Announcement: Quiz Friday, Oct 31

What is the difference between the giant, horizontal, and asymptotic-giant branches? What is the Helium flash? Why can't high-mass stars support themselves in hydrostatic equilibrium by fusing Iron?

What is the main sequence lifetime? Does it increase or decrease as mass increases? Why does the MS phase last longer than the horizontal branch phase? What is "thermal equilibrium"? What is "hydrostatic equilibrium"?

What is the difference in outcomes for a star with $M < 4\ M_{sun}$, $4M < M < 8\ M_{sun}$, $M > 8M$?

What is the Chandrasekhar mass? What is a neutron star? What is a white dwarf? What is a supernova? Are there different kinds? What is the difference between the singularity and the event horizon for a black hole?

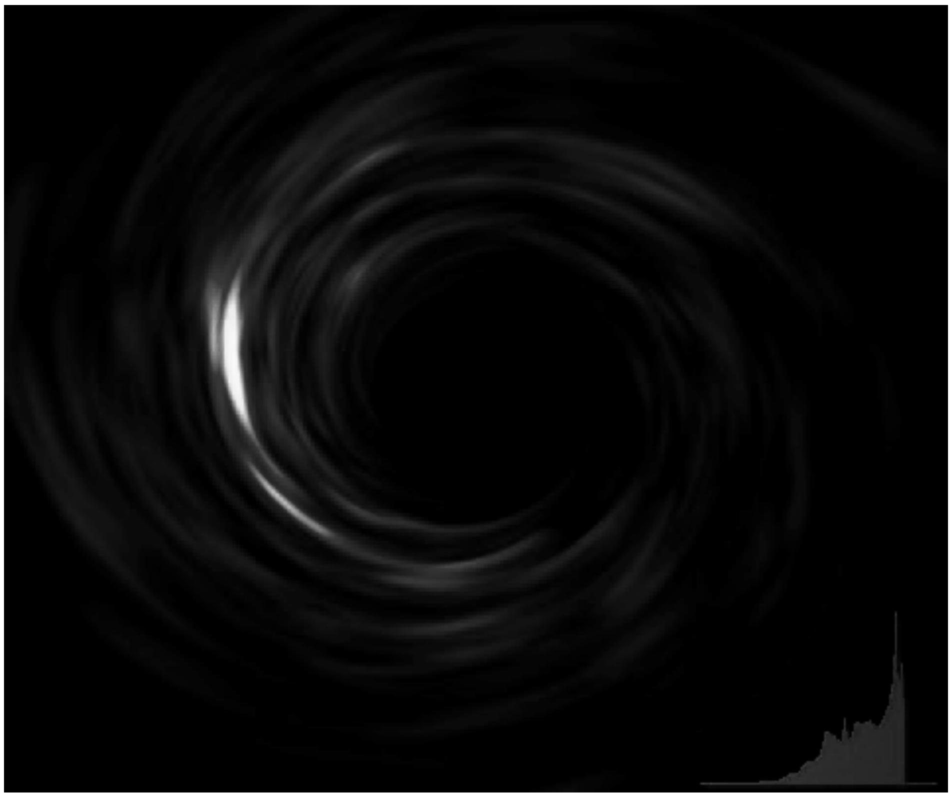
Why are there no stars with mass less than ~ $0.1\ M_{sun}$? What is the maximum mass of a star? How do we know that fusion is occurring in the core of the Sun?

Light is bent/deflected by a strong gravitational field.

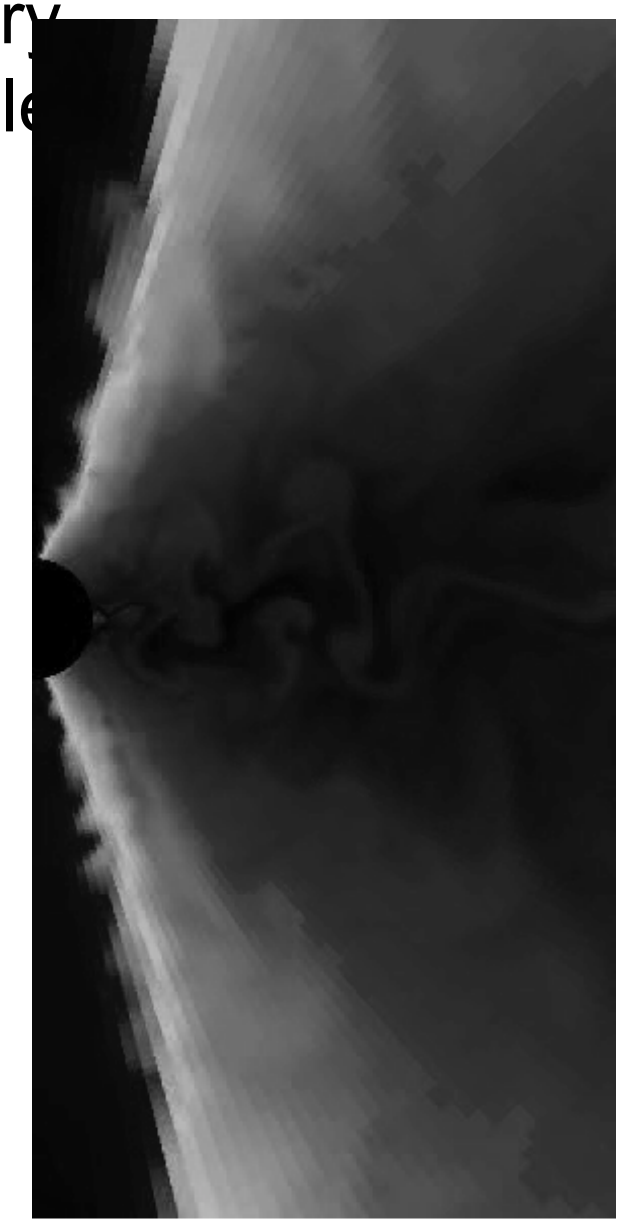
10 M_{sun} Black Hole at a distance of 600 km.

Matter glows because it becomes very hot as it "accretes" onto the black hole

Matter "falls" in to the black hole via an "accretion disk."



Armitage & Reynolds



Stone

X-Ray Binaries

Bright, variable X-ray sources identified by X-ray satellites:

- –
  companion is invisible.
- Gas from the visible star is dumped on the companion, disk forms, heats up, and emits X-rays.

Estimate the mass of the unseen companion from the orbit.

- Black hole candidates will have $M > 3\ M_{sun}$

Artist’s Conception of an X-Ray Binary

Black Hole Candidates

X-ray binaries with unseen companions of mass > 3 M_{sun}, too big for a Neutron Star.

Currently ~20 confirmed black hole candidates:

- First was Cygnus X-1: 7 – 13 M_{sun}
- Largest is GRS1915+105: 10 – 18 M_{sun}
- Most are in the range of 4 – 10 M_{sun}

Estimated to be ~1 billion stellar-mass black holes in our Galaxy alone.

Black Holes are not totally Black!

“Classical” General Relativity says:

- Black Holes are totally black.
- Can only grow in mass and size
- Last forever (nothing gets out once inside)

But,

General Relativity does not include the effects of Quantum Mechanics.

Evaporating Black Holes

Black Holes evaporate very slowly by emitting Hawking Radiation:

- Very cold thermal radiation (T~10 nK)
- Bigger black holes are colder (evaporate slowly)

Takes a very long time…

- 5 M_{sun} black hole takes ~10^{73} years.
- ~10^{63} times the present age of the Universe.

Not important today for massive BHs. But, a BH the mass of **me** would evaporate in ~10^{-10} s.

