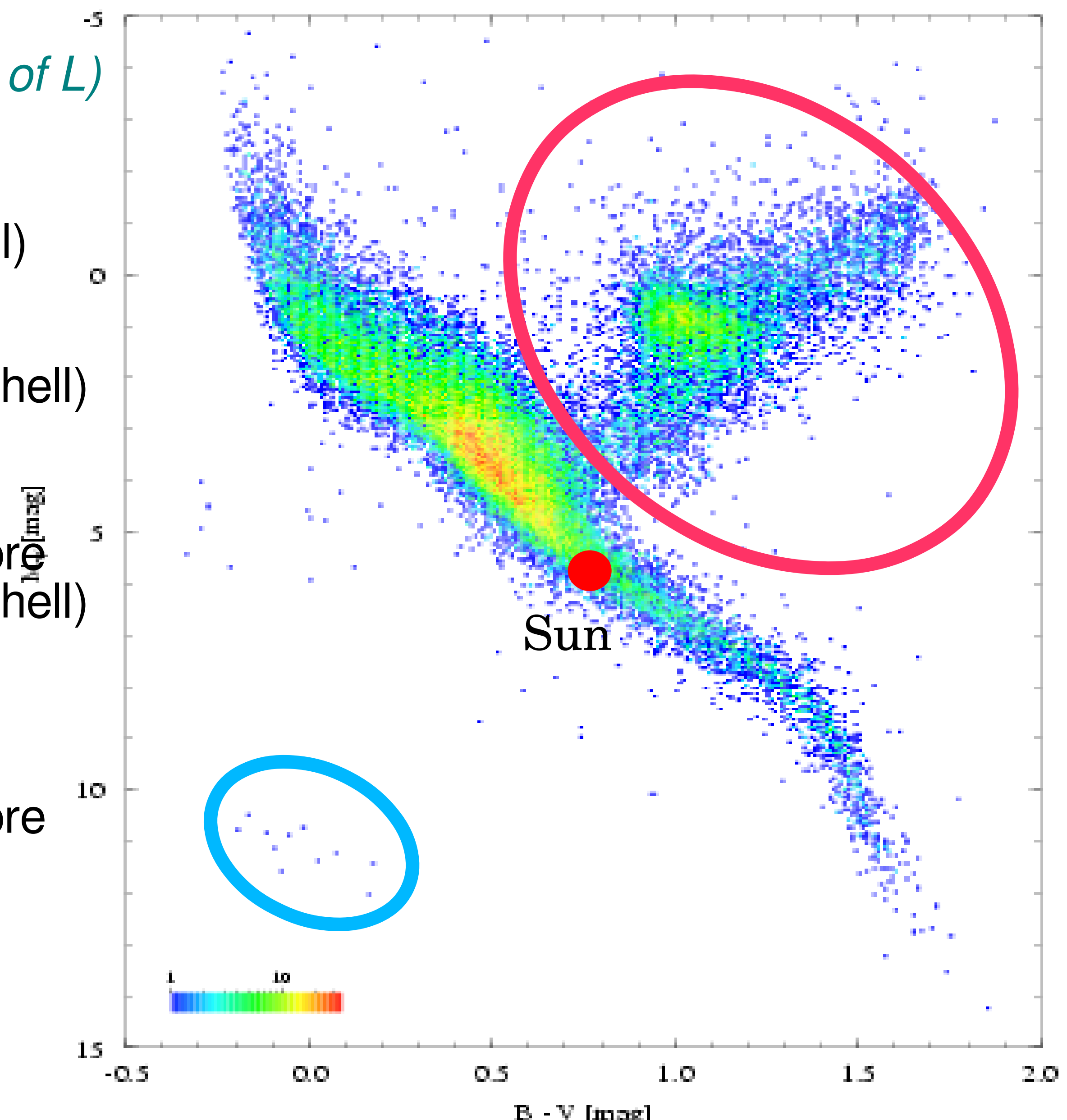
Stars: beyond the Main Sequence

Main-sequence
1) first and dominant stage in life,
2) H → He in the core *(subtle rise of L)*
3) >80% stars in MS

Low-mass stars
1) Ascend Red Giant Branch (H shell)
2) Red clump/Horizontal branch
   (He → C in core, H shell)
3) Asymptotic Giant Branch (H, He shell)
4) Env. ejection → White Dwarf

