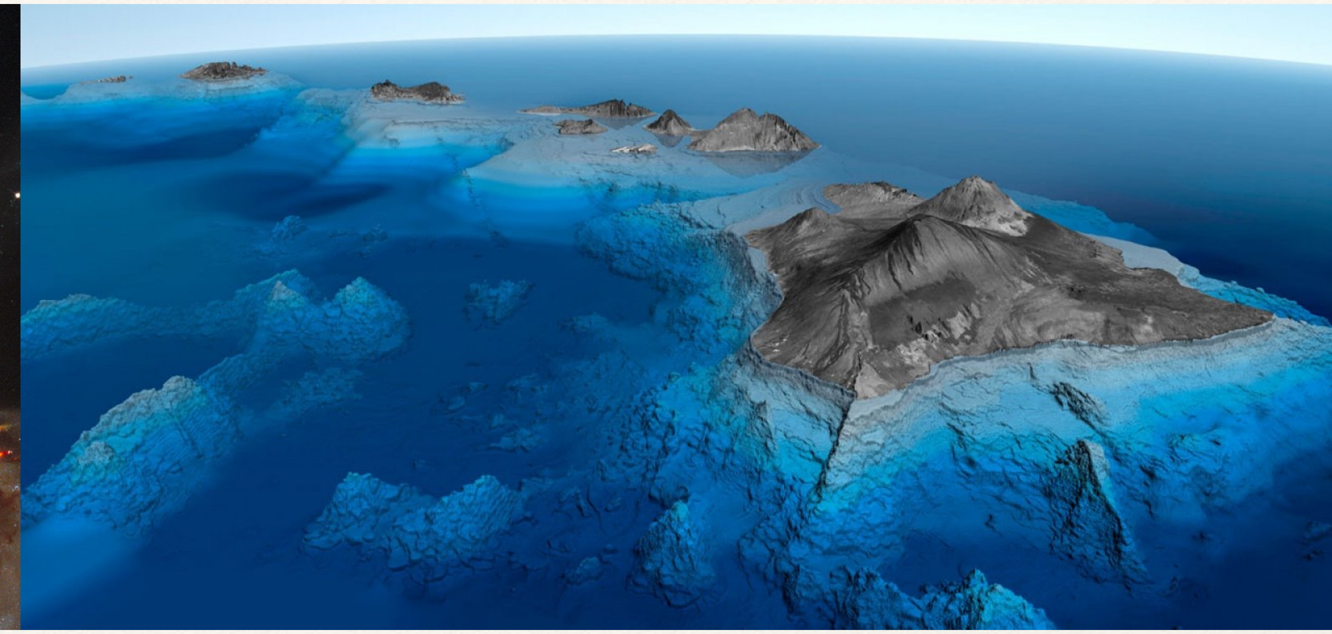
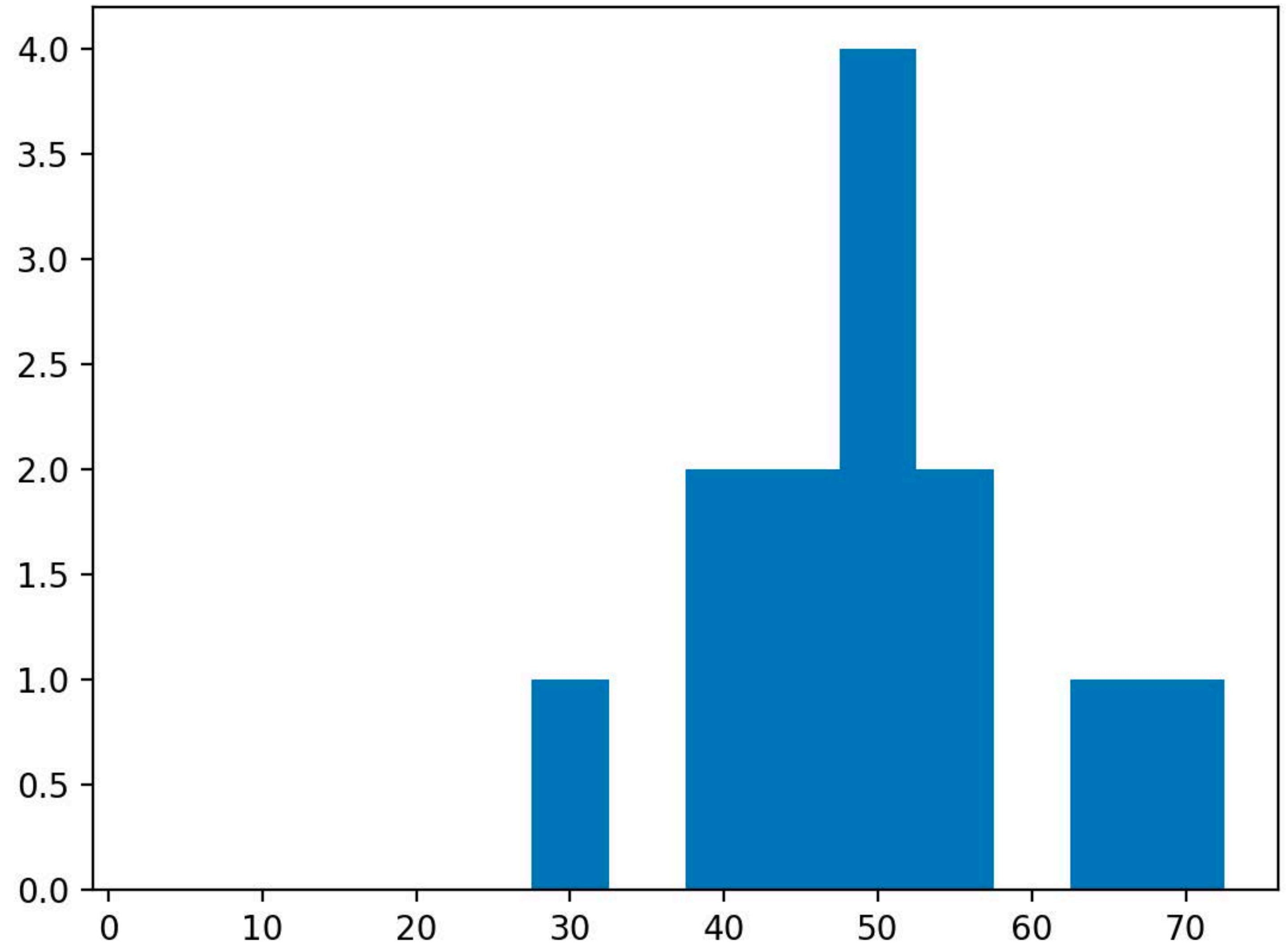


Getting to know the "island universes" out there.

Galaxies I

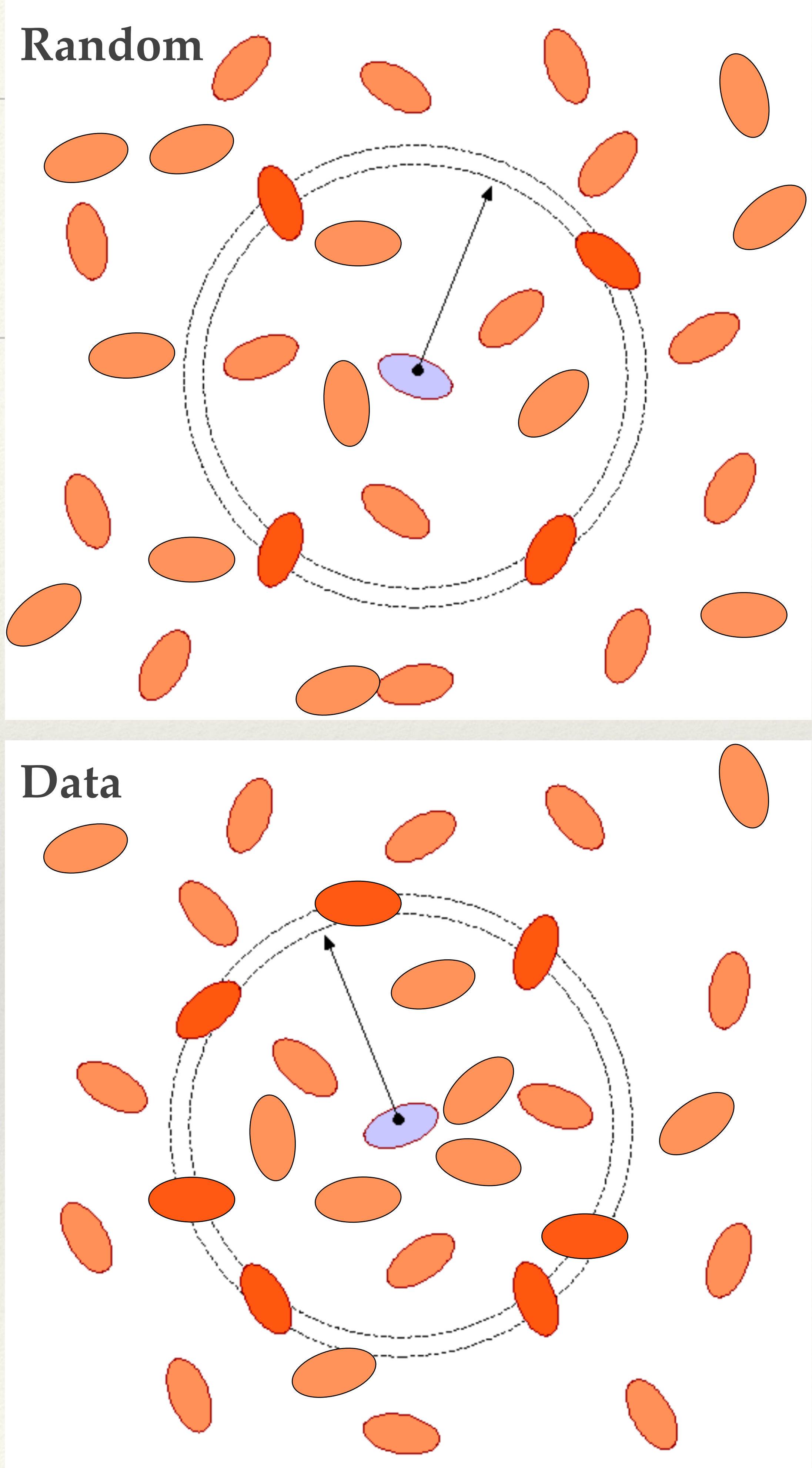
ASTR 555
Dr. on olt man

Midterm grade distibution (out of 70)



Warm-up

- How do these diagrams relate to measuring the clustering of galaxies?



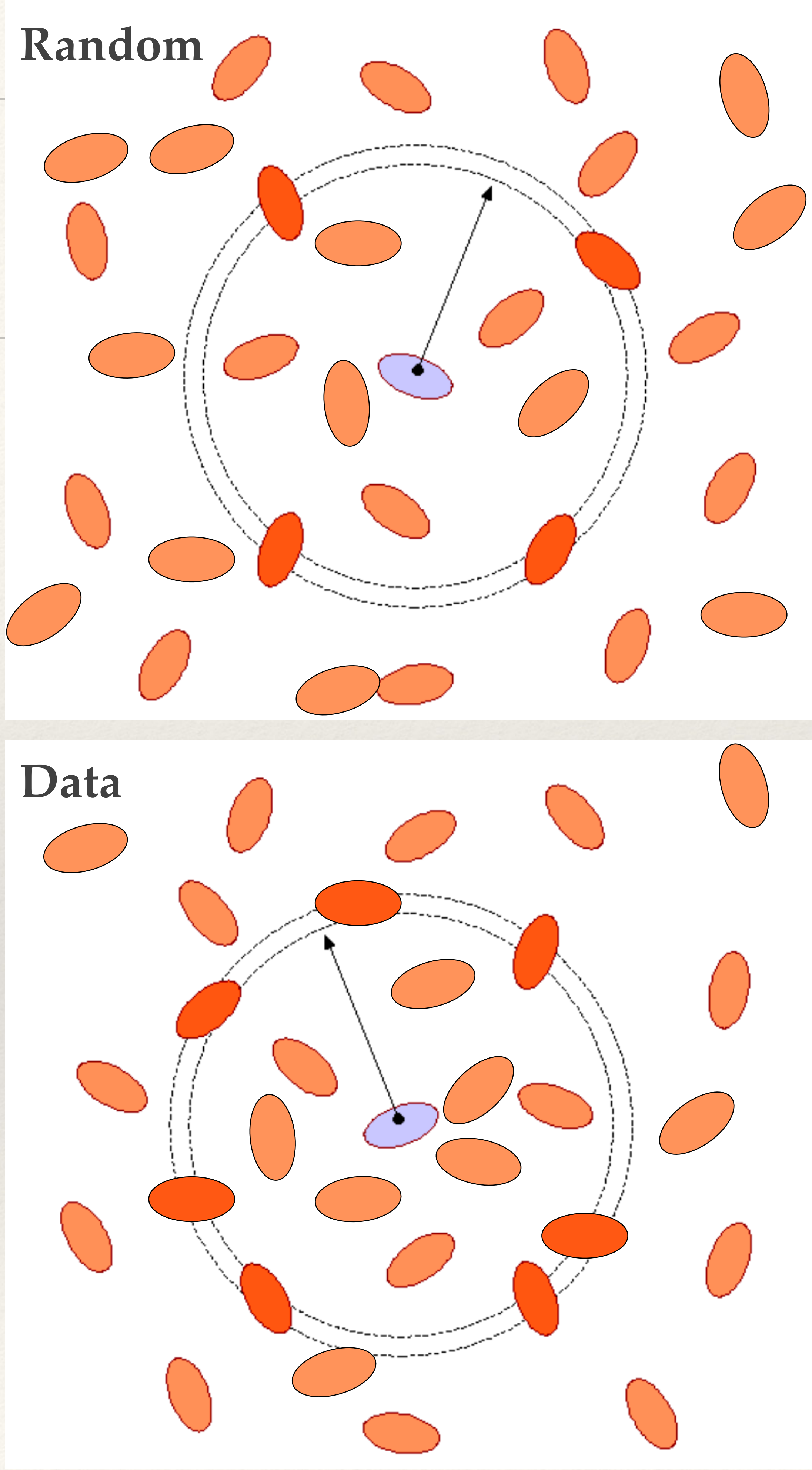
https://home.strw.leidenuniv.nl/~bouwens/galstrdyn/lecture10_2016.pdf

Warm-up

- How do these diagrams relate to measuring the clustering of galaxies?

- Measure spatial two point correlation function **ξ(r)** using estimators, e.g.,:

$$\xi_{LS}(\mathbf{r}) = \frac{DD(\mathbf{r}) - 2DR(\mathbf{r}) + RR(\mathbf{r})}{RR(\mathbf{r})}$$



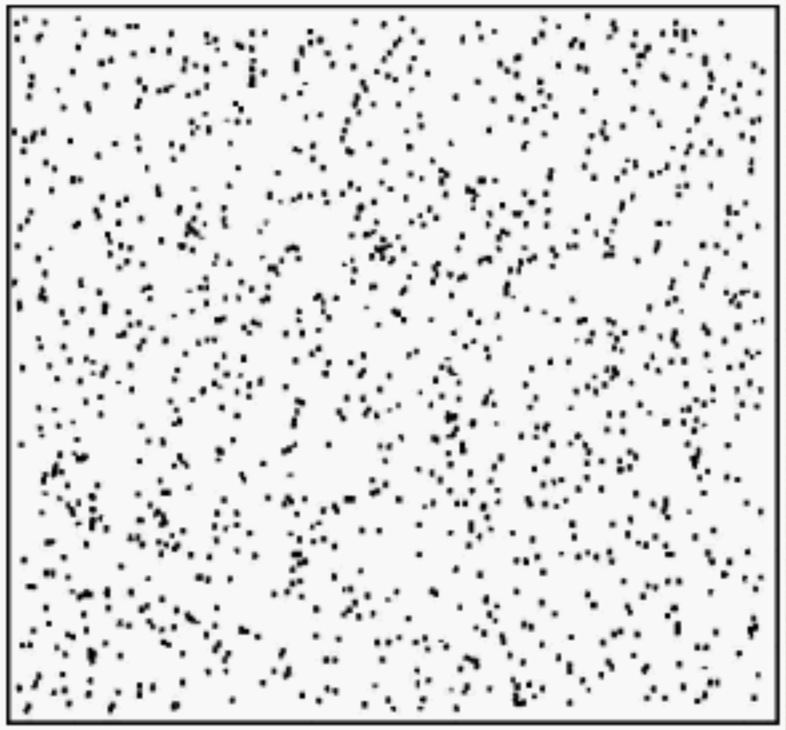
https://home.strw.leidenuniv.nl/~bouwens/galstrdyn/lecture10_2016.pdf

Warm-up

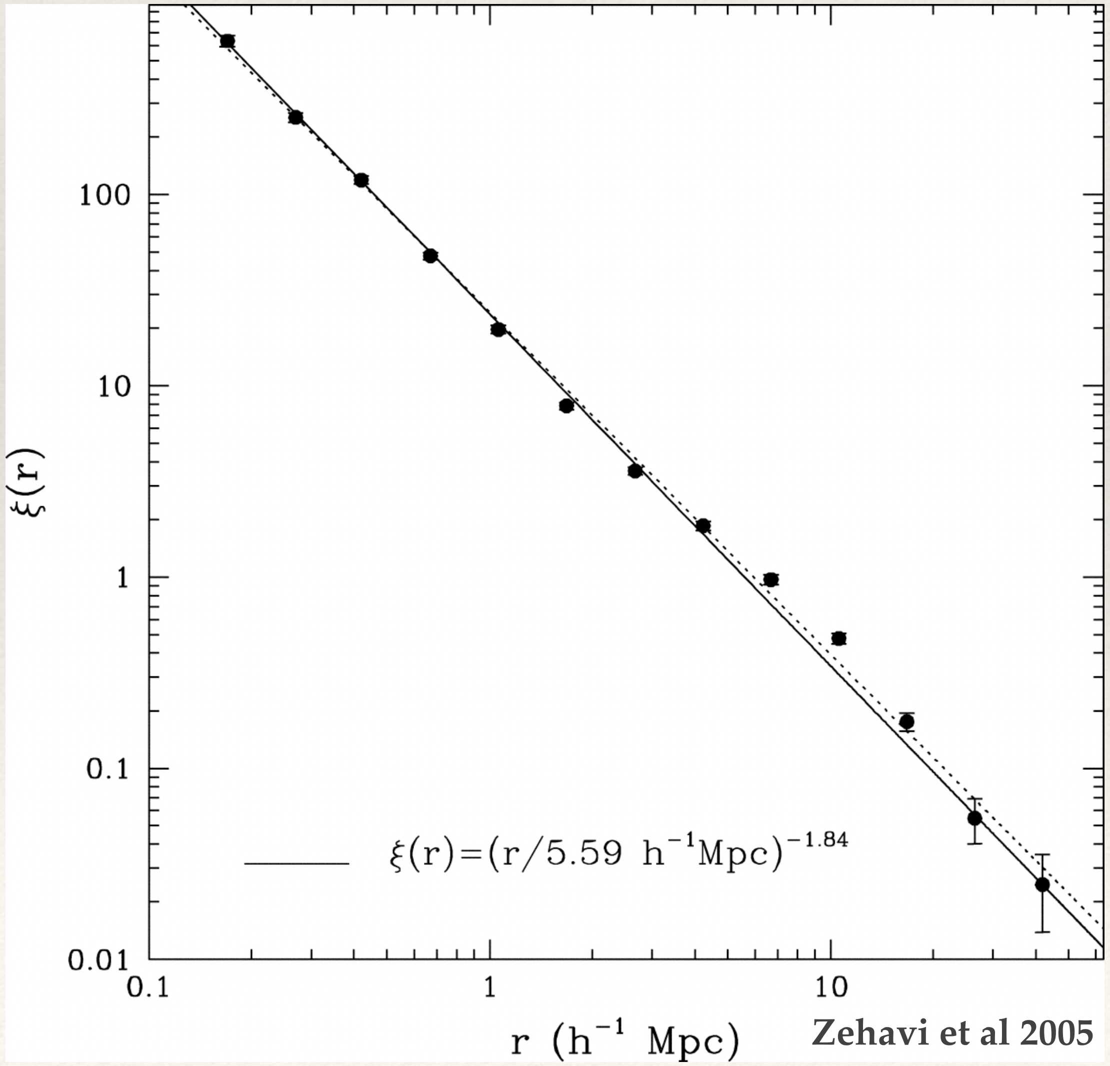
- How do these diagrams relate to measuring the clustering of galaxies?

