CHAPTER 11

EVOLUTION OF WHITE DWARFS

remnants of stars M < ~8 solar masses

AGB STARS

outstanding features

1. Nuclear burning takes place in shells, leading to a long series of thermal pulses

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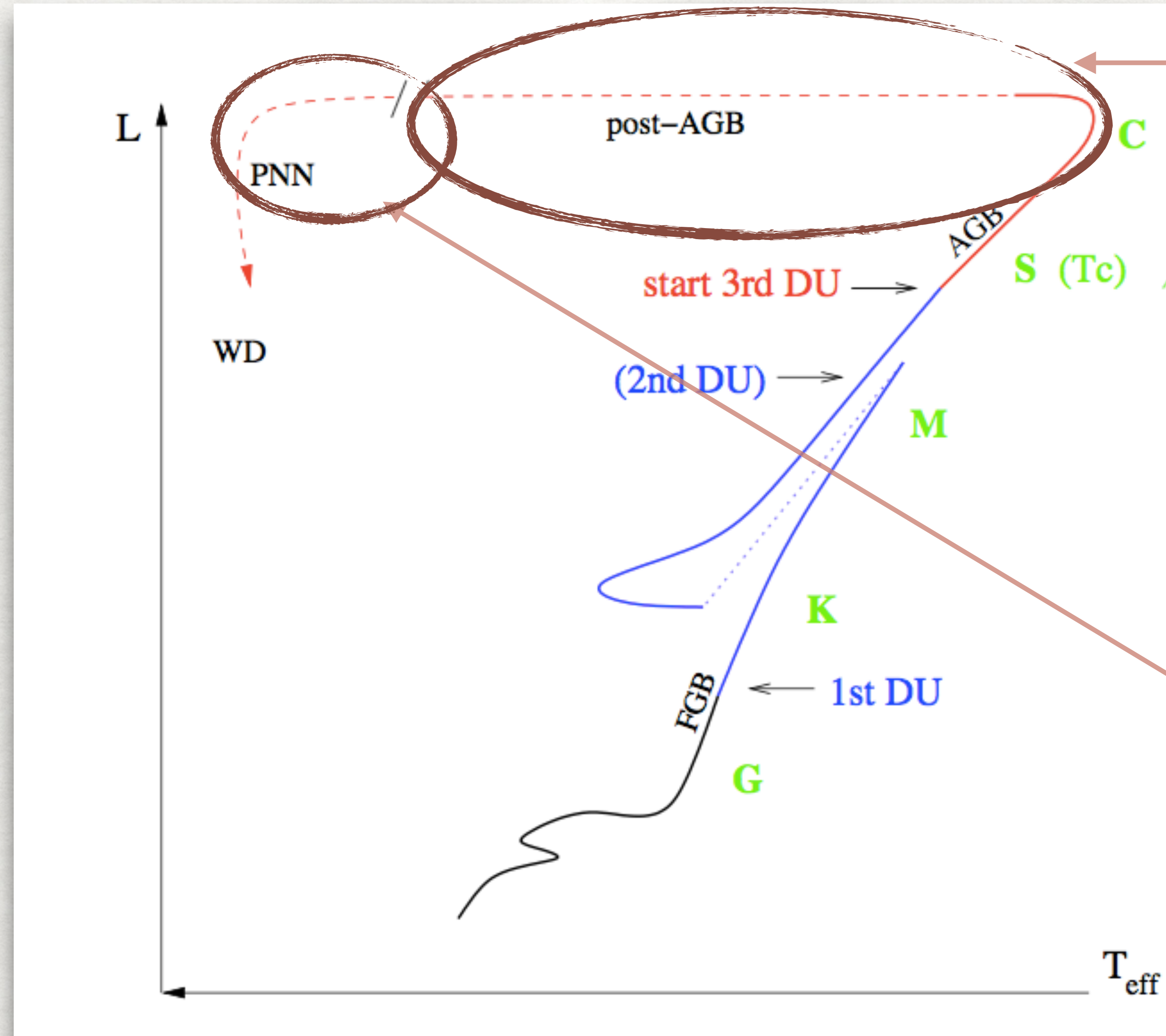
outstanding features

1. Nuclear burning takes place in shells, leading to a long series of thermal pulses

2. The luminosity is uniquely determined by the core mass, independently by the total mass

3. A strong stellar wind develops as a result of the high radiation pressure in the envelope and the star loses significant fraction of its mass

TOWARDS A WHITE DWARF



in the *post AGB* star follows an horizontal track

- L ~constant given by H-burning shell
- R of (left over) envelope contracts
- => T_{eff} increases for Stefan-Boltzmann's law

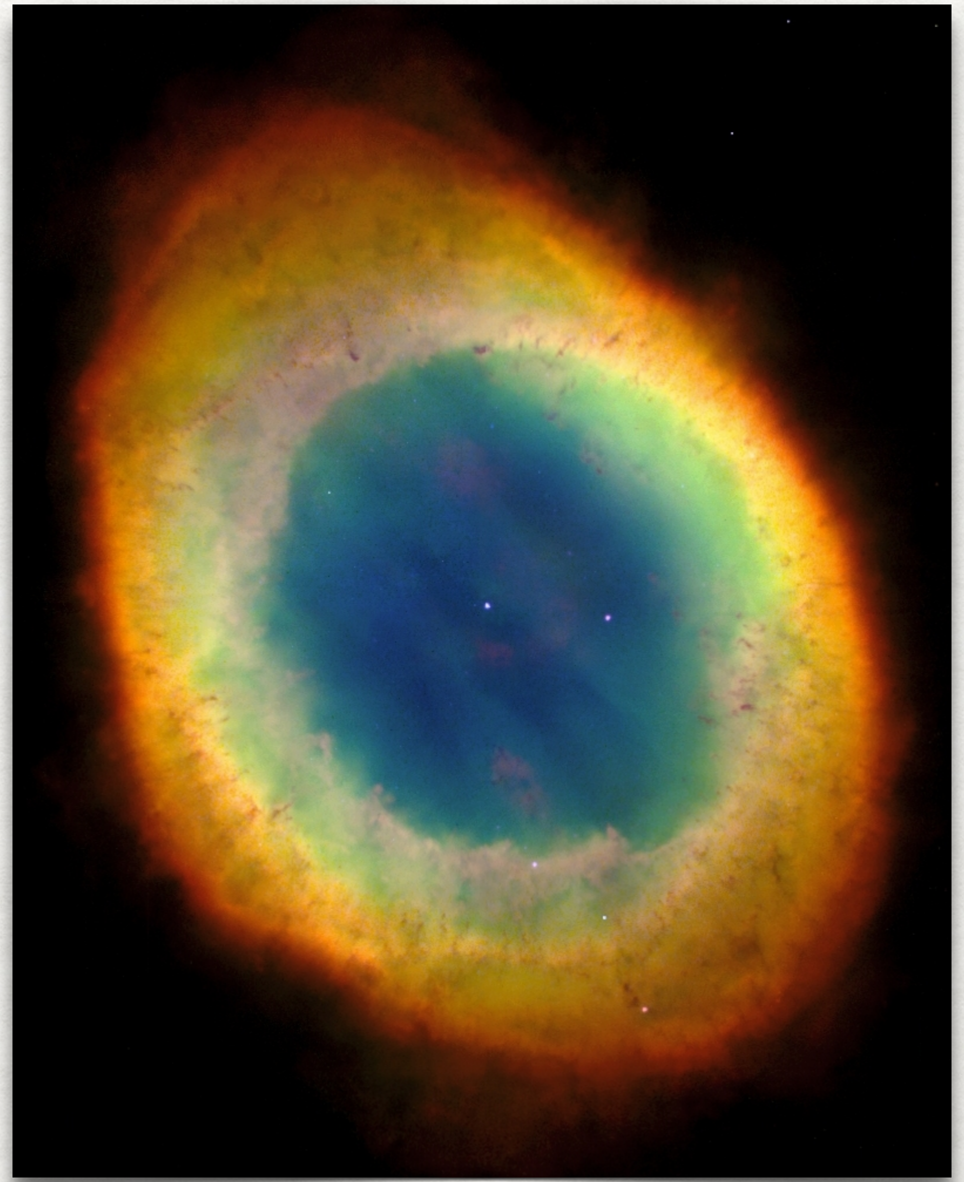
Planetary nebula phase :

