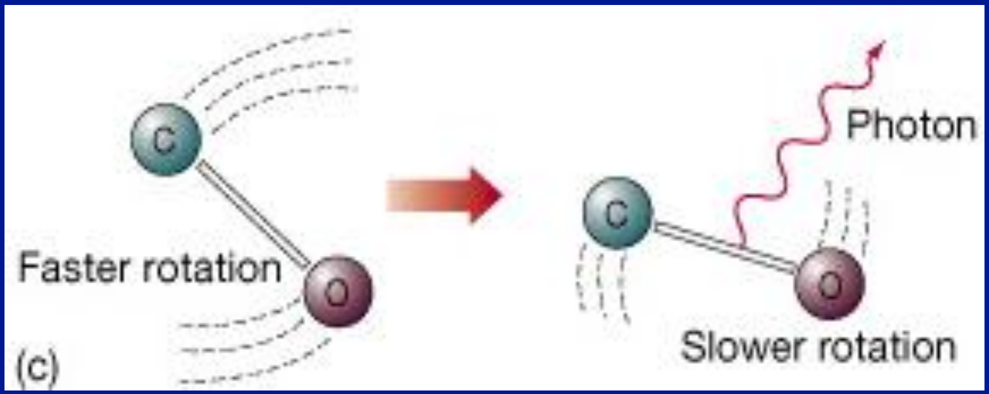
We can observe emission from molecules. Most abundant is H_2 (don't confuse with H II), but its emission is extremely weak, so other "trace" molecules observed:

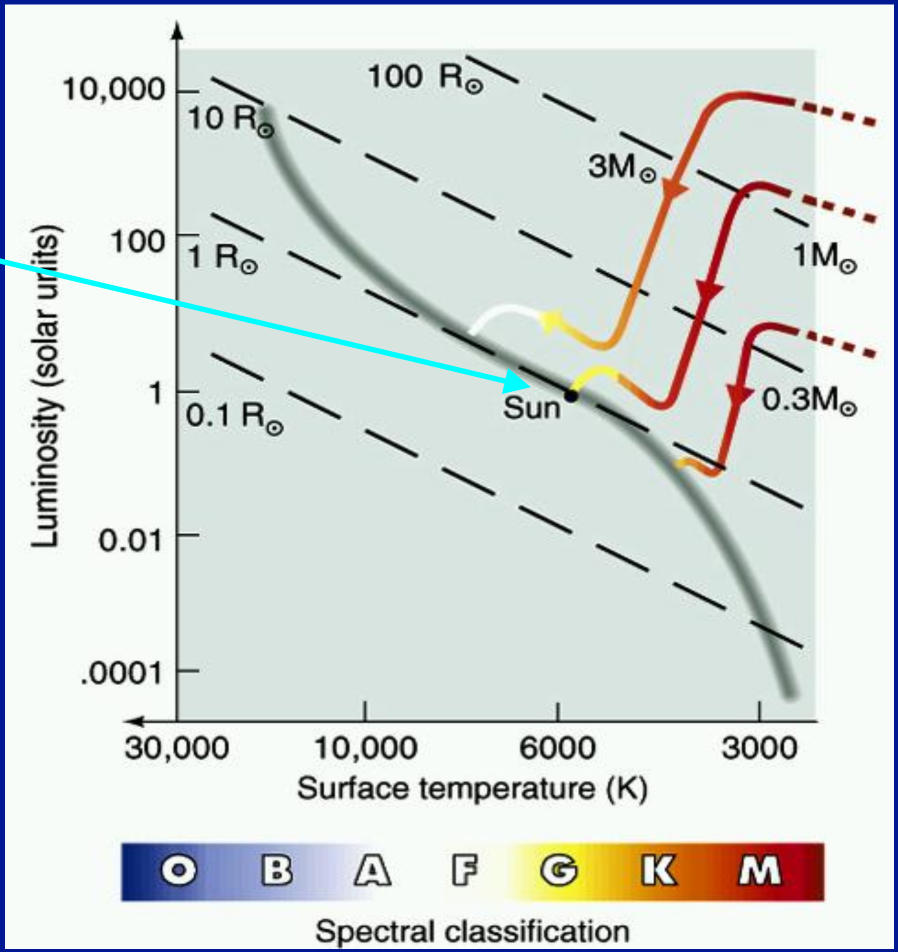
CO	(carbon monoxide)
H_2O	(water vapor)
HCN	(hydrogen cyanide)
NH_3	(ammonia)
etc. . .	

These emit photons with wavelengths near 1 mm when they make a rotational energy level transition. Observed with radio telescopes.



Finally, fusion starts, stopping collapse: a star!

Star reaches Main Sequence at end of Hayashi Track



One cloud (10^3 - 10^6 M_{Sun}) forms many stars, mainly in clusters, in different parts at different times.

Massive stars (50-100 M_{Sun}) take about 10^6 years to form, least massive (0.1 M_{Sun}) about 10^9 years. Lower mass stars more likely to form. In Milky Way, a few stars form every year.

Stellar Evolution: Evolution off the Main Sequence

Main Sequence Lifetimes

Most massive (O and B stars): millions of years

Stars like the Sun (G stars): billions of years

Low mass stars (K and M stars): a trillion years!

While on Main Sequence, stellar core has H -> He fusion, by p-p chain in stars like Sun or less massive. In more massive stars, "CNO cycle" becomes more important.

Evolution of a Low-Mass Star
(< 8 M_{sun} , focus on 1 M_{sun} case)

- All H converted to He in core.

- Core too cool for He burning. Contracts. Heats up.

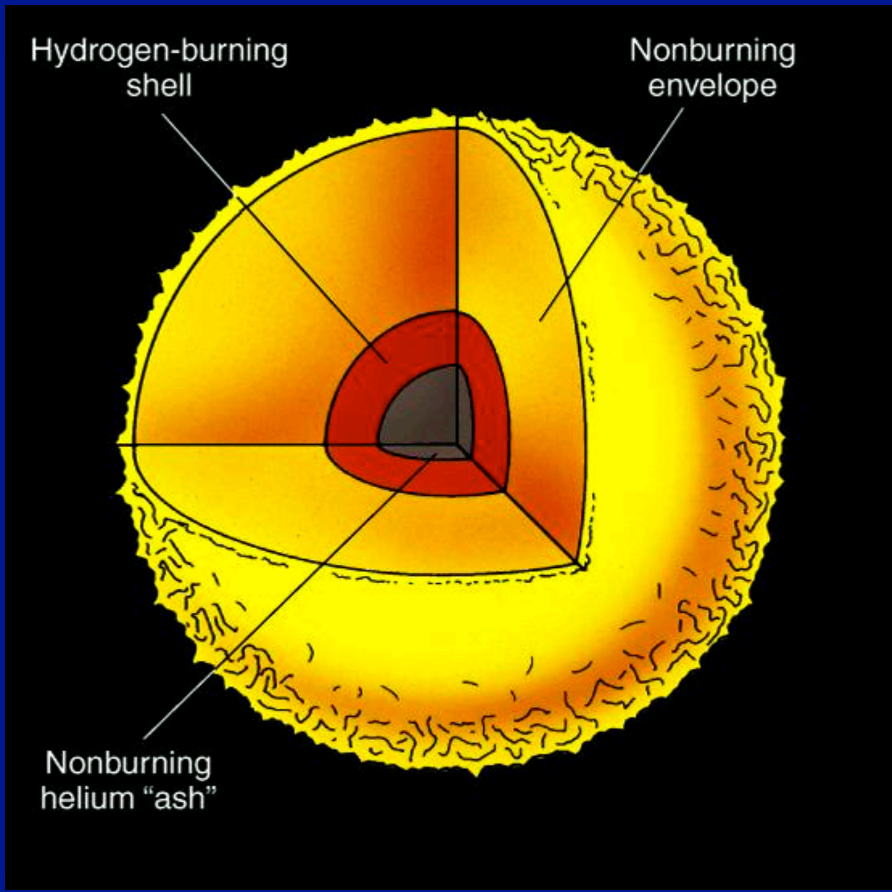
- H burns in shell around core: "H-shell burning phase".

- Tremendous energy produced. Star must expand.

- Star now a "Red Giant". Diameter ~ 1 AU!

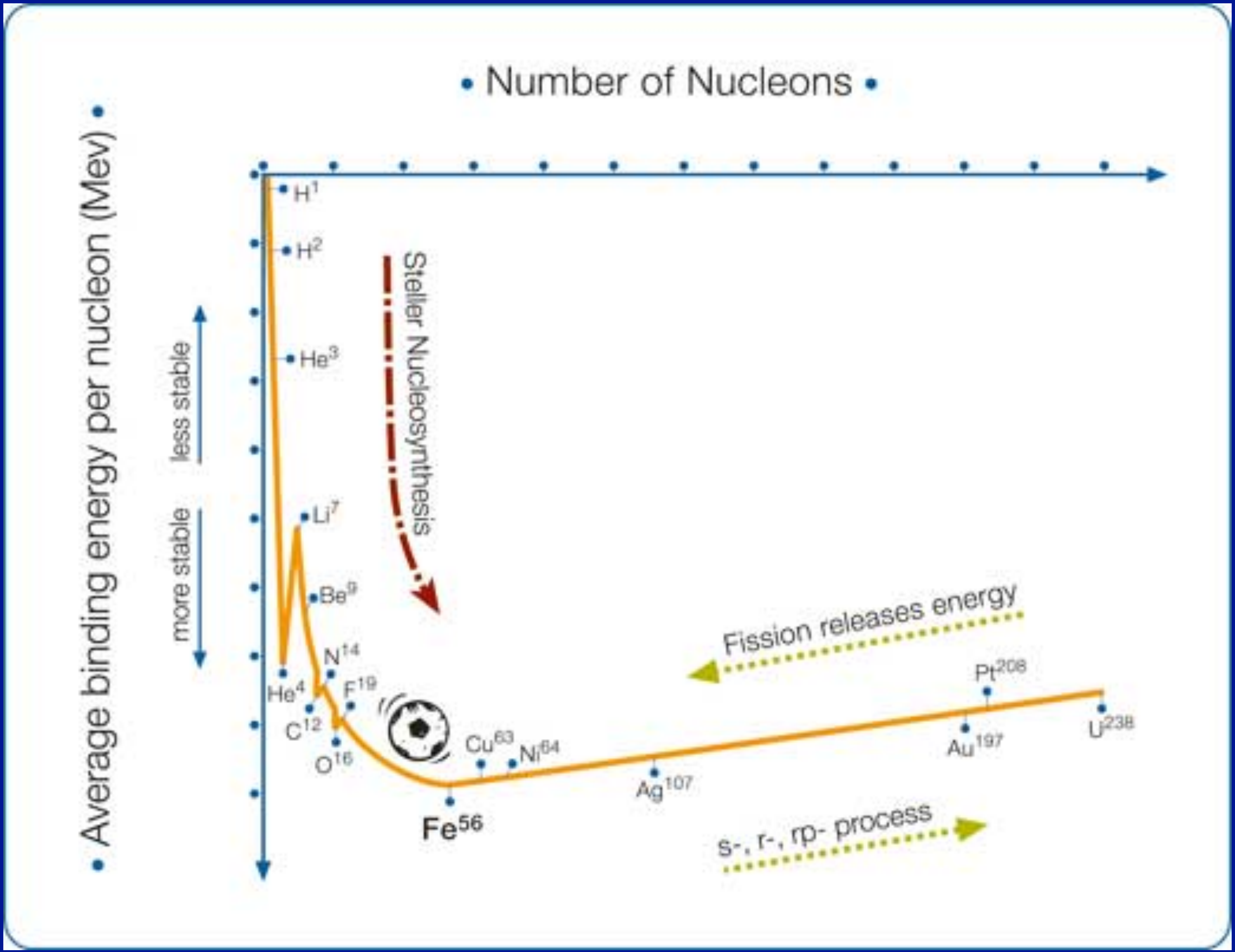
- Phase lasts ~ 10^9 years for 1 M_{Sun} star.

