Astronomy 120

Prof. Kenney Class 8 June 6, 2018

differences in textbook editions…10th ed vs 8th & 9th ed

- all chapter assignments starting with ch 21 on are shifted by 1 in 10th edition relative to 8th, 9th editions (neutron stars had own chapter 21 in 8th & 9th, in 10th is part of ch 20 on "deaths of stars")

- e.g. black holes ch 22—>21 (8+9th → 10th)
- e.g. our galaxy ch 23—>22 (8+9th → 10th)

- updated syllabus on class website
- different syllabi for 10th vs 8+9th editions
- "sec 0" means stuff before section 1

midterm exam ?

- Saturday June 16 ?
- morning 10am-noon ?
- afternoon 1-3pm ?

No need to memorize formulae

- Help sheet with formulae will be given with exams

- Help sheet on astro120 website
  (on “Useful Info” page)

Today in Astro 120!!!!!

What is a star?

What are different types of stars?

What is a main sequence star?

What is the energy source of stars?

How long do stars live?

What will happen to our Sun?

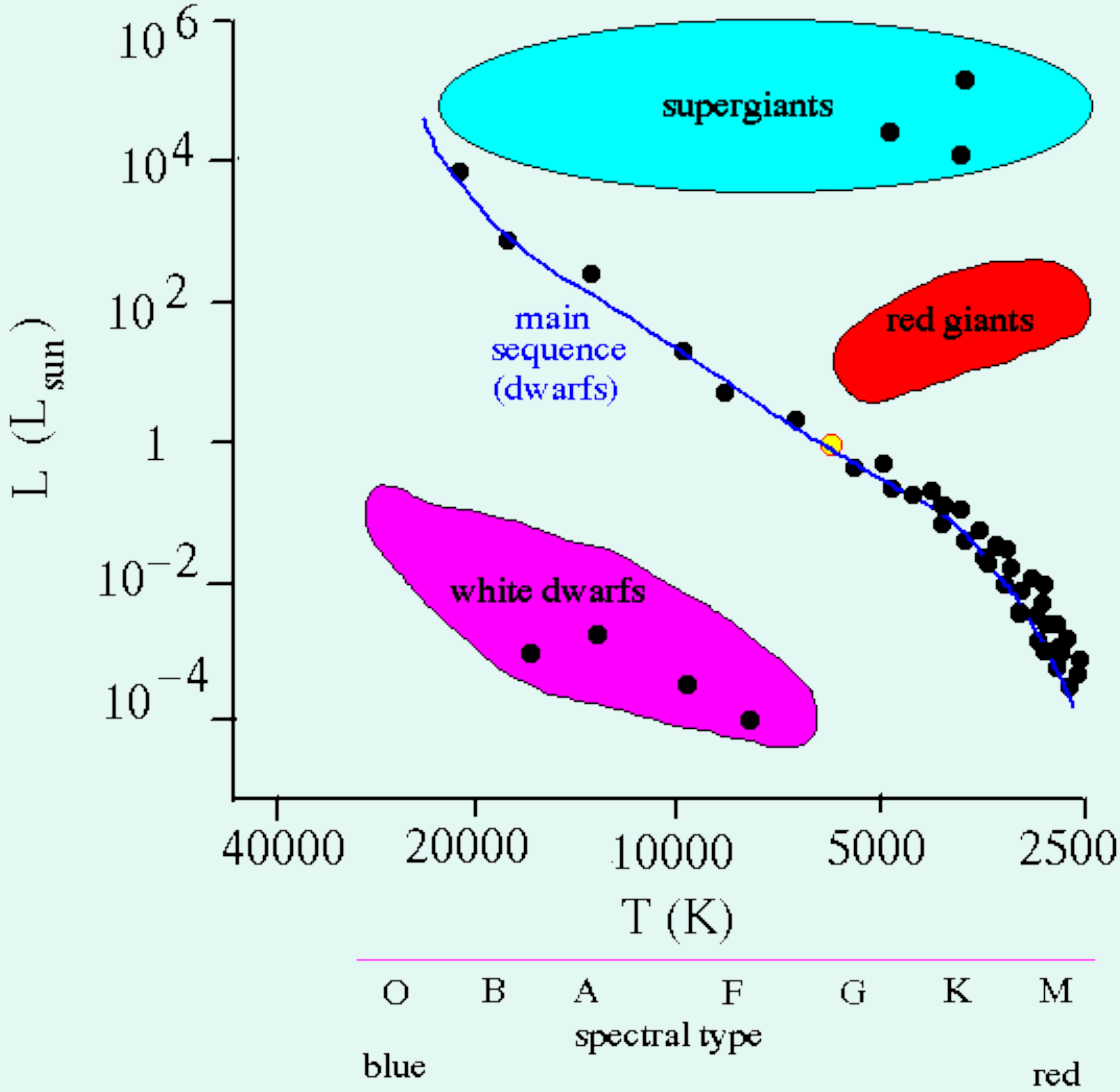
How do stars evolve?

How do stars of different masses "die"?

What are the 3 types of stellar corpses?

why does this happen ?

HR diagram – schematic with types of stars



The story of any star's evolution is the story of its constant battle to ___

A. balance the effects of gravity

B. fuse its entire supply of hydrogen

C. maintain its core temperature

D. maintain its high mass

E. lose 5 pounds

- **Initial mass** is the most important fundamental property of a star, since it determines ***the entire life history of a star***

- Initial mass determines:

  L, T, color, size, lifetime

- The Main sequence is a mass sequence…

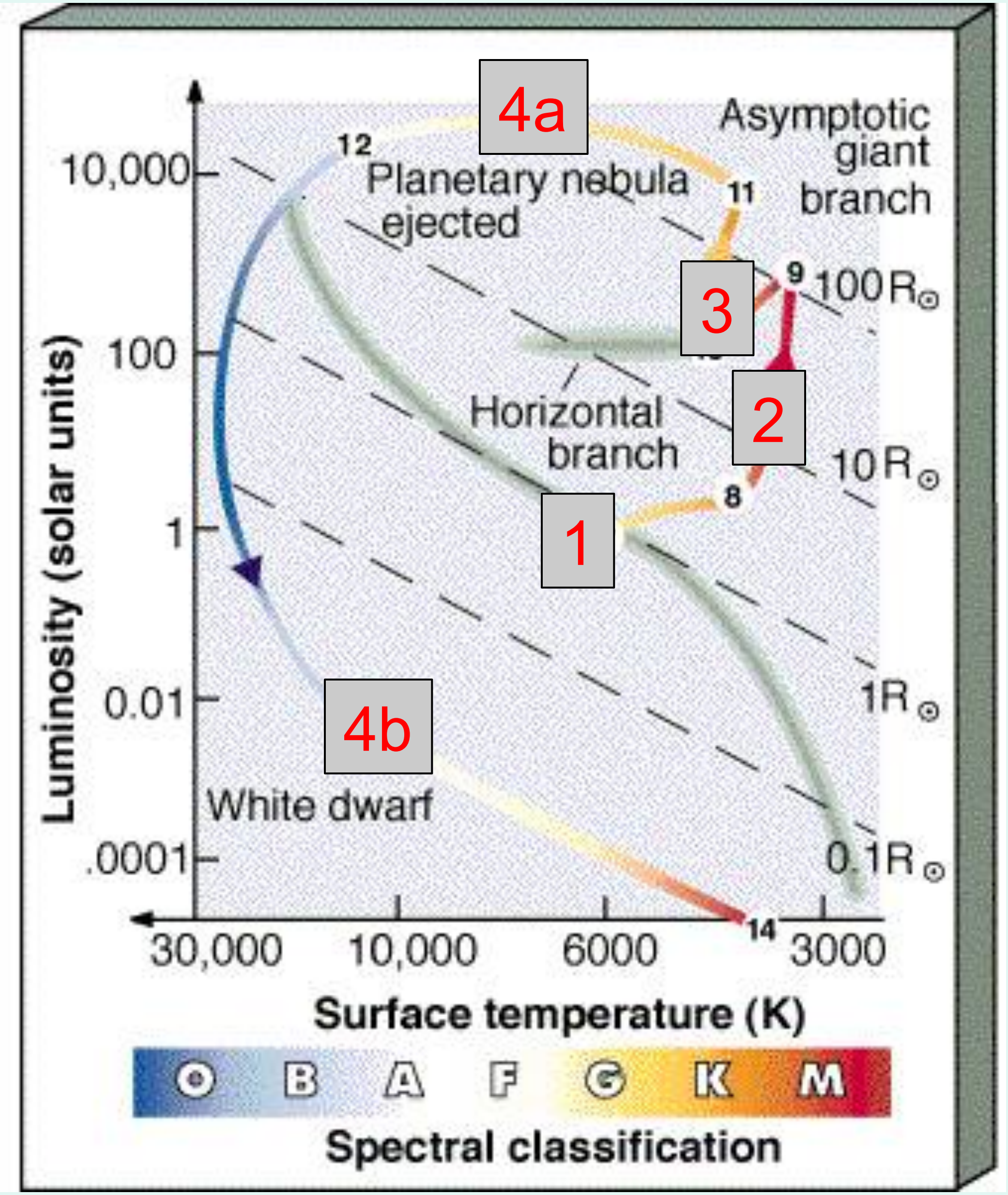
… and stars of different masses evolve differently

to simplify, we'll divide stars into 2 mass classes:

A. low mass stars like the Sun, 0.1-4 M_{sun}

B. massive stars >10 M_{sun}

Evolution of low mass stars like Sun ($M \sim 0.1\text{-}4\ M_{sun}$)



1. **Main sequence** (fusing H in core)

2. **Red Giant I** (fusing H in shell, no fusion in core)

3. **Red Giant II** (H fusion in shell, He fusion in core ; He flash & horizontal branch)

4. (a) **Planetary Nebula/** (b) **White Dwarf**

Evolution of low mass stars like Sun ($M \sim 0.1\text{-}4\ M_{sun}$)

1. **Main sequence**

- While a star is burning H in its core, it lies along a curve in the LT (HR) diagram referred to as the "main sequence"

- After it consumes all H in the core, the star "evolves off the main sequence"

Evolution of low mass stars like Sun ($M \sim 0.1\text{-}4\ M_{sun}$)

2. **Red Giant I** (fusing H in shell, no fusion in core)

After it fuses all of H in core to He, there is no more H fuel in core to provide the energy & pressure to balance gravity

So you'd think that the star would collapse (& not expand/get bigger)

But what happens…

Core shrinks & heats up

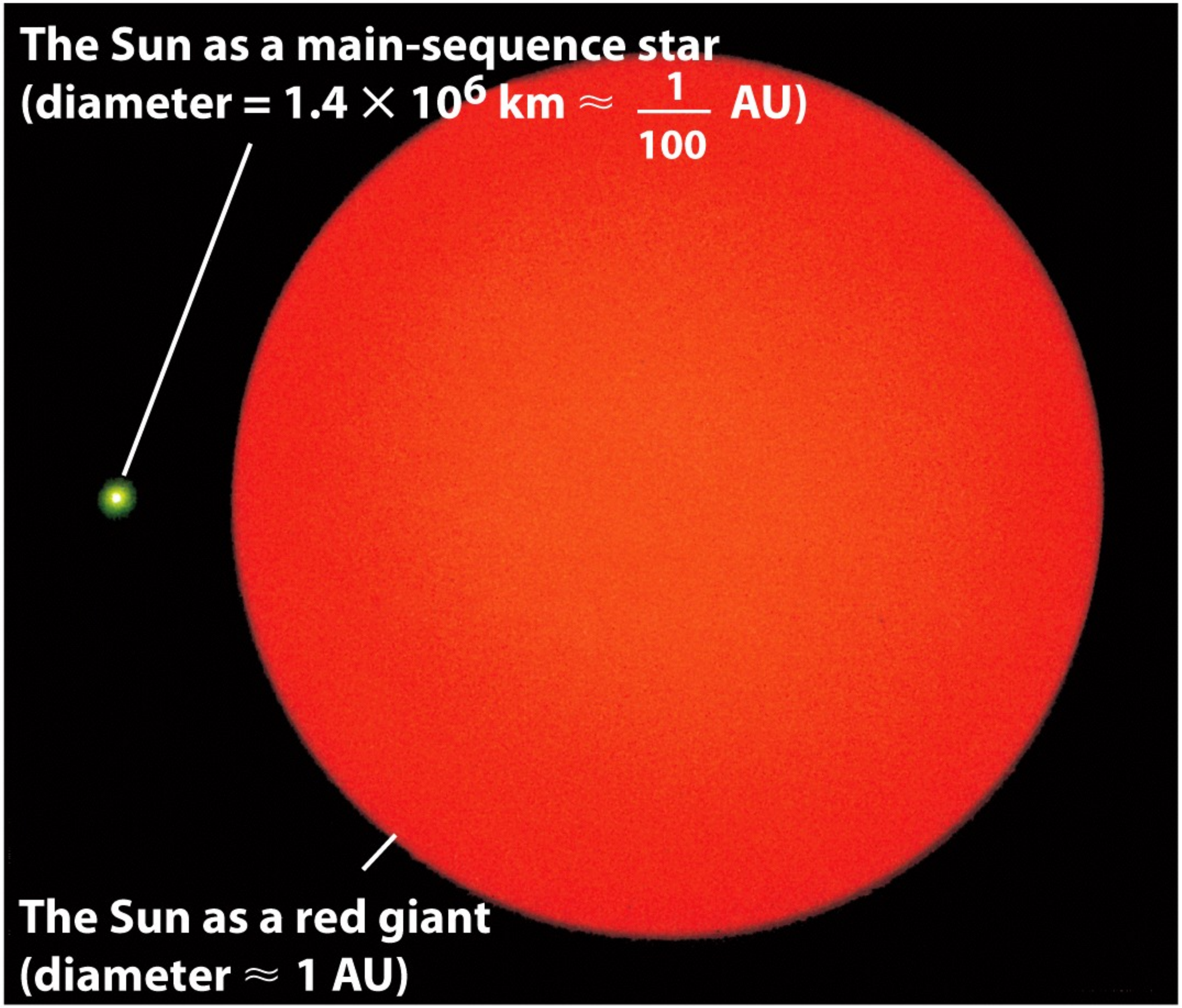
Until layer /shell of H outside core

Becomes hot enough to fuse H->He

Temp rises rapidly in this "H burning shell"

Which then expands dramatically

Star increases in size by a factor of ~100 to become Red Giant



The Sun today and as a red giant

Figure 19-4a

Universe, Tenth Edition

Why does a Red Giant star become so large?

