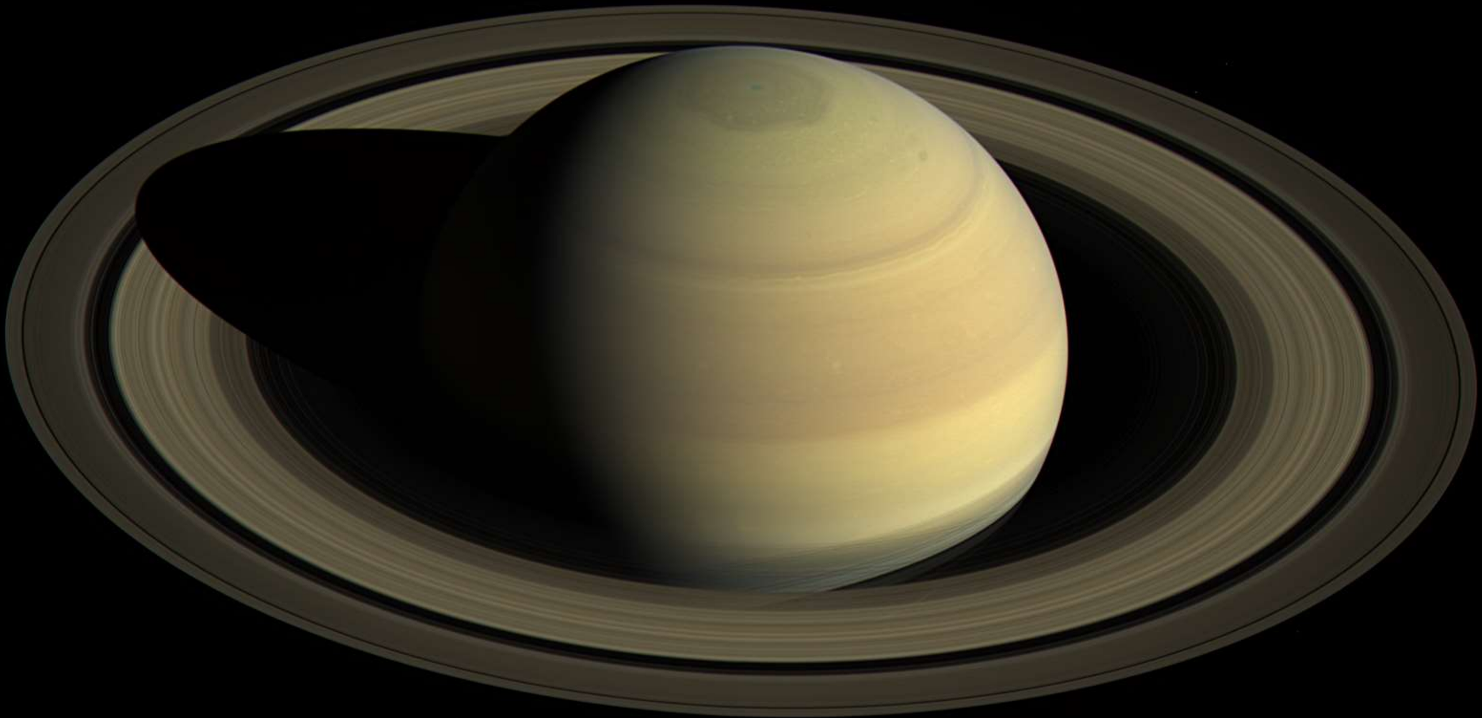
AST 2002
Introduction to Astronomy



A Few Quick Things…

E-mailing me: Must have AST2002 in the subject

Mary Hinkle, Graduate Teaching Assistant:

Office Hours: Mon 1:30-3:00pm. PSB 316

My office hours: Mon 3:00-4:00pm. PSB 308
Tue 3-4 pm. PSB 308

Last Midterm: Mon 9th April. (Best of 2 will count towards final grade)

Final: Friday 27th April. 7am-9:50 am. (on all chapters)

LAST Knights Under the Stars Event – Thursday 19th April

Opportunity to make up the 1% extra credit that was offered (if you haven't been yet, worth 2%) – Last chance for extra credit..

What Have We Covered, What's Next?

Chapter 13: Star Stuff

13.1. Star Birth

- How do stars form?
- How massive are newborn Stars?

13.2. Life as a Low-Mass Star

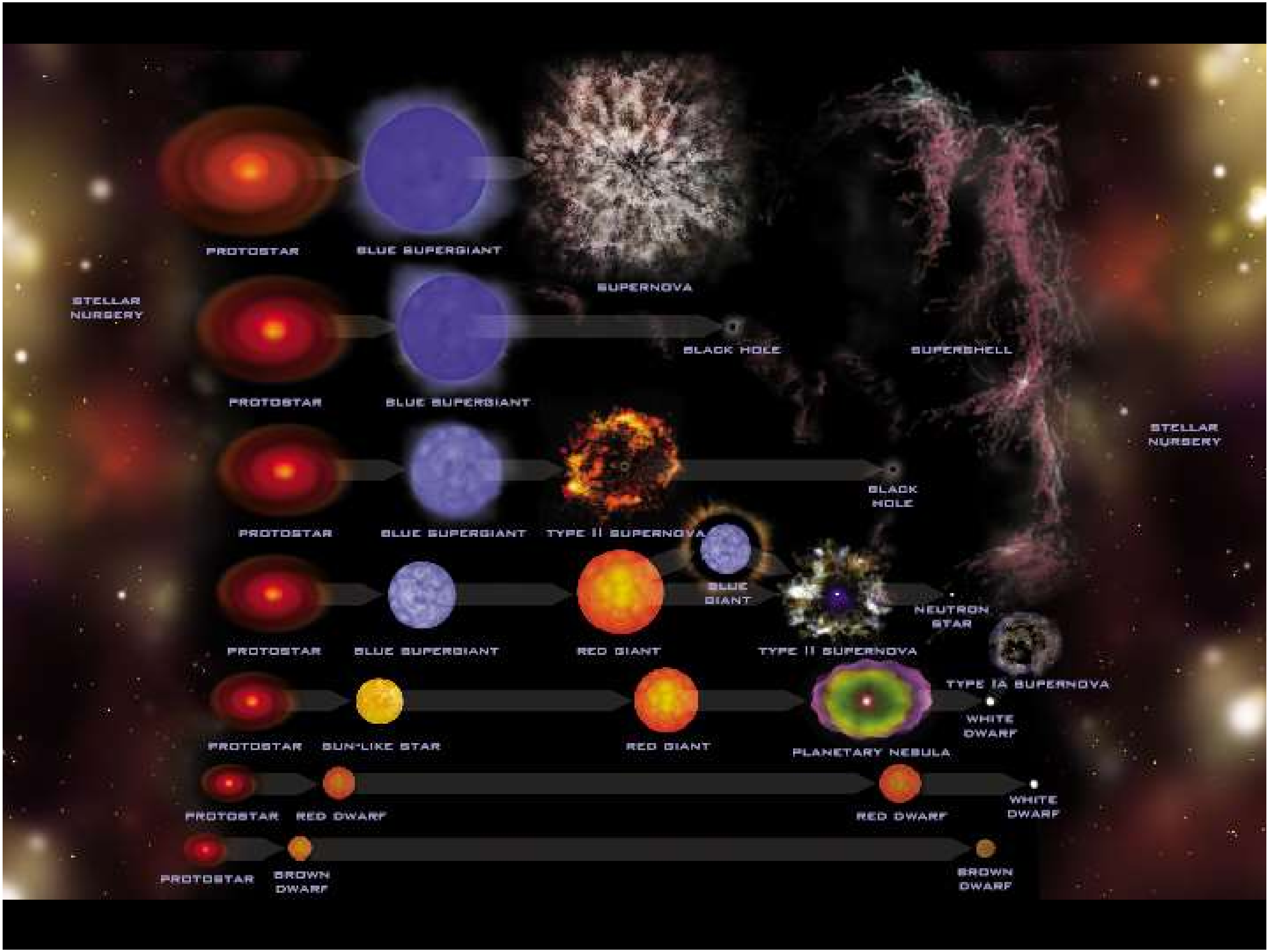
- What are the stages of a low-mass star?
- How does a low-mass star die?

13.3. Life as a High-Mass Star

- What are the life stages of a high-mass star?
- How do high-mass stars make the elements necessary for life?
- How does a high-mass star die?

13.4. Stars in Close Binaries

- How are the lives of stars with close companions different?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RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

Categories of Stellar Mass

The life of stars falls into approximately three categories, based on stellar mass…

Low Mass Stars:

- Have birth masses below 2 M_{Sun}
- Lower limit ~0.08 M_{Sun}

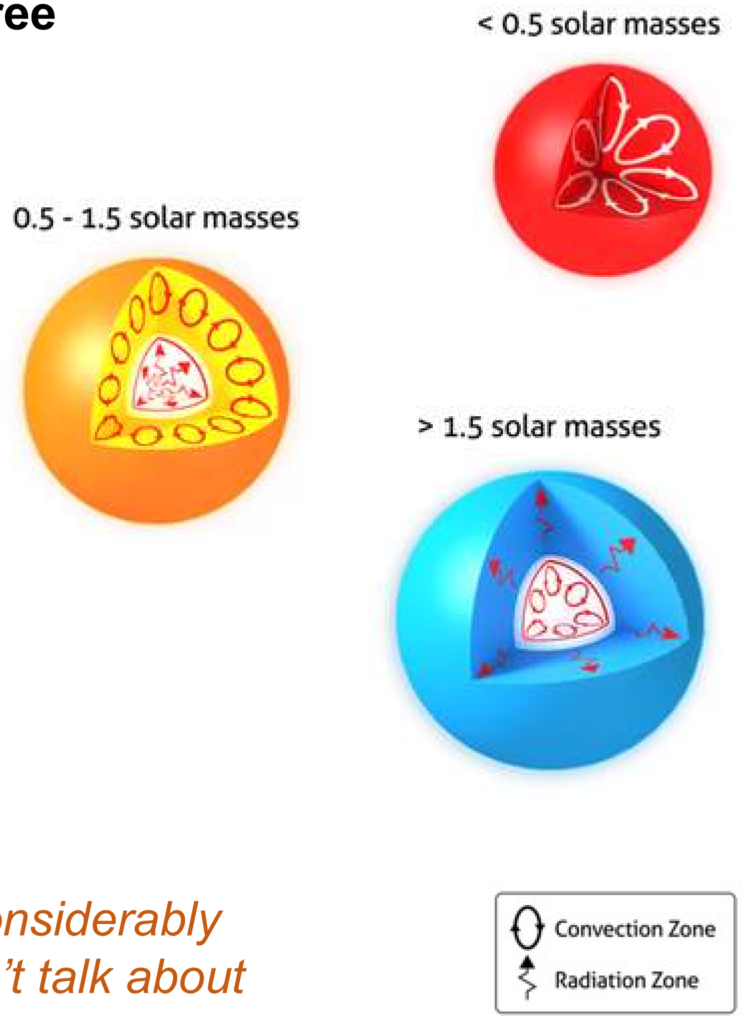
Intermediate Mass Stars:

- Have birth masses from 2-8 M_{Sun}

High Mass Stars:

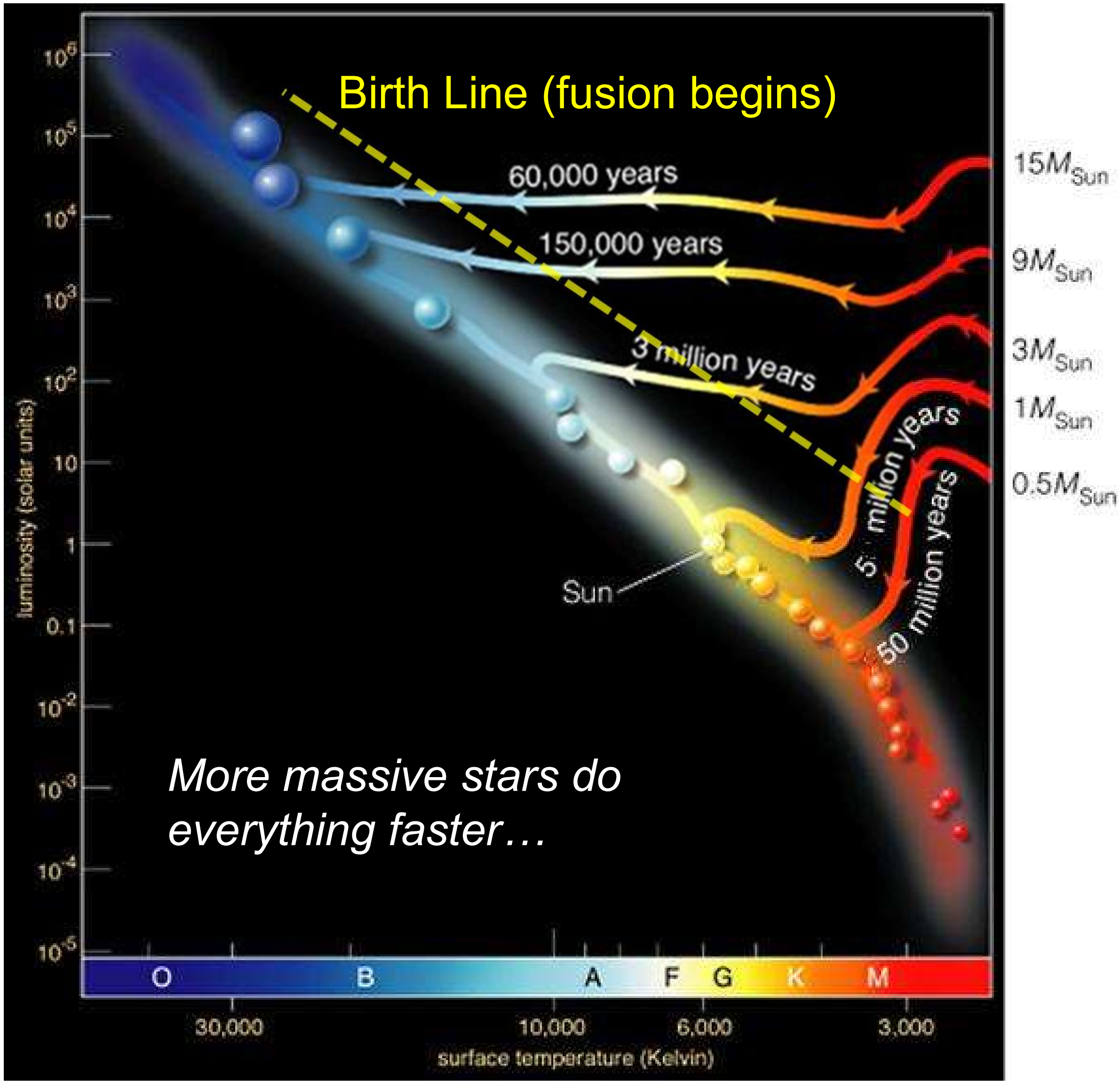
- Have birth masses over ~8 M_{Sun}
- Upper limit ~300 M_{Sun}

