Recap: stellar evolution

Brown Dwarf below 0.08 M⊙

No Hydrogen burning technically not a stars

very low-mass stars between 0.08 M⊙ and 0.8 M⊙

Hydrogen burning → Helium White Dwarf

(No star with M<0.7 M⊙ has actually evolved off the main sequence)

low-mass stars between 0.8 M⊙ and 2 M⊙

develop a degenerate helium core after the main sequence, leading to a relatively long-lived red giant branch phase. The ignition of He is unstable and occurs in a so-called helium flash

Low-mass stars shed their envelopes by a strong stellar wind at the end of their evolution and their remnants are CO white dwarfs

intermediate-mass stars between 2 M⊙ and 8-10 M⊙

massive stars more massive than 8-10 M⊙

Recap: stellar evolution

very low-mass stars between 0.08 M⊙ and 0.8 M⊙

Very low-mass stars after burning H in the shell, do not reach the temperature to burn Helium and that will end as **He white dwarfs** soon after the RSG branch

low-mass stars between 0.8 M⊙ and 2 M⊙

develop a **degenerate helium core** after the main sequence, leading to a relatively long-lived red giant branch phase. The ignition of He is unstable and occurs in a so-called **helium flash**

Low-mass stars shed their envelopes by a strong stellar wind at the end of their evolution and their remnants are **CO white dwarfs**

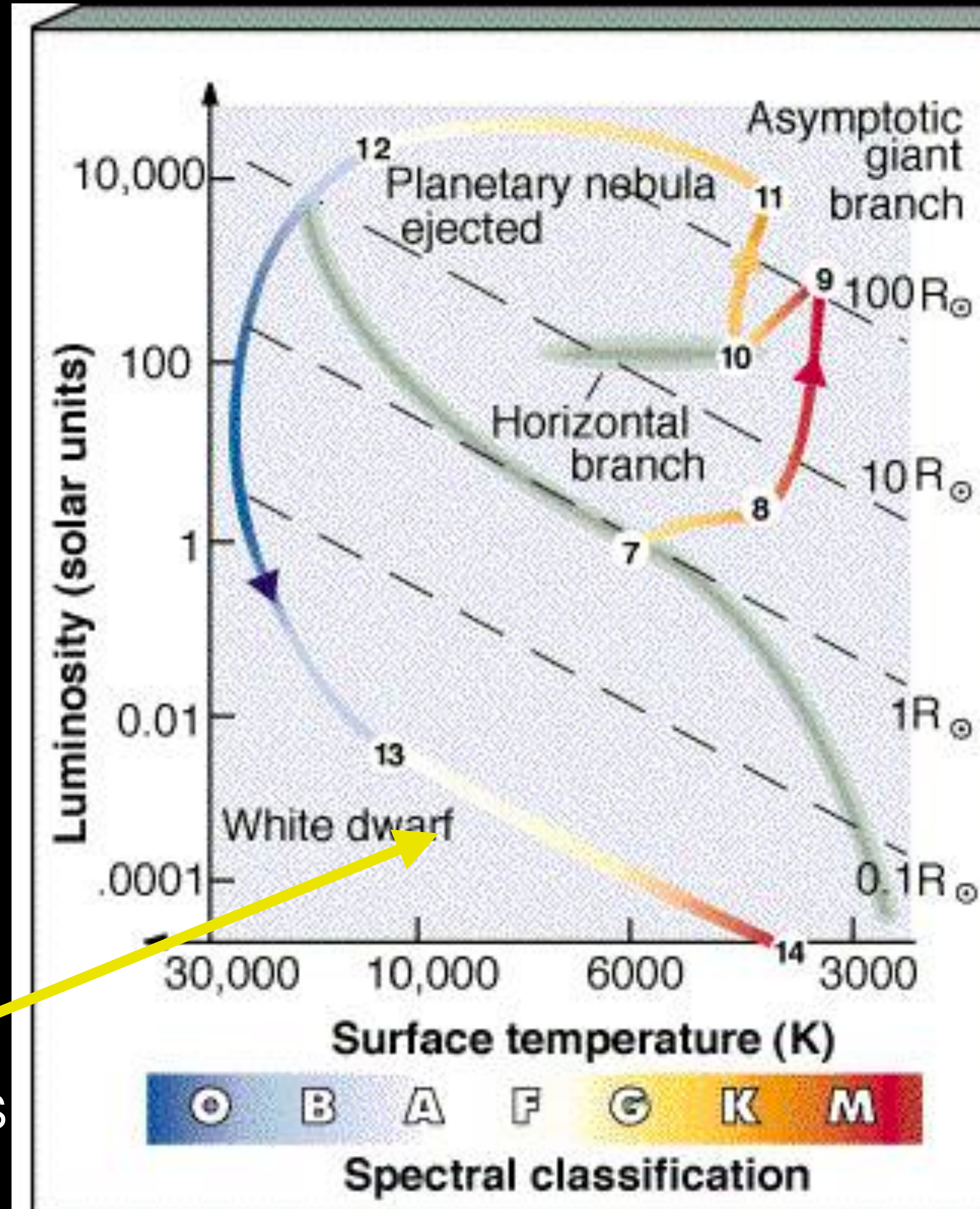
intermediate-mass stars between 2 M⊙ and 8-10 M⊙

develop a **helium core** that remains **non-degenerate**, and they ignite helium in a **stable manner**. After the central He burning phase they form a **carbon- oxygen core that becomes degenerate**. Intermediate-mass stars shed their envelopes by a strong stellar wind at the end of their evolution and their **remnants are CO white dwarfs**

massive stars more massive than 8-10 M⊙

low mass stars

Main sequence:
H fuses to He in core.
Red giant:
H fuses to He in shell around He core.
Helium core burning:
He fuses to C in core while H fuses to He in shell.
Double shell burning:
H and He both fuse in shells.
Planetary nebula leaves white dwarf behind.



intermediate mass stars

Main sequence:
H fuses to He in core.

CNO

Red giant:
H fuses to He in shell around He core.

No helium flash

Helium core burning:
He fuses to C in core while H fuses to He in shell.

Double shell burning:
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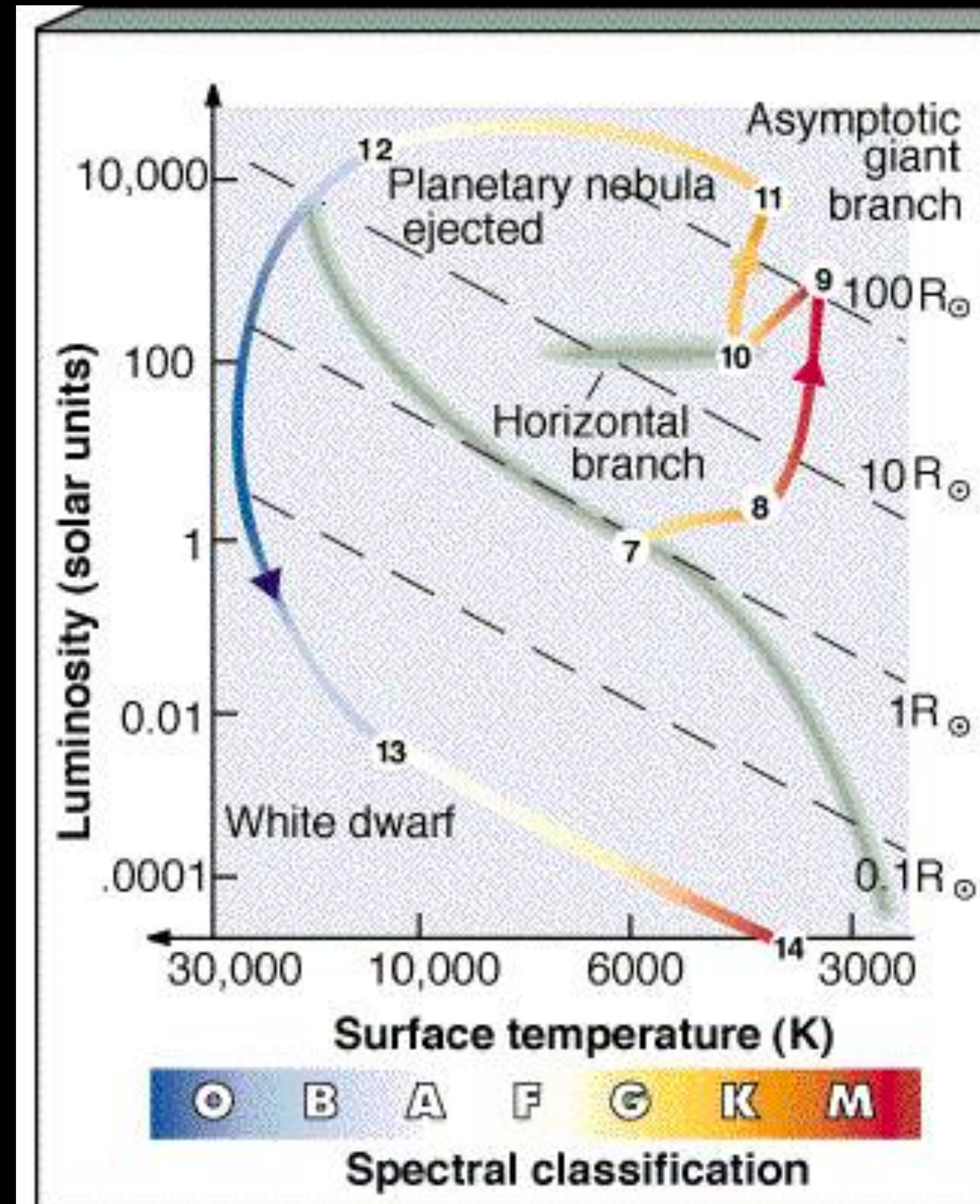
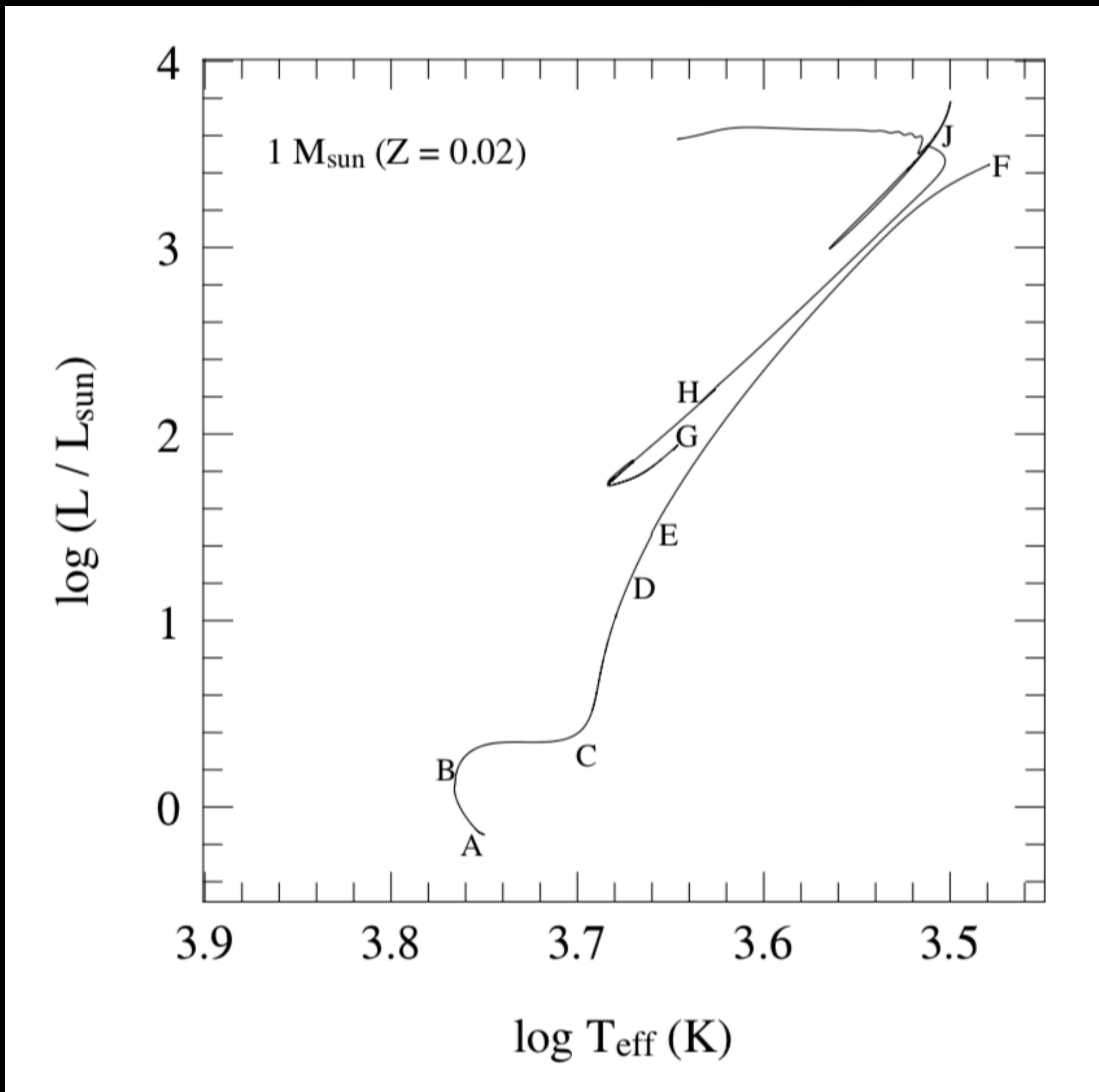
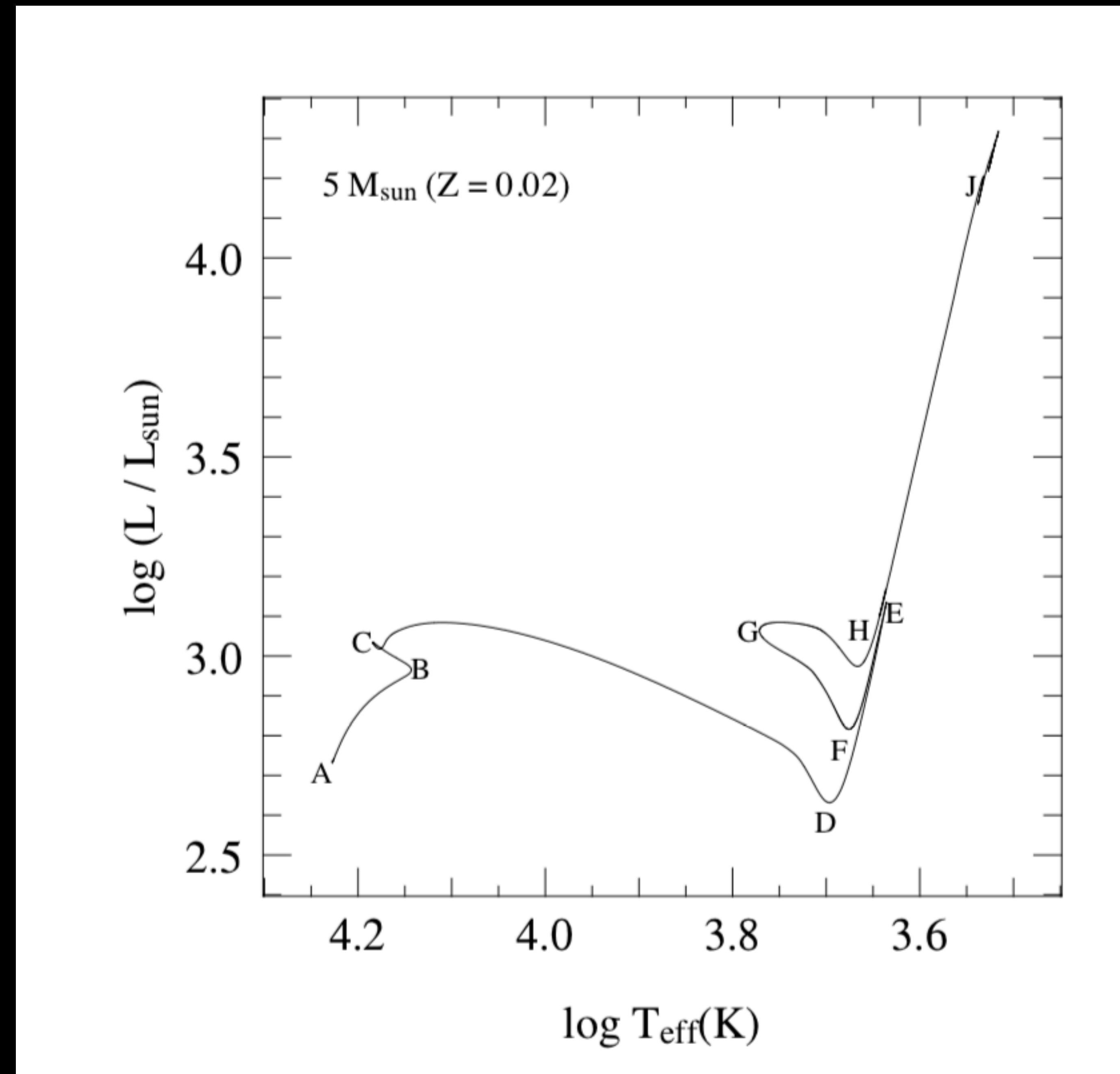
Planetary nebula leaves white dwarf behind.