A. Pressure overcomes gravity because core fusion stops

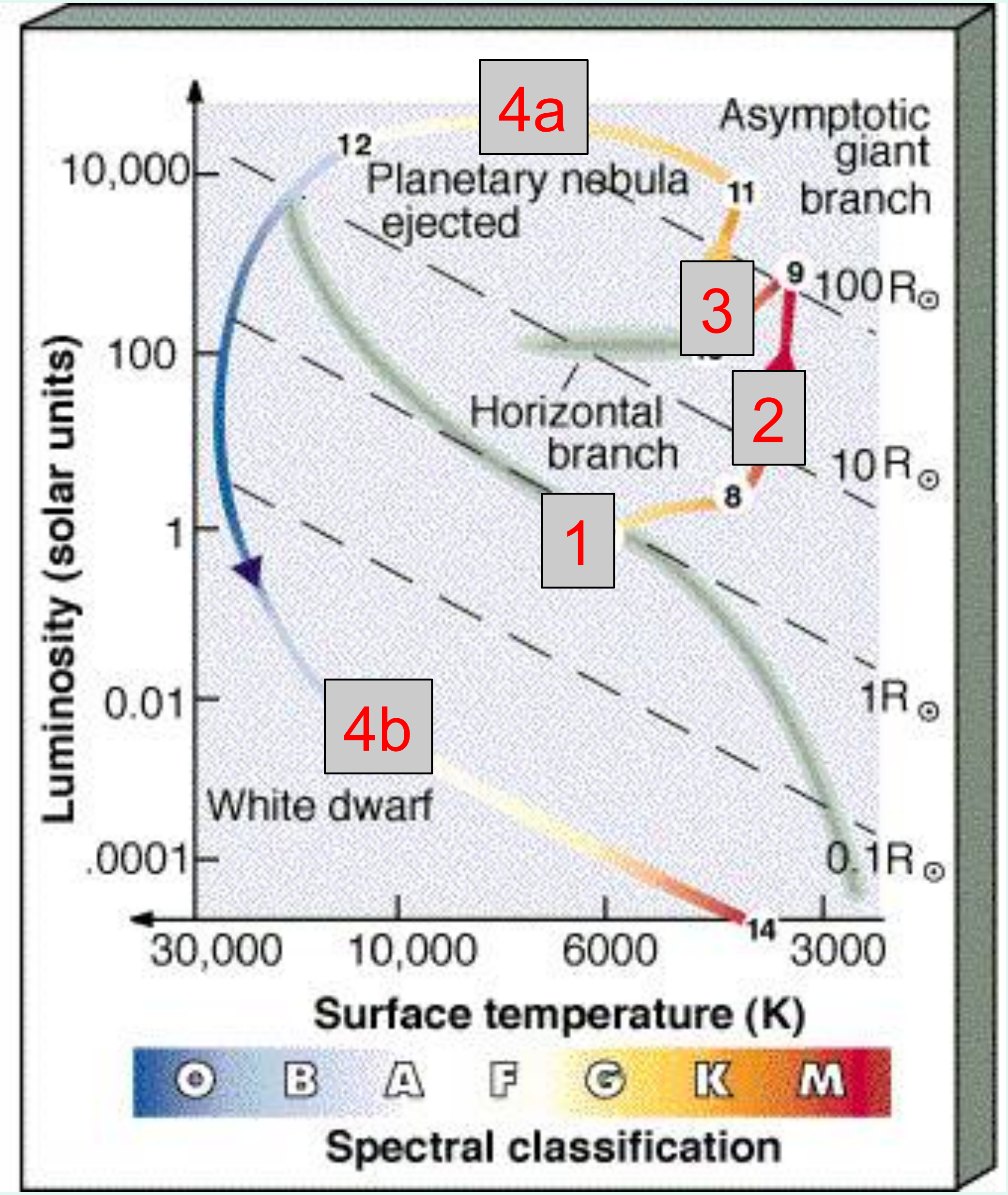
B. Fusion occurs outside core so not as much overlying weight to keep star compressed

C. The increase in luminosity forces star to expand

D. Shell expands dramatically since energy produced during core fusion is finally released

E. Hormonal imbalance

Evolution of low mass stars like Sun ($M \sim 0.1\text{-}4\ M_{sun}$)



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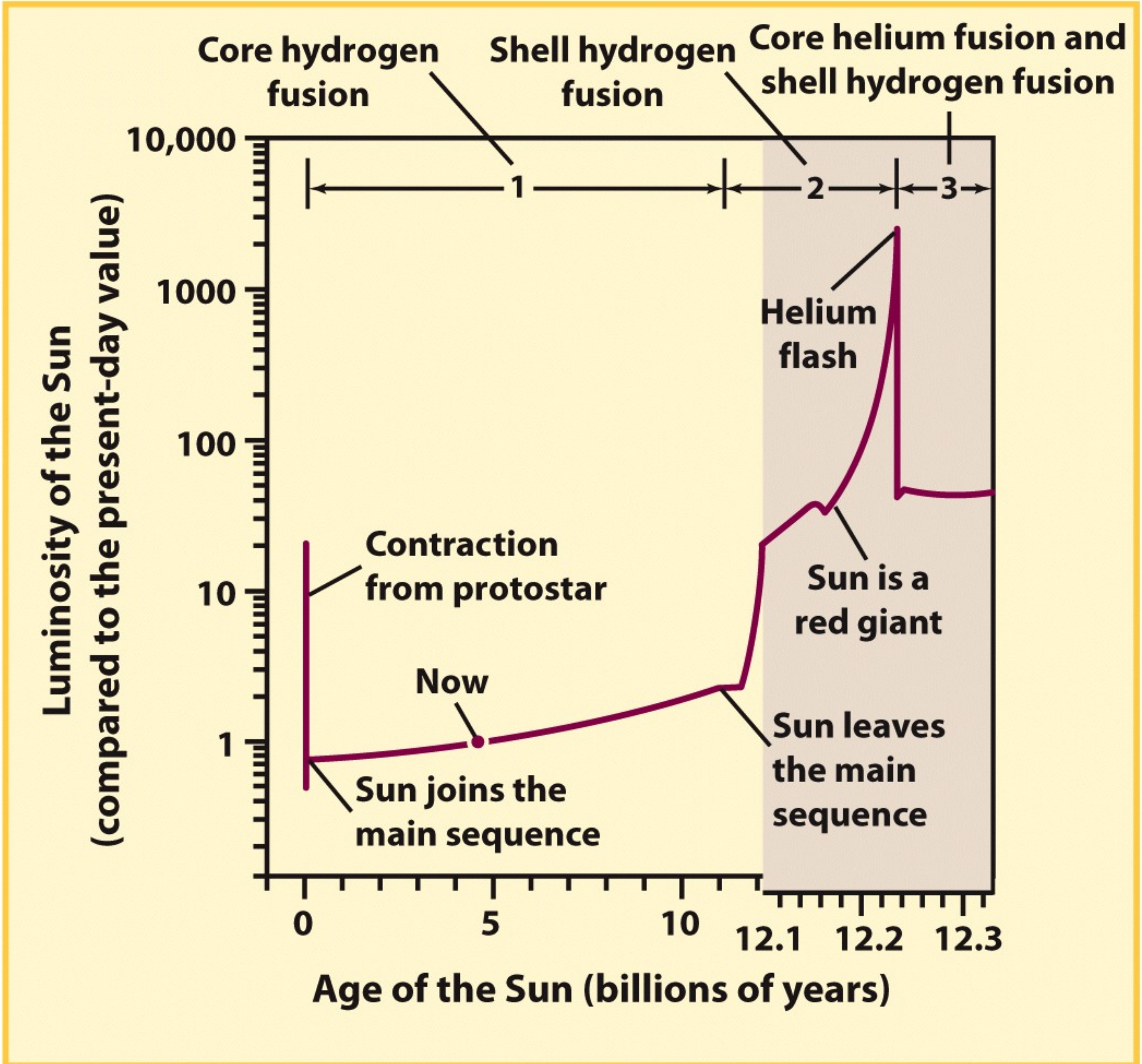


Figure 19-8
Universe, Tenth Edition

Evolution of low mass stars like Sun ($M \sim 0.1\text{-}4\ M_{sun}$)

3. **Red Giant II** (H fusion in shell, He fusion in core)
(He flash & horizontal branch)

meanwhile….

The He core continues to slowly shrink & heat up

UNTIL core gets hot enough to

fuse He -> C,O

when T(core) = 10^8 K

*ANIM 20-1- stellar evolution: structure vs. location in HR diagram

picture star as an onion, with multiple layers

in each layer:

*what are main elements? (increasingly heavier elements toward core)

*is fusing occurring?

Low mass stars never get hot enough to fuse anything heavier than He

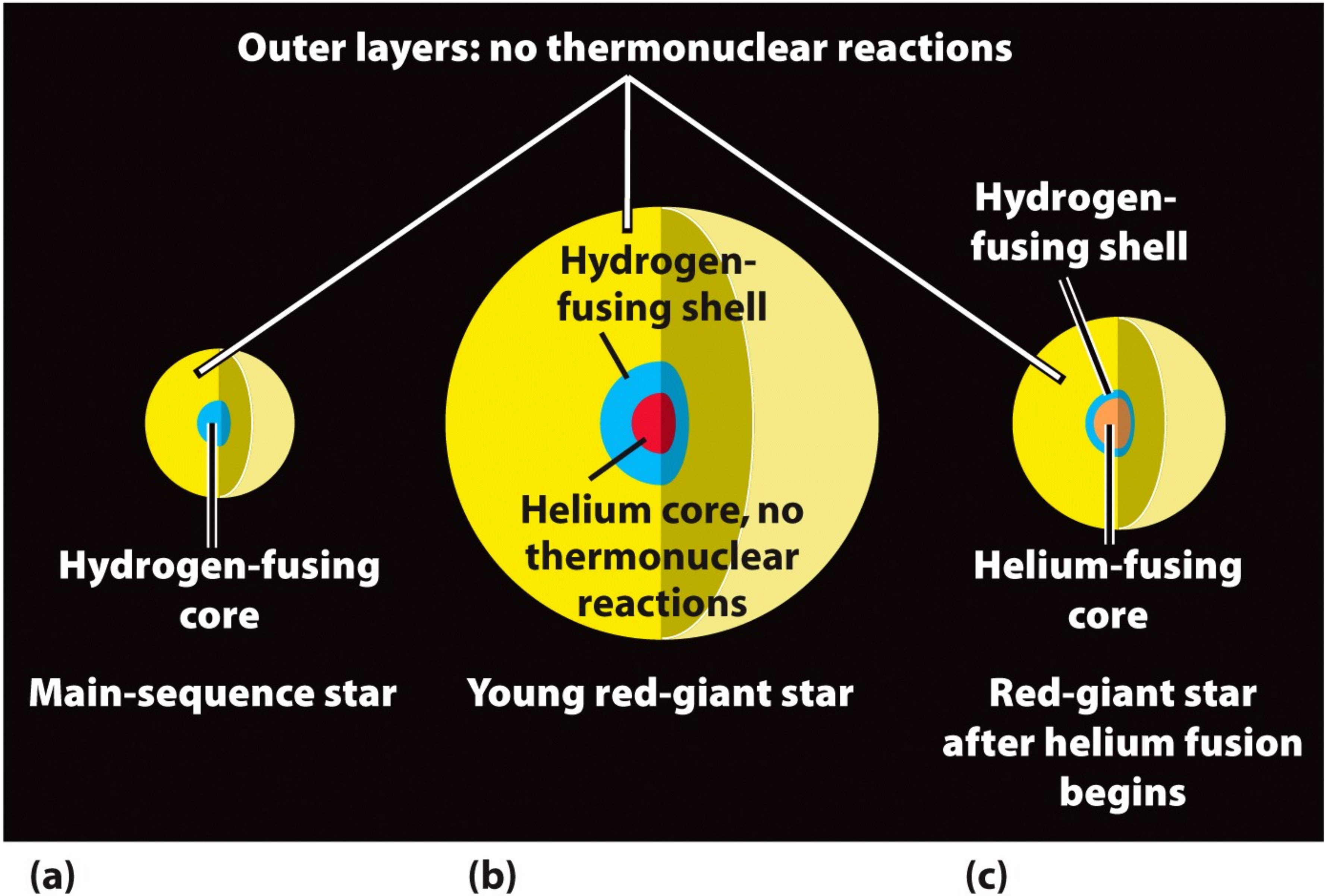


Figure 19-6
Universe, Tenth Edition

Evolution of low mass stars like Sun ($M \sim 0.1\text{-}4\ M_{sun}$)

4. Planetary Nebula/White Dwarf

eventually (after more interesting developments that you don’t need to know…)

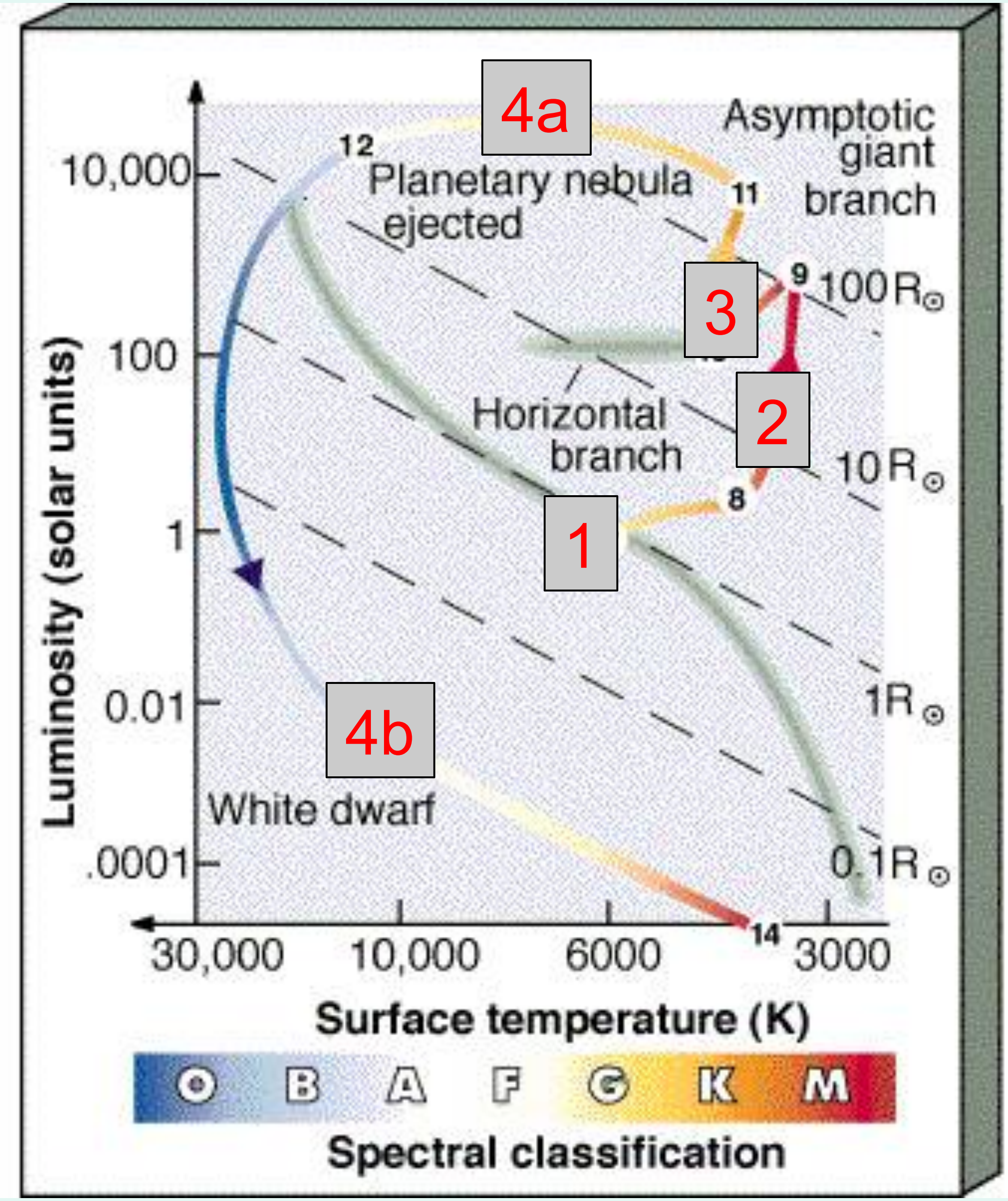
envelope/outer layers of star are ejected into space to form Planetary Nebula and core becomes white dwarf

basic idea: outer layers of star heat up so much that they expand so much that outer layers are ejected

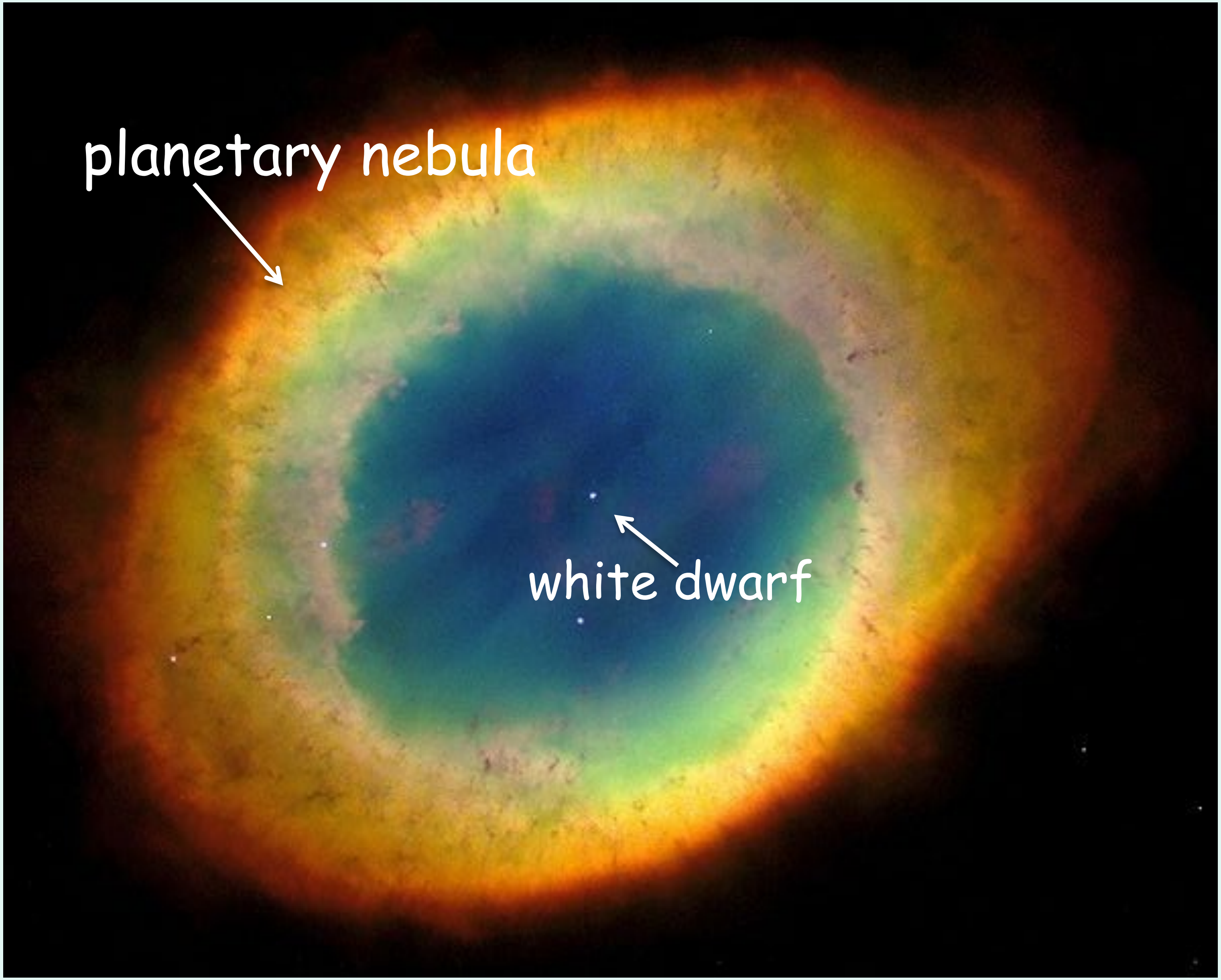
* pressure wins over gravity!

