# Stellar Evolution Overview

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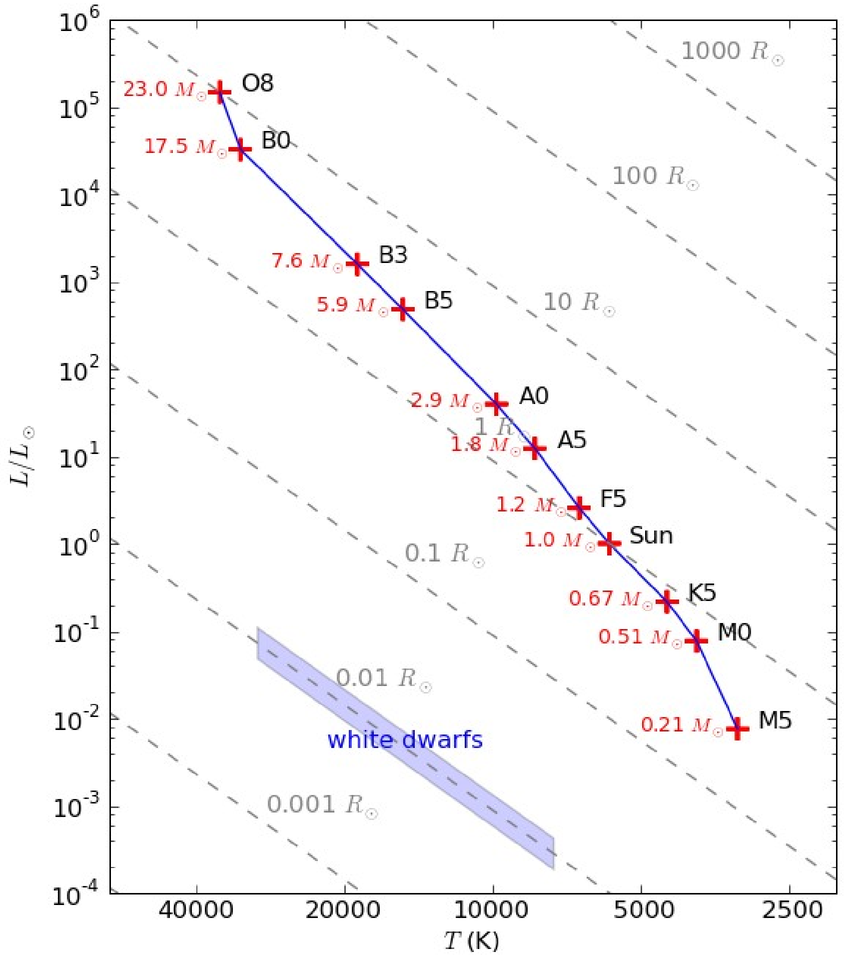
- These slides are largely based on HKT Ch. 2

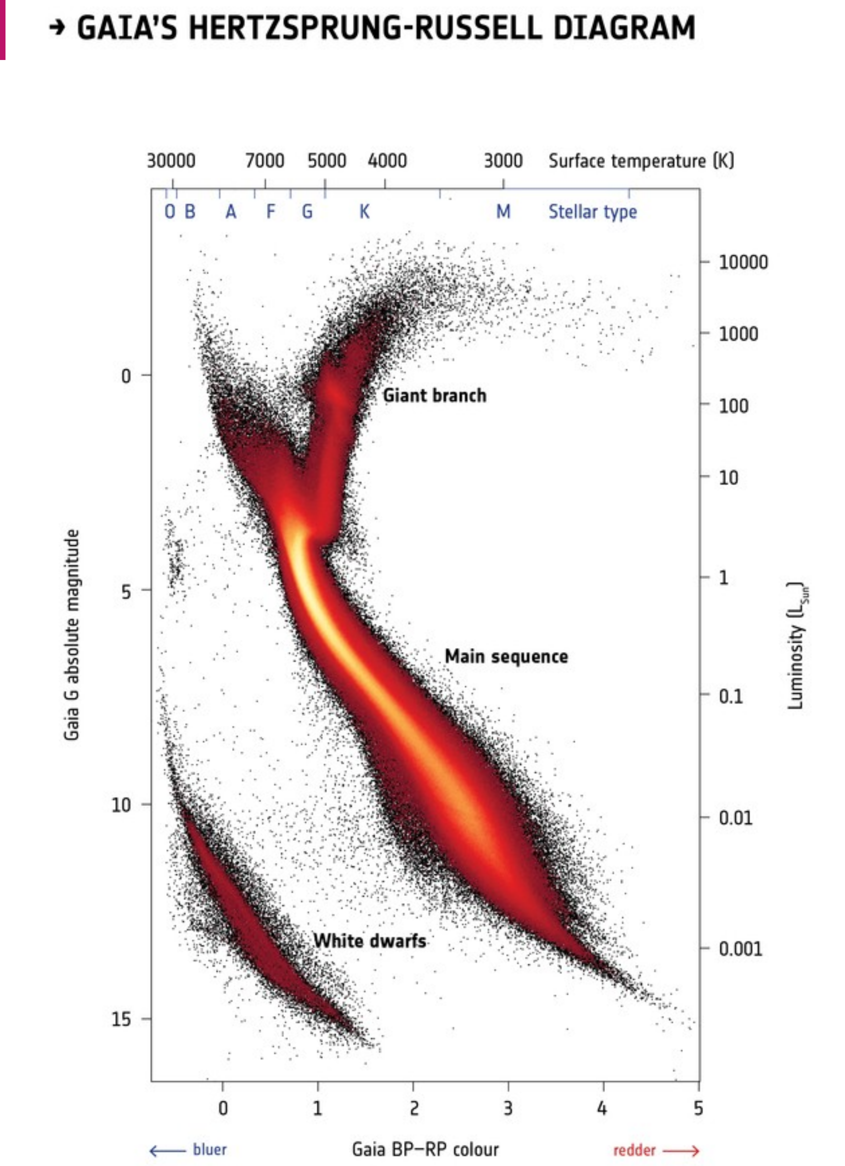
# Stellar Evolution Overview

- We will go through the qualitative aspects of stellar evolution, following Ch. 2 of your text closely.
- We'll defer the sections about explosions and close binaries until later
- After this, we'll spend the next few weeks building up the physical ideas needed to integrate the equations of stellar structure
- Most of the ideas presented here come from one-dimensional stellar evolution calculations
  - Basically solving the 4 equations of stellar structure we just described.
  - Of course, we need to check with observations!

# H-R Diagram



23.0 $M_\odot$
O8
17.5 $M_\odot$
B0
7.6 $M_\odot$
B3
5.9 $M_\odot$
B5
2.9 $M_\odot$
A0
1.8 $M_\odot$
A5
1.2 $M_\odot$
F5
1.0 $M_\odot$
Sun
0.67 $M_\odot$
K5
0.51 $M_\odot$
M0
0.21 $M_\odot$
M5
1000 $R_\odot$
100 $R_\odot$
10 $R_\odot$
1 $R_\odot$
0.1 $R_\odot$
0.01 $R_\odot$
0.001 $R_\odot$
white dwarfs
$L/L_\odot$
$T$ (K)

→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM
Surface temperature (K)
Stellar type
Giant branch
Main sequence
White dwarfs
Gaia G absolute magnitude
Luminosity ($L_{Sun}$)
Gaia BP−RP colour
bluer
redder

- Masses measured via radial velocities from GAIA

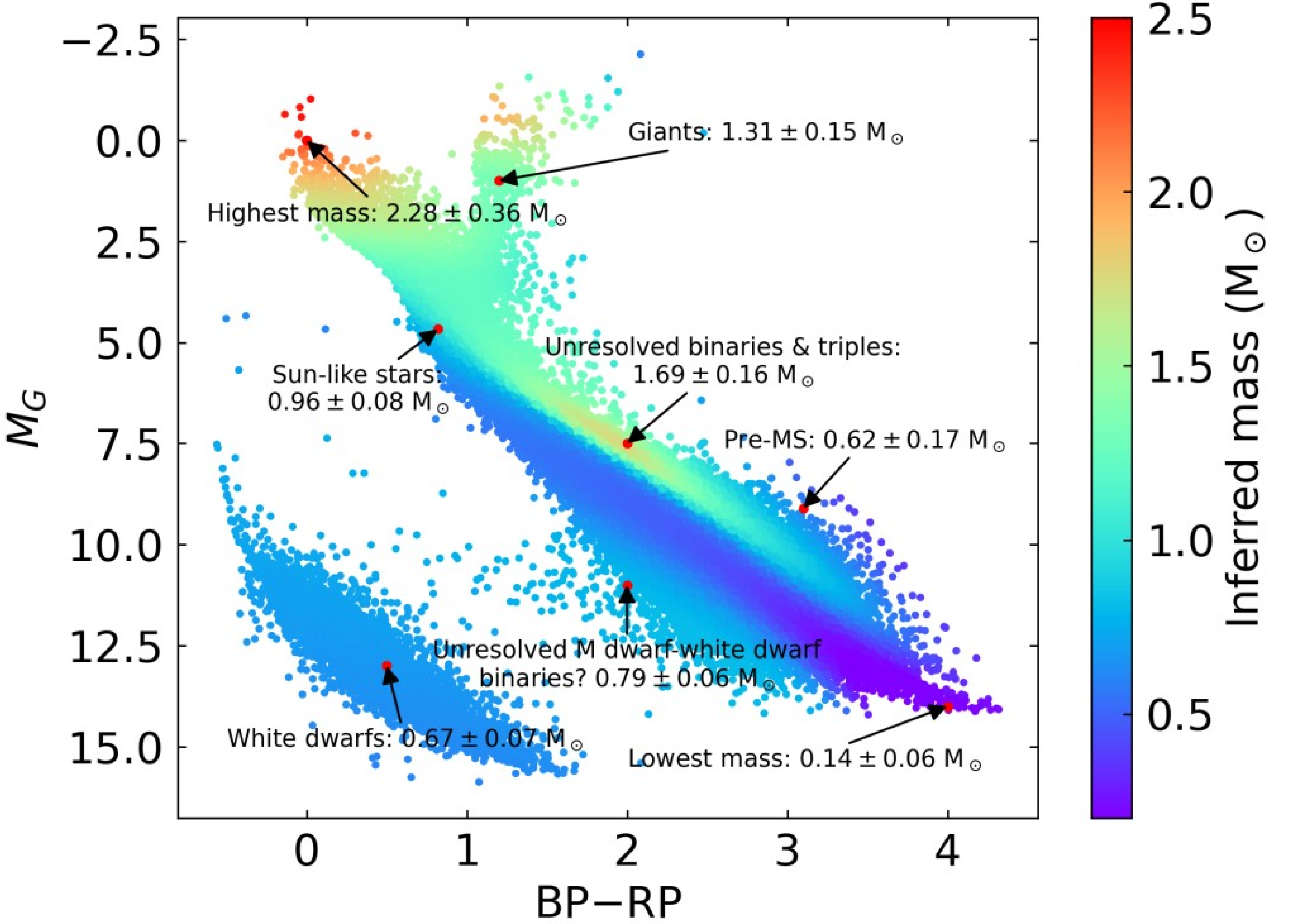



**Figure 12.** Same results as Fig. 5, the measured dynamical masses across the Hertzsprung-Russell diagram. Here we highlight several interesting masses in the diagram.

(Hsiang-Chih Hwang et al. 2023)

# How Do We Determine Stellar Fates?

- Equations of stellar structure

$$\frac{dP}{dM} = -\frac{GM(r)}{4\pi r^4}$$
$$\frac{dr}{dM} = \frac{1}{4\pi r^2 \rho}$$
$$\frac{dL}{dM} = \epsilon$$
$$\frac{dT}{dM} = -\frac{3}{4ac}\frac{\kappa}{T^3}\frac{L}{(4\pi r^2)^2}$$

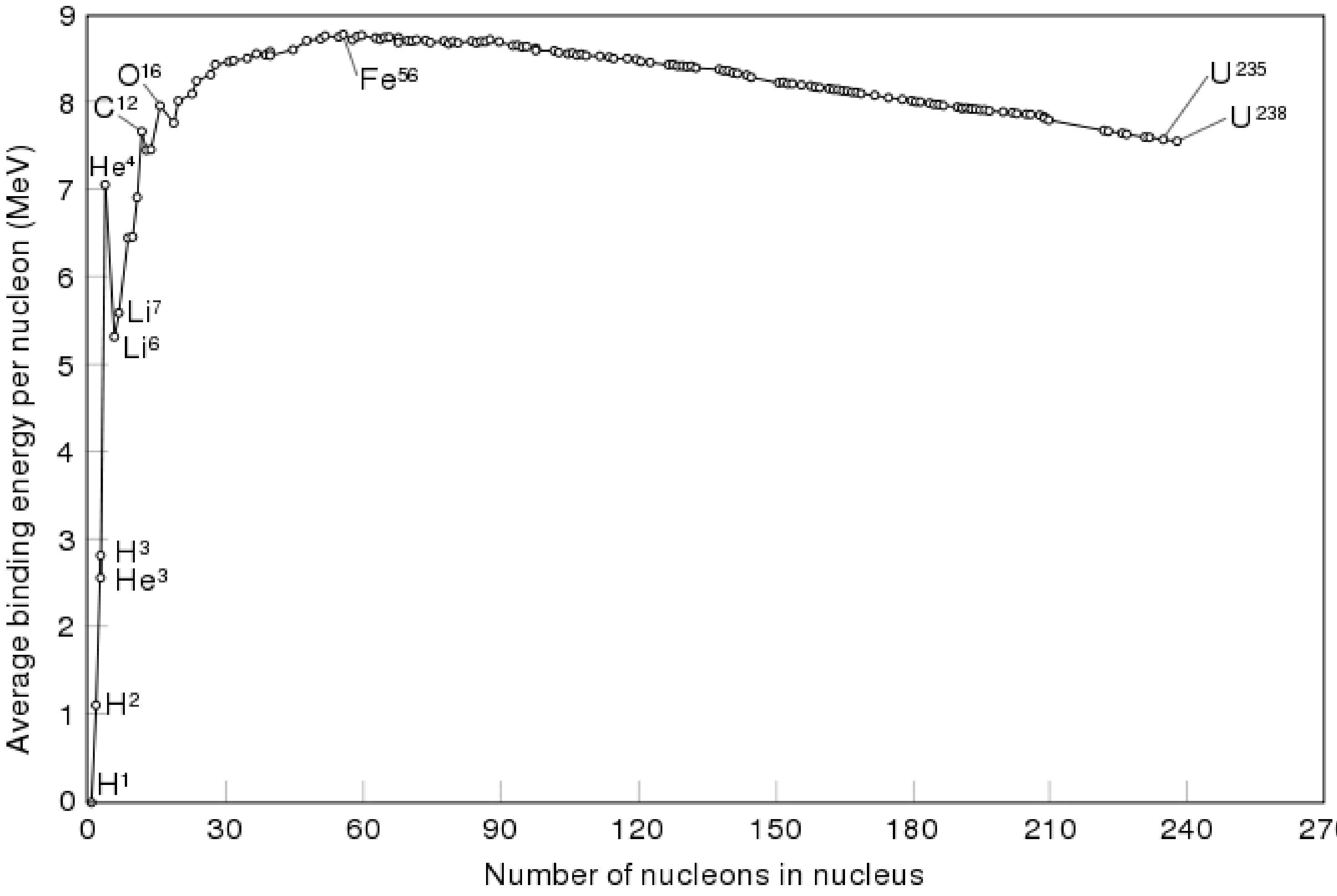
This is for radiative transfer—
convection will have a different
relation

- Microphysics: expressions for opacity, EOS, nuclear energy
- Boundary conditions
  - Accurate models will take into account the stellar atmosphere for the T outer BC

# Equations of State

- Gas pressure:
  - Arises from thermal motions of ions, electrons, and atoms
  - Obeys ideal gas law: $P \propto \rho T$
- Radiation pressure
  - "photon pressure"
  - $P \propto T^4$
  - Important in massive stars
- Electron degeneracy pressure
  - High densities: electrons packed together tightly, Pauli exclusion applies
  - Very weakly T dependence:
    - $P \propto \rho^{5/3}$ (non-relativistic)
    - $P \propto \rho^{4/3}$ (relativistic)

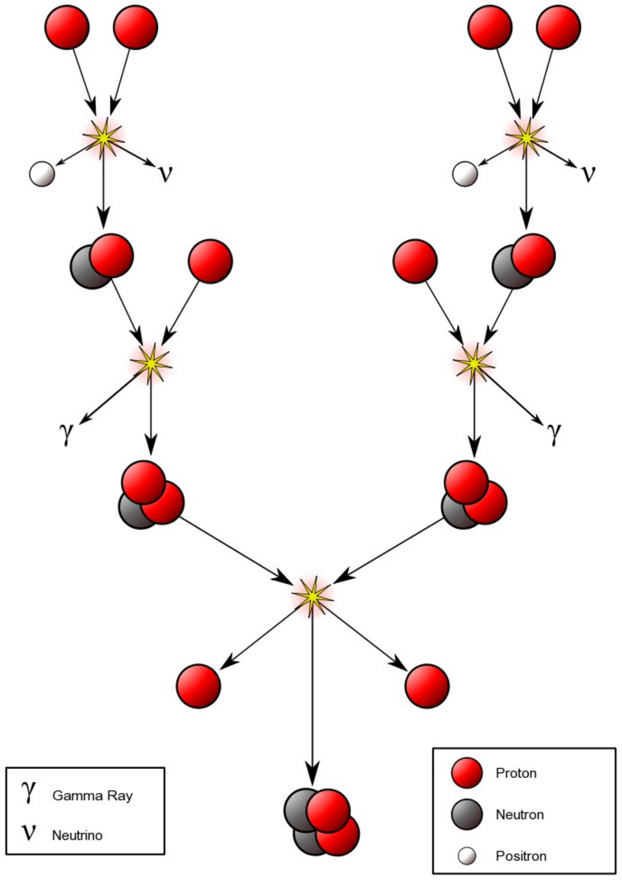
# Nuclear Fusion Overview



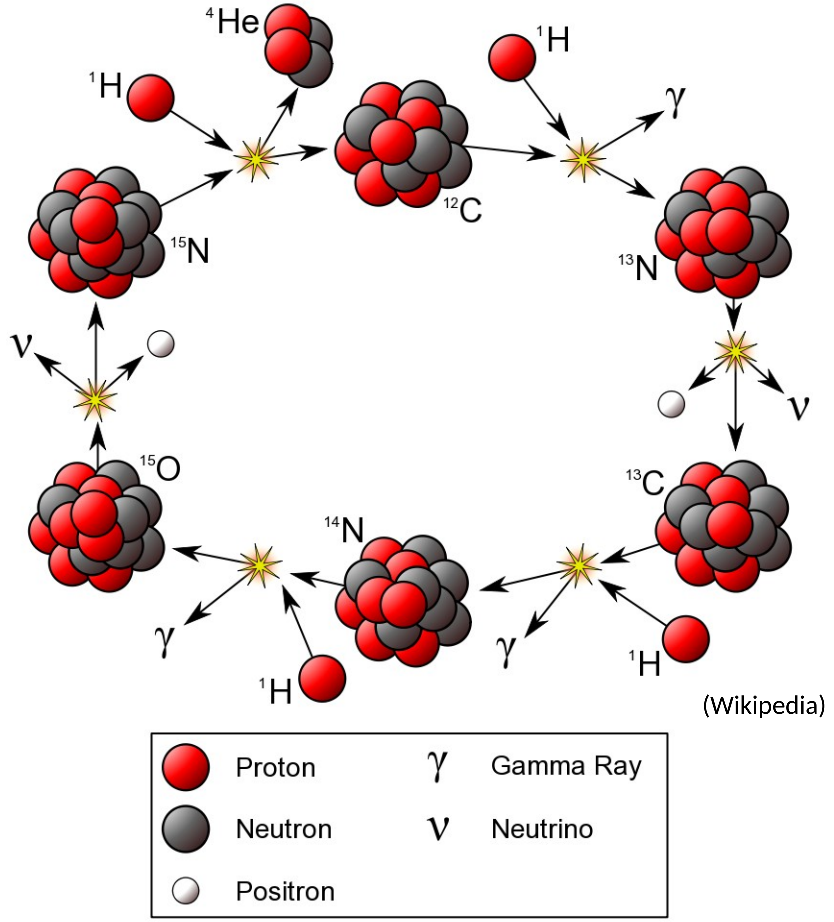

(Wikipedia/Fastfission)

# Hydrogen Burning

- Two processes at play: pp-chain and CNO cycle




$$\dot{\epsilon} \sim X^2 \rho T^4$$




(Wikipedia)

$$\dot{\epsilon} \sim X Z \rho T^{16}$$

# Hydrogen Burning

- Each process takes 4 H and makes one $^4$He
- Releases binding energy equivalent to 0.03 $m_p$
- Most of the energy stays in the star (neutrinos escape)

- CNO dominates in massive stars (transition ~1.5 solar masses):
  - Need higher T to overcome Coulomb barrier with C, N, O
  - Goes faster than pp (once you can do it: don't have to wait for the weak reaction to kick off pp
- CNO has much strong T dependence:
  - Energy generation is strongly peaked toward center
  - Cores of massive stars are convective

# Hydrogen Burning

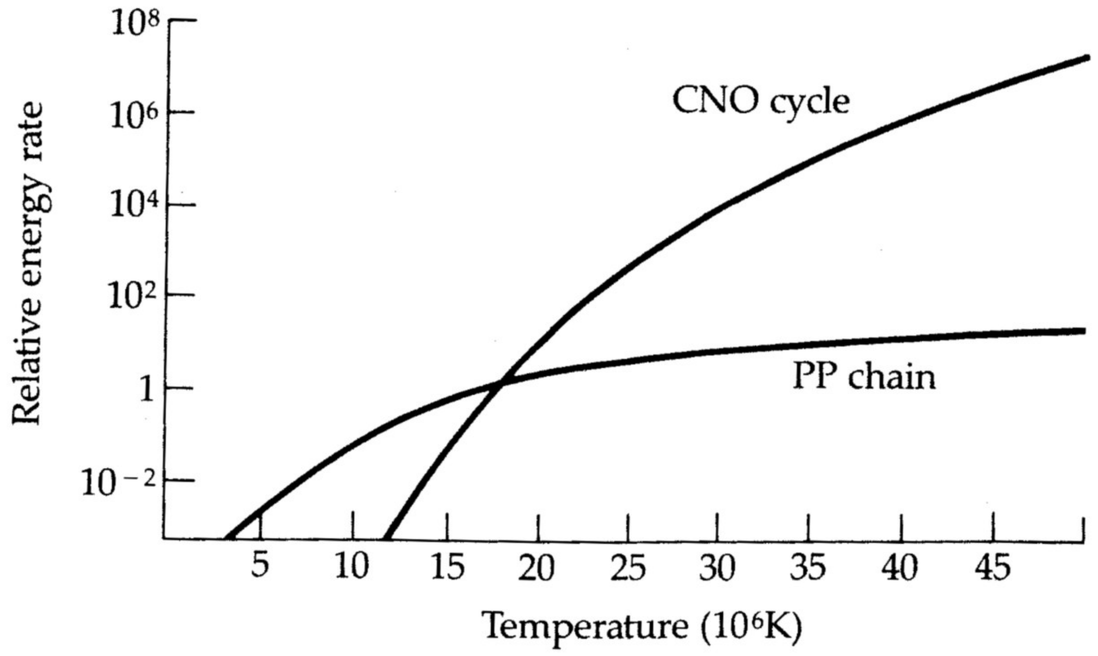


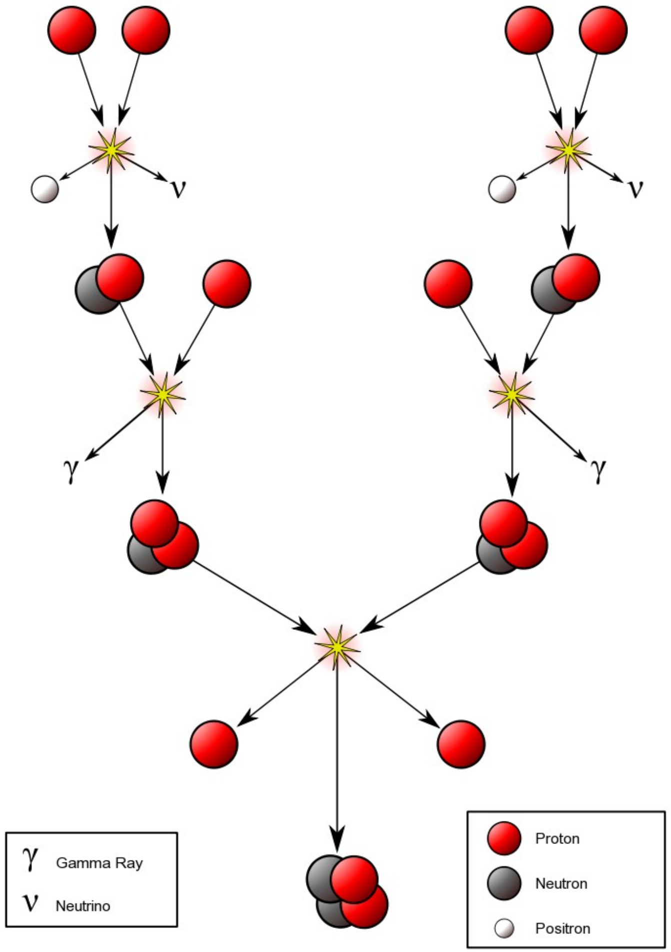

**Figure 16 – 2**

Energy-generation rates. The rates for the PP chain and CNO cycle are compared as a function of temperature for Population I stars. Note the crossover at about 18 million K.

(Zelik & Smith)

# Some Nuclear Physics Bits

- With the pp chain, why we don't just fuse d + d to He
  - Rate of production of d is very slow
  - The odds of one d finding another in a sea of protons is very small
    - Reaction depends on $X(d)^2$
- Why no stable nuclei with A = 8?
  - $^4$He is so tightly bound that the equilibrium abundance heavily favors 2 α over one $^8$Be



# Key Principles

- Hydrostatic equilibrium
  - More massive stars have higher central pressures:

$$P_c \approx \frac{GM_\star^2}{R_\star^4}$$

  - Therefore more massive stars have hotter interiors
- Fusing heavy elements requires higher T
  - Need to overcome the Coulomb barrier

$$F_{\text{electric}} = \frac{(Z_1 e)(Z_2 e)}{r^2}$$

- Degenerate cores
  - More massive cores are smaller (consequence of HSE)

# Uniqueness

- Why can't the Sun be twice the size? (following Hester et al.)
  - Take the Sun and double R, keeping M and T constant
  - R is larger but T is the same → L increases ($L \propto R^2T^4$)
  - Energy conservation: larger surface L → more energy needs to be produced at the core
  - M is the same but R is 2× larger, so g is smaller everywhere:
    - Central P is smaller
    - Central T is smaller
    - Fusion reactions proceed more slowly
  - Contradiction reached

# Overview

- Stellar models match observations very well: M, L, surface T, composition, …
  - The equations of stellar structure + our understanding of microphysics does a good job

# Dimensional Analysis

- Mass-Luminosity relationship
  - Assume that we are an ideal gas
  - Radiative transfer holds throughout the star
  - Composition and opacity are constant and independent of $\rho$, $T$ (good for electron scattering)
- Can we explain what we see in the HR diagram?

