Basics of stellar evolution theory II

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National Astronomical Observatory of Japan

This lecture is based on the following materials.

An Introduction to the Theory of Stellar Structure and Evolution (D. Prialnik, Cambridge University Press, 2009)

Stellar Structure and Evolution (R. Kippenhahn, A. Weigert, & A. Weiss, Springer, 2012)

Physics, Formation and Evolution of Rotating Stars (A. Maeder, Springer, 2009)

Stellar Evolution Physics (I. Iben, Cambridge University Press, 2012)

https://www.astro.ru.nl/~onnop/education/stev_utrecht_notes/

Stellar evolution theory

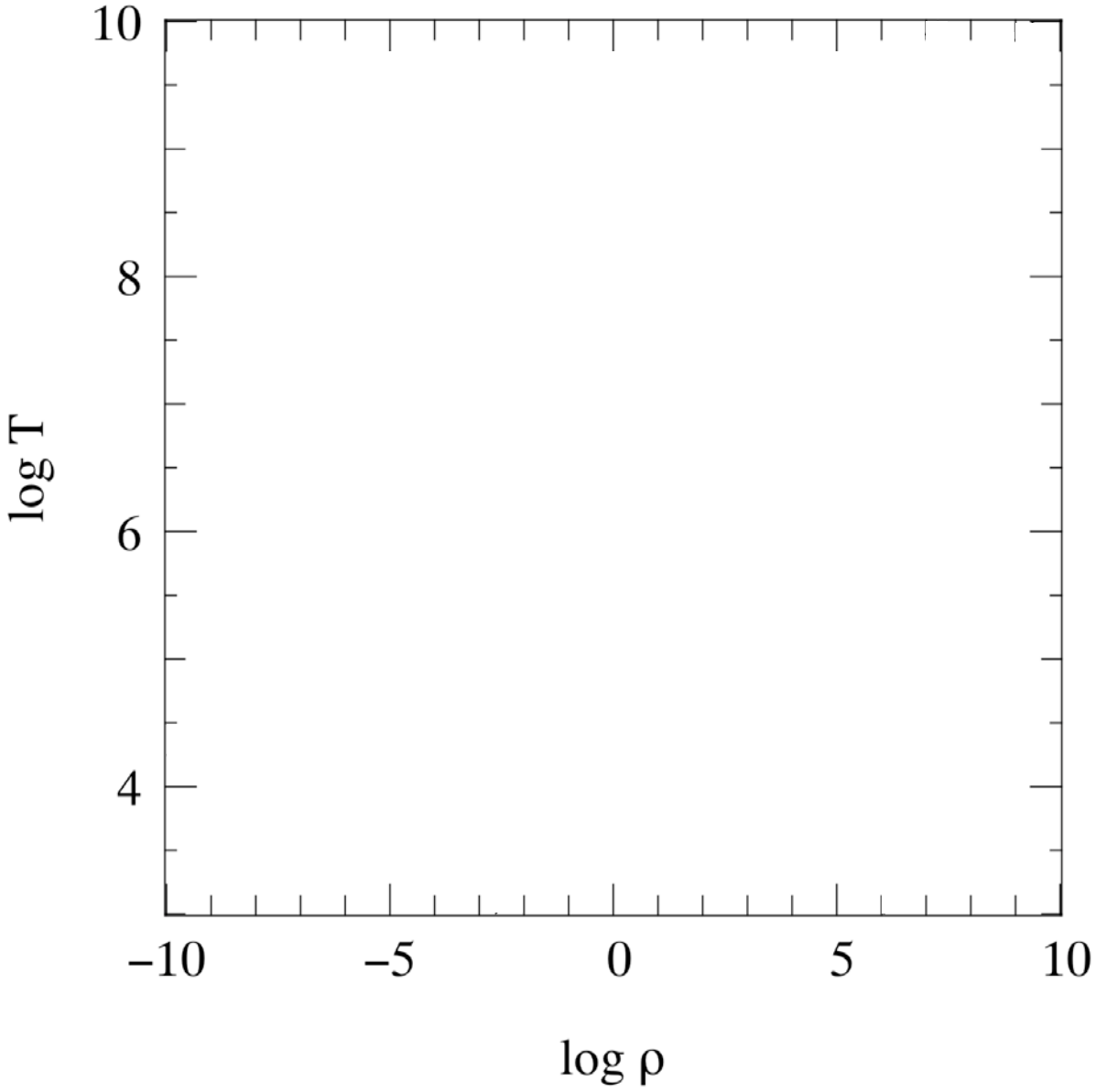
- Based on physics summarized in the previous lecture, we consider how (massive) stars change themselves over time

- Evolution at the center

- Evolution at the surface

Evolution at the center of stars

Characterizing the (log T, log ρ) plane



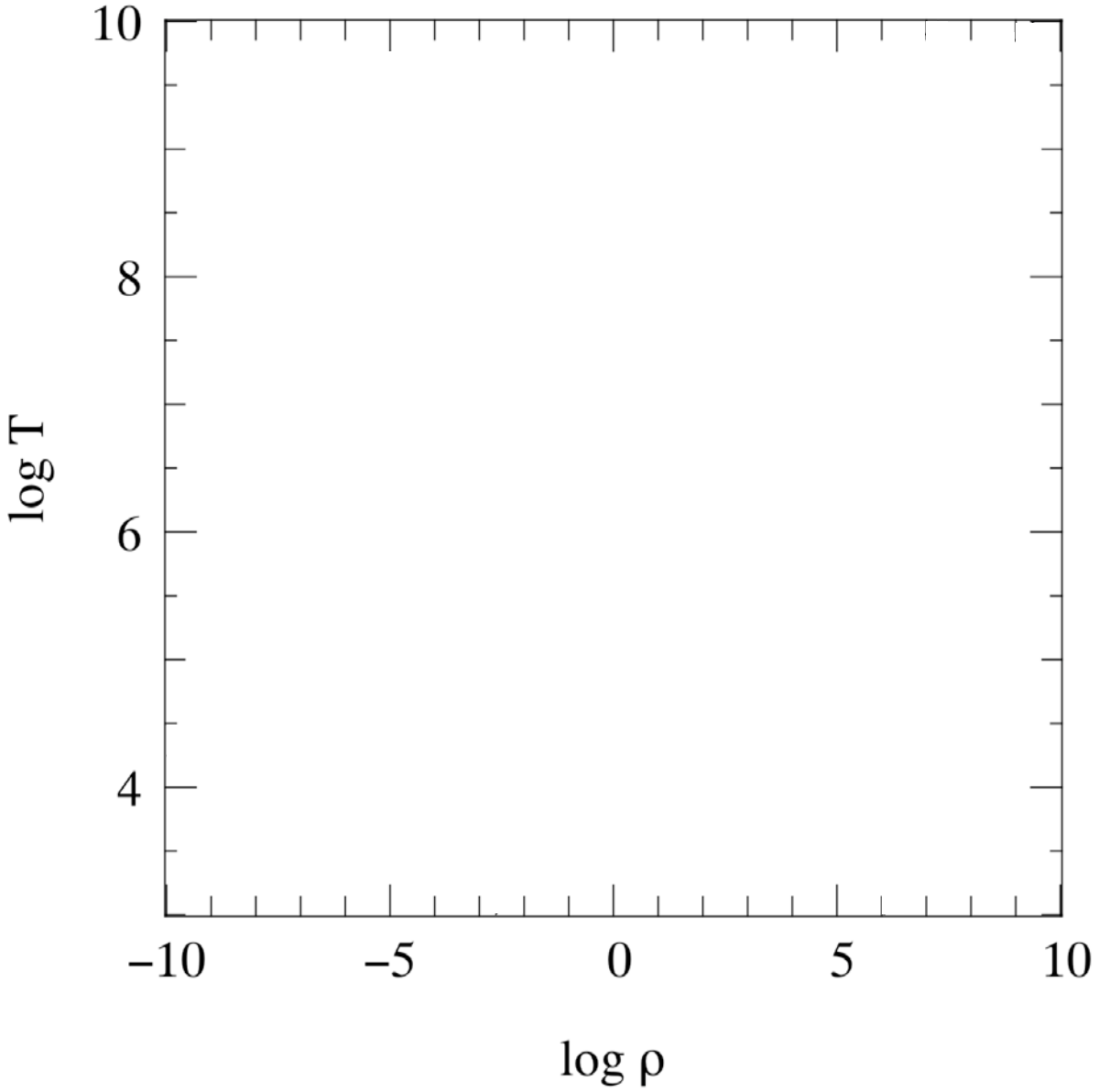
Ideal gas EoS vs degenerate EoS

$$P_{\rm gas} = \frac{\Re}{\mu}\rho T$$

$$P_{\rm e,deg} = K_1 \rho^{5/3}$$

$$P_{\rm gas} \simeq P_{\rm e,deg}$$

$$\log T \simeq \frac{2}{3}\log\rho + \text{const}\,.$$



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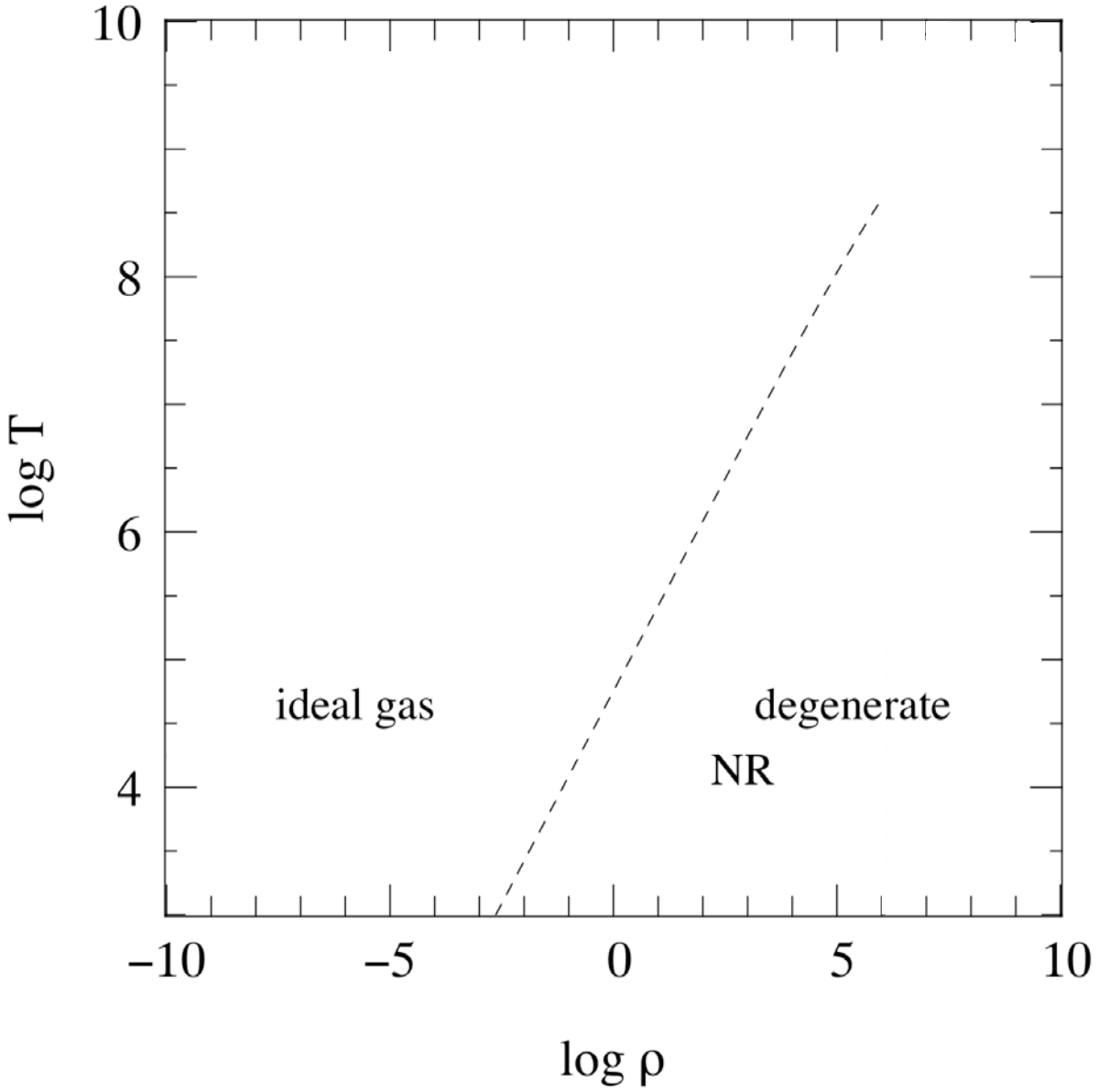

Degenerate EoS vs relativistic-degenerate EoS

$$P_{\mathrm{e,deg}} = K_1 \rho^{5/3}$$

$$P_{\mathrm{e,r-deg}} = K_2 \rho^{4/3}$$

$$P_{\mathrm{e,deg}} \simeq P_{\mathrm{e,r-deg}}$$

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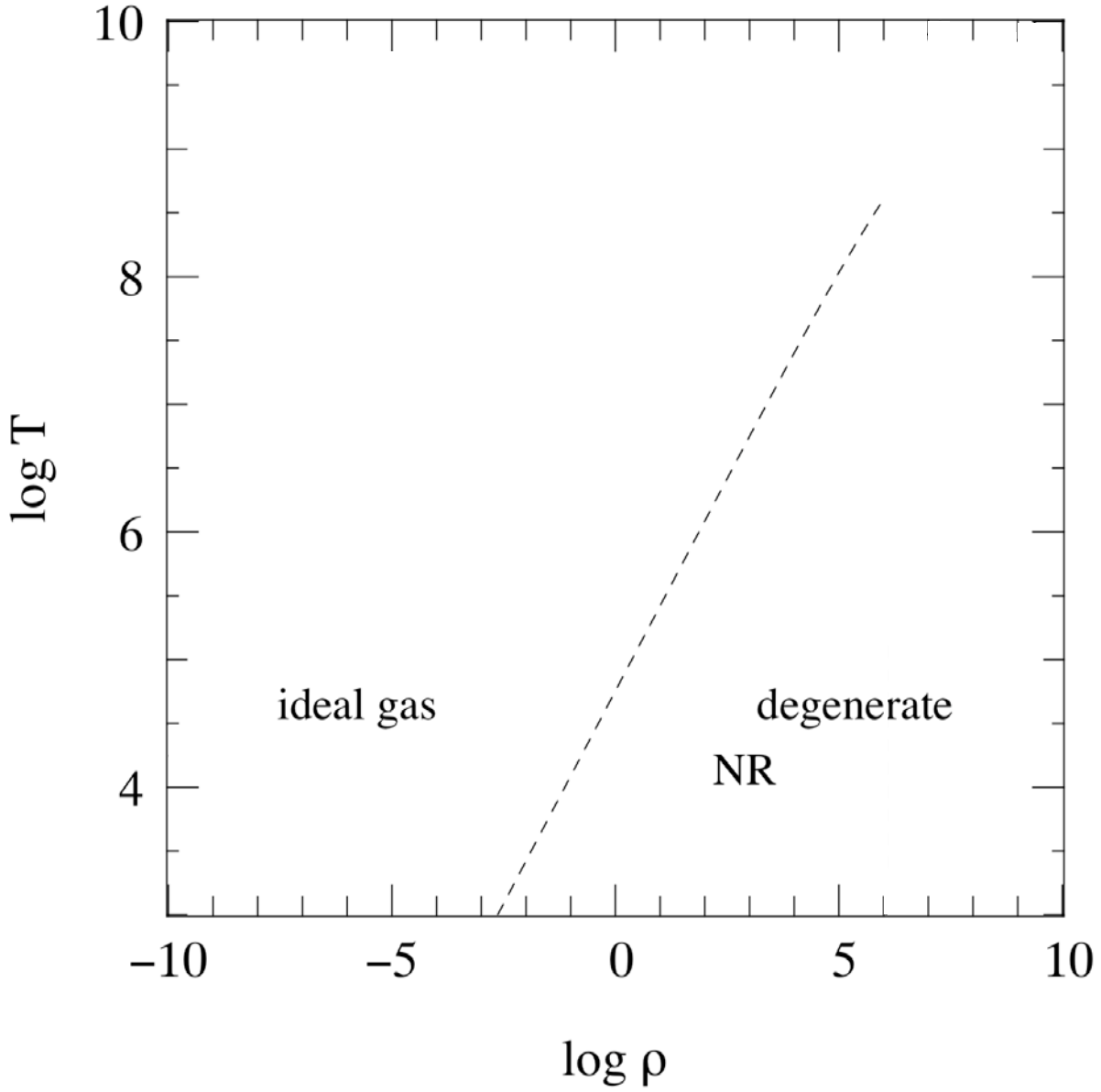