low vs intermediate mass stars





Recap: stellar evolution

very low-mass stars between $0.08\ M_\odot$ and $0.8\ M_\odot$

Very low-mass stars after burning H in the shell, do not reach the temperature to burn Helium and that will end as **He white dwarfs** soon after the RSG branch

low-mass stars between $0.8\ M_\odot$ and $2\ M_\odot$

develop a **degenerate helium core** after the main sequence, leading to a relatively long-lived red giant branch phase. The ignition of He is unstable and occurs in a so-called **helium flash**

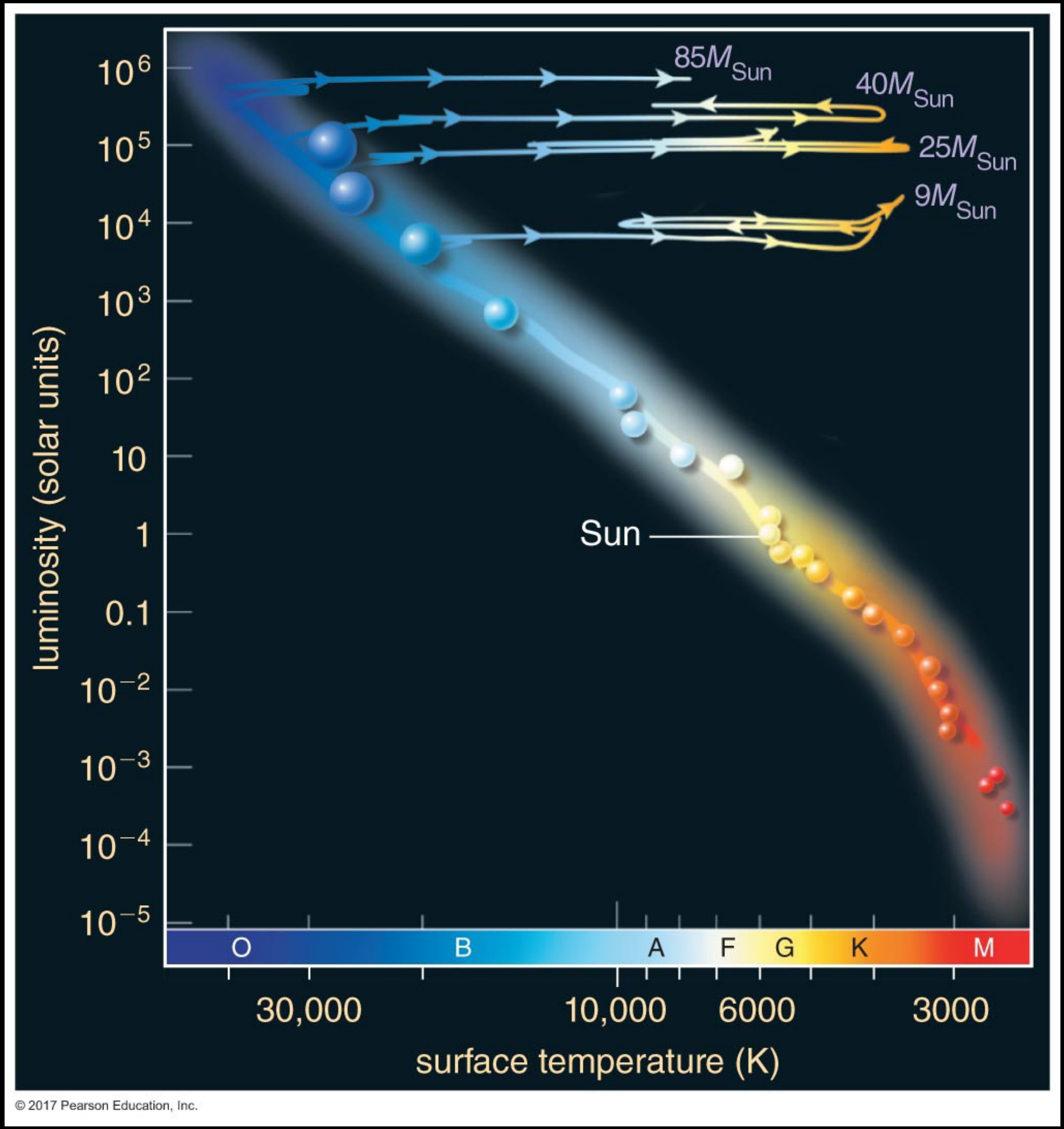
Low-mass stars shed their envelopes by a strong stellar wind at the end of their evolution and their remnants are **CO white dwarfs**

intermediate-mass stars between $2\ M_\odot$ and $8\text{-}10\ M_\odot$

develop a **helium core** that remains **non-degenerate**, and they ignite helium in a **stable manner**. After the central He burning phase they form a **carbon- oxygen core that becomes degenerate**. Intermediate-mass stars shed their envelopes by a strong stellar wind at the end of their evolution and their **remnants are CO white dwarfs**

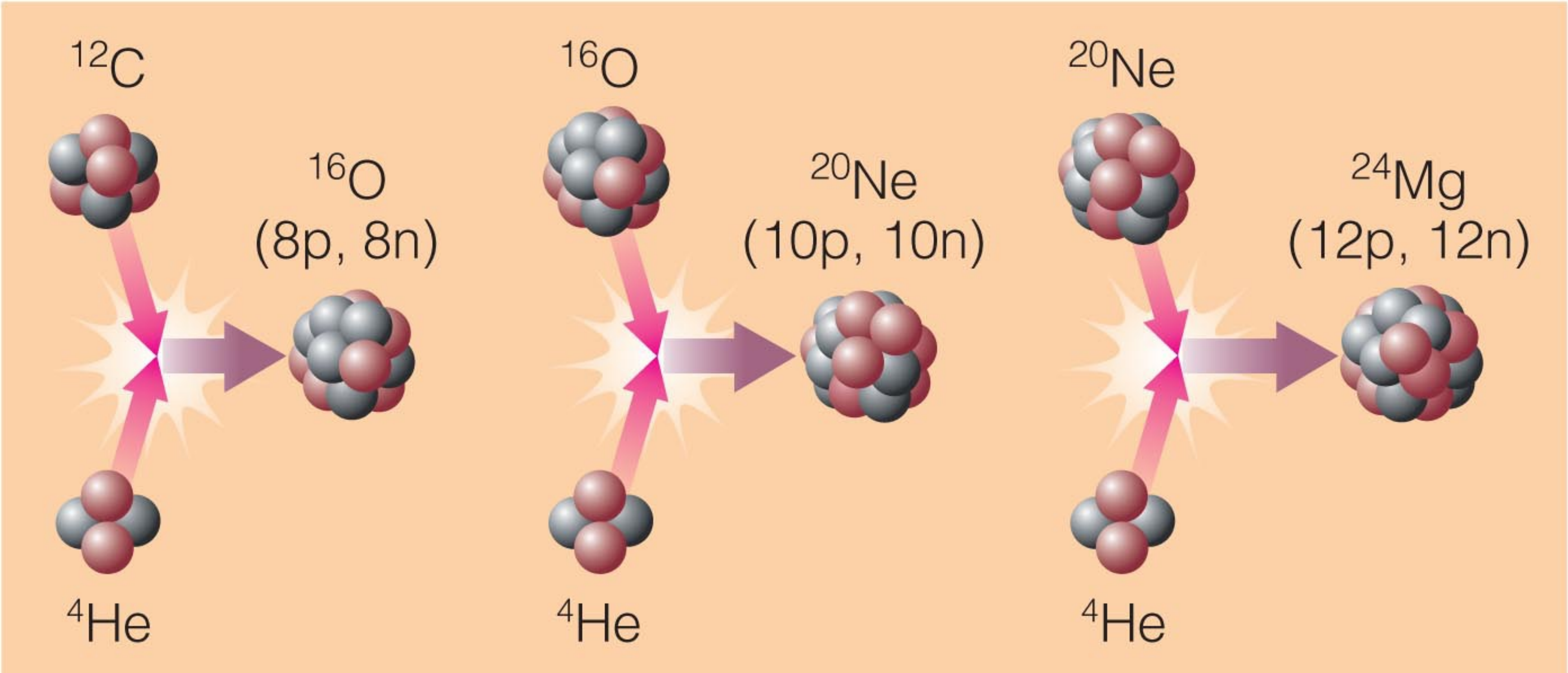
massive stars more massive than $8\text{-}10\ M_\odot$