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

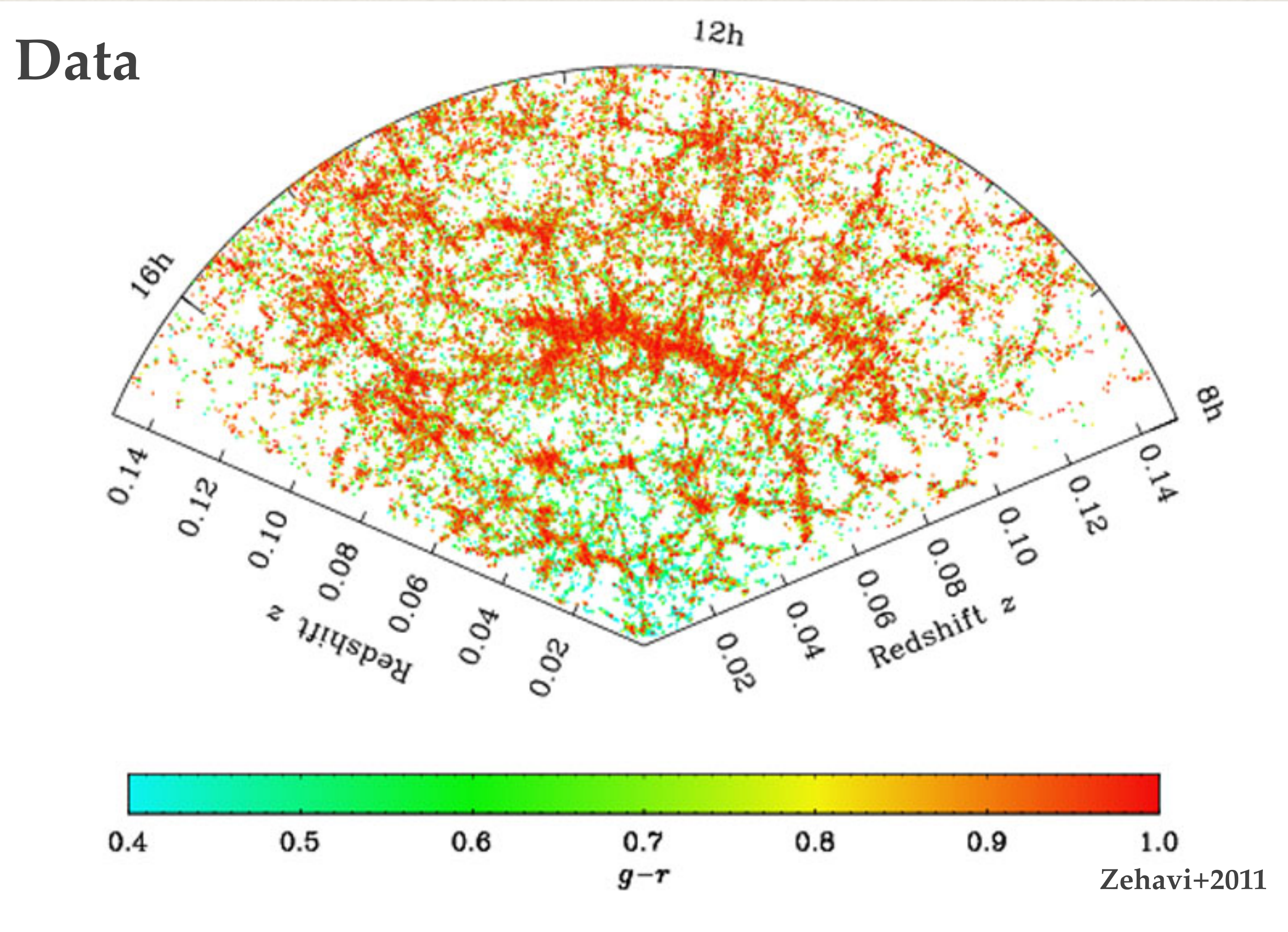
Random



https://telescoper.wordpress.com/2009/04/04/points-and-poisson-davril/



Zehavi et al 2005



Zehavi+2011

Course Overview

- Modules:
  - Observing Galaxies — the main techniques used for observing galaxies
  - Galaxy Population — the observed properties of galaxies
  - **Building Blocks — the basic building blocks that make up individual galaxies: stars, gas, black holes, dark matter**
  - Milky Way — our own Galaxy

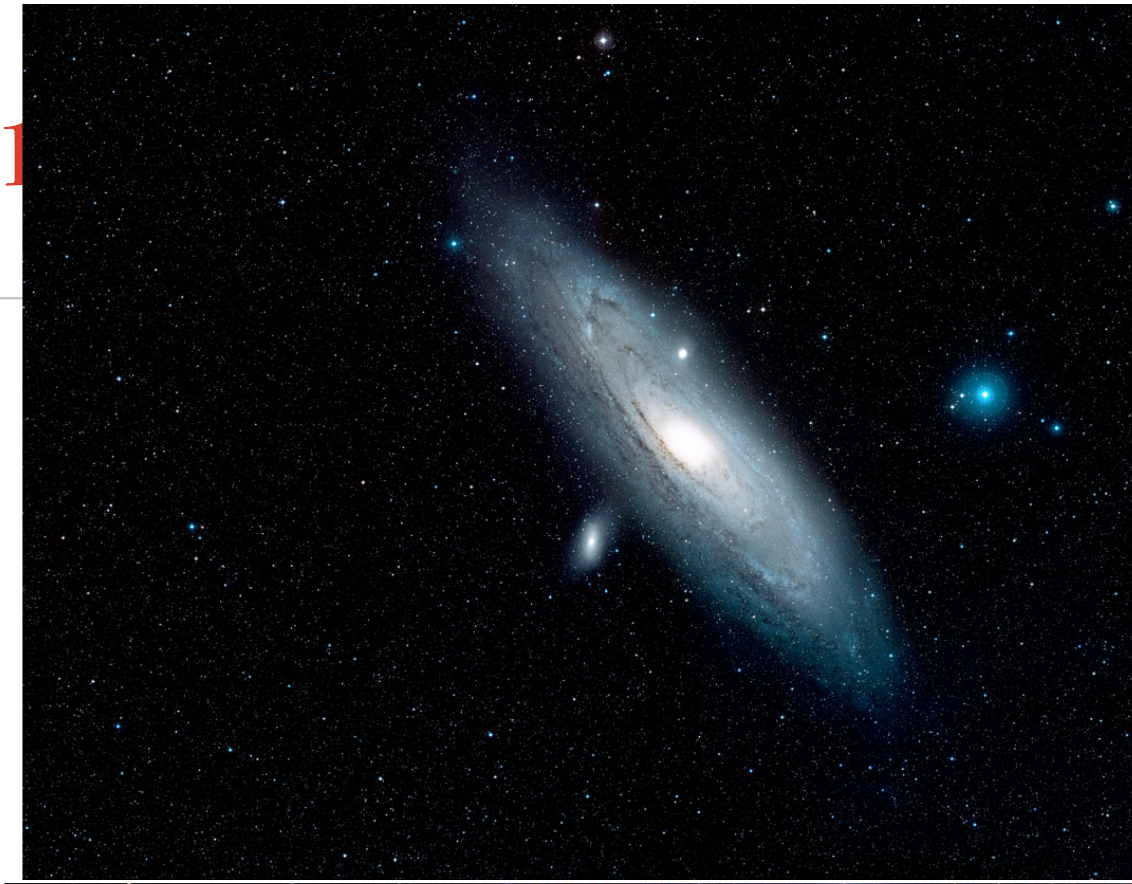
Outline for Today

- Building Blocks - Stars and Stellar Populations:
    - Overview / Review of Stellar Evolution and the HR Diagram

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

M31 (NASA, ESA, DSS2, Davide De Martin)

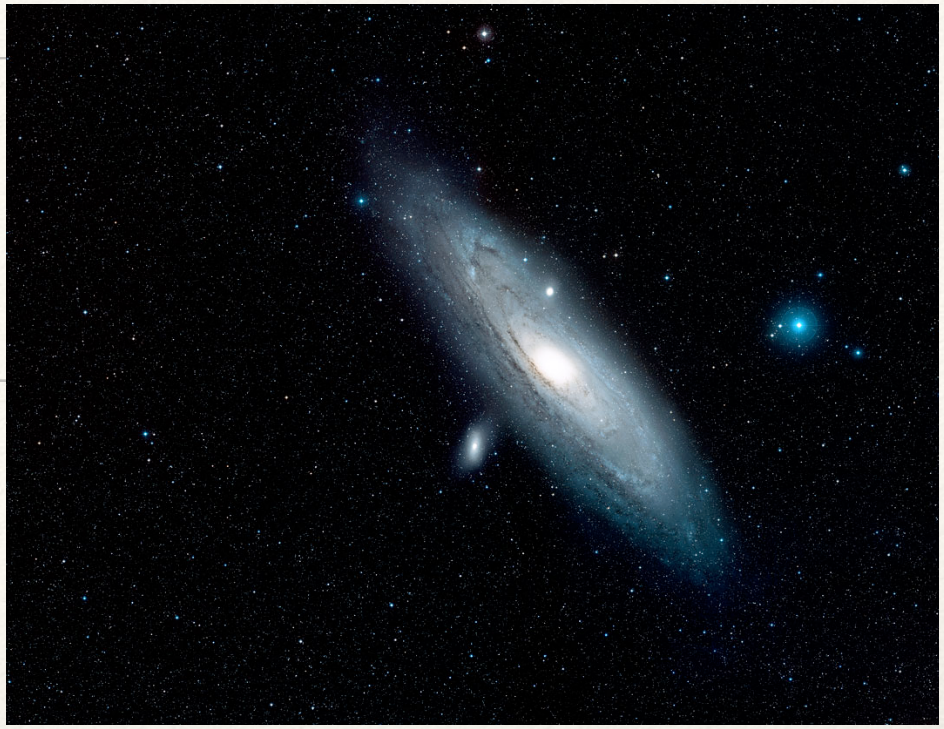
Stars and Stellar Populatio



- One component of galaxies are stars
- **Observable**:
  - spectral energy distributions (or colors) of stellar component
  - for most galaxies, as unresolved light (can't separate out individual stars)
  - for nearby galaxies, can see individual stars, brighter stars are easier than fainter; also depends on spatial resolution (e.g., ground vs space)
- **Stellar population**:
  - a stellar population is a collection of stars
  - unresolved stellar population SED depends on relative numbers and types of stars

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

M31 (NASA, ESA, DSS2, Davide De Martin)



Stars and Stellar Populations

- How can we relate what we **observe** about a stellar population to the **intrinsic characteristics**?
- Stars exist with range of temperatures and luminosities
- **Underlying population characteristics:**
  - relative number of stars as a function of mass, composition, and age
  - generally referred to as the star formation history
    - sometimes that is used to describe distribution of ages only
  - need to understand how these population characteristics translate to observables

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

--> Stellar structure & evolution!

Stars and Stellar Populations: Stellar Evolution

- Stars o not e ist with arbitrary combinations of temperature an luminosity

Russell-Vogt Theorem:

The mass and chemical composition of a star uniquely determine its radius, luminosity, internal structure, and subsequent evolution.

- bservable properties of stars epen almost only on their mass age an chemical composition

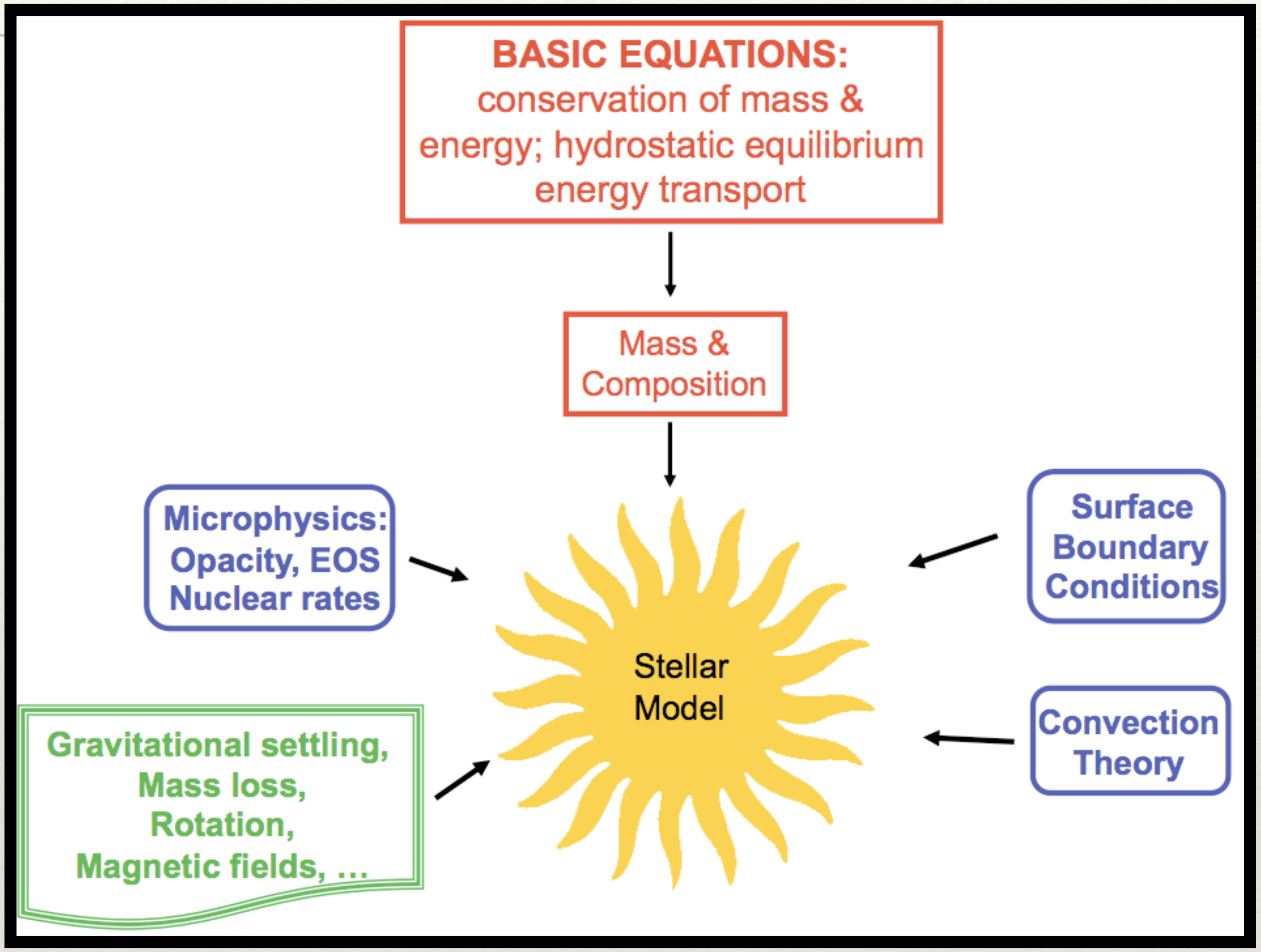
Stars and Stellar Populations: Stellar Evolution

- Overview/Review of Stellar Evolution
  - Assume spherical symmetry and that the star is quasi-stable
- Physical parameters of star (luminosity, radius, temperature) connected by a set of differential equations

What are the equations that govern stellar structure and evolution?

Building Blocks - Stars and Stellar Populations: Stellar Evolution

- Overview/Review of Stellar Evolution
  - Assume spherical symmetry and that the star is stable (at least for a time)
  - Physical parameters of star (luminosity, radius, temperature) connected by a set of differential equations



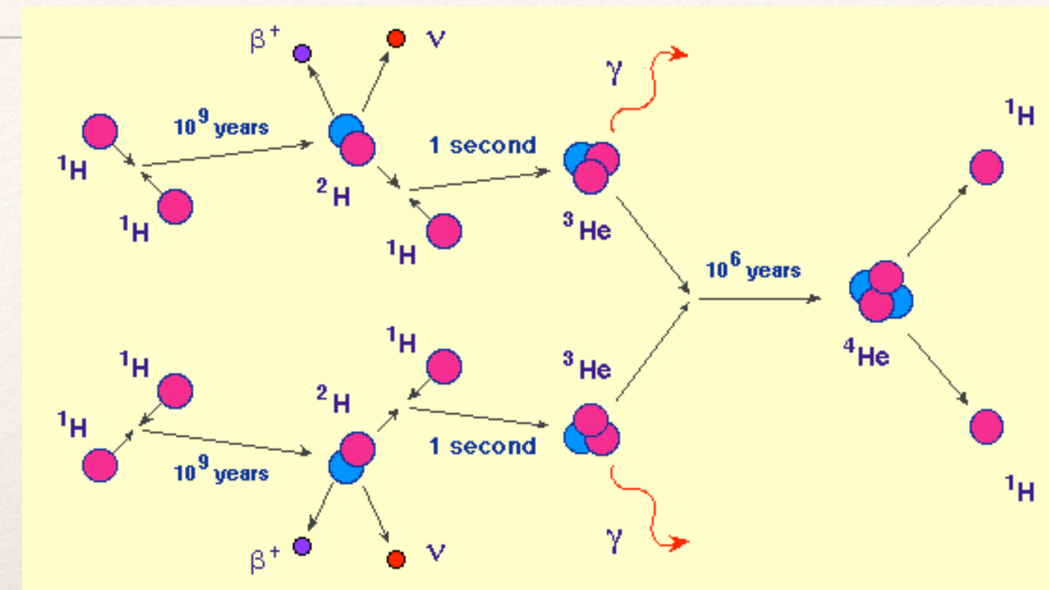
Hydrostatic equilibrium (dP/dr)
Mass conservation (dM/dr)
Energy generation (dL/dr)
Energy transport (dT'dr)

Building Blocks - Stars and Stellar Populations: Stellar Evolution

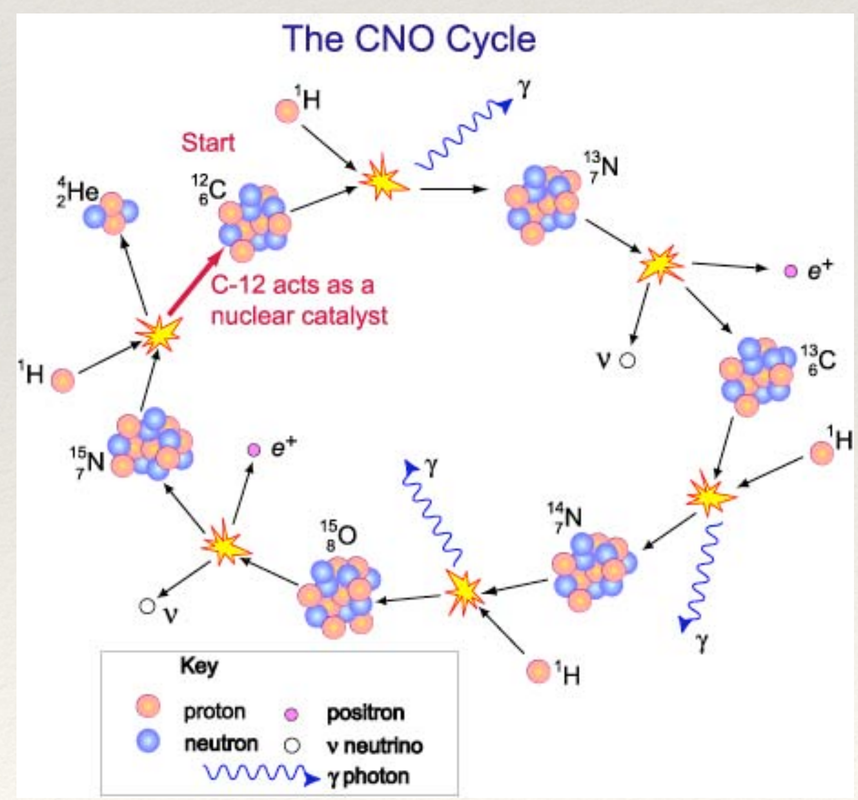
- Additional ingredients:
  - **Equation of state**: P = P($\boldsymbol{\rho}$, T, X),

    where X = chemical composition
  - **Opacity**: κ = κ($\boldsymbol{\rho}$, T, X)
  - **Energy generation rate**: ε = ε($\boldsymbol{\rho}$, T, X)
    - e p-p chain — dominant in lower mass, cooler stars like the Sun
    - e CNO cycle — dominant in higher mass, hotter stars
    - e triple alpha process

