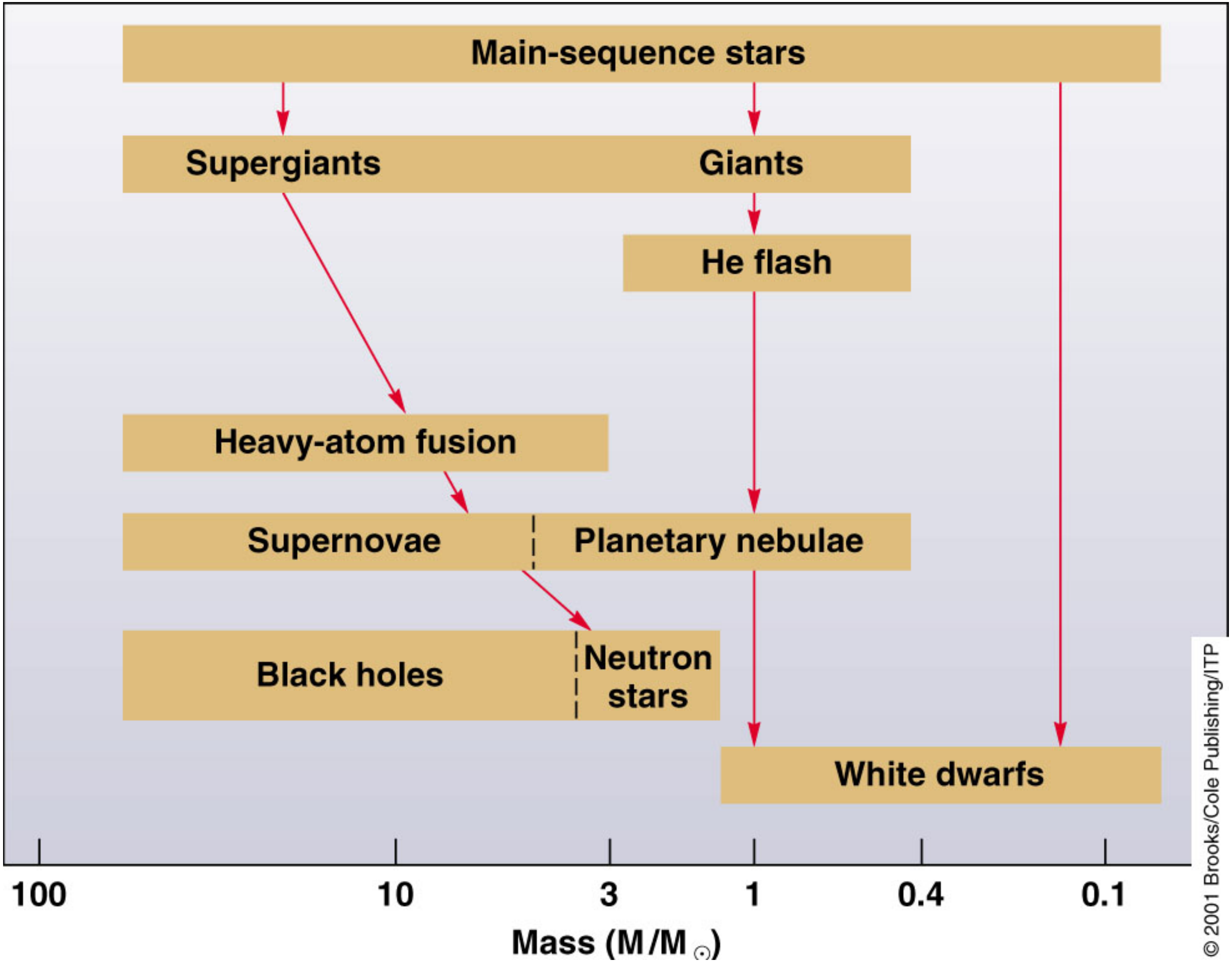
White dwarfs


Main-sequence stars
Supergiants
Giants
He flash
Heavy-atom fusion
Supernovae
Planetary nebulae
Black holes
Neutron stars
White dwarfs
100
10
3
1
0.4
0.1
Mass (M/M☉)

Degenerate objects

In the leftover core of a dead star…

- degeneracy pressure supports the star against the crush of gravity

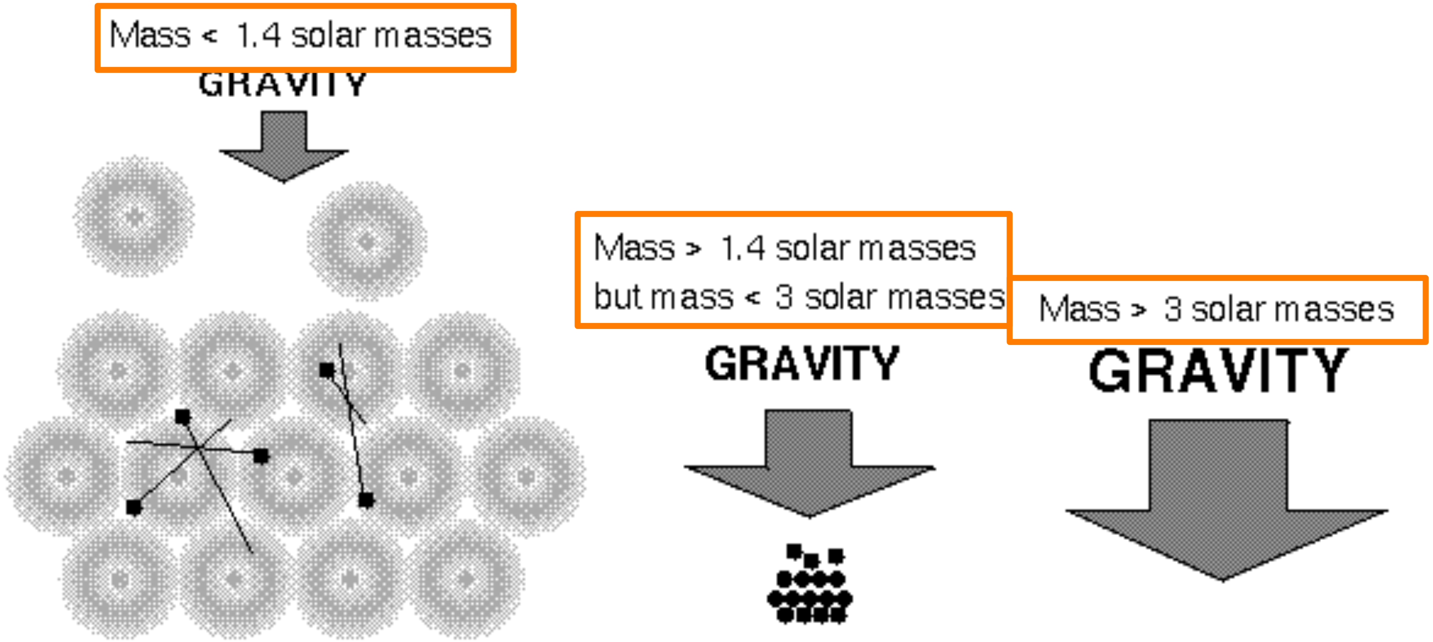
A degenerate star which is supported by:

- *electron degeneracy* pressure is called a **white dwarf**
- *neutron degeneracy* pressure is called a **neutron star**

If the remnant core is so massive that the force of gravity is greater than neutron degeneracy pressure…

- the star collapses out of existence and is called a **black hole**

The bizarre stellar graveyard



White Dwarf

Electrons run out of room to move around. Electrons prevent further collapse. Protons & neutrons still free to move around.