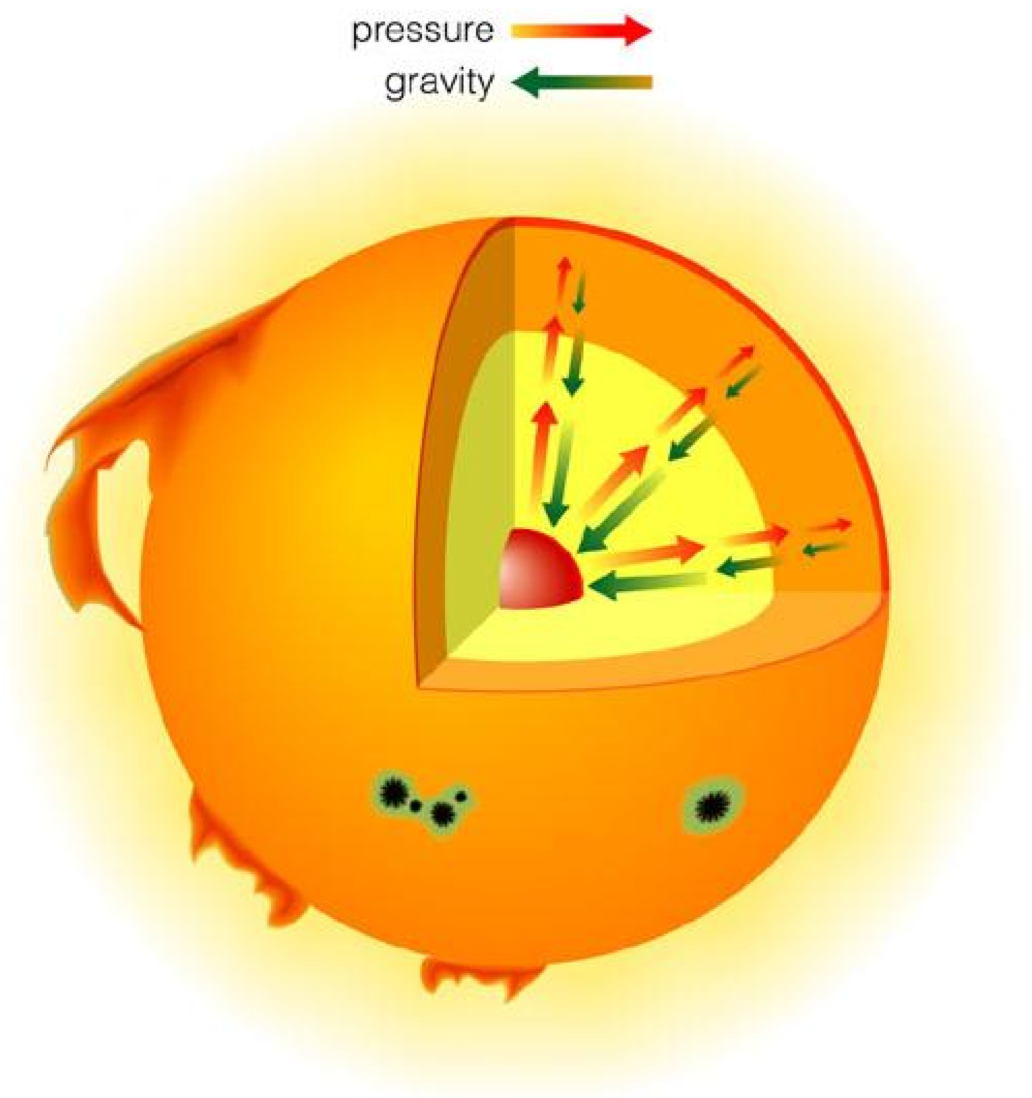
Intermediate-mass stars
1) Expand at L~const, ignite He in core
2) Asymptotic Giant Branch (H, He shell)
   Some: "super-AGB" (H, He, C shell)
3) Env. ejection → White Dwarf

High-mass stars
1) Expand at L~const, ignite He in core
2) Fusion in stages, up to Si → Fe
3) Core collapse → Neutron star, Black hole



Hipparcos HRD

Star's life: Protracted battle with gravity



ALWAYS

To support weight:

⇒ need high pressure

MOSTLY

⇒ need high temperature

⇒ will loose energy

⇒ need energy source:
- Gravitational contraction
- Nuclear fusion

Ultimately,
Can something else than thermal pressure balance gravity?

Degeneracy for a White Dwarf or degenerate core

using wave-particle duality

$$M=1M_{\odot}, R=6000\ km,\ electron\ mean\ spacing\ d\ \sim\ \frac{1}{n_e^{1/3}}\ \sim\ 10^{-12}\ m$$

$$De\ Broglie\ wavelength\ \lambda\ \sim\ \frac{h}{p}\ \sim\ \frac{h}{m_e v}\ \sim\ 10^{-12} m\ \left(\frac{10^9 K}{T}\right)^{1/2}$$

$\rightarrow$ *typically* $\lambda > d$ *in white dwarfs*

1. *Wave nature of electrons becomes relevant*
2. *Electrons are fermion: they do not like to be close; this exclusion provides pressure*

electron degeneracy pressure: $P\ \propto\ n_e^{5/3}\ \propto\ \rho^{5/3}\ \rightarrow\ R\ \propto\ M^{-1/3}$

