Outline

- Main sequence life time
- Stellar evolution
- Reactions with heavier nuclei
- Dating a stellar cluster

- Early voting Tuesday 10/14 - Thursday 10/16:
  - Burge 11:00am-2:00pm
  - Hillcrest 4:00pm-7:00pm

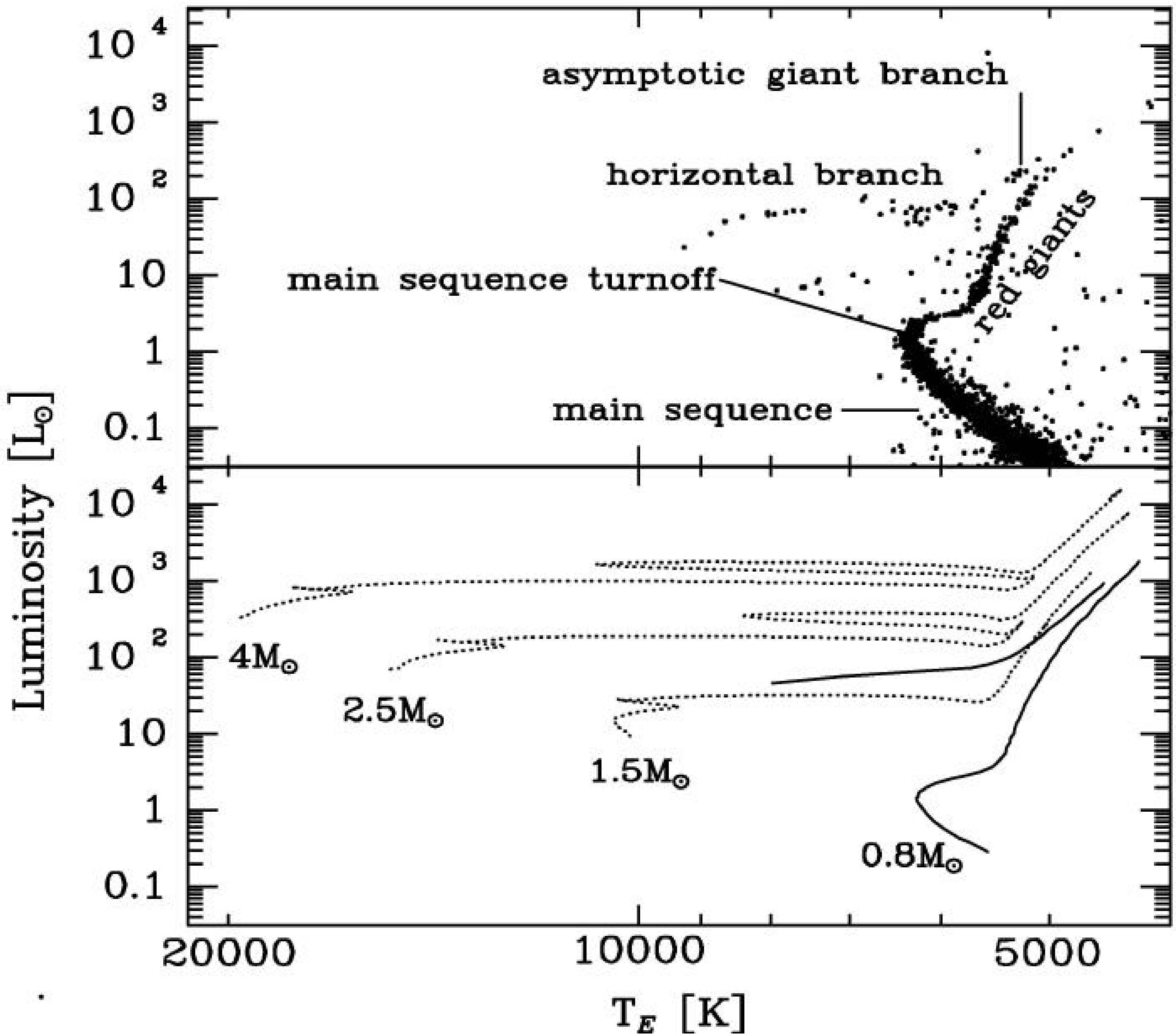
Main Sequence Lifetime

- Previous found dependence of stellar luminosity on mass, $L \propto M^{\alpha}$.
  - $\alpha \approx 3.5$ for 2-20 $M_{\odot}$, $\alpha \approx 1$ for > 20 $M_{\odot}$.
- Source of energy is nuclear reactions, total available energy $E \propto M$.
  - Total energy $E = L \times t_{ms}$, where t_{ms} is lifetime on main sequence.
  - Thus $t_{ms} \propto M/L \propto M^{1-\alpha}$
- Note $t_{ms} \approx 1\times10^{10}$ years for 1 $M_{\odot}$
  - $\alpha \approx 3.5 \rightarrow t_{ms} \propto M^{-2.5}$, e.g. $t_{ms} \approx 2\times10^{7}$ years for 10 $M_{\odot}$
  - $\alpha \approx 1 \rightarrow t_{ms} \propto M^{0}$, $t_{ms} \approx 3\times10^{6}$ years for > 30 $M_{\odot}$
- Age of universe ~ 1.4×10^{10} years.
  - Low mass stars still on main sequence, even if formed very early.

Evolved Stars

- Even while on main-sequence, a star can move in the HR diagram because its luminosity and surface temperature change. This causes the main sequence to have a finite width on the HR diagram.
- Star moves off the main sequence when hydrogen burning in the core stops due to build up of Helium.
  - Hydrogen then burns in a shell surrounding the core.
  - The star expands into 'red giant'. “The huge expansion of the star's envelope is difficult to explain by means of some simple and intuitive argument, but it is well understood and predicted robustly the equations of stellar structure.”

HR Diagram for M3



Evolved Stars

- To model how stars age, one needs to track the change in abundances as a function of position within the star.
  - This changes the energy generation profile and thus all the other profiles.
  - Regions with convection have uniform abundances – convection occurs on time scales much faster than composition change due to nuclear burning.
- All large motions on the HR diagram correspond to changes in location or type of nuclear burning.
  - Main sequence turnoff – core H burning shutting down
  - Red giant branch – inert He core, H shell burning
  - Horizontal branch – He core burning, H shell burning
  - Asymptotic giant branch – inert C+O core, He shell burning, H shell burning