- Example: Arcturus

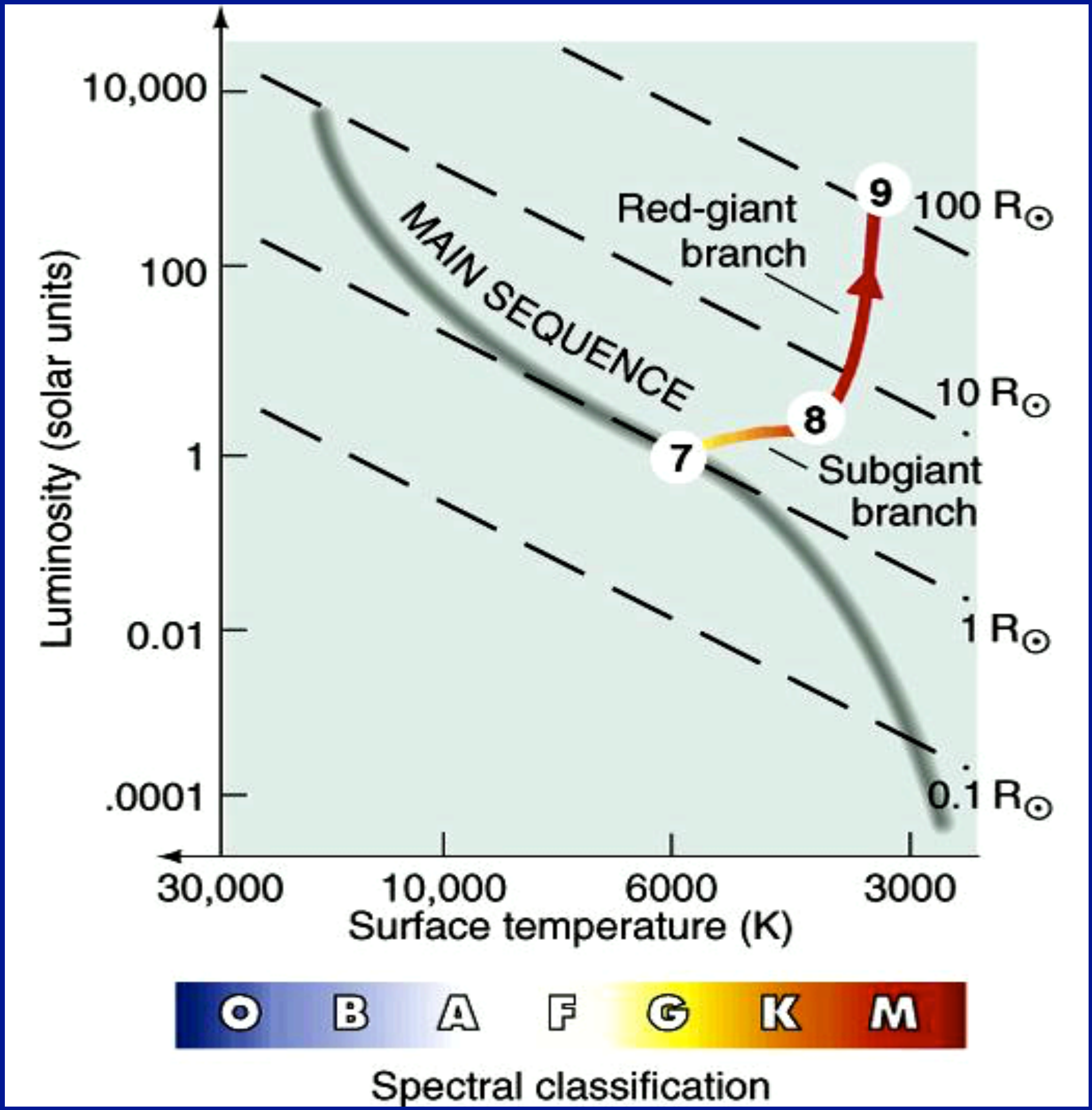


Red Giant

Binding Energy per nucleon



Red Giant Star on H-R Diagram



Eventually: Core Helium Fusion

- Core shrinks and heats up to 10^8 K, helium can now burn into carbon.

"Triple-alpha process"

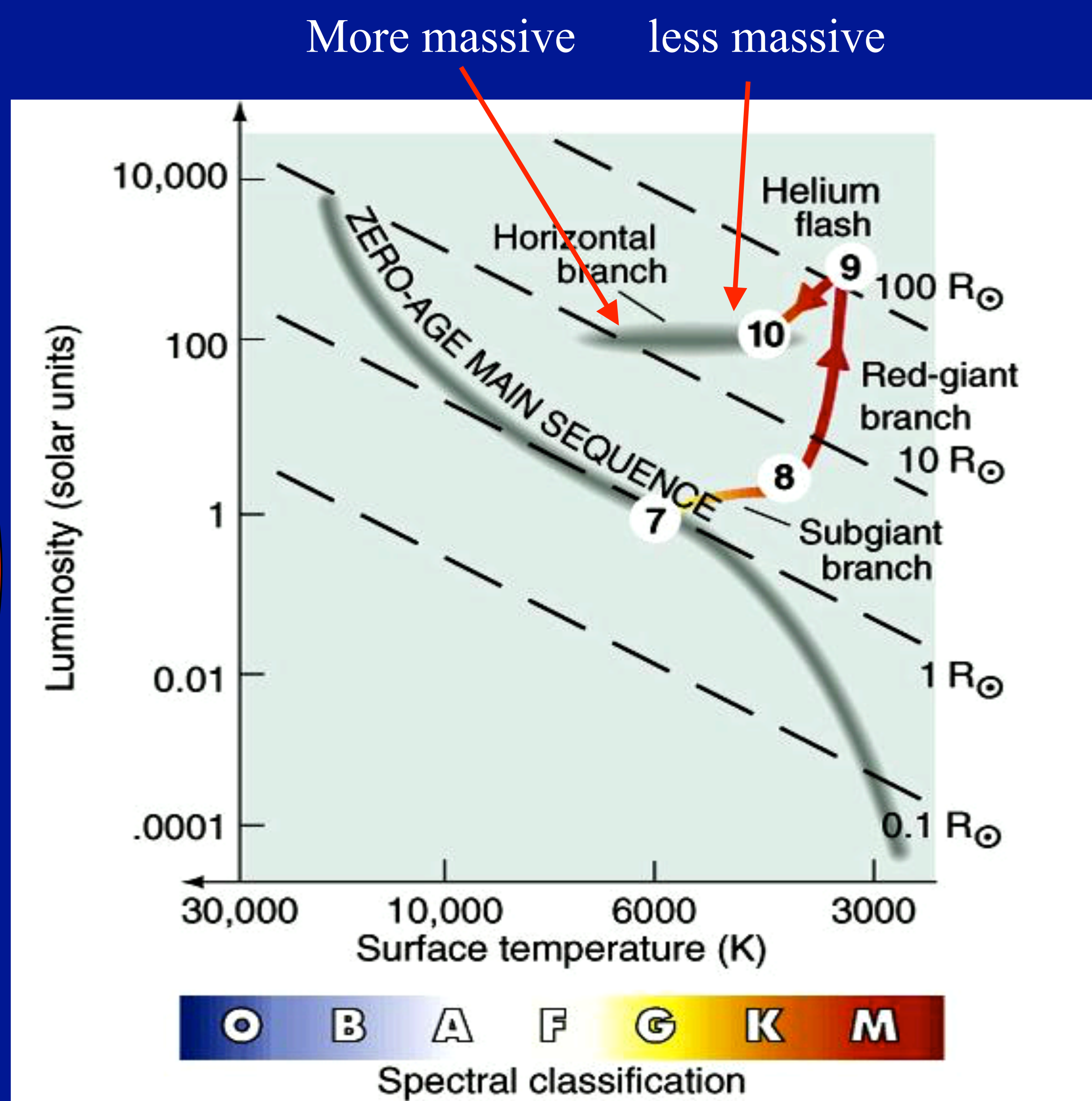
$$^{4}He + {}^{4}He \rightarrow {}^{8}Be - \text{energy}$$
$$^{8}Be + {}^{4}He \rightarrow {}^{12}C + \text{energy}$$

- Occurs in a runaway process: "the helium flash". Energy from fusion goes into re-expanding and cooling the core. Takes only a few seconds! This slows fusion, so star gets dimmer again.

- Then stable He -> C burning. Still have H -> He shell burning surrounding it.

- Now star on "Horizontal Branch" of H-R diagram. Lasts ~10^8 years for 1 M_{Sun} star.

Horizontal branch star structure



Helium Runs out in Core

- All He -> C. Not hot enough for C fusion.

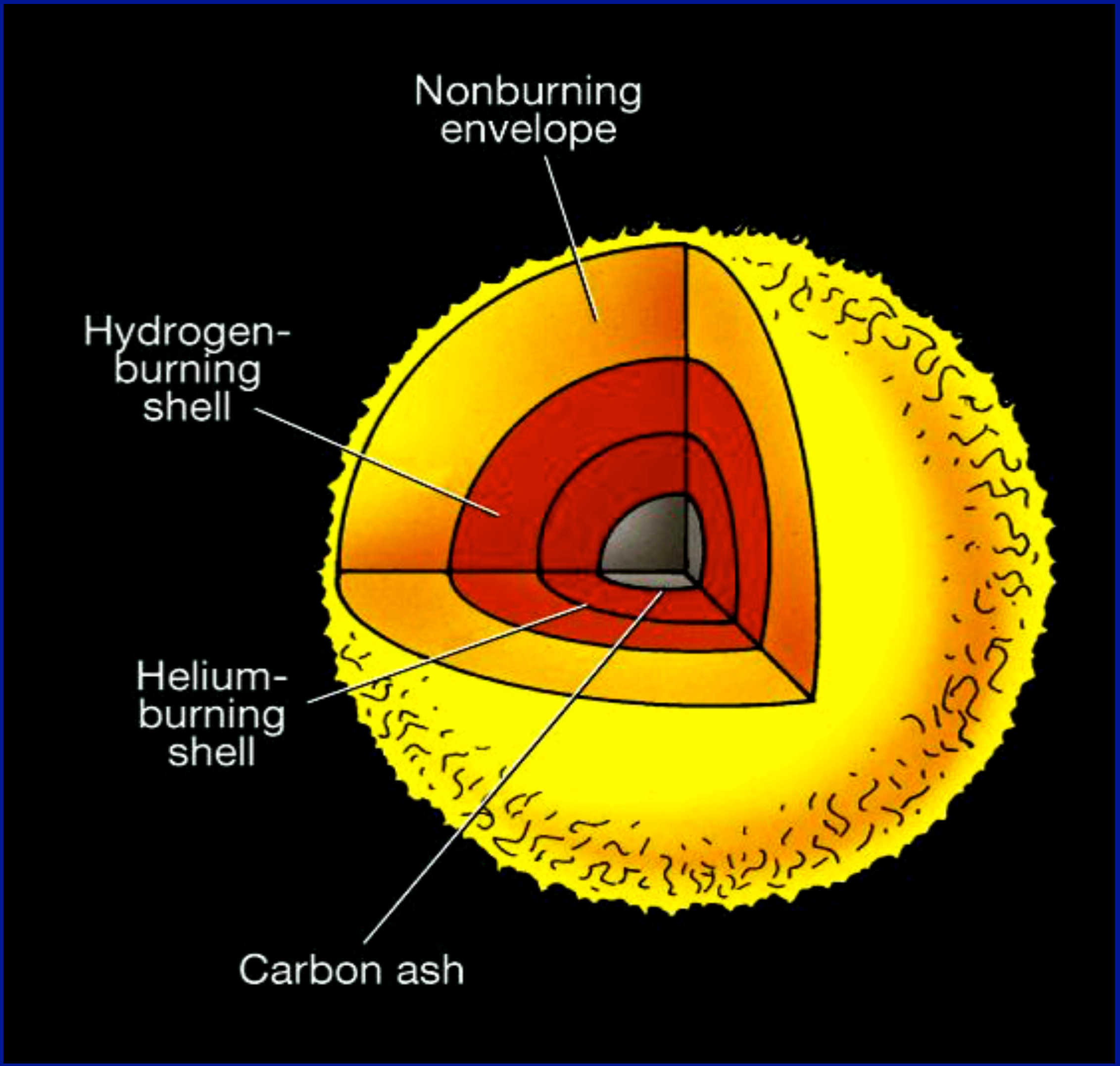
- Core shrinks and heats up.