When T_{eff} reaches 30000 K photons causes atoms in the ejected envelope to shine by fluorescence

PLANETARY NEBULAE

Herschel 1780 through they look like Uranus…

Dumbbell nebula
1st nebula observed 1764 by Messier



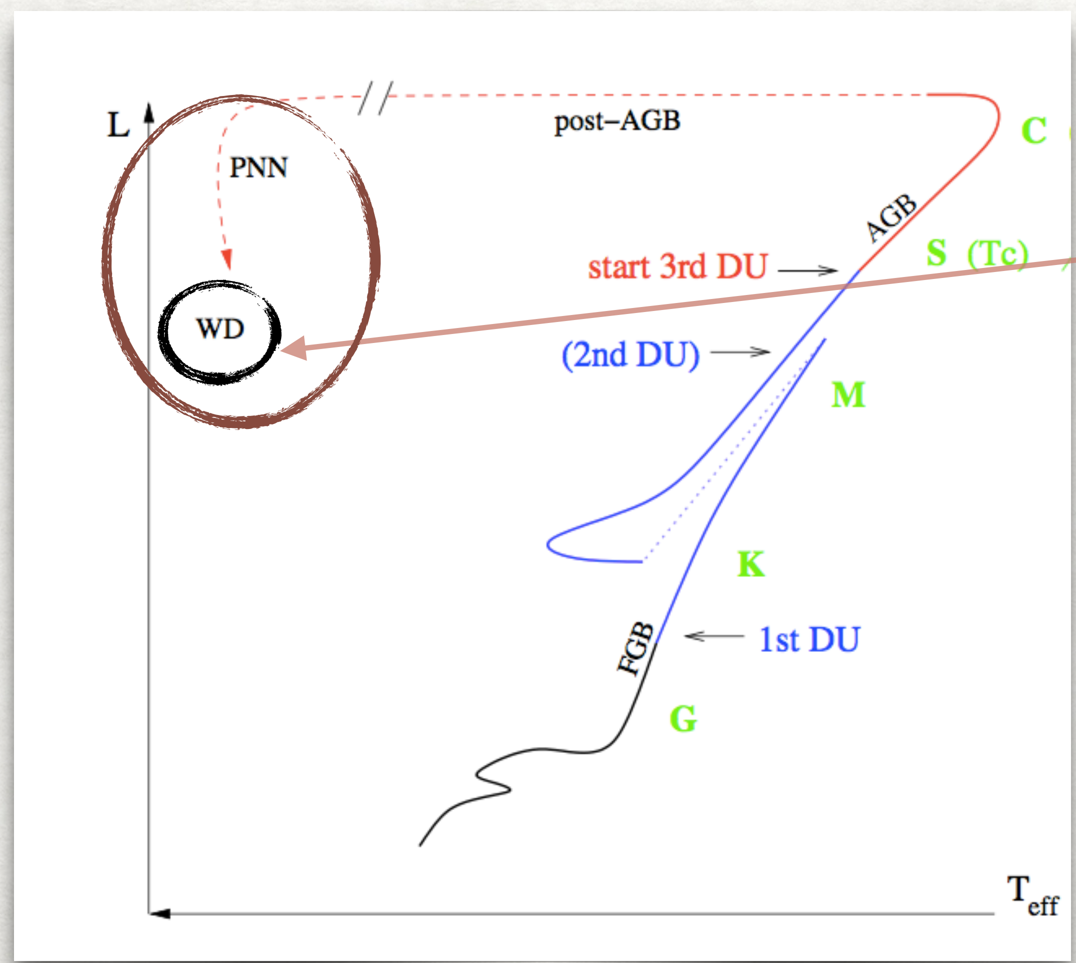
Ring nebula
2nd nebula observed 1779 (by Darquier)

LATE PLANETARY NEBULA PHASE

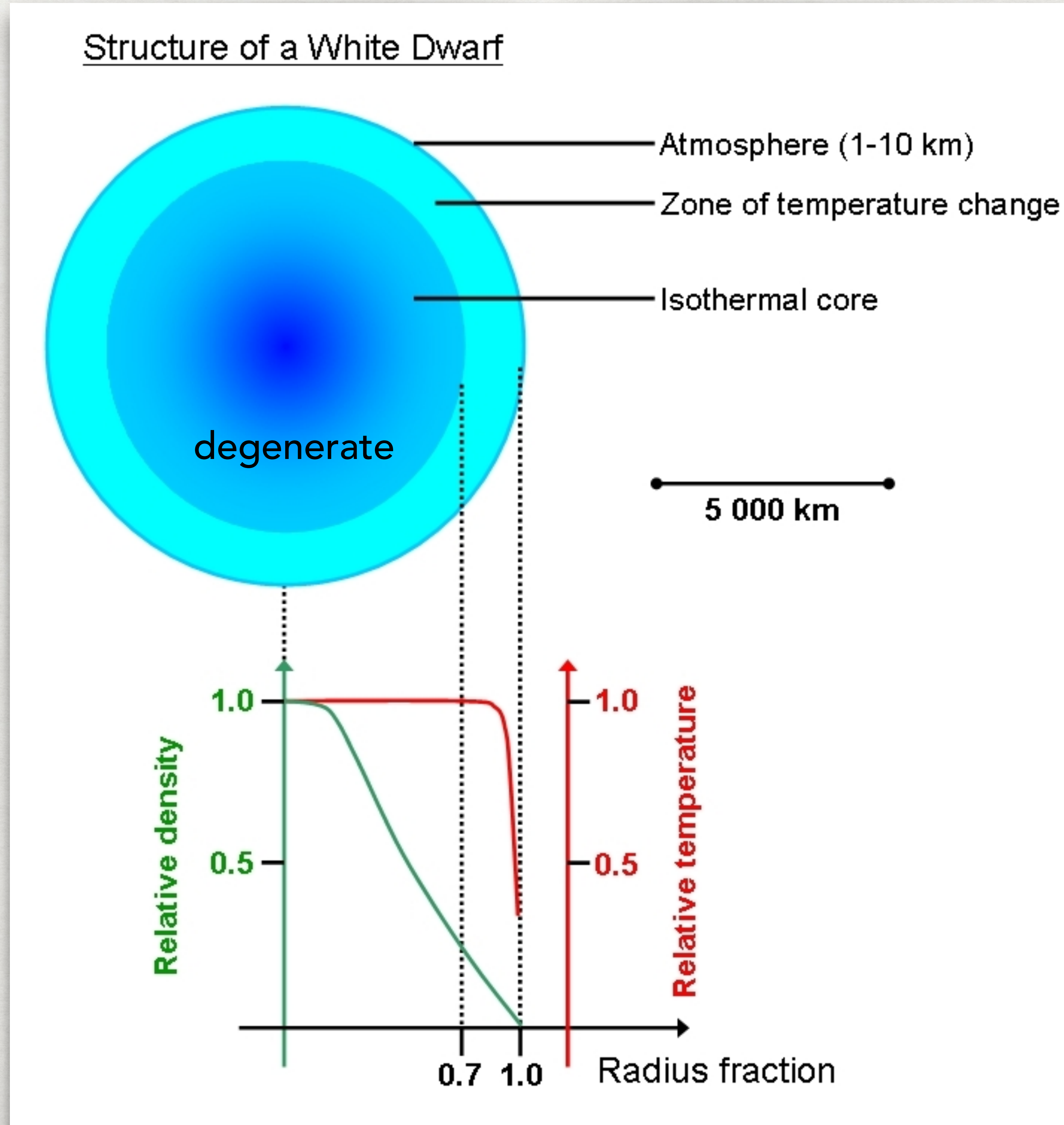
The H-fusion stops when the mass in the H-burning shell ~10^{-3}-10^{-4} M_{sun}

