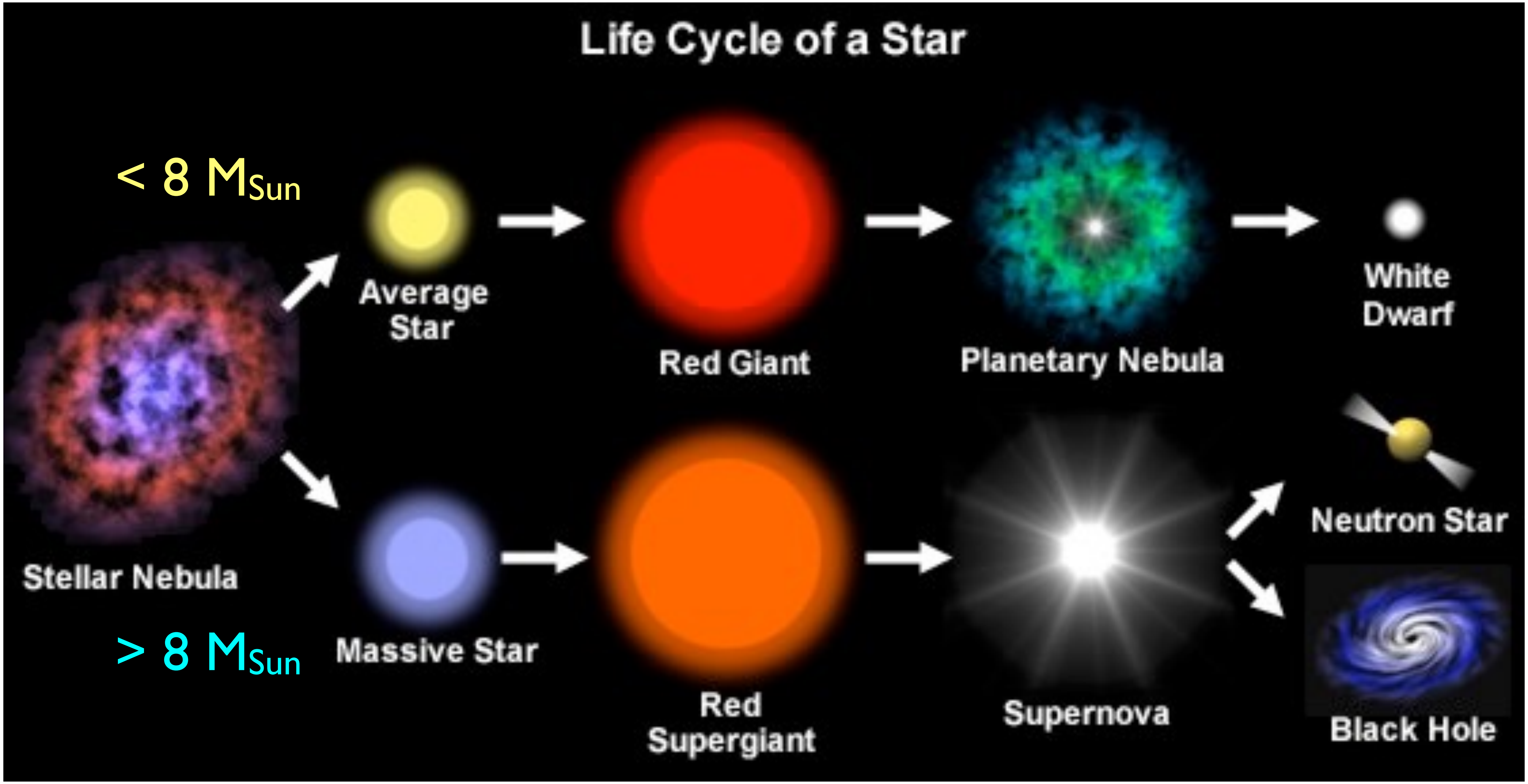
Lecture 16: High-Mass Stellar Evolution

Lamers & Levesque Ch. 22-27



Group project

presentation, like our lecture: basic physics of the topic, relevant equations/derivations, examples, etc.

3-person groups: 15–20 minutes total
2-person groups: 10–15 minutes total

rough draft of slides due one week in advance

Lecture Date	Group	Members: Topic
Apr 22 (Fri)	1	Haonan Cheng, Yoon Choi, Matthew Wang: Stellar Initial Mass Function
Apr 22 (Fri)	2	Frank Genty, Anthony Pizzarelli, Khovesh Ramdin: Brown Dwarfs
Apr 22 (Fri)	3	Barbara Benda, Avery Kiihne, Harshill Patel: First Stars and Reionization
Apr 26 (Tue)	4	George Kharchilava, Geet Purohit, Anish Seth: Exoplanet Host Stars
Apr 26 (Tue)	5	Ava Marie Friedrich, Seung Hee Sung: Helioseismology
Apr 26 (Tue)	6	Rujuta Mokal, Michael Wozniak, Orion Yeung: Standard Candles
Apr 29 (Fri)	7	Aidan Boyce, Kailash Raman: MESA code
Apr 29 (Fri)	8	Arya Lakshmanan, Ina Park, Brandon Shane: Magnetars
Apr 28 (Fri)	9	Bradley Butler, Christine Carvajal, Connor Lane: LIGO Black Holes

More mass, more problems

1. rotation

see L&L Chapter 25, Ekström et al. (2012)

no convection in outer layers → no dynamo to produce strong B fields
→ no magnetic braking of rotation → fast rotation throughout lifetime
→ changes structure & (differential) rotational mixing

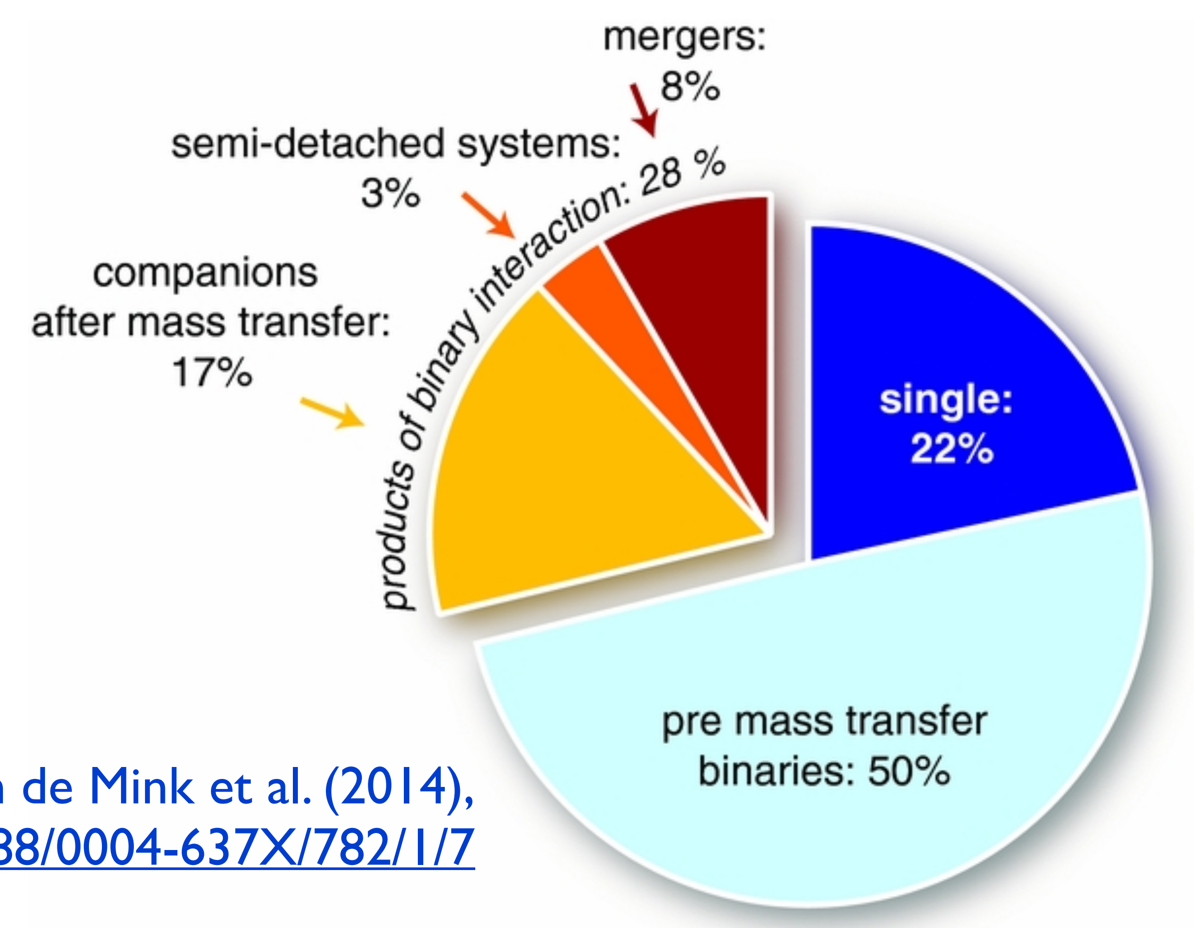
2. mass loss

see L&L Chapters 22, 24

high luminosity → radiation pressure driven stellar winds
→ significant mass loss → changes structure, evolution, & lifetime of star

3. binaries

next week; see L&L Chapters 29, 30
70-80% of massive stars are in
binary systems that will interact



from de Mink et al. (2014),
http://dx.doi.org/10.1088/0004-637X/782/1/7

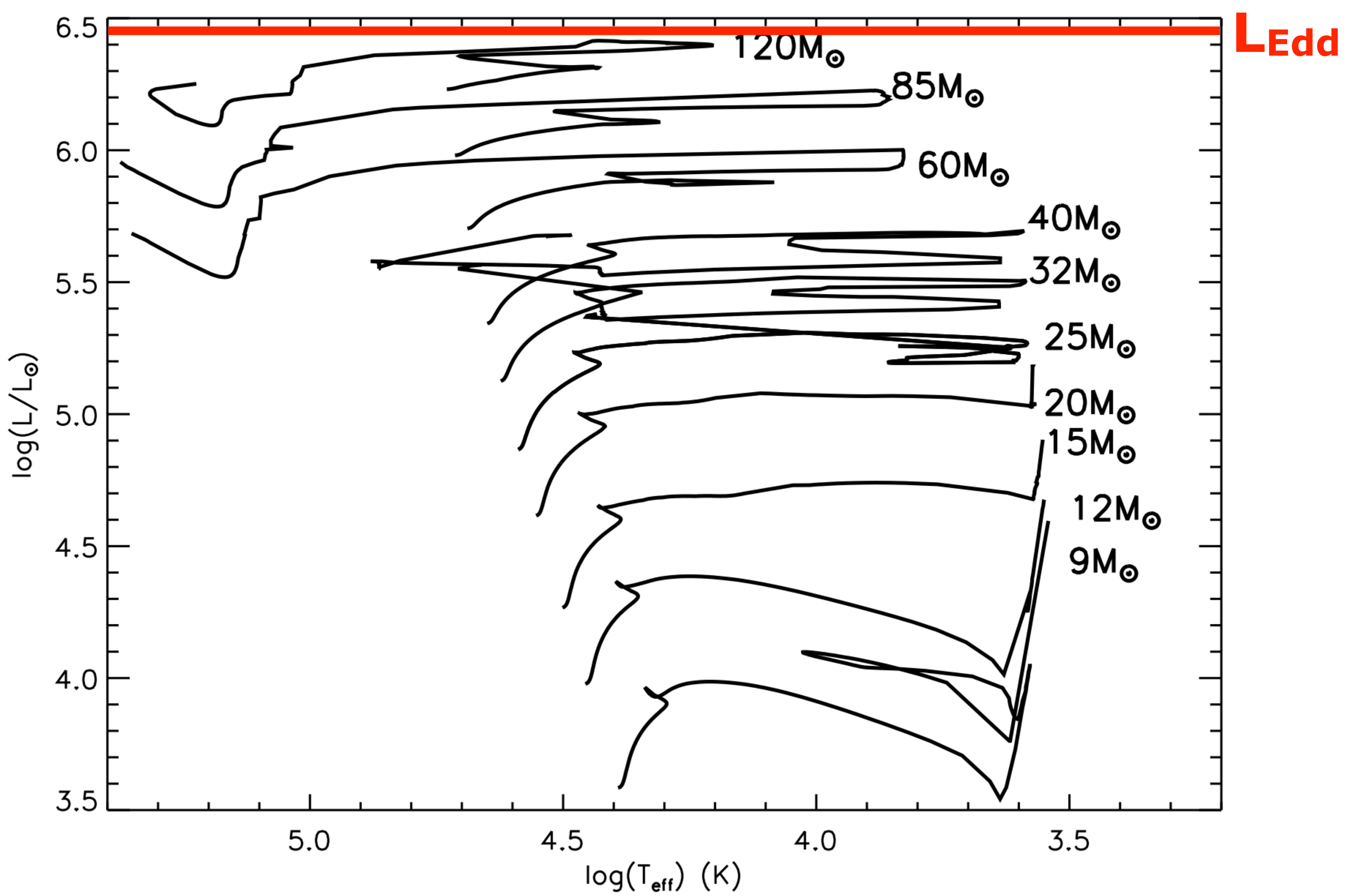
Massive Stars - Eddington Limit

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

$$\boxed{L_* < 4\pi cGM/\kappa = L_{\mathrm{Eddington}}}$$

PS 3, #2

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



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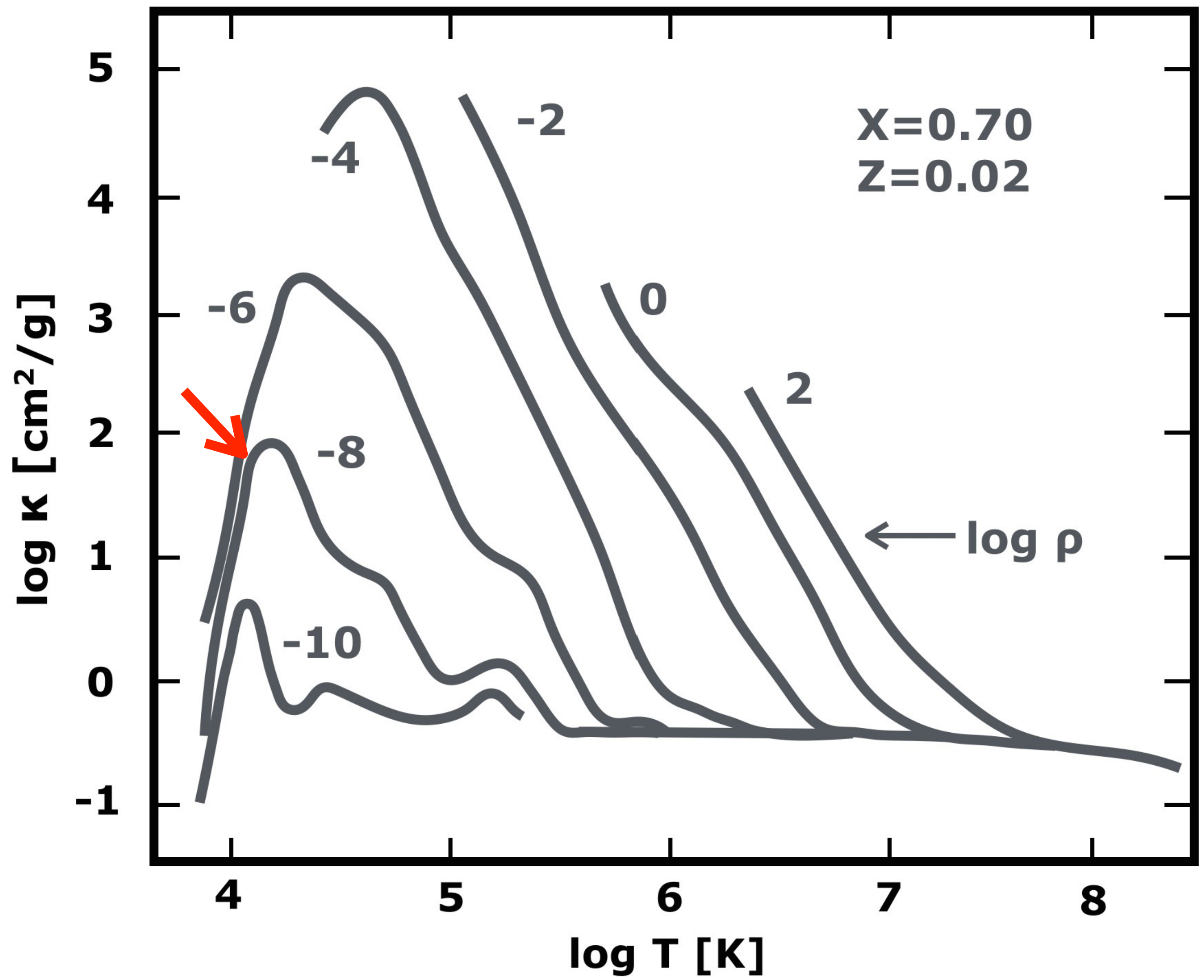
Opacity:

— there's a peak in κ above κ_{es} at low T and for low ρ

— $L_{Edd} \sim 1/\kappa$, so L_{Edd} will drop in this regime



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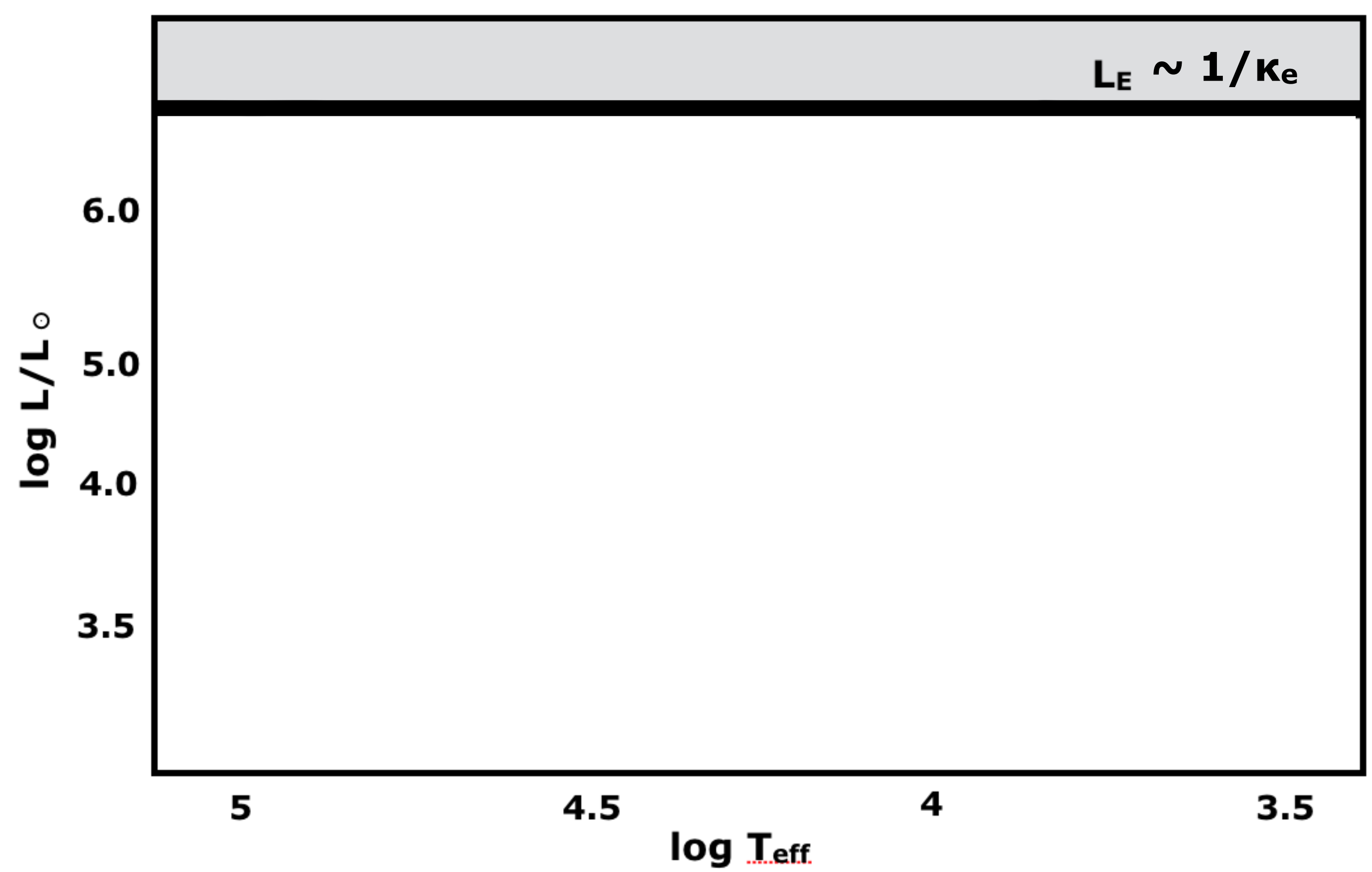

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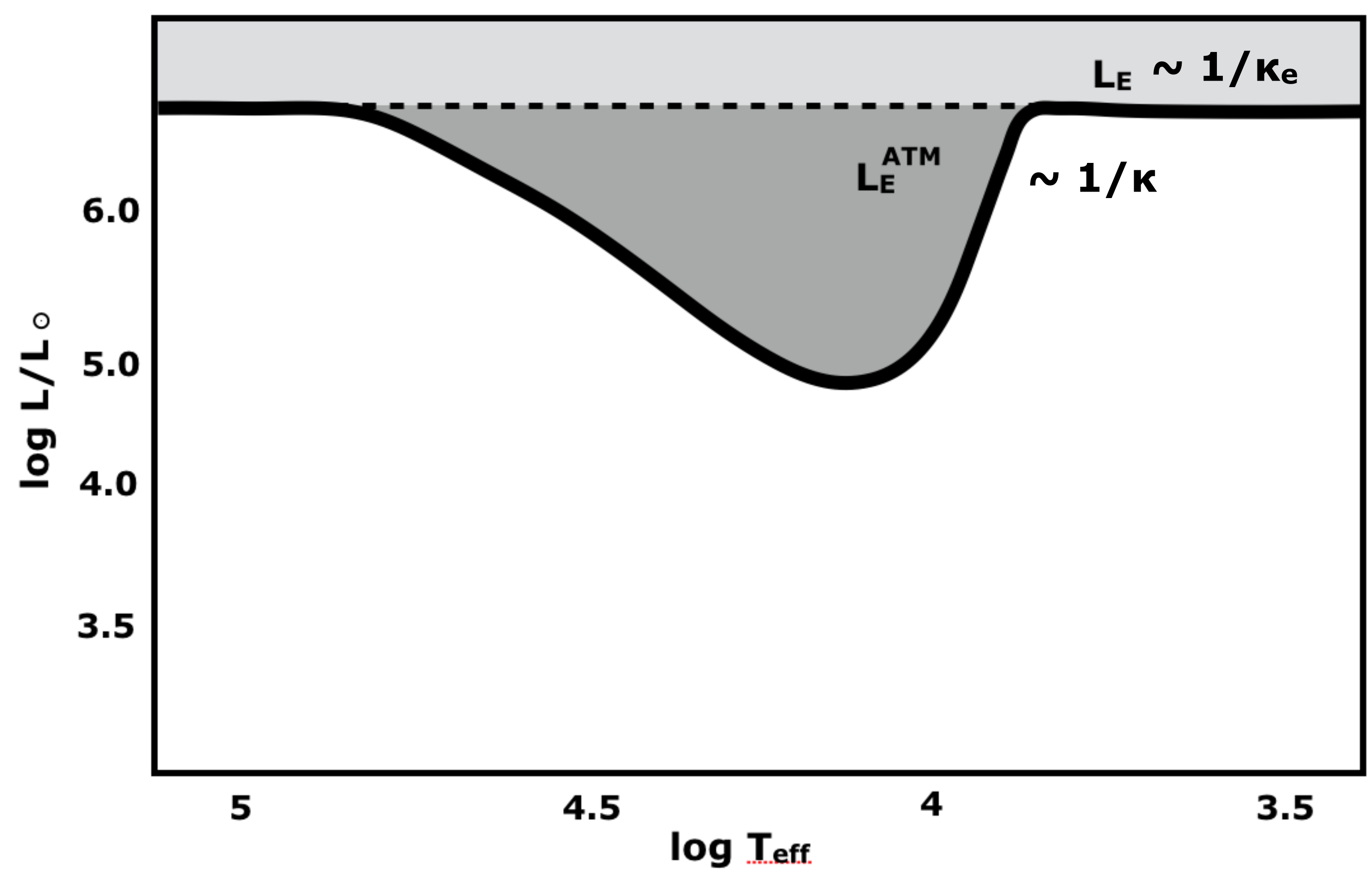
Opacity:

— there's a peak in κ above κ_{es} at low T and for low ρ

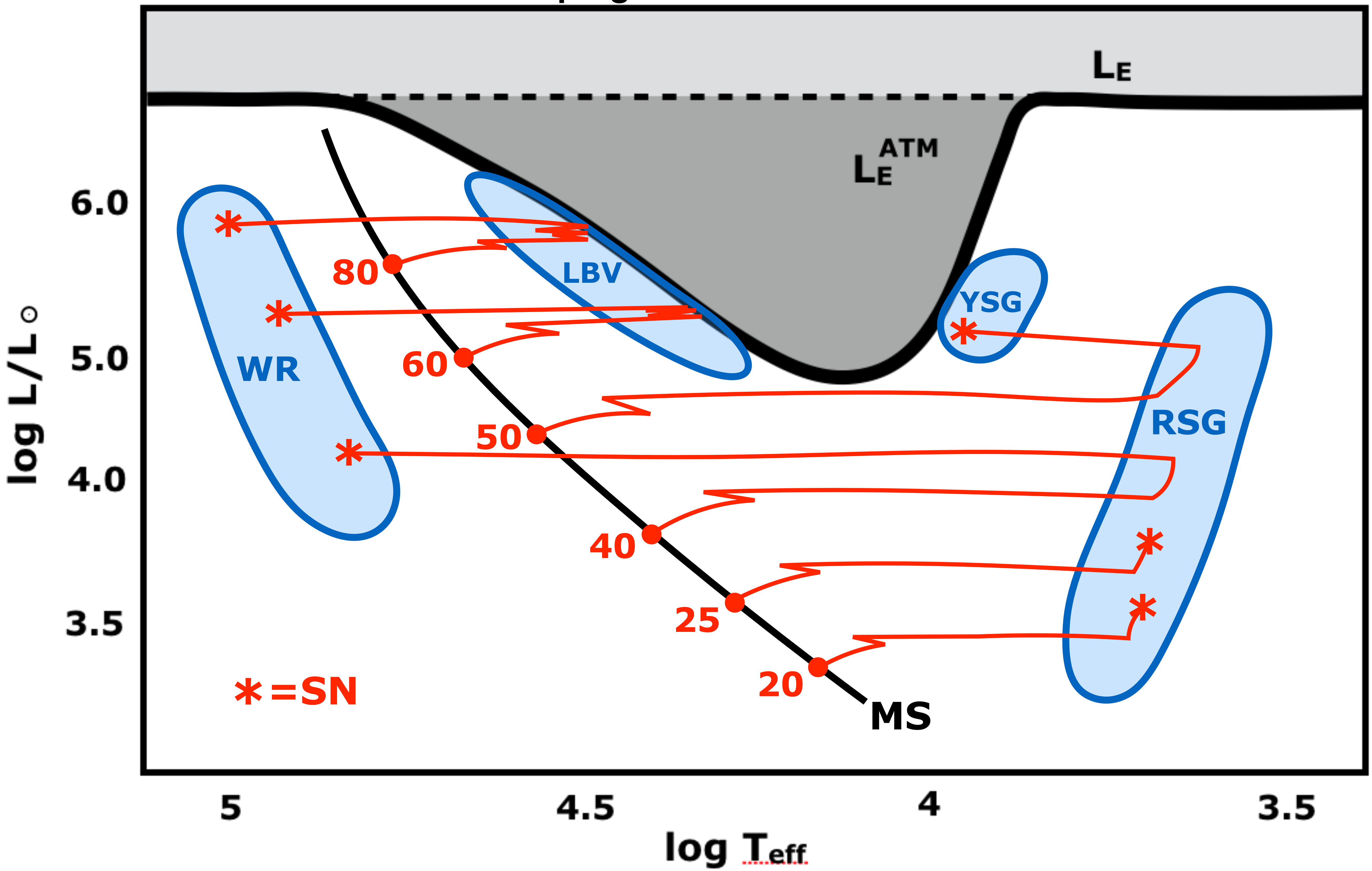
— $L_{Edd} \sim 1/\kappa$, so L_{Edd} will drop in this regime

— imposes a decreasing L_{Edd} at high luminosities that bottoms out around T_{eff}~10,000 K



Massive Stars - Eddington Limit

MS=Main Sequence RSG=Red Supergiant WR=Wolf-Rayet
YSG=Yellow Supergiant LBV=Luminous Blue Variable