Stronger gravity => more compact.

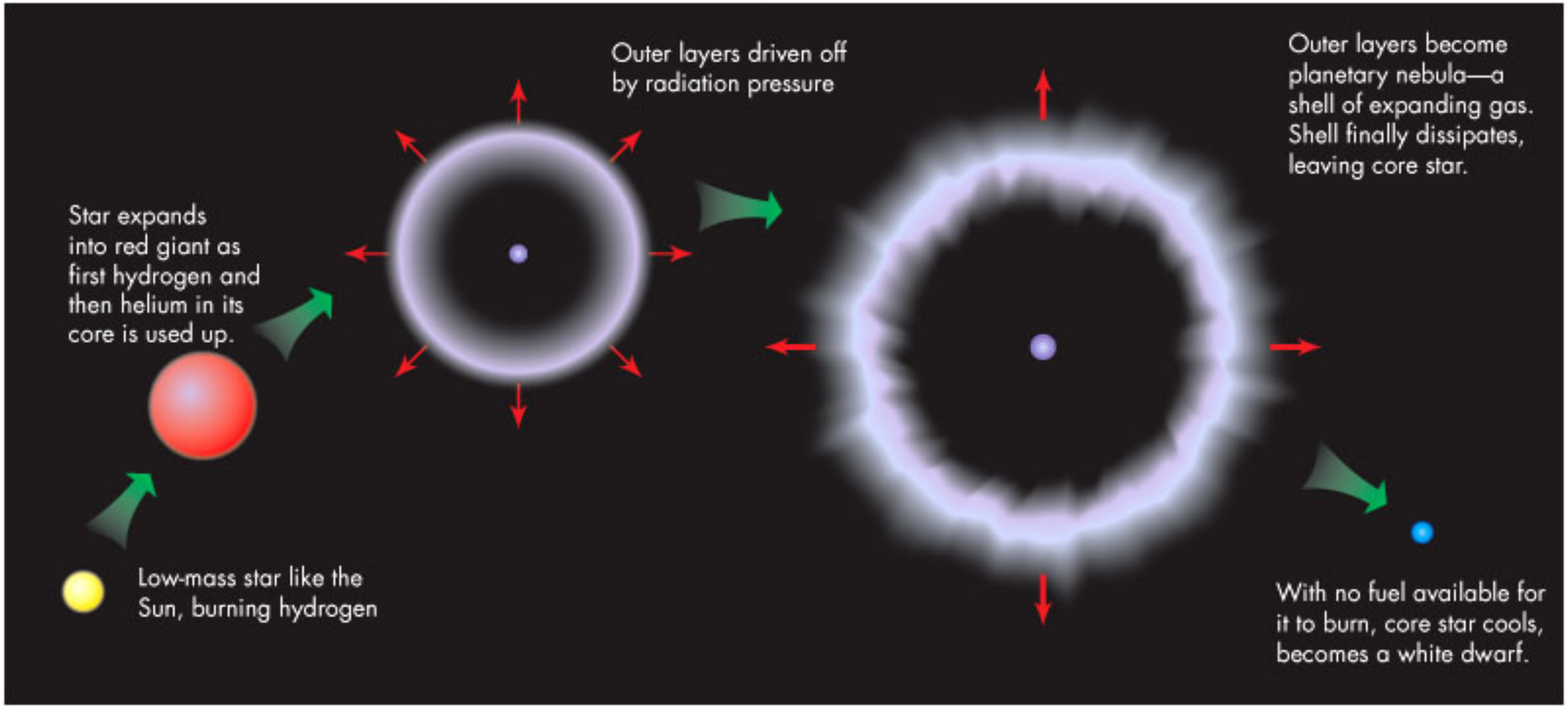
Neutron Star

Electrons + protons combine to form neutrons. Neutrons run out of room to move around. Neutrons prevent further collapse. Much smaller!