* no hydrostatic equilibrium in outer layers

Evolution of low mass stars like Sun ($M \sim 0.1\text{-}4\ M_{sun}$)

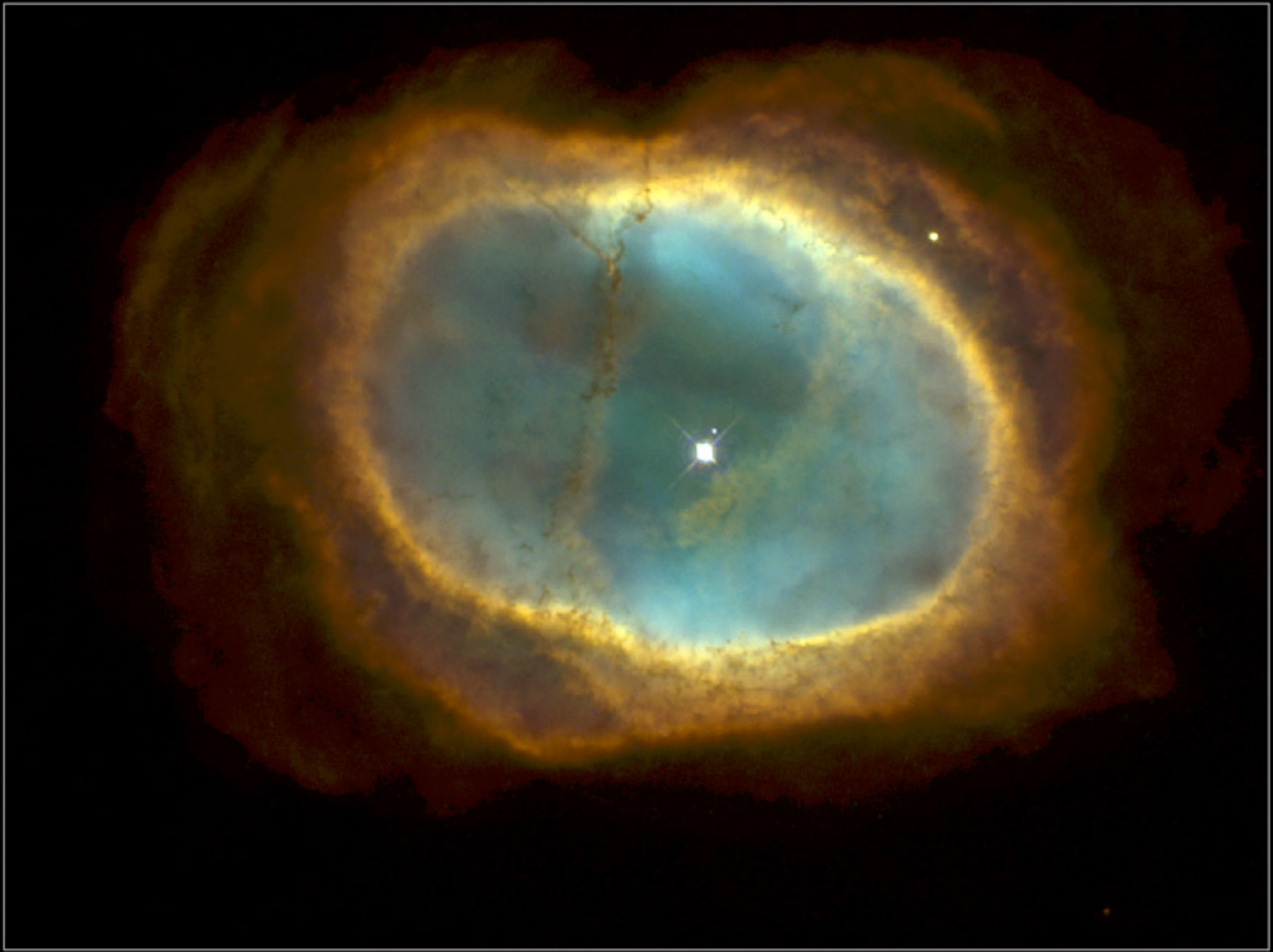


- At end of red giant phase of life, outer envelope of star ejected into space as "planetary nebula"
- Injects elements H, He, C, N, O into space – including elements C, N, O made by fusion in star's interior
- core of star becomes White dwarf star, slowly cools over time



Ring Nebula image taken with Hubble Space Telescope

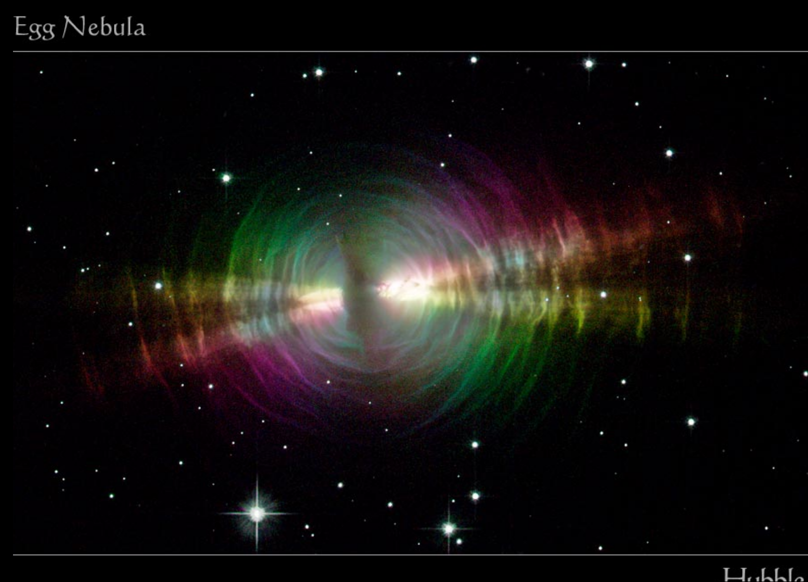
Planetary Nebula NGC 3132

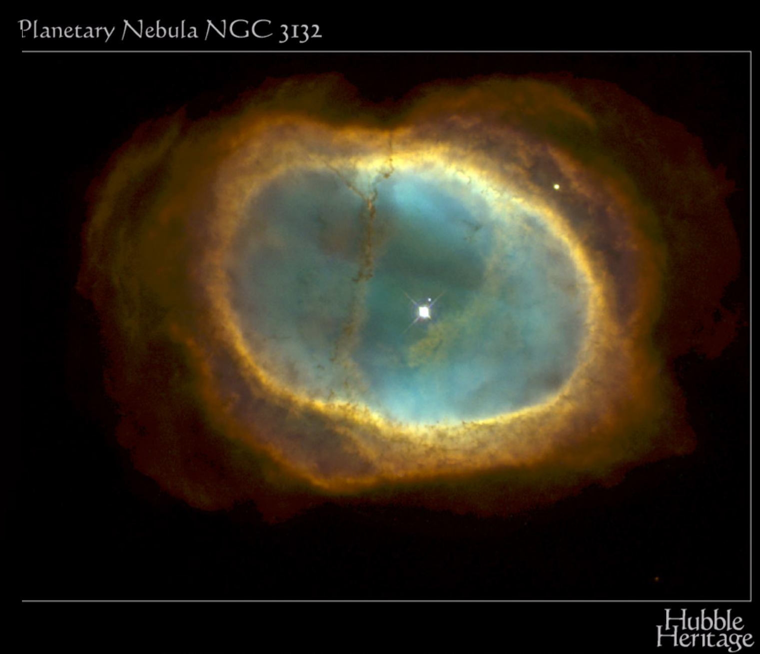


Hubble Heritage

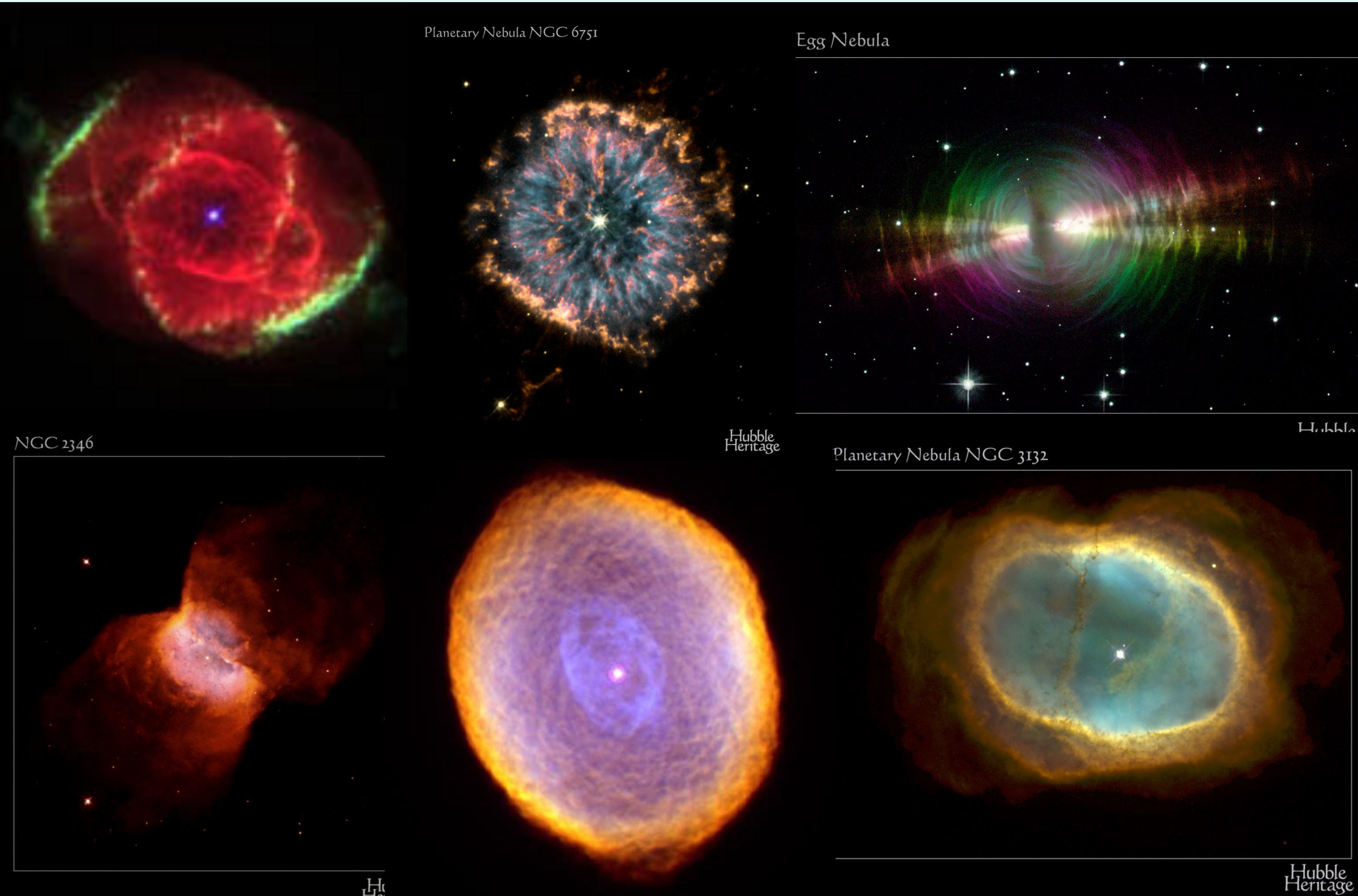
PRC98-39 • Space Telescope Science Institute • Hubble Heritage Team

