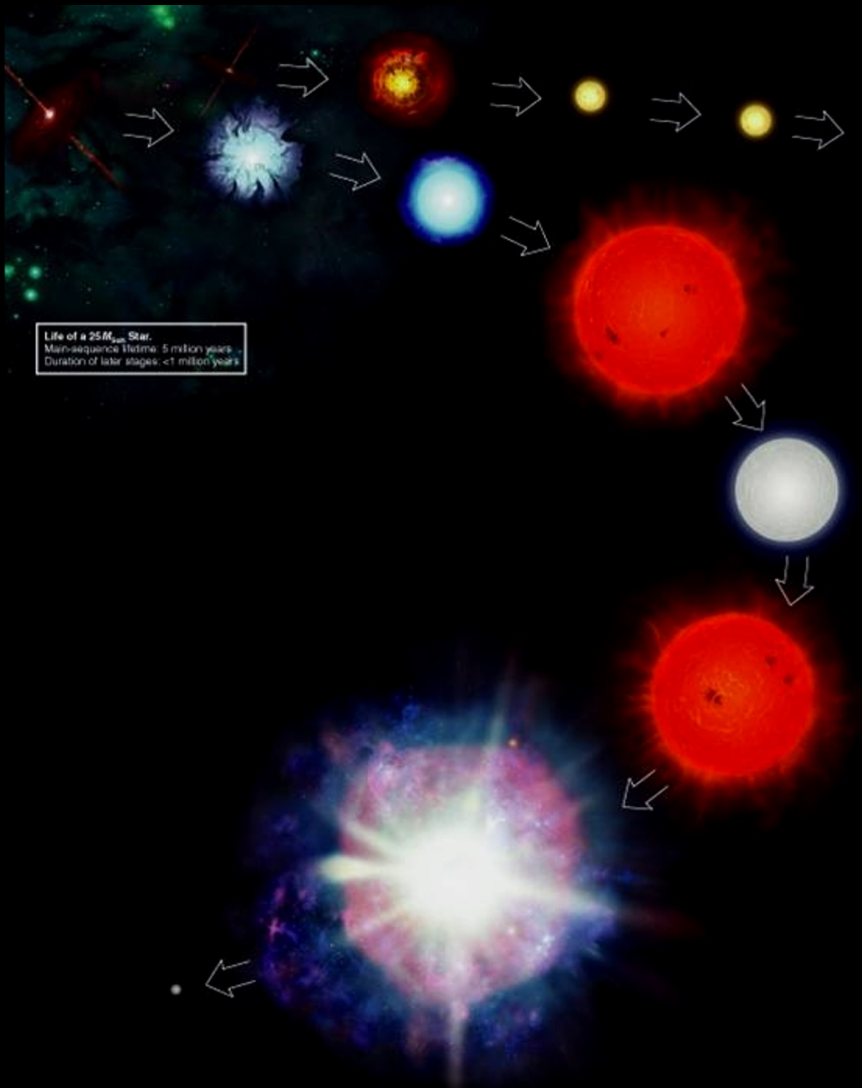
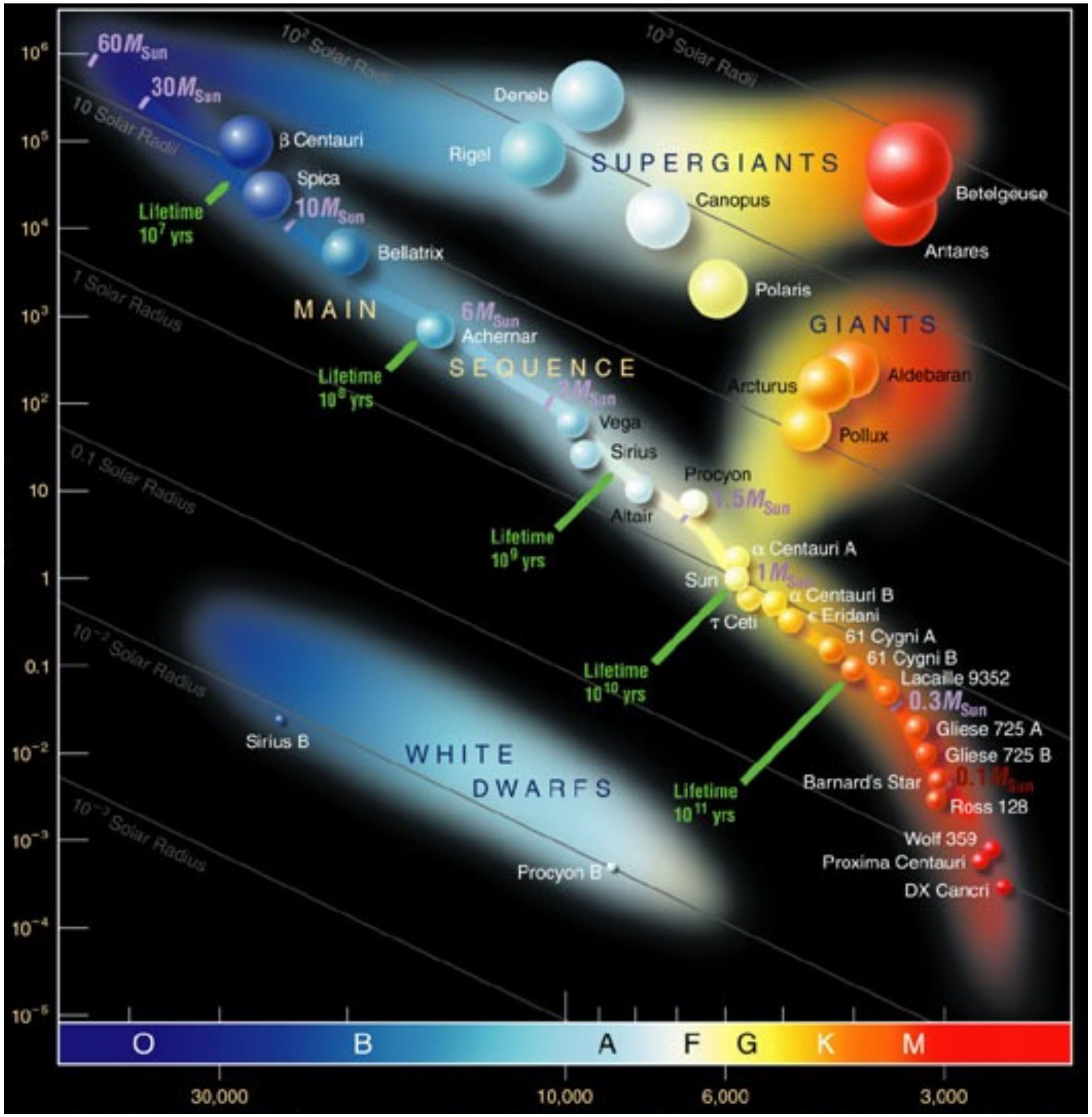
Lecture18:
High Mass Stellar Evolution

Life stages of a high-mass star



Life Stages of High-Mass Stars



High mass stars leave MS quickly to become **supergiants**

Think/Pair/Share

What happens when a high-mass star's core runs out of helium?

A. The core collapses and the star explodes.
B. Carbon fusion begins in the core.
C. The core expands and cools off.
D. Helium fuses in a shell around the core.

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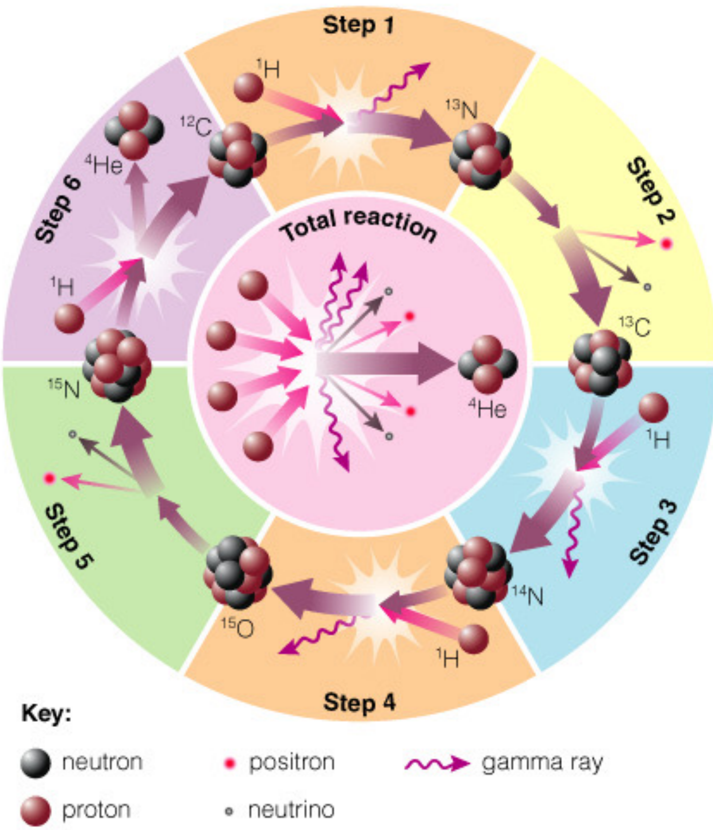
Life Stages of High-Mass Stars

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

    1. Hydrogen core fusion (main sequence)
    2. Hydrogen shell burning (*super*giant)
    3. Helium core fusion (*super*giant)
    4. ***Multiple***-shell burning beyond carbon

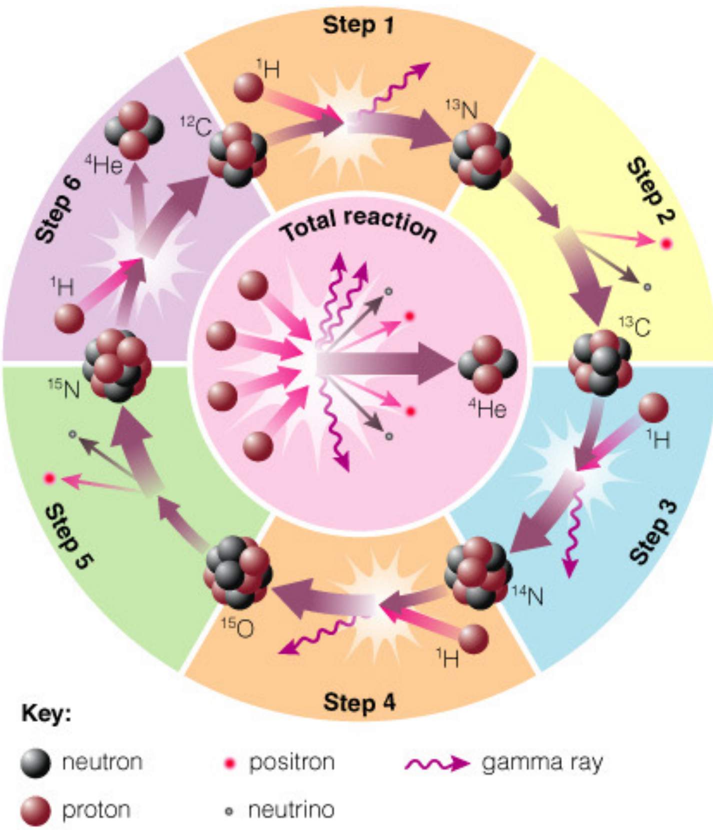
So how do high-mass stars make heavy elements?