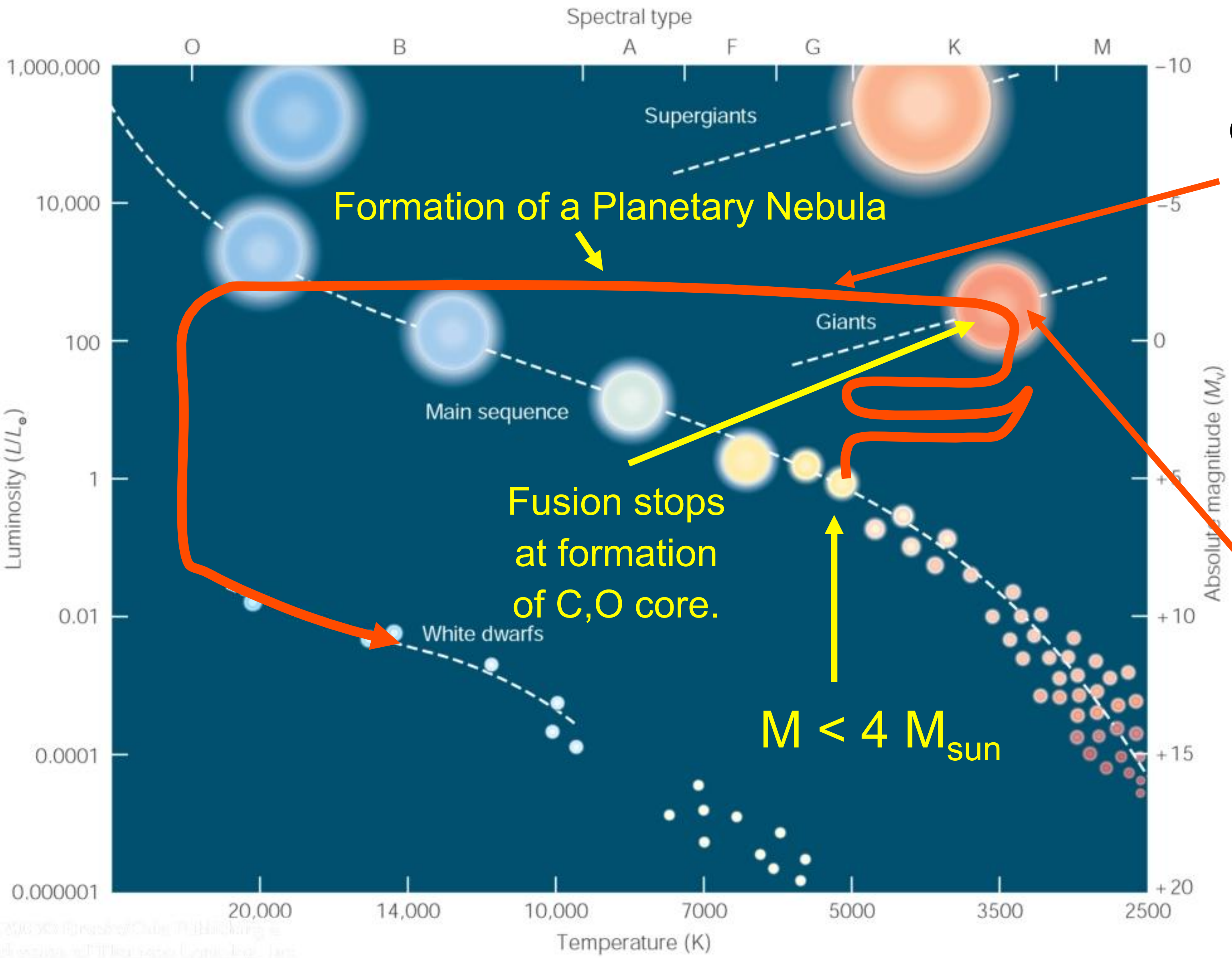
Black Hole

Gravity wins! Nothing prevents collapse.

White dwarfs in stellar evolution



$M<8M_{\odot}$: after the red giant phase, the star gets rids of its outer layers becoming a planetary nebula. When the shell dissipates, only the core star (white dwarf), with a degenerate nucleus, is left



Core collapses; outer shells bounce off the hard surface of the degenerate C,O core

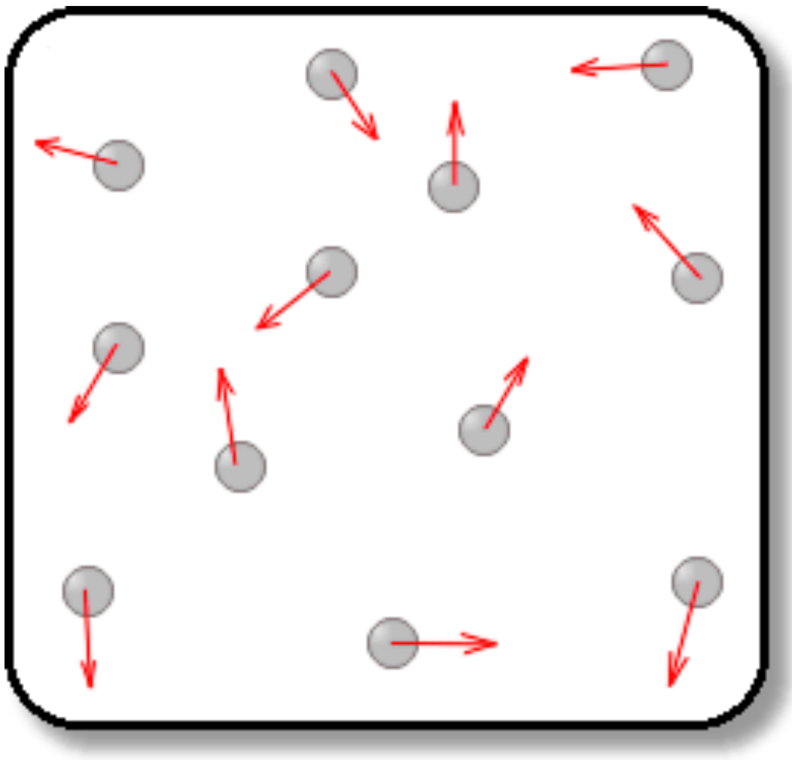
C,O core becomes degenerate

White dwarf: main properties

- 1.4 Solar masses (Chandrasekhar limit) and below
- After a Red Giant has shed its planetary nebula, if a mass of 1.4 times that of our Sun or lower remains, the star collapses due to gravity and becomes a white dwarf
- A 1.4 $M_{\odot}$ star can exert an outward pressure equal to the inward force of gravity. The pressure comes from Electron Degeneracy
- The more massive a White dwarf the smaller its radius
- A White Dwarf just at this mass has the highest density and the smallest radius possible for electron degeneracy to keep it stable. More mass and the star will gravitationally collapse further
- The high surface gravity causes lighter elements to be separated by heavier elements ➔ observed H-dominated and He-dominated spectra

Normal gas

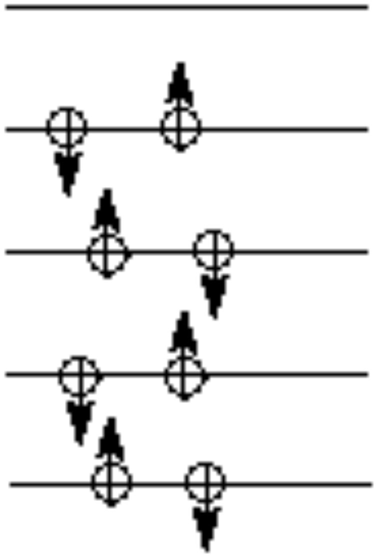
- Pressure is the force exerted by atoms in a gas
- Temperature is how fast atoms in a gas move



- Hotter → atoms move faster → higher pressure
- Cooler → atoms move slower → lower pressure

$$PV = NkT$$

Electron energy level



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

- Only two electrons (one up, one down) can go into each energy level (*Pauli Exclusion Principle*).
- In a *degenerate gas*, all low-energy levels are filled according to Pauli principle.
- Electrons have energy, and therefore are in motion and exert pressure even if temperature is zero.
- White dwarfs are supported by electron degeneracy.

Electron degeneracy pressure

Pauli Exclusion principle – two particles cannot be in the same quantum state (i.e. quantum numbers that describe energy level, spin must differ).