Life tracks of high-mass stars



- High Luminosity for entire lifetime (which is short)
- Notice that they do not end up as white dwarfs…

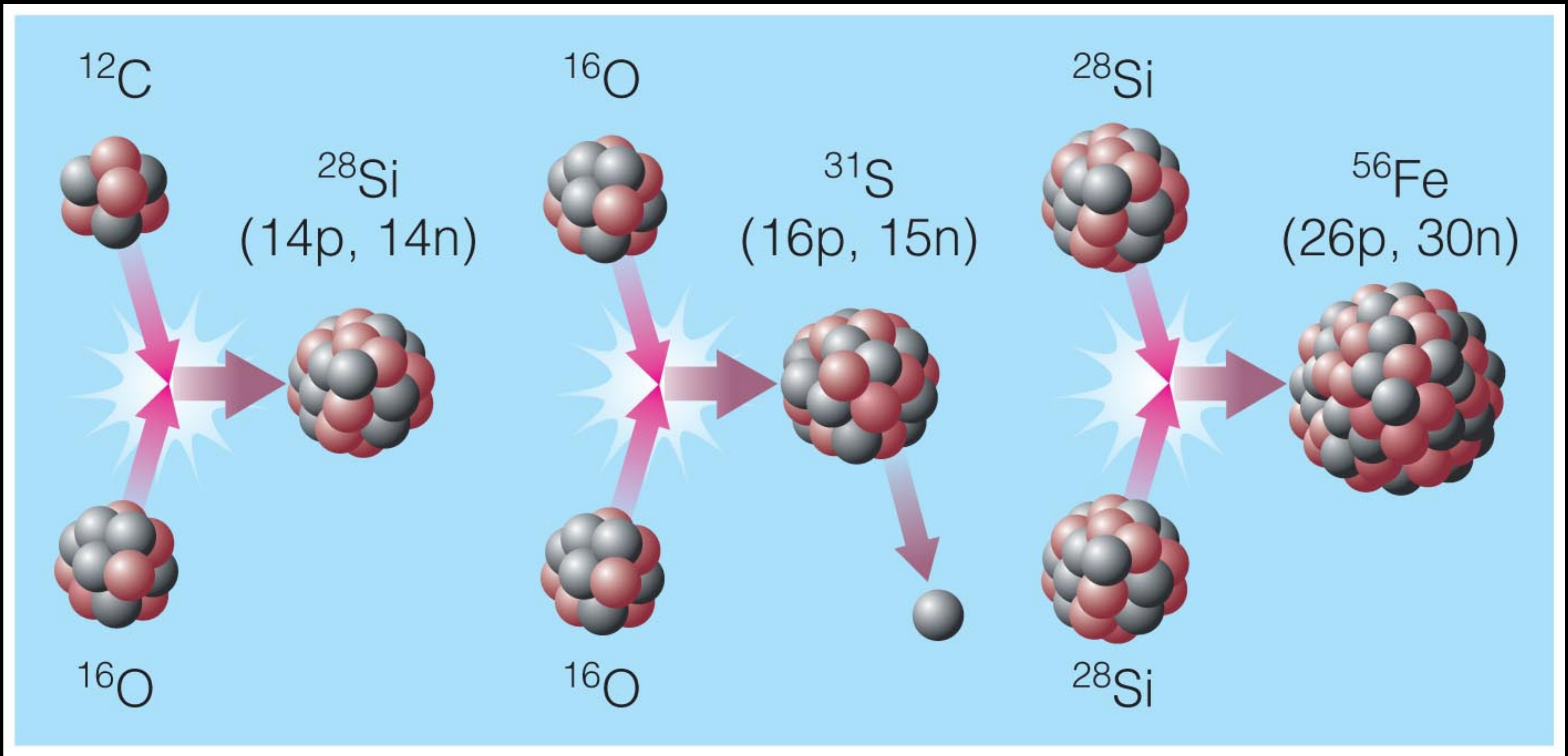
Helium capture: fusion beyond Carbon



a Helium-capture reactions.

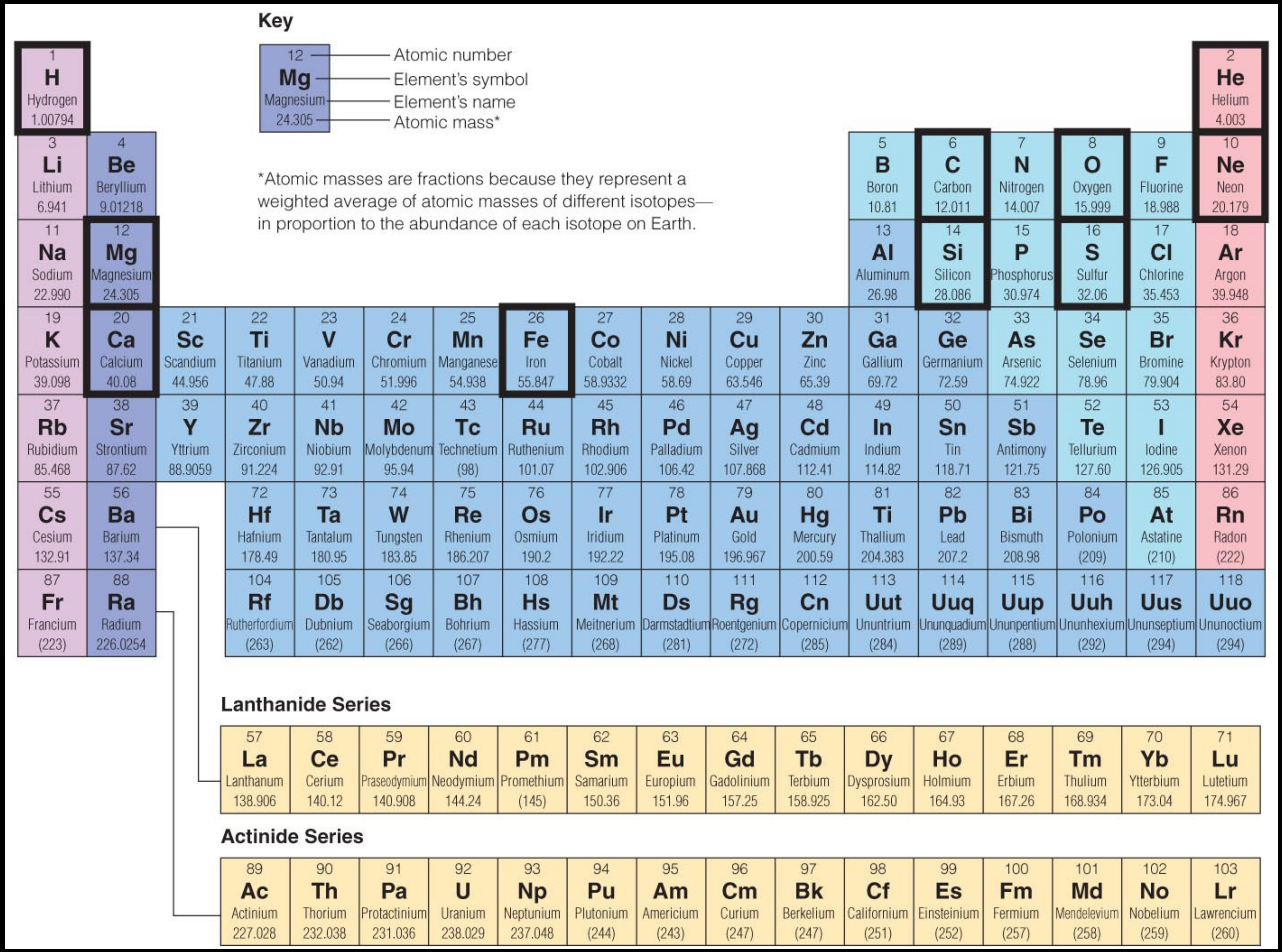
- In massive stars, high core temperatures allow helium to fuse with heavier elements

Advanced nuclear burning

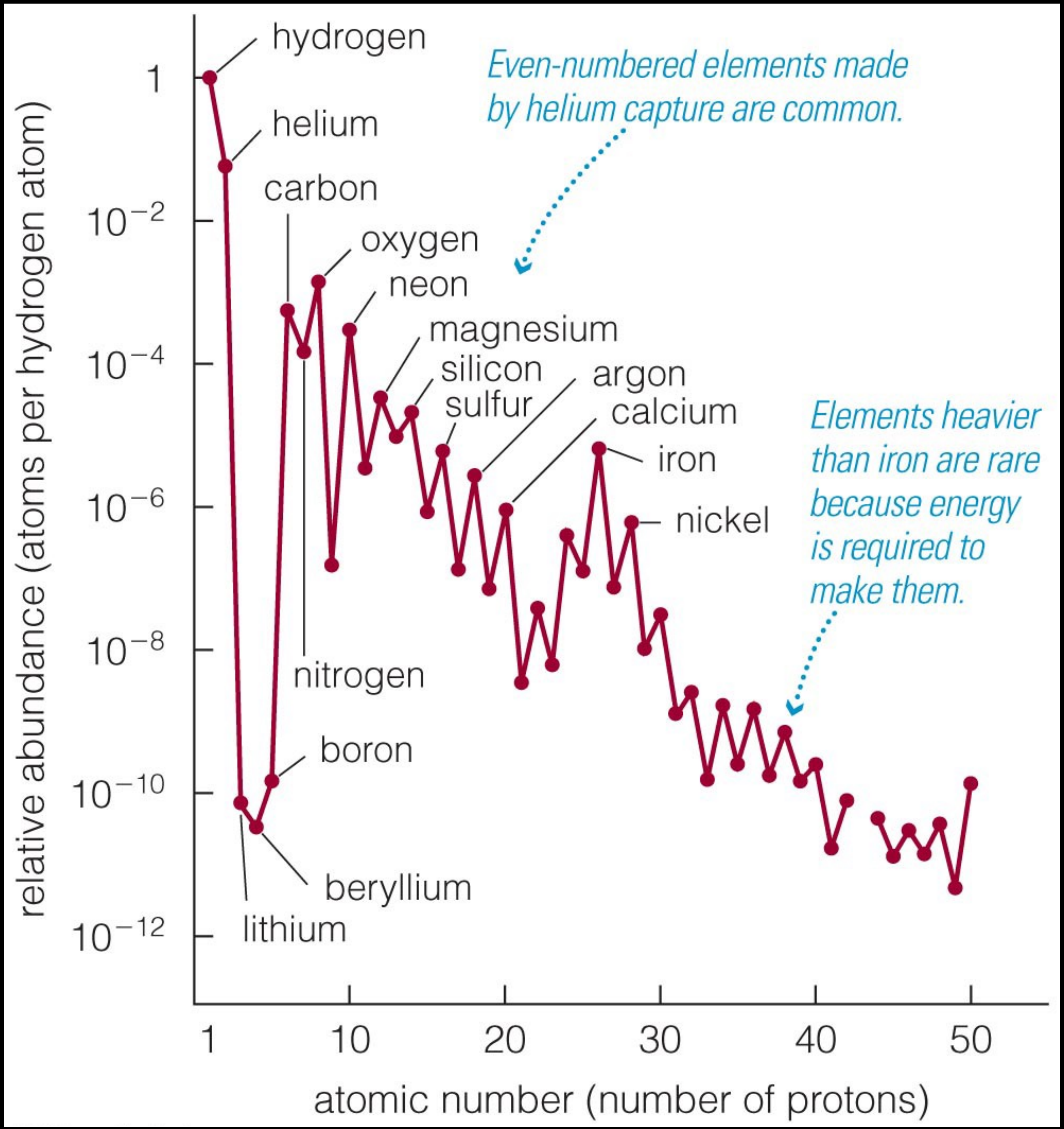


- Core temperatures in stars with $M > 8\ M_{Sun}$ allow fusion of elements as heavy as **iron**

Origin of the elements!