Luminosity decreases, its ionisation power drops and the wind moves outward the nebula (left over envelope) with a 10 km/s speed

The nebula grows in size and disperse: duration 10^4-10^5 yr



We are left with a degenerate C+O core that cools down: a white dwarf


Structure of a White Dwarf
Atmosphere (1-10 km)
Zone of temperature change
Isothermal core
degenerate
5 000 km
1.0
0.5
Relative density
1.0
0.5
Relative temperature
0.7
1.0
Radius fraction

WD COOLING

In the radiative layer:

$$\frac{dT}{dP} = \frac{T}{P}\nabla_{\rm rad} \propto \frac{L}{M}\frac{\kappa}{T^3}$$

where

Kramer opacity + ideal gas:

$$\kappa = \kappa_0 \rho T^{-7/2} \propto P T^{-4.5}$$

$$P = (\mathcal{R}/\mu)\rho T$$

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$$T^{17/2} \propto P^2$$

with P(R) = T(R) =0
zero boundary condition

using ideal gas law

$$\rho \propto T^{13/4}$$

with constants

$$\boxed{\rho = B^{-1/}\frac{\mu}{\mathcal{R}} T^{-13/4} \quad \text{with} \quad B = \frac{17}{4}\frac{3}{16\pi a c G}\frac{\bar{\kappa}_0 \mu}{\mathcal{R}}\frac{L}{M}}$$

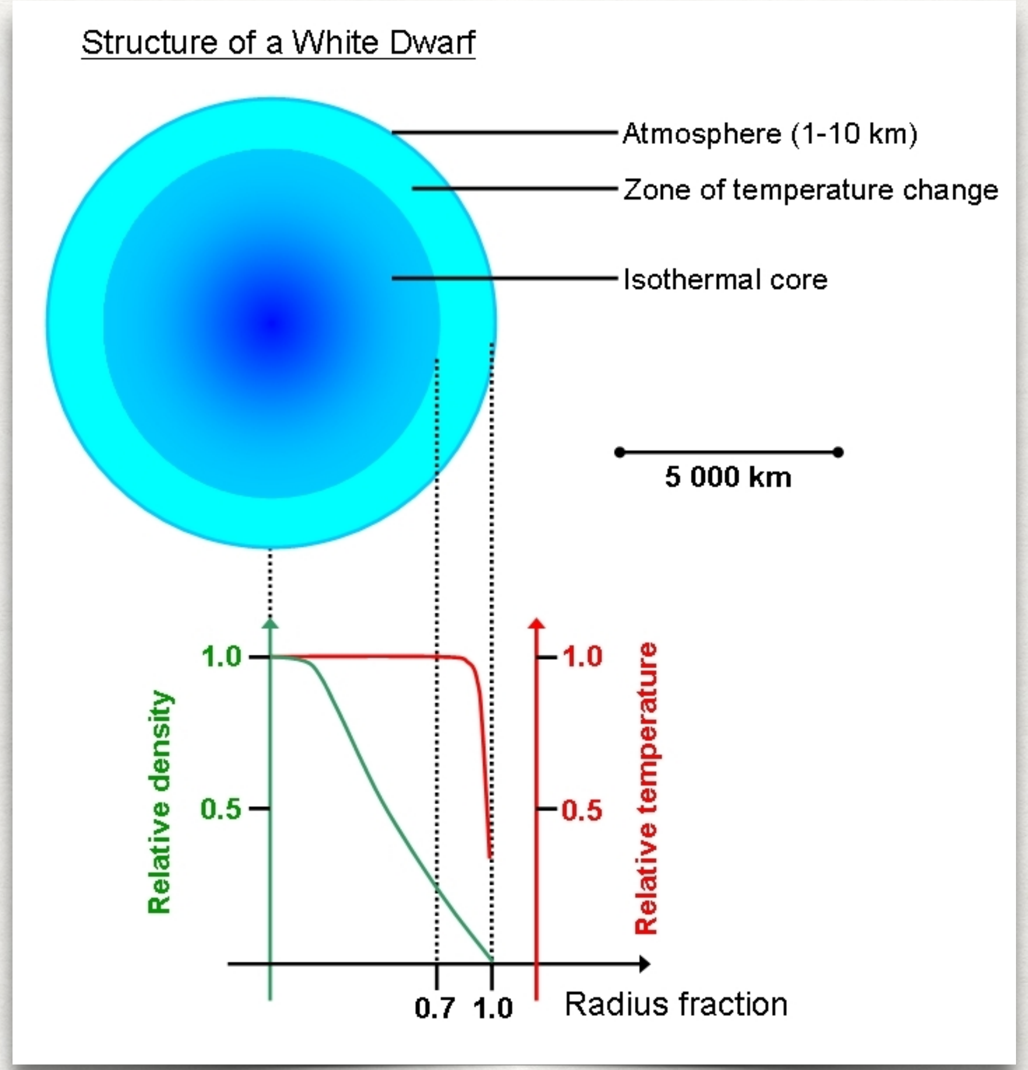
WD COOLING: TEMPERATURE

At the boundary between Atmosphere and degenerate core:

$$\rho_\mathrm{b} = B^{-1/} \frac{\mu}{\mathcal{R}} T_\mathrm{b}^{-13/4}$$

$$\frac{\mathcal{R}}{\mu_\mathrm{e}} \rho_\mathrm{b} T_\mathrm{b} = K_\mathrm{NR} \left(\frac{\rho_\mathrm{b}}{\mu_\mathrm{e}}\right)^{5/3}$$

$$\Rightarrow \quad T_\mathrm{b} \propto (L/M)^{2/7}$$



The isothermal core temperature is then:

$$T_\mathrm{c} \approx 8 \times 10^7 K \left(\frac{L/L_\mathbf{sun}}{M/M_\mathbf{sun}}\right)^{2/7} \leq 2.4 \times 10^7 K \qquad M = 0.6 M_\mathrm{sun} \ \text{ and } \ L = 10^{-2} L_\mathrm{sun}$$

cold core, T smaller than Fermi Temperature

WD COOLING: RADIATED ENERGY

Virial theorem for degenerate gas with no nuclear energy says: **luminosity** radiated away comes from **decrease of internal energy**