Degenerate gas - compressed/cooled gas such that all electrons are in lowest energy levels allowed by exclusion principle

Heisenberg Uncertainty principle - $\Delta p \, \Delta x \geq h/2\pi$

Since particle's location (Δx) is extremely confined, momentum (Δp) is very uncertain and particles are moving extremely fast → this leads to high pressure for a degenerate gas.

$$P = 2(h/2\pi)^2 \, (Z/A)^{5/3} \, (\rho/m_p)^{5/3} \, /m_e$$

A is the atomic mass number, Z is the charge number (# of e^- carried by each ion)

Chandrasekhar found the maximum pressure exerted by a degenerate electron gas with v = c allowing for special relativistic effects. This pressure corresponds to a maximum mass of 1.44 $M_\odot$.

Some calculations (I)

$$\Delta x \Delta p \approx \hbar$$

Heisenberg's uncertainty principle

Δx=distance between electrons ≈ $1/n_e^{1/3}$

Δp=uncertainty on the momentum of the particles

n_e=number of electron per unit volume

N_e=total number of electrons available

$$p \approx \Delta p \approx \hbar / \Delta x \approx \hbar n_e^{1/3}$$

Momentum of an electron

$$E \approx \frac{1}{2} m_e \mathrm{v}^2 = \frac{p^2}{2m_e} \approx \frac{\hbar^2 n_e^{2/3}}{2m_e}$$

Energy of a typical electron (≈Fermi energy)

$$E_{tot,\deg} \approx N_e E = \frac{N_e \hbar^2 n_e^{2/3}}{2m_e}$$

Total degeneracy energy

Some calculations (II)

$$N_e = M\frac{Z}{Am_p} = \frac{M\beta}{m_p}$$

$$n_e = \frac{N_e}{V} \approx \frac{N_e}{R^3}$$

M=Mass of the star
Z=number of electrons per atom
A=atomic mass (number of nucleons per atom)
R=radius of the star
β=Z/A

$$E_{tot} = \frac{N_e \hbar^2 n_e^{2/3}}{2m_e} = \frac{N_e^{5/3}\hbar^2}{2m_e R^2} = \frac{\hbar^2 \beta^{5/3}}{2m_e m_p^{5/3}} M^{\frac{5}{3}} R^{-2}$$

Equilibrium: $E_{tot,deg} = E_{gr} = GM^2/R$

$$\frac{\hbar^2 \beta^{5/3}}{2m_e m_p^{5/3}} M^{\frac{5}{3}} R^{-2} = \frac{GM^2}{R} \rightarrow R = \frac{\hbar^2 \beta^{5/3}}{2Gm_e m_p^{5/3}} M^{-\frac{1}{3}}$$

$$R \propto M^{-1/3}$$

Some calculations (III)

$$R \approx 2\times 10^4 \left(\frac{\beta}{0.5}\right)^{5/3} \left(\frac{M}{M_{sun}}\right)^{-1/3} \text{ km}$$

Not-relativistic case

$$P = \frac{n_e}{m_e} p^2 \propto \rho^{5/3}$$

Pressure depends only on density [≠f(T,ρ)]

$$E \approx pc \approx \hbar n_e^{1/3} c$$

Relativistic case

$$E_{tot,\deg} = N_e E \approx \frac{\hbar \beta^{4/3} c}{m_p^{4/3}} M^{\frac{4}{3}} R^{-1}$$

$$M_{Ch} \approx \left(\frac{\hbar \beta^{4/3} c}{G m_p^{4/3}}\right)^{3/2} \approx 5.9 \beta^2 M_{sun}$$

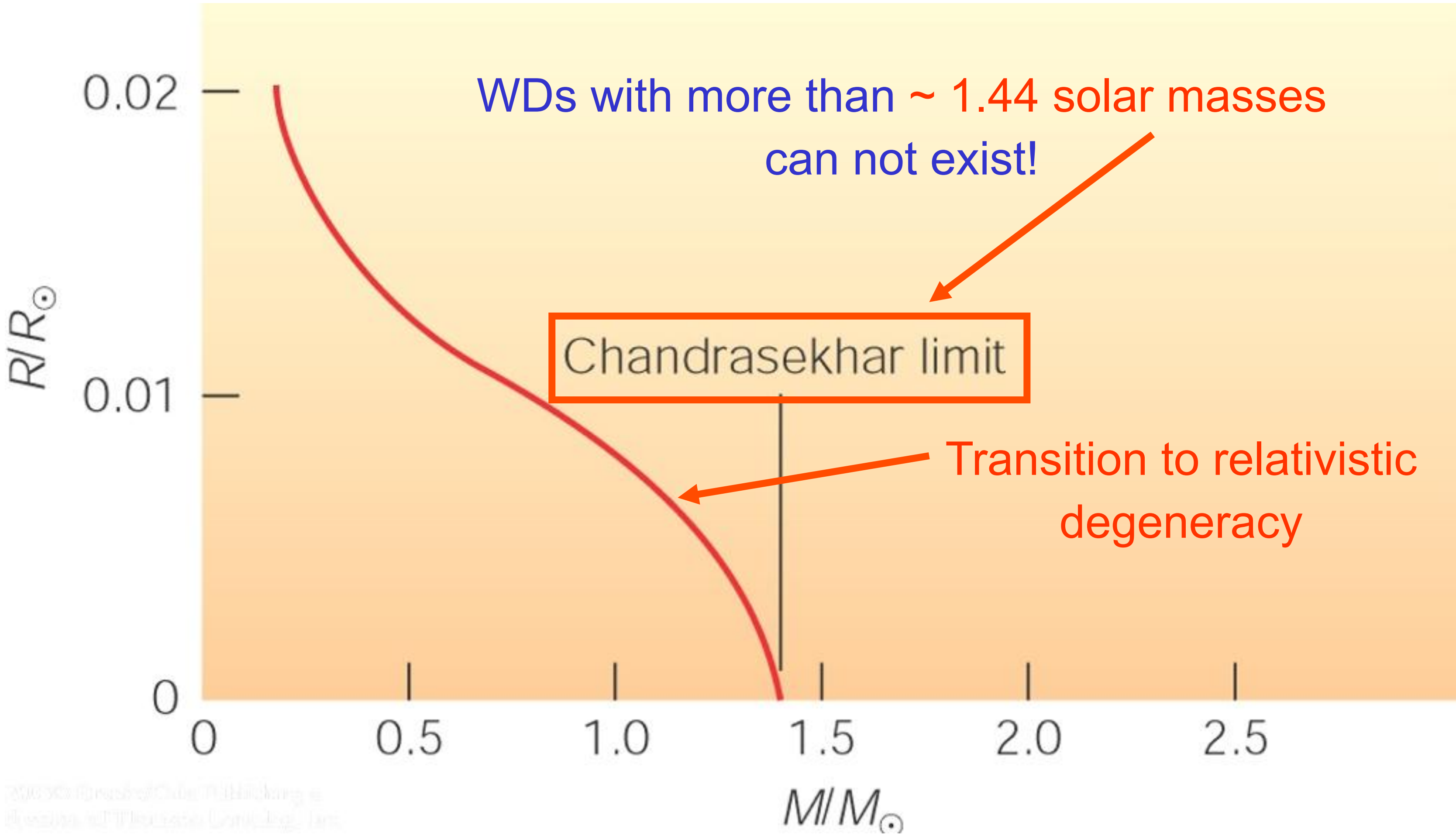
$$P \approx 0.8 \hbar c \beta^{4/3} \left(\frac{\rho}{m_p}\right)^{4/3} \propto \rho^{4/3}$$

Chandrasekhar mass (limit for a WD) ≈ 1.4$M_{\odot}$ → gravity overcomes the resistence of P_{deg}. The resulting collapse raises T → C+O in the core starts to fuse → explosive wave propagating through the core rapidly → solar mass of radioactive ^{56}Ni and ~10^{52} erg release of energy, disrupting the ★

The Chandrasekhar limit

The more massive a white dwarf, the smaller it is.