Main elements created by fusion in massive stars

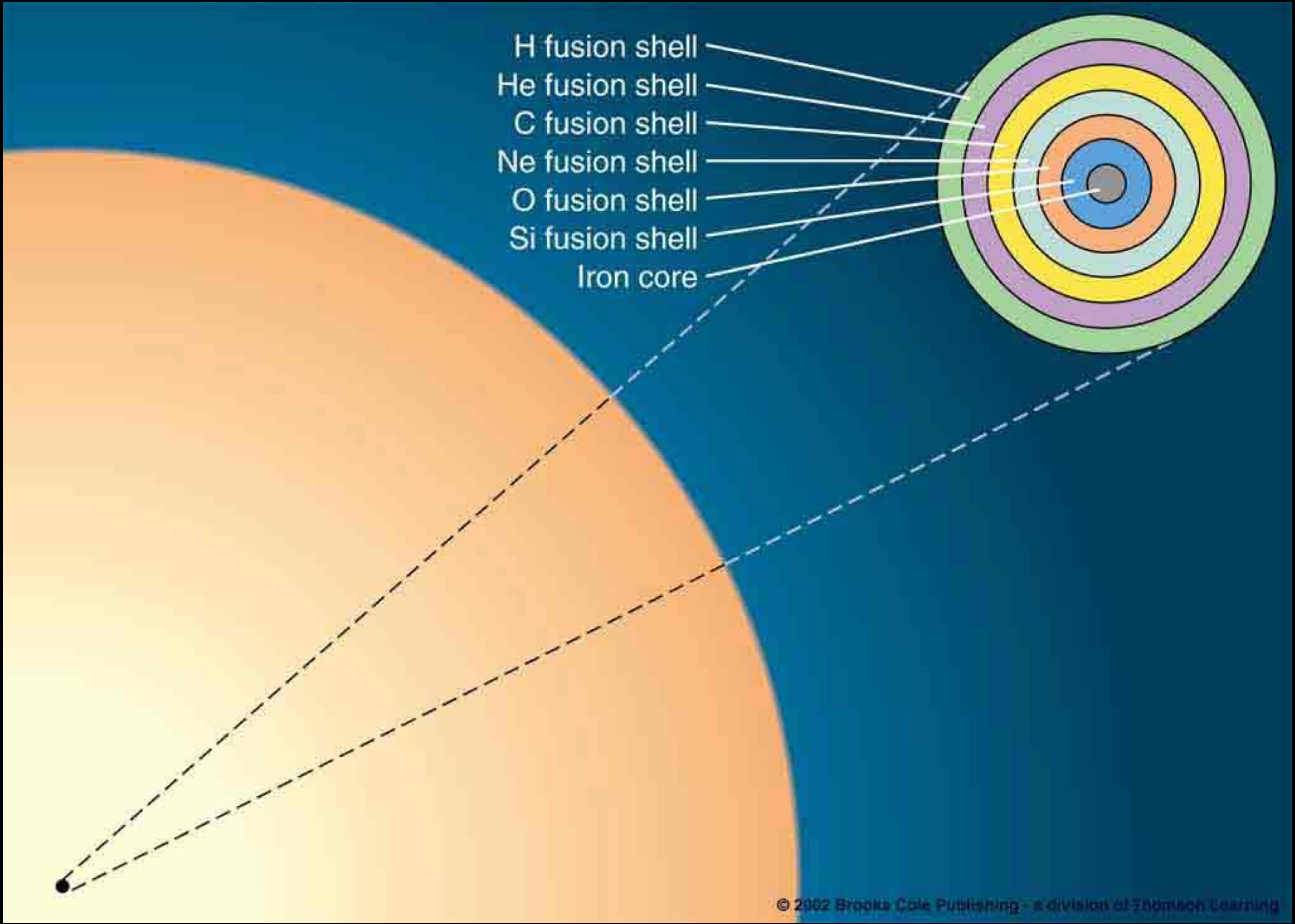


Abundances of elements in the Solar System

Evidence that this process really happens!

Main elements created by fusion in massive stars

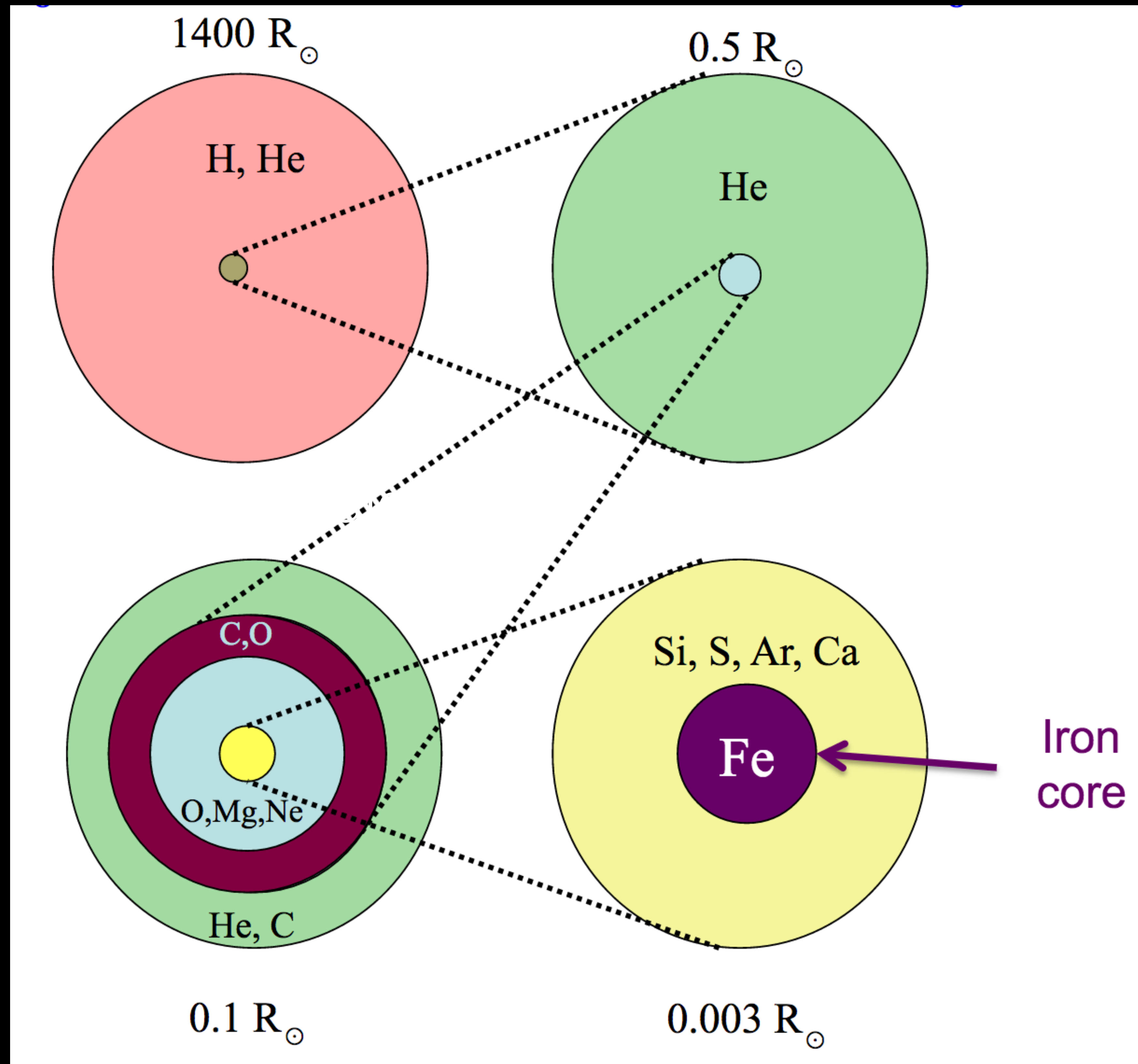
High-mass stars keep on going past He fusion, with many repetitions of the cycle



25 solar masses stars

The radius of the core is small comparing to the radius of the star

The mass of the core is usually few solar masses

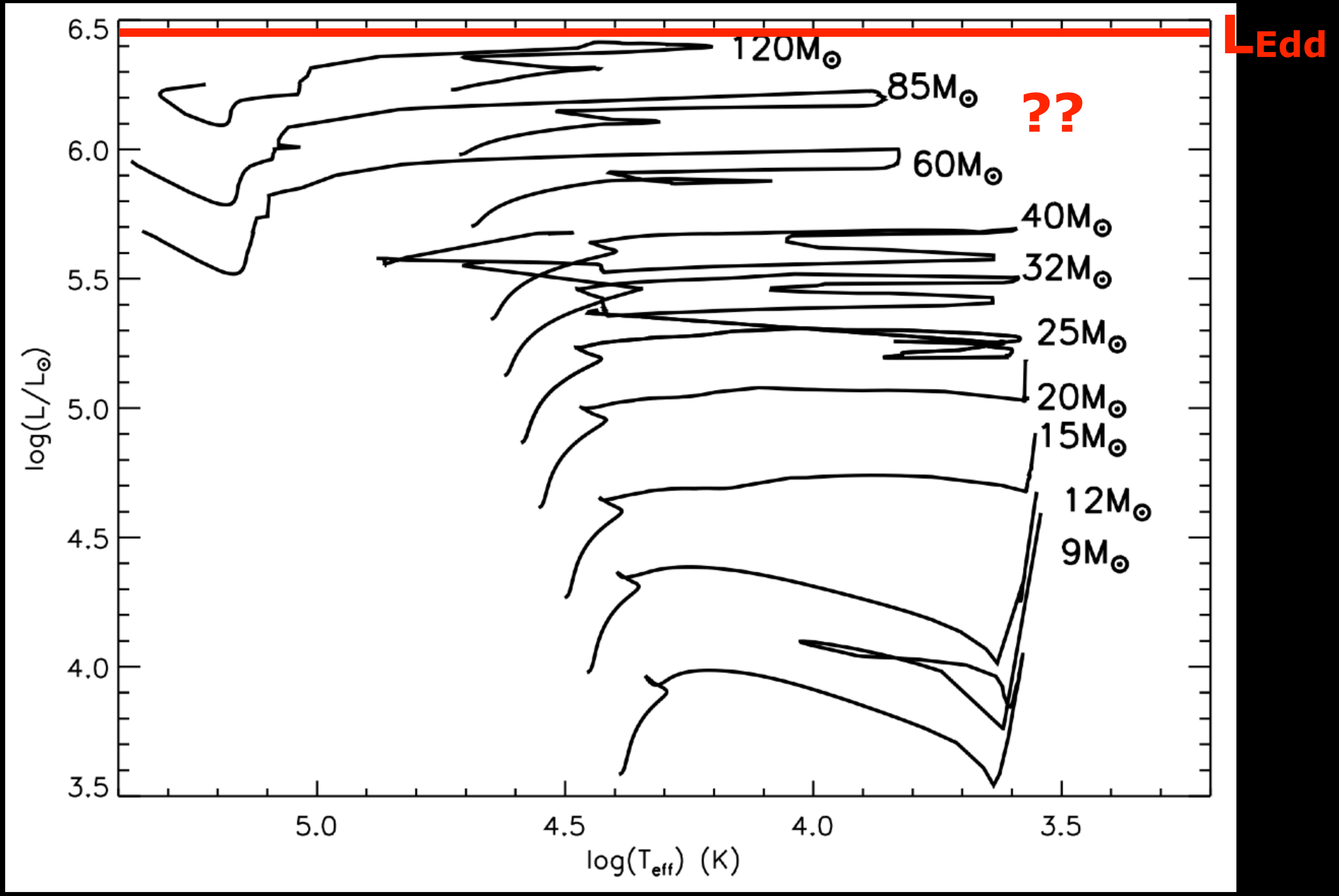


Massive Stars - Eddington Limit

Massive stars' extremely high luminosities place them near the Eddington limit for P_{rad}:

$$\boxed{L_* < 4\pi c G M / \kappa = L_{\rm Eddington}}$$

For massive stars $L_{Edd} \sim 3\text{-}4 \times 10^6\ L_\odot$ with M ~150-200$M_\odot$