Note: *Convection and radiation zones vary considerably and are switched for high mass stars (we won't talk about this in depth here).*



Entering the Main Sequence

Hayashi tracks of protostars



Birth Line (fusion begins)

More massive stars do everything faster…

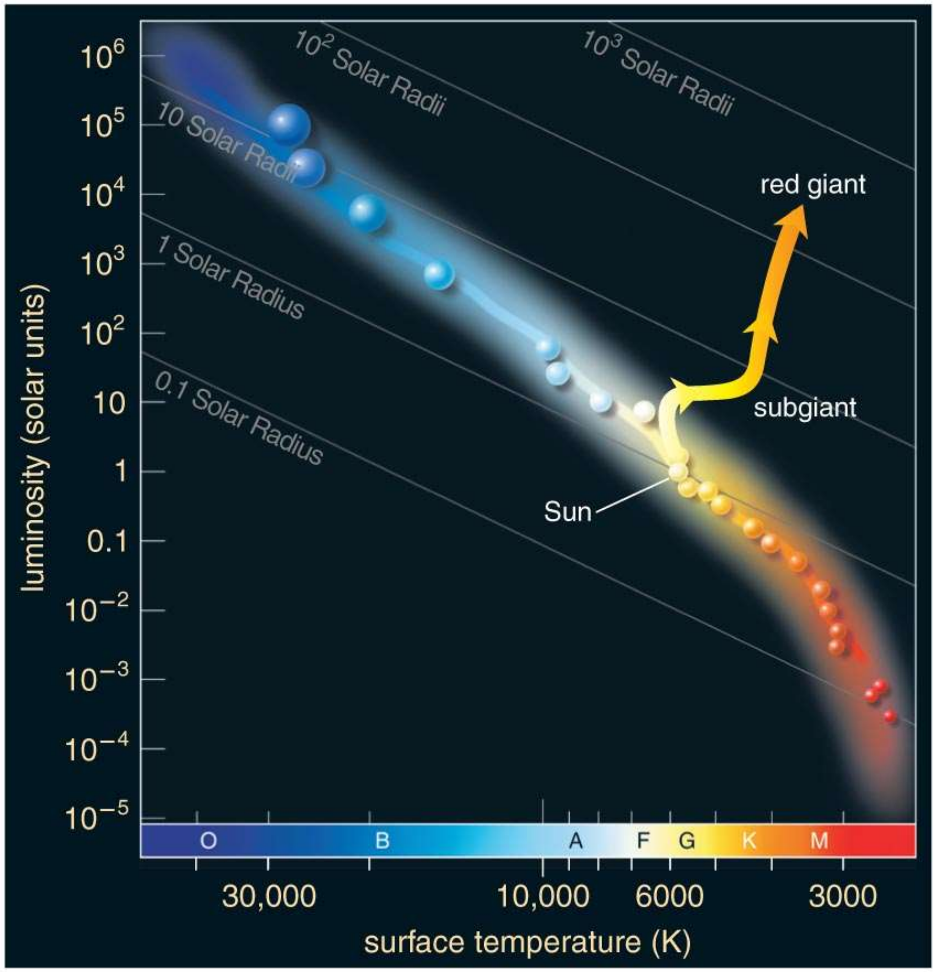
As stars begin to collapse under gravity:

- They warm up, and have high luminosities and surface areas…
- After 10 million K is reached, fusion begins slowing down gravitational collapse…

Hydrostatic Equilibrium:

- They are not considered main sequence stars until the radiation pressure from fusion and gravity is balanced

Life Track After Main Sequence

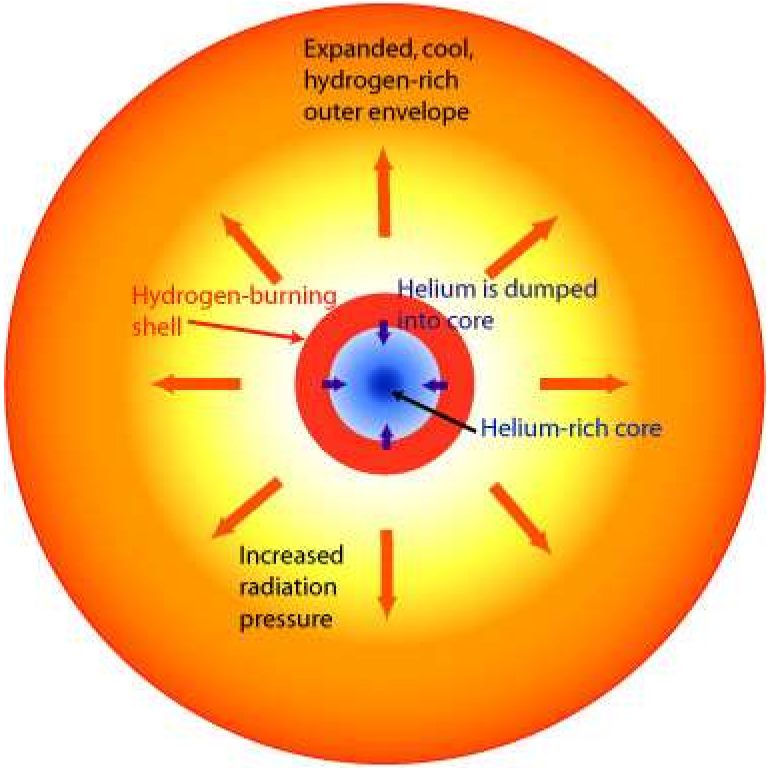


- Stars spend approximately 90% of their lives on the main sequence, regardless of mass

- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over.

The Red Giant Brach:

A Broken Solar Thermostat



Hydrogen Shell Burning on the Red Giant Branch

Helium generated from the proton-proton chain accumulates in the core, but it is not hot enough for He fusion (100 million K).

Helium collapses as far as degeneracy will allow, the temperature surrounding the He core becomes sufficient for hydrogen fusion in a shell around the core (proton-proton chain)

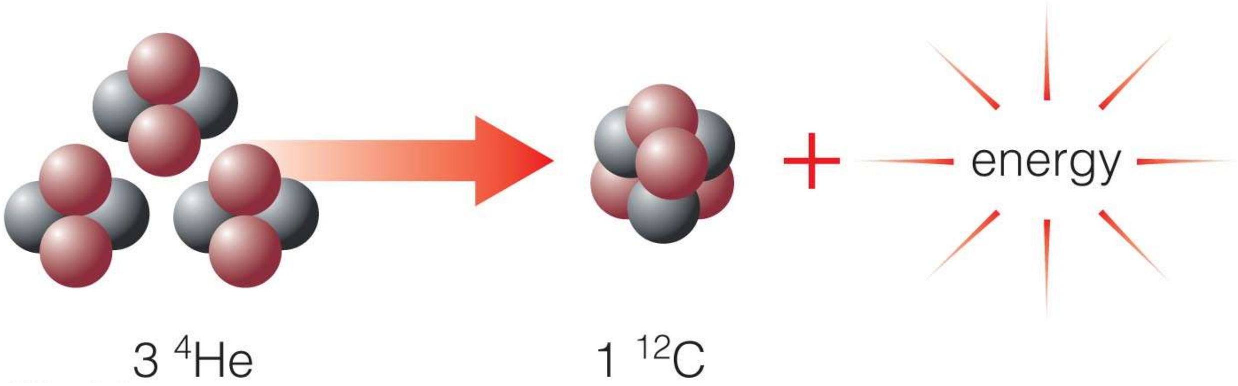
This proceeds at an ever-increasing rate…

- More helium is dumped on degenerate core (cannot expand)
- Higher temperatures make proton-proton chain more efficient..

Luminosity increases by ~ 1000 times
Radius increases by ~ 100 times
Increased mass loss from 10^{-17} *to* 10^{-7} $M_{\odot}$ *year*

Helium Fusion

the Triple Alpha Process



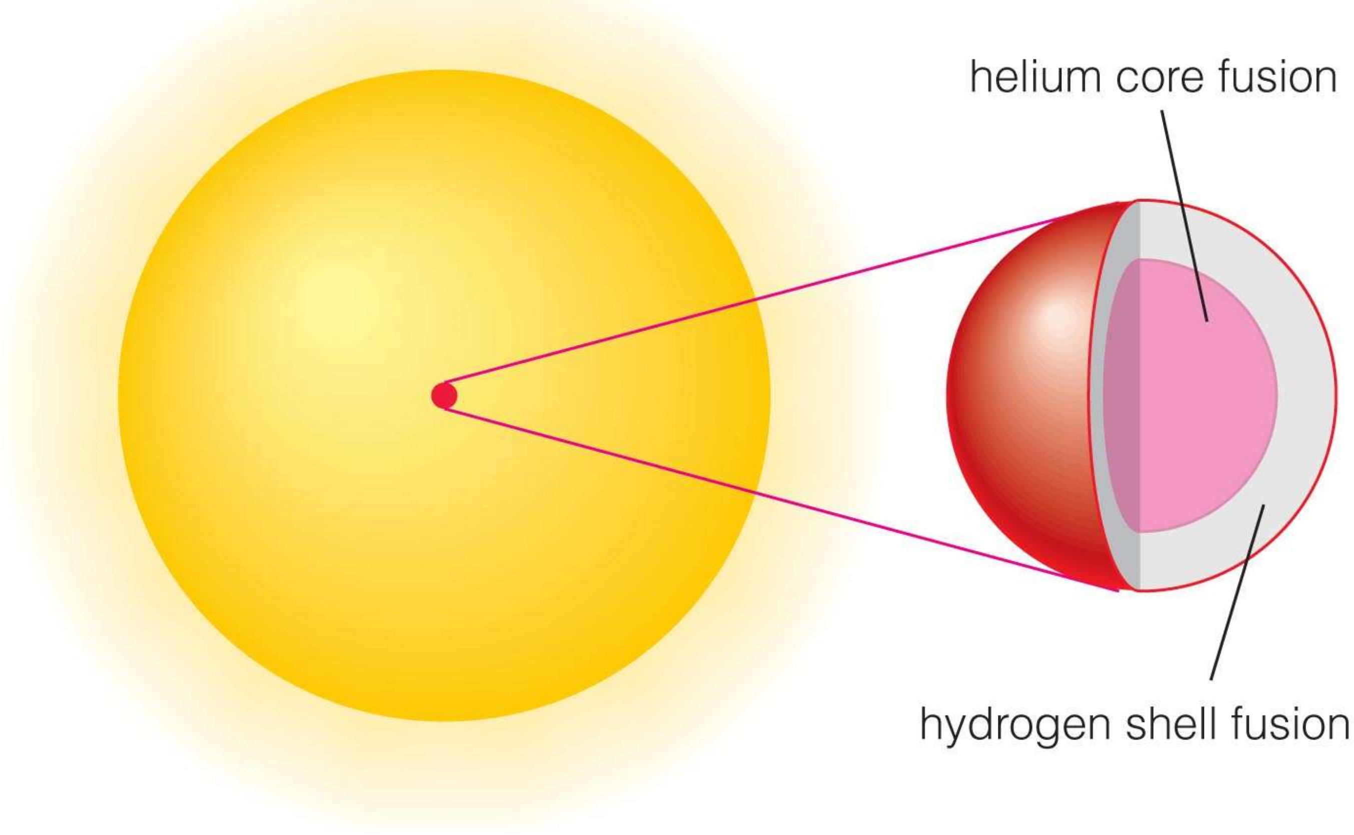
- Occurs once the collapsing Helium core reaches 100 million K
- Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion; the larger charges from two protons in each nucleus leads to greater repulsion so higher velocities are needed to overcome this.
- The fusion of two helium nuclei forms an unstable form of Beryllium, which returns to helium unless another helium nucleus also reacts before this decay occurs to make carbon (and oxygen)

The Helium Flash

- The thermostat is broken in a low-mass red giant because degeneracy pressure supports the core, which is independent of temperature and cannot contract further (while degeneracy pressure is sufficient).
- **That means that He-burning won't immediately cause the core to expand back outward.**
- The core temperature rises rapidly when helium fusion begins.
- The helium fusion rate skyrockets until thermal pressure takes over and expands the core again.
  - ***This process takes a few minutes to propagate through the entire core***

The Horizontal Branch

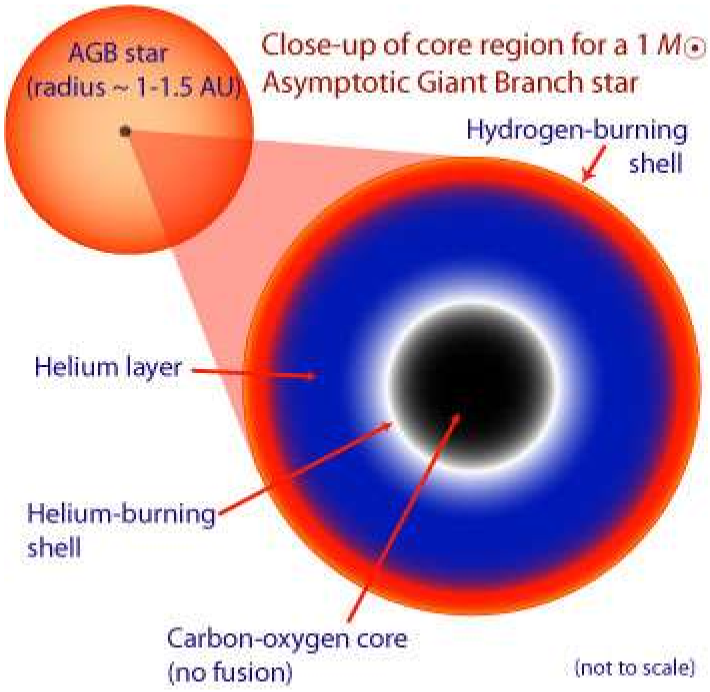
A brief (100 Myr) return to normalcy



- Helium fusion in the core, with hydrogen shell fusion on the outside
- Helium core-fusion stars neither shrink nor grow considerably because the core thermostat is temporarily fixed, moves back to main sequence.