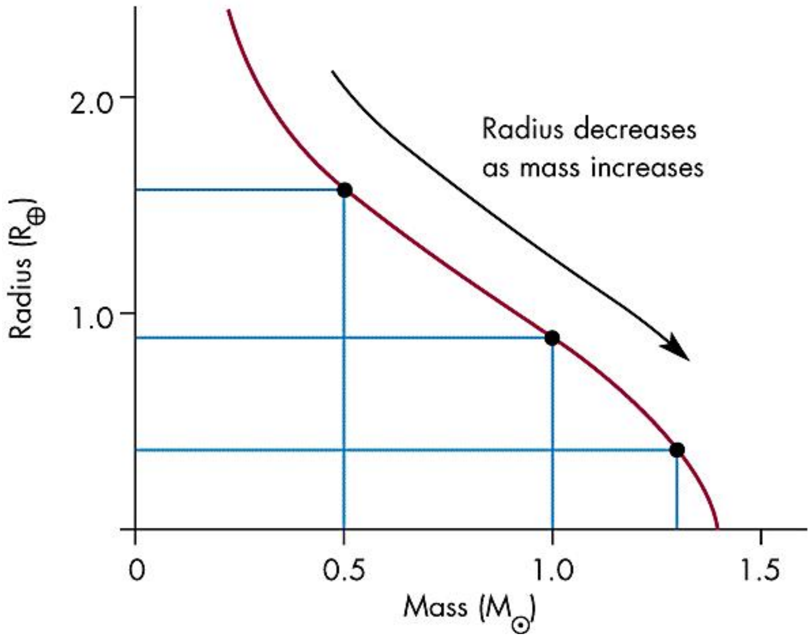
$R_{WD} \sim M_{WD}^{-1/3}$ => $M_{WD} V_{WD}$ = const. (non-rel.)



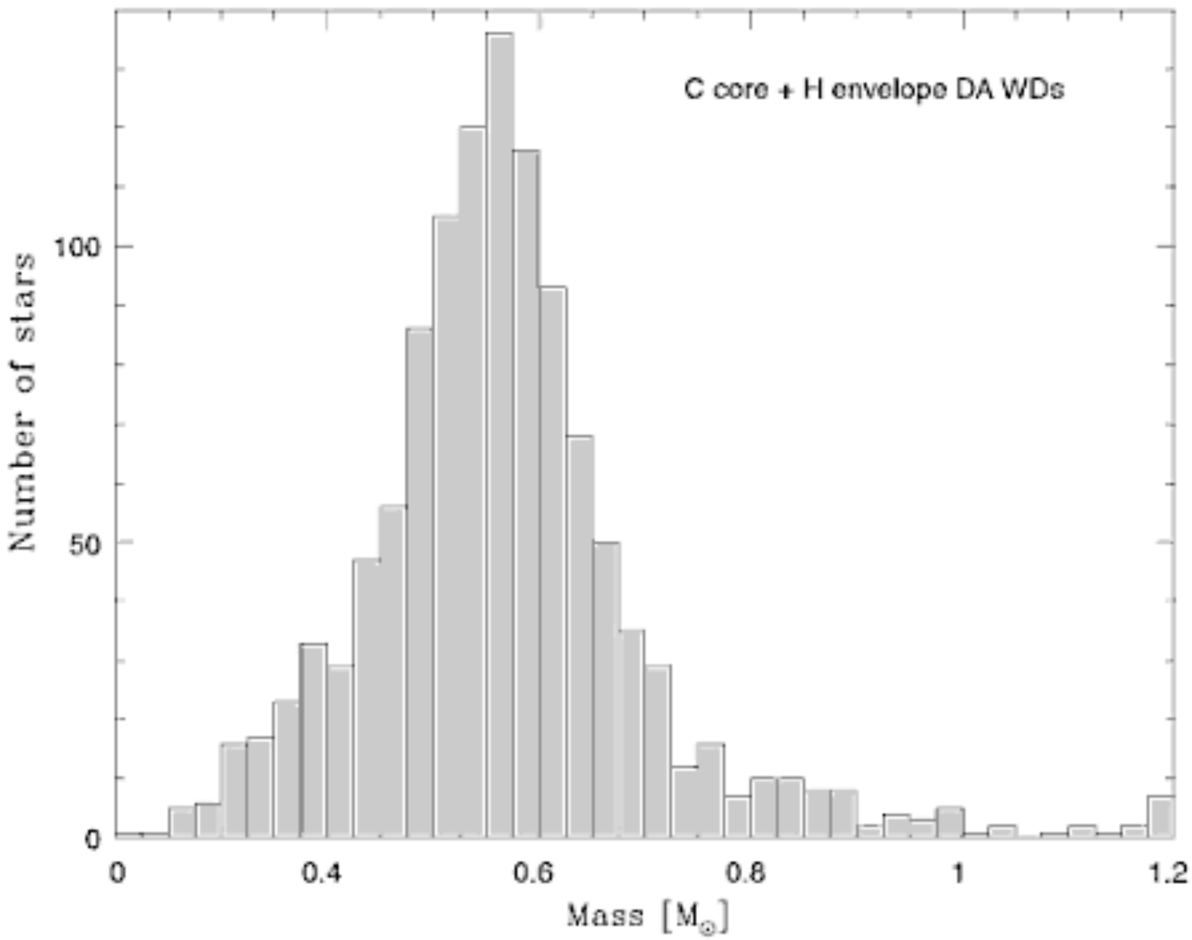
WDs with more than ~ 1.44 solar masses can not exist!