Fusion in a high mass star



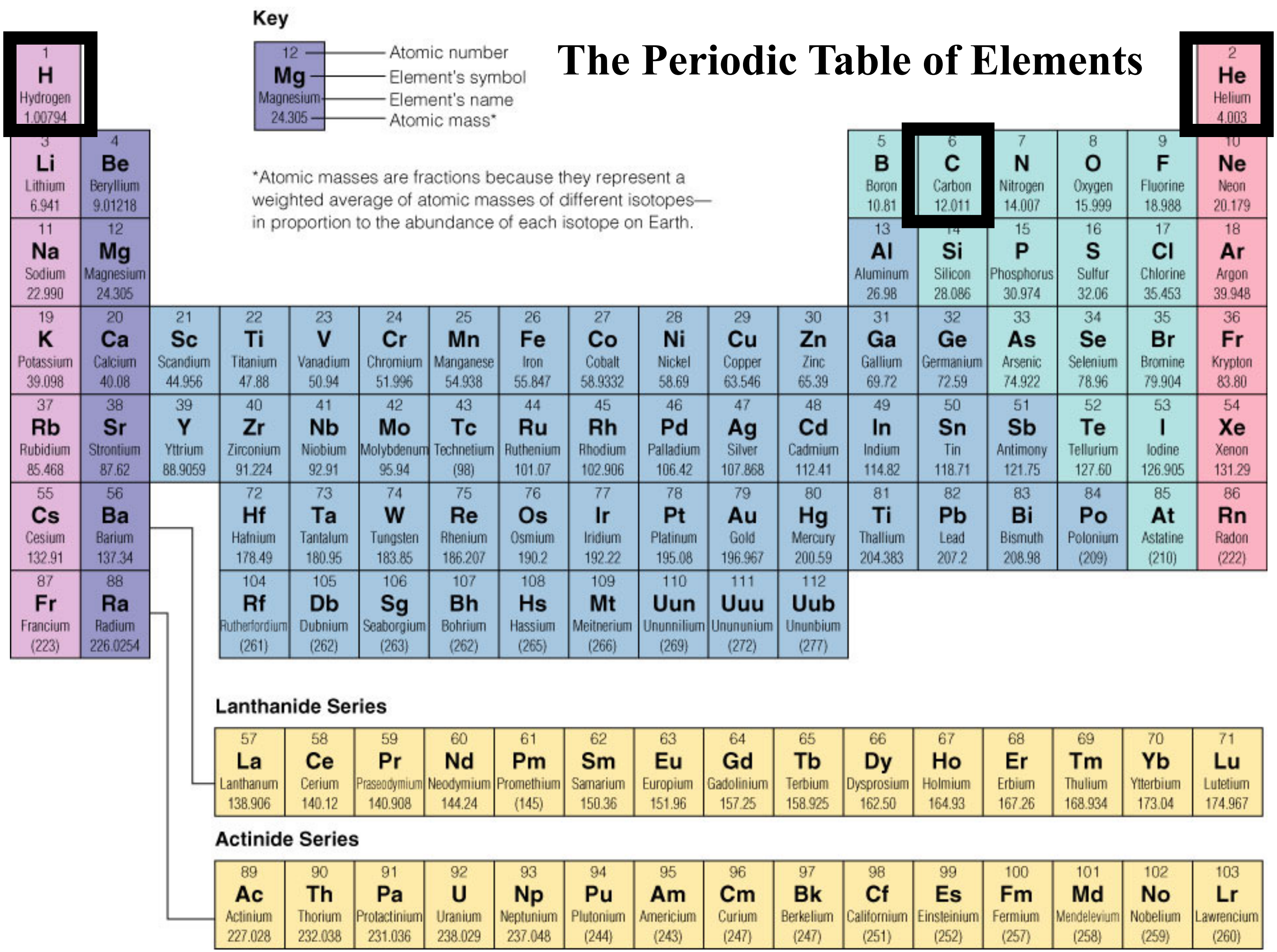
- High-mass main sequence stars fuse H to He **at a higher rate** using carbon, nitrogen, and oxygen as catalysts (**CNO cycle**).
- Greater core temperature enables H nuclei to overcome greater repulsion of heavier elements in the process.
- *Higher fusion rate is why high-mass stars have a higher luminosity and shorter life than low-mass stars.*

Fusion in a high mass star



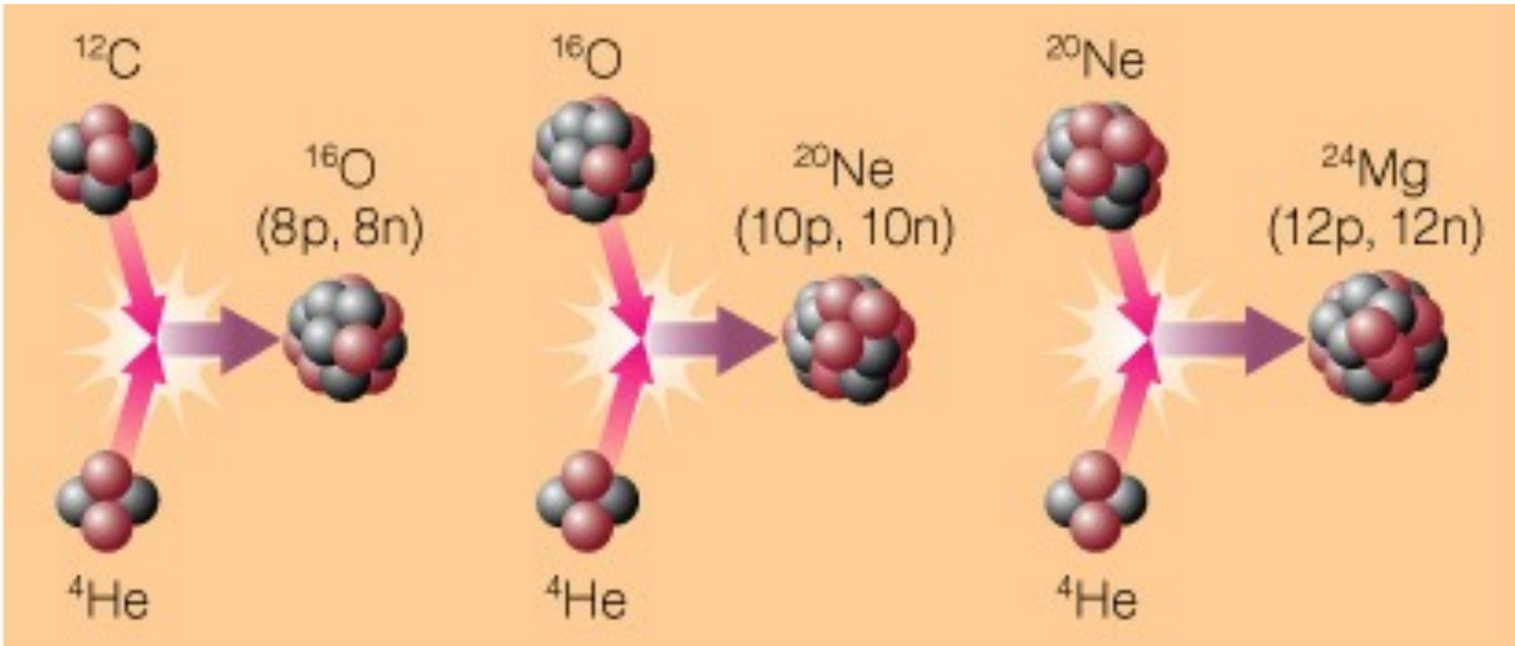
- Hydrogen fuses to Helium in just few million years
- Helium fuses to carbon in just a few hundred thousand years
- Core collapses further - temp, density, pressure increase further
- *Fusion of carbon and heavier elements can begin at 600 million K but only lasts a few hundred years!*

How do high-mass stars make heavy elements?