Tests of Stellar Evolution

Astronomy 1101

How do we test stellar evolution? Neutrinos observed from Sun, but …

H-R Diagrams of Star Clusters

Ages from the <u>Main-Sequence Turn-off</u>

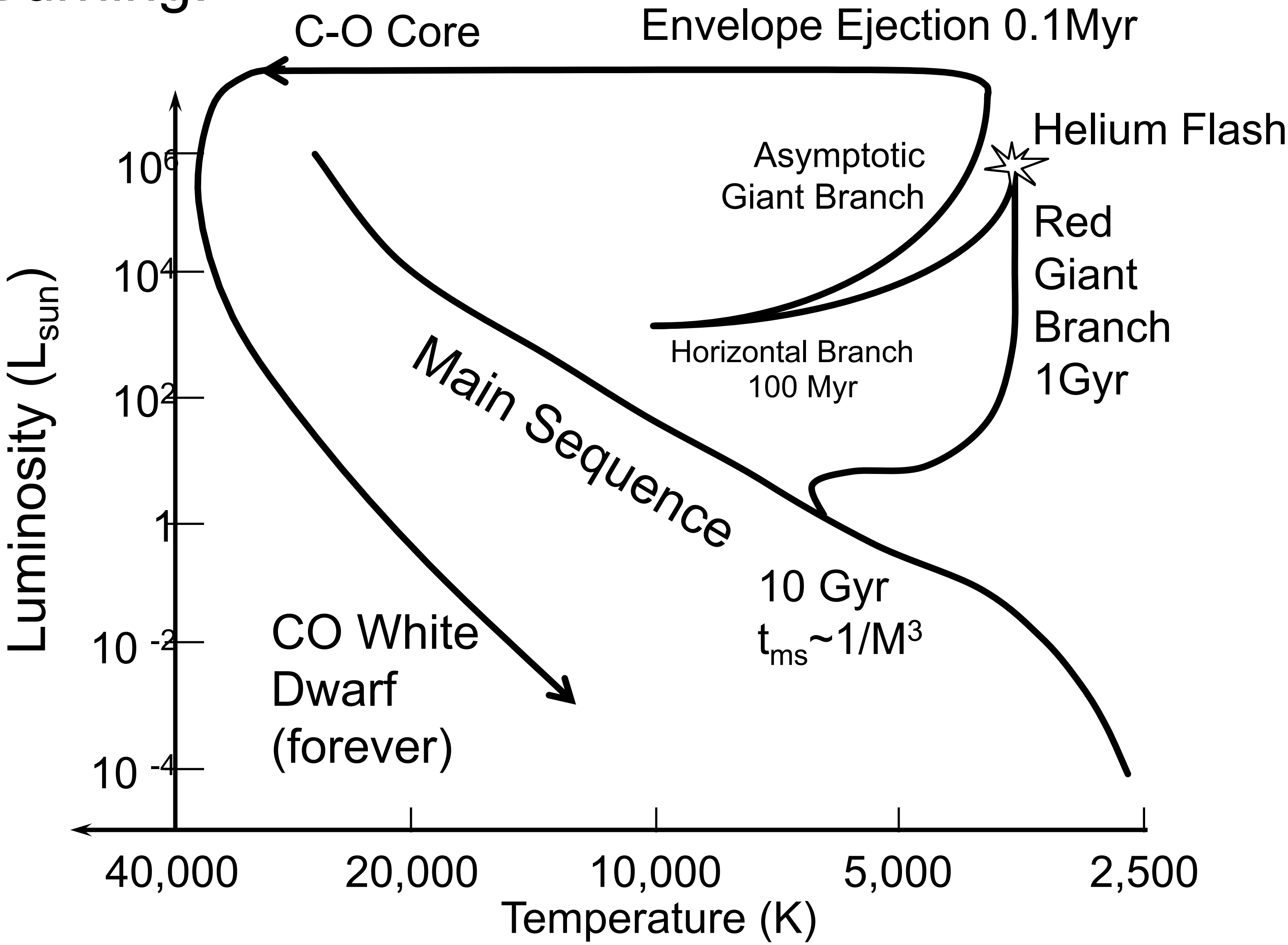
Open Clusters

- Young clusters of ~1000 stars
- Blue Main-Sequence stars & few giants

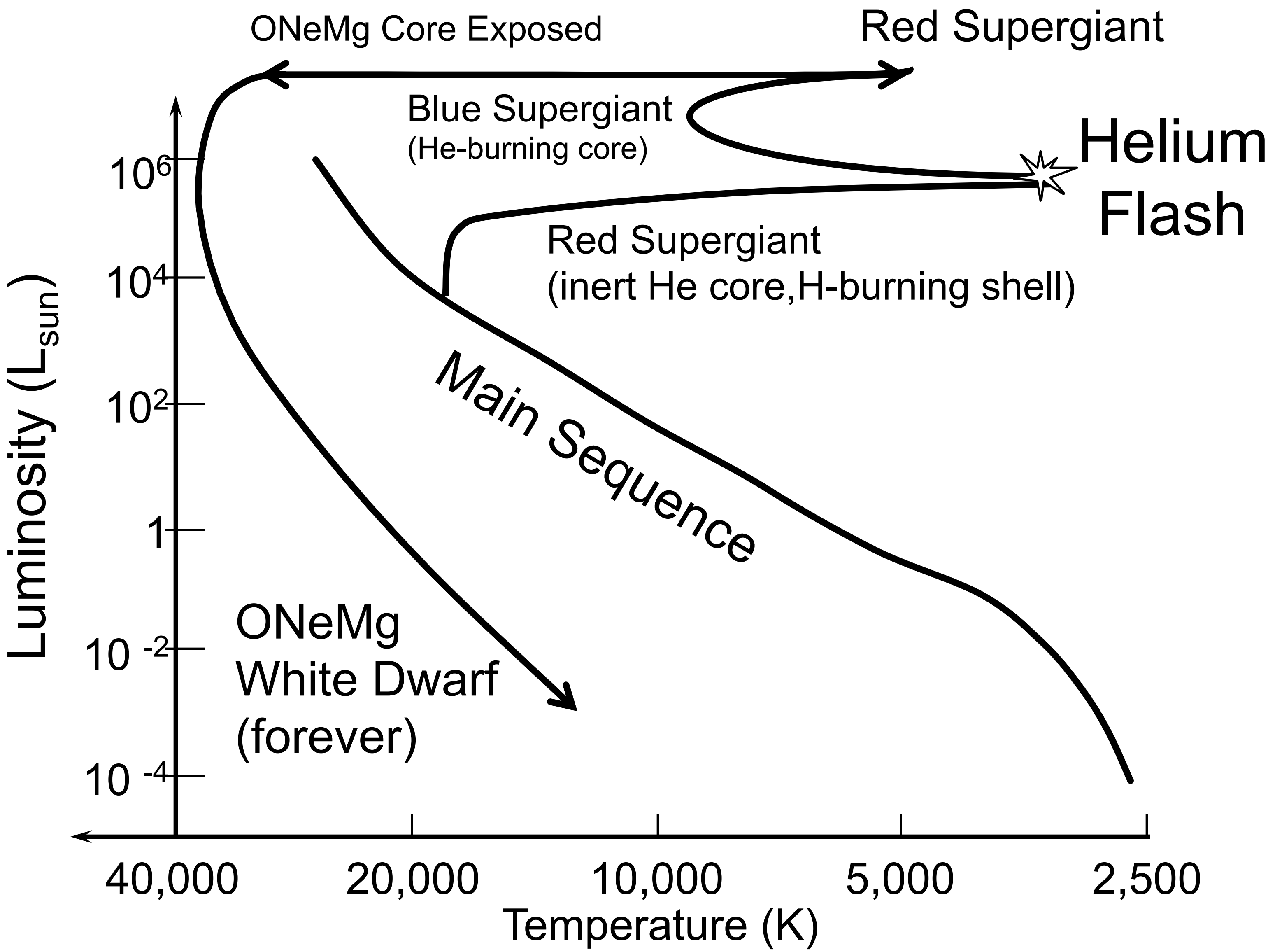
Globular Clusters

- Old clusters of a ~100,000 stars
- No blue Main-Sequence stars & many giants

Evolution of Low-Mass stars $M < 4\ M_{sun}$
No C Burning!

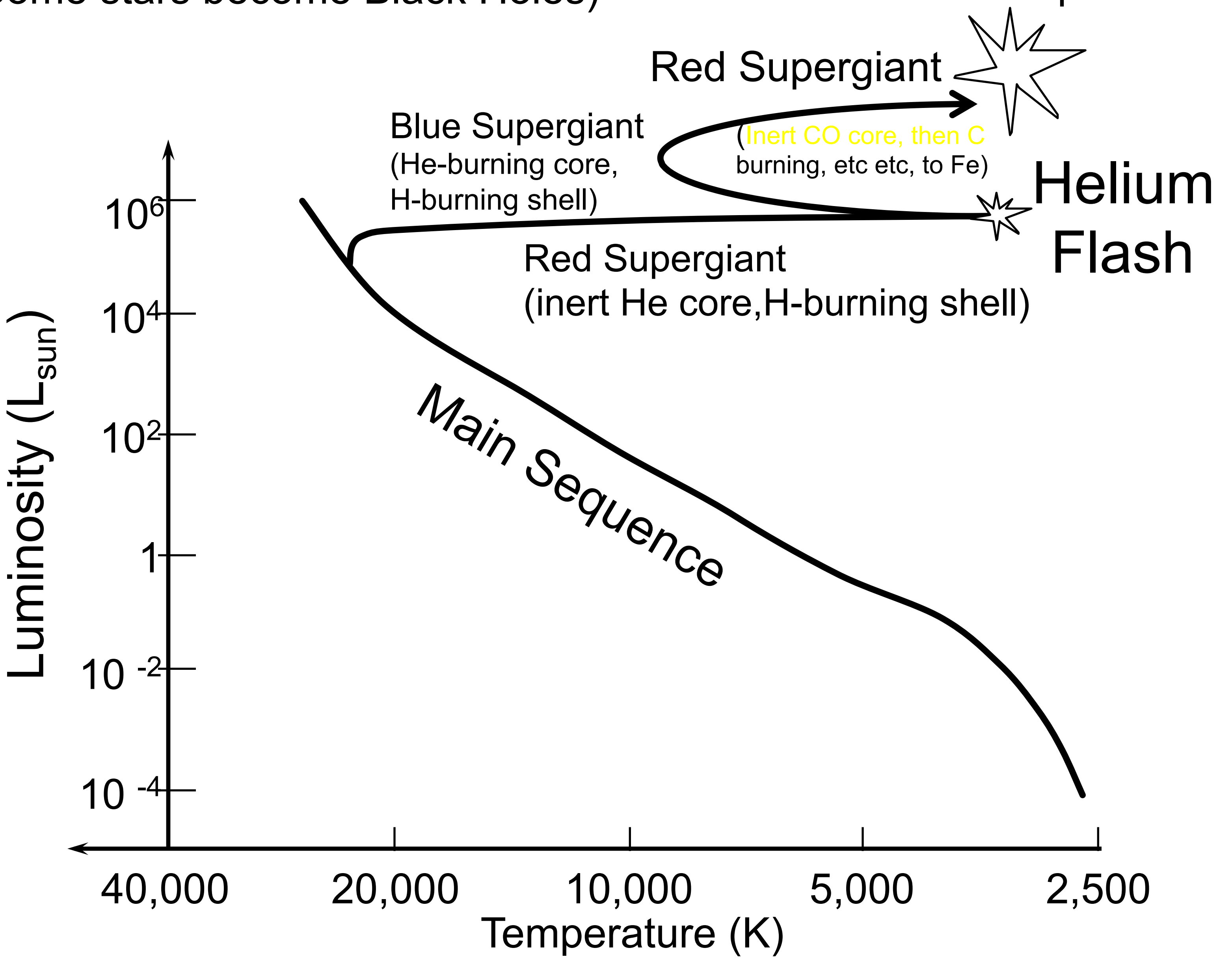


Intermediate Mass stars: $4 < M < 8\ M_{sun}$
C-burning, but nothing heavier



Massive stars: M > 8 M_{sun}

(Note: Some stars become Black Holes)



Testing Stellar Evolution

The Problem:

- Stellar Evolution happens on billion-year time scales.
- Astronomers only live for 10’s of years.
- So, how do we test our picture of stellar evolution?

