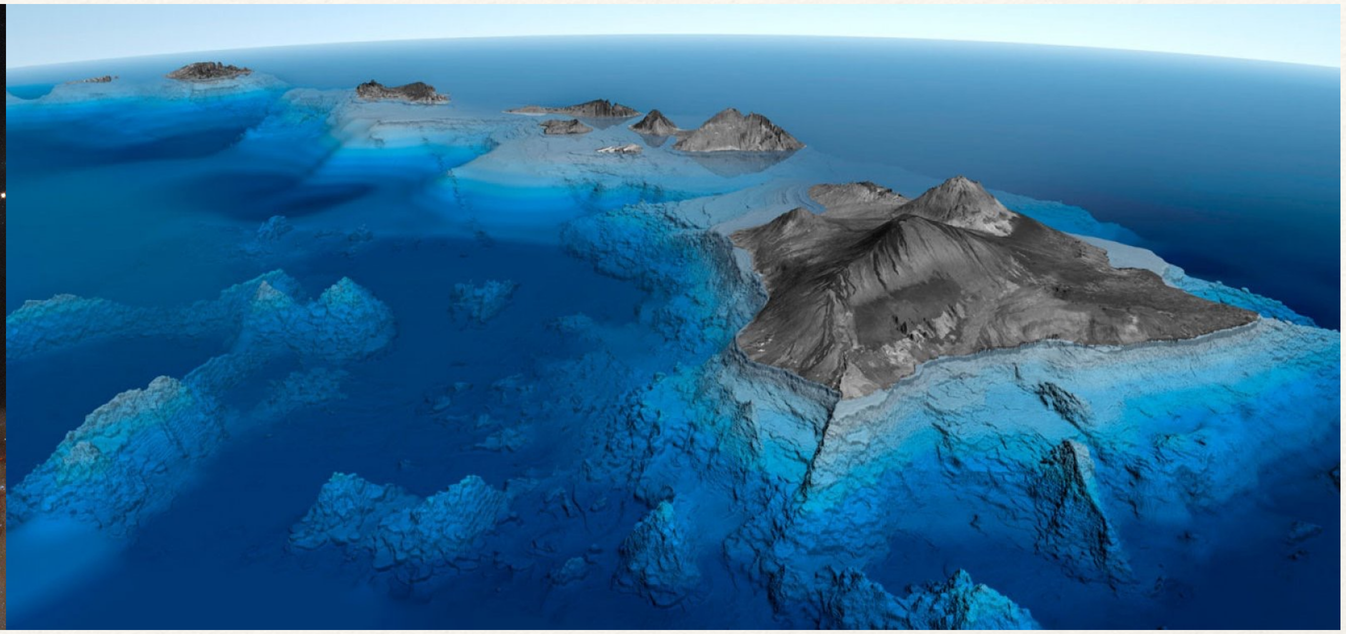


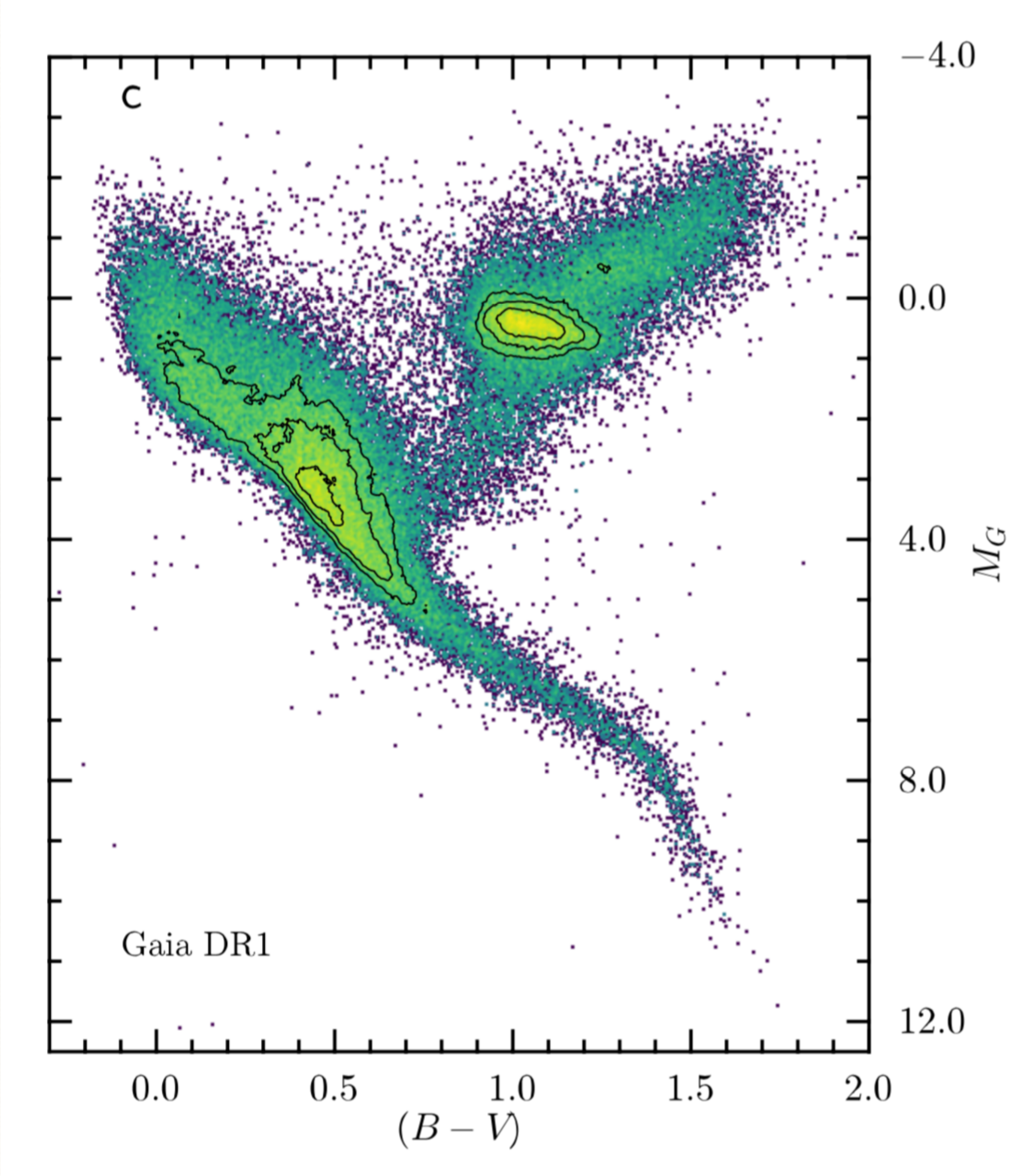
Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Moire Prescott

Warm-up

- What is the physical relationship between an HR diagram vs. a CMD? An isochrone vs. an evolutionary track?
- Why are giant stars redder/cooler than Main Sequence stars?
- Why are metal-rich stellar populations redder?



Brown et al. 2016

Wa

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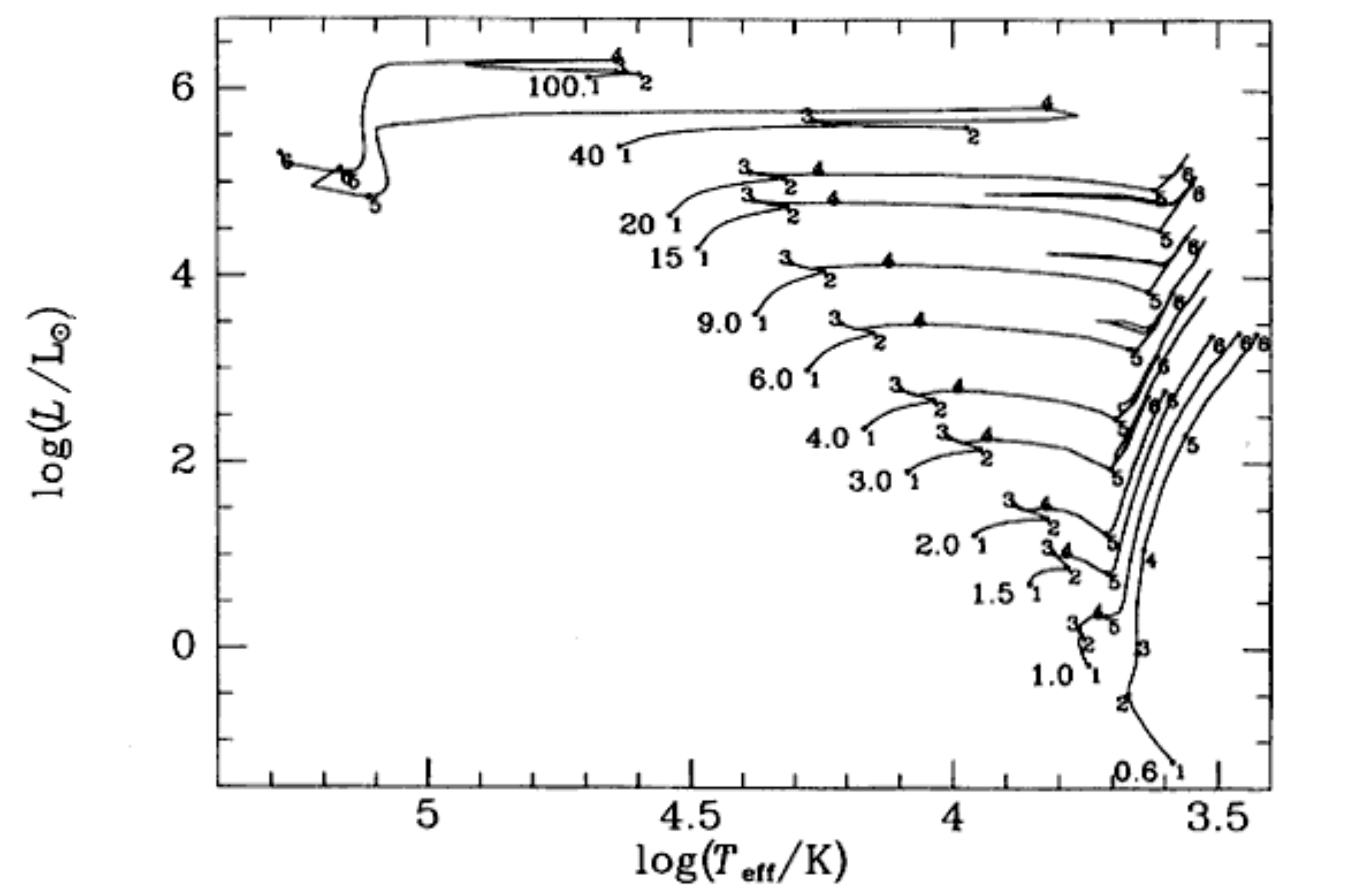
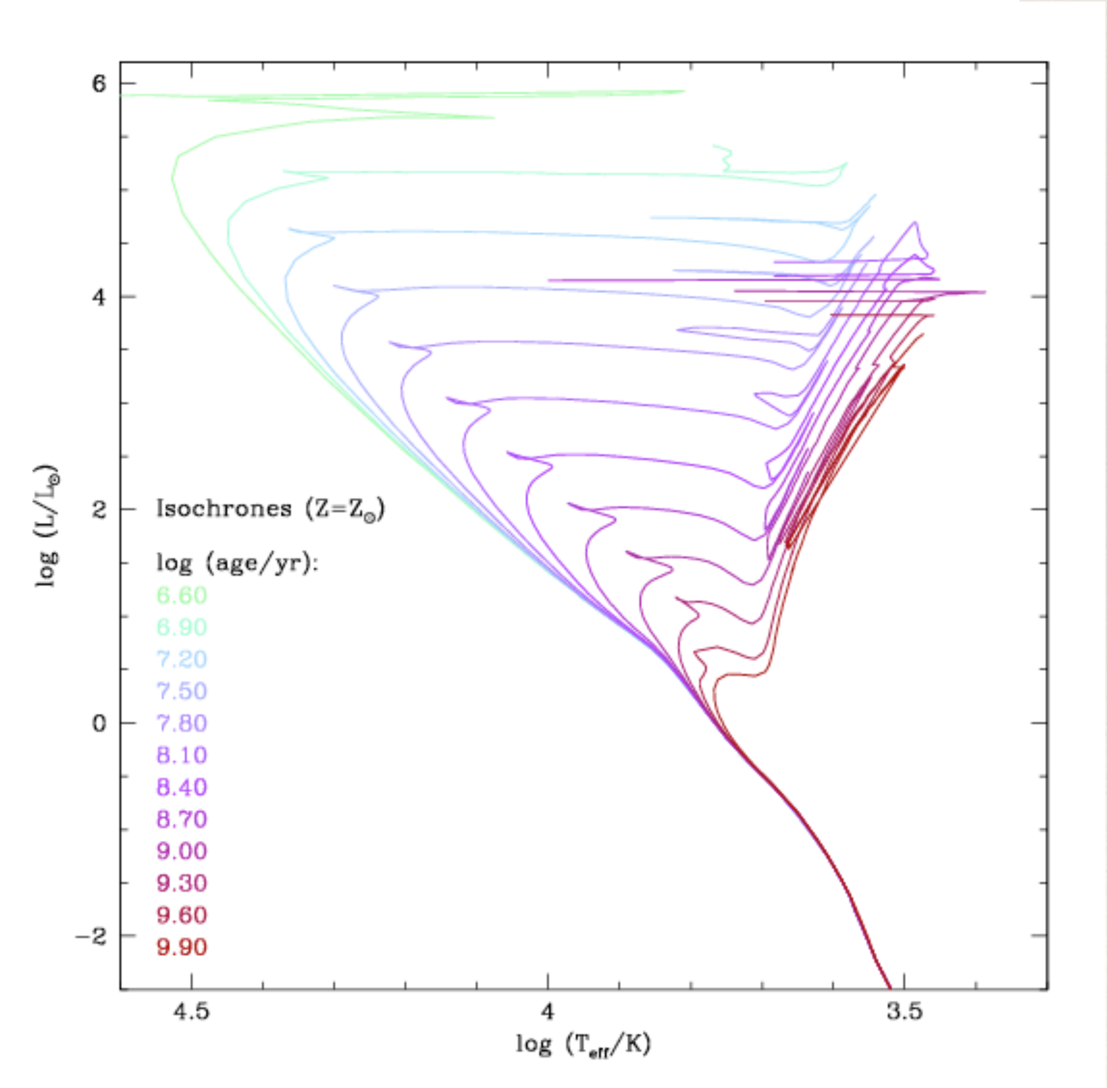


Figure 5.2 Evolutionar
masses from 0.6 $\mathcal{M}_\odot$ to
Table 5.2 gives the time
1. To avoid confusion t
for the further tracks of
published in Bressan *et*

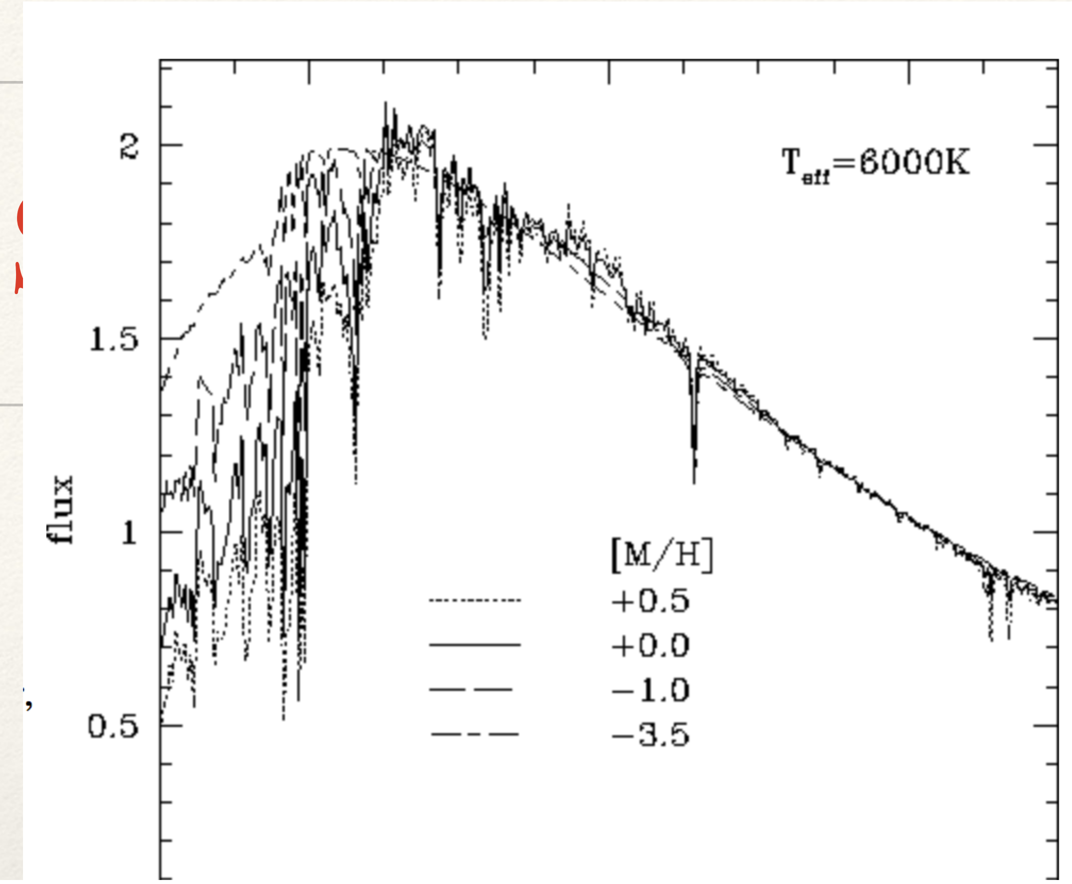
Bressan et al. 1993



da Cunha 2008

Building Blocks - Stars and S

- **Metallicity Effects**:
    - Higher metallicity increases internal opacity and atmospheric absorption (line blanketing in blue)
    - **More metal-rich populations redder**



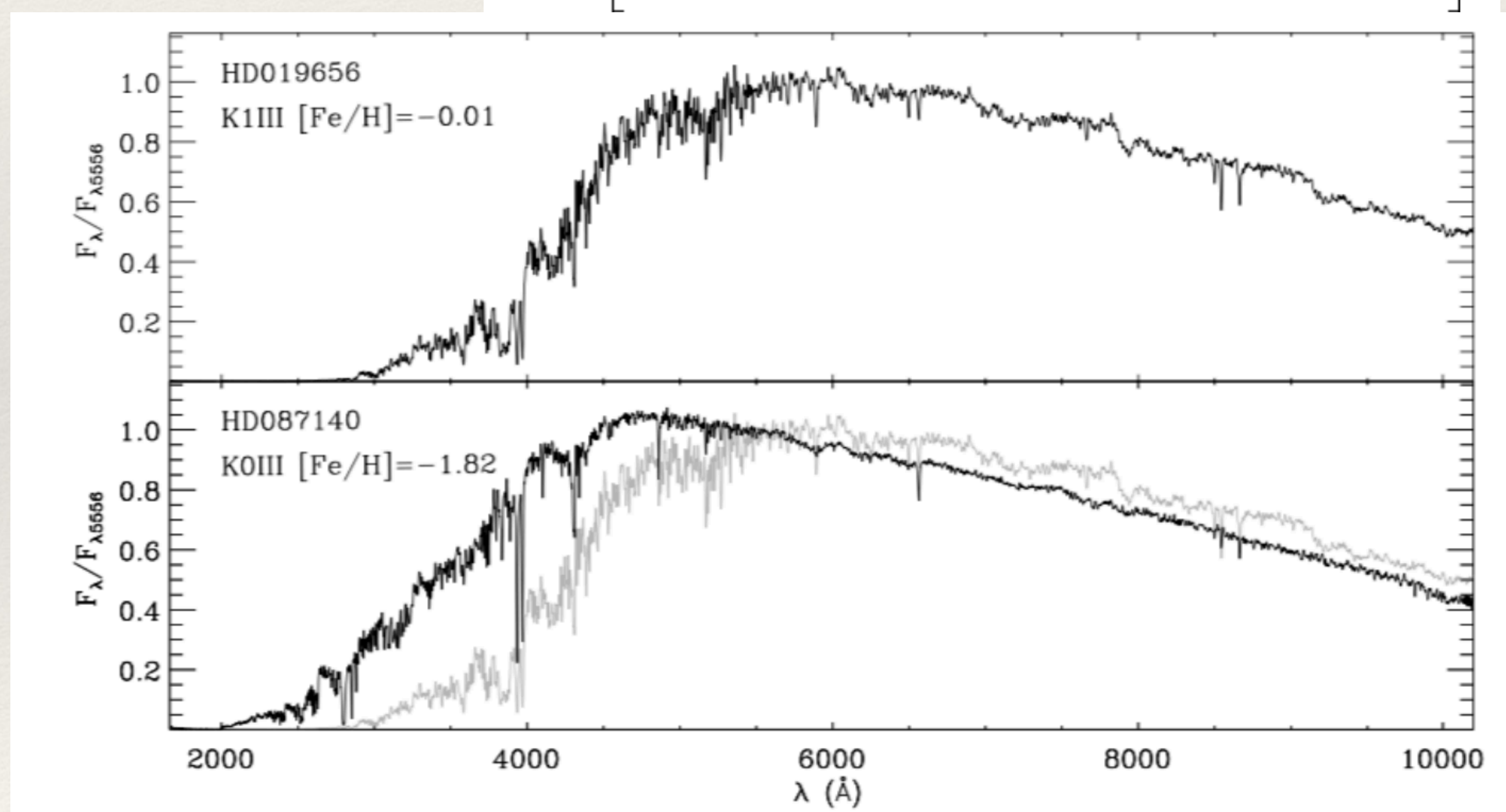


Figure 3: Comparison of STIS spectra of two K giants with very different metallicity. The metal rich star is overplotted as the grey line in the lower panel. This comparison highlights the need for a wide range of not only temperatures but abundances in stellar libraries for proper modeling of composite systems.