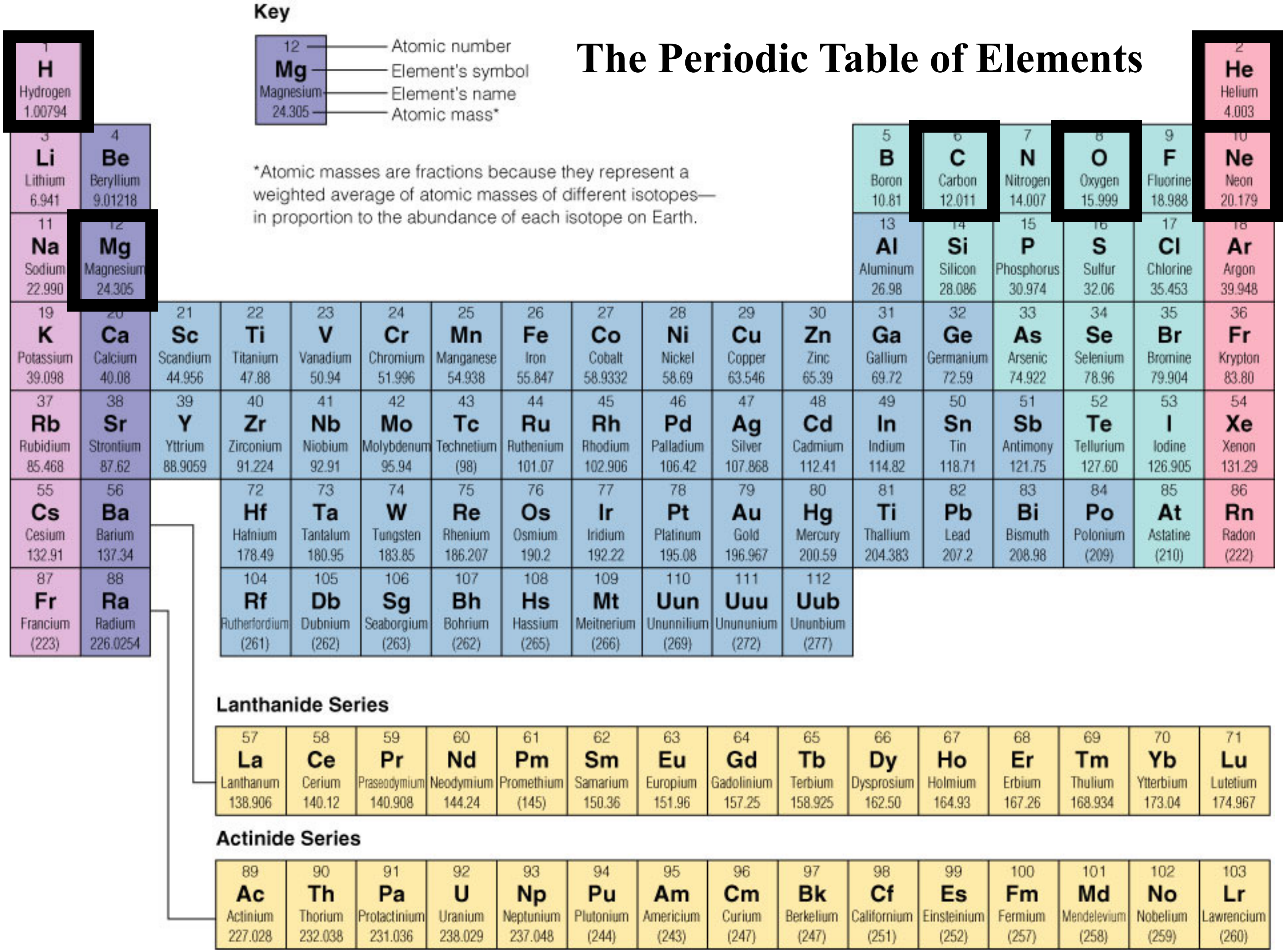
- Big Bang made 75% H, 25% He – *stars make all other elements*
- Helium fusion can make carbon in low-mass stars.

Helium Capture



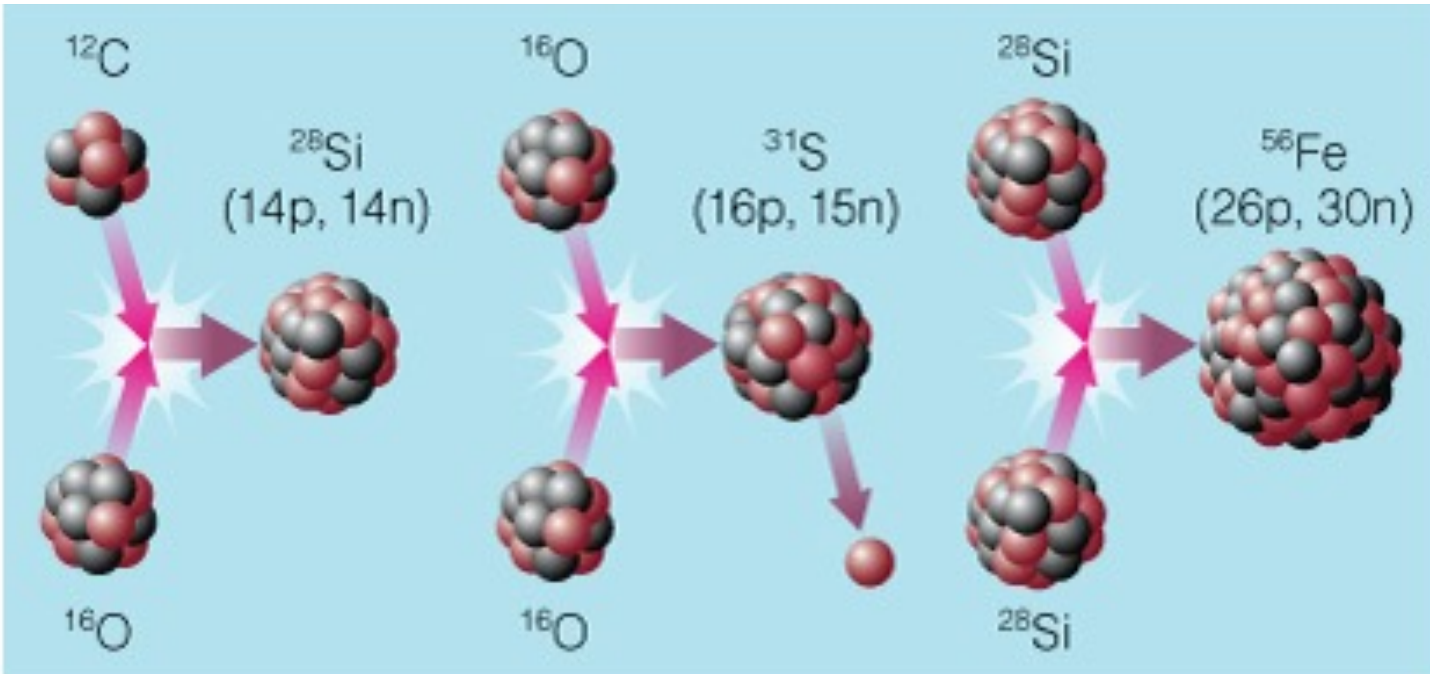
- Very high core temperatures in high mass stars allow helium to fuse with heavier elements.

The Periodic Table of Elements



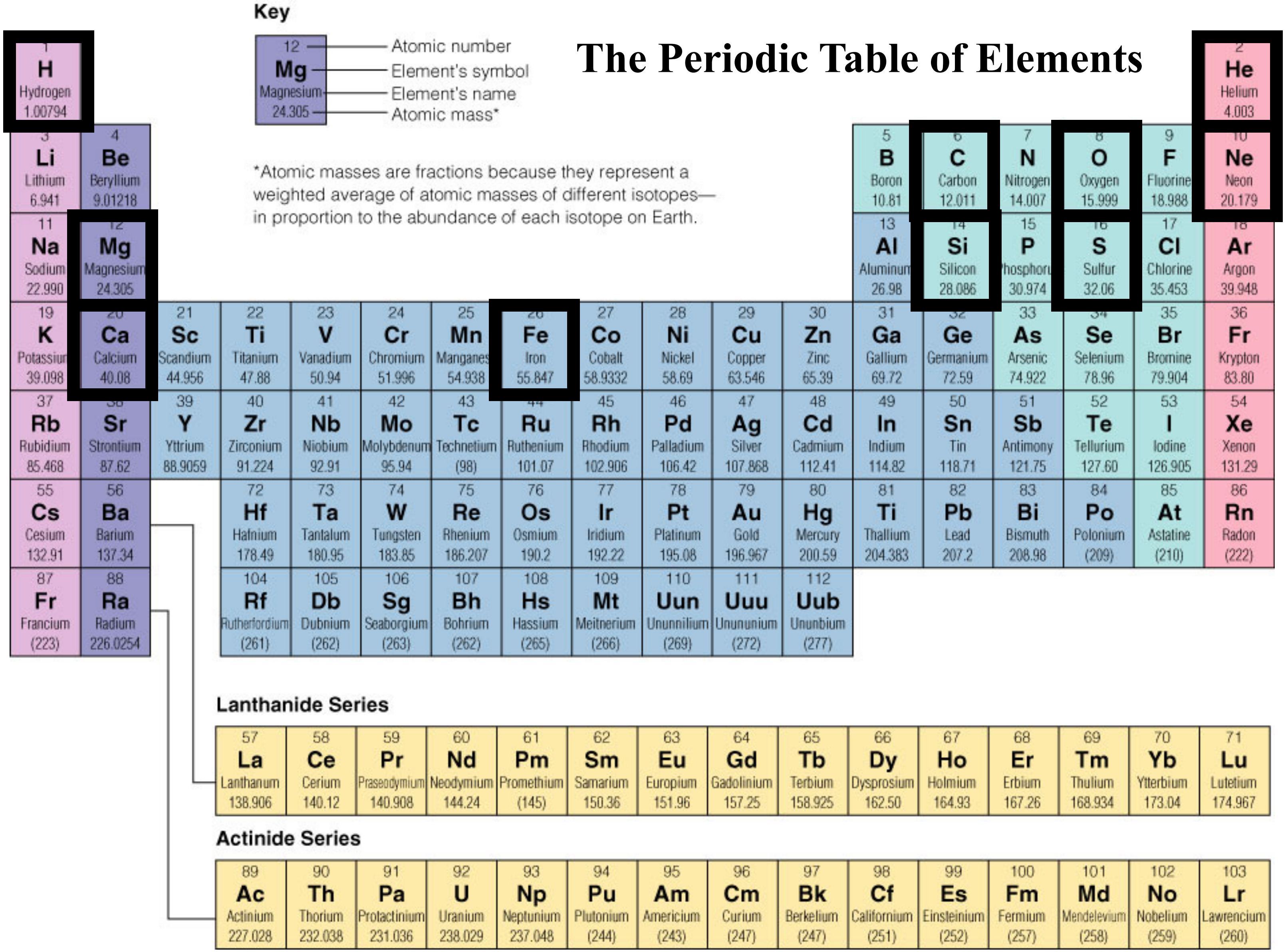
Helium capture can change C into O, O into Ne, Ne to Mg.