Massive Stars - Eddington Limit

Humphreys-Davidson Limit

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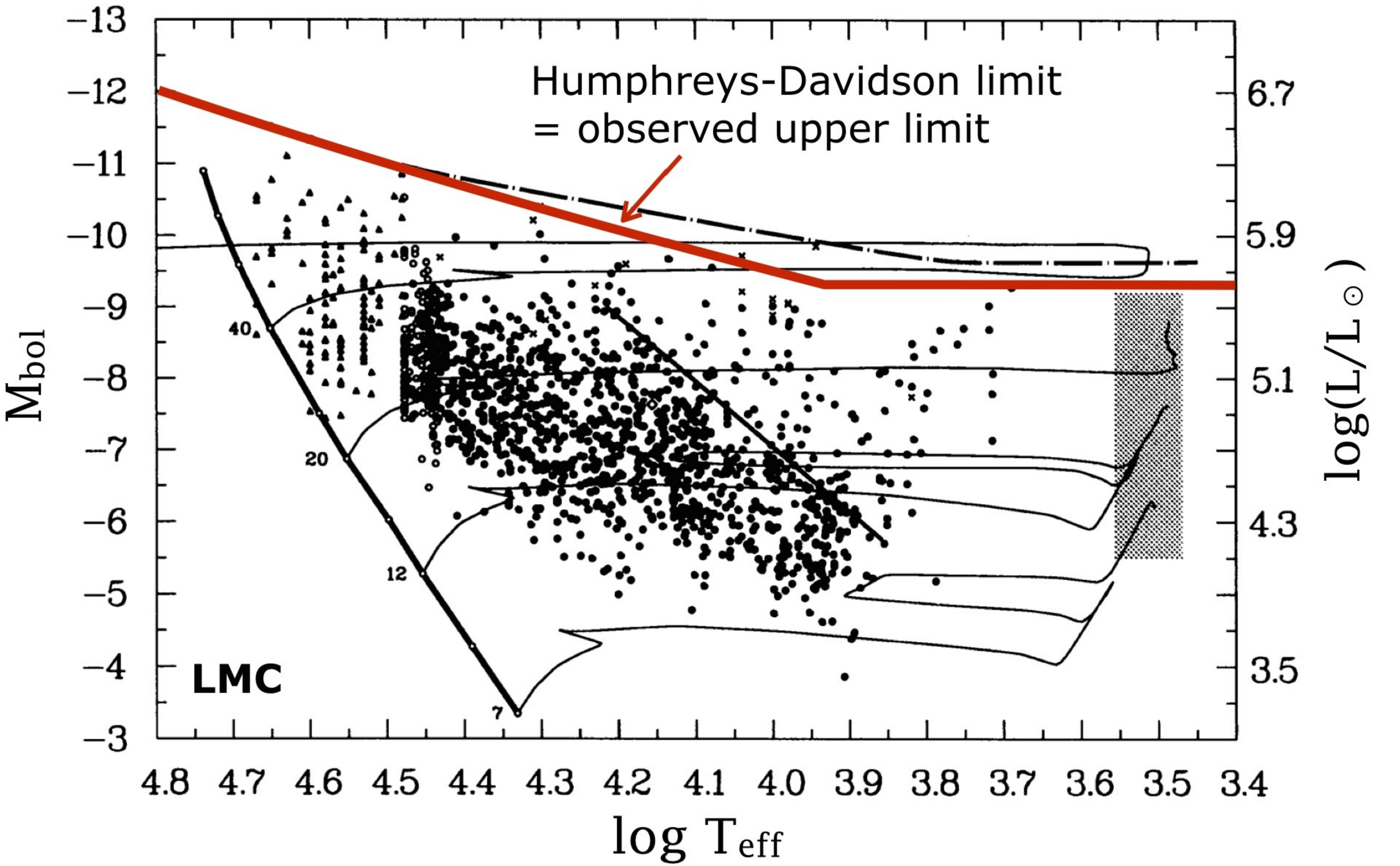
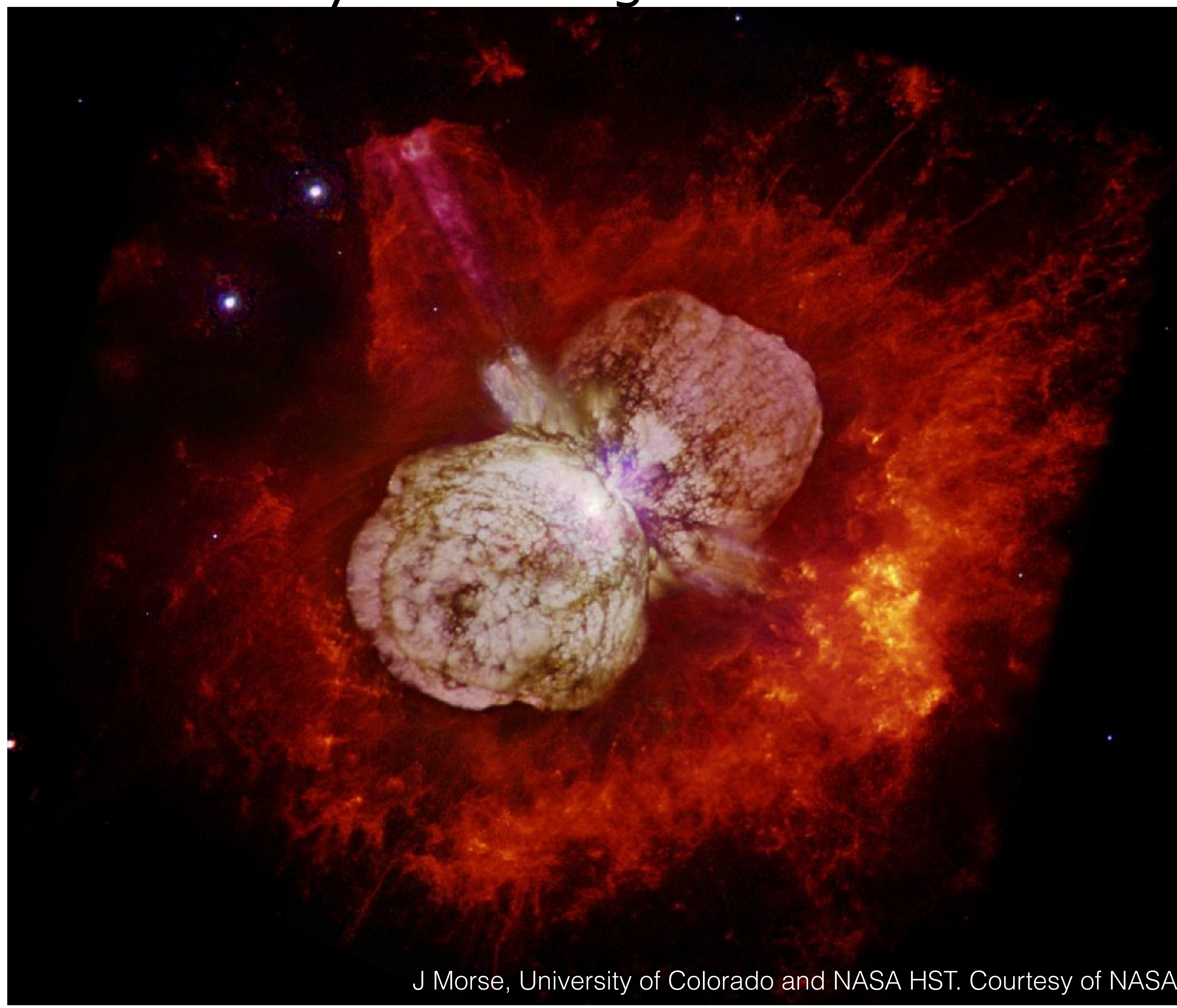


Massive Stars - LBVs

Luminous blue variables (LBVs) are luminous ($L/L_\odot > 3 \times 10^5$) supergiants that show large and irregular variations on timescales ranging from weeks to years along with occasional large eruptions.

The most famous examples are P Cygni and η Carinae.

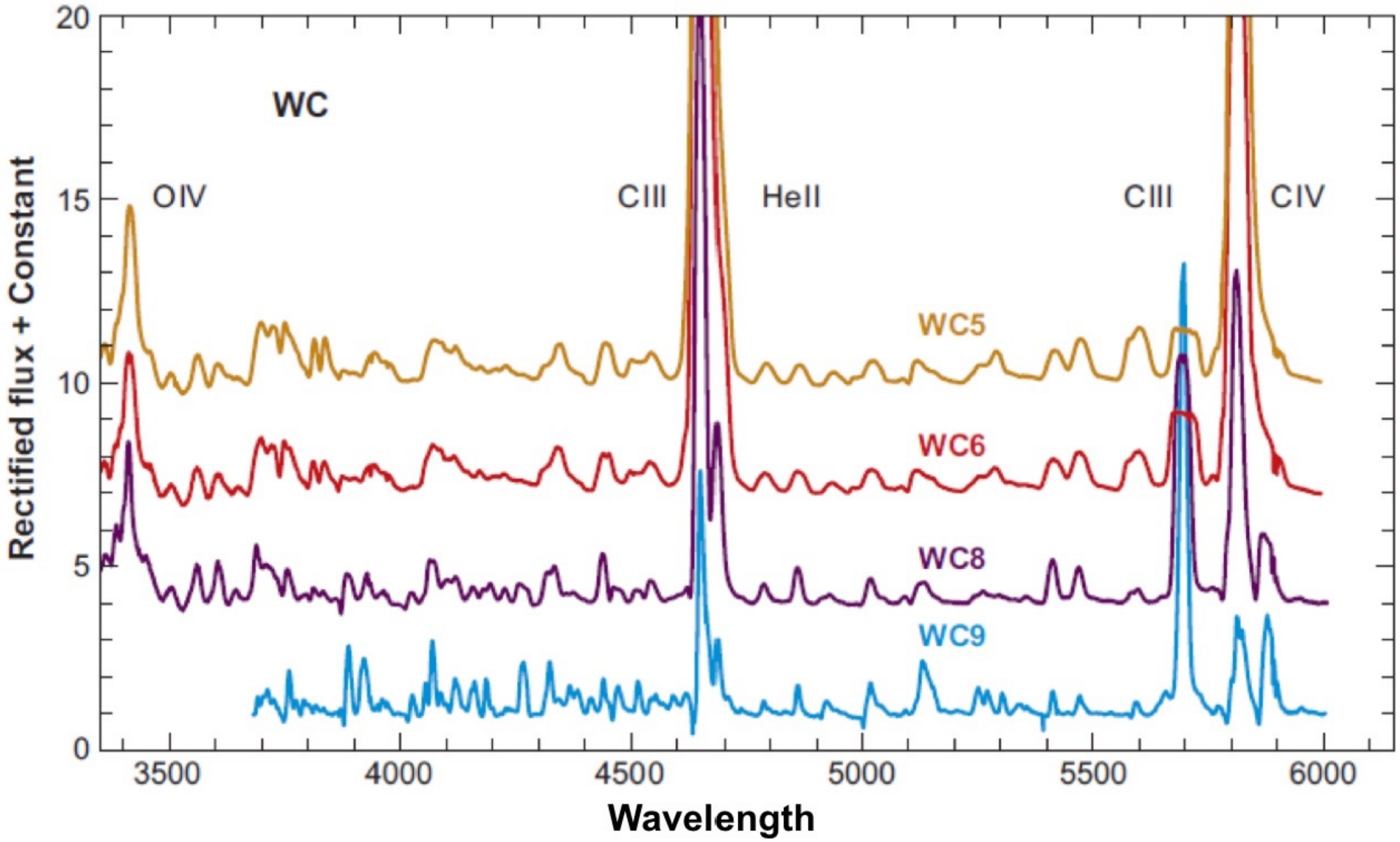
η Car underwent a series of outbursts in 1838-1856; its circumstellar nebula has a mass of $\sim 20 M_\odot$

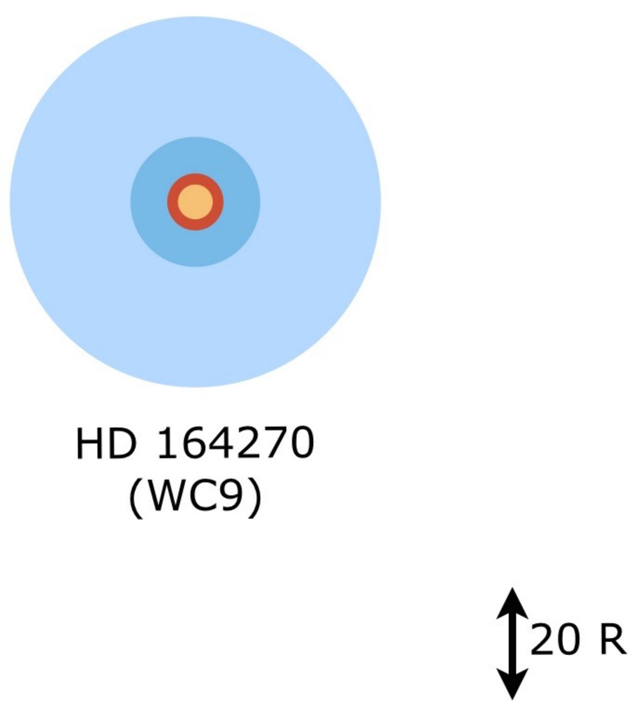


J Morse, University of Colorado and NASA HST. Courtesy of NASA.

Massive Stars - Wolf-Rayet Stars

WR stars are $L \sim 10^{5-6}\ L_\odot$ with such high mass loss rates that we only see the wind, not the photosphere, in their spectrum.





WNL = some H, He-rich, N-rich, $T_{eff} \sim$ 30,000 - 40,000 K

WNE = He-rich, N-rich, C-poor, T_{eff} > ~40,000 K

WC = He-rich, C-rich, T_{eff} > ~40,000 K

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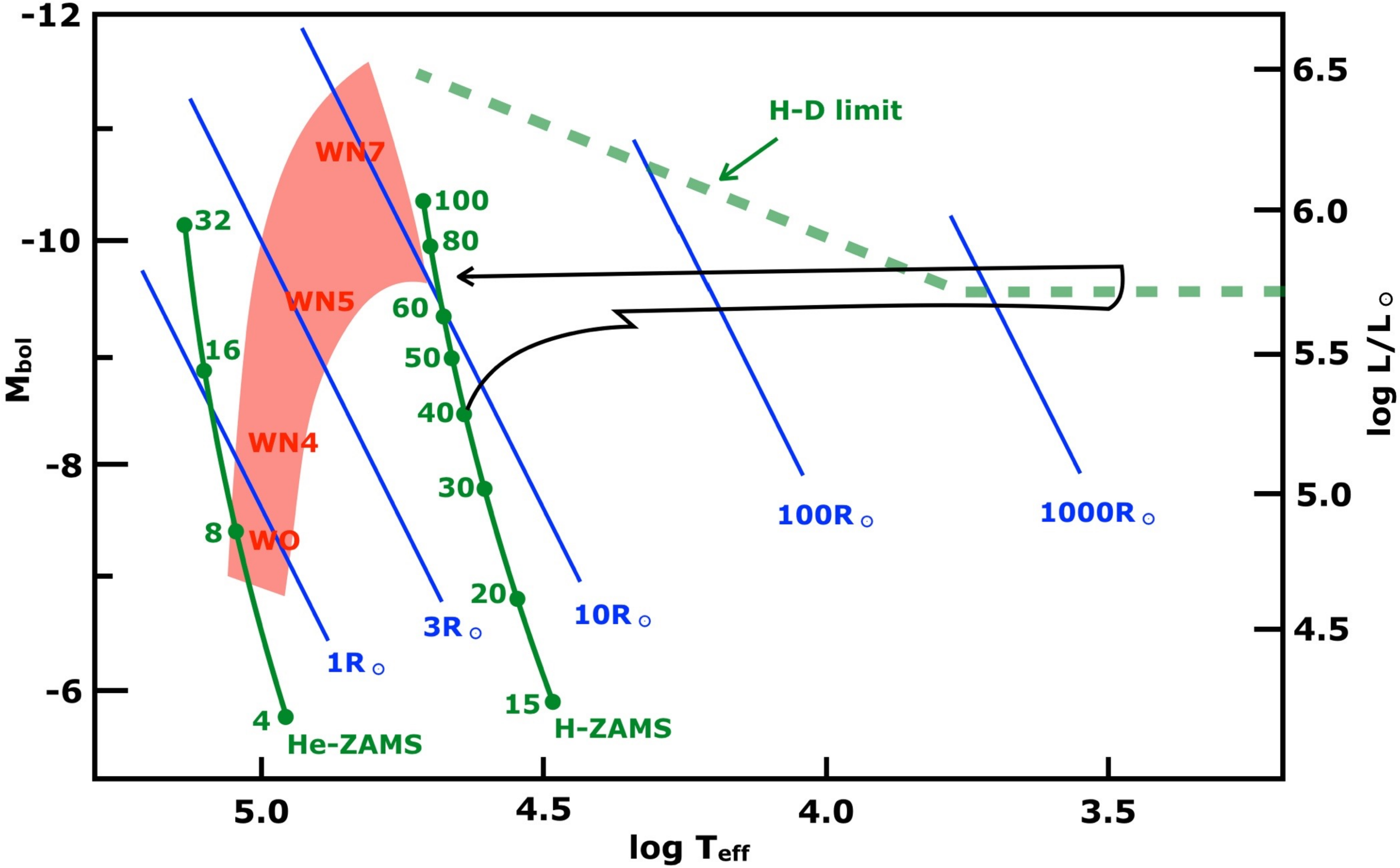
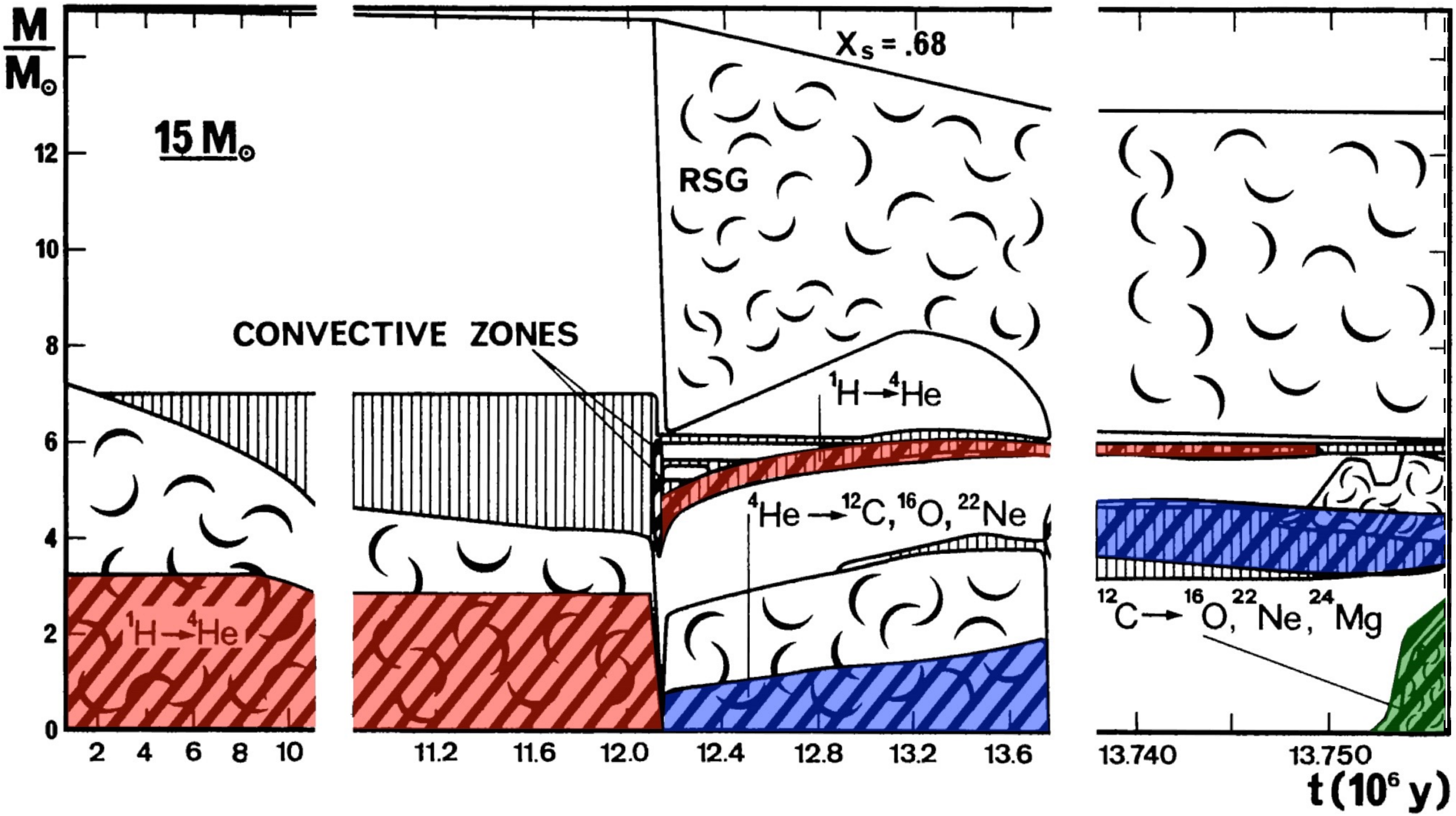


