^5

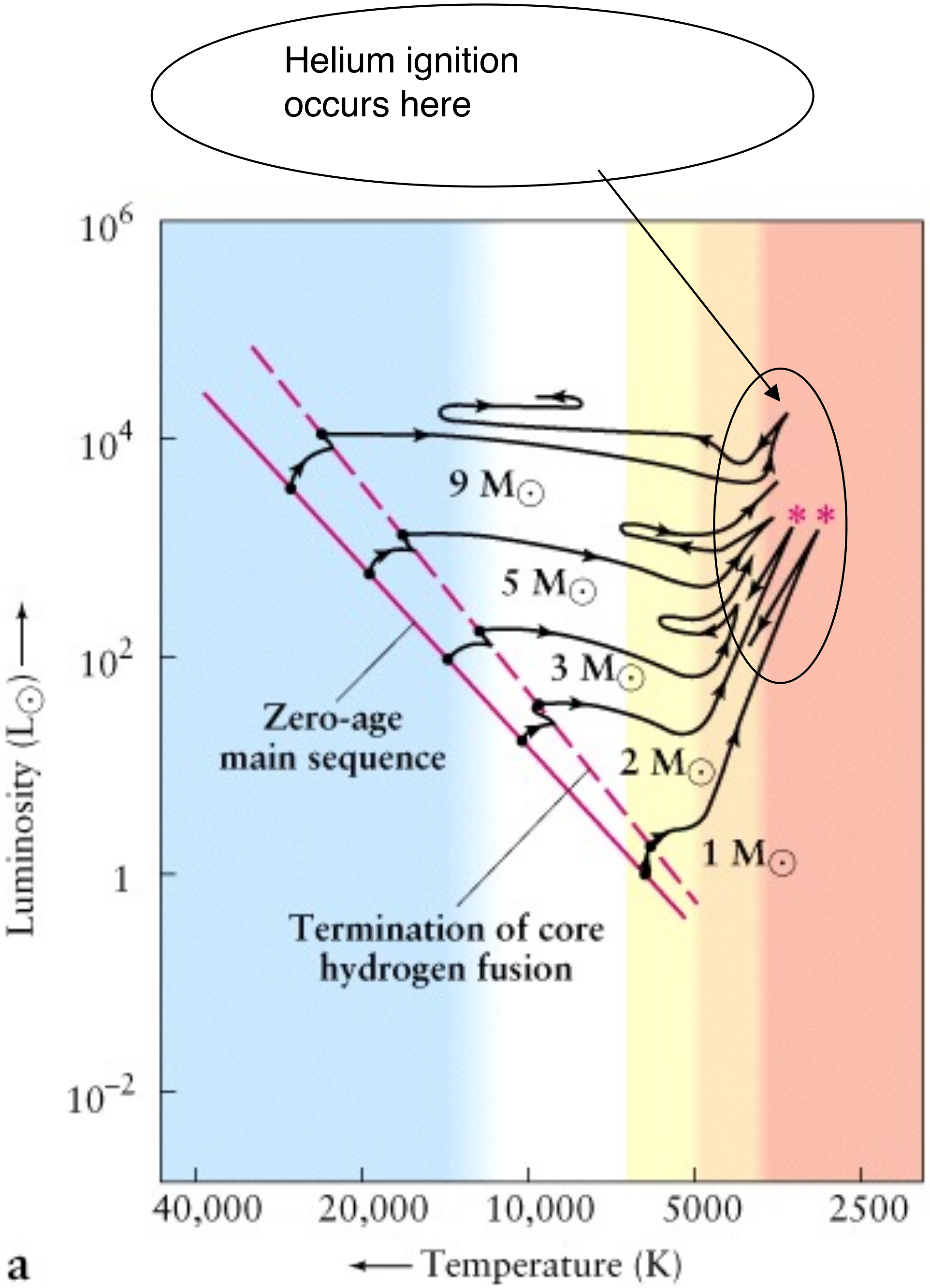


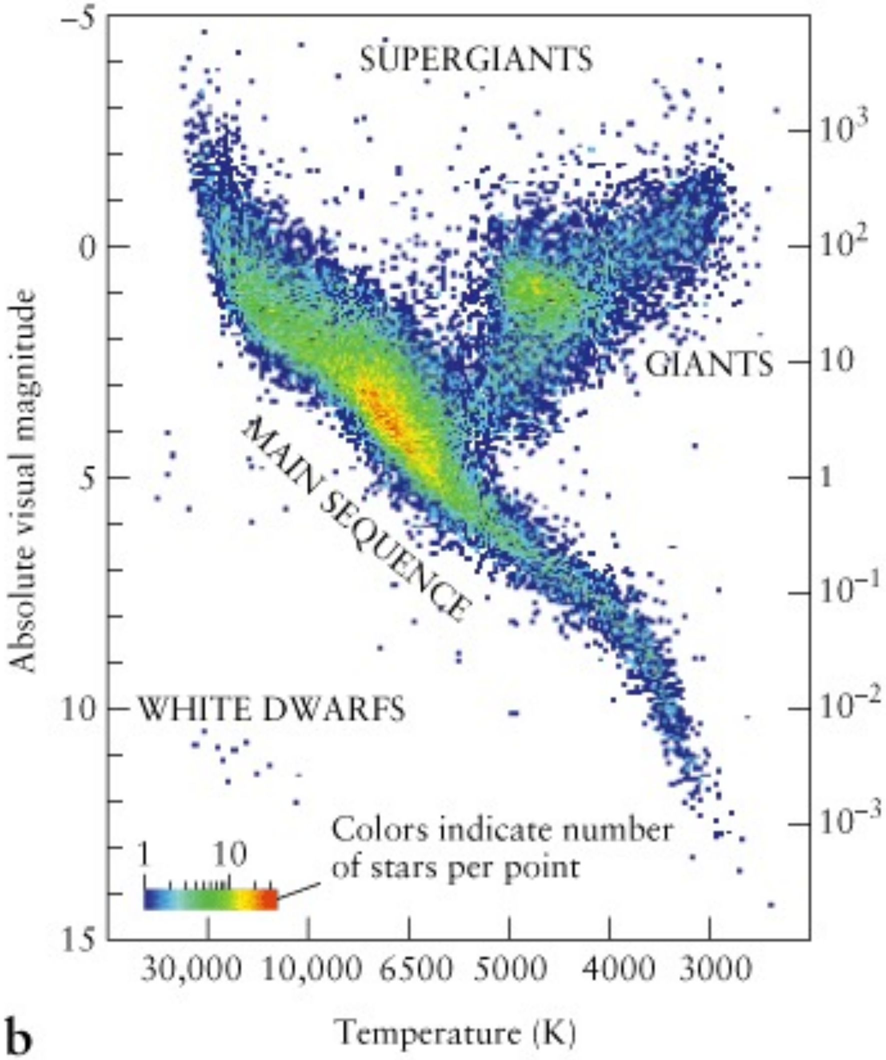
These are theories, and we cannot see deep down into stars. How can we test whether these models are viable?

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

Theoretical tracks:

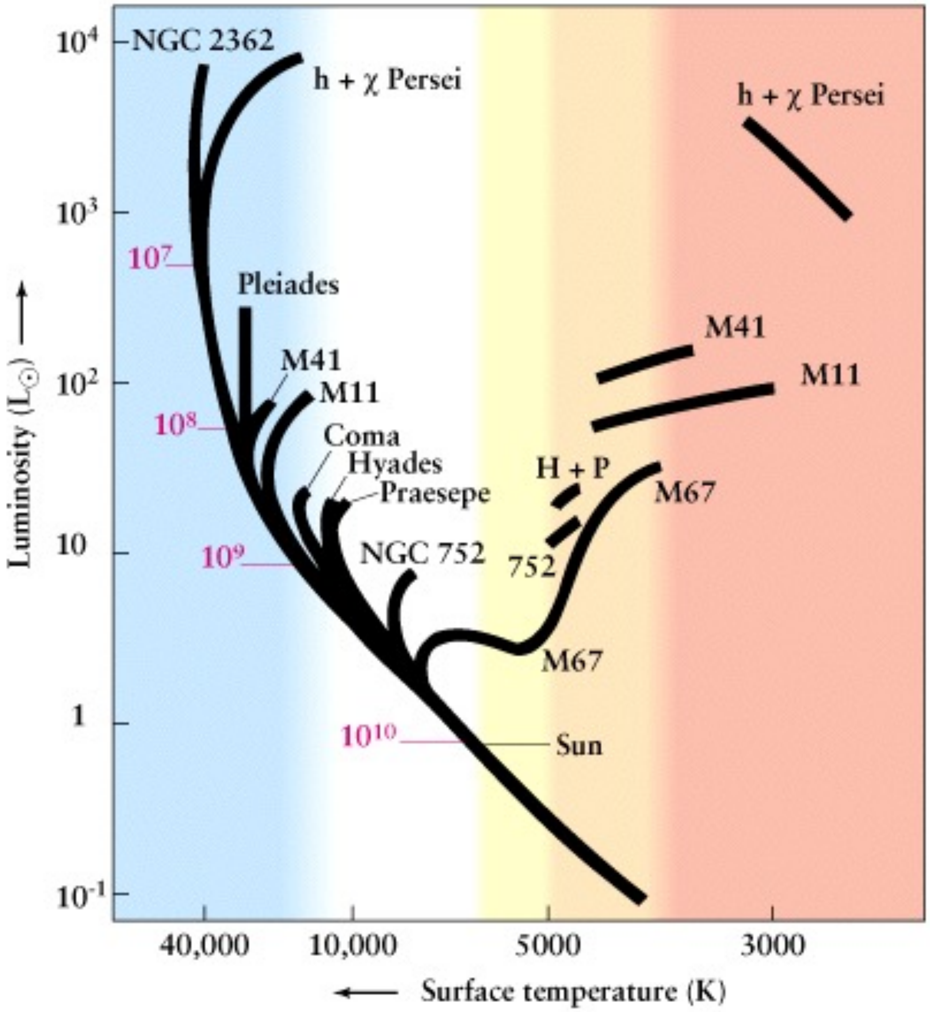



Helium ignition occurs here


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

Comparison theory and observations

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

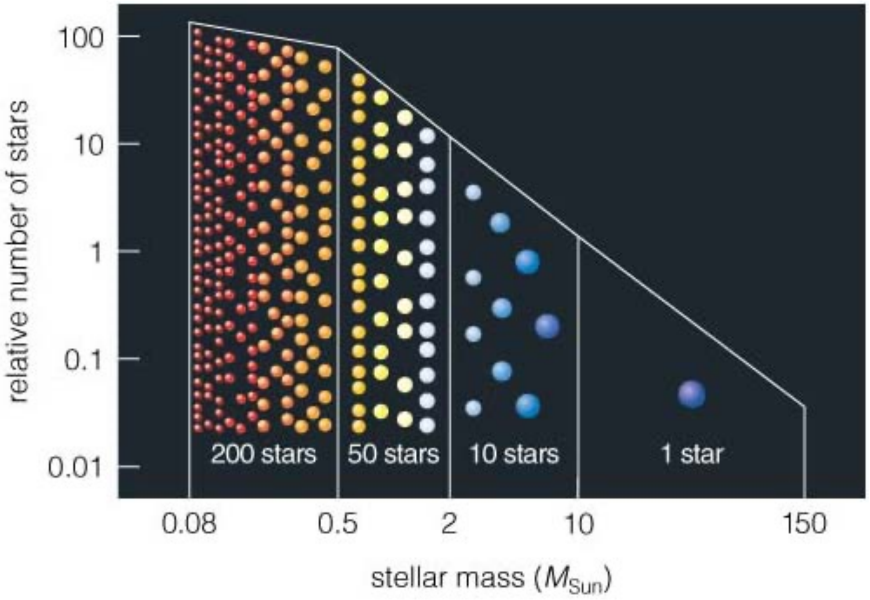


HR Diagram - Worksheet #5

Sketch the HR Diagram for an Open Cluster with age 10^8 years.