The Solution:

- Make H-R Diagrams for star clusters with a wide range of ages.

What do you see? Think infants!

Star Clusters

Groups of 100-1000's of stars moving together through space.

All stars in a cluster...

- are at the same distance, so it is easy to measure their *relative* Luminosities
- have (almost) the same age ("coeval"); all the stars were born at the same time.
- have the same chemical composition; formed from the same gas blob (giant molecular cloud)
- have a wide range of stellar masses

Snapshot of how stars of *different masses* look at the *same age* (and composition)!

Galaxy with star clusters

The Main Sequence, Revisited

The Main Sequence is a Mass Sequence:

- High-mass stars are hot and high luminosity.
- Low-mass stars are cool and low luminosity.

Main Sequence Lifetime depends on Mass:

- High-mass stars have short M-S lifetimes
- Low-mass stars have long M-S lifetimes.

M-S Lifetime: $t_{ms} \sim 1/M^3$

Also, Low-Mass stars take longer to form (reach the M-S) than High-Mass stars.

Progressive Evolution

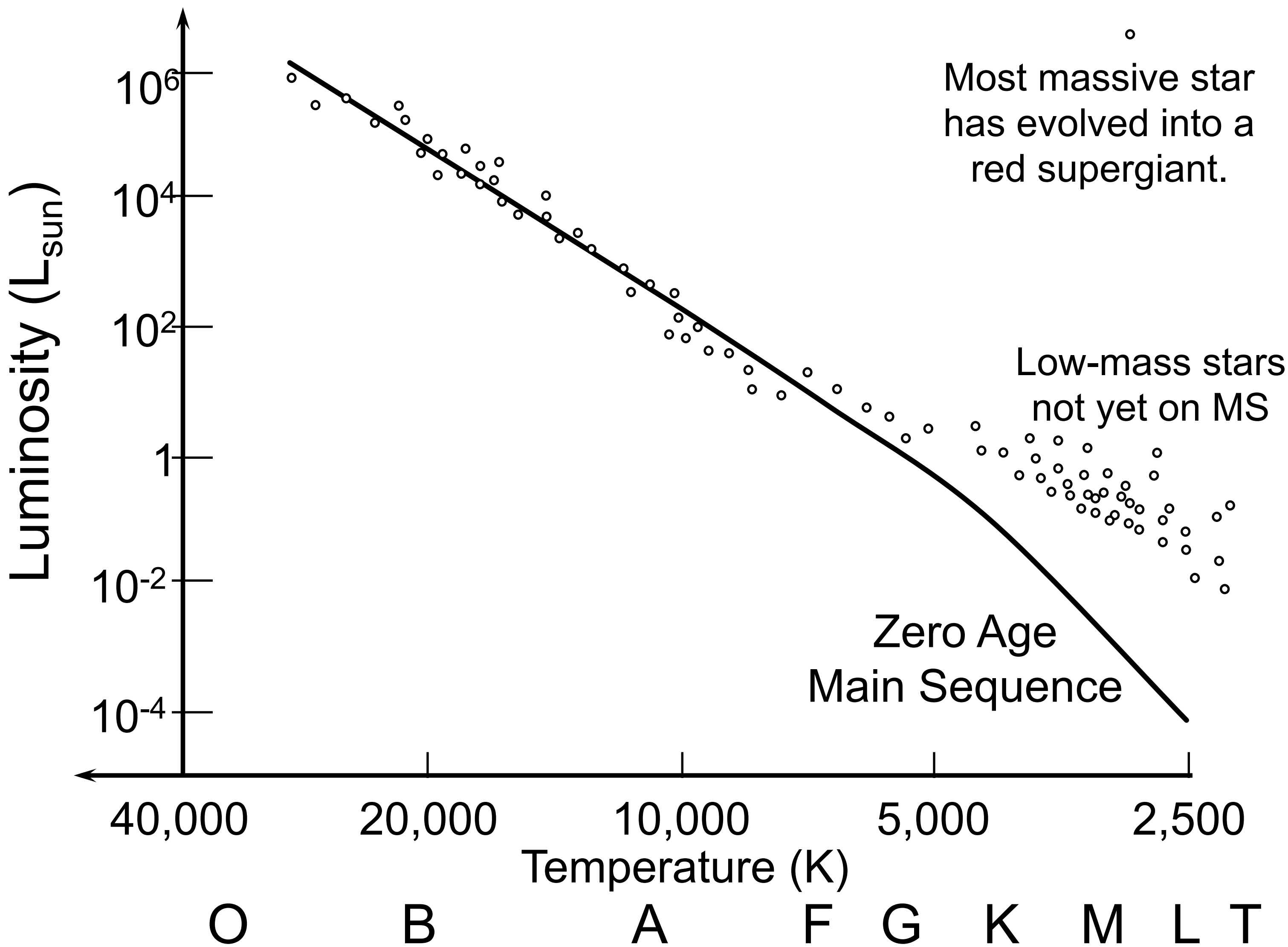
As a cluster ages:

- High-mass stars reach the M-S first, with the low-mass stars still approaching.
- High-mass stars run out of hydrogen in their cores first, evolving into supergiants.
- As successively lower mass stars run out of hydrogen in their cores, they too evolve off the MS.

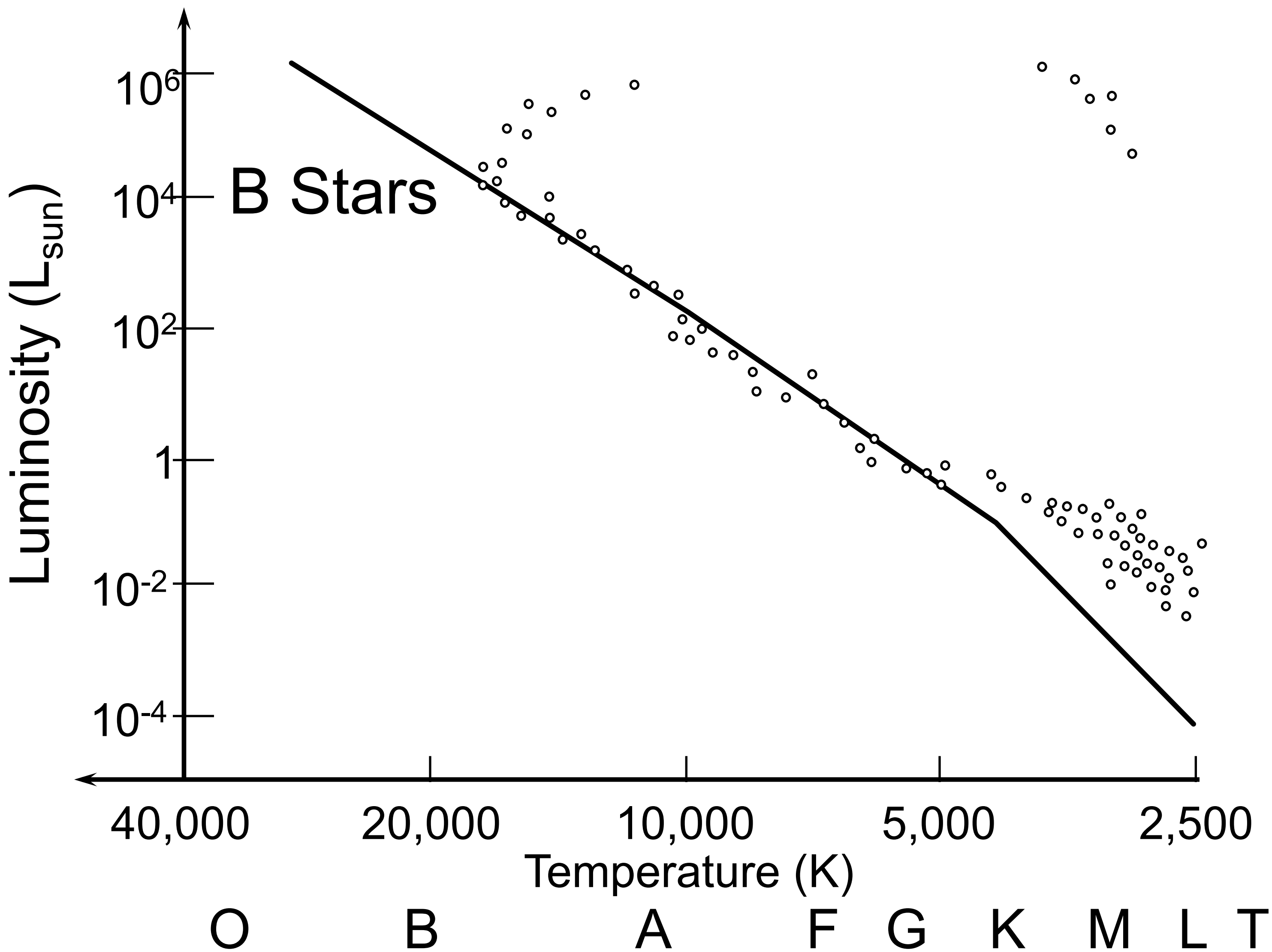
Effect is that stars peel off the Main Sequence from the top (high-mass end) on down as the cluster ages.