# Dimensional Analysis

- In dimensionless form:

$$P_\star \sim \frac{GM_\star^2}{R_\star^4}$$

$$\rho_\star \sim \frac{M_\star}{R_\star^3}$$

$$L_\star \sim \frac{ac}{\kappa}\frac{T_\star^4 R_\star^4}{M_\star}$$

$$L_\star \sim q_0 \rho_\star T_\star^n M_\star$$

$$P_\star \sim \frac{k_B}{\mu m_u}\rho_\star T_\star$$

- Combining these (white board), we find:

$$T_\star \sim \frac{\mu m_u}{k_B}\frac{GM_\star}{R_\star}$$

$$L_\star \sim \frac{M_\star^3 \mu^4}{\kappa}$$

$$R_\star \sim \mu^{(n-4)/(n+3)} M_\star^{(n-1)/(n+3)}$$

$$\rho_\star \sim M_\star^{2(3-n)/(n+3)}$$

# Dimensional Analysis

- Luminosity:

$$L_\star \sim -\frac{4ac}{3}\frac{T_\star^3}{\kappa}(4\pi R_\star^2)^2\frac{T_\star}{M_\star}$$
$$\sim \frac{ac}{\kappa}\frac{T_\star^4 R_\star^4}{M_\star}$$
$$\sim M_\star^3\left[\frac{ac}{\kappa}\left(\frac{\mu m_u G}{k_B}\right)^4\right]$$

- This expression works well over a wide range on the MS
- For low mass stars, the opacity is ρ / T dependent → steeper dependence on M
  - Note: we could be fancy and include the Z dependence here
- Note: higher opacity = smaller luminosity (harder for radiation to get out)

# Dimensional Analysis

- Radius:

$$R_\star \sim \mu^{(n-4)/(n+3)} M_\star^{(n-1)/(n+3)}$$

  - Low mass stars, pp-chain (n ~ 4)

$$R_\star \sim M_\star^{3/7}$$

  - High mass stars. CNO (n ~ 16)

$$R_\star \sim \mu^{12/19} M_\star^{15/19}$$

- In both cases, $R_*$ increases with mass (unlike WDs)

# Dimensional Analysis

- Density:

$$\rho_\star \sim M_\star^{2(3-n)/(n+3)}$$

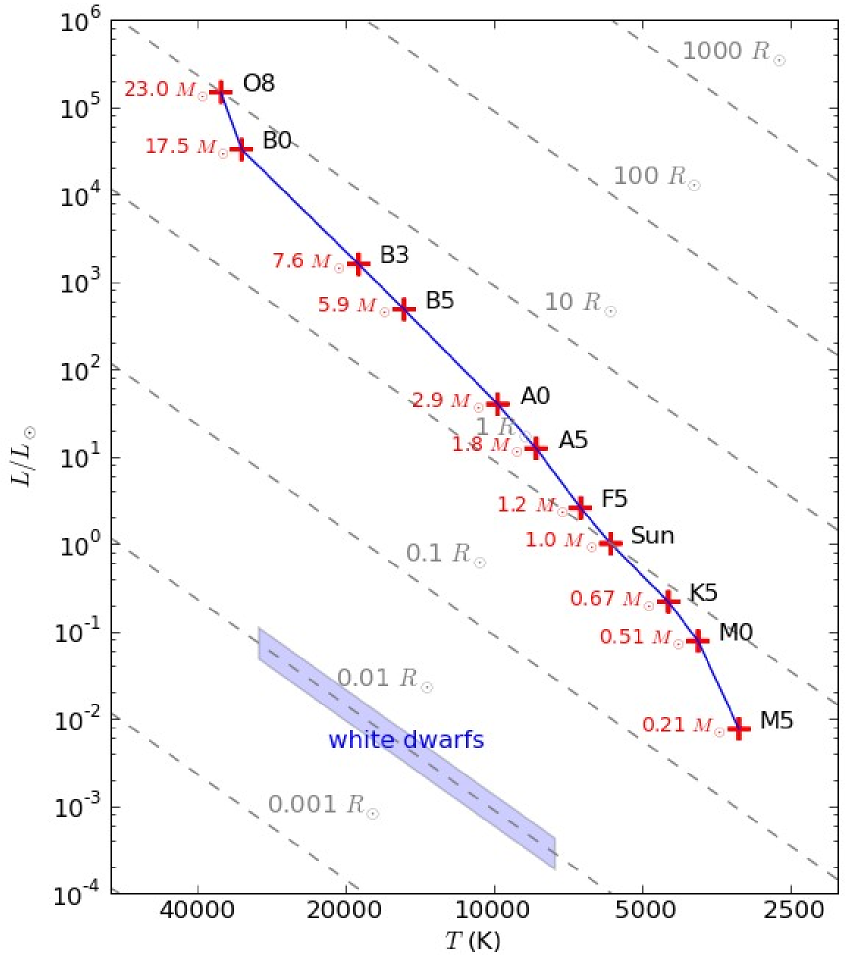
- For n > 3 (both pp and CNO), density decreases with mass
  - Low mass stars are denser than high mass
  - Degeneracy can become more important for low mass stars

# Dimensional Analysis

- Similar estimates can be made for other quantities.
- Note, T here is interior temperature
  - HR diagram plots effective temperature:

$$T_{\rm eff} \sim \frac{L^{1/4}}{R^{1/2}}$$

  - Use this relation to relate to the temperature you see in the HR diagram



# Dimensional Analysis

- We find:
  - pp chain:

$$\log L_\star \sim \frac{28}{5} \log T_{\rm eff} + \text{const}$$

  - CNO:

$$\log L_\star \sim \frac{76}{9} \log T_{\rm eff} + \text{const}$$

# Stellar Lifetimes

- We can estimate the MS lifetime of stars
- Fuel reserves (nuclear potential energy) ~ mass of the star

$$t_{\rm MS} \sim \frac{E_{\rm nuclear}}{L} \sim \frac{M}{M^3} \sim M^{-2}$$

- On the lower part of the MS, we will have

$$t_{\rm MS} \sim M^{-3}$$

- This immediately tells you that O, B stars are *very* short lived!
  - Also, it turns out that they are formed far less readily that less massive stars
  - Very rare
- Low mass M dwarfs will essentially never evolve

# Minimum Mass

- We can find the temperature in terms of mass:

$$T_\star \sim M_\star^{4/(n+3)}$$

- Low mass stars are dominated by pp, n = 4:

$$T_\star \sim M_\star^{4/7}$$

- H won't burn below $4 \times 10^6$ K, so we find:

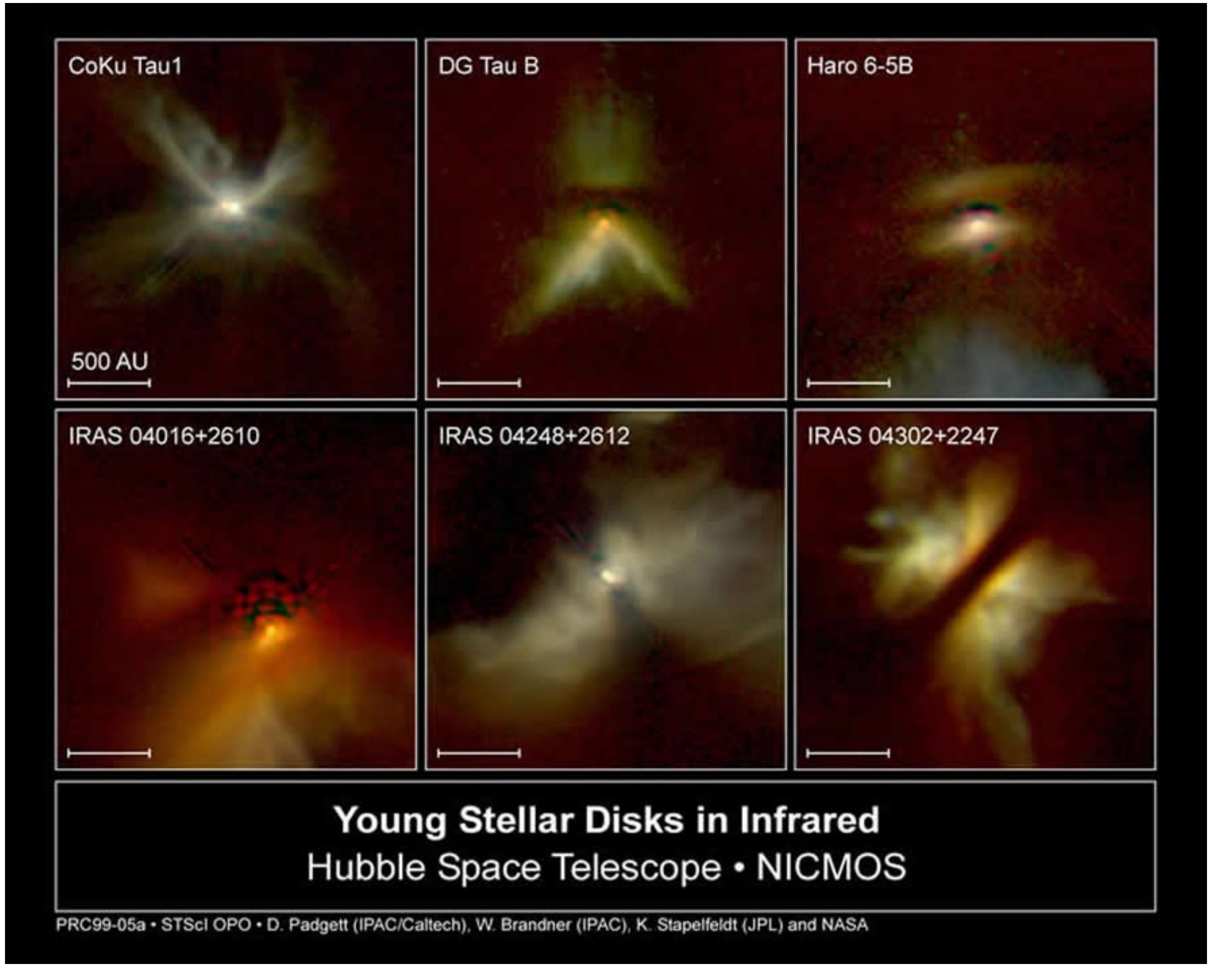
$$M_{\rm min} \sim \left(\frac{4 \times 10^6\ \rm K}{1.5 \times 10^7\ \rm K}\right)^{7/4} M_\odot \sim 0.1\ M_\odot$$

$$L_{\rm min} \sim \left(\frac{M_{\rm min}}{M_\odot}\right)^3 L_\odot \sim 10^{-3}\ \rm L_\odot$$

  - This is the lower end of the main sequence

# Young Stellar Objects

- We'll consider star formation later
  - Basic idea: cloud collapses under its own self-gravity on the K-H timescale (short)
- Important initial condition:
  - Protostars are convective: this means that the composition is uniform (well-mixed)
- Fun bit: we often observe disks around young stars—solar system formation! (more on that later)



# Pre-Main Sequence Evolution

- Pre-MS evolution (Kelvin-Helmholtz contraction)

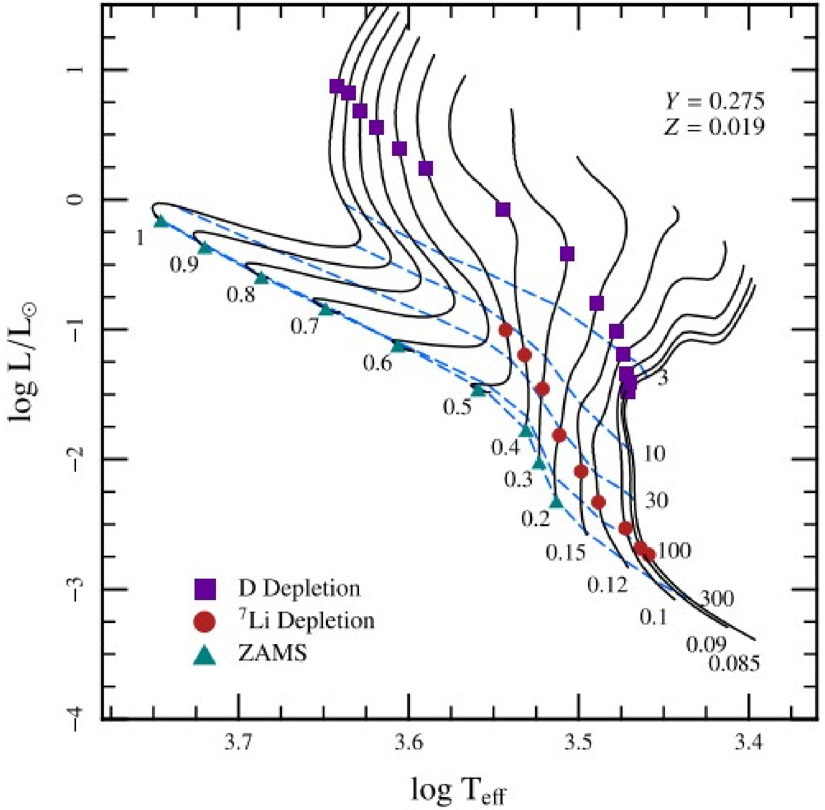



**Figure 15.** Location in the Hertzsprung-Russell (H-R) diagram for $0.085\,M_\odot < M < 1\,M_\odot$ stars as they arrive at the main sequence for $Y = 0.275$ and $Z = 0.019$. The mass of the star is noted by the values at the bottom of the line. The dashed blue lines are isochrones for ages of 3, 10, 30, 100 and 300 Myr, as noted to the right. The purple squares (red circles) show where D ($^7$Li) is depleted by a factor of 100. The green triangles show the ZAMS.

(MESA paper)

# ZAMS

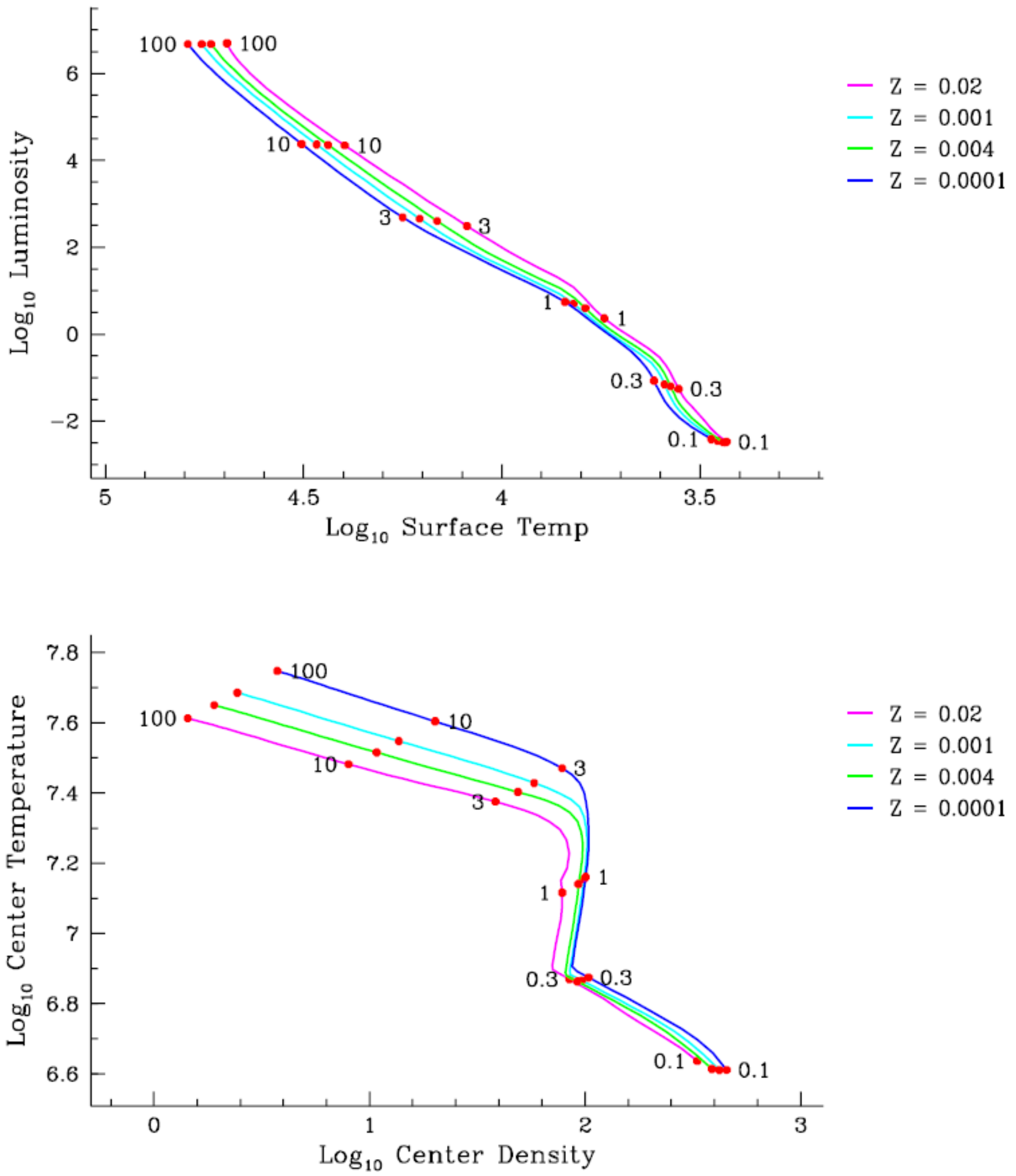
- Zero Age Main Sequence (ZAMS):
  - Point where star is first on the main sequence
- Most important quantities: mass and metalicity
  - Structure and evolution follow from these properties
- Limits to stellar masses:
  - Lower limit: too small for fusion to take place (brown dwarfs and planets live here)
  - Upper limit: radiation pressure blows apart the star
- Stars spend most of their life on the MS

# ZAMS

- Surface temperature also scales with mass
- Lower mass stars (again $M < 1.5$ solar):
  - Cooler T means neutral H present—opaque in UV
  - Convective transport dominates in the outer layers
- Higher mass stars:
  - Outer layers are ionized, radiation transport dominates
- Stars are not convective throughout (except $M < 0.3$ solar), so ash produced in the core is not brought to the surface
- Lower mass ($M < 1.5$ solar) stars are slow rotators
  - Related to convective outer regions and magnetic field generation
- Metals = higher surface opacity
  - Higher opacity → we see less deeply into a star, i.e. we see a cooler layer
  - Metal poor stars appear "bluer" than metal rich stars (for same mass, etc.)

# ZAMS

- Notice at the low end, stars with the same mass, but lower Z are more luminous
  - Dimensional analysis told us that!
- But… it you look at the main sequence, lower Z have the main sequence beneath that of higher Z




(Bill Paxton)

ZAMS Hertzsprung-Russell and Temperature-Density Plots. Numbers show mass in solar units.

# Mass Cuts

- Mass plays a big role in the outcome of stellar evolution

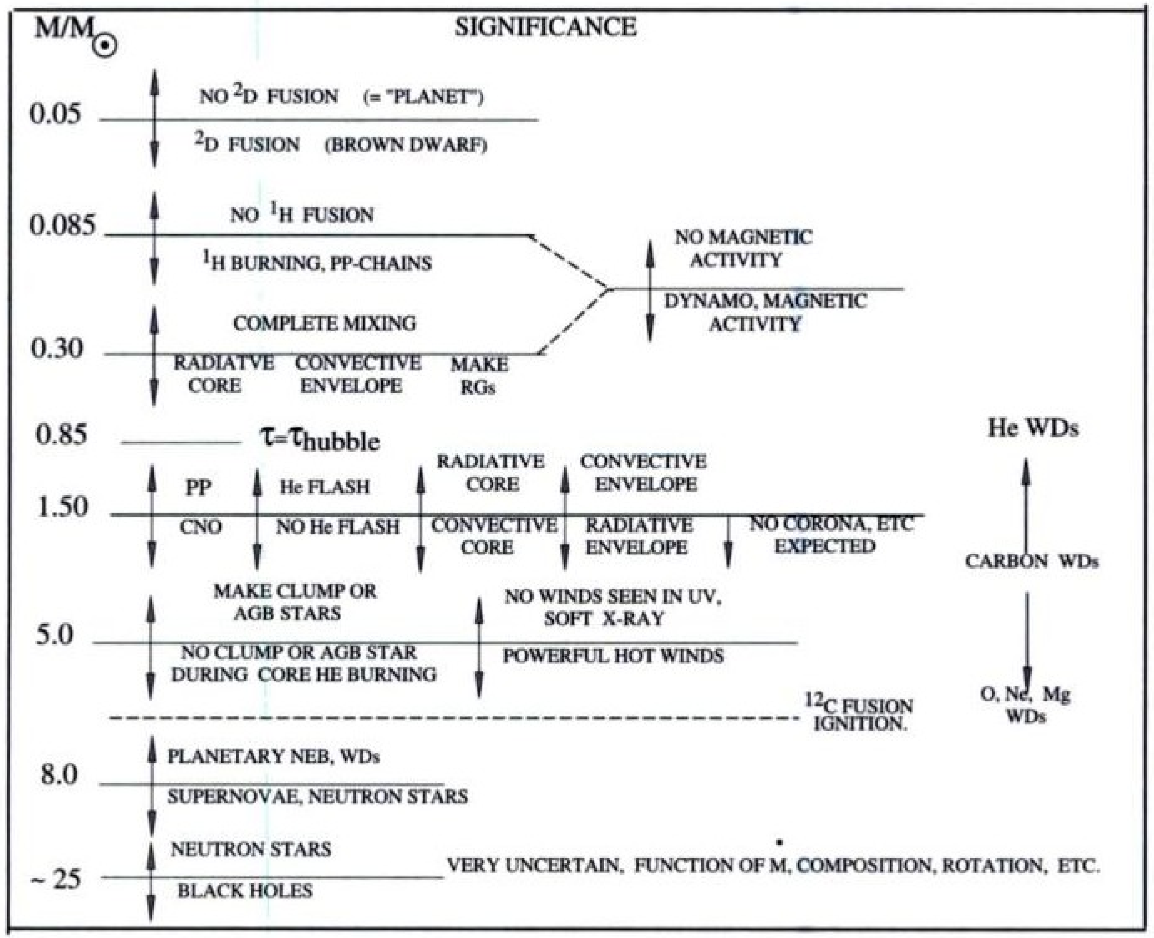



**Fig. 2.4.** Our "Mass Cut" diagram showing the fate of single stars in various mass classes. See text.

(Hansen, Kawaler, Trimble)

# Brown Dwarfs

- Very low mass (~0.08 solar masses)—too cool to burn H
  - Deuterium can still fuse, so a little energy is generated
  - Very low effective temperatures
  - Many now discovered.
- Even smaller in mass: planets! (Jupiter-like)

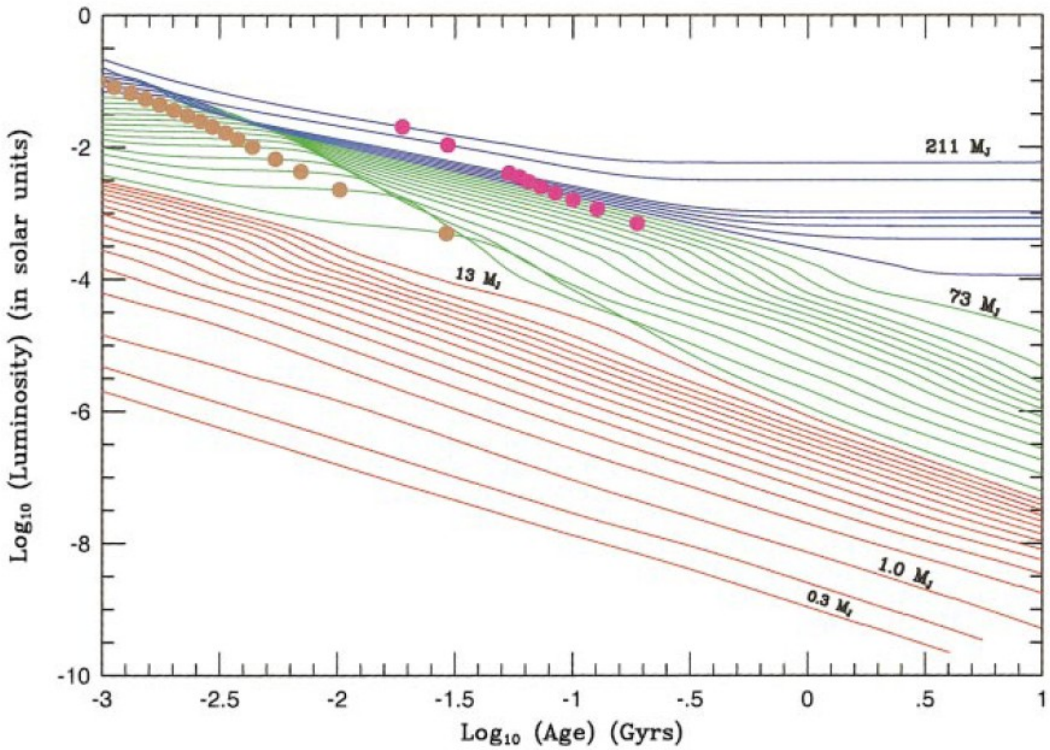
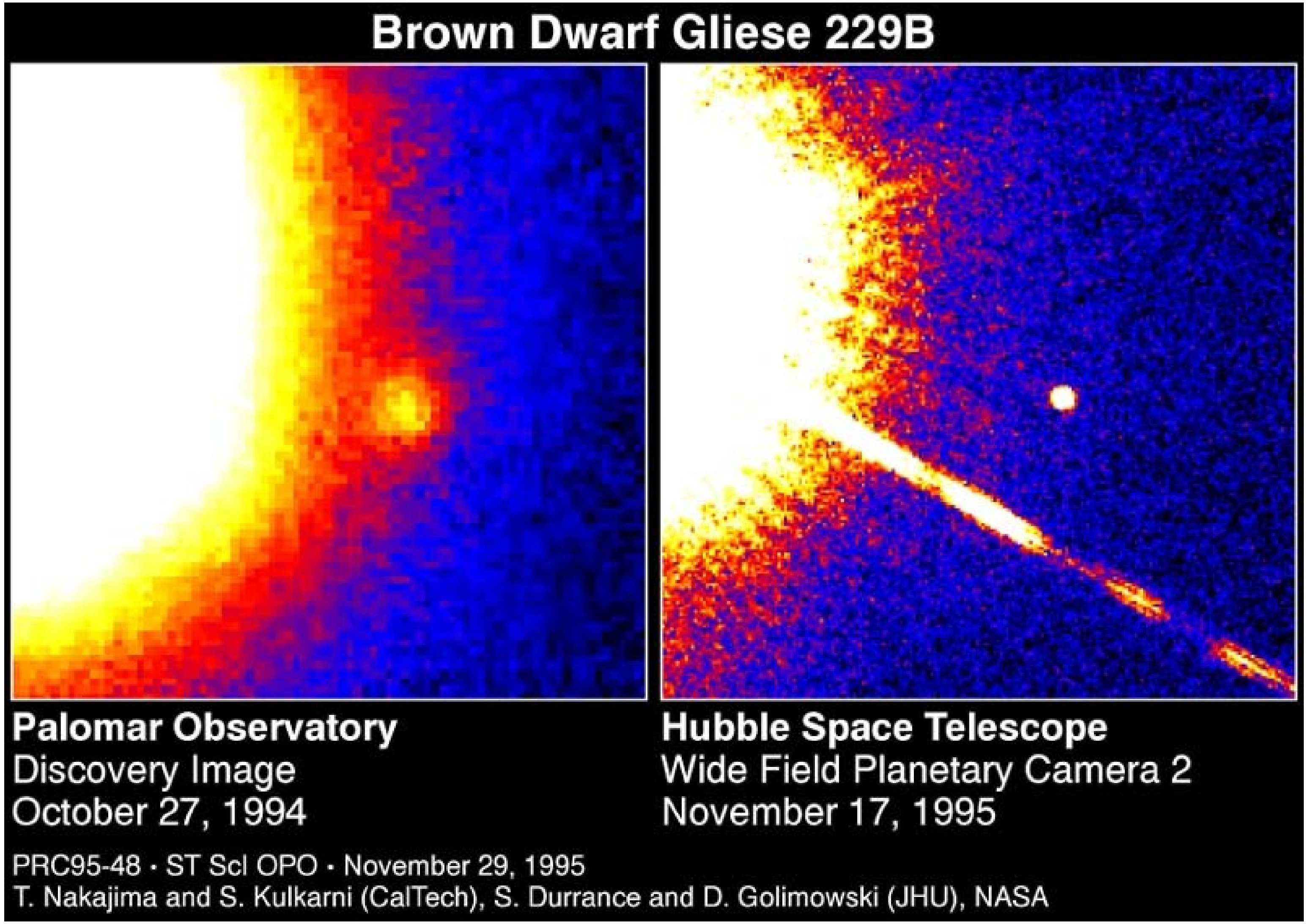



FIG. 1. Evolution of the luminosity (in $L_\odot$) of isolated solar-metallicity red dwarf stars and substellar-mass objects versus age (in years). The stars are shown in blue, those brown dwarfs above 13 $M_J$ are shown in green, and brown dwarfs/giant planets equal to or below 13 $M_J$ are shown in red. Though the color categories are based on deuterium or light hydrogen burning, they should be considered arbitrary *vis à vis* whether the object in question is a brown dwarf or a planet, sensibly distinguished on the basis of origin. The masses of the substeller objects/stars portrayed are 0.3, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0 11.0, 12.0, 13.0, and 15.0 $M_J$ and 0.02, 0.025, 0.03, 0.035, 0.04, 0.045, 0.05, 0.055, 0.06, 0.065, 0.07, 0.075, 0.08, 0.085, 0.09, 0.095, 0.1, 0.15, and 0.2 $M_\odot$ ($\equiv$211 $M_J$). For a given object, the gold dots mark when 50% of the deuterium has burned and the magenta dots mark when 50% of the lithium has burned. Note that the lithium sequence penetrates into the brown dwarf regime near 0.065 $M_\odot$, below the HBMM. Figure based on Fig. 7 of Burrows *et al.*, 1997 [Color].