Variety of Planetary Nebulae

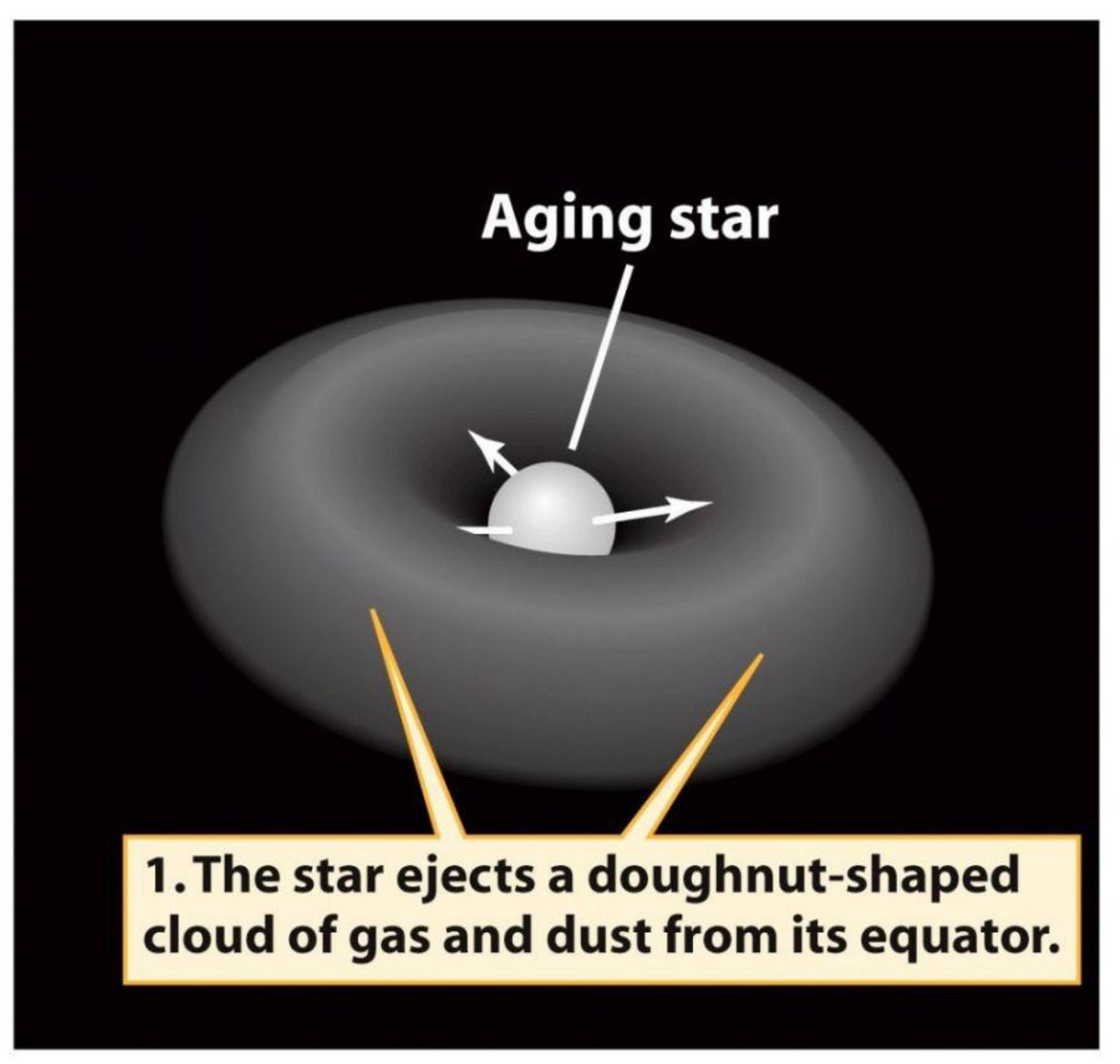


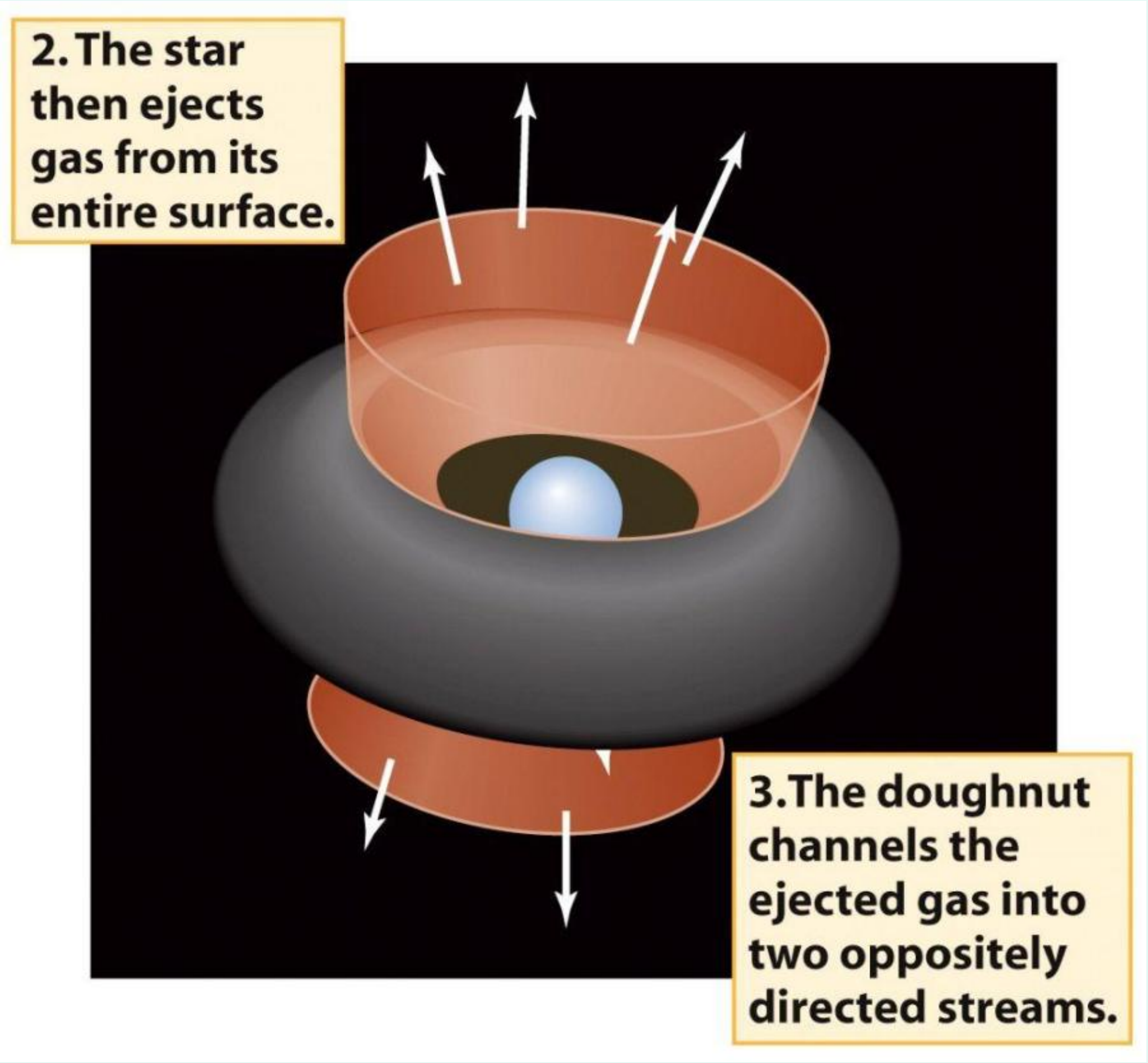


Variety of Stellar Death Nebulae

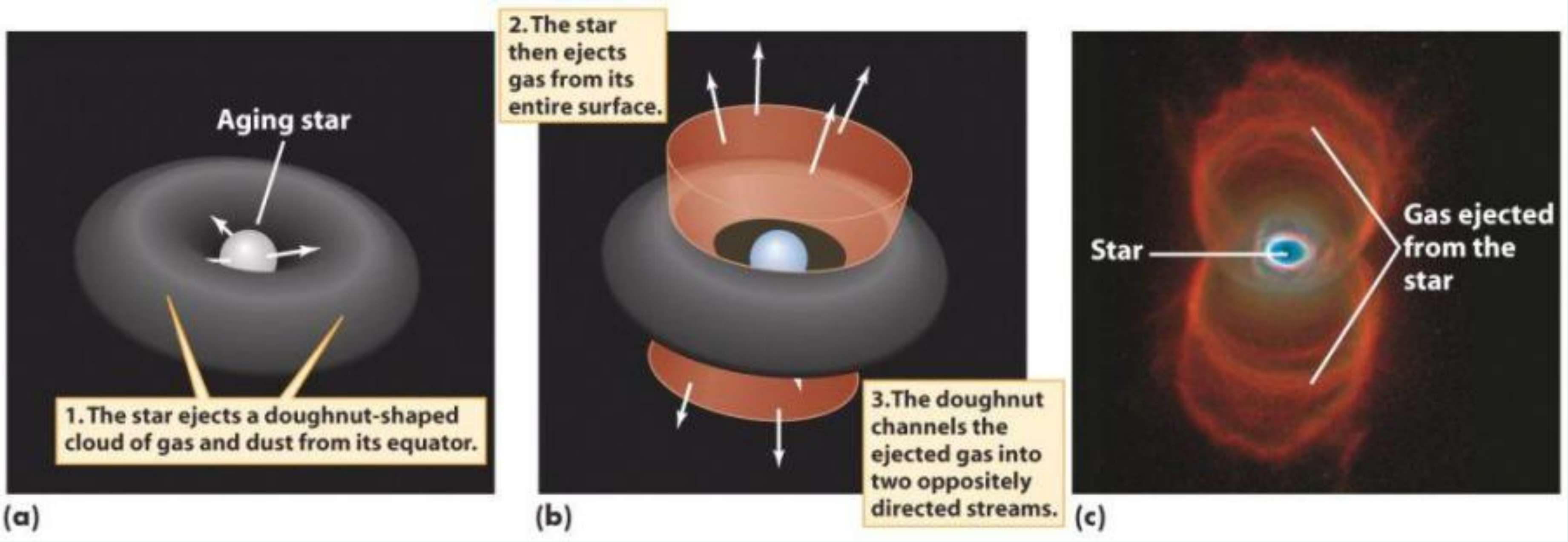


Planetary Nebula with "hourglass" shape


Aging star
1. The star ejects a doughnut-shaped cloud of gas and dust from its equator.


2. The star then ejects gas from its entire surface.
3. The doughnut channels the ejected gas into two oppositely directed streams.

Formation of planetary nebula



Evolution of massive stars ($M>10M_{sun}$)

- High mass stars are rare but play important role in galactic evolution & origin of life

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Evolution of massive stars ($M>10M_{sun}$)

- High mass stars are rare but play important role in galactic evolution & origin of life
- Because they *make new elements* (nucleosynthesis) and they *redistribute them* (SN explosions)
- They fuse

  H->He

  He-> C,O

  C,O -> Ne, Si, Mg,… eventually Fe

Why does fusion of heavier elements occur in more massive stars?

A. Cores initially contain more heavy elements

B. Cores are hotter so they have faster particles

C. Stronger gravity pulls particles together faster

D. They live longer so particles have more time to form heavier elements

E. The anti-matter weakens the electrostatic repulsion

higher temperatures are needed to fuse heavier elements

- nuclei need to get very close for attractive strong nuclear force to dominate repulsive electrostatic force

- Heavier nuclei have more protons so more electric charge hence stronger electrostatic repulsion; nuclei need to move faster in order to get close enough to fuse

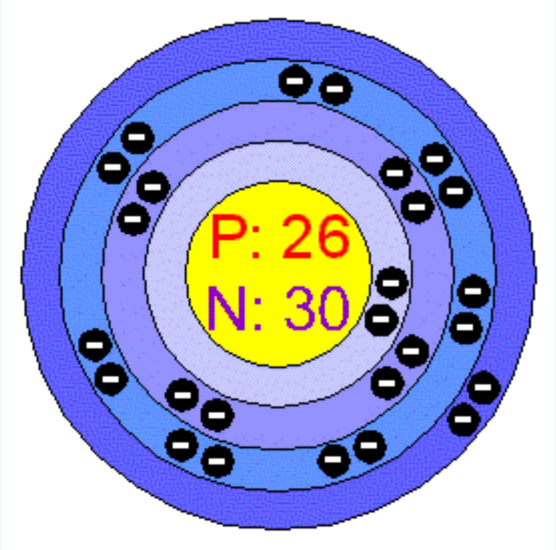
- More massive stars get higher core temperatures since higher pressures and temperatures needed to balance stronger gravity

"Iron is the ultimate slag heap of the universe."

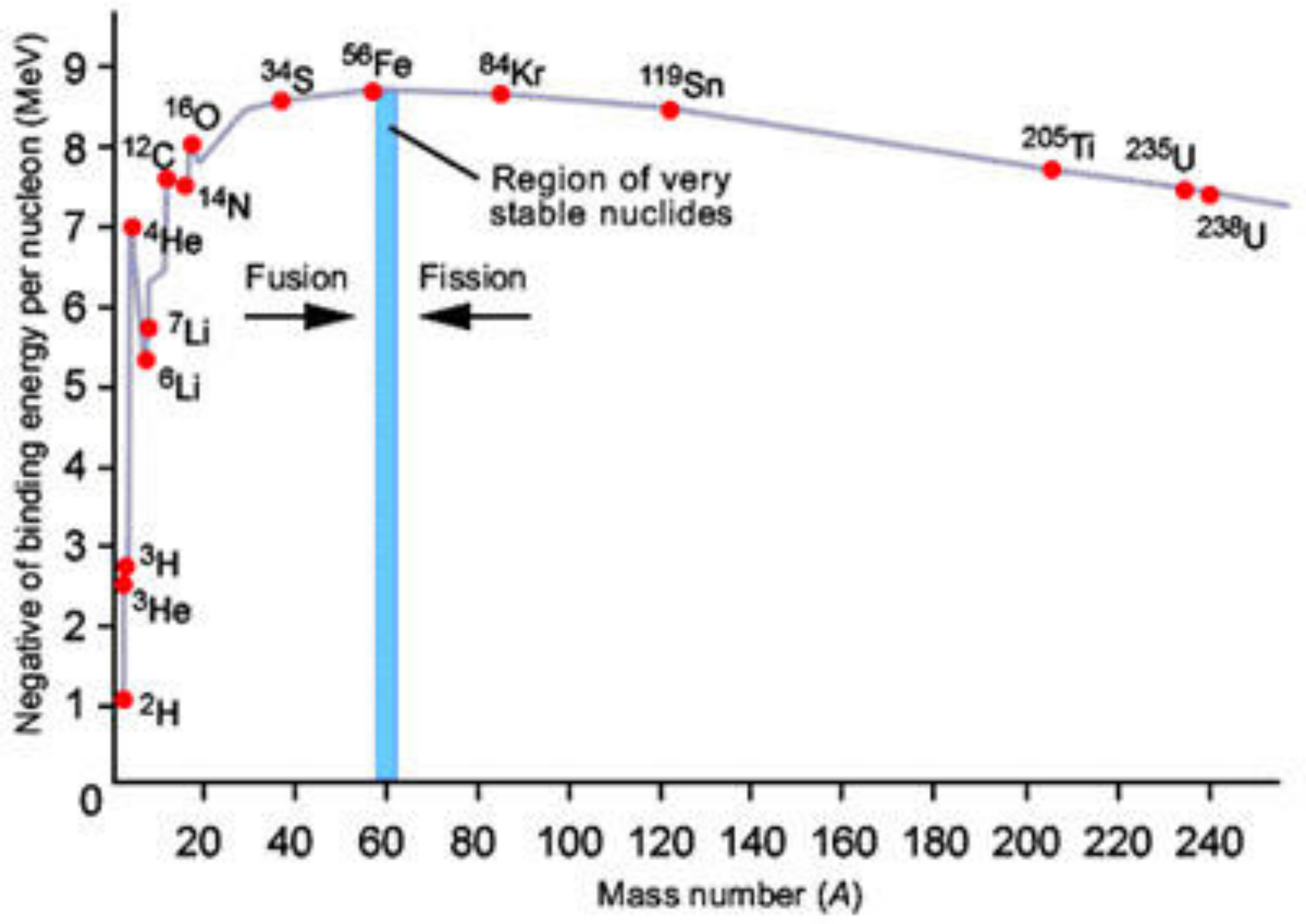
Frank Shu, real astronomer

Iron ^{56}Fe 26 protons, 30 neutrons

- The most strongly bound nucleus!
- Nuclear reactions involving Fe *require energy* rather than *release energy*



Iron is the most tightly bound nucleus



For elements **lighter than** Fe:

Elem 1 + Elem 2 → (bigger) Elem 3 + energy

Lighter than Fe | Lighter than Fe | Lighter than Fe

Energy released by fusion!

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Elem 1 + Elem 2 → (bigger) Elem 3 + energy

Lighter than Fe | Lighter than Fe | Lighter than Fe

Energy released by fusion!

e.g, $^{1}H + ^{2}H \longrightarrow ^{3}He + \gamma$

For elements **lighter than** Fe:

Elem 1 + Elem 2 → (bigger) Elem 3 **+ energy**

Lighter than Fe | Lighter than Fe | Lighter than Fe

Energy released by fusion!

For elements **heavier than** Fe:

Elem 4 + Elem 5 **+energy** → (bigger) Elem 6

Fe or heavier | anything

Energy *required for* fusion!