Star cluster

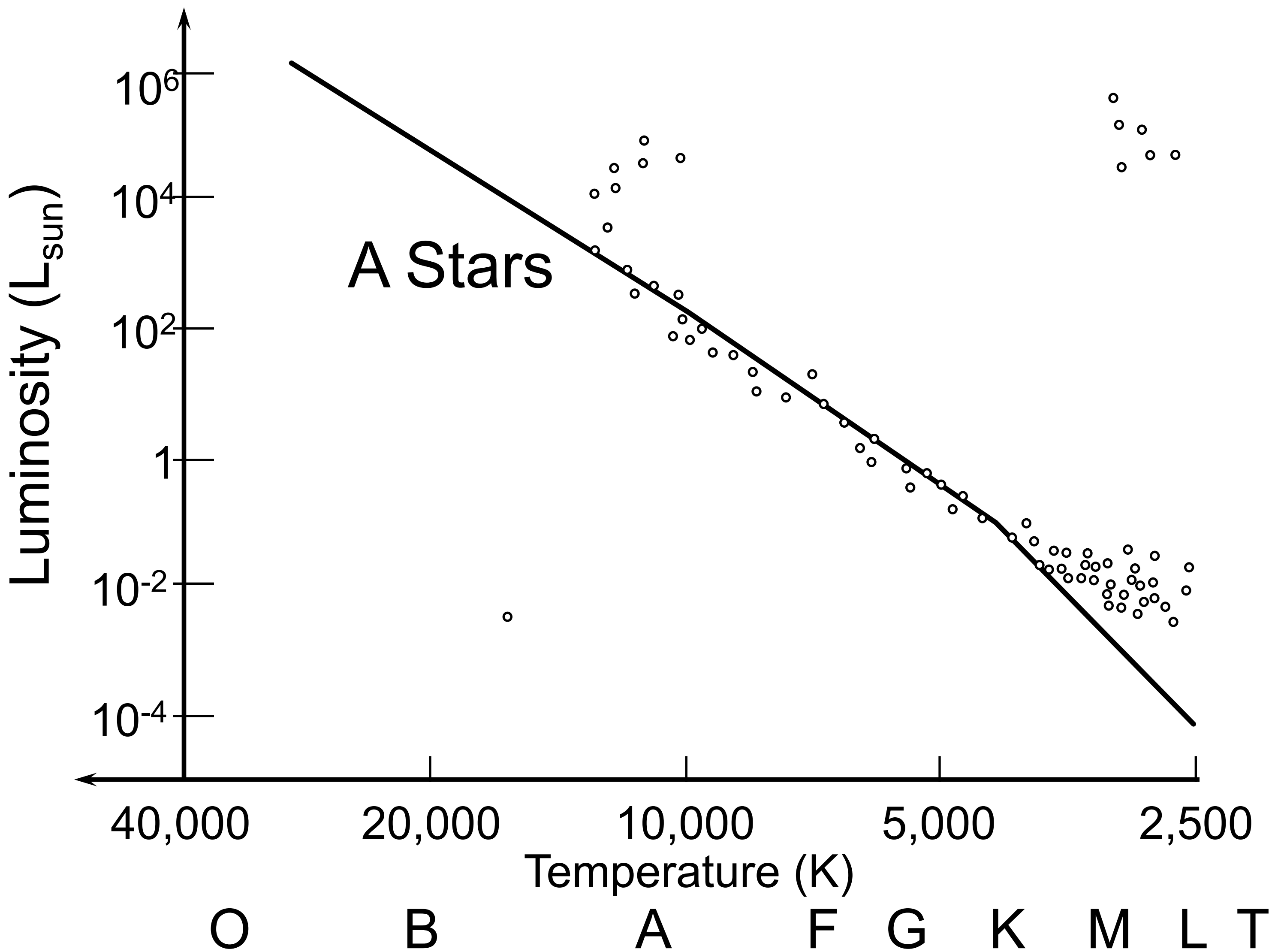
~1 Myr old cluster



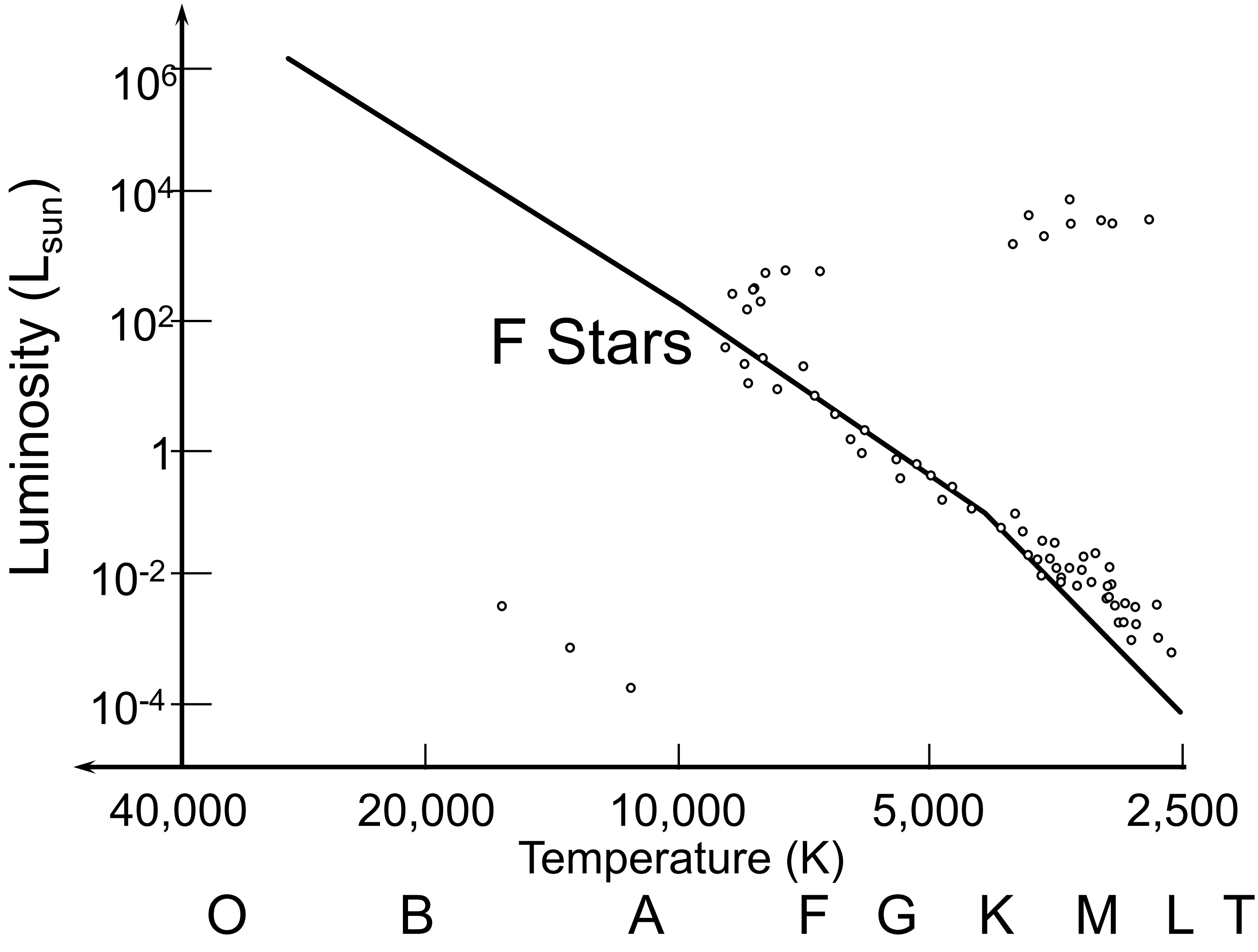
~10 Myr old cluster

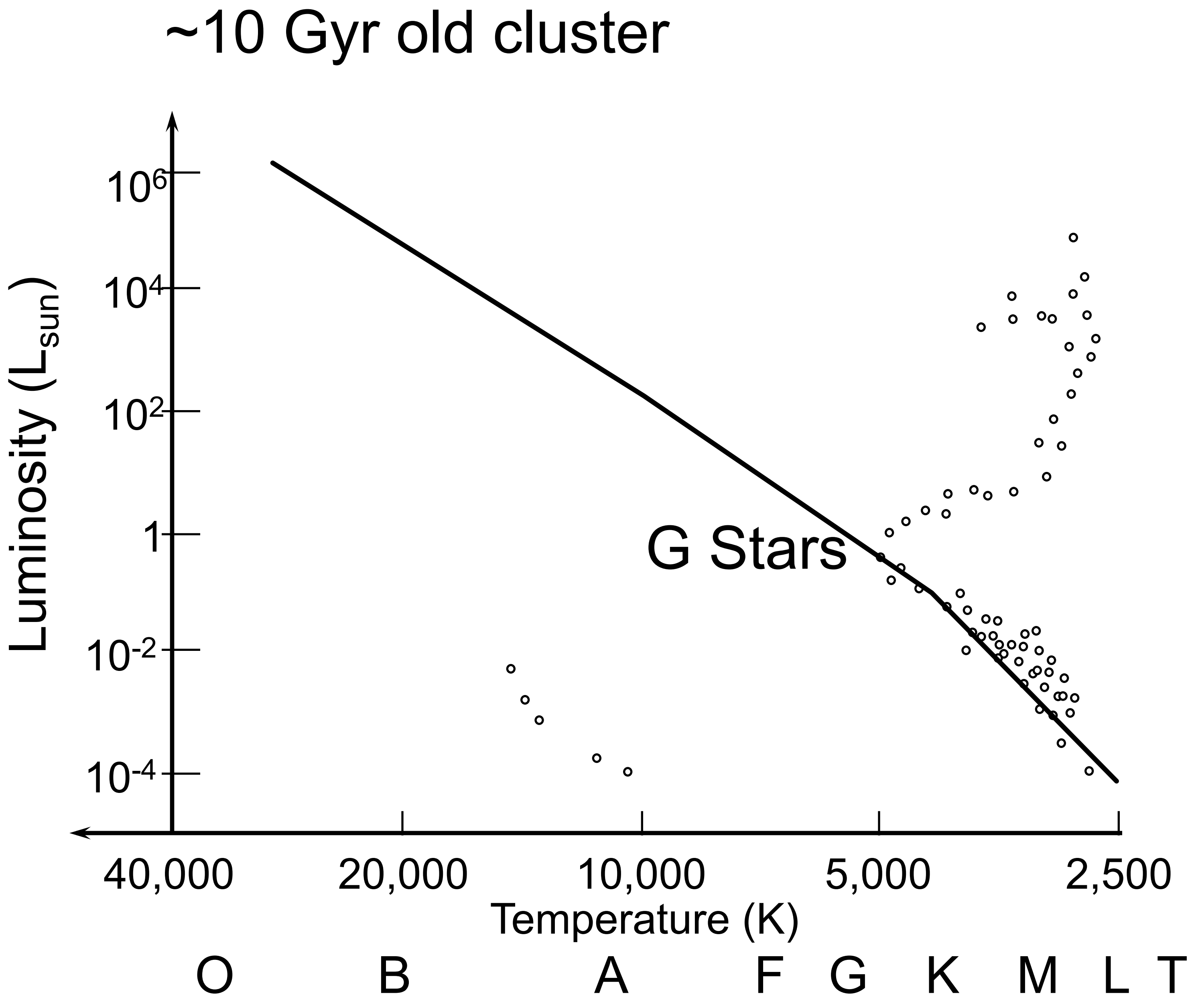


~100 Myr old cluster



~1 Gyr old cluster




~10 Gyr old cluster
Luminosity (L_sun)
10^6
10^4
10^2
1
10^-2
10^-4
G Stars
40,000
20,000
10,000
5,000
2,500
Temperature (K)
O
B
A
F
G
K
M
L
T