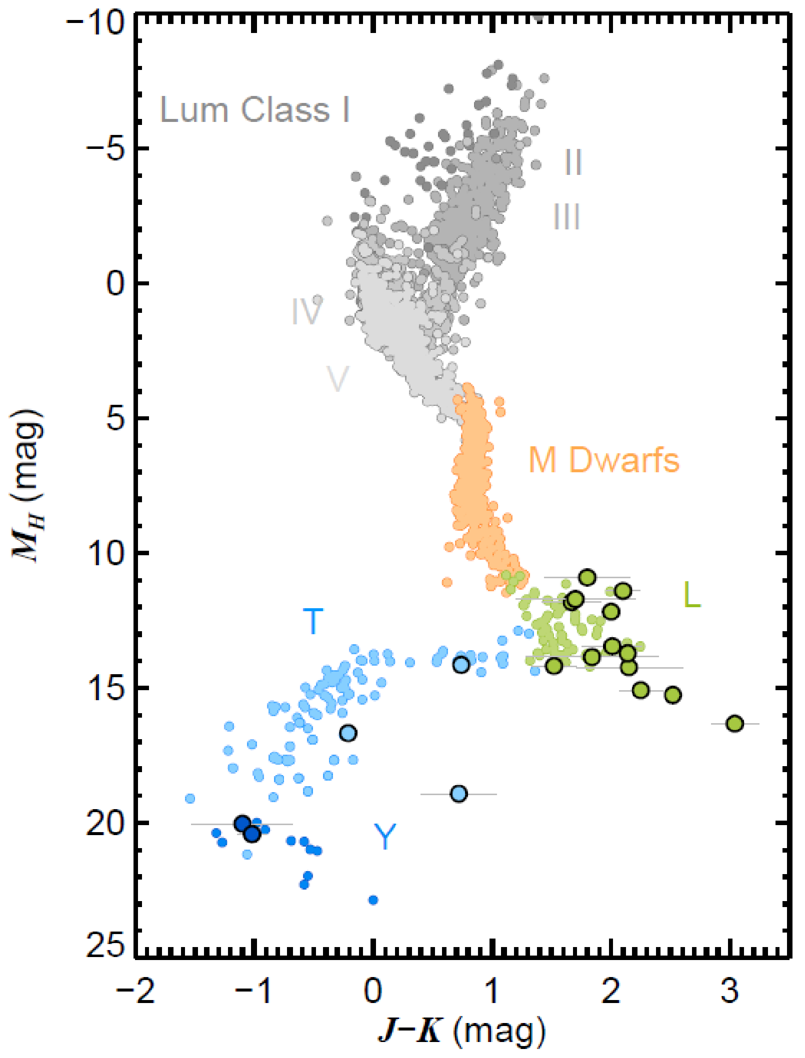
# Brown Dwarfs

- First known brown dwarf



# Extended HR Diagram

- Low mass dwarfs follow a different sequence

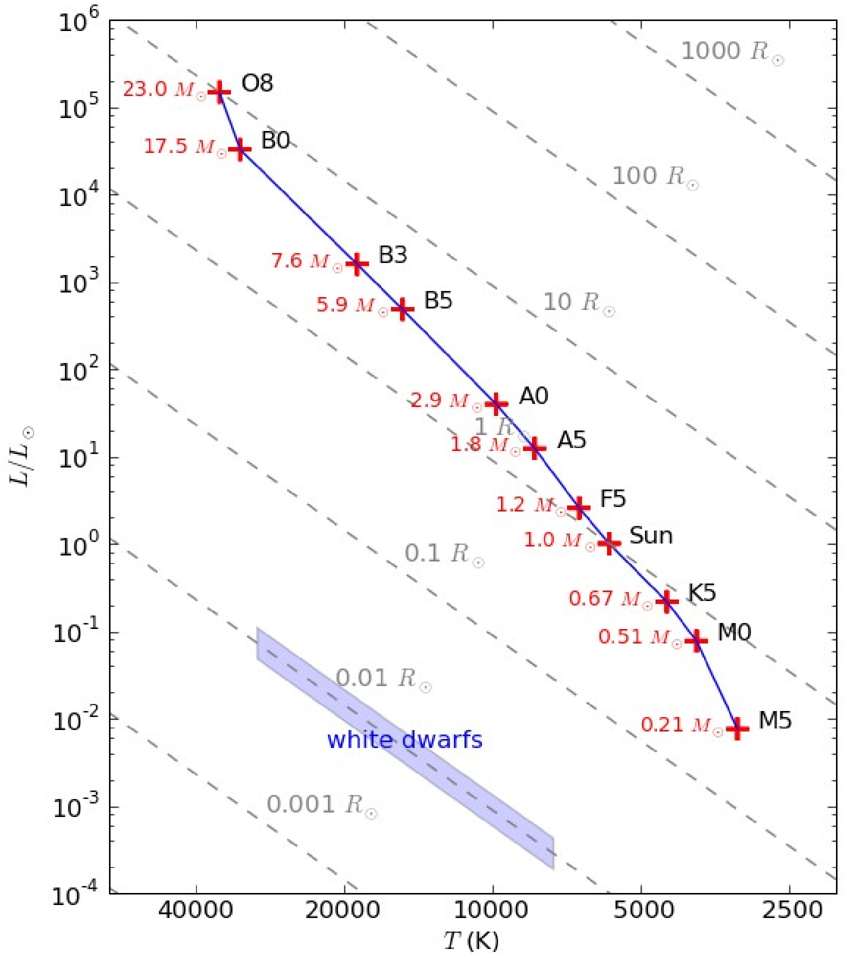



(Bowler 2016)

FIG. 7.— The modern color-magnitude diagram spans nearly 35 magnitudes in the near-infrared and 5 magnitudes in $J$–$K$ color.

# Life on the Main Sequence

- Evolution is slow
- Changes do have to happen though:
  - Each time you fuse, you go from 8 independent particles to 3 (counting electrons)
  - Pressure support therefore changes
  - Star must contract a bit to recover, reactions speed up
  - Star brightens



# Evolving Off the Main Sequence

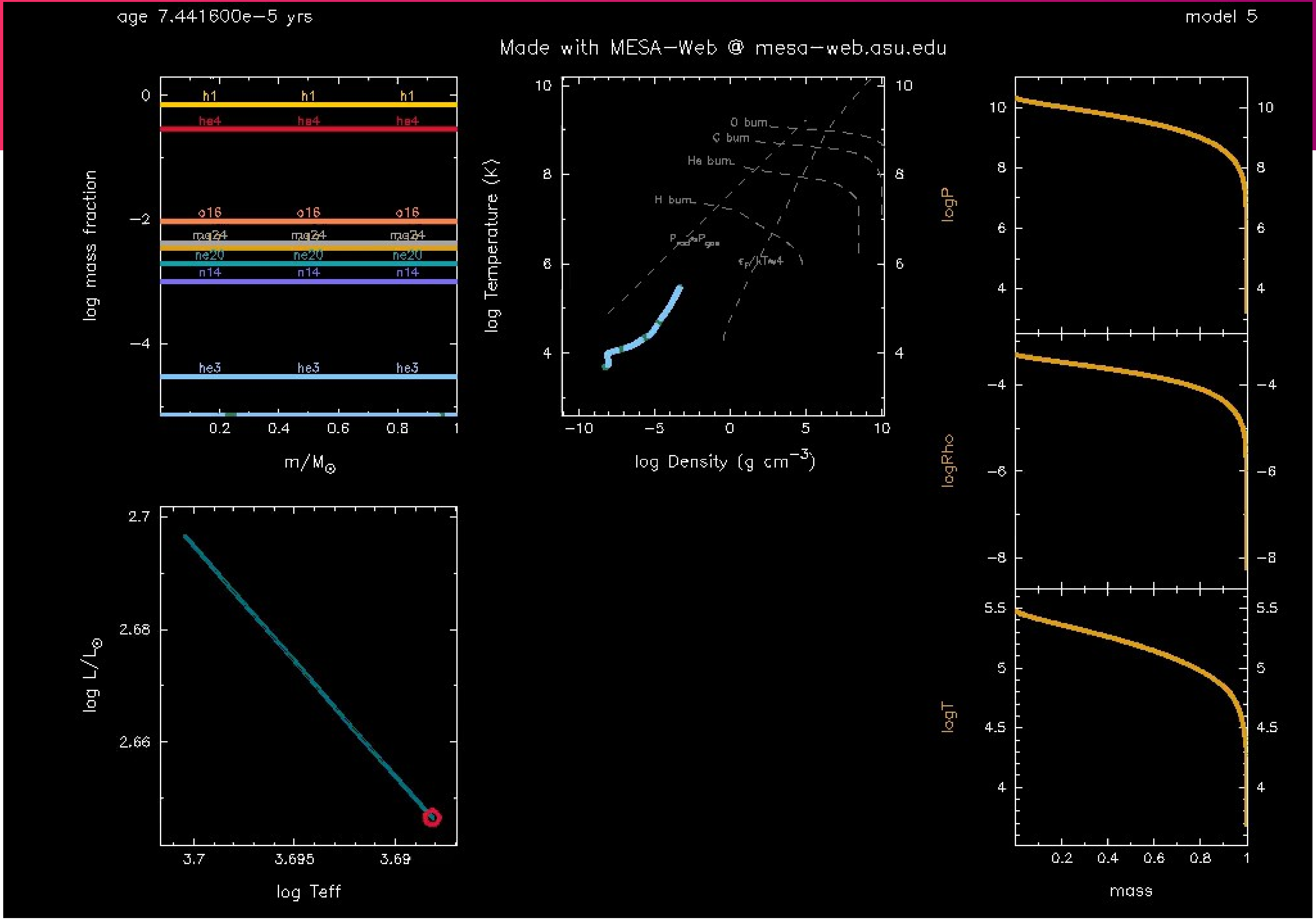
- We’ll now look at the result of stellar evolution calculations to get a feel for the fate of stars
- Then we’ll spend a few weeks building up the input physics
- Finally we’ll return to stellar structure, learn how to (approximately) solve the equations, and revisit the evolution with more physical intuition

# Evolving Off the Main Sequence

- We'll consider stars > 0.3 solar masses
  - Lower are fully convective and will take > $10^{12}$ years to burn all their H—we'll never see them evolve!
- Mass loss (winds, binary interactions) can affect the basic ideas
- Eventually, we use up all of the H in the core (inner ~10% by mass)
  - Still radiating
  - Core begins to contract—needs to increase pressure to account for loss of energy from reactions
  - Virial theorem: core heats up
  - Too cool for He burning to commence (yet)

# H Shell Burning

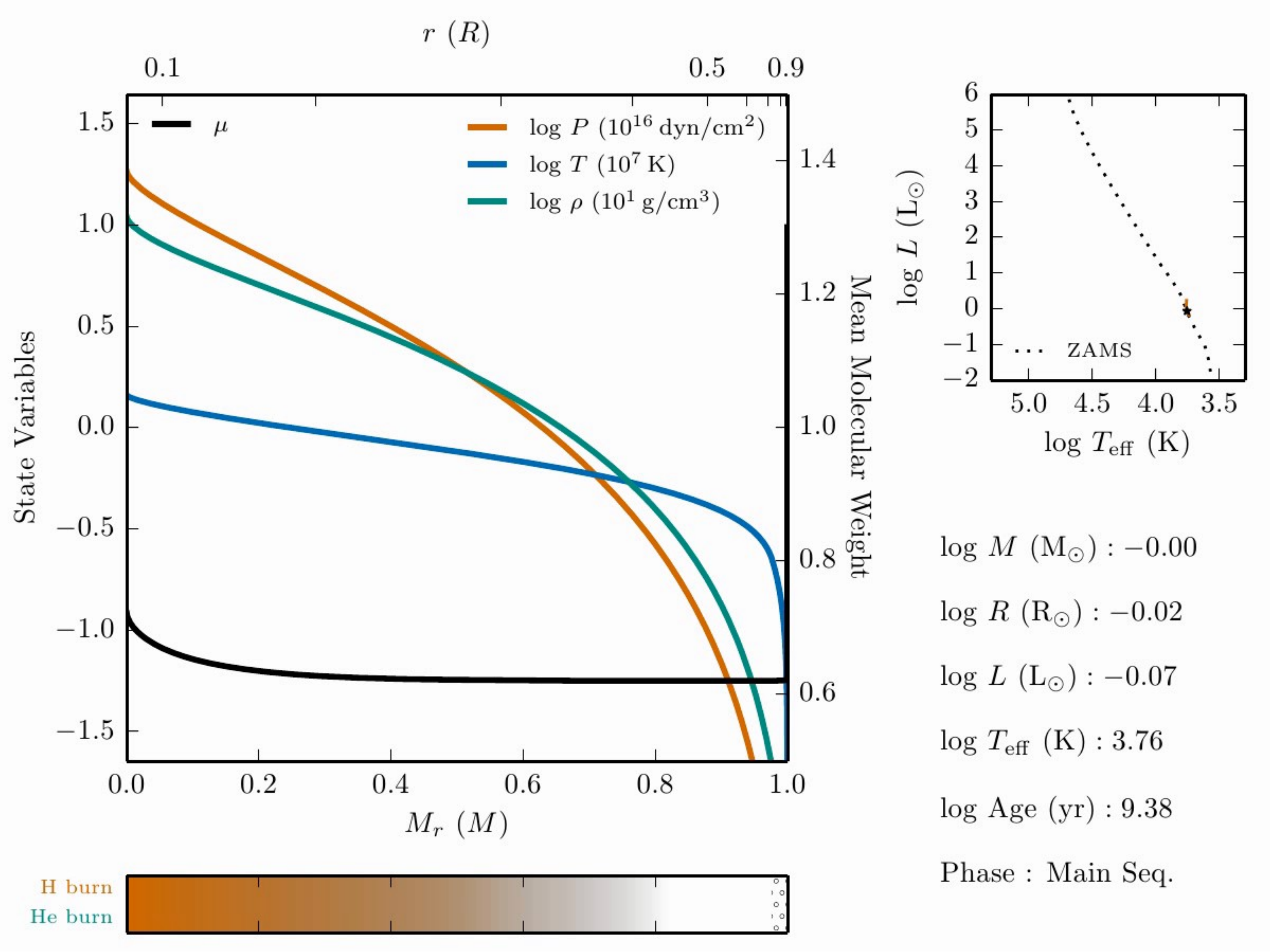
- Just outside the core, there is H
  - As core contracts, g at base of H envelope increases
  - HSE: P must increase (the material now weighs more)
  - H ignites outside of the core: H shell burning
- He core continues to contract
  - Reaches extreme densities: degenerate
  - He ash from shell increases core mass: radius shrinks (degenerate)
- Outer layers expand: red giant phase
  - L is greater than MS phase (shell T is high)
  - CNO burning takes place here
- At first, star moves to right (cooler T) on the HR diagram
- Thermal equilibrium reestablished
  - Outer layers become convective (higher opacity at surface makes radiation inefficient)
  - Some H-burning ashes dredged up at this point (since convection reaches to the shell)
  - Limit to how cool the star can get (caused by opacity at the photosphere)—star begins moving up in the HR diagram


age 7.441600e-5 yrs
model 5
Made with MESA-Web @ mesa-web.asu.edu
log mass fraction
h1
he4
o16
mg24
ne20
n14
he3
m/M⊙
log Temperature (K)
log Density (g cm^-3)
O burn
C burn
He burn
H burn
logP
logRho
logT
mass
log L/L⊙
log Teff

# Red Giant Phase

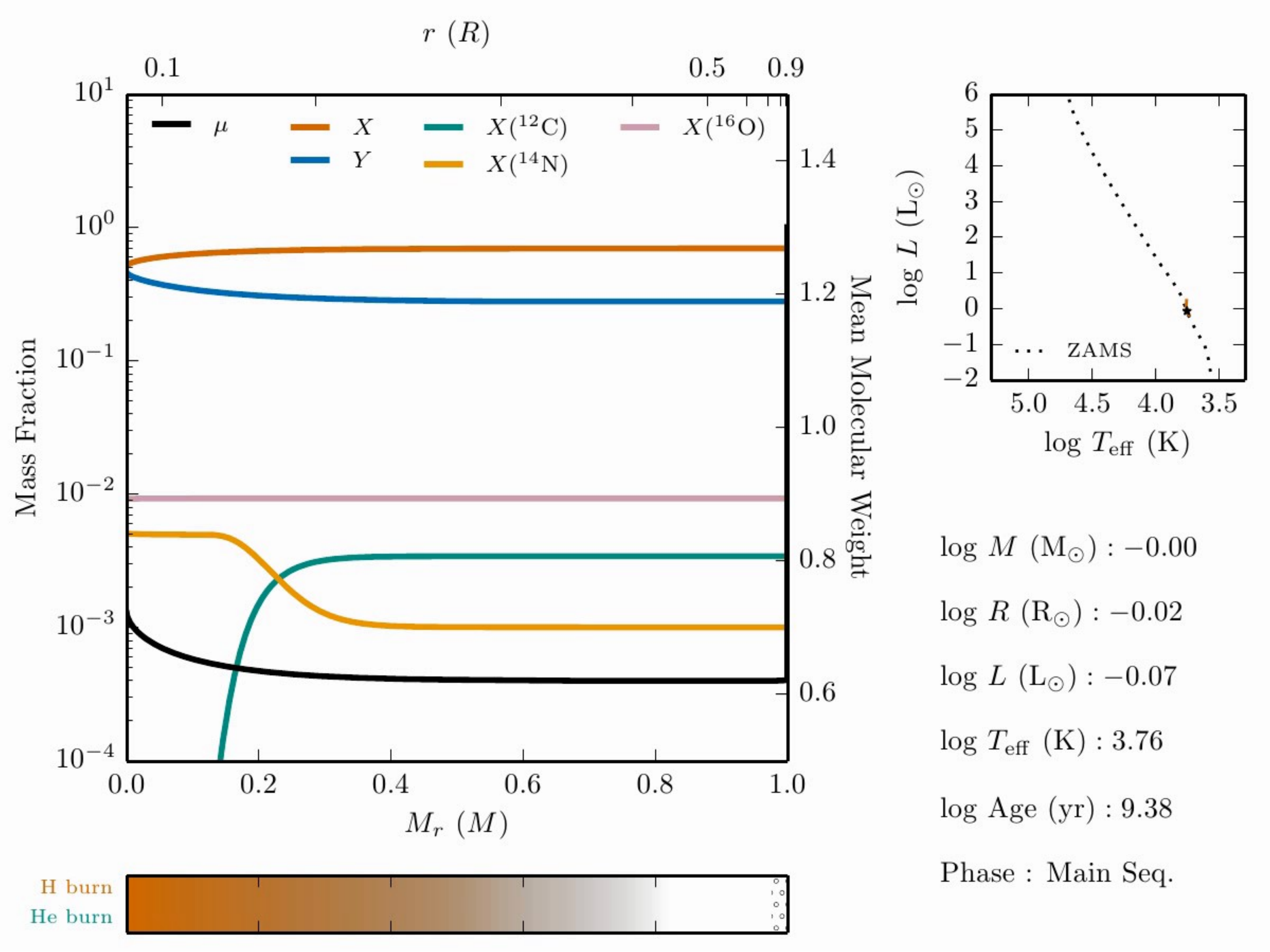
- Let's look just at the main sequence up to core H depletion
  - Movies from Rich Townsend
  - http://www.astro.wisc.edu/~townsend/static.php?ref=mesa-movies

# 1 M$_\odot$ Star



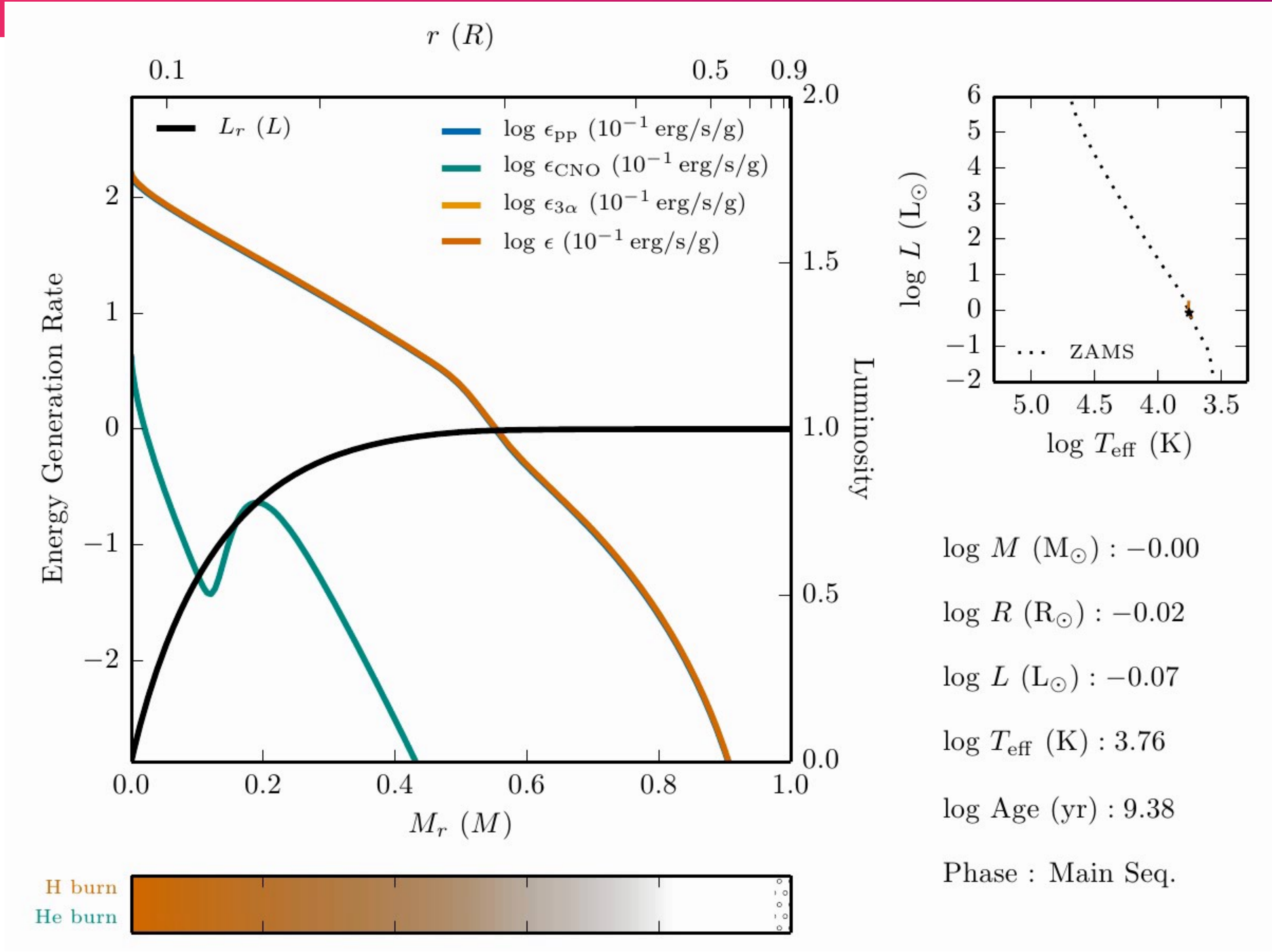
r (R)
0.1
0.5
0.9
μ
log P (10^16 dyn/cm^2)
log T (10^7 K)
log ρ (10^1 g/cm^3)
State Variables
Mean Molecular Weight
M_r (M)
H burn
He burn
log L (L⊙)
log T_eff (K)
ZAMS
log M (M⊙) : −0.00
log R (R⊙) : −0.02
log L (L⊙) : −0.07
log T_eff (K) : 3.76
log Age (yr) : 9.38
Phase : Main Seq.

# 1 $M_\odot$ Star



r (R)
0.1
0.5
0.9
μ
X
Y
X(¹²C)
X(¹⁴N)
X(¹⁶O)
Mass Fraction
Mean Molecular Weight
Mr (M)
H burn
He burn
log L (L⊙)
log Teff (K)
ZAMS
log M (M⊙) : −0.00
log R (R⊙) : −0.02
log L (L⊙) : −0.07
log Teff (K) : 3.76
log Age (yr) : 9.38
Phase : Main Seq.

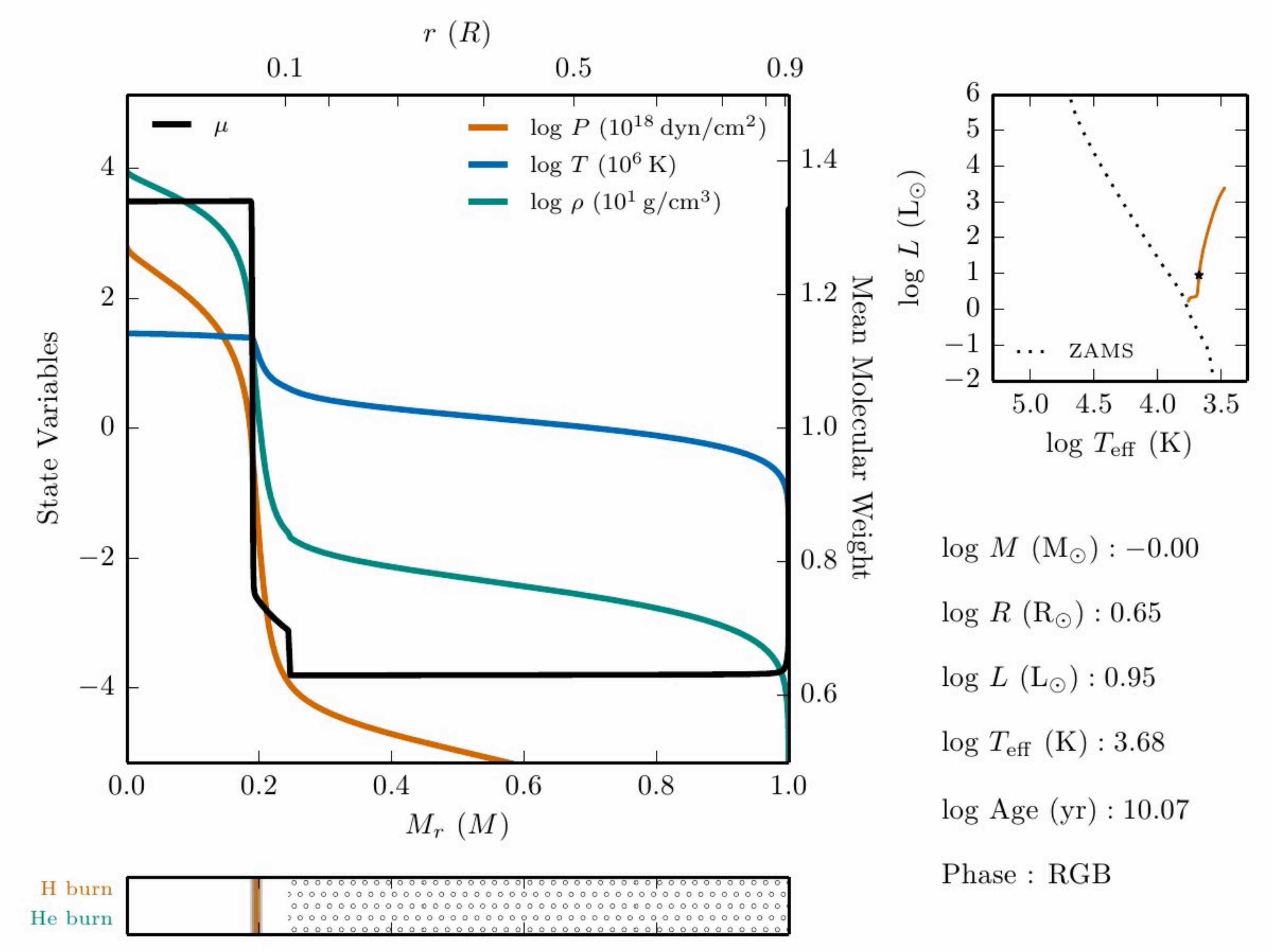
# 1 M$_\odot$ Star


$r$ ($R$)
0.1
0.5
0.9
$L_r$ ($L$)
log $\epsilon_{\rm pp}$ ($10^{-1}$ erg/s/g)
log $\epsilon_{\rm CNO}$ ($10^{-1}$ erg/s/g)
log $\epsilon_{3\alpha}$ ($10^{-1}$ erg/s/g)
log $\epsilon$ ($10^{-1}$ erg/s/g)
Energy Generation Rate
Luminosity
$M_r$ ($M$)
H burn
He burn
log $L$ (L$_\odot$)
log $T_{\rm eff}$ (K)
ZAMS
log $M$ (M$_\odot$) : −0.00
log $R$ (R$_\odot$) : −0.02
log $L$ (L$_\odot$) : −0.07
log $T_{\rm eff}$ (K) : 3.76
log Age (yr) : 9.38
Phase : Main Seq.