Transition to relativistic degeneracy

Mass vs. radius relation



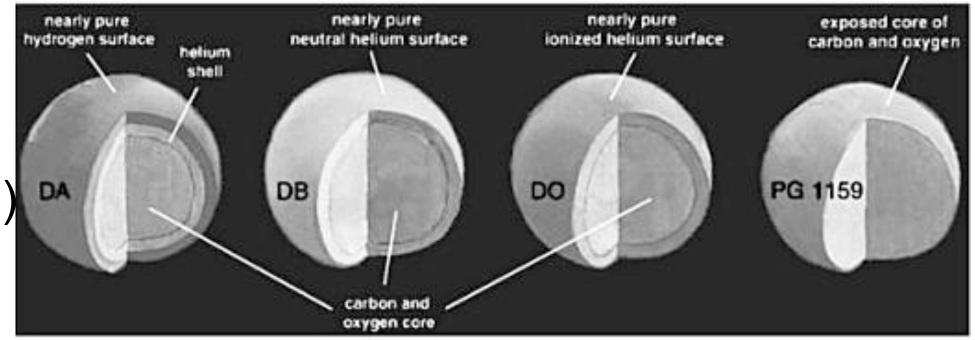
Mass distribution



White dwarf: classification

Surface compositions

- DA: strong H lines (≈80% pop.)
- DB: strong He I lines (≈15% pop.)
- DO: strong He II lines
- DC: no strong lines (continuous spectrum)
- DZ: strong metal lines (excluding C)
- DW: strong C lines



DA – H-rich, H Balmer lines, normal stellar evolution

not-DA – H-poor, He lines ➔ late He-shell flash in the early cooling phase

➔ re-traces the post-AGB evolution

➔ H burns again + convective mixing

➔ He, C, and O-rich materials dredged up to the surface

not-DA ↓ typically very hot

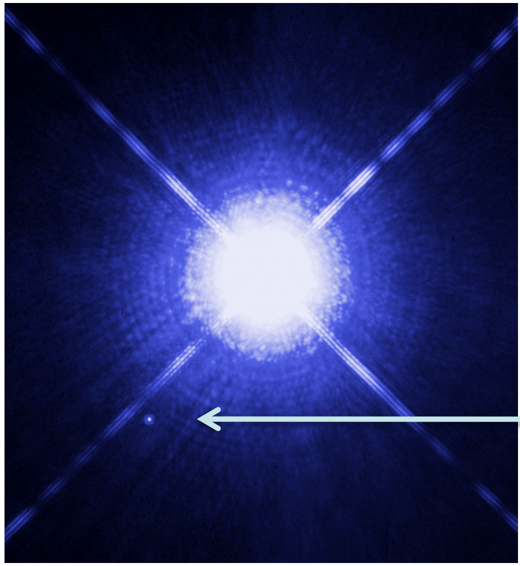
DA: wide range of T (lower envelope of DO temperatures)

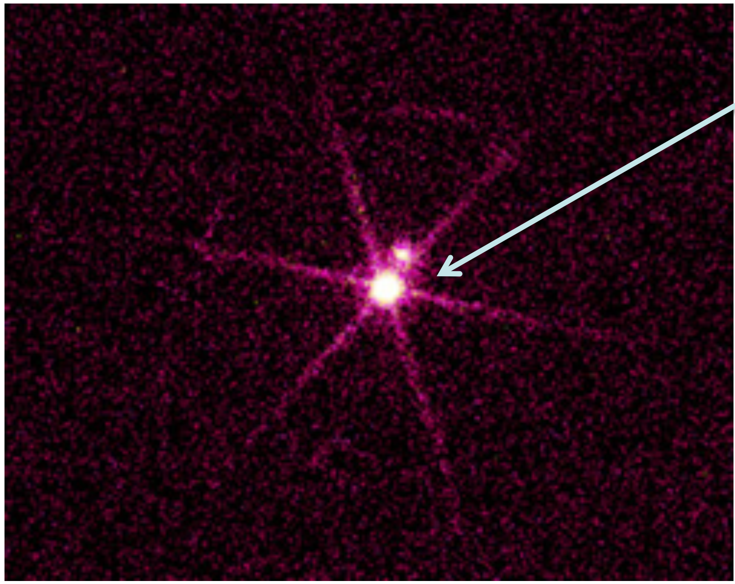
DO: T≈45000−120000 K (HeII)

DB: T≈12000−30000 K (HeI)

DC: T<12000 K

White dwarfs in X-rays





First example:

Sirius B - discovered in 1862

$M \approx 1\ M_\odot$

$L \approx 0.03\ L_\odot$

$T_e \approx 27{,}000$ K

$\Rightarrow R \approx 0.008\ R_\odot$

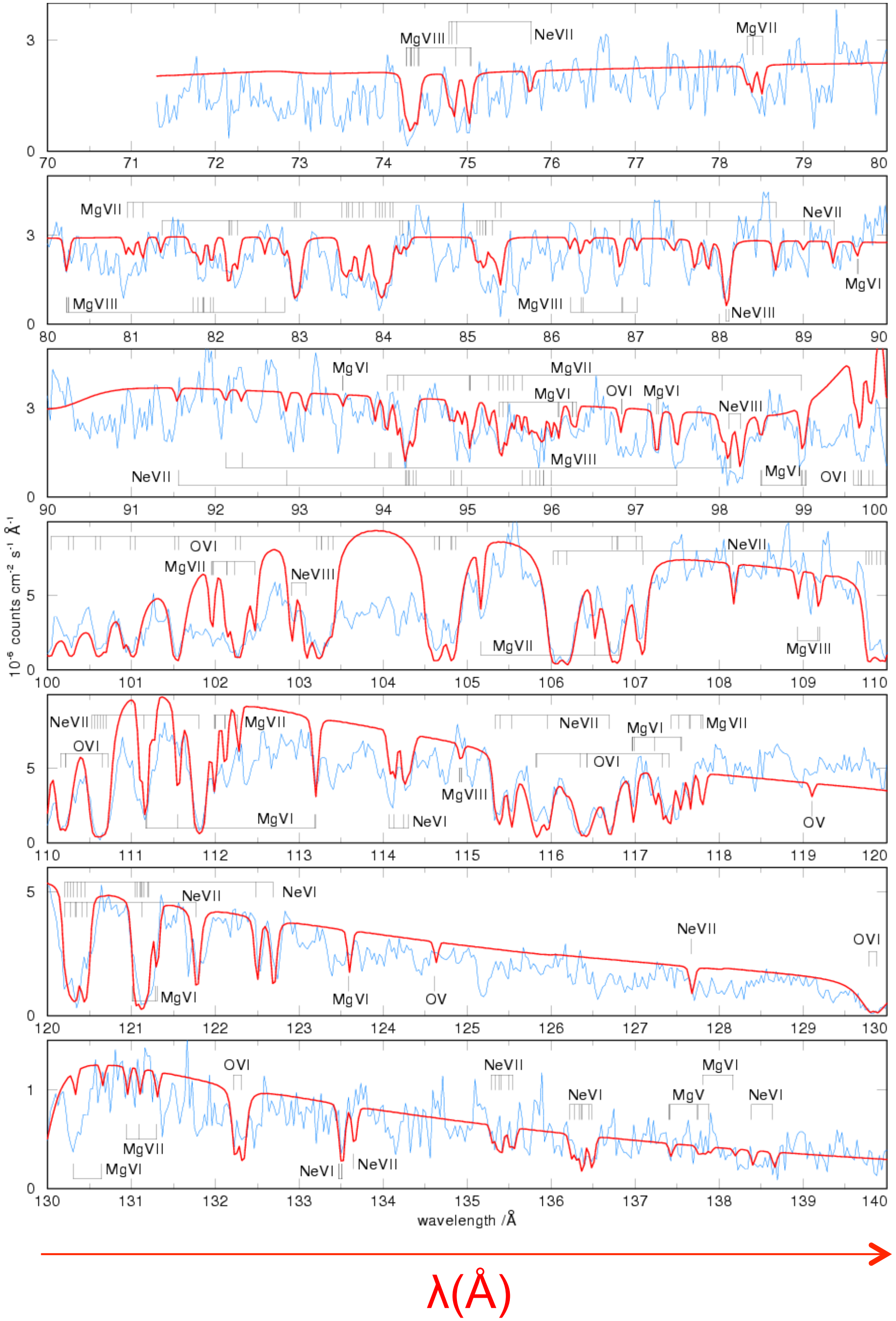
$\Rightarrow \rho \approx 3 \times 10^6\ g/cm^3$