Solve for the evolution of a star over time



http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html



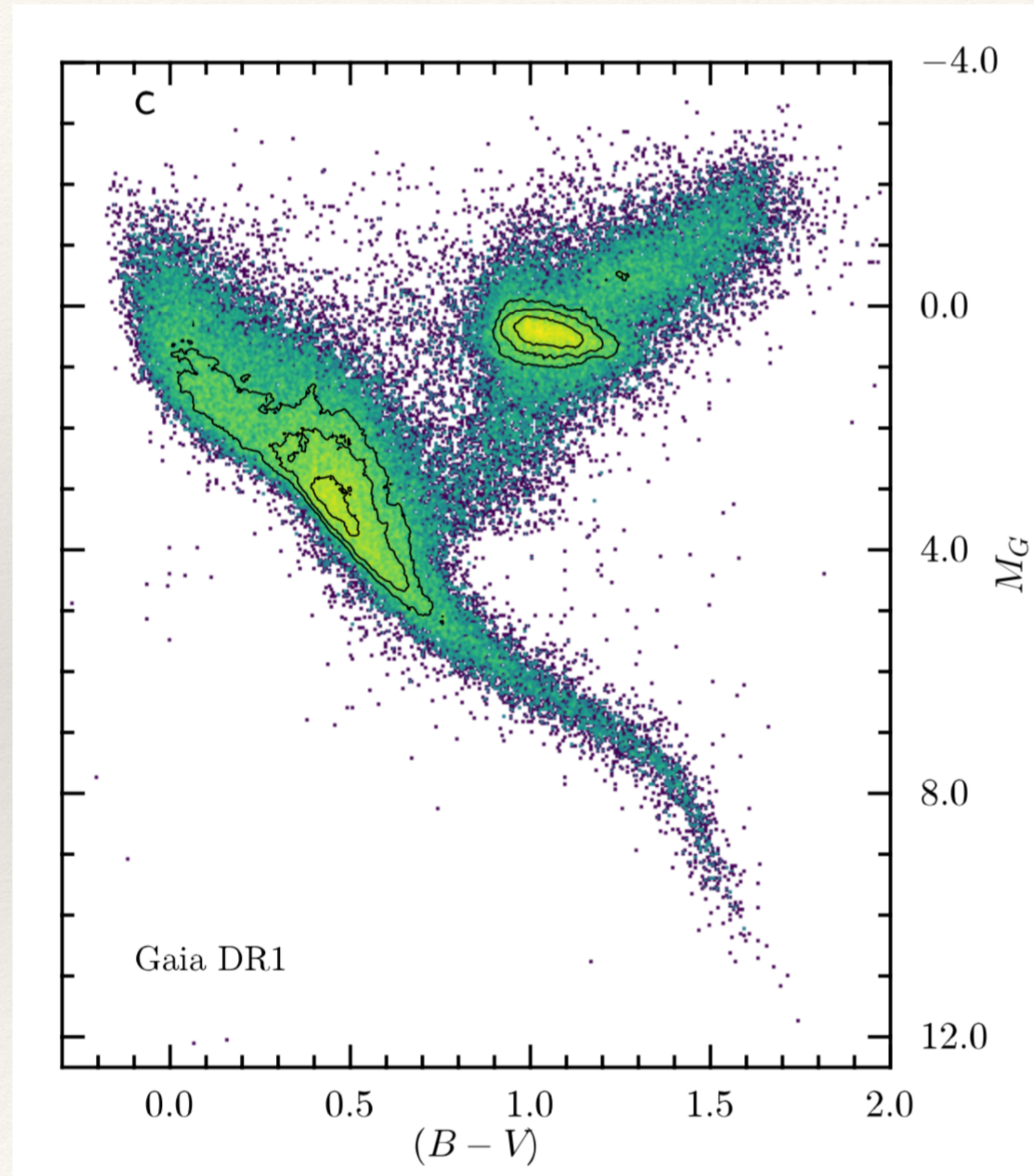
http://outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_mainsequence.html#mscno

Stars and Stellar Populations: Stellar Evolution

- Key tool of stellar evolution: Hertzsprung-Russell (HR) Diagram
- Color vs. absolute magnitude
- underlying properties: temperature vs. luminosity
- main sequence = mass sequence
  -

H

R



Brown et al. 2016

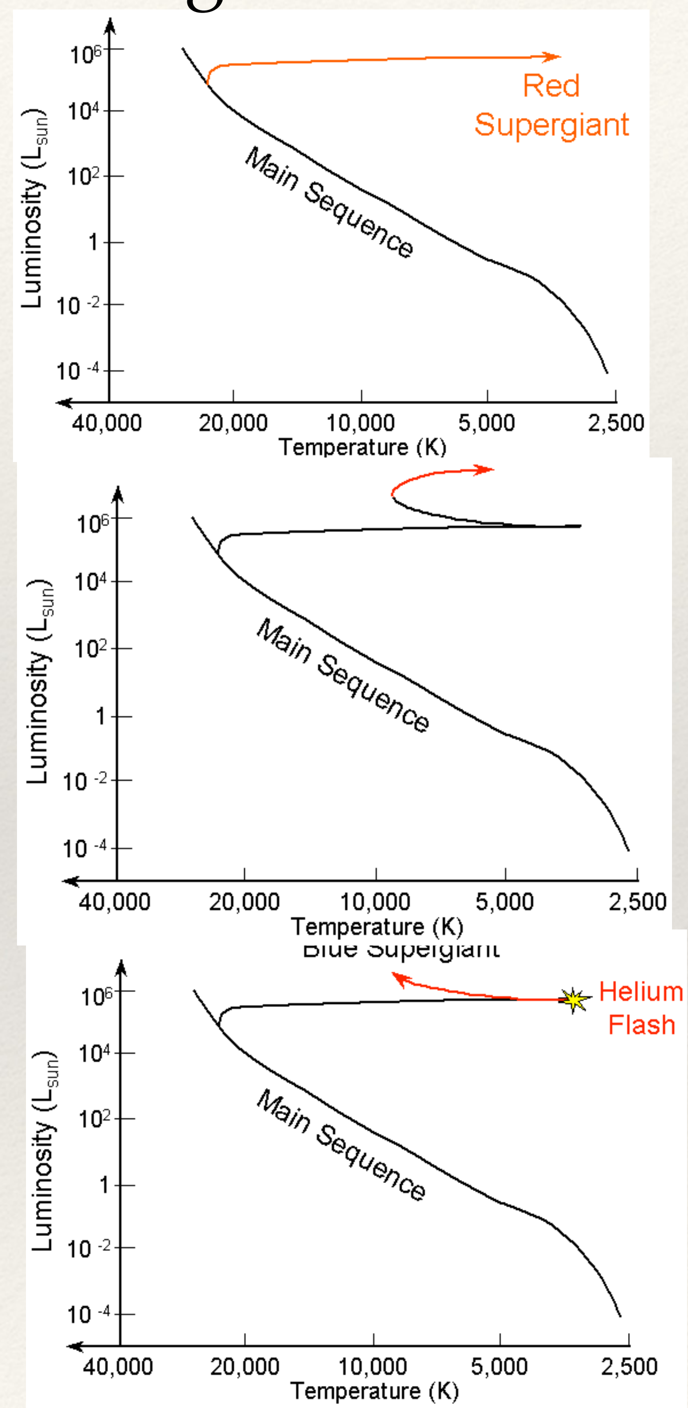
Thought Question

- Consider the main stages of stellar evolution for a single low mass star:
  - Sketch where the star is on the HR diagram in each stage
  - What is going on inside the star at each stage?

Stars and Stellar Populations: Stellar Evolution

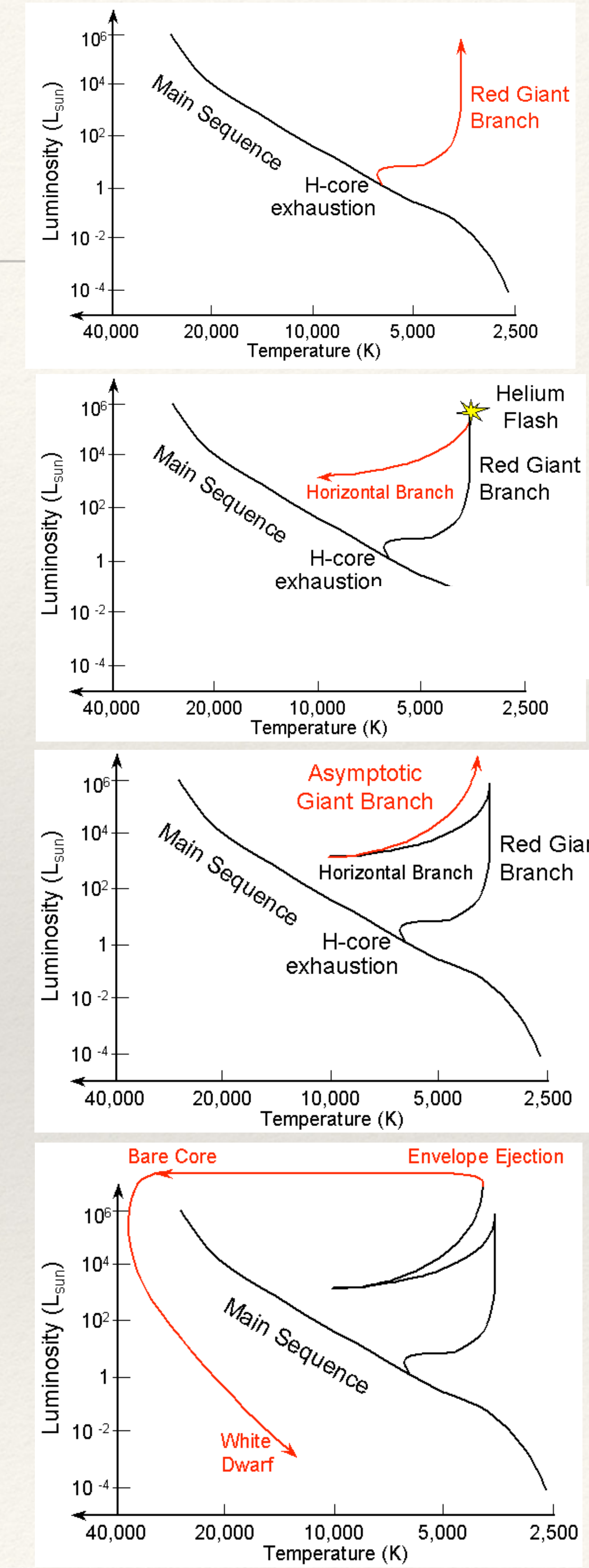
- Main Stages of Stellar Evolution:
  - Hydrogen core burning: **Main Sequence**
  - Hydrogen shell burning: **Giant Branch** (for lower mass stars)
  - Helium core burning: **Horizontal Branch**
  - Helium shell burning: **Asymptotic Giant Branch**
    - End stages (lower mass stars): **White Dwarf**
  - Other nuclear burning (for high mass stars)
    - End stages (higher mass stars): **Supernova**

higher mass



lots more, fast!

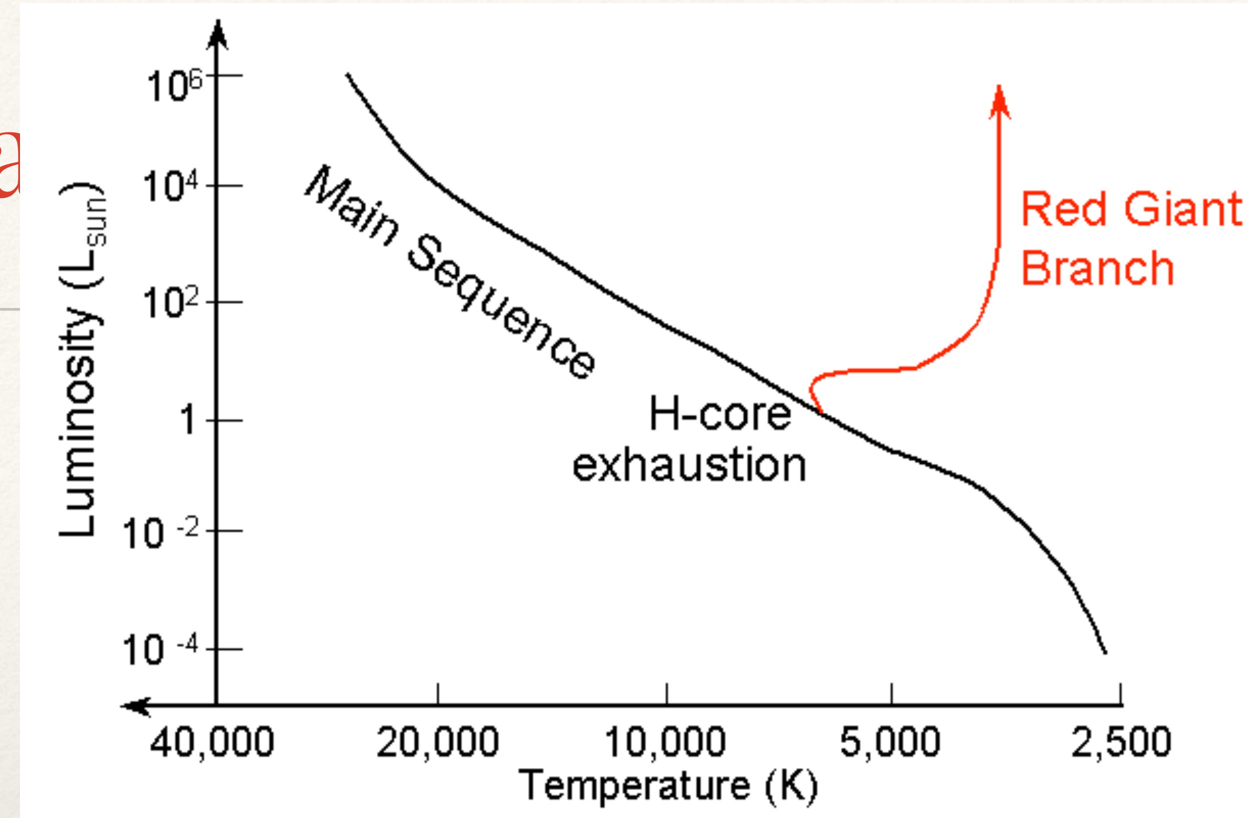
lower mass



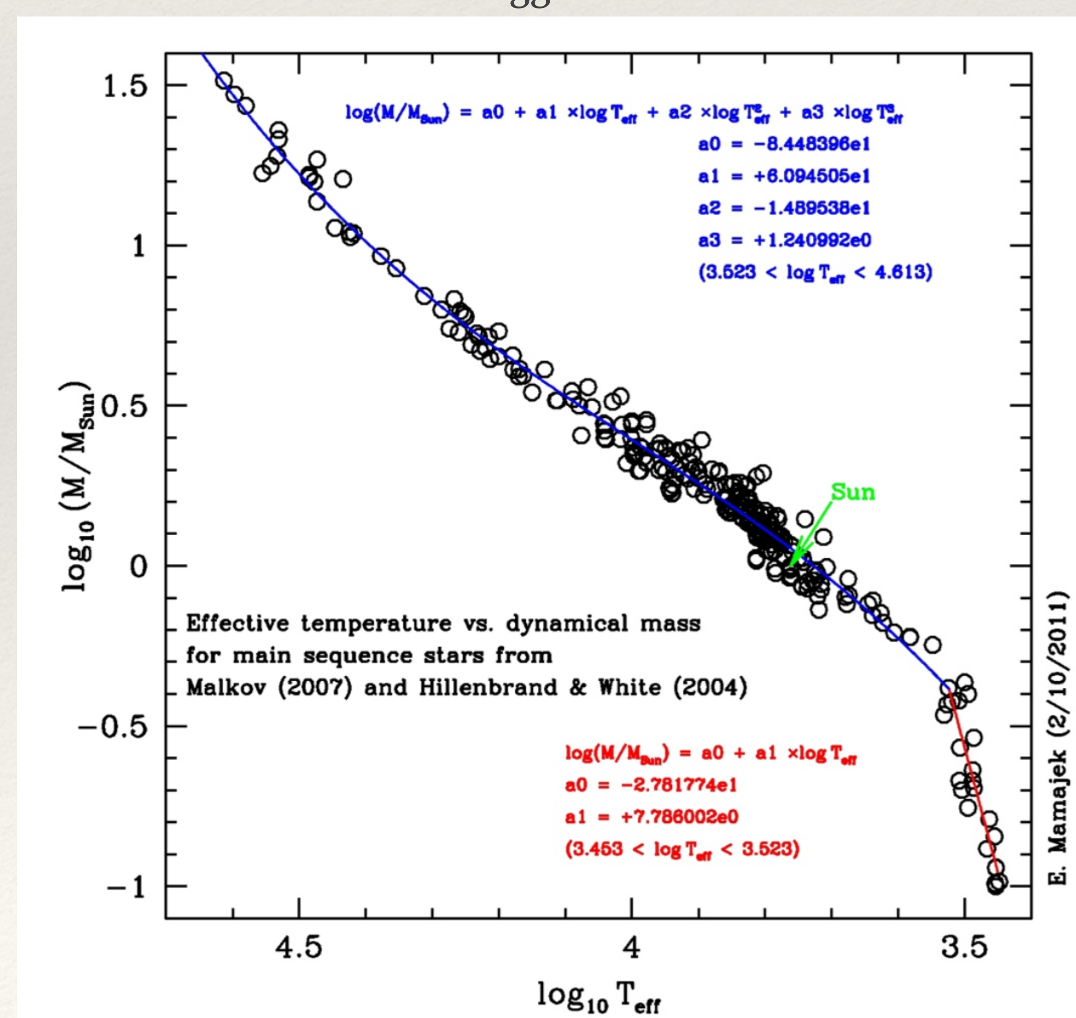
Credit: Richard Pogge

Stars and Stellar Popula

- **Main Sequence (MS)**
  - = Mass Sequence
  - find that, roughly, **L α M**$^{3.5}$
  - Given that more massive stars also have more raw material to process, what does this imply about the scaling of main sequence lifetime with mass of a star?