Sirius B (1 $M_{\odot}$*) smaller than typical white dwarfs (0.6* $M_{\odot}$*)*

(compare with MS: $P\ =\ n k T$ *plus* $T \sim constant\ \rightarrow\ R\ \propto\ M$*)*

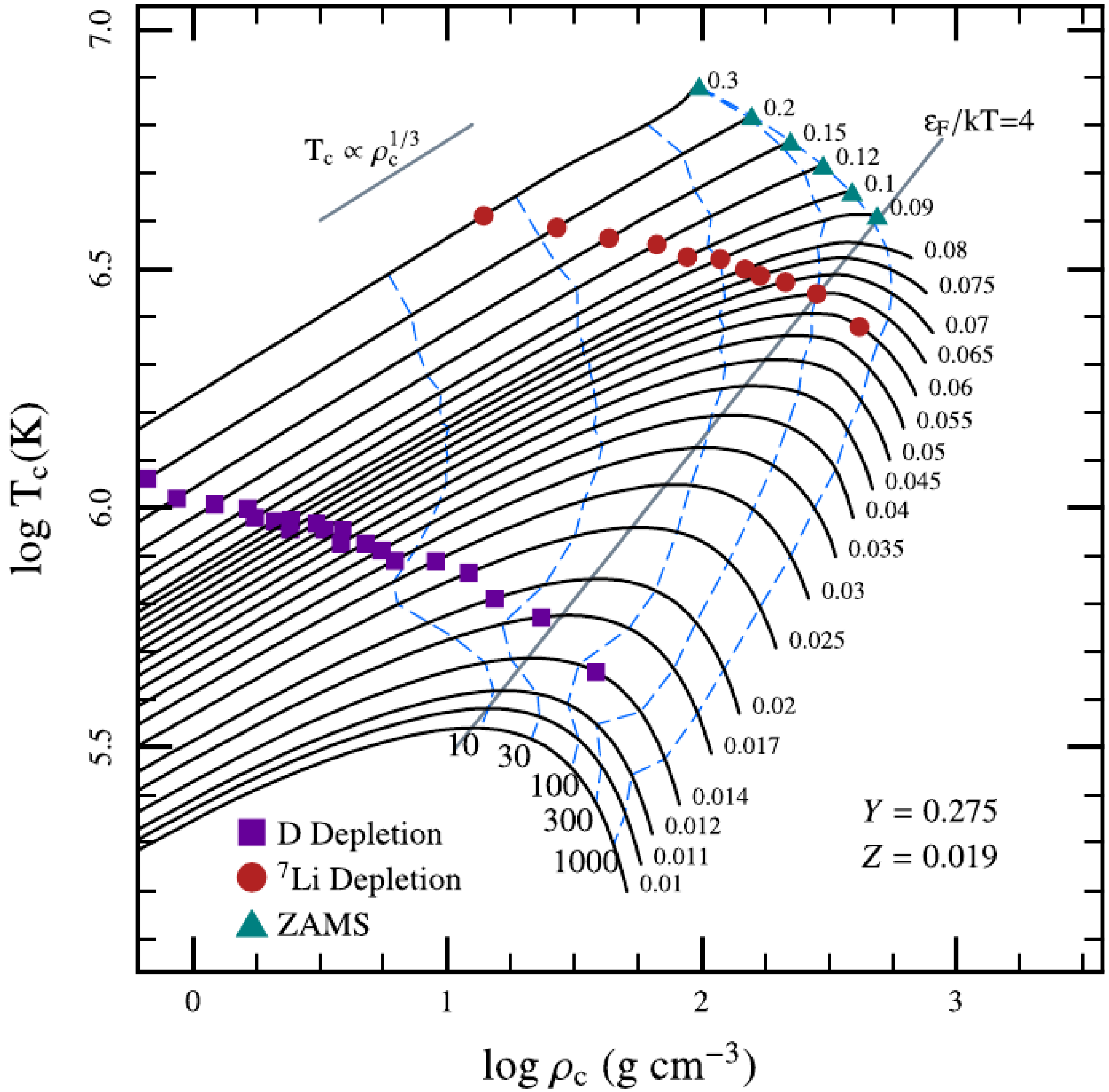
Can $M\ \rightarrow\ \infty$*? No, would need* $v\ >\ c\ \rightarrow$ *Chandrasekhar limit:* $M < 1.4 M_{\odot}$

White dwarfs are supported against gravity by pressure from degenerate electrons (ions irrelevant). This pressure depends only on density, not on temperature.

-- also centre of evolved low-mass stars, brown-dwarfs, Jupiter, metals...

Brown dwarf (M < 0.08 M$_\odot$)

no H fusion → never becomes star



Paxton et al., 2011, ApJS 192:3

Ultimately,
Can something else than thermal pressure balance gravity?