The Asymptotic Giant Branch

The thermostat is broken again…



Luminosity increases by ~ 10,000 times
Radius increases by ~ 300-1000 times
Increased mass loss to 10^{-6} – 10^{-4} $M_\odot$ year

The Helium in the core has been turned to carbon and oxygen

Fusion of carbon requires temperatures of 600 million K (only occurs in Stars of ~ 8 solar masses)

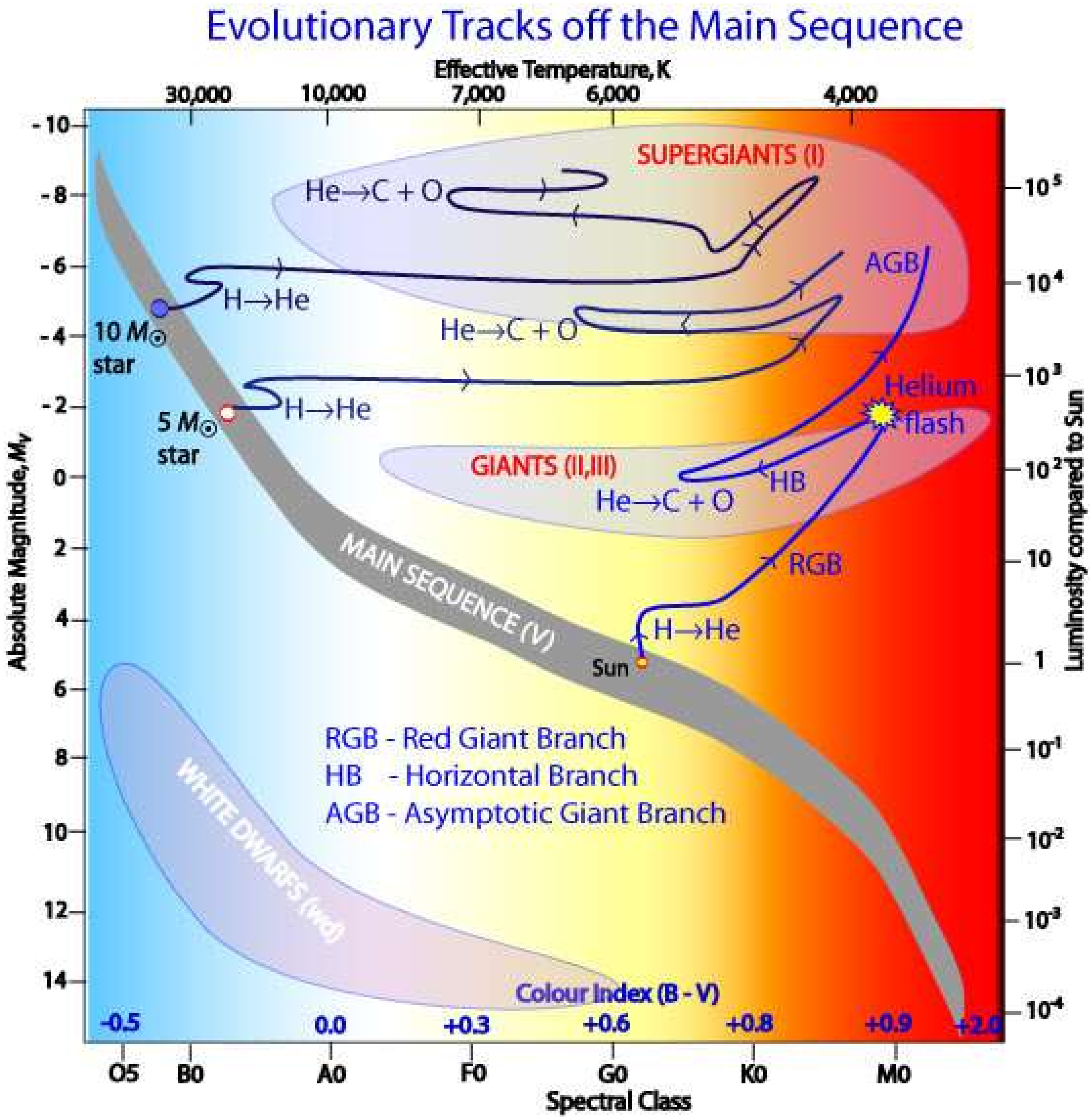
As carbon/oxygen core contracts, the layers surrounding it become hot enough for He fusion

→ **Onion like structure**

- Carbon/Oxygen core
- Helium burning shell
- Outer Hydrogen burning shell

Heavier elements can be generated in He shell through so-called ***s-process***

Life Track Exiting Main Sequence



For a Solar Mass Star:

Red Giant Branch

- **Inert (degenerate) helium core, hydrogen fusion in shell**

Helium Flash

- **Helium begins fusion (triple-alpha process), degeneracy is removed**

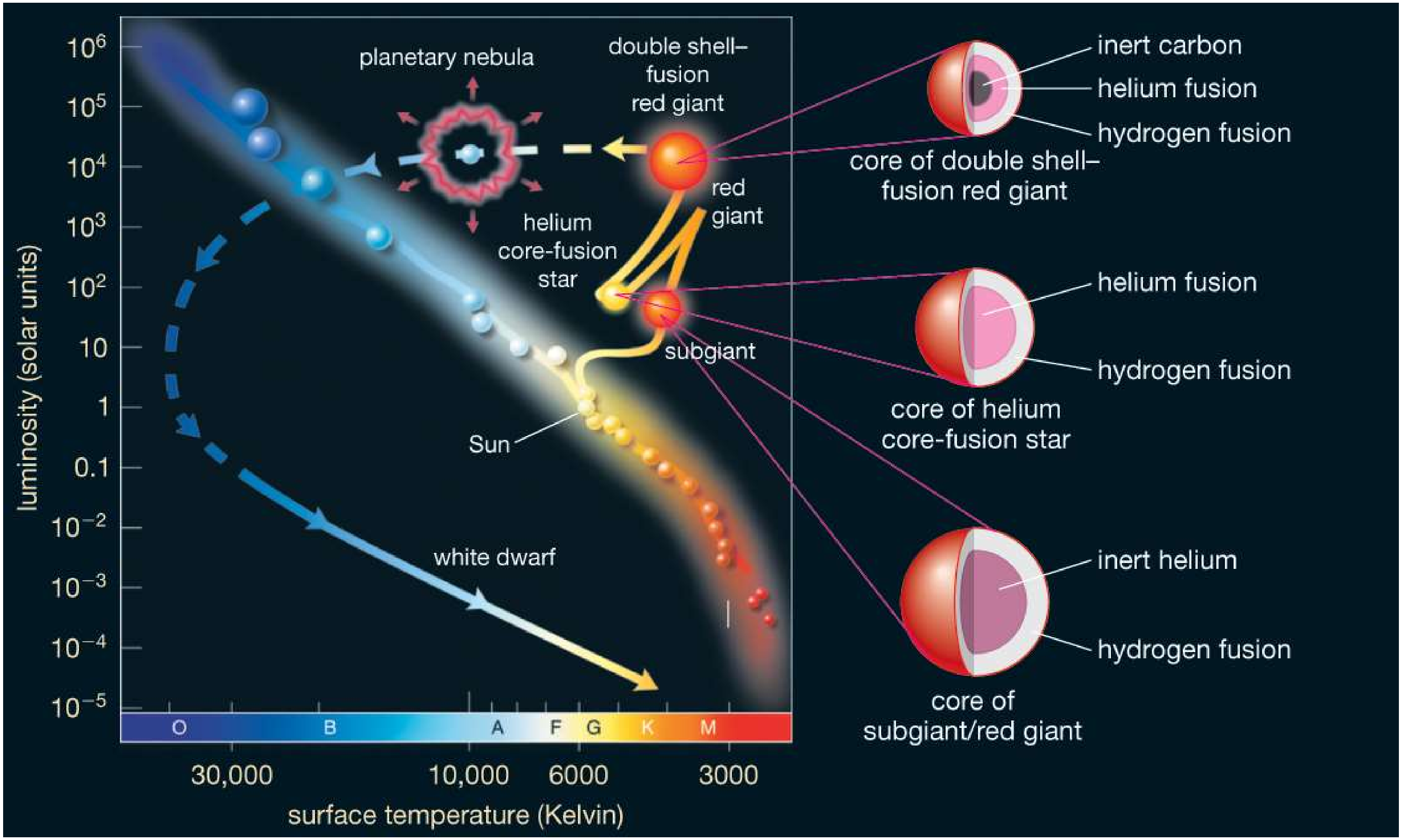
Horizontal Branch

- **Helium fusion in core with hydrogen shell**
- **Moves towards main sequence**
- **Smaller, but hotter star…**

Asymptotic Giant Branch

- **Carbon/Oxygen core**
- **Helium and hydrogen fusion shells**

Life Track of a Sun-Like Star



Examples of Planetary Nebula

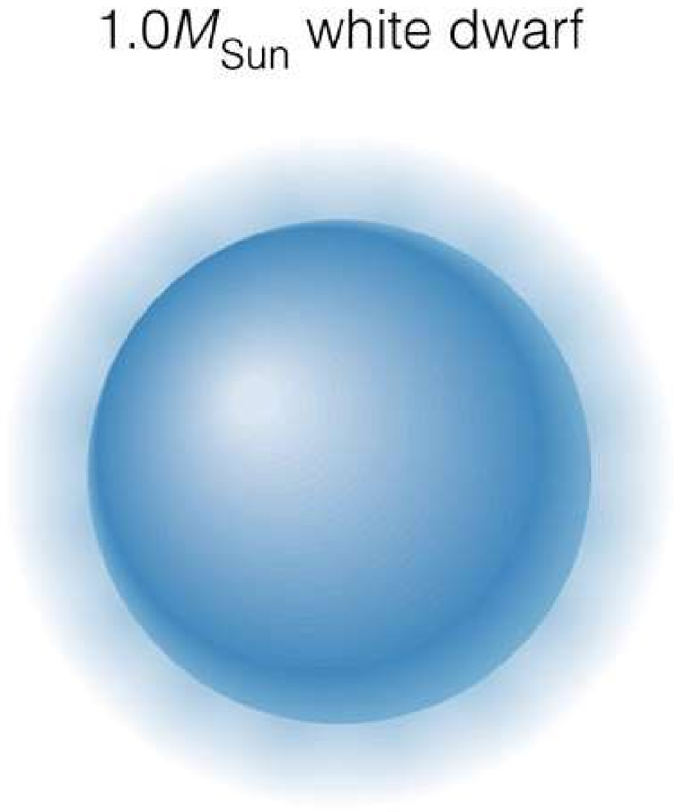

Helix nebula


Cat’s eye Nebula


Eskimo Nebula

- The white dwarf core can still be millions of degrees kelvin in temperature (but cools off fast)
- Intense UV light ionizes the ejected outer layers of the star

Leaving Behind a White Dwarf…



- White Dwarf’s are the remaining cores of low-mass stars
- A white dwarf is about the same size as Earth

The White Dwarf Limit

S. Chandrasekhar

- Einstein's theory of relativity says that nothing can move faster than light
- When electron speeds in white dwarf approach speed of light, electron degeneracy pressure can no longer support it
- Chandrasekhar found (at age 20!) that this happens when a white dwarf's mass reaches 1.4 M_{sun}
- He actually puzzled this out on the boat from India to England before he started his grad studies in physics. (Once at Cambridge his advisor told him he was crazy and to drop this work…. it won him the Nobel Prize)

iClicker Question

After the Sun becomes a red giant star and makes carbon in its core, why will it not make heavier elements?

A. It will have ran out of fuel
B. It will be near the end of its life, and doesn’t have time
C. It will not be massive enough to make it hot enough for further reactions
D. The heavier elements will all go into a planetary nebula
E. A and B

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iClicker Question

What stops the contraction of a brown dwarf?

A. Density
B. Nuclear reactions which create hot gas
C. The core becomes solid
D. Degeneracy pressure
E. None of the above