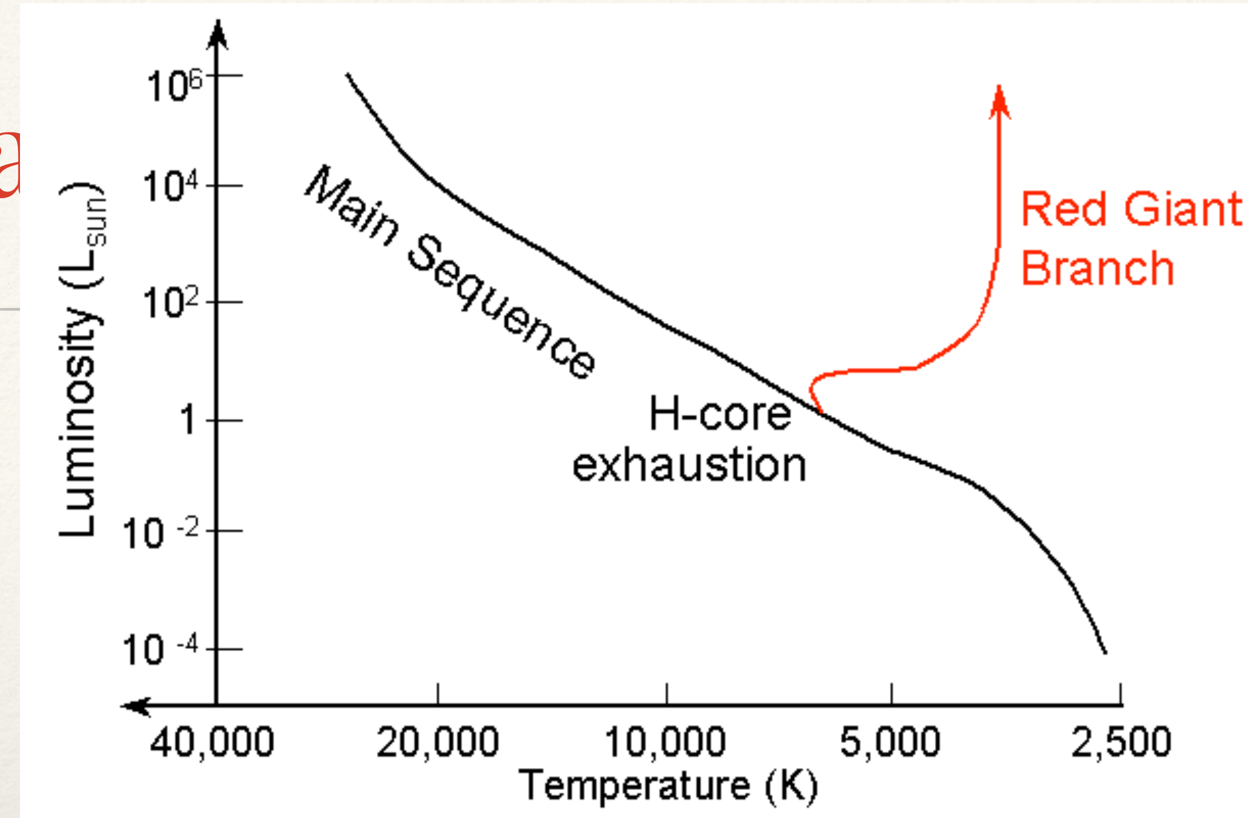


Credit: Richard Pogge



Stars and Stellar Popula

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



Credit: Richard Pogge

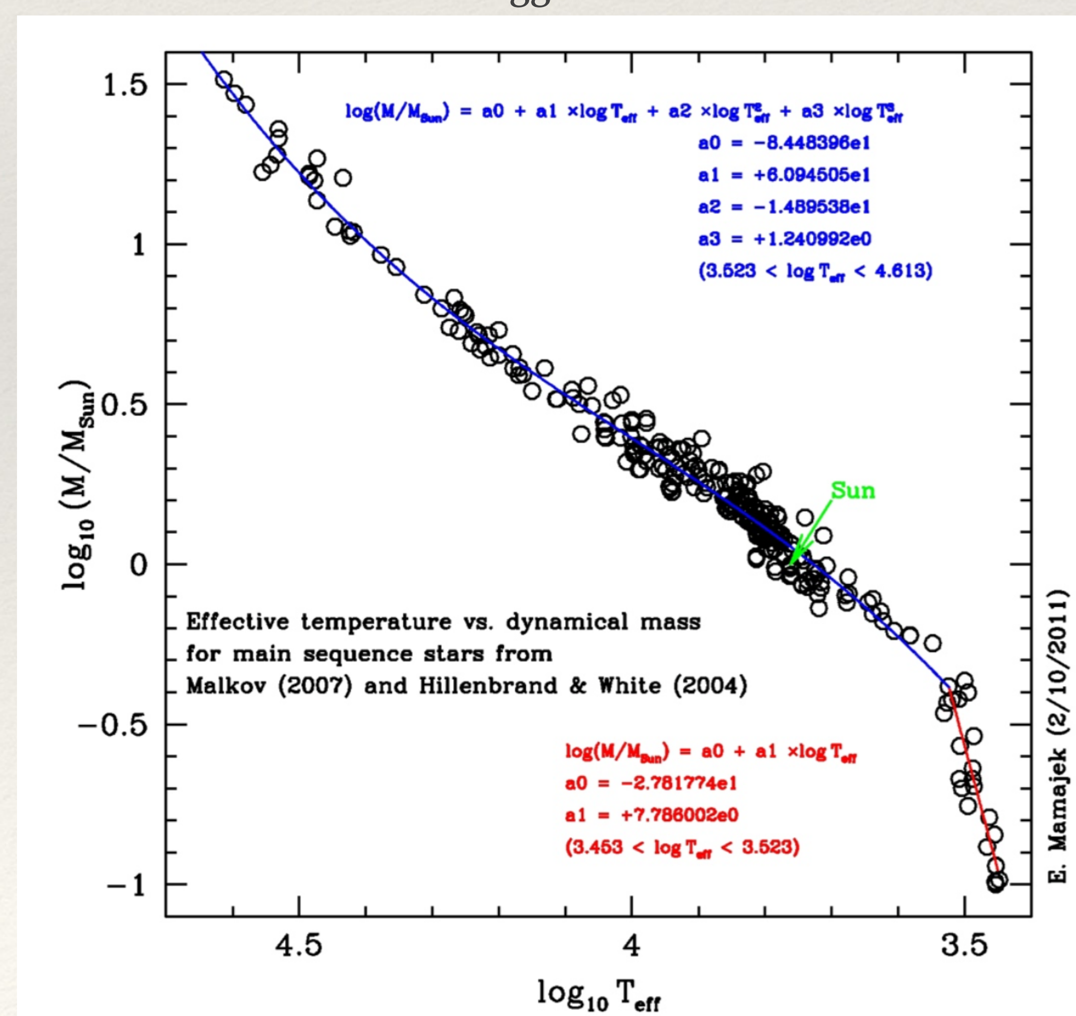


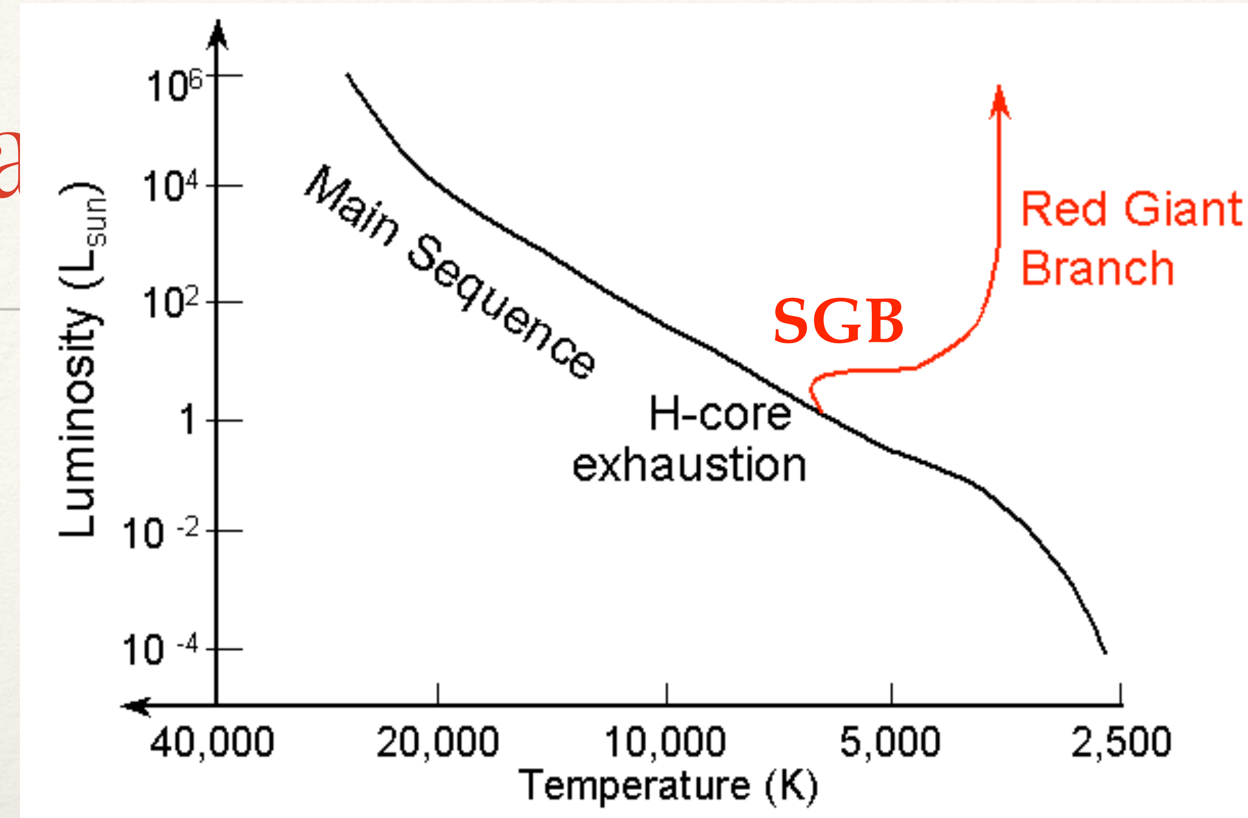
table 21-1 Approximate Main-Sequence Lifetimes

Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetim (10^6 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

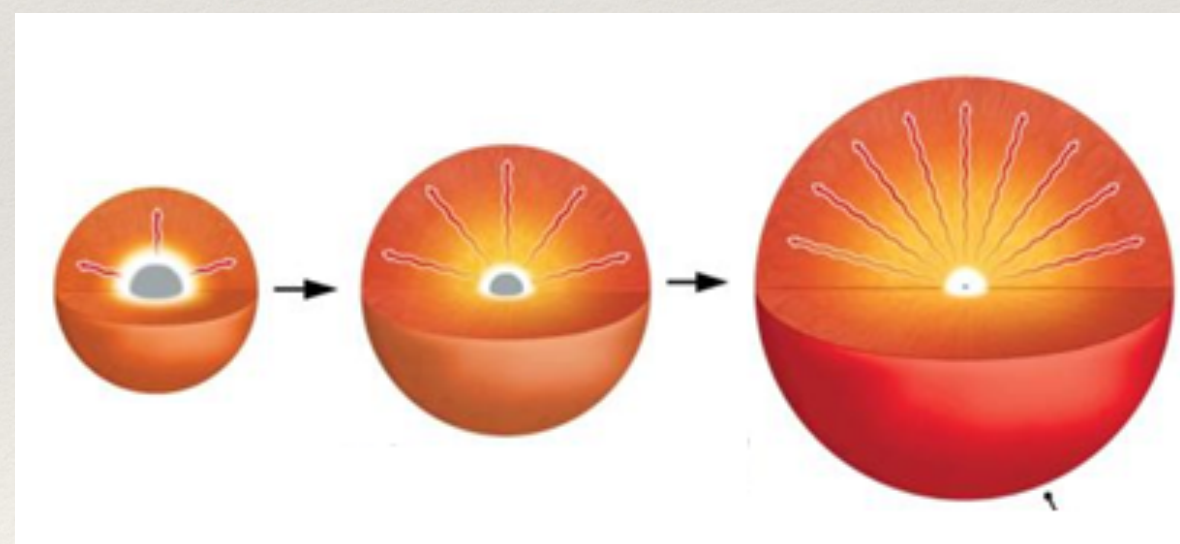
The main-sequence lifetimes were estimated using the relationship $t \propto 1/M^{2.5}$ (see Box 21-2).

Stars and Stellar Popula

- **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 — so e s all **mass loss** ossi le

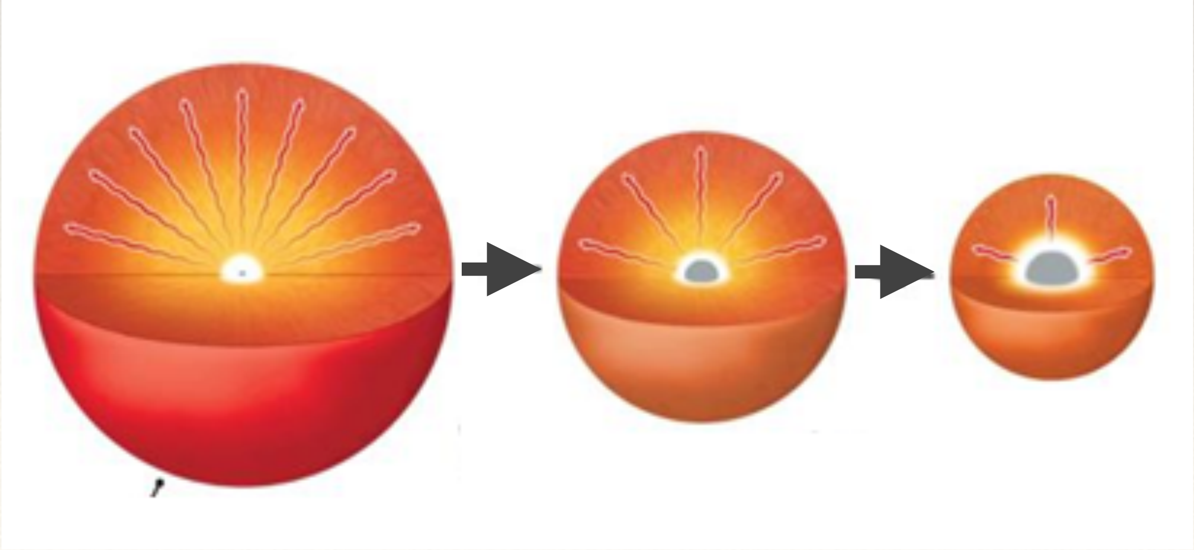


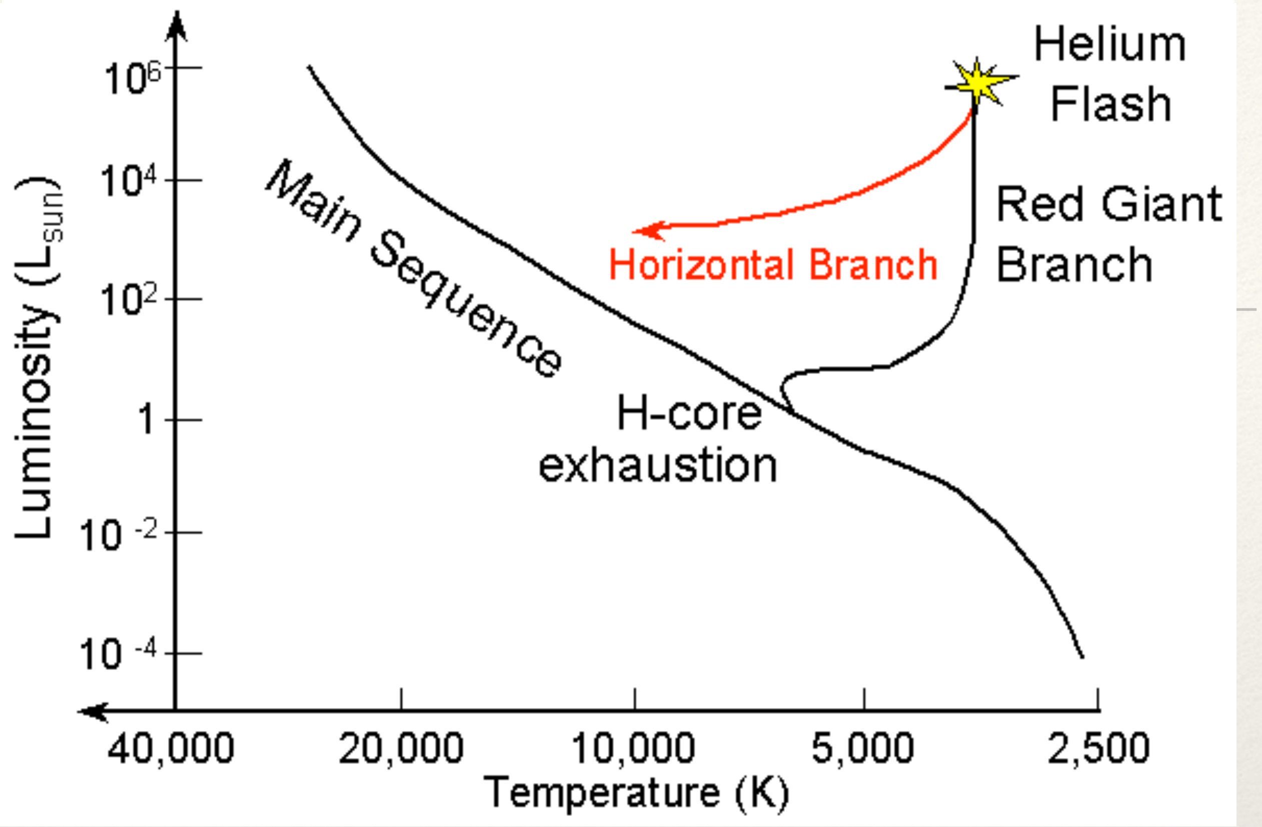
Credit: Richard Pogge



Stars and Stellar Popula

- **Core helium burning**
  - Core temperature reaches 100 million K — He fusion ignites
    - for lower mass stars, does this "instantaneously" in a "helium flash"
    - for higher mass stars (>2-3 solar masses, transition is more gradual
  - Star readjusts:
    - Core expands, decreasing shell output — lower L
    - Envelope shrinks — higher T



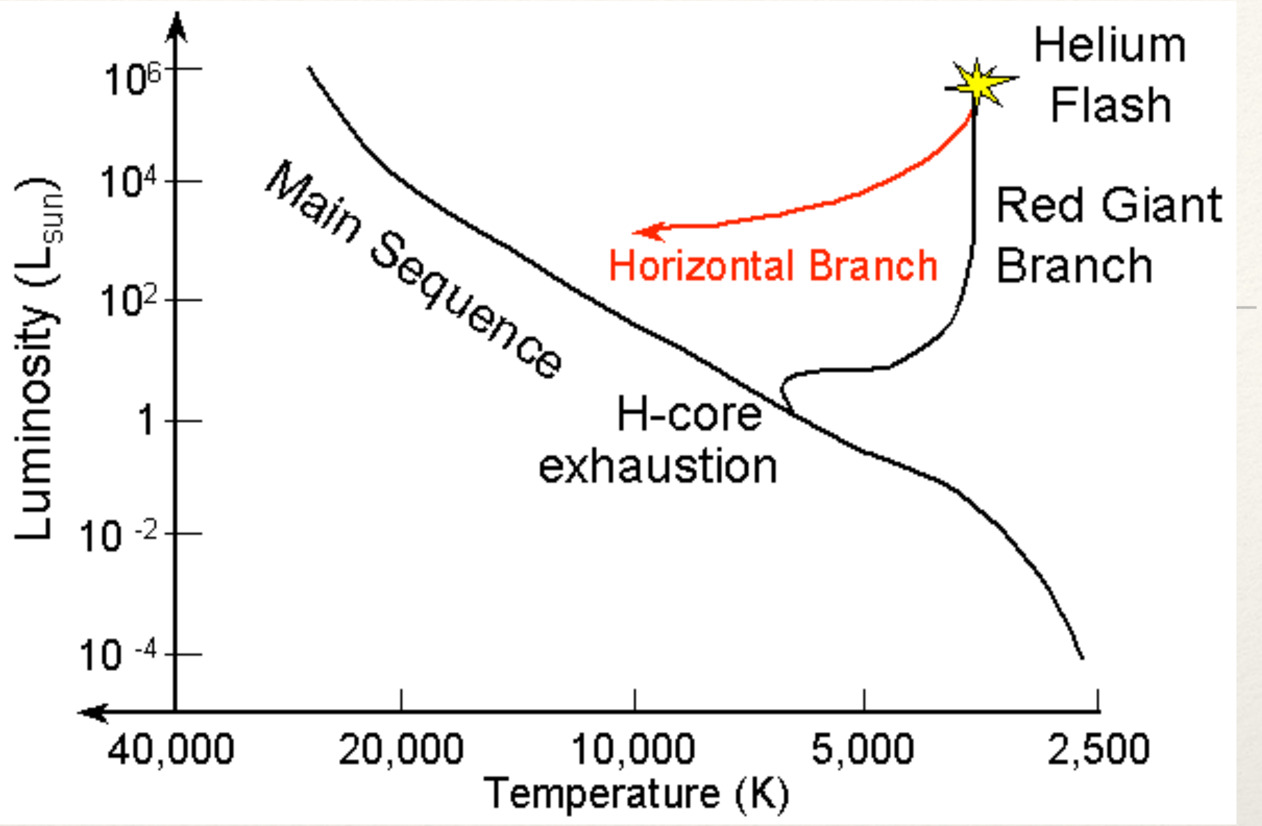


Credit: Richard Pogge

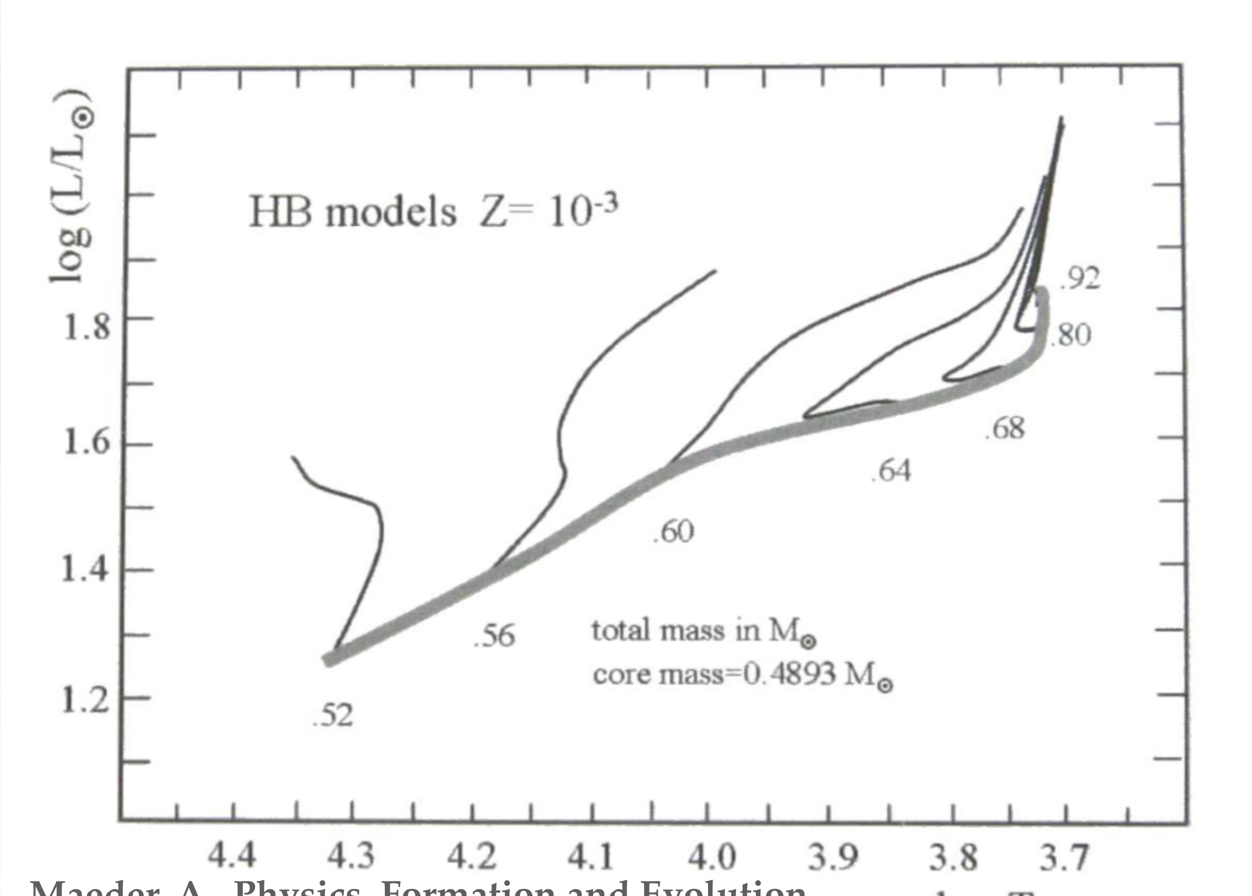
- Luminosity of He-fusing stars depends on core mass, which is similar for all lower-mass stars
- Gives rise to a **Horizontal Branch (HB) for low mass stars**