Below ~0.08 M$_\odot$,
objects become degenerate before becoming hot enough to ignite H fusion
→ *Brown dwarfs*

Below ~0.013 M$_\odot$,
no fusion at all (not even D)
→ *Planet?*

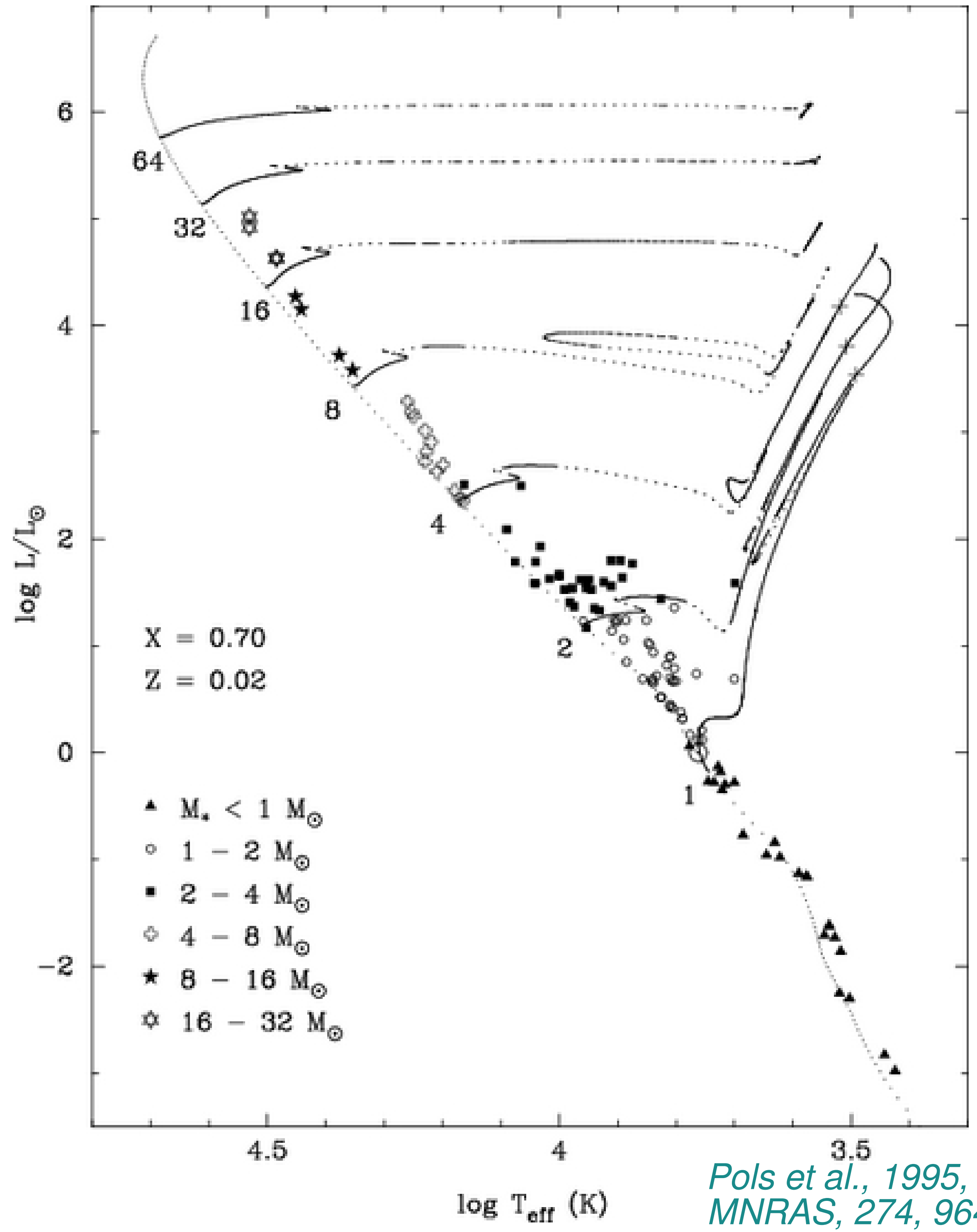
Low-mass star ($M < 8\ M_\odot$)