https://faculty.virginia.edu/ASTR5610/lectures/ABUNDANCES/abundances.html

Building Blocks - Stars ar

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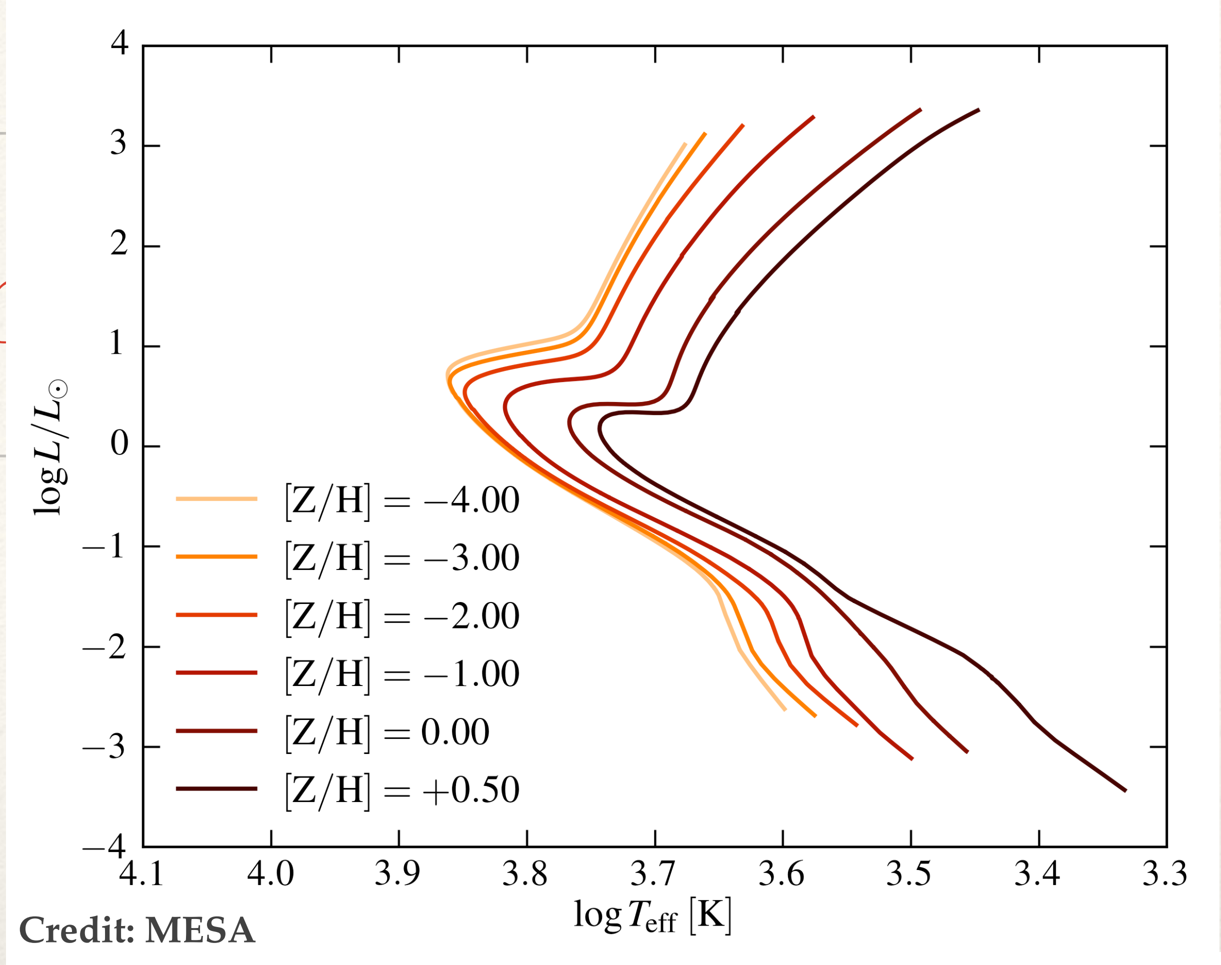
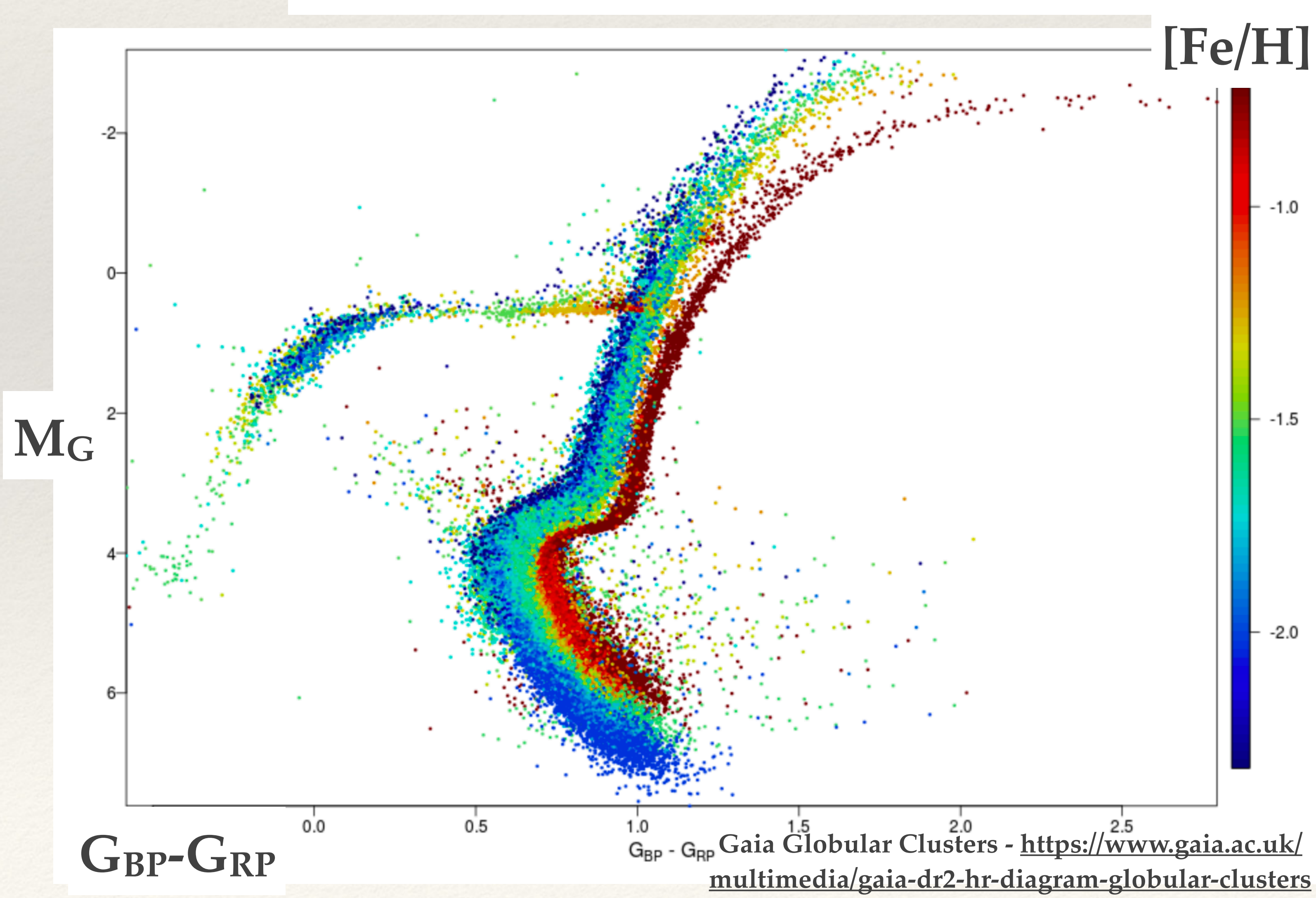




Gaia Globular Clusters - https://www.gaia.ac.uk/multimedia/gaia-dr2-hr-diagram-globular-clusters

Building Blocks - Stars and Stellar Populations

- Metallicity terminology:
  - Often given as mass fractions:
    - Hydrogen (X), Helium (Y), and heavier elements (Z), where X+Y+Z=1
  - Solar abundance: X~0.73, Y~0.25, Z~0.02
  - Note that Z contains lots of different elements! (astronomers just call them all "metals")
  - Also denoted using:

$$[Fe/H] = \log((Fe/H)/(Fe/H)_{Sun})$$

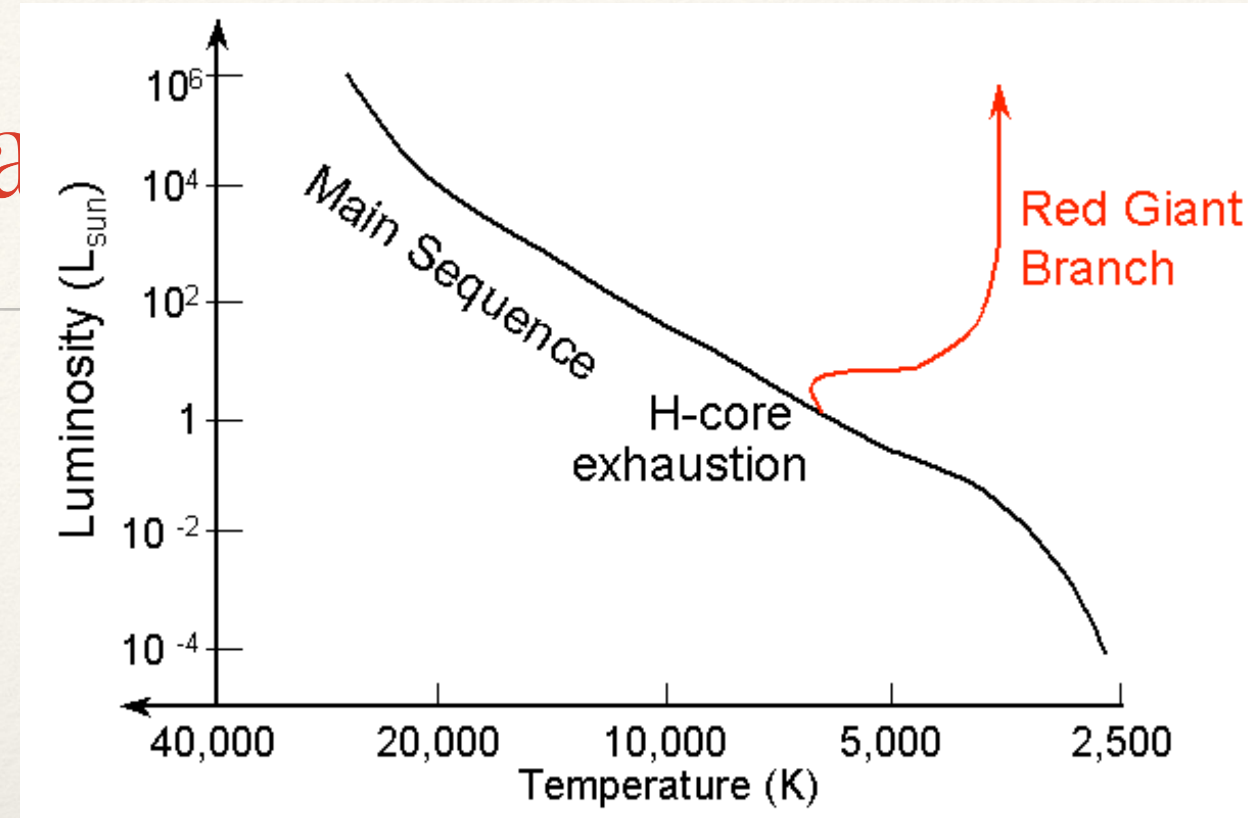
Outline for Today

- Building Blocks - Stars and Stellar Populations:
  - Overview/Review of Stellar Evolution and the HR Diagram
  - CMD Features
  - Effect of metallicity/age/binaries

M31, Southwest arm, NGC 206 (Credit: Robert Gendler)

Stars and Stellar Popula

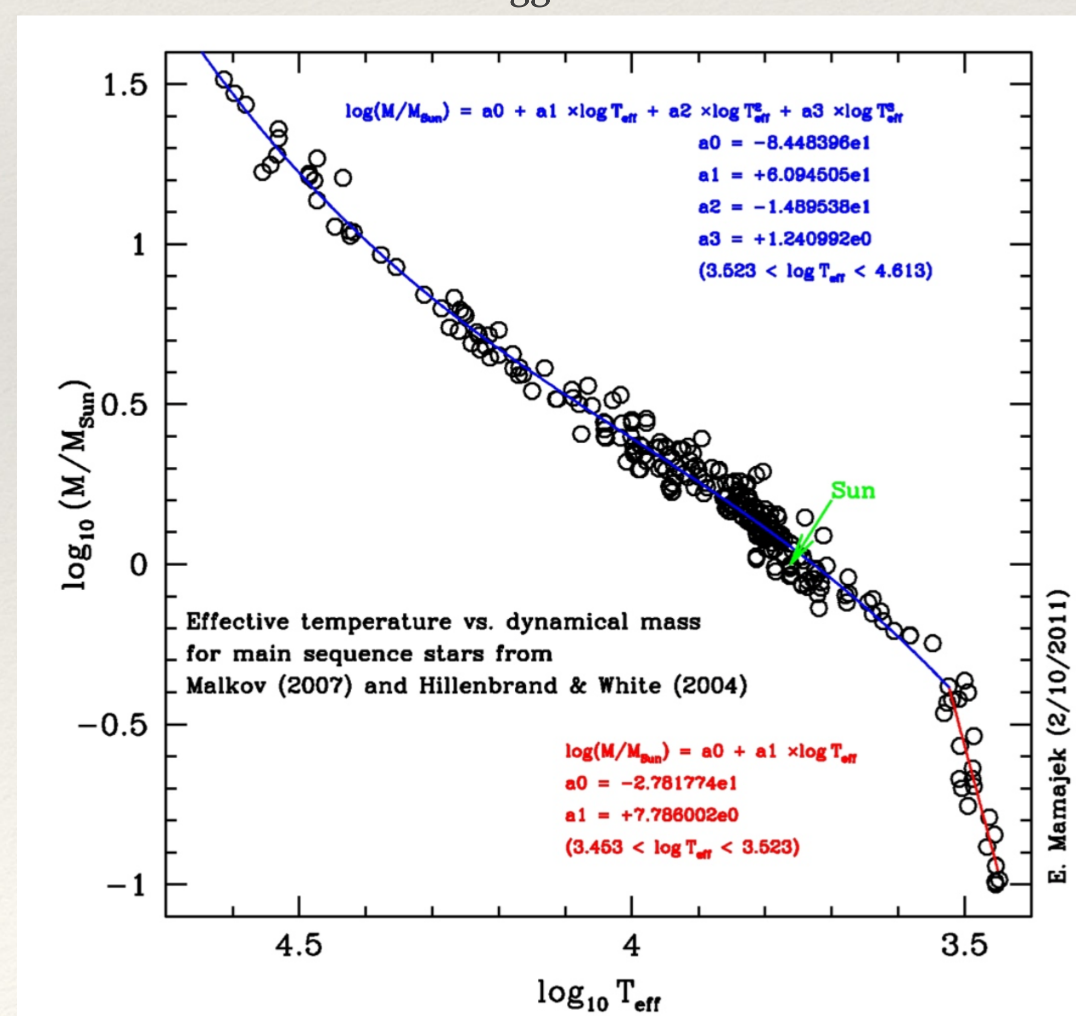
- **Main Sequence (MS)**
  - = Mass Sequence — **$L \propto M^{3.5}$**
  - Lifetime scales with mass — **$t_{MS} \propto M^{-2.5}$**
  - Luminosity class — **dwarfs**



Credit: Richard Pogge

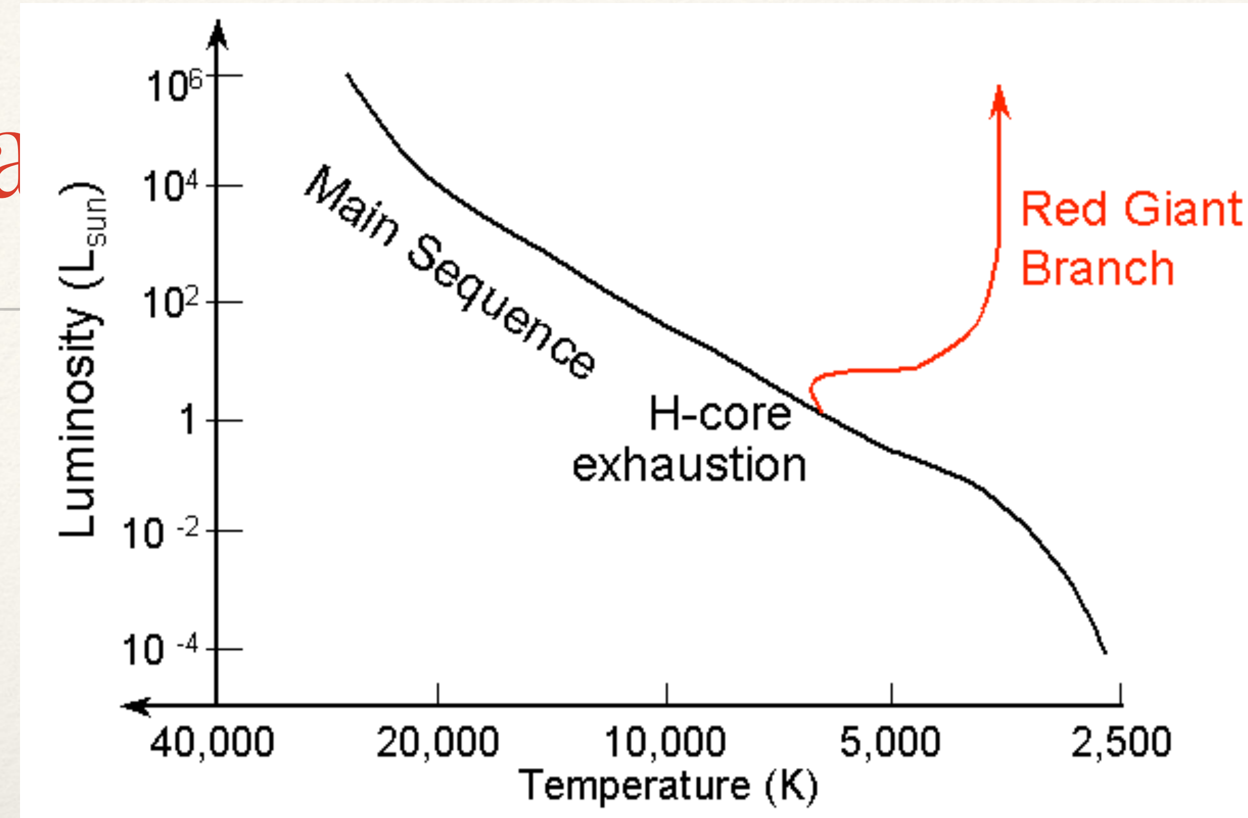
table 21-1 Approximate Main-Sequence Lifetimes				
Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetim (10⁶ years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000
0.50	4000	M	0.03	700,000

The main-sequence lifetimes were estimated using the relationship $t \propto 1/M^{2.5}$ (see Box 21-2).