# Red Giant Phase

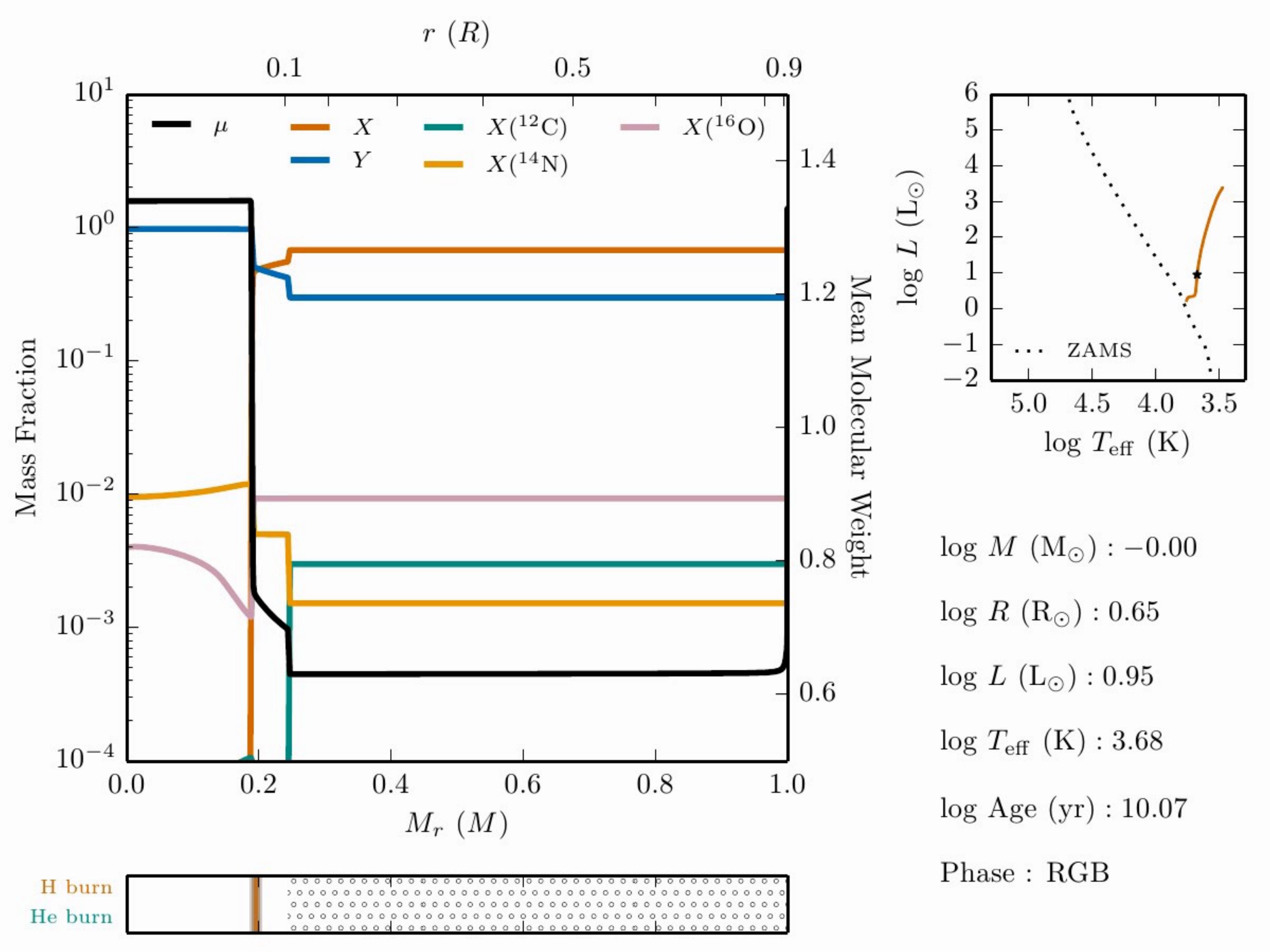
- Now the red giant phase—this is what we'll talk about next
  - Movies from Rich Townsend
  - http://www.astro.wisc.edu/~townsend/static.php?ref=mesa-movies

# 1 $M_\odot$ Star



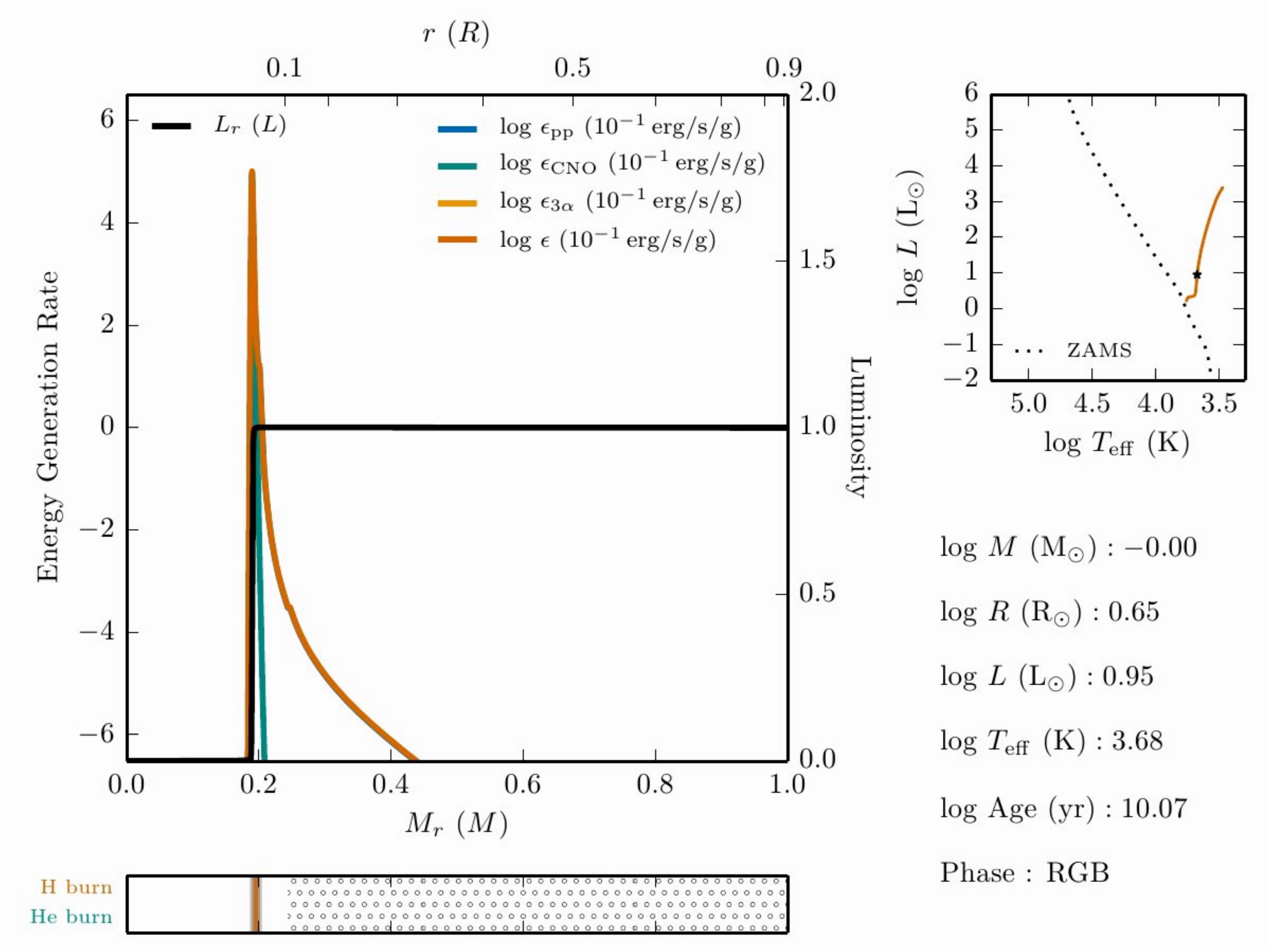
$r$ ($R$)
0.1
0.5
0.9
$\mu$
log $P$ ($10^{18}$ dyn/cm$^2$)
log $T$ ($10^6$ K)
log $\rho$ ($10^1$ g/cm$^3$)
State Variables
Mean Molecular Weight
4
2
0
−2
−4
1.4
1.2
1.0
0.8
0.6
0.0
0.2
0.4
0.6
0.8
1.0
$M_r$ ($M$)
H burn
He burn
log $L$ ($L_\odot$)
log $T_{\rm eff}$ (K)
ZAMS
5.0
4.5
4.0
3.5
log $M$ ($M_\odot$) : −0.00
log $R$ ($R_\odot$) : 0.65
log $L$ ($L_\odot$) : 0.95
log $T_{\rm eff}$ (K) : 3.68
log Age (yr) : 10.07
Phase : RGB

# 1 $M_\odot$ Star



$r$ ($R$)
0.1
0.5
0.9
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
Mass Fraction
$\mu$
$X$
$Y$
$X(^{12}\mathrm{C})$
$X(^{14}\mathrm{N})$
$X(^{16}\mathrm{O})$
1.4
1.2
1.0
0.8
0.6
Mean Molecular Weight
0.0
0.2
0.4
0.6
0.8
1.0
$M_r$ ($M$)
H burn
He burn
log $L$ ($L_\odot$)
6
5
4
3
2
1
0
−1
−2
ZAMS
5.0
4.5
4.0
3.5
log $T_{\mathrm{eff}}$ (K)
log $M$ ($M_\odot$) : −0.00
log $R$ ($R_\odot$) : 0.65
log $L$ ($L_\odot$) : 0.95
log $T_{\mathrm{eff}}$ (K) : 3.68
log Age (yr) : 10.07
Phase : RGB

# 1 $M_\odot$ Star



$r$ $(R)$
0.1
0.5
0.9
$L_r$ $(L)$
$\log\,\epsilon_{\rm pp}$ $(10^{-1}$ erg/s/g)
$\log\,\epsilon_{\rm CNO}$ $(10^{-1}$ erg/s/g)
$\log\,\epsilon_{3\alpha}$ $(10^{-1}$ erg/s/g)
$\log\,\epsilon$ $(10^{-1}$ erg/s/g)
Energy Generation Rate
Luminosity
$M_r$ $(M)$
H burn
He burn
$\log L$ $(L_\odot)$
$\log T_{\rm eff}$ (K)
ZAMS
$\log M$ $(M_\odot)$ : $-0.00$
$\log R$ $(R_\odot)$ : 0.65
$\log L$ $(L_\odot)$ : 0.95
$\log T_{\rm eff}$ (K) : 3.68
log Age (yr) : 10.07
Phase : RGB

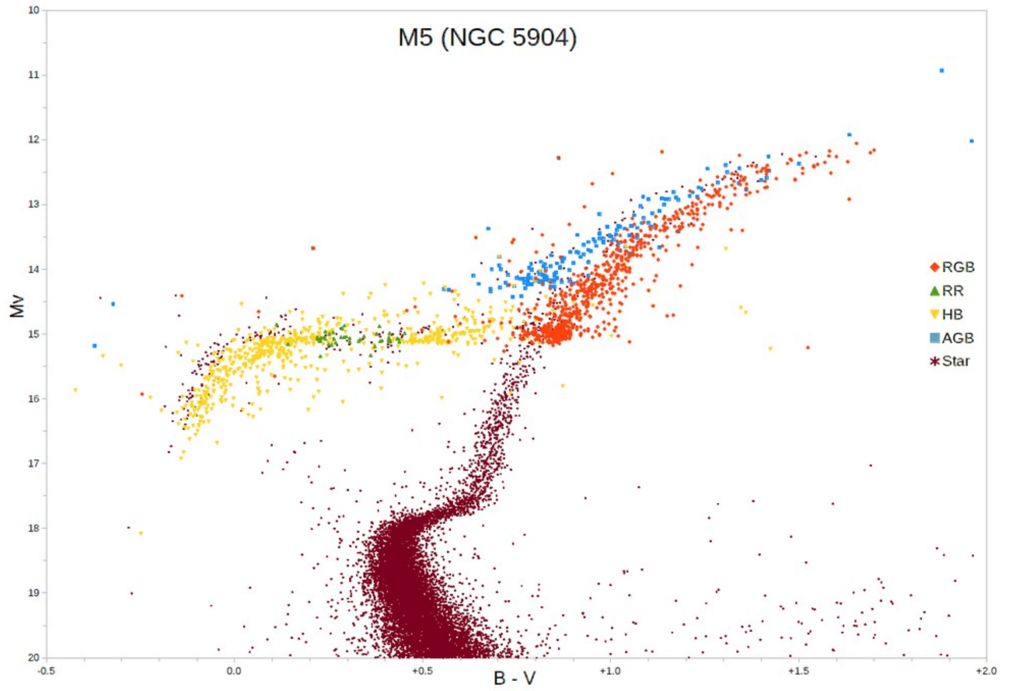
# He Ignition

- He ignition requires T ~ $10^8$ K
- Very low mass stars (M < 0.4 solar masses) never reach the temperature needed for He ignition
  - Leave He white dwarf behind
- Stars more massive than ~1.5 – 2 solar masses reach the He ignition T while the core is not degenerate

- In-between: helium flash!
  - Explosive ignition of He
  - Degeneracy means increase in T gives no pressure relief
  - Difficult phase of evolution to model (very dynamic!)
  - Actually happens off-center (neutrino emission cools center)

# Core He Burning

- Low mass stars (0.7 – 2 M⊙) have He flash
  - Lifts degeneracy, core expands, cools
    - Envelope contracts, heats
  - Shell burning drops in L (due to core expansion)
    - Star descends off red giant branch onto horizontal branch
    - Teff increases due to radius decrease
    - He burning lifetime ~ $10^8$ yr
  - He cores here all ~ same mass
    - Envelopes mass dictates difference between stars
    - High envelope mass → cooler $T_{ef}$f (red)
      - H burning dominates, convective envelope
    - Smallest envelope masses (blue)
      - Weaker H burning shells, radiative envelops



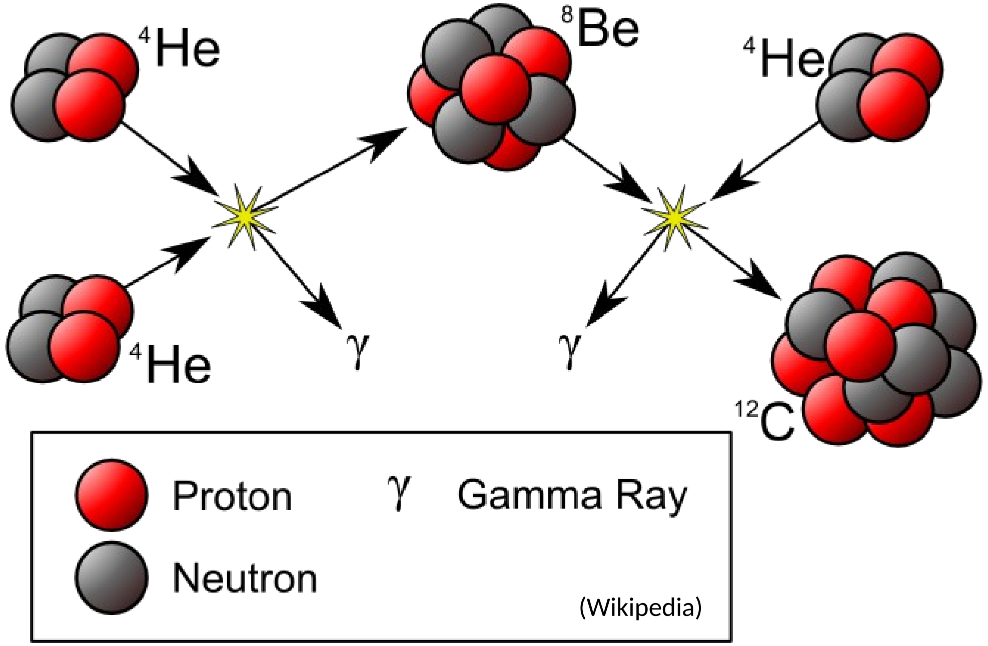

15,000 stars in the Messier 5 globular cluster are plotted on a colour-magnitude diagram. Known red giant branch (RGB), RR Lyrae variable (RR), horizontal branch (HB), and asymptotic giant branch (AGB) stars are marked.
(Lithopsian/Wikipedia)

# Core He Burning

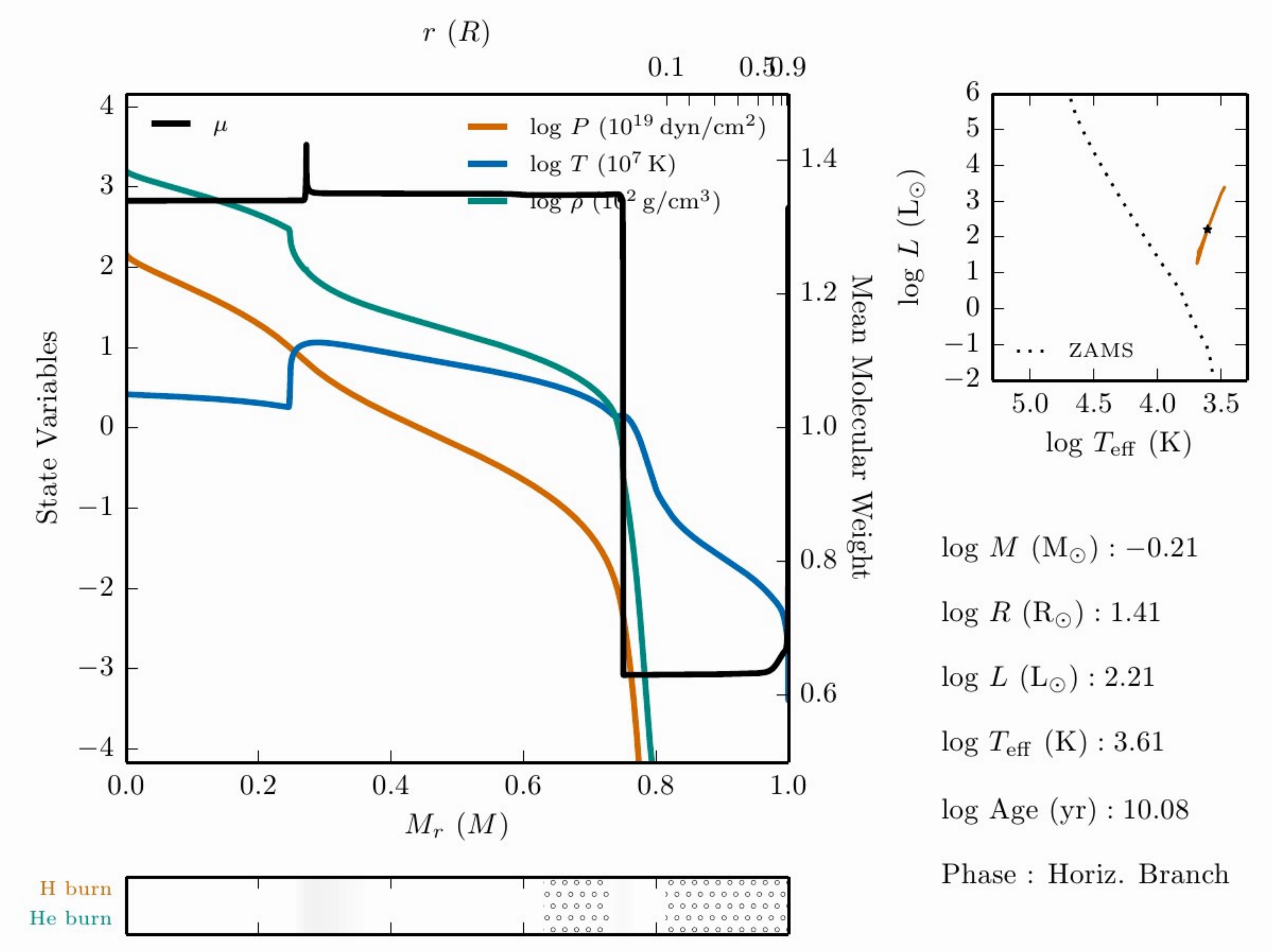
- Intermediate mass stars (2 - 10 $M_\odot$)
  - He ignites easily once T ~ $10^8$ K—no He flash
    - He luminosity steadily increases
    - H luminosity decreases
  - T at H shell base drops, envelope cools, contracts (around when $L_H \sim L_{he}$)
    - Star leaves red giant branch (some loop to higher $T_{eff}$)
  - He main sequence is close to RGB
  - Envelope instability, longer pulse periods: Cepheids

# 3-alpha Process

- Consider: $^4He + ^4He \rightarrow ^8Be + \gamma$
  - $^8Be$ has less binding energy / nucleon than the two alphas
  - $^8Be$ rapidly decays
  - Salpeter & Hoyle: equilibrium—always some $^8Be$ around
- At $\rho \sim 10^5$ g cm$^{-3}$, $T \sim 10^8$ K: one $^8Be$ for every $10^9$ $^4He$ nuclei (Shu)
  - $^8Be + ^4He \rightarrow ^{12}C + \gamma$
- Net: $3\ ^4He \rightarrow ^{12}C + 2\gamma$
  - $\epsilon \sim \rho^2 T^{40}$