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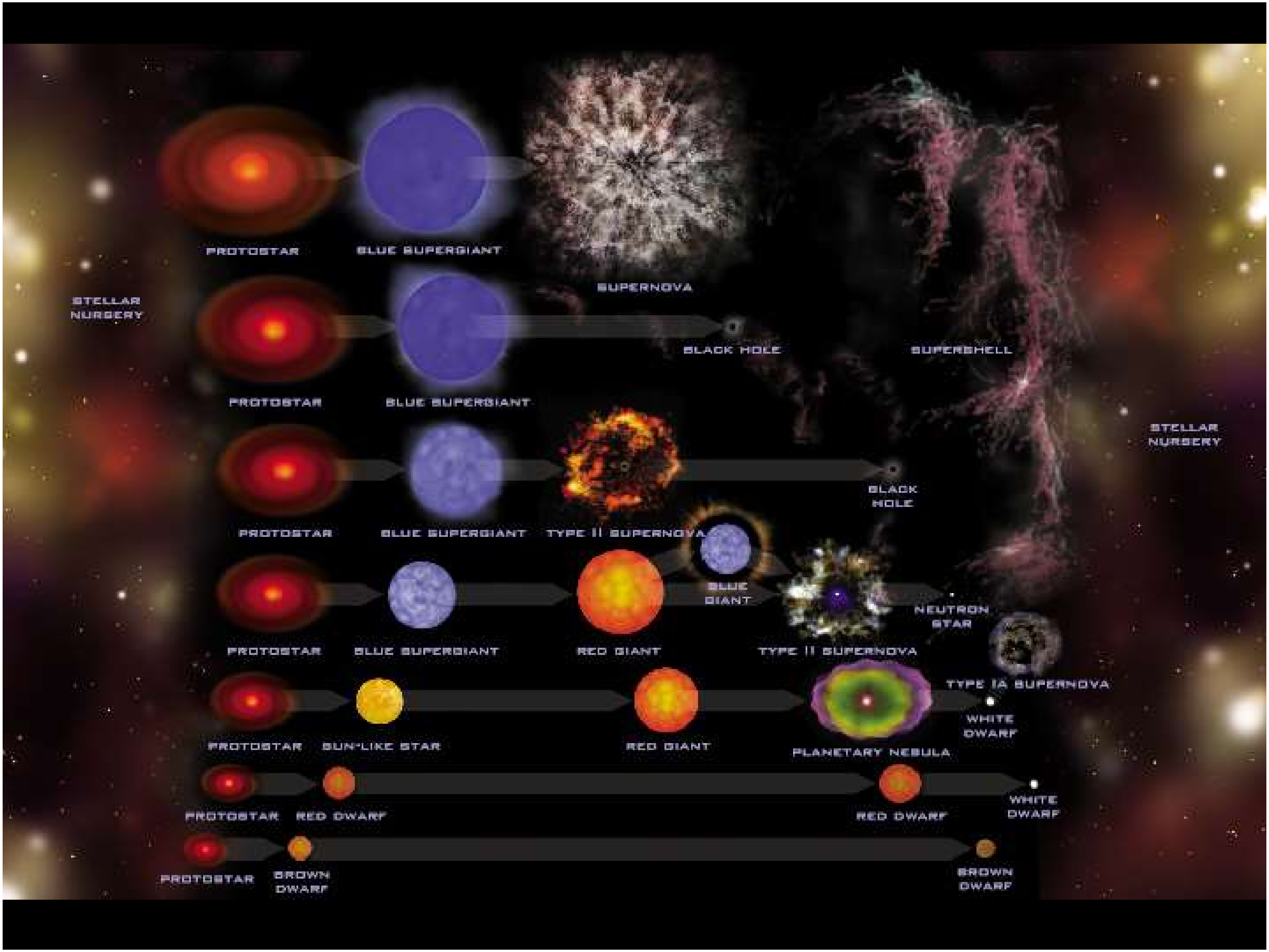
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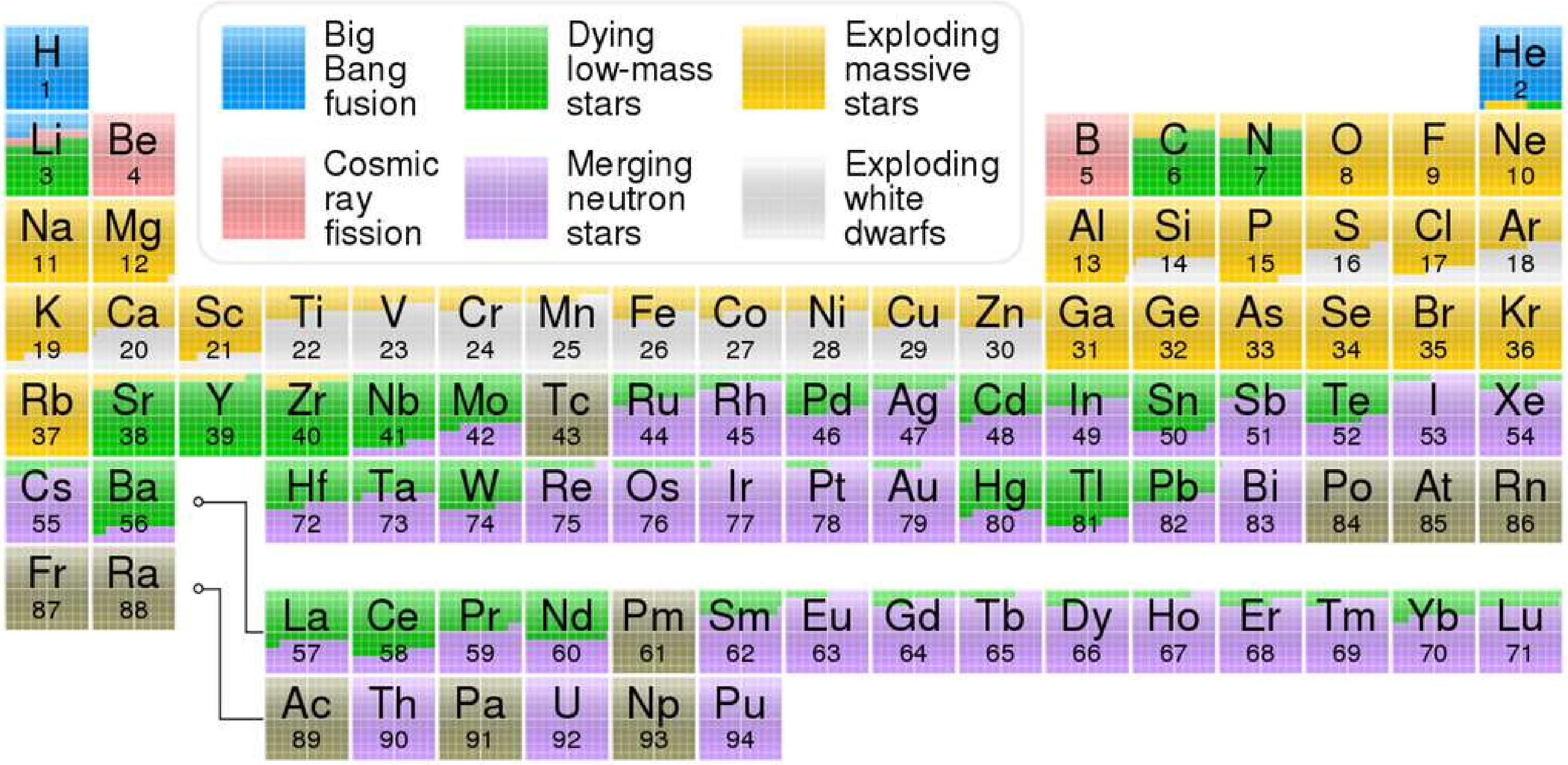
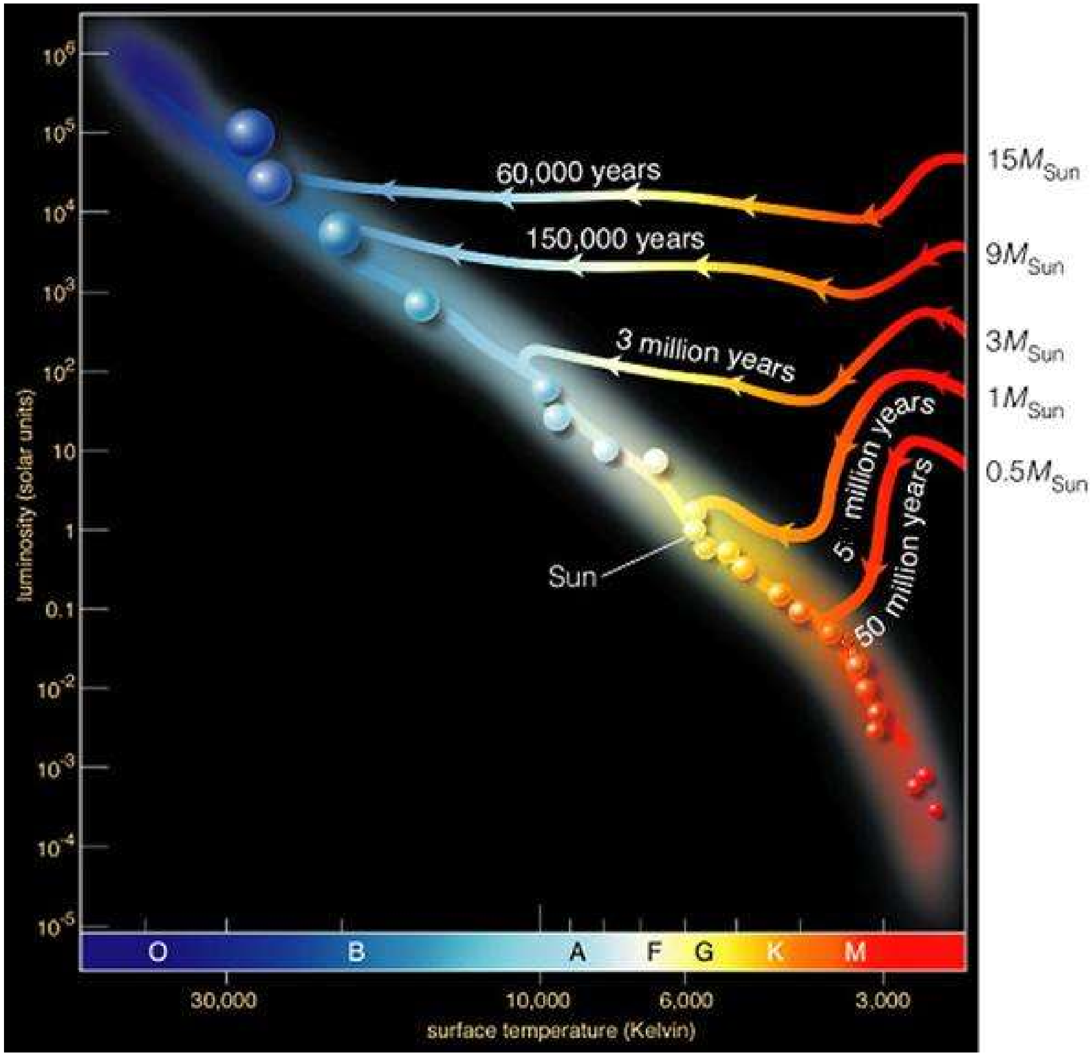
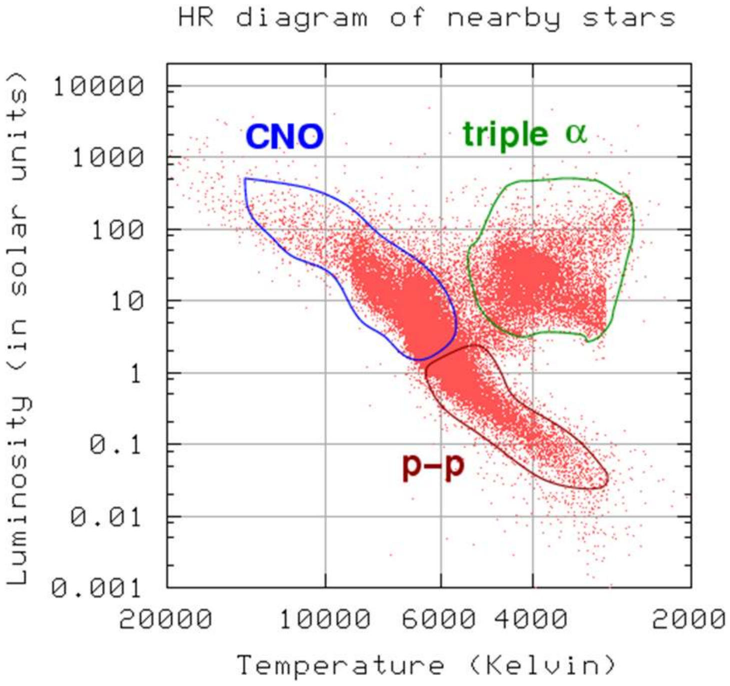
Where were the Elements Made?



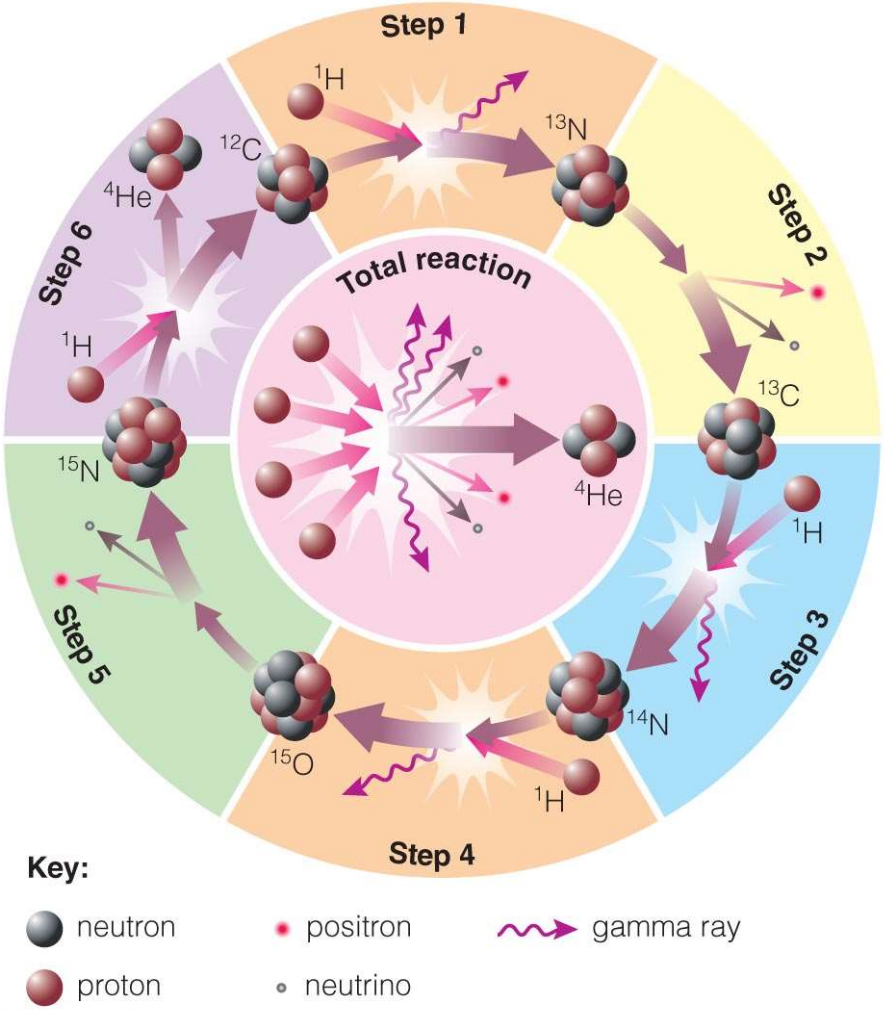
Life as a High-Mass Star



- More massive stars collapse into a star faster
- Fusion is more efficient at higher temperatures and pressures.
- In fact, a whole new fusion process is possible. The CNO cycle possible at ~ 1.5 M_{Sun}



The CNO Cycle



Stars with $M > 1.5\ M_{Sun}$ have sufficient temperatures and pressures to initiate this process (~ 15 million K needed)

The reaction is ***equivalent*** to the proton-proton chain reaction.

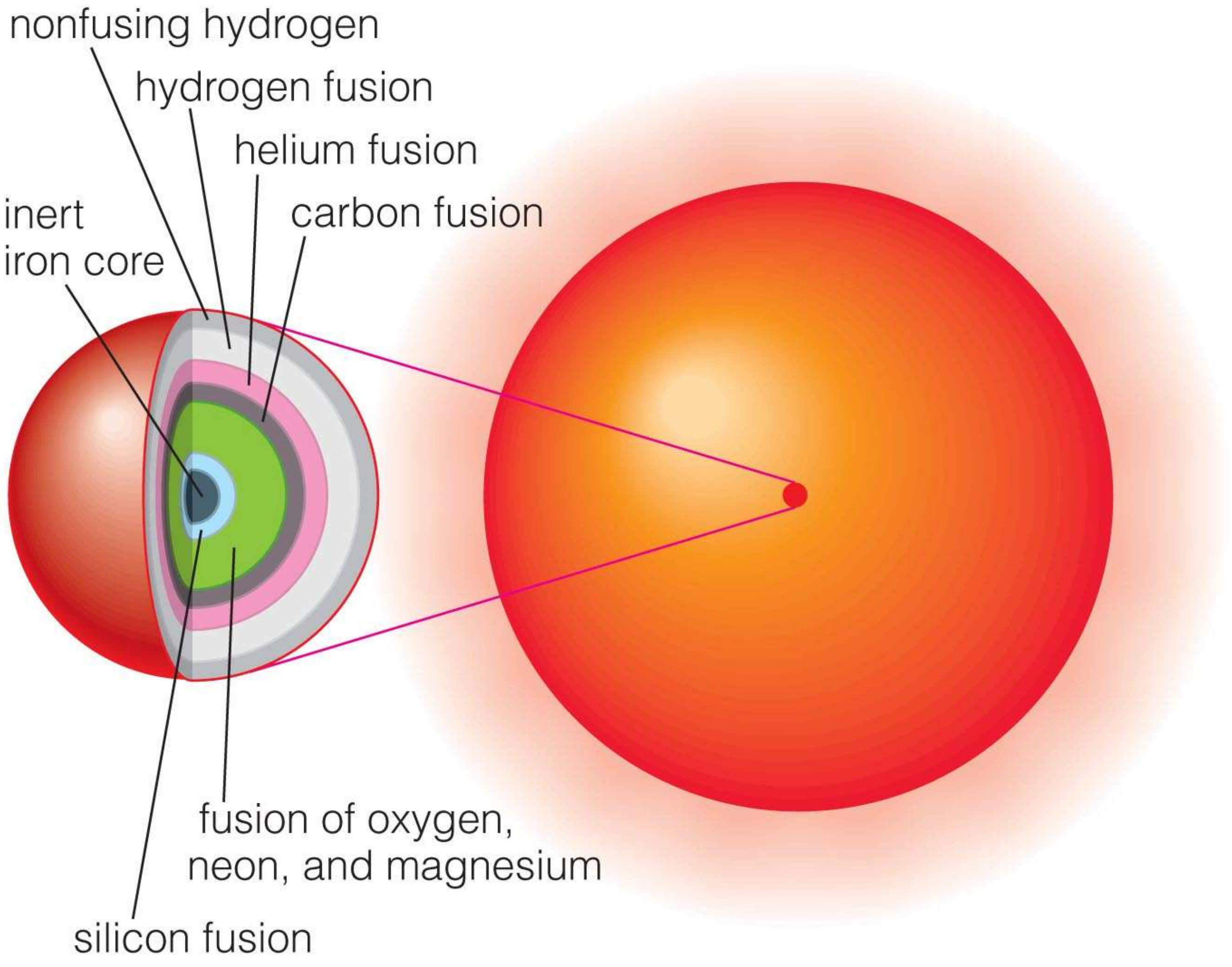
- Overall, four 4 protons are consumed, and a helium nucleus is generated
- The ^{12}C acts as a catalyst in this reaction (it returns to its original state)
- This reaction proceeds more efficiently than the proton-proton reaction which makes more massive stars even more luminous