No change in electron internal energy 'cause fill up lowest states up to Fermi energy.
<u>The only energy source available is thermal energy stored in non-degenerate ions:</u>

$$E_{\rm in} = c_{\rm V} M T_{\rm c} \quad \text{with} \quad c_{\rm V} = \frac{3}{2}\mathcal{R}/\mu_{\rm ion}$$

Cv: specific heat per unit mass at constant V

from energy argument:

from self consistent structure:

$$L = \frac{dE_{\rm in}}{dt} = -c_V M \frac{dT}{dt} \quad \text{and} \quad L = T_{\rm c}^{7/2}\frac{M}{\alpha}$$

from L=L

$$T_{\rm c}^{7/2} = -\alpha c_{\rm V}\frac{dT_{\rm c}}{dt}$$

WD COOLING: TIMESCALE

$$T_c^{7/2} = -\alpha c_V \frac{dT_c}{dt}$$

Integrating between initial time t0 and t :

$$\tau \equiv = t - t_0 = \frac{2}{5}\alpha C_V \left(T_c^{-5/2} - T_{c,0}^{-5/2}\right)$$

At later times, when Tc << Tc,0

$$\tau \approx \frac{2}{5}\alpha c_V T_c^{-5/2} = \frac{2}{5} c_V \alpha^{2/7} \left(\frac{L}{M}\right)^{-5/7}.$$

$$\tau \approx \frac{1.05 \times 10^8 \text{ yr}}{\mu_{\text{ion}}} \left(\frac{L/L_\odot}{M/M_\odot}\right)^{-5/7}.$$

Mastel law

WD COOLING: DISCUSSION

Mestel law (1952)

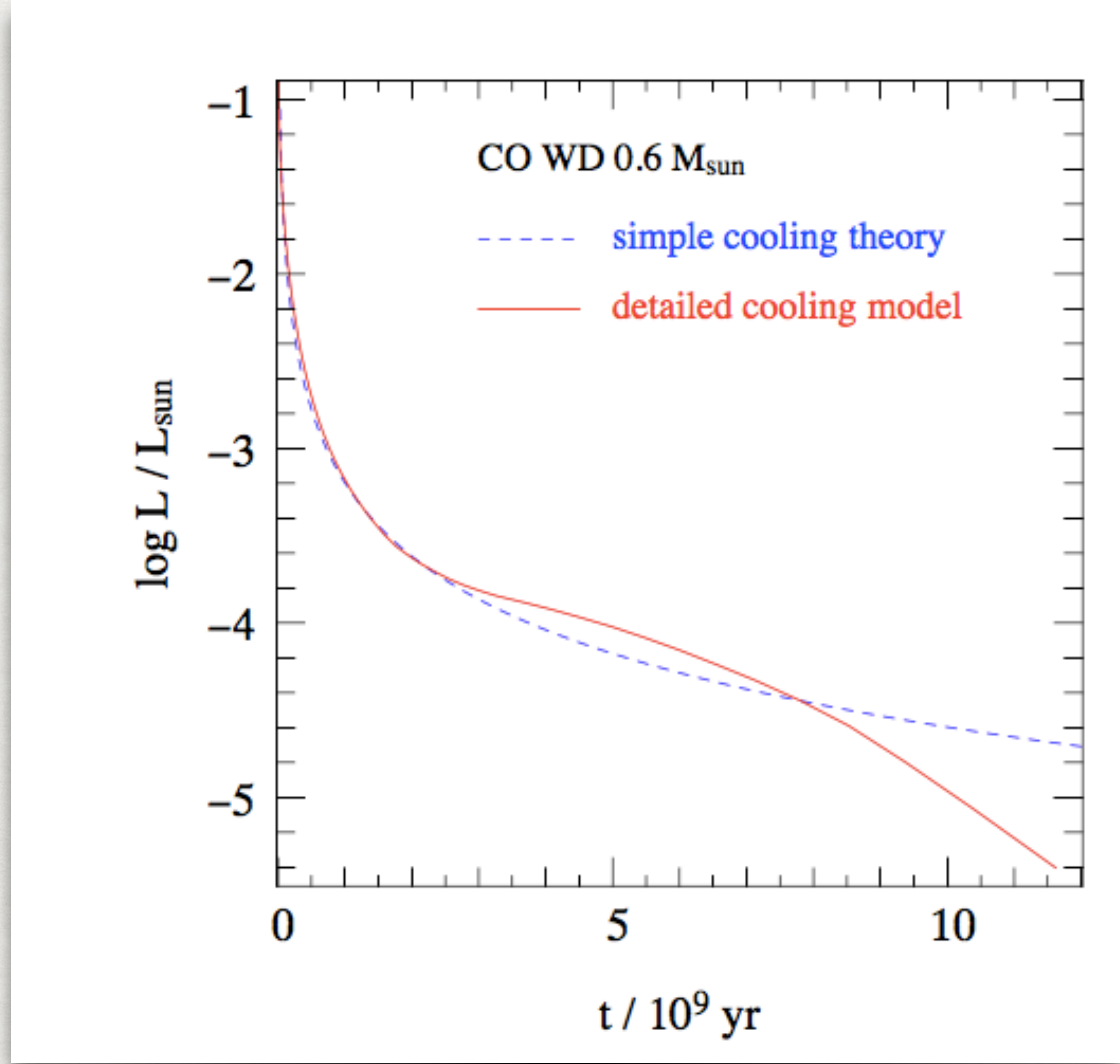
$$\tau \approx \frac{1.05 \times 10^8\,\mathrm{yr}}{\mu_{\mathrm{ion}}} \left(\frac{L/L_\odot}{M/M_\odot} \right)^{-5/7}.$$

- More massive WD2 : evolve slower, because large energy reservoir $\tau = E_{\mathrm{in}}/L$
- Inversely proportional to the mean mass per ion, because for a given mass there are less energy carrier => less total internal energy

$$\tau = E_{\mathrm{in}}/L = c_{\mathrm{V}} M T_{\mathbf{c}} \propto M/\mu_{\mathrm{ion}} T_{\mathrm{c}} = N_{\mathrm{ion}} T_{\mathrm{c}}$$

- For a C-O white dwarf $\mu_{\mathrm{ion}} \approx 14$

$$\tau \approx 10^8 \text{ yr at } \mathrm{L} = 10^{-2} \mathrm{L_{sun}} \text{ and } \mathrm{M} = 0.6 \mathrm{M_{sun}}$$