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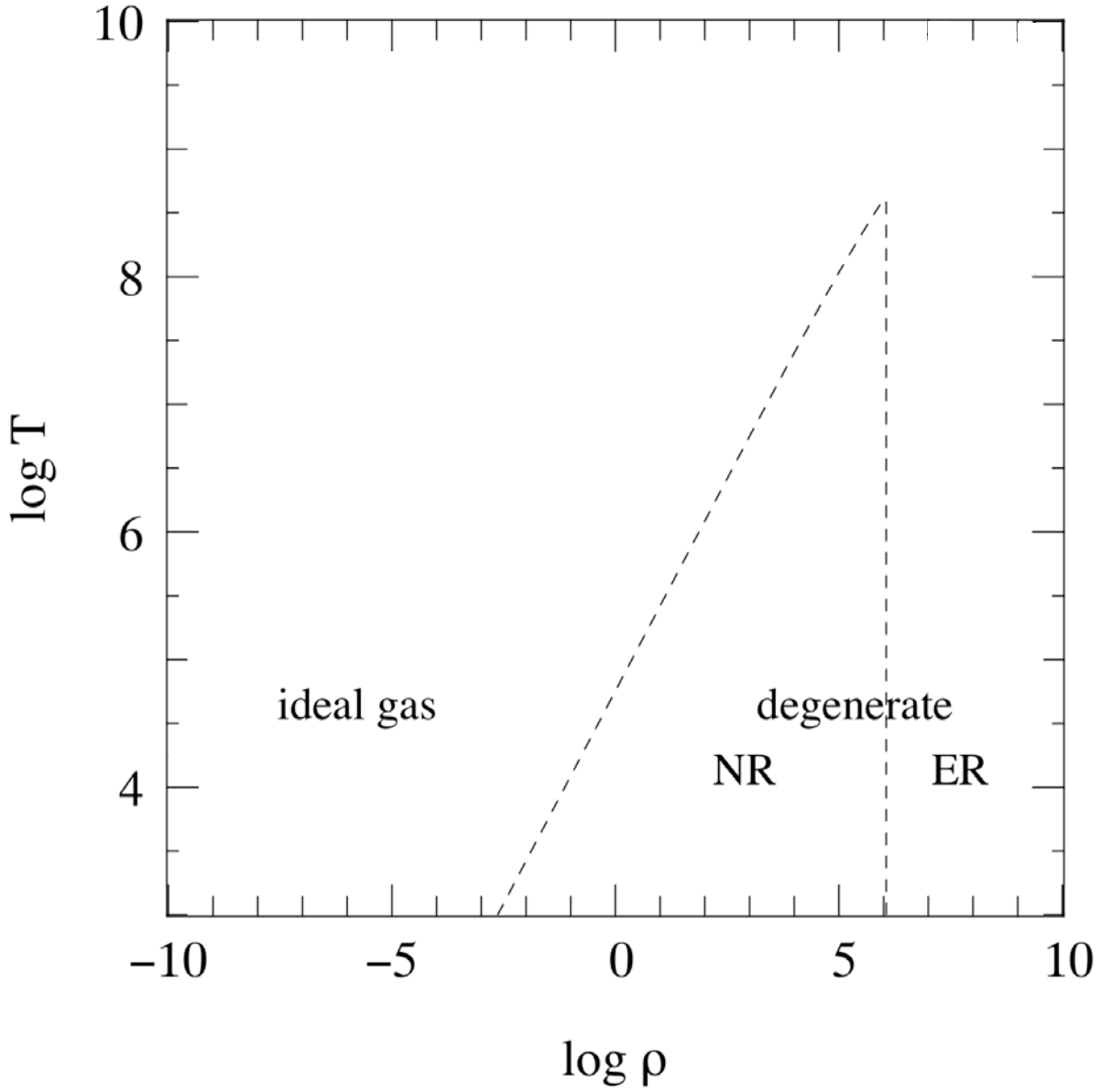

Relativistic-degenerate EoS vs ideal gas EoS

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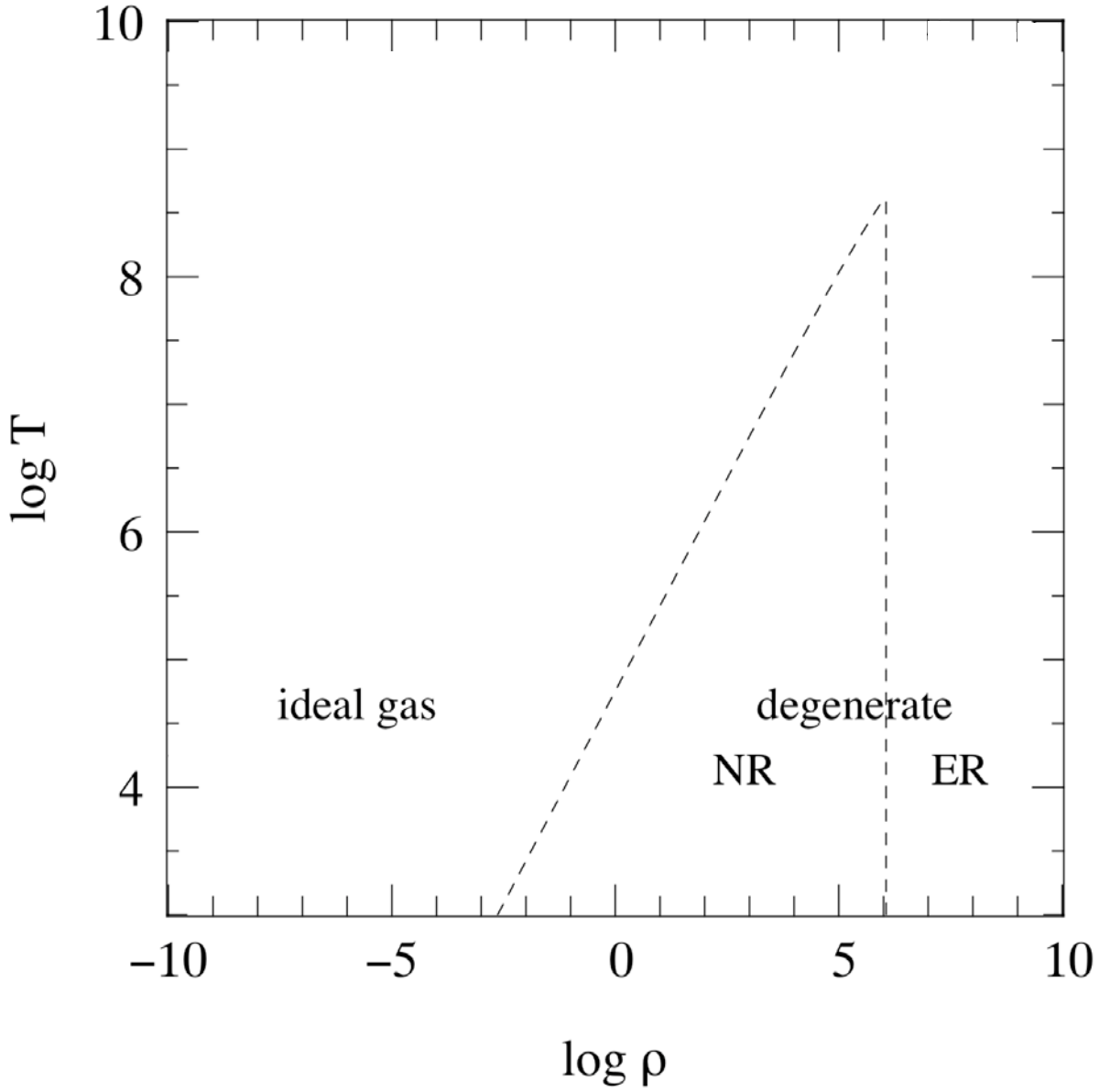

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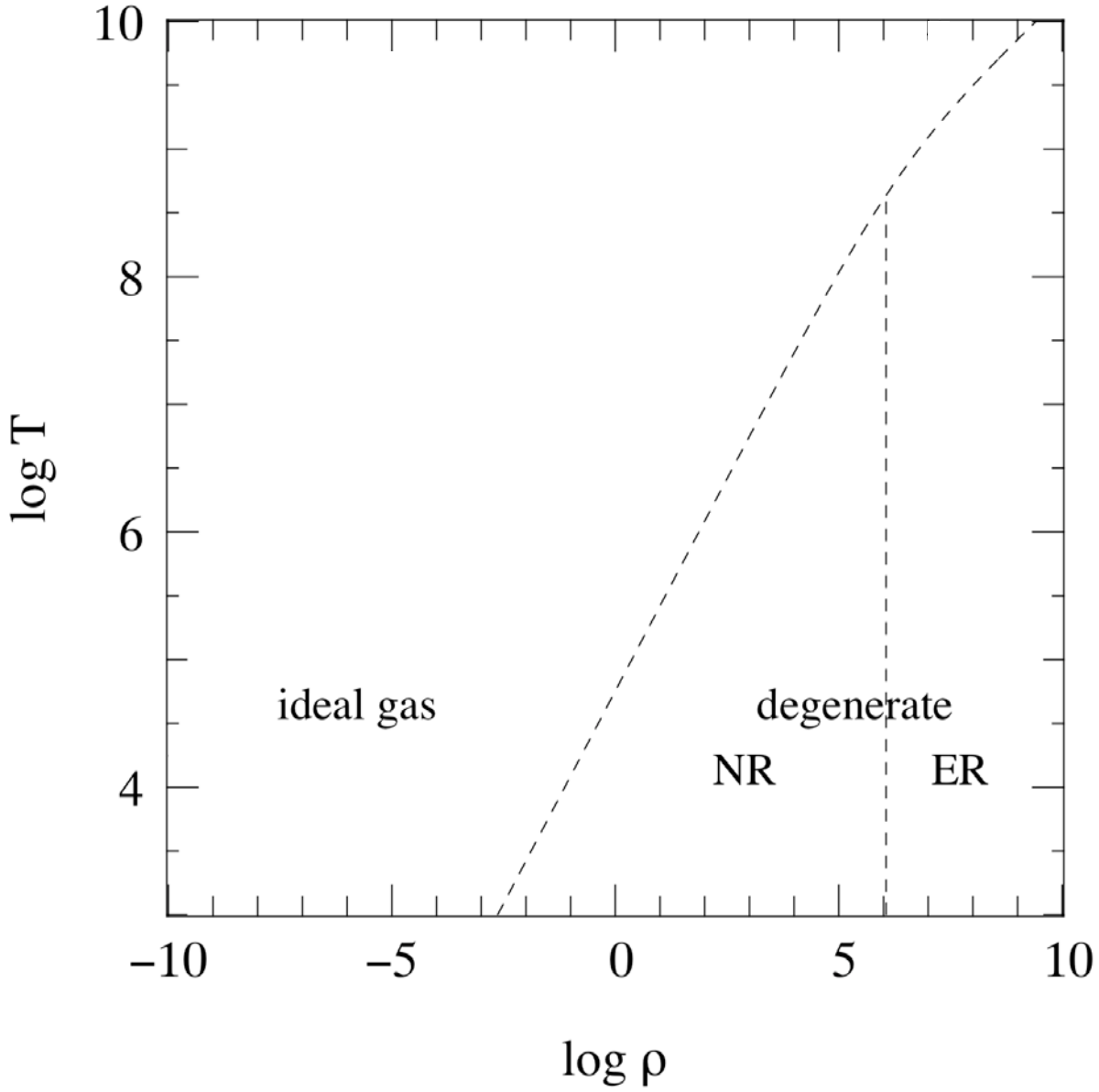