Like all desperate measures, each fix is less successful than the first…

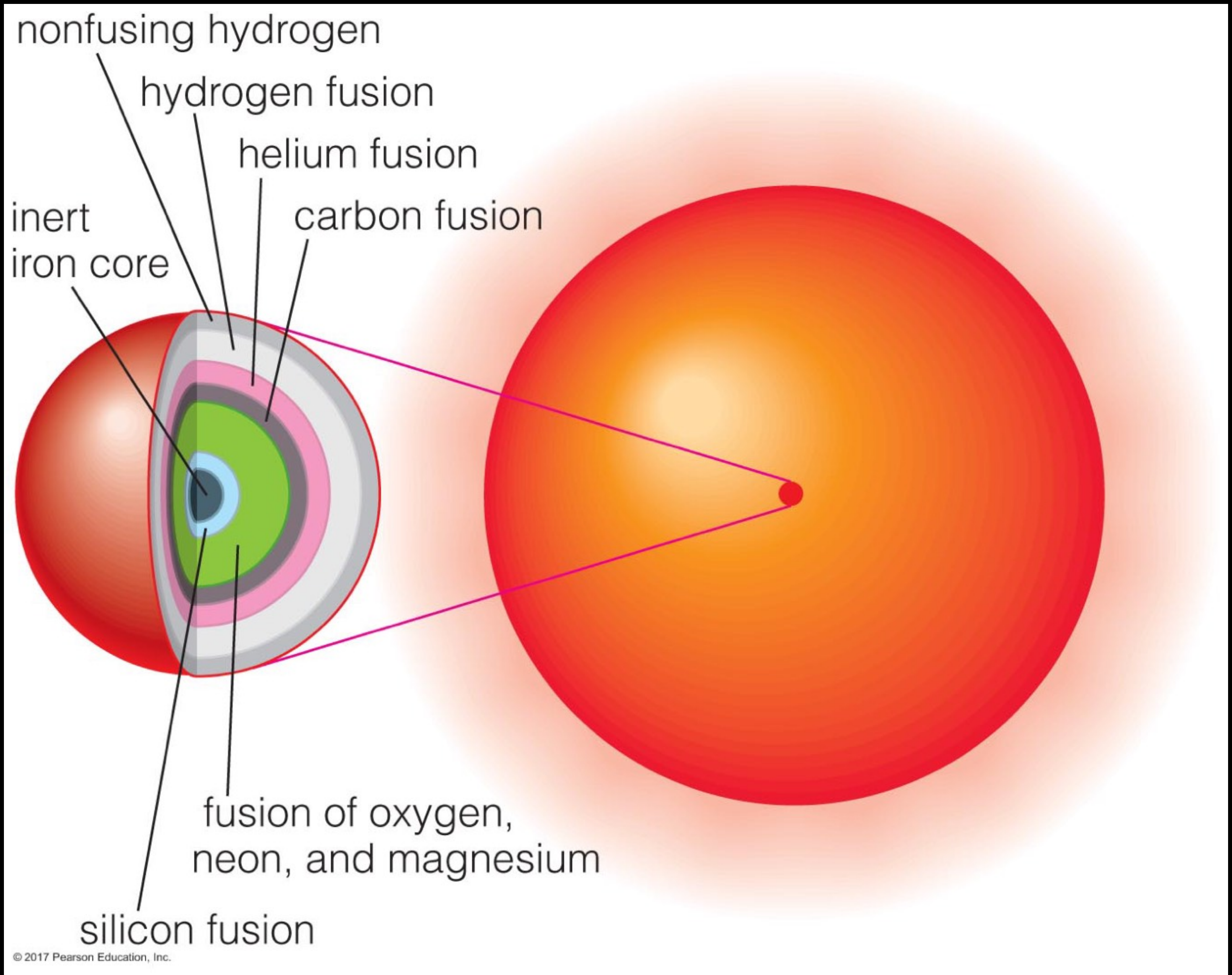
- Core is hotter and hotter each time
- Burn rate is faster and faster…
- …but less and less energy is released per fusion reaction
  - (energy difference between H and He is particularly large; He to C is smaller; further reactions are smaller still)

Each Cycle is shorter than the one before!

For a massive star…

- H-burning: lasts 7 million years
- He-burning: lasts 500,000 years
- C-burning: lasts 600 years
- Ne-burning: lasts 1 year
- O-burning: lasts 6 months
- Si-burning: lasts 1 day!
- And then what?

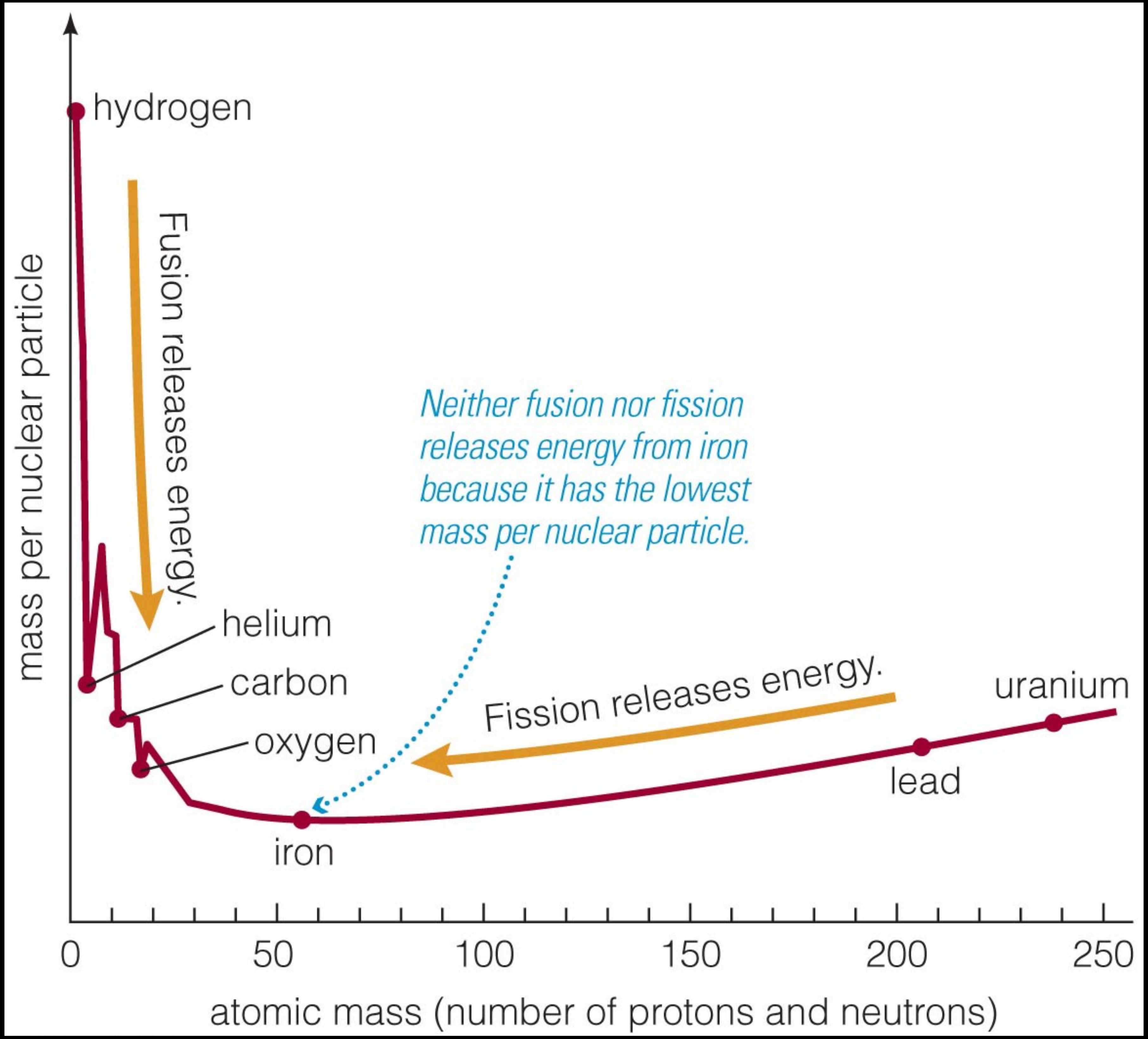
You cannot get fusion energy out of iron!



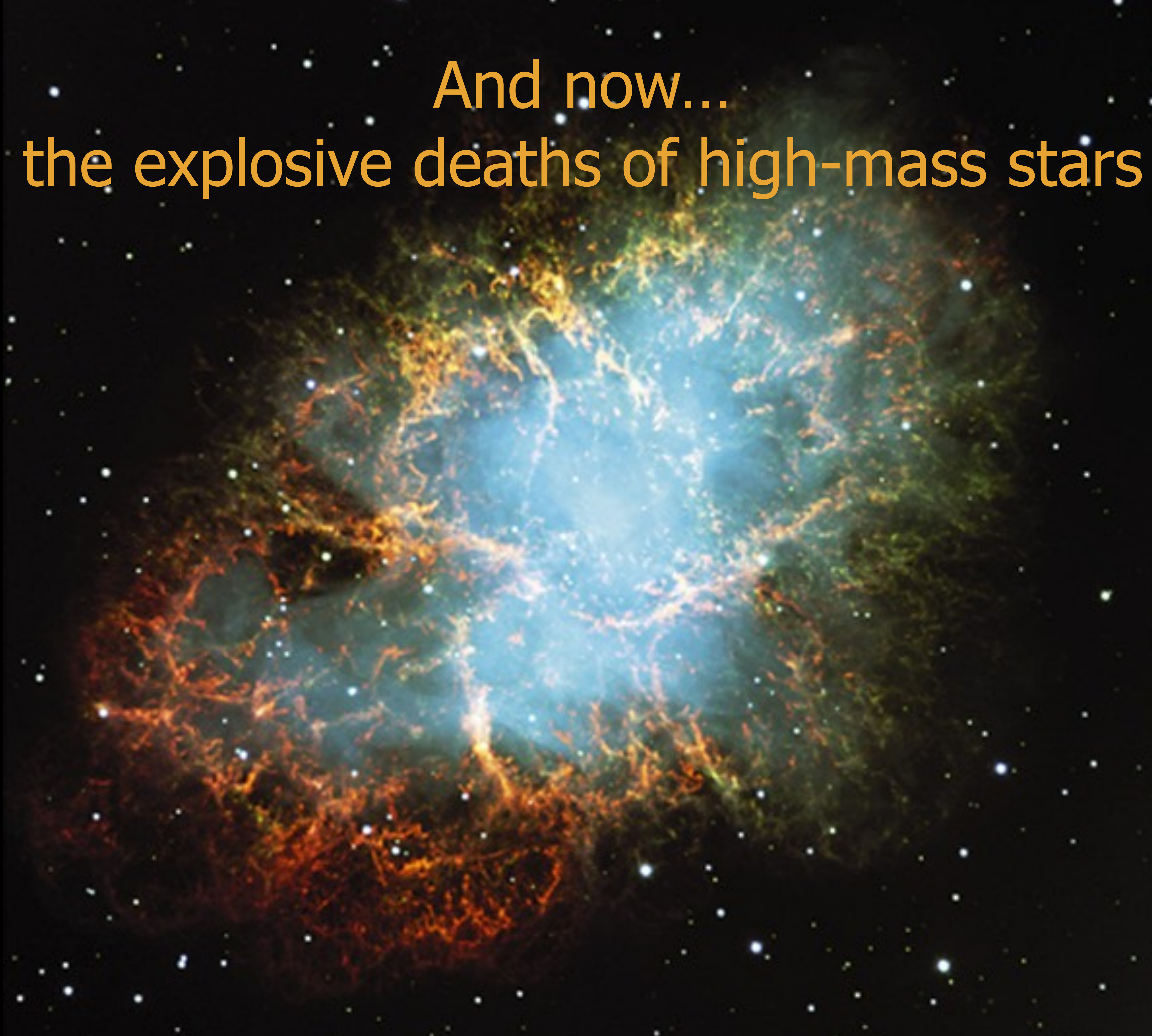
Remember:
4H→He produces energy because, while both have 4 nuclear particles, He has less total mass (by 0.7%)

(Not to scale. Core is tiny!)