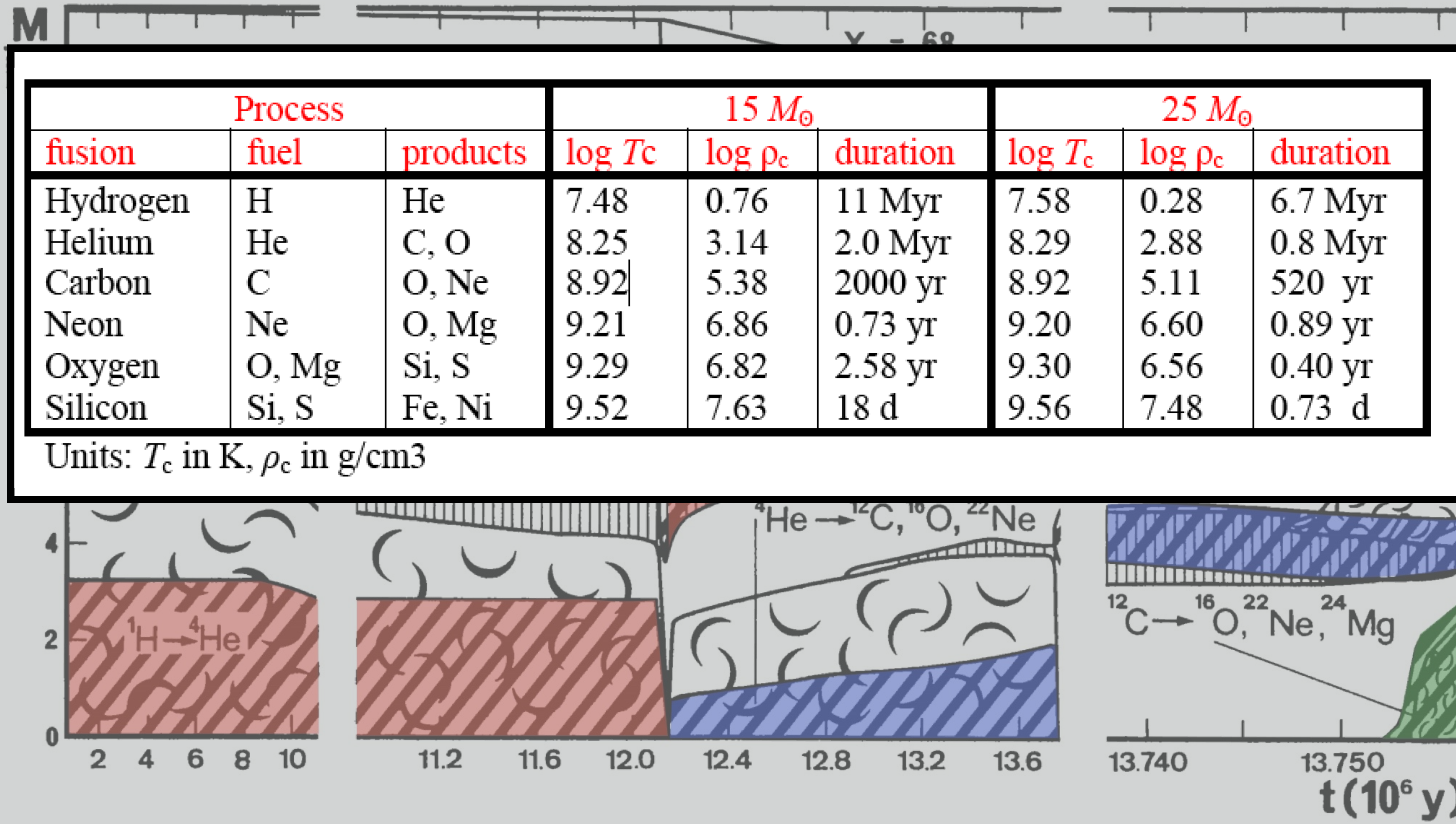
Adapted from Moffat A.F.J., Drissen L., Robert C, 'Observational Connections Between LBV'S and Other Stars, With Emphasis On Wolf-Rayet Stars. In: Davidson K., Moffat A.F.J., Lamers H.J.G.L.M. (eds) Physics of Luminous Blue Variables', vol 157, 1989, p 223, © Kluwer Academic Publishers 1989. With permission of Springer.

Massive Stars - intermediate mass



t = 13.753 Myr: core C fusion starts

Massive Stars - intermediate mass



Process			$15\,M_\odot$			$25\,M_\odot$		
fusion	fuel	products	log Tc	log ρ_c	duration	log T_c	log ρ_c	duration
Hydrogen	H	He	7.48	0.76	11 Myr	7.58	0.28	6.7 Myr
Helium	He	C, O	8.25	3.14	2.0 Myr	8.29	2.88	0.8 Myr
Carbon	C	O, Ne	8.92	5.38	2000 yr	8.92	5.11	520 yr
Neon	Ne	O, Mg	9.21	6.86	0.73 yr	9.20	6.60	0.89 yr
Oxygen	O, Mg	Si, S	9.29	6.82	2.58 yr	9.30	6.56	0.40 yr
Silicon	Si, S	Fe, Ni	9.52	7.63	18 d	9.56	7.48	0.73 d

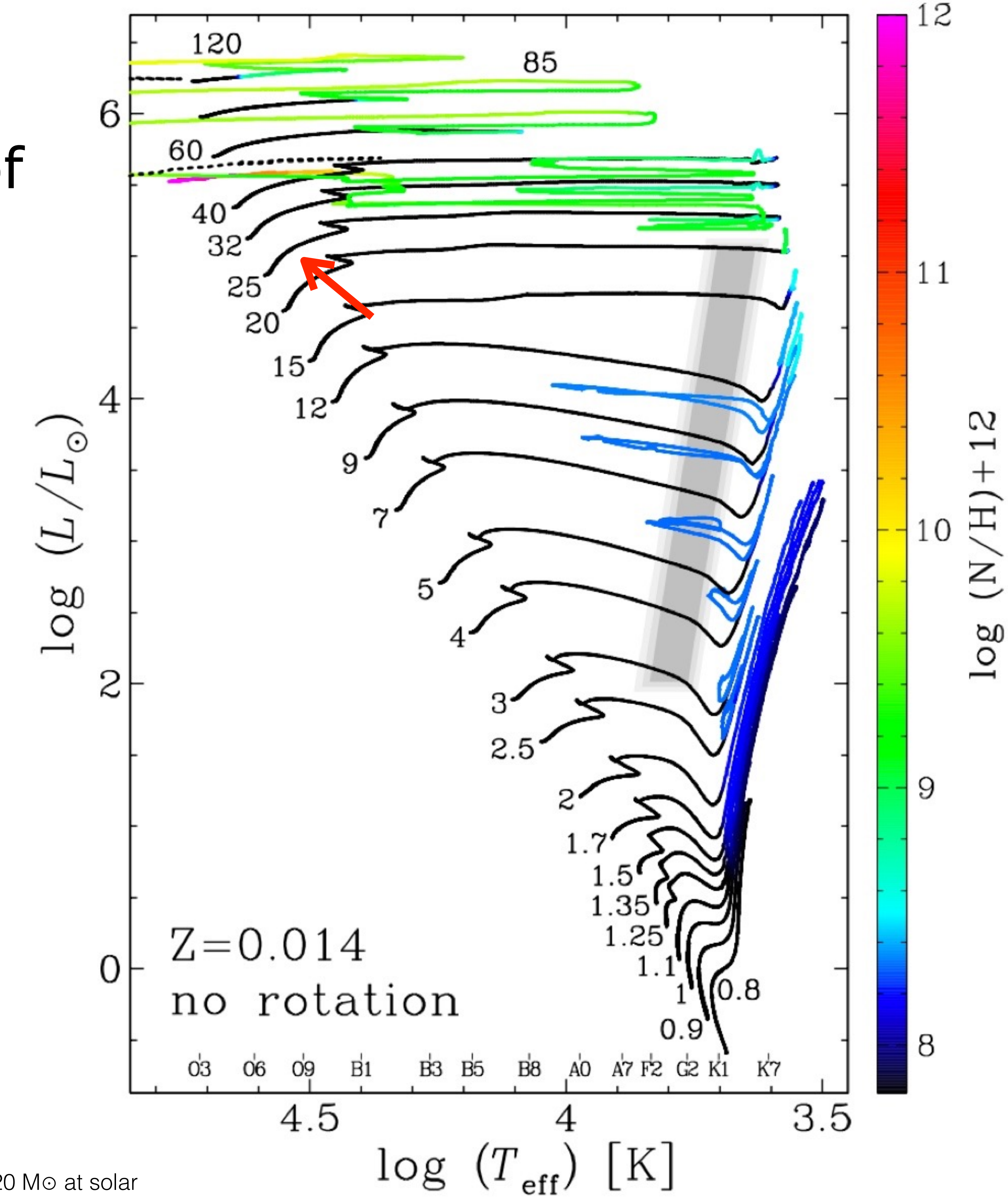
Units: T_c in K, ρ_c in g/cm3

t = 13.753 Myr: core C fusion stars

Massive Stars - high mass

25-120M⊙

—widening MS at higher masses (stars losing 5-30% of their initial mass)



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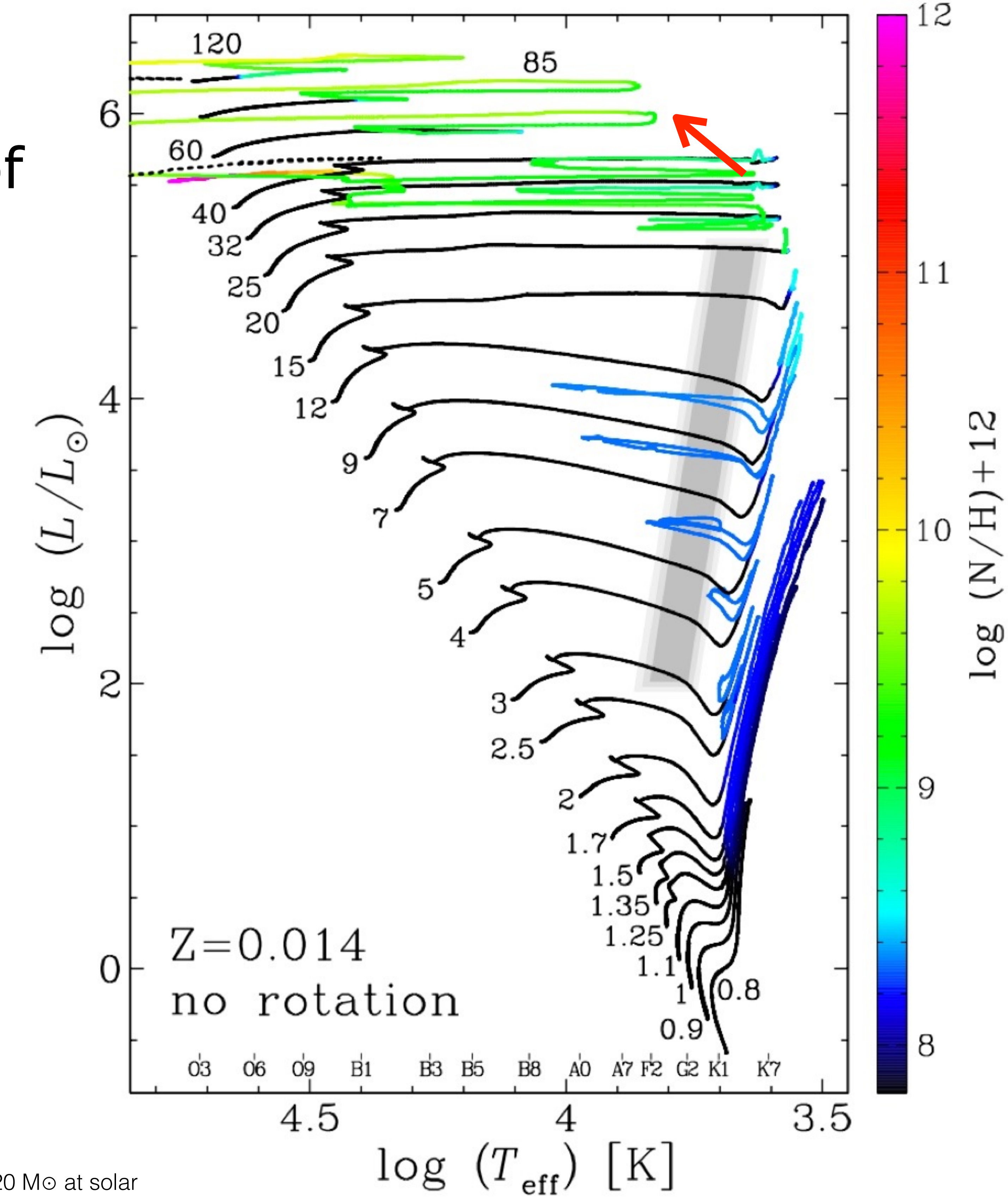
Massive Stars - high mass