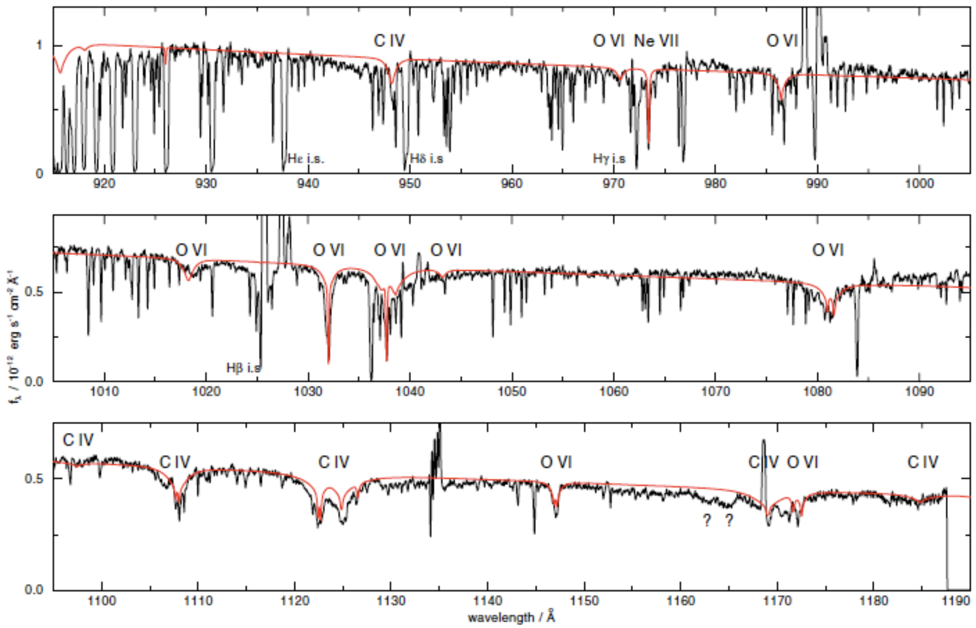
What causes the UV and soft X-ray emission

- *High-energy photons in the deep and hot inner layers of the star* are responsible for the emission, well parameterized by pure H models for atmospheres. The low opacity of the atmosphere allows soft X-ray emission to be detected
- At T_{eff}<40,000, these models predict an X-ray flux which is often much larger than that measured
- Original surveys with *ROSAT* (RASS) predicted more X-ray bright WDs than actually discovered

➔ Indications of the presence of metals in the atmosphere, increasing the opacity to X-ray photons, but strong ionization reduces the opacity in the soft X-ray band

- X-ray emission is expected to be soft, but some (<10) WDs are hard X-ray emitters (50% of which are among the hottest WDs) ➔ thermal origin from very deep photospheric layers?
- PG1159 star-class: non-DA progenitors, T>140,000K: high C+O abundance and He in their photospheres. Hot enough to suppress He II opacity





H1504+65: *Chandra* and *FUSE* high-resolution spectra + model (red line)

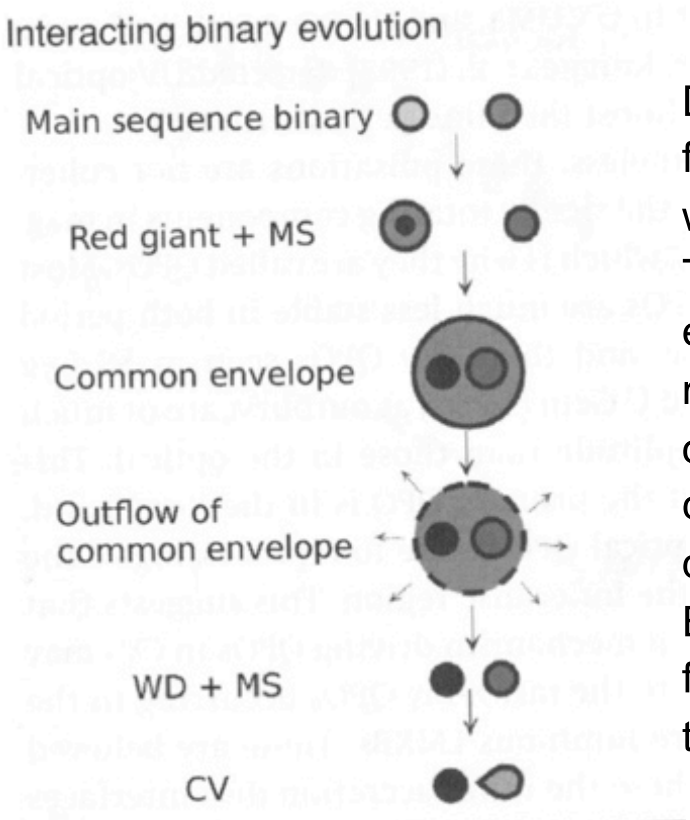
Naked CO WD or WD with O-Ne-Mg core after C burning?