Life Stages of High-Mass Stars

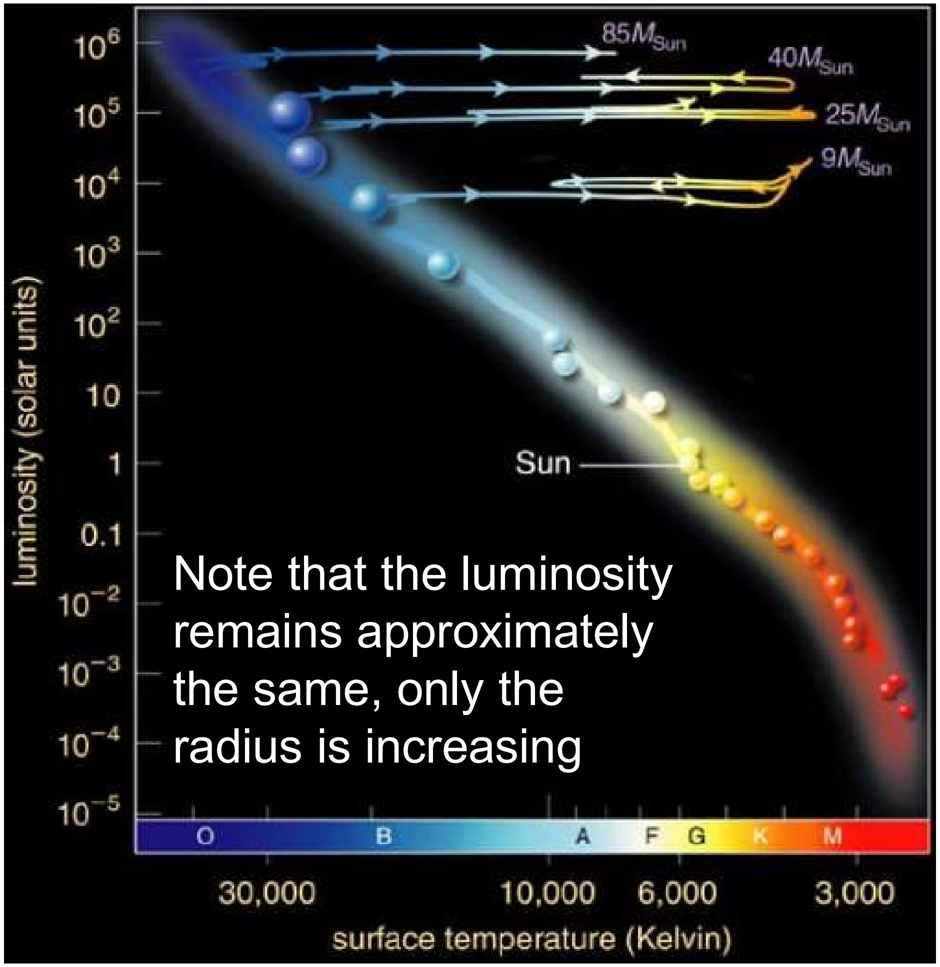
Late life stages of high-mass stars are similar to those of low-mass stars:

- Hydrogen core fusion (main sequence)
    - 90% of the lifetime of the star (few million years for 25M_{Sun})
- Hydrogen shell fusion (supergiant)
- Helium core fusion (supergiant)
    - Few hundred thousand years…
- Multiple layers shell fusion (supergiant)
    - Carbon-burning (few hundred years)
    - Neon burning (few years)
    - Oxygen burning (few months)
    - Silicon burning (perhaps a day)

Multiple Shell Burning



The Complicated Zig-Zagging Paths of Dying High-Mass Stars

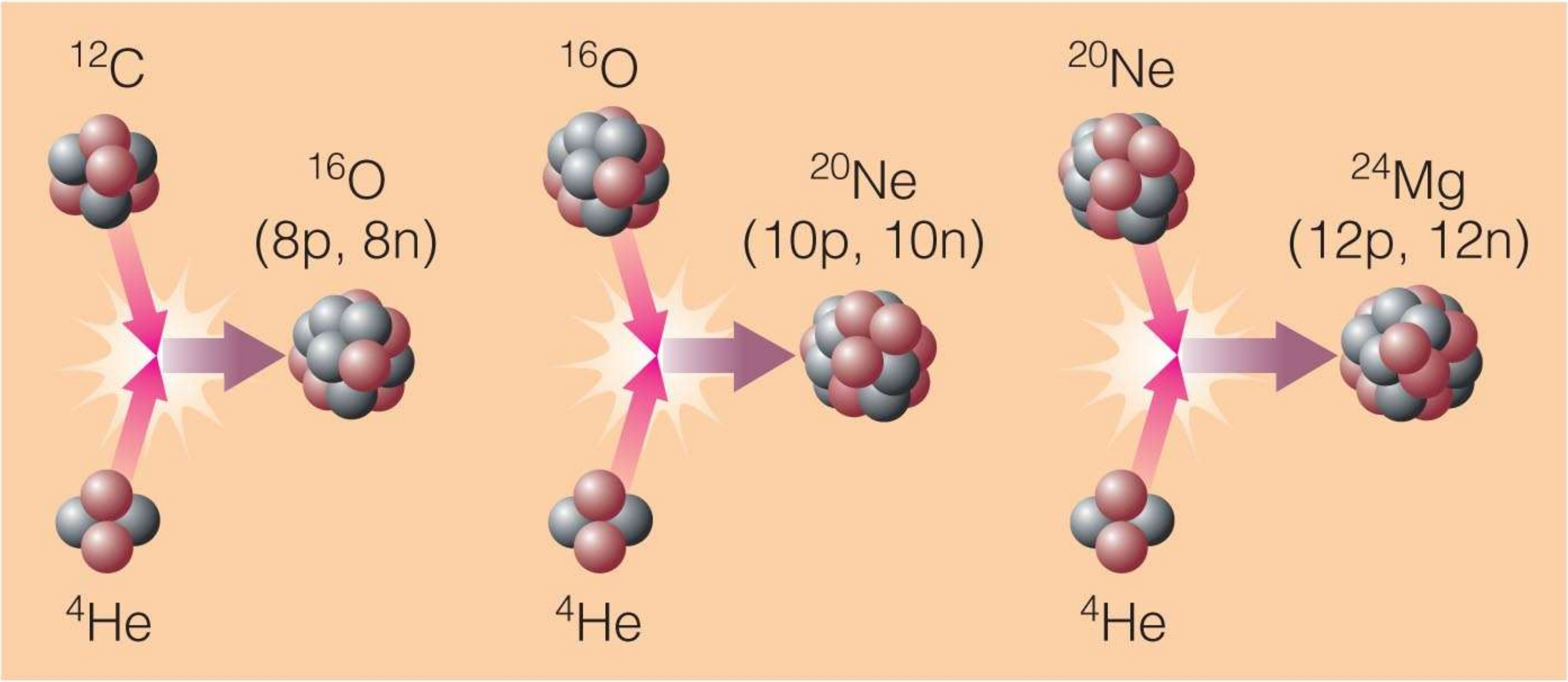


Note that the luminosity remains approximately the same, only the radius is increasing

The general process is similar as before:

- As the core runs out of each element, the core contracts
- In doing so, the core gets hot enough to start burning the next element (this is a gradual process, unlike for low mass stars (degeneracy does not play a role here)
- The shell surrounding each successive layer gets hot enough for shell fusion which propagates through the outer layers of the star, increasing the radius
- *For intermediate mass stars there may be some contraction and stalling between stages…*

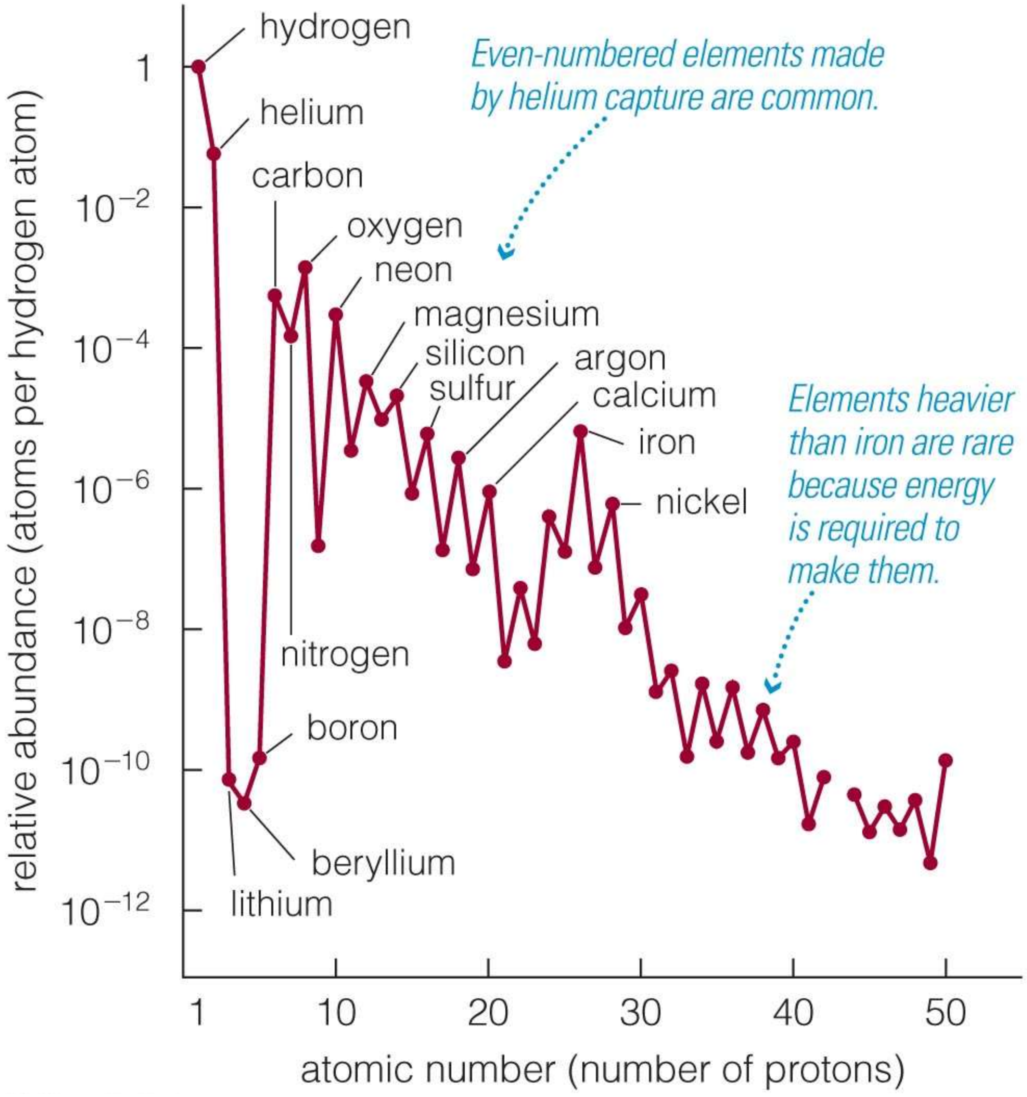
Helium Capture Processes



a Helium-capture reactions.

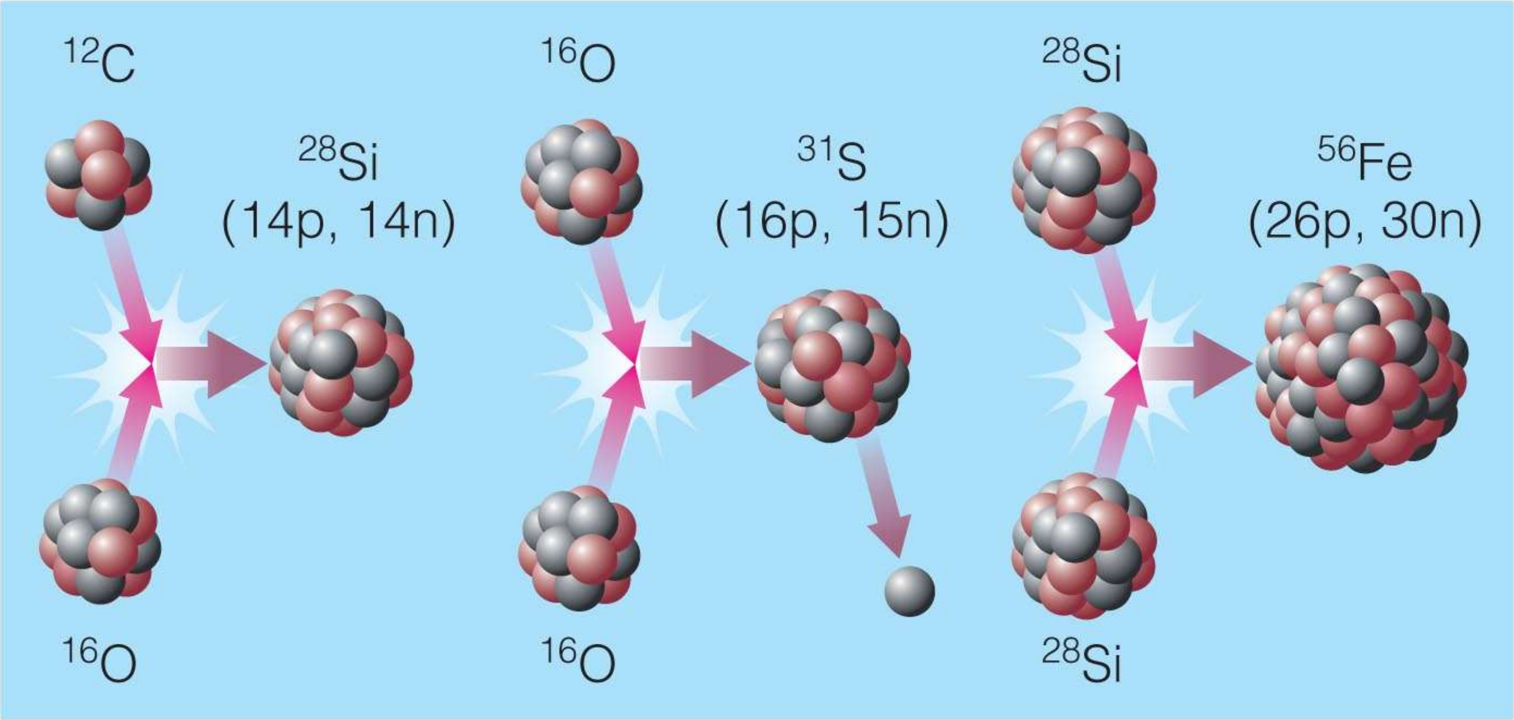
High core temperatures allow helium to fuse with heavier elements.