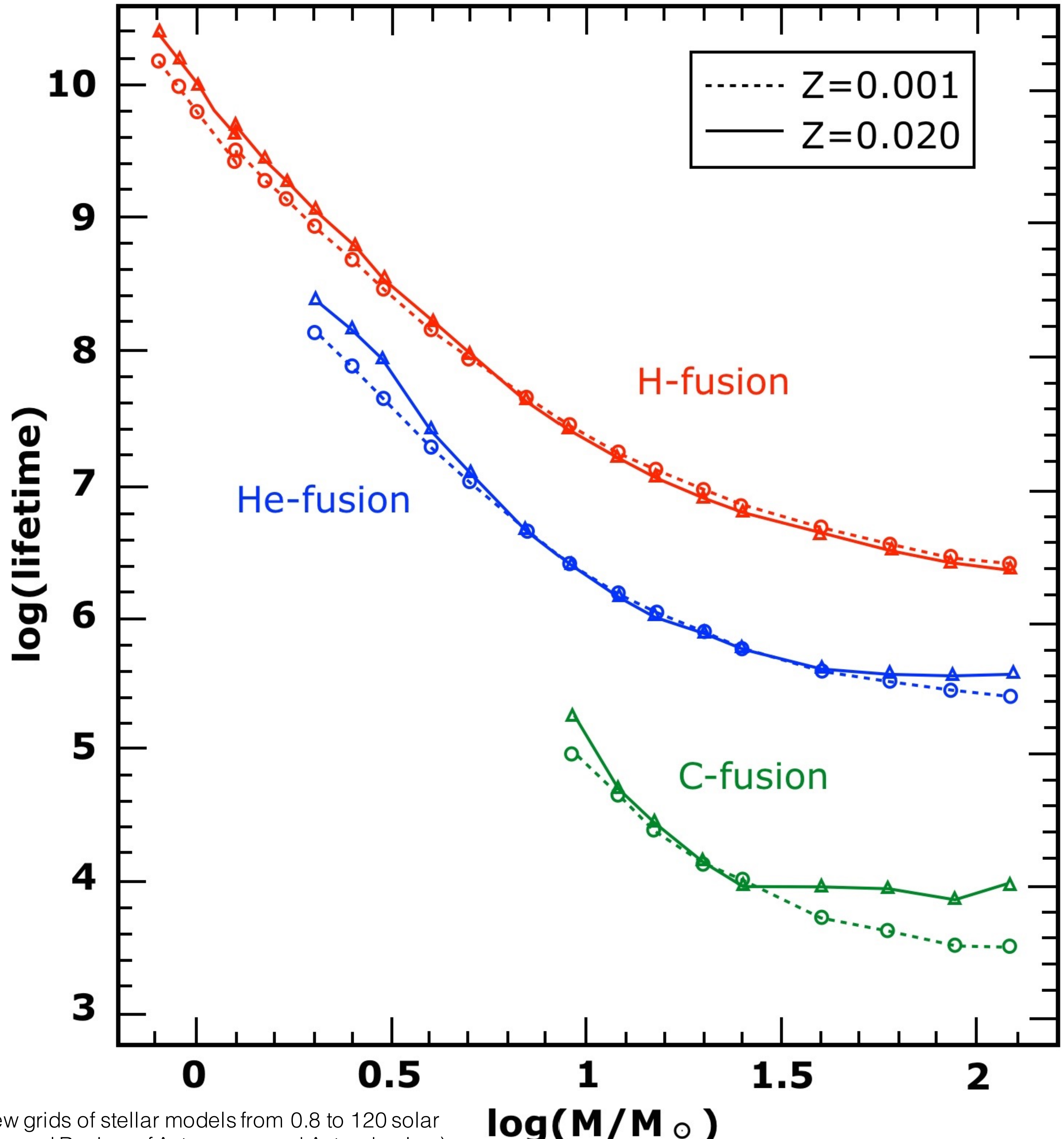
25-120M⊙

—widening MS at higher masses (stars losing 5-30% of their initial mass)

—Humphreys-Davidson limit at >50M⊙



Massive Stars - high mass



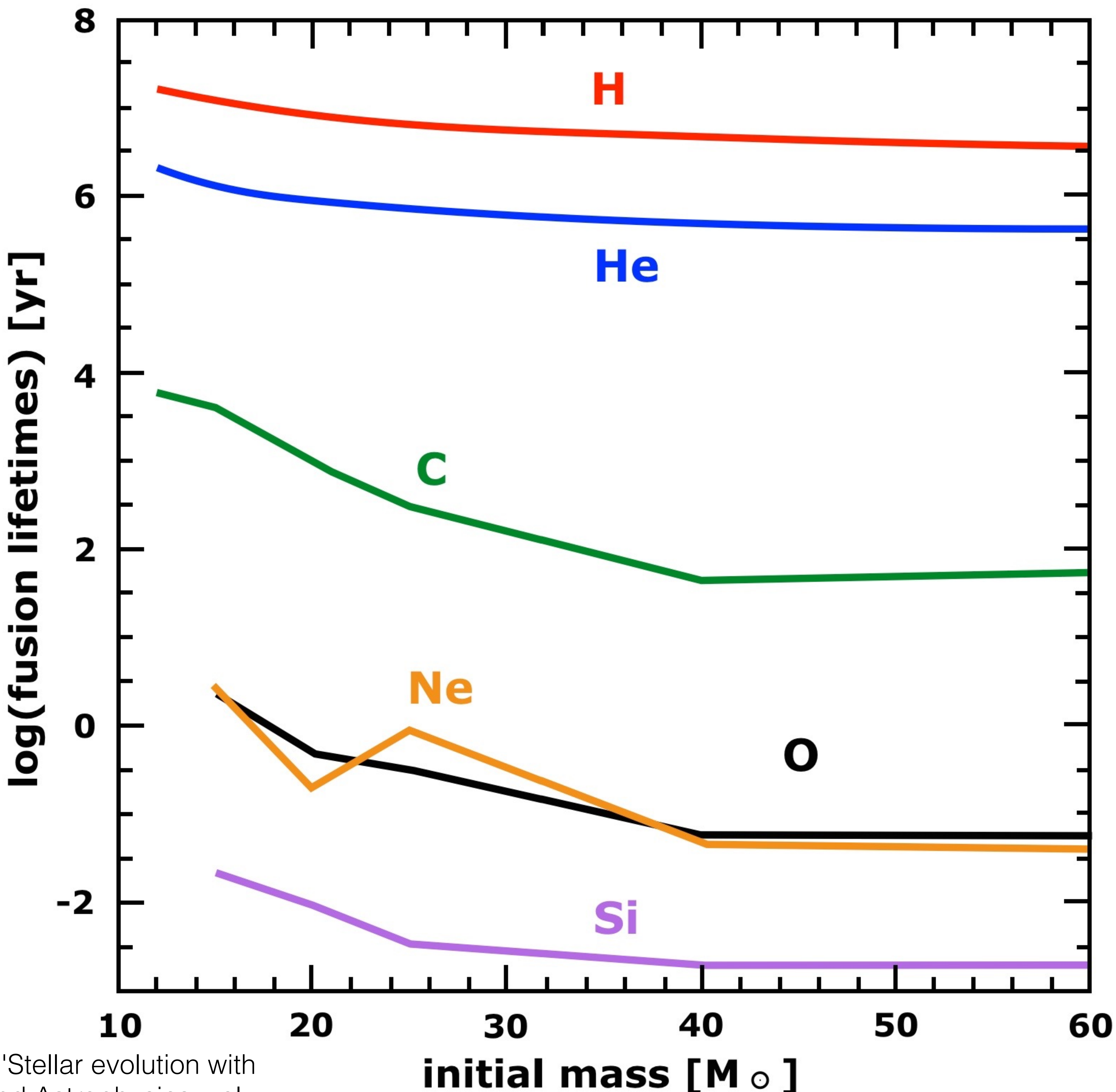
Reproduced from Schaller G et al, ''New grids of stellar models from 0.8 to 120 solar masses at Z = 0.020 and Z = 0.001', Annual Review of Astronomy and Astrophysics), vol. 96, no. 2, p. 269-331. 1992. Reproduced with permission. © ESO.

Massive Stars - pre-SN stages...

Late evolution phases proceed at increasing speed.

— mainly due to decreasing ϵ_n as atomic mass goes up

— also neutrinos take increasing fraction of energy away in O-fusion and Si formation

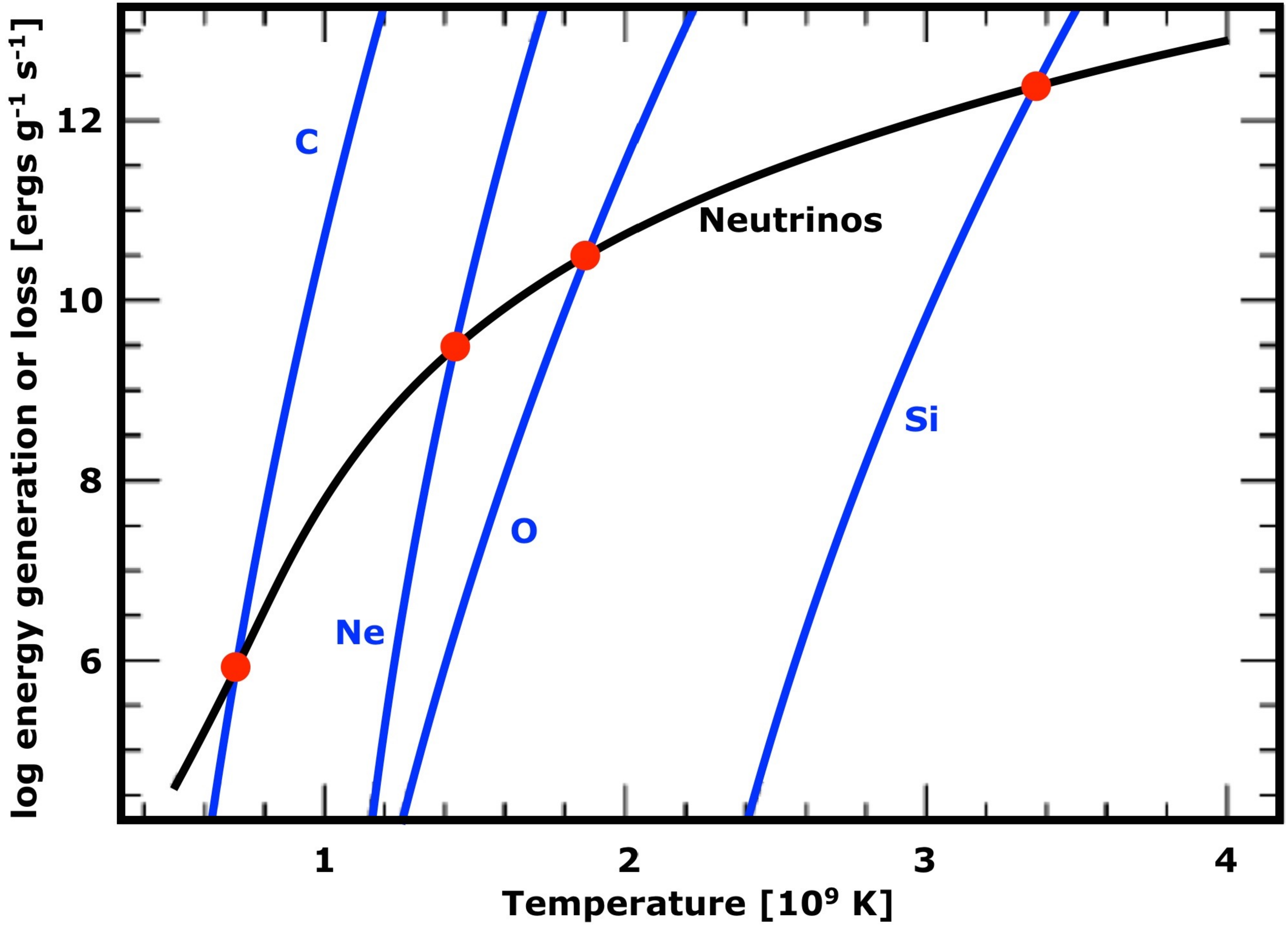


Reproduced from Hirschi, Maeder, Meynet 2004, 'Stellar evolution with rotation. XII. Pre-supernova models' Astronomy and Astrophysics, vol 425, p.649-670, 2004. Reproduced with permission. © ESO.

Massive Stars - pre-SN stages...

T_c of massive stars during late fusion phases is set by:

$$\epsilon_{\mathrm{n}} = \epsilon_{\nu} + \epsilon_{\mathrm{therm}} \approx \epsilon_{\nu}$$



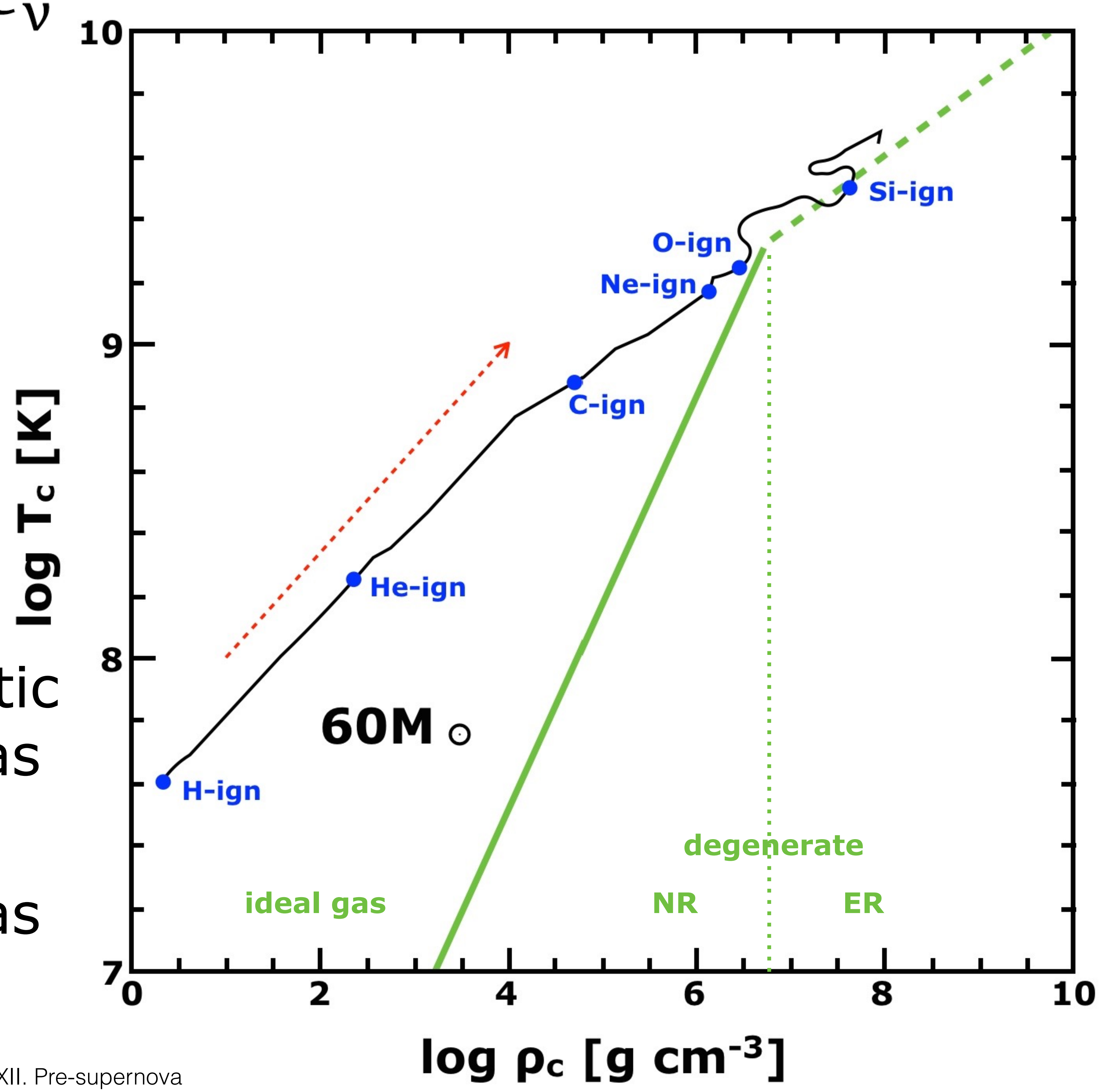
Massive Stars - pre-SN stages...