Evolved Stars

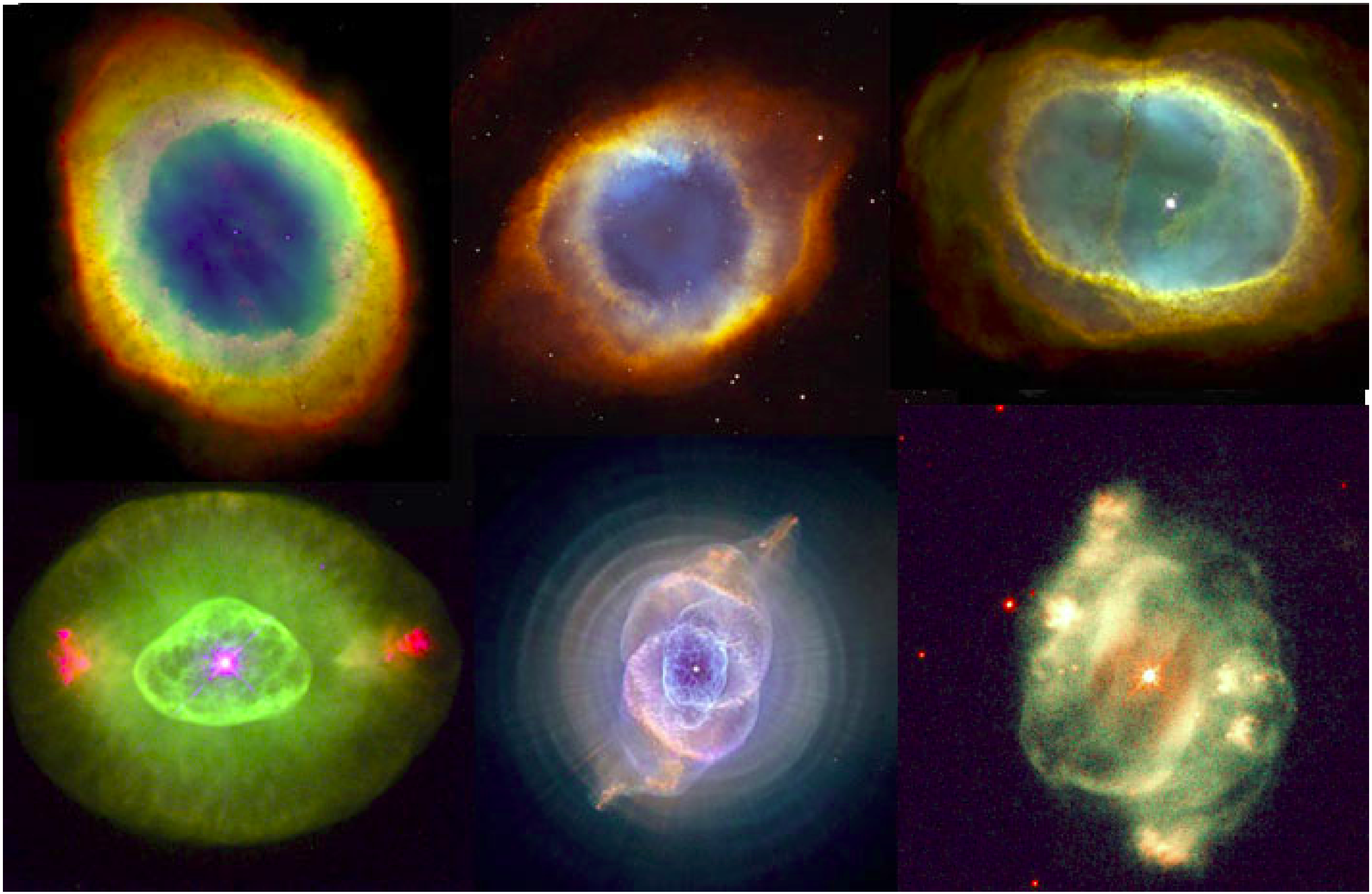
- He burning: $^4He + ^4He + ^4He \rightarrow ^{12}C + \gamma$ (7.275 MeV)
  - Triple reaction is unlikely, occurs through $^4He + ^4He \rightarrow ^8Be + \gamma$, but ^8Be has lifetime of only 10^{-16} seconds.
  - Cross-section for $^4He + ^8Be \rightarrow ^{12}C + \gamma$ is greatly enhanced due to existence of an excited state of ^{12}C with same energy as $^4He + ^8Be$, a "resonance".