Iron has the least mass per nuclear particle: END OF THE LINE!



And now…
the explosive deaths of high-mass stars

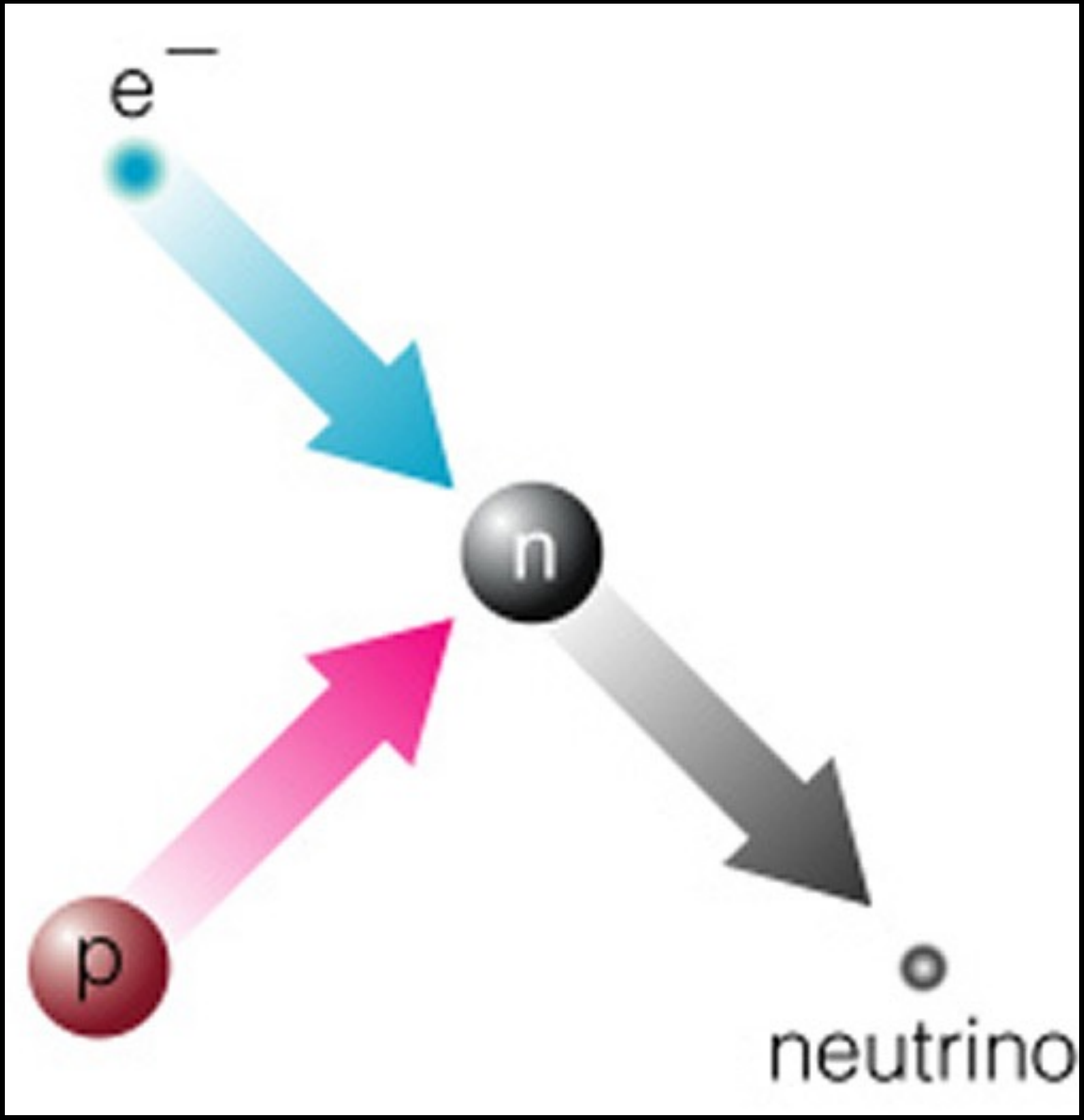


Death throes of a high-mass star

- Once a star fuses iron in its core, it is completely out of fuel
  - Low-mass stars don’t even make it to iron, because their cores do not get hot enough
  - High-mass stars do fuse up to iron, at which point they can no longer release any energy from fusion
- The core collapses!
- The star does not detonate, because iron cannot release any energy from fusion…

Death throes of a high-mass star

- Electrons **MERGE** with protons to form neutrons!
  - This also produces neutrinos as a by-product



The star's core becomes solid **NEUTRONS**!!!

- Neutrons behave like electrons, and can support the core with degeneracy pressure
  - Neutrons can handle (slightly) more pressure
- The process emits tons of neutrinos!
- Mass of the core is crammed into a sphere only 10 km in diameter!!!! (~size of Davis!)
- It's as dense as the nucleus of an atom!
- Like a nucleus, but with atomic number > 10^{57}

"NEUTRON STAR"

Death throes of a high-mass star

- The core collapses stop because of the degeneracy pressure of the neutrons.

Death throes of a high-mass star

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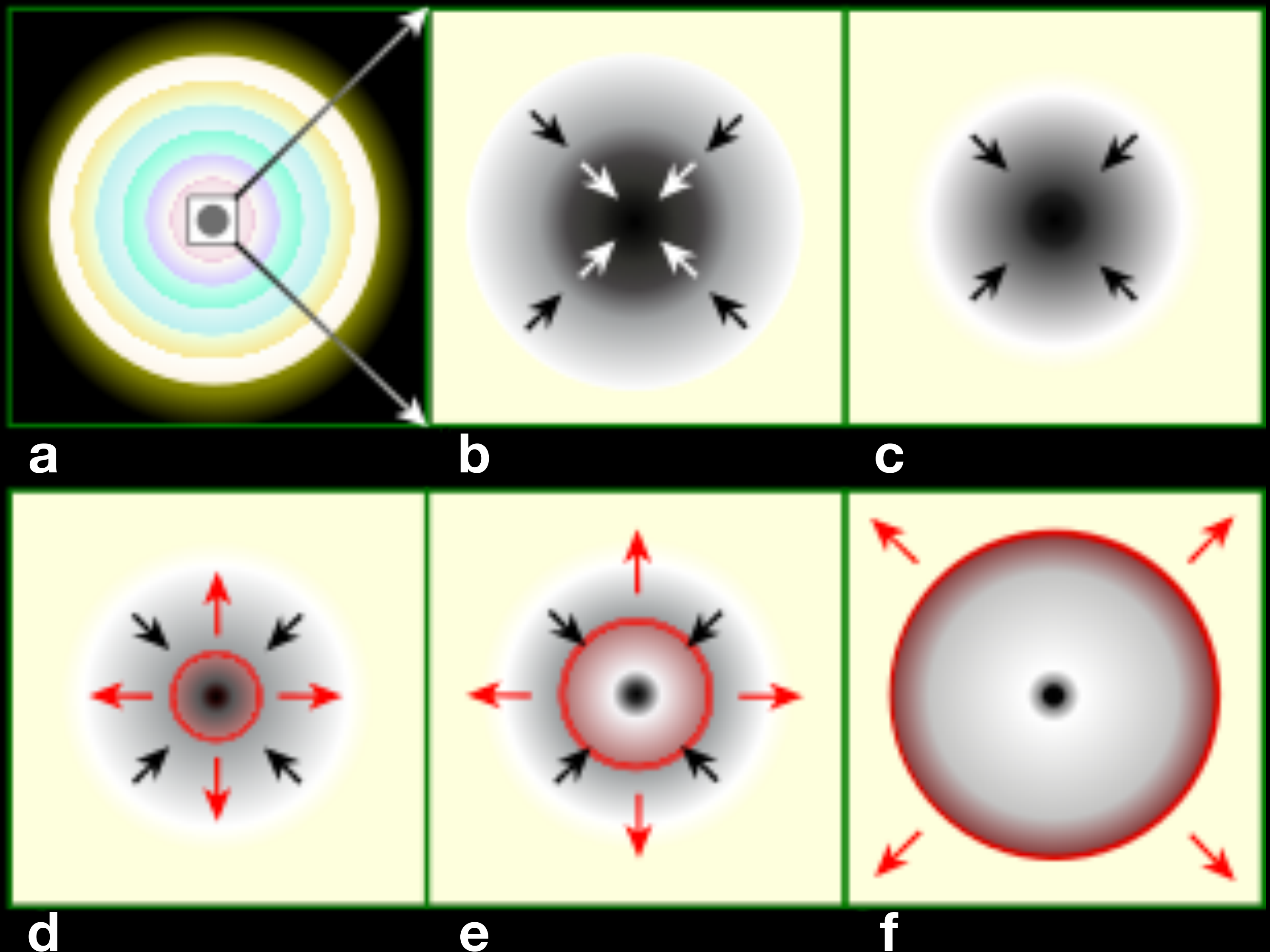
- The process emits tons of neutrinos!
- Neutrino energy release (1%) that accelerate the external part of the star (ejecta) to ~10,000 km/s
- A shock propagate and burn more elements.
- Explosion burning (Nickel produced)

Supernova Explosion



Within a massive, evolved star (a) the onion-layered shells of elements undergo fusion, forming an iron core (b) that reaches Chandrasekhar-mass and starts to collapse. The inner part of the core is compressed greater than nuclear density (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is re-invigorated by neutrino interactions. The surrounding material is blasted away (f), leaving only a degenerate remnant

Supernova!

(plural = “Supernovae”)

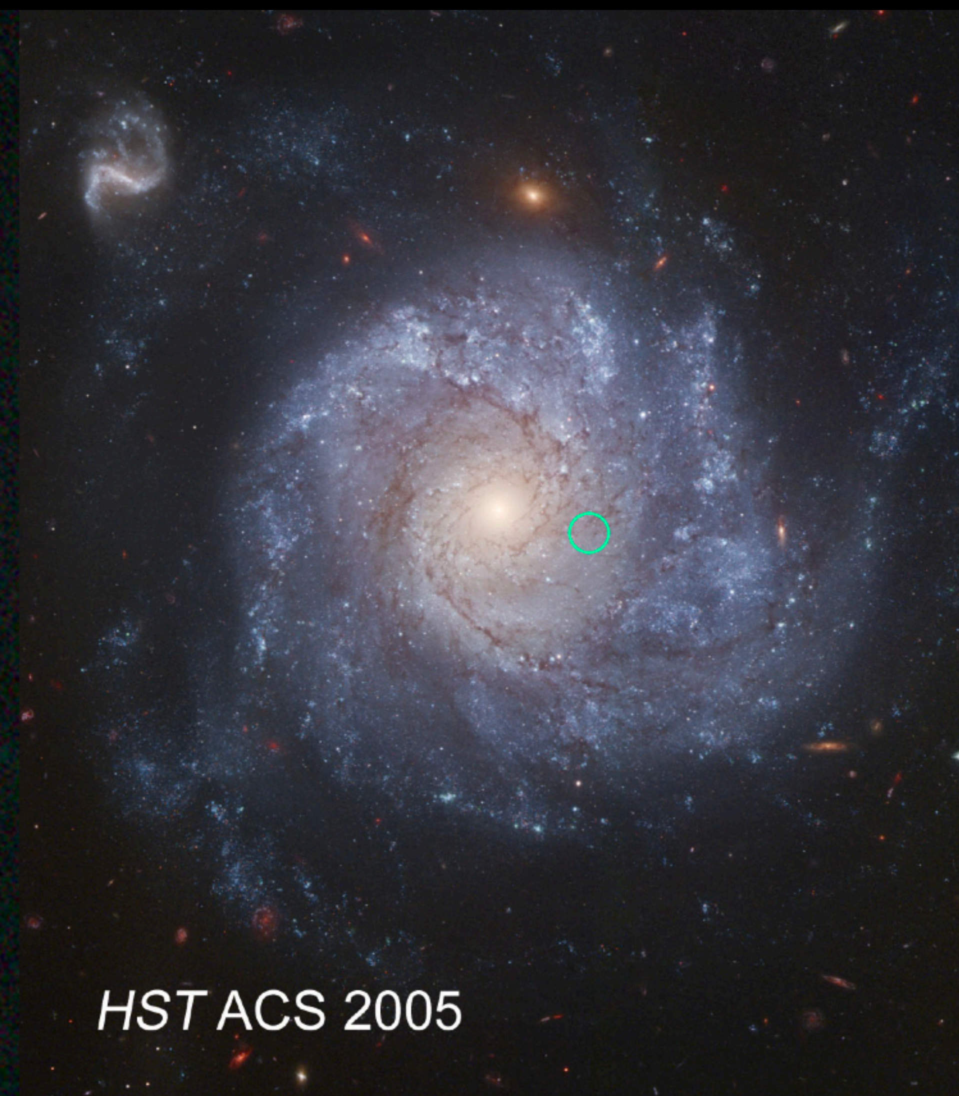
What we have described is a “core collapse supernova”.
There are also other types of supernovae.