- Get new helium burning shell (inside H burning shell).

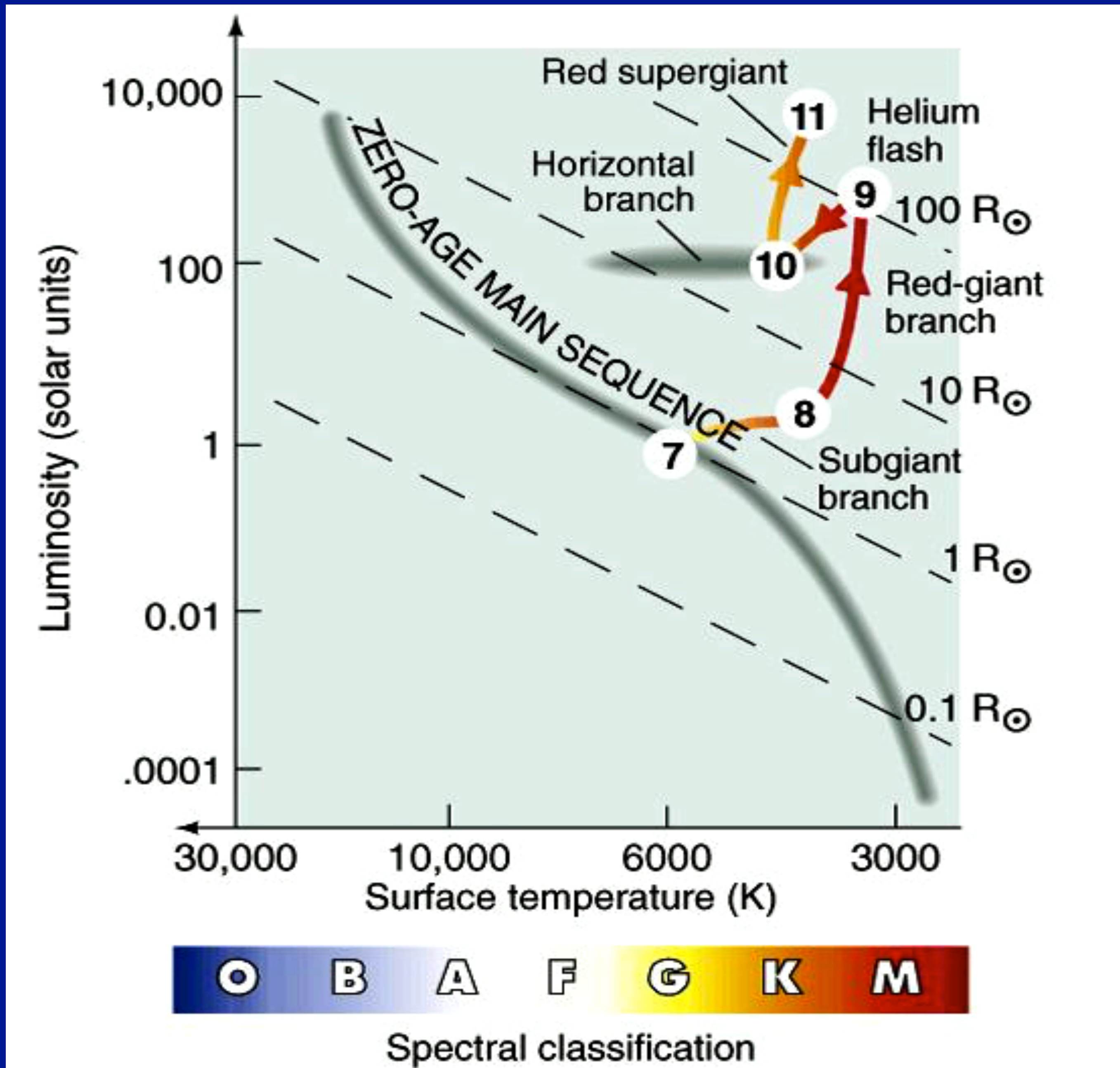
- High rate of burning, star expands, luminosity way up.

- Called "Red Supergiant" (or Asymptotic Giant Branch) phase.

- Only ~10^6 years for 1 M_{Sun} star.



Red Supergiant



Red supergiant
Helium flash
Horizontal branch
Red-giant branch
Subgiant branch
ZERO-AGE MAIN SEQUENCE
11
9
10
8
7
10,000
100
1
0.01
.0001
Luminosity (solar units)
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
30,000
10,000
6000
3000
Surface temperature (K)
O
B
A
F
G
K
M
Spectral classification

"Planetary Nebulae"

- Core continues to contract. Never gets hot enough for carbon fusion.

- Helium shell burning becomes unstable -> "helium shell flashes".

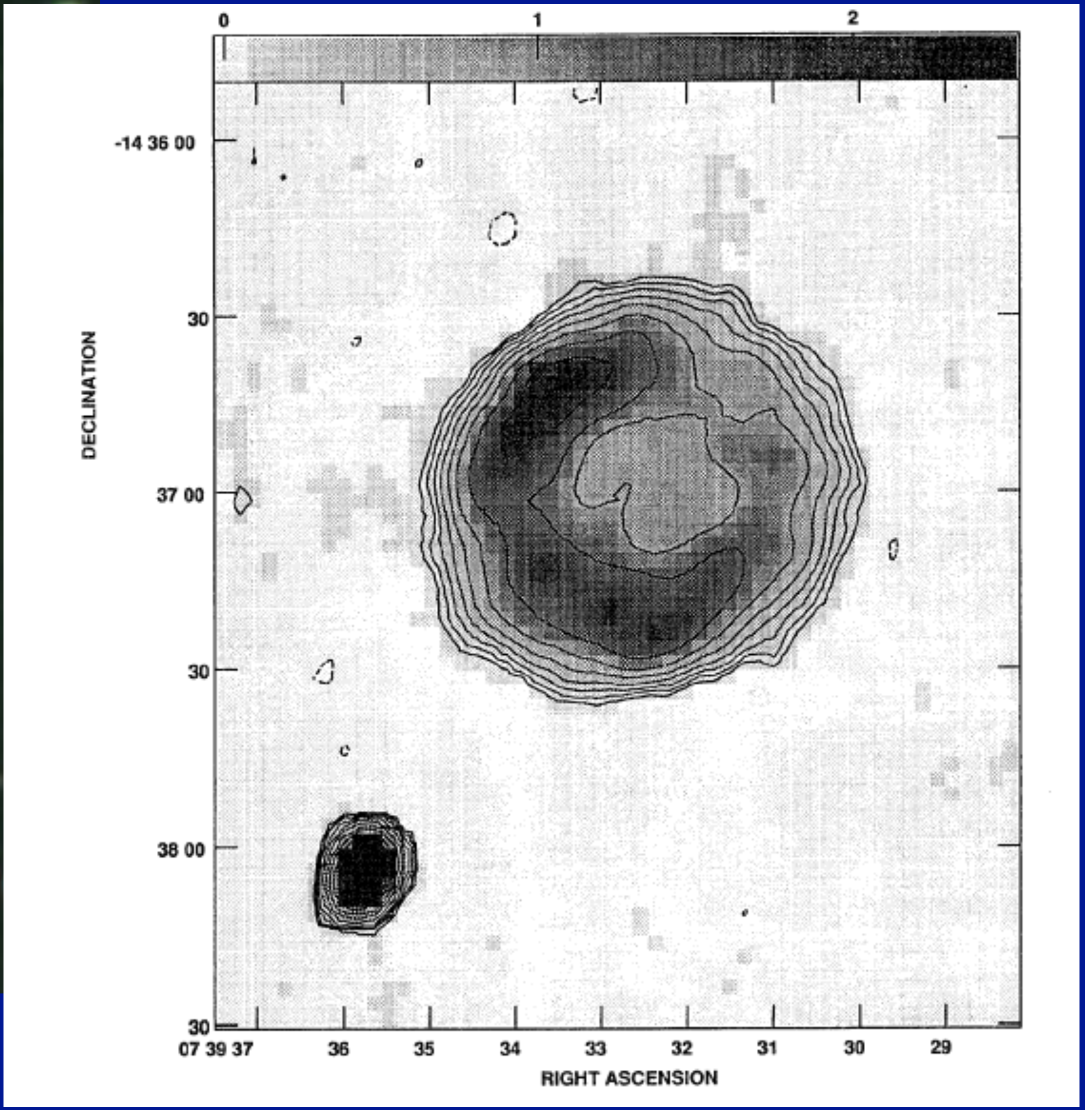
- Whole star pulsates more and more violently.

- Eventually, shells thrown off star altogether! 0.1 - 0.2 M_{Sun} ejected.

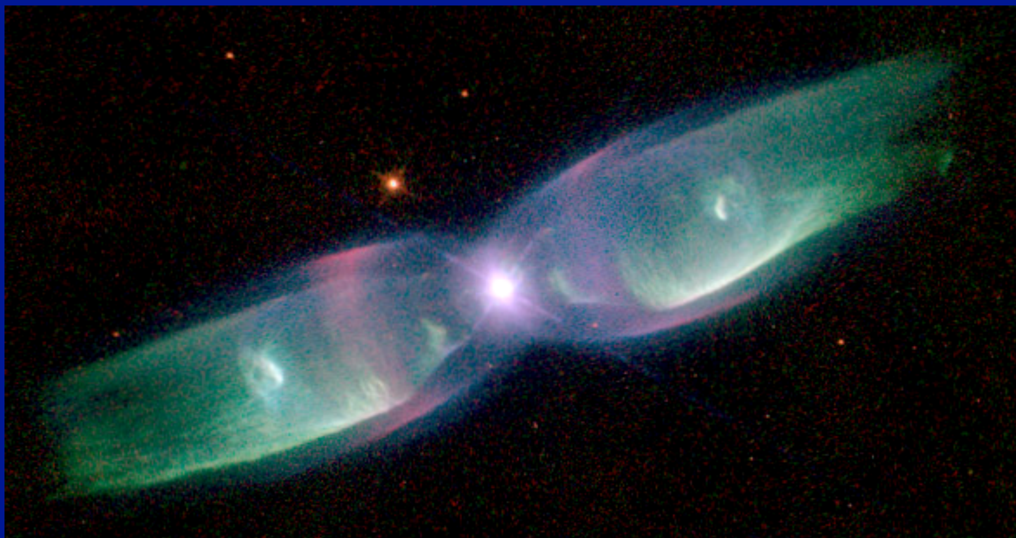
- Shells appear as a nebula around star, called "Planetary Nebula" (awful, historical name, nothing to do with planets).