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



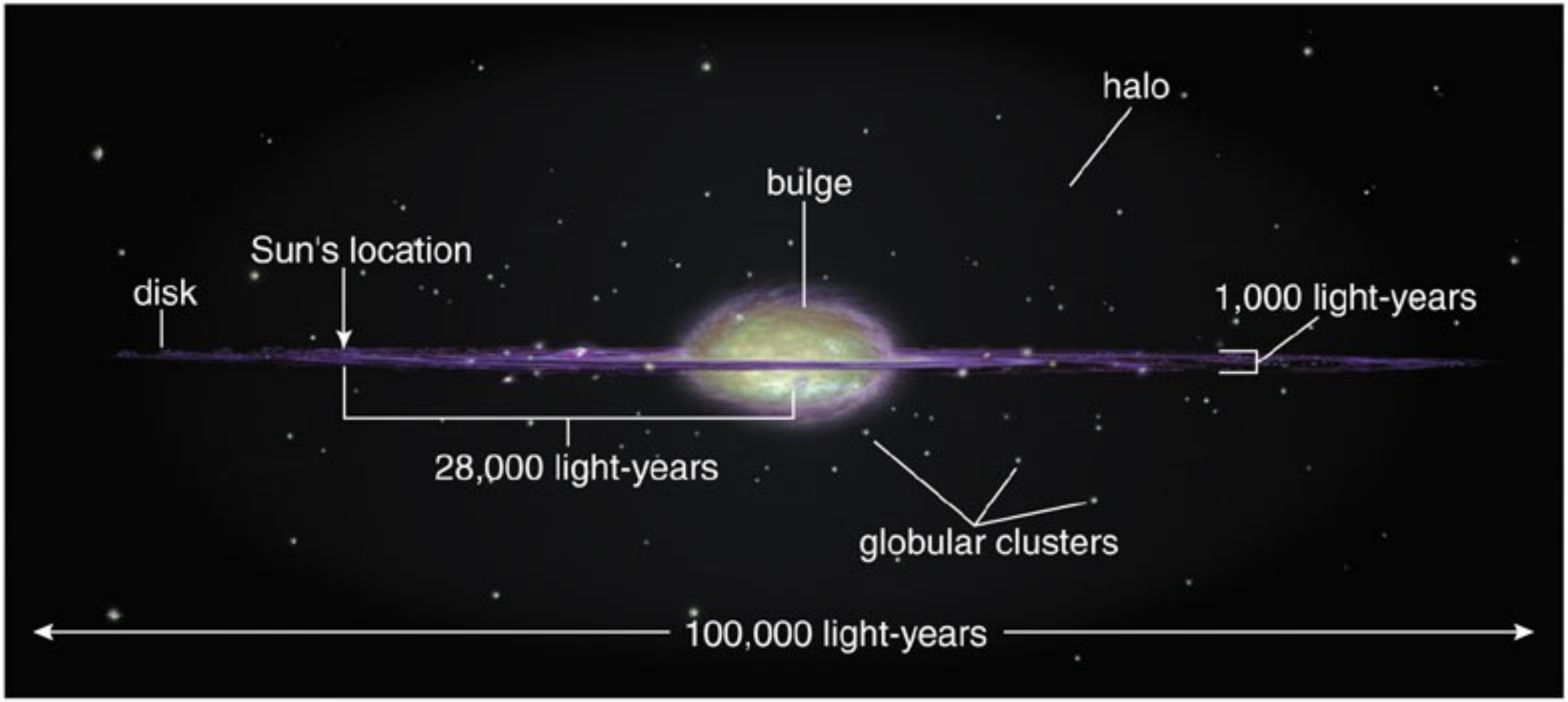
Open clusters

- 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.