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 Populatic

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

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

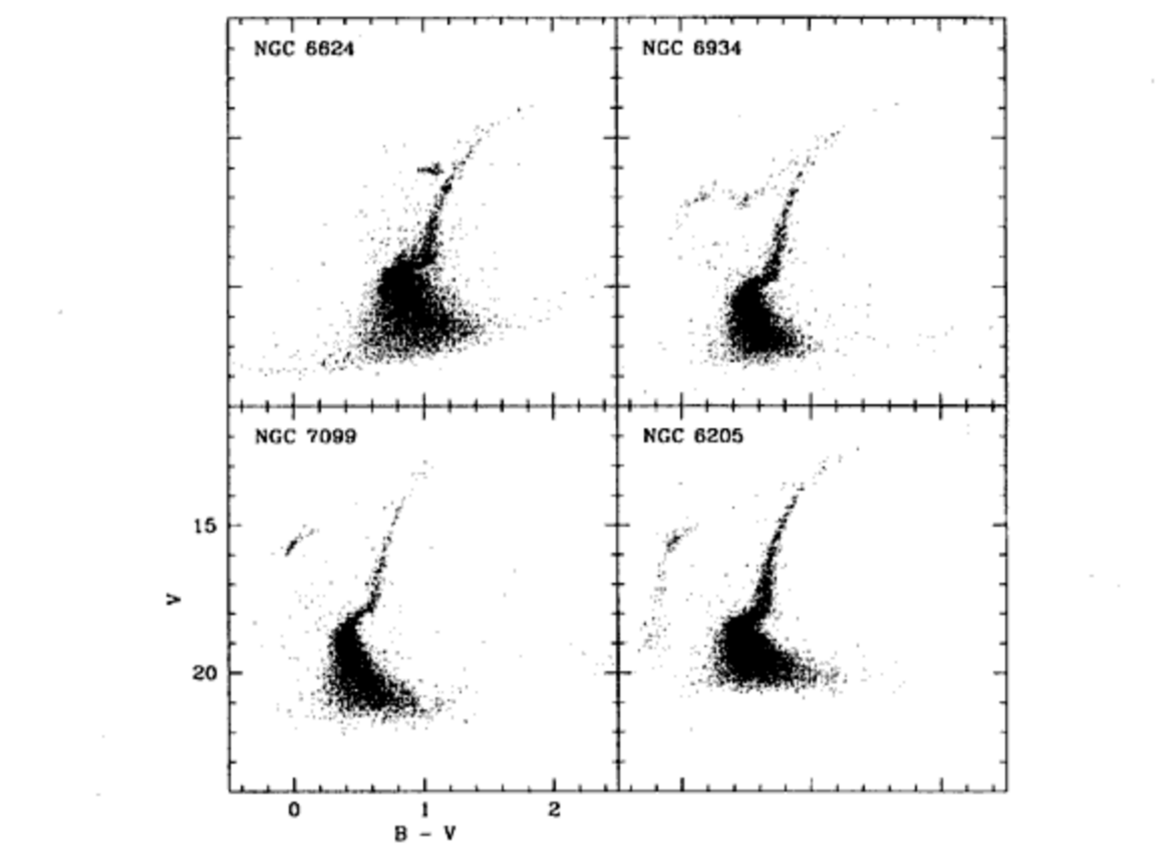
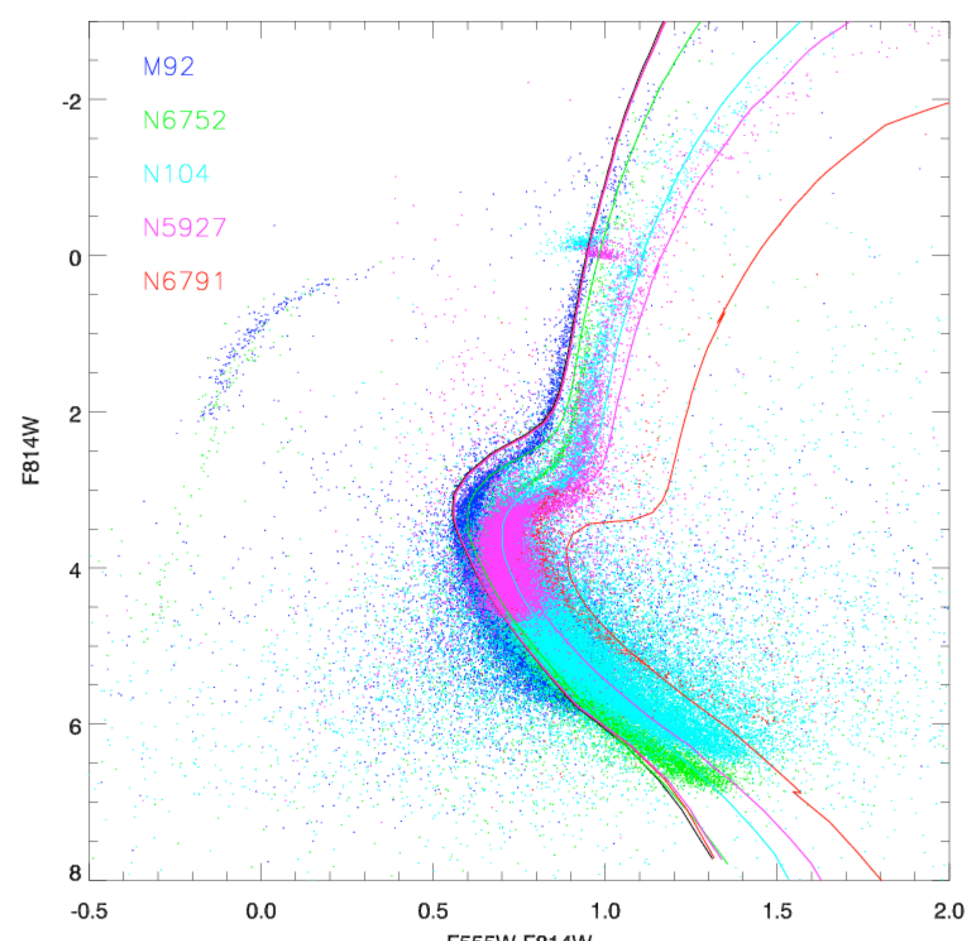


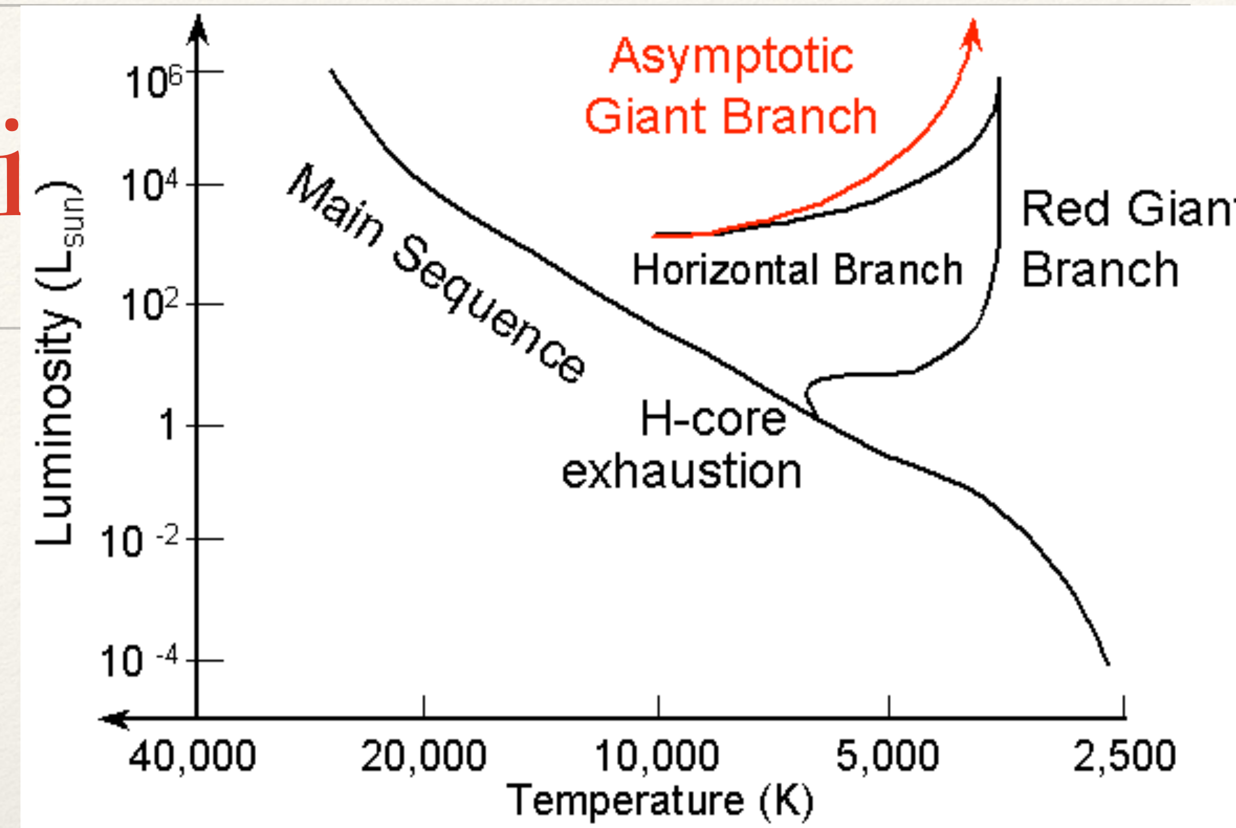
FIGURE 4. Clusters with four very different types of horizontal branch. (Data courtesy of M. Zoccali & G. Piotto [private communication]; source is HST archival images of the centers of globular clusters.)



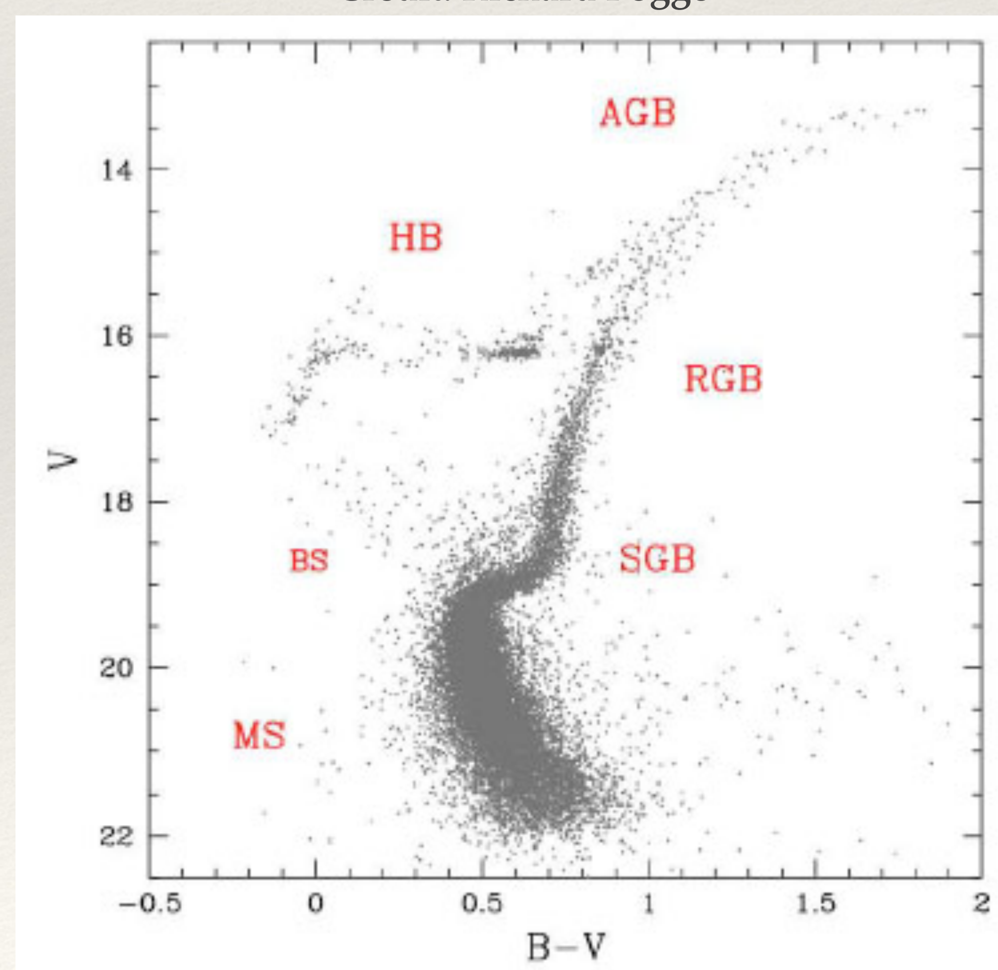
Ross, Holtzman et al.

Stars and Stellar Populati

- **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!) for ol   er populations
    - or interme   iate age   few   yr   stars i.e, stars with more mass,   goes to higher luminosity than   can be responsible for significant amount of light from a stellar population



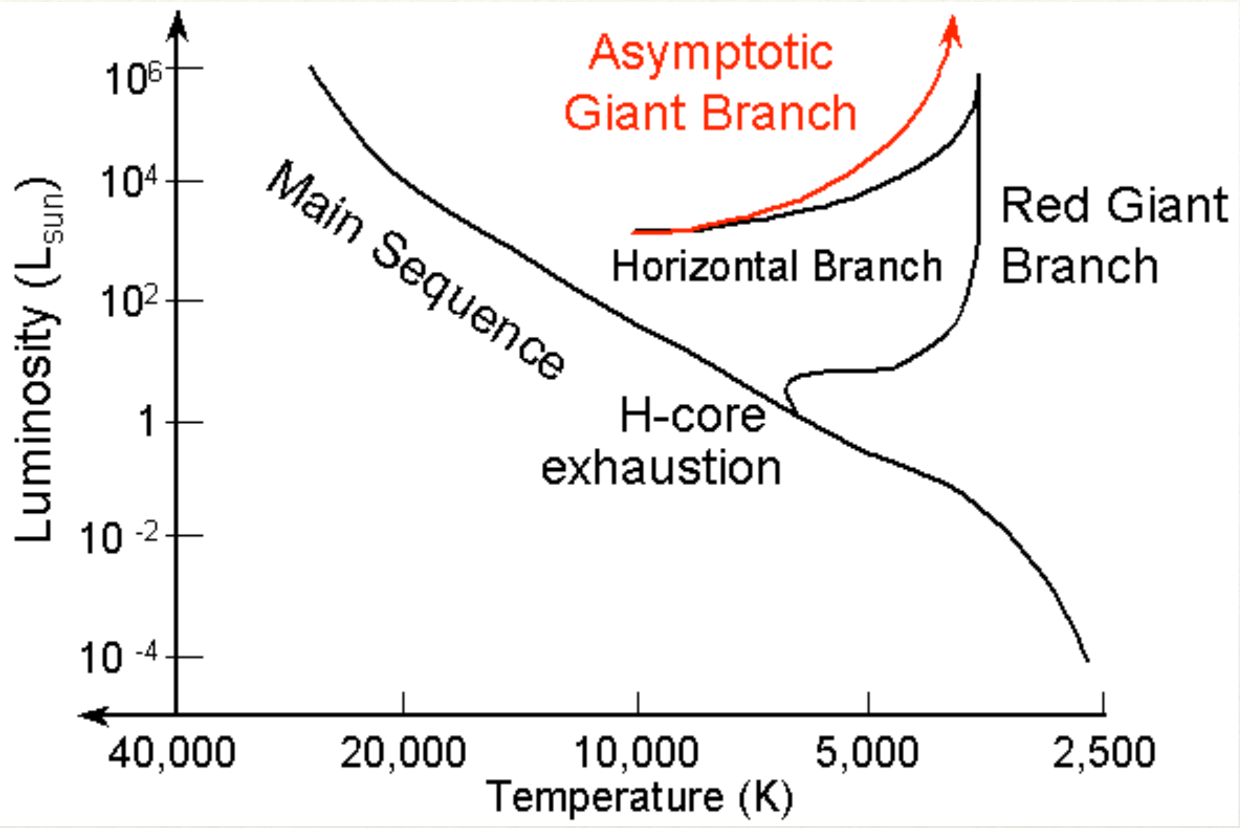
Credit: Richard Pogge



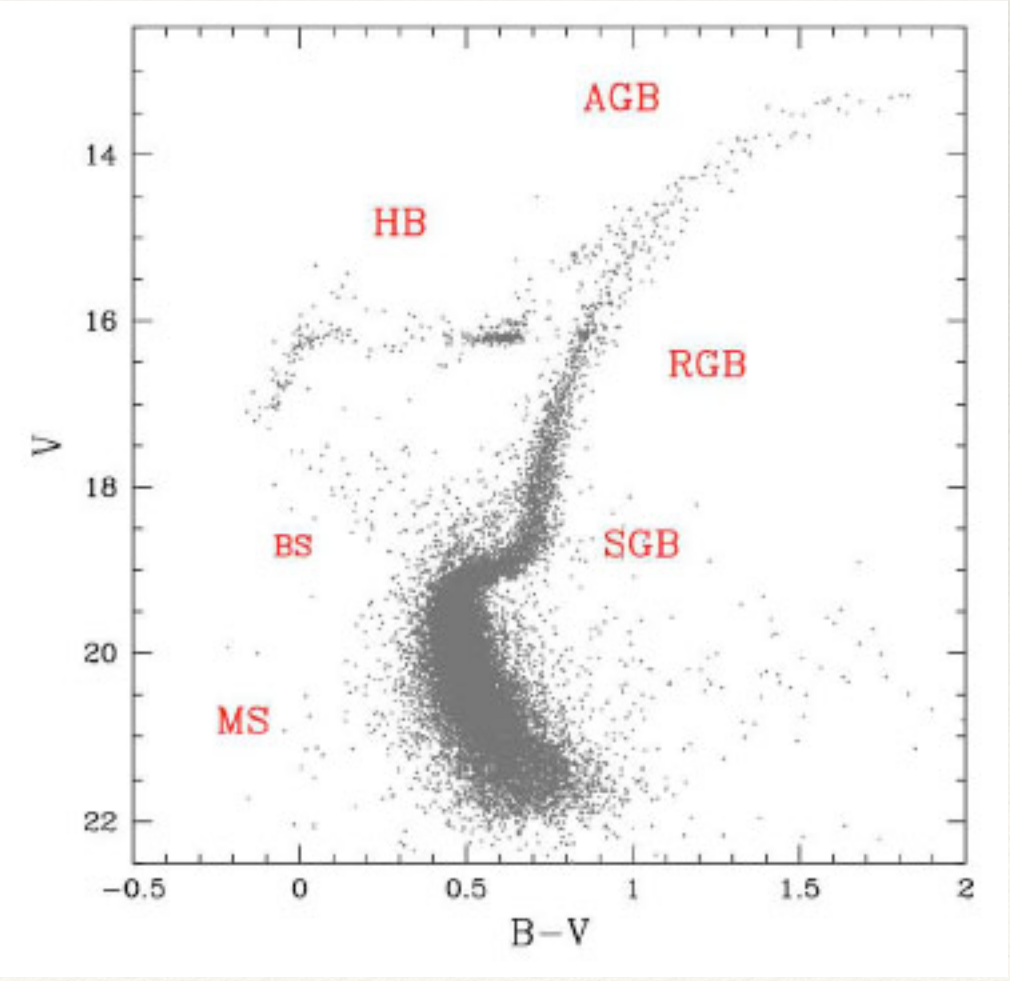
Maraston 2003

Stars and Stellar Populati

- **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)
  - stars can be important sources of chemical enrichment for some elements