gradual exhaustion of H & He
ends due to mass loss

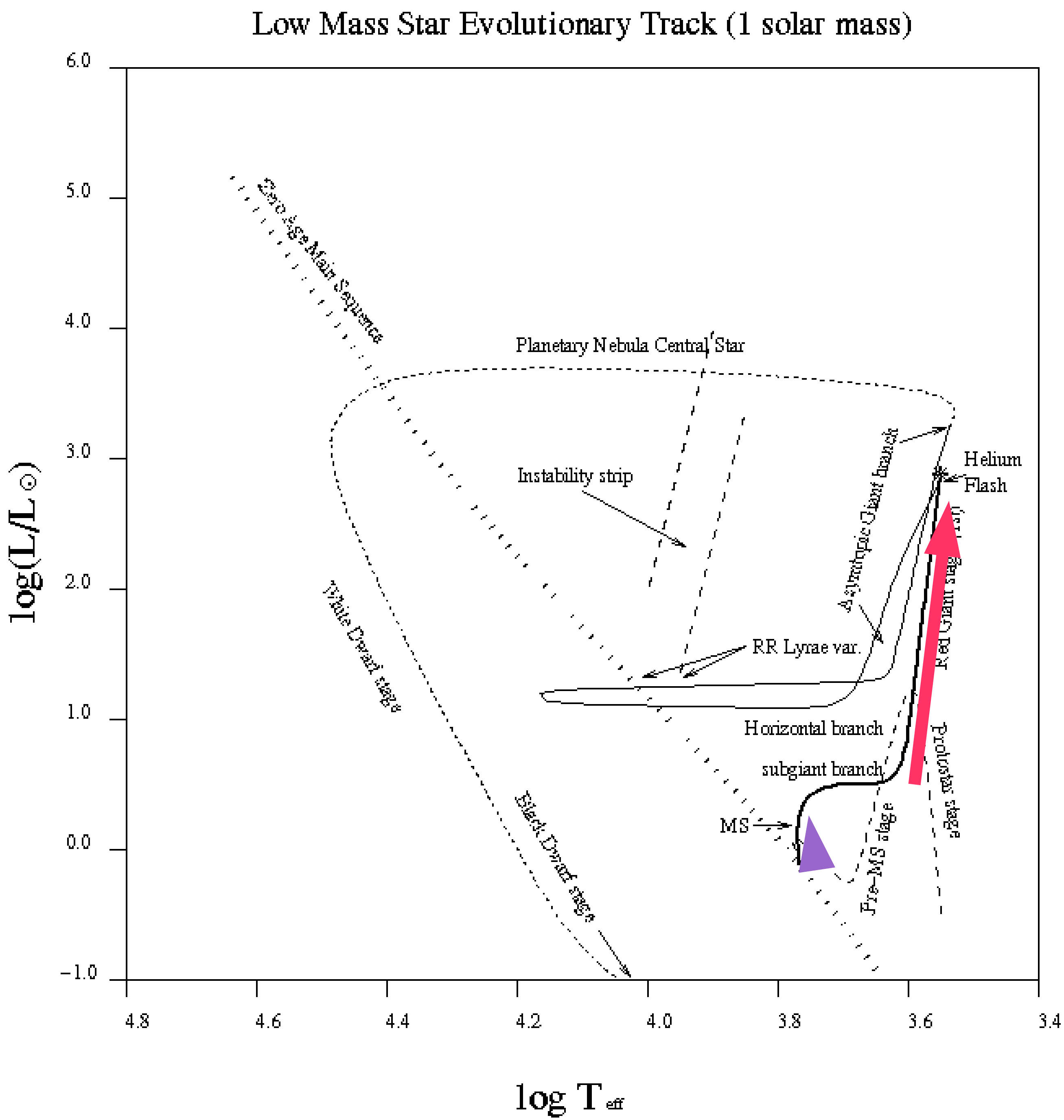
Main sequence ↓	Core H burning; for $\sim 1 M_\odot$, $dM/dt \sim 10^{-14}\ M_\odot/yr$, live $\sim 10^{10}$ yr $(M/M_\odot)^{-3}$
Red Giant ↓	Dense core + tenuous envelope; $\sim 100\ R_\odot$, $\sim 10^8$ yr, shell H burning, mass loss $dM/dt \sim 10^{-7}\ M_\odot/yr$; envelope convective, core shrinks *(why?)*
Red clump/Horizontal Branch ↓	$T_{core} \sim 10^8$ K, He fuses in core, but H shell dominates L; ~10% of main-sequence lifetime; move to blue if metal-poor
Asymptotic Giant ↓	C/O core + extremely tenuous envelope, $\sim 600\ R_\odot$; $\sim 10^6$ yr, $10^5\ L_\odot$, shell He/H burning, He shell flashes; end of AGB: $dM/dt \sim 10^{-5}\ M_\odot/yr$, removes whole envelope
White dwarf	Dense C/O, $\sim 0.6\ M_\odot$, $\sim 0.01\ R_\odot$, e^- degeneracy, cools from $\sim 10^5$ K to few 10^3 K in $\sim 10^{10}$ yr
+planetary nebula	Few $0.1\ M_\odot$, expansion speed ~20 km/s, fluoresces for $\sim 10^4$ yr

Net effect of a star's life: mass loss → metal enrichment of the interstellar medium

Evolutionary tracks:
what happens depends on mass



Pols et al., 1995, MNRAS, 274, 964



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

Main-sequence

Earlier: lower L; paradox of the 'faint young sun'