H and Chi Persei

M35 and NCG
2158 in Gemini


halo
bulge
Sun's location
disk
1,000 light-years
28,000 light-years
globular clusters
100,000 light-years

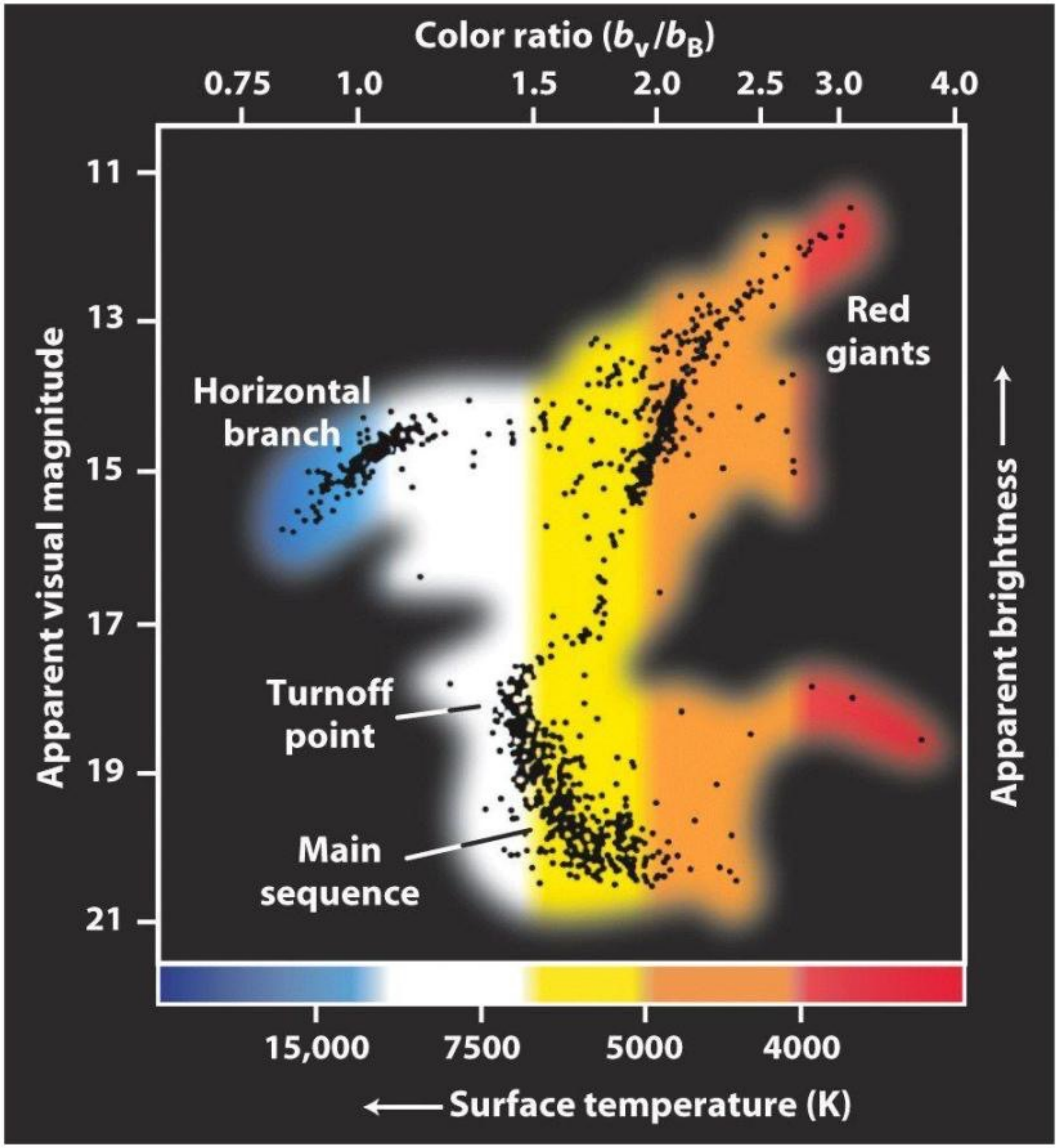