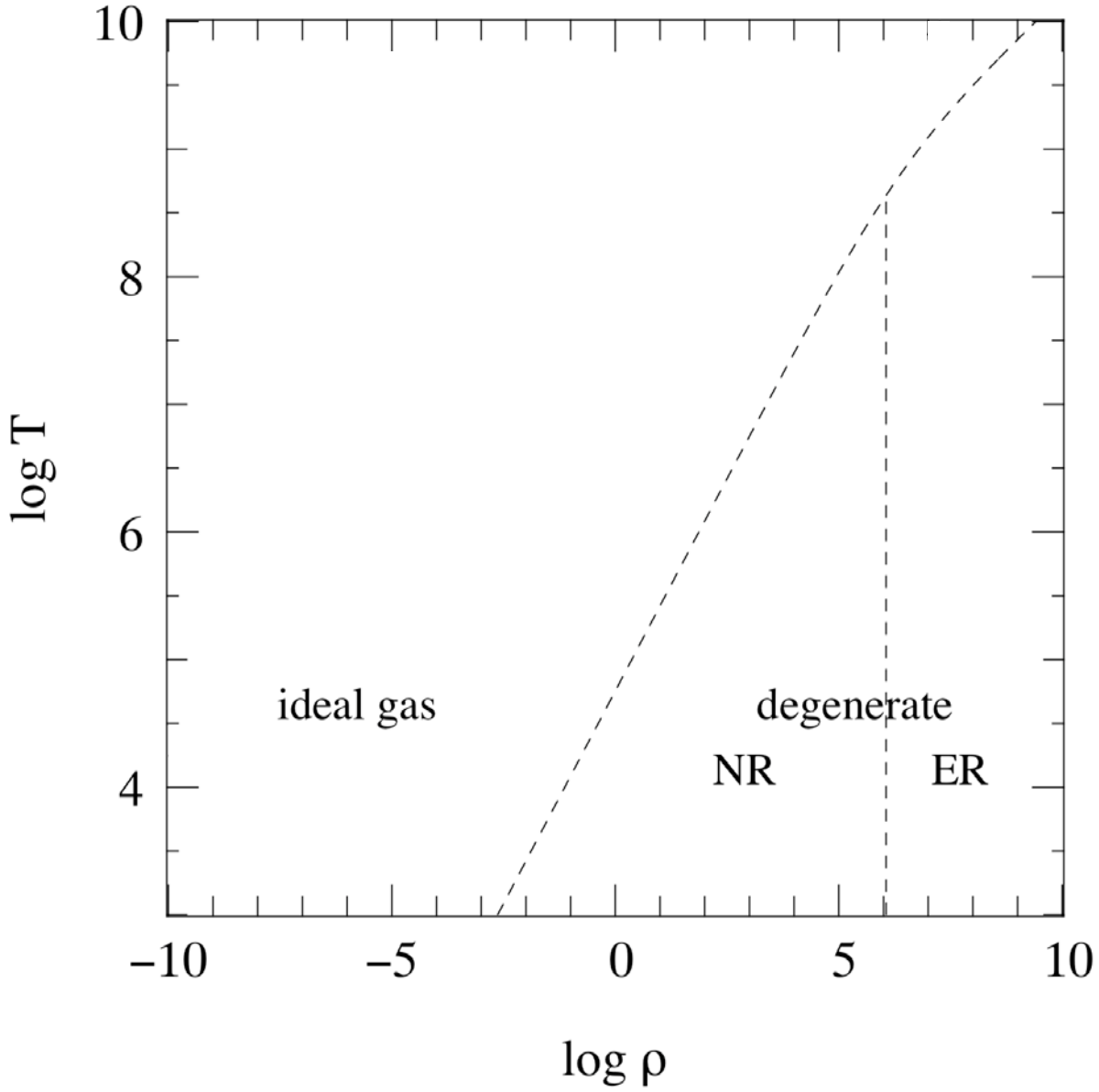
Ideal gas EoS vs radiation EoS

$$P_{\rm gas} = \frac{\Re}{\mu}\rho T$$

$$P_{\rm rad} = \frac{1}{3}aT^4$$

$$P_{\rm gas} \simeq P_{\rm rad}$$

$$\log T \simeq \frac{1}{3}\log\rho + \text{const}\,.$$



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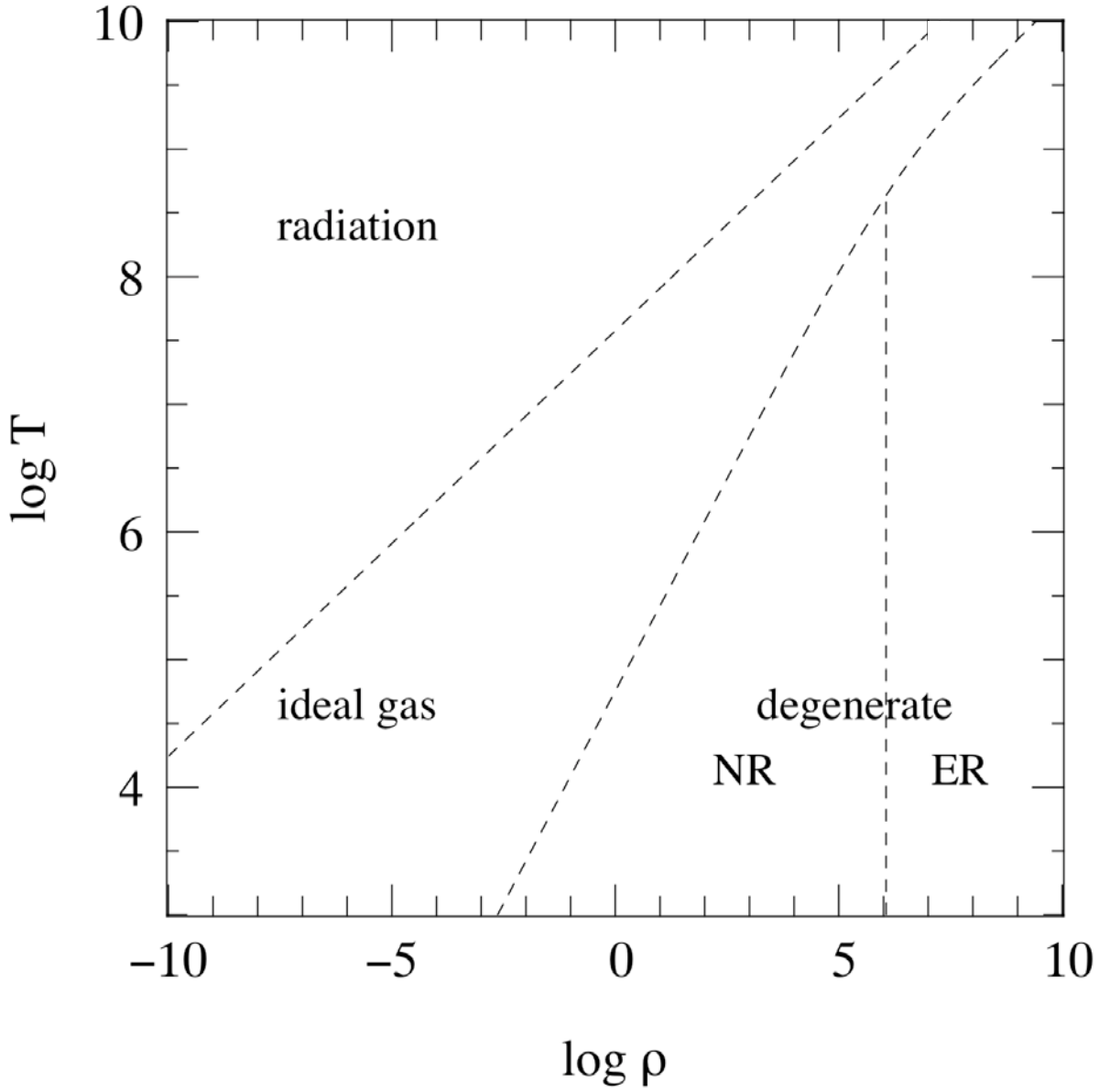
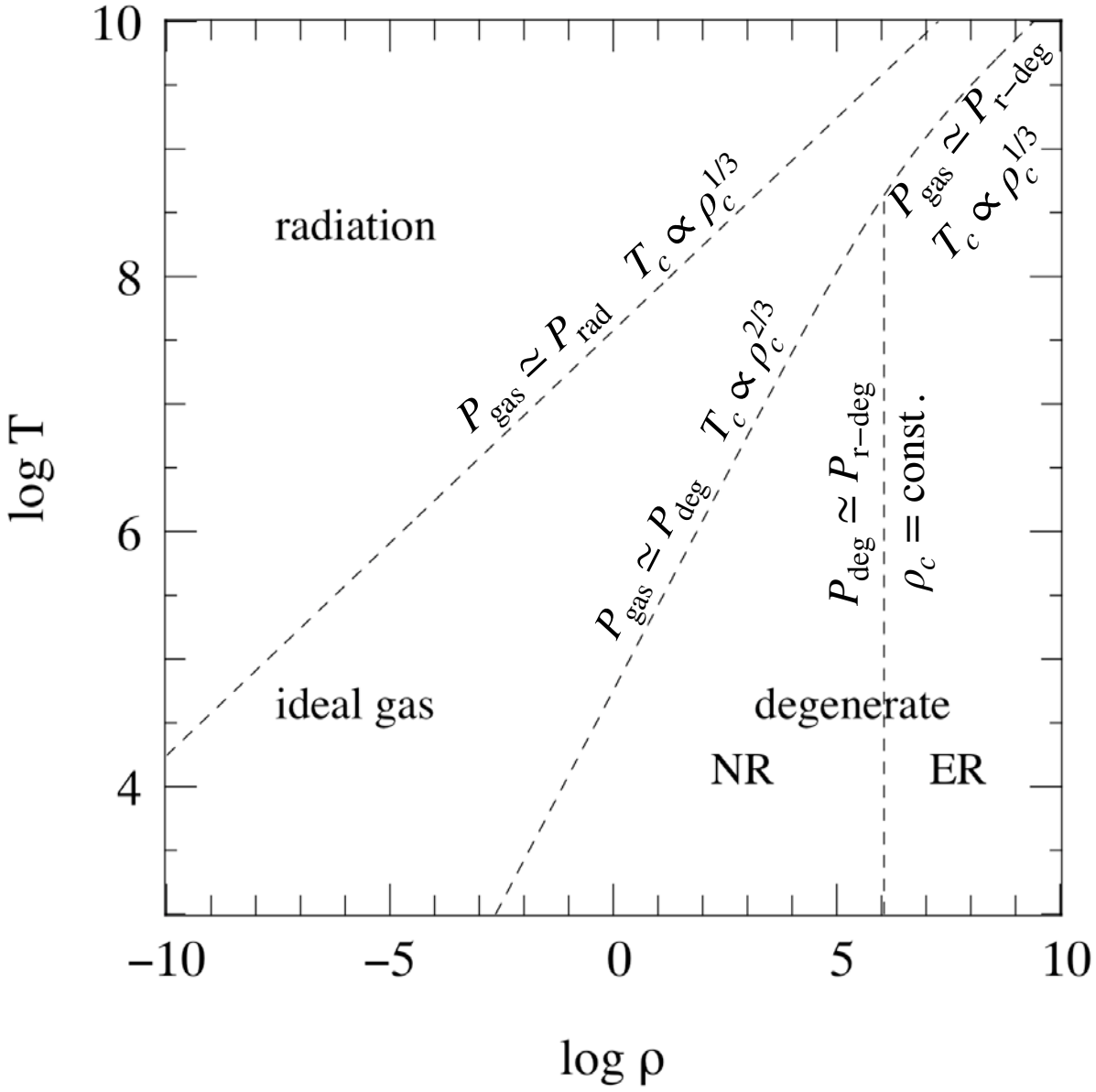


Characterizing the (log T, log ρ) plane



Density and temperature at stellar center

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho$$

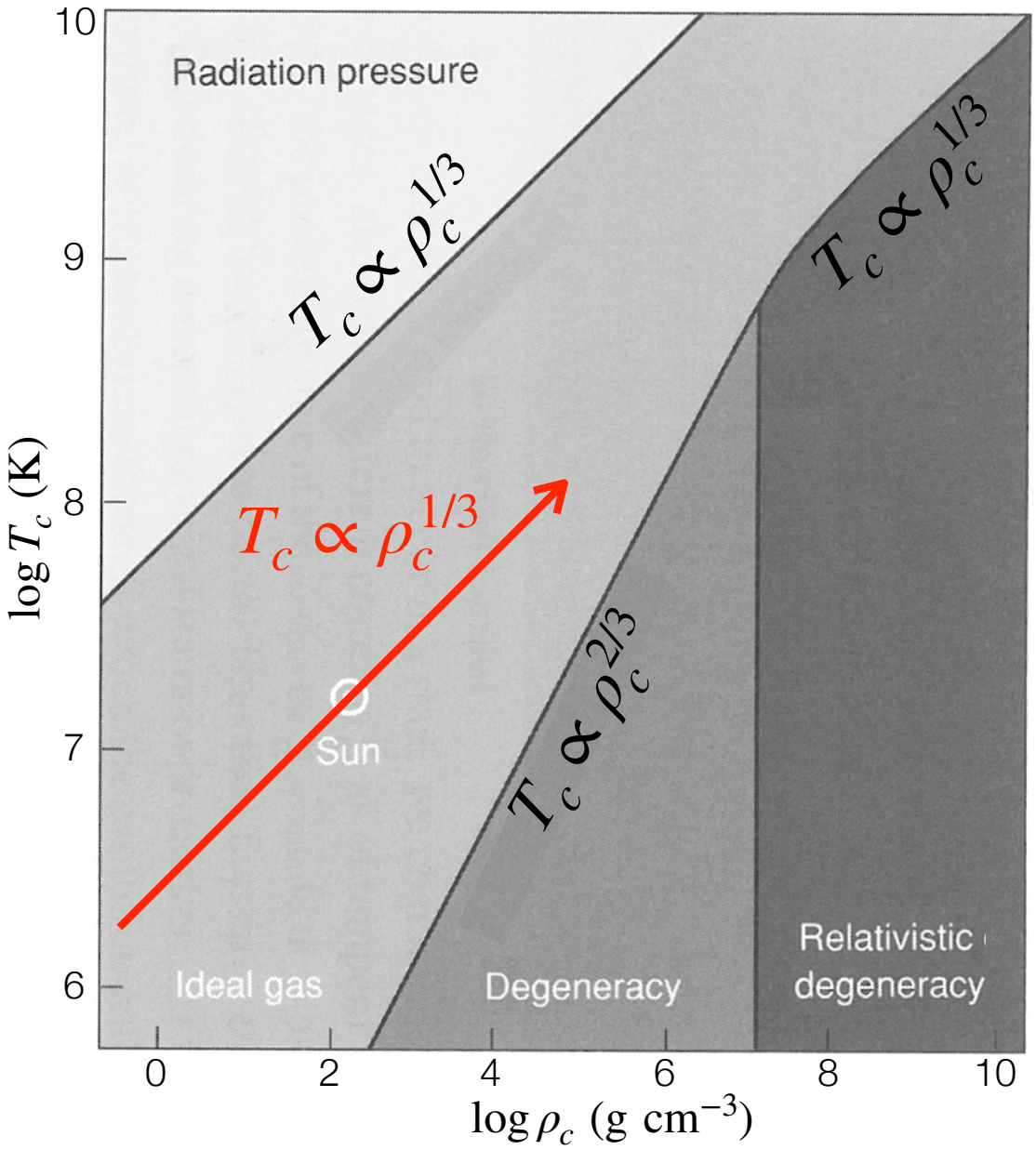
$$\frac{0 - P_c}{R - 0} \sim -\frac{G(M/2)}{(R/2)^2}\bar{\rho} \qquad \bar{\rho} = M/(4\pi R^3/3)$$

$$P_c \propto GM^{2/3}\bar{\rho}^{4/3} \propto GM^{2/3}{\rho_c}^{4/3}$$

$$P_c = \frac{\mathfrak{R}}{\mu}\rho_c T_c$$

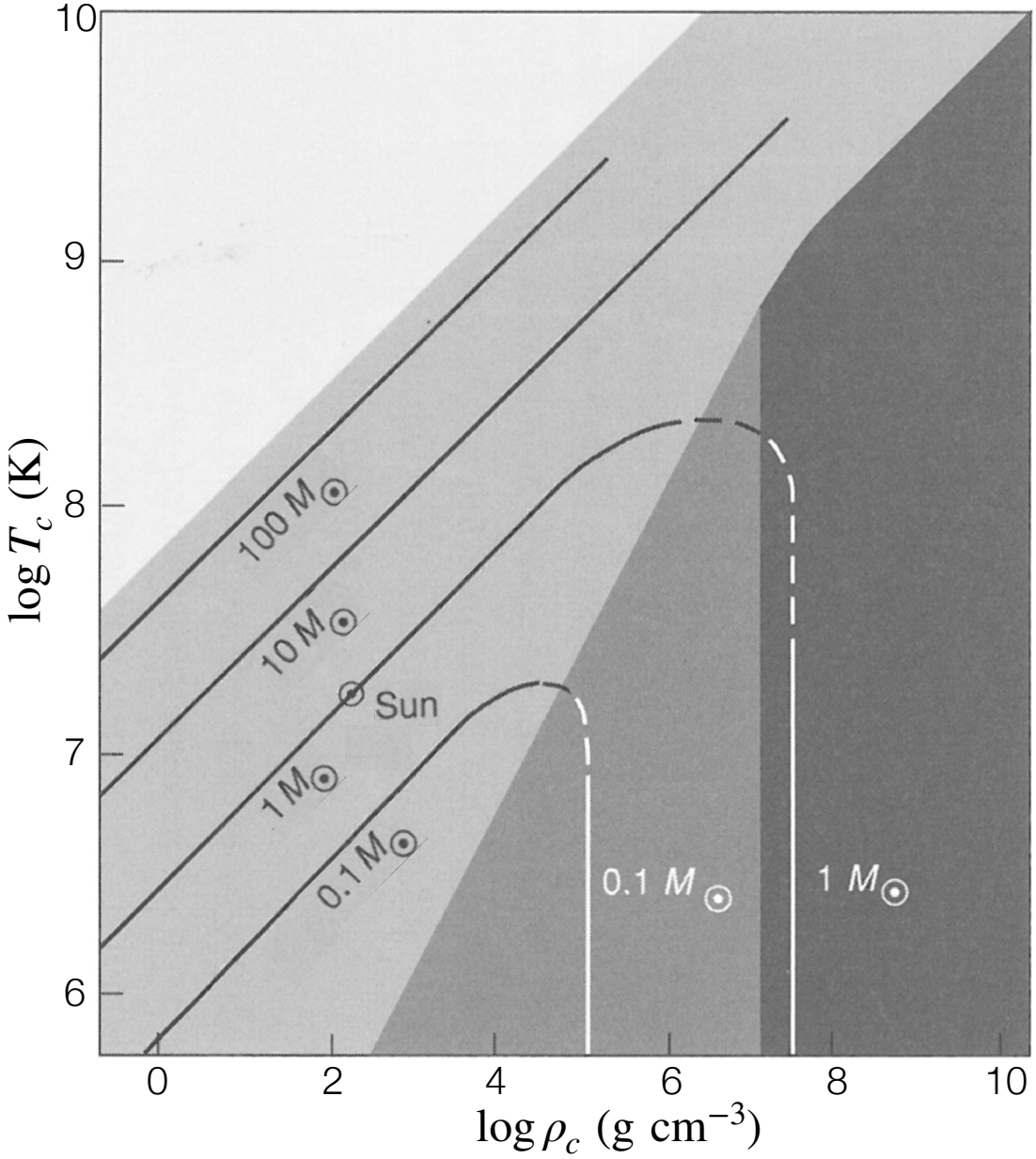
$$\rho_c \propto \frac{T_c^3}{M^2} \qquad T_c \propto M^{2/3}\rho_c^{1/3}$$

Density and temperature evolution at stellar center



$$T_c \propto M^{2/3} \rho_c^{1/3}$$

Density and temperature evolution at stellar center



gas:

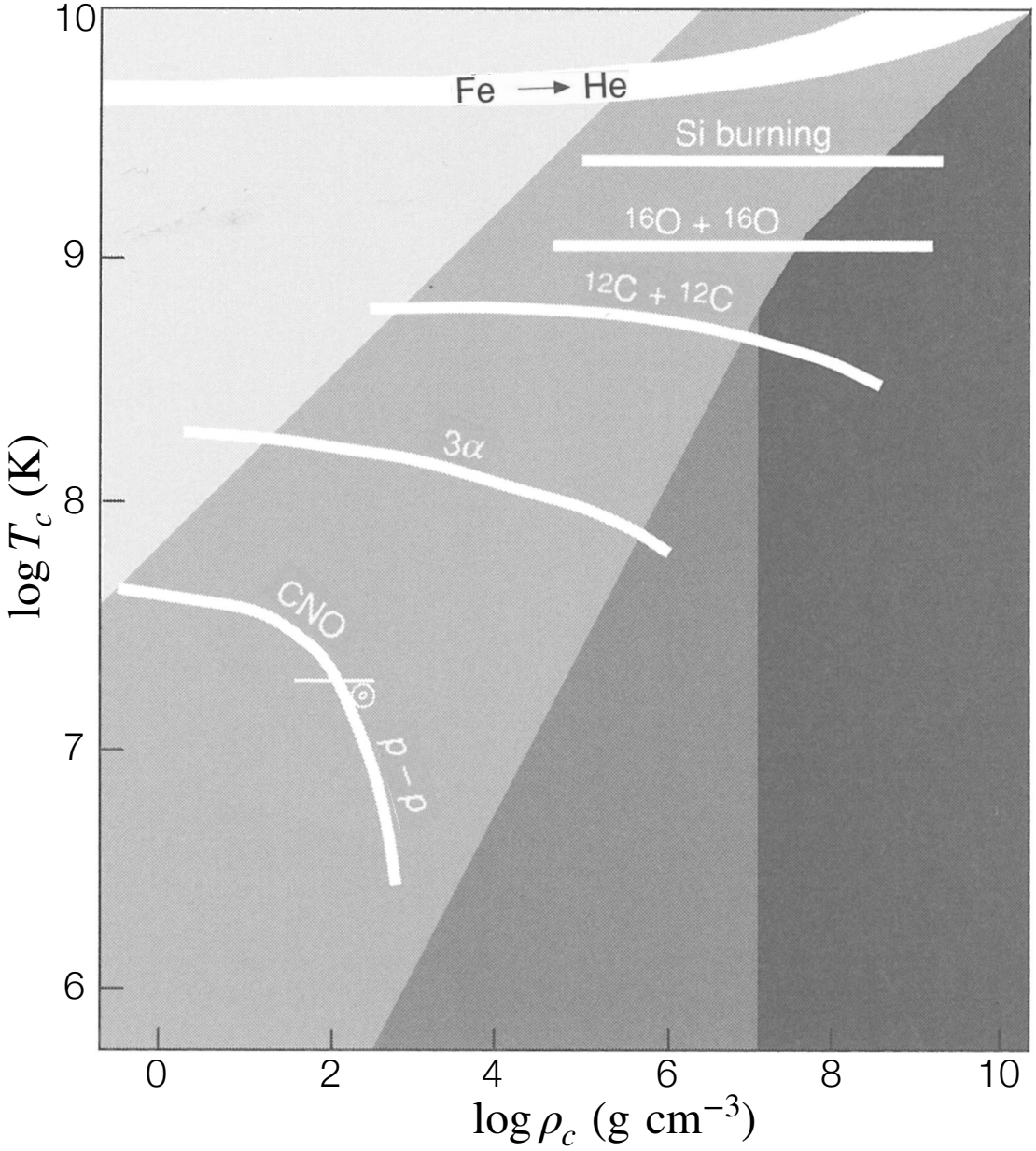
$$T_c \propto M^{2/3} \rho_c^{1/3}$$

$$\rho_c \propto \frac{T_c^3}{M^2}$$

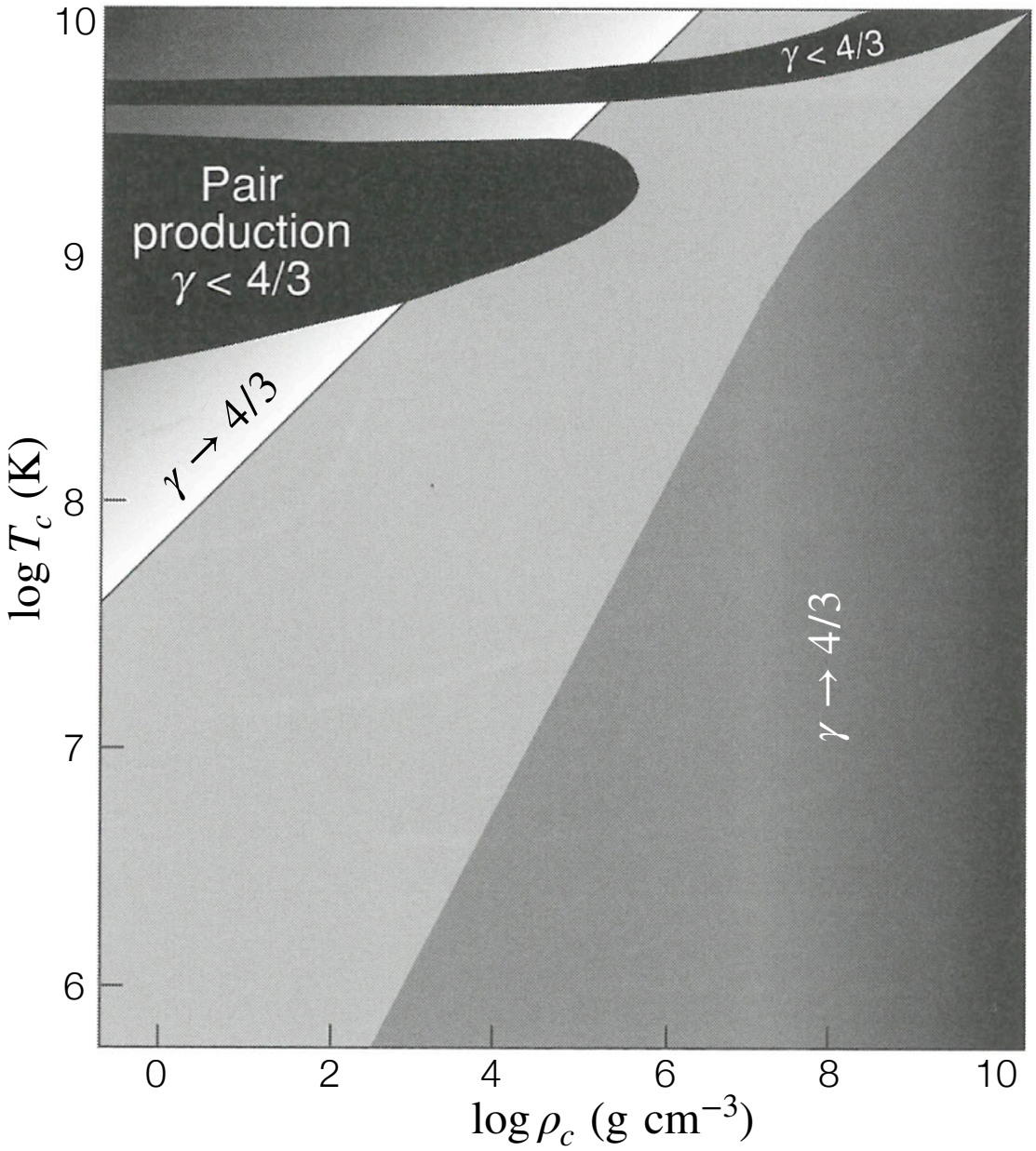
degenerate:

$$\rho_c \propto M^2$$

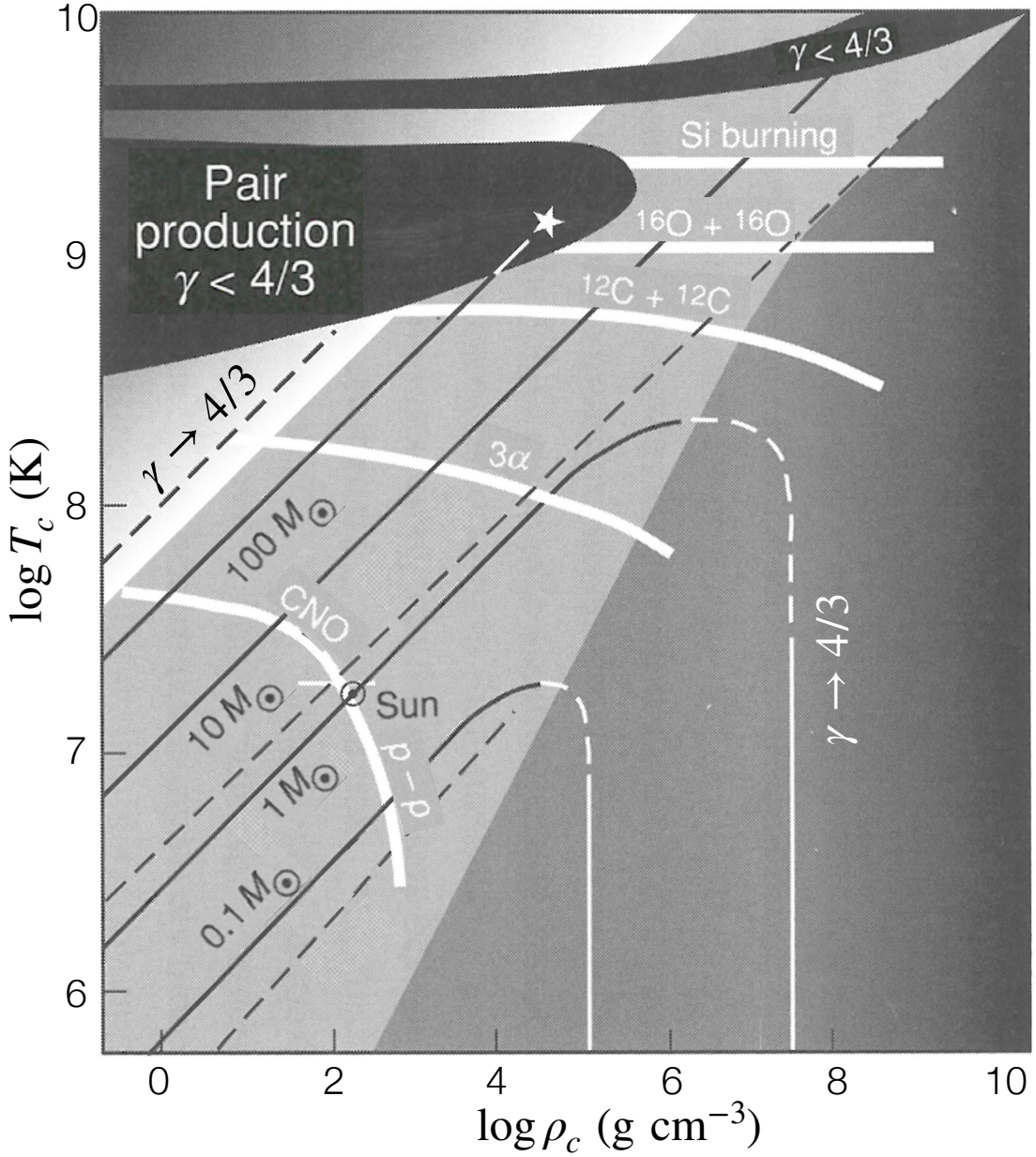
Nuclear burning at stellar center



Unstable regions



Density and temperature at stellar center: summary



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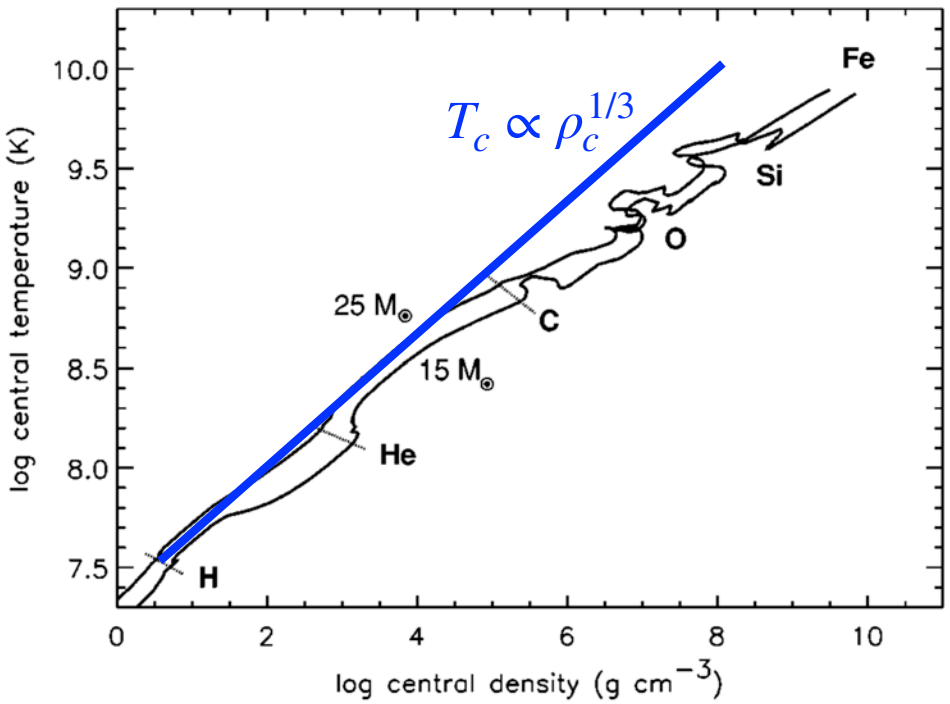
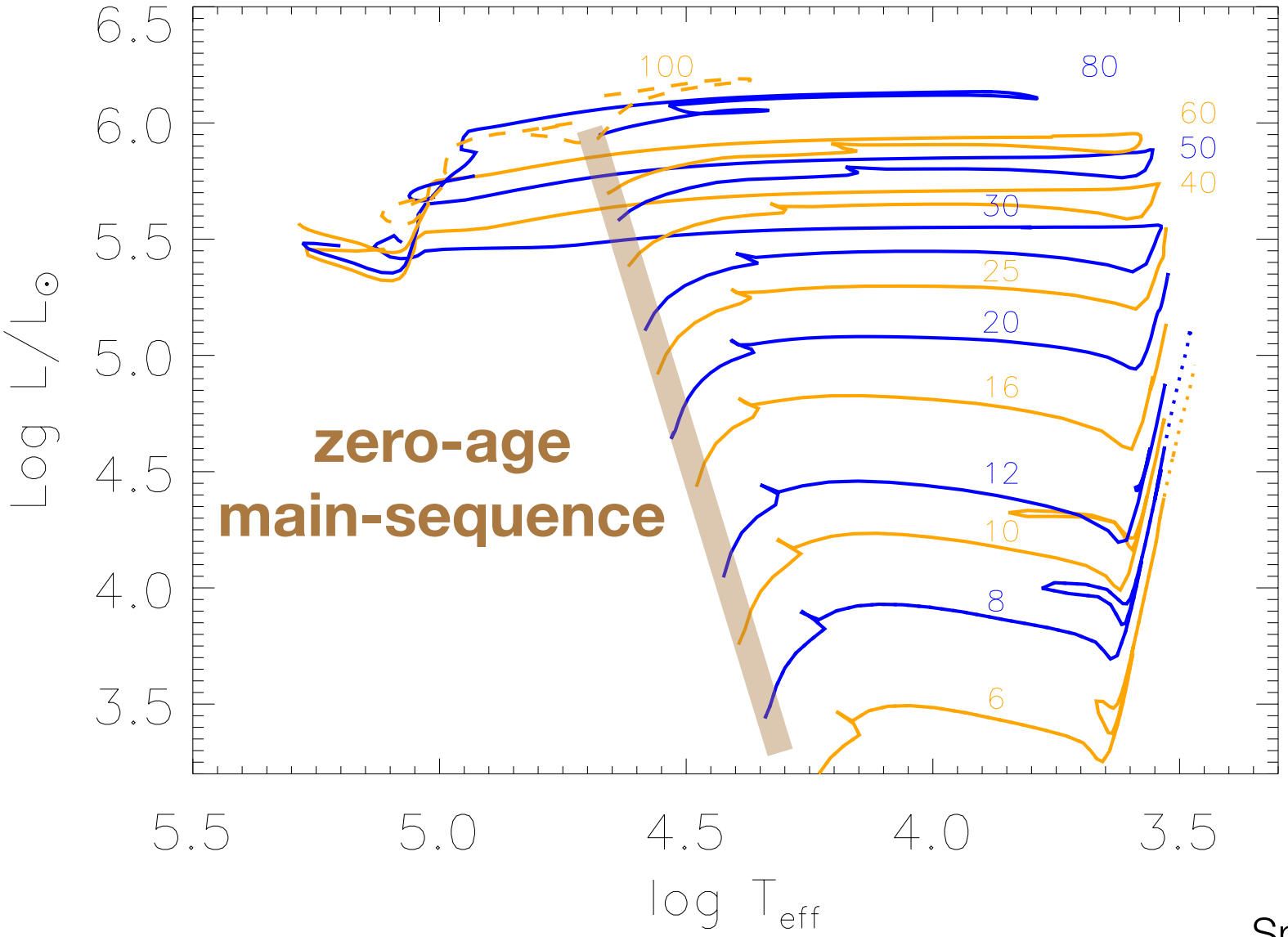


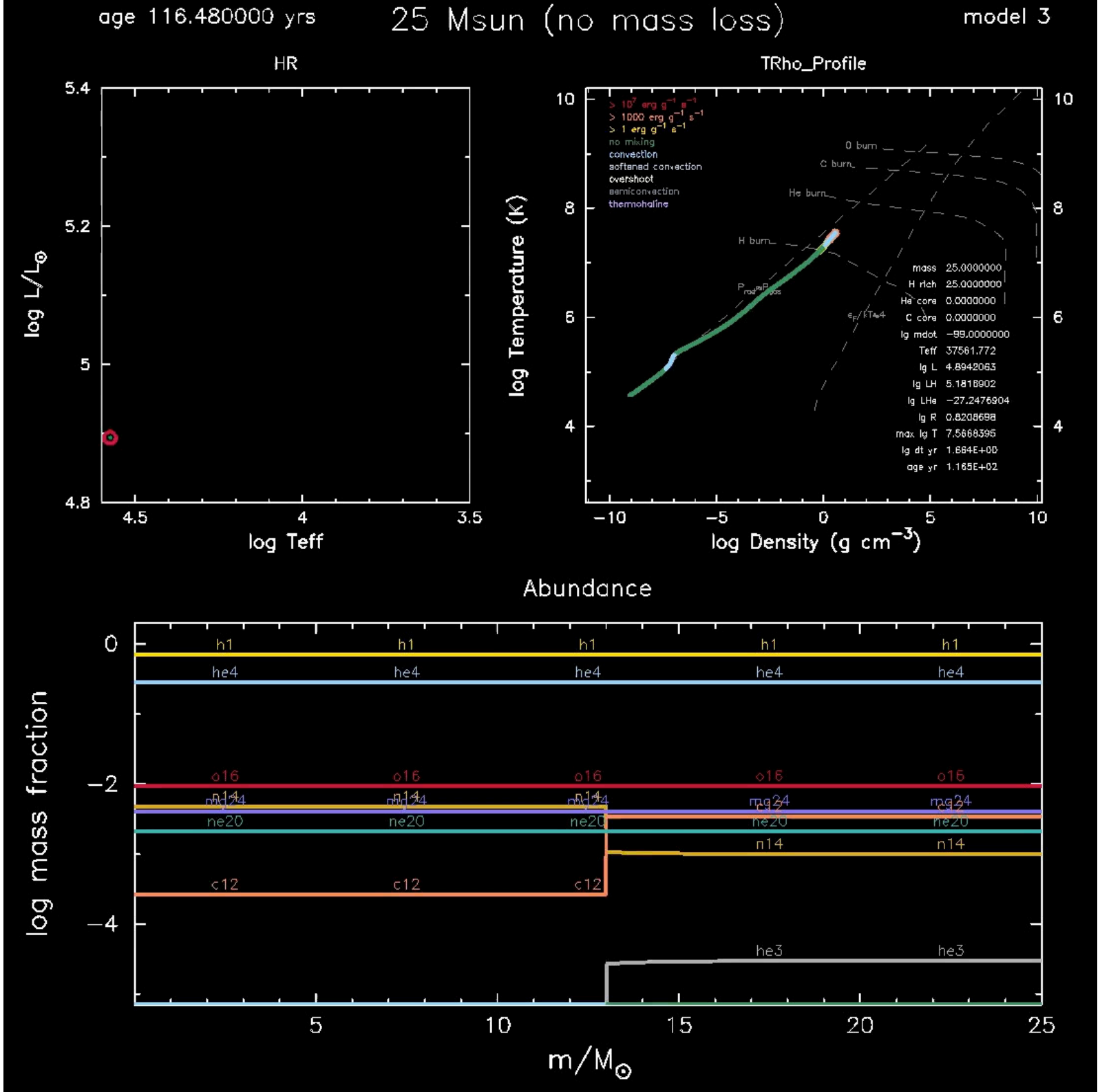
Woosley et al. (2002)