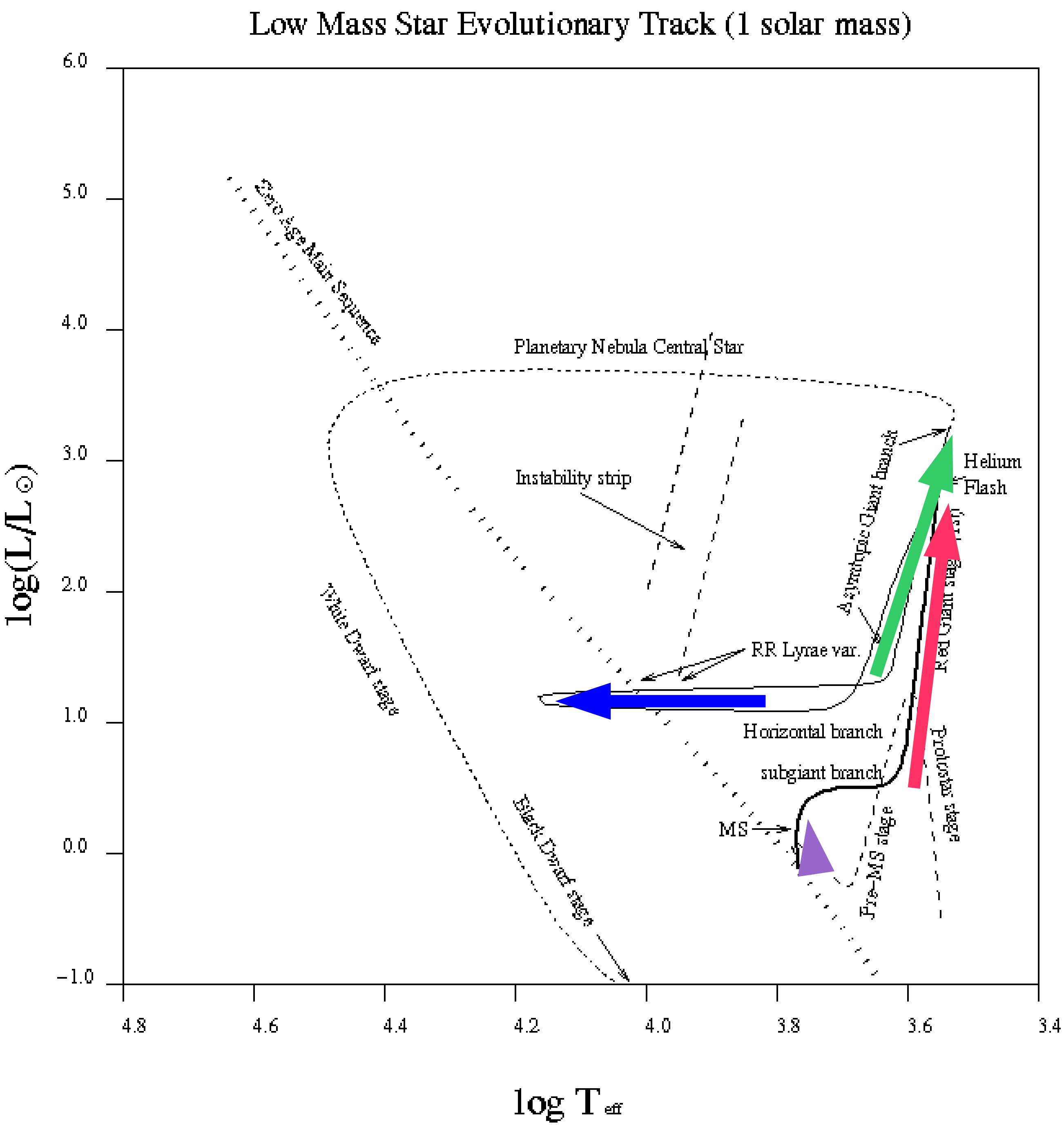
Red giant branch

Shell H burning around degenerate He core.
Dense core sets properties of shell; e.g., $T \sim M_{core}/R_{core}$.
Thus, core determines L.
Star *has to* transport this → large radius increase.

As core increases, so does T (and L drastically; why?)

Until He ignites → He flash

From http://www.ngcsu.edu/Academic/Sciences/physics/jones/astr1020home/evoltracks.htm



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

Main-sequence
Earlier: lower L; paradox of the 'faint young sun'