Credit: Richard Pogge

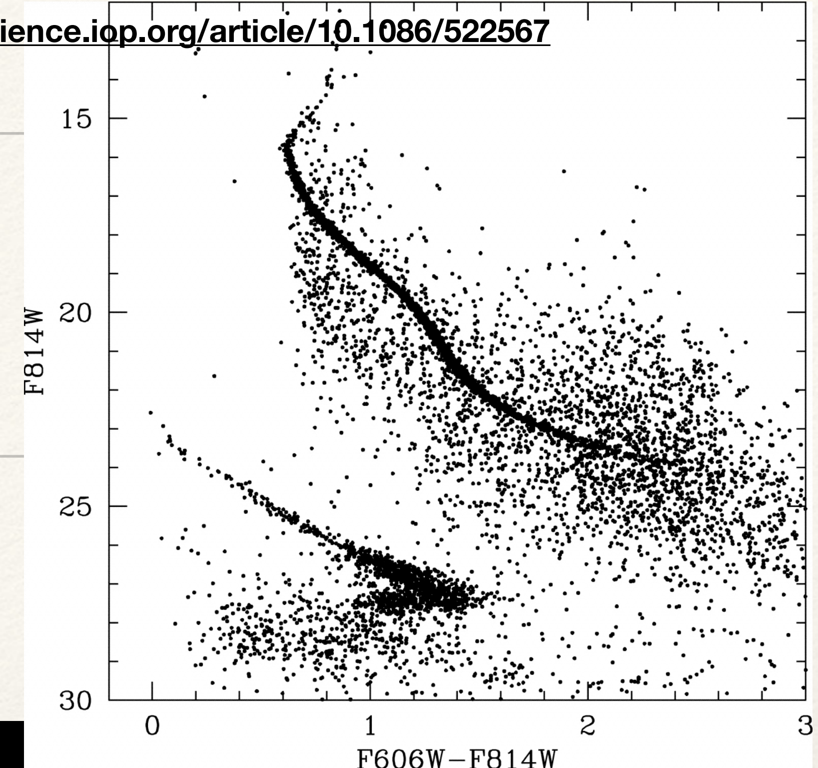


Maraston 2003

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

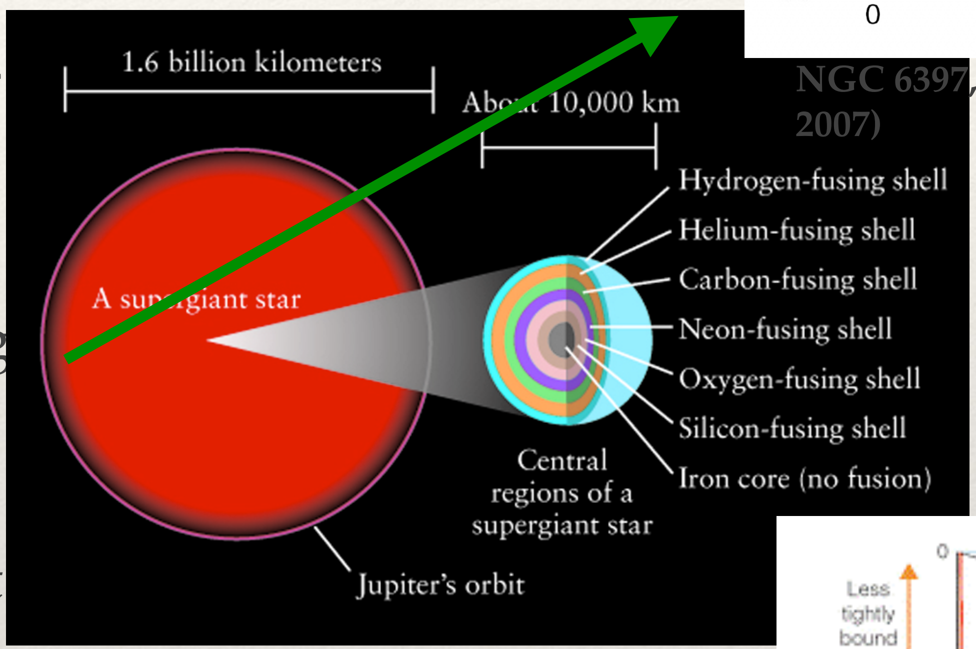
Stars and Stellar Populations

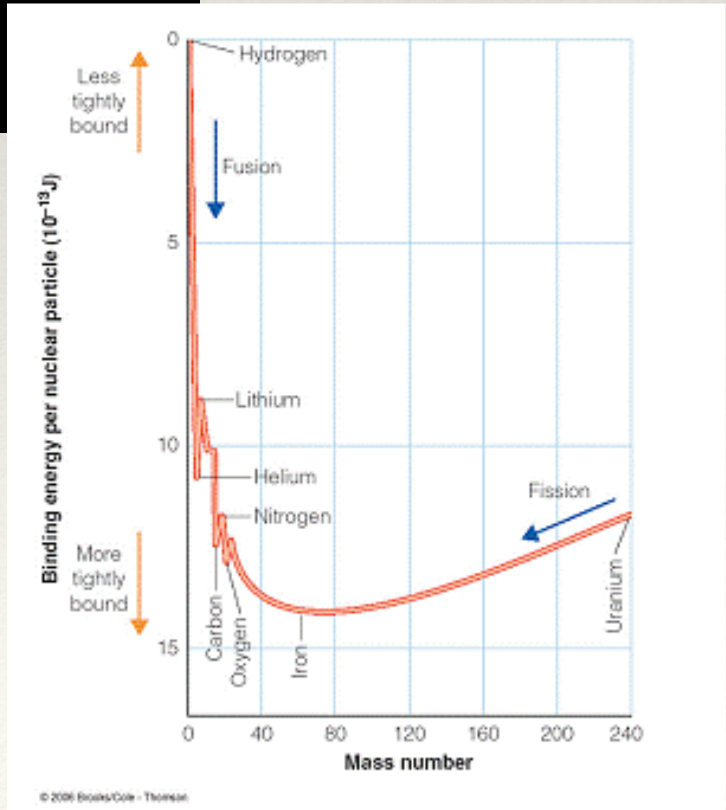
MS



NGC 6397, nearby globular cluster (Hansen e
2007)

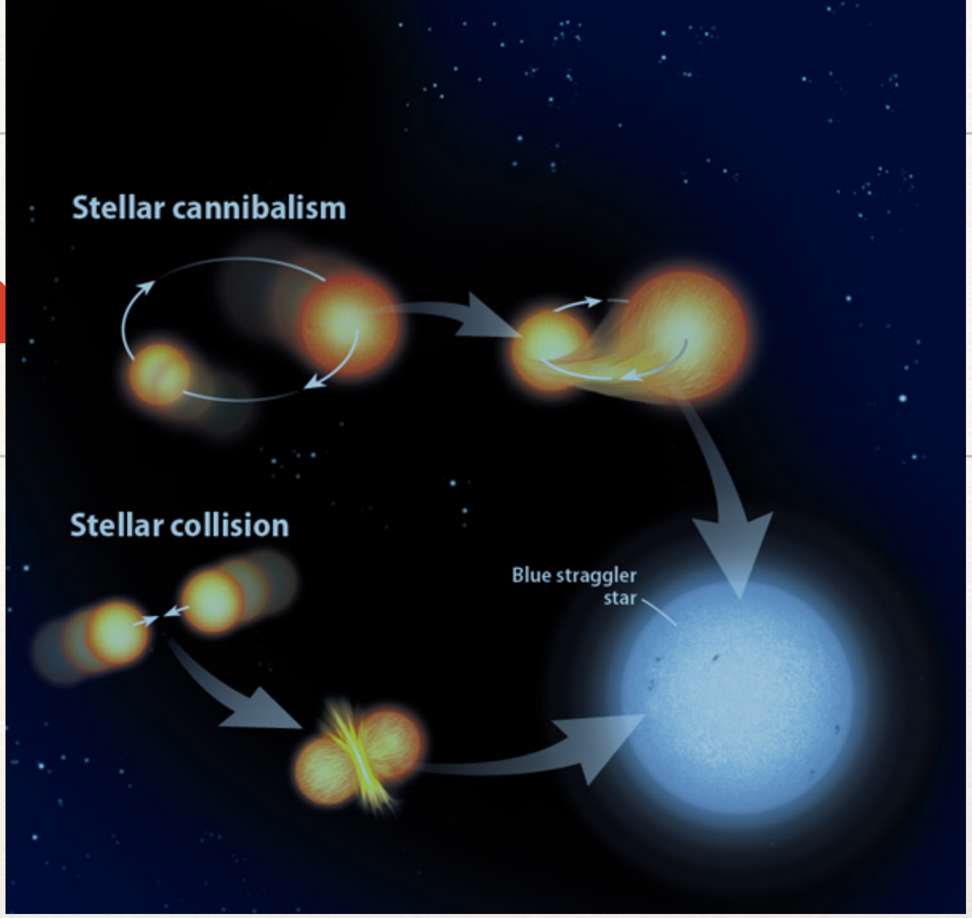
- **End stages of stellar evolution:**
  - Lower mass stars (< 8 Mo):
    - **Planetary nebula** — expelled mass lit up briefly
    - **White dwarf** — leftover hot core of star, lands on cooling sequence
  - Higher mass stars (>8 Mo):
    - Continue fusing up to Iron, looping back and forth across the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



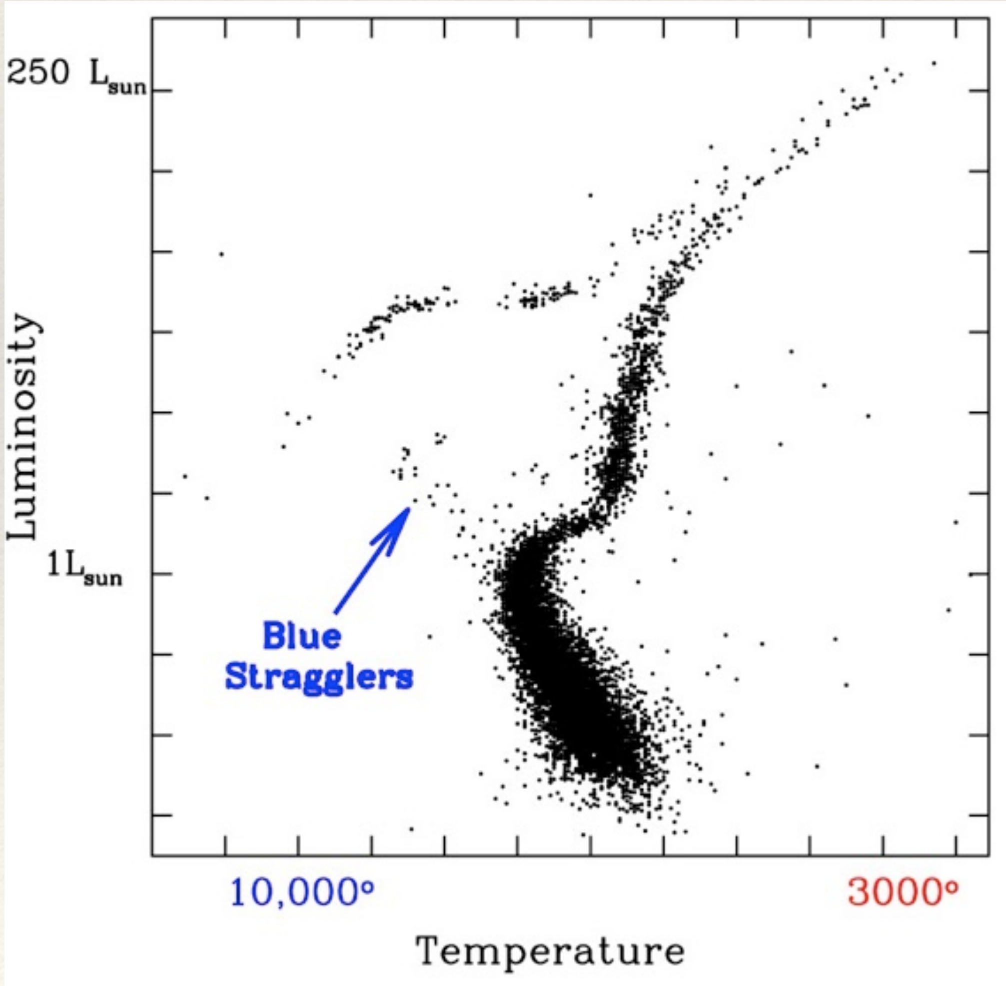


Stars and Stellar Populations

- **Binary stars complicate stellar population modeling:**
  - ~50% of stars are in 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



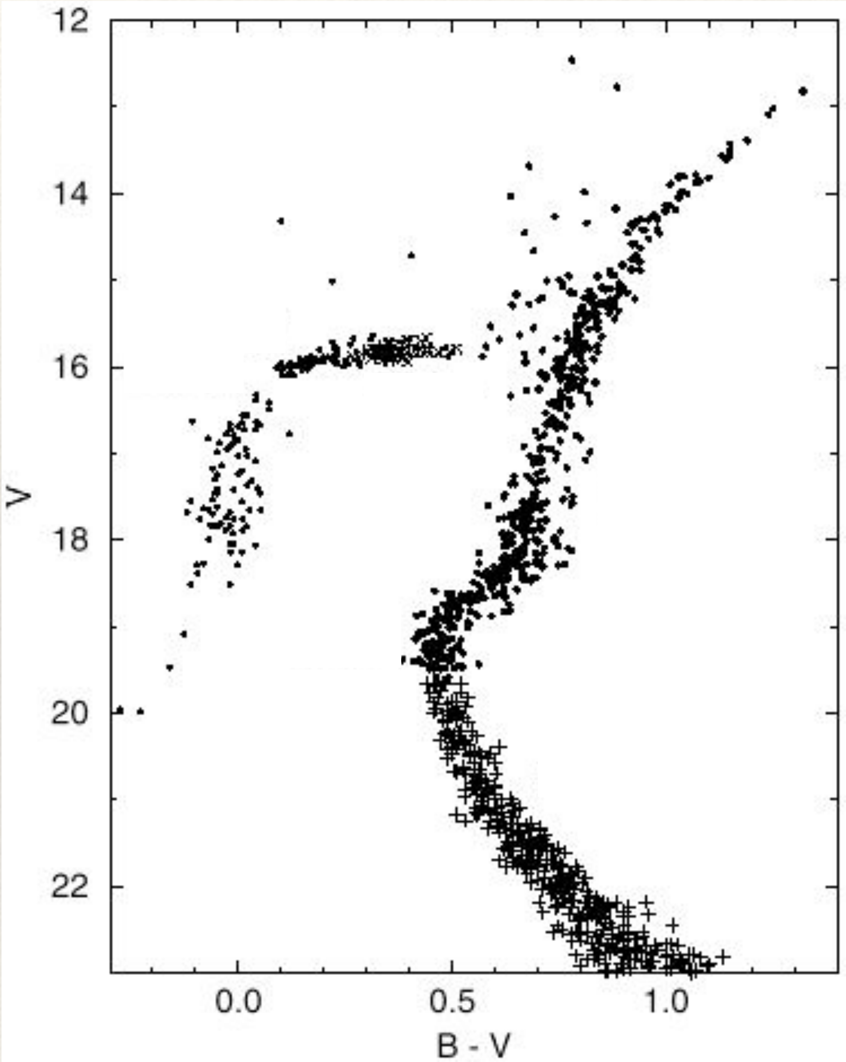
Credit: Astronomy Magazine



Cosmic-Lab Project

Thought Questions

- What features can you identify in this CMD?
- What is going on inside stars at different location in this CMD?
- What type of object do you think this is a CMD of?



M15 (Krauss 2000)

Stars and Stellar Populations: Stellar Evolution

- Stellar evolution models predicts evolution for a given mass — an **evolutionary track**
- Stellar evolution fairly well (but not perfectly) understood:
  - uncertainties generally larger for later stages