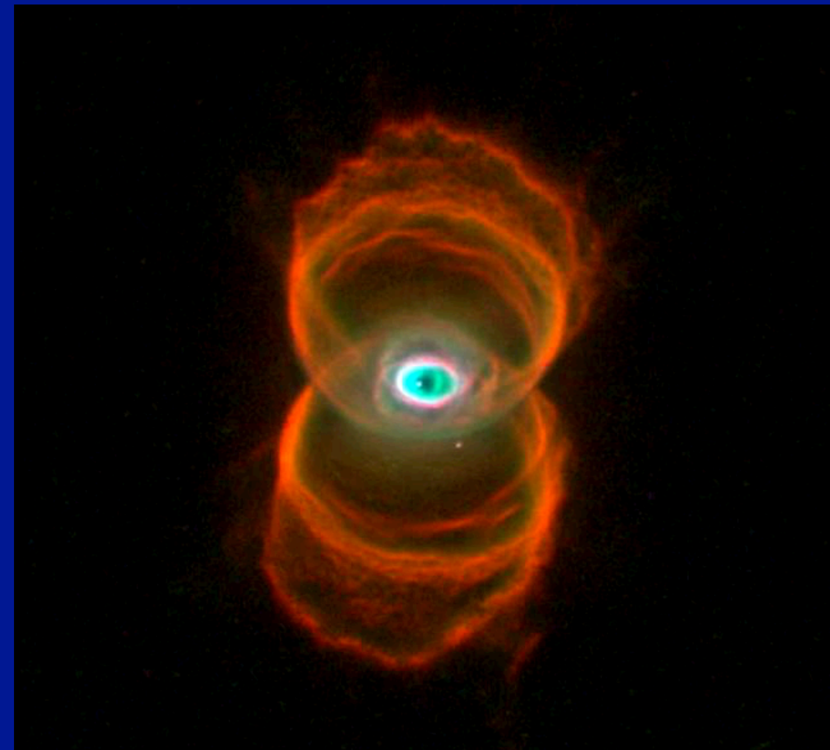
NGC2438

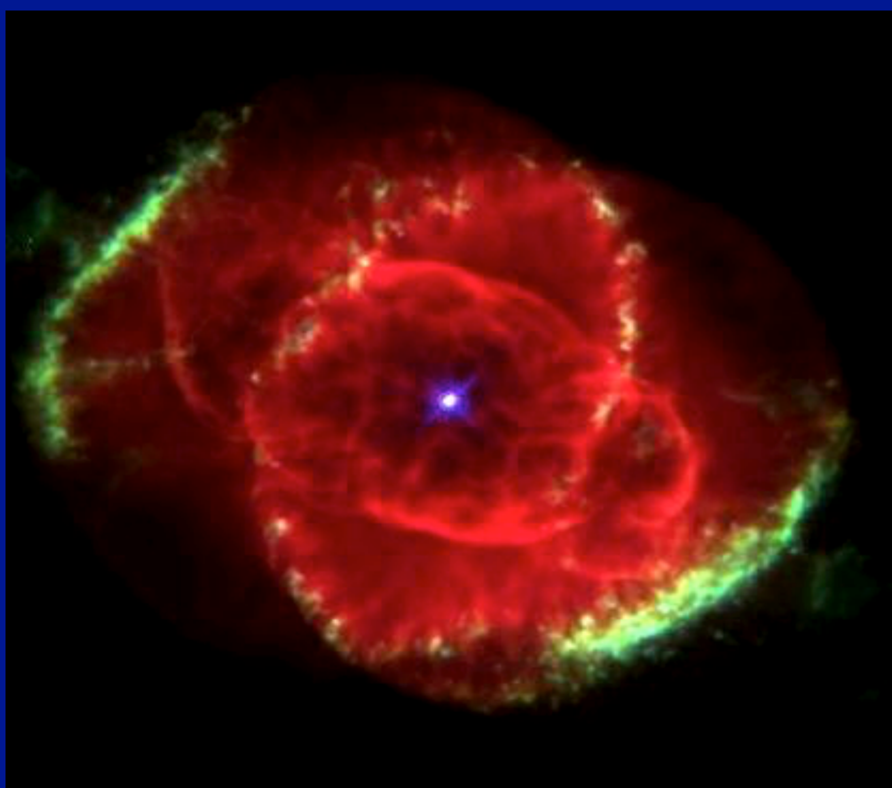
AAT 3.9m



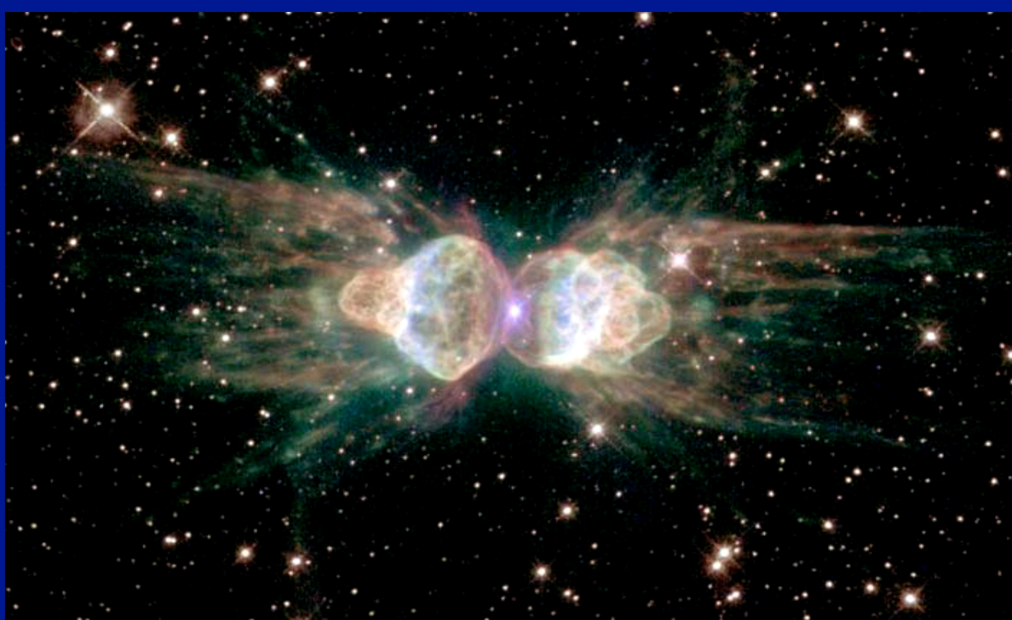
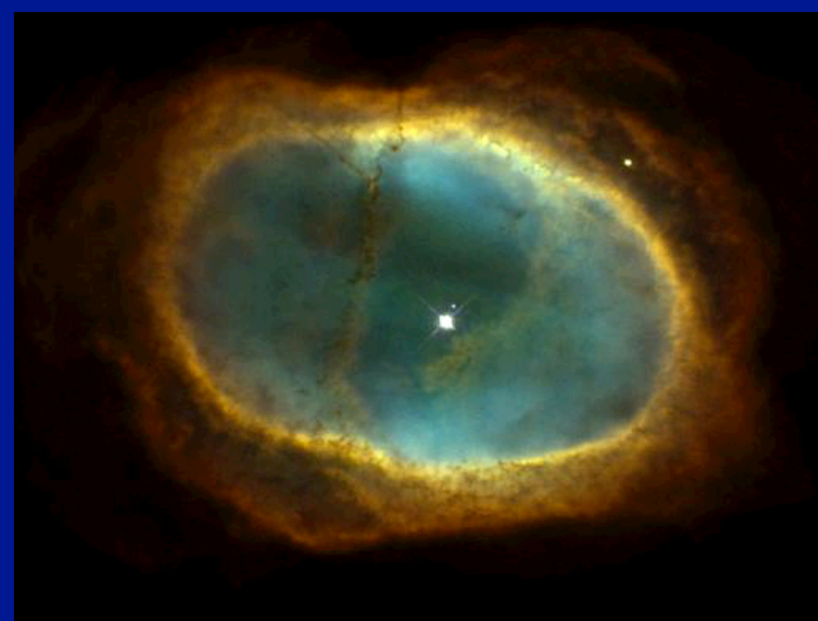
1.5 GHz VLA image from Taylor & Morris









Clicker Question:

What is the Helium Flash?

A: Explosive onset of Helium fusing to make Carbon

B: A flash of light when Helium fissions to Hydrogren

C: Bright emission of light from Helium atoms in the Sun

D: Explosive onset of Hydrogen fusing to Helium

Clicker Question:

What is happening in the interior of a star that is on the main sequence on the Hertzsprung-Russell diagram?

A: Stars that have reached the main sequence have ceased nuclear "burning" and are simply cooling down by emitting radiation.

B: The star is slowly shrinking as it slides down the main sequence from top left to bottom right.

C: The star is generating energy by helium fusion, having stopped hydrogen "burning."

D: The star is generating internal energy by hydrogen fusion.

Clicker Question:

What causes the formation of bipolar planetary nebulae?

A: A progenitor star with a rapid rotation

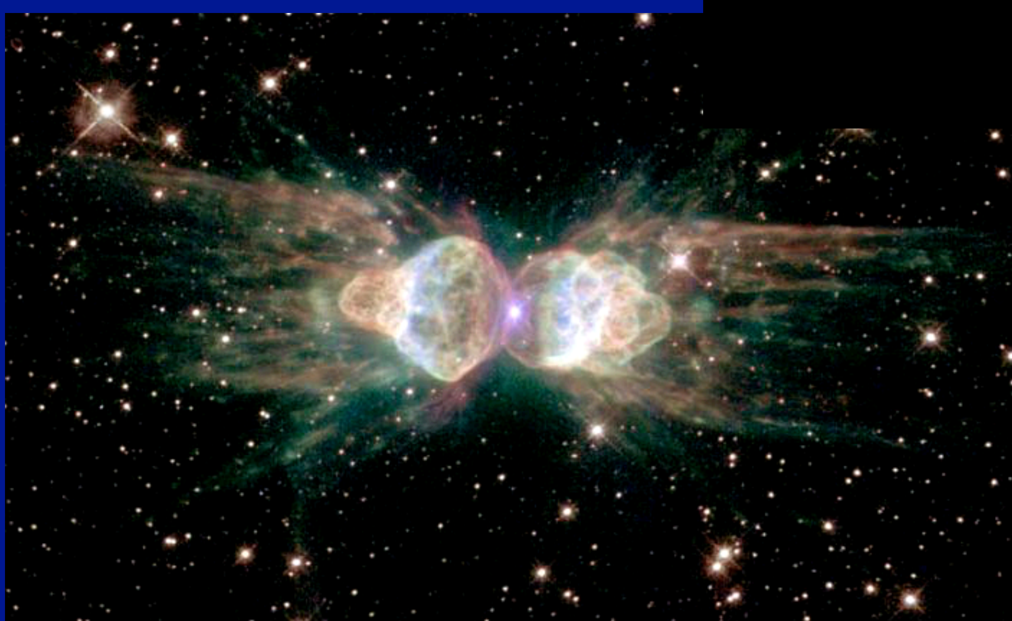
B: A progenitor star in a dense environment

C: A progenitor star in a binary system

D: A progenitor star with strong magnetic fields

Bipolar

Planetary nebulae



White Dwarfs

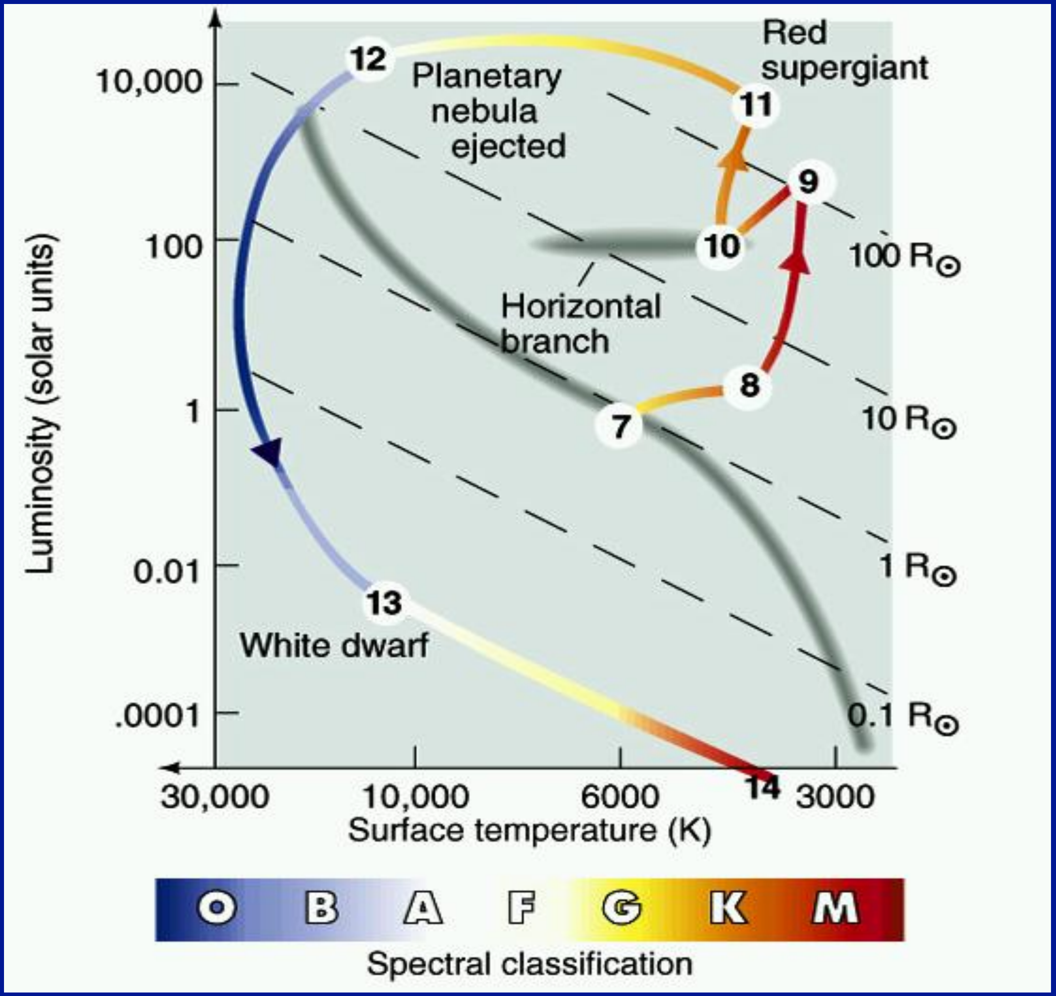
- Dead core of low-mass star after Planetary Nebula thrown off.