Detailed models that take into account **crystallisation**:

- have a slower cooling after 2 Gyr, because extra latent heat is generated, while forming the crystal structure (Cv increases)
- faster cooling beyond 7 Gyr, after crystallisation is completed because Cv decreases

CHAPTER 12

THE EVOLUTION OF MASSIVE STARS

i.e. $M > 8$ solar masses

MASSIVE STARS’ EVOLUTION

UNIQUE CHARACTERISTICS

- Massive stars’ evolution has ingredients different from the lower mass evolution and **physics that we could (mostly) neglect so far becomes very important**: it’s modelling however may be challenging (e.g. rotation, mass loss, binarity)

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- Massive stars' evolution has ingredients different from the lower mass evolution and **physics that we could (mostly) neglect so far becomes very important**: it's modelling however may be challenging (e.g. rotation, mass loss, binarity)

- Nuclear burning rans all the way to the complicated and not completely understood fusions **e.g. O and Si-burning phase**

Massive stars' evolution is comparably more uncertain than that of lower mass stars

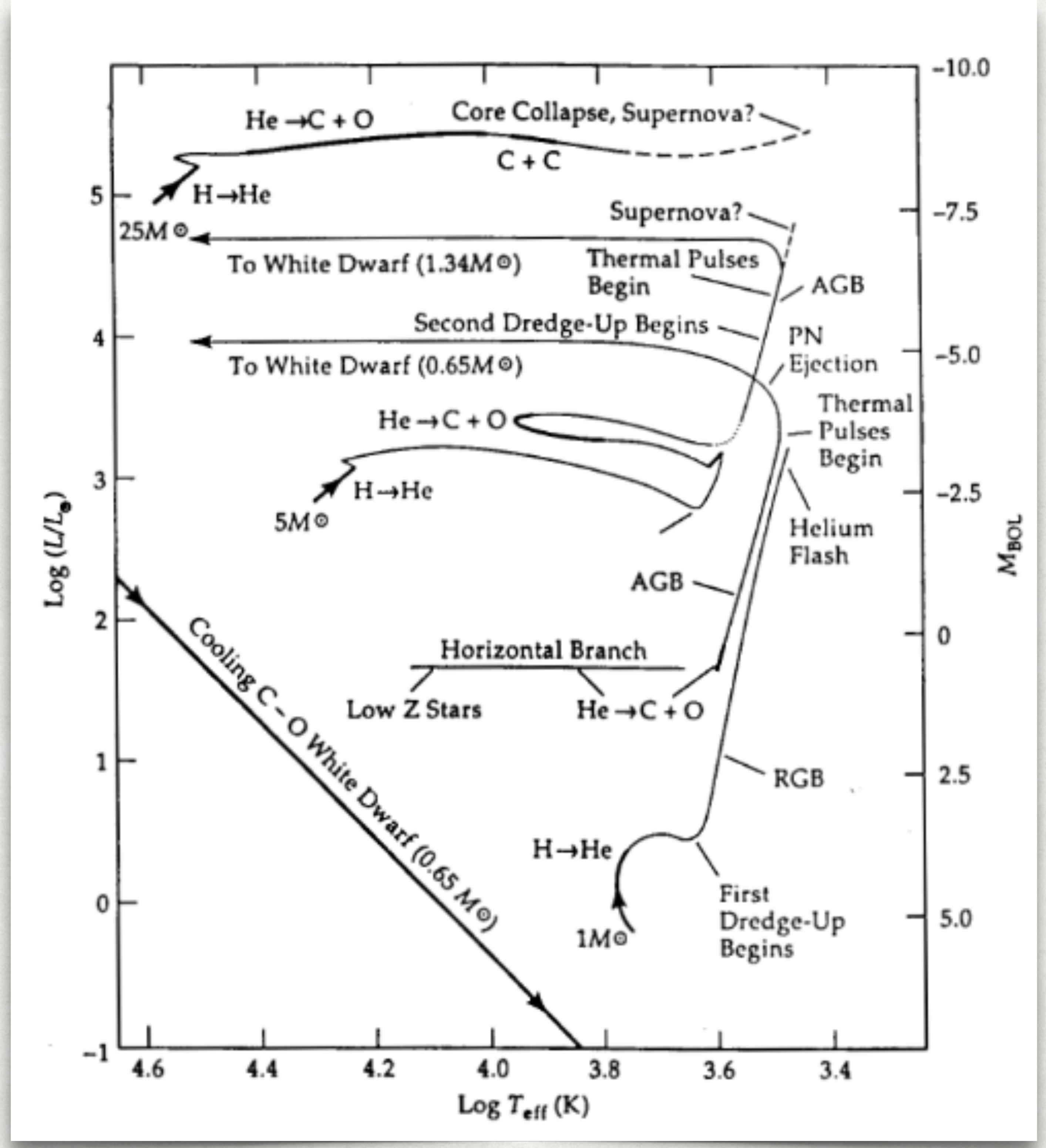
MASSIVE STARS' EVOLUTION

MAIN FEATURES

1. **Luminosity close to Eddington critical limit** since main sequence, despite the internal chemical and structural changes

LUMINOSITY

=> evolution on H-R almost horizontal between high and low T_{eff}



LUMINOSITY

1. Luminosity close to Eddington critical limit

it is a consequence of the growing importance of radiation pressure

we derived the Eddington limit in Lecture 4 by requiring

$$\frac{1}{\rho}\frac{dP_{\rm rad}}{dr} \leq \frac{Gm}{r^2} \Rightarrow l \leq \frac{Gm4\pi c}{\kappa\rho} = 3.8\times 10^4 \left(\frac{m}{M_{\rm sun}}\right)\left(\frac{0.34}{\kappa}\right) L_{\rm sun} \equiv L_{\rm edd}$$

at each r. When $P_{tot} \sim P_{rad}$, hydrostatic equilibrium (e.g. at the surface) requires

$$\frac{1}{\rho}\frac{dP_{\rm rad}}{dr} = \frac{GM}{R^2} \rightarrow L \sim L_{\rm Edd}$$