Advanced Nuclear Burning



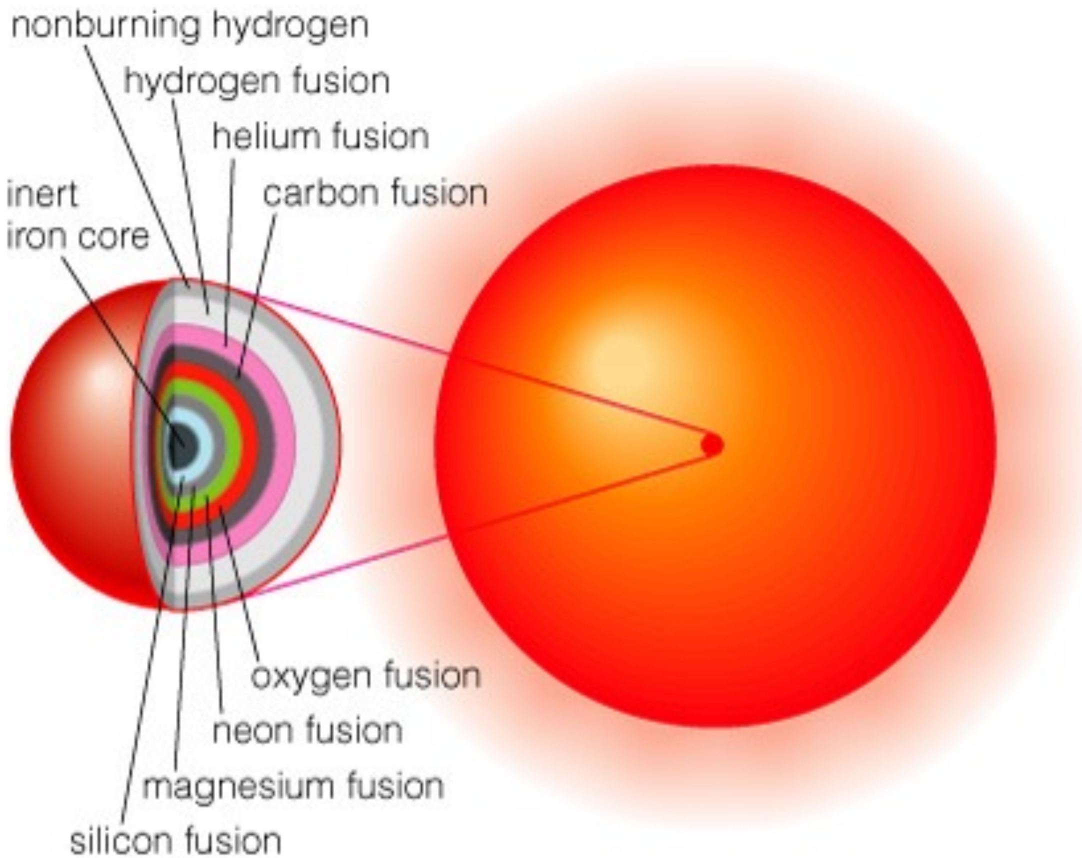
- Core temperatures in stars with $>8M_{\mathrm{Sun}}$ allow fusion of elements as heavy as *iron*!

The Periodic Table of Elements



Advanced reactions in stars make elements like Si, S, Ca, and Fe.

Multiple-Shell Burning

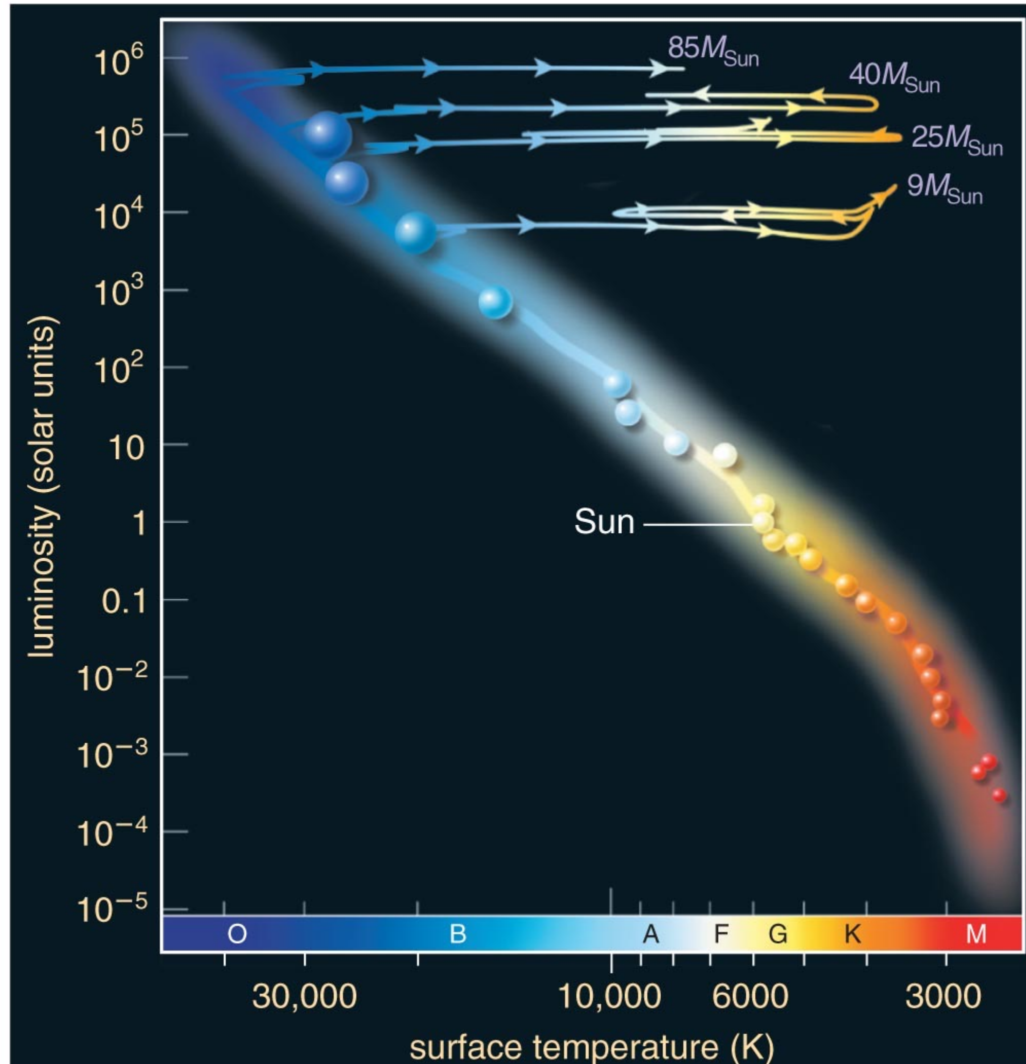


- Advanced nuclear fusion proceeds in a series of nested shells.
- Progressively heavier elements are created by fusion: *nucleosynthesis*.
- Ignition of next heavier element in core (and new shell) do what to star?

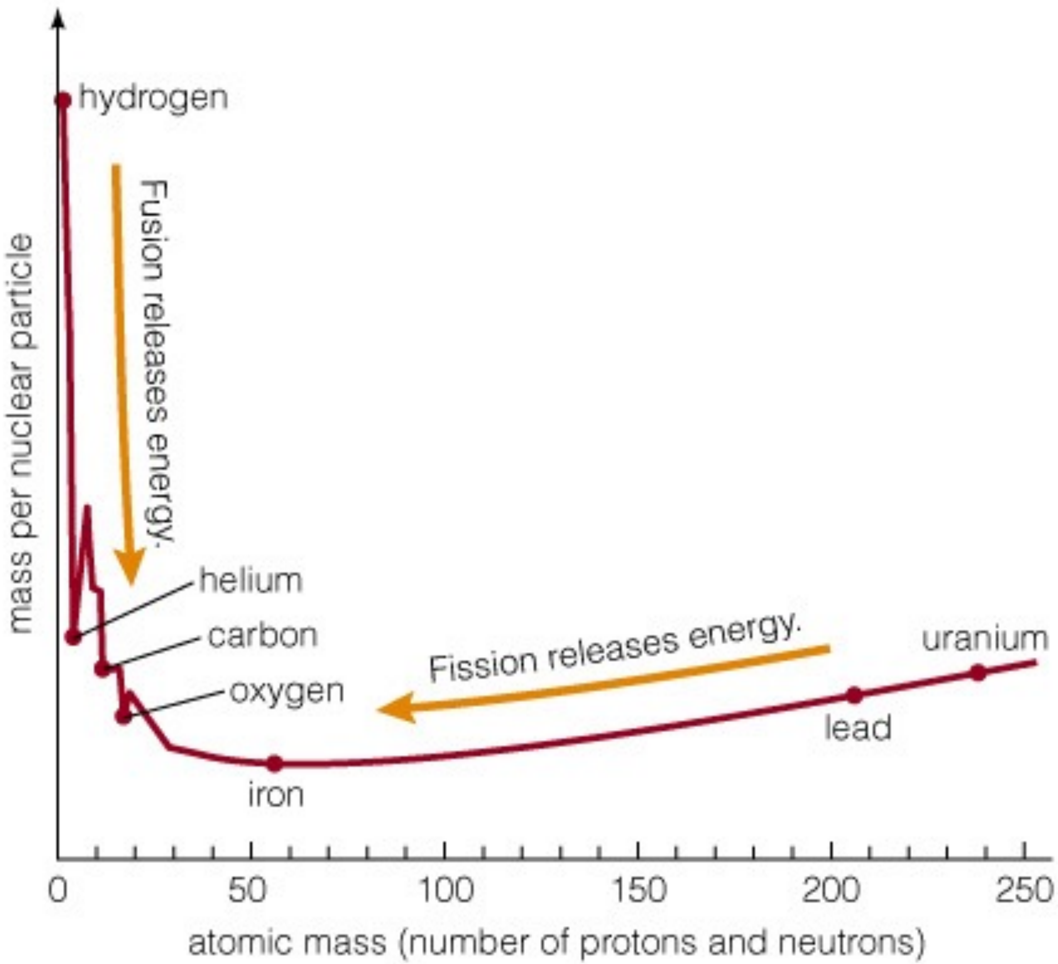
High mass life tracks

High mass stars change from red to blue supergiants – and back!

- Core ignites fusion of new element and fusion of new shell – increased luminosity expands star, cools surface.
- Core finishes fusion of element – decreased luminosity contracts star, heats surface.