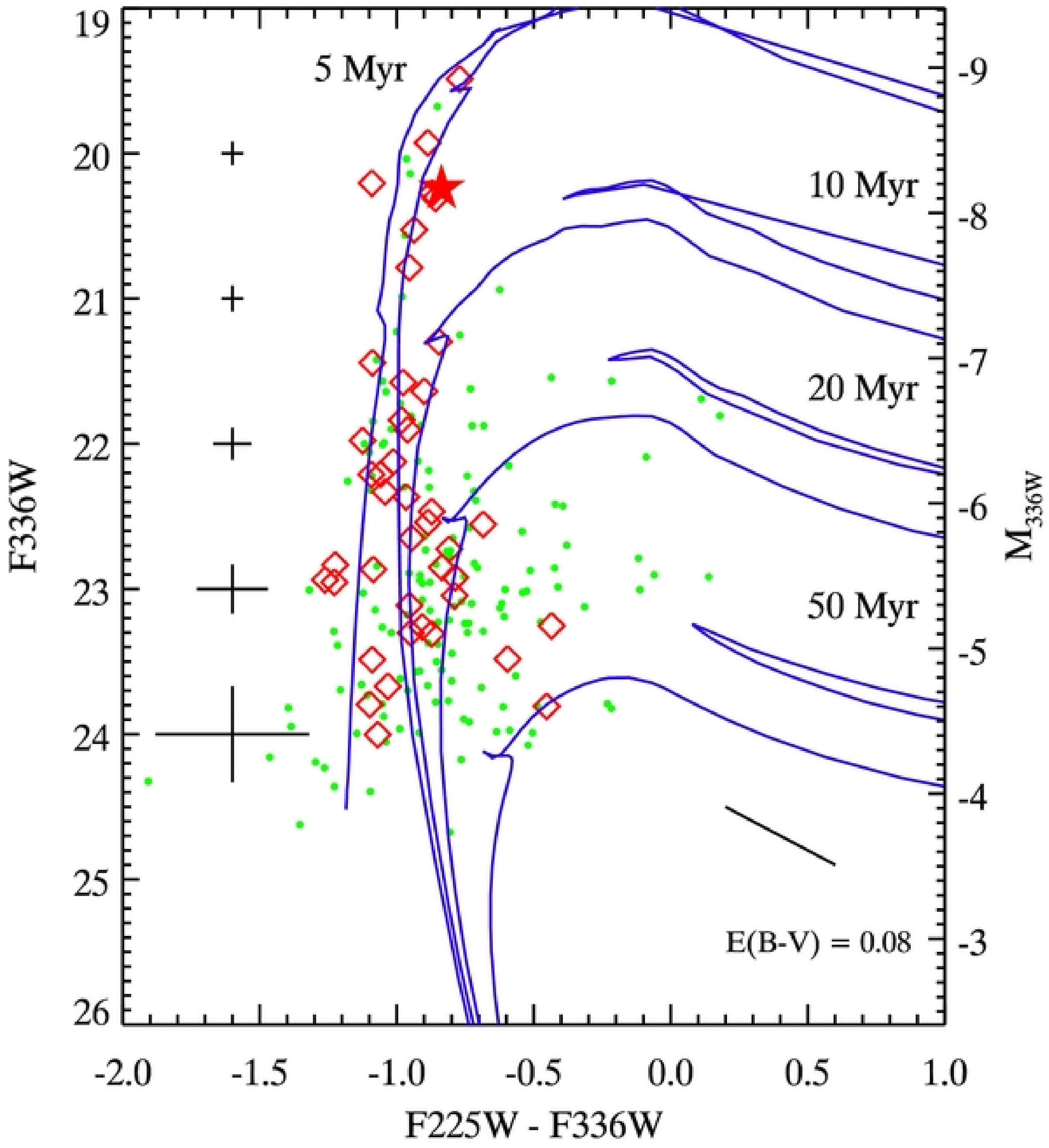
- He burning also produces O and N
  - $^4He + ^{12}C \rightarrow ^{16}O + \gamma$
  - $^4He + ^{16}O \rightarrow ^{20}N + \gamma$

Evolved Stars

- Giant stars tend to be highly convective
  - convective mixes nuclear burning products throughout the star
- Surface gravity of giant stars is low
  - giants tend to have strong winds and high mass loss rates
  - AGB stars experience 'thermal pulses' that are periods of enhanced helium shell burning. These drive strong mass loss.
- For stars < 8 $M_{\odot}$, end of AGB, leaves a hot CNO core and the outer layers are blown off.
  - Excitation of gas lost from star by hot remnant (white dwarf) produces a 'planetary nebula'.

Evolved Stars





- Blue lines – 'isochrones' = stars of same age, but different masses
- Red star – X-ray binary
- Red diamonds – stars in cluster around binary
- Green dots – other stars

Homework

- For next class:
  - No homework