Evolution seen from the surface of stars

Surface evolution



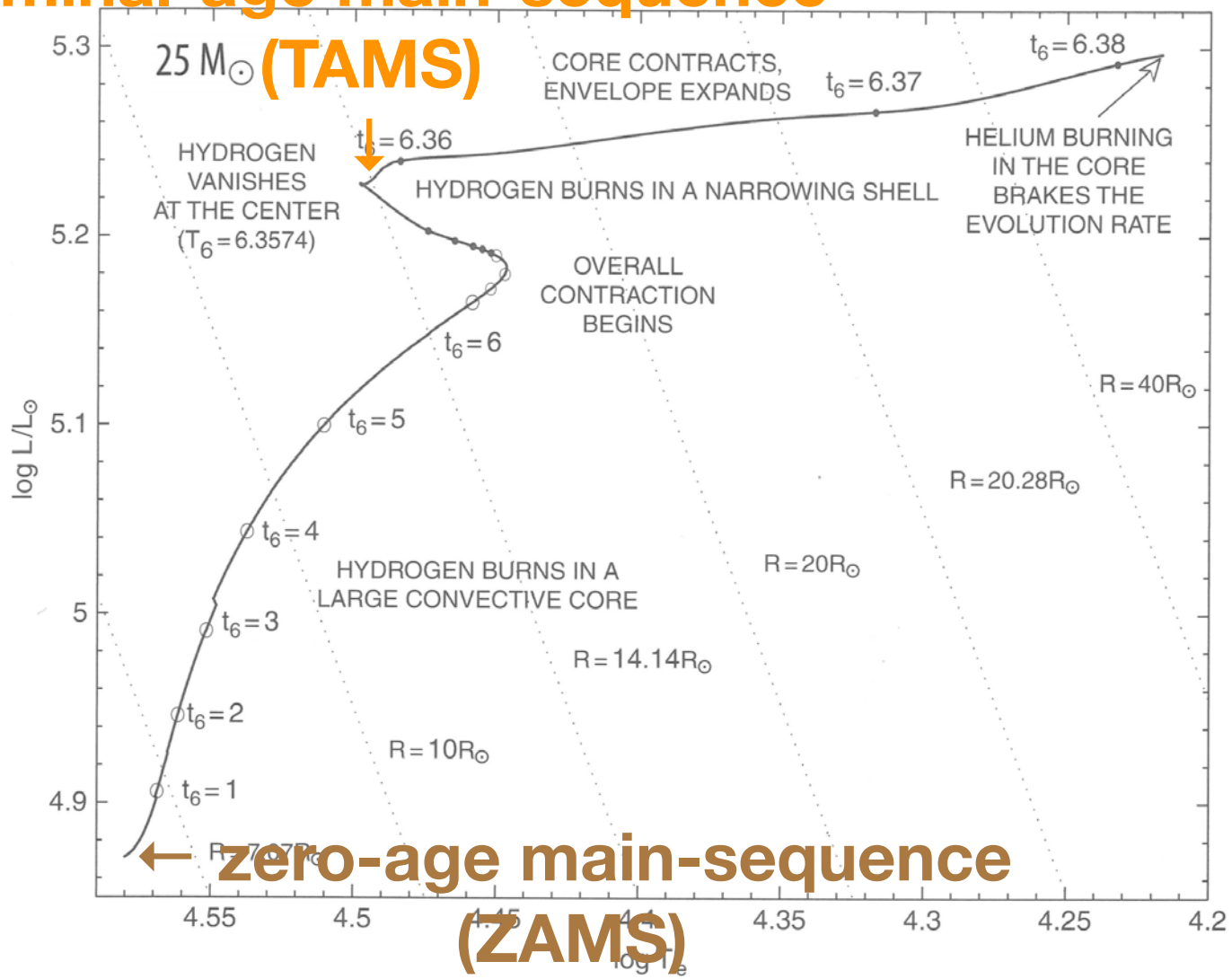
Smartt (2015)



Calculated by the MESA code (Paxton et al. 2011)

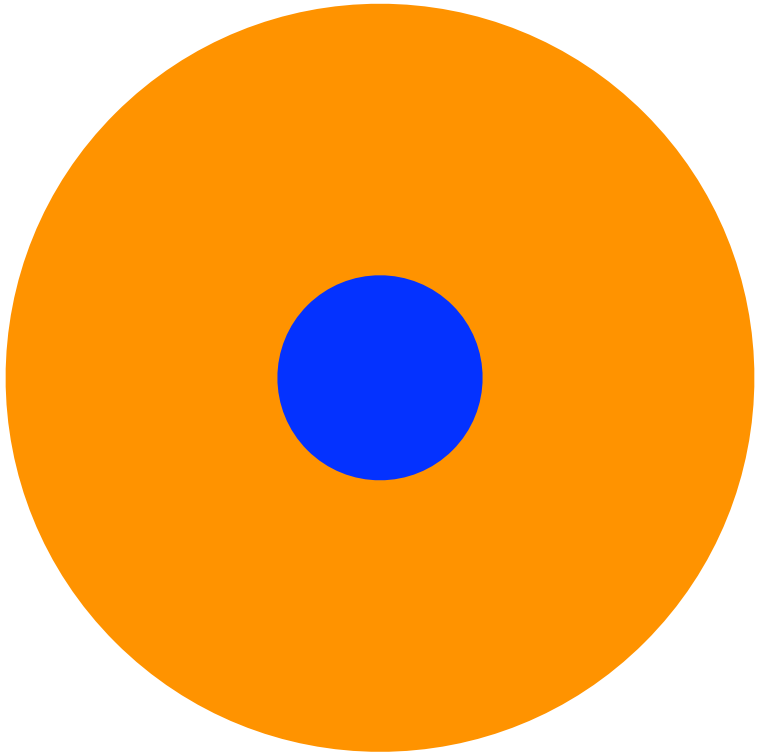
Surface evolution

terminal-age main-sequence (TAMS)



← zero-age main-sequence (ZAMS)

Expansion of the envelope



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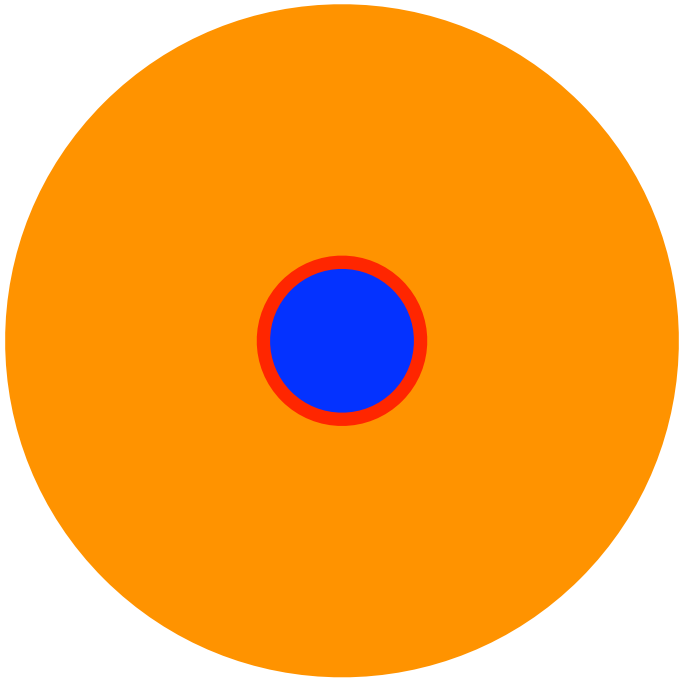


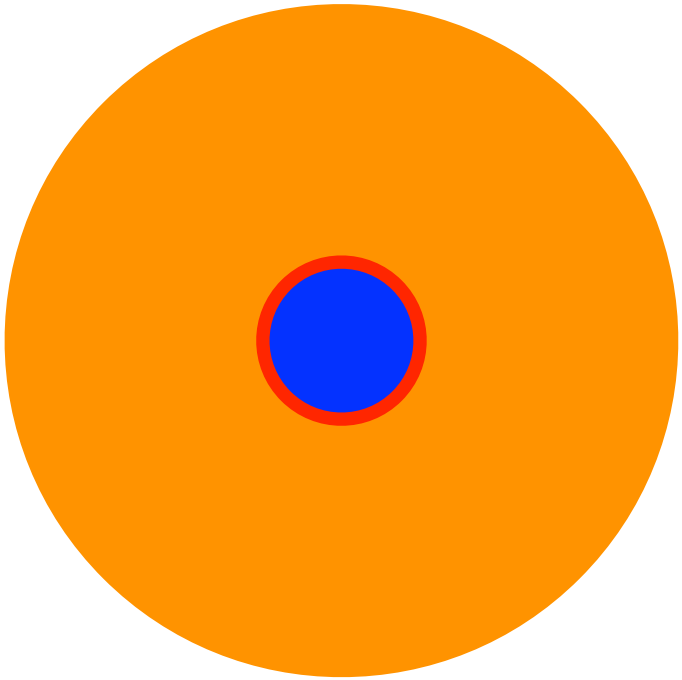
Expansion of the envelope

“mirror principle”

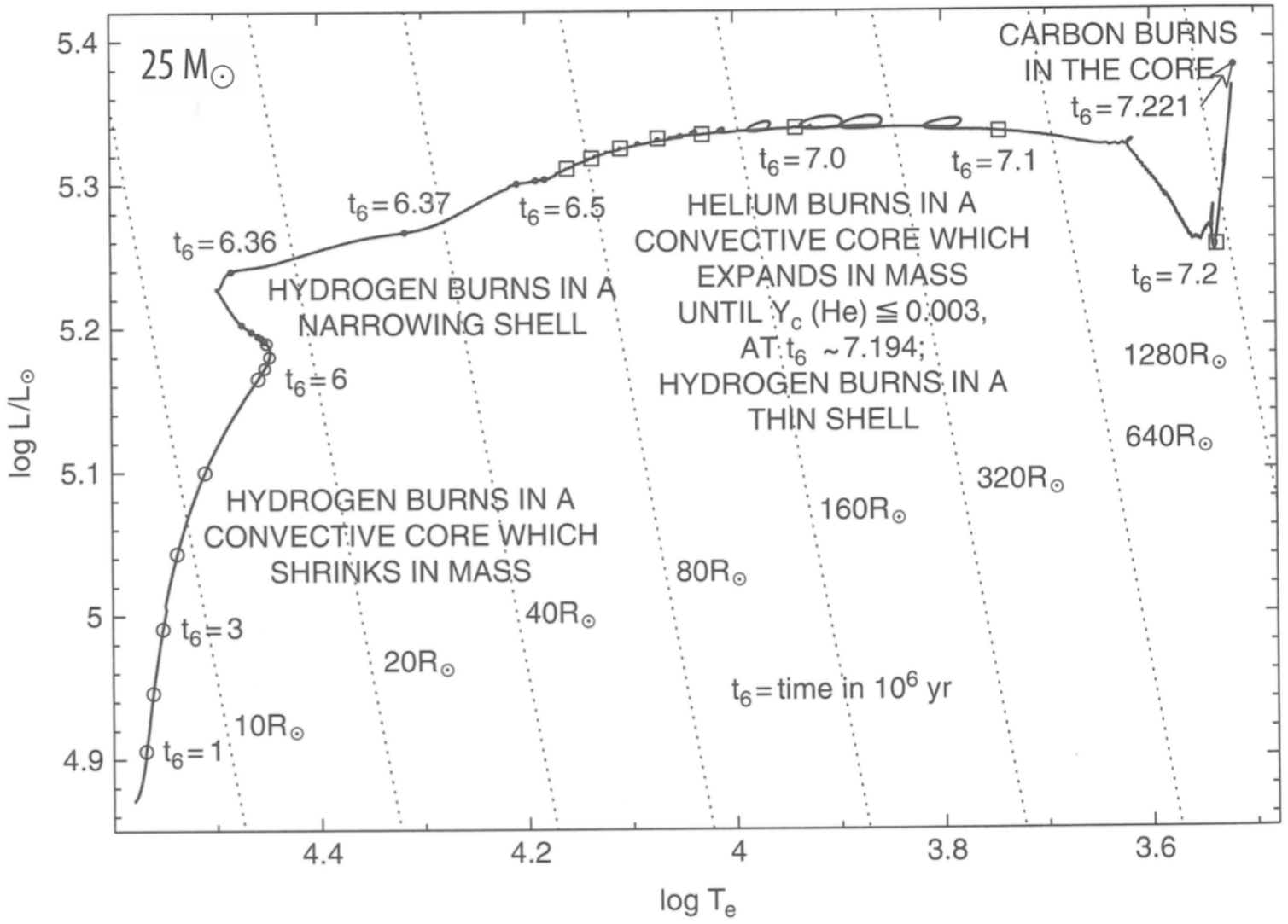
Whenever a star has an *active shell-burning source*, the burning shell acts as a *mirror* between the core and the envelope.

core contraction => envelope expansion

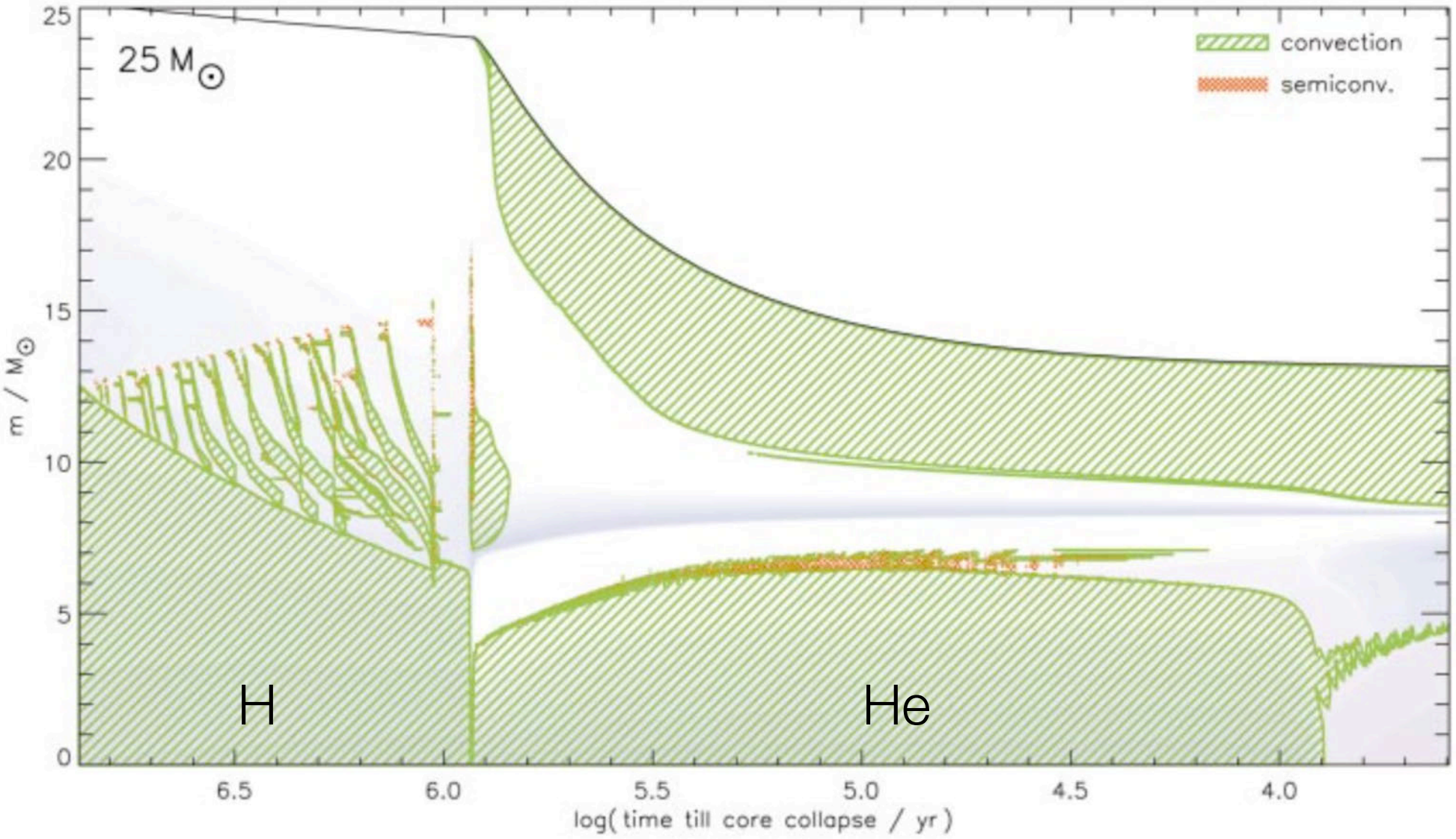
core expansion => envelope contraction



Surface evolution



Kippenhahn diagram



Woosley et al. (2002)