Evidence for Helium Capture Processes



We observe Higher abundances of elements with even numbers of protons

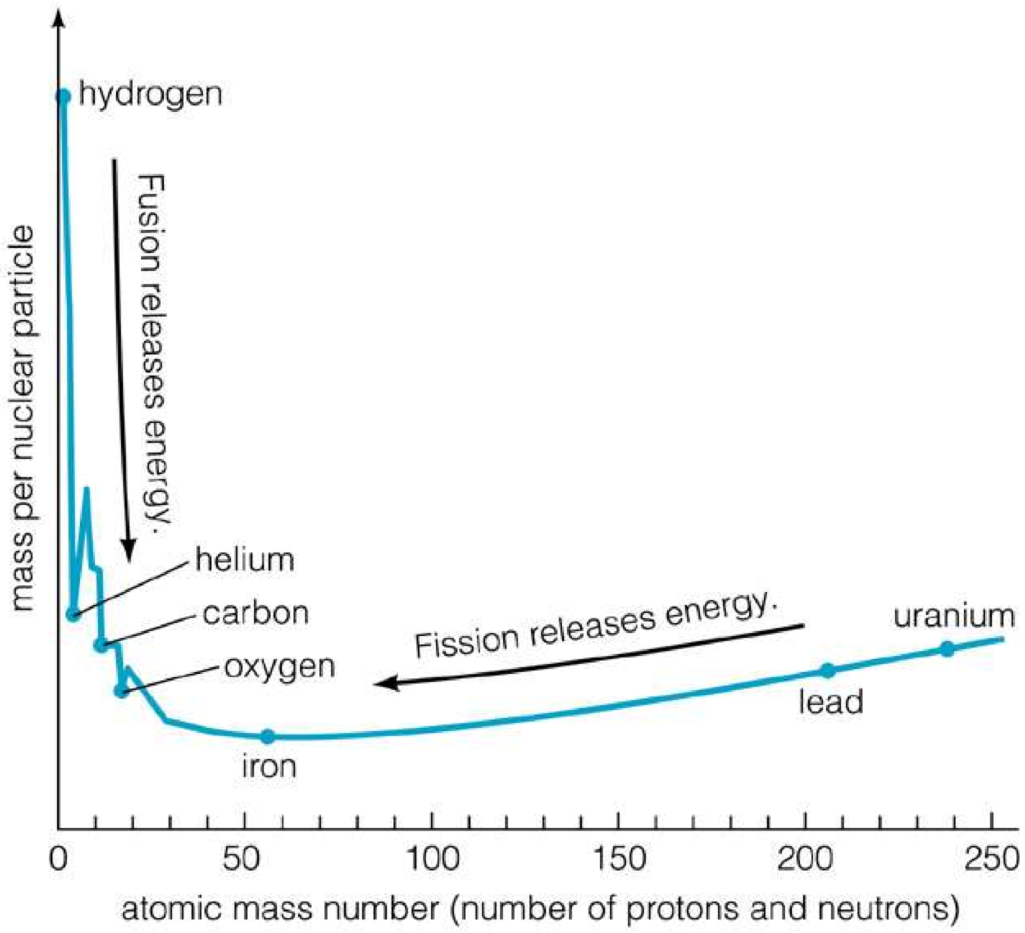
Advanced Nuclear Burning



b Other reactions. (Note: Fusion of two silicon nuclei first produces nickel-56, which decays rapidly to cobalt-56 and then to iron-56.)

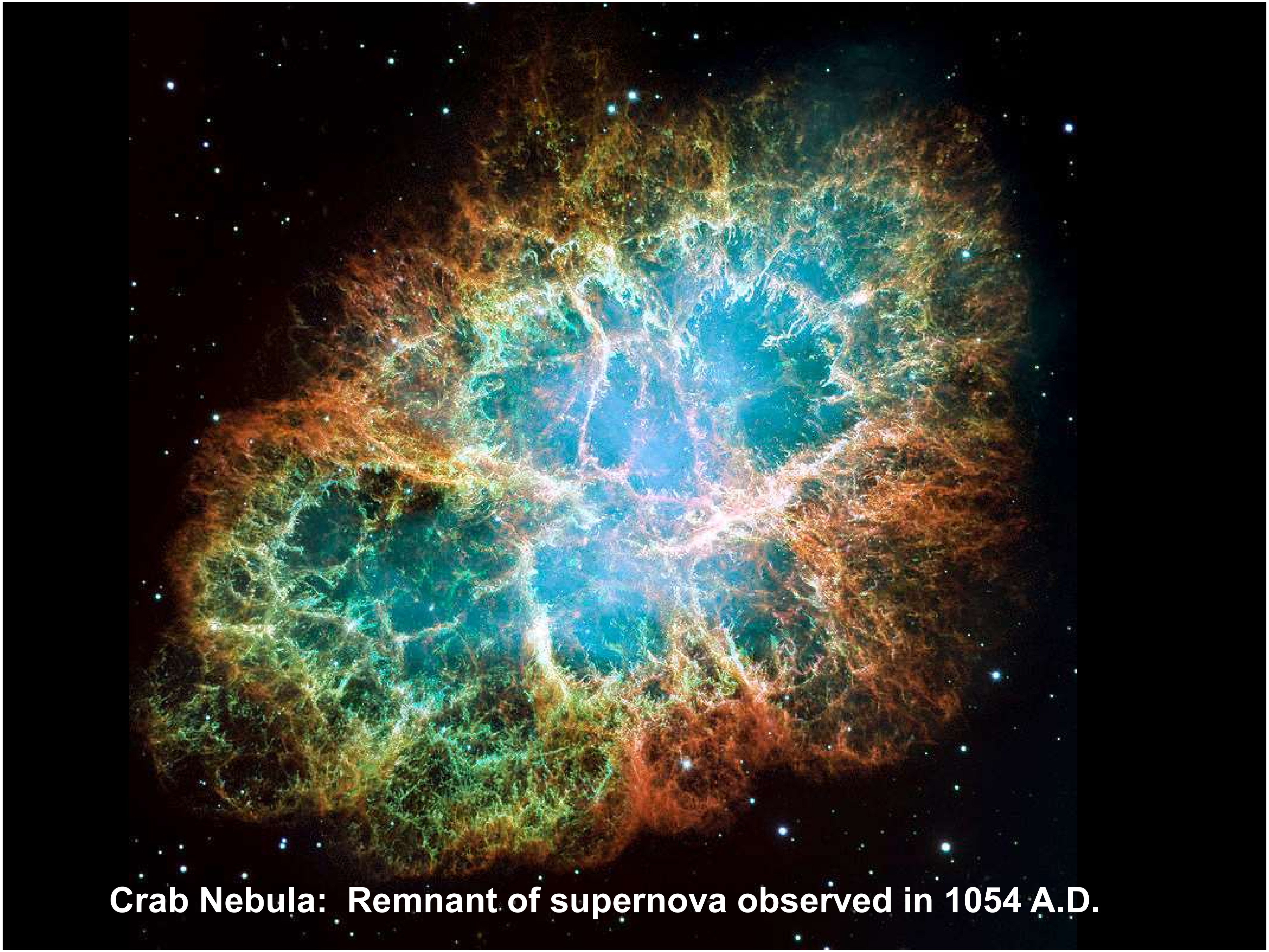
Core temperatures in stars with >8M_{Sun} allow fusion of elements as heavy as iron. ***Why does it stop at Iron?***

Iron – The End of the Line?



- The amount liberated per reaction generally drops as you approach ^{56}Fe.
- ^{56}Fe is bottom of the energy valley. Making heavier elements is possible, but will require energy input.
- To make the elements beyond Fe requires two processes….
  - **R-process**
  - **S-process**

Once we have a core of Iron….
…What happens next?



Crab Nebula: Remnant of supernova observed in 1054 A.D.

Supernova remnant N 63A

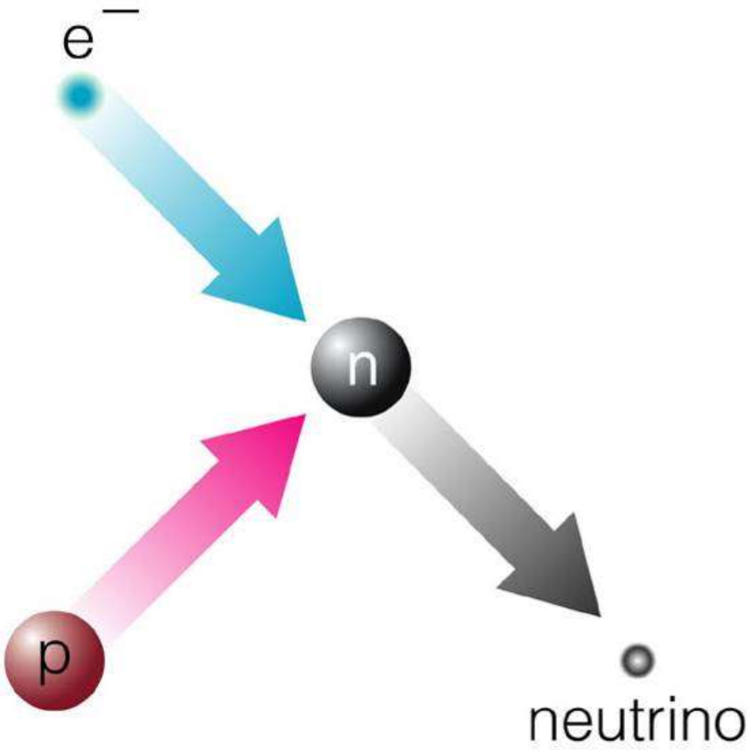
before

after

Supernova 1987A is the nearest supernova observed in the last 400 years (168,000 light-years away)

The next nearby supernova?

What is happening?



Remember that the Chandrasekhar limit of 1.4 Msun indicates that this is the upper limit that electron degeneracy pressure can stop further collapse…

Eventually gravity wins…

The electrons and protons combine to form neutrons…

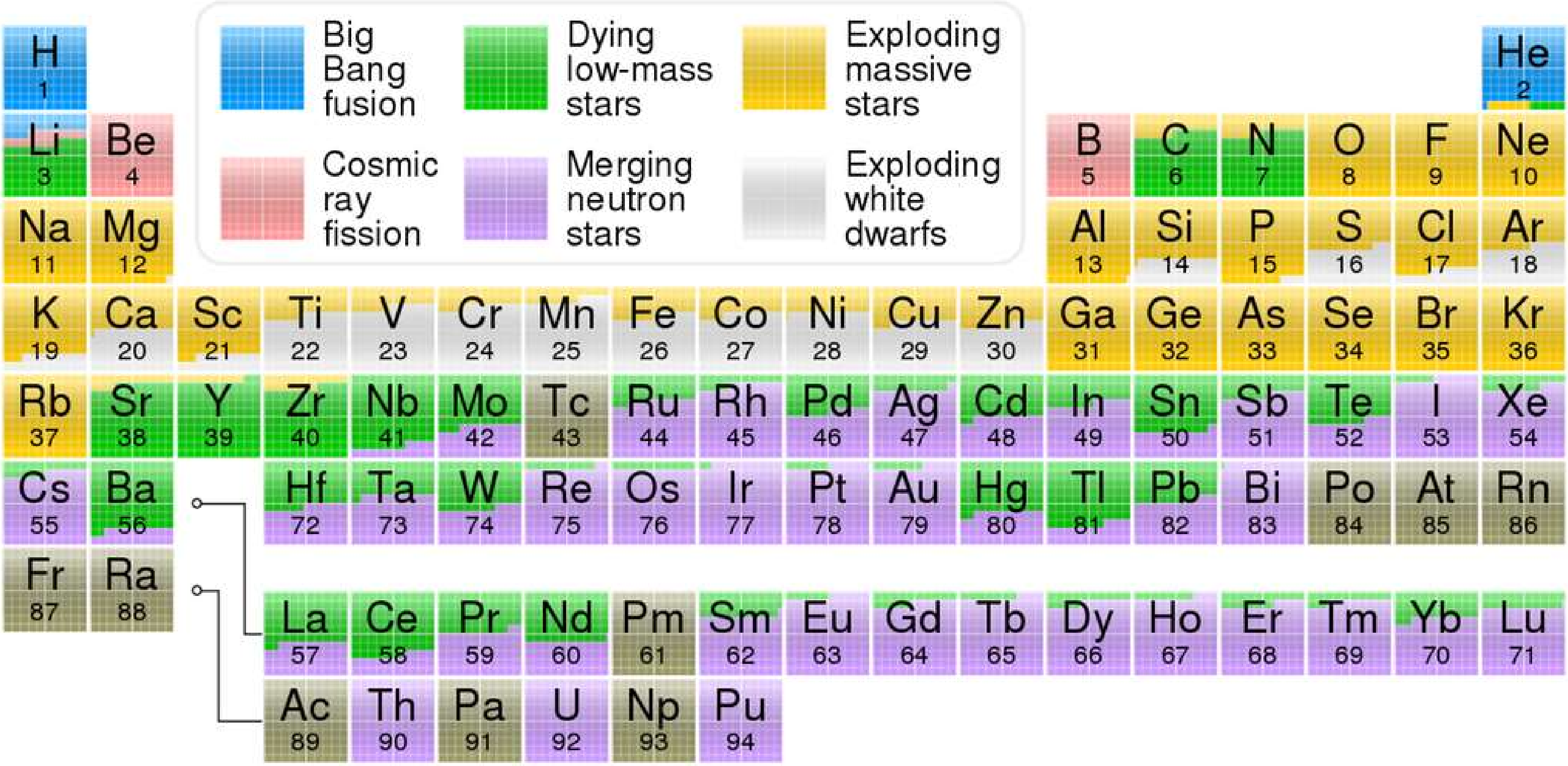
A neutron star forms within seconds and is only ~10 Km diameter…

The outer layers are suddenly in free-fall… so what causes them to explode so violently?