MASSIVE STARS' EVOLUTION

MAIN FEATURES

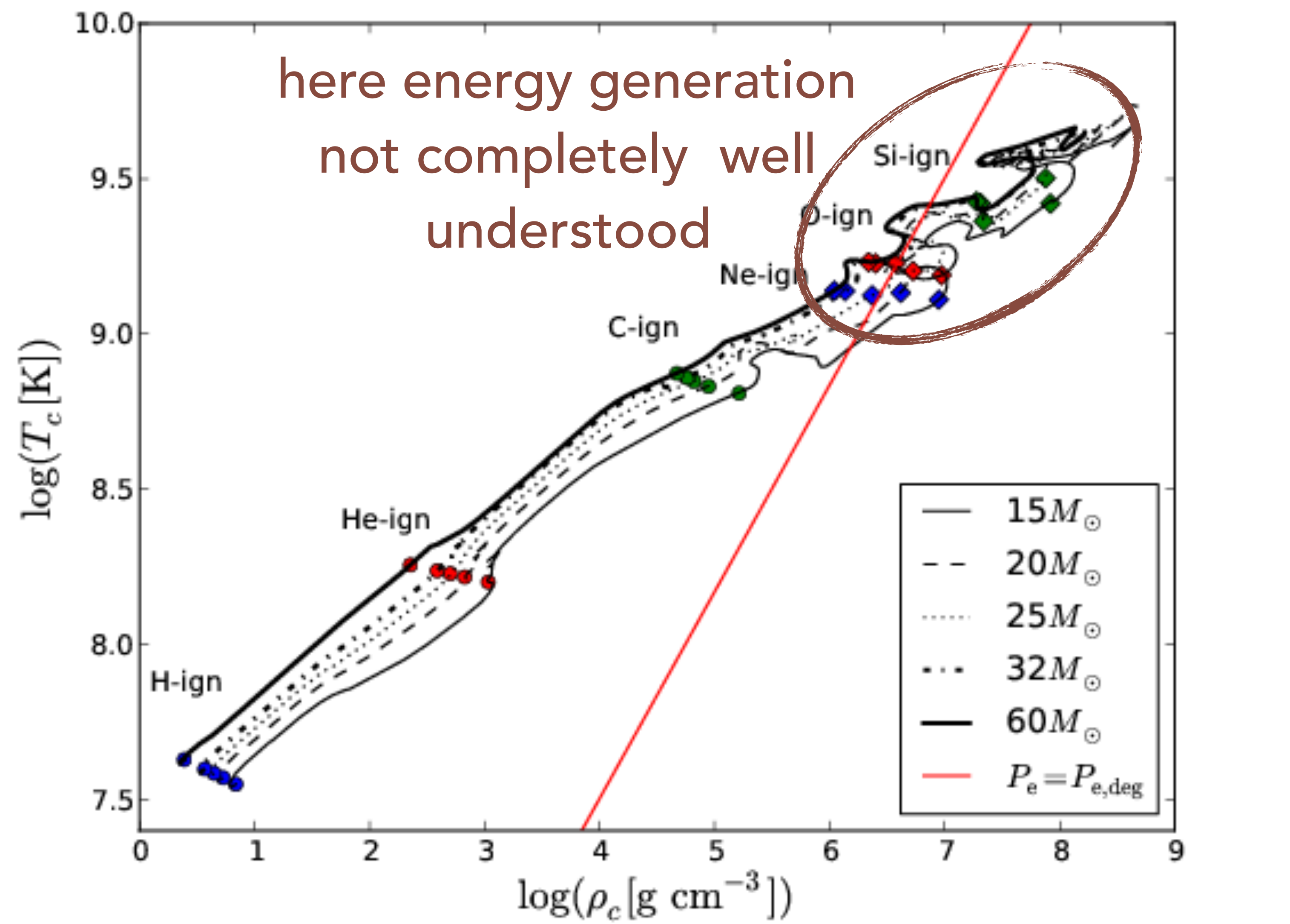
1. <u>Luminosity close to Eddington critical limit</u> since main sequence, despite the internal chemical and structural changes

2. Electrons in their core <u>**do NOT become degenerate**</u> until the final burning stages, towards an <u>**iron core**</u>

NUCLEAR FUSION

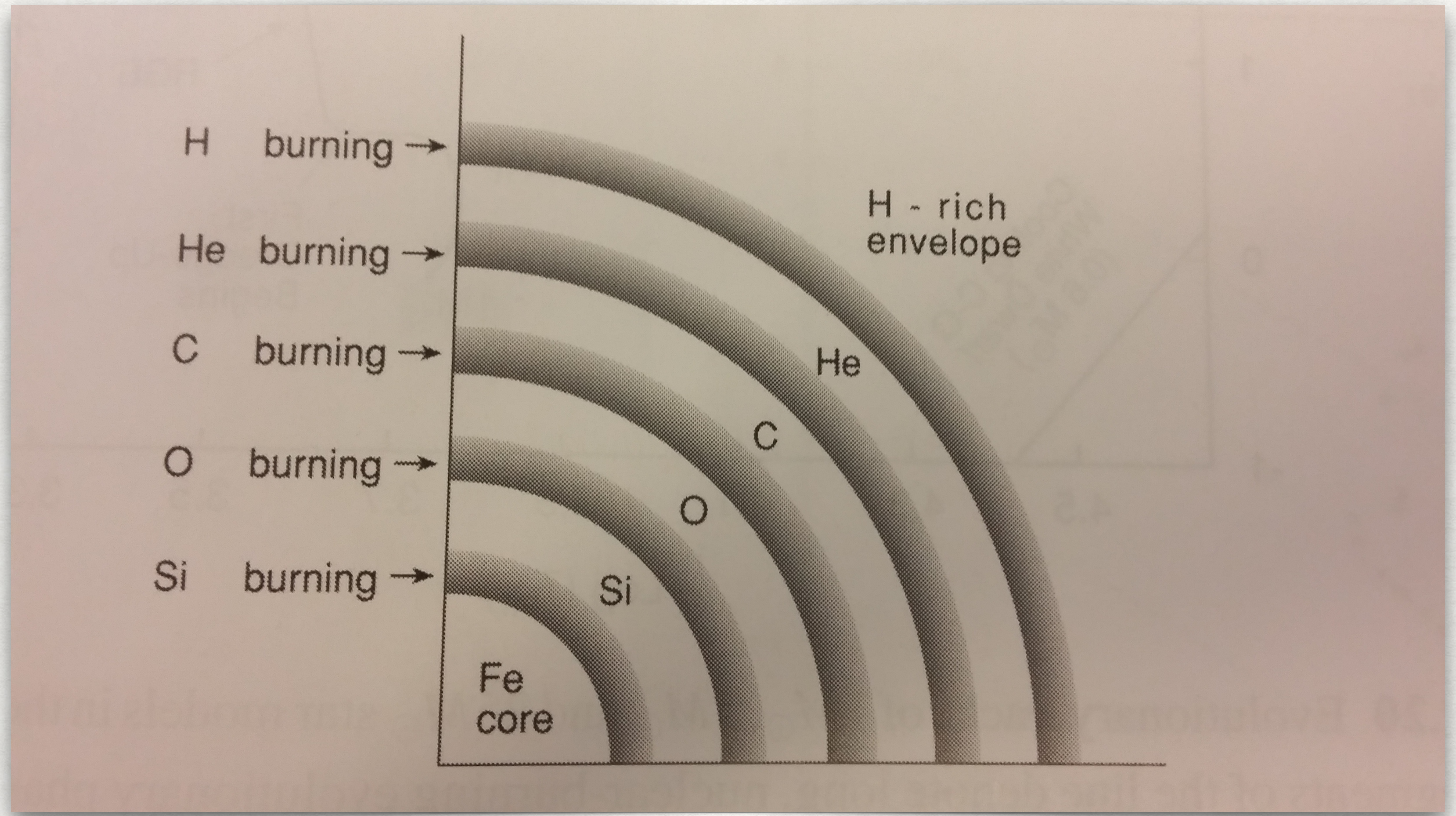
<u>=> Succession of core contractions</u> causes H and He burning to be succeeded by heavier element fusion in the core: C, then O and finally S,Si burning

in the core



NUCLEAR FUSION

=> <u>burning of lighter elements move to outer shells</u>



From D. Prialnik

NEUTRINO LOSSES

=> From C burning on temperatures are high enough (> 5 10^8 K) for *neutrino losses* that are the *main energy loss* channel:

$$L_\nu \gg L_{\mathrm{Edd}}$$

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$$L_{\rm nuc} = L_\nu + L_{\rm Edd}$$