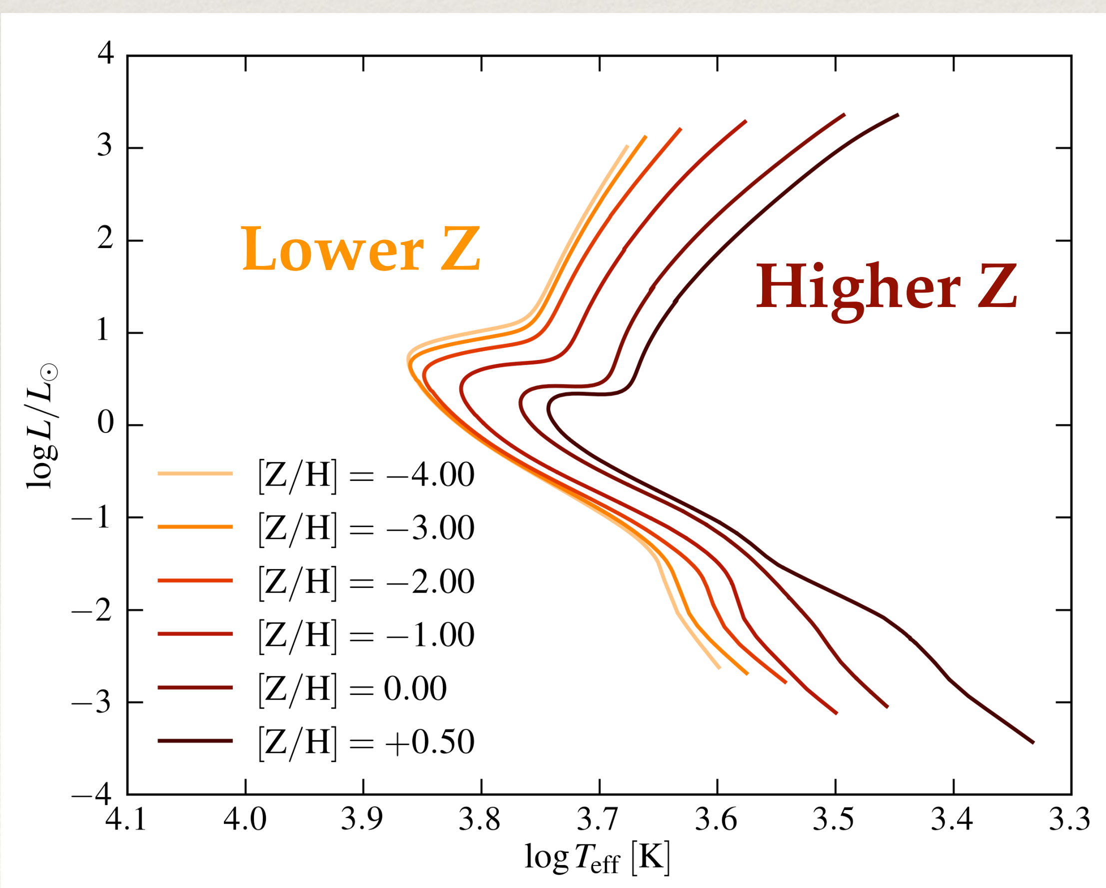


Stars and Stellar Popula

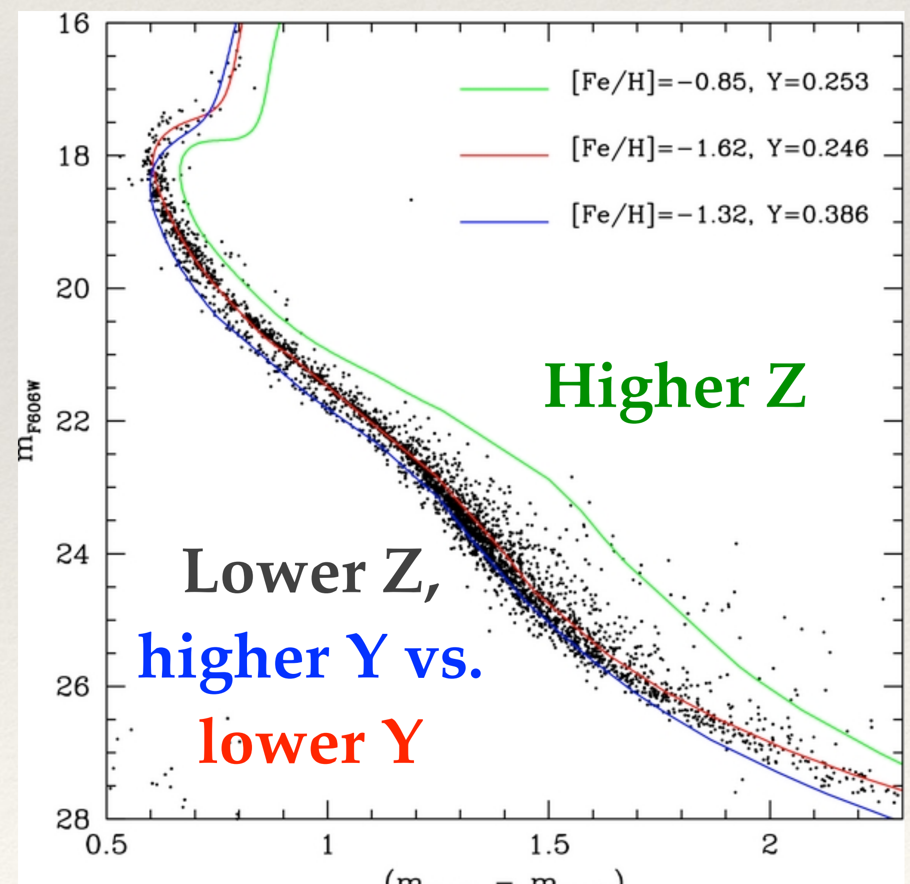
- **Main Sequence (MS)**
  - Shifts towards redder colors and cooler T for higher metallicities
  - Also shifts due to He abundance



Credit: Richard Pogge



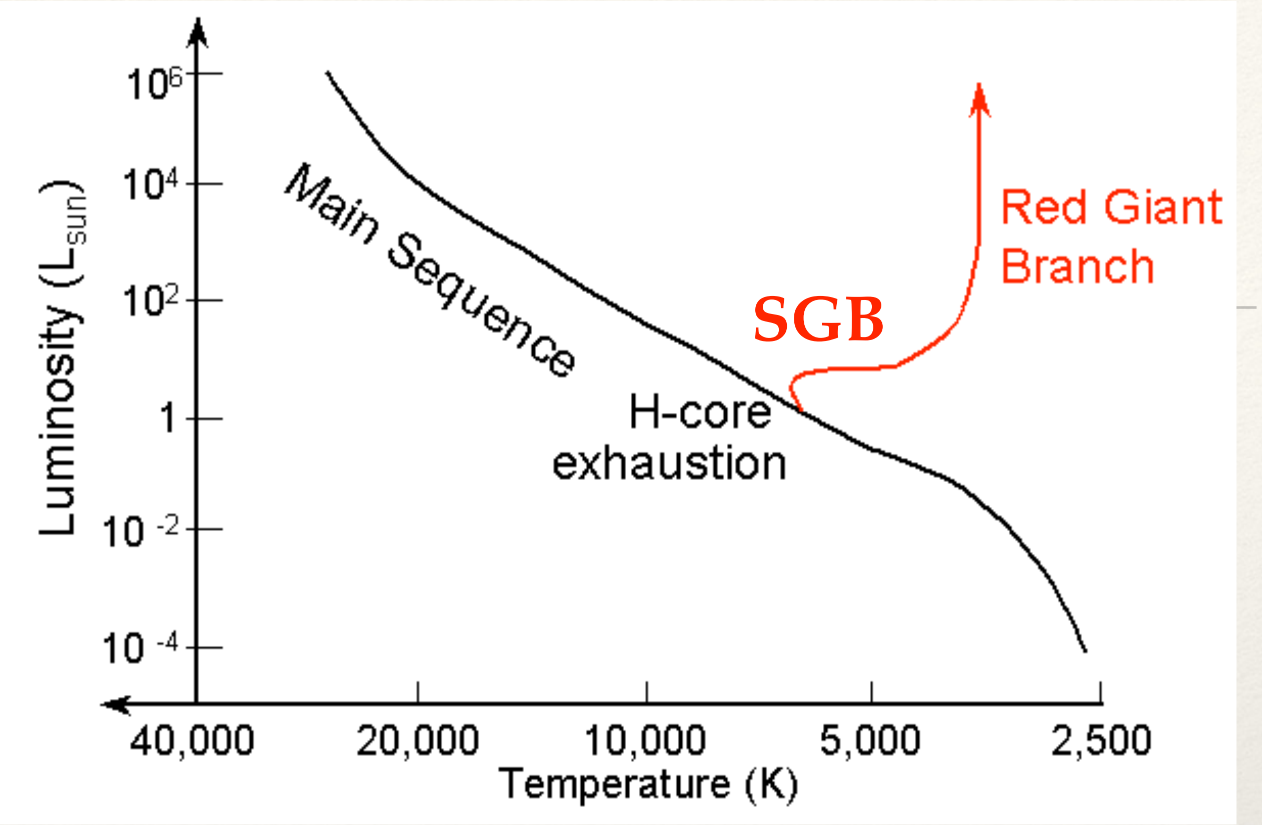
Credit: MESA



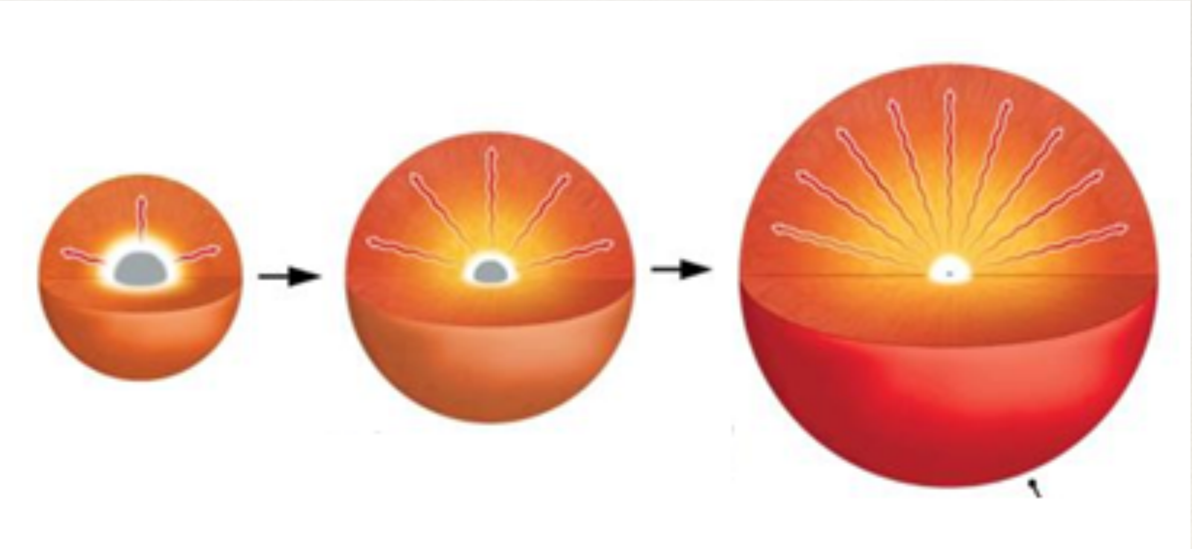
Omega Cen (King et al. 2012)

Stars and Stellar Popula

- **Sub-Giant Branch (SGB)**
  - Runs out of core H, core starts to contract
  - H shell ignites, envelope starts to expand and cool
- **Red Giant Branch (RGB)**
  - Shell contracts, heats — increases L
  - Envelope cools, higher T gradient **increases convection** — increases L
  - Deeper convection zone **dredges up** heavier elements from interior
  - Loosely bound envelope more easily expelled via radiation pressure — **mass loss**

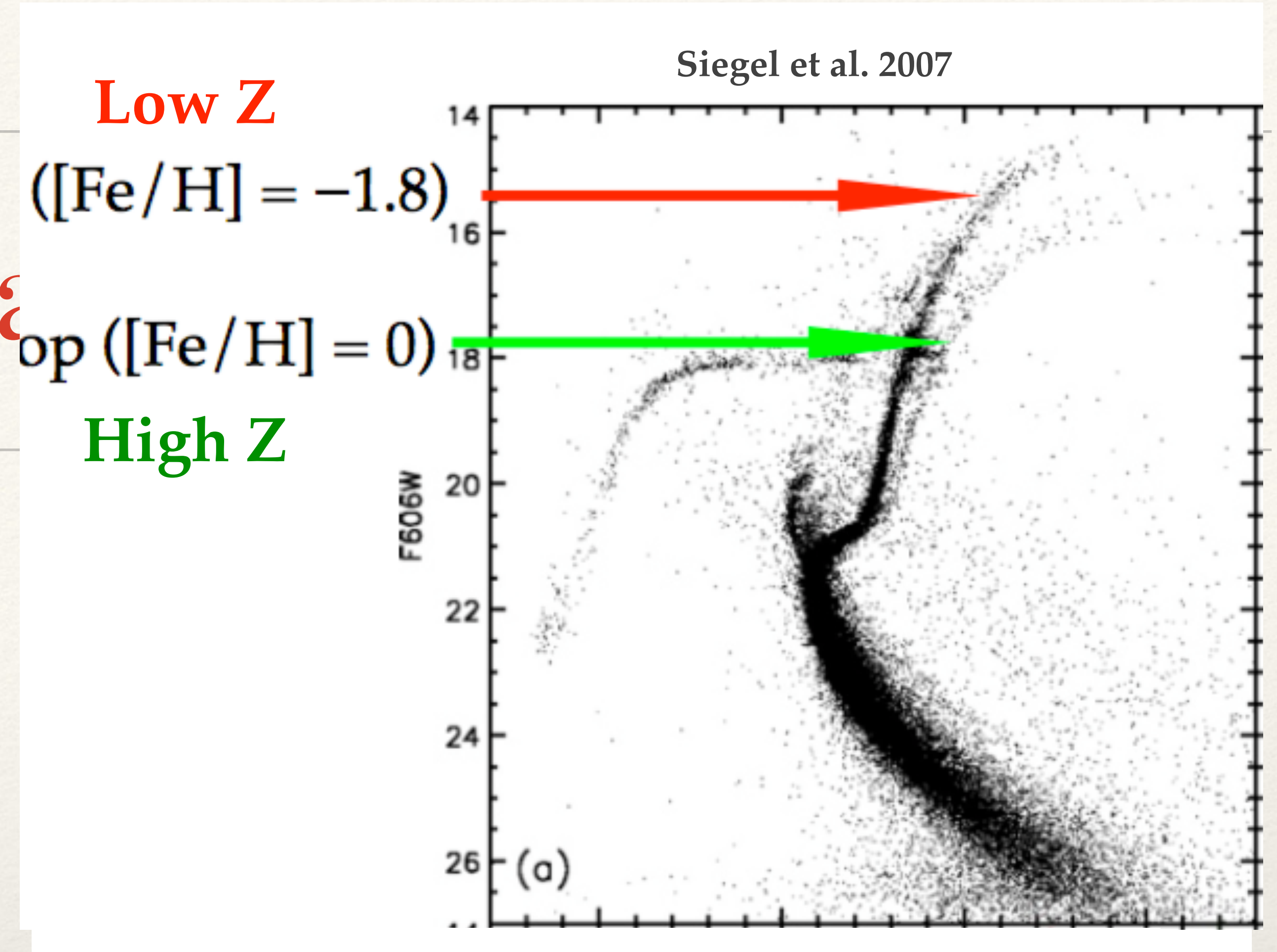


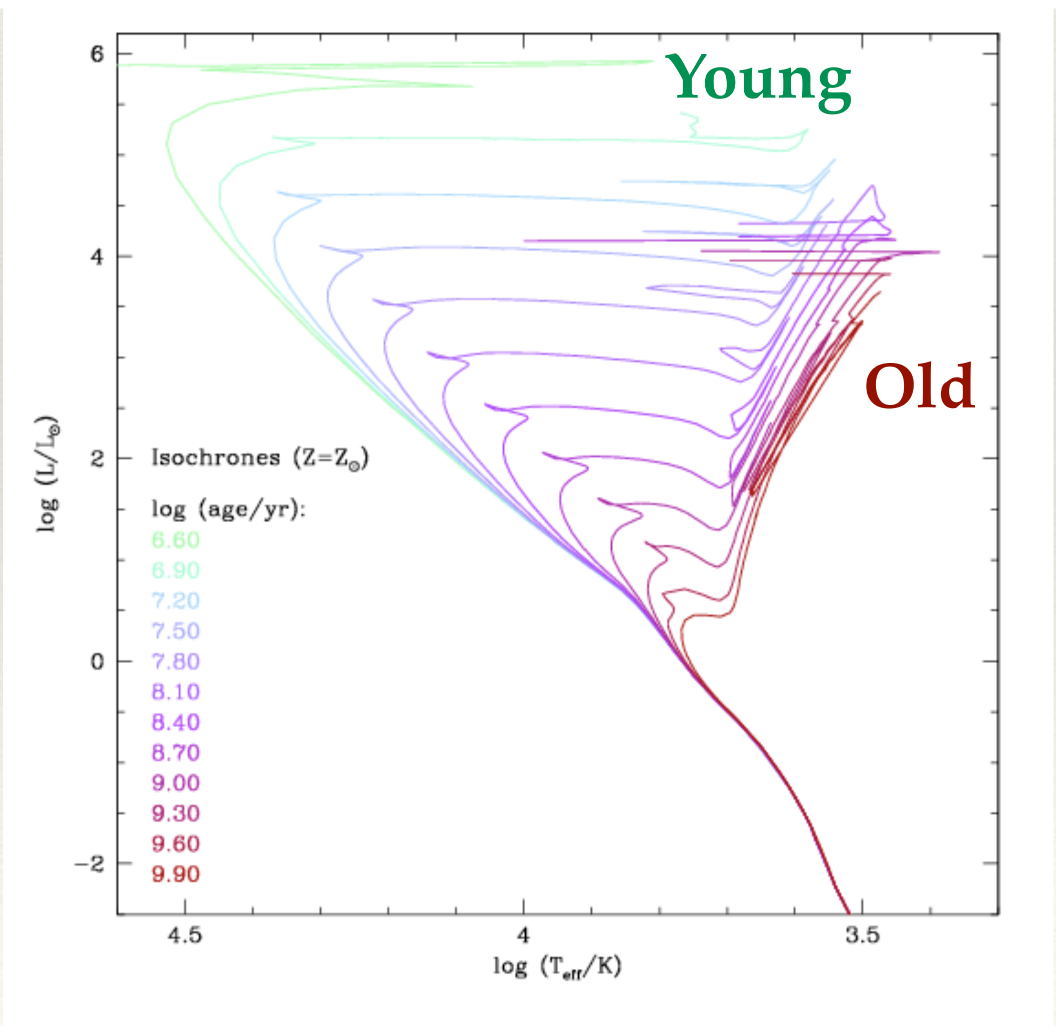
Credit: Richard Pogge



Stars and Stellar Popula

- **Red Giant Branch (RGB)**
  - Temperature and shape of RGB depends on mass, age, & metallicity
  - Evolutionary tracks of stars of different initial masses converge on RGB
    - Shell output tied to core mass — all have similar core masses

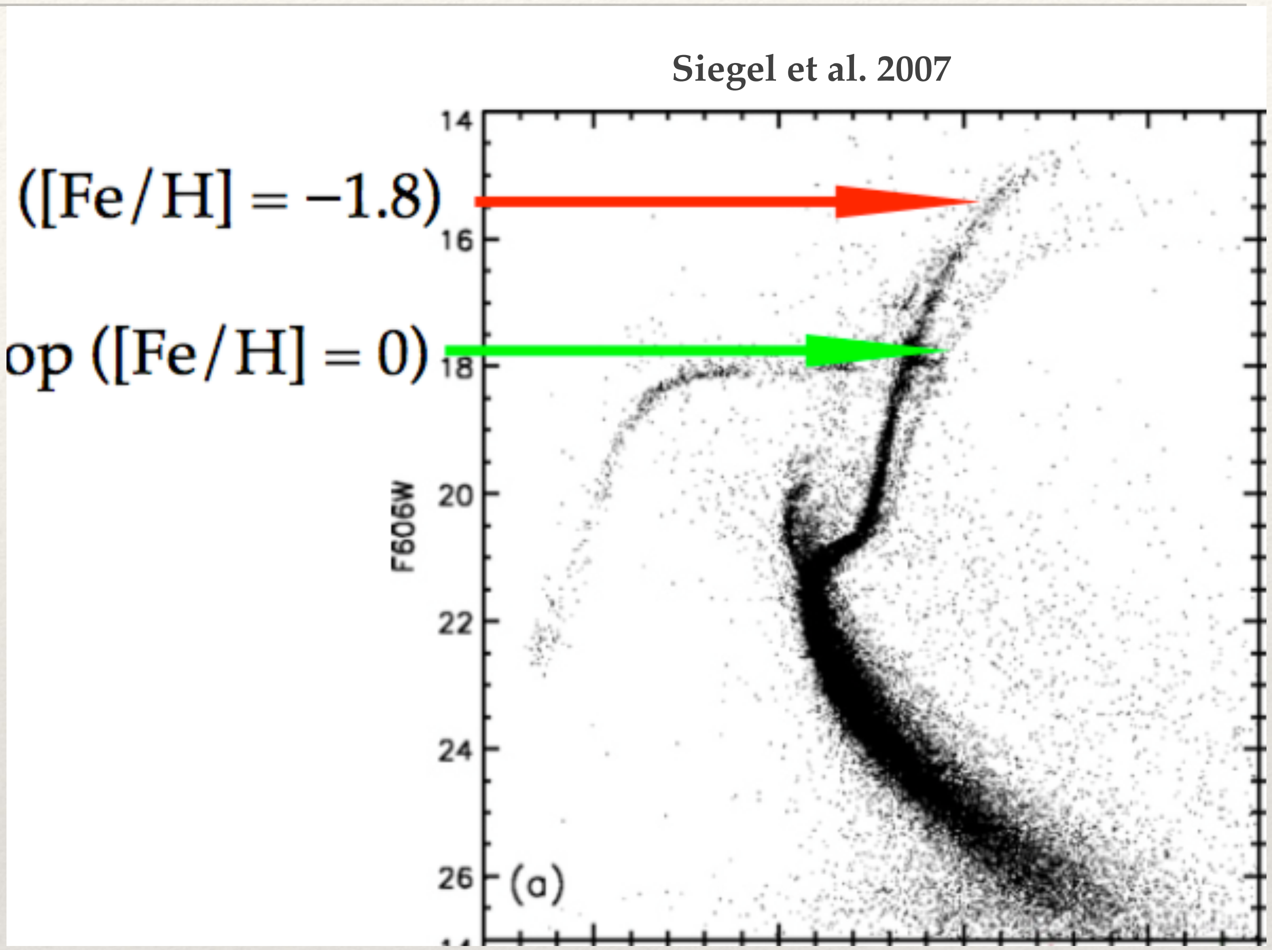




da Cunha 2008

Thought Question

- How does the tip of the Red Giant Branch appear to depend on metallicity in this plot?
- But didn't we say that the Tip of the Red Giant Branch was a good distance indicator?
- What's going on?