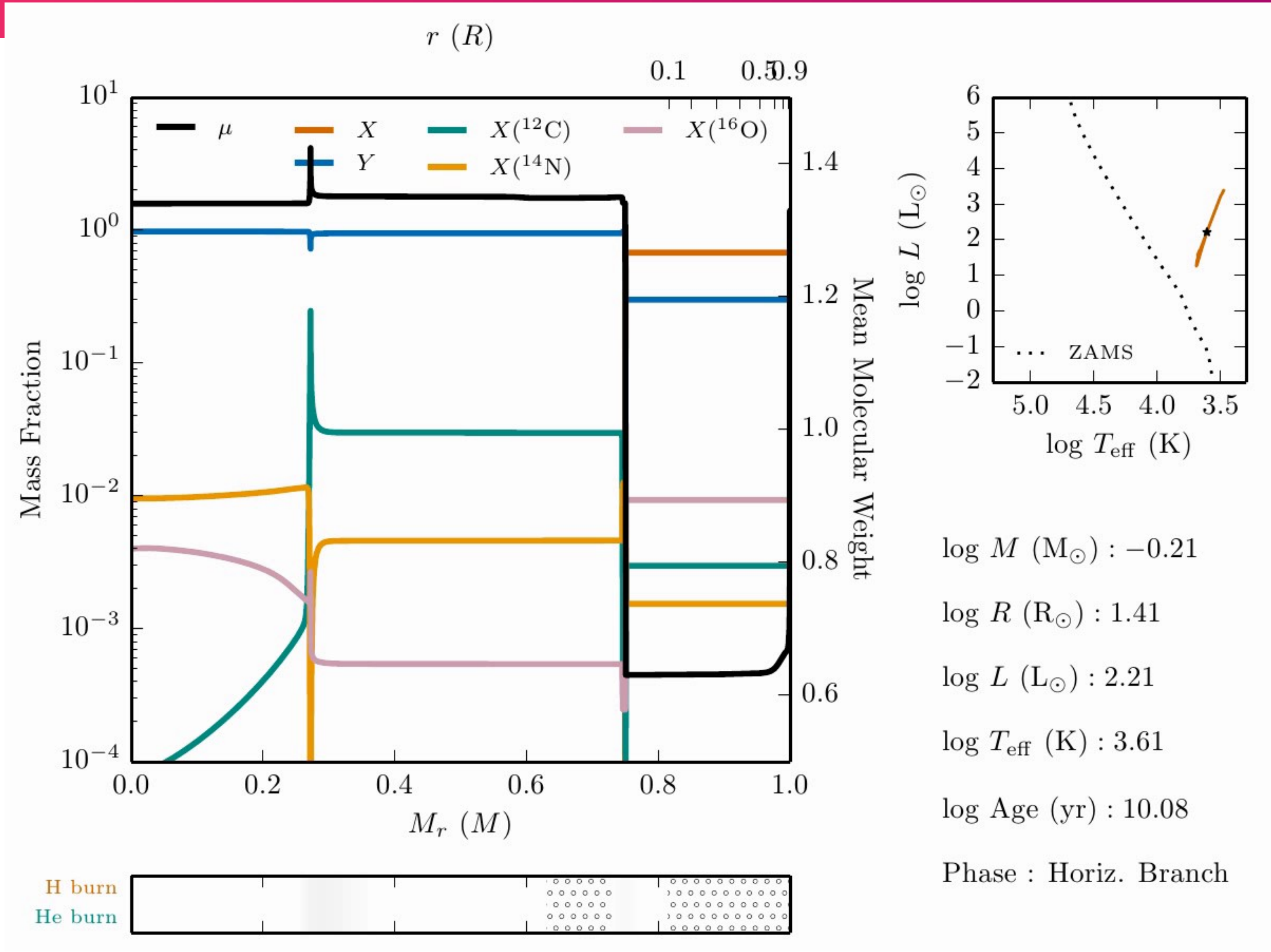
# 1 M$_\odot$ Star






He flash

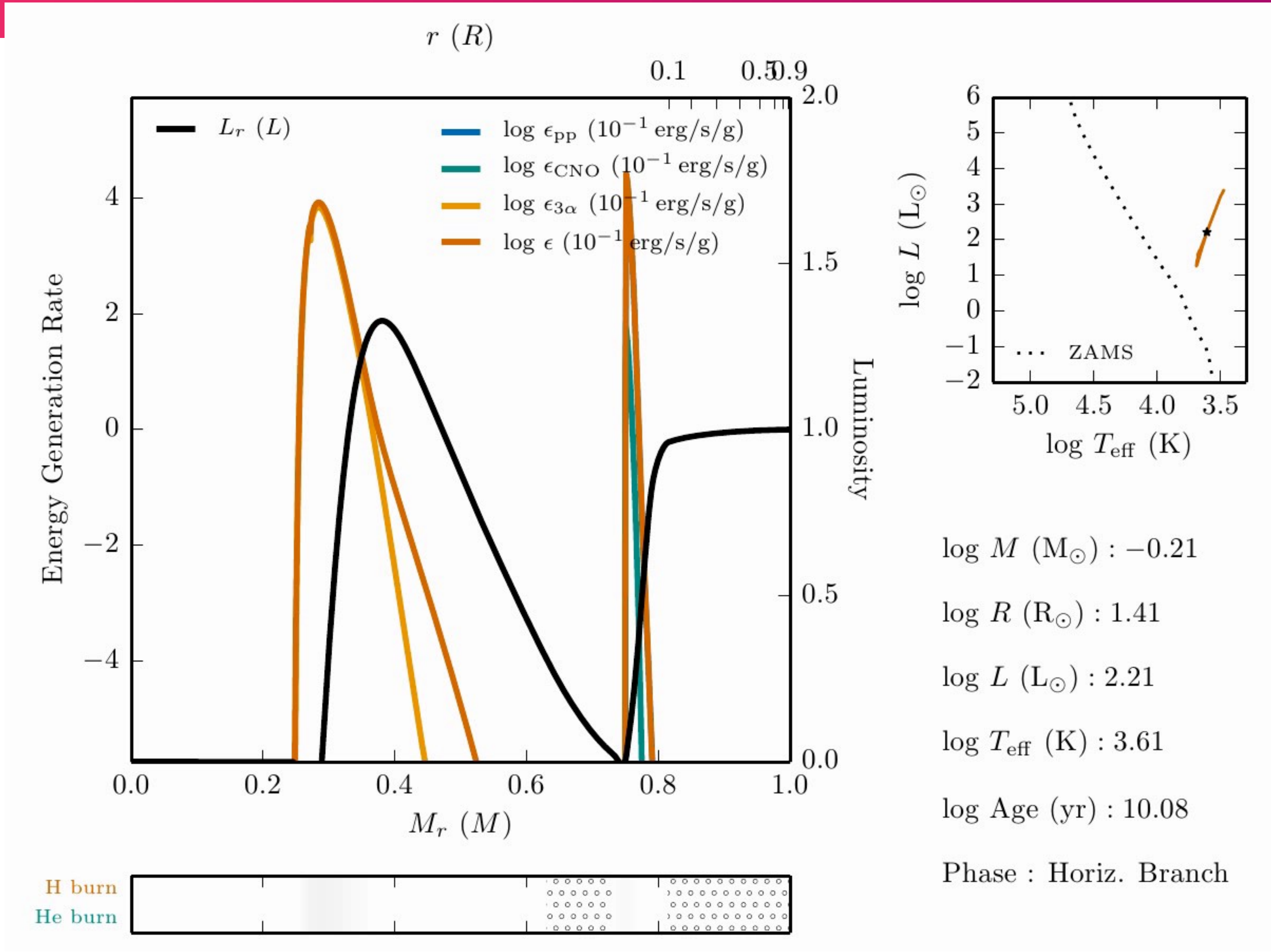
# 1 M$_\odot$ Star






He flash

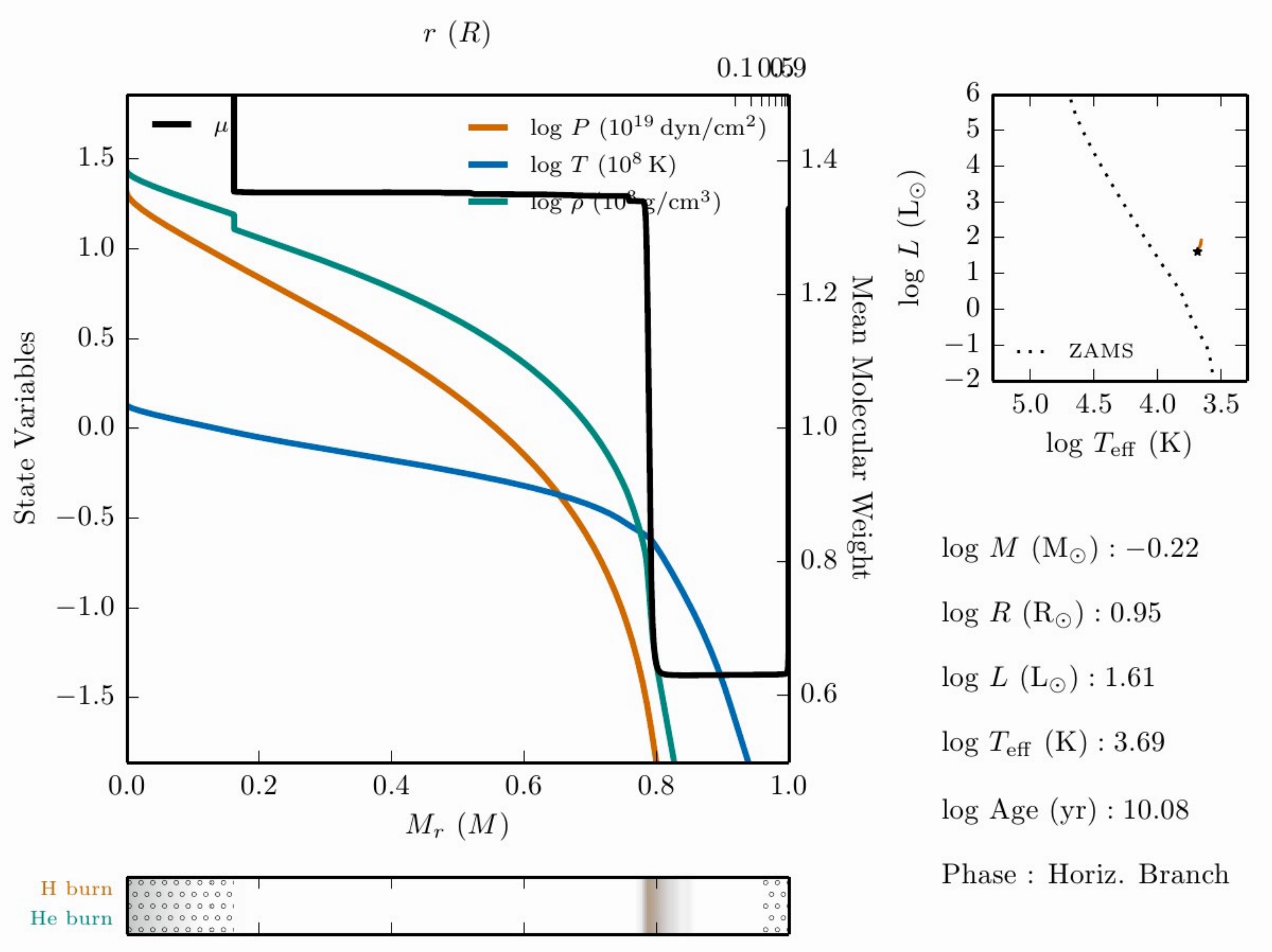
# 1 M$_\odot$ Star






He flash

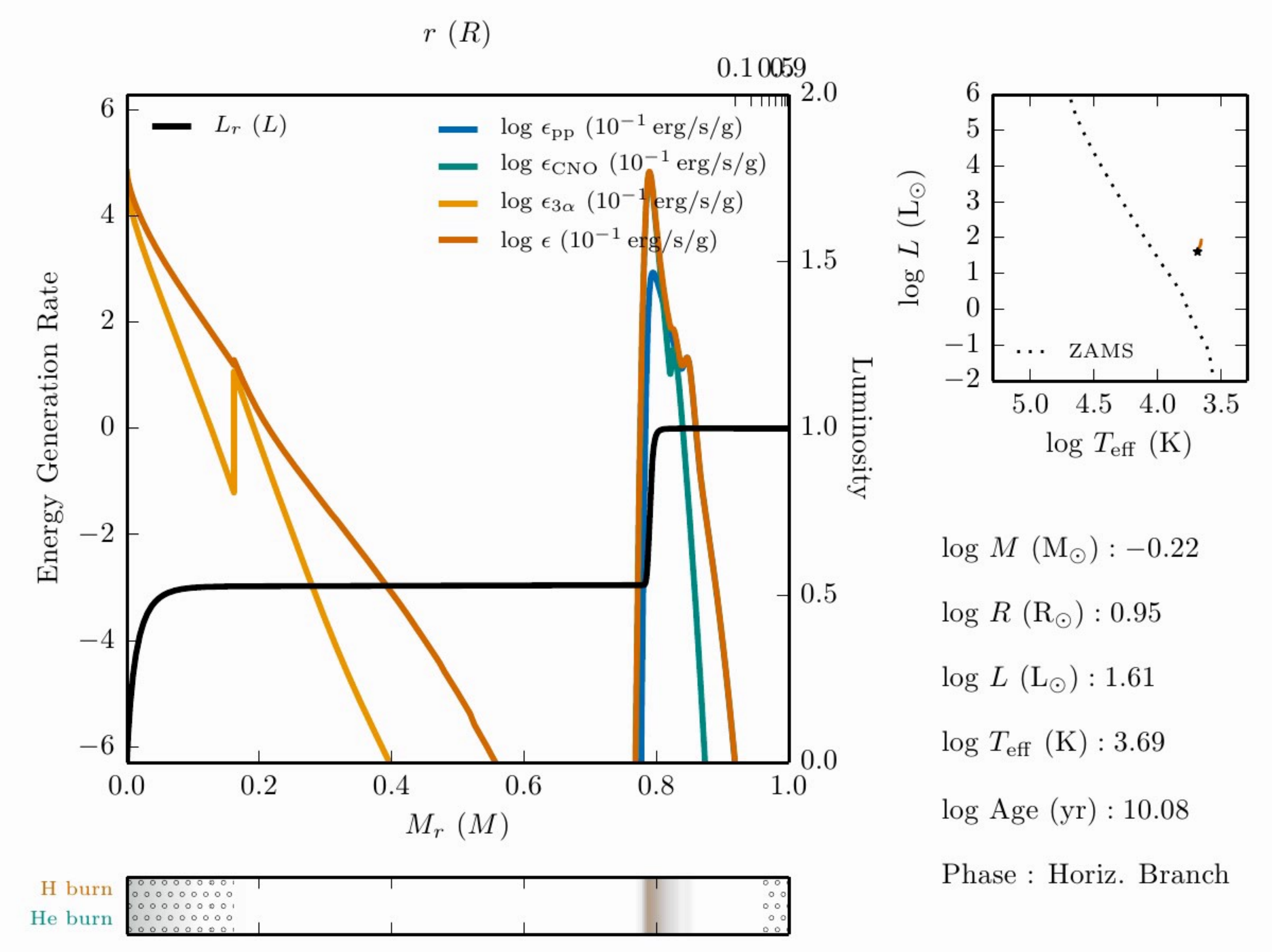
# 1 M$_\odot$ Star






He burning

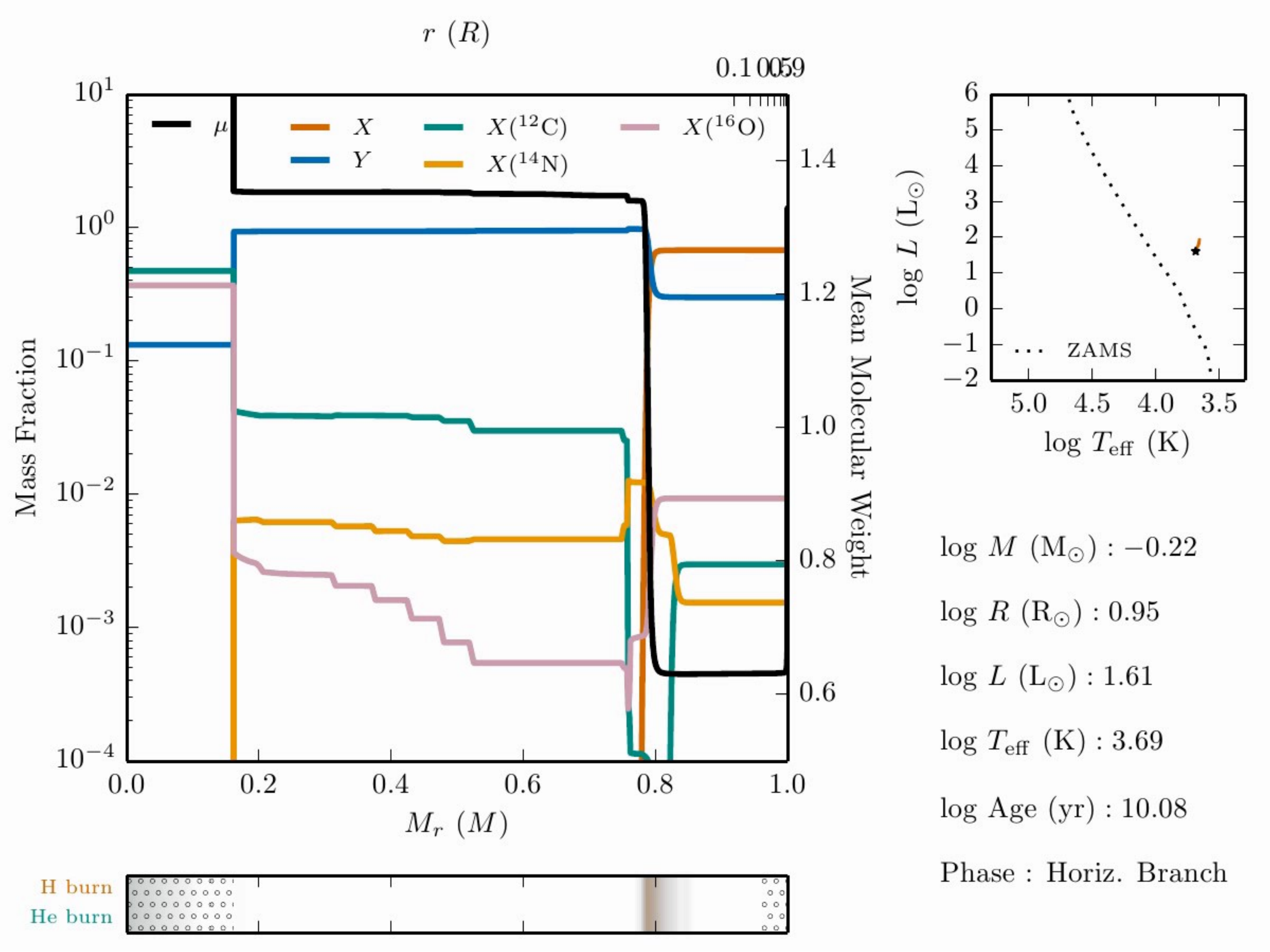
# 1 $M_\odot$ Star






He burning

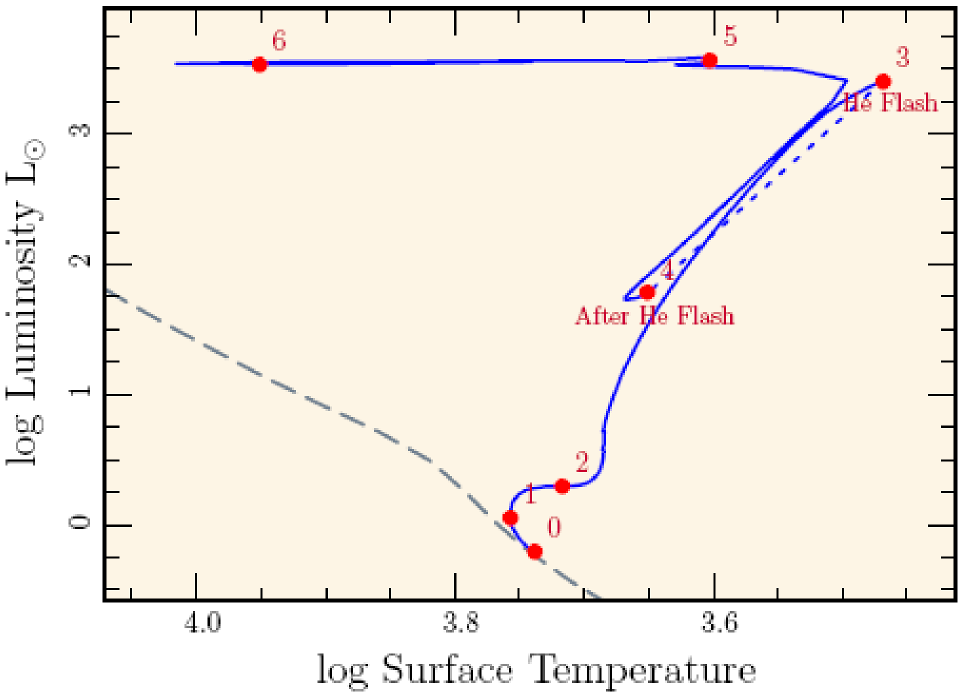
# 1 M$_\odot$ Star

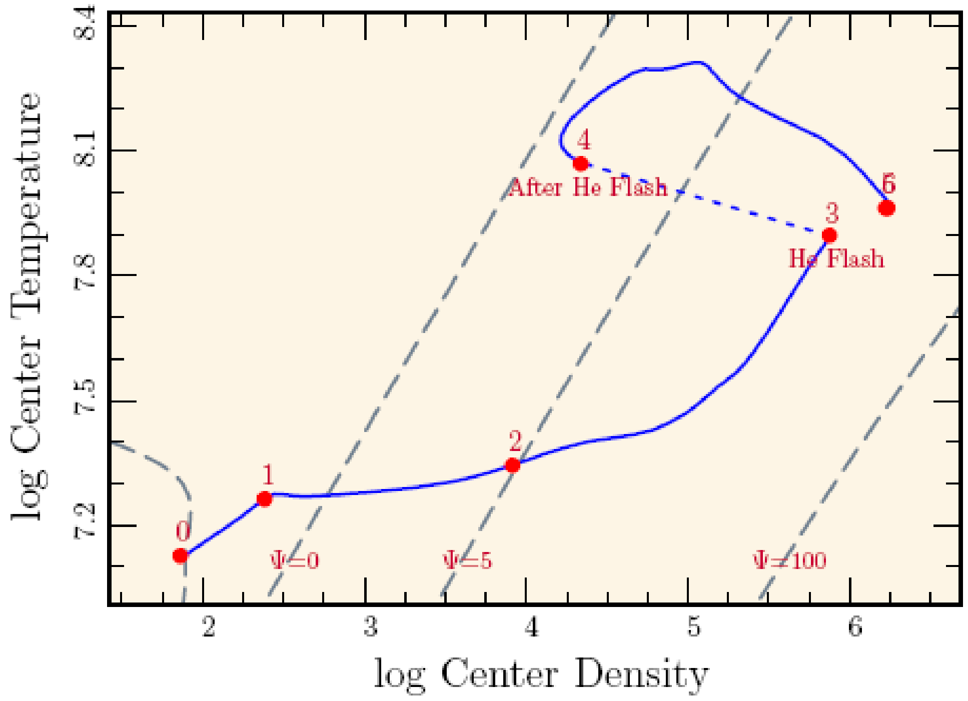





He burning

# Sun’s Evolution




| | Age | Mass |
|---|---|---|
| 0 | 0.00 | 1.000 |
| 1 | 7.73 | 0.999 |
| 2 | 11.85 | 0.997 |
| 3 | 12.72 | 0.754 |
| 4 | 12.99 | 0.751 |
| 5 | 13.12 | 0.565 |
| 6 | 13.12 | 0.565 |

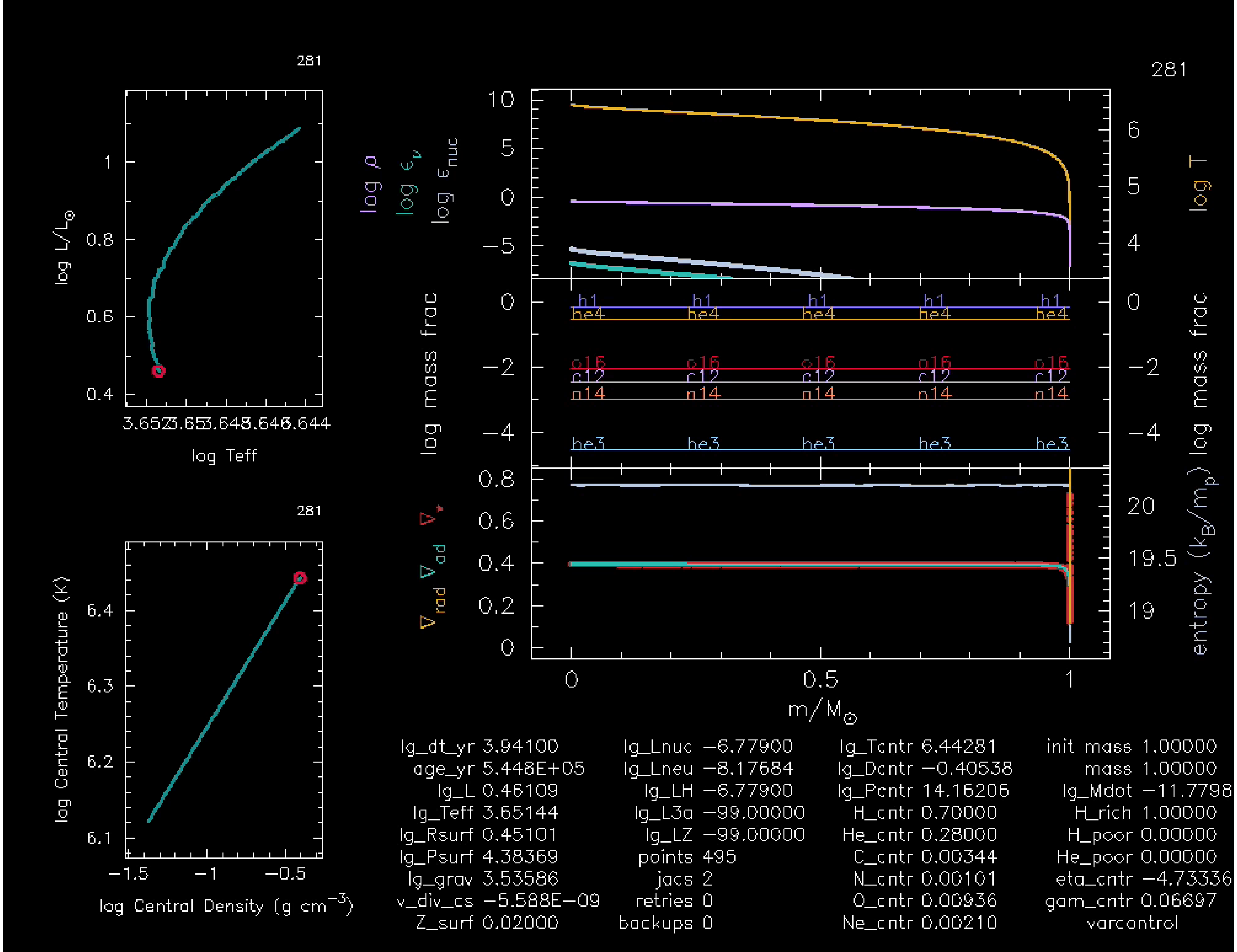


(from Bill Paxton, EZ Stellar Evolution)

# He Burning

- Core expands rapidly after He flash, envelope contracts (opposite of red giant)
- L decreases (because T drops from expansion)
- Star is now on the horizontal branch: "He main sequence"
  - Shorter phase than MS (L is higher, fuel is less)
- Process now repeats
  - He core exhaustion followed by He shell burning
  - H shell still exists (outside of He shell): double shell burning!
  - Ascends the asymptotic giant branch
  - Carbon core forms
- Evolution is sensitive to mass loss
  - Outer layer of AGB weakly bound
  - Winds, pulsations cause mass loss

Zingale


281
log L/L$_\odot$
log Teff
3.652 3.65 3.648 3.646 3.644
281
log Central Temperature (K)
log Central Density (g cm$^{-3}$)
log ρ
log ε$_\nu$
log ε$_{nuc}$
log T
log mass frac
h1
he4
o16
c12
n14
he3
∇$_{rad}$ ∇$_{ad}$ ∇$_*$
entropy (k$_B$/m$_p$)
m/M$_\odot$
lg_dt_yr 3.94100
age_yr 5.448E+05
lg_L 0.46109
lg_Teff 3.65144
lg_Rsurf 0.45101
lg_Psurf 4.38369
lg_grav 3.53586
v_div_cs −5.588E−09
Z_surf 0.02000
lg_Lnuc −6.77900
lg_Lneu −8.17684
lg_LH −6.77900
lg_L3a −99.00000
lg_LZ −99.00000
points 495
jacs 2
retries 0
backups 0
lg_Tcntr 6.44281
lg_Dcntr −0.40538
lg_Pcntr 14.16206
H_cntr 0.70000
He_cntr 0.28000
C_cntr 0.00344
N_cntr 0.00101
O_cntr 0.00936
Ne_cntr 0.00210
init mass 1.00000
mass 1.00000
lg_Mdot −11.7798
H_rich 1.00000
H_poor 0.00000
He_poor 0.00000
eta_cntr −4.73336
gam_cntr 0.06697
varcontrol

# Low Mass Evolution

- Evolution of different masses—note the 2 solar mass star ignites He without becoming nearly as degenerate

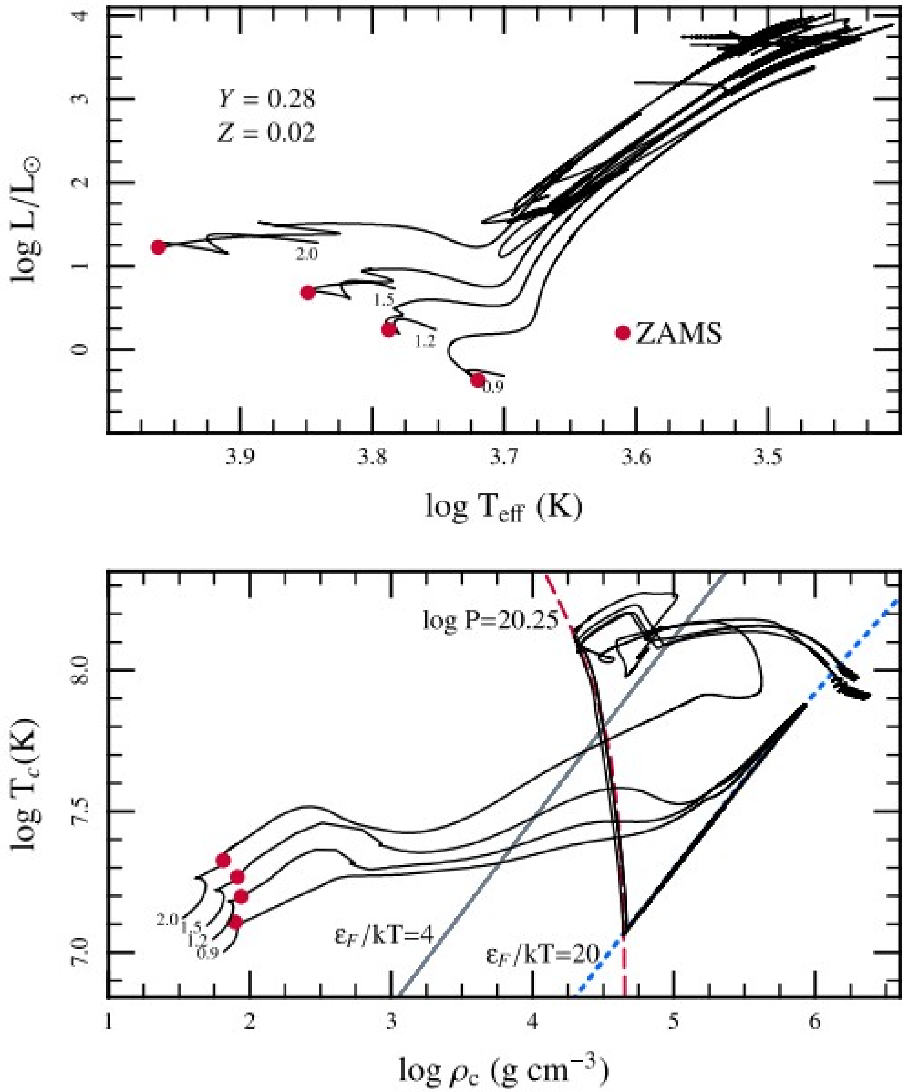
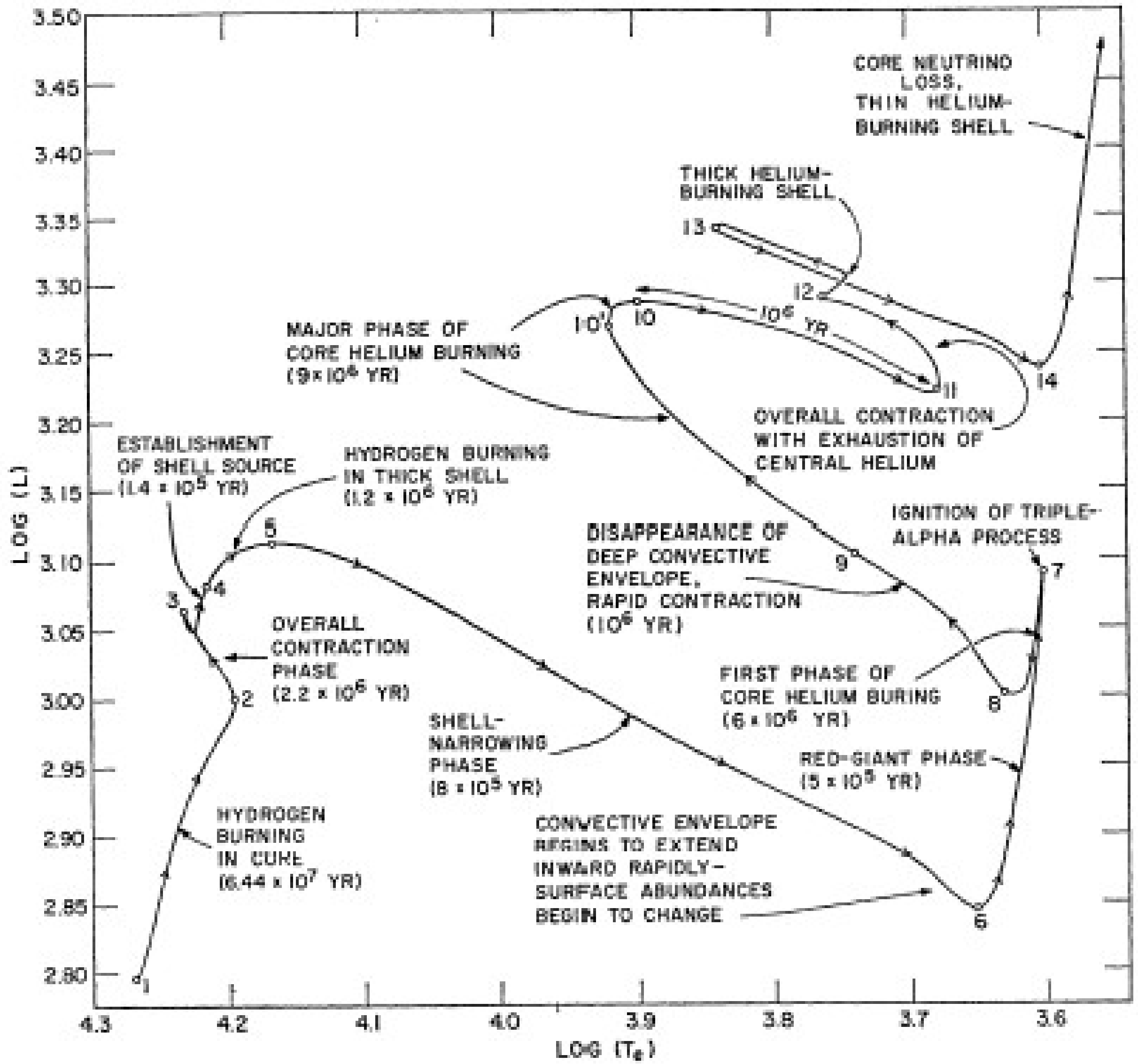


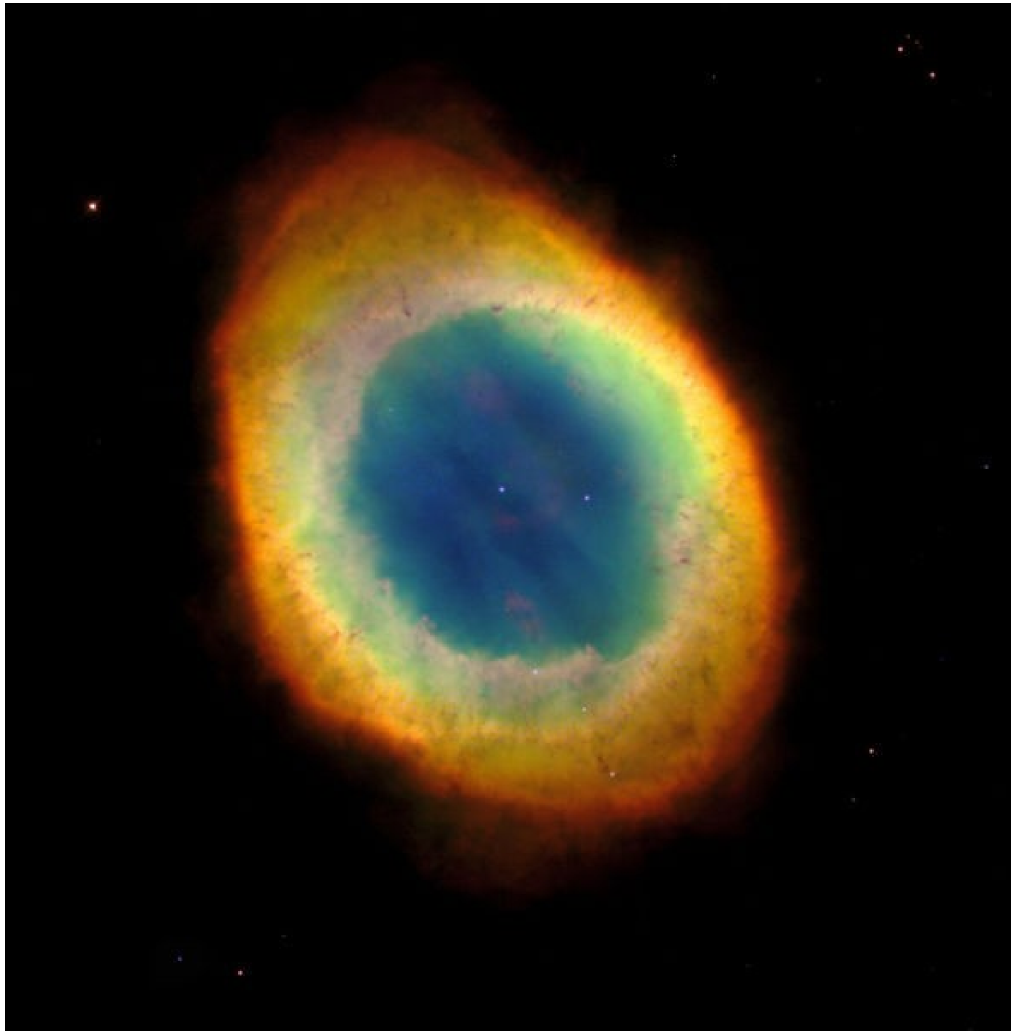

**Figure 14.** Evolution from MESA star of 0.9, 1.2, 1.5, and 2 $M_\odot$ stars with $Z = 0.02$ up to the end of the TP-AGB. The top panel shows their evolution in the H-R diagram, where the solid red point is the ZAMS. The bottom panel shows the evolution in the $T_c - \rho_c$ plane, exhibiting the He core flash and later evolution of the C/O core during the thermal pulses. The dashed blue (heavy gray) line shows a constant electron degeneracy of $\epsilon_F/k_BT = 20(4)$. The dashed red line is for a constant pressure of $\log P = 20.25$; relevant to the He core flash.

