Chapter 10

The deaths of stars

The deaths of stars

10.1 The fate of low-mass stars

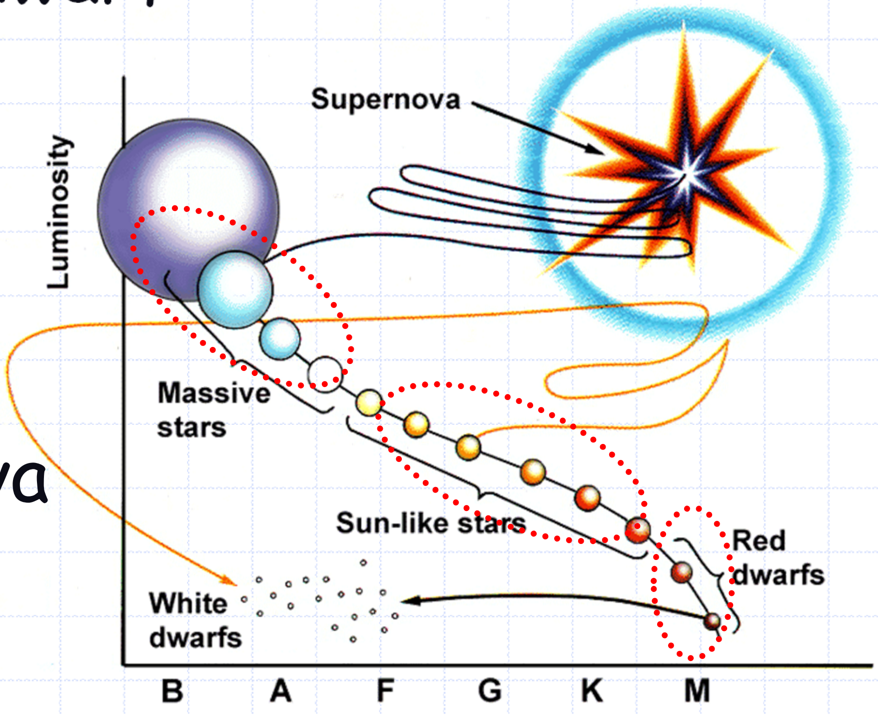
Summary

The fate depends on masses

10.1 ✓Red dwarf → white dwarf

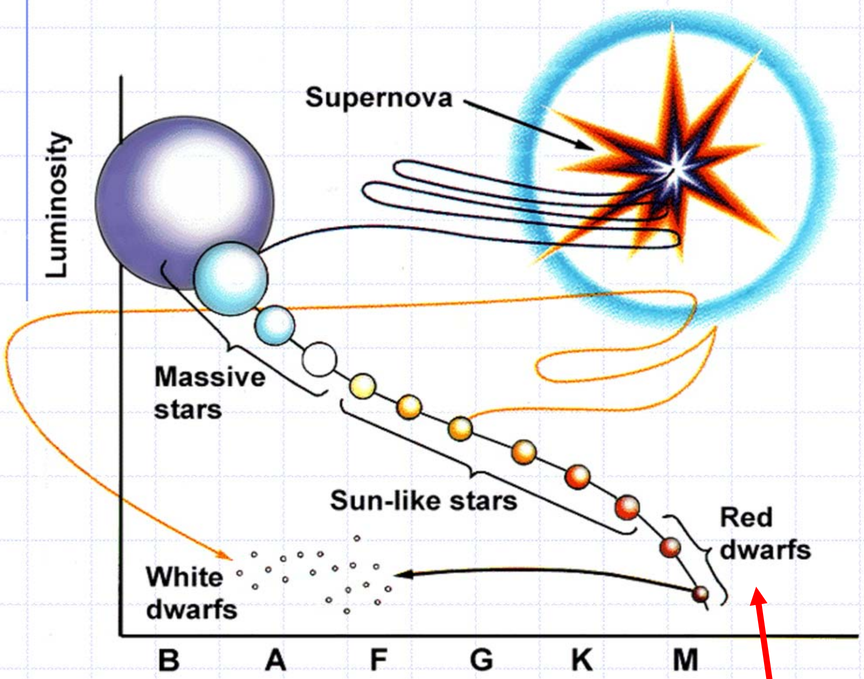
10.2 ✓Sun-like star → red giant; core → white dwarf

10.4 ✓Massive star → supergiant → supernova →..



10.1 The fate of low-mass stars

Red dwarfs (紅矮星)

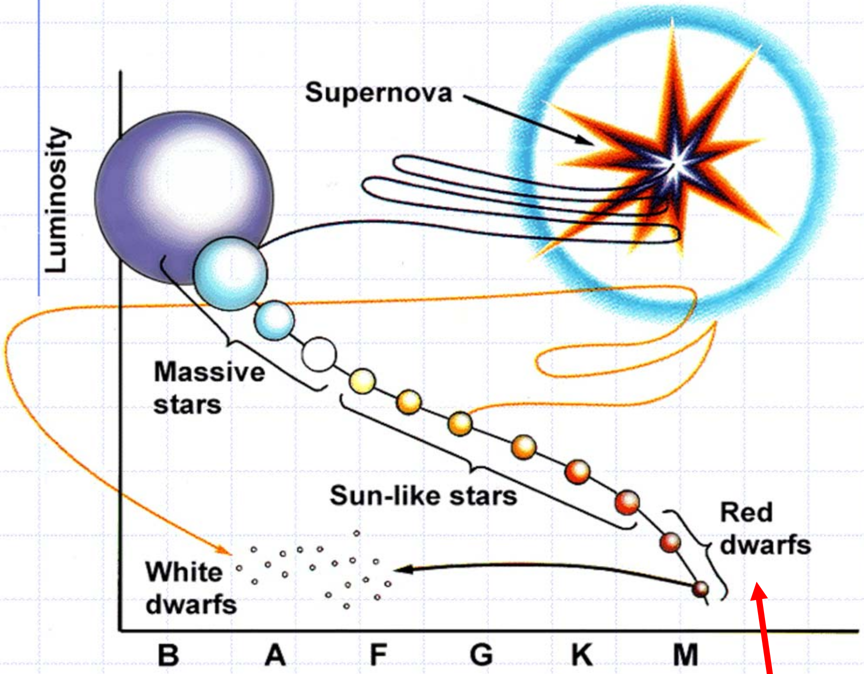


Burn slowly, long life, 100's billion years

- ✓ mass $< 0.4\ M_{\odot}$
- ✓ convection throughout the star, so gas is well-mixed.
- ✓ Hydrogen and helium ashes distributed uniformly inside the star
- ✓ no hydrogen-burning shell; will *not* form giants

10.1 The fate of low-mass stars

Red dwarfs (紅矮星)



Burn slowly, long life,
100's billion years

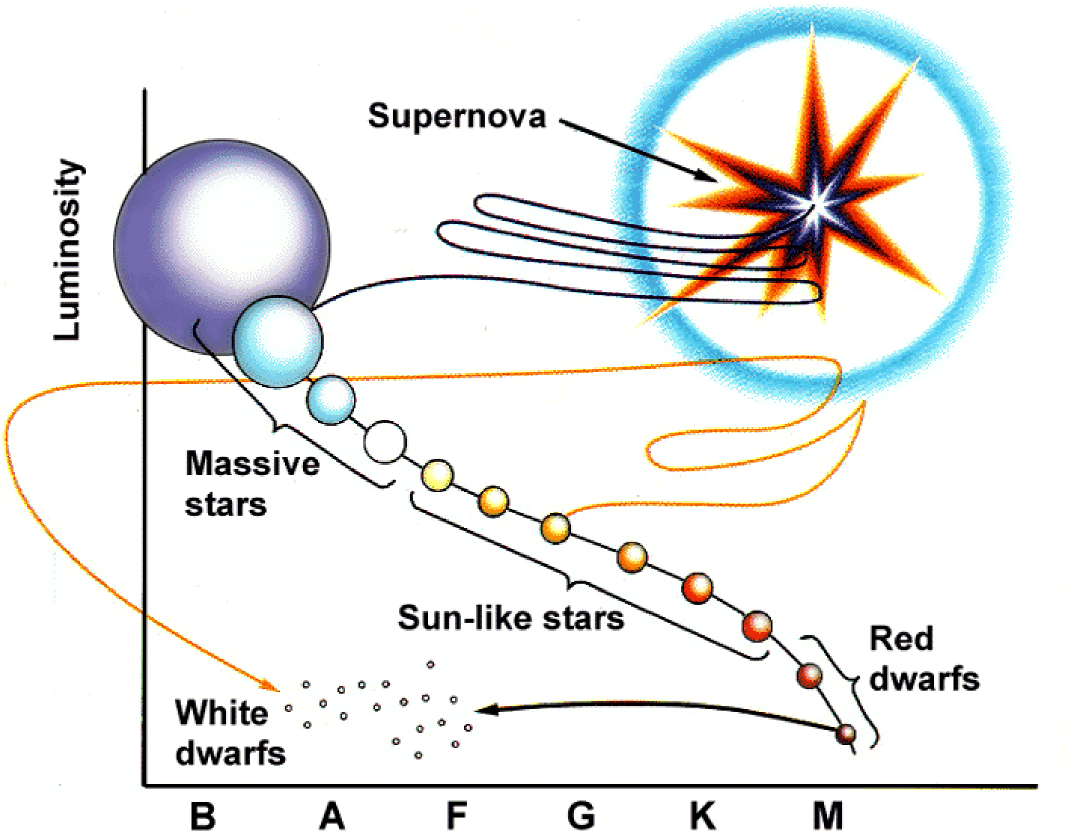
- ✓ *not* massive enough to a high temp to start helium fusion
- contract slowly when fuels are used up, so
- getting smaller, hotter
- move from right to left on H-R diagram
- become white dwarfs

10.2 The fate of Sun-like stars

SUN-LIKE STAR

- ✓ $0.4\ M_\odot < \text{mass} < 4\ M_\odot$
- ✓ due to gravity, producing *dense* and *hot* core
- ✓ Radiation by hydrogen burning shell produces swelled, *less dense* and *cool* out layer
- ✓ Rapid expansion causes the star *more luminous*