=> Very short nuclear timescales w.r.t. main sequence

$$\tau_{\rm nuc} = E_{\rm nuc}/L_\nu \ll E_{\rm nuc,H}/L_{\rm Edd}$$

NUCLEAR TIMESCALE

=> Very short nuclear timescales w.r.t. main sequence

$$\tau_{\rm nuc} = E_{\rm nuc}/L_\nu \ll E_{\rm nuc,H}/L_{\rm Edd}$$

because :

1) Photon Luminosity does not change much and $L_\nu \gg L_{\rm Edd}$

NUCLEAR TIMESCALE

=> Very short nuclear timescales w.r.t. main sequence

$$\tau_{\rm nuc} = E_{\rm nuc}/L_\nu \ll E_{\rm nuc,H}/L_{\rm Edd}$$

because

2) heavy elements release far less energy per unit mass then fusion of light material:

H: p-p : 6.55 MeV per nucleon

C: 0.54 MeV per nucleon

O: ~0.3 MeV per nucleon

Si: < 0.18 MeV per nucleon

K-H TIMESCALE

=> Contraction phases on a thermal timescale, between fusion phases, also speed up because of increase of energy losses

Overall *less than a few 1000 years* pass between the onset of C-burning to formation of Iron core !

NUCLEAR BURNING

SUMMARY

2. Electrons in their core do NOT become completely degenerate until the final burning stages

=> in (rapid) succession H, He, C,O and Si fusion in core

=> onion-shell chemical structure

=> N*eutrino losses* to dominate in post He burning evolution

=> *Nuclear and gravitational energy production* needs to compensate for neutrino losses

=> nuclear and thermal timescales speeds up enormously

MASSIVE STARS' EVOLUTION

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3. **Mass Loss is important trough evolution, including the main sequence**

MASS LOSS

MASS LOSS IMPORTANT SINCE MAIN SEQUENCES

stellar winds erode the envelope at 10^{-8} - 10^{-4} M_{sun} /yr

Eta Carine

$L \sim 5\ 10^{6}\ L_{sun}$

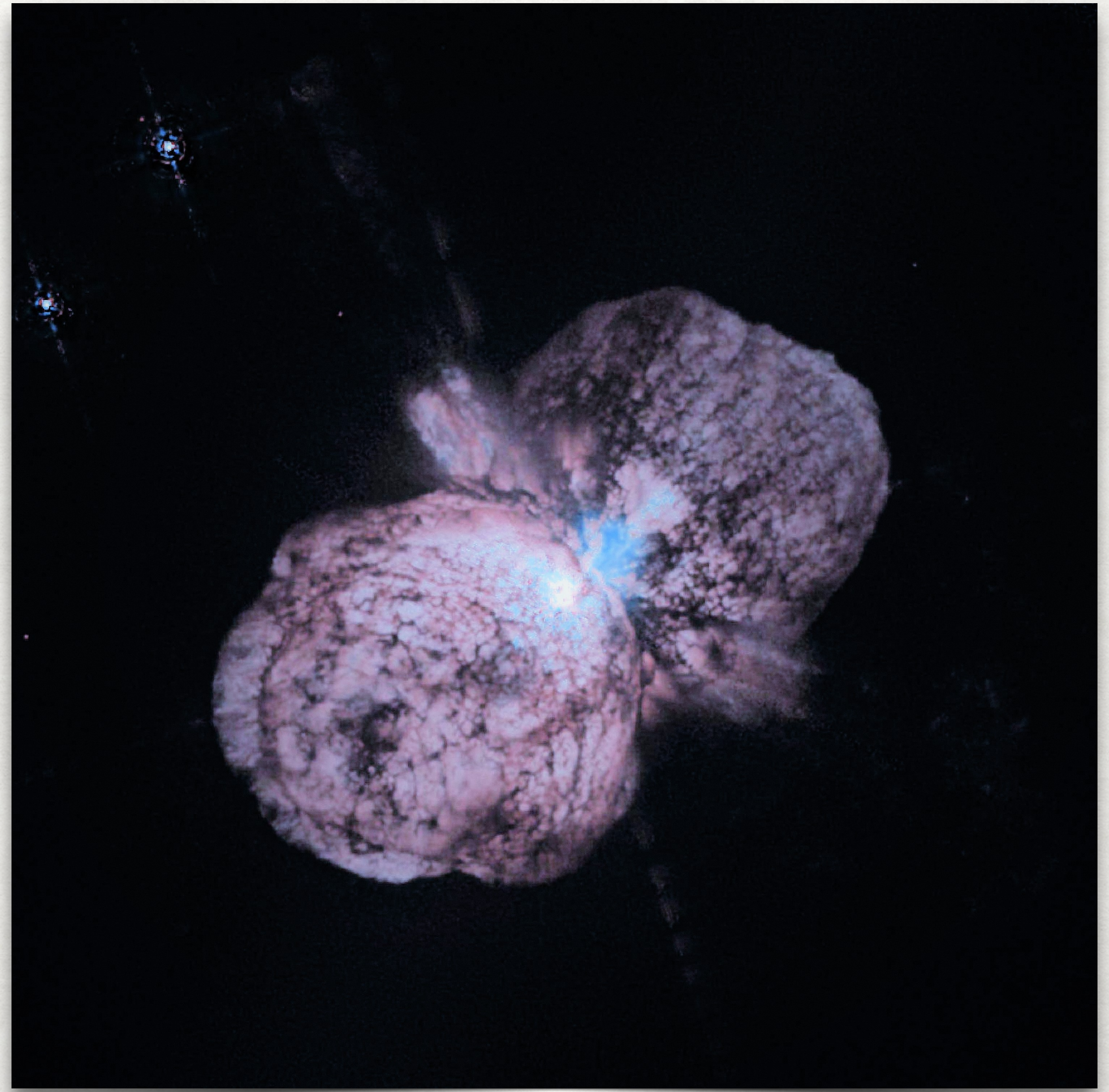
$M \sim 100\ M_{sun}$

luminous blue variable:

- the most luminous stars observed
- unstable, recurrent mass loss > 10^{-3} M_{sun}/yr in outbursting
- on its way to become a Wolf-Rayet star

Last outburst ~ mid 1800s

ejected 10 M_{sun} rich in nitrogen



MASS LOSS

THE IMPORTANCE INCREASES <u>WITH MASS</u> AND <u>EVOLUTIONARY PHASE</u>

$M \lesssim 15\,M_\odot$	MS (OB) $\rightarrow$ RSG ($\rightarrow$ BSG in blue loop? $\rightarrow$ RSG) $\rightarrow$ SN II mass loss is relatively unimportant, $\lesssim$ few $M_\odot$ is lost during entire evolution