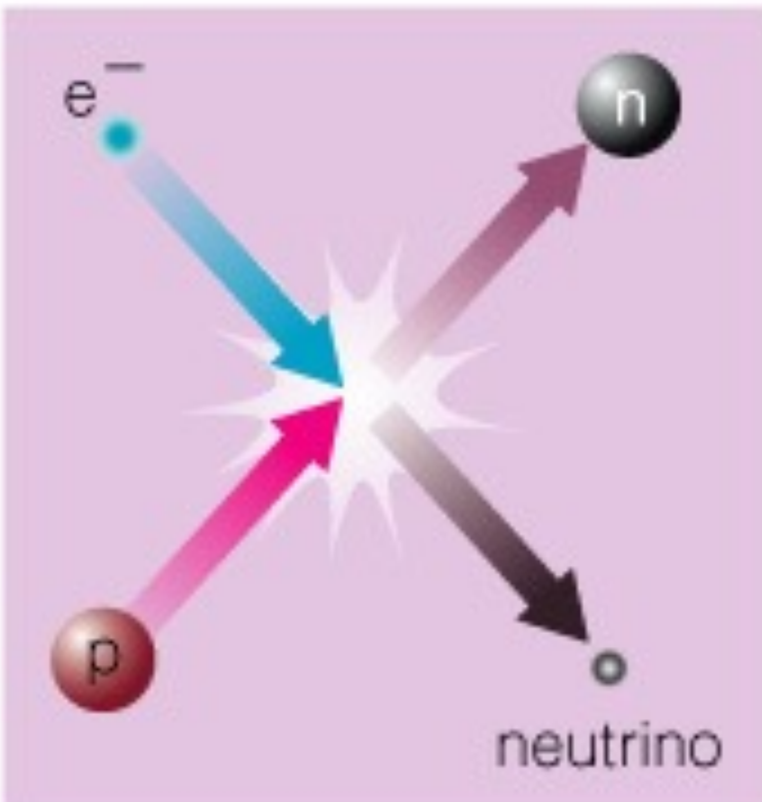
Iron - ~~fusion~~



- Fusion releases energy because source elements have greater mass than elements created
- Iron is a dead end for fusion because *nuclear reactions involving iron do not release energy*
- Elements heavier than iron can only release energy via fission

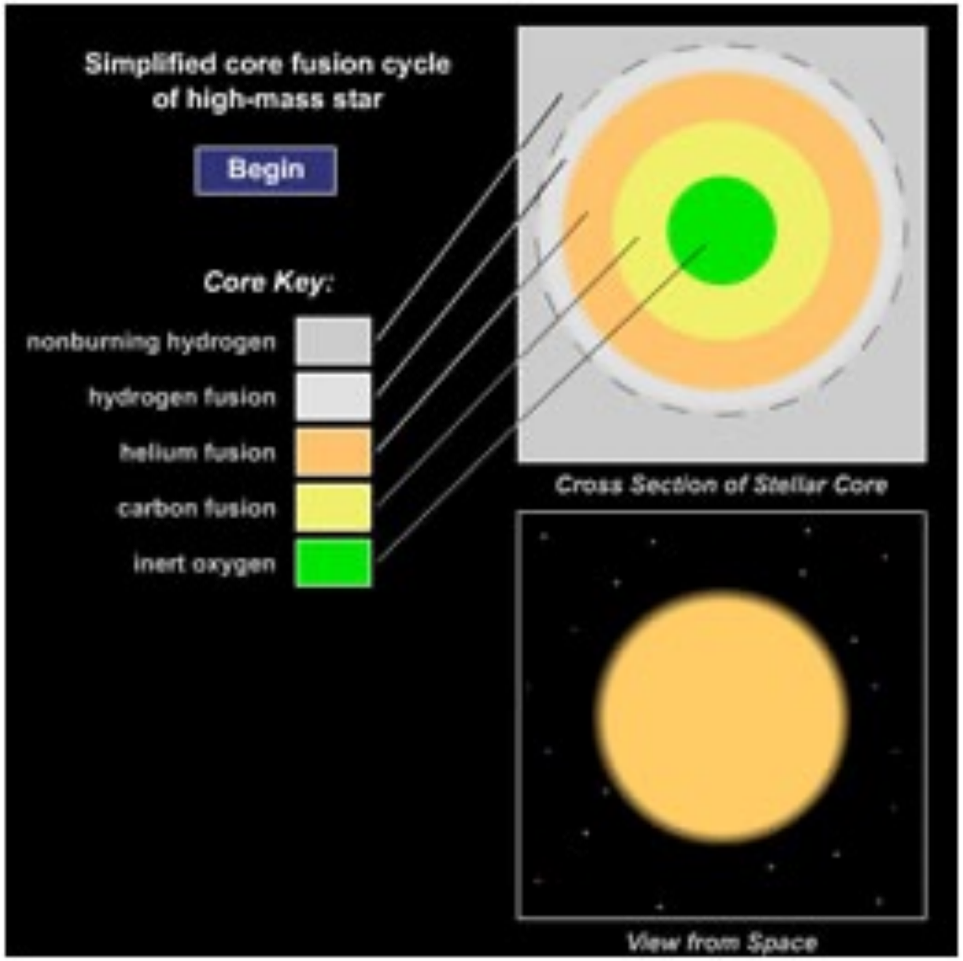
How does a high-mass star die?

Core collapse

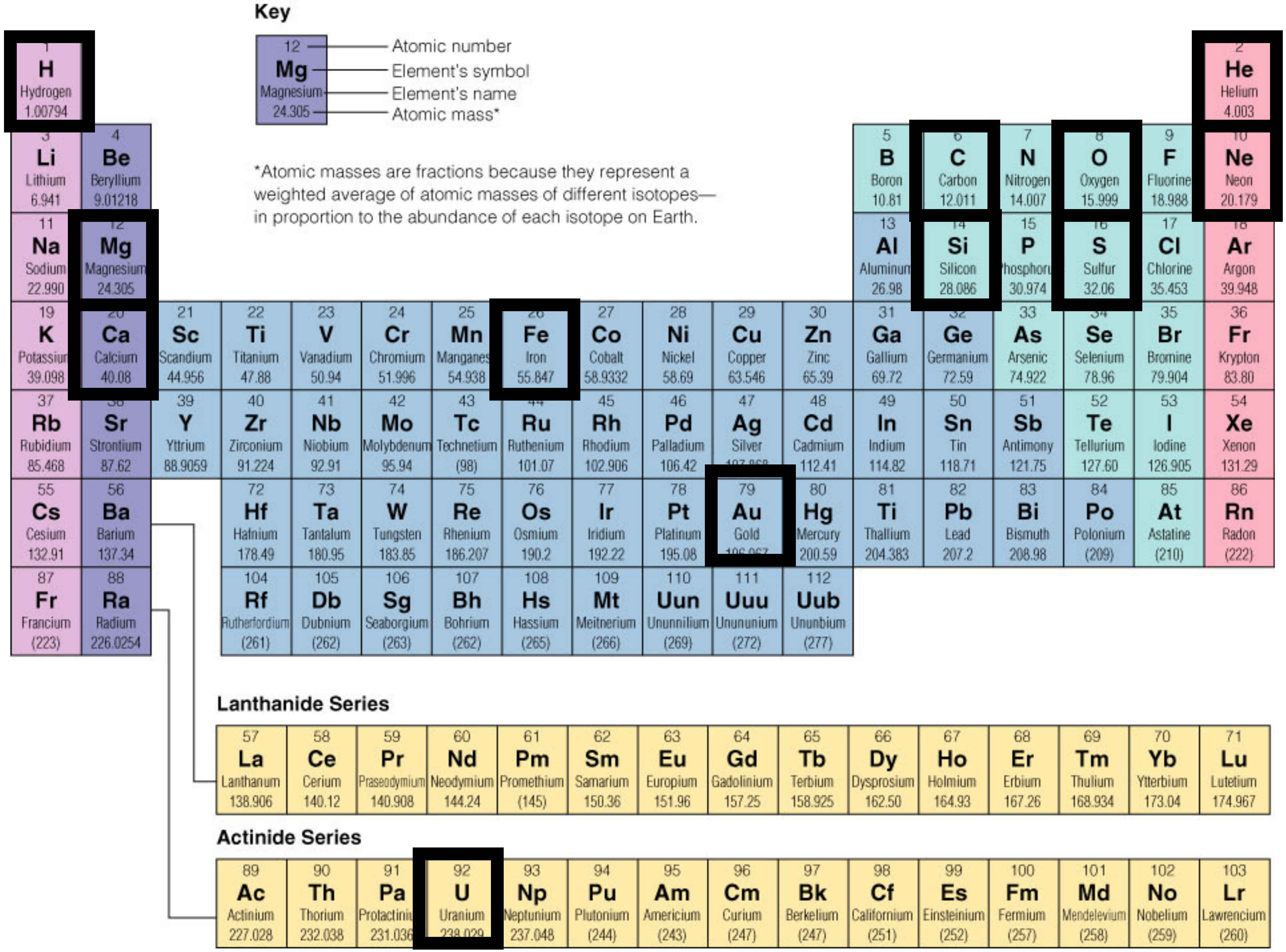


- Iron builds up in the core until electron degeneracy pressure can no longer resist gravity.
- Gravity overcomes the electron degeneracy pressure.
- *Electrons are forced to combine with protons, making neutrons* (and neutrinos).

Supernova!