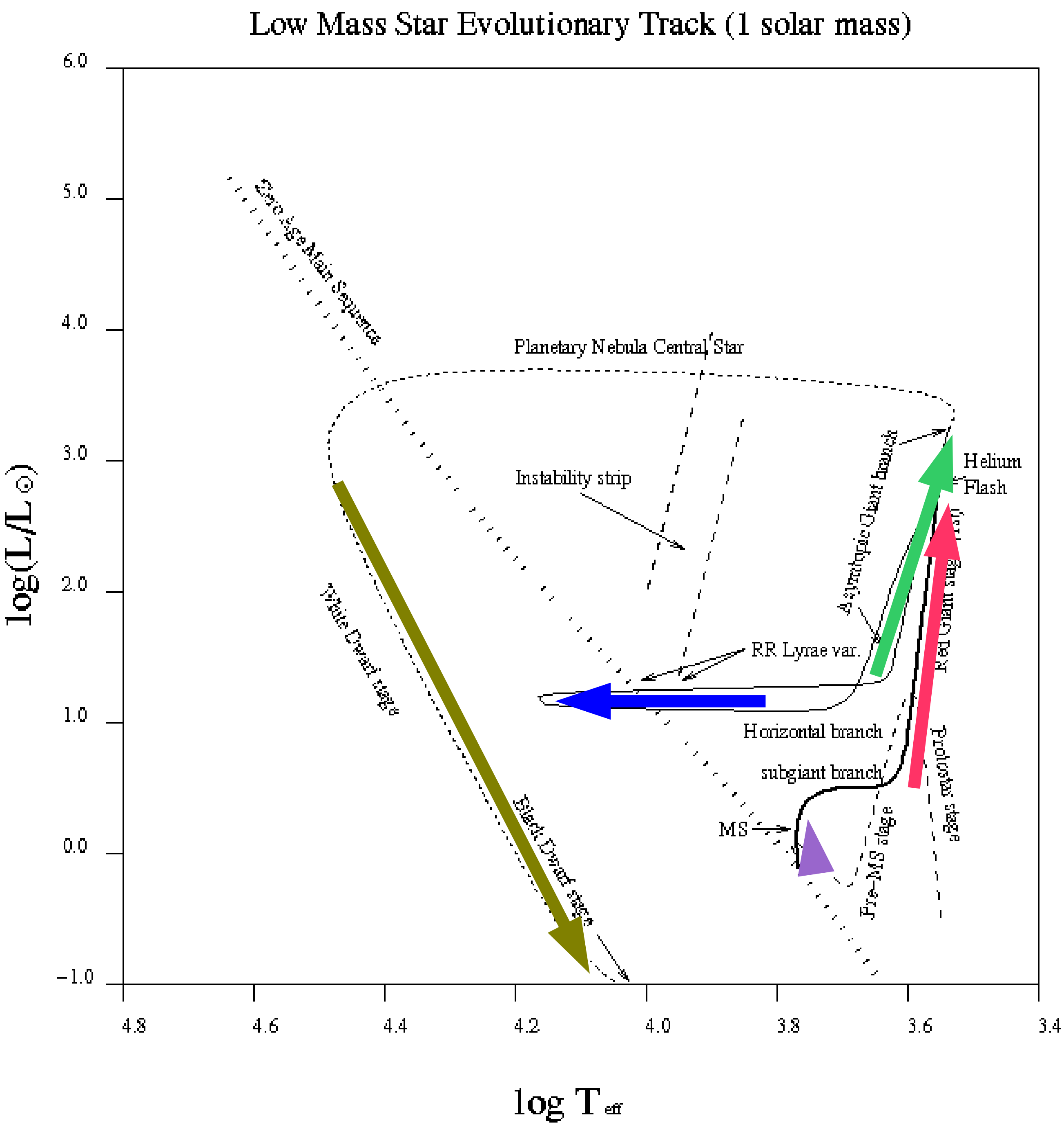
Red giant branch
Shell H burning
Big, luminous (cook planets)

Red clump/Horizontal branch
Core He burning
Core bigger → T_{shell} lower
→ less luminous, less big
Hotter if metal-poor

Asymptotic Giant branch
Shell H & He burning
Luminosity increases with increasing core mass, star becomes very big.

Ends when L so high that envelope blown off

From http://www.ngcsu.edu/Academic/Sciences/physics/jones/astr1020home/evoltracks.htm



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

Main-sequence
Earlier: lower L; paradox of the 'faint young sun'

Red giant branch
Shell H burning
Big, luminous (cook planets)