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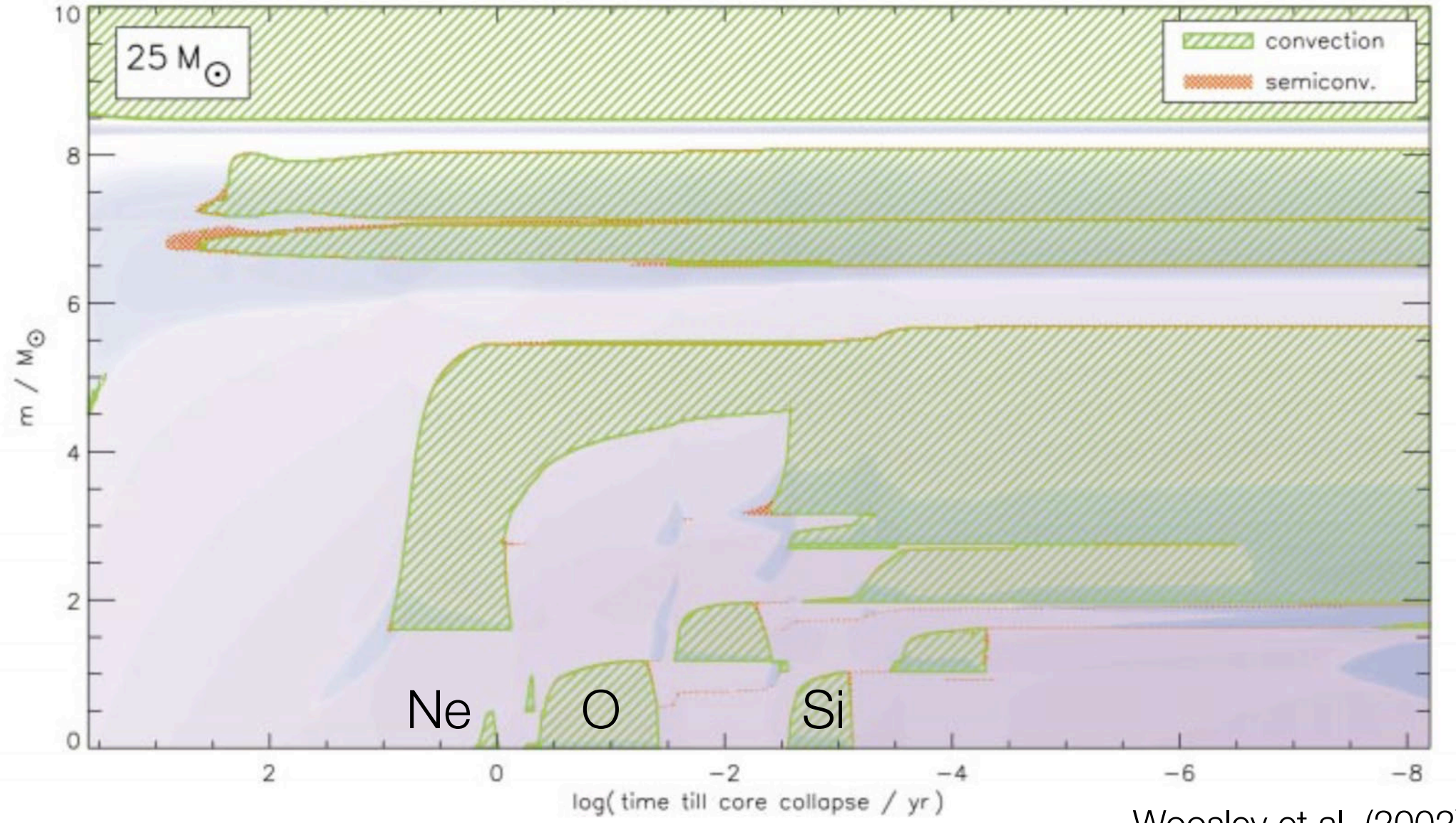
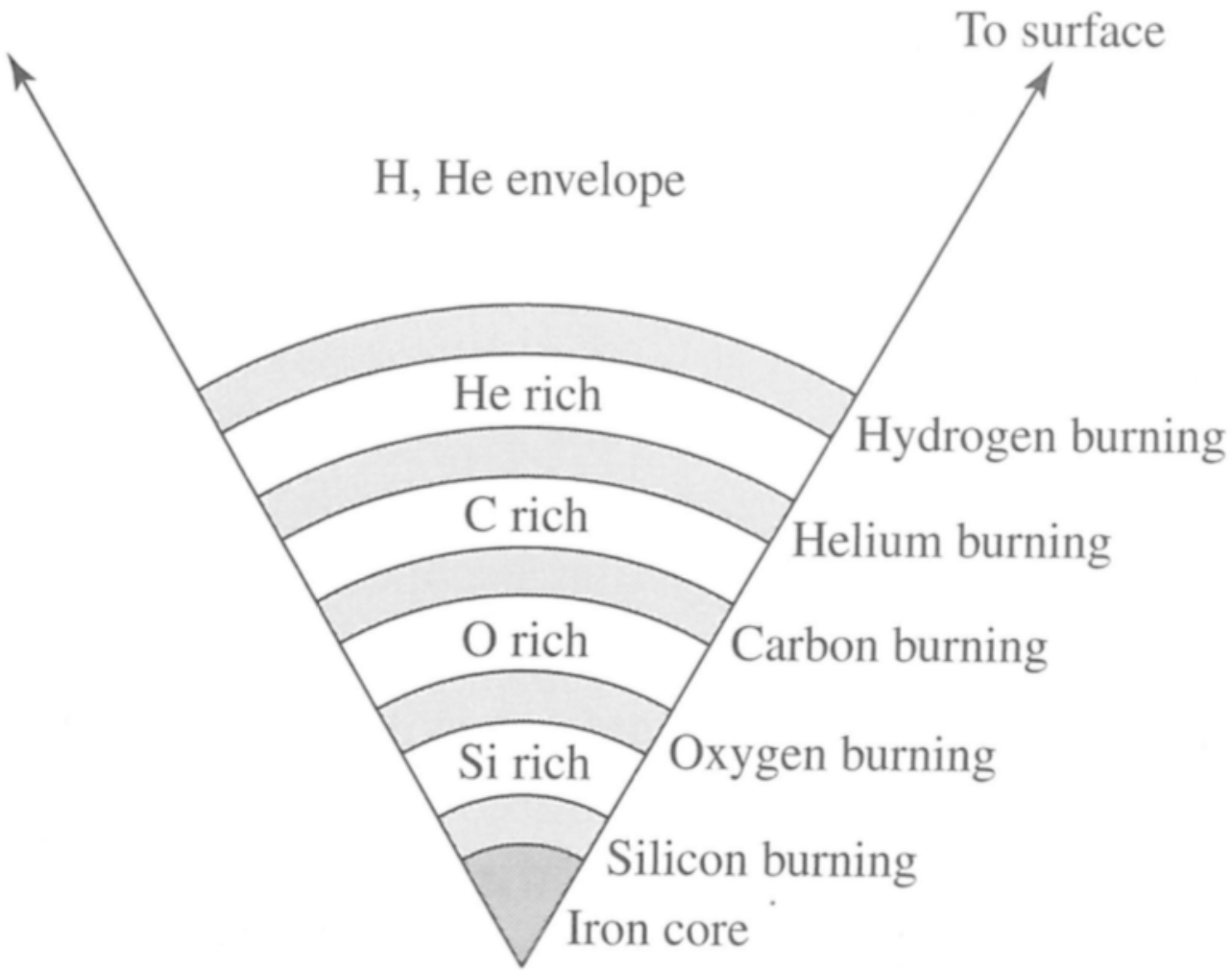
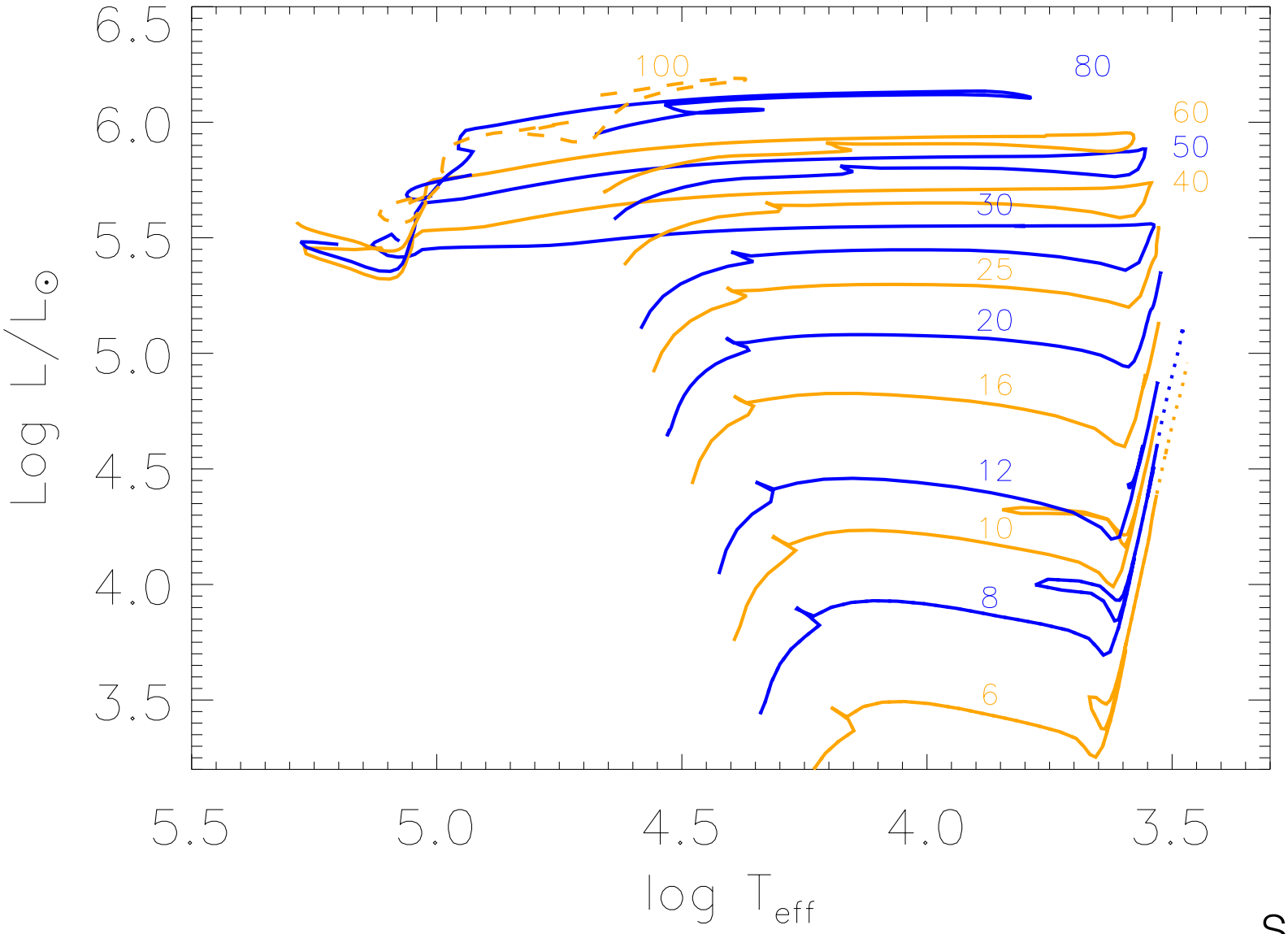


Woosley et al. (2002)

The final stellar structure

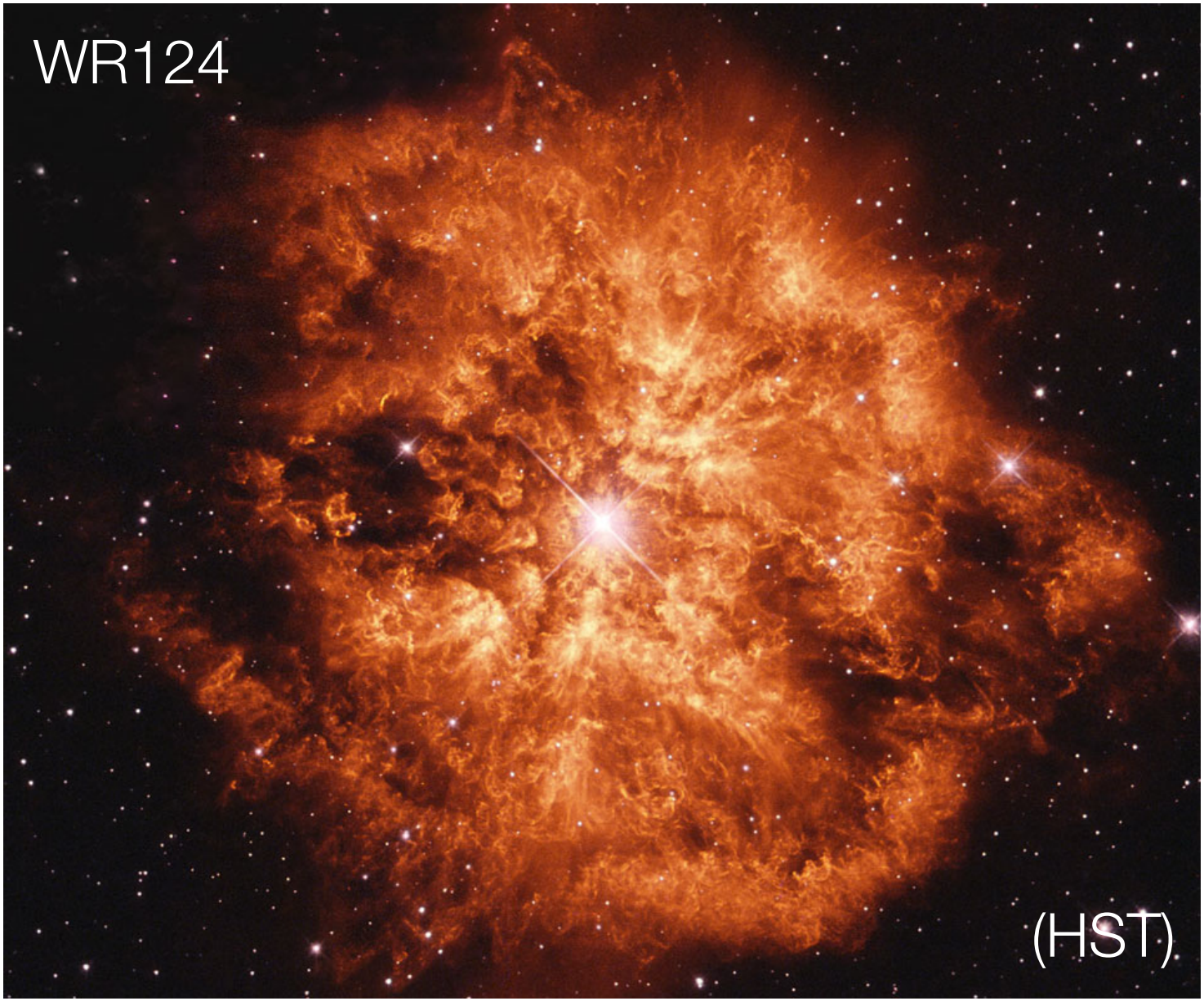


Mass loss



Smartt (2015)

Mass loss from massive stars



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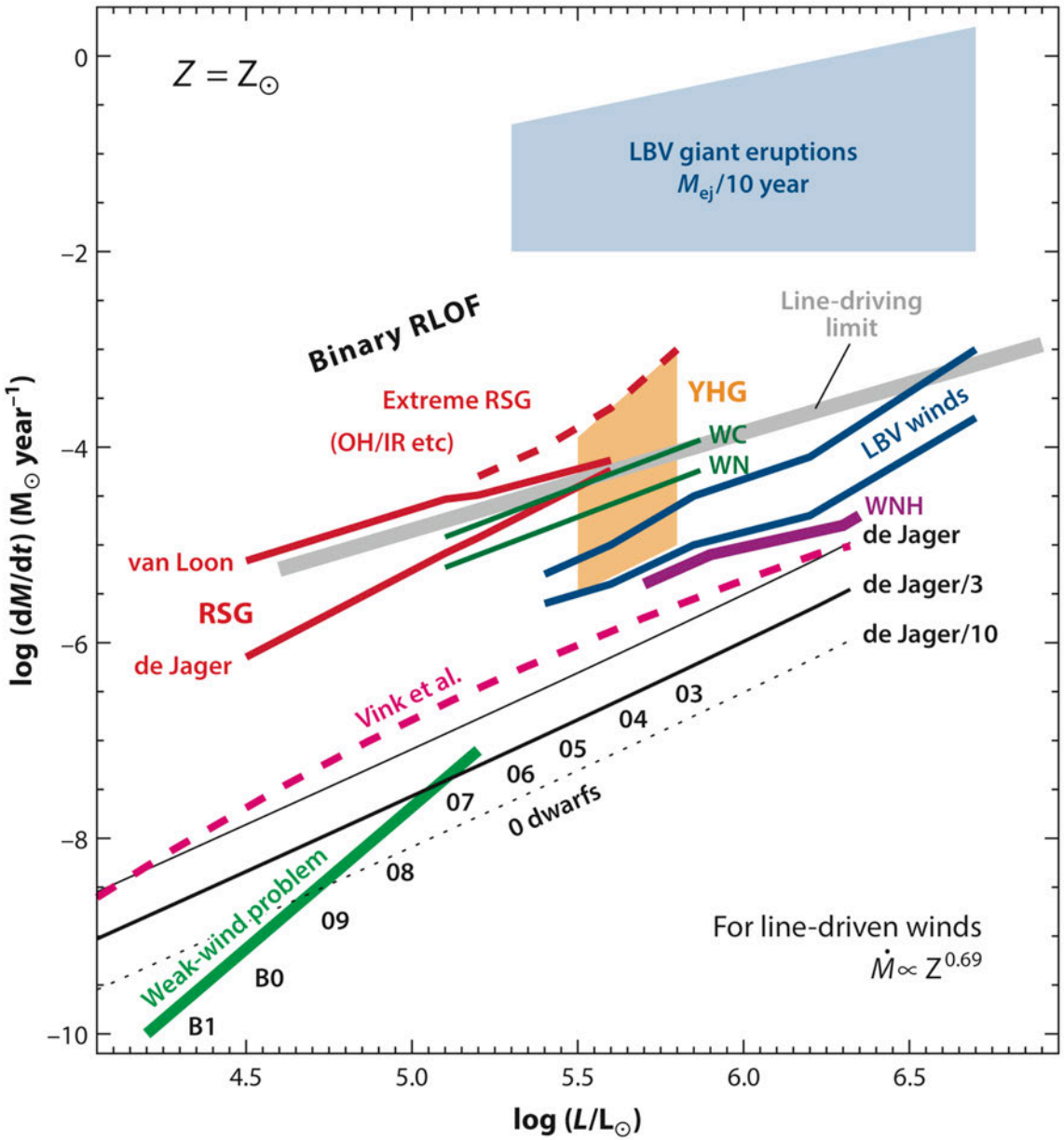