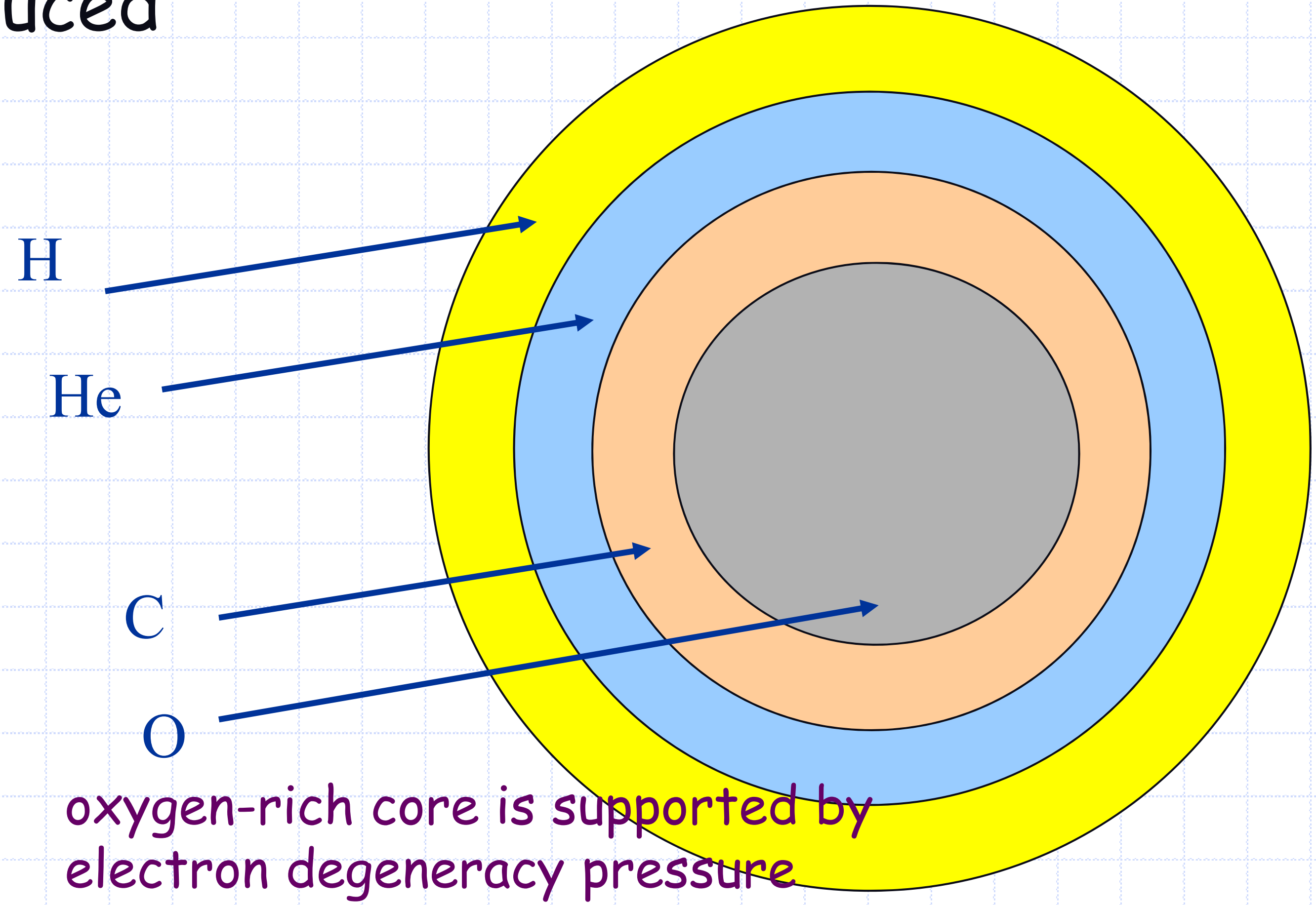
10.2 The fate of Sun-like stars



- ✓ The star becomes red giant, and moves to right of the H-R diagram

10.2 The fate of Sun-like stars

- Process repeats until oxygen-rich core produced

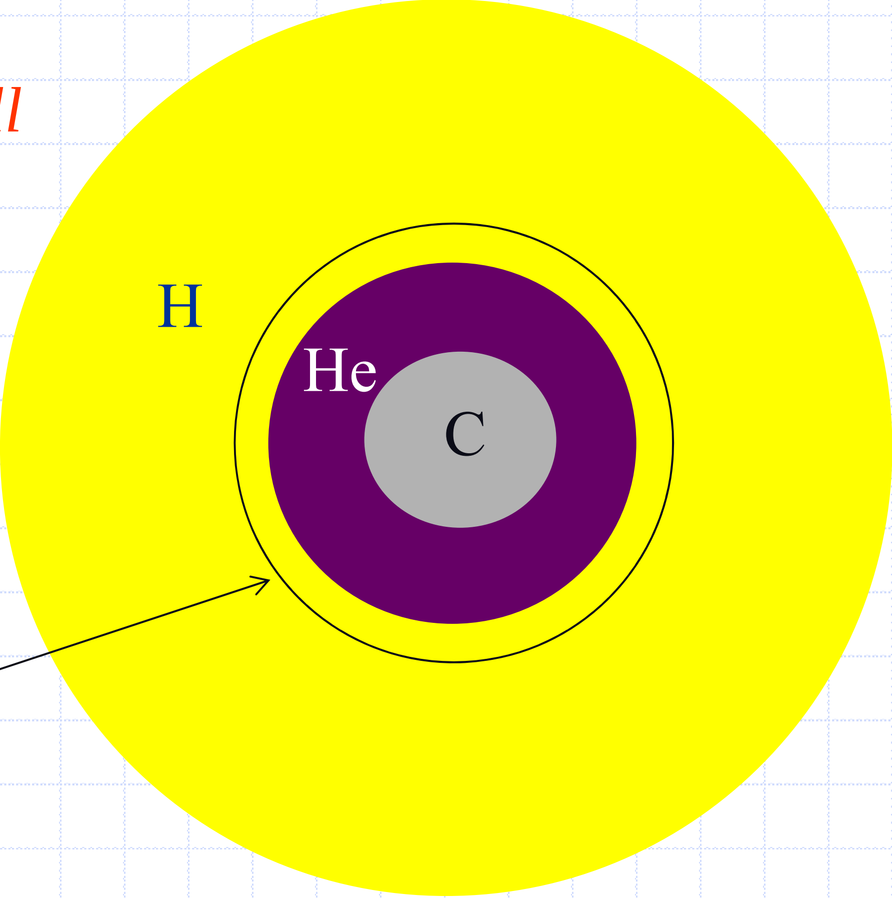


oxygen-rich core is supported by electron degeneracy pressure

10.2 The fate of Sun-like stars

Helium shell flash causes mass loss

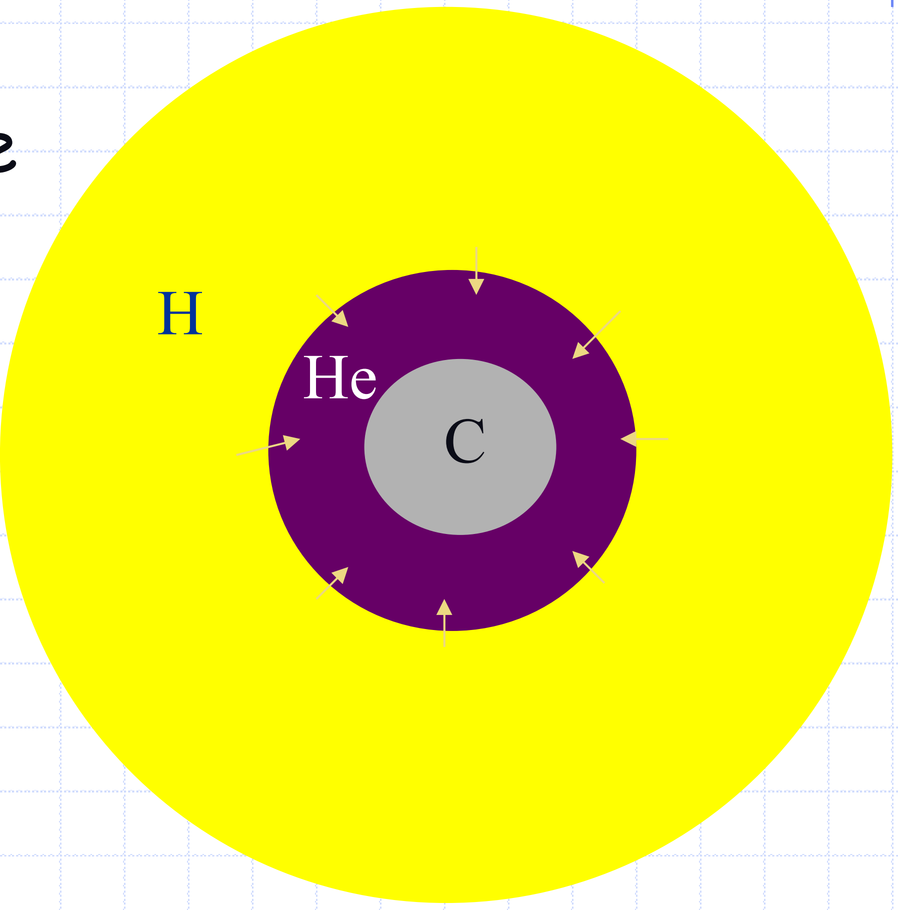
- After helium fusion for a long time, *helium-burning shell* is created outside the core
- Then, as helium in the shell is used up gradually, the shell contracts
- It heats up peripheral hydrogen-rich shell just outside the helium-burning shell; causes hydrogen fusion, producing helium



10.2 The fate of Sun-like stars

Helium shell flash causes mass loss

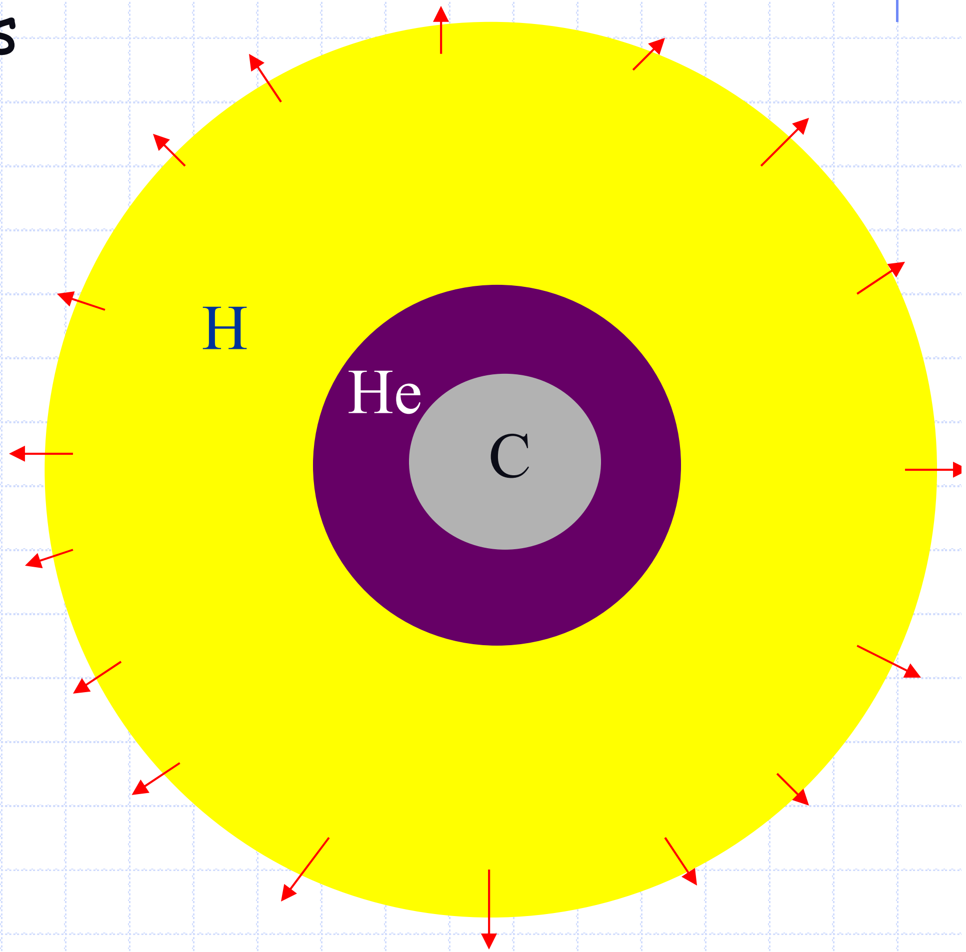
- ✓ Newly produced helium rains downward onto the helium-burning shell. Hence,
- ✓ the helium-burning shell gains extra helium

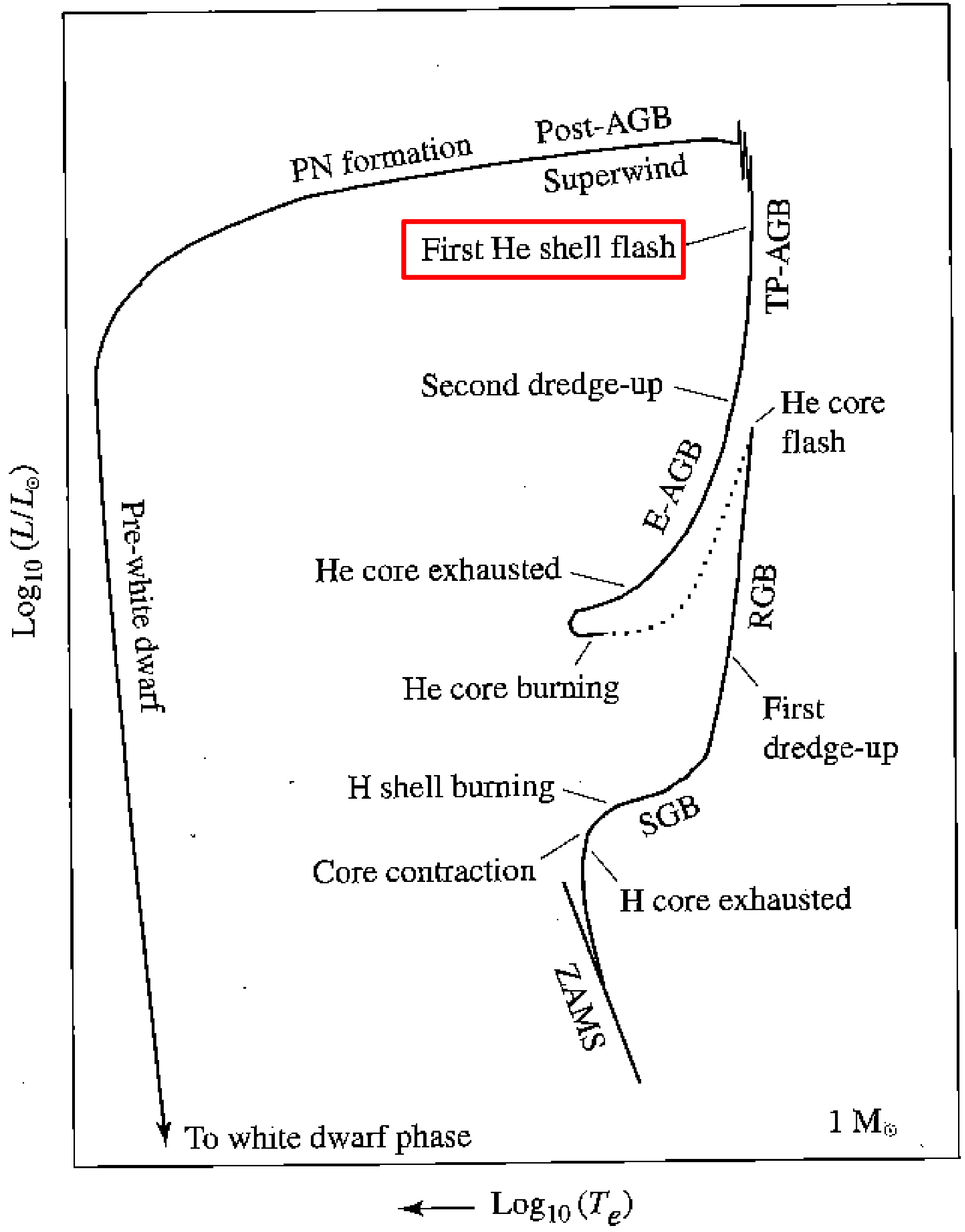


10.2 The fate of Sun-like stars

Helium shell flash causes mass loss

- ✓ helium-burning shell becomes more violent, producing *helium shell flashes*, provided that temperature reaches certain critical value
- ✓ The energy released pushes peripheral hydrogen-rich shell outward; hence decreases in temperature and ceases hydrogen burning
- ✓ Process re-starts again





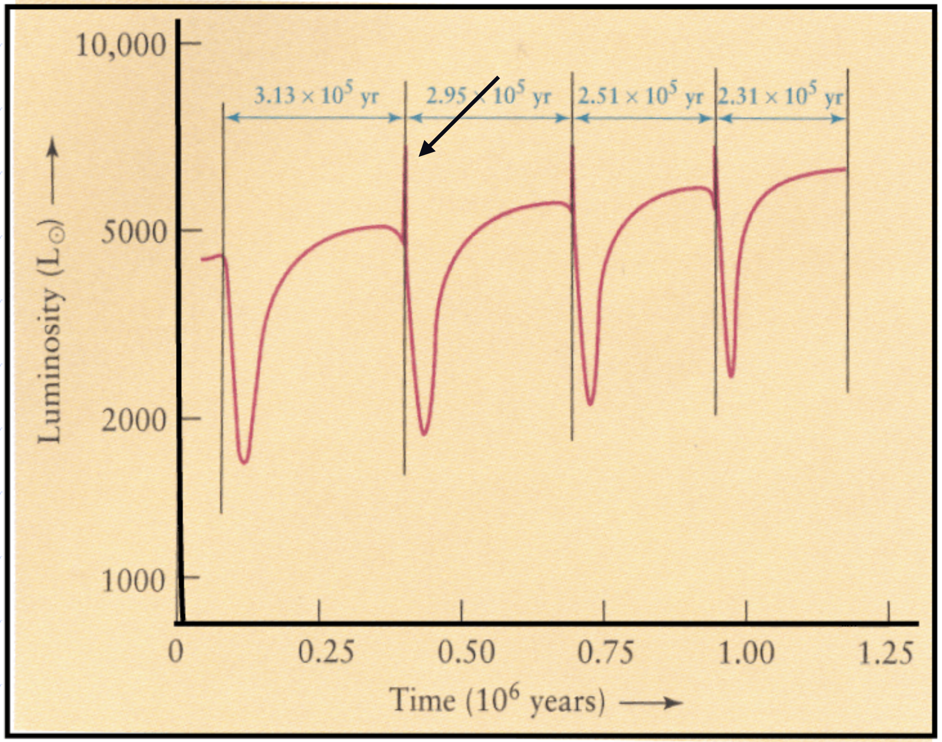
PN formation
Post-AGB
Superwind
First He shell flash
TP-AGB
Second dredge-up
He core
flash
E-AGB
He core exhausted
RGB
He core burning
First
dredge-up
H shell burning
SGB
Core contraction
H core exhausted
ZAMS
Pre-white dwarf
To white dwarf phase
1 M⊙
Log10 (L/L⊙)
Log10 (Te)