T_c of massive stars during late fusion phases is set by:

$$\epsilon_n = \epsilon_\nu + \epsilon_{therm} \approx \epsilon_\nu$$

central temp $T_c \sim \rho_c^{1/3}$

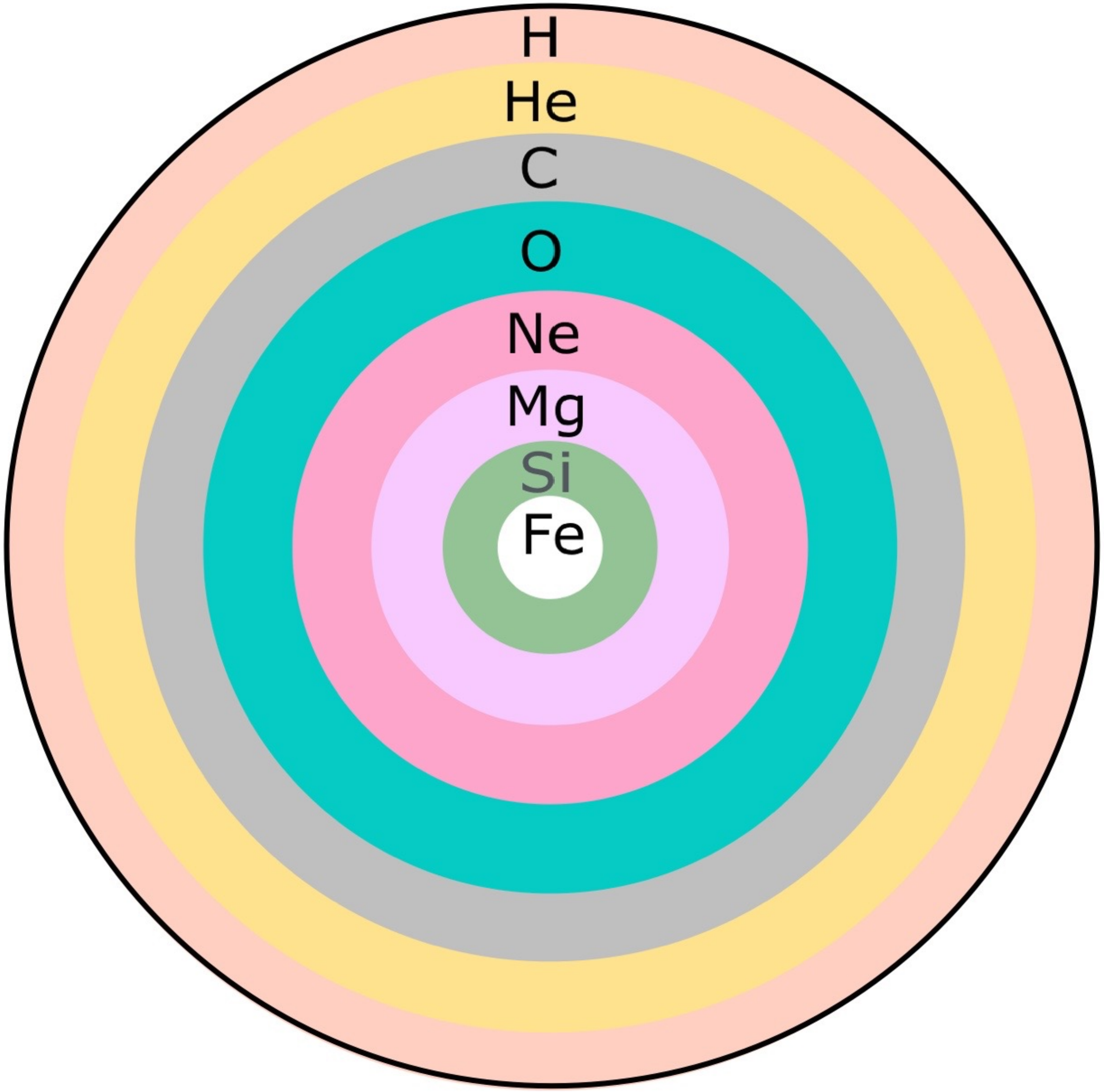
equilibrium is set by the values of T_c and ρ_c needed to produce the net $L_{nucl}-L_\nu$ required to stay in hydro-static and thermal equilib.



— boundary; non-relativistic degenerate and ideal gas

- - - boundary; relativistic degenerate and ideal gas

Massive Stars - intermediate mass



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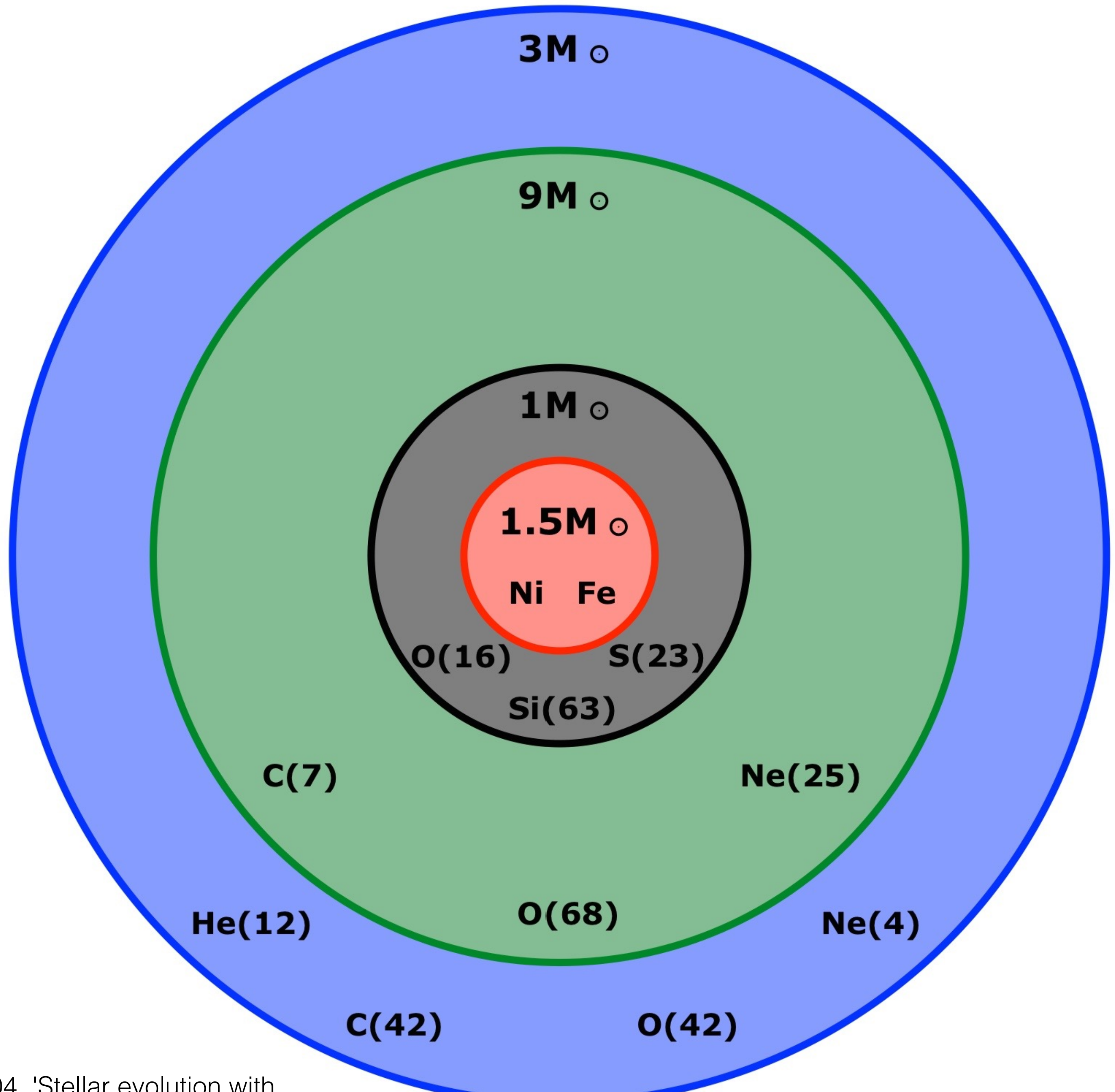
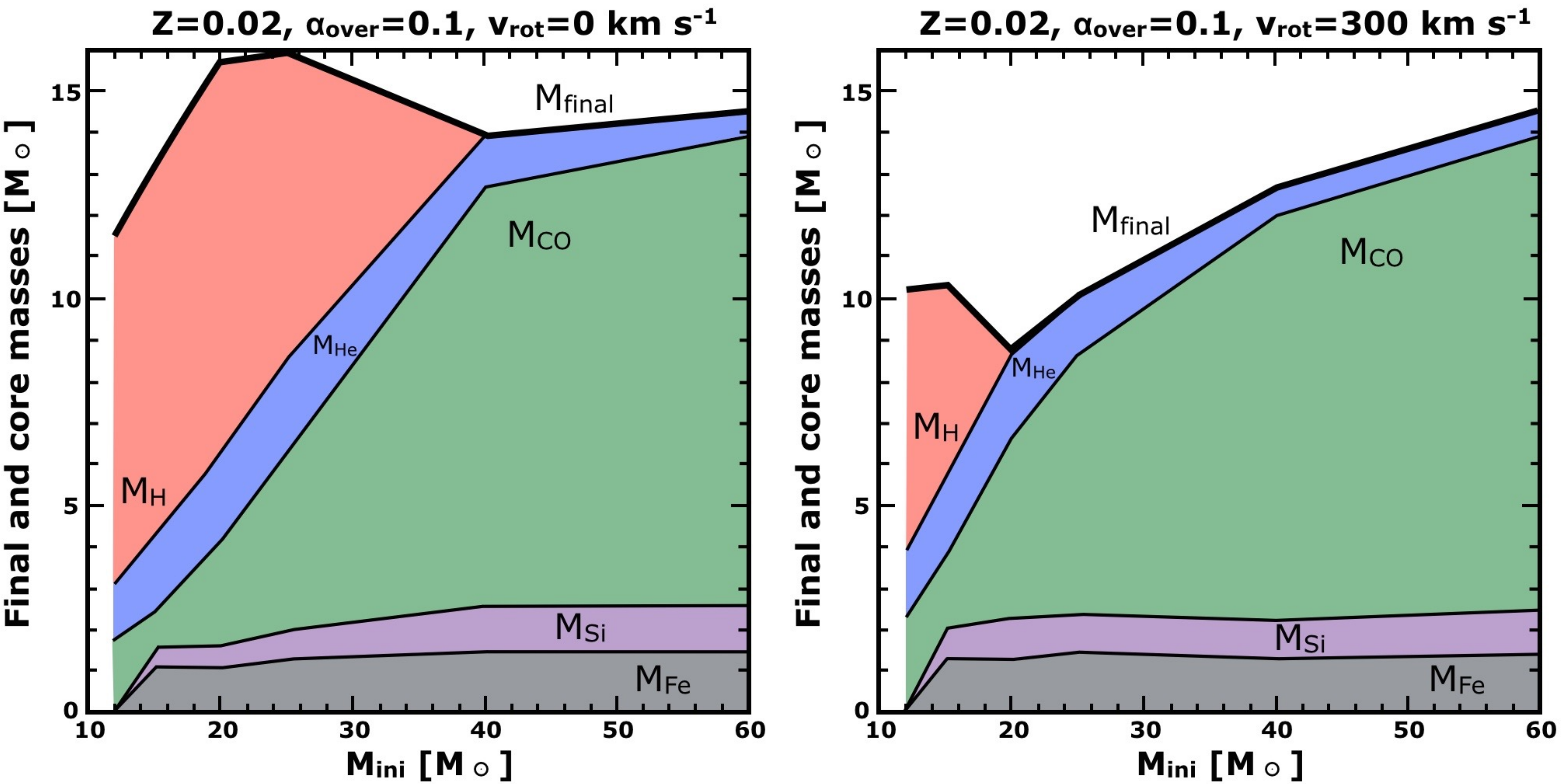
Massive Stars - pre-SN stages…

In the immediate pre-SN stage a massive star has an "onion skin" chemical structure; below is the example for a *rotating* massive star with the results of He, C, O, and Si fusion:

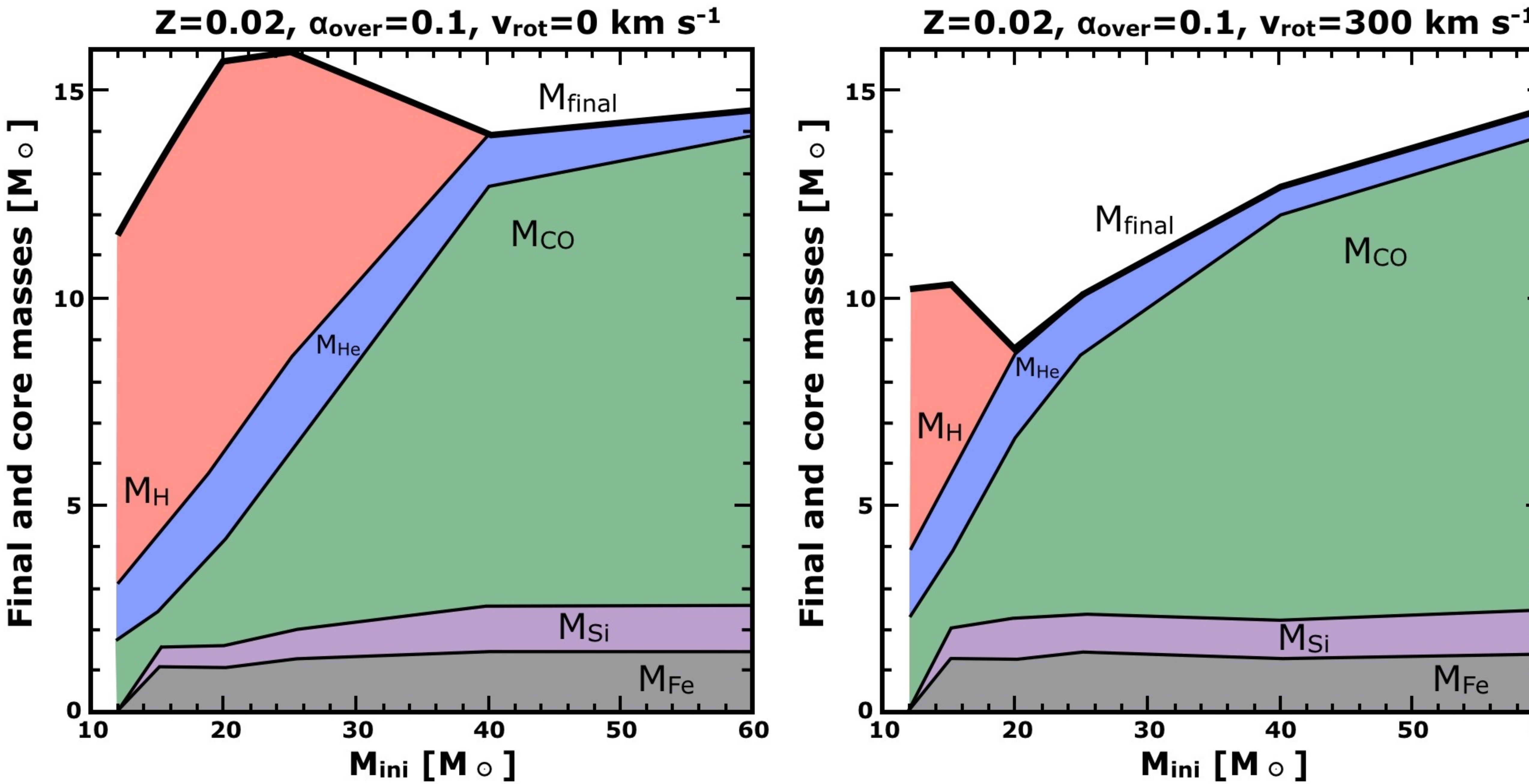


Massive Stars - pre-SN stages...