Supernova Explosion

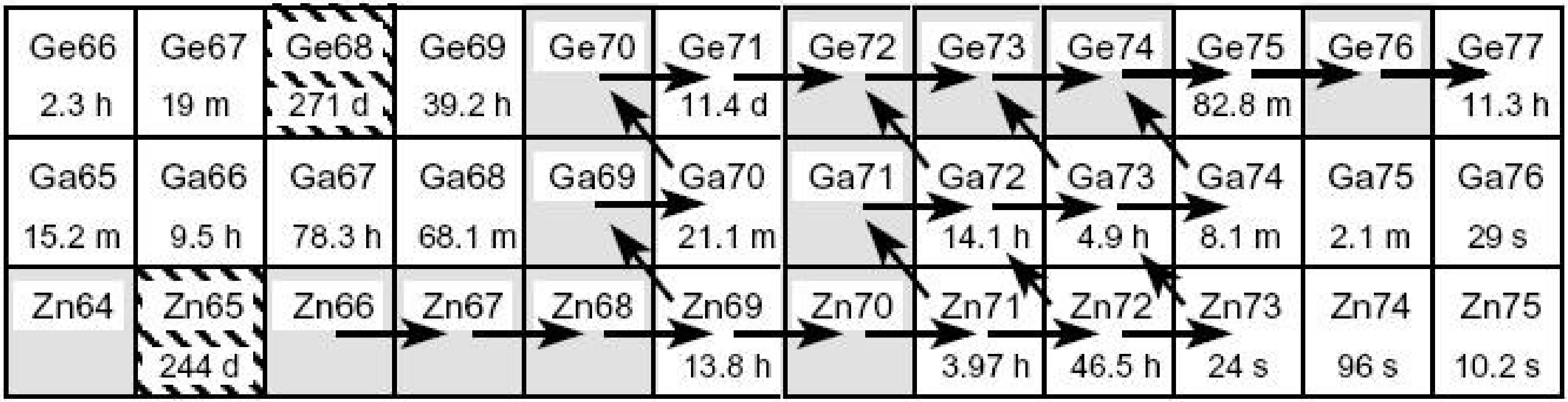
https://www.youtube.com/watch?v=e-91PbbaKI8

Where were the Elements Made?



S-Process (Slow Process)

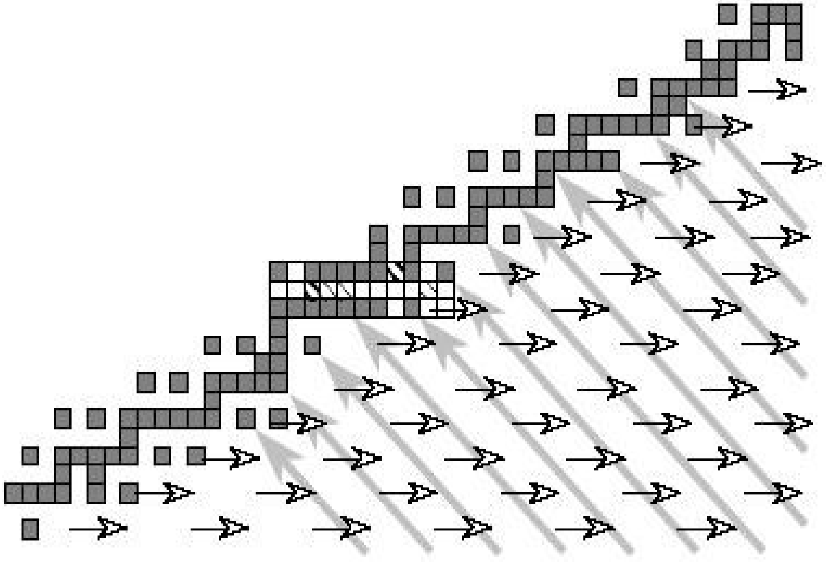
- Occurs in outer layers of giant stars
- Some reactions liberate neutrons.
- The larger nuclei tend to have a larger capture cross-section for neutrons and can absorb lots of neutrons.
- This puts energy into the atom, pumps up its atomic number, and pushes it into really unstable isotopes (look at ^{66}Zn going to ^{73}Zn.
- Then beta decay turns a neutron into a proton, pushing the atom up the periodic chart.
- This makes about 75% of isotopes heavier than Fe



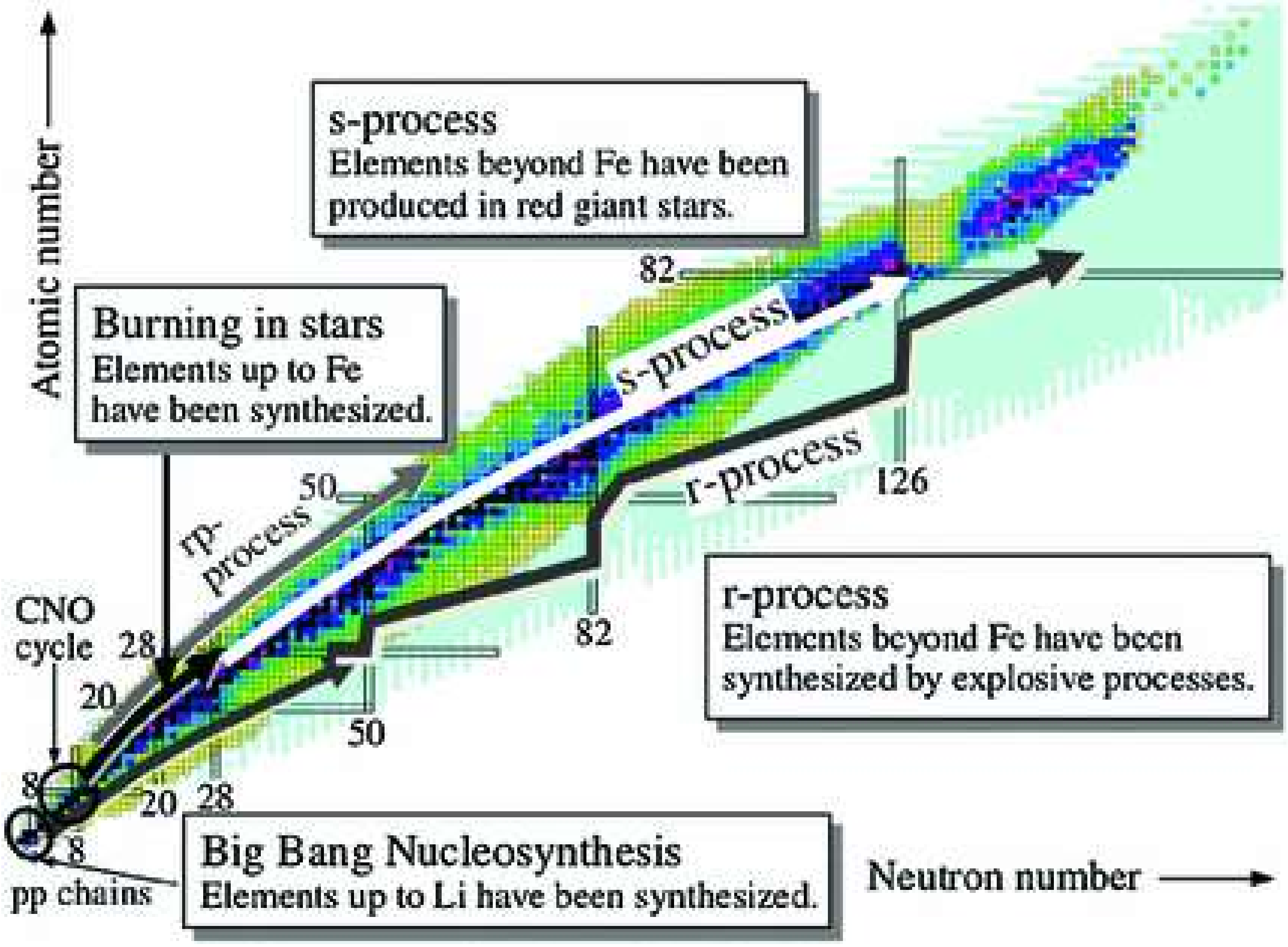
Ge66 2.3 h	Ge67 19 m	Ge68 271 d	Ge69 39.2 h	Ge70	Ge71 11.4 d	Ge72	Ge73	Ge74	Ge75 82.8 m	Ge76	Ge77 11.3 h
Ga65 15.2 m	Ga66 9.5 h	Ga67 78.3 h	Ga68 68.1 m	Ga69	Ga70 21.1 m	Ga71	Ga72 14.1 h	Ga73 4.9 h	Ga74 8.1 m	Ga75 2.1 m	Ga76 29 s
Zn64	Zn65 244 d	Zn66	Zn67	Zn68	Zn69 13.8 h	Zn70	Zn71 3.97 h	Zn72 46.5 h	Zn73 24 s	Zn74 96 s	Zn75 10.2 s

R-Process (Rapid Process)

- Occurs while the supernova is in the process of ripping apart a star, the stellar material is flooded with neutrons.
- During the few seconds (or milliseconds) of the explosion neutrons are absorbed much faster then the atoms can decay, so the isotopes are pushed far to the right on the chart.
- THEN decay begins and continues moving up and to the left until stable configurations are reached.
- BUT so many neutrons are absorbed during this RAPID process that it allows nuclides to decay to a wide range of stable configurations.



Element Formation Overview



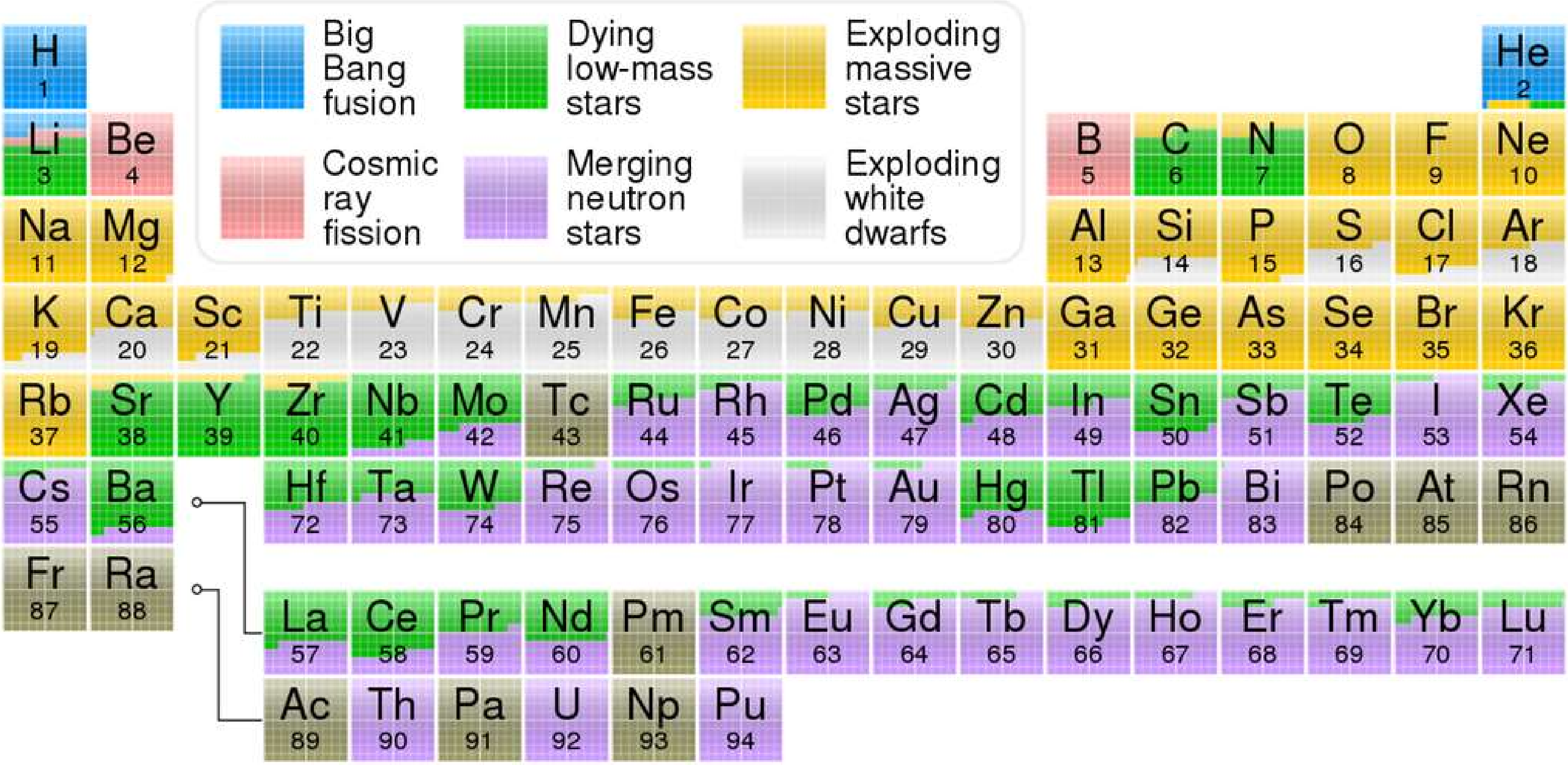
s-process
Elements beyond Fe have been produced in red giant stars.

Burning in stars
Elements up to Fe have been synthesized.

r-process
Elements beyond Fe have been synthesized by explosive processes.

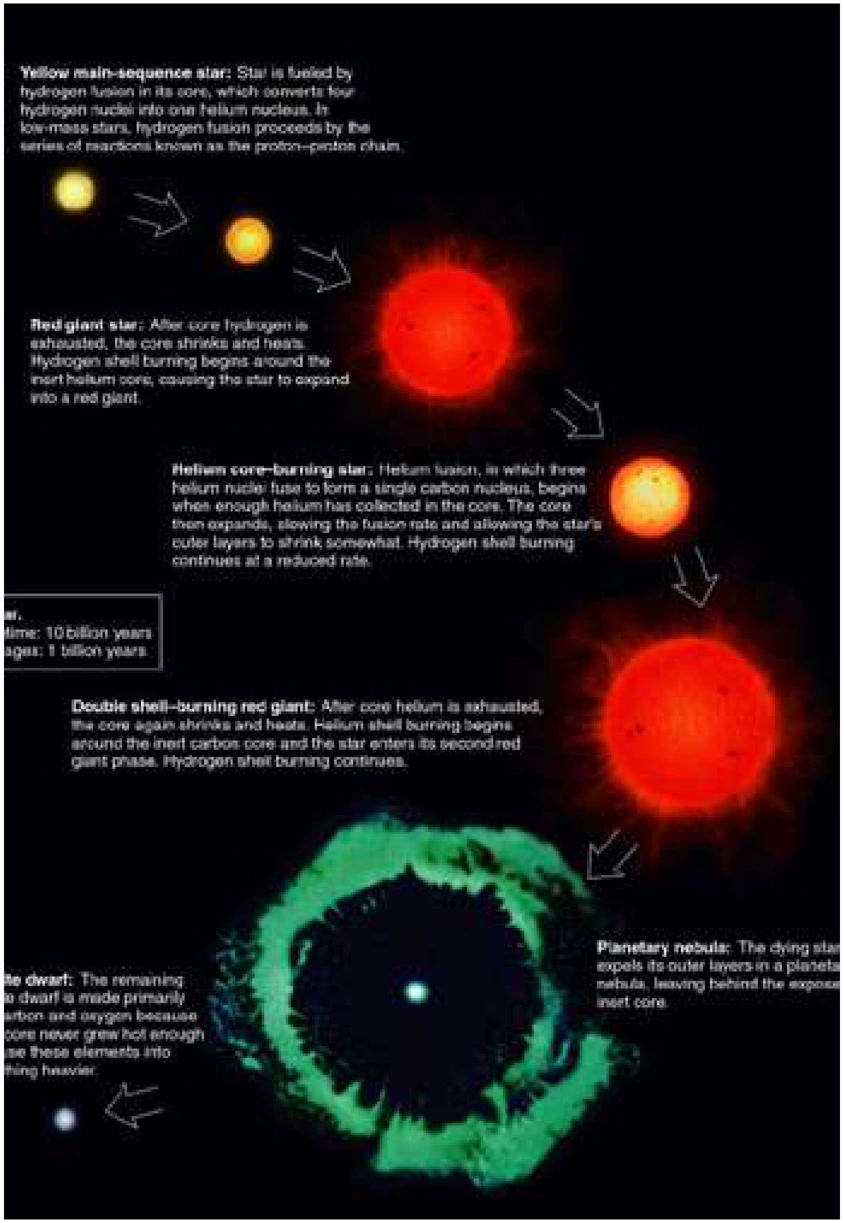
Big Bang Nucleosynthesis
Elements up to Li have been synthesized.