Thought Question

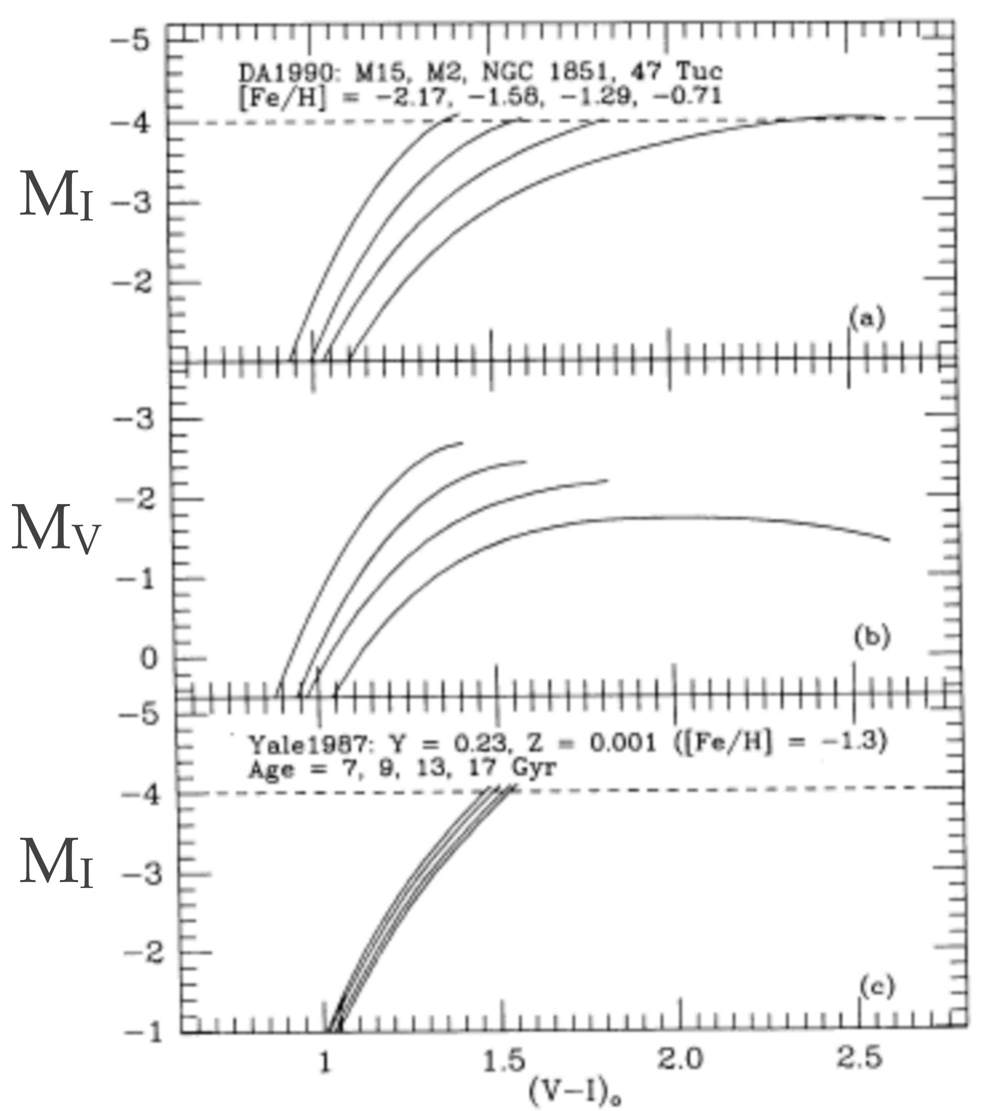
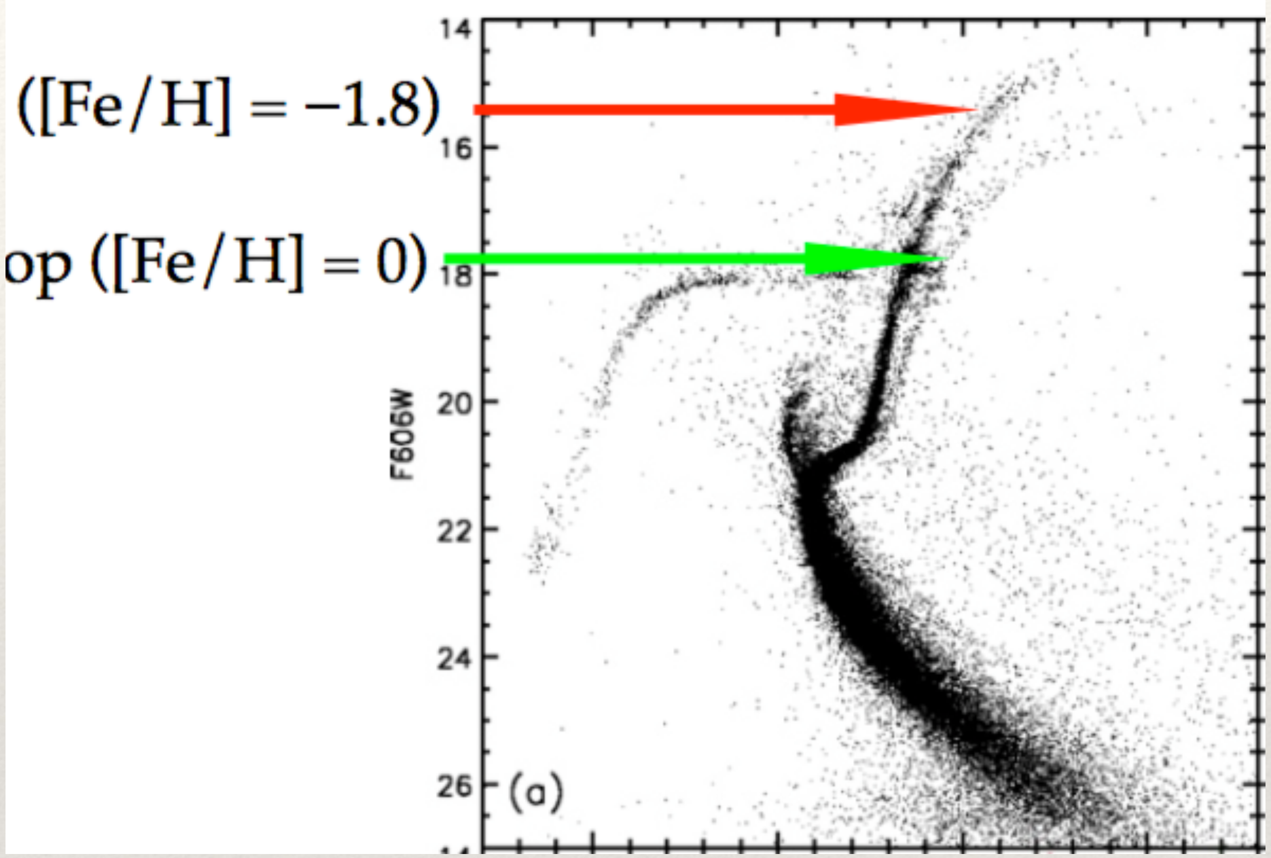


FIG. 1.—(*a*) Empirical loci in the $M_I - (V - I)_0$ diagram of the red giant branch for Galactic globular clusters: M15, M2, NGC 1851, and 47 Tuc, the metallicities of which are [Fe/H] = −2.17, −1.58, −1.29, −0.71 dex, respectively. Note that the *I* magnitude of the tip of the red giant branch changes little due to metallicity. (*b*) An $M_V - (V - I)_0$ diagram with the same sequence as in (*a*). Note that the *V* magnitude of the tip of the red giant branch changes by ~1.3 mag for the metallicity range of −2.2 < [Fe/H] < −0.7 dex. (*c*) An $M_I - (V - I)_0$ diagram showing a set of Revised Yale theoretical isochrones for [Fe/H] = −1.3 dex and ages of 7, 9, 13, and 17 Gyr. Note how insensitive the *I* magnitude of the tip of the red giant branch is to age.

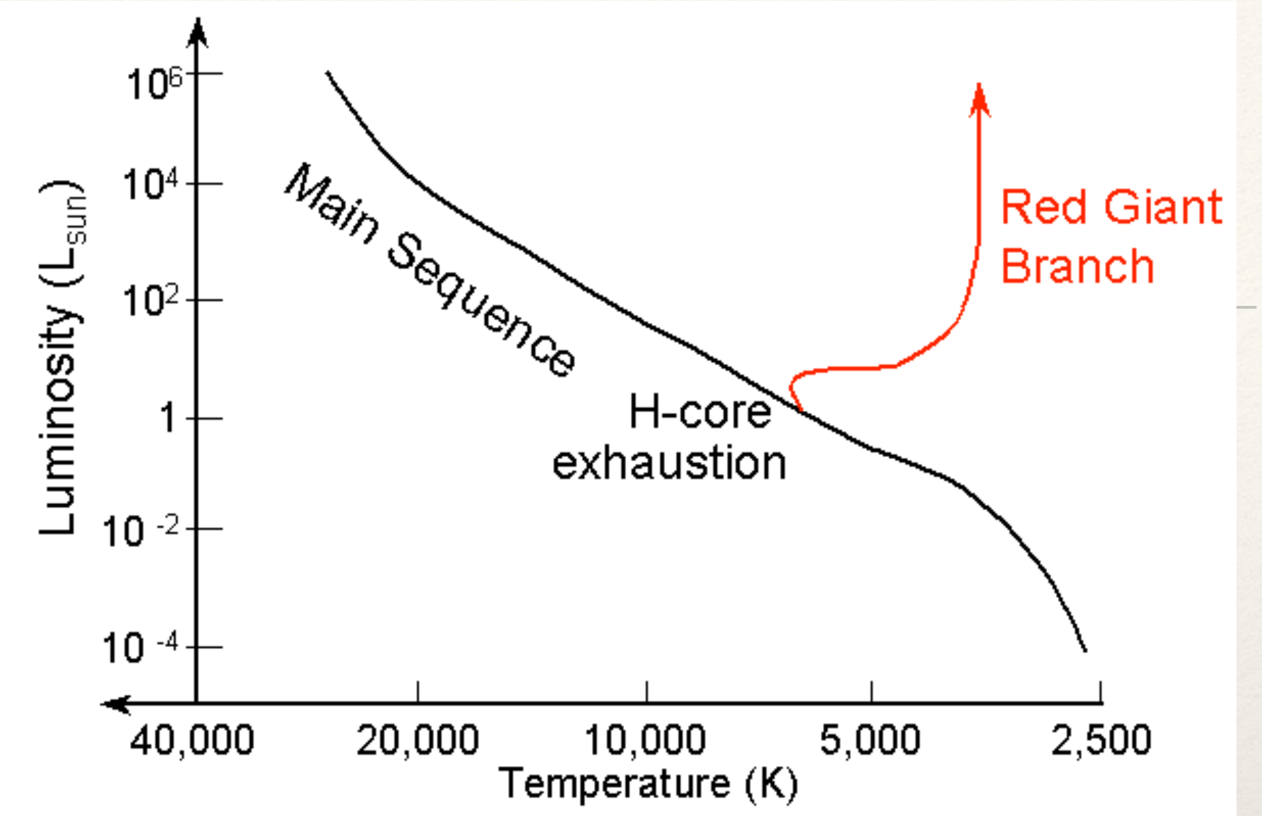
Lee et al. 1993

Siegel et al. 2007



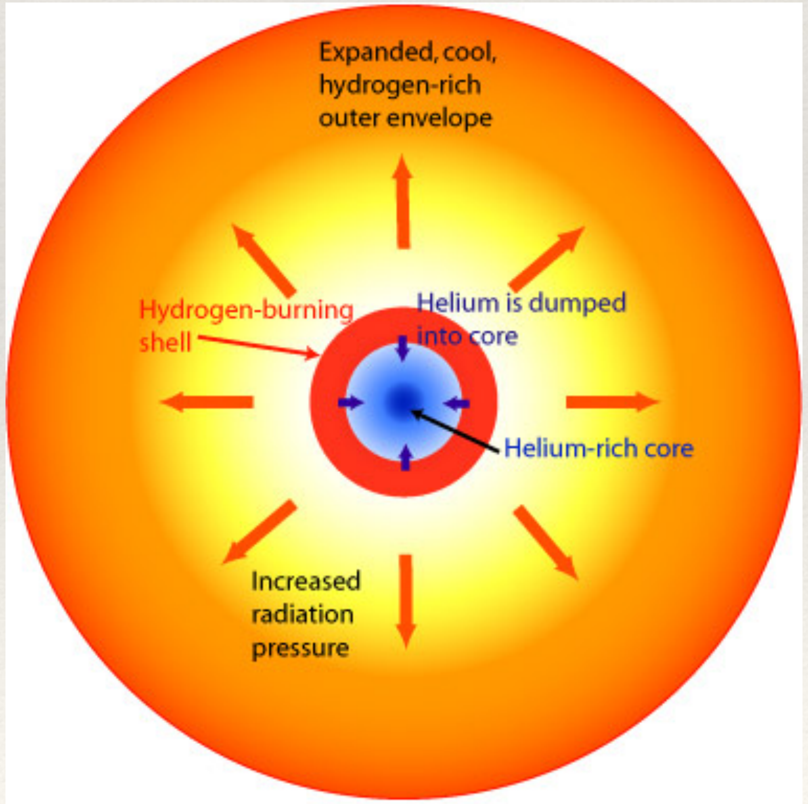
- TRGB — nearly constant luminosity regardless of age and metallicity **at long wavelengths**

Stars and Stellar Popula



Credit: Richard Pogge

- **Red Giant Branch (RGB) — Features**
  - **Tip of RGB**
    - Set by He fusion ignition
    - Close to **constant luminosity** regardless of age or metallicity
      - **Distance indicator!**
  - **RGB bump**
    - H-fusing shell crosses chemical discontinuity from first dredge-up
    - Lower efficiency fusion causes pile up of stars at same L
    - Location depends on mass, age, and metallicity