(MESA paper)




(Iben, Ann. Rev. Astron. Astroph. 1967)

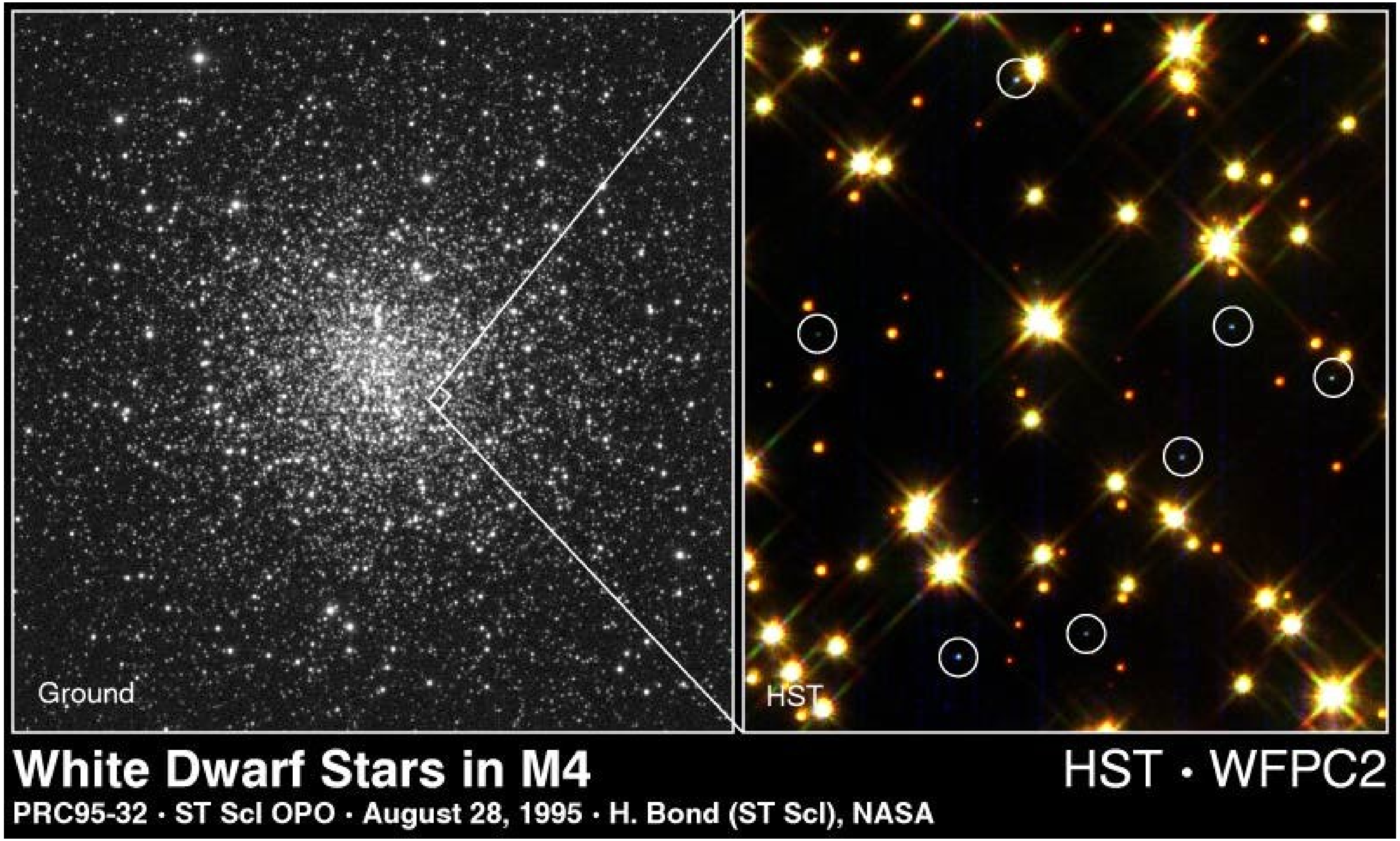
- For masses < 8 solar masses (or so)
  - The star is not massive enough to ignite the C core
  - Ejected shells with hot exposed core: planetary nebula phase
  - CO white dwarf left behind
    - This is what happens with our Sun
  - Some stars at the higher end of this range can burn C, and leave ONeMg WDs behind
  -



M57 (NASA/ESA)

# White Dwarfs

Cooling white dwarfs are observed—they can tell us about the age of the Universe (they take a long time to cool—Ch. 10, later…)

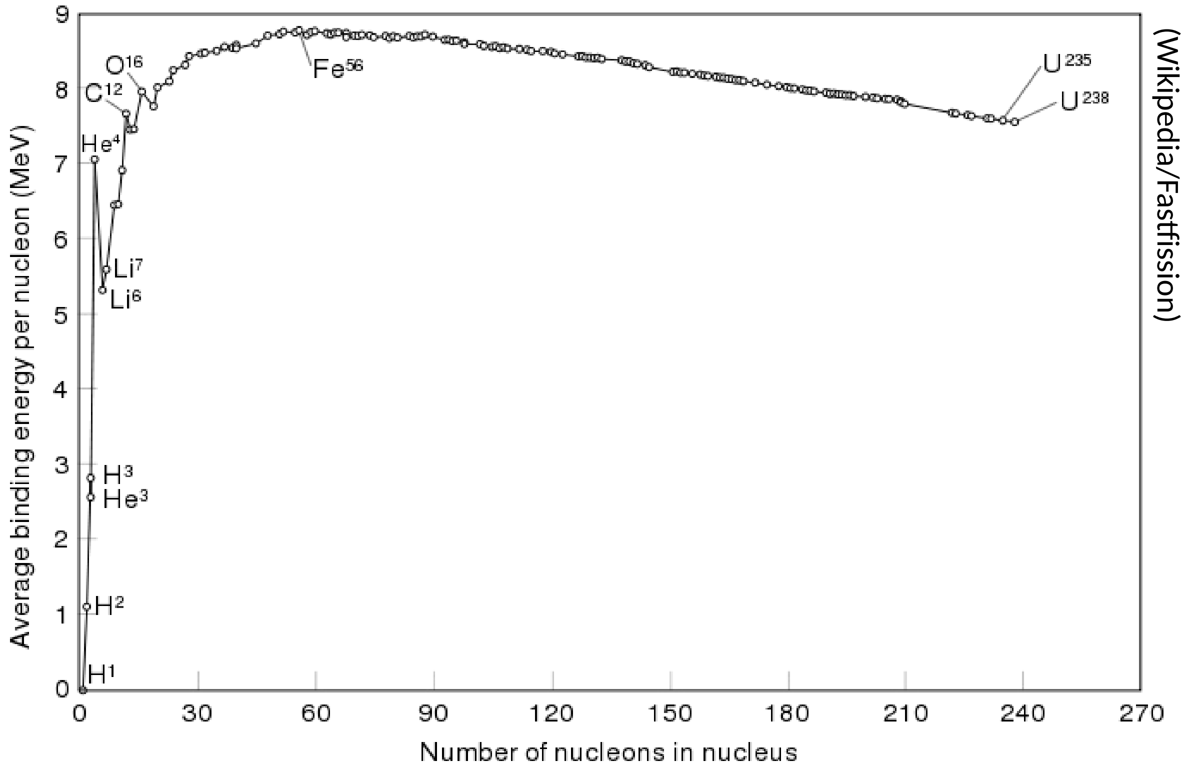





http://antwrp.gsfc.nasa.gov/apod/ap000910.html

# High Mass Evolution

- Evolution of higher mass stars
  - Burning can continue for stars with M > ~8 solar masses
  - Lifetimes are VERY short
  - Remember: most of the energy available comes from H burning




(Wikipedia/Fastfission)

# High Mass Evolution

| *core burning state* | *9 $M_\odot$ star* | *25 $M_\odot$ star* | *core temperature* |
|---|---|---|---|
| H burning | 20 million years | 7 million years | (3-10) $\times 10^7$ K |
| He burning | 2 million years | 700,000 years | (1-7.5) $\times 10^8$ K |
| C burning | 380 years | 160 years | (0.8-1.4) $\times 10^9$ K |
| Ne burning | 1.1 years | 1 year | (1.4-1.7) $\times 10^9$ K |
| O burning | 8 months | 6 months | (1.8-2.8) $\times 10^9$ K |
| Si burning | 4 days | 1 day | (2.8-4) $\times 10^9$ K |

(table from Hester et al. Ch. 17)

# Other Burning

- C burning
  - Primary reactions:

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{23}\mathrm{Na} + {}^{1}\mathrm{H}$$
$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He}$$

  - Less likely (due to structure of Mg nuclear levels)

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

  - Note that these are extremely T sensitive
    - Electron screening can be important at high densities

- Neon burning follows (not O!)
  - Carbon burning makes lots of $^{20}$Ne
  - Photodisintegration becomes important and $^{20}$Ne can alpha-capture

$$^{20}\mathrm{Ne} + \gamma \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He}$$
$$^{20}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

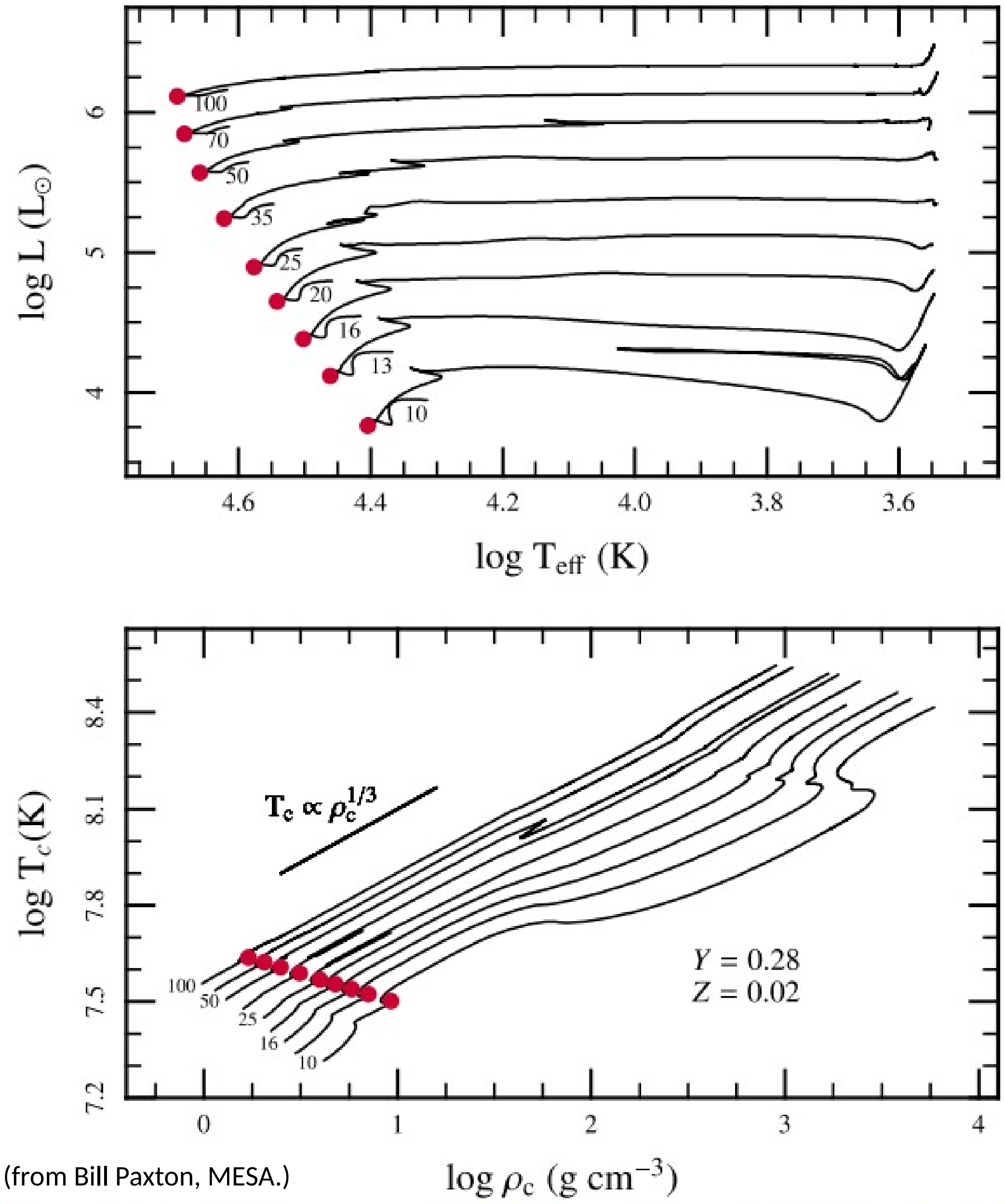
  - Lots of $^{16}$O builds up
- Oxygen burning primarily makes silicon and sulfur

# Other Burning

- Silicon burning is more complex
  - Coulomb barrier to large to directly fuse 2 $^{28}Si$ nuclei
  - Photodisintegration starts to occur
    - Photon energies ~ binding energy / nucleon—nuclei can break apart
  - Nuclear statistical equilibrium results
    - Burning proceeds by alpha-captures
    - Balance of forward and inverse reactions
    - Small imbalance leads to production of iron-group nuclei

# High Mass Evolution

- Evolution of higher mass stars
  - Evolution of outer layers is pretty much decoupled from what's happening in the core (too fast)




(from Bill Paxton, MESA.)

**Figure 29.** Top: H-R diagram for 10–100 $M_\odot$ models from the PMS to the end of core Helium burning for $Z = 0.02$ but with zero mass loss. Bottom: trajectories of the central conditions in the $T-\rho$ plane over this same evolutionary period.

# High Mass Evolution

- Advance burning stages lead to a "onion-skin" layering of nuclei

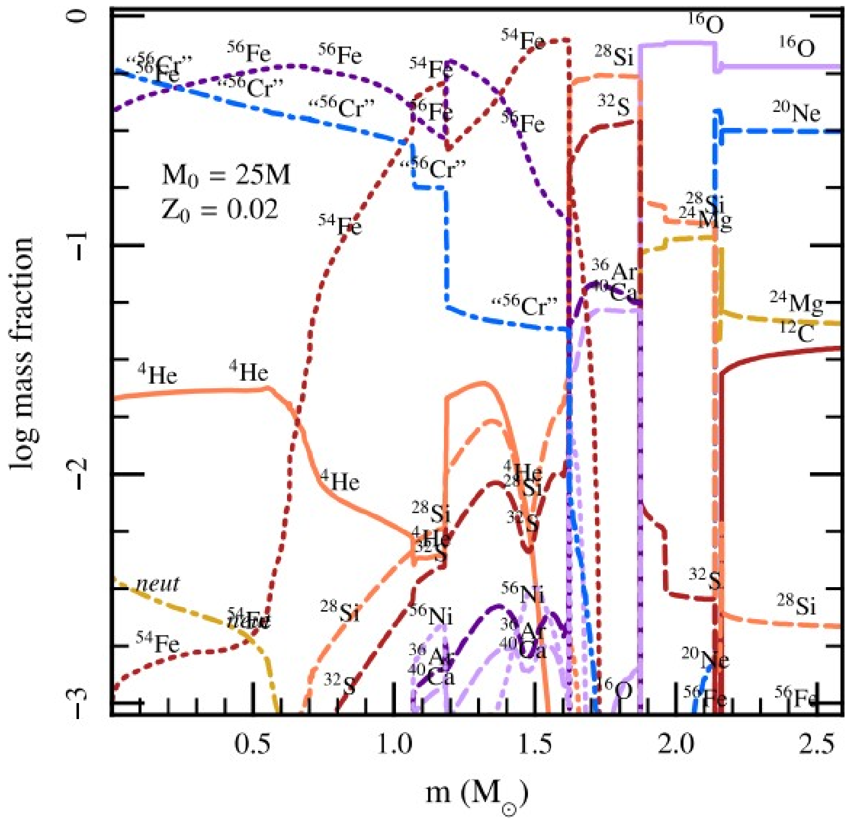
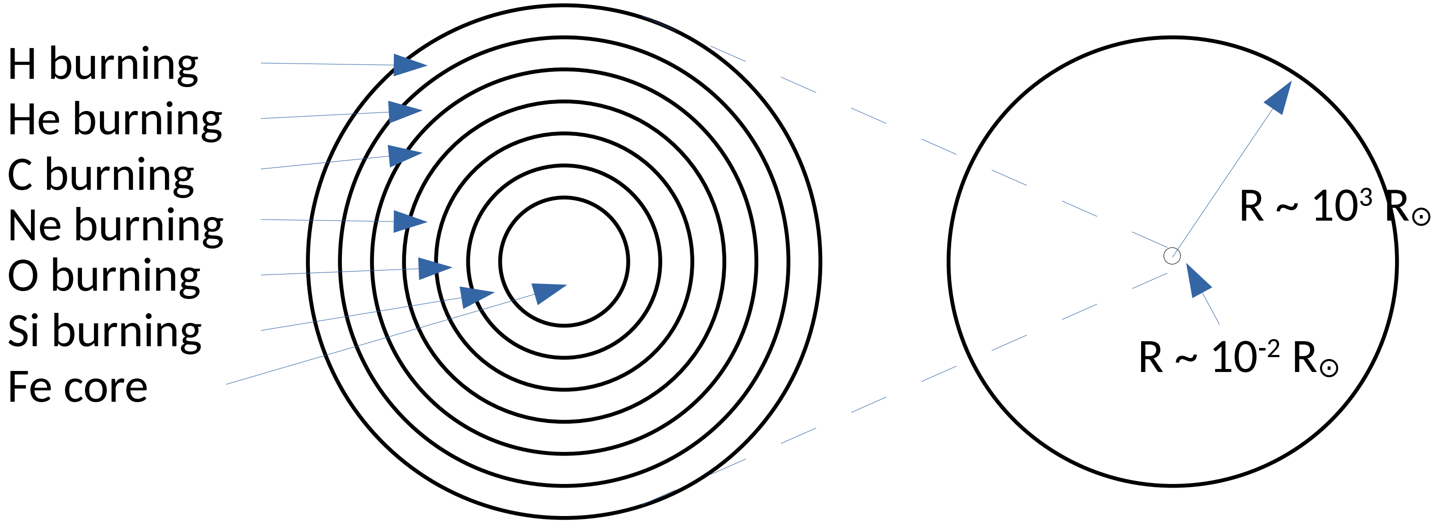
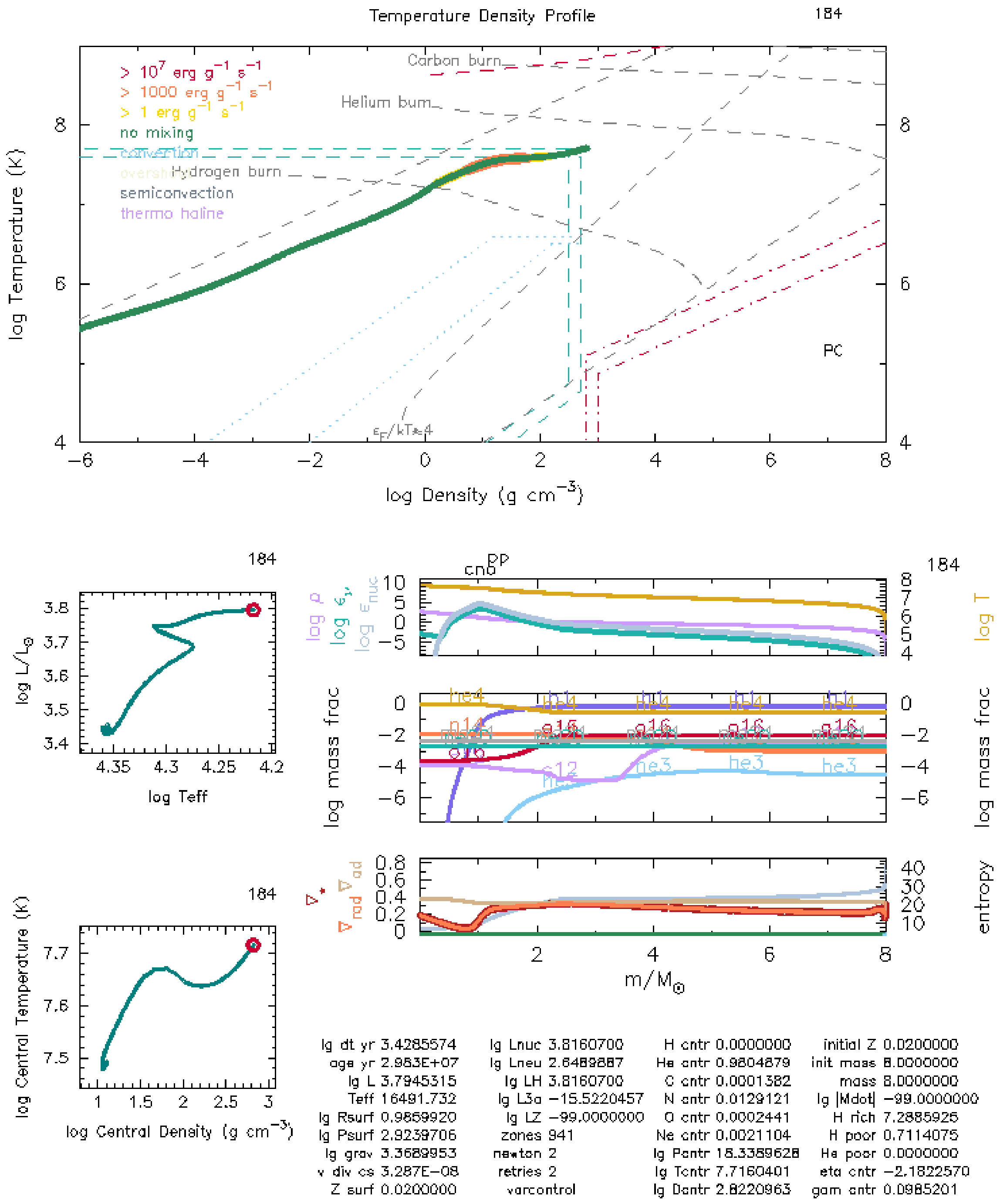



**Figure 31.** Mass fraction profiles of the inner 2.5 $M_\odot$ of the solar metallicity $M_i = 25\,M_\odot$ model at the onset of core collapse. The reaction network includes links between $^{54}$Fe, $^{56}$Cr, neutrons, and protons to model aspects of photodisintegration and neutronization.

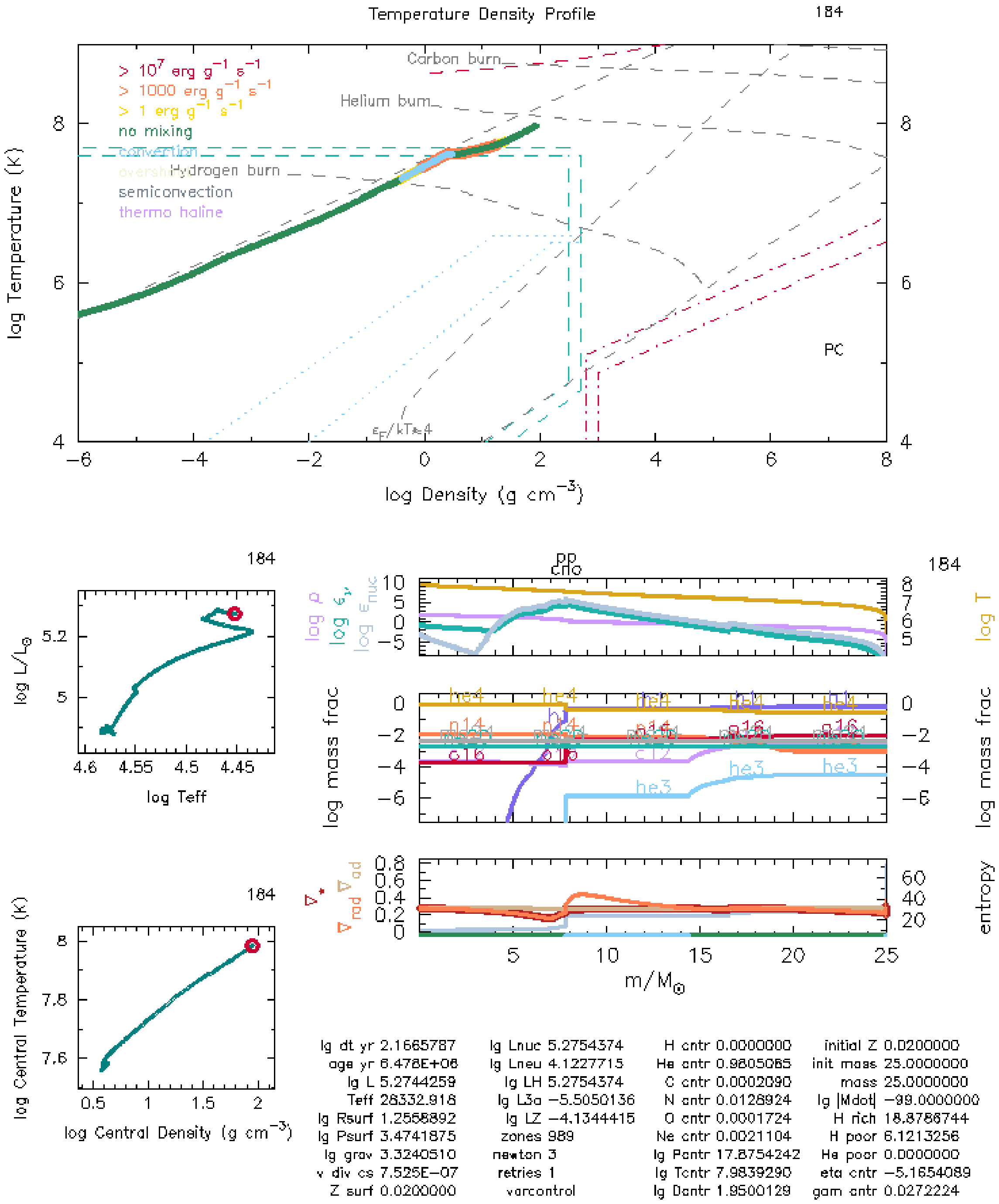
(from Bill Paxton, MESA.)