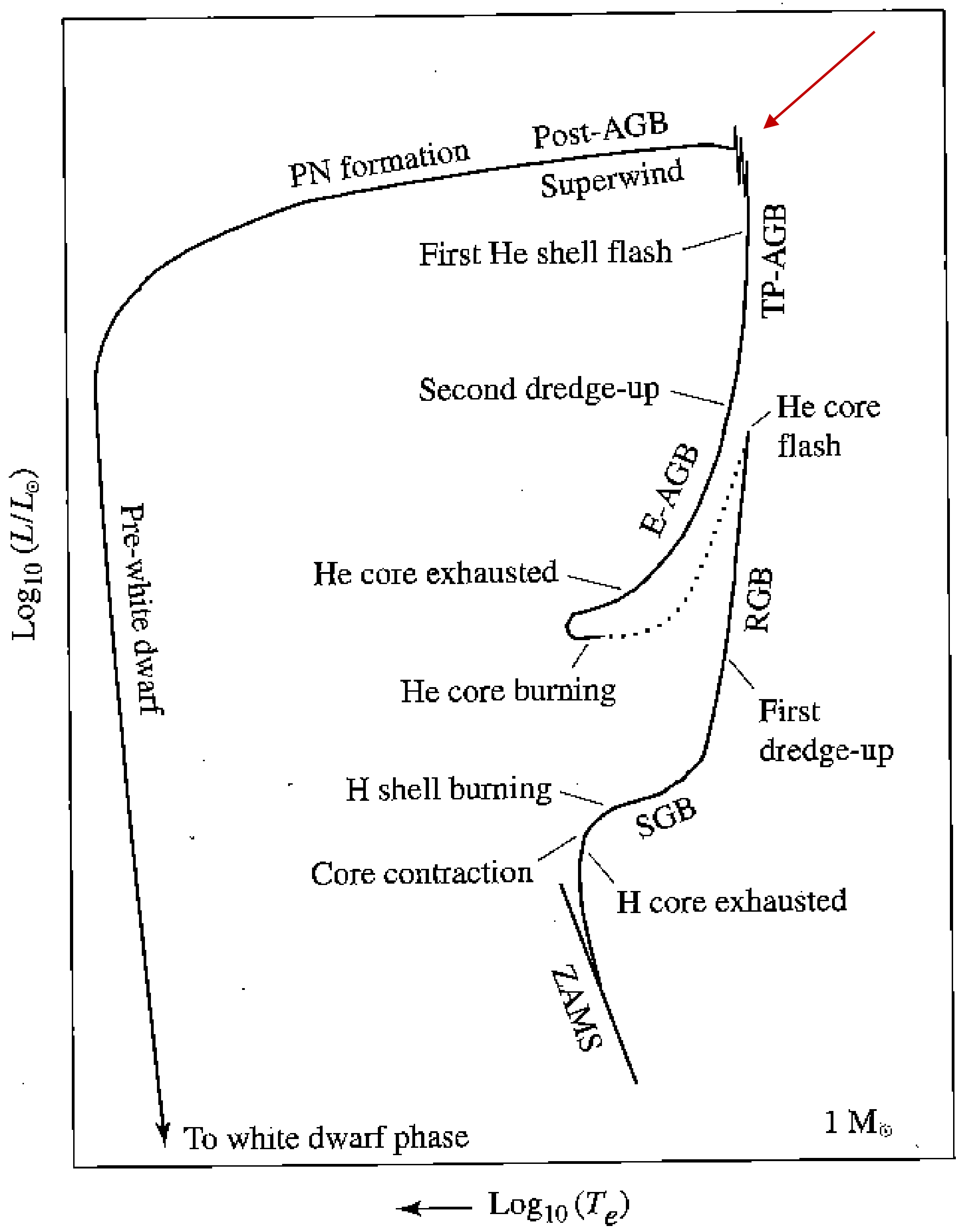
10.2 The fate of Sun-like stars

Helium shell flash causes mass loss

helium shell flashes

- ✓ causes luminosity increases, this phenomena is called *thermal pulse*,
- ✓ At intervals of about 300,000 years





Post-AGB
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Core contraction
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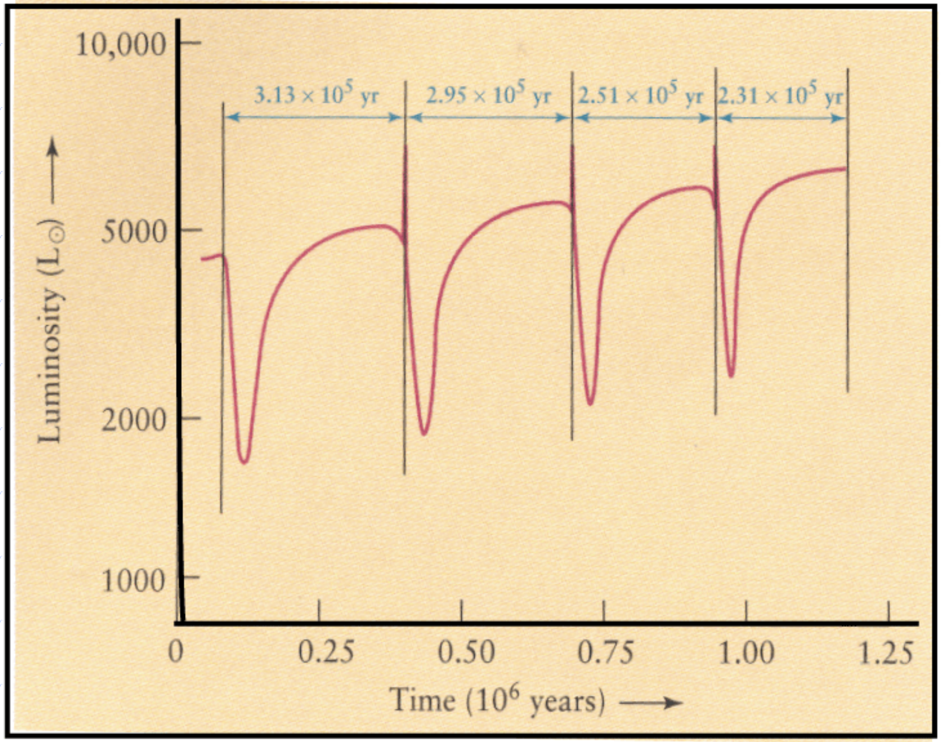
To white dwarf phase
1 $M_\odot$
$\mathrm{Log}_{10}(L/L_\odot)$
$\mathrm{Log}_{10}(T_e)$

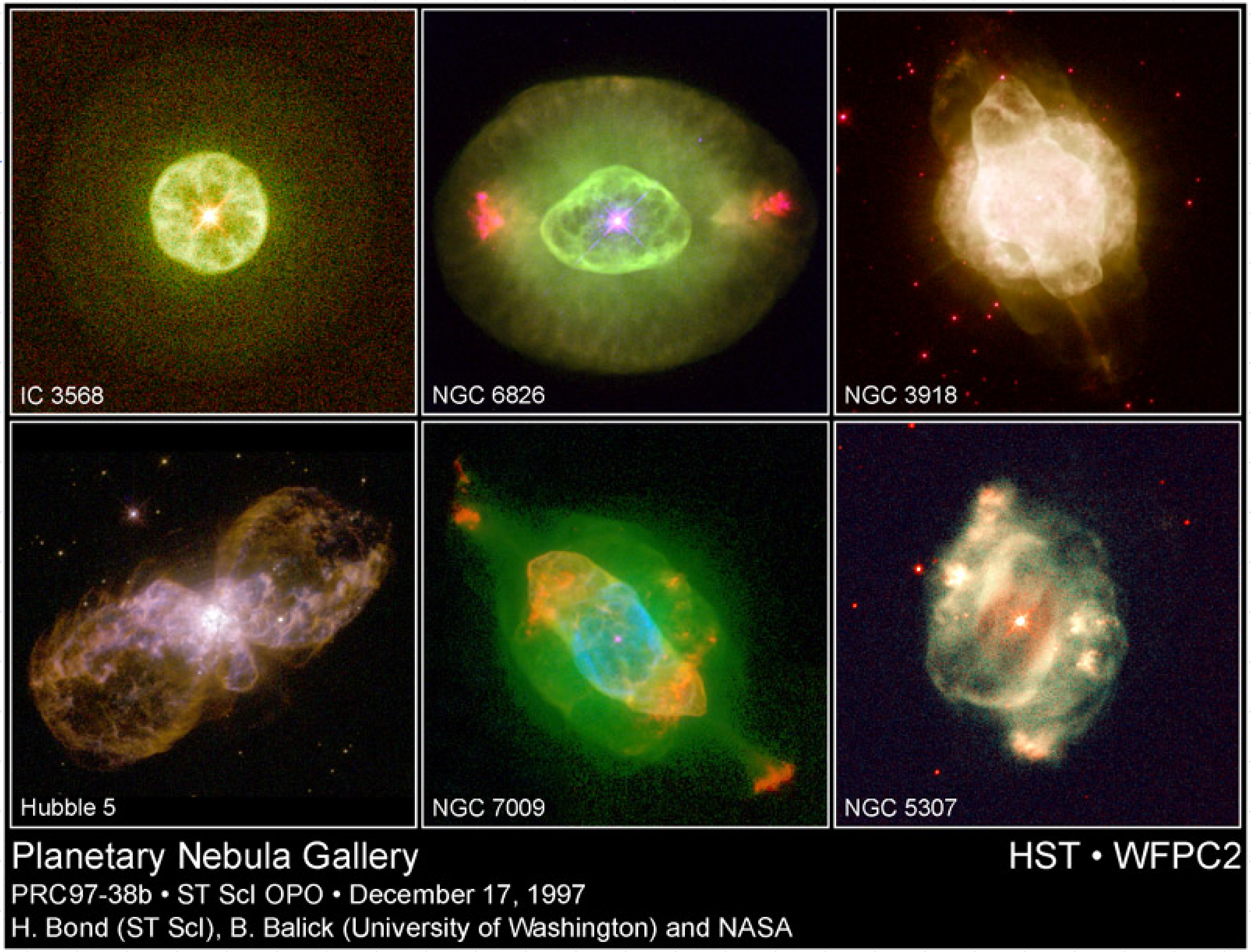
10.2 The fate of Sun-like stars

Helium shell flash causes mass loss

helium shell flashes

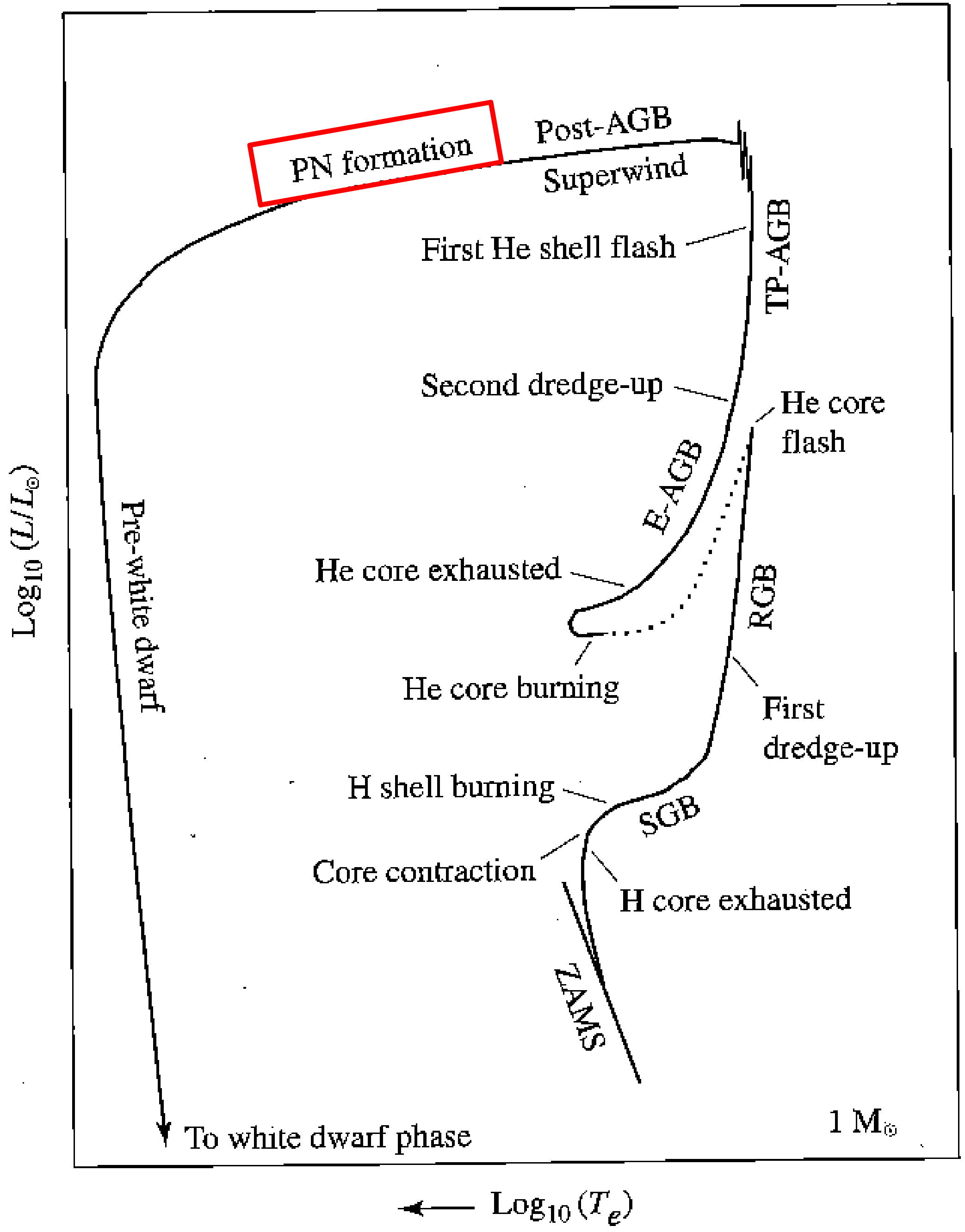
- ✓ During thermal pulse, outer layer of the giant may be detached completely from the core; radiation pressure further propels them away
- ✓ creating *planetary nebula* (行星狀星雲)
- ✓ may loss 50% of mass in ~10^5 years




IC 3568
NGC 6826
NGC 3918
Hubble 5
NGC 7009
NGC 5307
Planetary Nebula Gallery
HST • WFPC2
PRC97-38b • ST ScI OPO • December 17, 1997
H. Bond (ST ScI), B. Balick (University of Washington) and NASA

距地球約650光年、位於寶瓶座的行星狀星雲，「螺旋星雲」(Helix Nebula)，有 ”the eye of God”之稱。

位於天龍座的貓眼星雲 (Cat‘s Eye Nebula)



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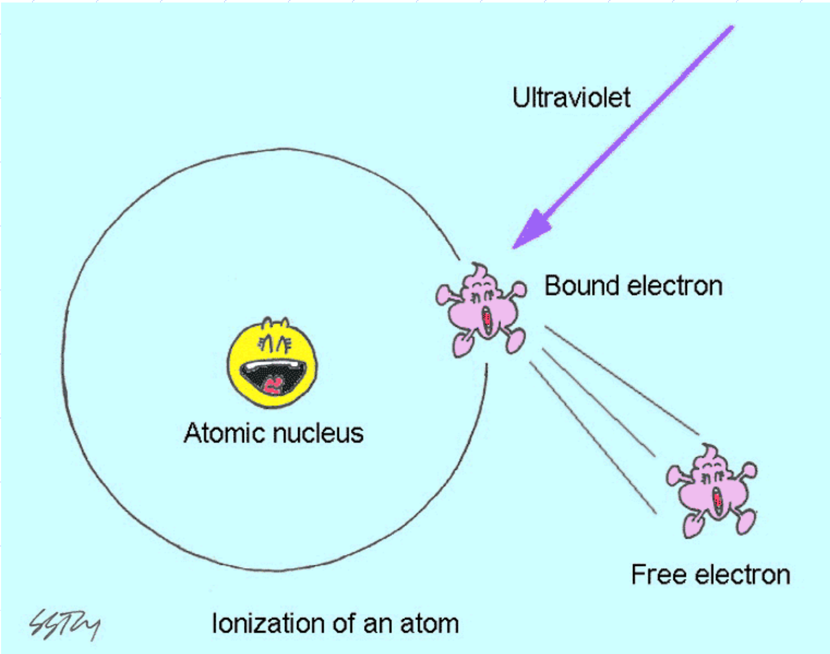
Log10 (Te)