- Mass: few tenths of a M_{Sun} .

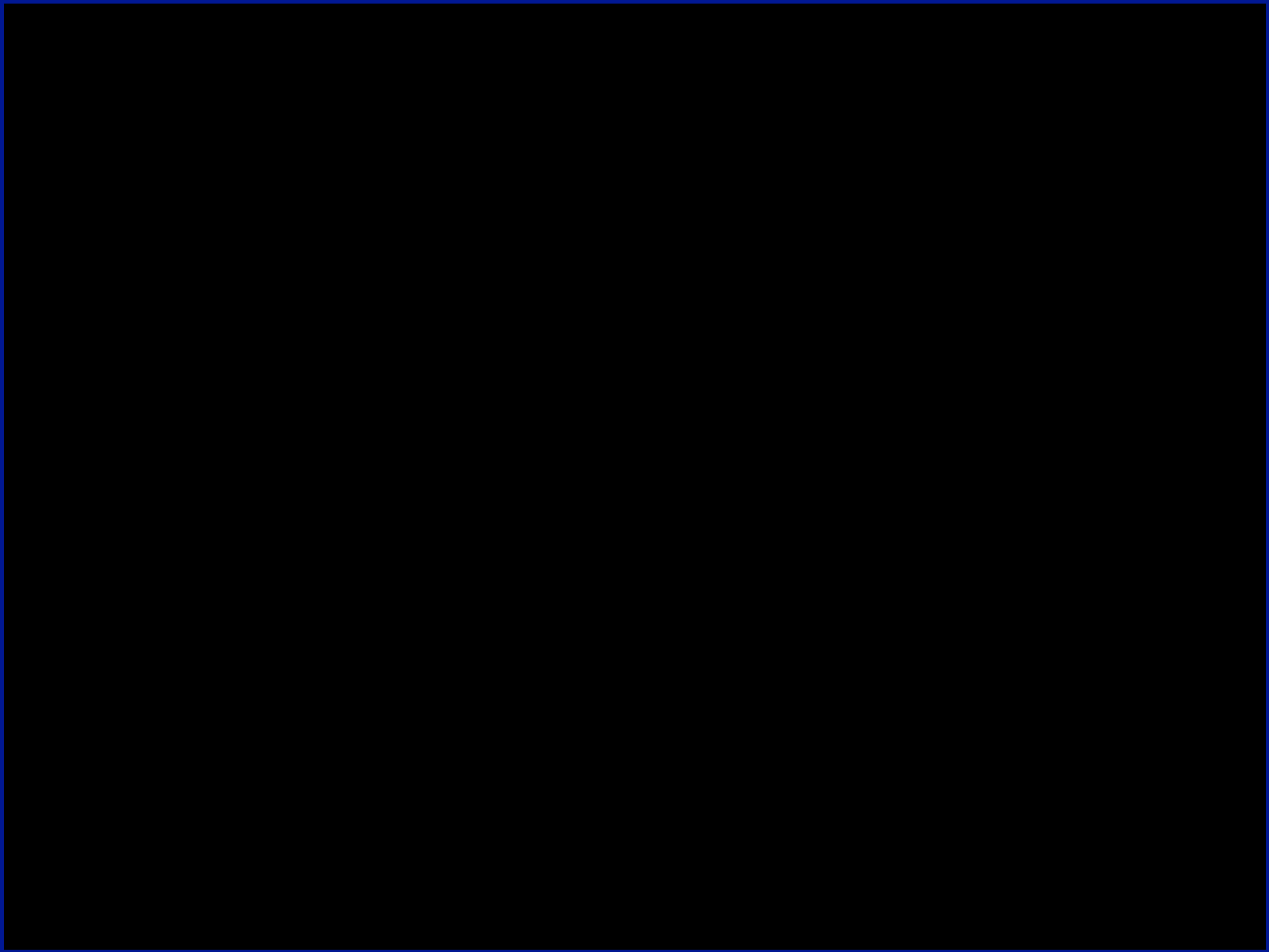
-Radius: about R_{Earth} .

- Density: 10^6 g/cm^3! (a cubic cm of it would weigh a ton on Earth).

- White dwarfs slowly cool to oblivion. No fusion.