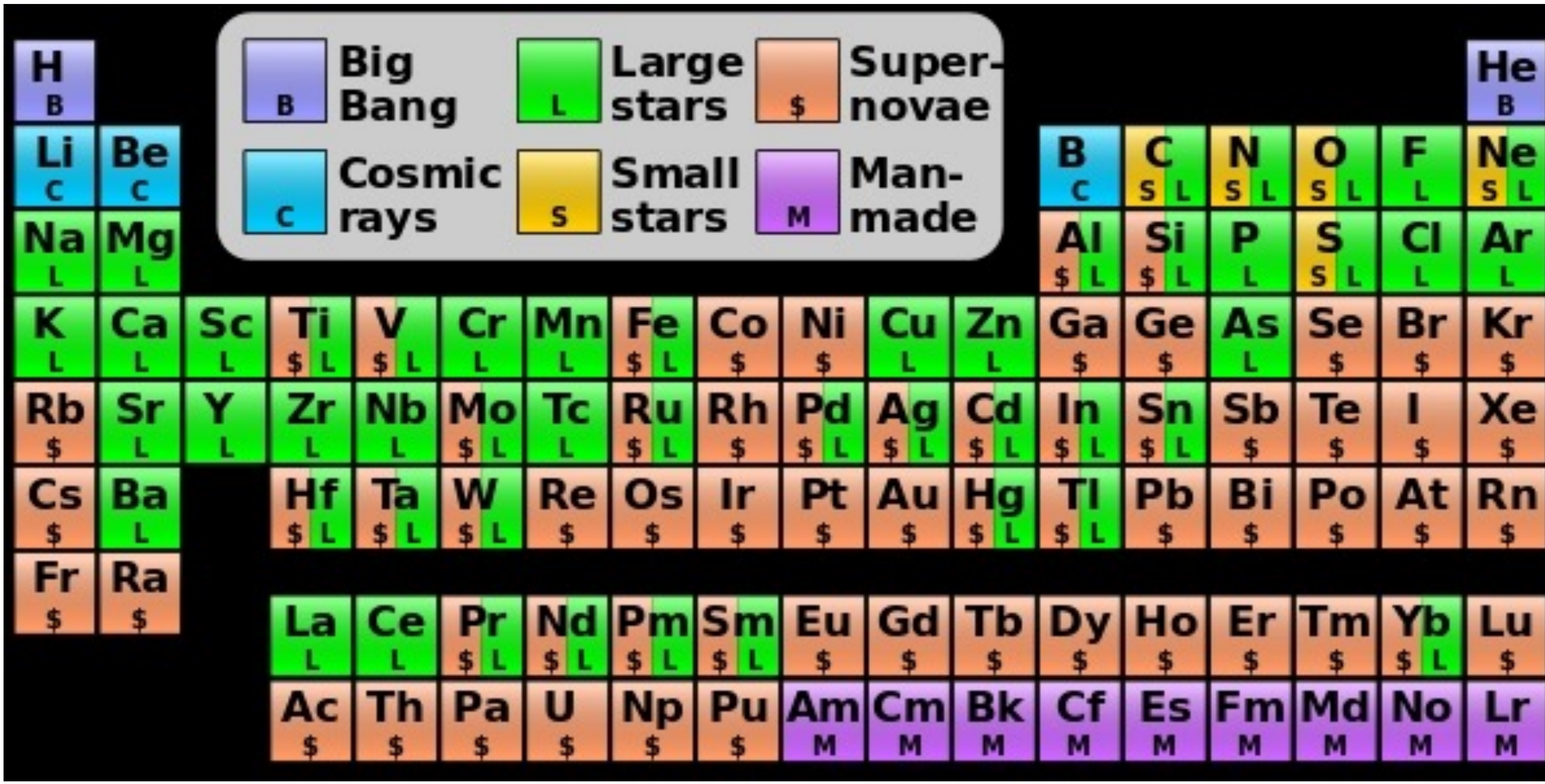


- With no support, core suddenly collapses.
- Only *neutron* degeneracy can stop collapse of most supergiants.
- Core "bounces", creating a titanic **supernova** explosion.
- Iron core collapses into a **neutron star** just a few km across!



Vast amounts of energy (100x Sun's *lifetime* energy!) and neutrons are released enabling elements heavier than iron such as Au and U to form.

The Formation of the Elements

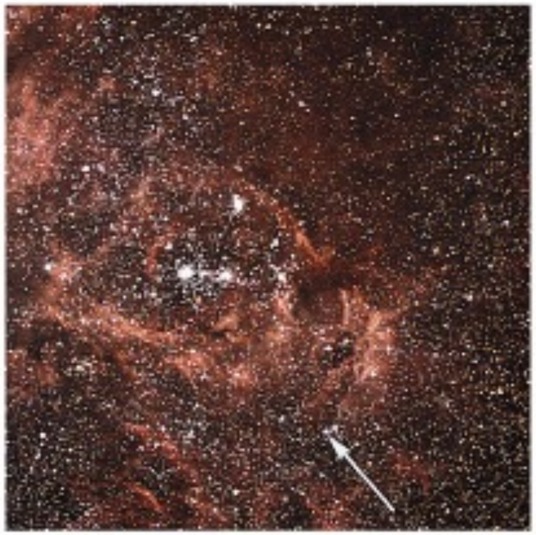


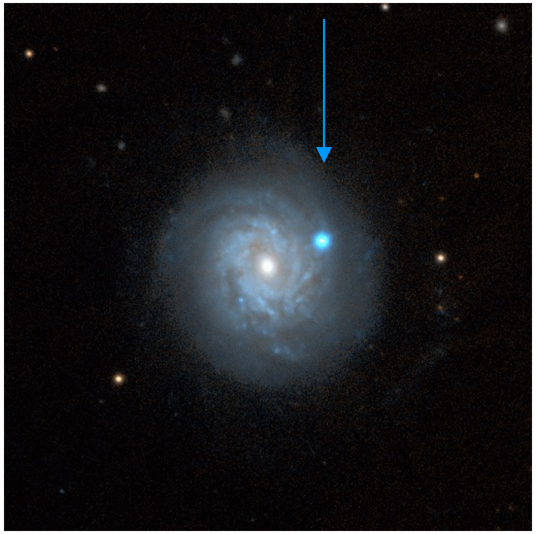
Supernova Remnant

- Energy released by the collapse of the core drives outer layers into space.
- The Crab Nebula is the remnant of a supernova seen in A.D. 1054.
- Expanding material (heavy elements) enriches the ISM.

PLAY Multiwavelength Crab Nebula

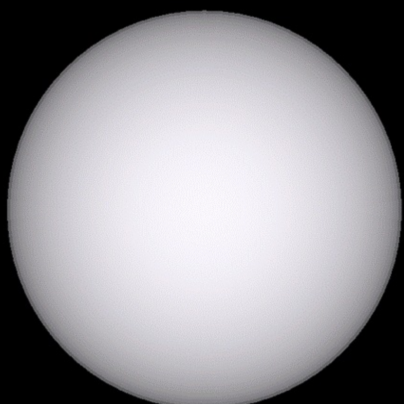
Supernova 1987A





- The closest supernova in the last four centuries was seen in 1987; it taught us much about SN.
- SN are seen on other galaxies regularly.

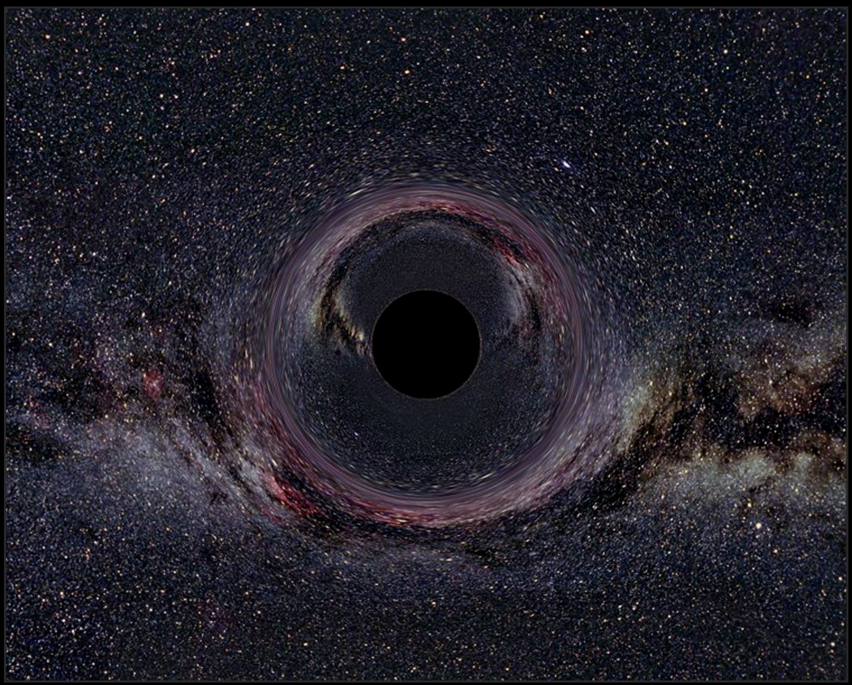
Neutron stars



$M=1.5\ M_{sun}$
$R \approx 10$ km
$V_{esc} \approx 0.7c$

- Gravity crushes the core (about the size of Earth and the mass of the Sun) to unimaginable density – entire star is of nuclear density just 10 km across!
- One cm^3 would weigh 100 *million* tons!
- In most massive stars, **neutron** degeneracy finally stops the collapse.
- The star a literally a giant atomic nucleus – a ball of neutrons about 10 km in diameter.

Black holes



- In a few of the most massive stars (> 30 M_{Sun}), even neutron degeneracy cannot stop the collapse.
- Gravity ultimately crushes the star out of the observable universe!
- Gravity is so strong that even light can no longer escape.
- No physical surface but enormous gravity source remains.

What have we learned?

Begin 3 minute review

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 (main sequence, red *super*giant, etc).

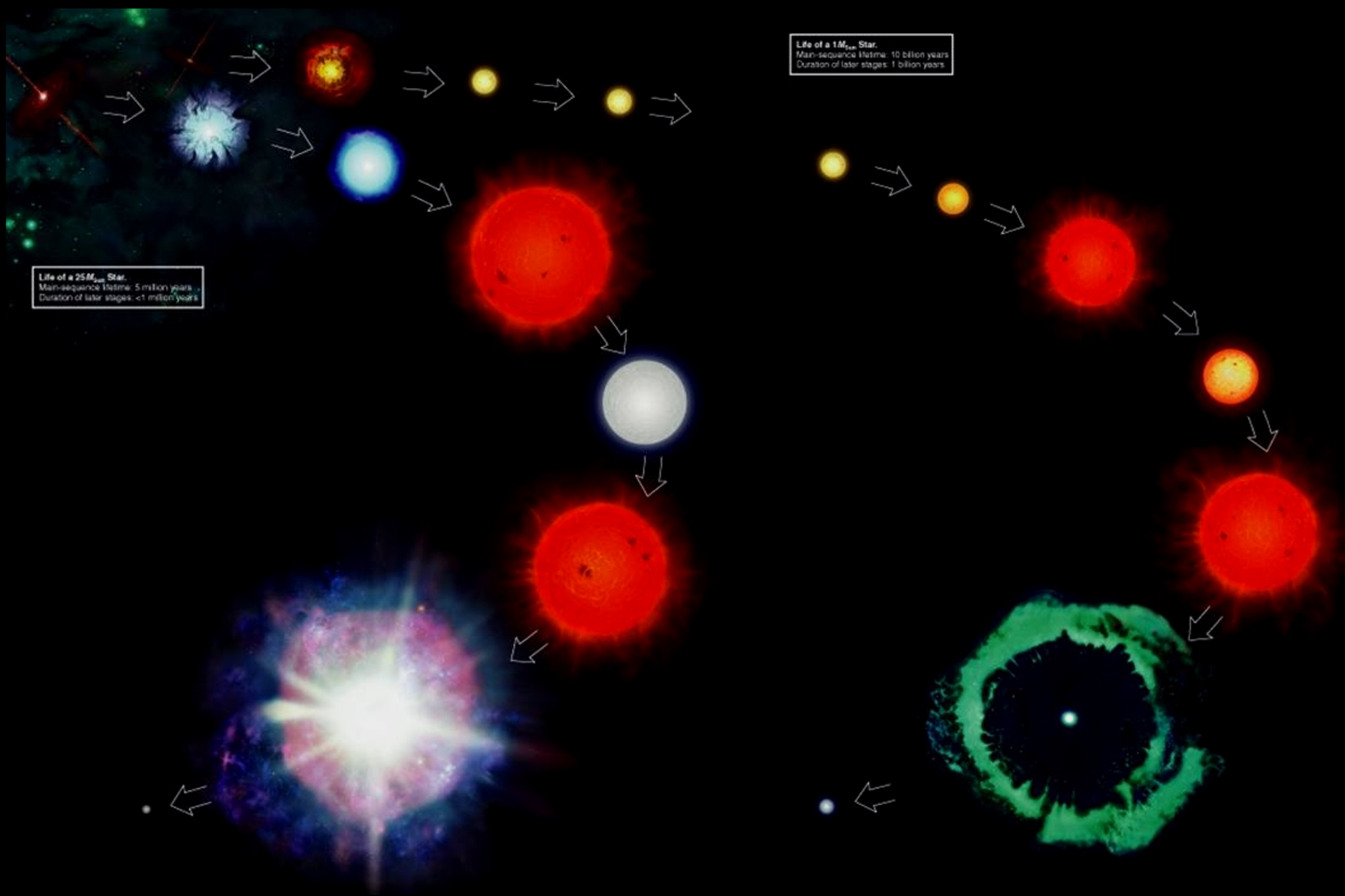
How do high-mass stars make heavy elements?