Where were the Elements Made?



Elements in Purple only confirmed in the past year or so…

Low-Mass Star Summary



Yellow main-sequence star: Star is fueled by hydrogen fusion in its core, which converts four hydrogen nuclei into one helium nucleus. In low-mass stars, hydrogen fusion proceeds by the series of reactions known as the proton–proton chain.

Red giant star: After core hydrogen is exhausted, the core shrinks and heats. Hydrogen shell burning begins around the inert helium core, causing the star to expand into a red giant.

Helium core-burning star: Helium fusion, in which three helium nuclei fuse to form a single carbon nucleus, begins when enough helium has collected in the core. The core then expands, slowing the fusion rate and allowing the star's outer layers to shrink somewhat. Hydrogen shell burning continues at a reduced rate.

ar.
time: 10 billion years
ages: 1 billion years

Double shell–burning red giant: After core helium is exhausted, the core again shrinks and heats. Helium shell burning begins around the inert carbon core and the star enters its second red giant phase. Hydrogen shell burning continues.

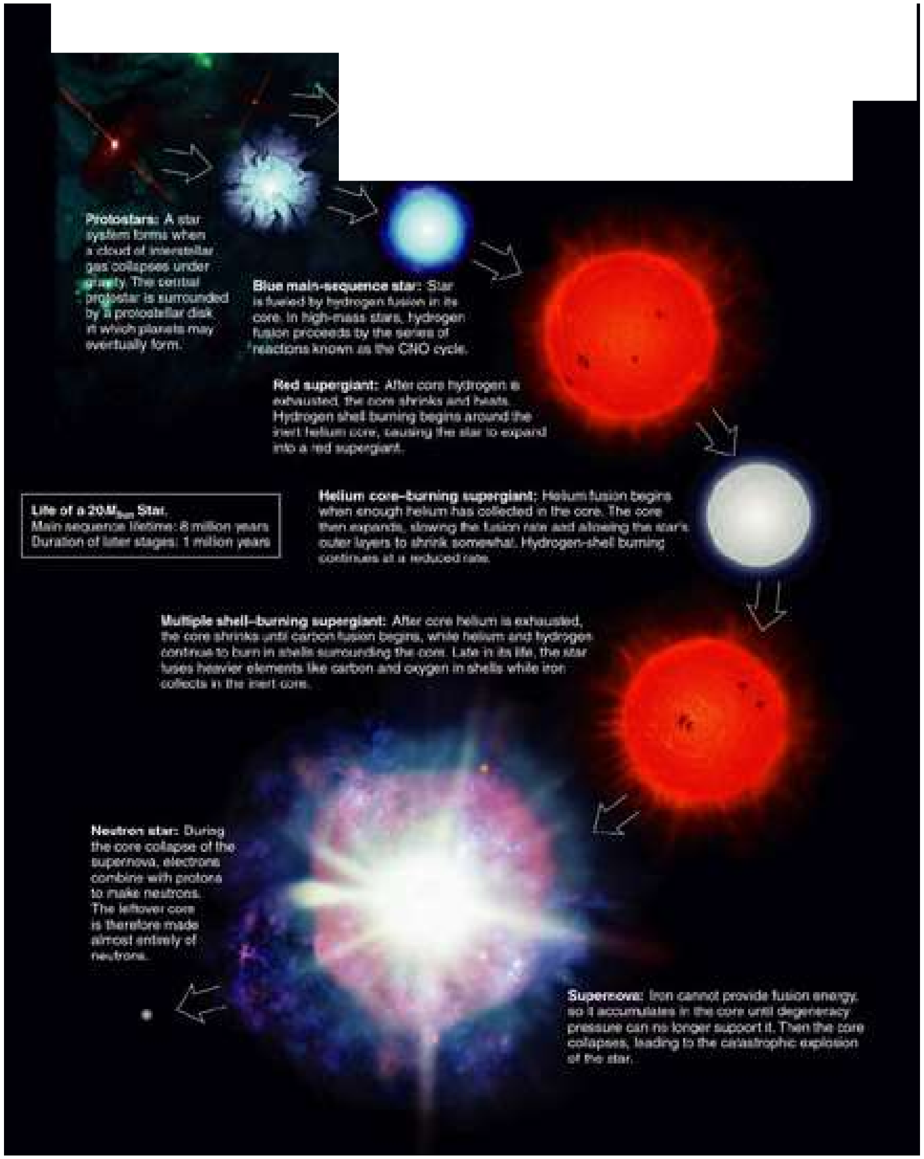
Planetary nebula: The dying sta
expels its outer layers in a planeta
nebula, leaving behind the expose
inert core.

te dwarf: The remaining
e dwarf is made primarily
arbon and oxygen because
core never grew hot enough
se these elements into
thing heavier.

Not to scale!

1. Main Sequence: H fuses to He in core
2. Red Giant: H fuses to He in shell around He core
3. Helium Core Burning:
   He fuses to C in core while H fuses to He in shell
4. Double Shell Burning:
   H and He both fuse in shells
5. Planetary Nebula leaves white dwarf behind

Life Stages of High-Mass Star



Protostars: A star system forms when a cloud of interstellar gas collapses under gravity. The central protostar is surrounded by a protostellar disk in which planets may eventually form.

Blue main-sequence star: Star is fueled by hydrogen fusion in its core. In high-mass stars, hydrogen fusion proceeds by the series of reactions known as the CNO cycle.

Red supergiant: After core hydrogen is exhausted, the core shrinks and heats. Hydrogen shell burning begins around the inert helium core, causing the star to expand into a red supergiant.

Life of a $20M_{Sun}$ Star.
Main sequence lifetime: 8 million years
Duration of later stages: 1 million years

Helium core–burning supergiant: Helium fusion begins when enough helium has collected in the core. The core then expands, slowing the fusion rate and allowing the star's outer layers to shrink somewhat. Hydrogen-shell burning continues at a reduced rate.

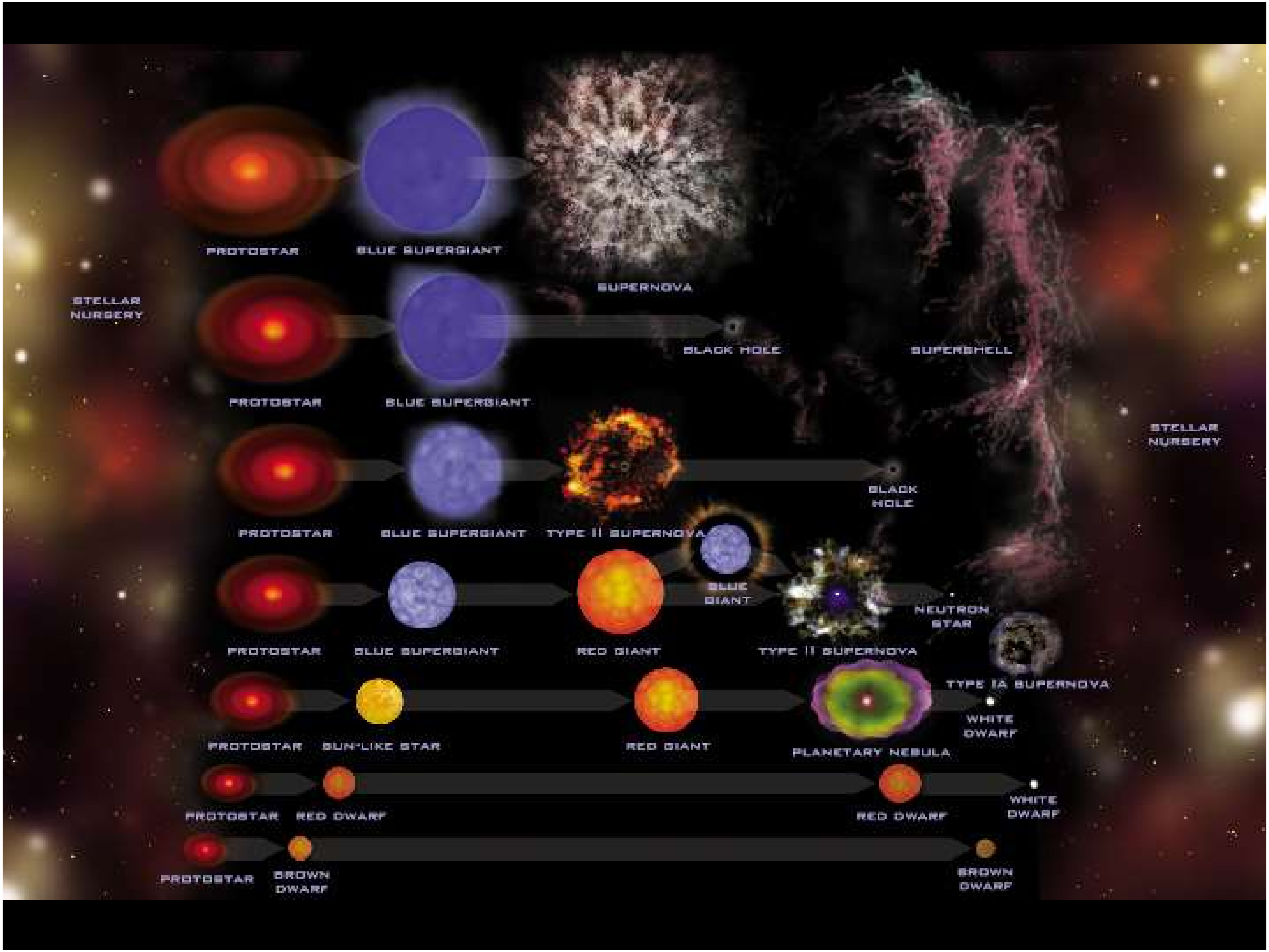
Multiple shell–burning supergiant: After core helium is exhausted, the core shrinks until carbon fusion begins, while helium and hydrogen continue to burn in shells surrounding the core. Late in its life, the star fuses heavier elements like carbon and oxygen in shells while iron collects in the inert core.

Neutron star: During the core collapse of the supernova, electrons combine with protons to make neutrons. The leftover core is therefore made almost entirely of neutrons.

Supernova: Iron cannot provide fusion energy, so it accumulates in the core until degeneracy pressure can no longer support it. Then the core collapses, leading to the catastrophic explosion of the star.

Not to scale!

1. Main Sequence: H fuses to He in core
2. Red Supergiant: H fuses to He in shell around He core
3. Helium Core Burning:
   He fuses to C in core while H fuses to He in shell
4. Multiple Shell Burning:
   Many elements fuse in shells
5. Supernova leaves neutron star behind (or black hole)


STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

What have we learned?

- What are the life stages of a high-mass star?
  - They are similar to the life stages of a low-mass star.
- How do high-mass stars make the elements necessary for life?
  - Higher masses produce higher core temperatures that enable fusion of heavier elements.
- How does a high-mass star die?
  - The iron core collapses, leading to a supernova.
  - Leaving behind a neutron star or a black hole.

13.4 Stars in Close Binaries

Our goals for learning:

- How are the lives of stars with close companions different?

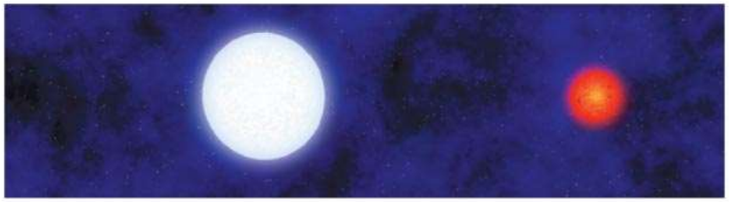
Thought Question

The binary star Algol (the Demon star) consists of a $3.7M_{\text{Sun}}$ main-sequence star and a $0.8M_{\text{Sun}}$ subgiant star.

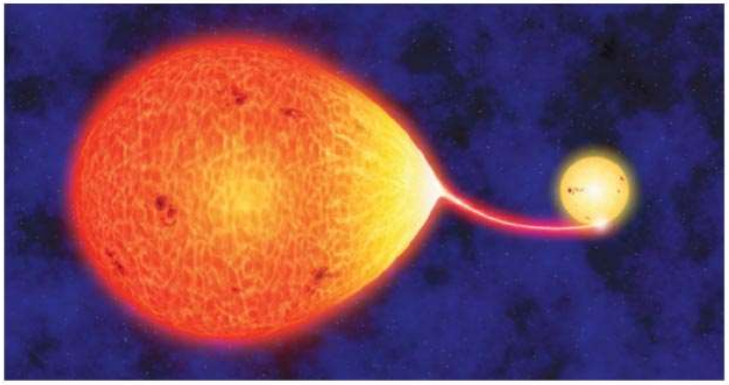
What's strange about this pairing?

How did it come about?

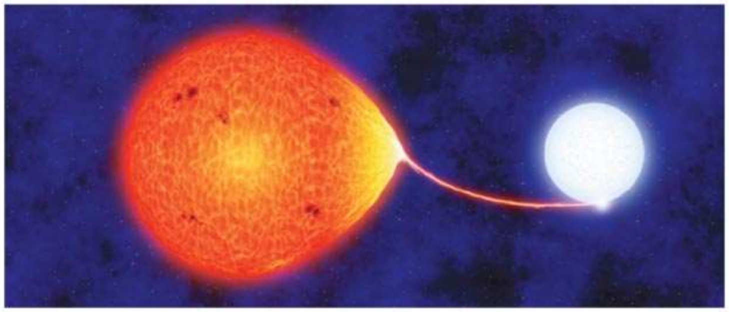
The Algol Binary Star System



Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.



Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

- Stars in Algol are close enough that matter can flow from the subgiant onto the main-sequence star.
- The star that is now a subgiant was originally more massive.
- As it reached the end of its life and started to grow, it began to transfer mass to its companion (*mass exchange*).
- Now the companion star is more massive.
- *What would happen if the companion star drawing mass were a ~ 1.4* M_{sun} *white dwarf?*

What have we learned?

How are the lives of stars with close companions different?

- Stars with close companions can exchange mass, altering the usual life stories of stars.

End of Todays Lecture