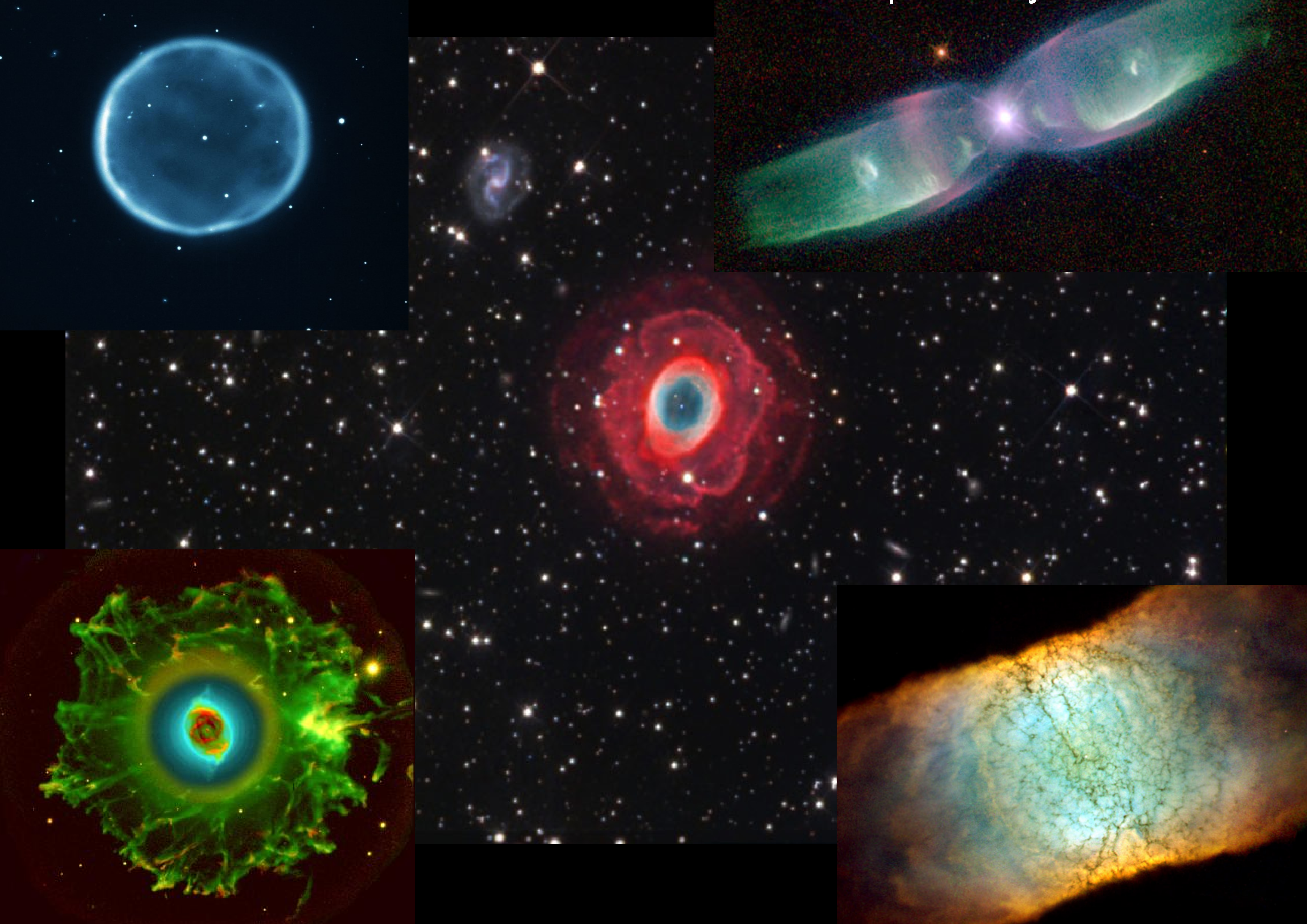
Red clump/Horizontal branch
Core He burning
Bit less big & luminous
Hotter if metal-poor

Asymptotic Giant branch
Shell H & He burning
Very big (engulfing planets)

White Dwarf branch
Naked stellar core
Born very hot
Cools off slowly

From http://www.ngcsu.edu/Academic/Sciences/physics/jones/astr1020home/evoltracks.htm

Mass loss terminates a star's life & fluoresces as planetary nebula



Extra Notes: Planetary Nebula

1) what are they?

Transient fluorescence around
new-born, hot white dwarfs
Live ~10^4 yr
Where is the gas from?
Slow expansion (20 km/s)

2) what are the colors?

'False colors,' montage of
narrow-band images
e.g.,red --> N I
green--> Hα
blue --> O III

3) why aren't they all spherical?

Rotation?
Binaries?

Extra Notes: degeneracy pressure

1. Wave nature of electrons becomes relevant

2. Electrons are fermion: they do not like to be close;
this exclusion provides pressure

Pauli's exclusion principle: $(\Delta x_i)^3 (\Delta p_i)^3 \sim \hbar^3$

Fermi momentum: $p_F \sim \dfrac{1}{\Delta x_i} \sim n_e^{1/3}$

Fermi energy: $E_F = \dfrac{1}{2} m_e v_F^2 = \dfrac{1}{2} \dfrac{p_F^2}{m_e} \propto n_e^{2/3}$

Pressure: $P \propto n_e E_F \propto n_e^{5/3} \propto \rho^{5/3}$

$\rightarrow R \propto M^{-1/3}$

(compare with MS: $P = n k T$ *plus* $T \sim$ *constant* $\rightarrow R \propto M$*)*

Can $M \rightarrow \infty$*?* *No, would need* $v > c$ $\rightarrow$ *Chandrasekhar limit:* $M < 1.4\, M_o$