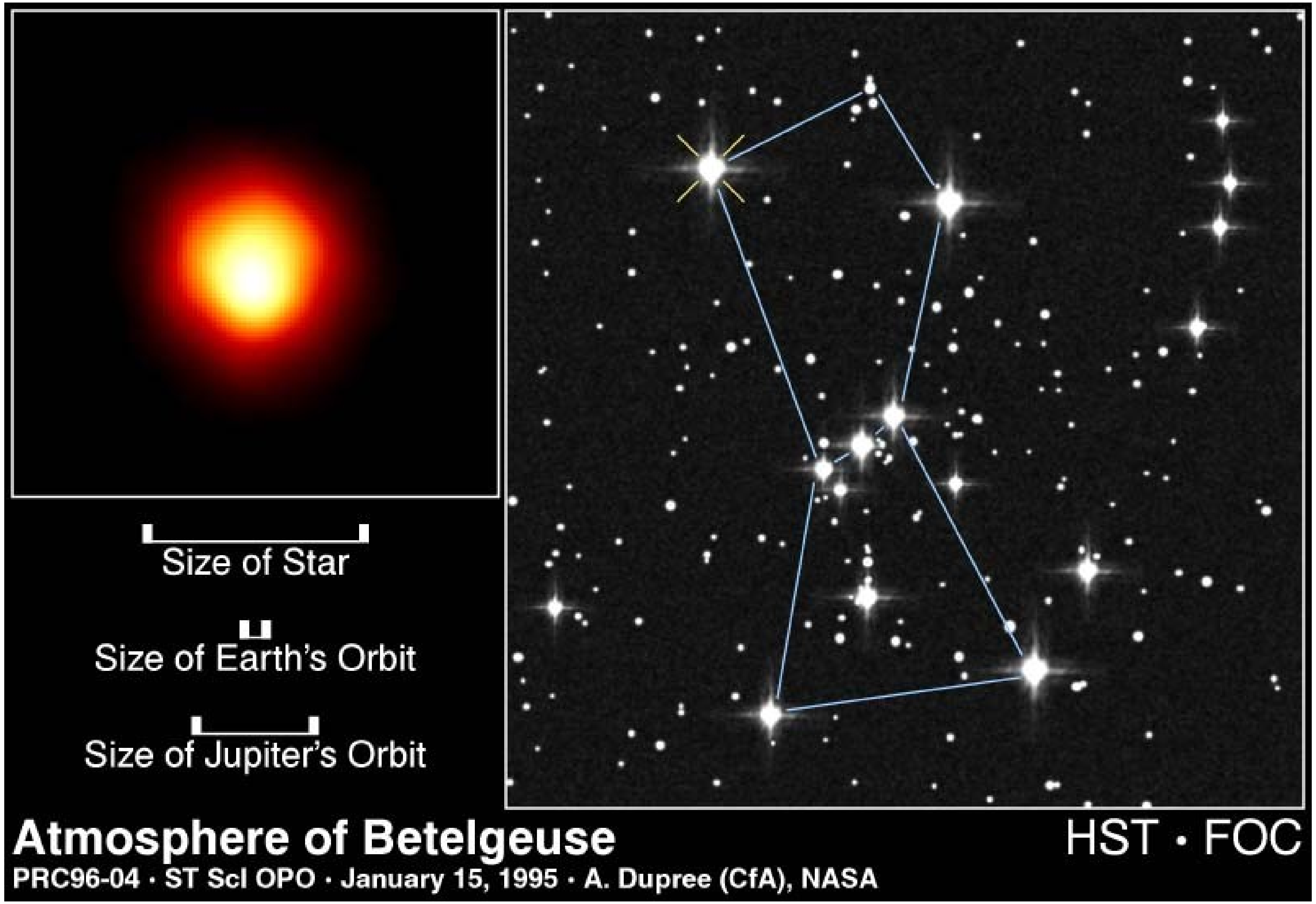
Zingale


Temperature Density Profile
184
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
overshoot
semiconvection
thermo haline
Carbon burn
Helium burn
Hydrogen burn
PC
εF/kT≈4
log Temperature (K)
log Density (g cm^-3)
184
log L/L☉
log Teff
184
log Central Temperature (K)
log Central Density (g cm^-3)
184
cno
pp
log ρ
log εν
log εnuc
log T
log mass frac
h1
he4
he3
c12
n14
o16
ne20
mg24
∇ad
∇rad
∇*
entropy
m/M☉
lg dt yr 3.4285574
age yr 2.983E+07
lg L 3.7945315
Teff 16491.732
lg Rsurf 0.9859920
lg Psurf 2.9239706
lg grav 3.3689953
v div cs 3.287E-08
Z surf 0.0200000
lg Lnuc 3.8160700
lg Lneu 2.6489887
lg LH 3.8160700
lg L3a -15.5220457
lg LZ -99.0000000
zones 941
newton 2
retries 2
varcontrol
H cntr 0.0000000
He cntr 0.9804879
C cntr 0.0001382
N cntr 0.0129121
O cntr 0.0002441
Ne cntr 0.0021104
lg Pcntr 18.3389628
lg Tcntr 7.7160401
lg Dcntr 2.8220963
initial Z 0.0200000
init mass 8.0000000
mass 8.0000000
lg |Mdot| -99.0000000
H rich 7.2885925
H poor 0.7114075
He poor 0.0000000
eta cntr -2.1822570
gam cntr 0.0985201

Zingale


Temperature Density Profile
184
Carbon burn
Helium burn
Hydrogen burn
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
overshoot
semiconvection
thermo haline
PC
log Temperature (K)
log Density (g cm^-3)
log L/L⊙
log Teff
log Central Temperature (K)
log Central Density (g cm^-3)
pp
cno
log ρ
log εν
log εnuc
log T
log mass frac
he4
h1
c12
n14
o16
he3
∇ad
∇rad
∇*
entropy
m/M⊙
lg dt yr 2.1665787
age yr 6.478E+06
lg L 5.2744259
Teff 28332.918
lg Rsurf 1.2558892
lg Psurf 3.4741875
lg grav 3.3240510
v div cs 7.525E-07
Z surf 0.0200000
lg Lnuc 5.2754374
lg Lneu 4.1227715
lg LH 5.2754374
lg L3a -5.5050136
lg LZ -4.1344415
zones 989
newton 3
retries 1
varcontrol
H cntr 0.0000000
He cntr 0.9805065
C cntr 0.0002090
N cntr 0.0128924
O cntr 0.0001724
Ne cntr 0.0021104
lg Pcntr 17.8754242
lg Tcntr 7.9839290
lg Dcntr 1.9500129
initial Z 0.0200000
init mass 25.0000000
mass 25.0000000
lg |Mdot| -99.0000000
H rich 18.8786744
H poor 6.1213256
He poor 0.0000000
eta cntr -5.1654089
gam cntr 0.0272224

# High Mass Evolution



# High Mass Evolution

- We are setting the stage for core-collapse
  - No more energy generation from fusion
  - Photodisintegration removes energy, dropping pressure support
  - High density means electrons are degenerate, but electron capture is allowed (since energies are high)
    - p + e becomes n
    - Less electrons, means less electron pressure

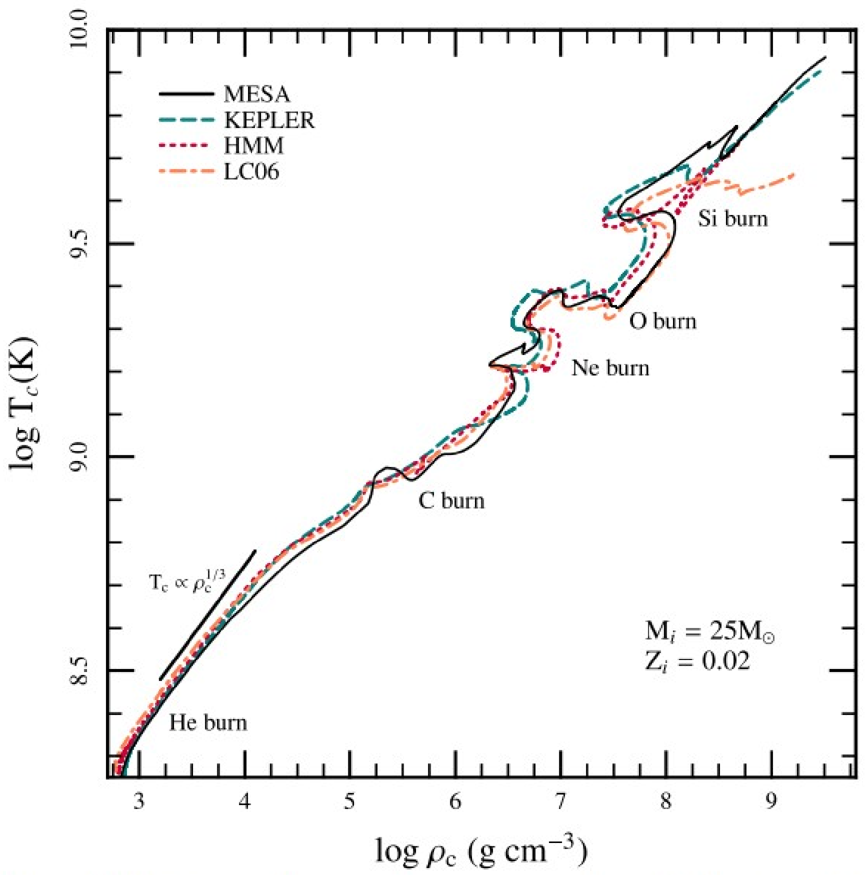



**Figure 30.** Evolution of the central temperature and central density in solar metallicity $M_i = 25\,M_\odot$ models from different stellar evolution codes. The locations of core helium, carbon, neon, oxygen, and silicon burning are labeled, as is the relation $T_c \propto \rho_c^{1/3}$.

(from Bill Paxton, MESA.)

# Boom!

- The collapse of the core releases an enormous amount of gravitational potential energy
- Collapse only stopped when another form of pressure can kick in to halt it
  - Neutron star (or black hole) results
- More on this later in the semester…

# Other Nucleosynthesis

- Supernovae have lots of Fe and lots of neutrons
  - r-process (rapid neutron capture) possible
- Slower neutron capture (s-process) occurs either in AGB stars or neutron star-neutron star mergers
  - Requires heavy “seed” nuclei

# r-process

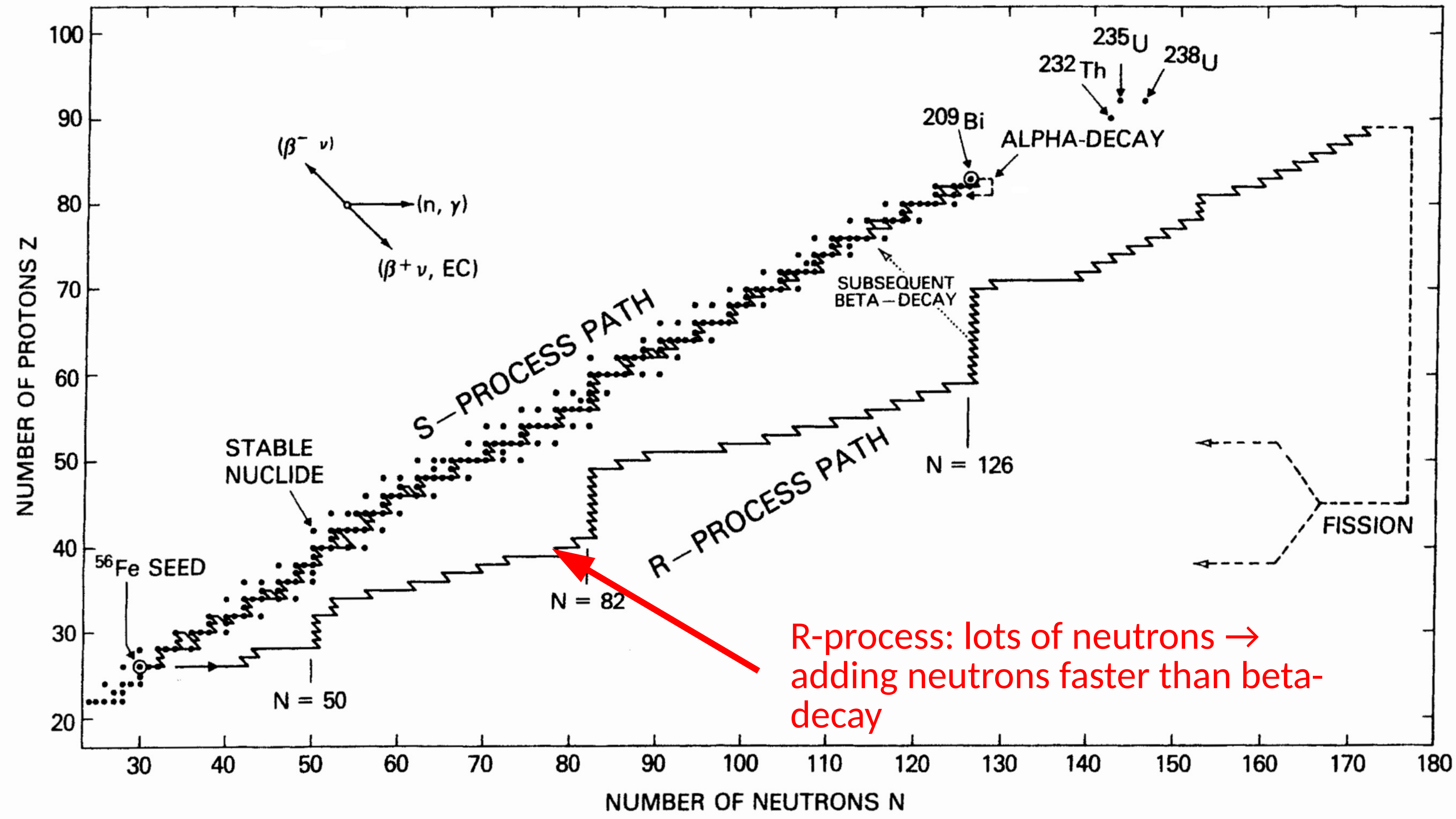



FIGURE 9.13. Neutron-capture paths for the *s*-process and the *r*-process are shown in the $(N, Z)$-plane. Both paths start with the iron-peak nuclei as seeds (mainly $^{56}Fe$). The *s*-process follows a path along the stability line and terminates finally above $^{209}Bi$ via $\alpha$-decay (Cla67). The *r*-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the $(N, Z)$-plane until $\beta$-delayed fission and neutron-induced fission occur (Thi83). The *r*-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons $cm^{-3}$.

(from Rolfs and Rodney, Cauldrons in the Cosmos)

# r-process

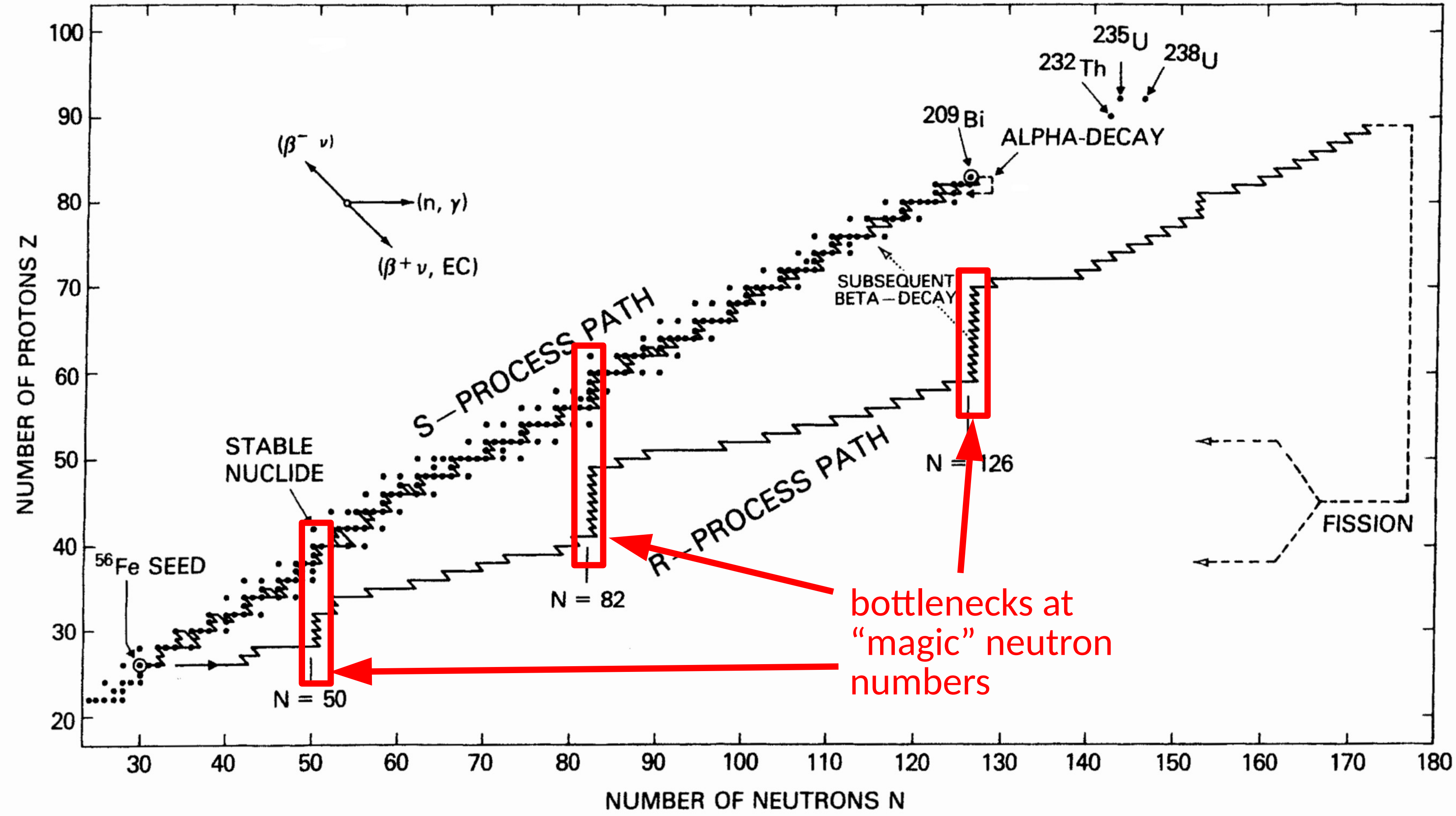



FIGURE 9.13. Neutron-capture paths for the *s*-process and the *r*-process are shown in the $(N, Z)$-plane. Both paths start with the iron-peak nuclei as seeds (mainly $^{56}Fe$). The *s*-process follows a path along the stability line and terminates finally above $^{209}Bi$ via $\alpha$-decay (Cla67). The *r*-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the $(N, Z)$-plane until $\beta$-delayed fission and neutron-induced fission occur (Thi83). The *r*-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm$^{-3}$.

(from Rolfs and Rodney, Cauldrons in the Cosmos)

# r-process

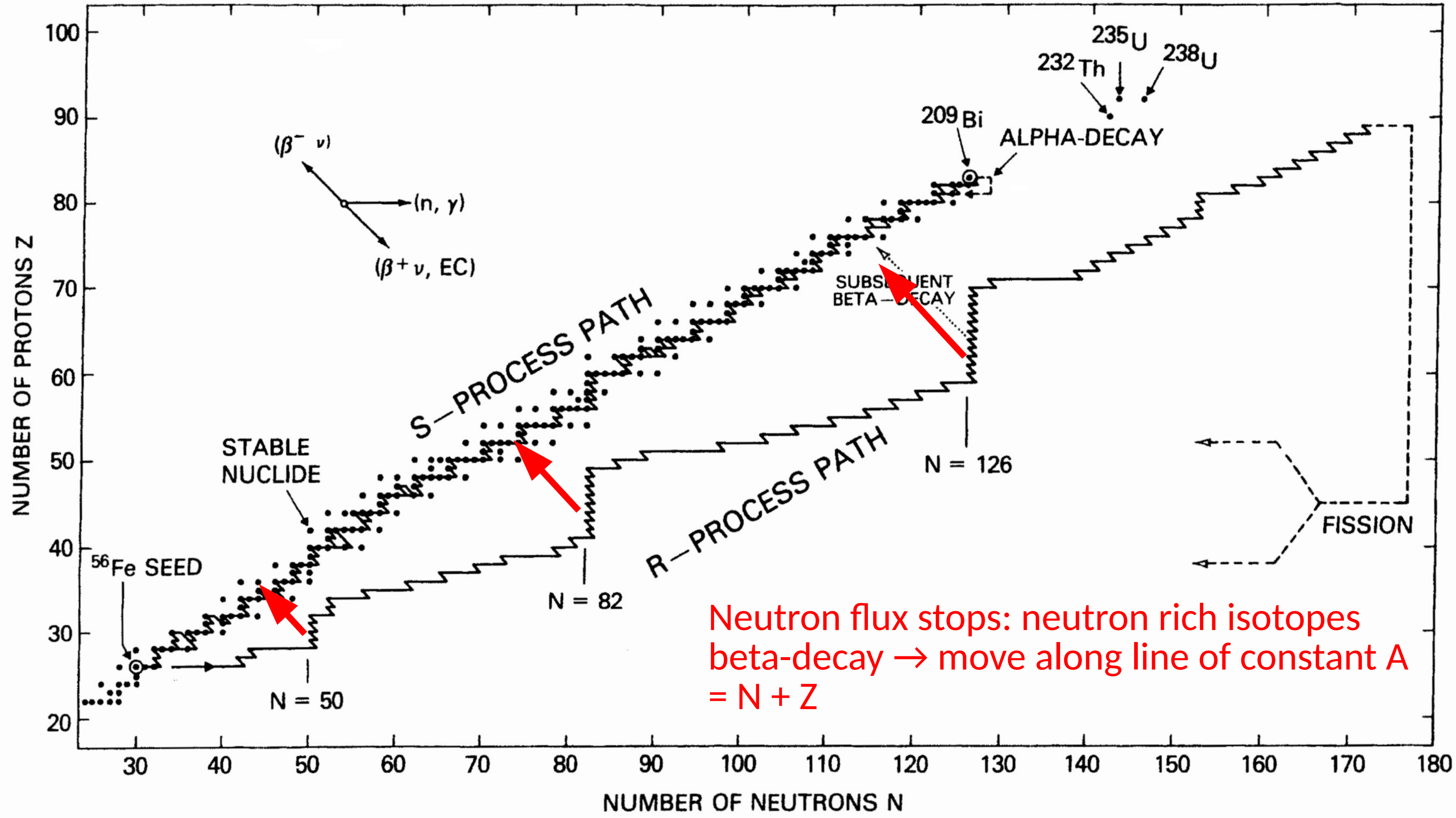
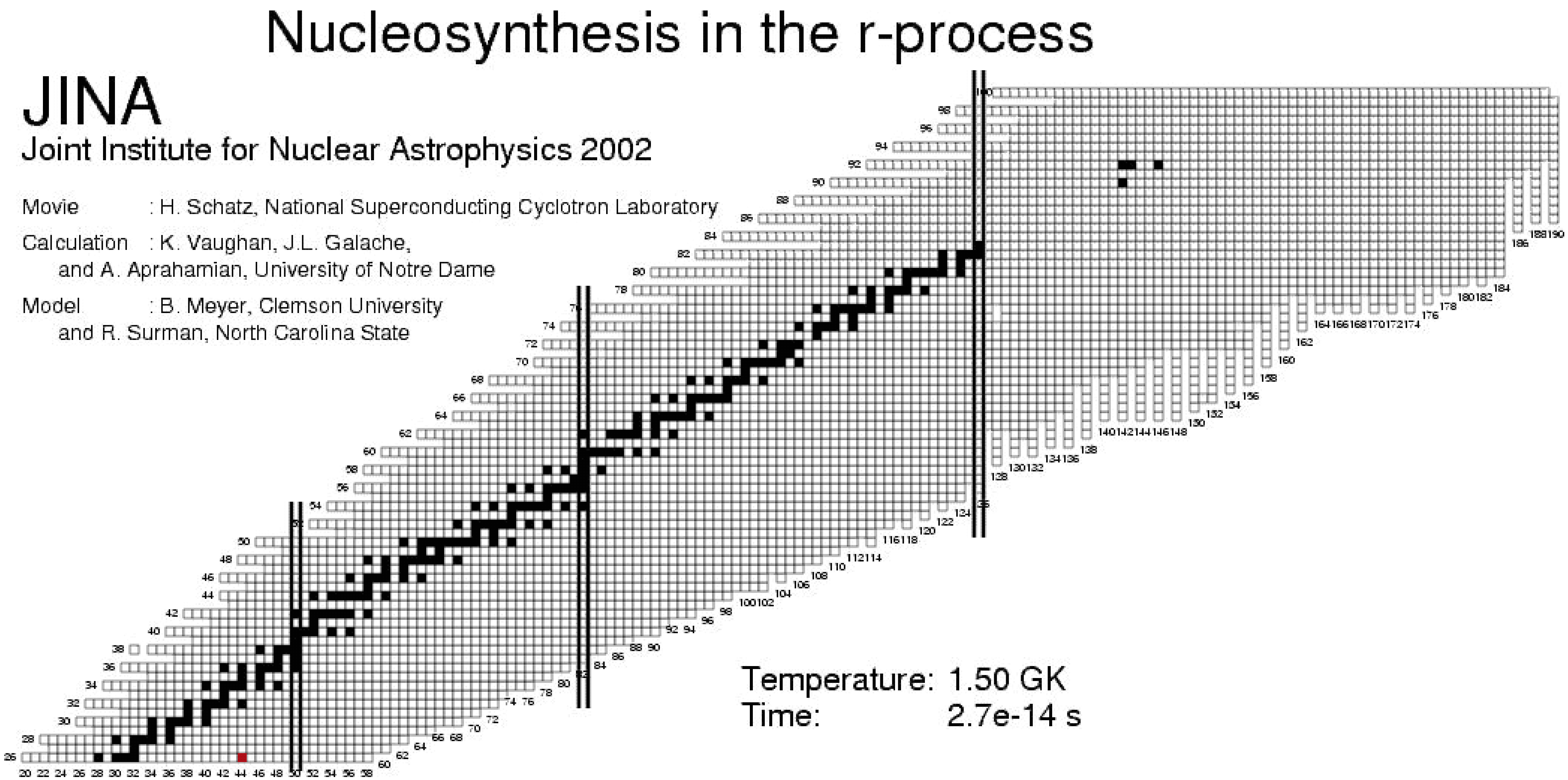



FIGURE 9.13. Neutron-capture paths for the *s*-process and the *r*-process are shown in the $(N, Z)$-plane. Both paths start with the iron-peak nuclei as seeds (mainly $^{56}$Fe). The *s*-process follows a path along the stability line and terminates finally above $^{209}$Bi via $\alpha$-decay (Cla67). The *r*-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the $(N, Z)$-plane until $\beta$-delayed fission and neutron-induced fission occur (Thi83). The *r*-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm$^{-3}$.