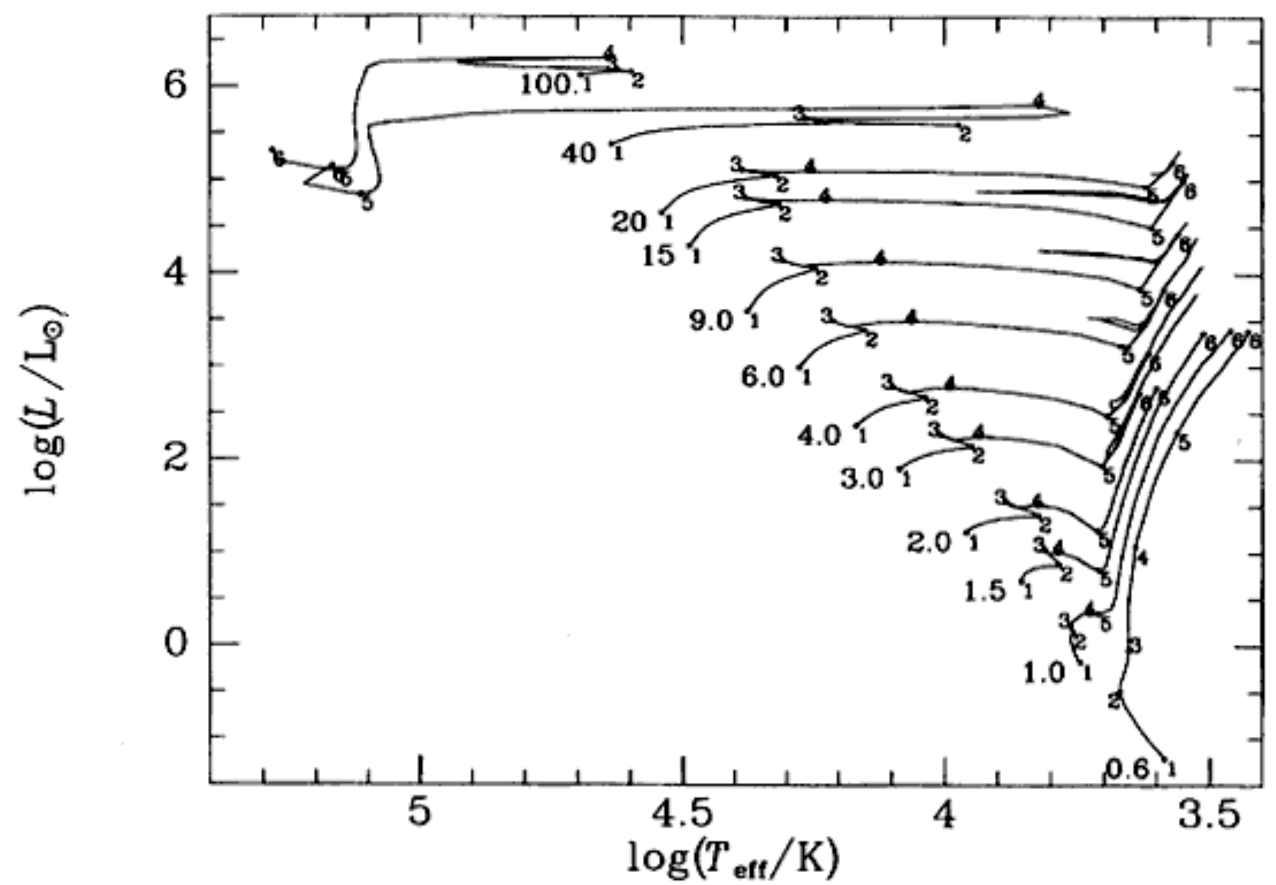
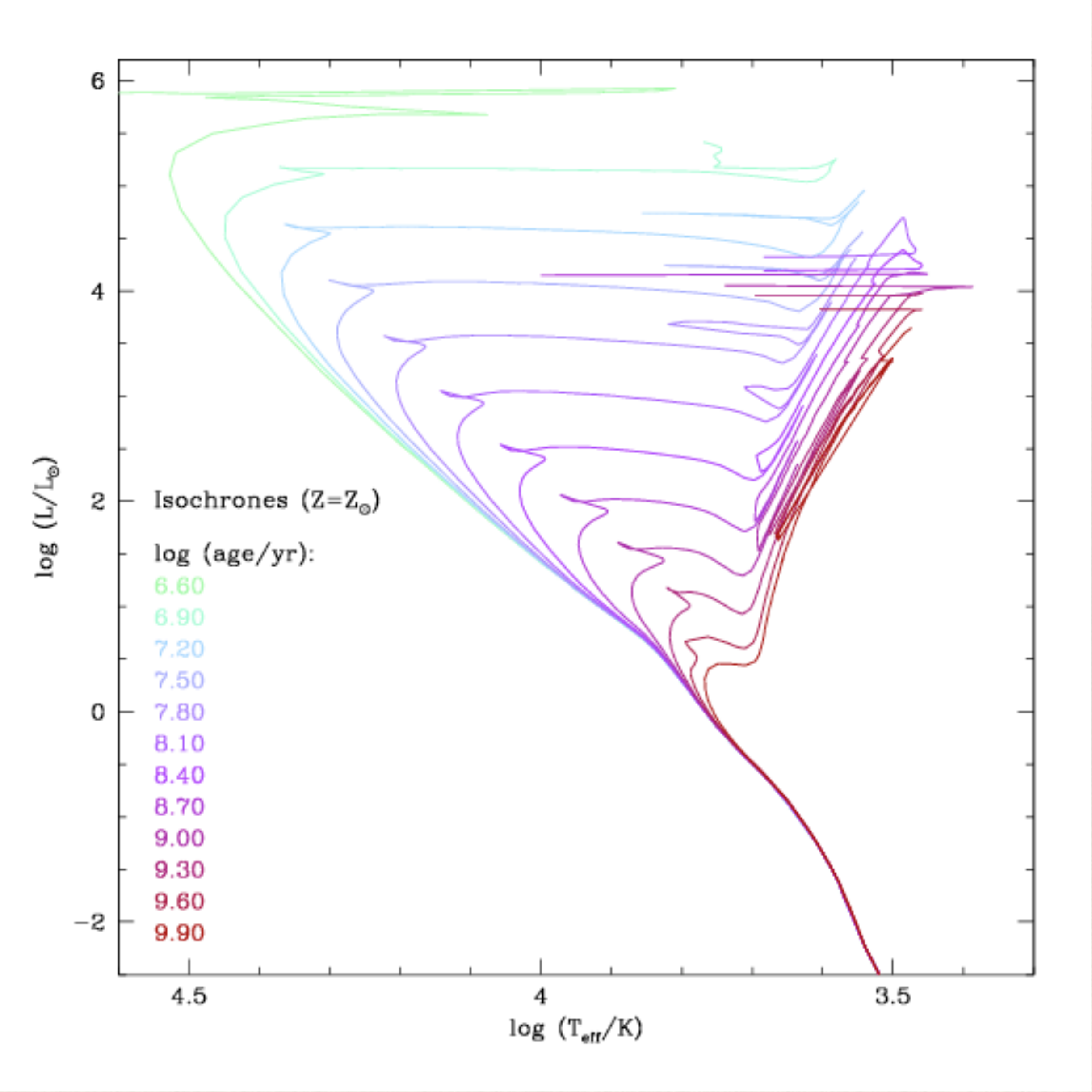


Figure 5.2 Evolutionary tracks for solar-metallicity stars $(Y, Z) = (0.28, 0.02)$ with initial masses from $0.6\,\mathcal{M}_\odot$ to $100\,\mathcal{M}_\odot$. On each track several points are marked and numbered. Table 5.2 gives the time it takes a star to reach each of these points starting from point 1. To avoid confusion tracks for $\mathcal{M} \leq 2\,\mathcal{M}_\odot$ terminate at the He flash – see Figure 5.3 for the further tracks of these stars. All models assume convective overshoot. [From data published in Bressan *et al.* (1993)]

Bressan et al. 1993

Stars and Stellar Populations: Stellar Evolution

- For a collection of stars with a range of masses, the cross section of properties at a fixed time is an **isochrone**
- Some well-known collections of evolutionary trac s isocrhones
  - Padova, BASTI (Teramo), Dartmouth, Yale-Yonsei, ictoria egina



da Cunha 2008

Stars and Stellar Populations

Russell-Vogt Theorem:

The mass and chemical composition of a star uniquely determine its radius, luminosity, internal structure, and subsequent evolution.

- **Stellar evolution models** predict radius, luminosity, as a function of age for given mass and composition
- Tied to quantities at surface of the star:
  - Effective temperature T_{eff}
  - Surface gravity **g** usually log g
- Use **stellar atmosphere models** (e.g., Kurucz, MARCS Phoeni ,TLUSTY, et al) and radiative transfer codes (Turbospectrum, Synspec, SYNTHE, MOOG, et al.) to predict spectra, colors, magnitudes

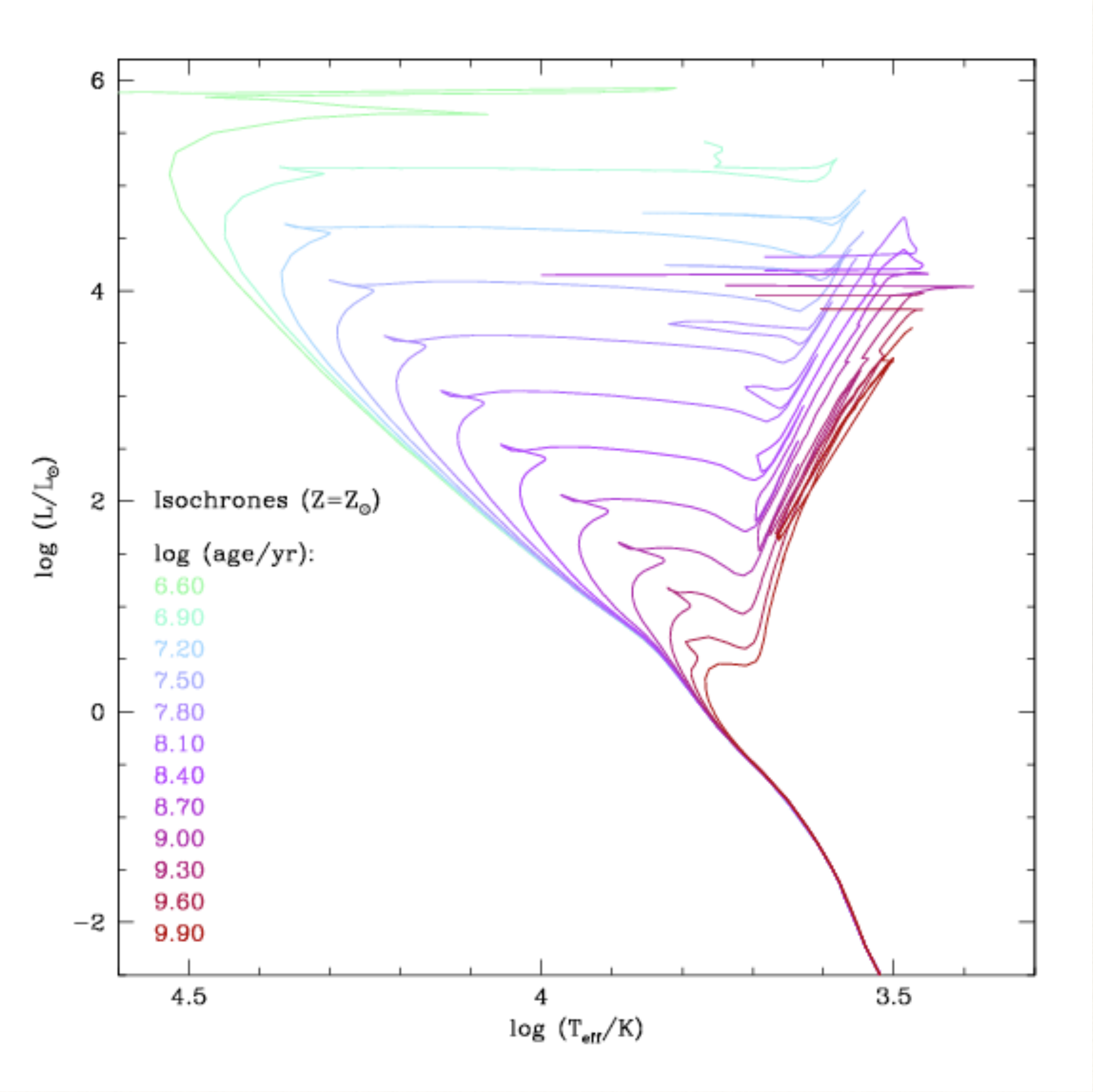
$$L = 4\pi R^2 \sigma T_{\rm eff}^4$$

$$g = \frac{GM}{r^2}$$

Stars and Stellar Populations : age effects

- A simple stellar population consistest of stars of a range of mass for a given age and metallicity
- How do age and metallicity of an SSP affect what we observe?

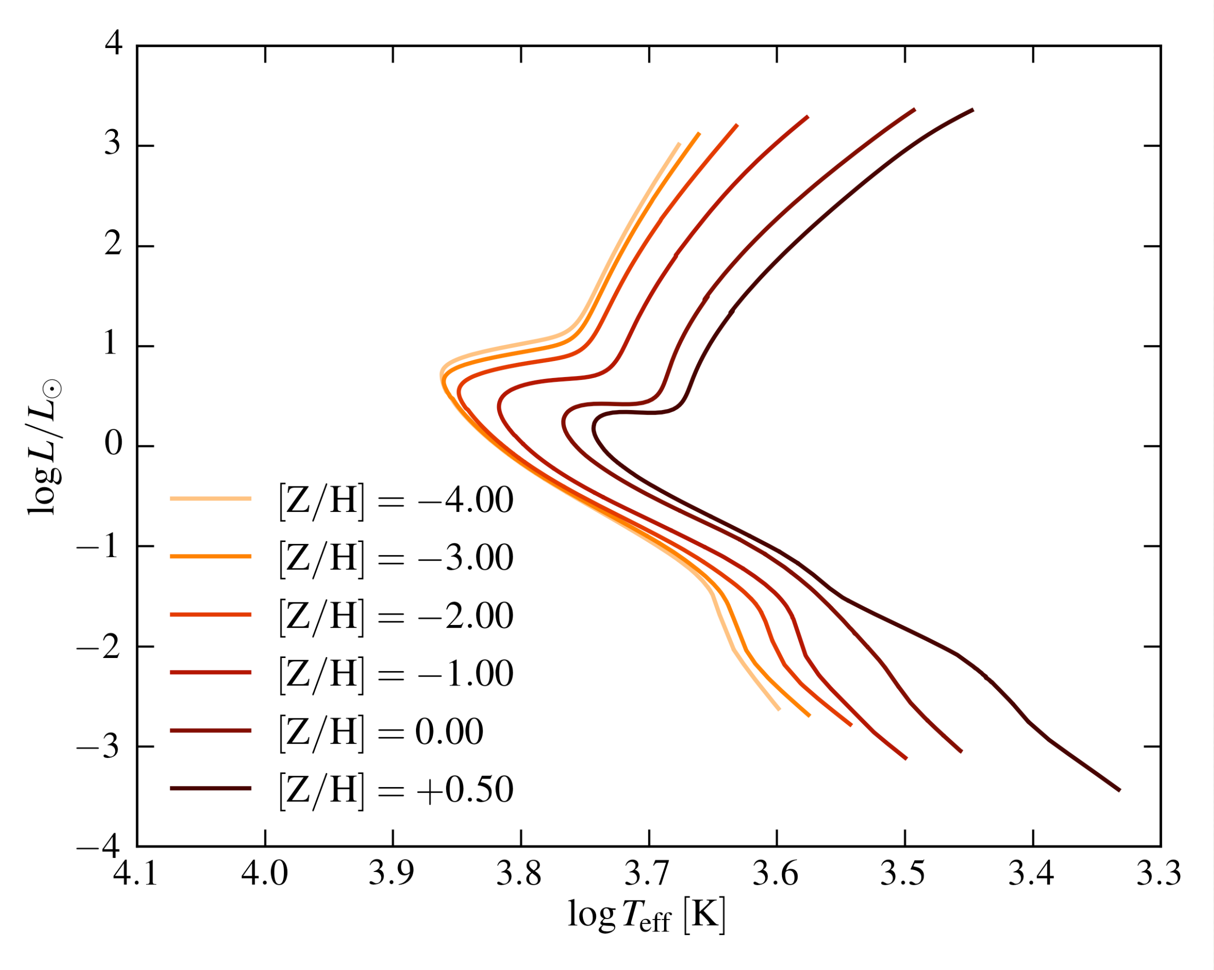
- **Age Effects**:
  - stars of decreasing masses evolve off the Main Sequence
  - see change in model isochrones



da Cunha 2008

Stars and Stellar Populations

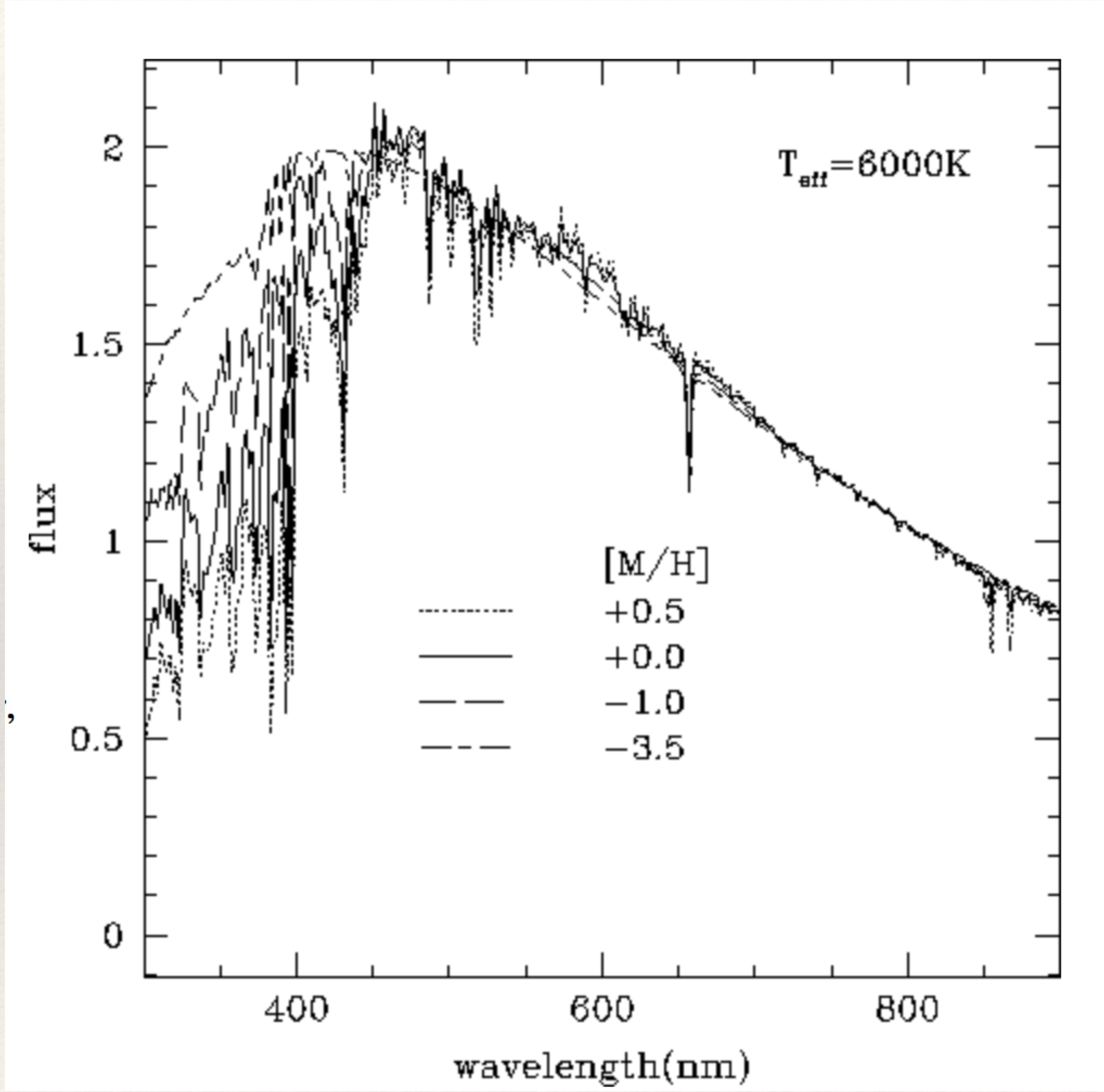
- **Metallicity Effects -- interior:**
  - Higher metallicity increases internal opacity
  - more metal-rich populations cooler and thus redder



Credit: MESA

Stars and Stellar Populations: metallicity effects

- **Metallicity Effects -- atmosphere**:
  - Higher metallicity increases atmospheric absorption
    - lots of metal lines in the blue — **line blanketing** (redder colors, even at same temperature)
  - both interior and atmospher contribute to making more metal-rich populations redder



http://burro.case.edu/Academics/Astr222/Galaxy/Structure/metals.html

Stars and Stellar Populations

- Metallicity terminology:
  - Sometimes given as mass fractions:
    - Hydrogen (X), Helium (Y), and heavier elements (Z), where X+Y+Z=1
  - Solar abundance: X~0.7, Y~0.28, Z~0.019
  - Note that Z contains lots of different elements! (astronomers just call them all "metals")
  - Observationally, usually denoted using "bracket notation":
    $[X/Y] = \log_{10}((X/Y) / (X/Y)_{Sun})$
    where X and Y are abundances (by number) of elements (or element groups X and Y, e.g
    $[Fe/H] = \log ((N(Fe)/N(H)) / (N(Fe)/N(H))_{Sun})$
  - Solar abundance: $[X/Y]_{Sun} = 0$!
  - Other notations : 12 + N(X)/N(H)