Once core turns into iron … *disaster!!*

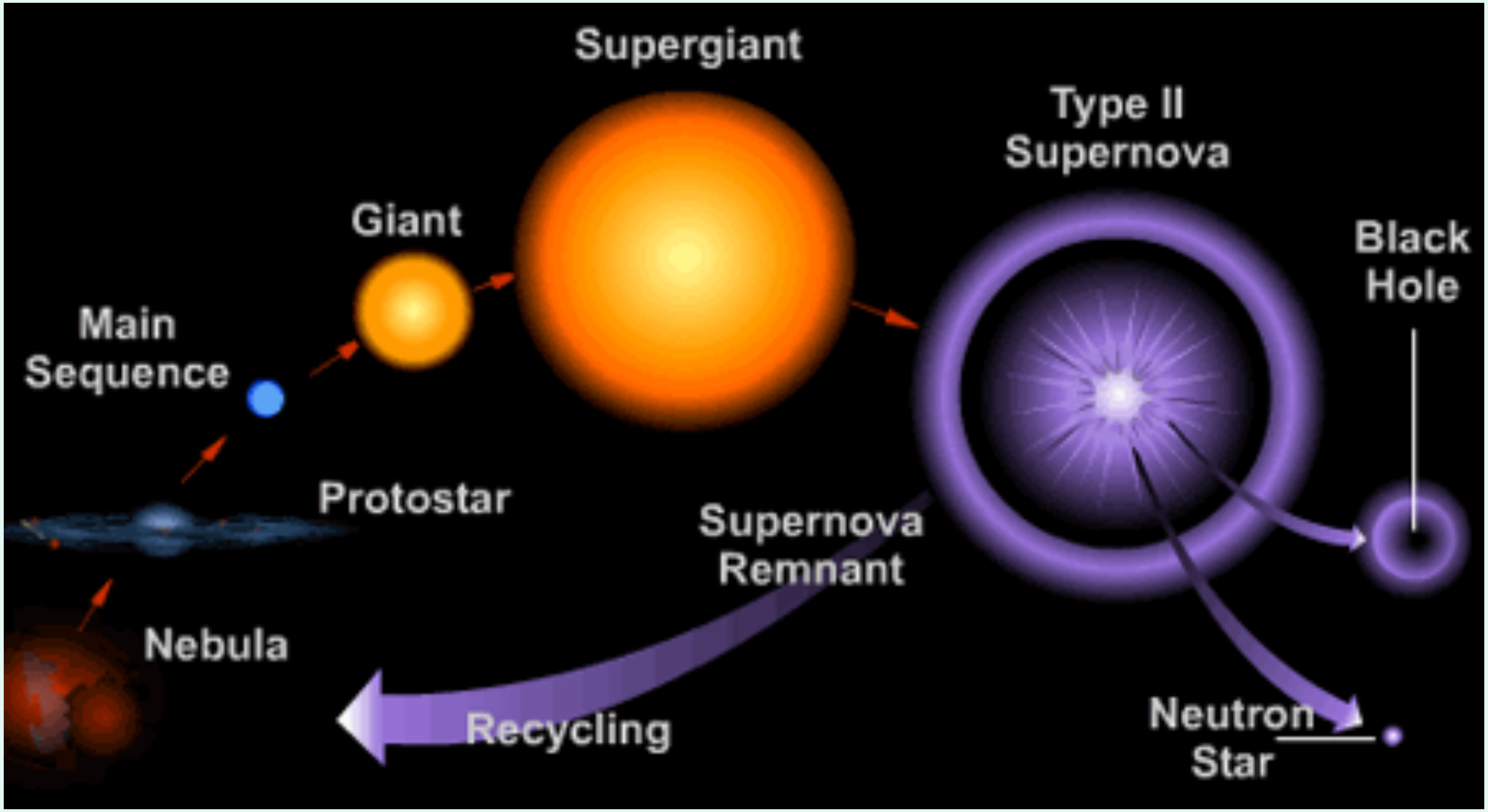
There is no more heat generated to support core of star against weight of overlying material

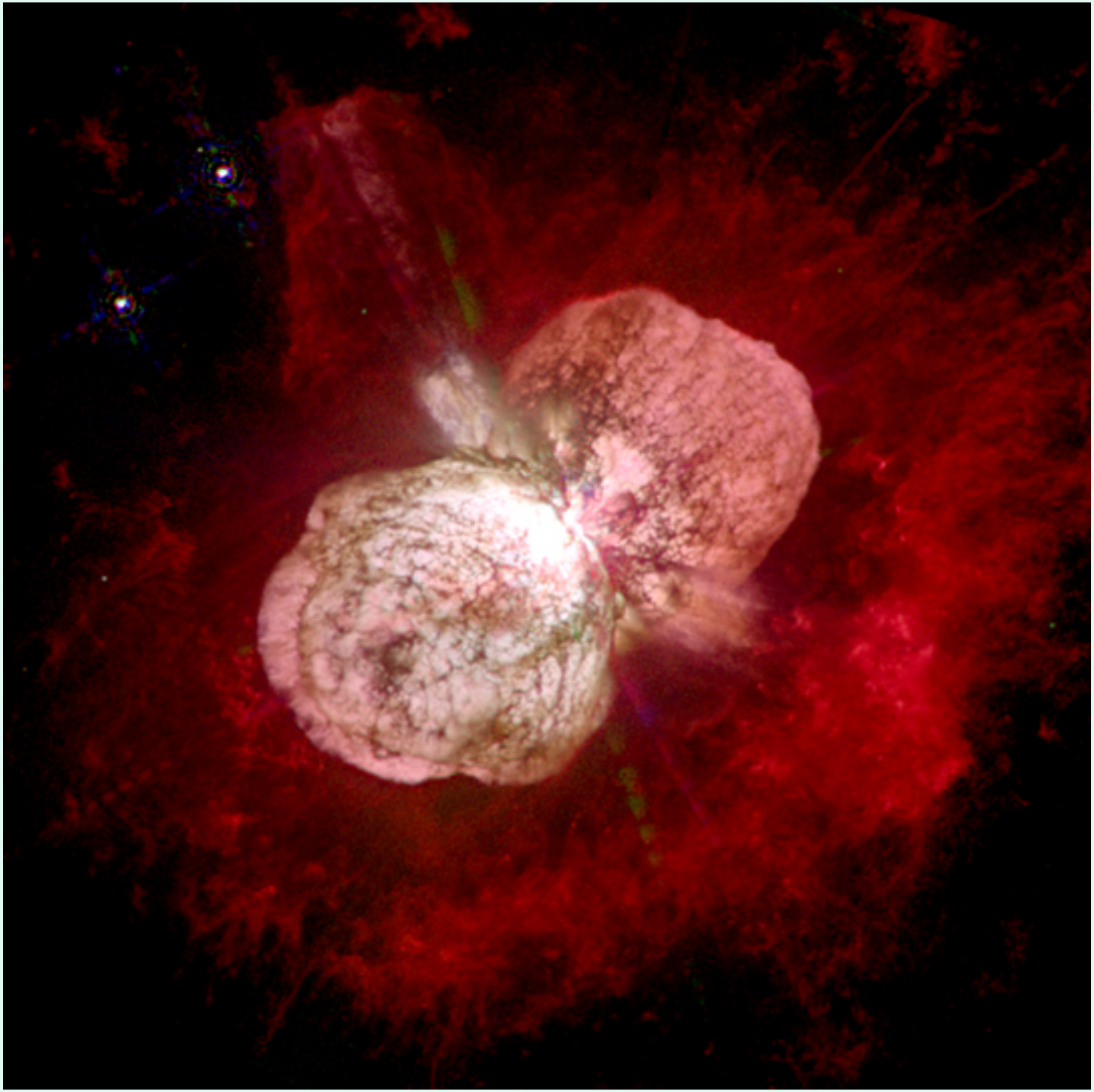
core collapses & star explodes in a Type II supernova

outer layers of star violently ejected into space

(carrying with it the elements heavier than He created during stellar evolution and the SN explosion)

Massive stars ($M > 8M_{sun}$) explode as Type II Supernovae

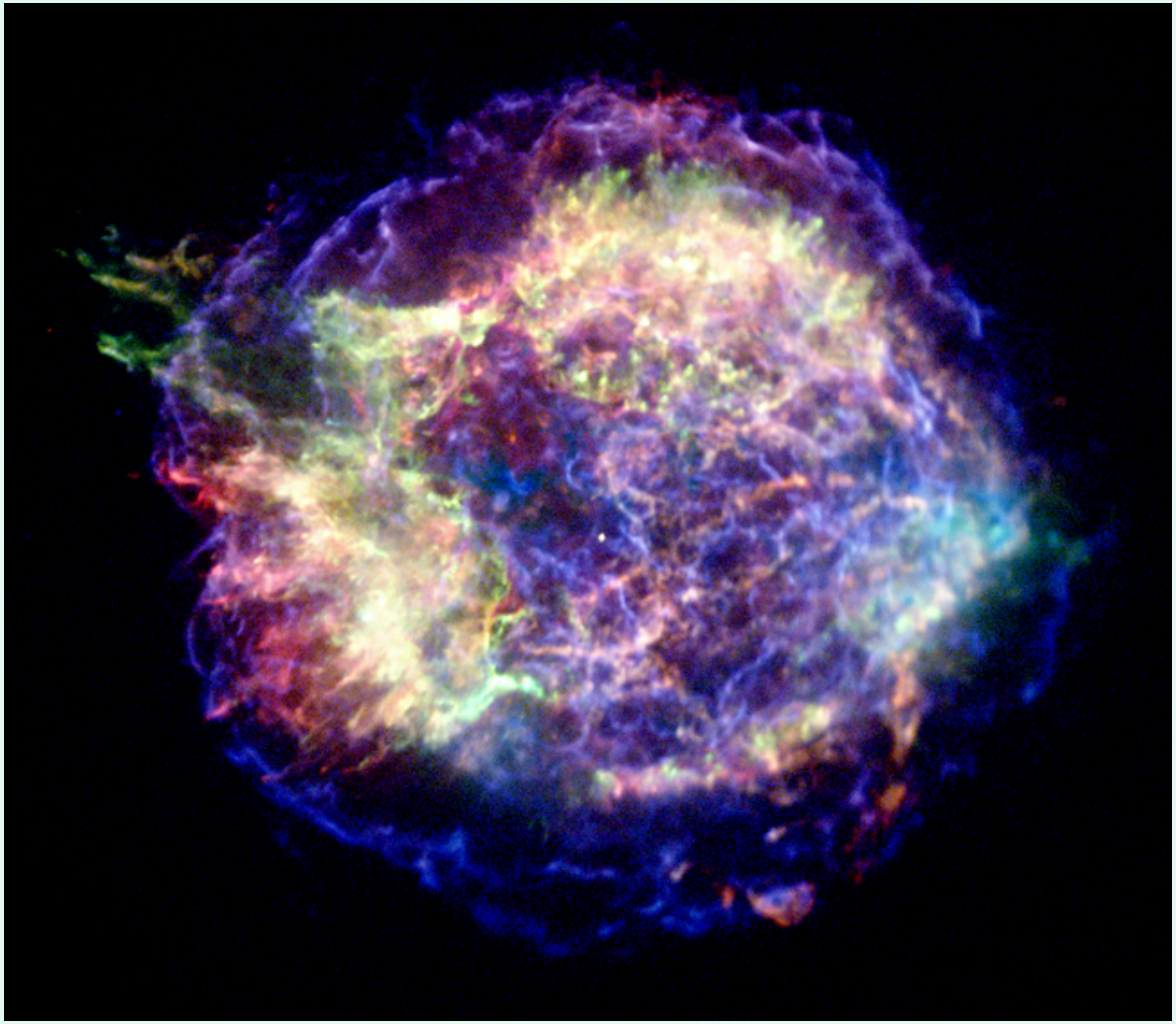




Eta Carina

Massive star ($\sim$100 M_{sun}) ejecting outer layers into space (before supernova stage)

Cassiopeia A Supernova Remnant from Type II supernova in 1680 A.D.



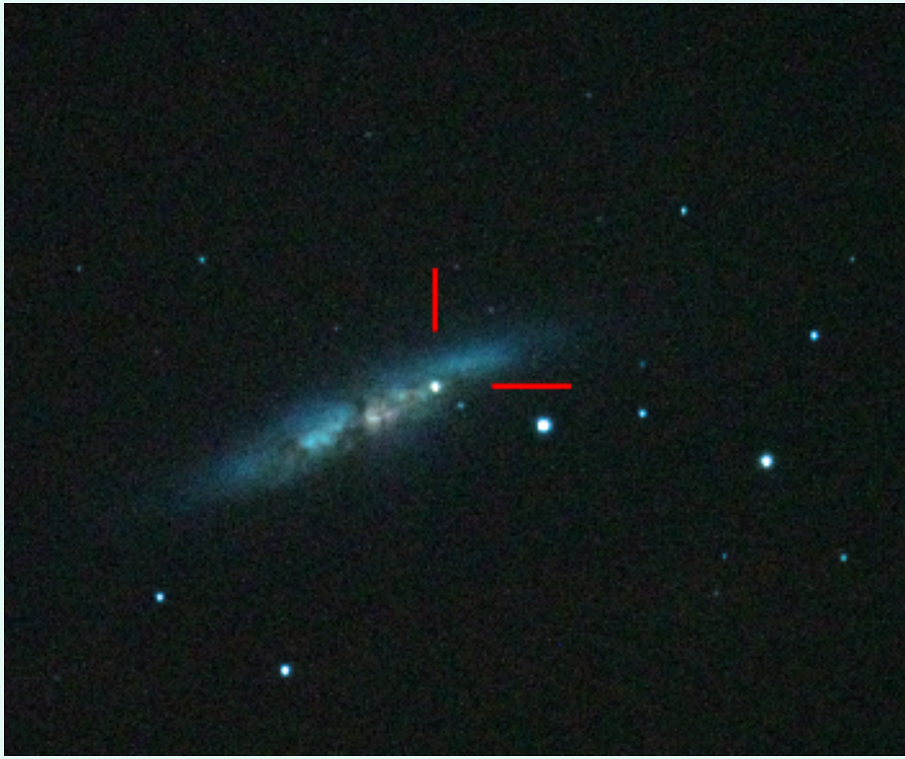
X-Ray image from Chandra telescope

Red & Yellow: low energy x-rays from debris of star

Blue: high energy x-rays from blast wave – high energy electrons

Nearby Supernova in Galaxy M82!!

The closest supernova in 27 years



M82 with supernova
January 28, 2014

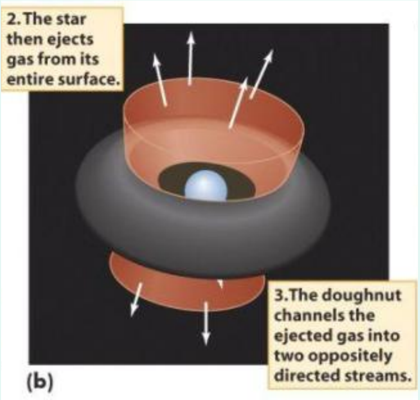
M82 before supernova
December 2013

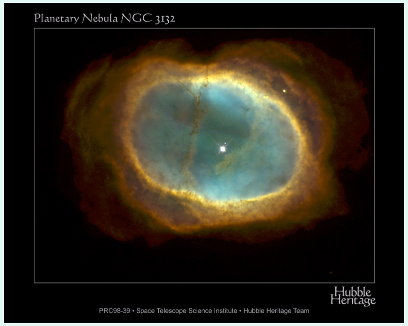
images taken at Leitner Family Observatory
(Yale's student & public observatory)

- elements…

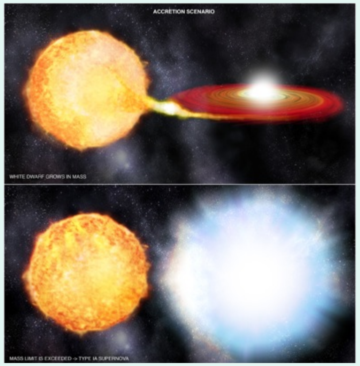
Recycling by stars back into space

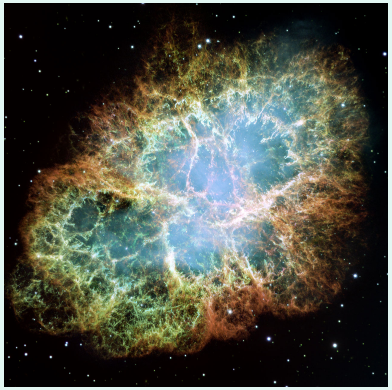
Low mass stars:
Planetary nebulae



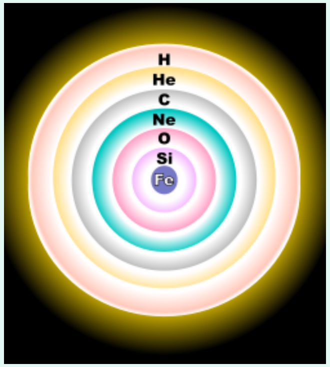


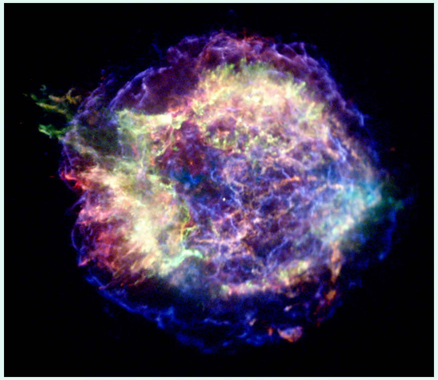
Medium mass stars in binaries:
Type Ia Supernovae





High mass stars:
Type II Supernovae
(& merging NS explosions)





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Elem 1 + Elem 2 → (bigger) Elem 3 + energy

Lighter than Fe | Lighter than Fe | Lighter than Fe

Energy released by fusion!