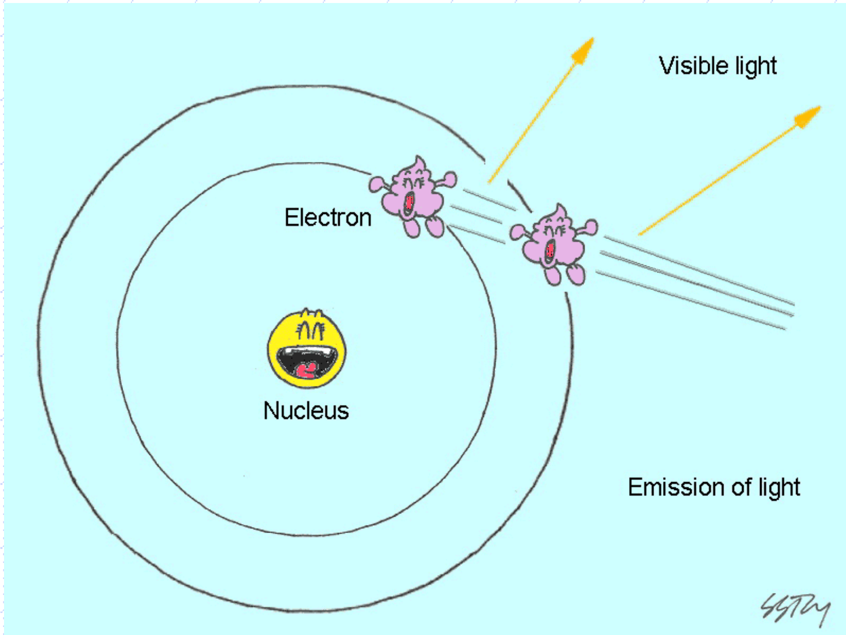
10.2 The fate of Sun-like stars

Planetary nebulae are visible



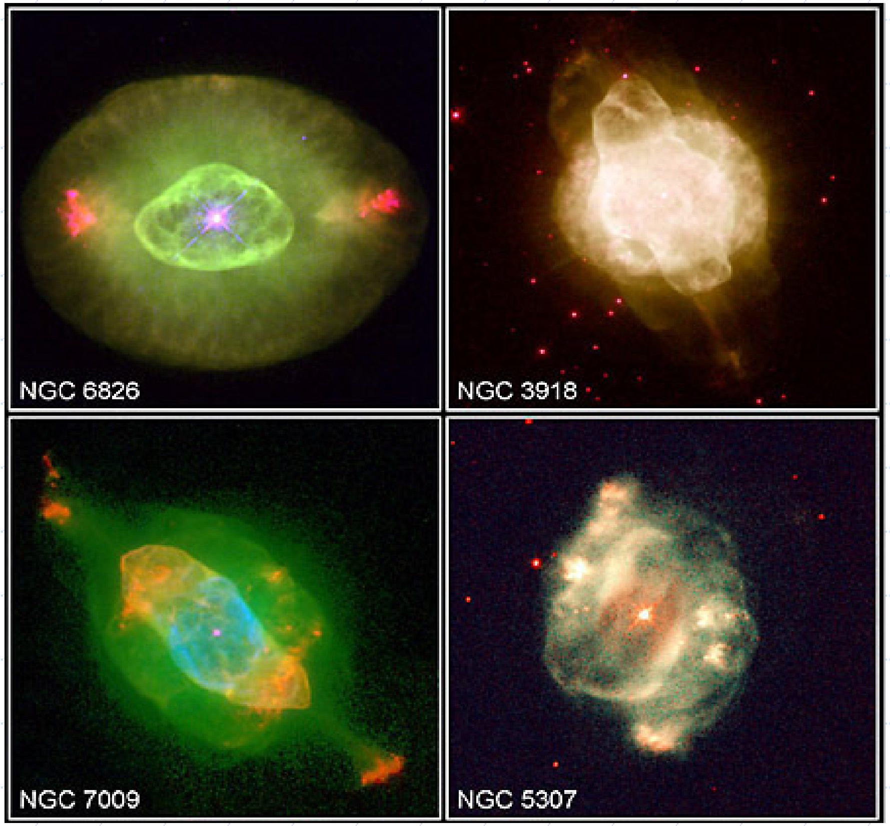
Ionized by UV from the central central star and nearby star

Emits light as recapture electrons



10.2 The fate of Sun-like stars

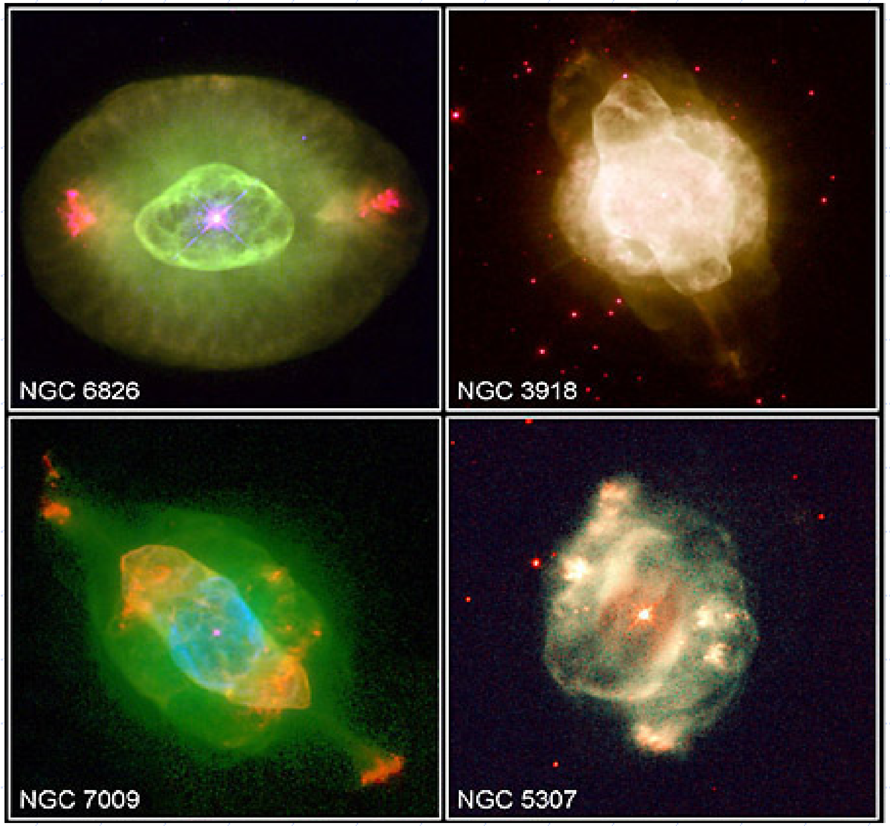
Why are nebulae visible?



- ✓Complicated shapes depends on mass distribution before explosion.
- ✓Speeds ~ 10-30 km/s (measured by Doppler effect)
- ✓Radii~0.3pc; ages~10^4yrs
- ✓Finally dissipate into interstellar medium

10.2 The fate of Sun-like stars

Why are nebulae visible?



- ✓Remaining core is *small*, *dense* and *hot*
- ✓As nuclear reactions gradually extinguished; *surface temperature still hot*; but *luminosity drops* because of its small size
- ✓Moves to lower-left side of H-R diagram, becoming a *white dwarf* (白矮星)

NGC 7293 Helix Nebula 3-D morphology animation
(https://www.youtube.com/watch?v=KXNSYo8ZdoU)

10.3 White dwarf (白矮星)

✓The carbon oxygen-rich core supported by *electron degeneracy pressure*

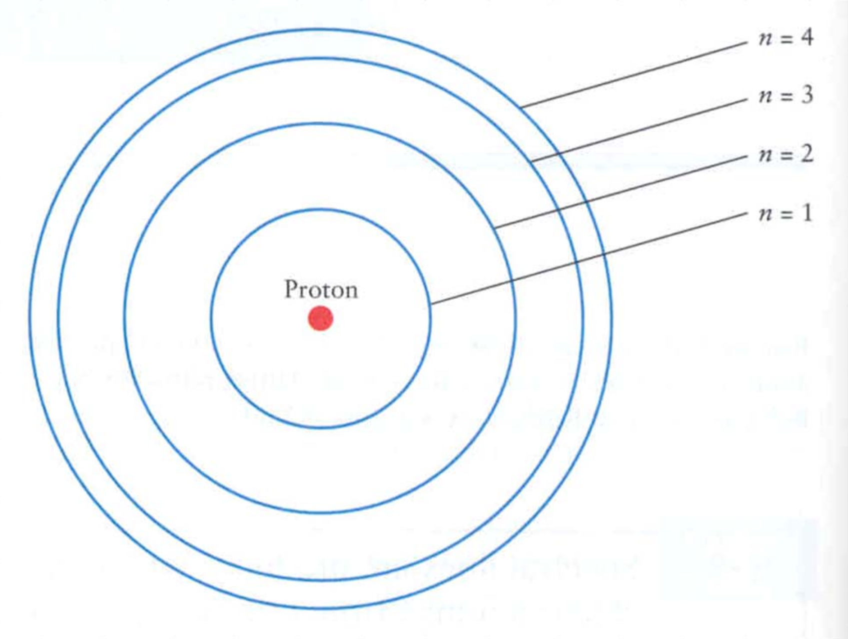
✓Nuclear reactions extinguish, and luminosity drops rapidly, but surface temperature is high

✓ Resides on the lower-left side of the H-R diagram - becomes a *white dwarf*.

Box 9.1 Degenerate-electron pressure

Pauli exclusion principle

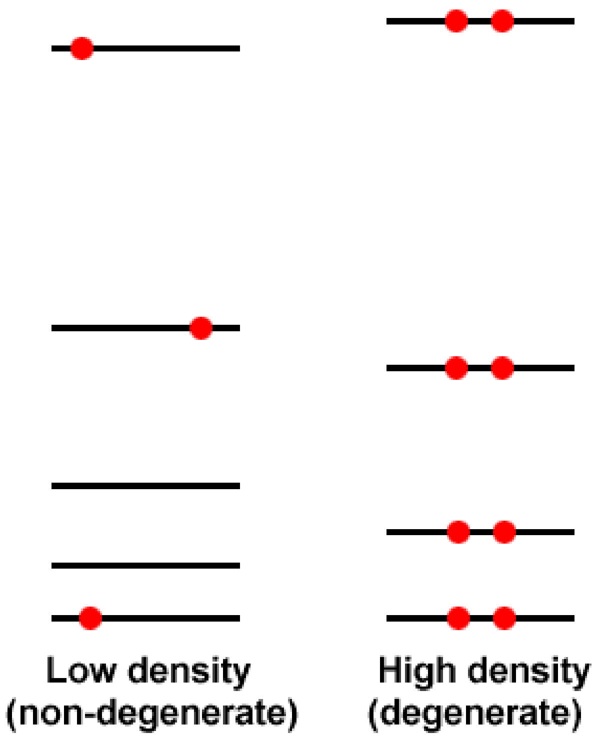
- Two identical *fermions* (e.g., electrons, neutrons, protons) cannot simultaneously occupy the same *quantum state* (e.g., locations and speeds)
- a quantum effect
- Analogous: two things cannot in the same place at the same time



e.g., 2 electrons in $n = 1$; 8 in $n = 2$; 18 in $n = 3$

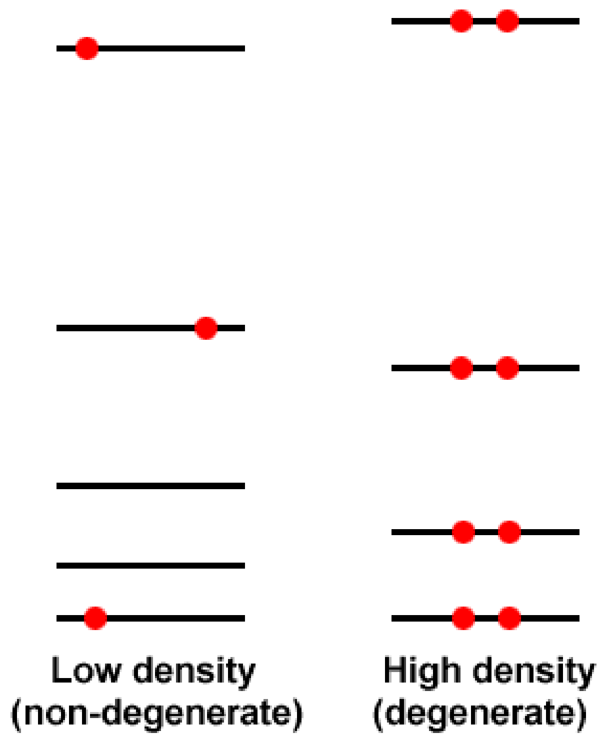
Box 9.2 Degenerate-electron pressure

- Since a red giant is hot and highly compressed, all atoms in the core are ionized
- The electrons fill up lower energy levels of the system as a whole (not an individual atom)
- By the Pauli exclusion principle, the core finally reaches a limit and can't be compressed any more