Supernova Explosion !!!


Supernovae in other galaxies can be as bright as the whole galaxy

We can see them at HUGE distances!

W. Li and A. V. Filippenko (University of California, Berkeley)

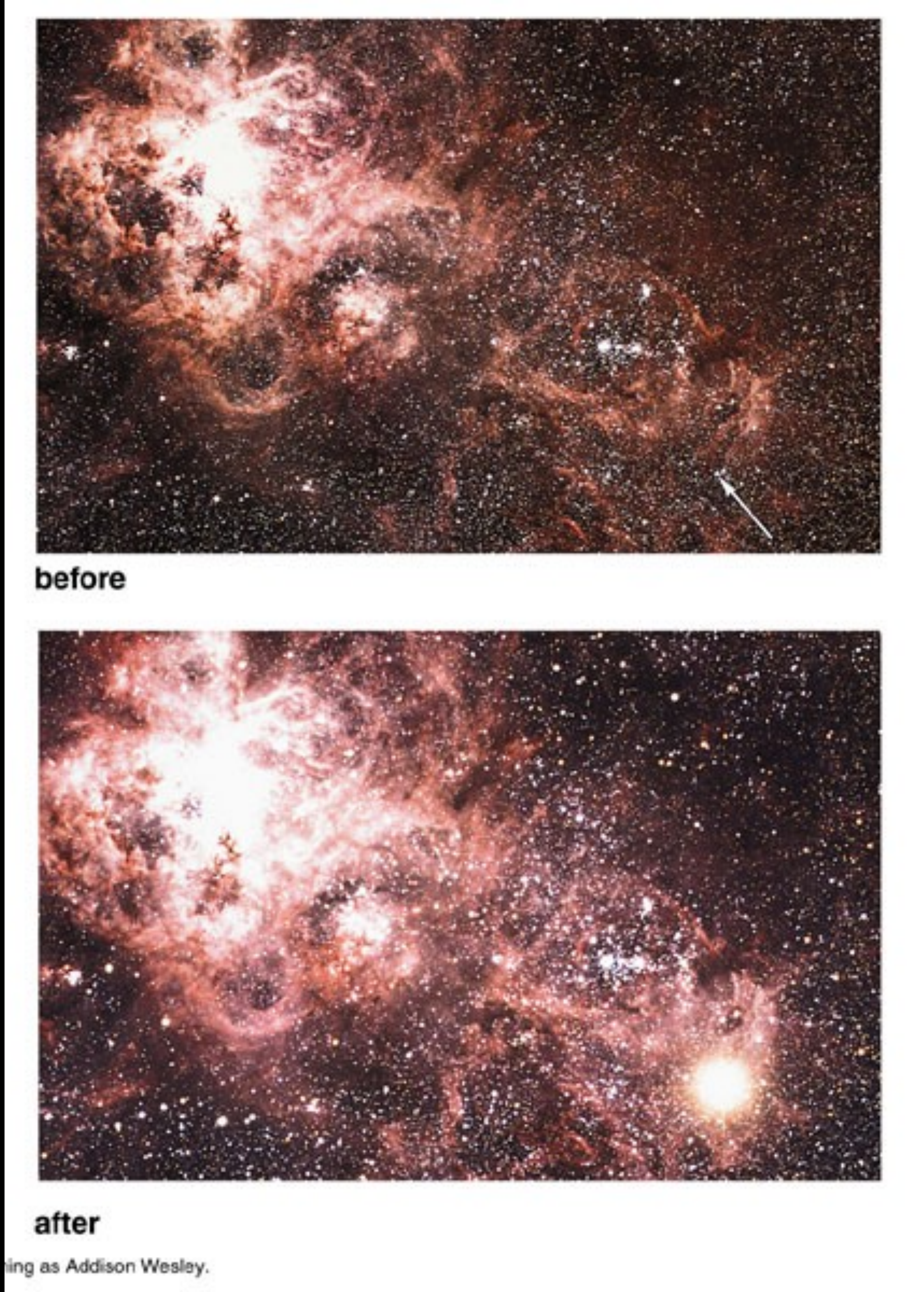


NASA, ESA, The Hubble Heritage Team (STScI/AURA), and A. Riess (STScI)

Supernovae in human history

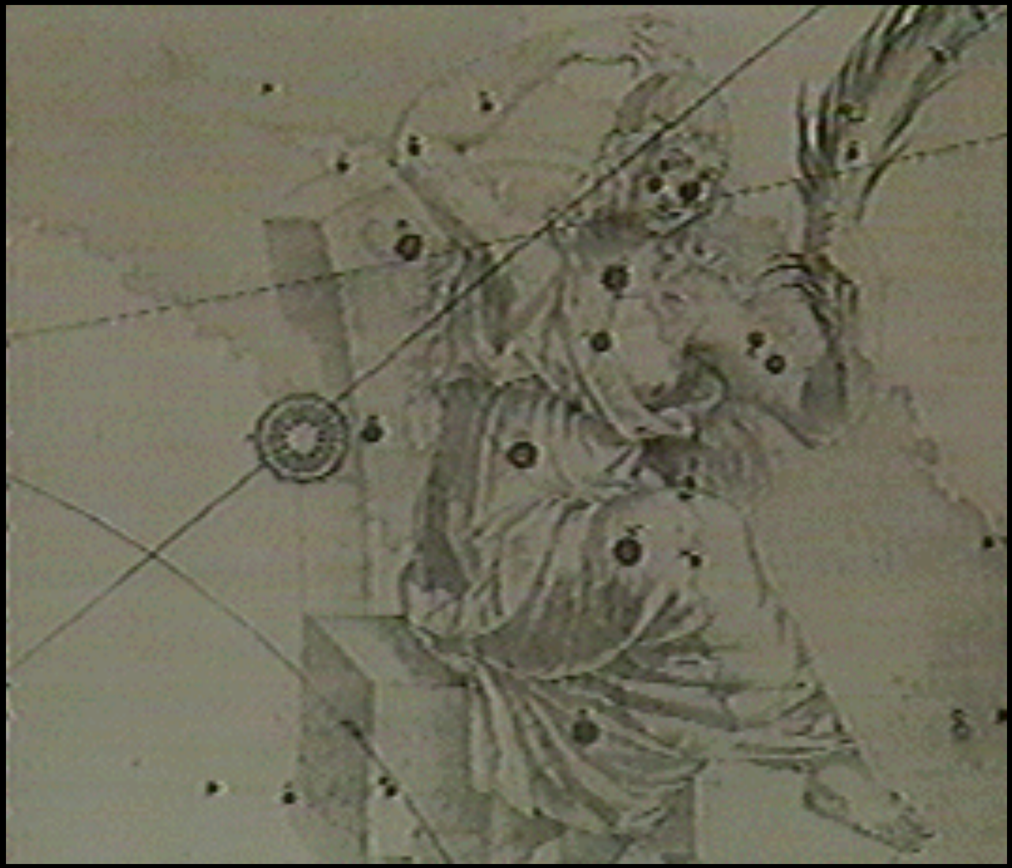
- Nearby supernovae can be seen with the naked eye
- Here are some nearby supernovae that we know about

Astronomers saw a supernova in the Large Magellanic Cloud in 1987



Another view

We know of other past supernovae from written and non-written history



Some of these were so bright, they could be seen in the day!

"In the first year of the period Chih-ho, the fifth moon, the day chi-ch'ou, a guest star appeared approximately several [degrees] southeast of Thien-juan. After more than a year it gradually became invisible"

- Official history of the Song Dynasty in China

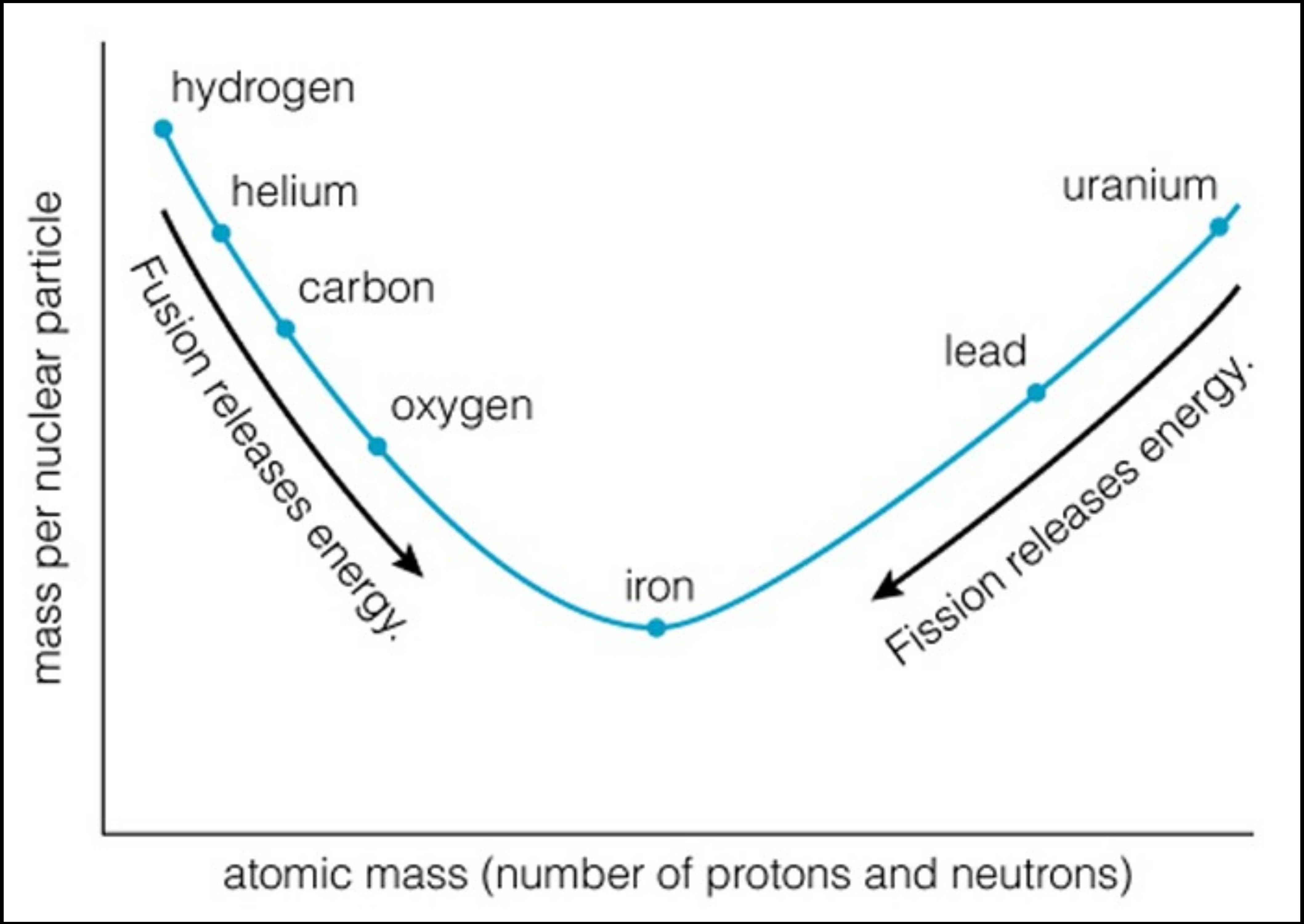
The Crab Nebula

- Supernova remnant
- Leftover from supernova on July 4 1054 CE, as recorded in China

How can the heaviest elements exist?