For elements **heavier than** Fe:

Elem 4 + Elem 5 +energy → (bigger) Elem 6

Fe or heavier | anything

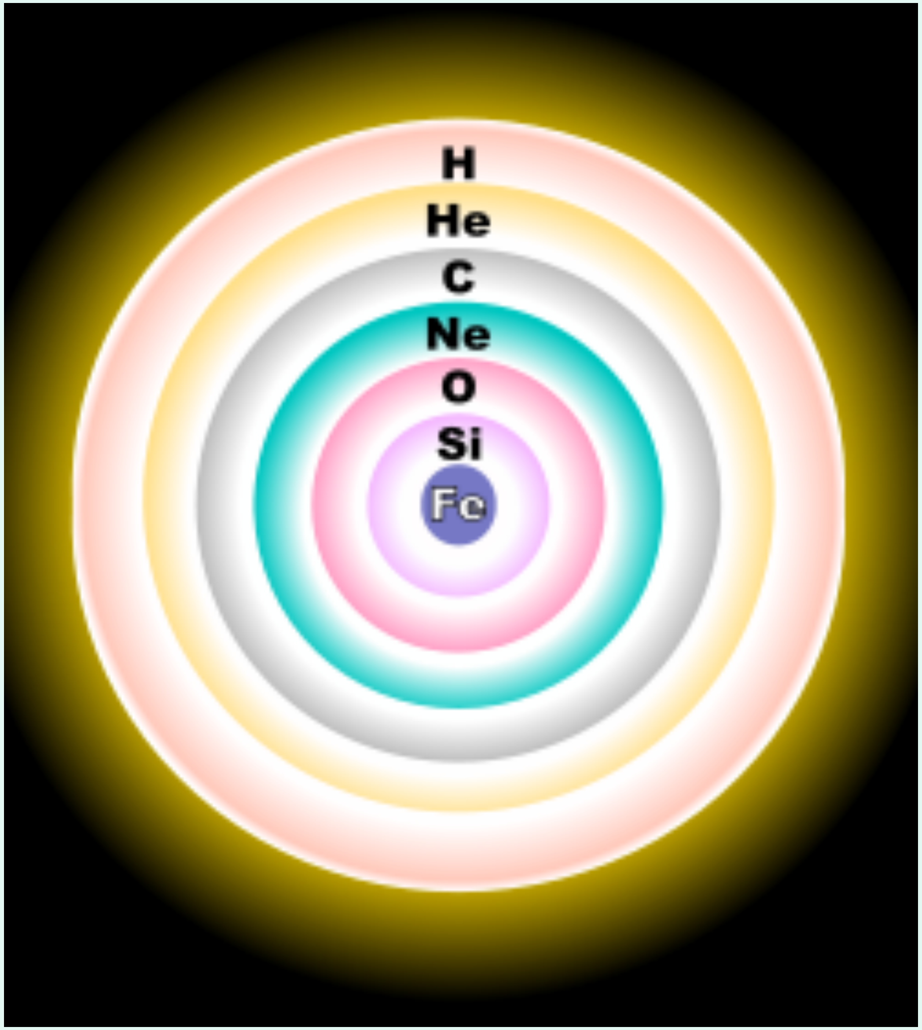
Energy *required for* fusion!

Elem 7 (+n) → (smaller) Elem 8 + Elem 9 +energy

Much heavier than Fe (e.g. ^{92}U)

Energy released by fission!

Structure of massive star before Type II Supernova explosion



- "α-elements" (O, Ne, Mg, Si, S, Ar, Ca and Ti) made by adding He (α particle) to C, O, etc; happens mostly in $M>10M_{sun}$ stars which return elements to space thru Type II SN

- Fe and other heavier elements made in core of star *during normal stellar evolution* get locked into neutron star or black hole core

For elements **lighter than** Fe:

Elem 1 + Elem 2 → (bigger) Elem 3 + energy

Lighter than Fe | Lighter than Fe | Lighter than Fe

Happens in stars! Energy released by fusion!

For elements **heavier than** Fe:

Elem 4 + Elem 5 +energy → (bigger) Elem 6

Fe or heavier | anything

Happens in supernovae & merging neutron stars! Energy *required for* fusion!

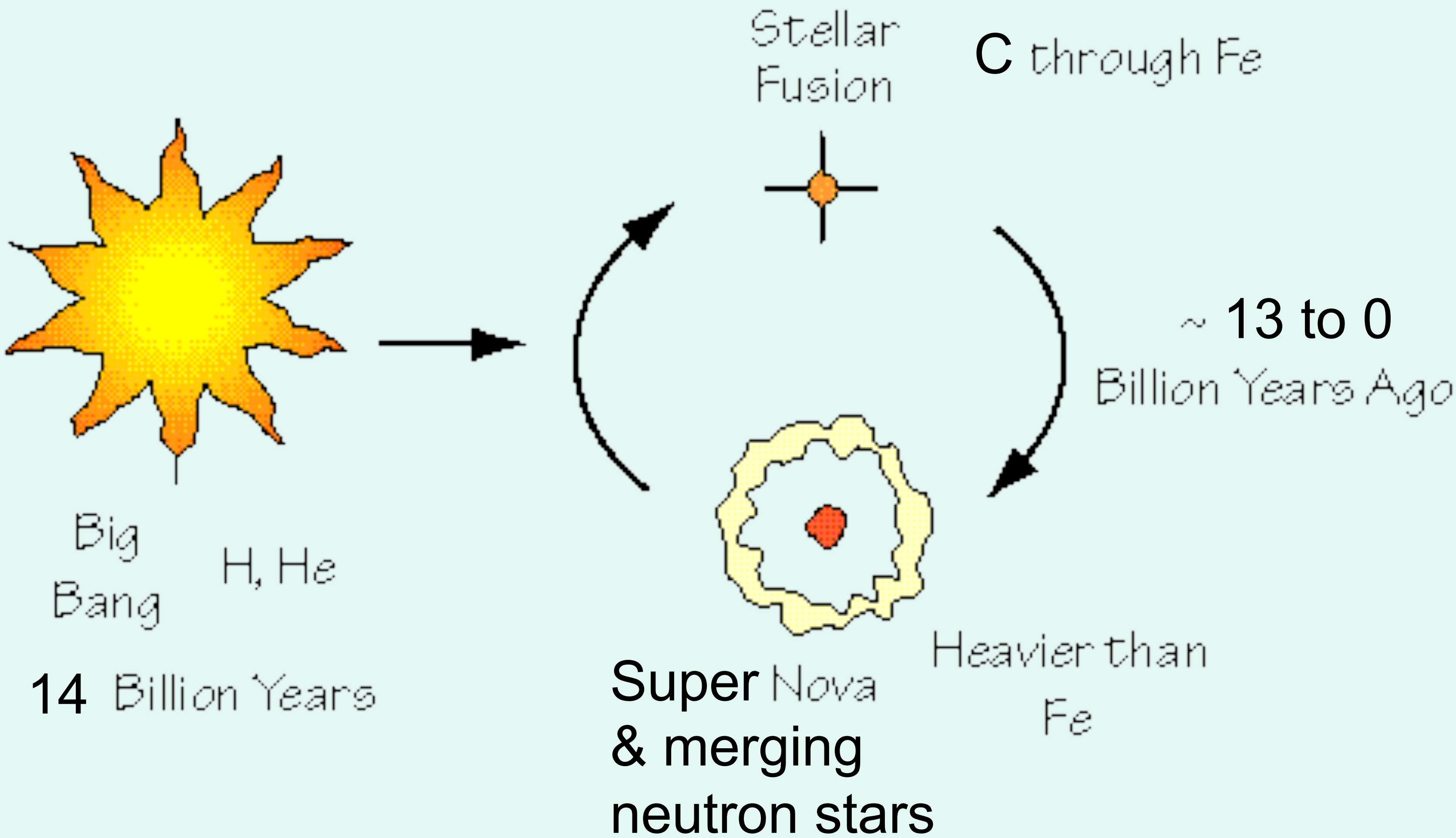
Elem 7 (+n) → (smaller) Elem 8 + Elem 9 +energy

Much heavier than Fe (e.g. ^{92}U)

Energy released by fission!

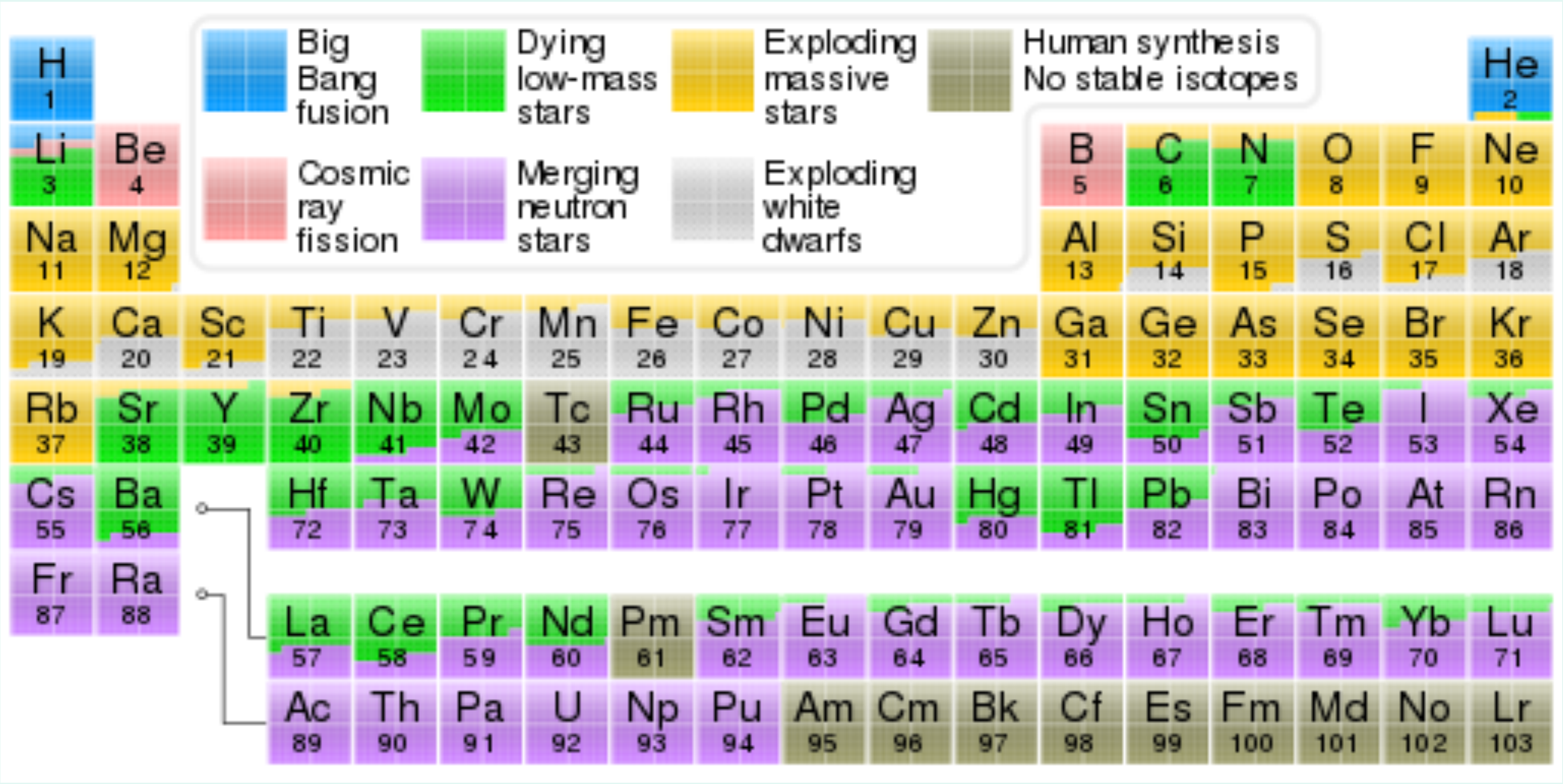
Doesn't Happen (much) in stars!

Formation of the elements in the universe
(oversimplified…)



nucleosynthesis periodic table

where are the elements made?



Where are elements made?

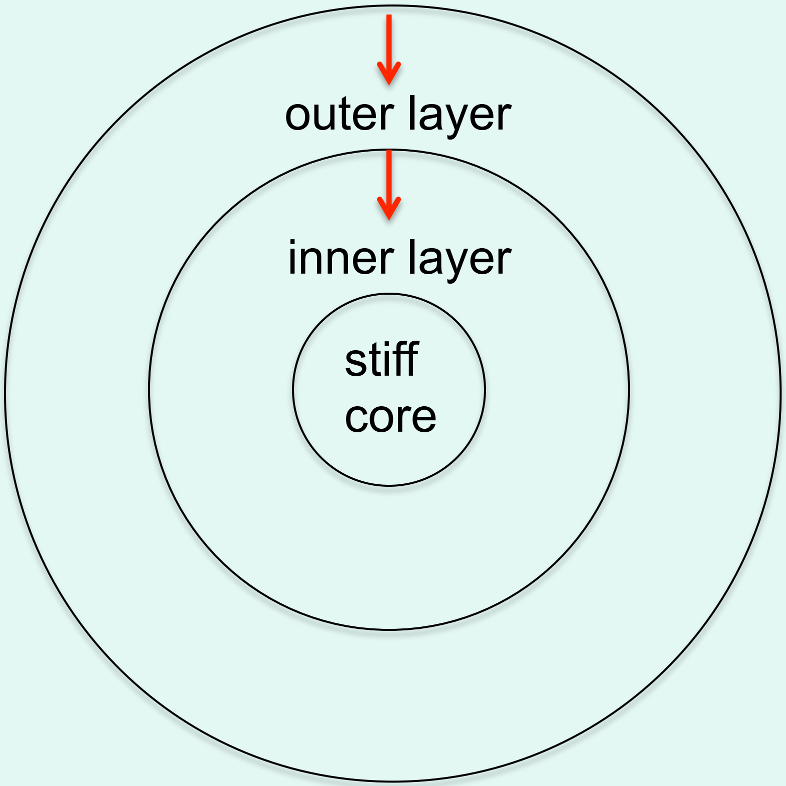
- BIG BANG made most of H, He
  (elements 1-2 in periodic table)

- STARS (stellar nucleosynthesis) make most of C,N,O,Si,Mg-> Fe
  (elements 6-26 in periodic table)

- SUPERNOVAE & MERGING NEUTRON STAR EXPLOSIONS (explosive nucleosynthesis) make most elements heavier than Fe (e.g. Ag, Au, Pt, Pb, U) (elements 27-100+ in periodic table) wait … I thought stars made a lot of helium…

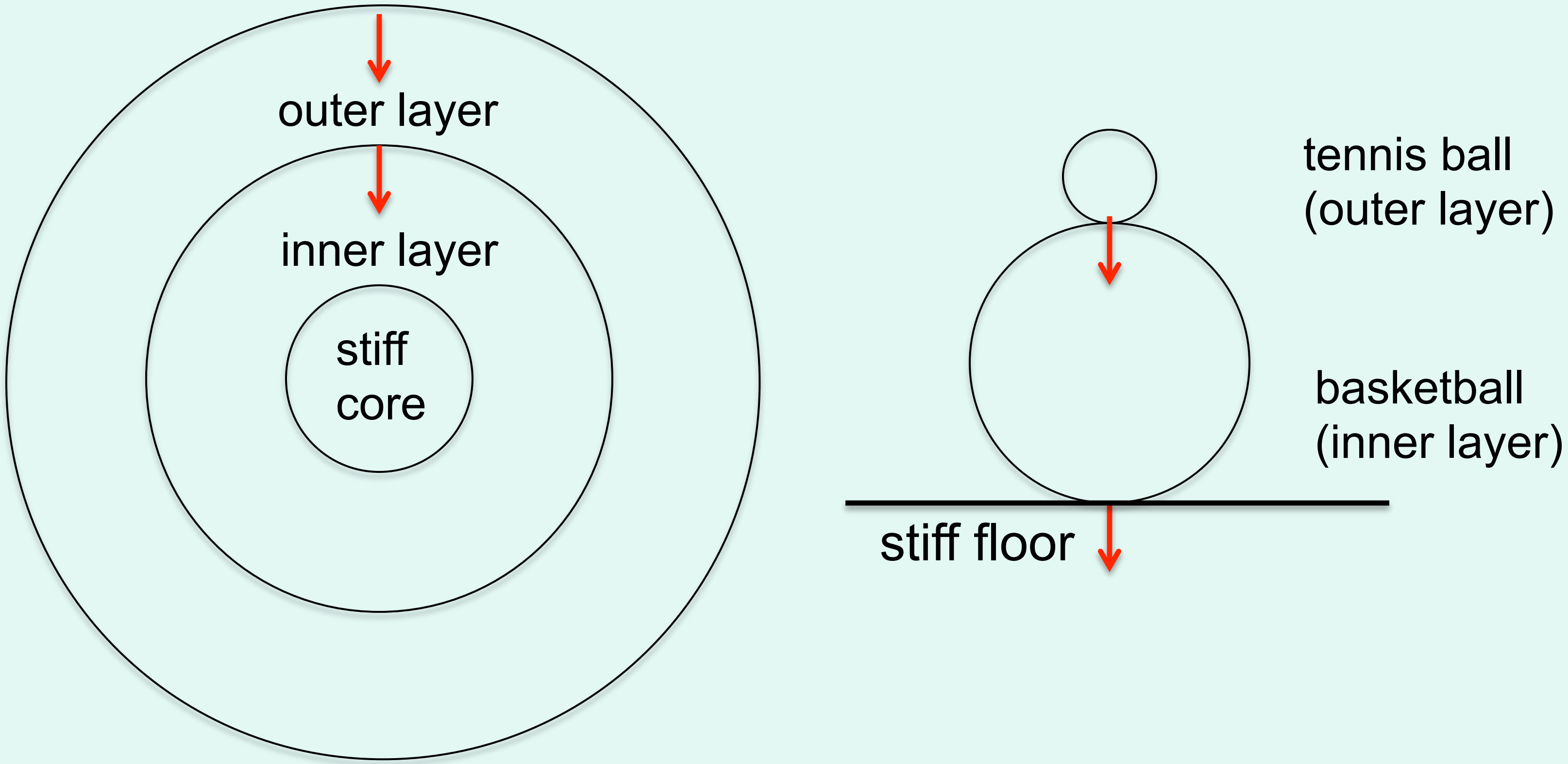
Q: Why does collapse of star lead to SN explosion? (Why does stuff going IN lead to stuff going OUT?)