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$15\,M_\odot \lesssim M \lesssim 25\,M_\odot$	MS (O) $\rightarrow$ BSG $\rightarrow$ RSG $\rightarrow$ SN II mass loss is strong during the RSG phase, but not strong enough to remove the whole H-rich envelope

e.g. $M = 25\,M_{sun}$: on MS: $5\ 10^{-8}$ - $5\ 10^{-7}\,M_{sun}/yr$ while in RSG phase $5\ 10^{-5}\,M_{sun}/yr$

MASS LOSS

THE IMPORTANCE INCREASES WITH MASS AND EVOLUTIONARY PHASE

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$25\, M_\odot \lesssim M \lesssim 40\, M_\odot$	MS (O) → BSG → RSG → WNL → WNE → WC → SN Ib the H-rich envelope is removed during the RSG stage, turning the star into a WR star

they become Wolf-Rayet stars:

- hot very luminous stars
- increased CNO abundances in their spectra
- surrounded by massive nebula
- inferred optically thick stellar wind~ 5 10^{-5} M_{sun}/yr
- =>expose H- or He-burning cores of massive stars

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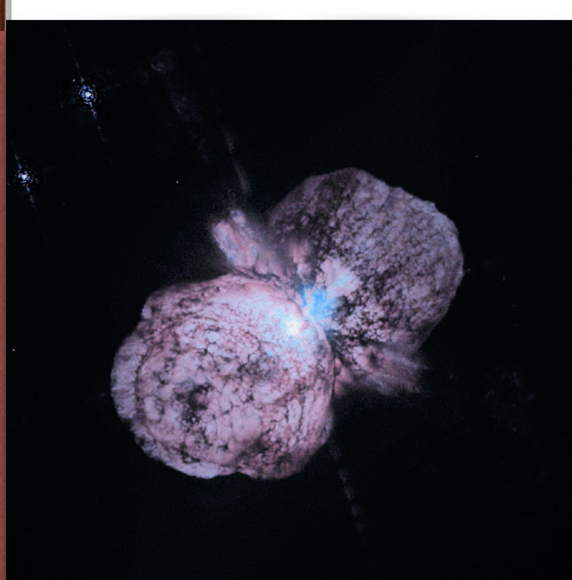
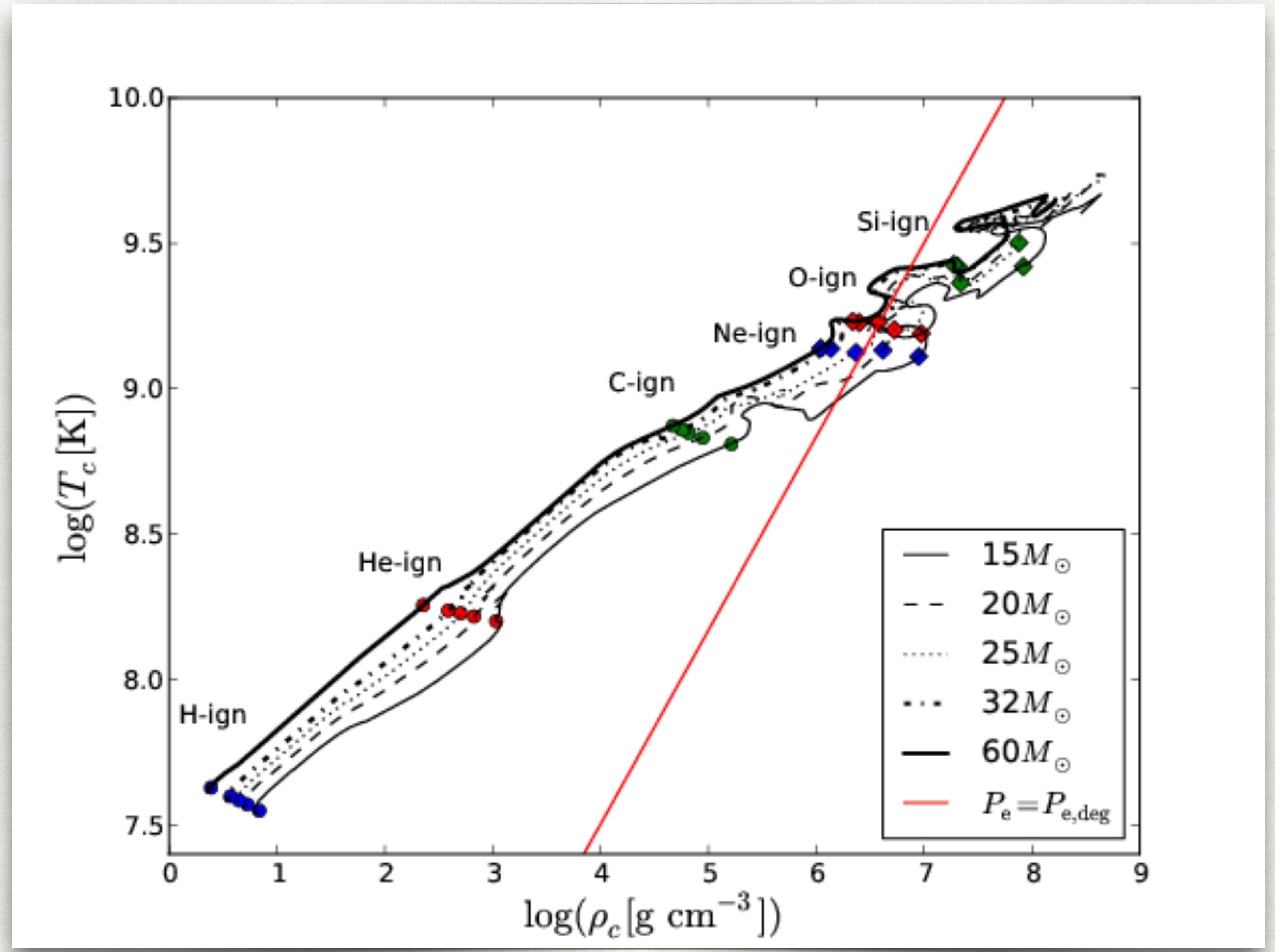
$M \gtrsim 40\,M_\odot$	MS (O) → BSG → LBV → WNL → WNE → WC → SN Ib/c an LBV phase blows off the envelope before the RSG can be reached



FOR M> 30 SOLAR MASSES

EVOLUTION IS QUITE SIMILAR FROM HE BURNING ON



MASSIVE STARS' EVOLUTION

GENERAL CHARACTERISTICS

1. Luminosity close to Eddington critical limit since main sequence, despite the internal chemical and structural changes

2. Electrons in their core do NOT become degenerate until the final burning stages, towards an iron core

3. **Mass Loss is important trough evolution, including the main sequence**

4. **Rotation affects evolution (rotational mixing, increase main sequence lifetime) + enhance mall loss**

ROTATION

- **rotational mixing of chemicals in the star:** prolong stellar lifetimes and alters surface abundances (e.g. brings up N)
- **angular momentum transfer in the star (meridional circulation)**
- **differential rotation in stars causes instability and mixing (e.g. shear mixing)**
- **enhancing mass loss (but winds can remove angular momentum)**

André Maeder and Georges Meynet
Rev. Mod. Phys. **84**, 25 – Published 17 January 2012

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6. **Supernovae => production of heavy elements and black holes and neutron stars**