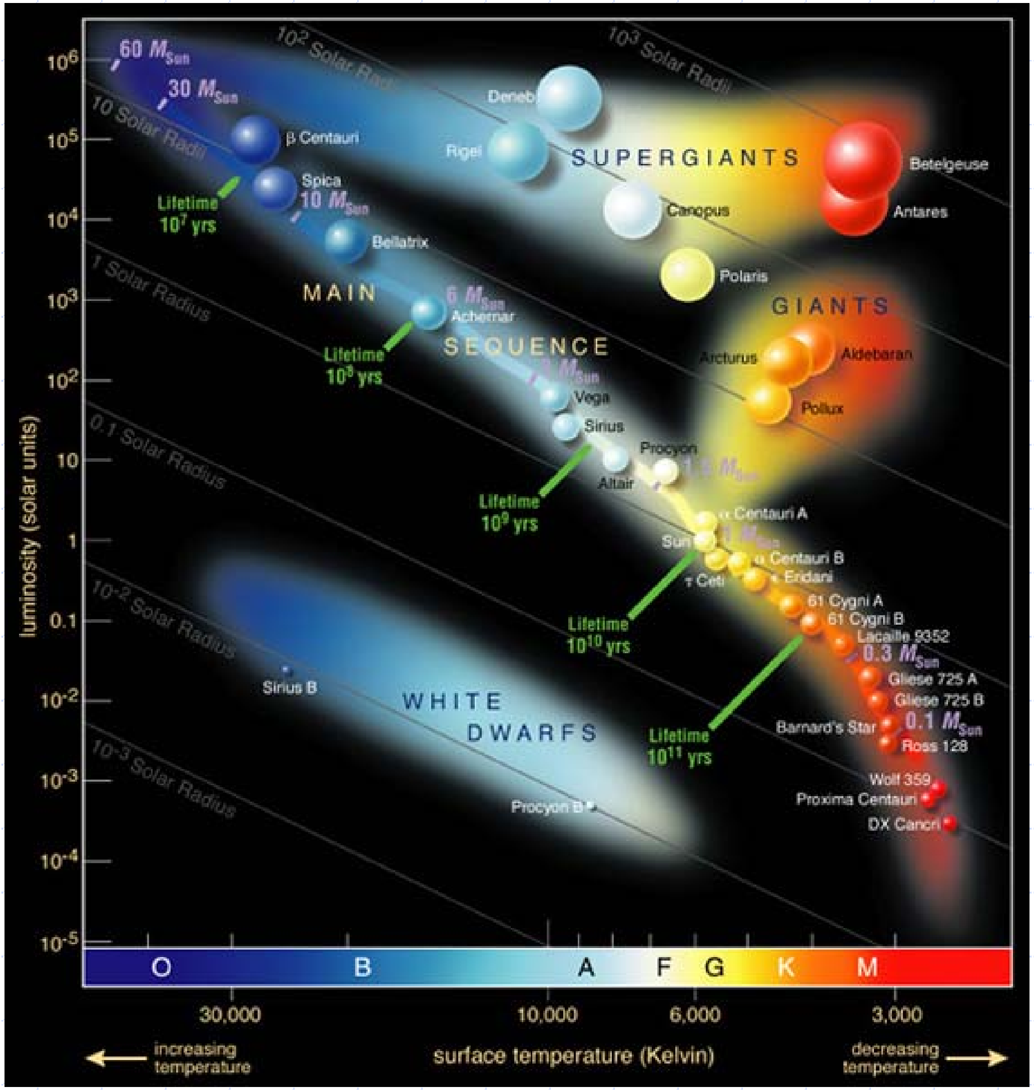


Box 9.2 Degenerate-electron pressure

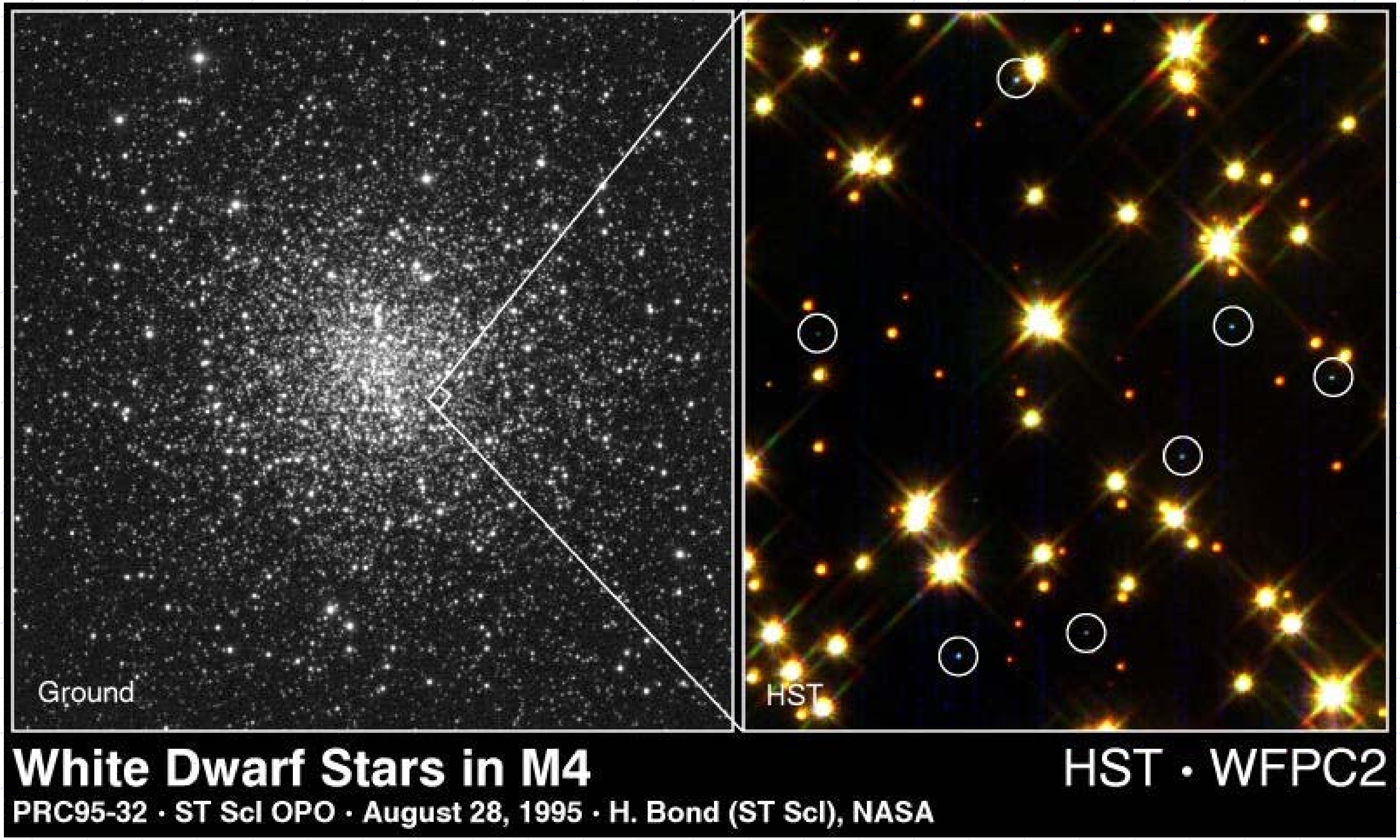
- producing a huge pressure to resist further any core contraction
- The core is *degenerate* and is supported by *degenerate electron pressure*
- The degenerate pressure is *independent* of temperature



10.3 White dwarf (白矮星)



10.3 White dwarf (白矮星)



10.3 White dwarf (白矮星)

- ✓ white dwarf: small, hot and dense (1 teaspoon of matter ~ 15 tons). e.g., Sirius B (天狼 B星): ~1 solar mass, 0.76 Earth's radius, surface temperature ~32,500 K, density ~ 3×10^6 g/cc
- ✓ Strong gravity on its surface (~10^5 times that of Earth's)
- ✓ white dwarf radiates energy slowly, becomes cold and dark after billions of years, becoming a *black dwarf* (黑矮星), ends with a quiet death

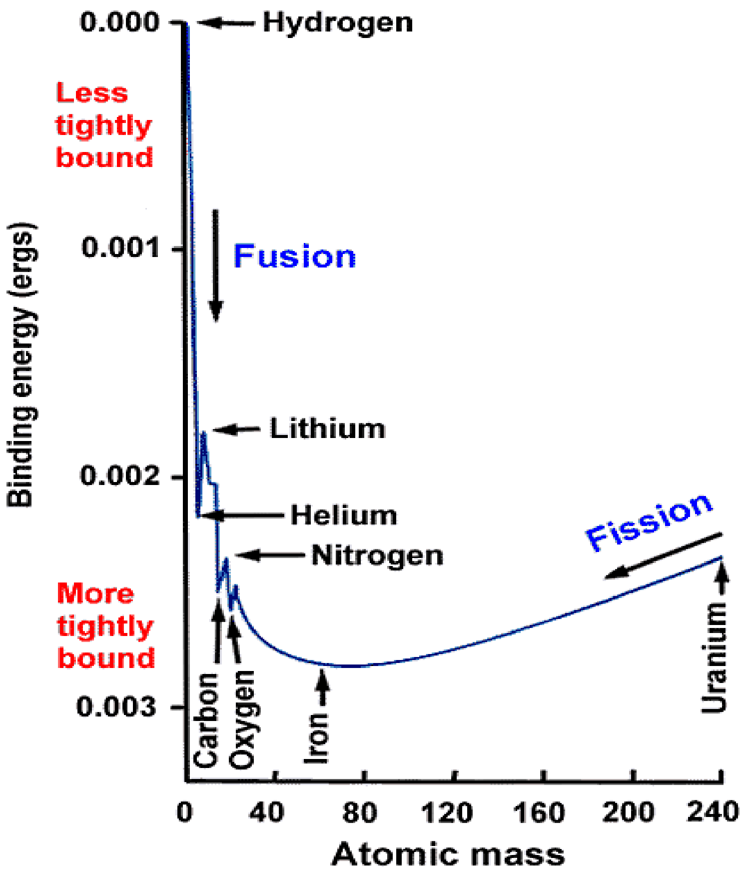
10.3 White dwarf (白矮星)

Chandrasekhar limit (錢德拉塞卡極限)

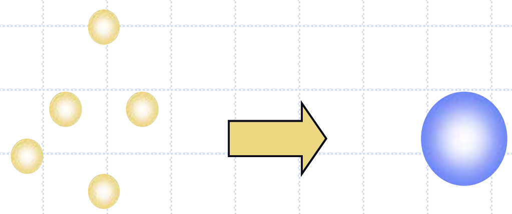
- ✓ The maximum mass of a white dwarf that the electron degeneracy pressure can support (core mass ≈ 1.4 solar mass).
- ✓ The degeneracy pressure can no longer resist gravity beyond this limit, i.e., the star will further collapse.

10.4 The fate of massive stars

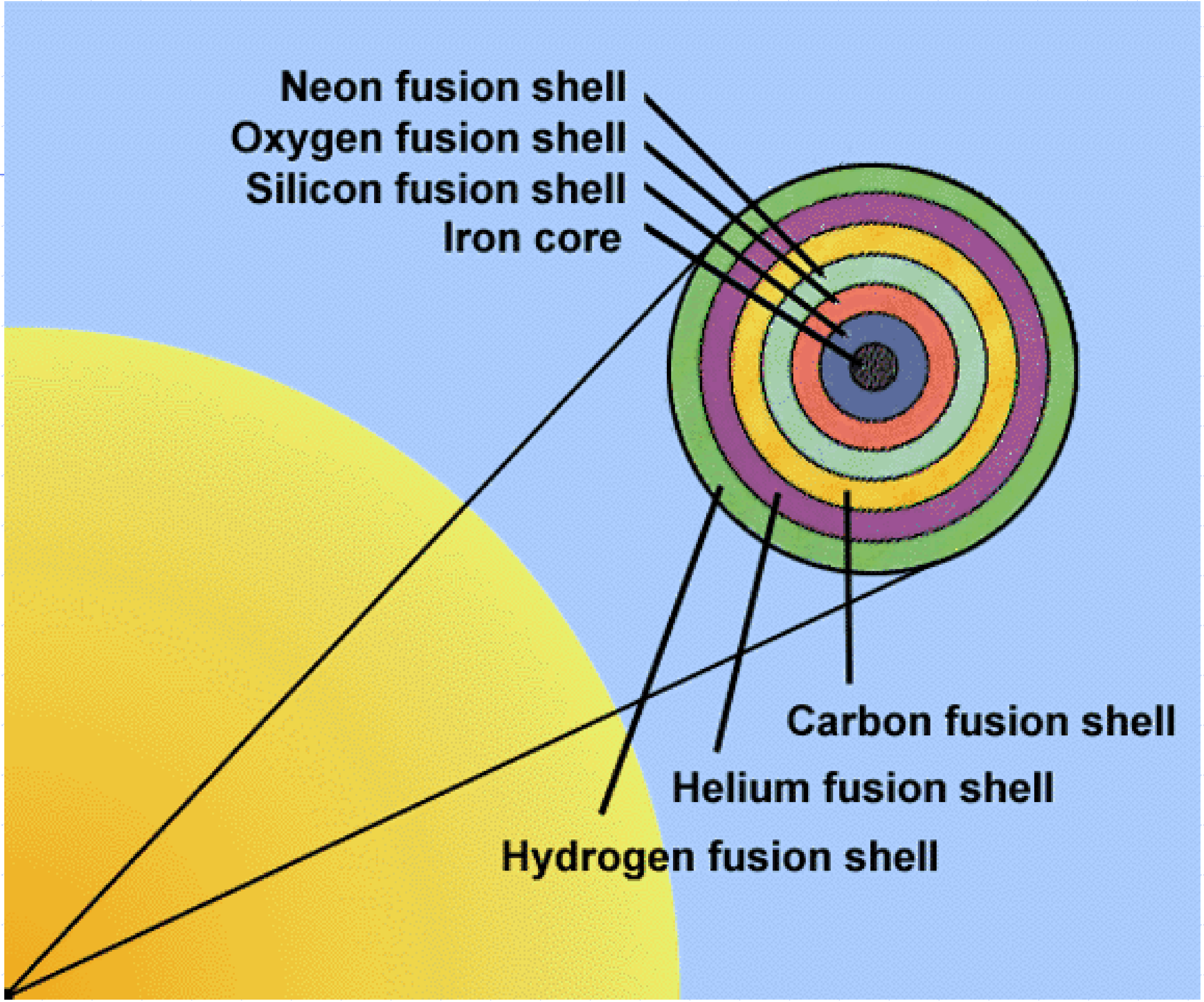
Element creations



- ✓ Mass of the star > $4\,M_\odot$
- ✓ continue burning of heavier and heavier elements until iron - the most tightly bounded elements



Binding energy ($E = mc^2$)


Neon fusion shell
Oxygen fusion shell
Silicon fusion shell
Iron core
Carbon fusion shell
Helium fusion shell
Hydrogen fusion shell

10.4 The fate of massive stars

Element creations

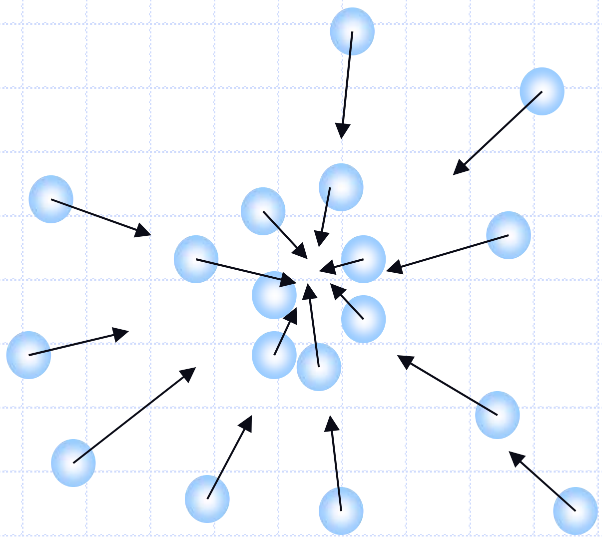
- Finally, iron core surrounded by fusion shells of various elements
- γ-ray radiations from the hot core may colloid with iron core, break down iron into lighter ones, e.g, α-particles. This process is called *photodisintegration*.
- Millions of years and several stages of thermonuclear reactions to build up an iron core; within a short period of time, photodisintegration undoes much of those millions of years effort!

10.4 The fate of massive stars

Supernova explosion and heavy elements created

- ✓ Now, mass ~ $15M_{\Theta}$, T ~ 8×10^{9} K, ρ ~ 10^{10} g cm^{-3}
- ✓ *Not even* electron degeneracy pressure can stop gravitational contraction
- ✓ the core contracts faster and faster

✓density goes higher and higher.