Hydrogen Shell Burning on the Red Giant Branch

https://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_postmain.html

Stars and Stellar Popula

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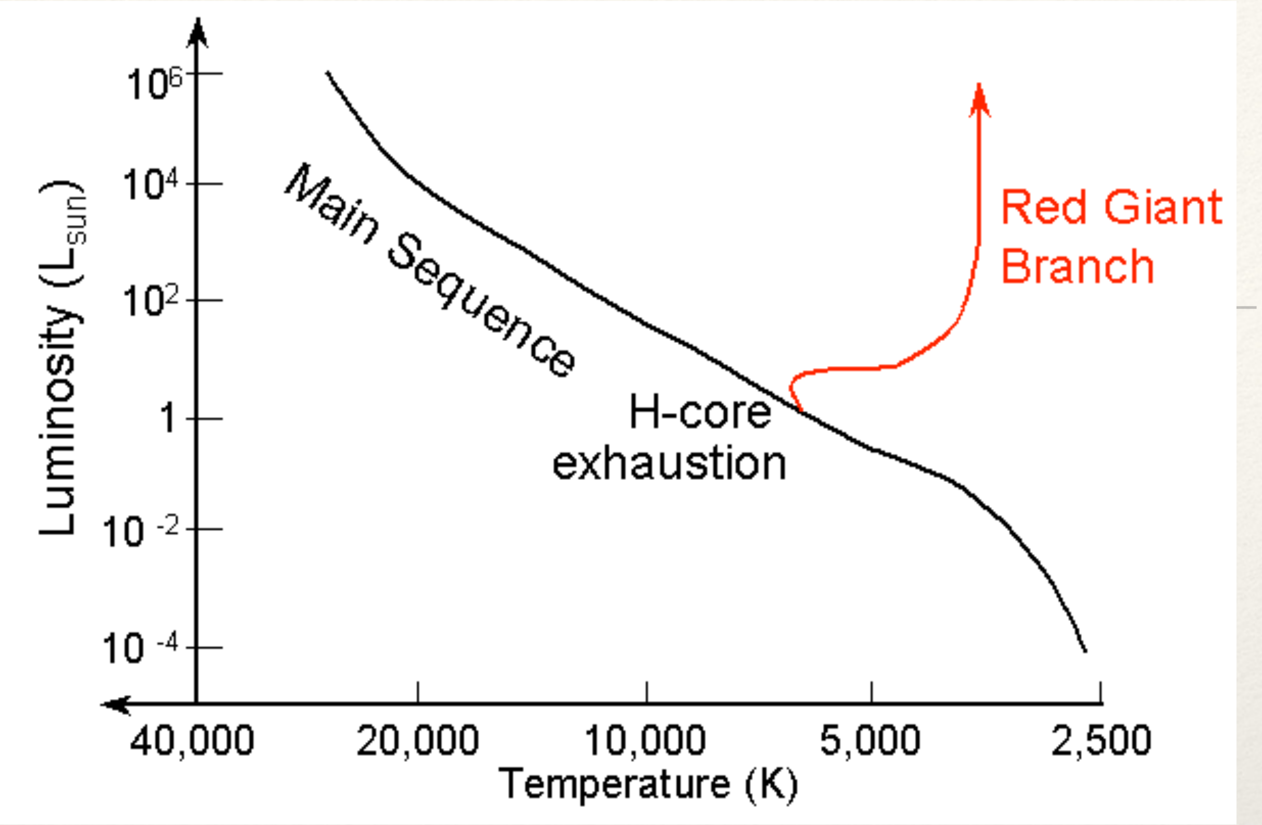
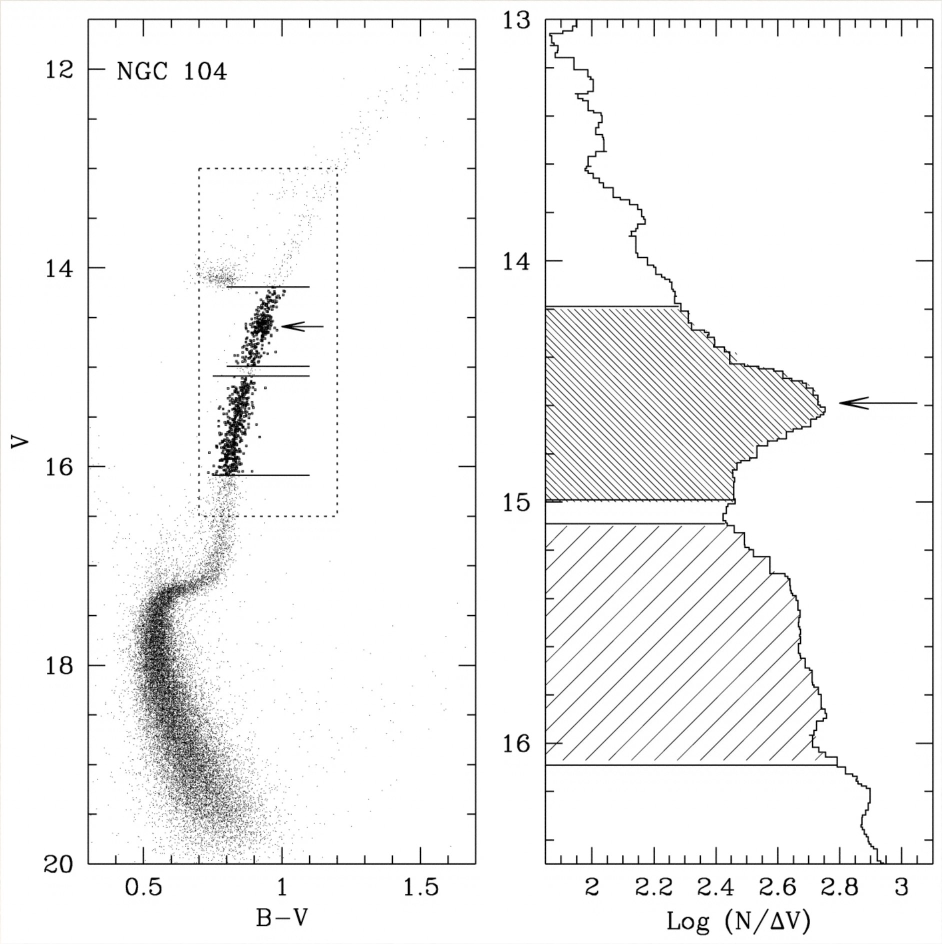
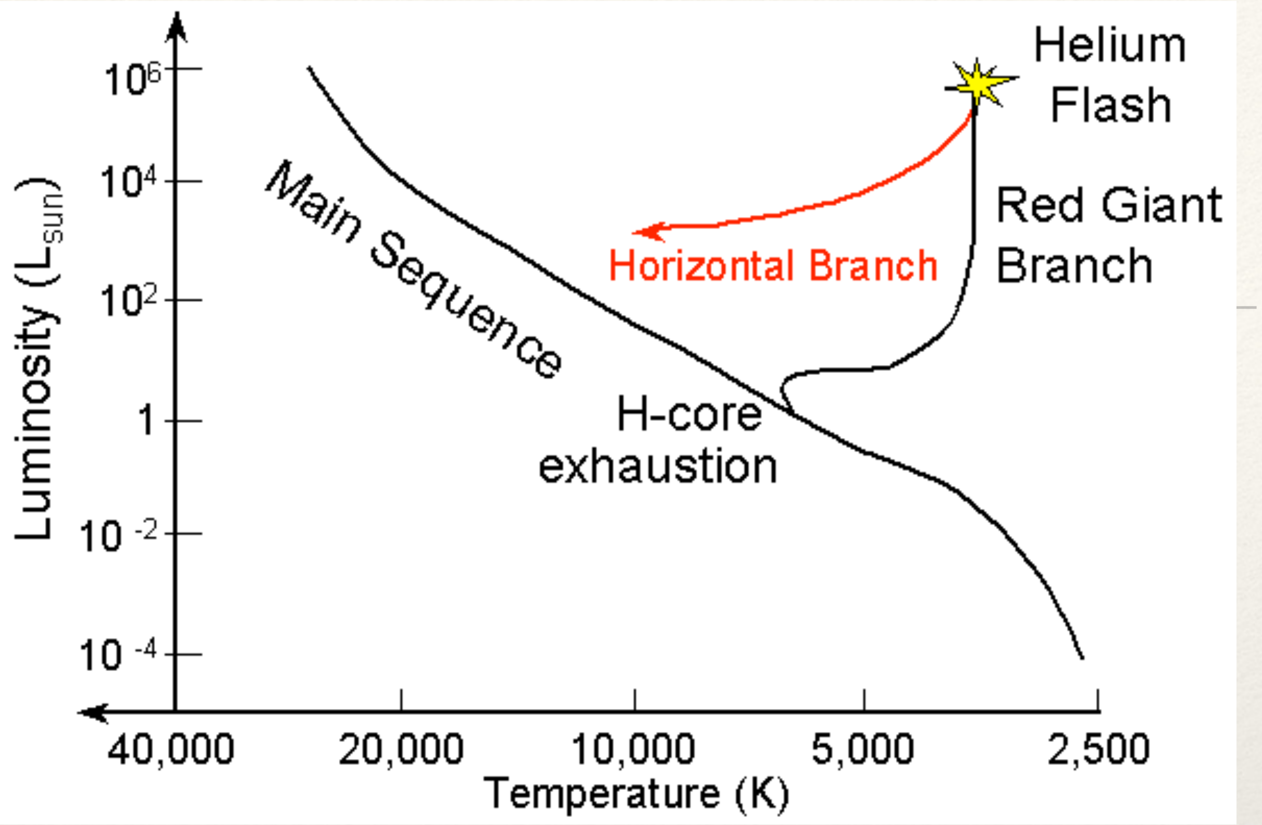


Credit: Richard Pogge



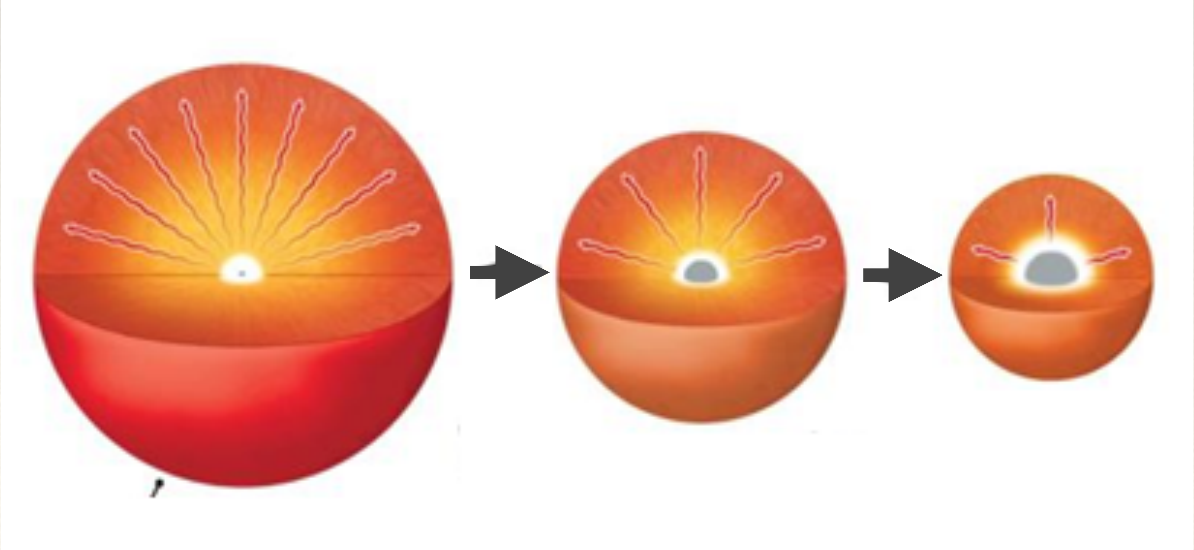
Bono et al. 2001

Stars and Stellar Popula



Credit: Richard Pogge

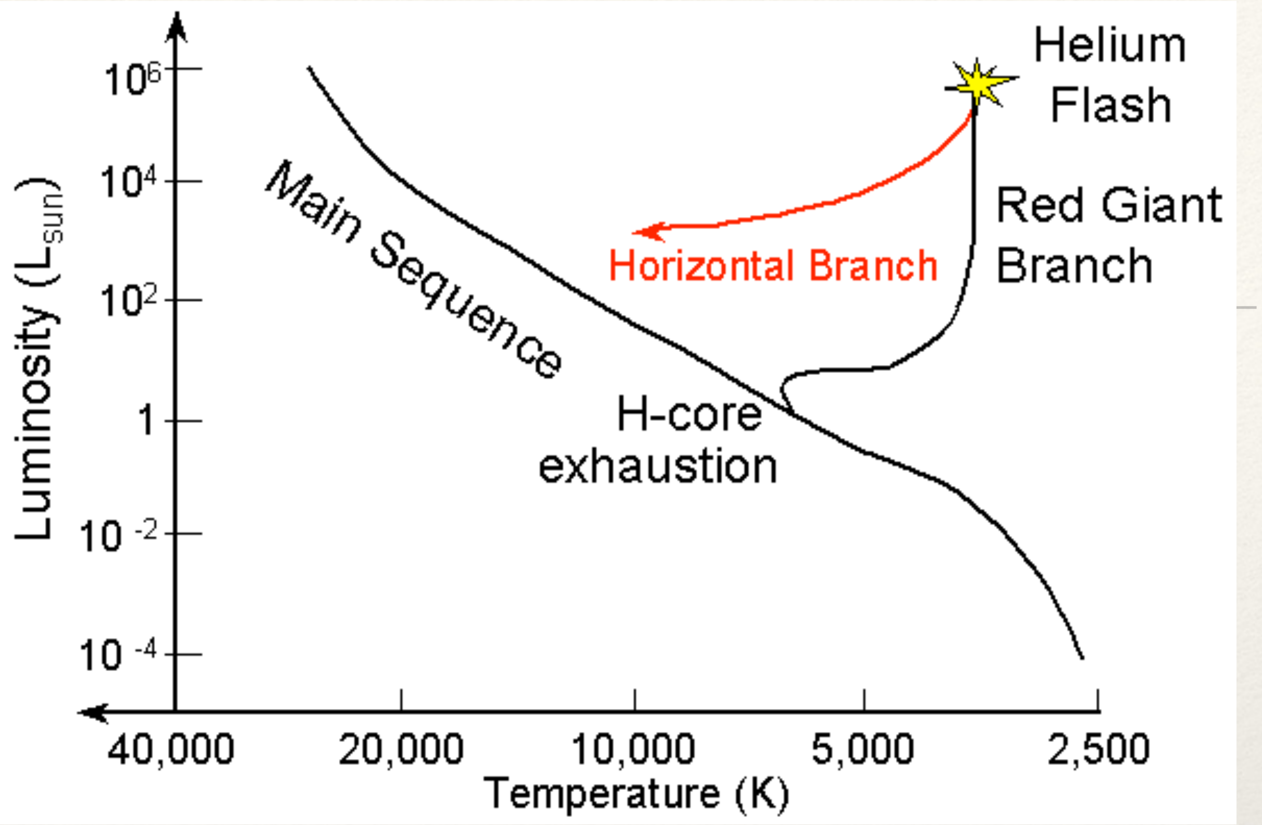
- **Horizontal Branch (HB)**
  - Core temperature reaches 100 million K — He fusion ignites
  - Star readjusts:
    - Core expands, decreasing shell output — lower L
    - Envelope shrinks — higher T



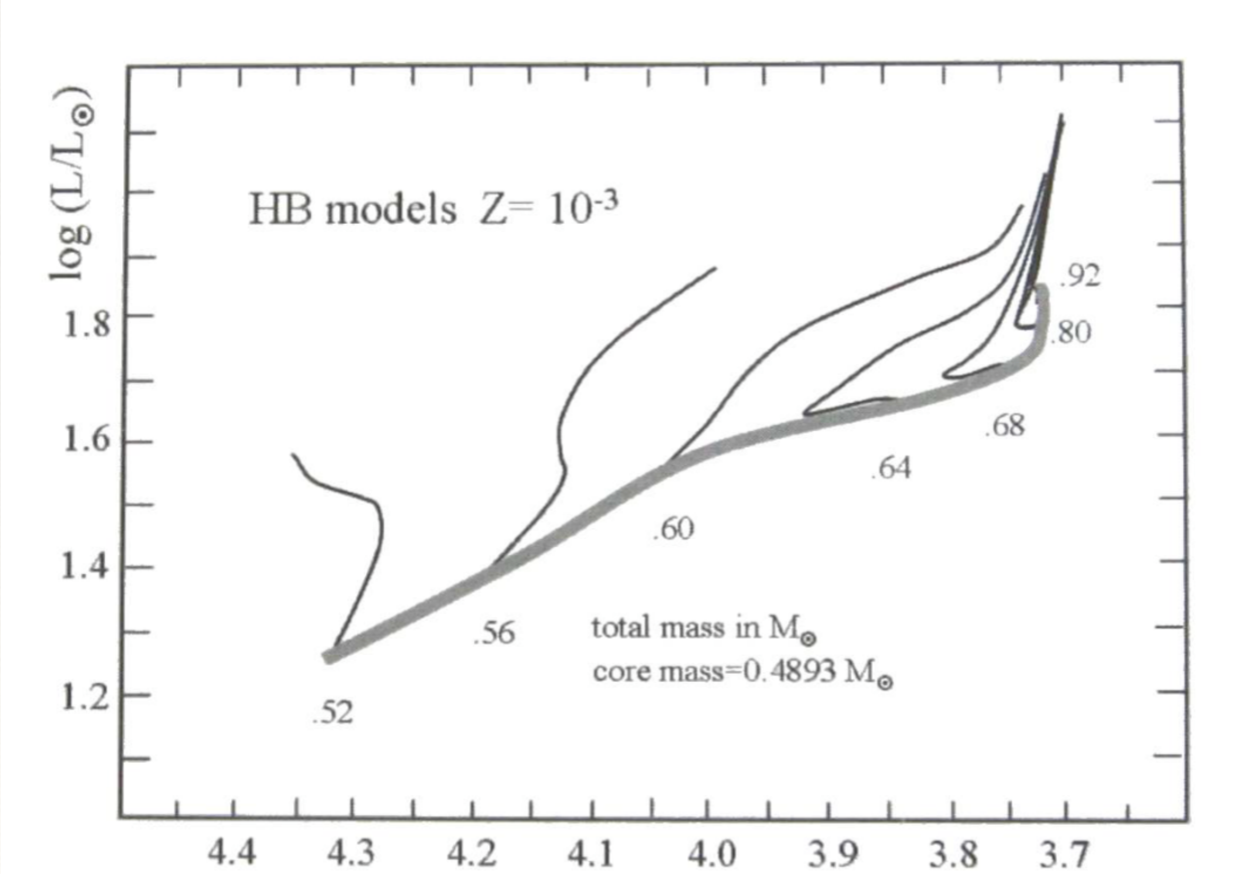
- Luminosity of He-fusing stars depends on core mass, which is similar for all lower-mass stars
- Gives rise to a **Horizontal Branch (HB)**

Stars and Stellar Popula

- **Horizontal Branch (HB)**
  - Location of a star on HB partly related to envelope mass:
    - Variable mass loss on RGB and at He flash gives a range of envelope masses
    - Stars with smaller envelopes (and radii) are bluer



Credit: Richard Pogge



Maeder, A., Physics, Formation and Evolution of Rotating Stars, Springer-Verlag

Stars and Stellar Populatio

https://faculty.virginia.edu/ASTR5610/lectures/globular_clusters/intro.html

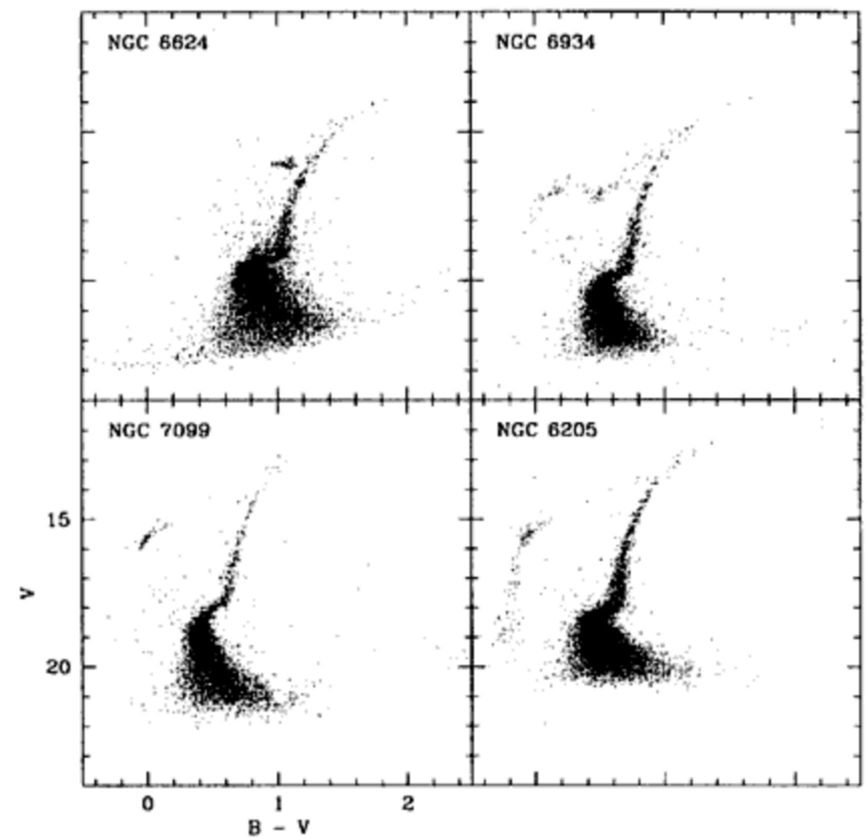
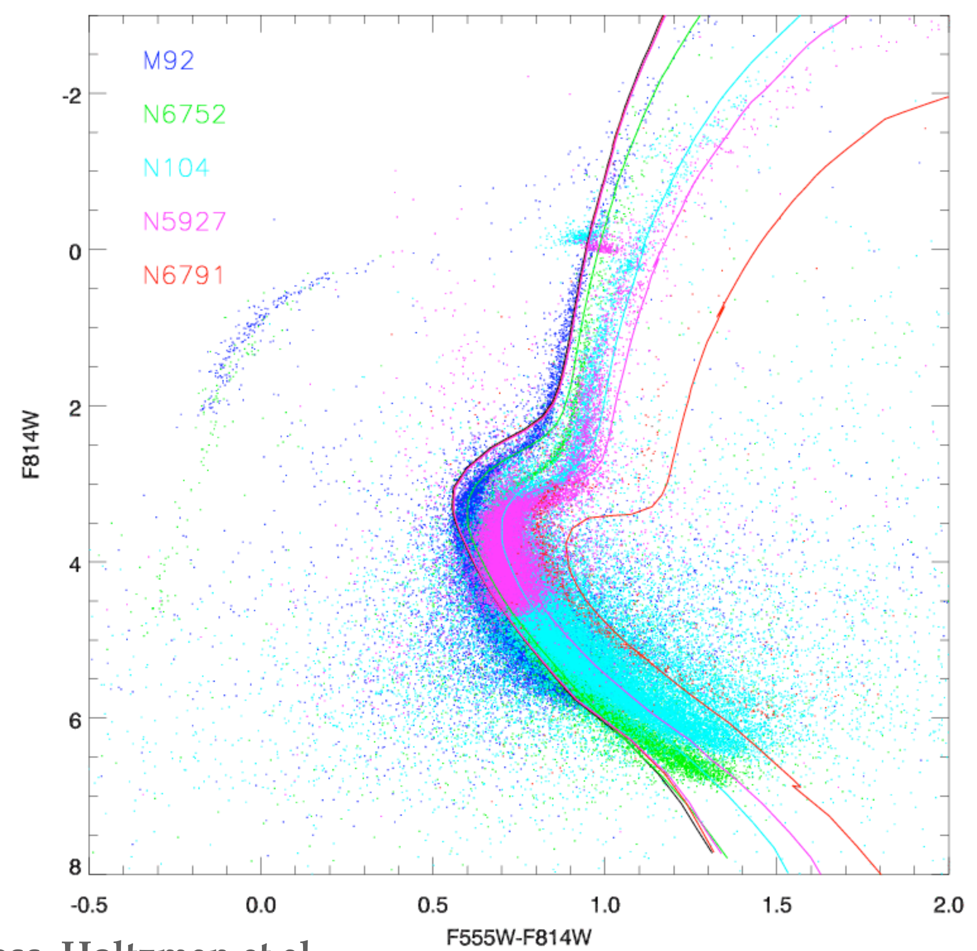


FIGURE 4. Clusters with four very different types of horizontal branch. (Data courtesy of M. Zoccali & G. Piotto [private communication]; source is HST archival images of the centers of globular clusters.)