why supernova explosion happens…



massive star during core collapse,
just before SN explosion

why supernova explosion happens…



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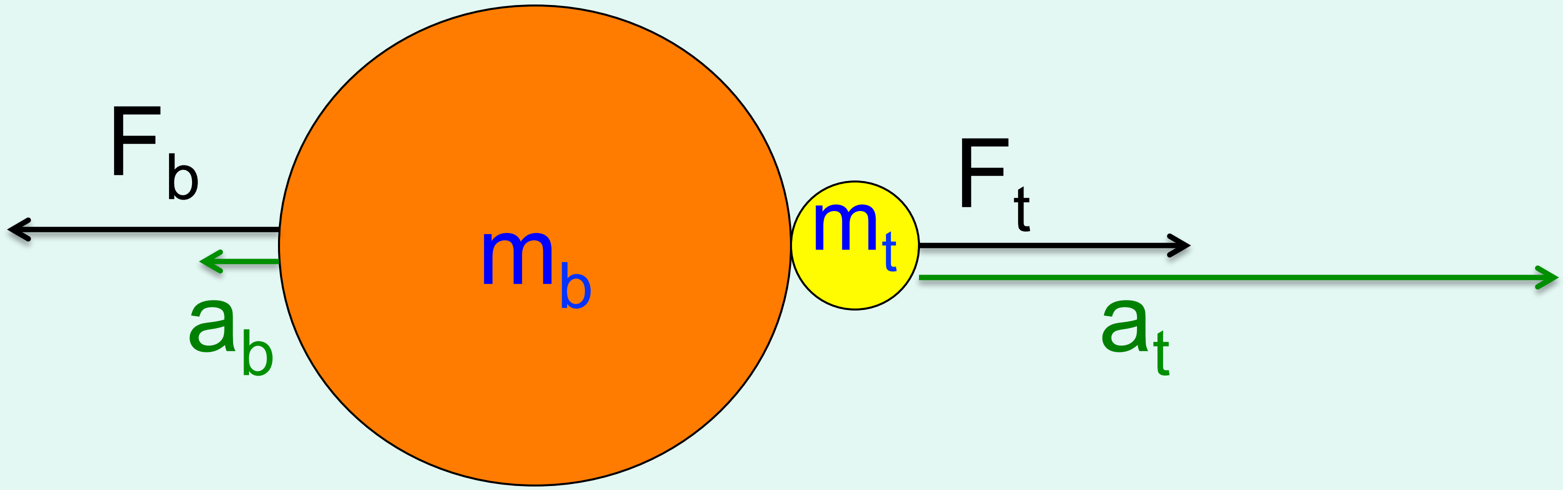


$F_b = m_b a_b$ (N2)

$F_t = m_t a_t$ (N2)

$F_t = F_b$ (N3)

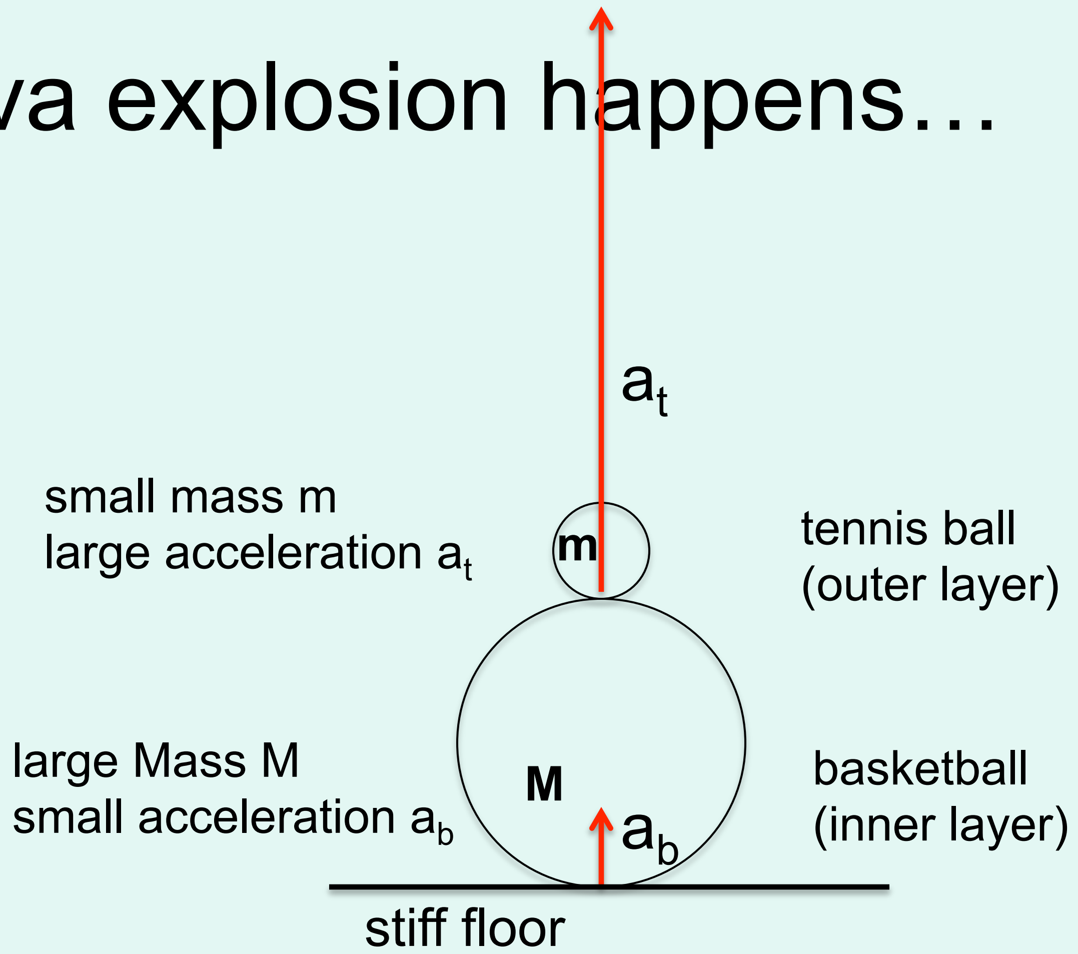
$m_t a_t = m_b a_b$

$a_t = (m_b/m_t)\ a_b$

if $m_b = 10\ m_t$

then $a_t = 10\ a_b$

why supernova explosion happens…



massive star during SN explosion

Types of stellar corpses (1)

for $M < 4M_{sun}$:

Outer parts ejected gently as Planetary Nebula

Core becomes white dwarf:

- $M_{WD} < 1\ M_{sun}$,
- $R_{WD} \sim 1\ R_{earth} \sim 10^4$ km
- WD supported by

  electron degeneracy pressure
- WD made of fully ionized nuclei of regular elements (mostly C,O) + free electrons (e-)

Types of stellar corpses (2)

For $4M_{sun} < M < 10M_{sun}$:

Outer parts ejected violently as Supernova

Core becomes neutron star:

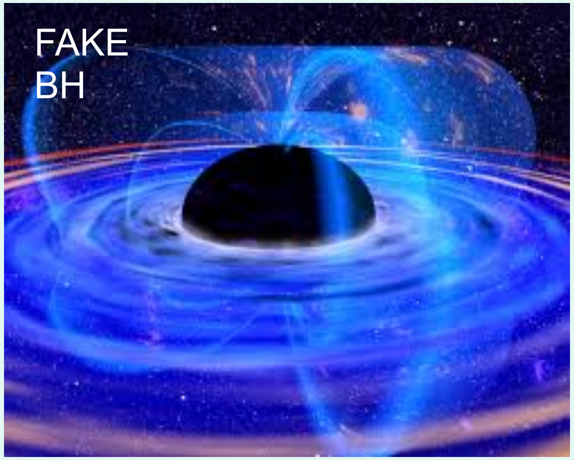
- $M_{NS} = 1.4\ M_{sun}$,
- $R_{NS} \sim 1\ R_{NewHaven} \sim 10$ km
- NS supported by

  neutron degeneracy pressure
- NS made of just neutrons! No elements! No nuclei! No electrons!

Types of stellar corpses (3)

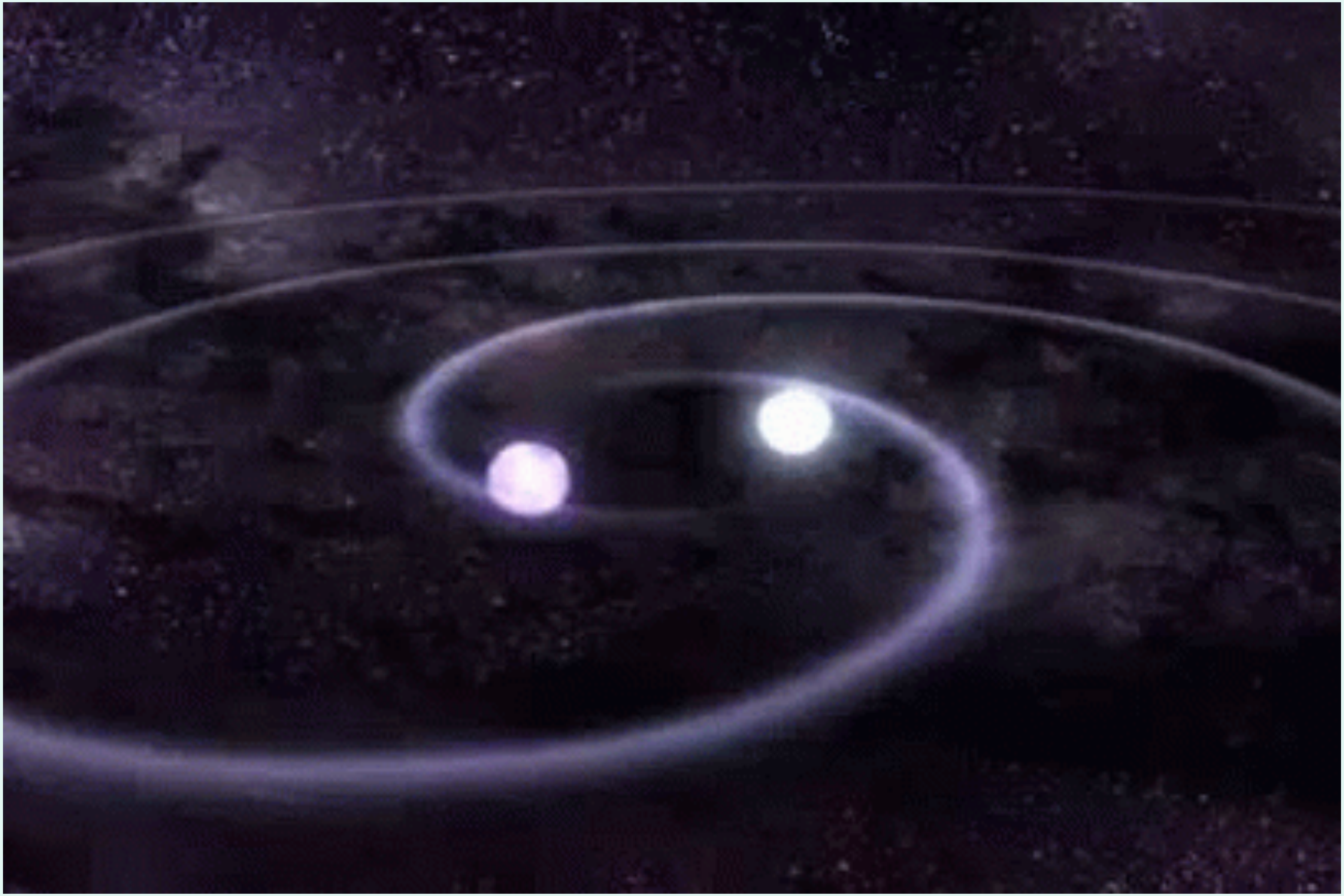
For $M > 10M_{sun}$

Outer parts ejected violently as Supernova



Core becomes black hole:

- $M_{BH} > 3\ M_{sun}$,
- $R_{BH} = R_{Schwarzschild} = 2GM/c^2$
  (R_{BH}=9 km for $M=3M_{sun}$)
- Nothing strong enough to balance gravity! Gravity finally wins!
- Black Hole made of …?