Higher masses produce much higher core temperatures that enable fusion of heavier elements - *nucleosynthesis*

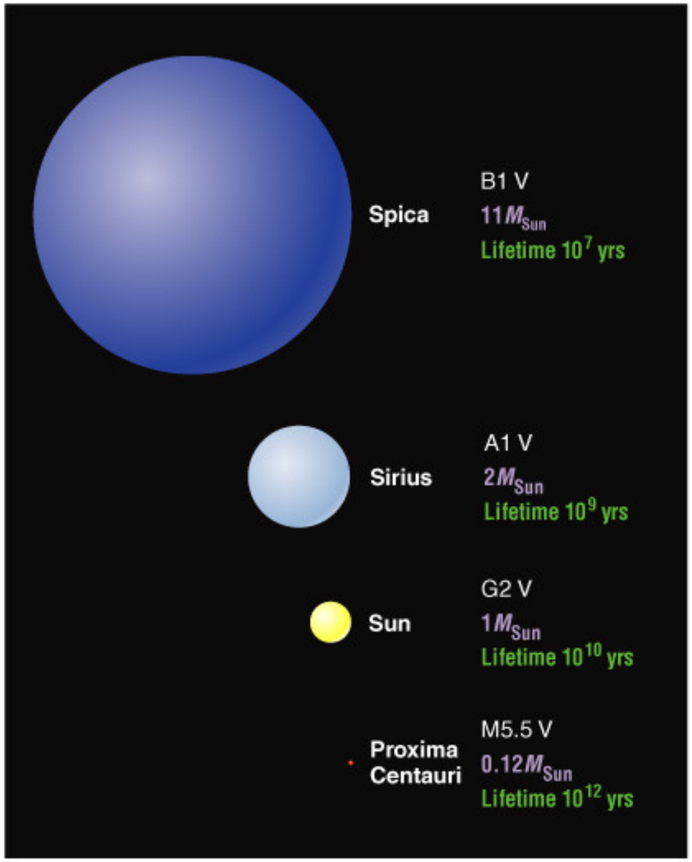
How does a high-mass star die?

The iron core collapses and bounces, leading to a supernova explosion.

How does a star's mass determine its life story?

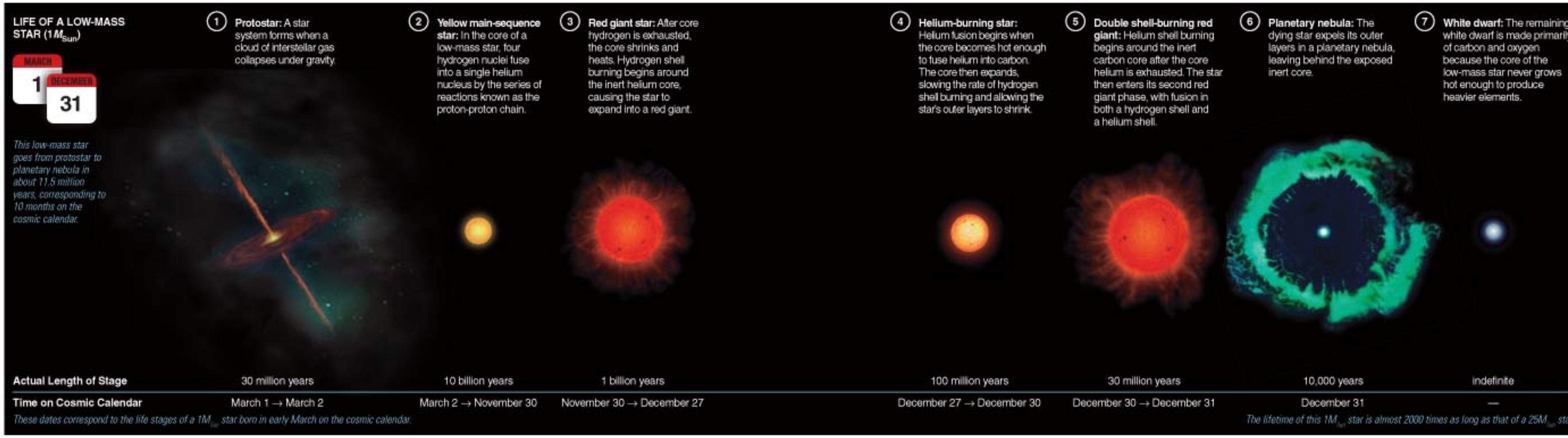


Role of Mass



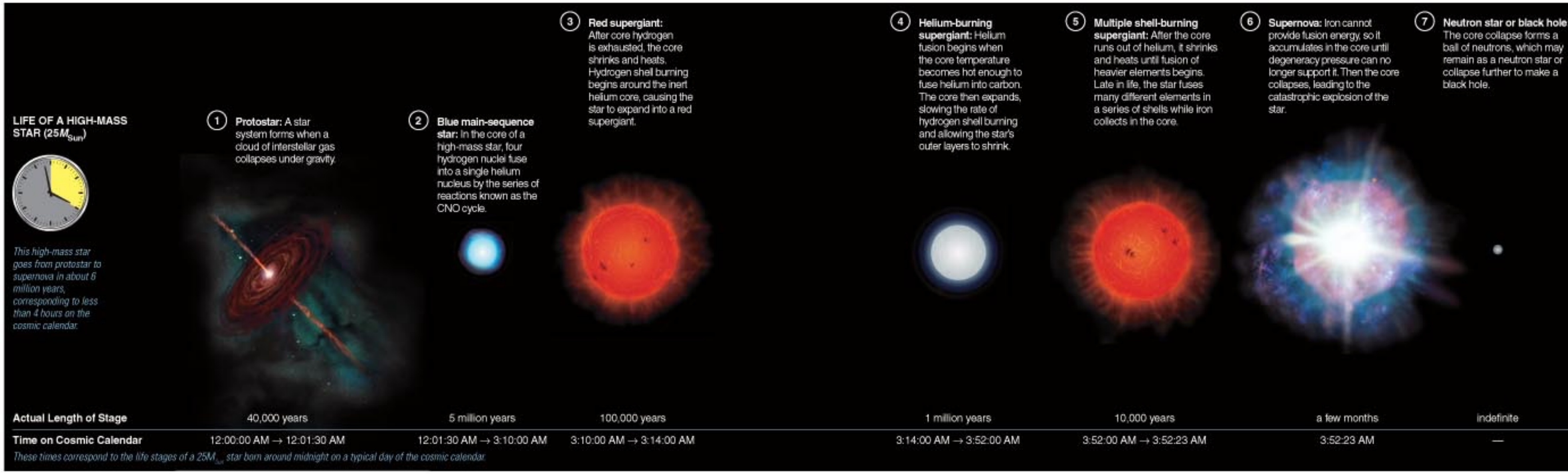
- *A star's mass determines its entire life story because it determines its core temperature.*
- **High-mass stars have short lives**, eventually becoming hot enough to make iron, and end in supernova explosions and neutron stars.
- **Low-mass stars have long lives**, never become hot enough to fuse carbon nuclei, and end as white dwarfs.

Life stages of **Low-Mass** stars



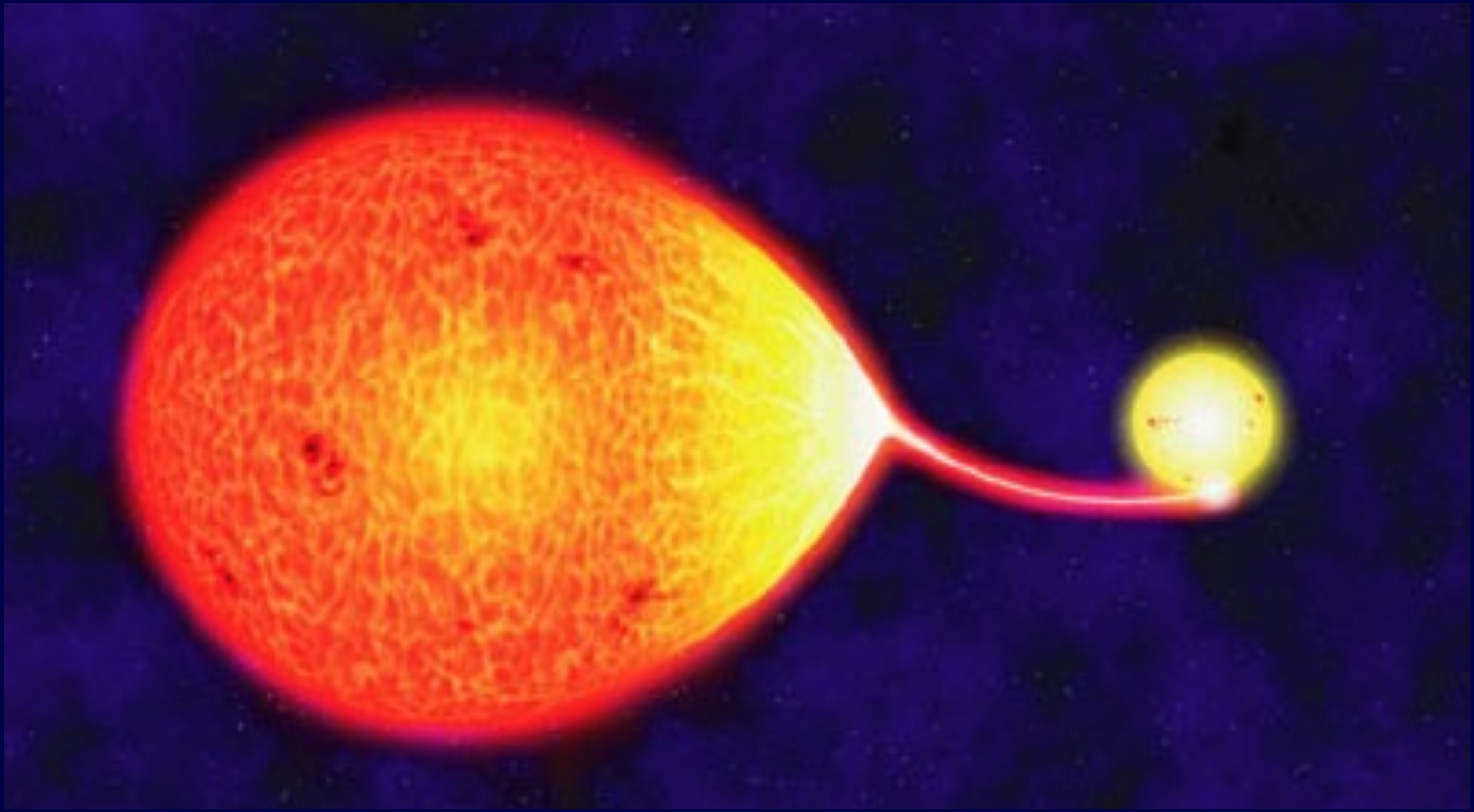
1. Protostar: Interstellar cloud collapse under gravity and heats up.
2. Main sequence: H fuses to He in core.
3. Red giant: H fuses to He in shell around inert He core.
4. Helium core burning: He fuses to C in core while H fuses to He in shell around the core.
5. Red Giant (again). Double shell burning: H and He both fuse in shells around an inert carbon core.
6. Planetary nebula: outer layers blown off.
7. White dwarf: primarily carbon, some oxygen.