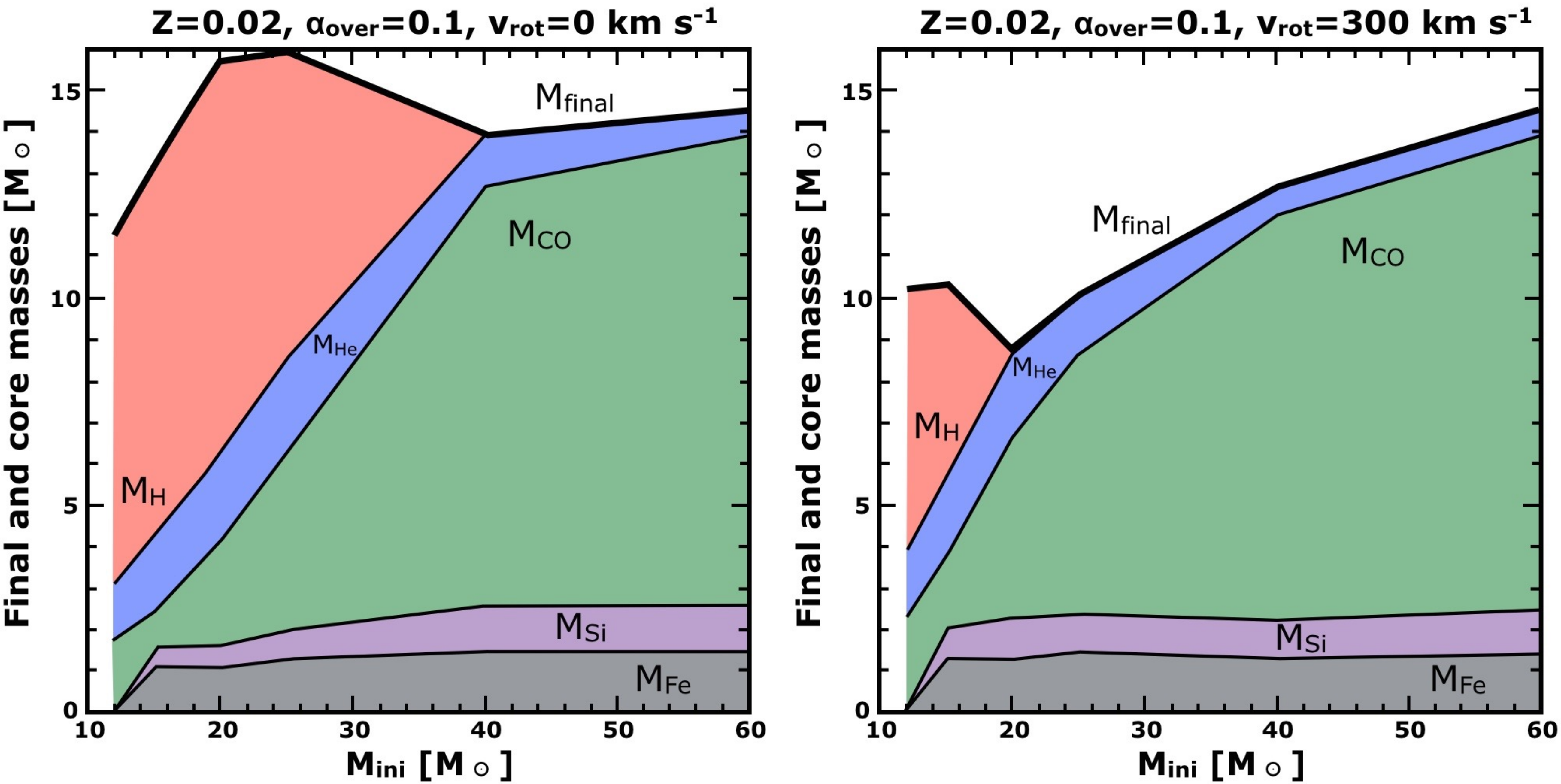
The mass distribution at the end of Si fusion (as a function of M_i) for solar metallicity stars that are non-rotating (left) and rapidly rotating (right).



Massive Stars - pre-SN stages...



Massive Stars - pre-SN stages...

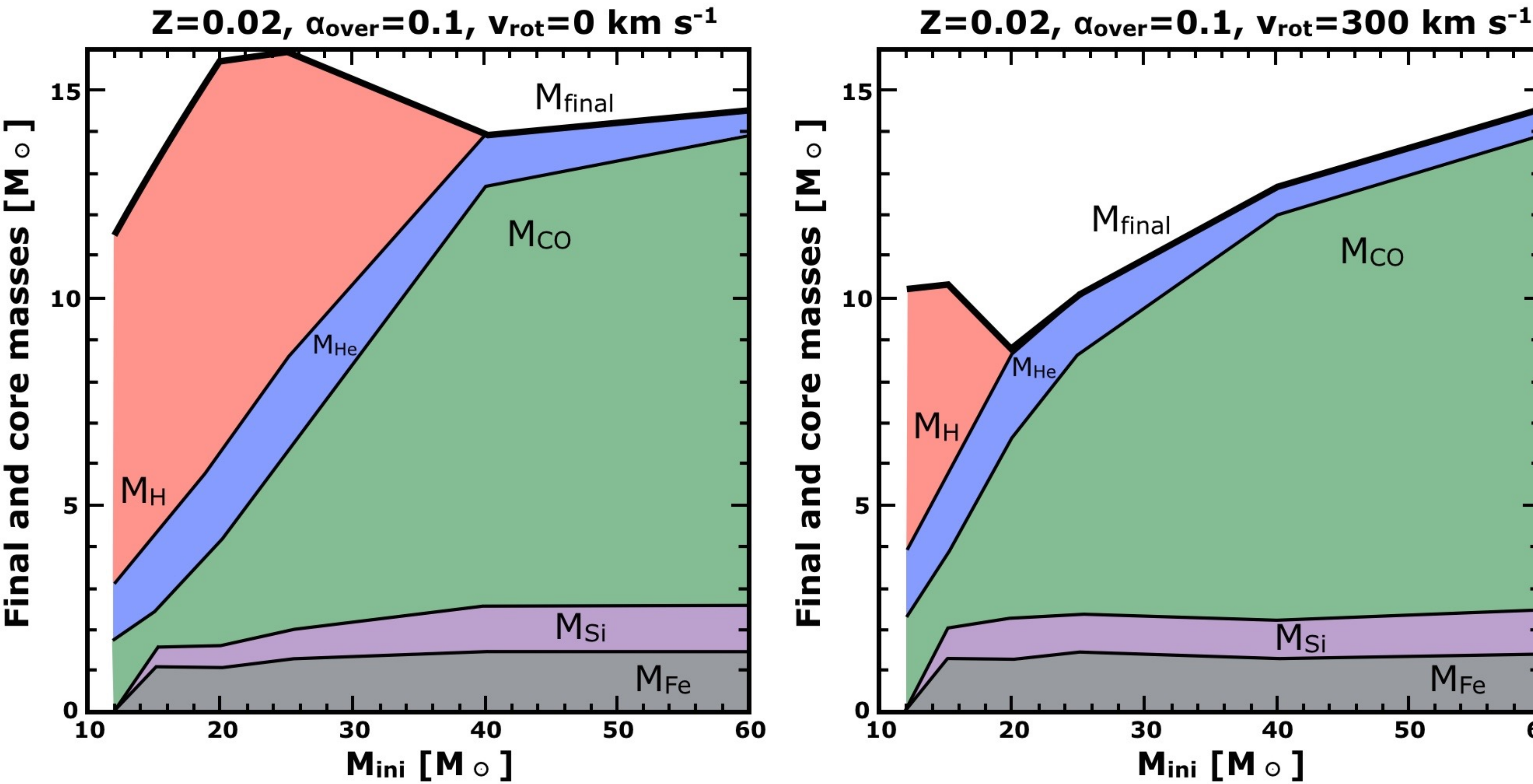


—at end of Si fusion rapidly rotating stars have lost more mass

—non-rotating stars with $M_i<40M_\odot$ still have H env when they explode; they die as RSGs. For rotating stars limit is $M_i<20M_\odot$

—all stars have ~1-2$M_\odot$ of He at the end of their lives

Massive Stars - pre-SN stages...

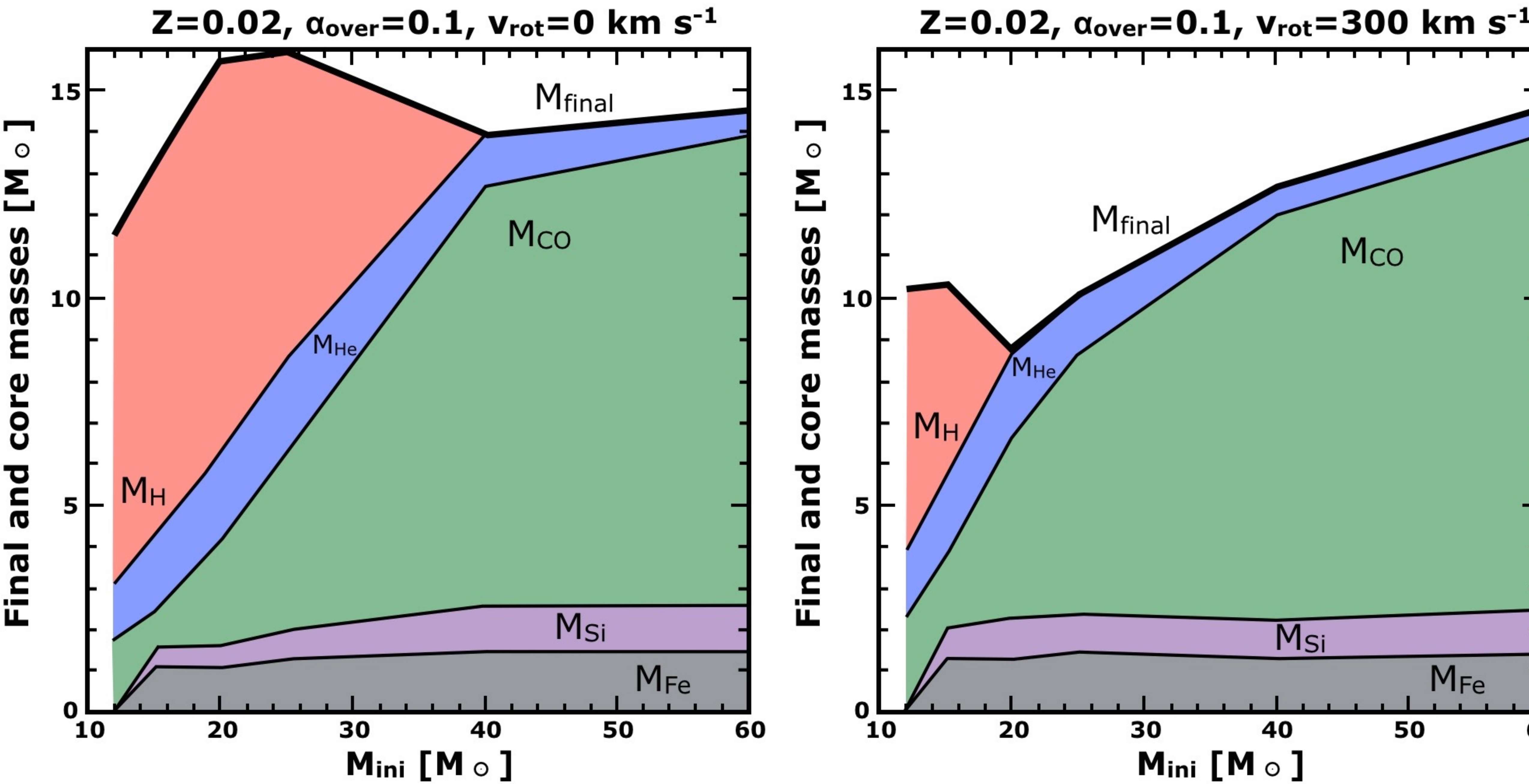


—rapidly rotating stars with $12M_\odot < M_i < 40M_\odot$ have higher mass fractions of C, O and Ne fusion products

—by end of Si fusion most mass is C and O

—stars with $M_i < 15M_\odot$ don't reach Ne, O, and Si fusion

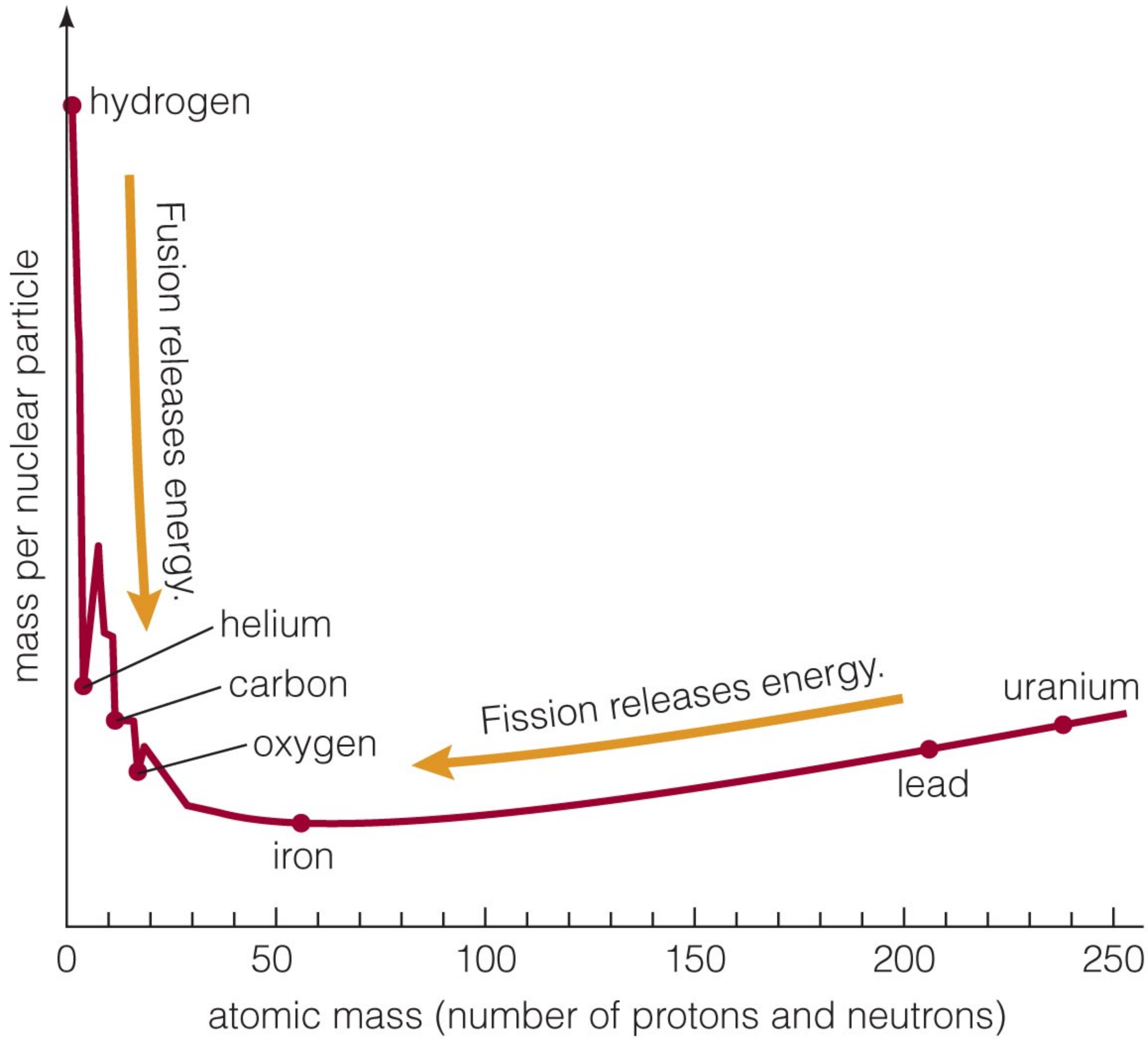
Massive Stars - pre-SN stages...