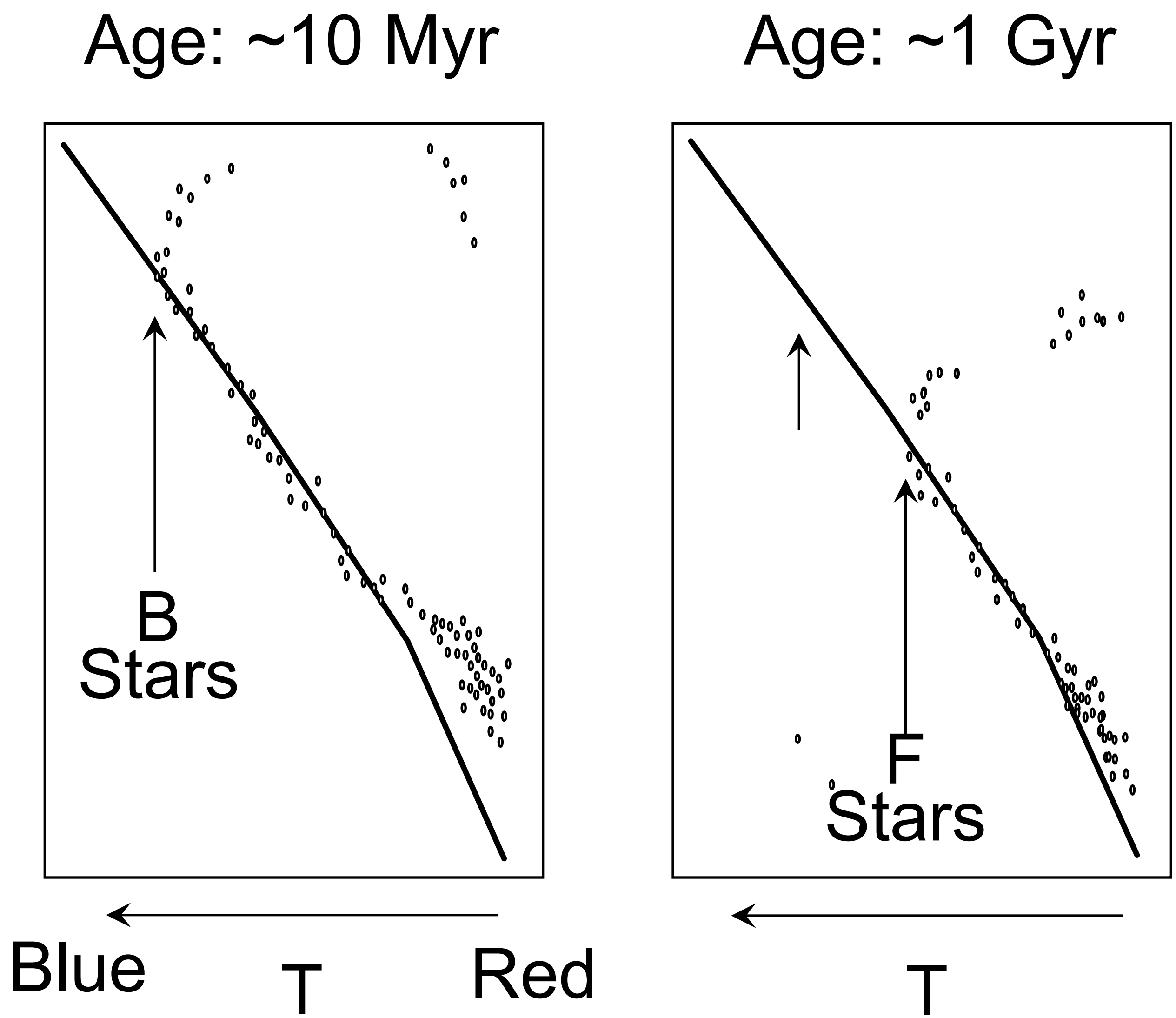
Main Sequence Turn-off

Point where the Main-Sequence **“turns off”** towards giant stars.

- As cluster ages, the stars at the turn-off are lower mass, redder, cooler, lower luminosity

Indicator of the cluster age:

- Older Clusters have redder and fainter turn-offs.
- As time goes by, less-massive stars leave MS.


Age: ~10 Myr
Age: ~1 Gyr
B
Stars
F
Stars
Blue
T
Red
T

Open Clusters

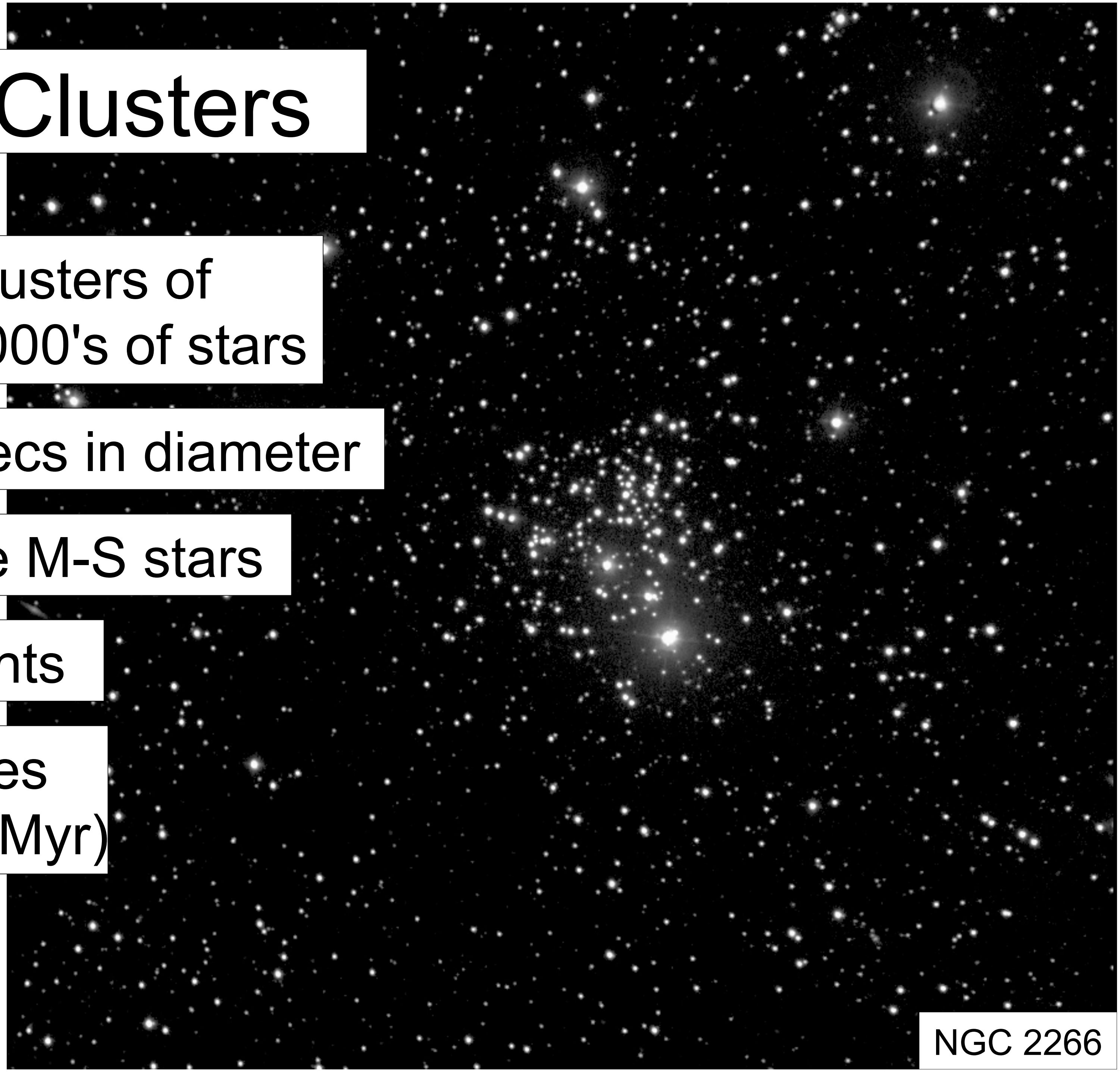
Sparse Clusters of 100’s – 1000's of stars

Few parsecs in diameter

Many blue M-S stars

A few Giants

Young Ages (100’s of Myr)