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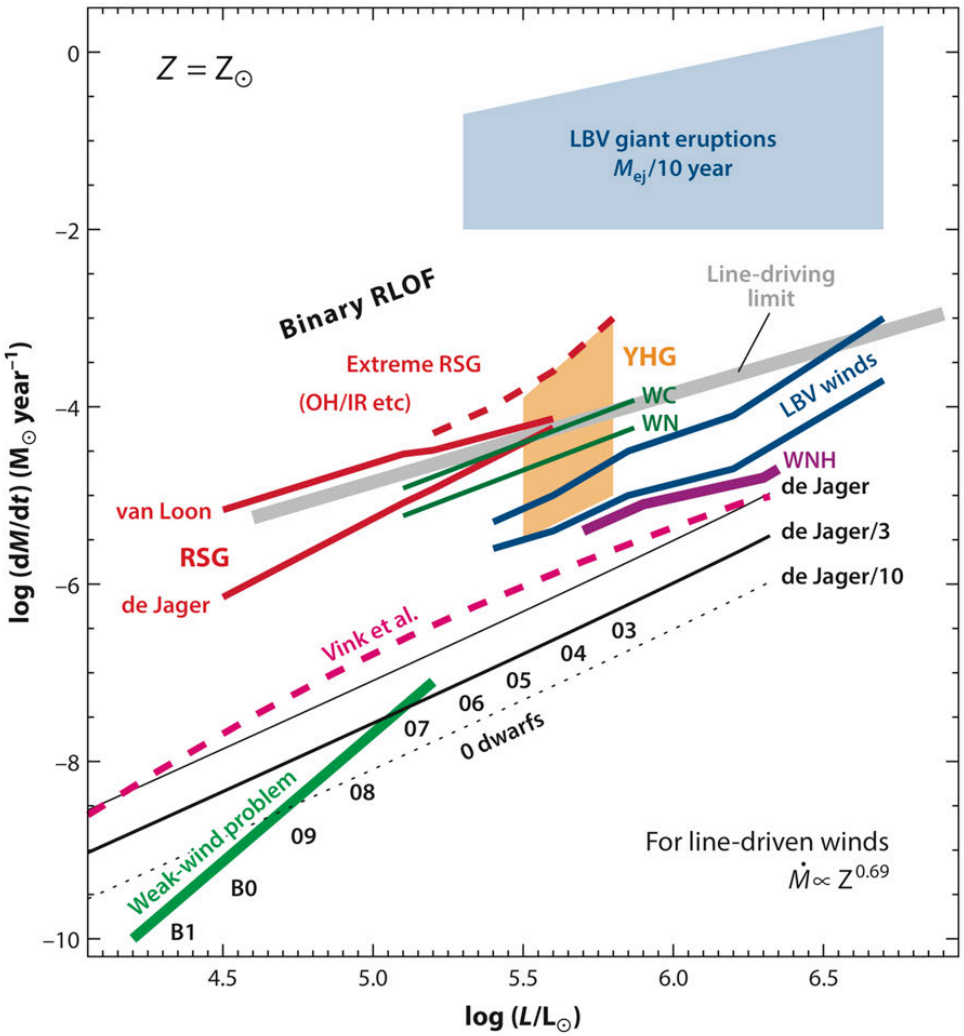
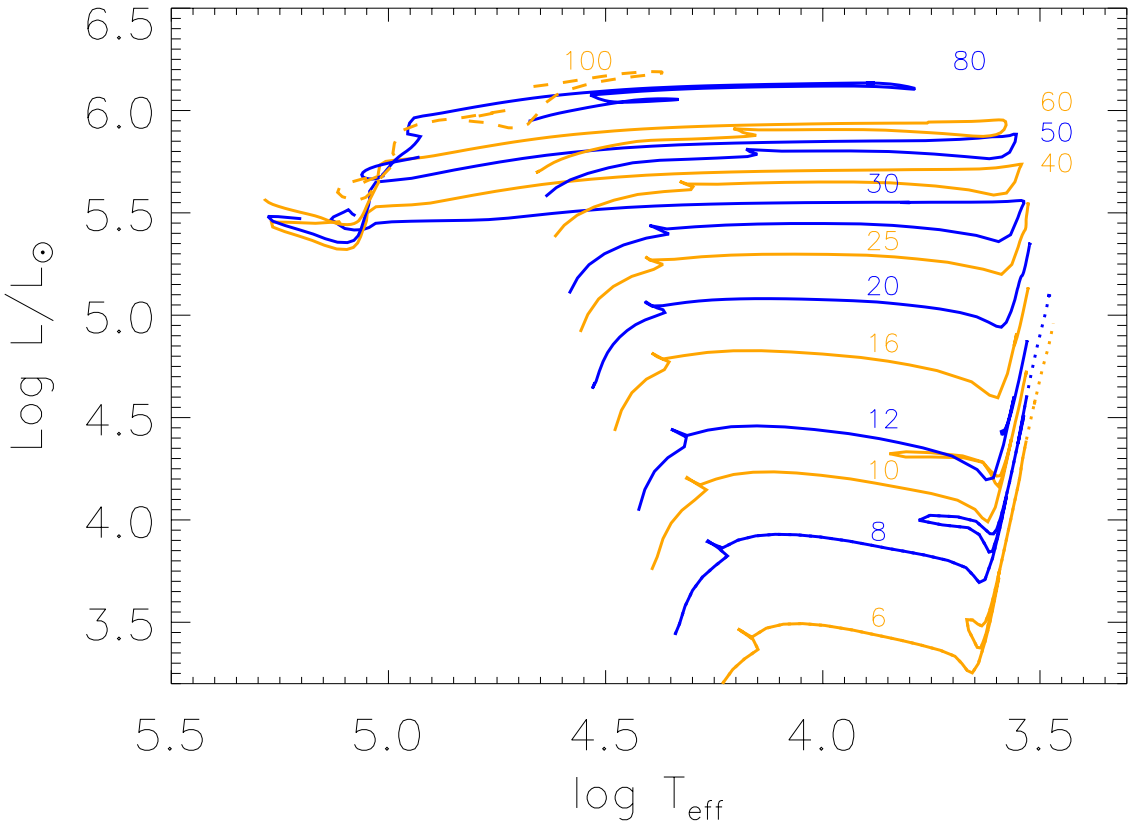
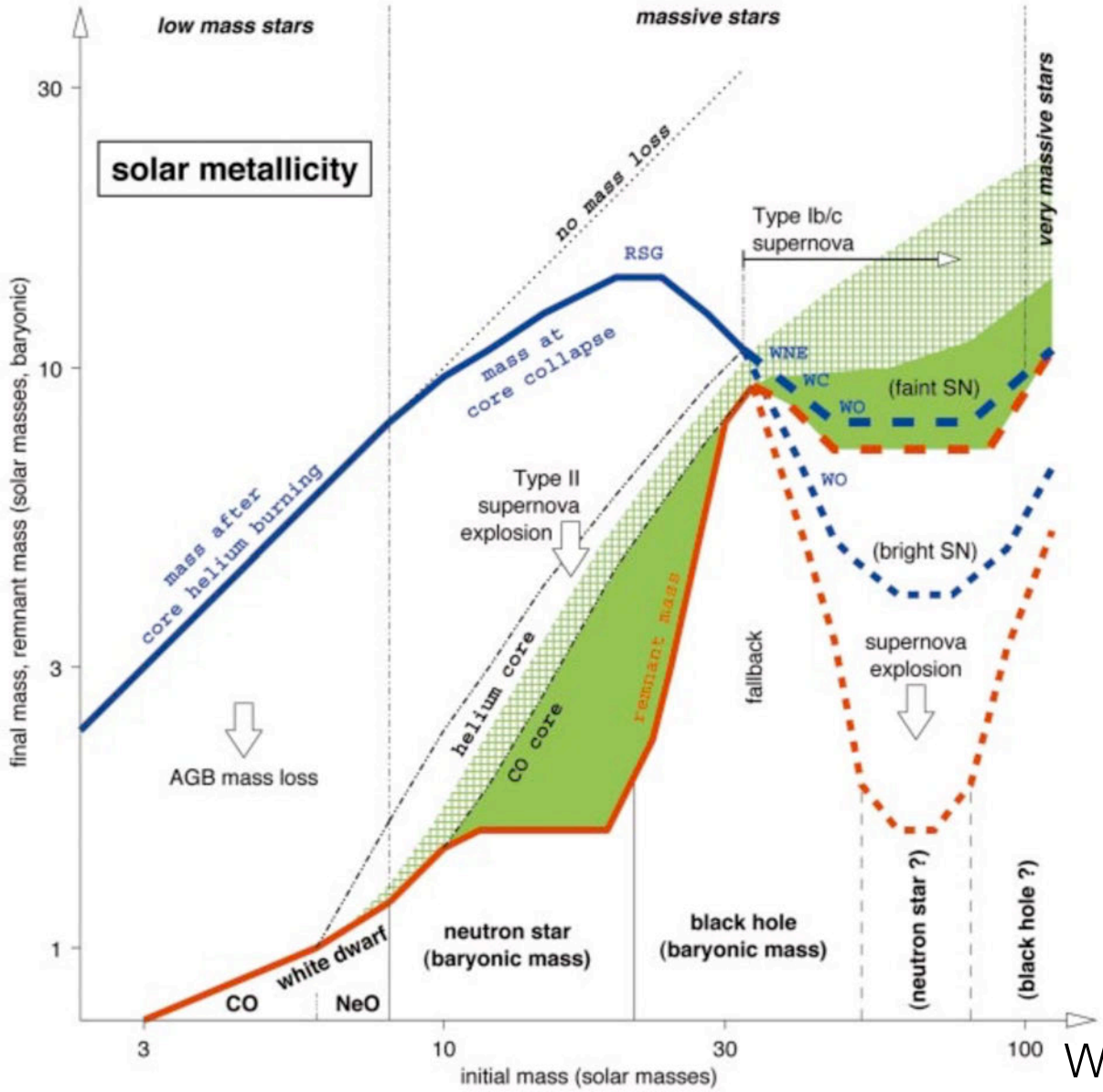


Smith (2014)



Smartt (2015)

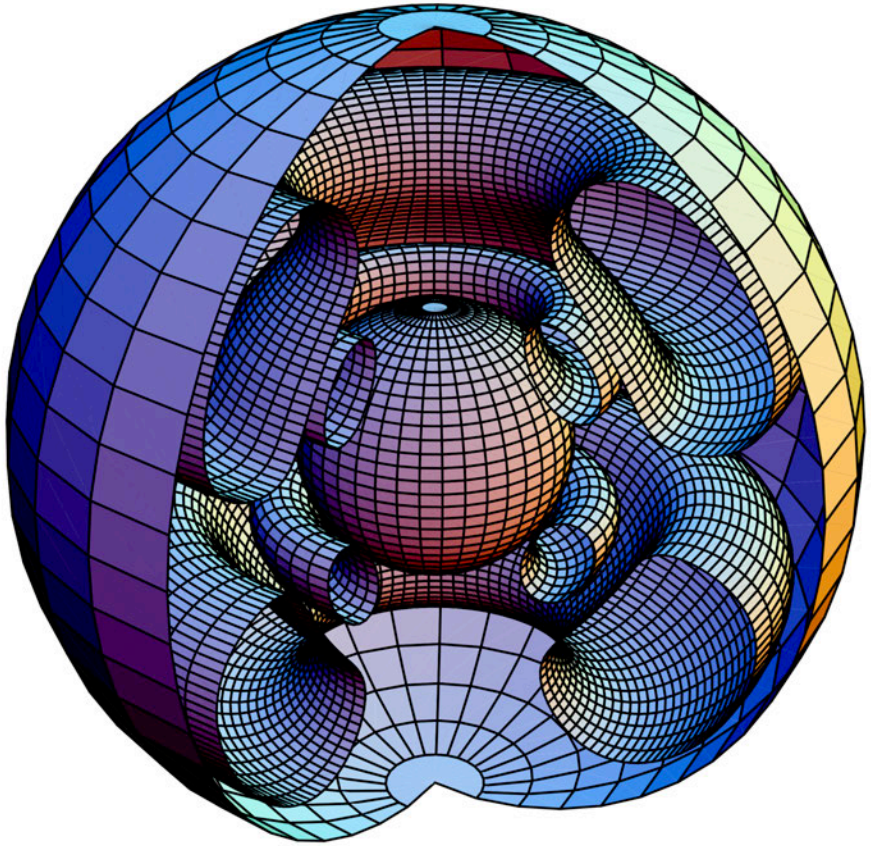
Final mass of stars

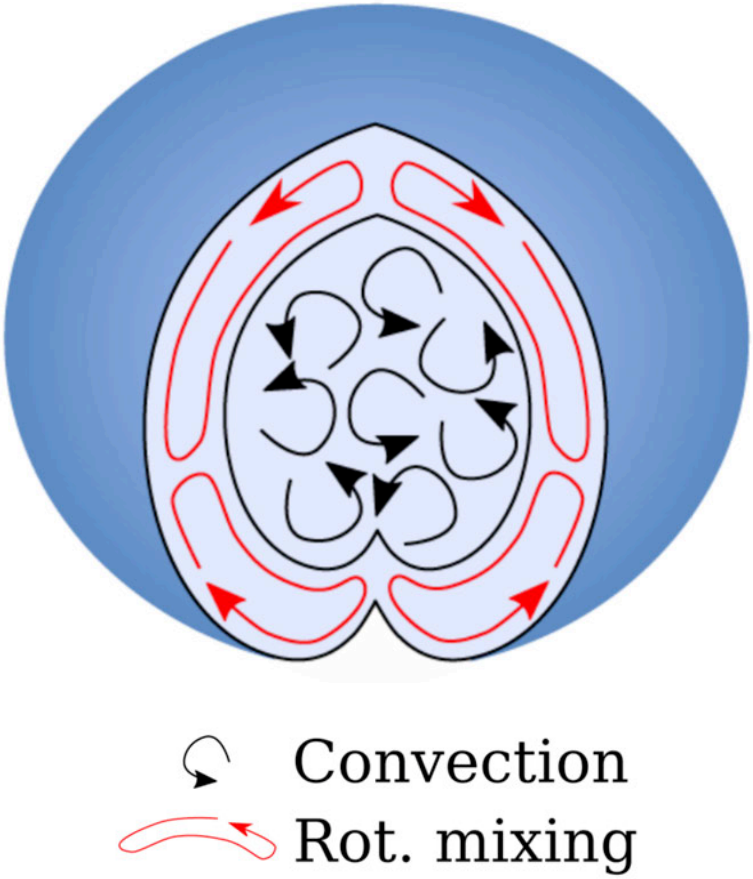


Woosley et al. (2002)