—stars with $M_i < 15 M_\odot$ don't reach Ne, O, and Si fusion

—the Fe core and Si shell make up $\sim 2 M_\odot$ in $M_i > 15 M_\odot$ stars

—the Fe core mass and Si shell are almost independent of rotation effects; T_c and ρ_c are almost independent of outer layers

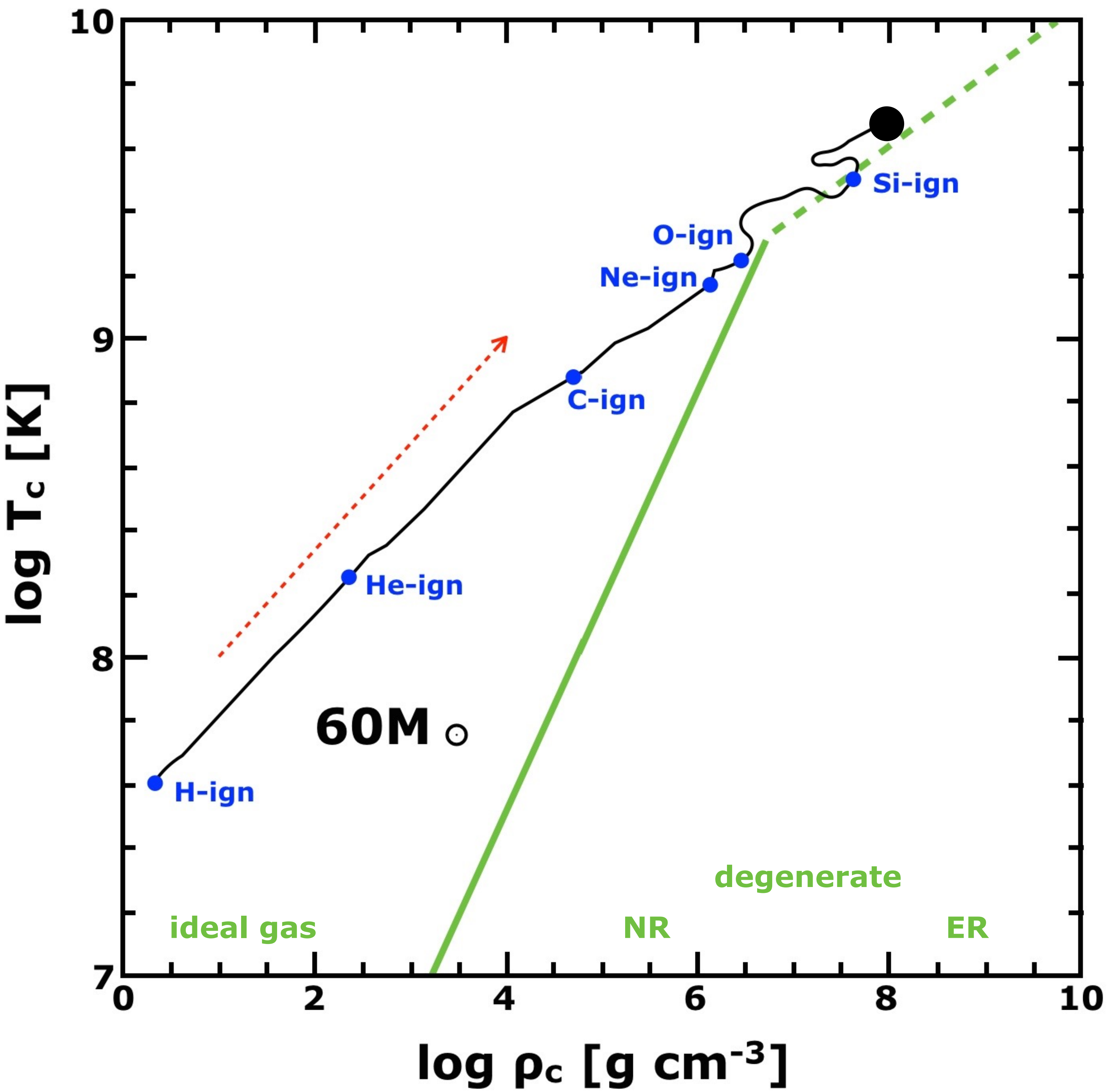


Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(This is because iron has lowest mass per nuclear particle.)

Supernovae - core collapse

When a star develops an Fe core, $T_c \sim 4 \times 10^9$ K and $\rho_c > 10^8$ g cm^{-3}



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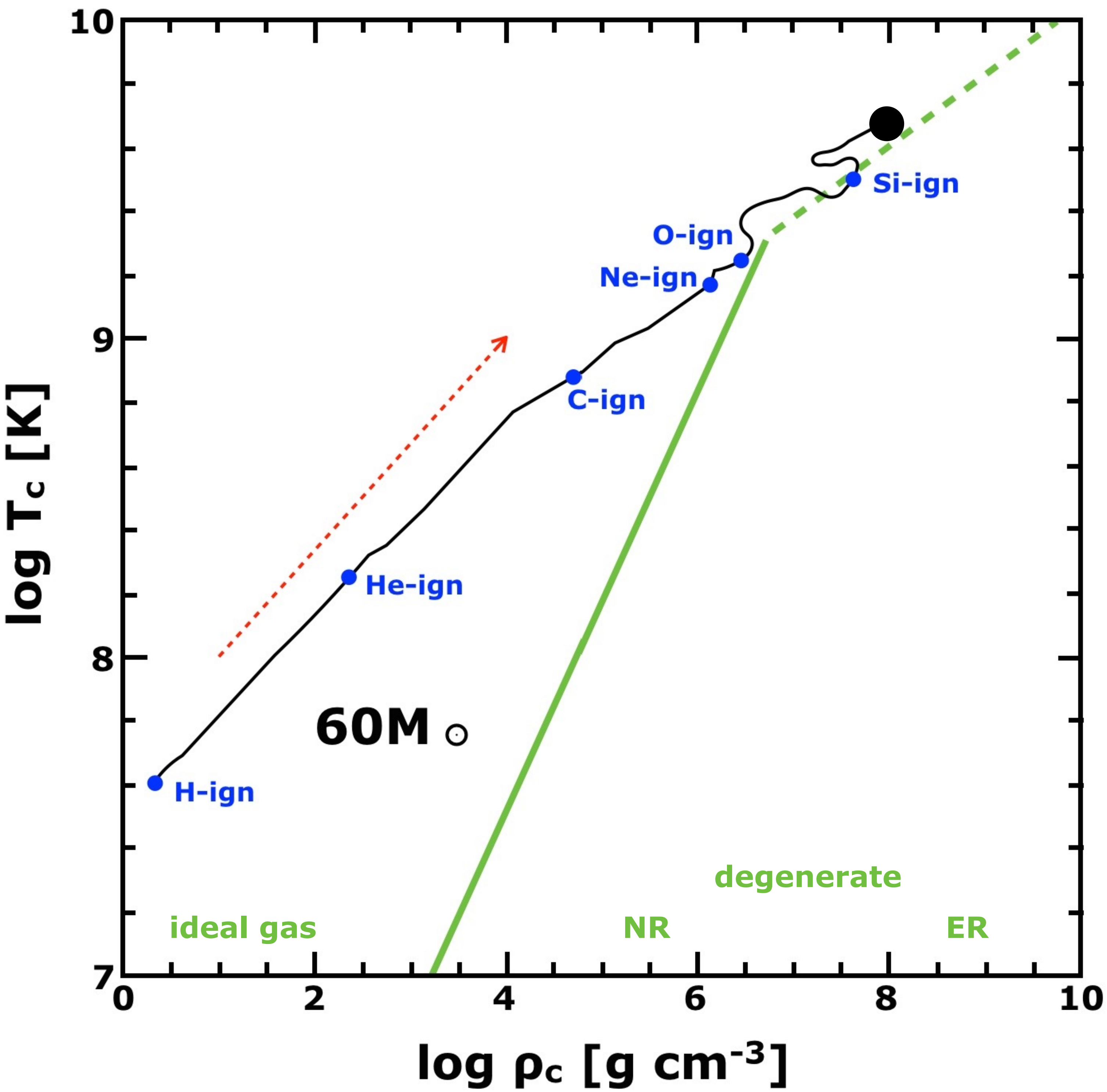


The core starts contracting, as it has in past transitions between fusion processes…

Once $T_c > 10^{10}$ K, Fe can be photodissociated:

$$^{56}\text{Fe} + \gamma \rightarrow 13\,^{4}\text{He} + 4\text{n}$$

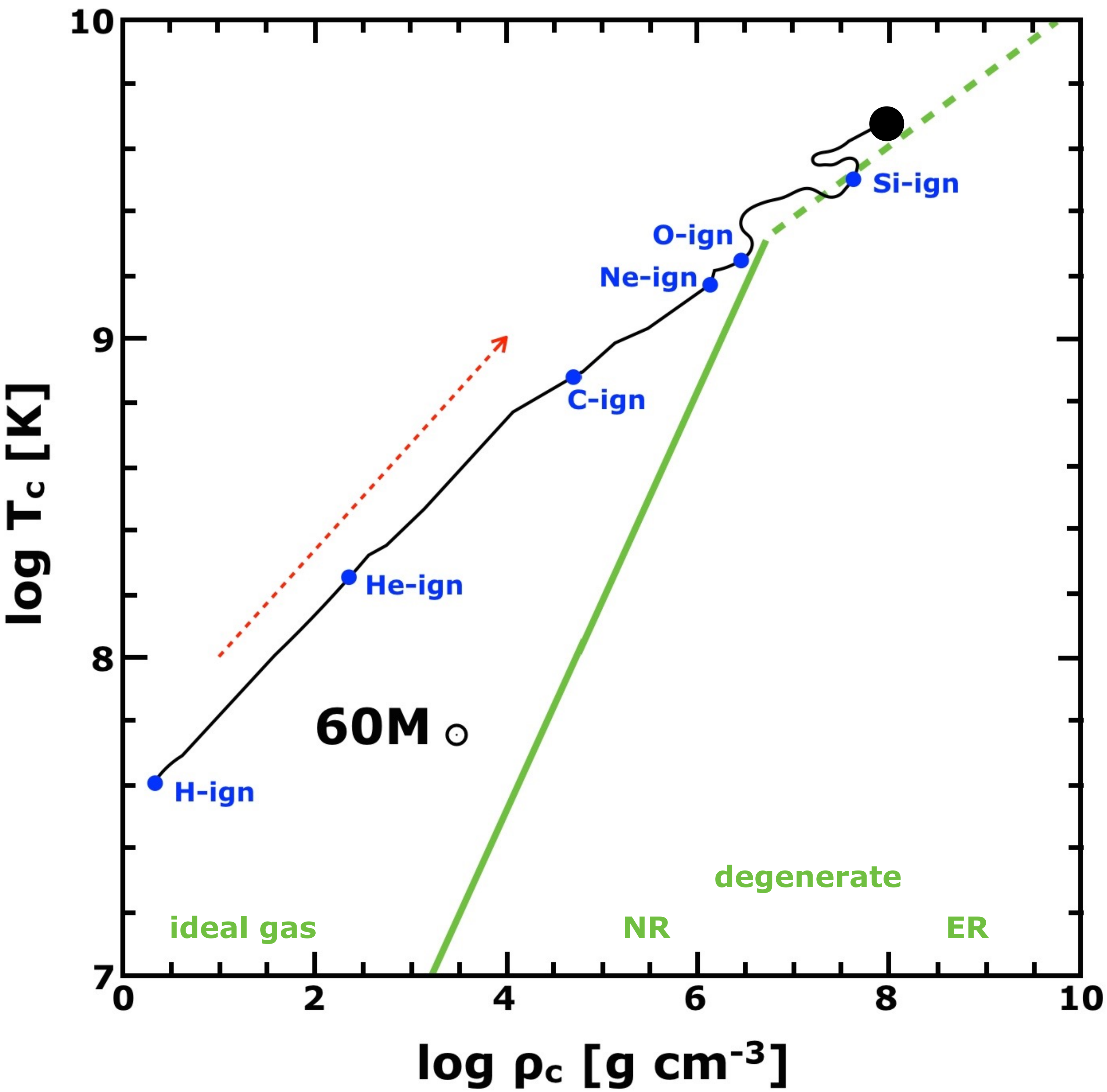
This is an endothermic reaction; core cools quickly, accelerating collapse.

(high ρ = millisec collapse)

$$t_{\rm ff} \sim \frac{1}{\sqrt{G\rho}}$$

Supernovae - core collapse

As core collapse continues, ρ_c increases without much T_c increase.



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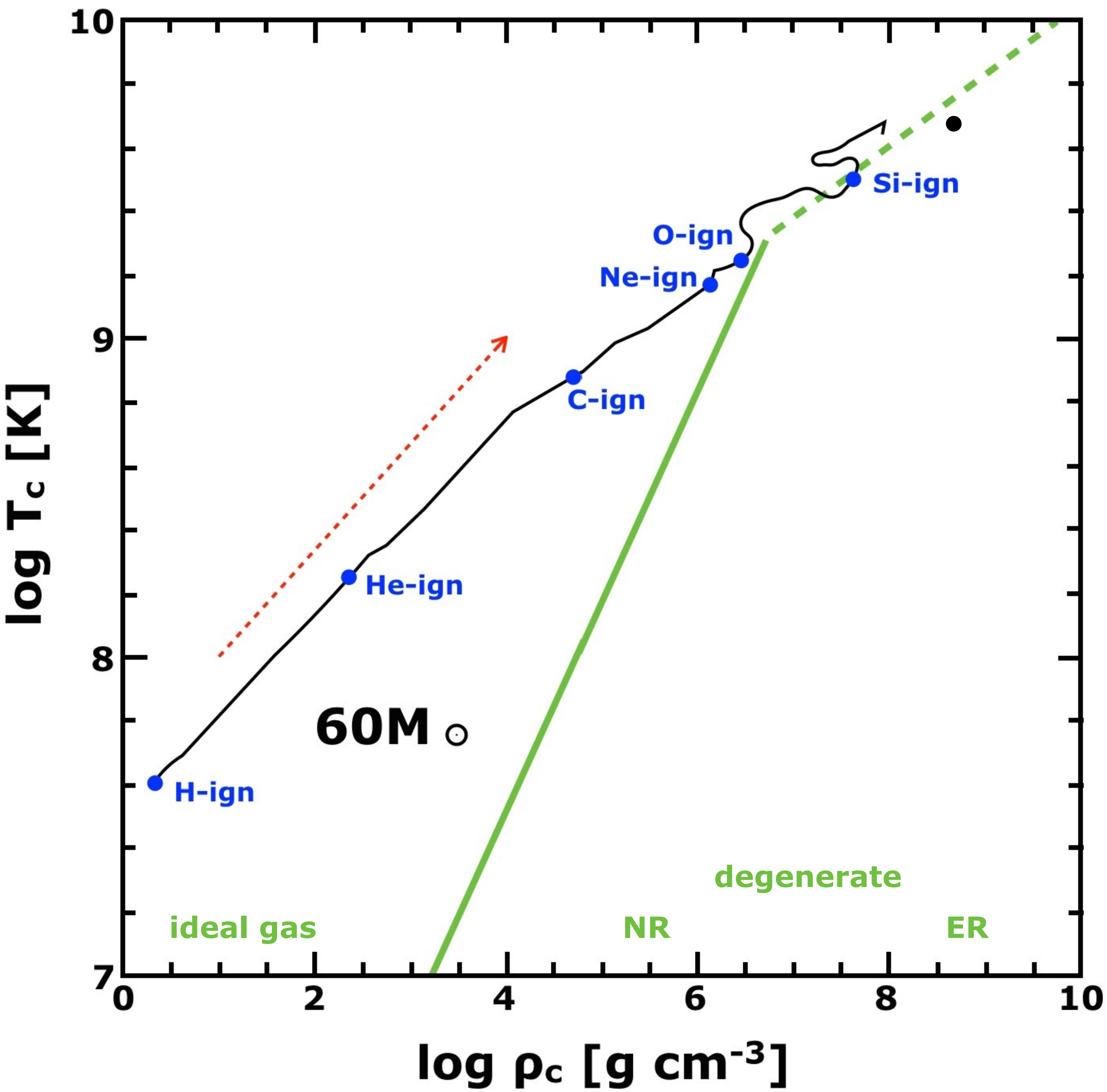

— e^-s are captured by p's, forming a degenerate n gas

— similar to WDs, degenerate neutron gas can support high P as long as degeneracy is not relativistic

— if $M_c < 2M_\odot$(ish), pressure of neutron gas stops collapse and a neutron star forms

— if $M_c > 2M_\odot$(ish), pressure cannot halt collapse and a black hole forms