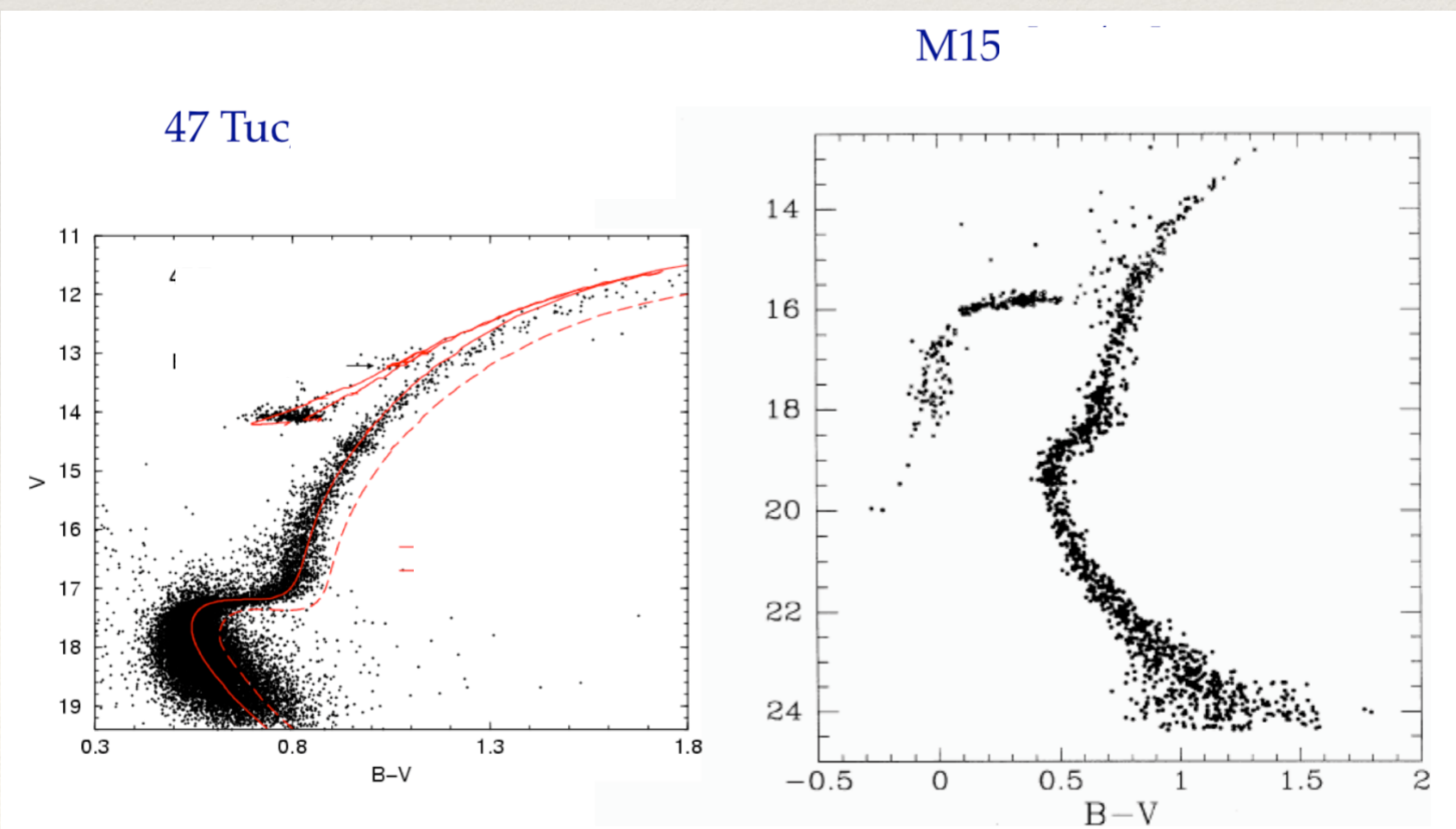
- **Horizontal Branch (HB)**
  - A Helium Core Fusing Sequence — but see a wide range in morphology!
  - Depends somewhat on metallicity:
    - Metal-poor — **blue Horizontal Branch (BHB)**
    - Metal-rich — pile up in **Red Horizontal Branch (RHB)**
    - Intermediate age (higher mass) stars — **Red Clump (RC)**

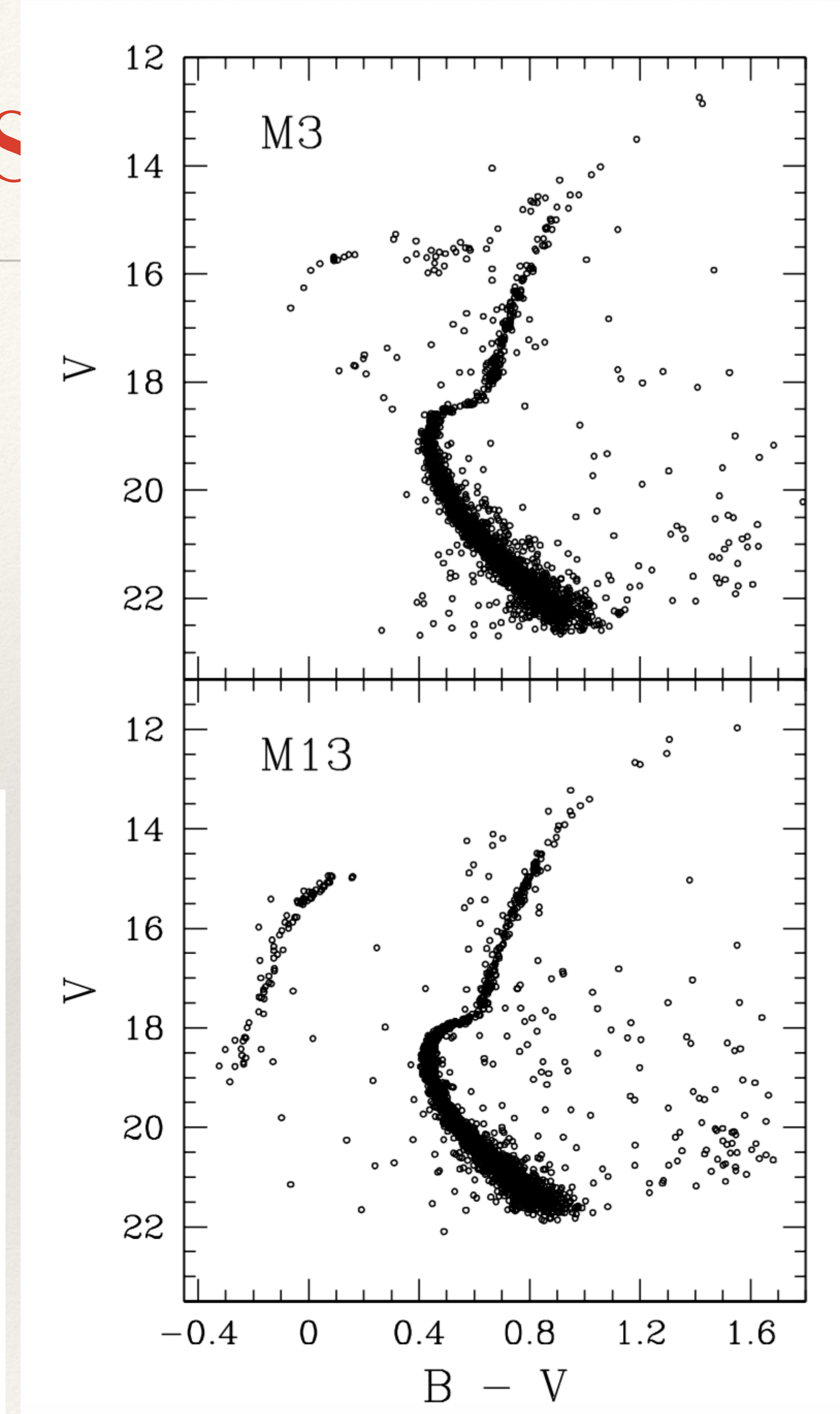


Ross, Holtzman et al.

Thought Ques

- Consider these two pairs of globular clusters.
  - Based on the HB morphology, which cluster in each pair is likely more metal-rich?





Rey et al. 2001

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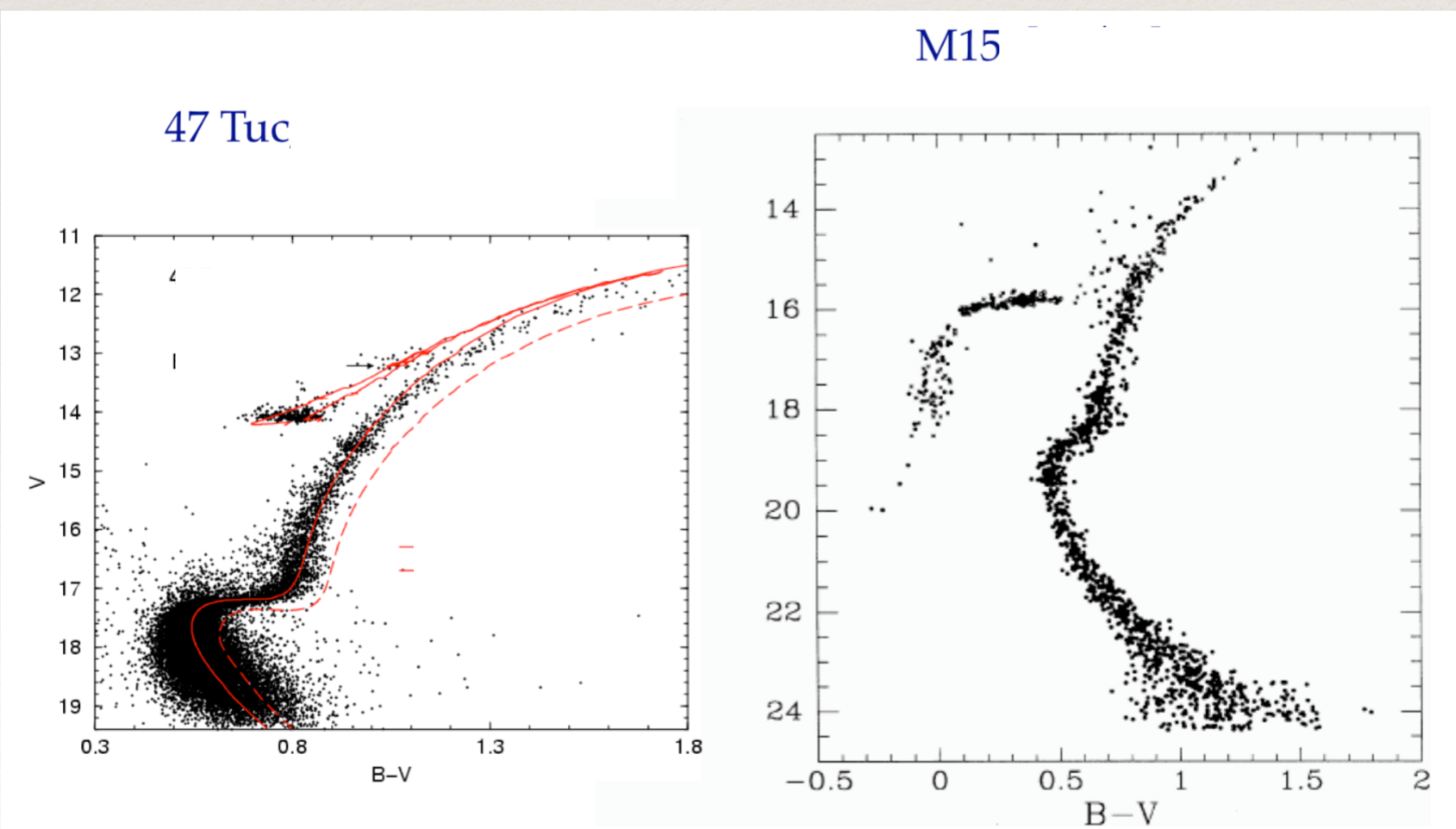
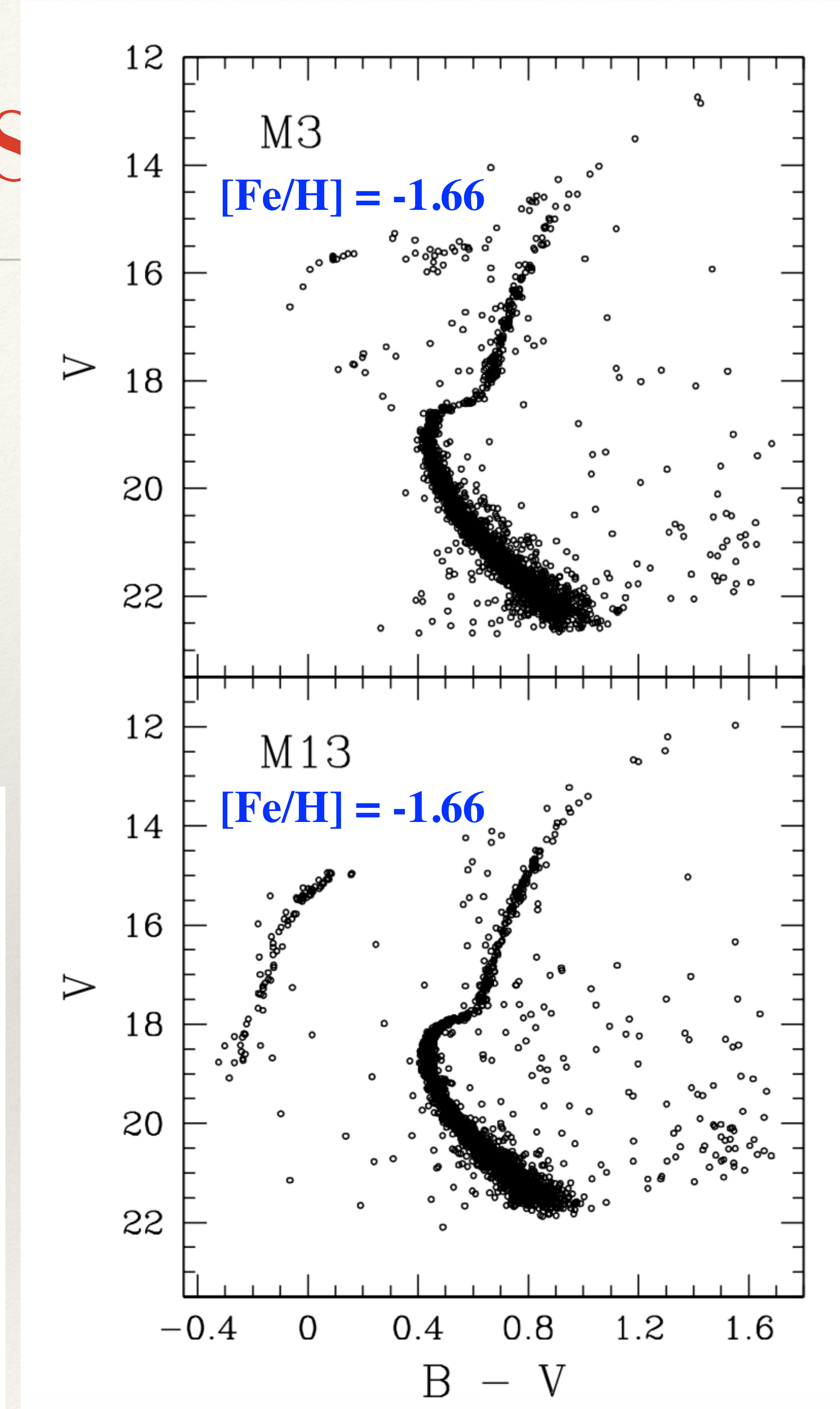
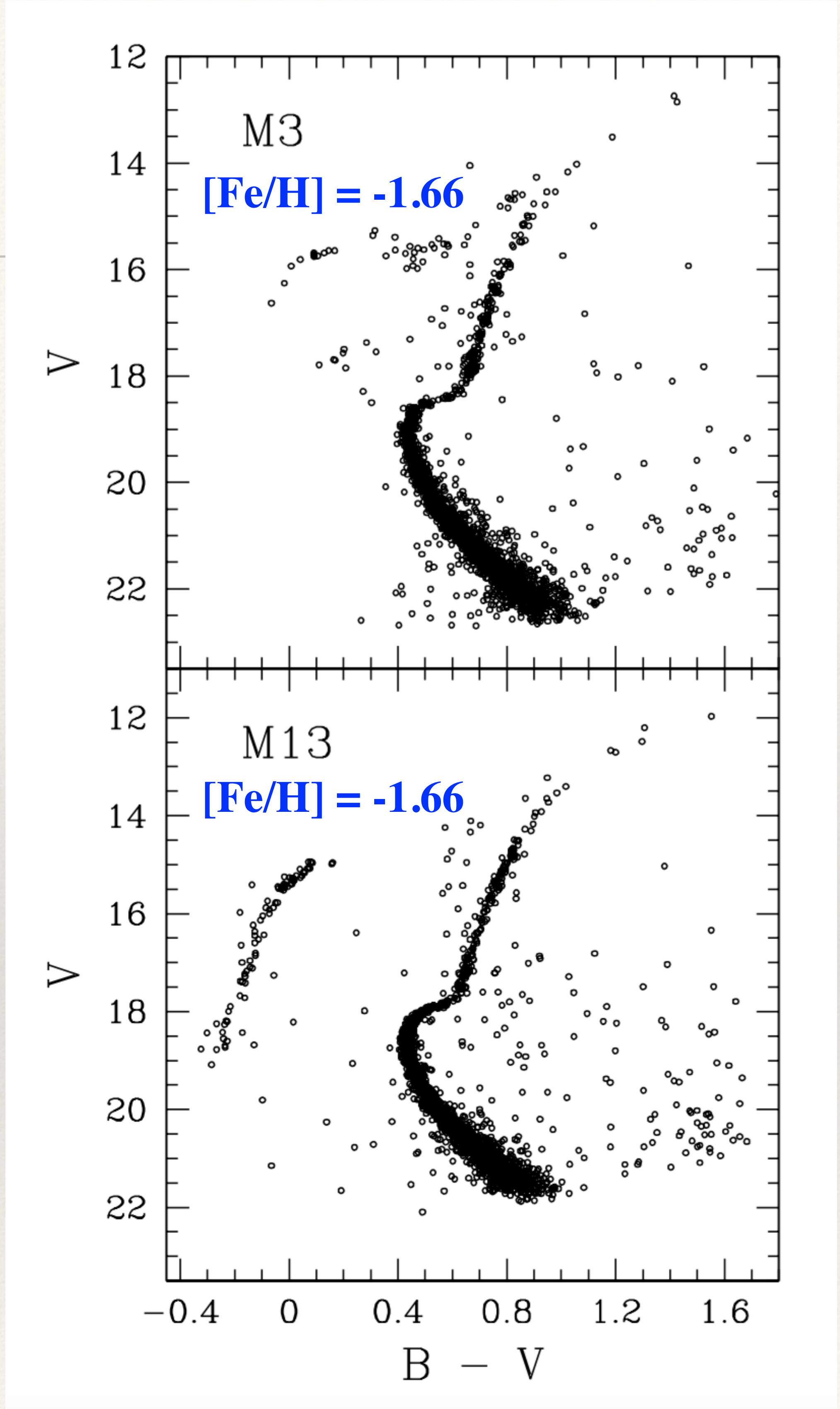