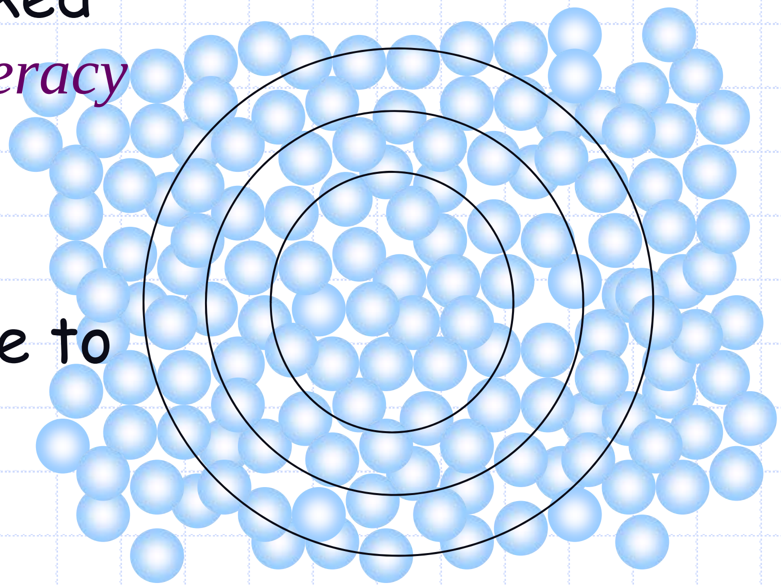
10.4 The fate of massive stars

Supernova explosion and heavy elements created

✓When density $\sim 10^{14}$ g cm^{-3}, electrons squeezed into atomic nuclei, combine with protons, forming neutron, i.e., $p^{+} + e^{-} \rightarrow n + \nu$

✓Neutrons and protons are packed together, creating *neutron degeneracy pressure*. (similar to electron degeneracy pressure)

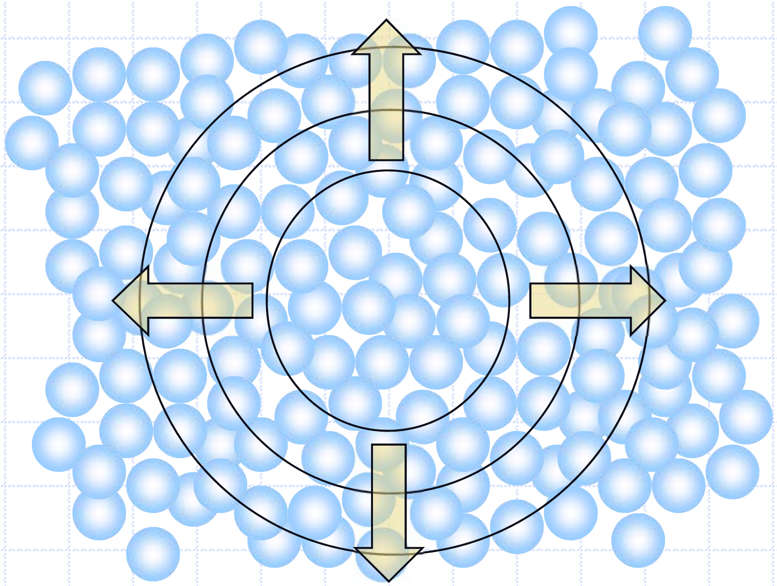
✓Thus, exerting strong pressure to resist further compression, reacting like a hard core.



10.4 The fate of massive stars

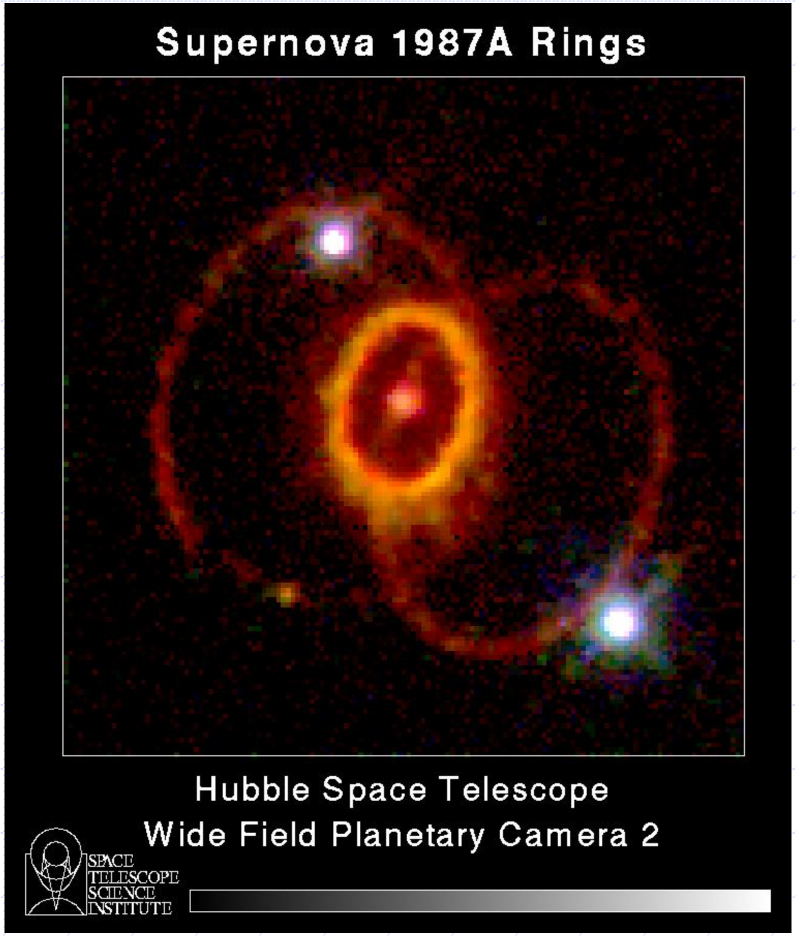
Supernova explosion and heavy elements created

- ✓ Triggering by the unstable nuclear reactions, inner core rebounds, building up powerful shock waves which propagate *outward*
- ✓ Outer layer is destroyed in a short time,
- ✓ Such a violent explosion is called supernova, sudden increase in the brightness
- ✓ equivalent to 10^{28} Mton of TNT



10.4 The fate of massive stars

SN 1987A in the Large Magellan Galaxy



Types of supernovae

- ✓ **Type II:** strong hydrogen lines in the supernova's spectrum
- ✓ from core collapse within a massive star, enough of the hydrogen from the outer layers remained before exploding
- ✓ Examples: the 1054 supernova in Taurus and SN 1987A in the Large Magellan Galaxy.

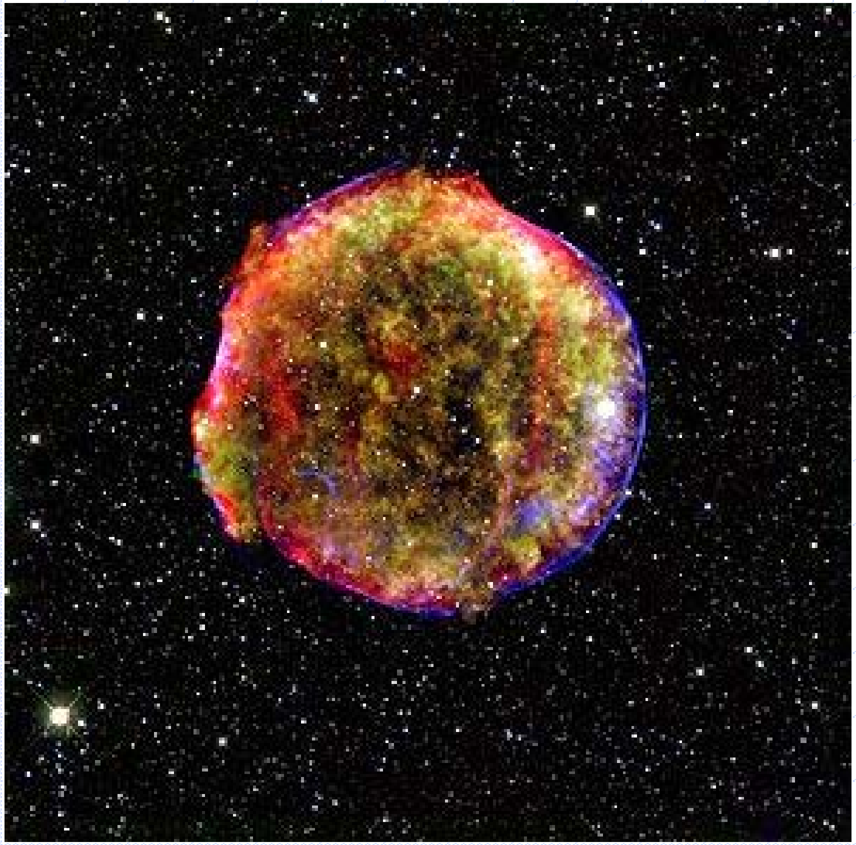
Types of supernovae

- ✓ Type Ib: no hydrogen in their spectra, but have a strong absorption line of unionized helium (He I).
  - ➢ result from core collapse in a massive star that lost the hydrogen from its outer layers.
- ✓ Type Ic: lack both hydrogen and helium lines in their spectra.
  - ➢ These also result from a massive star that undergo core collapse but lost both hydrogen and helium from their outer layers prior to the supernova explosion.

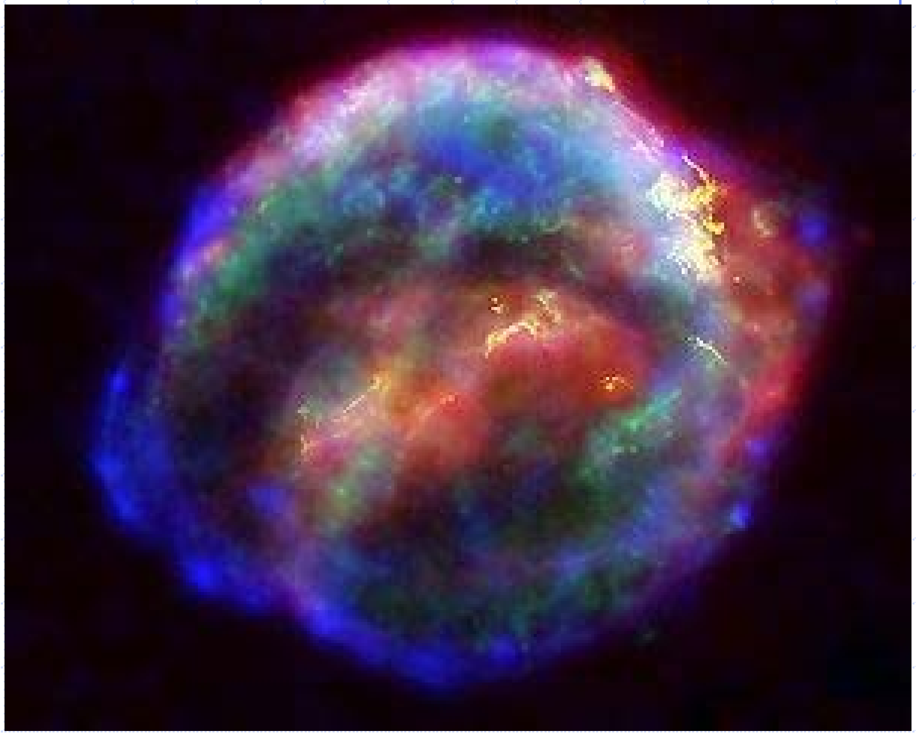
Types of supernovae

✓ **Type Ia:** no hydrogen or helium line in their spectra, but a prominent absorption line of ionized silicon (Si II, $\lambda = 635.5\,\text{nm}$).

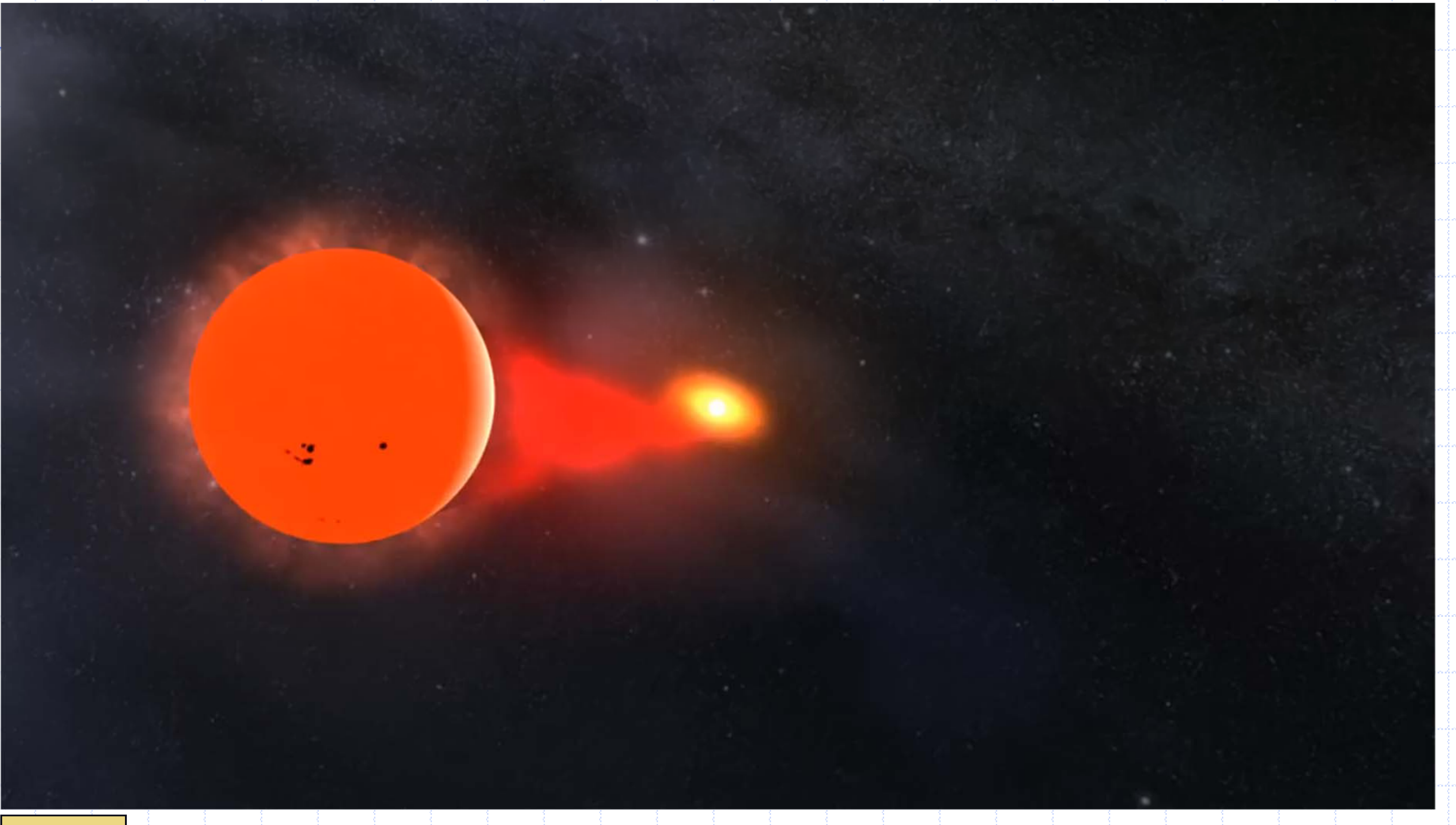
- produced by the explosion of a white dwarf star in a close binary system. Mass transfer from its companion (red giant), getting temperature increased and triggering supernova explosions.
- Before exploding, the white dwarf contained carbon and oxygen and no hydrogen or helium
- carbon-burning reaction produces Silicon and gives rise to the silicon absorption line.