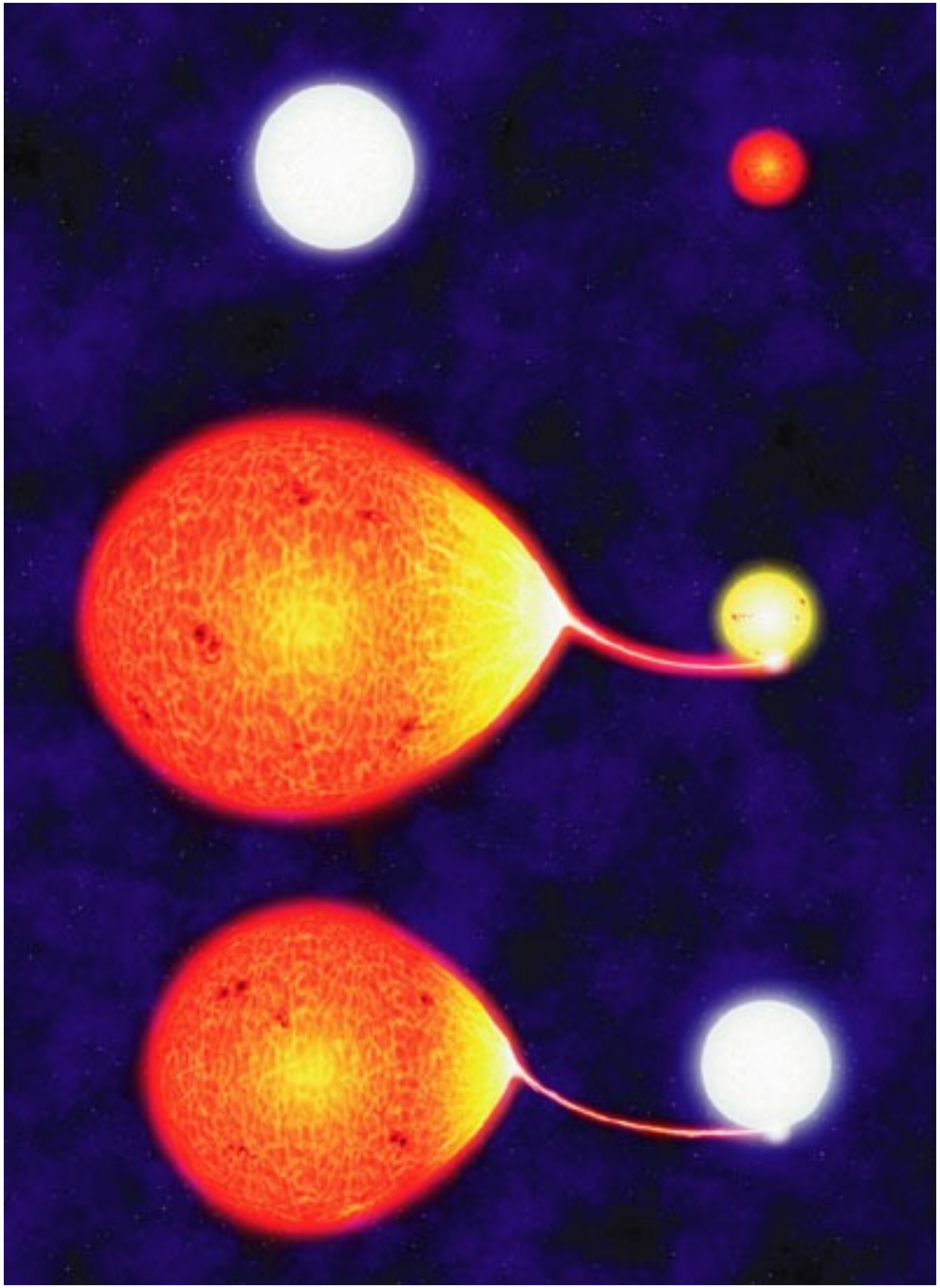
Life Stages of **High-Mass** Star



1. Protostar: Interstellar cloud collapse under gravity and heats up.
2. Main sequence: H fuses to He in core.
3. Red supergiant: H fuses to He in shell around inert He core.
4. Helium core burning supergiant: He fuses to C in core while H fuses to He in shell around the core.
5. Red supergiant (again). *Multiple* shell burning: H, He, C and heavier elements fuse in shells around an inert iron core.
6. Supernova: Titanic explosion as outer blown away by the rebound of the collapsing iron core. Heavy elements beyond synthesized.
7. leaves neutron star (or black hole) behind.

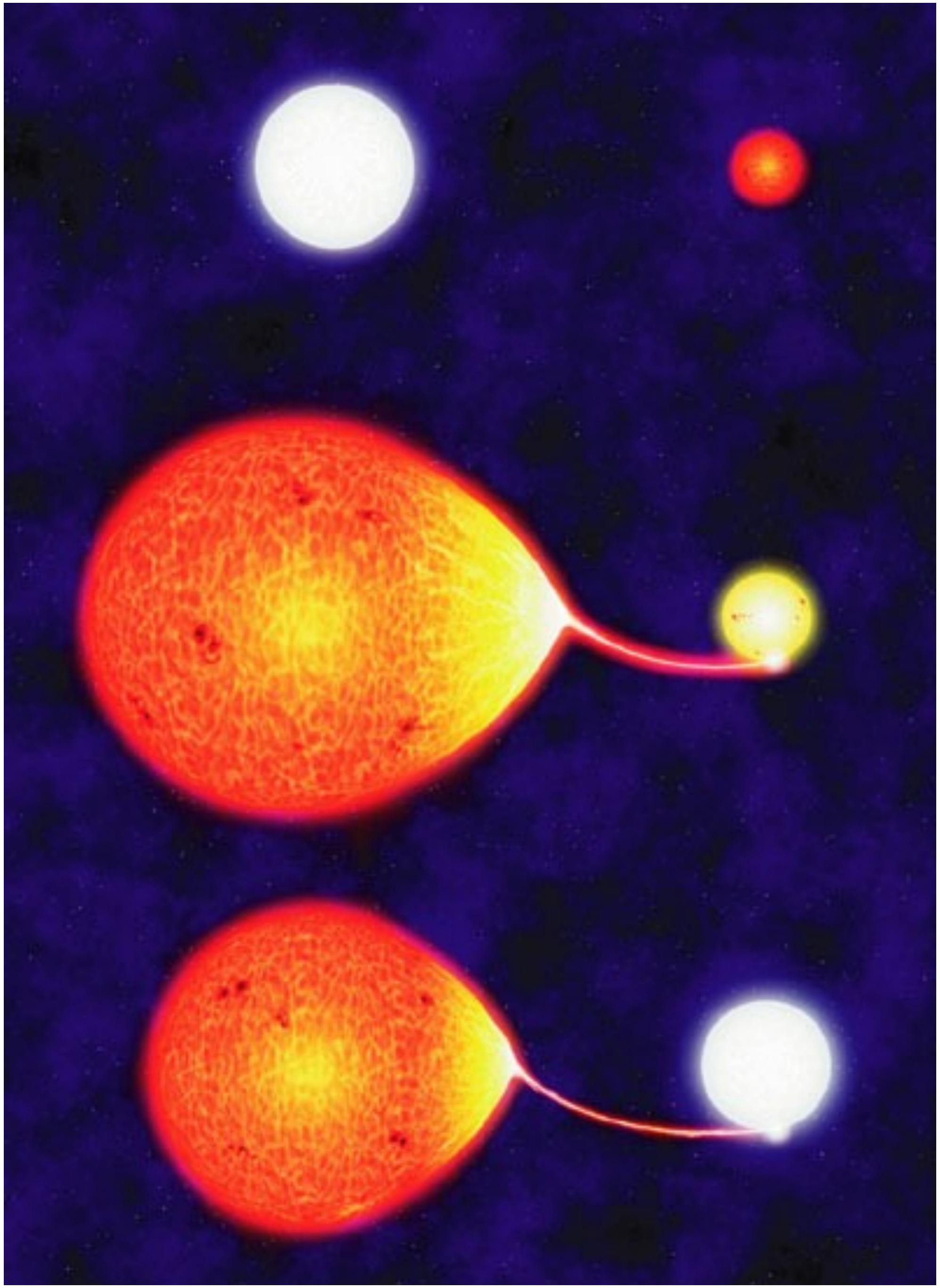
How are the lives of stars with close companions different?





Mass Transfer

Stars can be close enough that *matter can flow* from the subgiant onto the main-sequence star.



Mass Transfer

- The star that is now a subgiant was originally more massive.
- As it reached the end of its life and started to grow, it transferred mass to its companion (*mass exchange*).
- Now the companion star is more massive, may even evolve faster!

What have we learned?

Begin 3 minute review

What have we learned?

How does a star's mass determine its life story?

Mass determines how high a star's core temperature can rise and therefore determines how quickly a star uses its fuel and what kinds of elements it can make.

How are the lives of stars with close companions different?

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