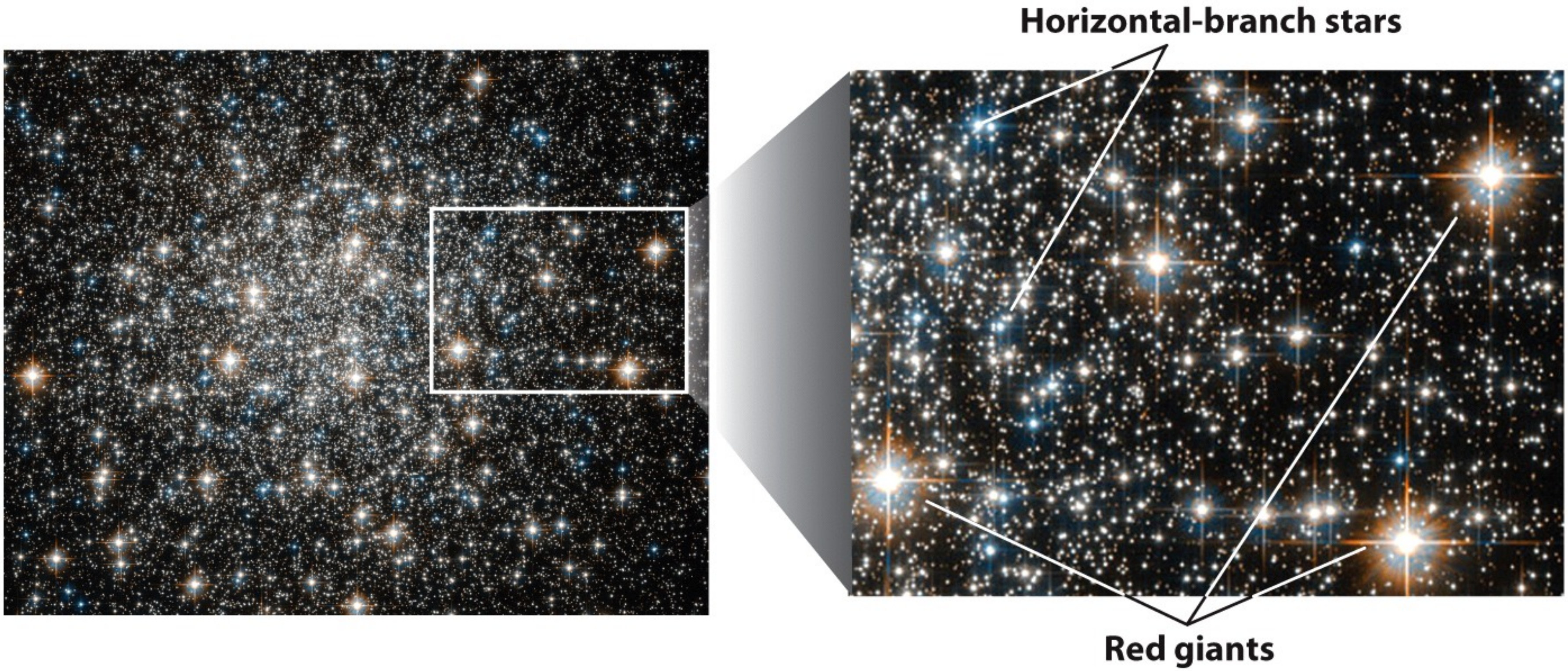
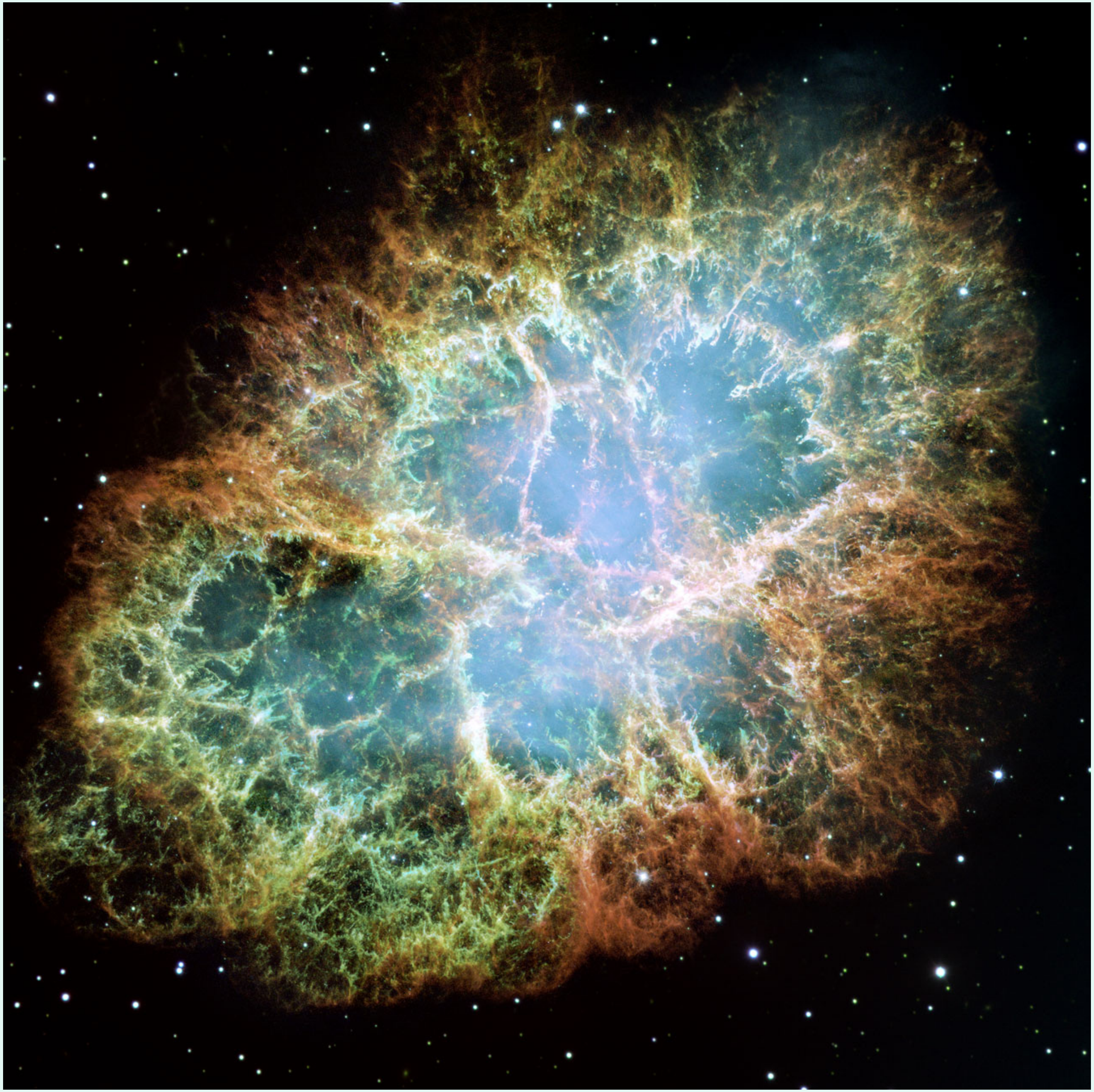
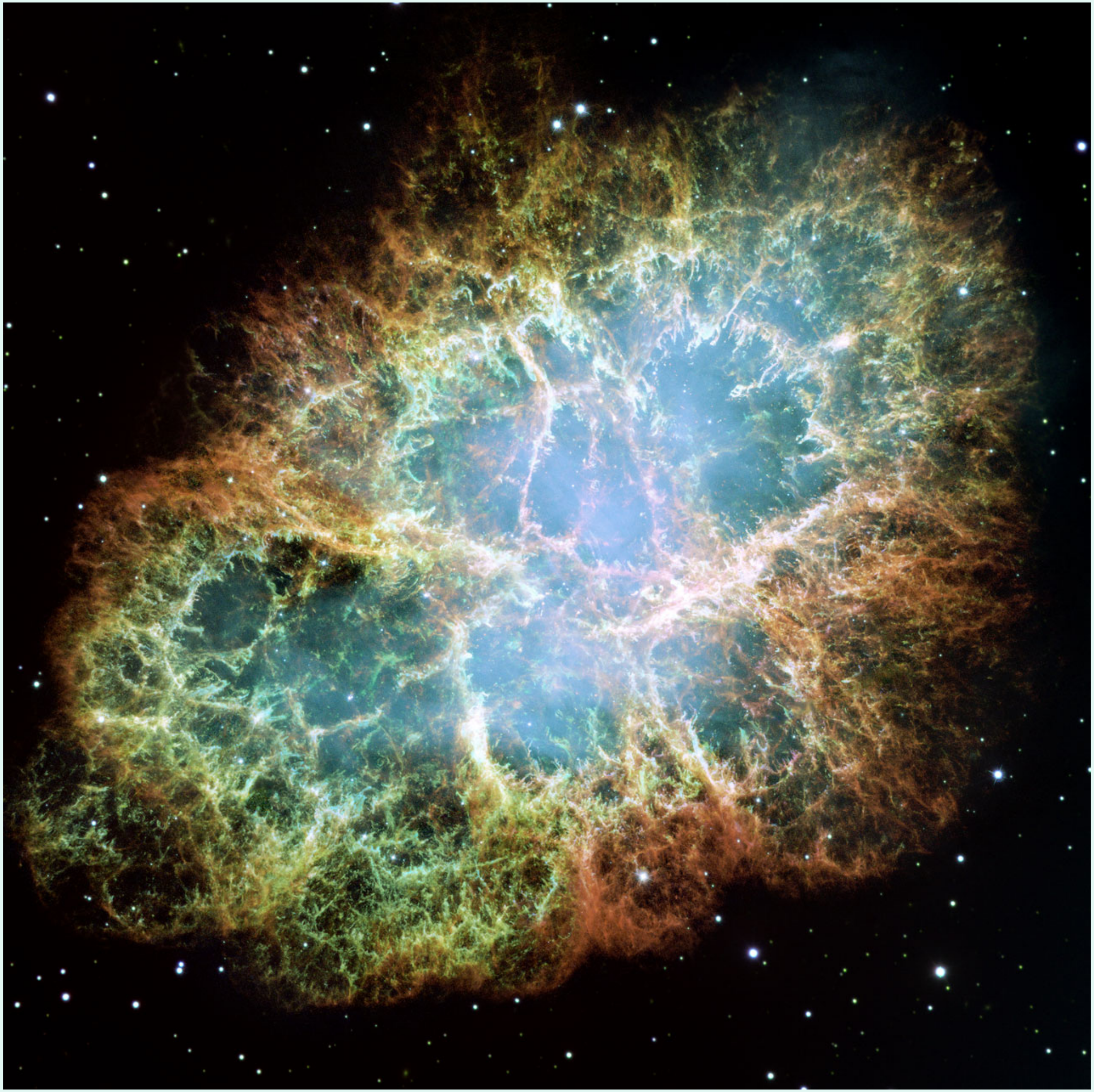


Figure 19-12
Universe, Tenth Edition
ESA/Hubble & NASA

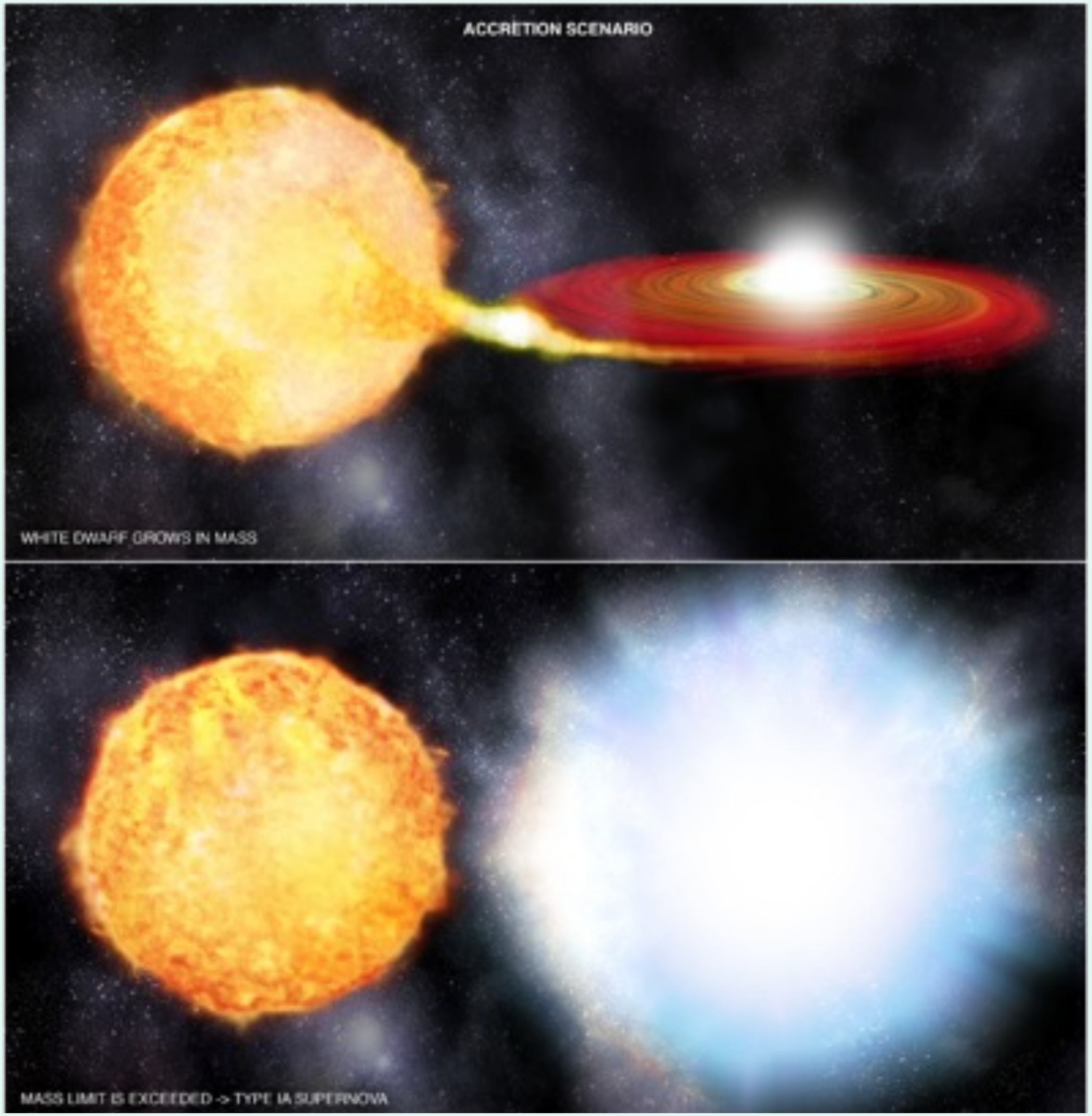


Crab Nebula produced by supernova explosion in 1054 AD



Crab Nebula Supernova Remnant

produced by Type Ia supernova explosion in 1054 A.D.



Type Ia Supernova

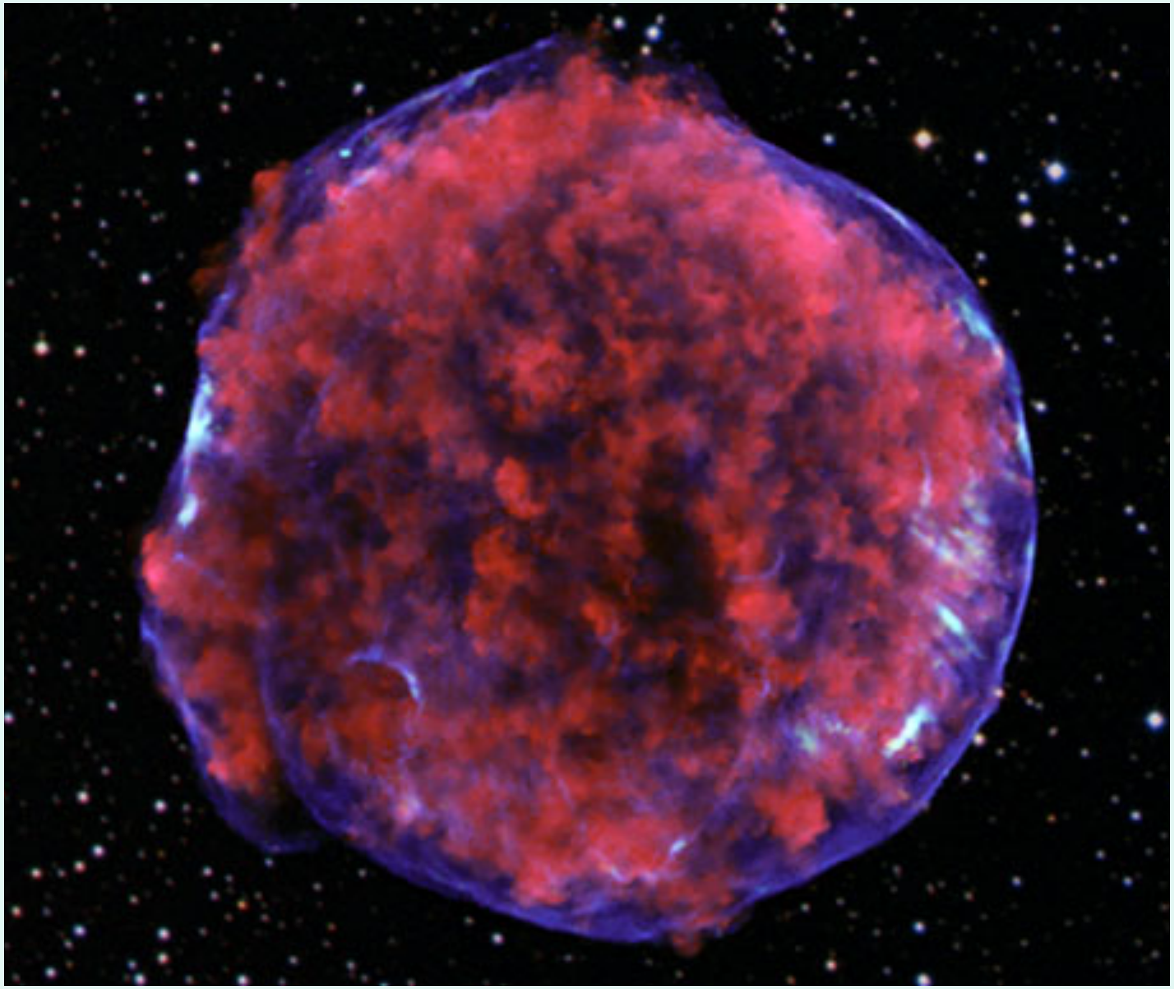
(from intermediate mass stars M ~ 3-8M_{sun})

White dwarf in binary pair accretes mass from companion, causing it to explode as supernova *if its mass exceeds "Chandrasekhar limit"*

Entire star explodes (probably), returning elements to ISM

Most of Mn, Fe, Co, Ni in ISM come from Type Ia SN

Tycho's Supernova Remnant
from Type Ia Supernova in 1572 A.D.



X-Ray image from Chandra telescope

Red: low energy x-rays from debris of star

Blue: high energy x-rays from blast wave – high energy electrons