NGC 2266

Globular Clusters

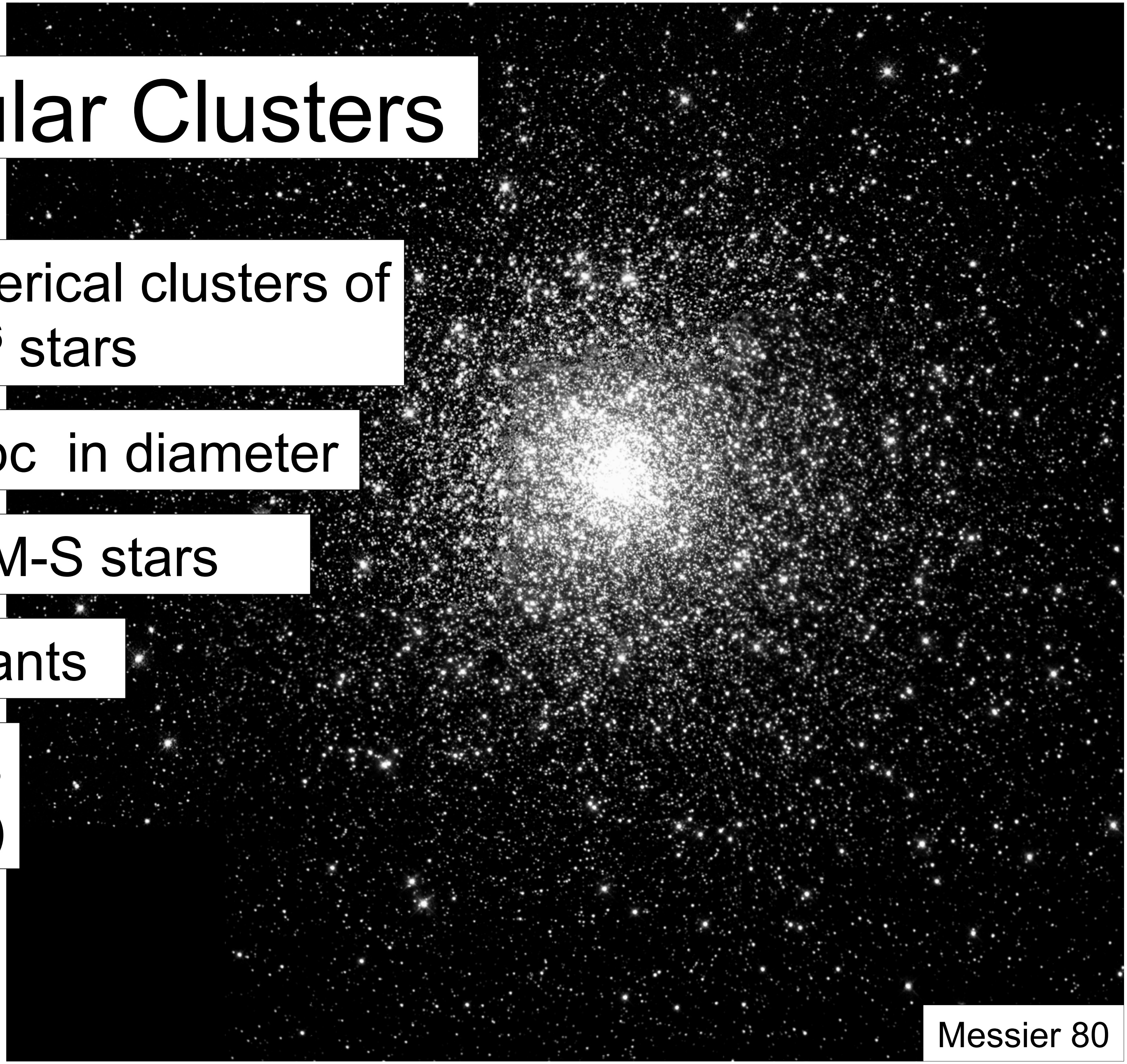
Rich spherical clusters of $10^5 – 10^6$ stars

10 – 30 pc in diameter

No blue M-S stars

Many Giants

Old Ages (few Gyr)



Messier 80

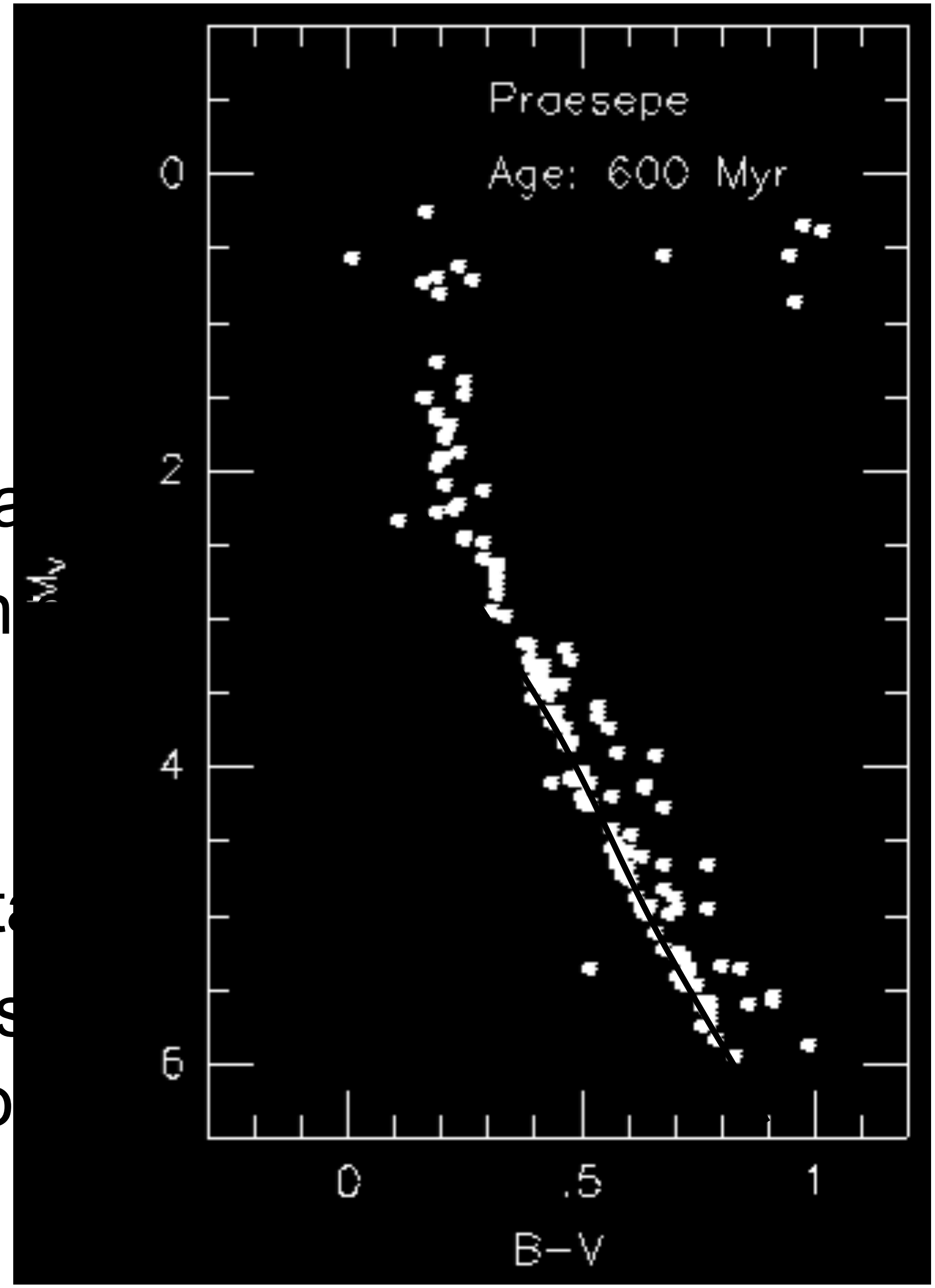
Open Clusters

H-R Diagrams of Open Clusters show:

- They are young to middle-aged
- Have blue Main-Sequence stars
- Few supergiants or giants
- Older Open clusters have more red giants
- Youngest still have gas clouds associated

Open Clusters

- Young to middle-aged
- Blue Main-Sequence sta
- Few supergiants or gian
- Old Open clusters have Red Giant stars
- No Horizontal Branch sta
- Youngest Open Clusters have associated gas clo