Tycho's supernova in Cassiopeia (仙后座) in 1572



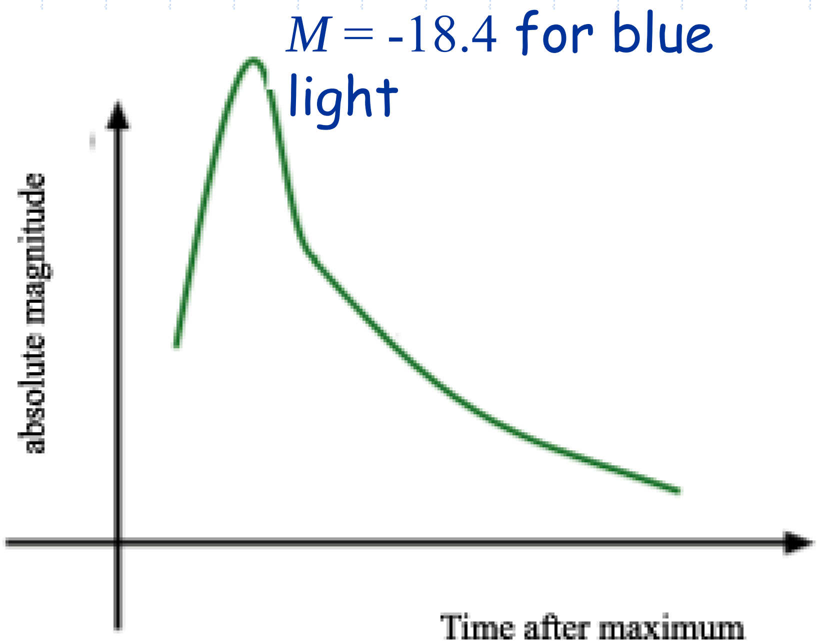
Kepler's Supernova in 1604



Type 1a Supernova Animation
(https://www.youtube.com/watch?v=-yEBVm5o97E)

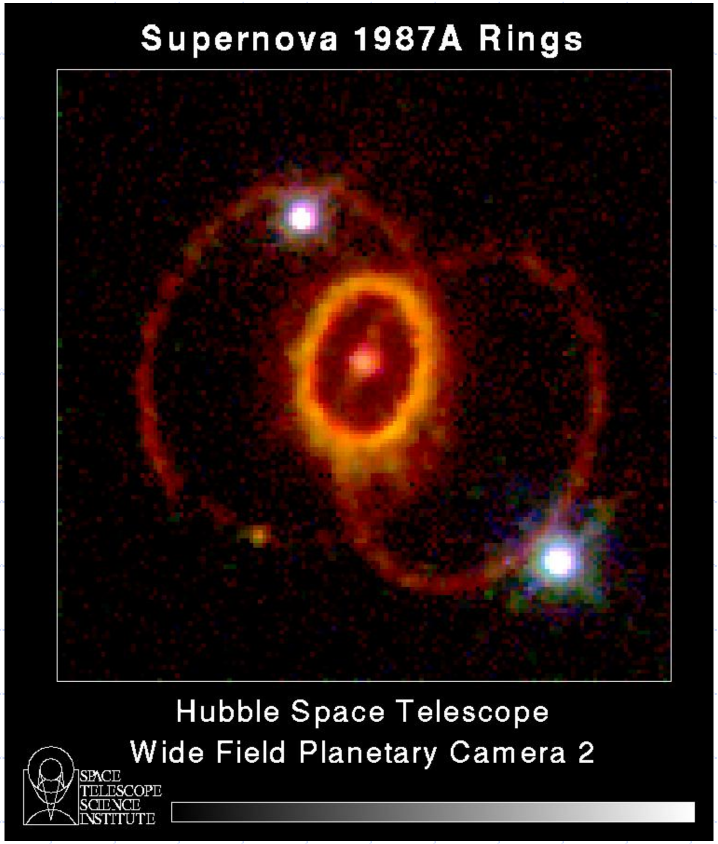
Types Ia supernovae as a standard candle

- Type Ia supernovae show a similar light curve.
- Use as a standard candle to measure extragalactic distance.
- Type Ib, Ic and II supernovae are dimmer than that from Type Ia by 1.5 - 2 magnitudes. .

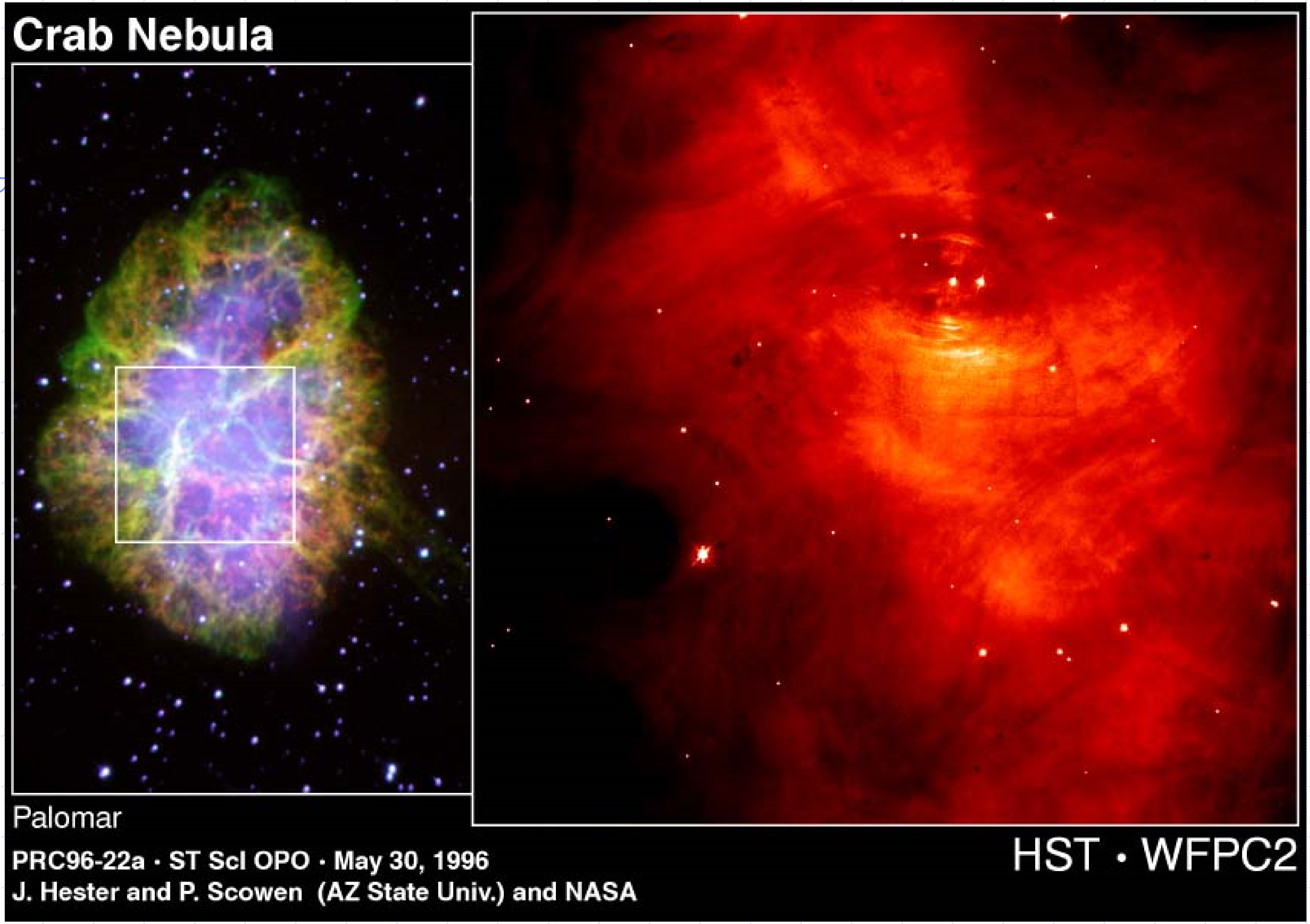


10.4 The fate of massive stars

Supernova remnant



SN 1987A and its three-ring circus



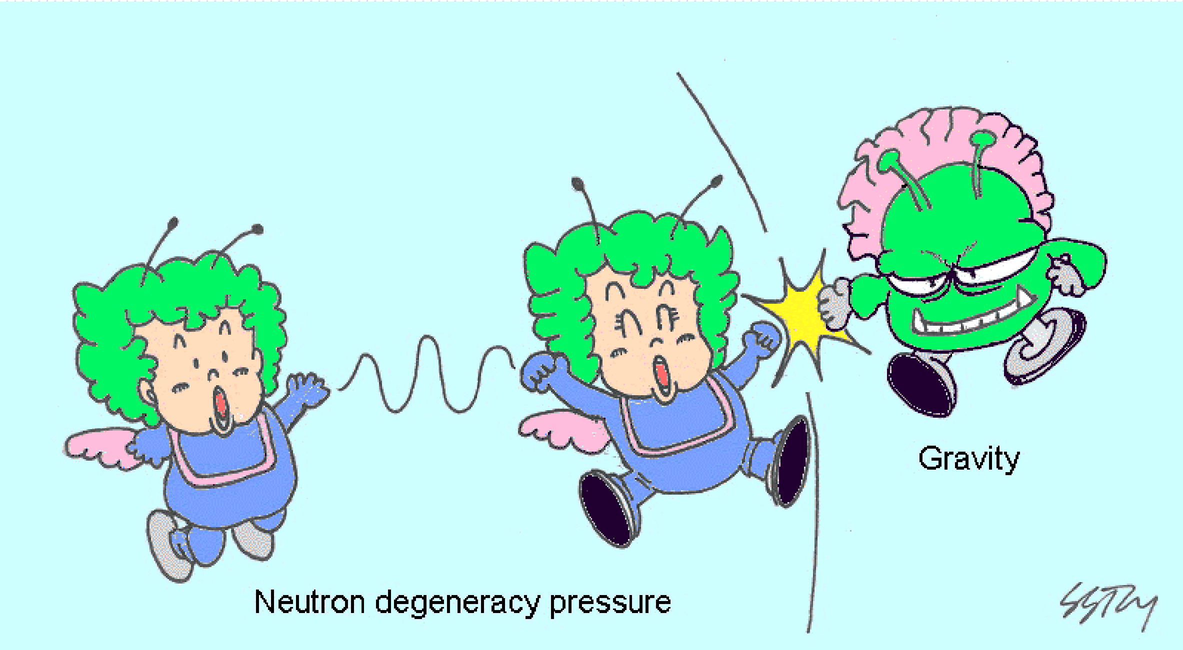
Crab Nebula (蟹狀星雲) M1 is the remnant of the supernova in 1054.

The 1054 supernova in Taurus (Type II)

Crab Supernova Explosion
(https://www.youtube.com/watch?v=aysiMbgml5g)

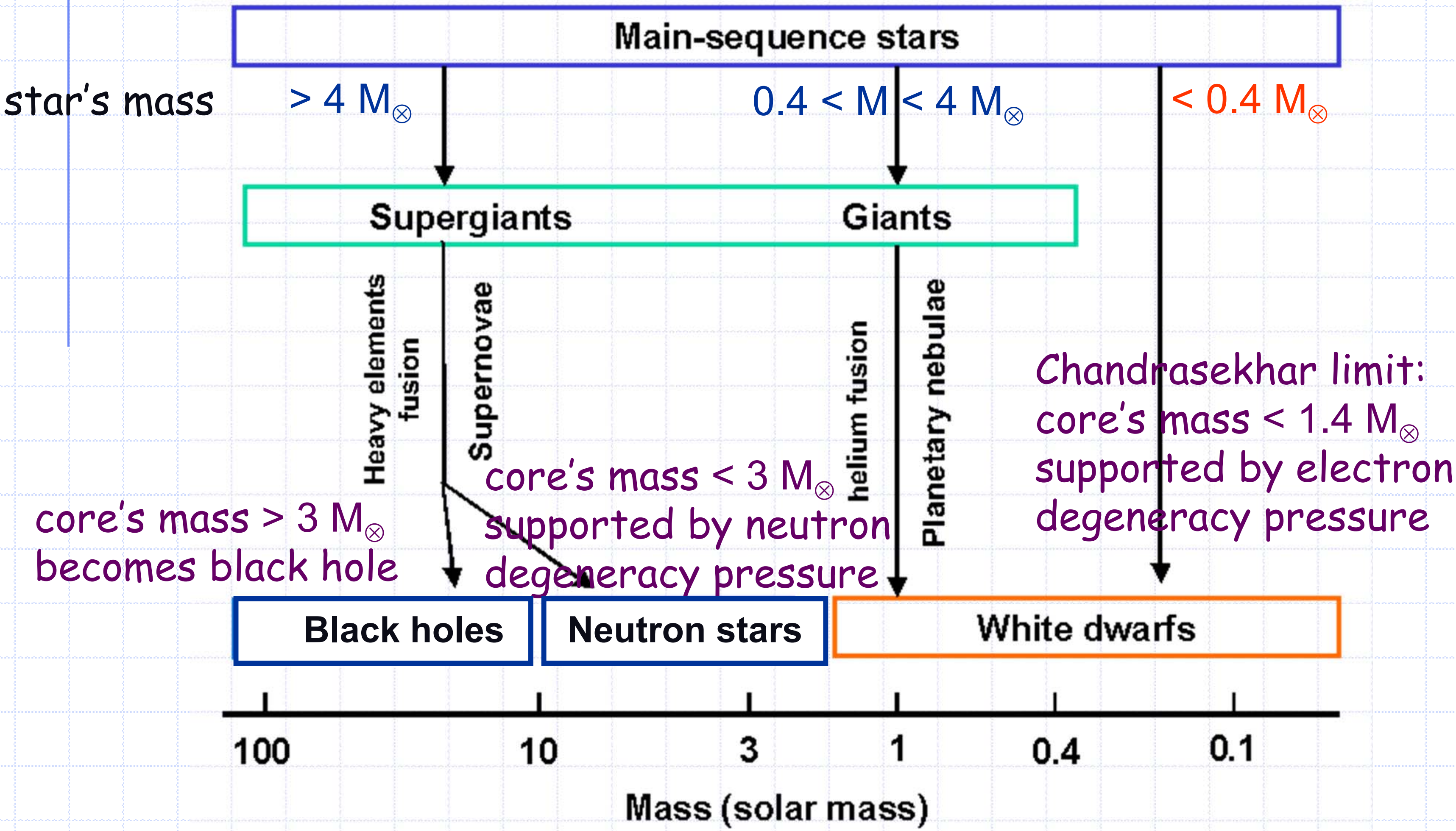
10.4 The fate of massive stars

Supernova explosion



- ✓ After supernova, the remaining neutron-rich core is small, extremely dense
- ✓ Becoming neutron stars or black holes, depending on core masses

10.4 The fate of massive stars

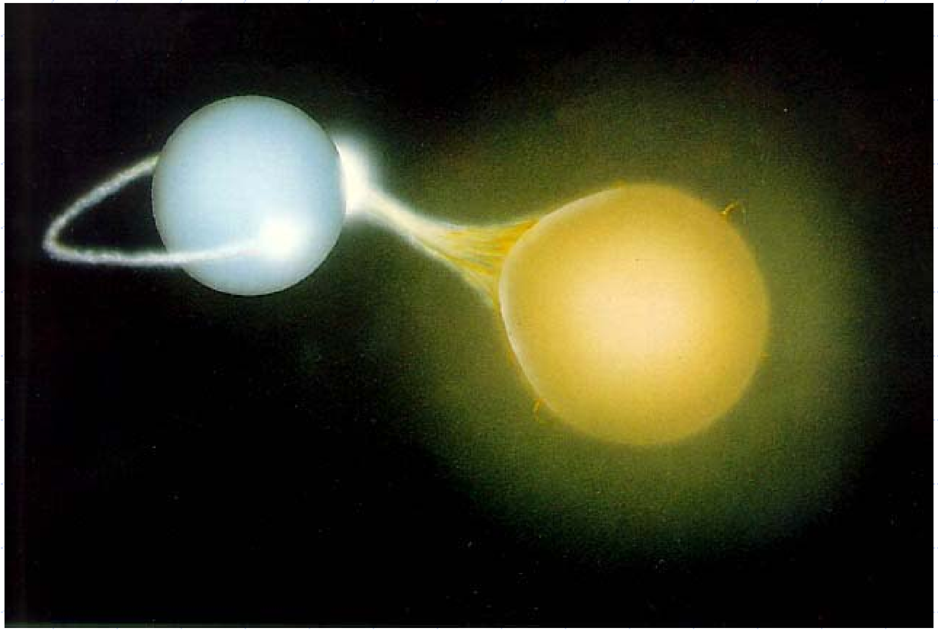


10.5 Fate of binary stars

✓In some binaries, one becomes a giant, its outer layer transfer to its companion.