Globular clusters

- 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

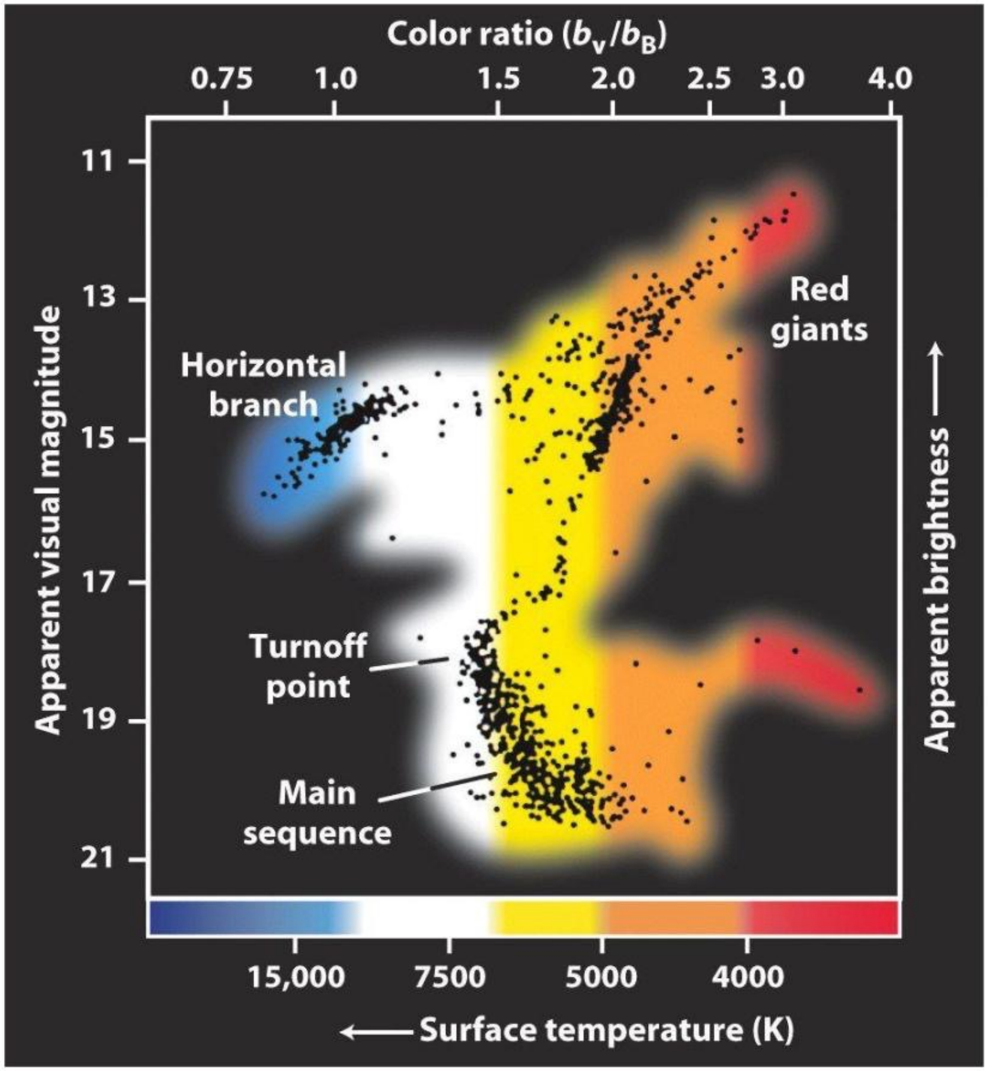
Typical globular cluster H-R diagram. Note low turnoff point, and many red giants. Age?