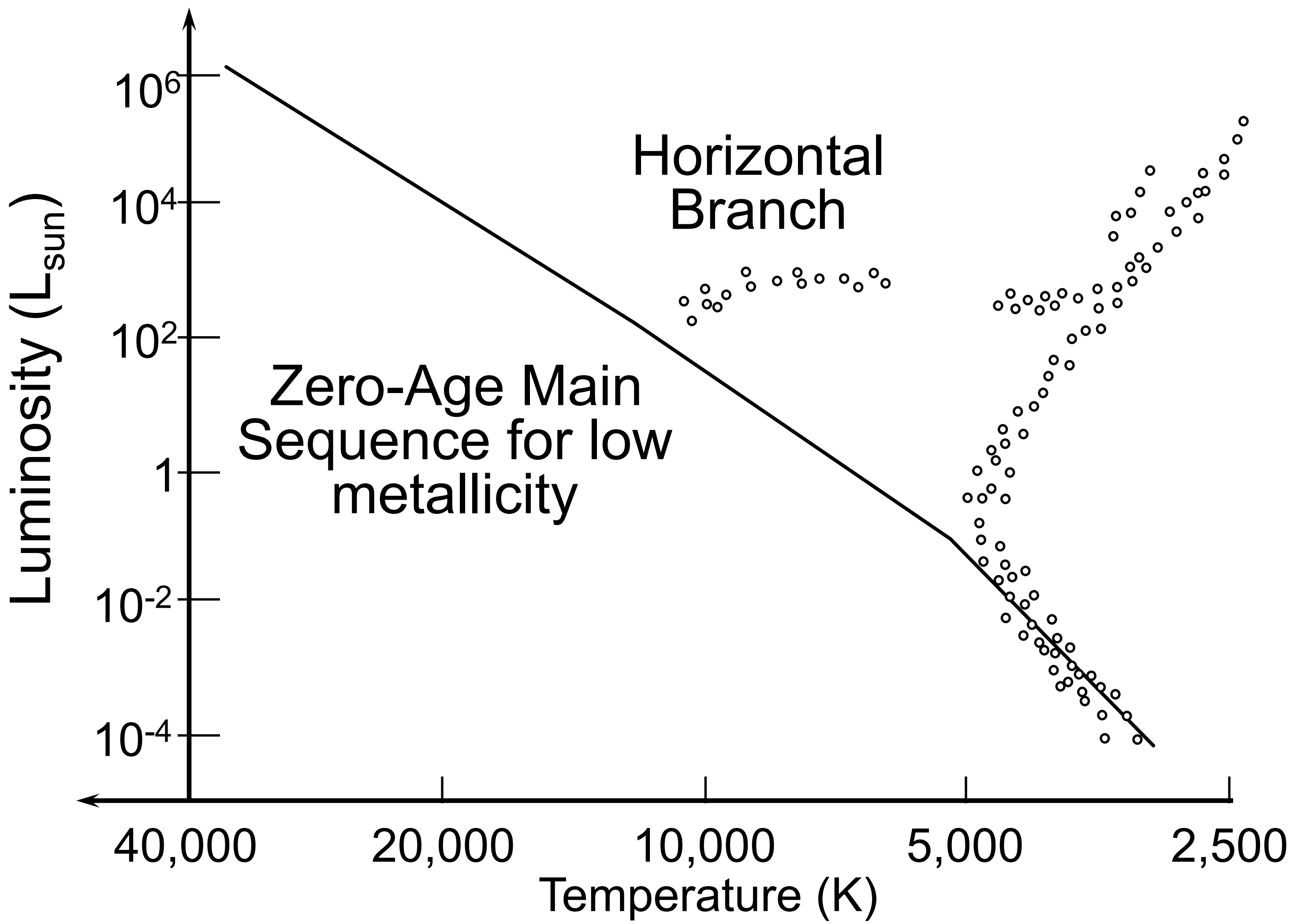


Globular Clusters

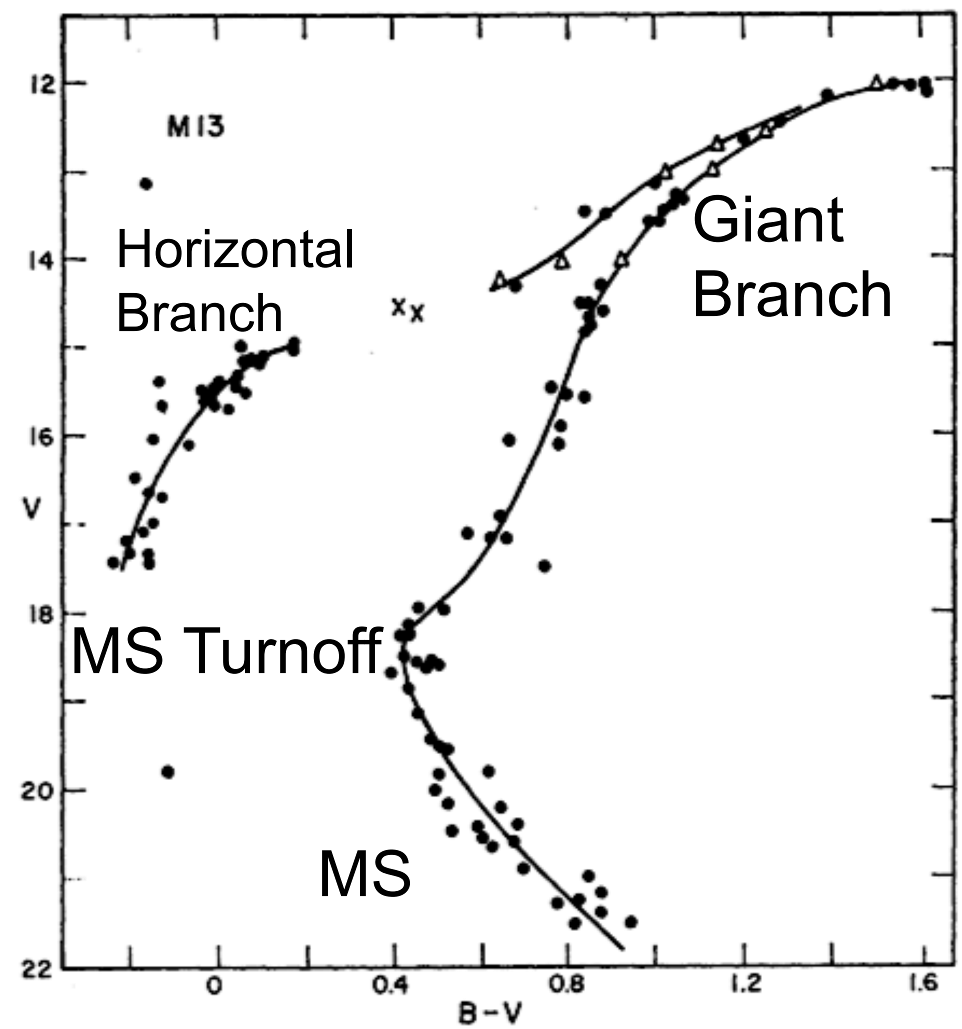
H-R Diagrams of Globular Clusters:

- Very old ages: 10−13 Billion Years
- Red turnoffs and no blue Main-Sequence stars
- Many Red Giants
- No Supergiants
- A prominent Horizontal Branch
- Slightly bluer and fainter Main Sequence due to having much less metals.