Rey et al. 2001

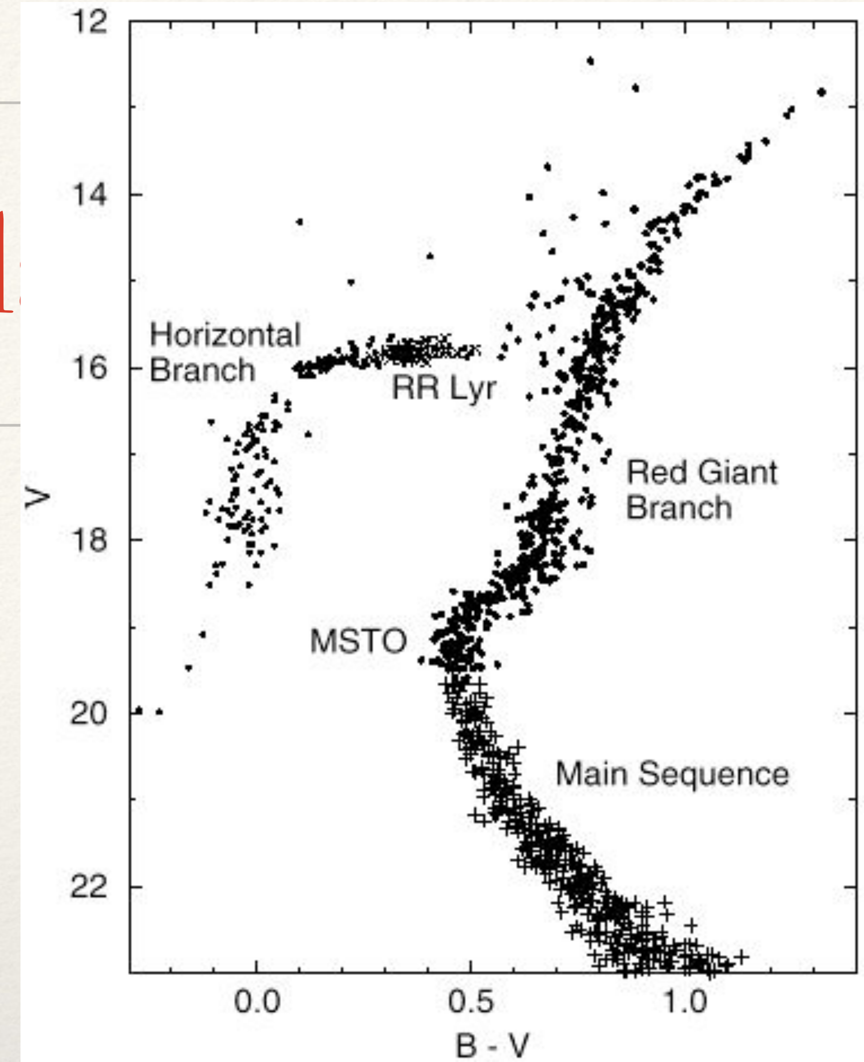
Stars and Stellar Populations

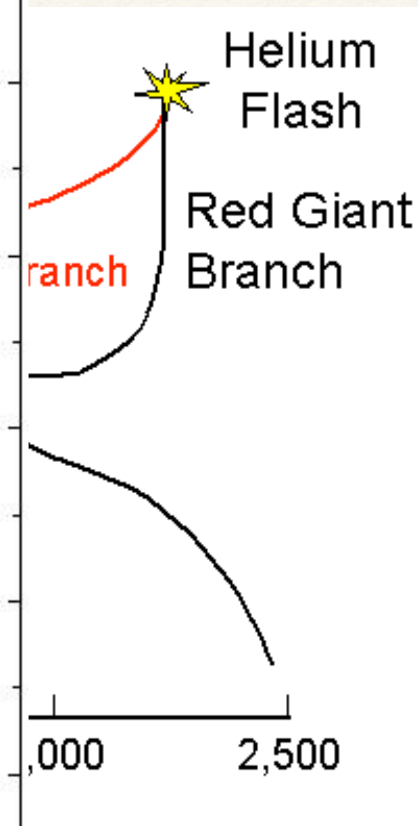
- Something else must be involved — **second-parameter problem**
- e.g. M3 and M13 have same metallicity but very different HB
- Likely age? Maybe also He abundance, CNO abundances, cluster concentration, or stellar rotation rates?



Rey et al. 2001

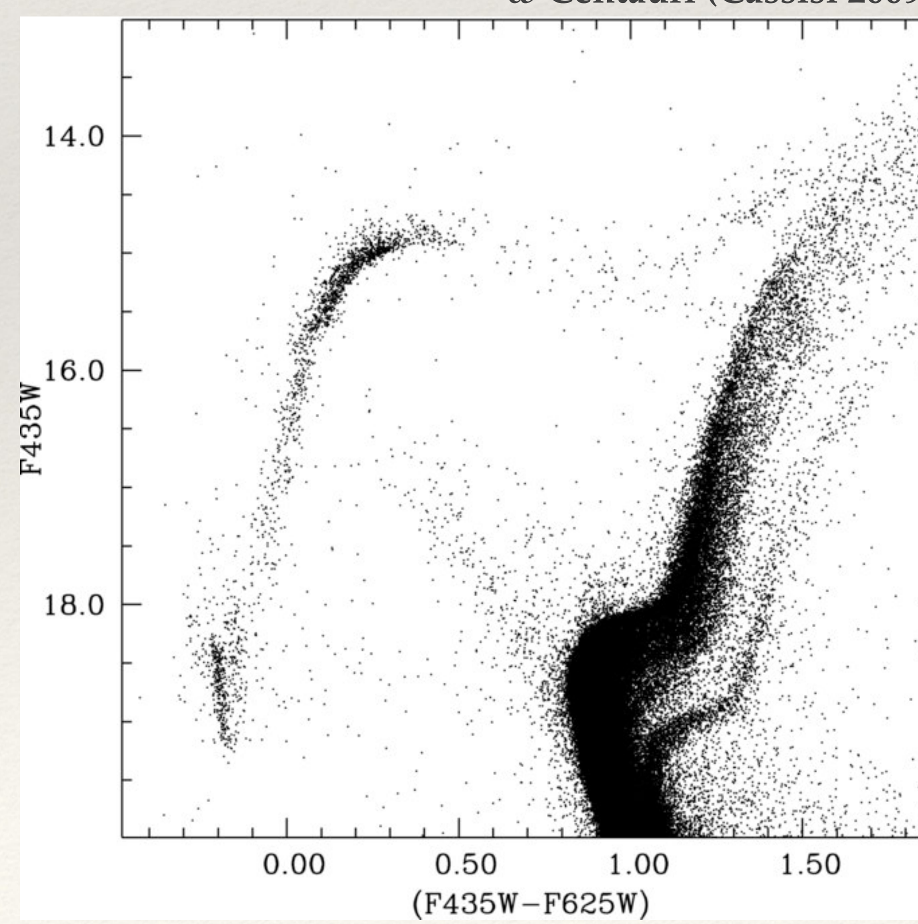
Stars and Stellar Popul





M15 (Krauss 2000)

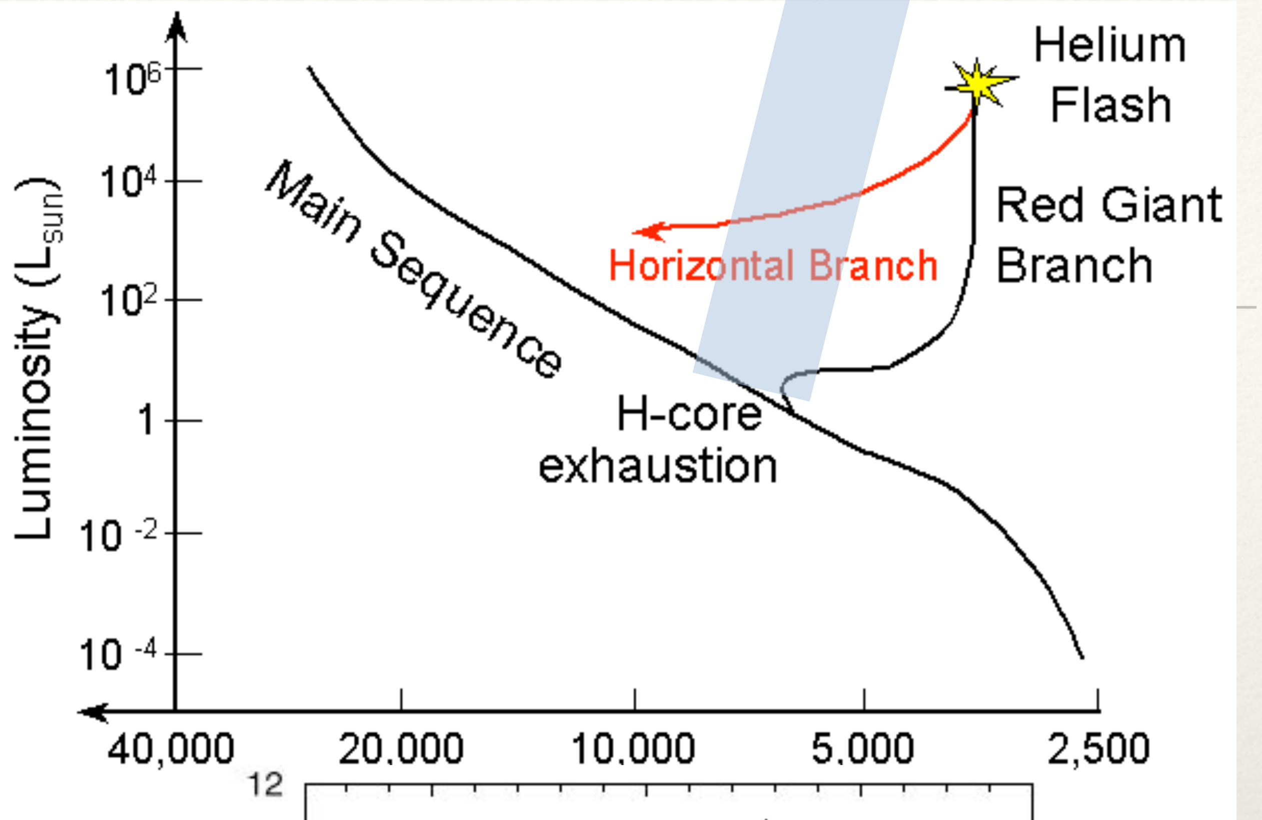
ω Centauri (Cassisi 2009)

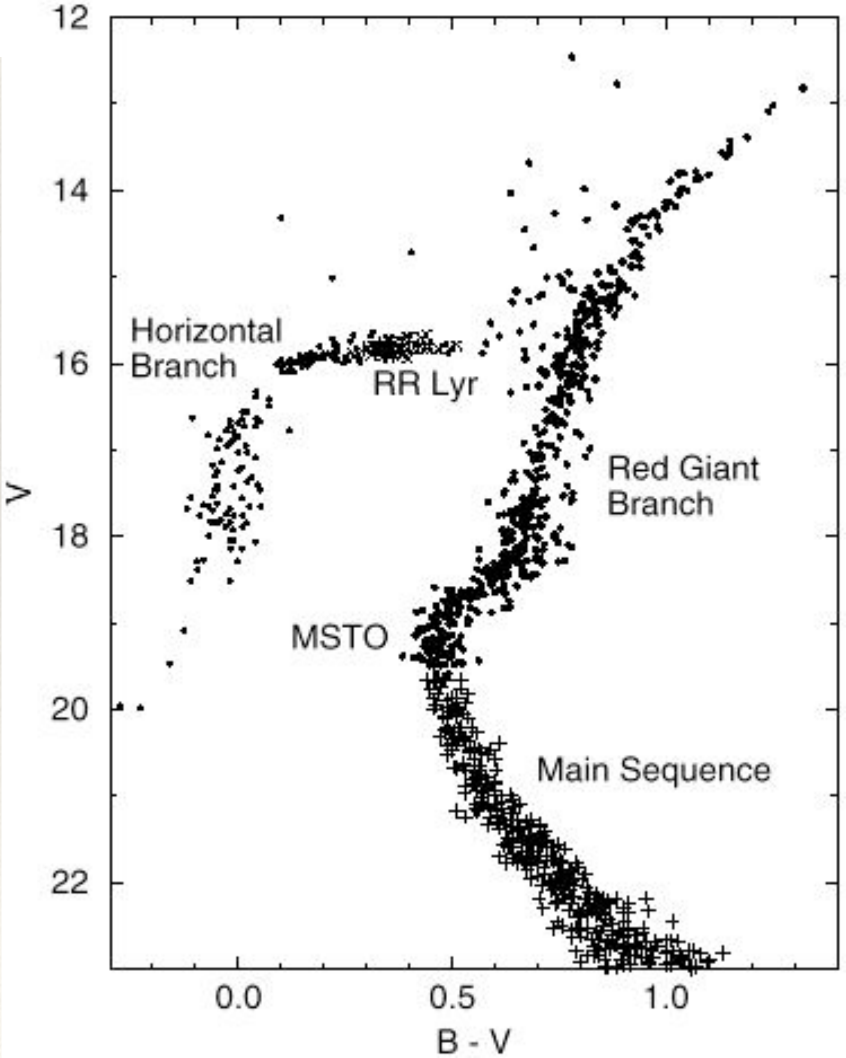


- **Horizontal Branch (HB) — Features**
  - Extreme Horizontal Branch
    - "blue tail" — may be extra mass loss combined with flux moving out of optical bands into UV at these T
    - "blue hook" — may be due to severe mass loss on RGB or He enrichment or rapid rotation during formation leading to mass loss

Stars and Stellar Popula

- **Horizontal Branch (HB)**
  - Where stars intersect **instability strip** — unstable to pulsations
  - Variable stars — RR Lyrae (plus Cepheids, delta Scuti, etc.)





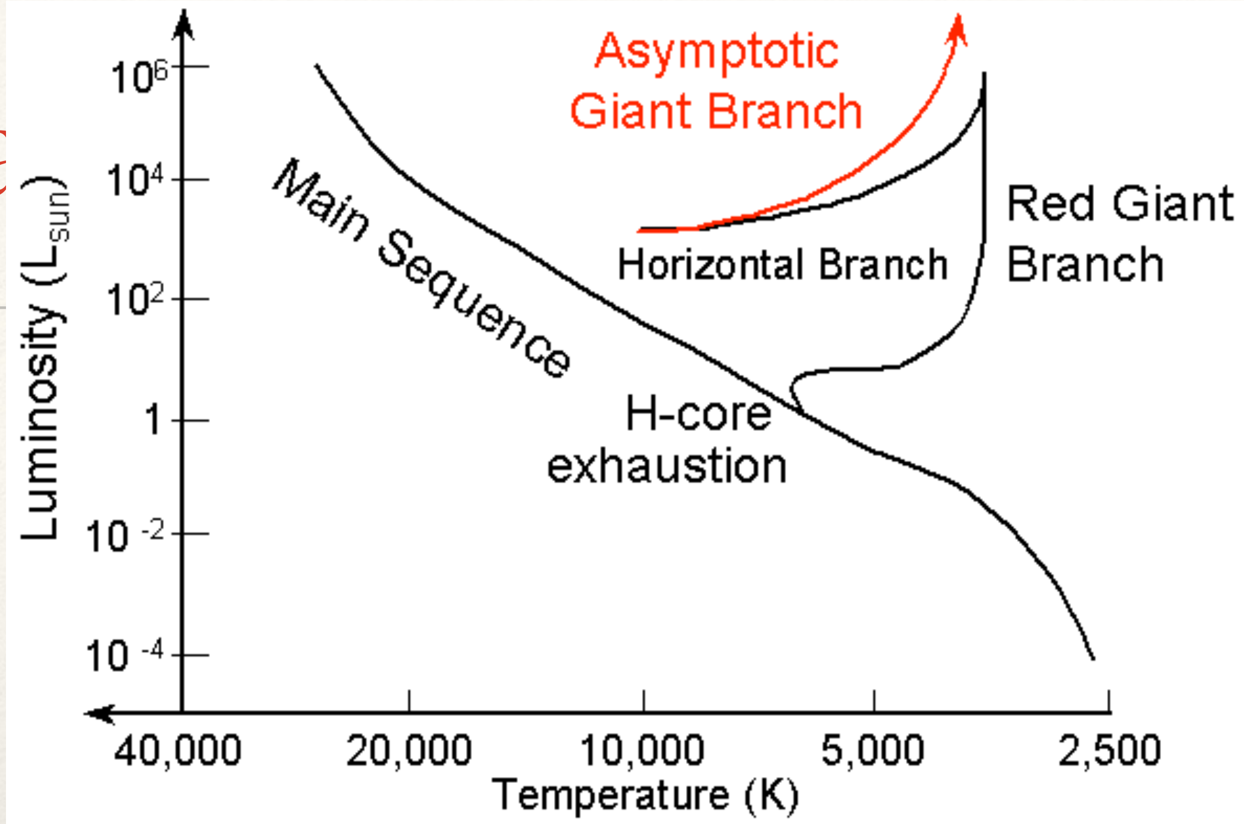
M15 (Krauss 2000)

Thought Question

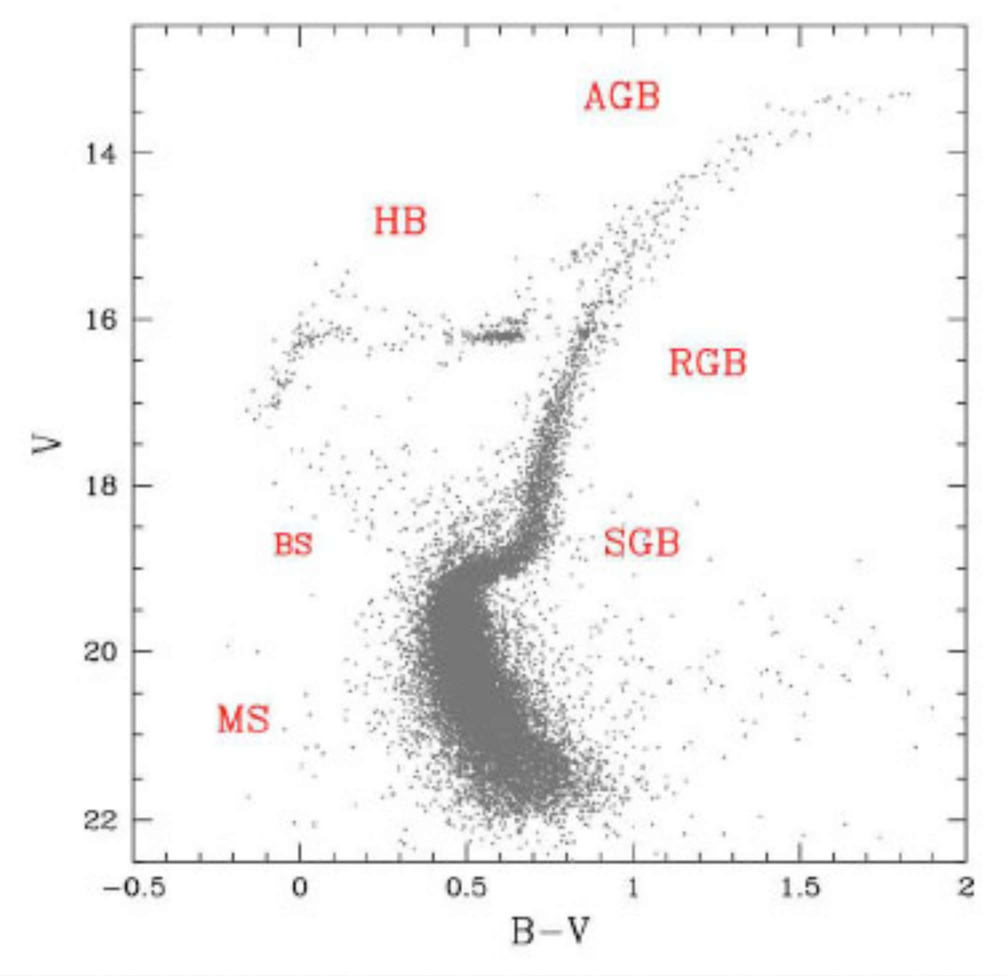
- What will happen physically to the star once it runs out of Helium in the core.
- Where will the star “move” on the HR diagram and why?

Stars and Stellar Popula

- **Asymptotic Giant Branch (AGB)**
  - Similar to RGB:
    - Run out of core He — core contracts, He shell ignites, envelope expands and cools, leading to the convection and dredge-ups
    - Star becomes redder and brighter, with luminosity set by core mass
    - Tip of AGB asymptotically approaches RGB (hence the name!)