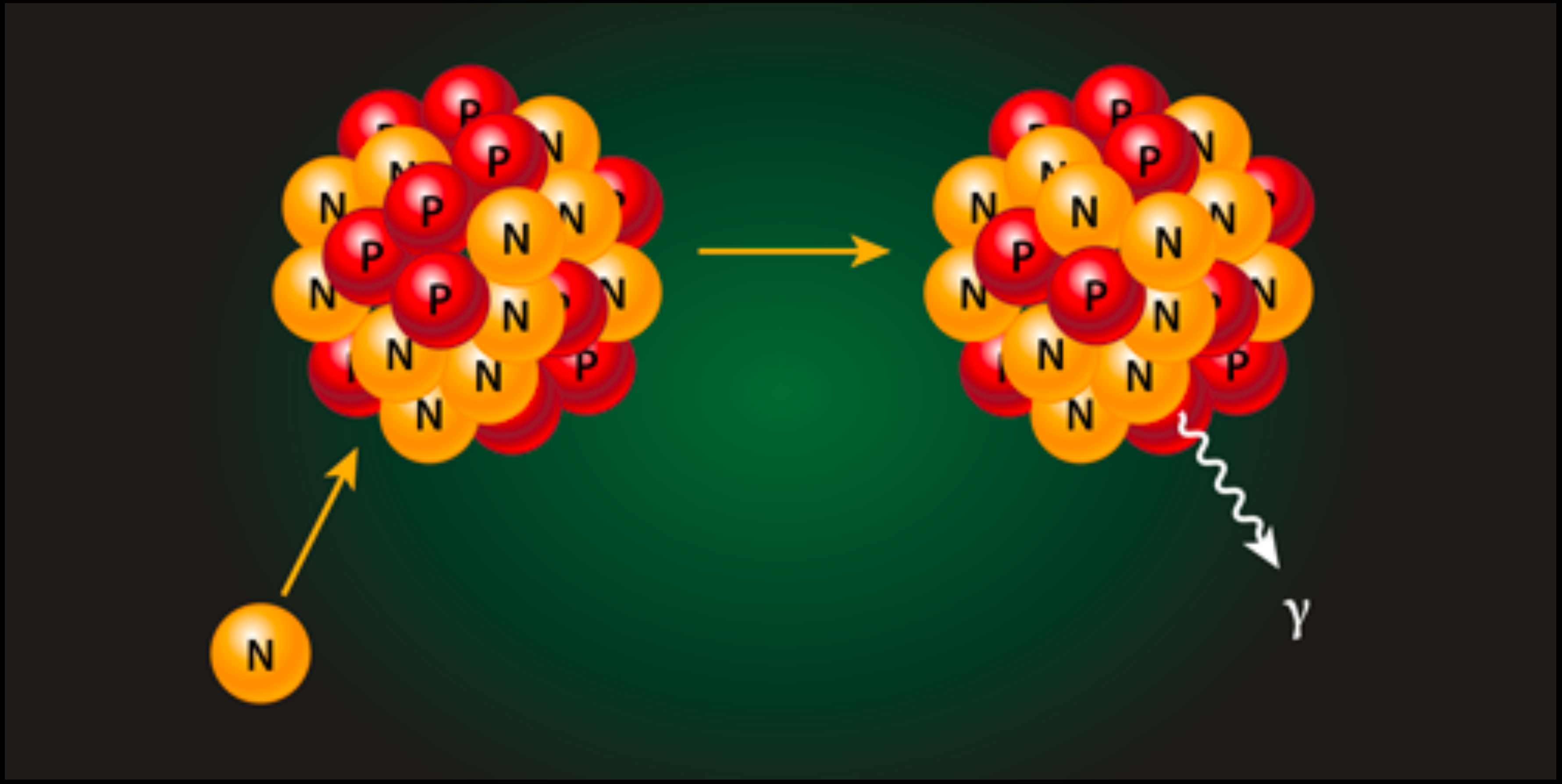
Iron has the least mass per nuclear particle.

Need to ADD ENERGY to make heavier nuclei!



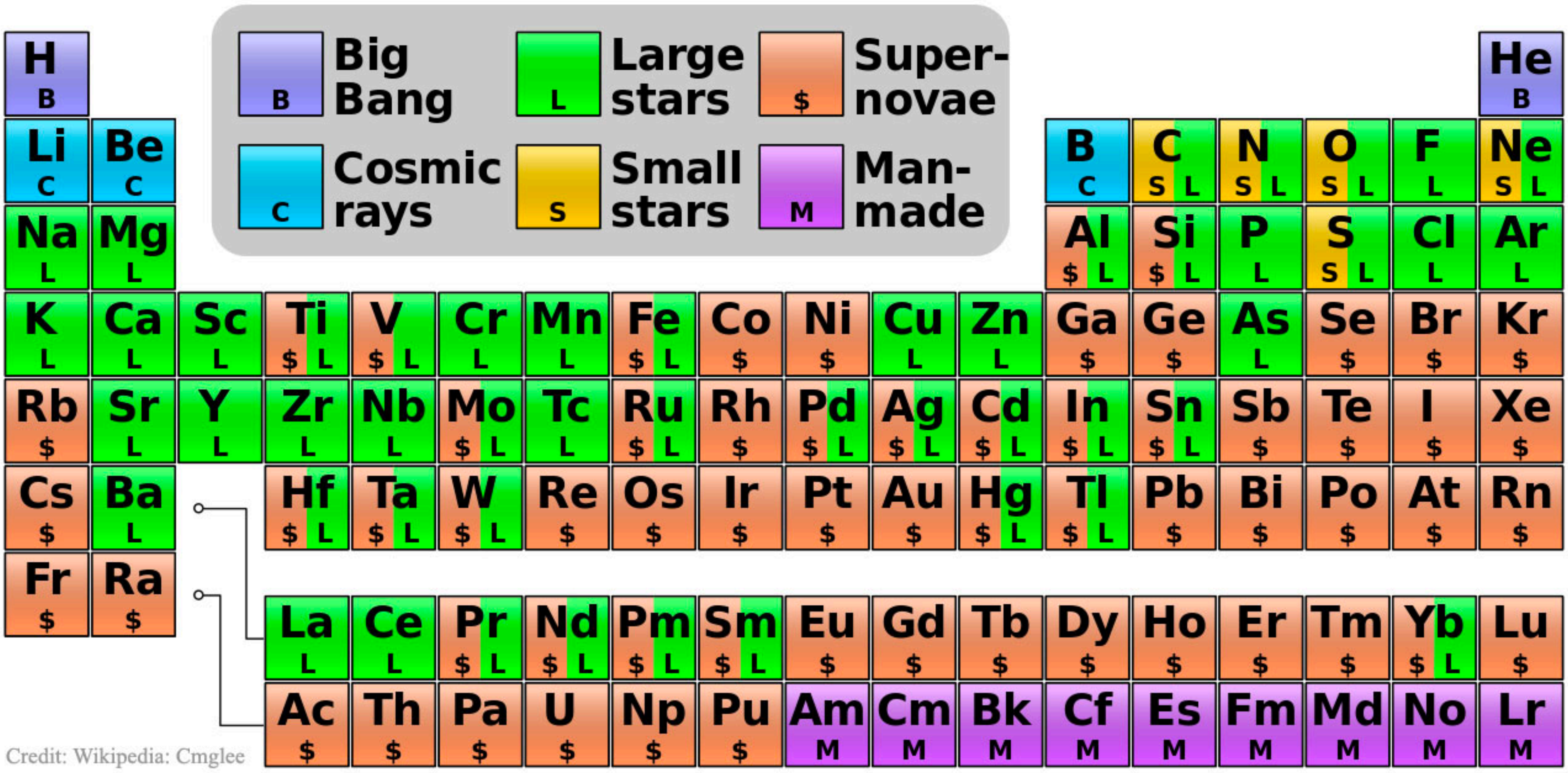
Supernovae are heavy-element factories!

- Expanding outer layers get bombarded with energetic neutrons from the inside
- This creates elements heavier than iron!
  - Kinetic energy of neutron is converted to mass-energy in the new nucleus



Now you can understand the origin of the elements!

Thanks, supernovae!



but this is not the final picture.
we will revised this later in the course ….

Recap: what have we learned?

- **What are the life stages of a high-mass star?**
  - Similar to life stages of a low-mass star
  - High-mass stars fuse heavier elements after leaving the main sequence

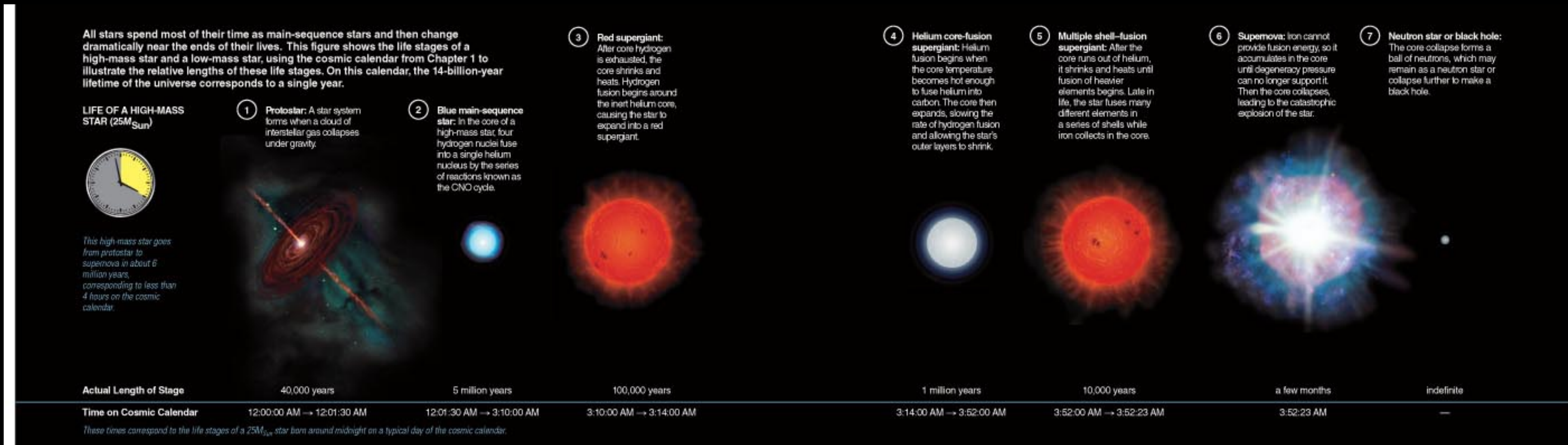
- **How do high-mass stars make heavy elements?**
  - Their higher masses produce higher core temperatures, which enables fusion of heavier elements
  - Eventually iron is produced in the core

- **How do high-mass stars die?**
  - The iron core collapses, since it cannot release any energy from fusion
  - The core turns into a gigantic ball of neutrons
  - This leads to a core-collapse **supernova**

Stellar evolution summary: role of mass

- A star's mass determines its entire “life track”, because it determines the core temperature.
- Low-mass stars with < 2 $M_{\odot}$ have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs.
- Intermediate-mass stars (2-8 $M_{\odot}$) can not fuse elements heavier than carbon, and still end as white dwarfs.
- High-mass stars with > 8 $M_{\odot}$ have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.

Stellar evolution summary: high-mass



- Main sequence: H fuses to He in core
- Red supergiant: H fuses to He in shell around He core
- Helium core burning: He fuses to C in core, while H fuses to He in shell
- Multiple shell burning: many elements fusing in shells
  - Core ultimately becomes iron
- **Supernova** explosion leaves behind a **neutron star**…
  - … or a **black hole (?!?!)**