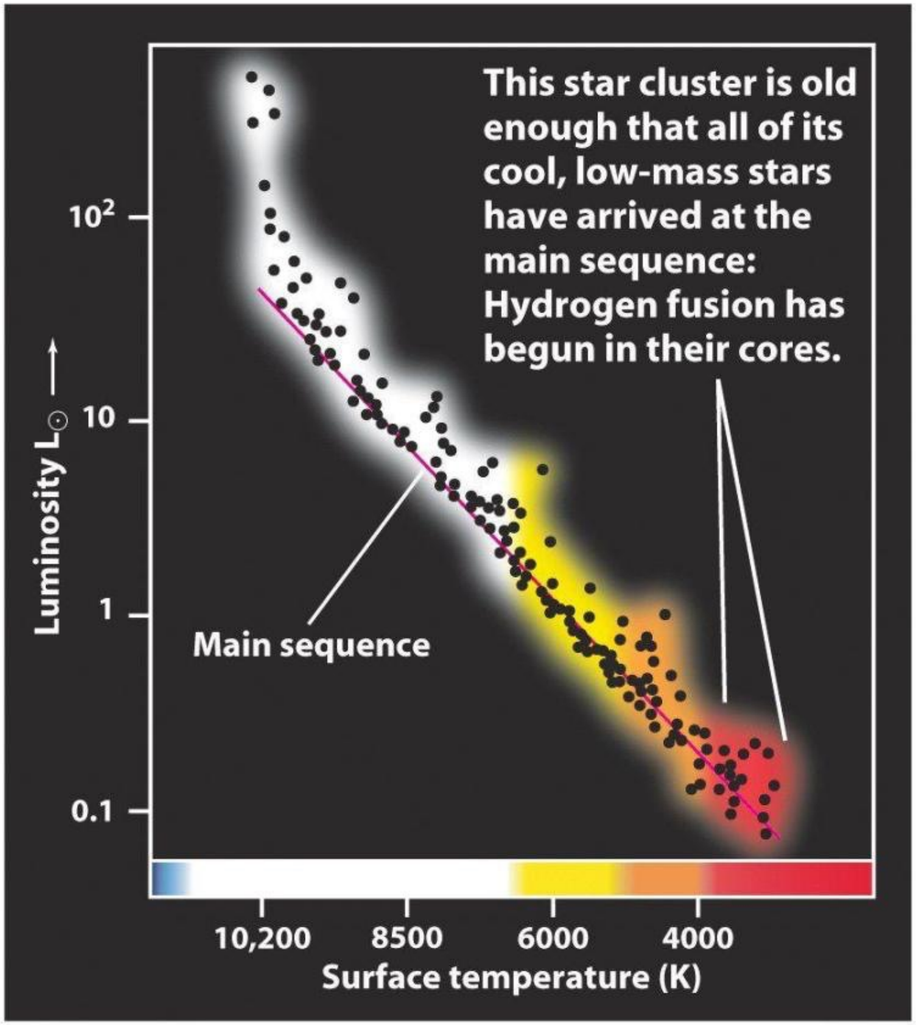


Compare to open cluster H-R diagram

Globular cluster

Open cluster





This star cluster is old enough that all of its cool, low-mass stars have arrived at the main sequence: Hydrogen fusion has begun in their cores.

An H-R diagram of the stars in the Pleiades

Key points

Post main sequence evolution

Sub Giant Branch (SGB)

- Red Giant Branch (RGB)
  - Horizontal Branch (HB)
    - Asymptotic Giant Branch (AGB)

Chapter 13