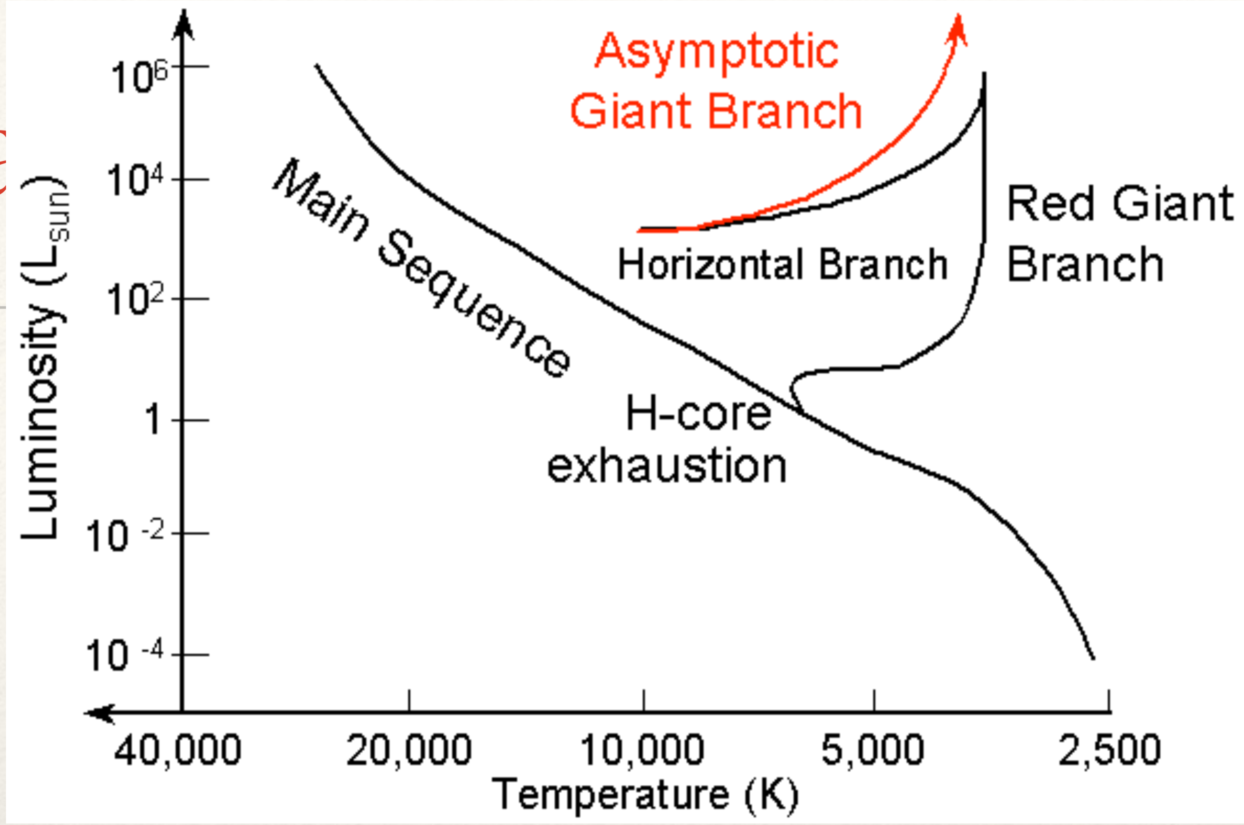
Credit: Richard Pogge



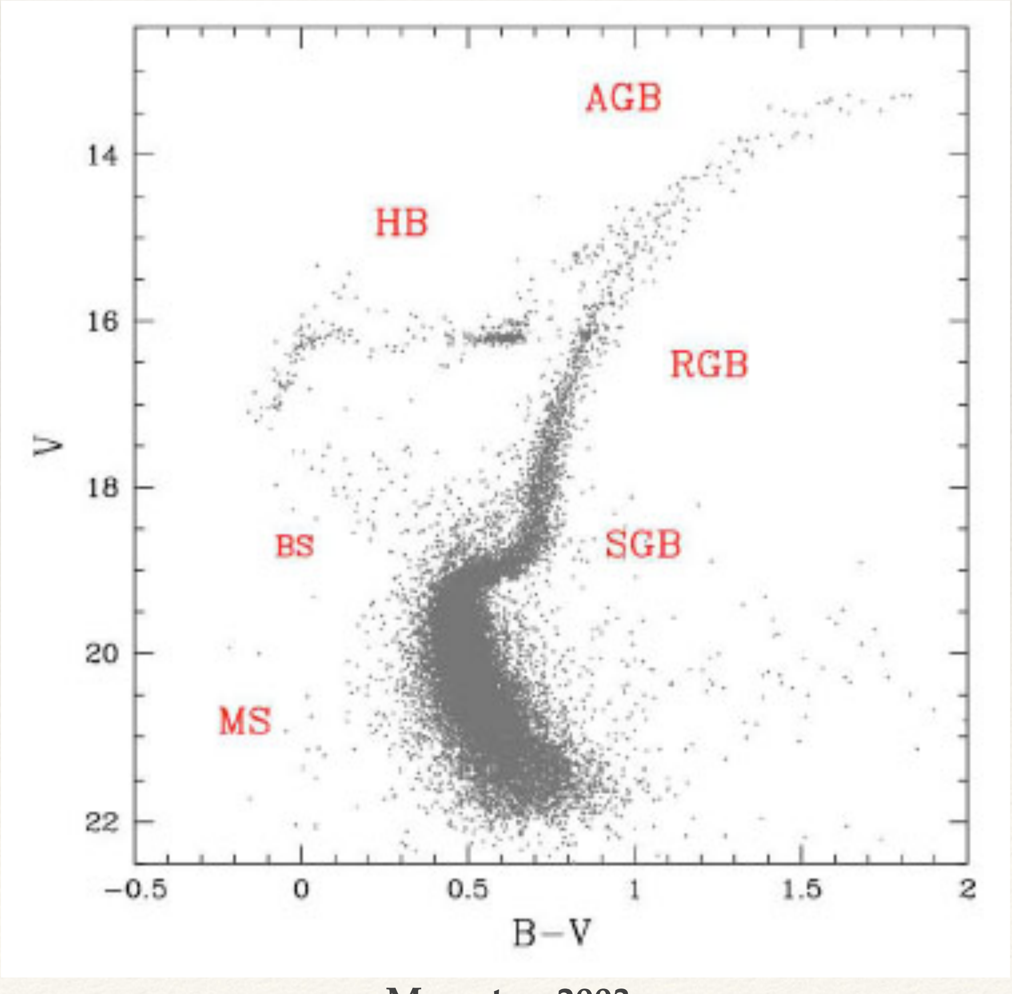
Maraston 2003

Stars and Stellar Popula

- **Asymptotic Giant Branch (AGB)**
  - Nuclear burning occurs in two shells – thermally unstable – leading to **thermal pulses**.
  - A strong stellar wind due to high radiation pressure in the envelope (and thermal pulses)
  - Metallicity effects:
    - Solar metallicity — AGB close to the RGB
    - Metal-poor — AGB and RGB well separated



Credit: Richard Pogge

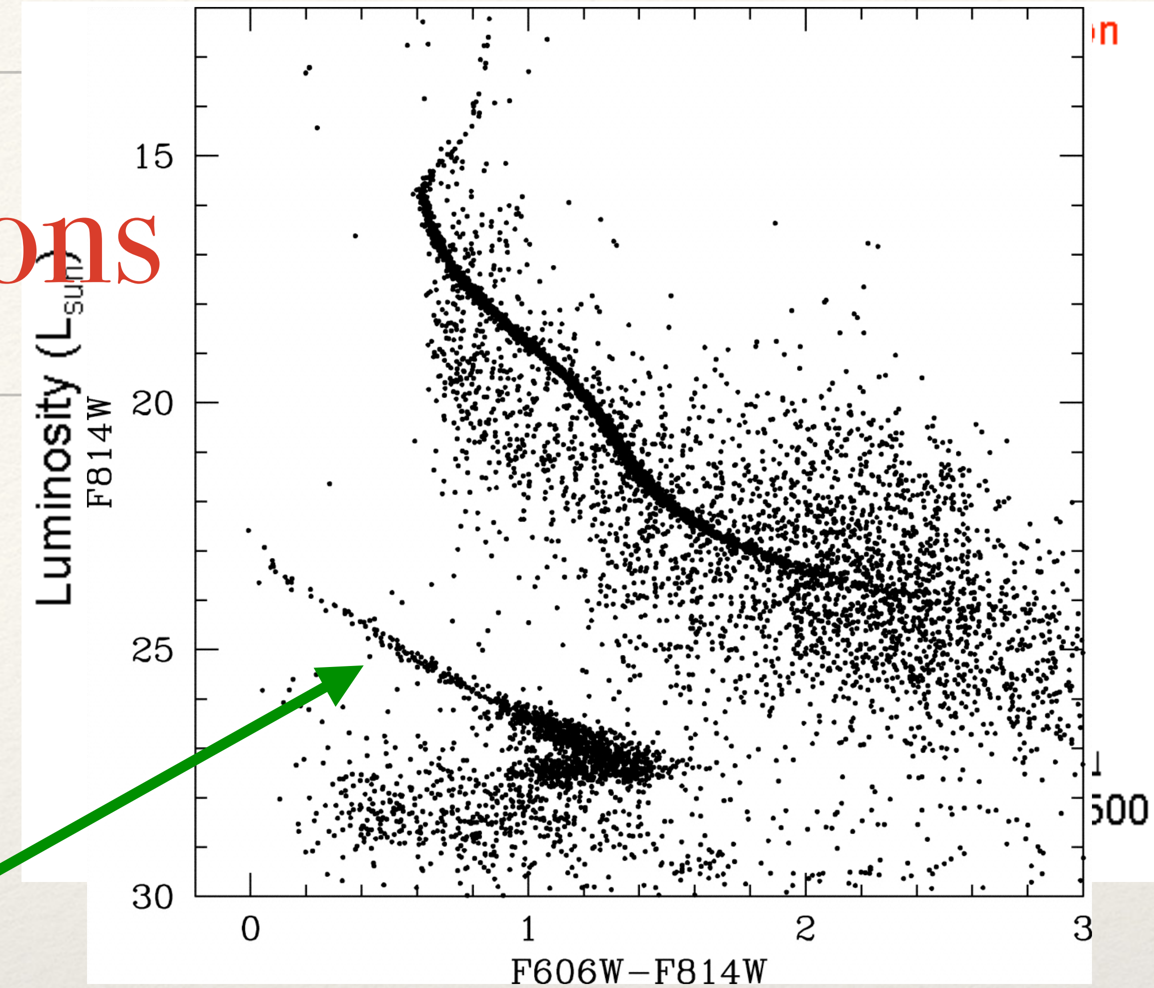


Maraston 2003

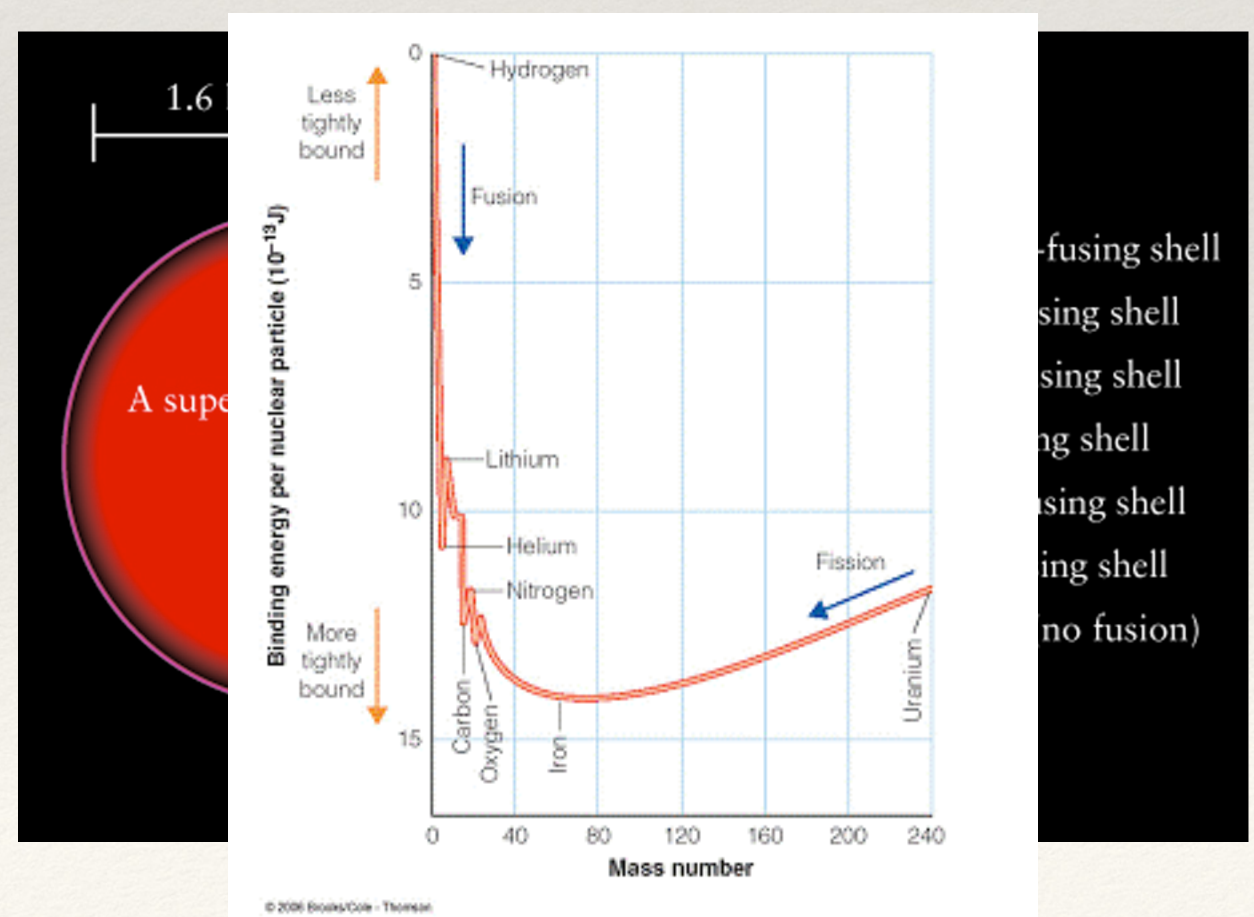
https://iopscience.iop.org/article/10.1086/522567

Stars and Stellar Populations

- **End stages of stellar evolution:**
  - Lower mass stars (< 8 M_{o}):
    - **Planetary nebula** — expelled mass lit up briefly
    - **White dwarf** — leftover hot core of star, lands on cooling sequence
  - Higher mass stars (>8 M_{o}):
    - Continue fusing up to Iron, looping back and forth across the HR diagram
    - **Supernovae** — generate significant fraction of heavy elements and input thermal and mechanical energy
    - **Neutron star** — mergers generate additional heavy elements

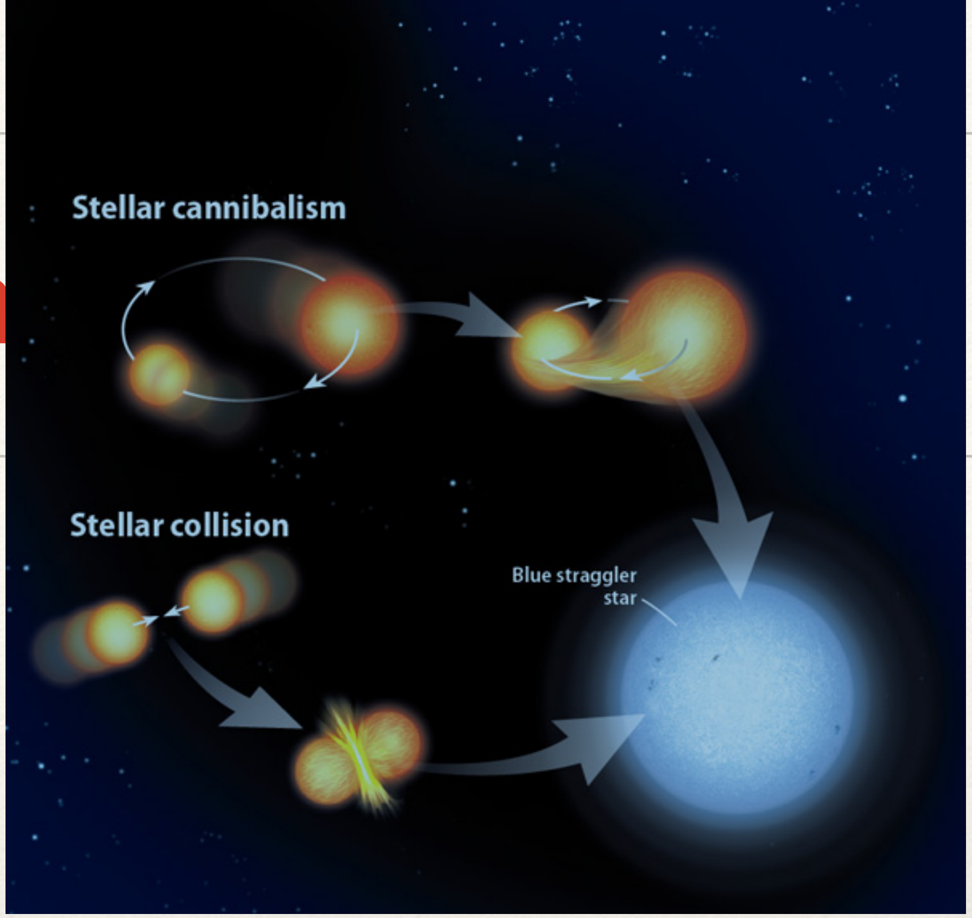


NGC 6397, nearby globular cluster (Hansen et al. 2007)

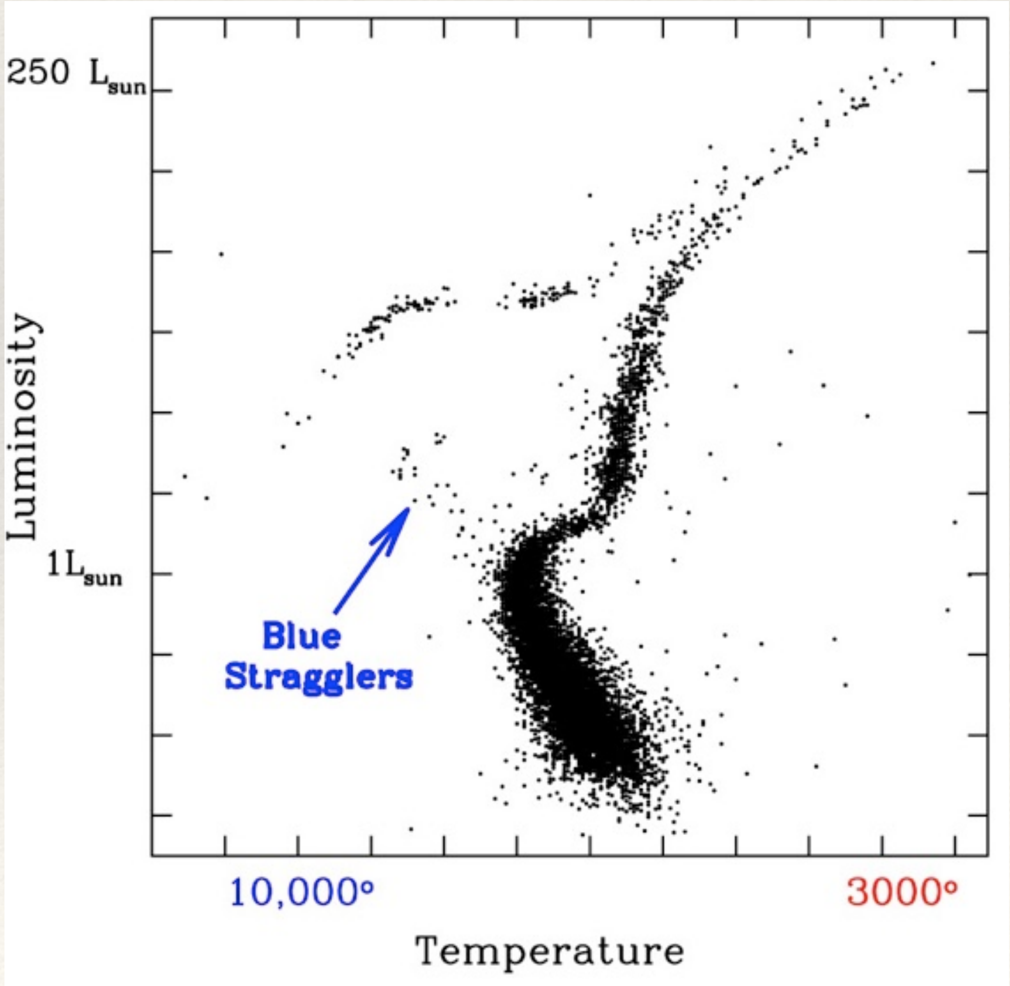


Stars and Stellar Populations

- **Potential importance of binaries:**
  - Unresolved (non-interacting) binaries — broaden sequences in CMD
  - Interacting binary stars:
    - **Blue Stragglers**: possible stellar merger/interaction products (e.g., M3, Sandage 1953)
    - **Supernova Type SNIa**: arise from binaries with a white dwarf, produce different heavy element abundances than core collapse SN



Credit: Astronomy Magazine



Cosmic-Lab Project