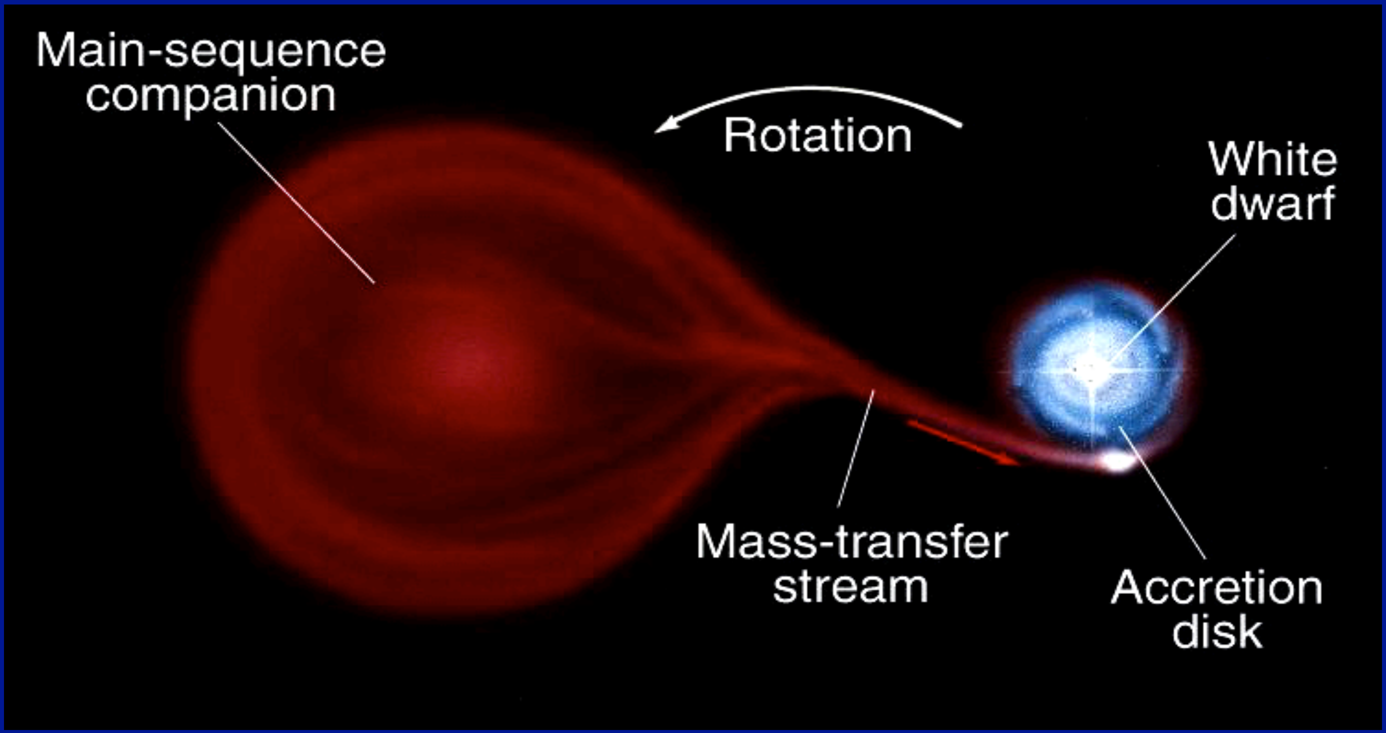
Death of a 1 solar mass star



Stellar Explosions

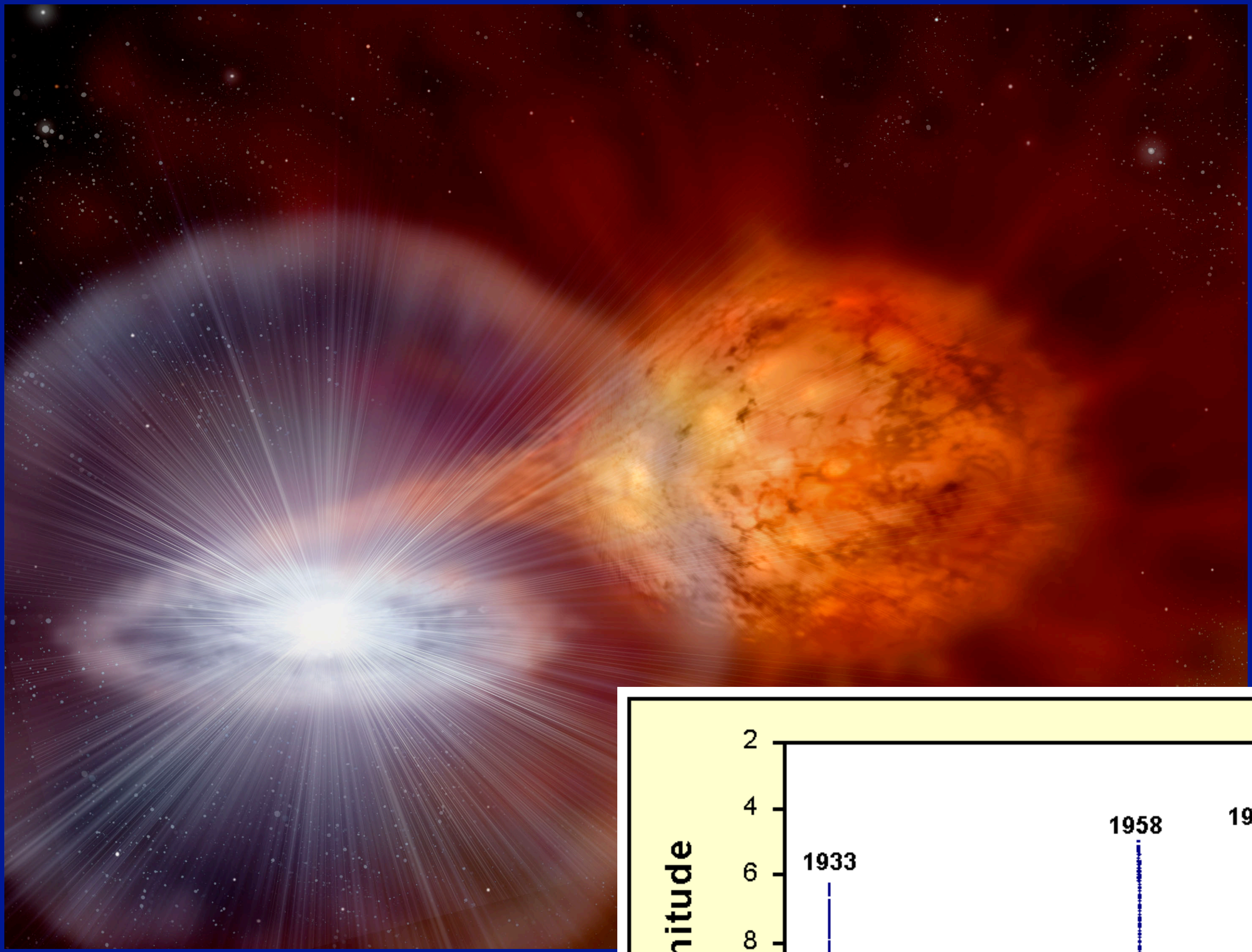
Novae

White dwarf in close binary system

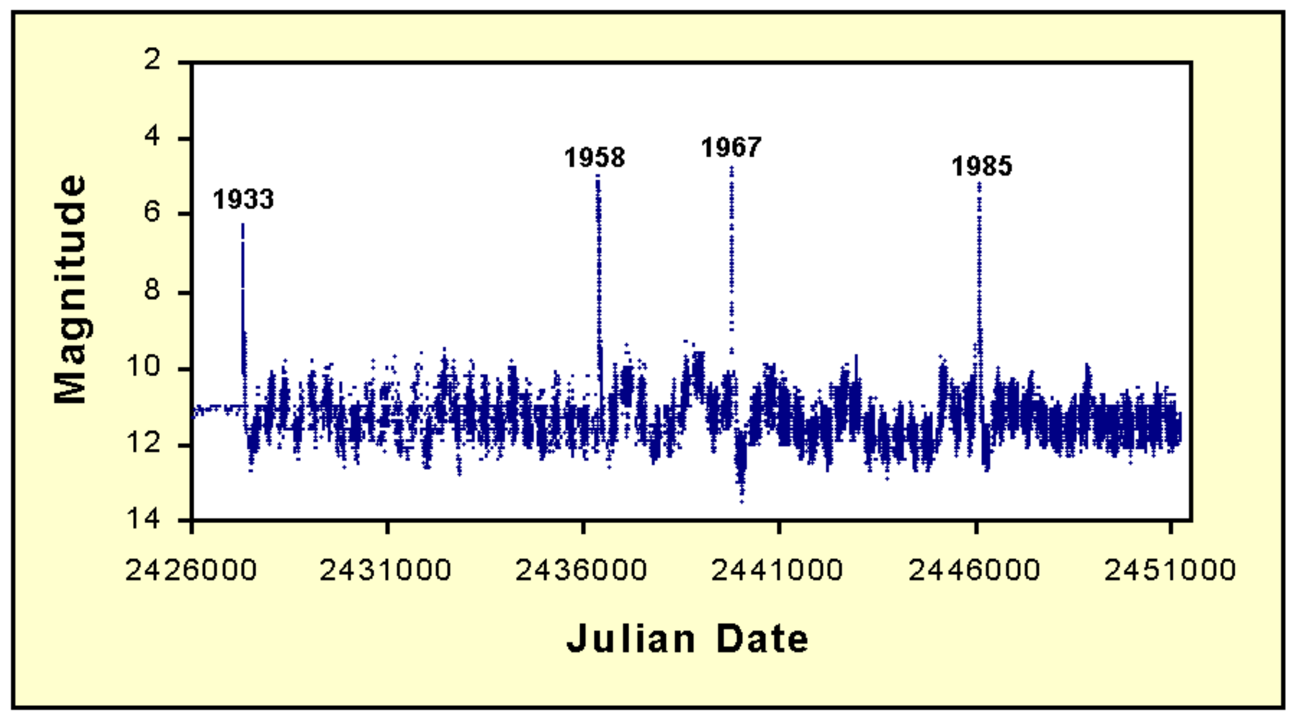


WD's tidal force stretches out companion, until parts of outer envelope spill onto WD. Surface gets hotter and denser. Eventually, a burst of fusion. Binary brightens by 10'000's! Some gas expelled into space. Whole cycle may repeat every few decades => recurrent novae.

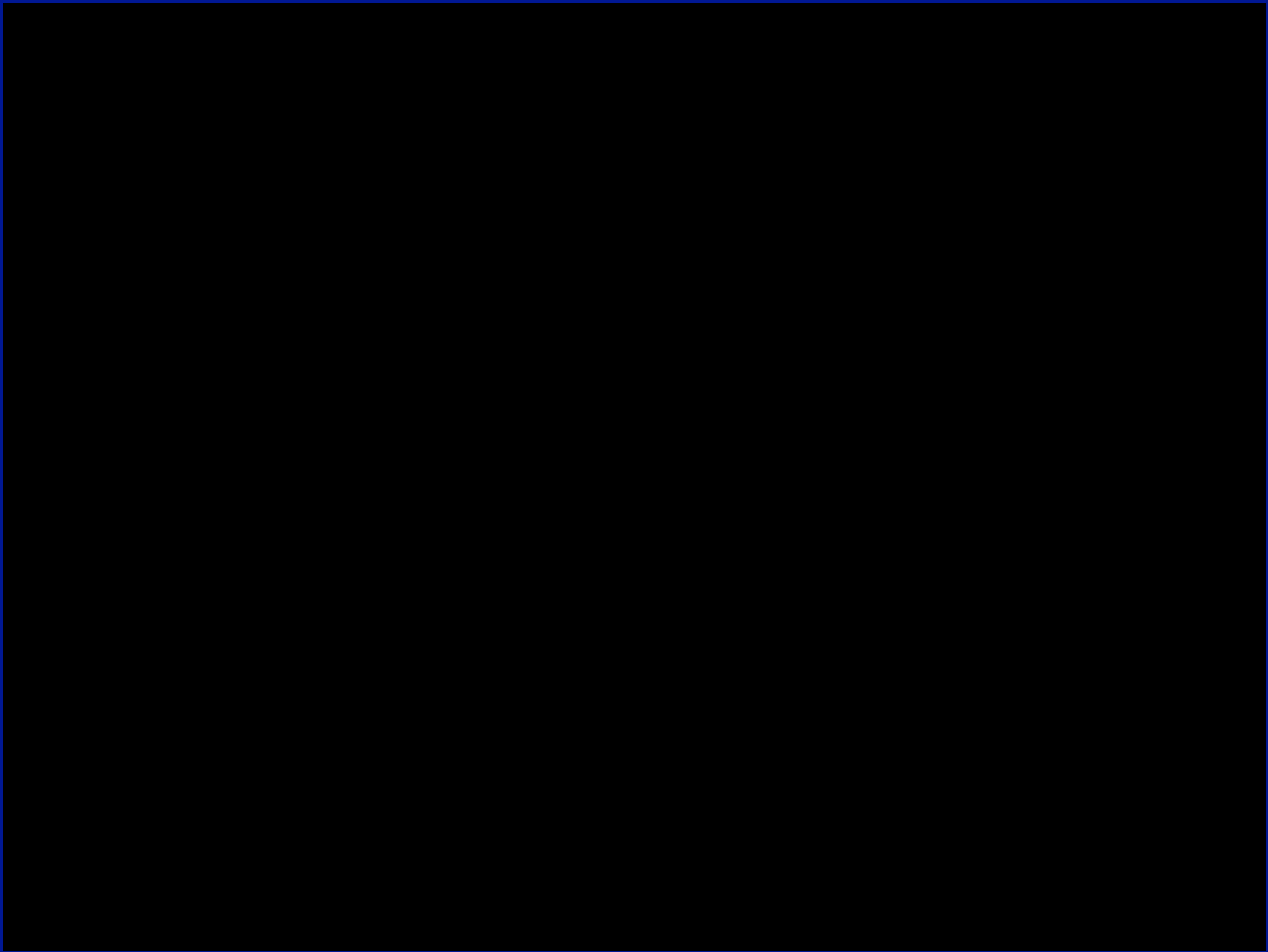
Novae



RS Ophiuci



Novae



Nova V838Mon with Hubble,
May – Dec 2002

4.2 pc

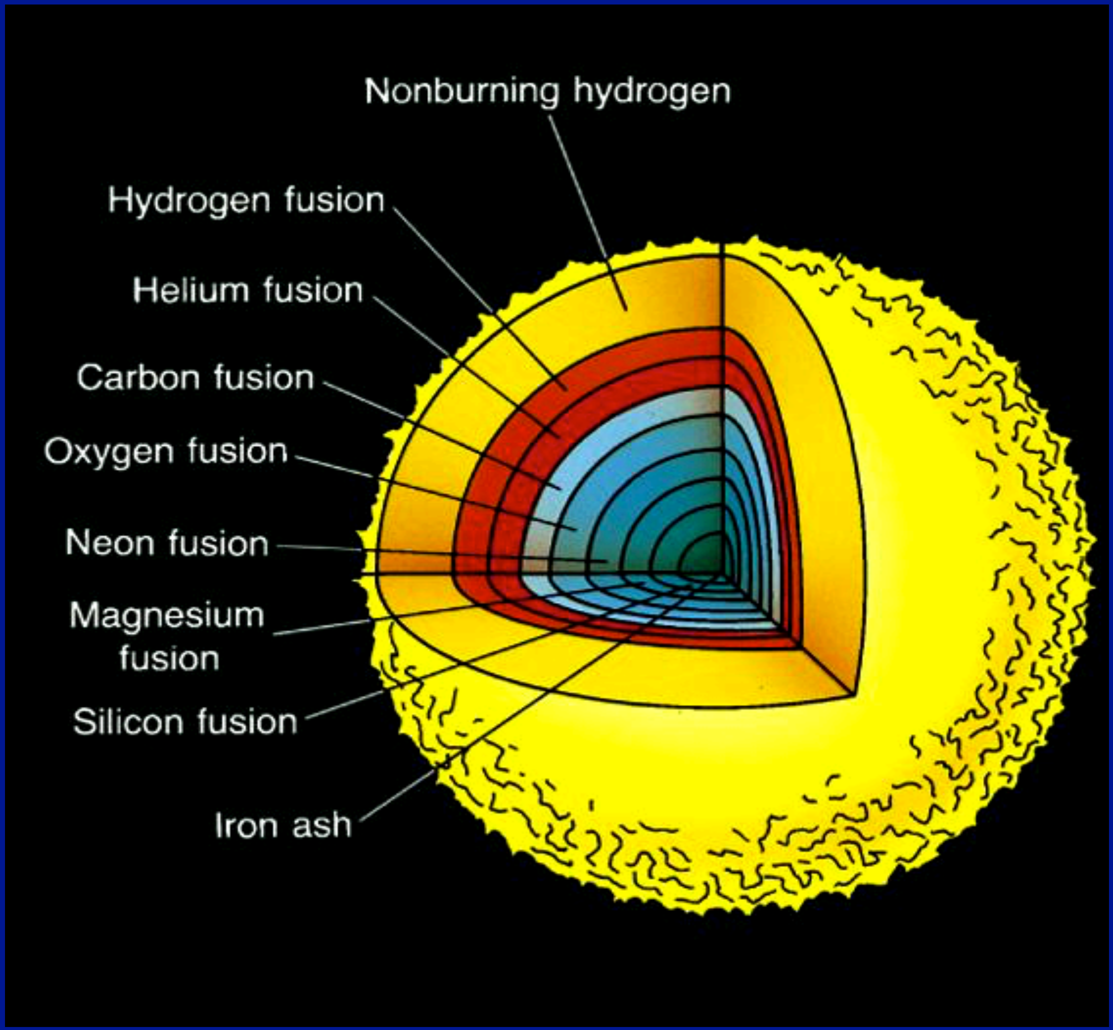
Evolution of Stars > 8 M_{Sun}

Higher mass stars evolve more rapidly and fuse heavier elements.

Example: 20 M_{Sun} star lives "only" ~10^7 years.

Result is "onion" structure with many shells of fusion-produced elements. Heaviest element made is iron.

Eventual state of > 8 M_{Sun} star



Fusion Reactions and Stellar Mass

In stars like the Sun or less massive, H -> He most efficient through proton-proton chain.

In higher mass stars, "CNO cycle" more efficient. Same net result:

4 protons -> He nucleus

Carbon just a catalyst.