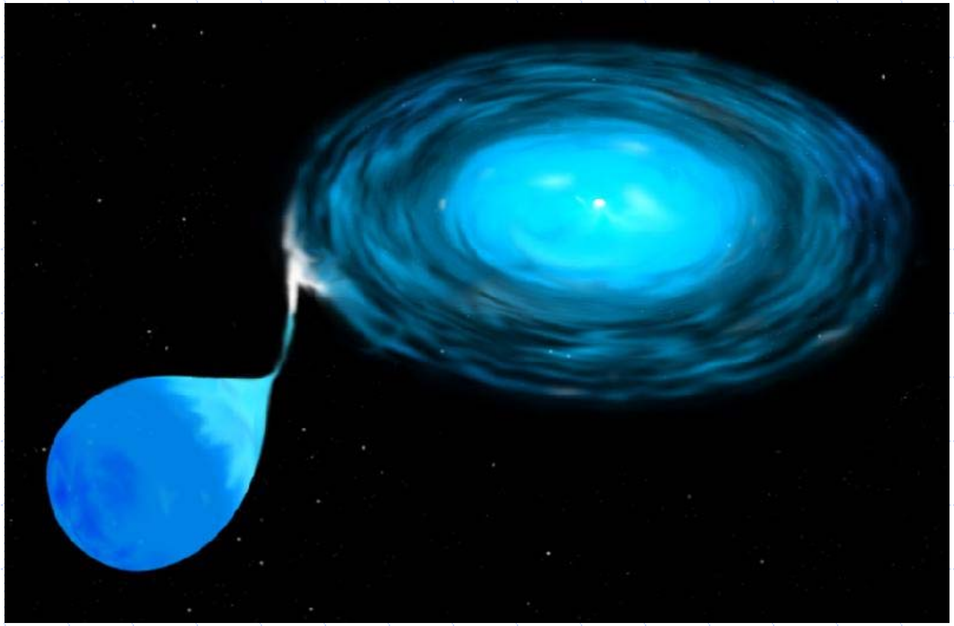
✓The companion gains and becomes more massive but still on the main sequence, i.e., *algol paradox*

✓If both stars are close, and become red giants, they may merge together to form *supergiant*

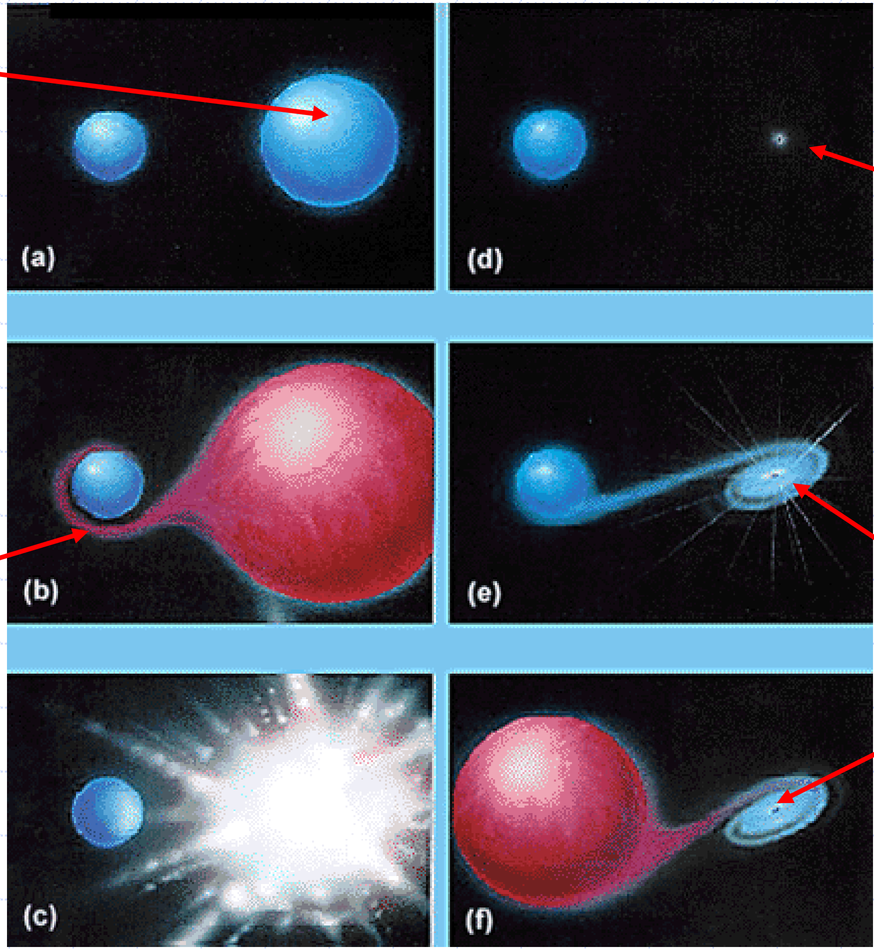


10.5 Fate of binary stars

✓If one becomes white dwarf, companion's matter not transfer directly into the white dwarf, but forming a whirlpool surrounding it, called *accretion disk*.



10.5 Fate of binary stars



more massive

becomes more massive

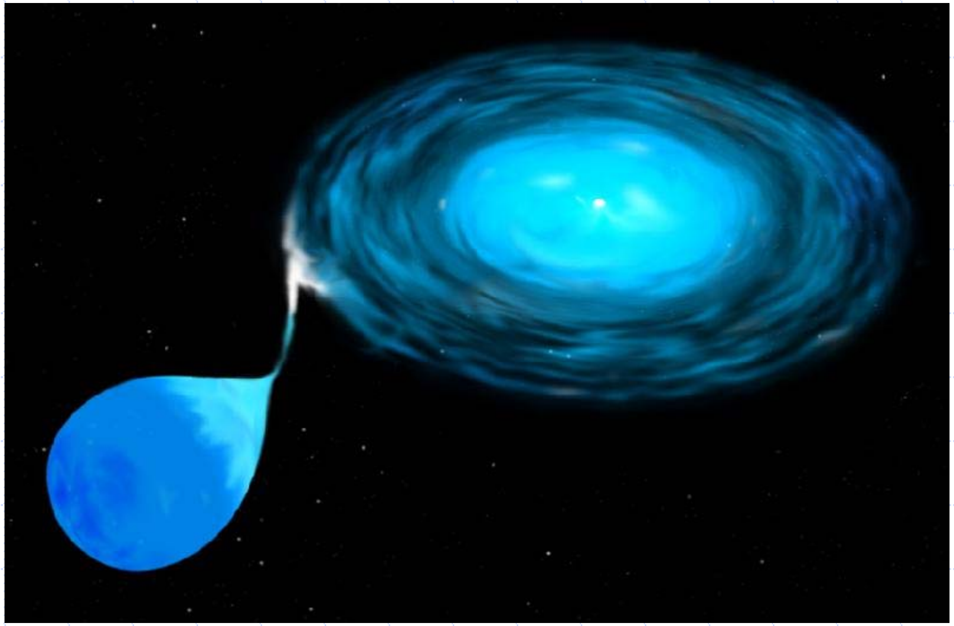
Becomes a white dwarf

accretion disk is formed, much mass is transferred from its companion

10.5 Fate of binary stars

✓Friction and tidal forces make the disk very hot (~ 1 million K), emitting high energy radiation (e.g. UV radiation, X-rays)

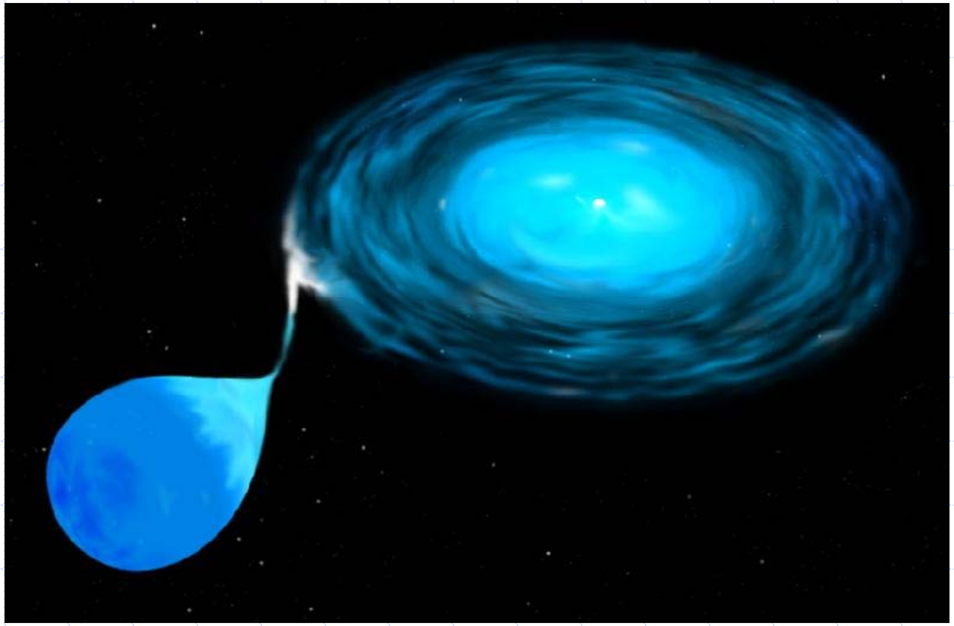
✓The white dwarf grows hotter and denser.



10.5 Fate of binary stars

✓Triggering by ignition of fusion and the instability, causes explosion, called *nova* as observed on the Earth, and

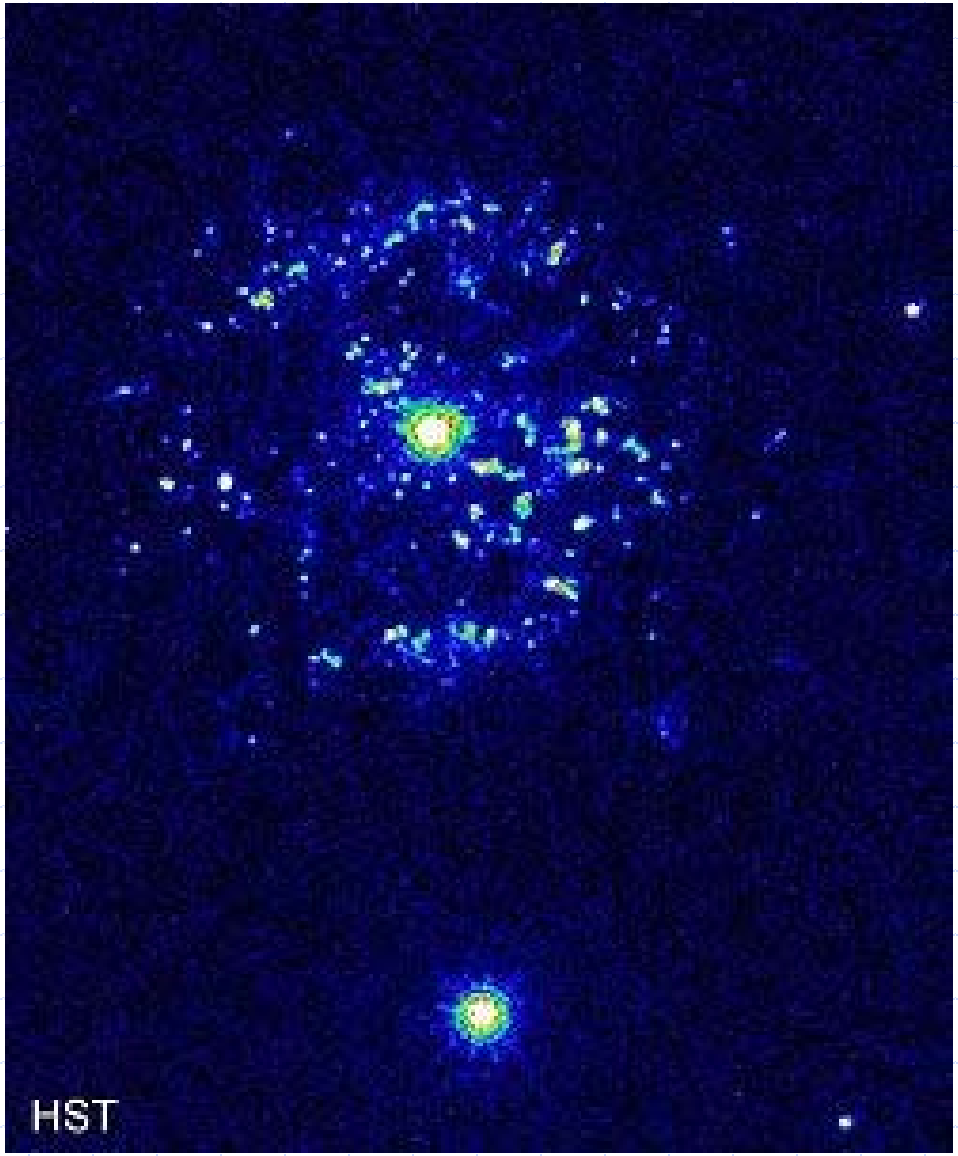
✓the explosion pushes the outer layer outward



10.5 Fate of binary stars

- Mass transfer may resume afterward
- the process repeats, it takes a few years to thousands of years to build an explosion again
- the star is also be called a *recurrent nova* (再發新星)

Example of recurrent nova: T Pyxidis (羅盤座T)



- ✓ apparent magnitude ~15.5
- ✓ But occurred eruptions with maximal magnitude of ~7.0 in 1890, 1902, 1920, 1944, 1966 and 2011
- ✓ Evidence indicates T Pyxidis have increased in mass, and is now close to the Chandrasekhar limit. It might then explode as a Type Ia supernova

Popular English nursery rhymes:

Twinkle, twinkle, little star,
How I wonder what you are!
……

You may sing that old English rhymes in the following way:

Twinkle, Twinkle little star,
I don’t wonder what you are;
For by spectroscopic ken,
I know you are hydrogen;
Twinkle, Twinkle little star,
I don’t wonder what you are.