Neutron flux stops: neutron rich isotopes beta-decay → move along line of constant A = N + Z

(from Rolfs and Rodney, Cauldrons in the Cosmos)

# r-process


Nucleosynthesis in the r-process
JINA
Joint Institute for Nuclear Astrophysics 2002
Movie : H. Schatz, National Superconducting Cyclotron Laboratory
Calculation : K. Vaughan, J.L. Galache, and A. Aprahamian, University of Notre Dame
Model : B. Meyer, Clemson University and R. Surman, North Carolina State
Temperature: 1.50 GK
Time: 2.7e-14 s

# Abundances

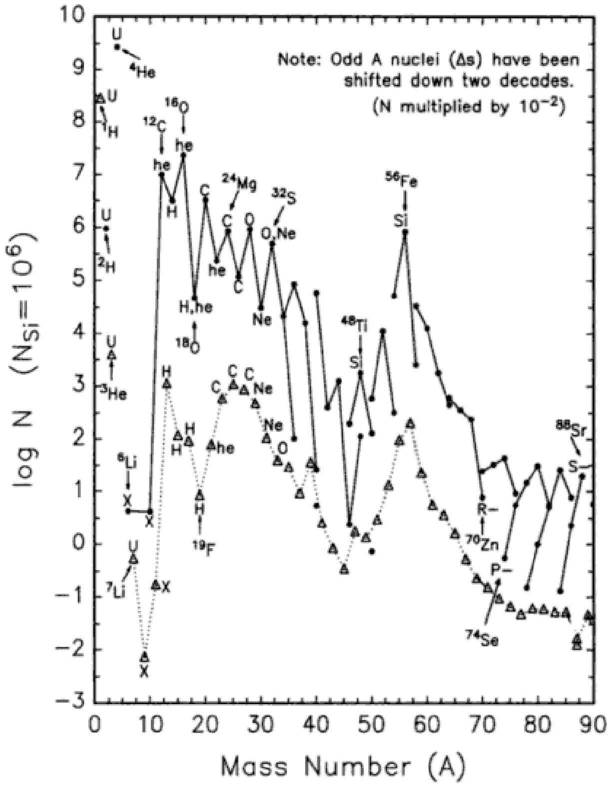



**Fig. 2.20.** Individual nuclide abundances for odd and even nuclides, taken primarily from Anders and Grevesse (1989). Triangles denote odd nuclides (which have been shifted down by two decades), whereas "dots" are for even. Some important nuclides are labeled. Sources (e.g., nuclear burning stages) are indicated for some nuclides: U means Big Bang; X from fragmentation of cosmic rays; H for hot (and hotter) hydrogen burning; he=helium burning; C, O, Ne, or Si=carbon, oxygen, neon, or silicon burning; and an occasional P-, S-, or R- for p-, s-, or r-process.

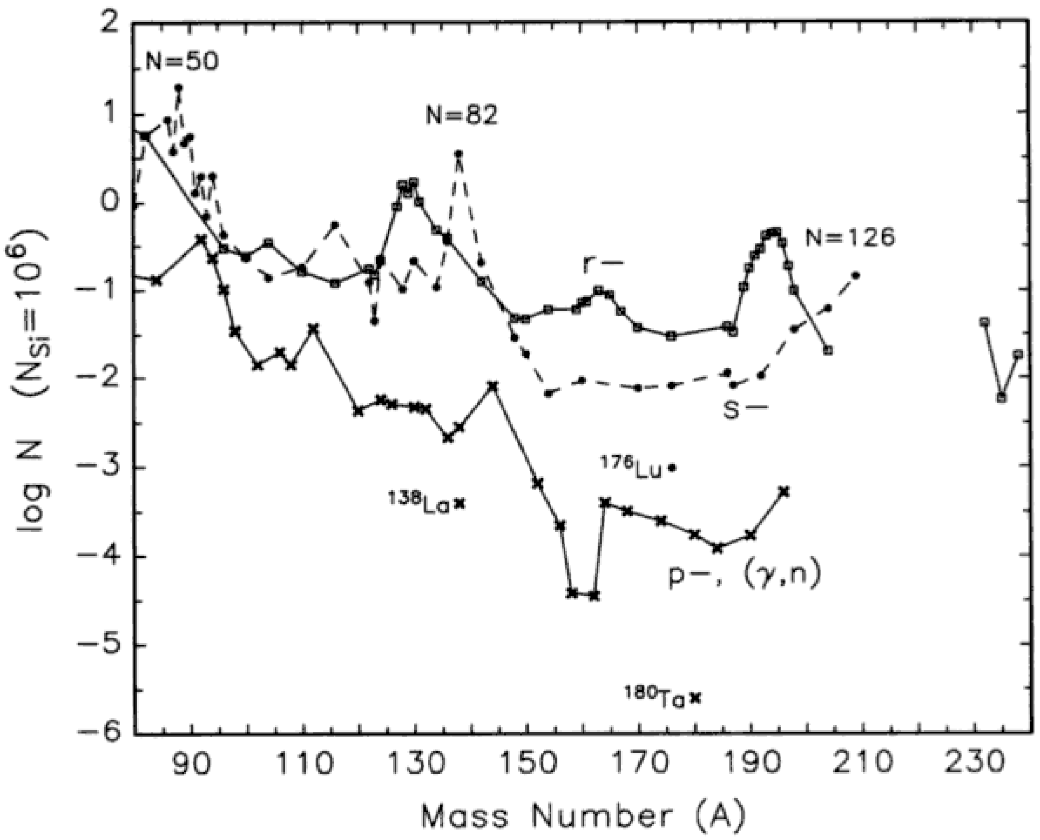



**Fig. 2.21.** This is a continuation of Fig. 2.16 but nuclides are identified by source mechanism, s- (●s), r- (□s), and p-process or $(\gamma, n)$ (×s).

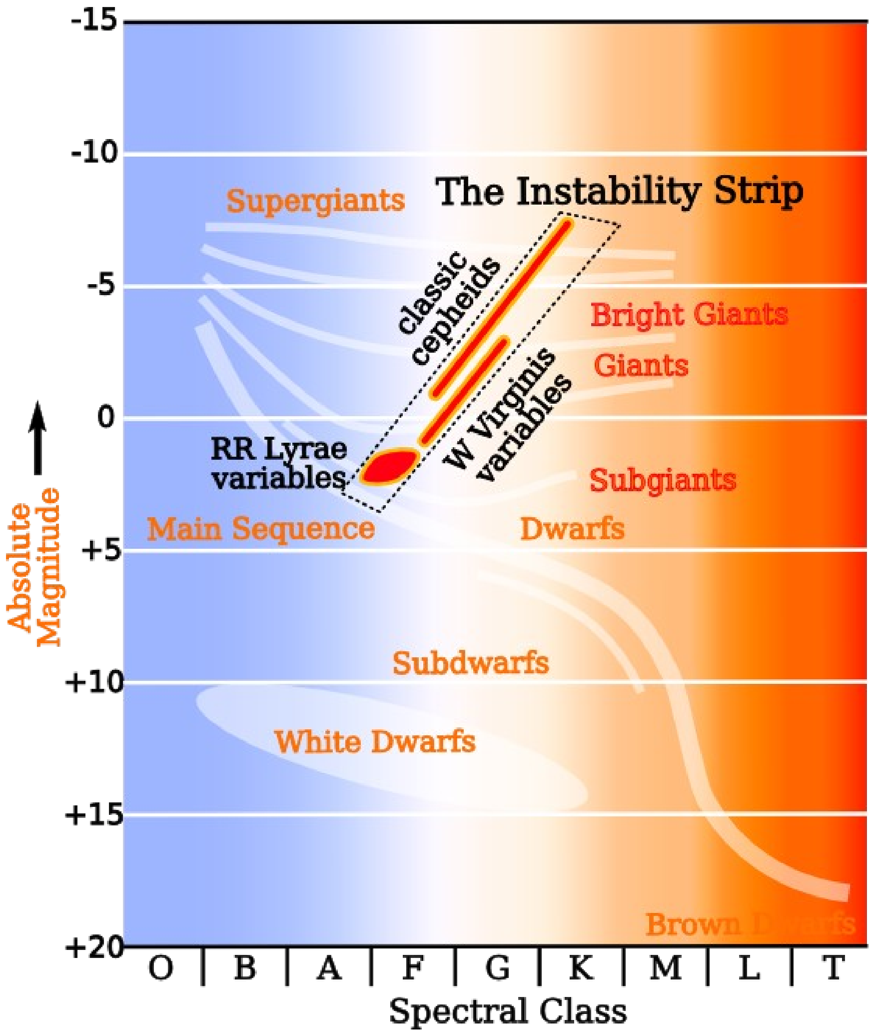


(from Hansen et al.)

# Variable Stars

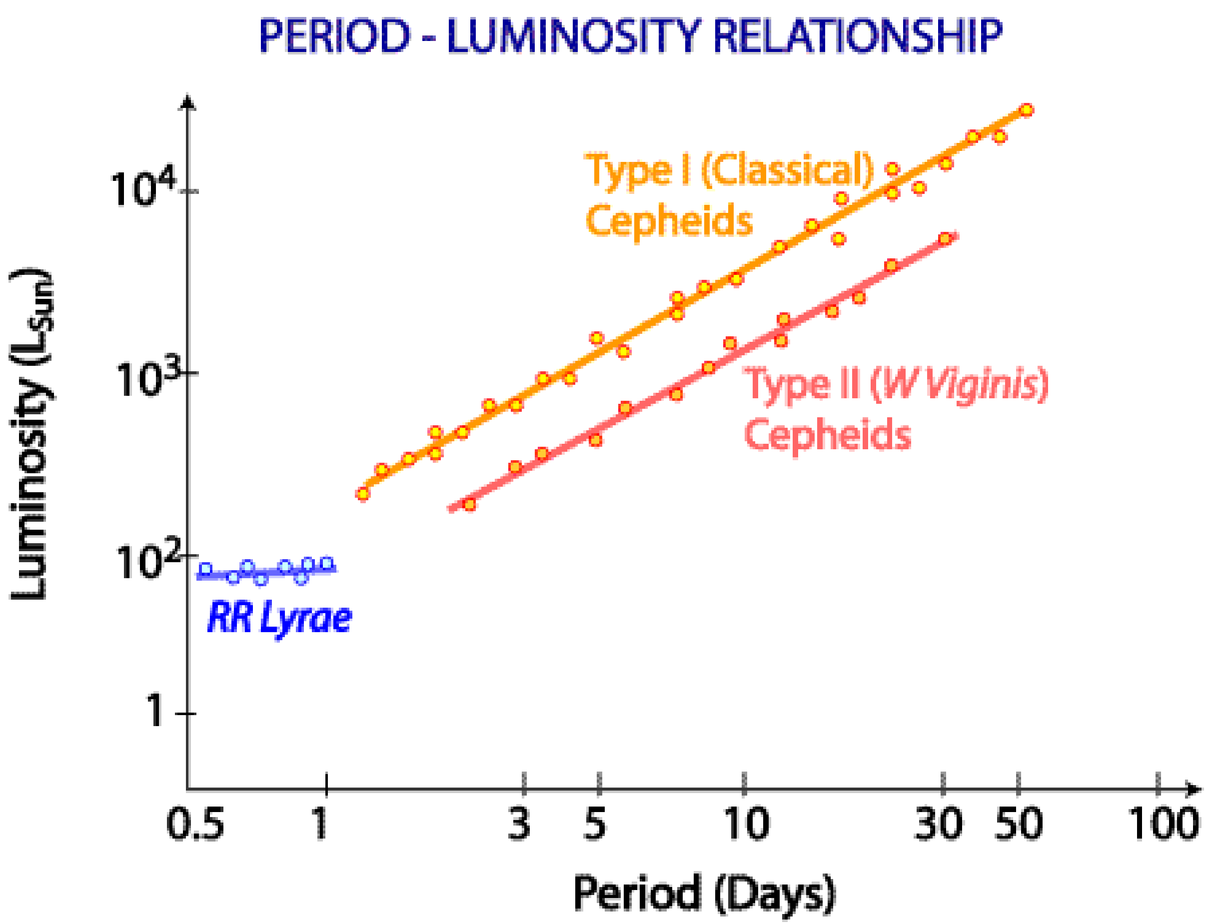
- There are LOTS of different types of variable stars—see your text
  - We'll ignore variability due to a companion
- Pulsational variables are the interesting class
  - Driven by an instability
  - Radial and non-radial modes are possible
- For radial pulsations, the period will be the dynamical timescale

$$t_{\mathrm{dyn}} \sim \frac{1}{\sqrt{G\rho}}$$

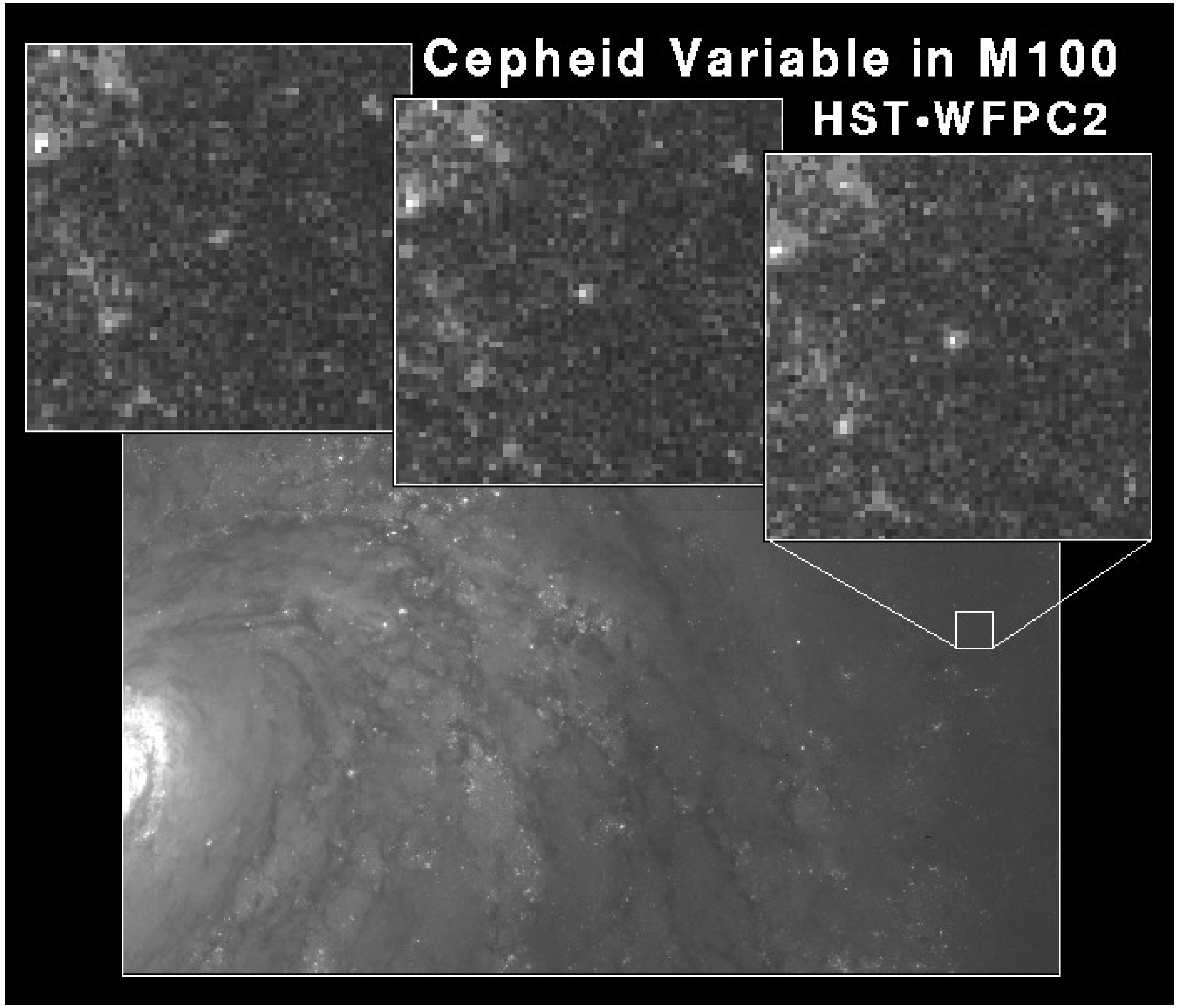



(Wikipedia/instability strip)

# Cepheids




http://outreach.atnf.csiro.au/education/senior/astrophysics/variable_cepheids.html



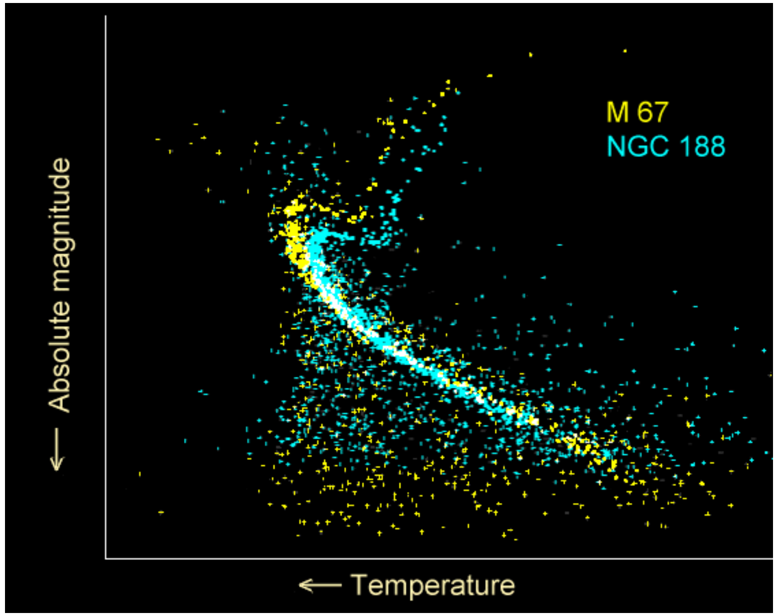

(NASA, HST, W. Freedman (CIW), R. Kennicutt (U. Arizona), J. Mould (ANU))

# Variable Stars

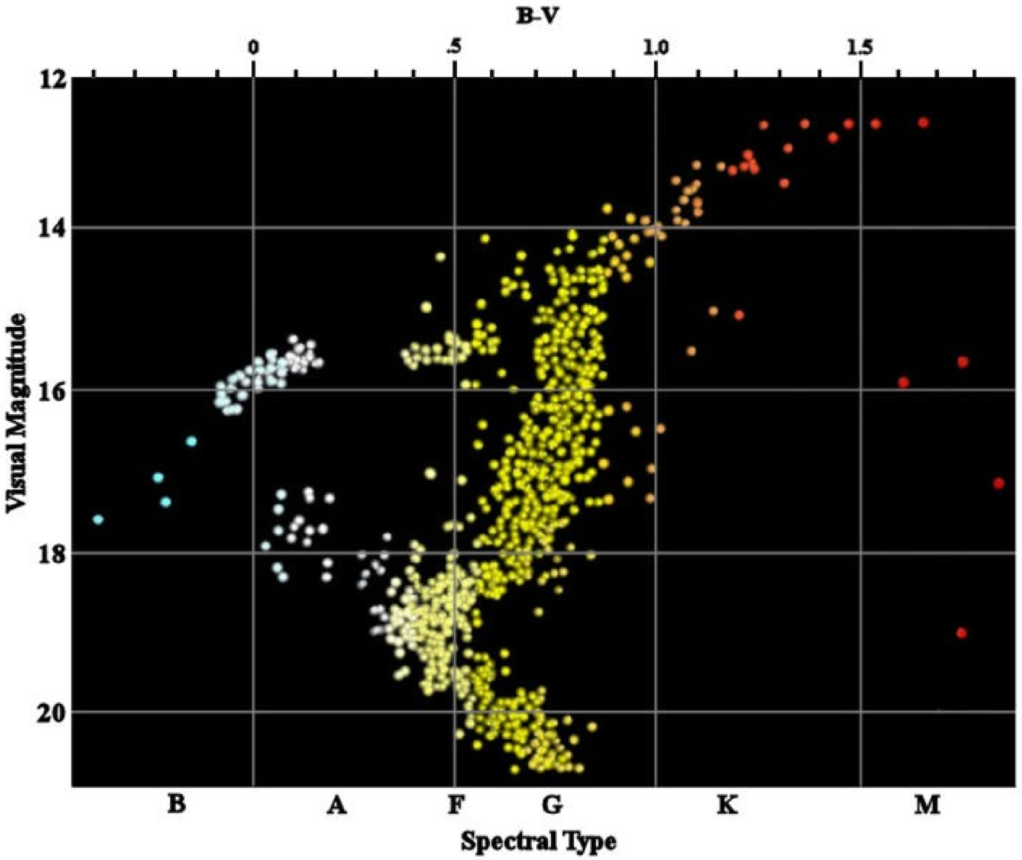
- Radial oscillations in a normal star (w/o considering opacity):
  - Decrease R → ρ increases → P, T increases.
  - P increase: star pushes back on outer layers—moves back toward the equilibrium radius.
  - Inertia causes the star to overshoot its equilibrium radius.
- Considering opacity for normal star ($\kappa \sim \rho T^{-7/2}$)
  - Decrease R → ρ increases → P, T increases.
  - Lower opacity: radiation becomes more efficient, cools star
  - P drops, overshooting damped
- In Cepheid, opacity from He II to He III increases as star compresses
  - Higher opacity: more radiation trapped
  - P increases, overshooting driven!

# Clusters

- Stars in a cluster all form at the same time
- Observing the HR diagram, you see a “turn-off point”
  - Allows you to estimate the age of the cluster



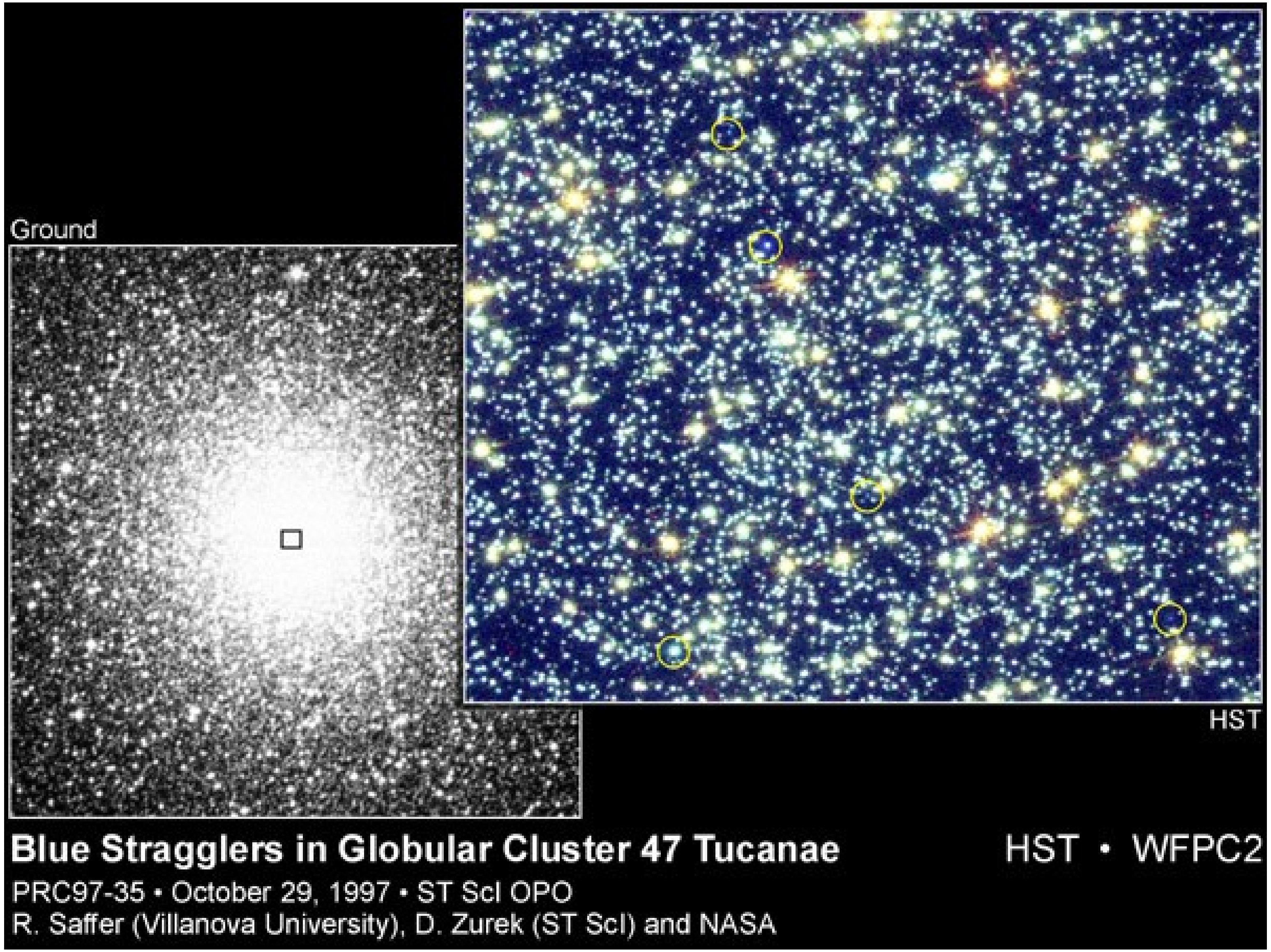

(Wikipedia)



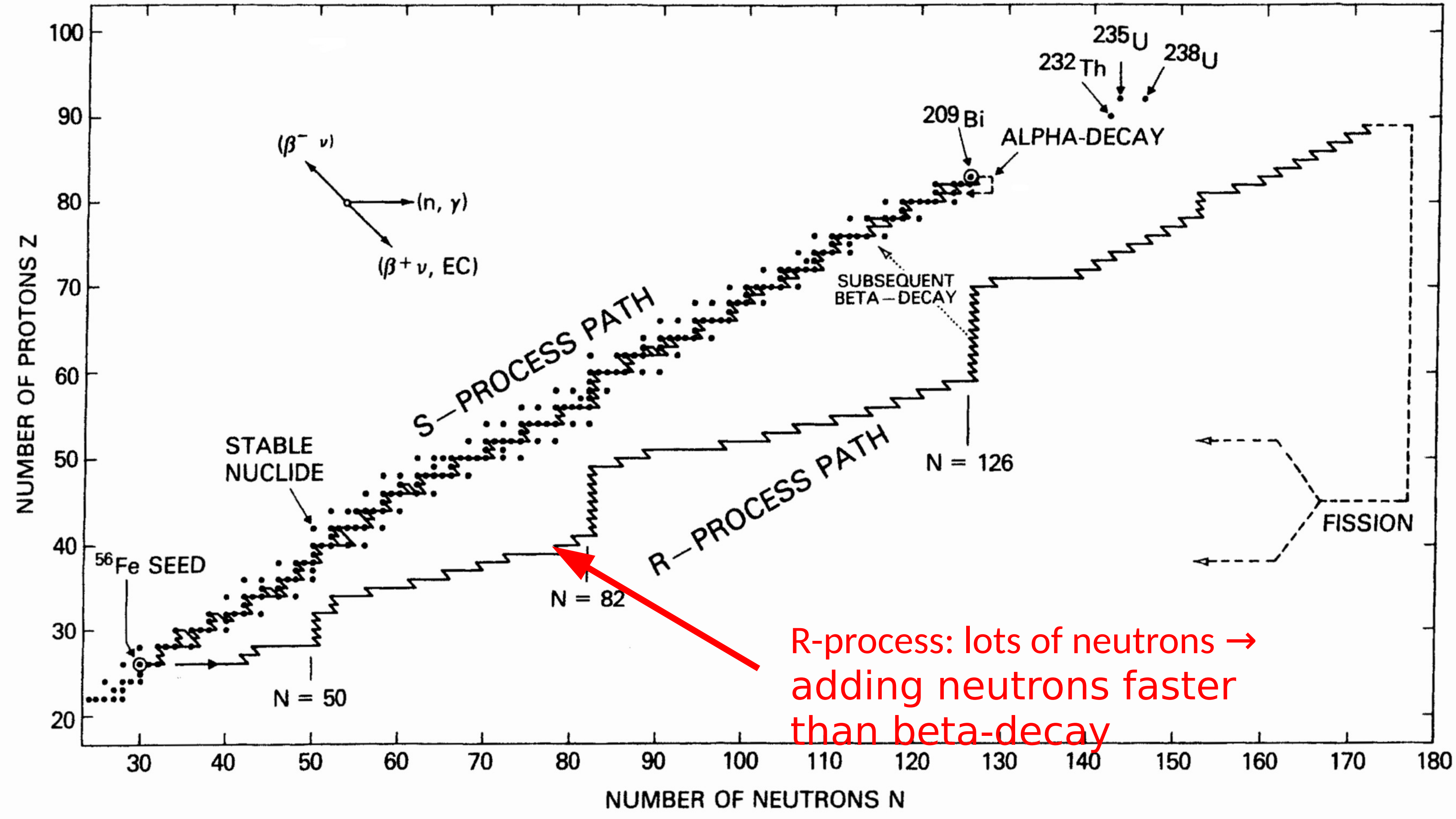

(Wikipedia)

Globular cluster M3 H-R diagram

# Blue Stragglers



# r-process




R-process: lots of neutrons → adding neutrons faster than beta-decay

FIGURE 9.13. Neutron-capture paths for the *s*-process and the *r*-process are shown in the (*N*, *Z*)-plane. Both paths start with the iron-peak nuclei as seeds (mainly $^{56}$Fe). The *s*-process follows a path along the stability line and terminates finally above $^{209}$Bi via α-decay (Cla67). The *r*-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the (*N*, *Z*)-plane until β-delayed fission and neutron-induced fission occur (Thi83). The *r*-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm$^{-3}$.

(from Rolfs and Rodney, Cauldrons in the Cosmos)