$^{12}C + ^{1}H \rightarrow ^{13}N$ + energy

$^{13}N \rightarrow ^{13}C$ + positron + neutrino

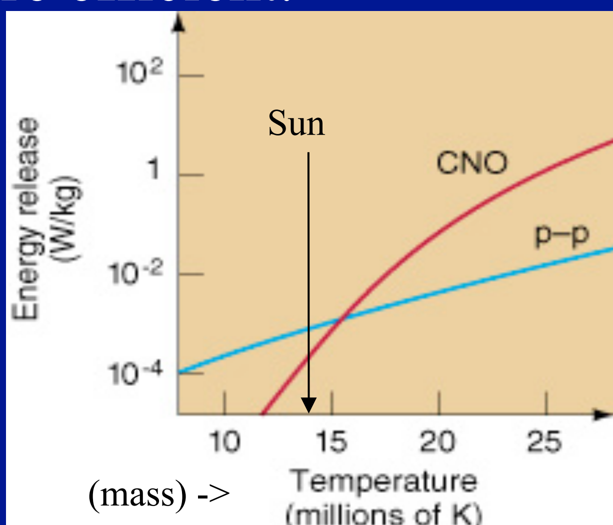
$^{13}C + ^{1}H \rightarrow ^{14}N$ + energy

$^{14}N + ^{1}H \rightarrow ^{15}O$ + energy

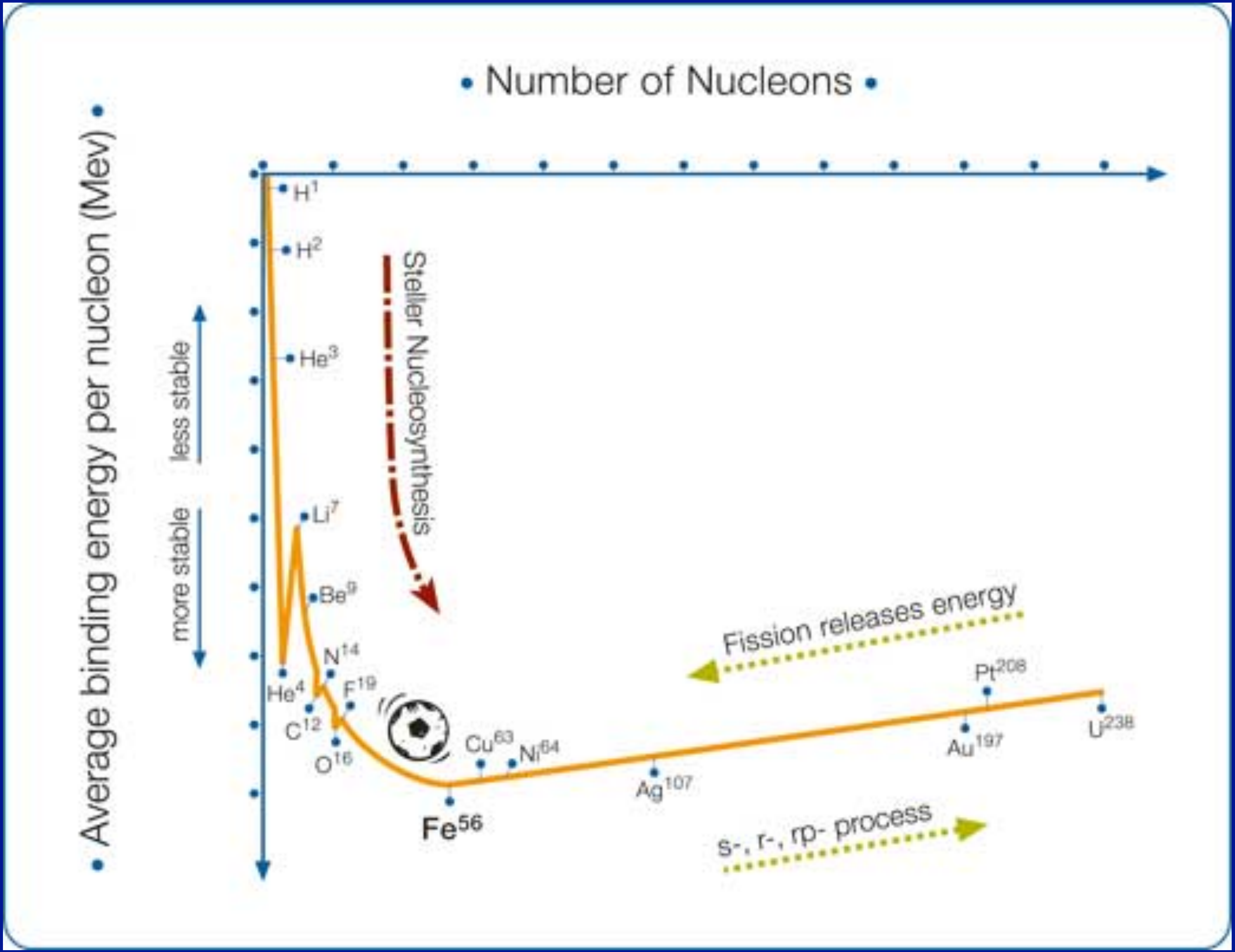
$^{15}O \rightarrow ^{15}N$ + positron + neutrino

$^{15}N + ^{1}H \rightarrow ^{12}C + ^{4}He$

Need T_{center} > 16 million K for CNO cycle to be more efficient.



Binding Energy per nucleon



Star Clusters

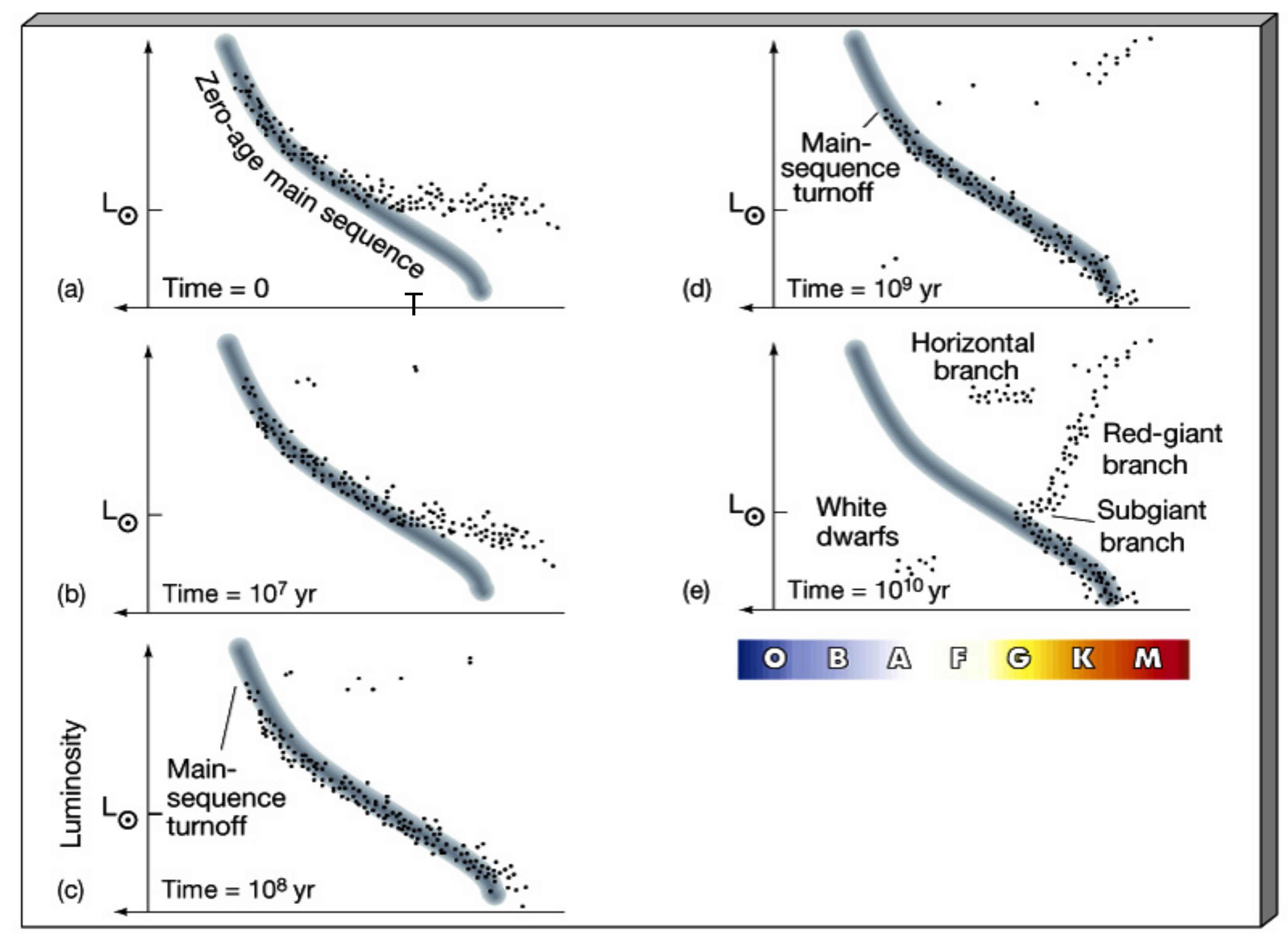
Galactic or Open Cluster

Globular Cluster

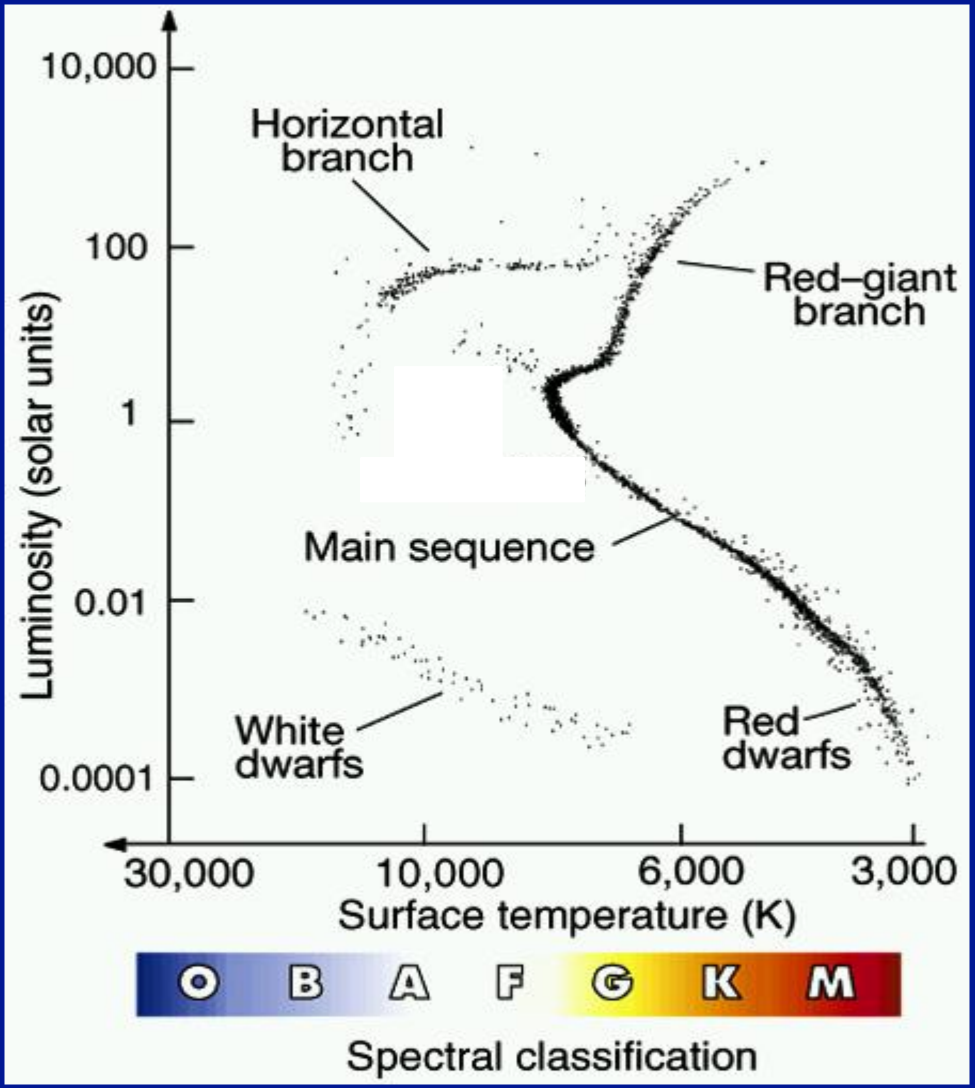
Extremely useful for studying evolution, since all stars formed at same time and are at same distance from us.