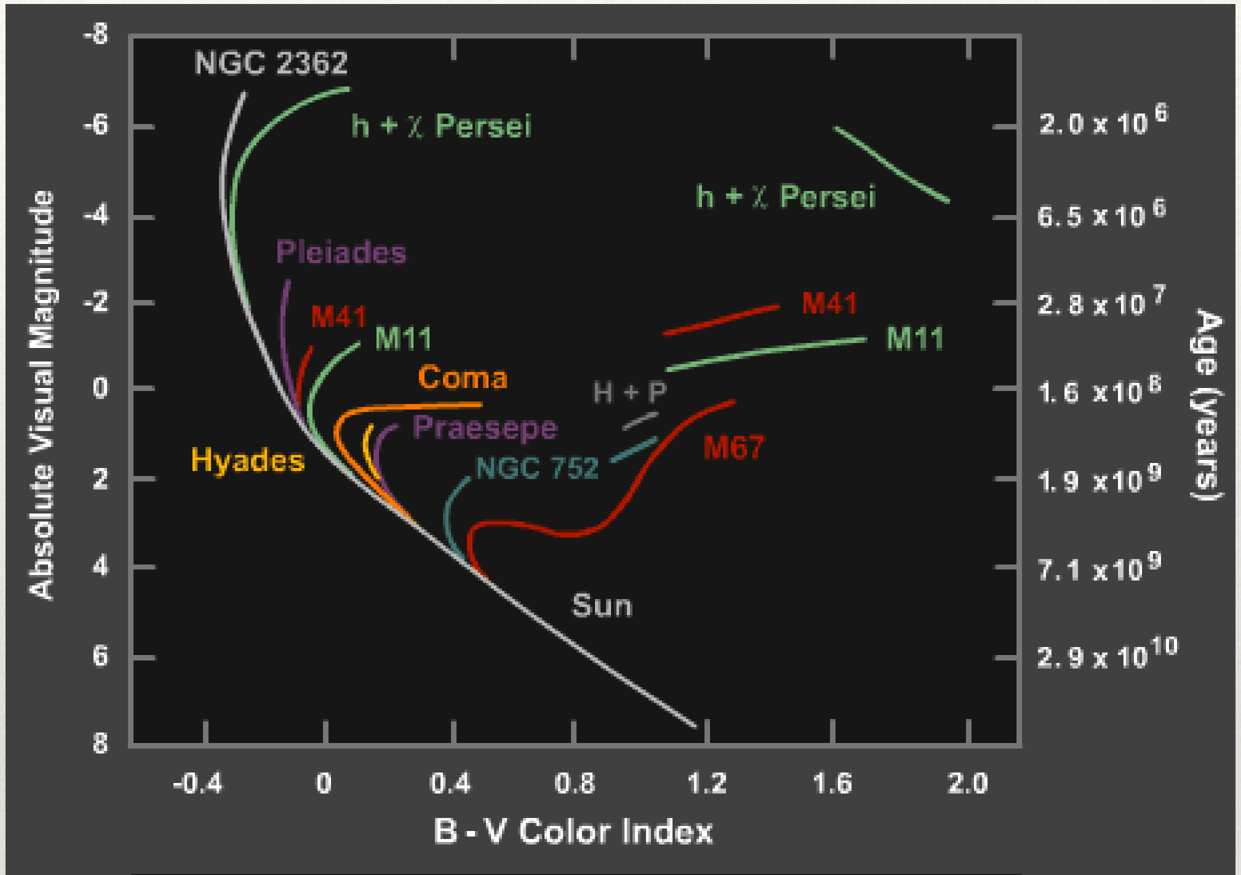
Stars and Stellar Populations

- Metallicity terminology:
  - What does [Fe/H] = -0.3 mean?
  - What does [alpha/Fe] = 0.3 mean?
  - If M refers to total metals, what does [M/H]= -1 mean?

$$[X/Y] = \log_{10} \left((X/Y) / (X/Y)_{Sun} \right)$$

Stars and Stellar Populations: Star clusters

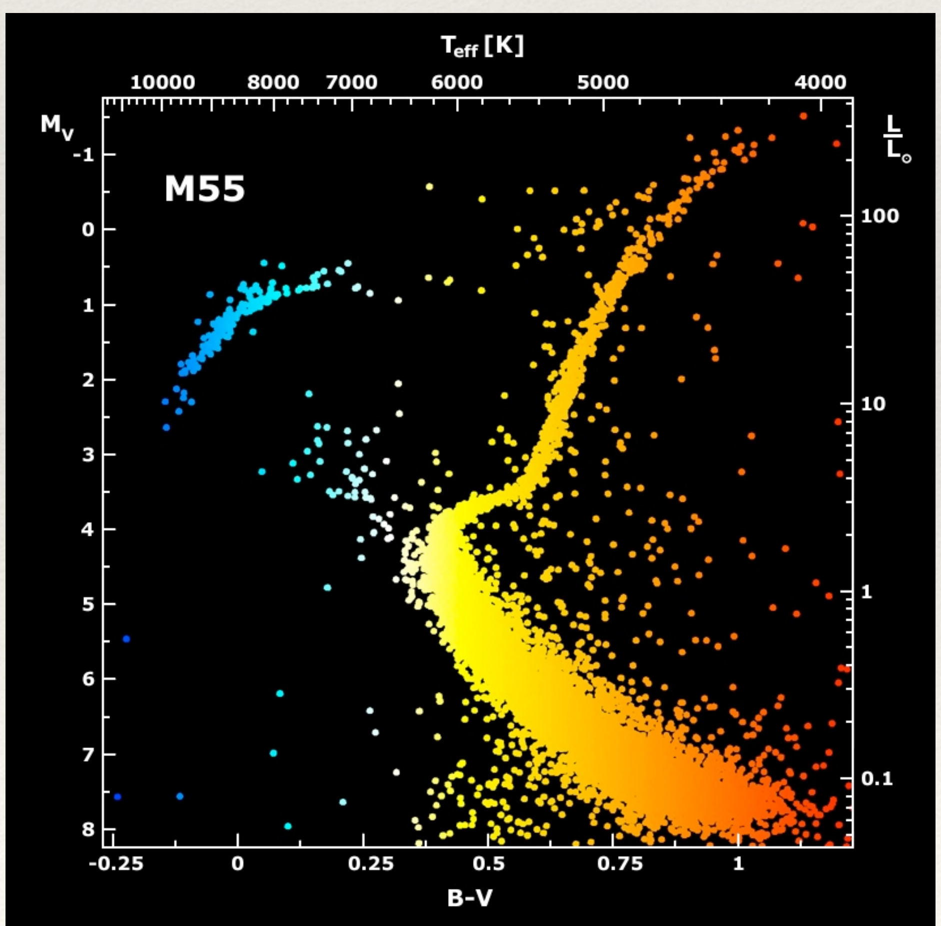
- Star clusters provide clear test and validation of evolutionary models
- Star clusters are approximate "simple stellar populations (SSP)" : set of stars of single age and composition, but range of masses
- To go from theoretical HR diagram to observed color-magnitude diagram (CMD), or vice versa, need to account for distance and reddening/extinction



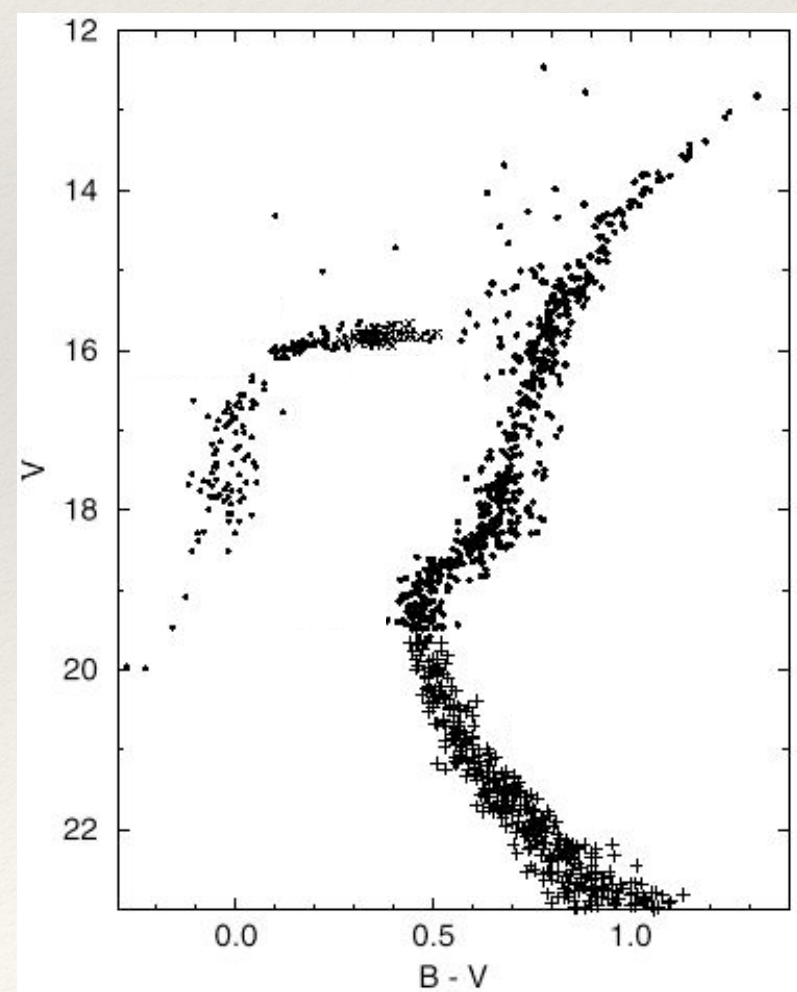
HR Diagrams for Various Open Clusters

Stars and Stellar Populations

- Galactic globular clusters:
  - cornerstone of understanding stellar evolution historically
  - in principle all stars same age and same metallicity

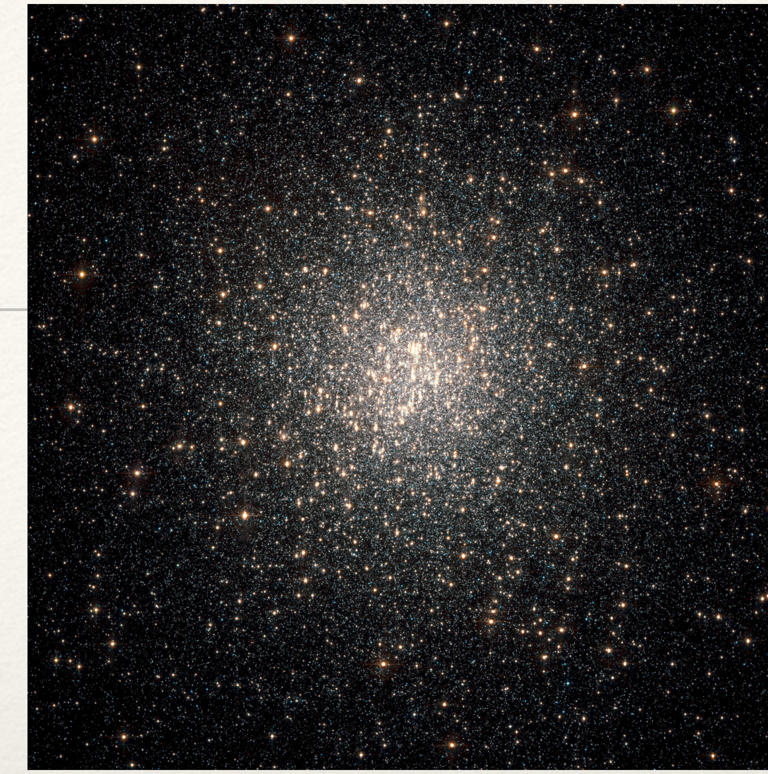


B.J. Mochejska, J. Kaluzny (CAMK), 1m Swope Telescope



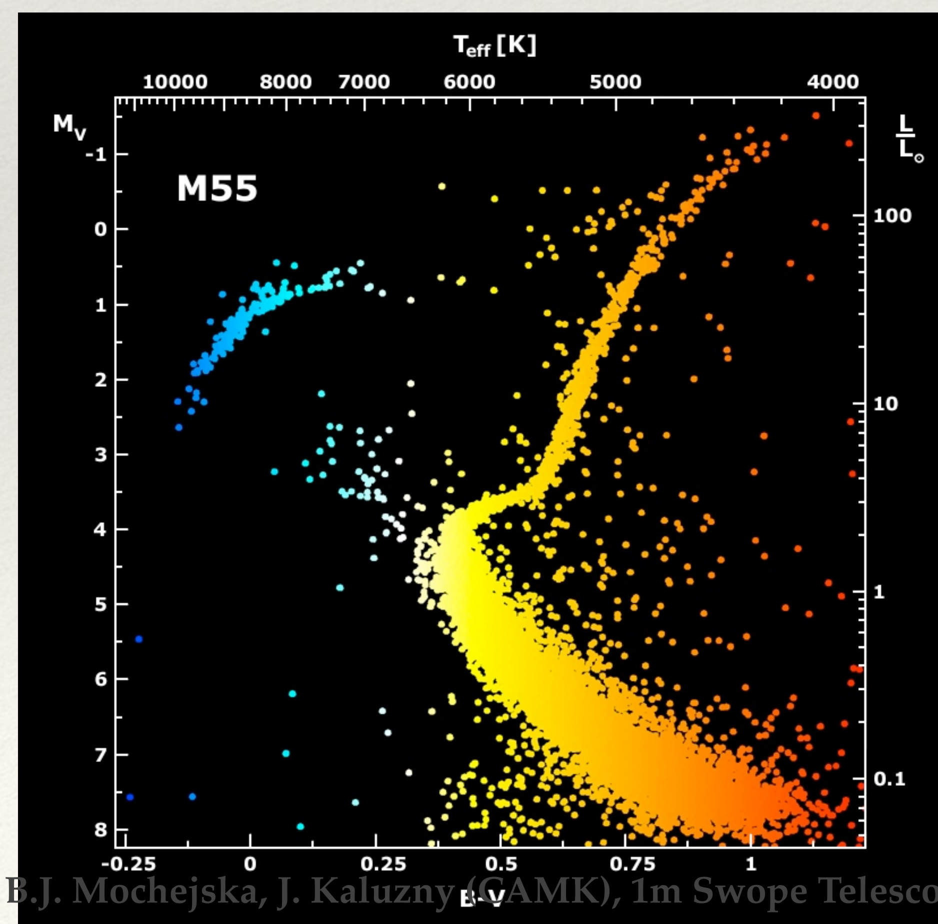
M15 (Krauss 2000)

Credit: NASA, ESA, G. Piotto (University of Padua) and A. Sarajedini (University of Florida)



Stars and Stellar Populations

- Globular clusters are in principle a "simple stellar population" (SSP)
- Now recognized that some clusters are not quite so simple!
  - multiple populations in clusters
  - second generation stars in globular clusters observed in CMDs and in chemical abundance patterns



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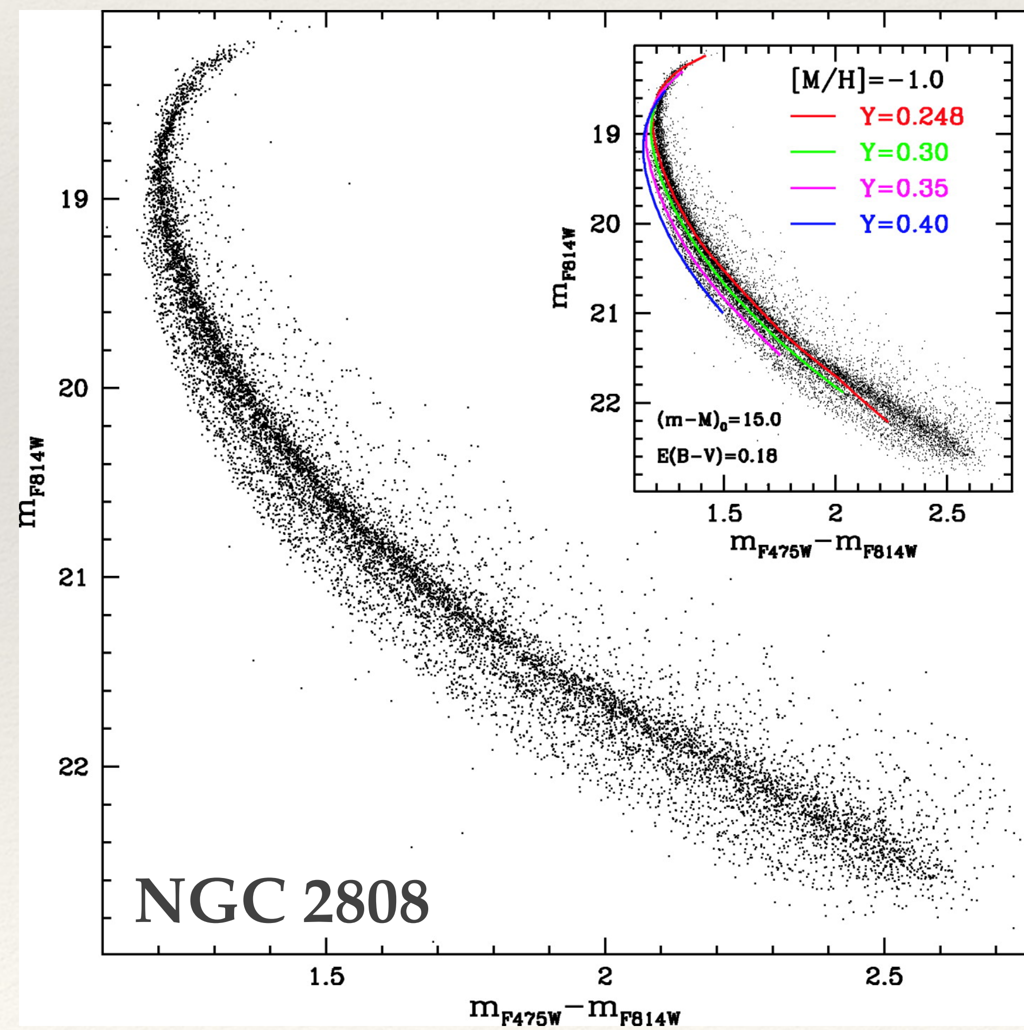
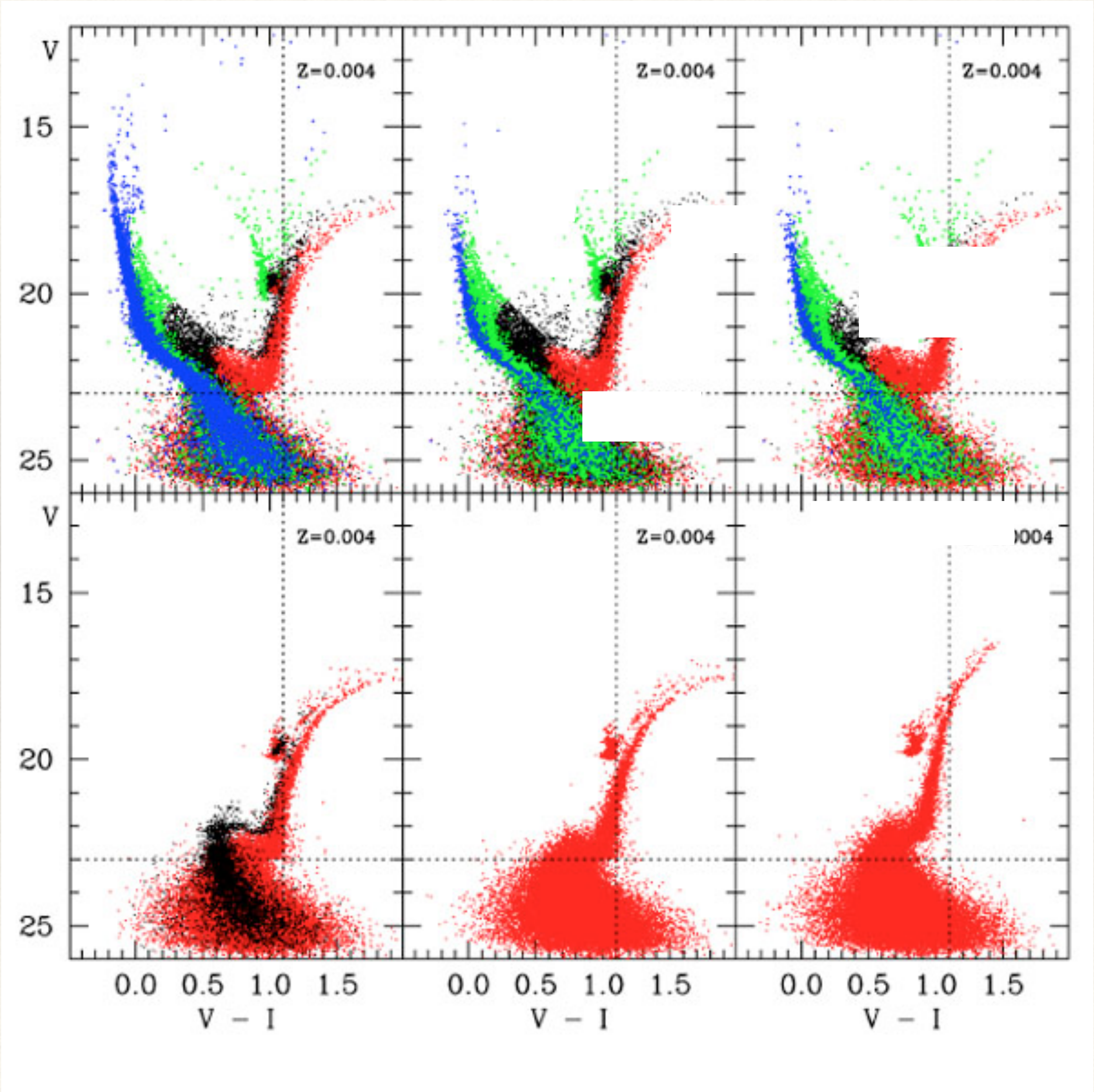


Piotto+2007 — https://iopscience.iop.org/article/10.1086/518503/fulltext/

Stars and Stellar Populations

- Galaxies are not simple stellar populations!
- Stars have range of ages and compositions
- HR diagrams may not look like those of star clusters, if there is a range of ages and / or metallicities



Cignoni & Tosi 2010