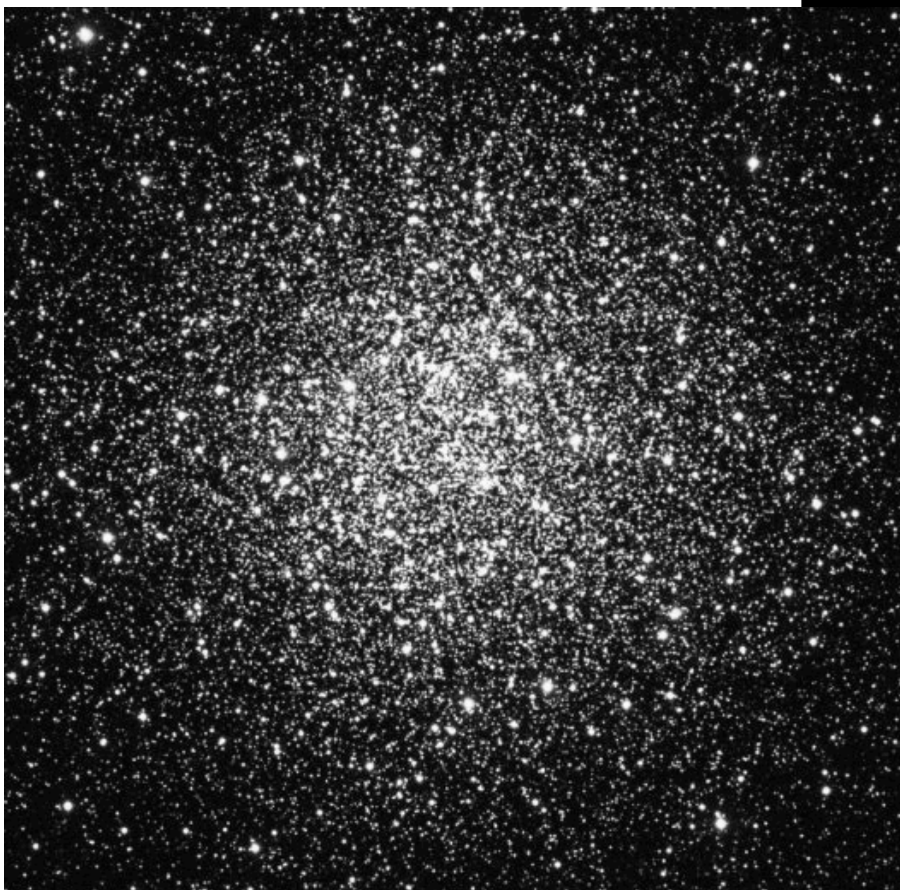
Typical Globular Cluster H-R Diagram

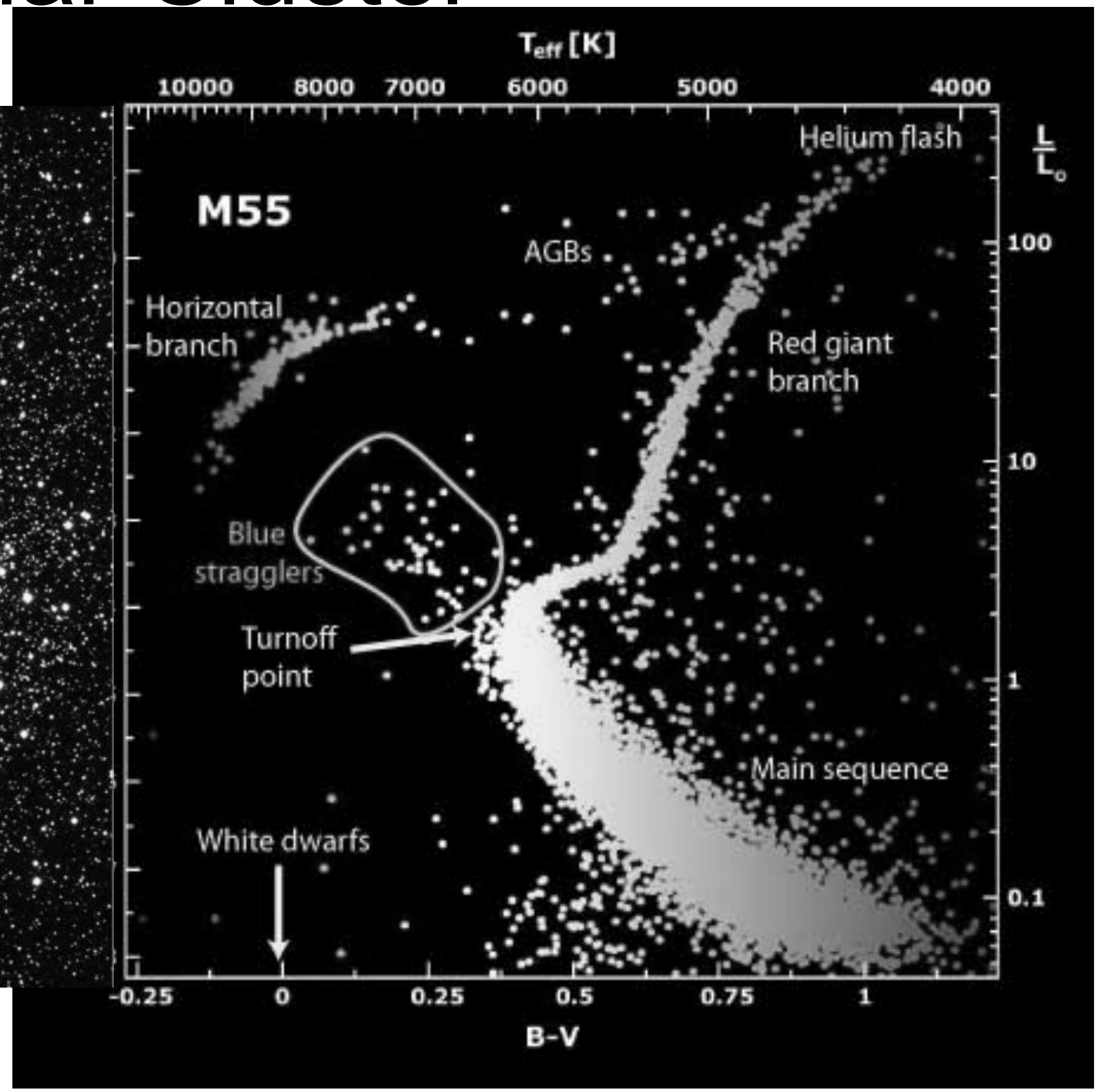


Globular Cluster HR Diagram

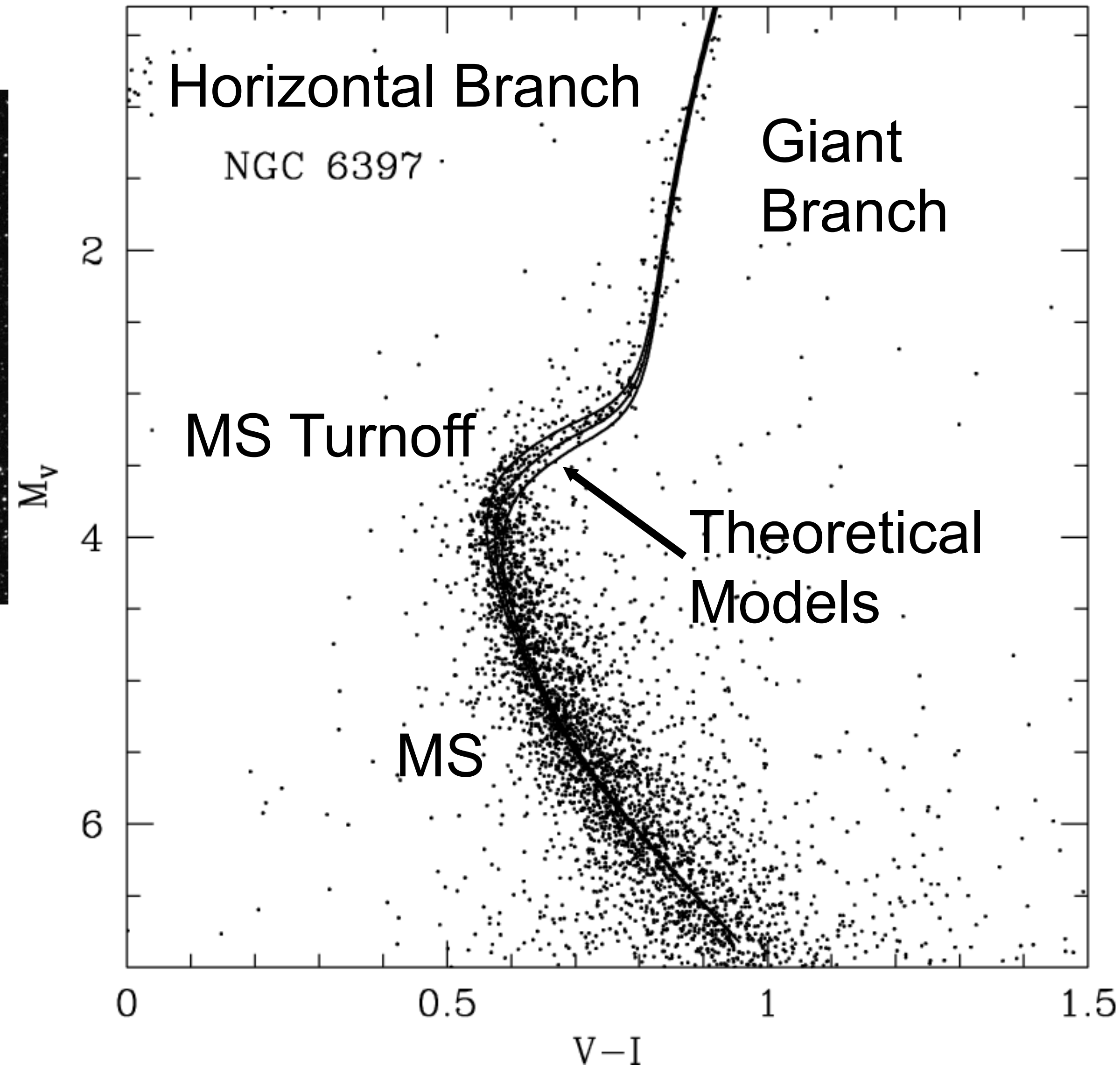


Another Globular Cluster





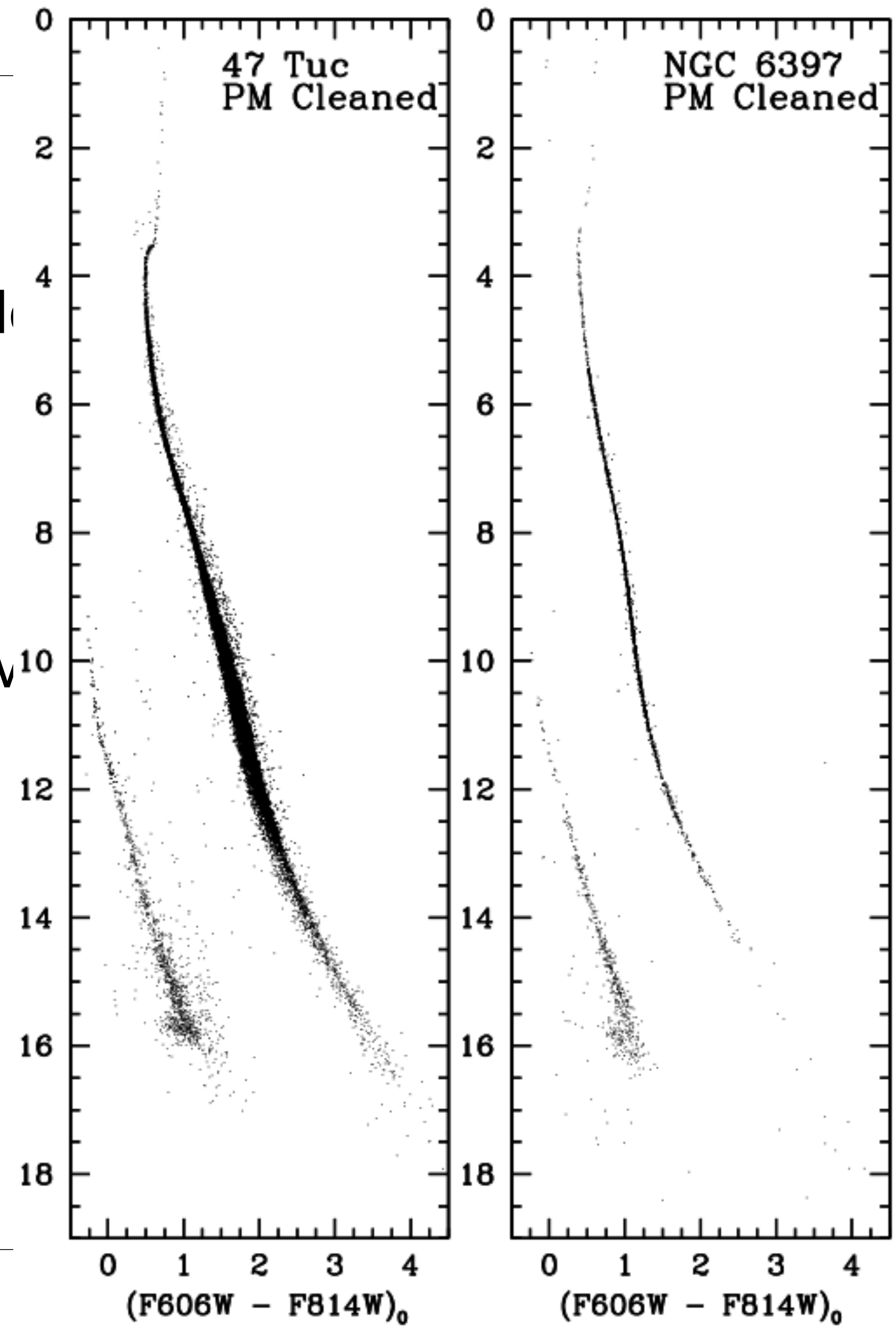
Globular Cluster HR Diagram



Globular Cluster HR Diagrams:

THIN MS and WD cooling sequence!

Youngest to oldest.



Conclusions of the Tests

Cluster H-R Diagrams give us a snapshot of stellar evolution, show the evolution of a coeval population.

Observations of clusters with ages from a few Million to 13 Billion years confirms much of our picture of stellar evolution: because we can compare with theoretical models of stellar evolution!

Theory predicts that stars should evolve from a MS, to red giants, to horizontal branch, to asymptotic giant branch, to white dwarfs, and they are seen to.

Hydrostatic equilibrium + Thermal equilibrium + Fusion