Comparing with theory, can easily determine cluster age from H-R diagram.

Following the evolution of a cluster on the H-R diagram

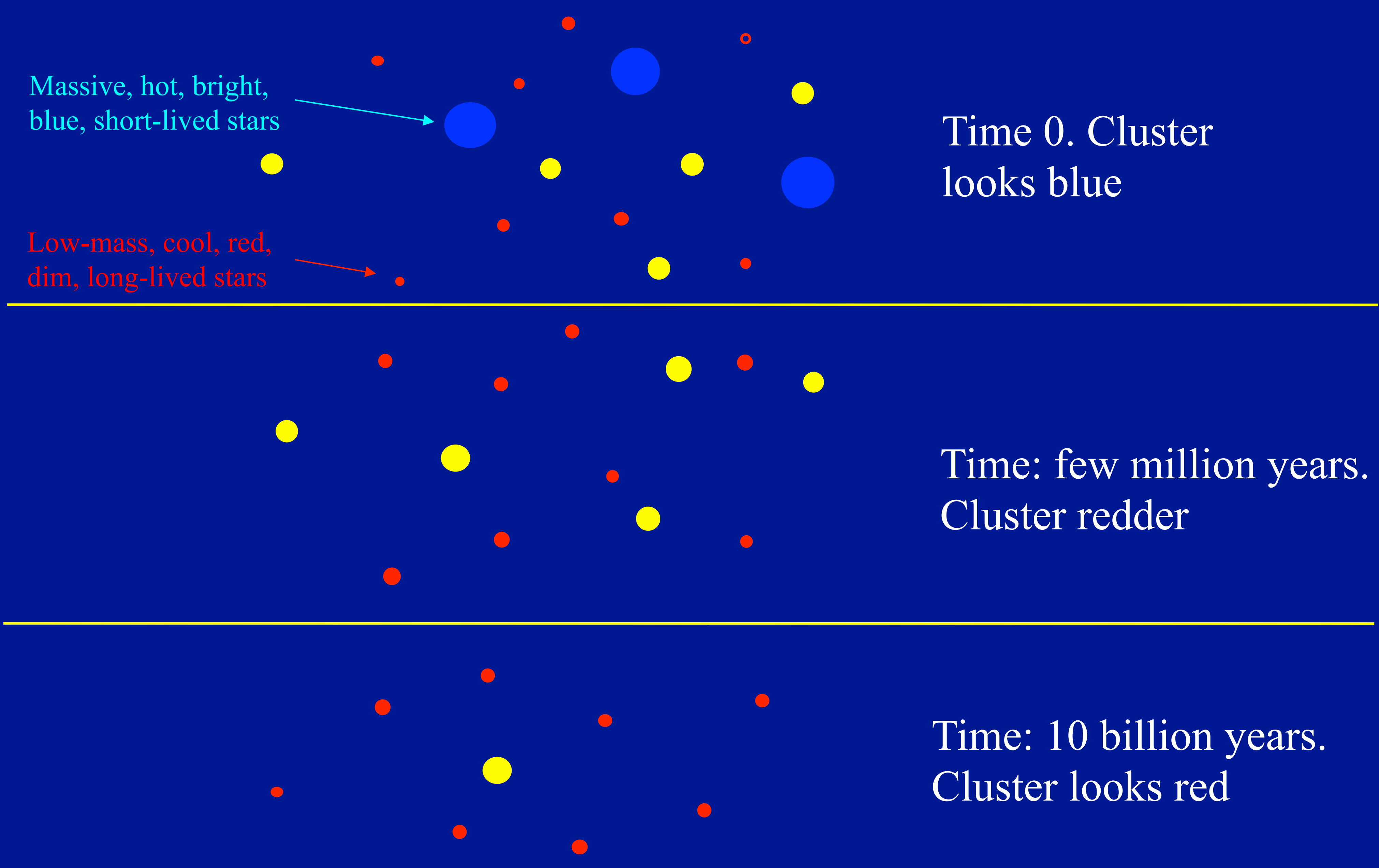


Globular Cluster M80 and composite H-R diagram for similar-age clusters.



Globular clusters formed 12-14 billion years ago. Useful info for studying the history of the Milky Way Galaxy.

Schematic Picture of Cluster Evolution



Clicker Question:

In which phase of a star's life is it converting He to Carbon?

A: main sequence

B: giant branch

C: horizontal branch

D: white dwarf

Clicker Question:

The age of a cluster can be found by:

A: Looking at its velocity through the galaxy.

B: Determining the turnoff point from the main sequence.

C: Counting the number of stars in the cluster

D: Determining how fast it is expanding

Clicker Question:

Why do globular clusters contain stars with fewer metals (heavy elements) compared to open clusters?

A: Open clusters have formed later in the evolution of the universe after considerably more processing

B: Metals are gradually destroyed in globular clusters.

C: Metals are blown out of globular clusters during supernova explosions

D: Metals spontaneously decay to lighter elements during the 10 billion year age of the globular cluster.

Death of a High-Mass Star

$M > 8\ M_{Sun}$

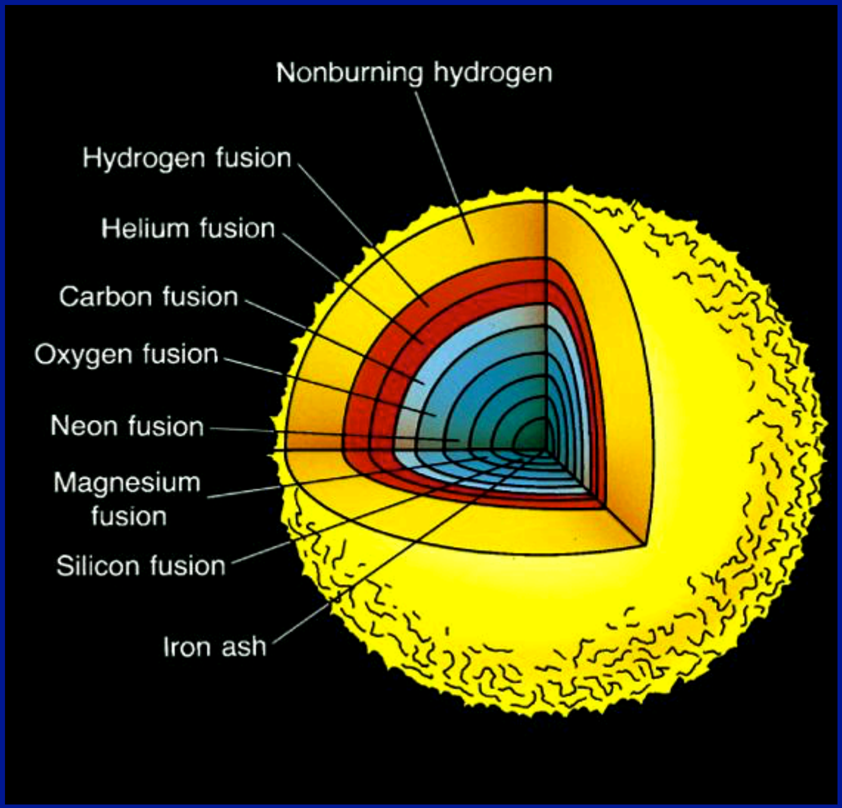
Iron core

Iron fusion doesn't produce energy (actually requires energy) => core shrinks and heats up

$T \sim 10^{10}$ K, radiation disrupts nuclei,

p + e => n + neutrino

Collapses until neutrons come into contact. Rebounds outward, violent shock ejects rest of star => A Core-collapse or Type II Supernova

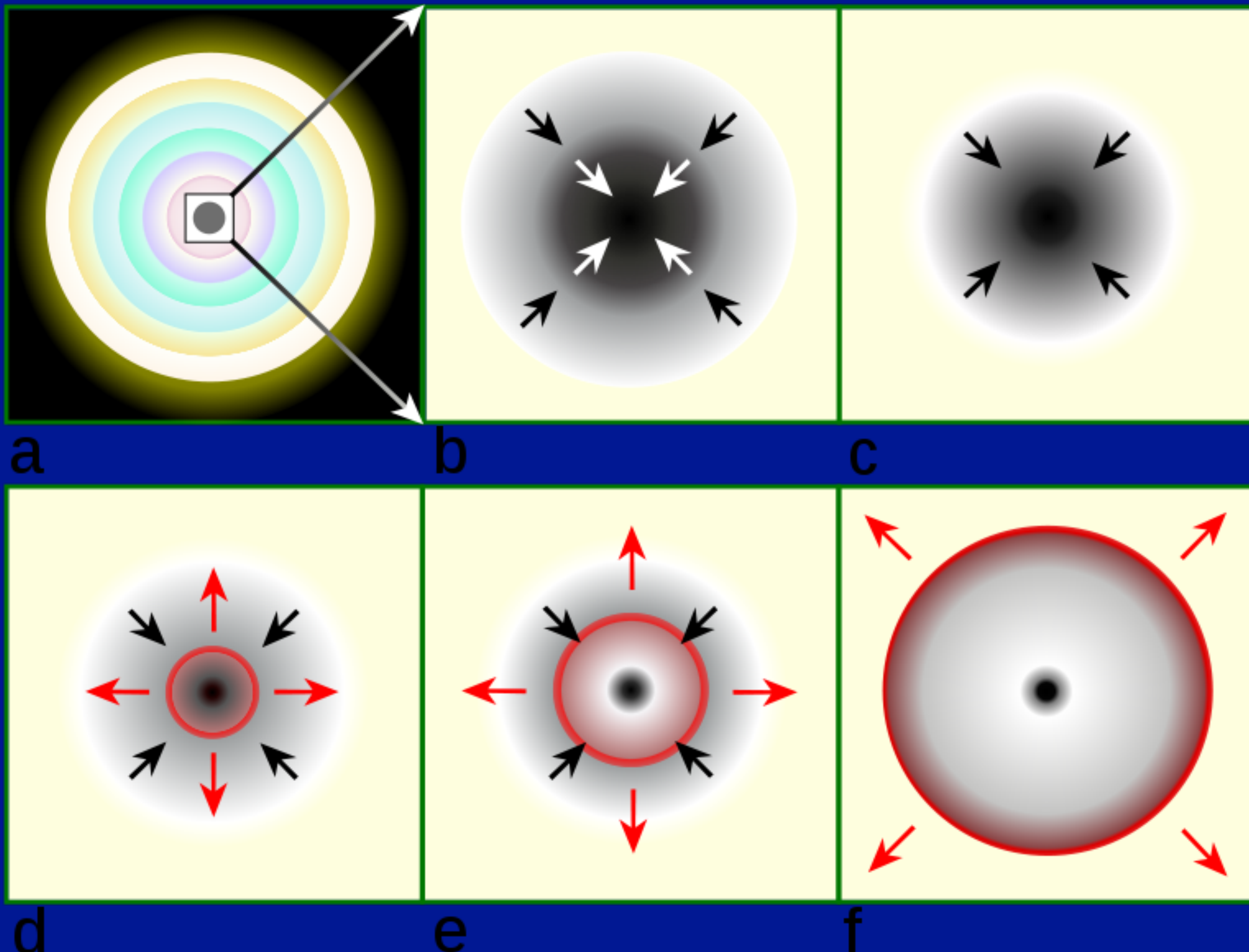


Ejection speeds 1000's to 10,000's of km/sec! (see DEMO)

Remnant is a "neutron star" or "black hole".

Such supernovae occur roughly every 50 years in Milky Way.

Core collapse



Example Supernova: 1998bw

SN 1998bw in Spiral Galaxy ESO184-G82

ESO PR Photo 39a/98 (15 October 1998)