T_{eff}≈200,000K (highest T measured)

Good models required to account for vertical stratification of chemical abundances

White dwarf in binary systems

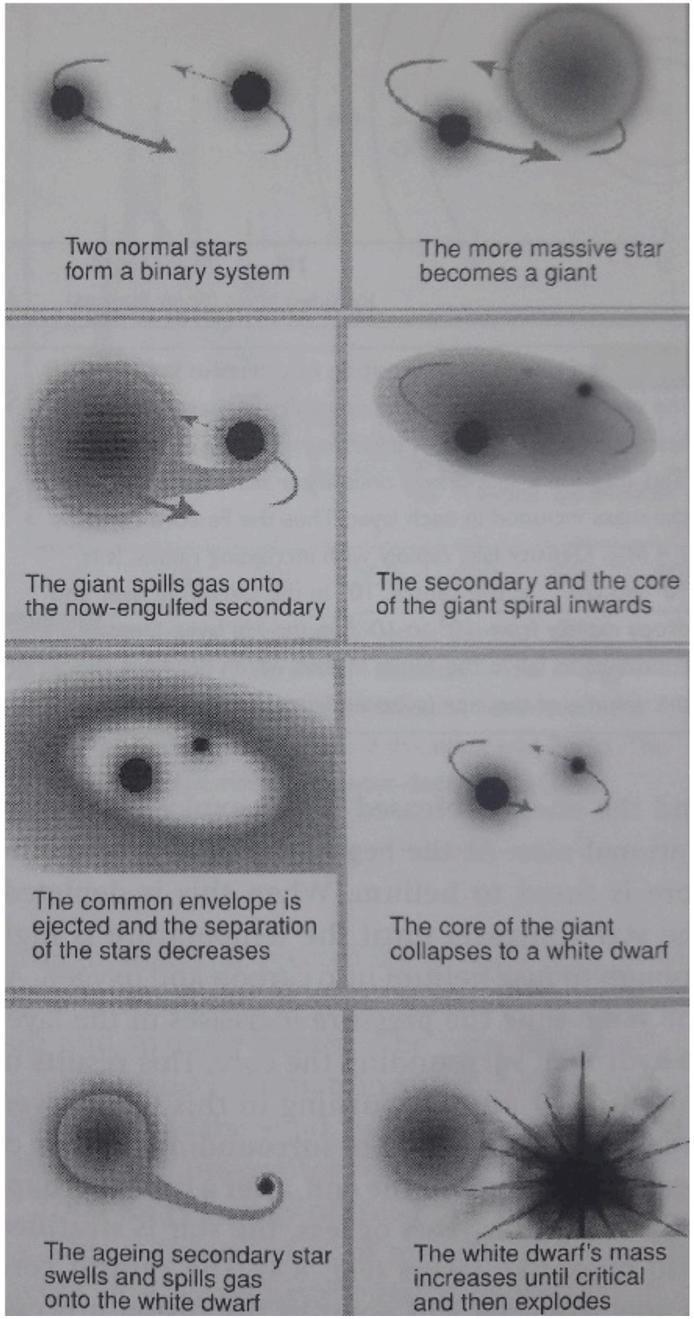
From main-sequence stars to a CV



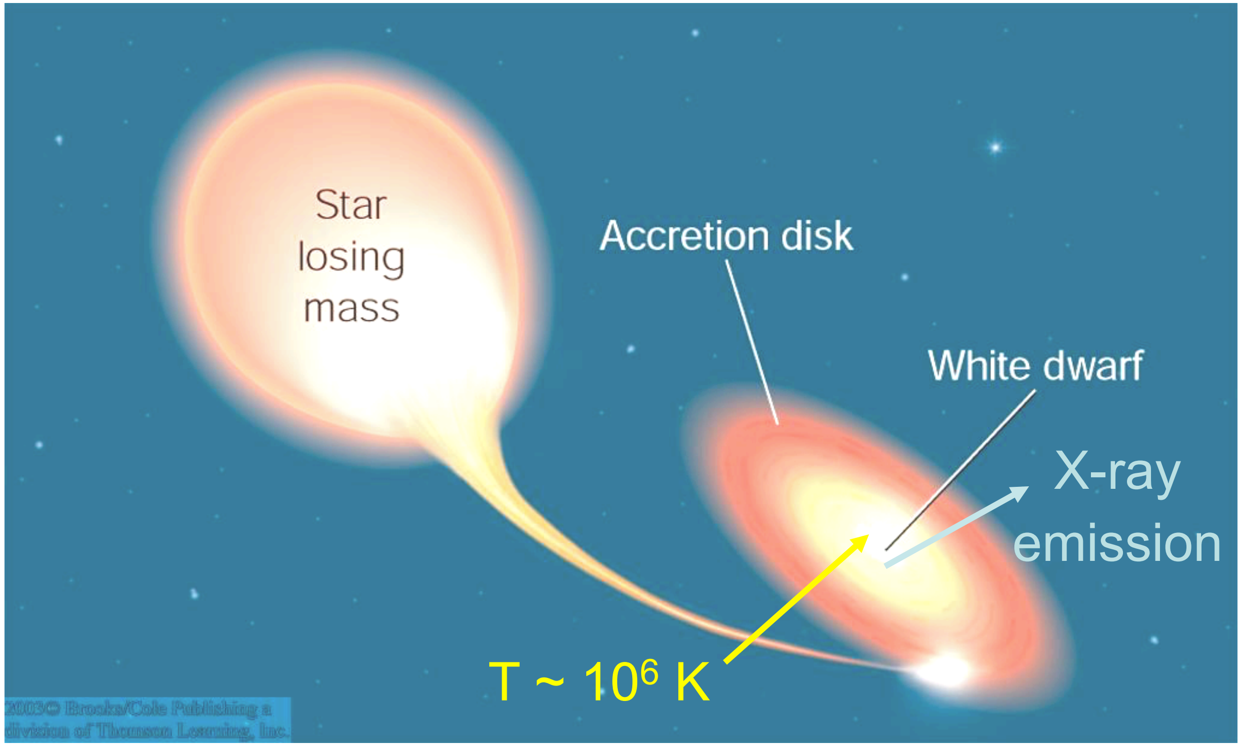
Double stars are easily produced in large star-forming regions (e.g., the Orion Nebula), with wide separations and orbital periods of years. The most massive star of the system will evolve more rapidly and start expanding into a red giant; its atmosphere will embrace the other star, which will then spiral in towards the core of the red giant (because of atmospheric drag) ➔ common tenuous envelope

Eventually the companion star will evolve and fill its own Roche lobe ➔ mass transfer onto the WD

From a binary star system to a WD explosion



White dwarfs in binary systems



Binary consisting of WD + MS or Red Giant star ➔ WD accretes matter from the outer layers of the companion star

Angular momentum conservation => accreted matter forms a disk, called accretion disk.

Matter in the accretion disk heats up to ~ 1 million K ➔ X-ray emission ➔ “X-ray binary”.