Rotation

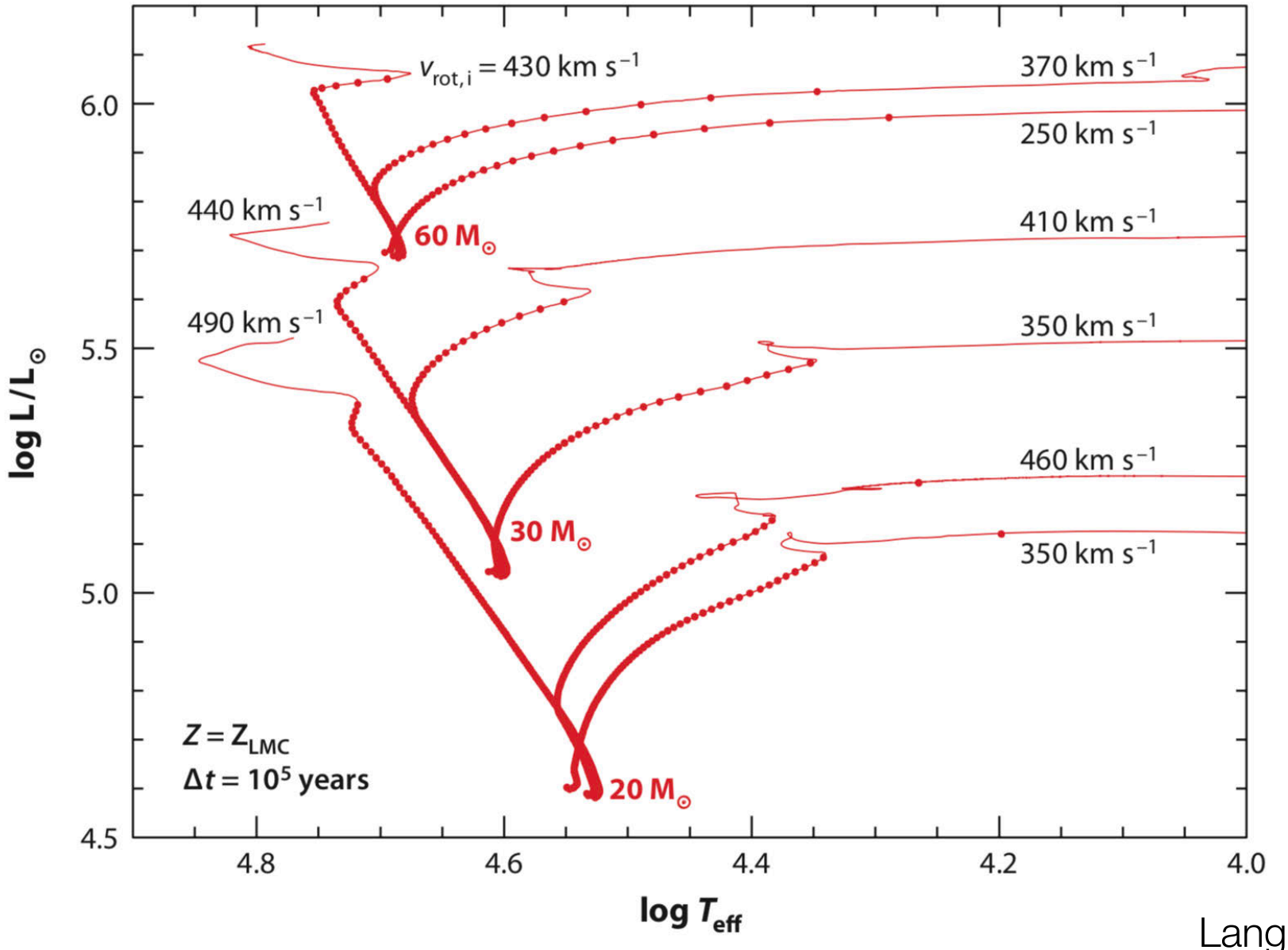
- Rotation induces extra mixing in stars
  - e.g., meridional circulation





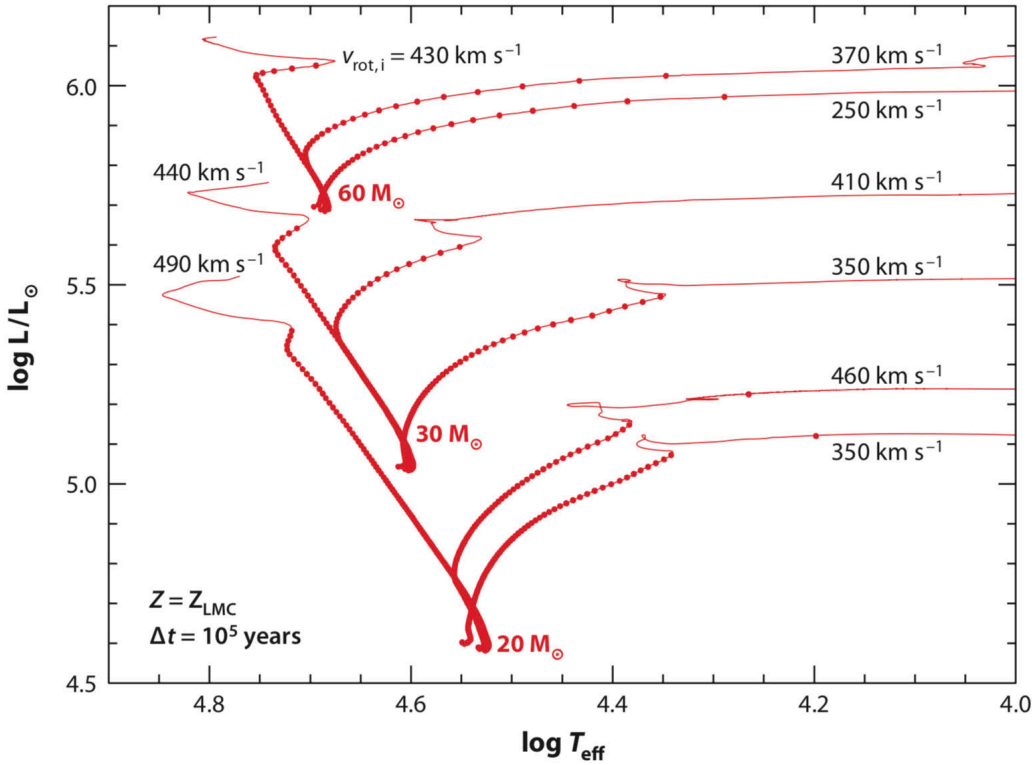
Marchant et al. (2017)

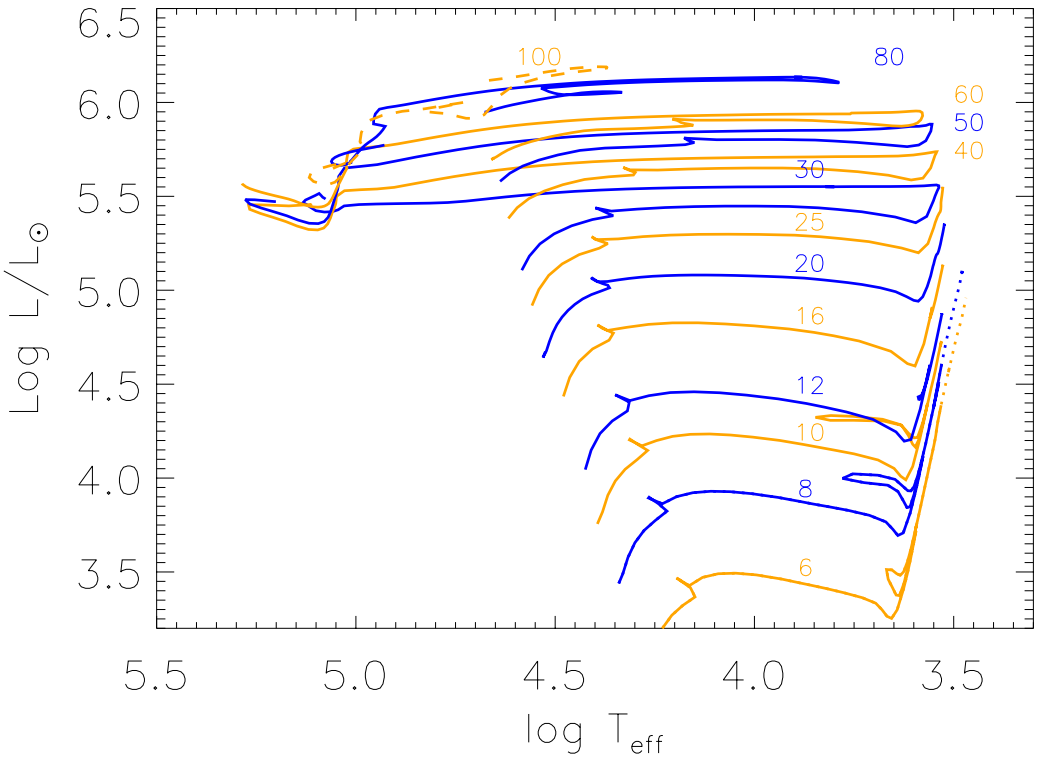
Rotation



Langer (2012)

Rotation



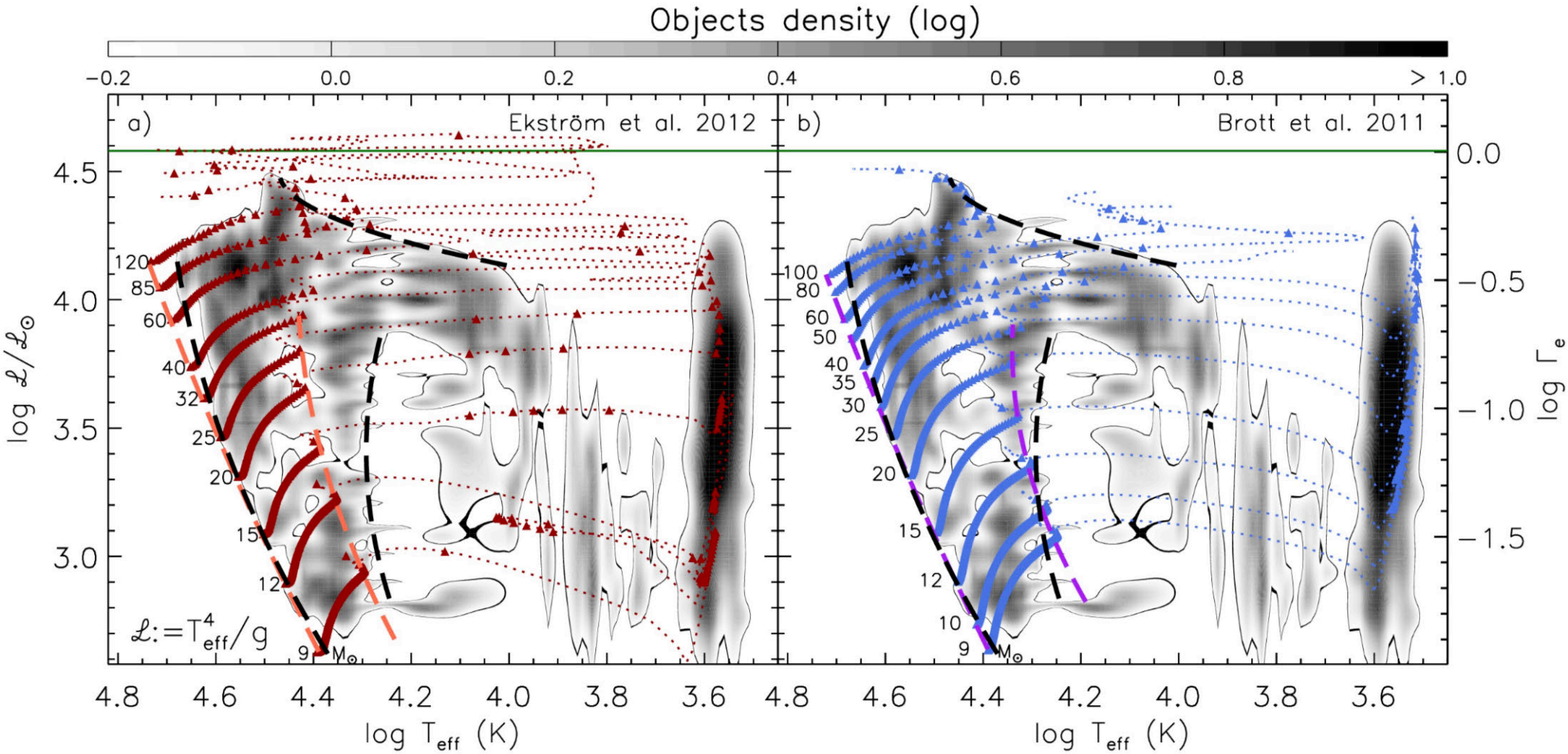


Langer (2012)

Smartt (2015)

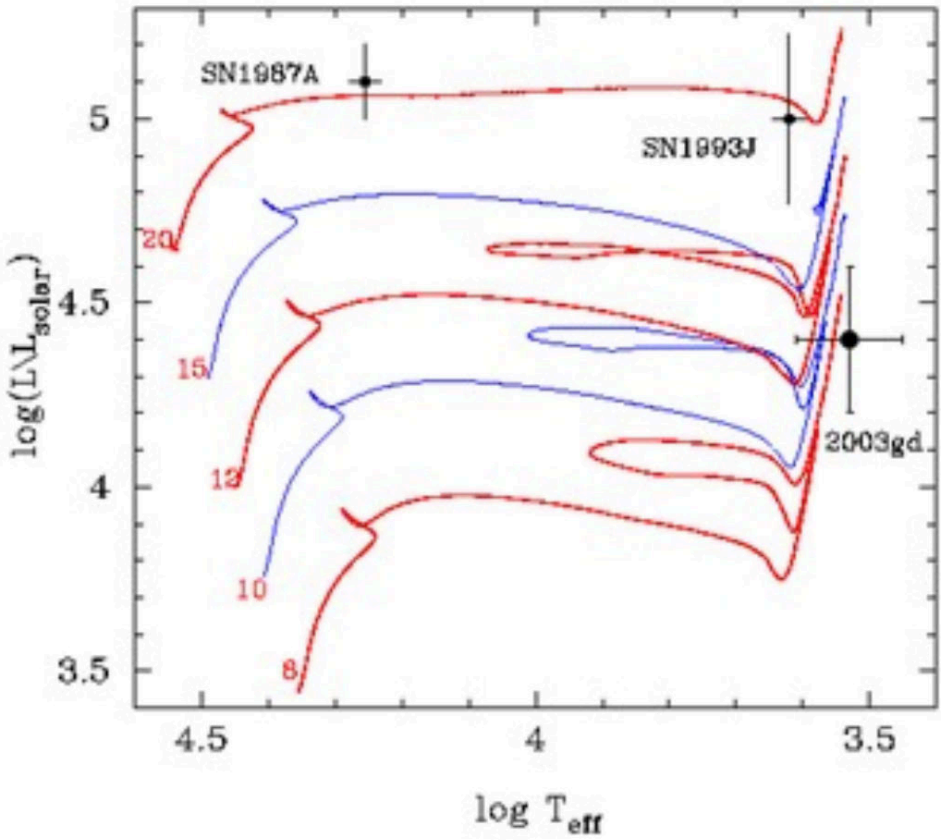
Many issues remain in stellar evolution theory

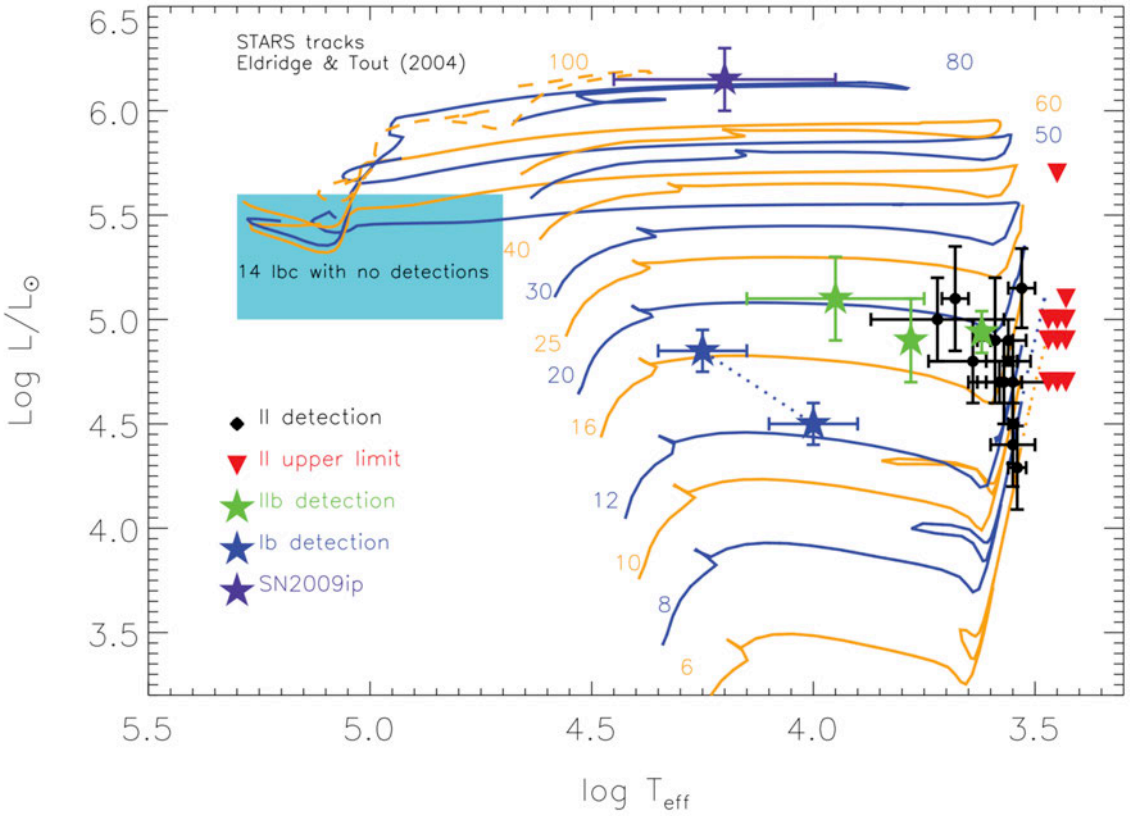
- even the main sequence is not understood!



Castro et al. (2014)

Impossible supernova progenitors





Smartt (2015)

Summary

- Stellar evolution at center
  - the evolutionary path and fate is solely determined by mass
  - follows $T_c \propto M^{2/3}\rho_c^{1/3}$
- Stellar evolution at surface
  - mass loss is important for massive stars
- there is other important physics
  - e.g., rotation
- many unsolved problems
  - main-sequence widths
  - impossible supernova progenitors