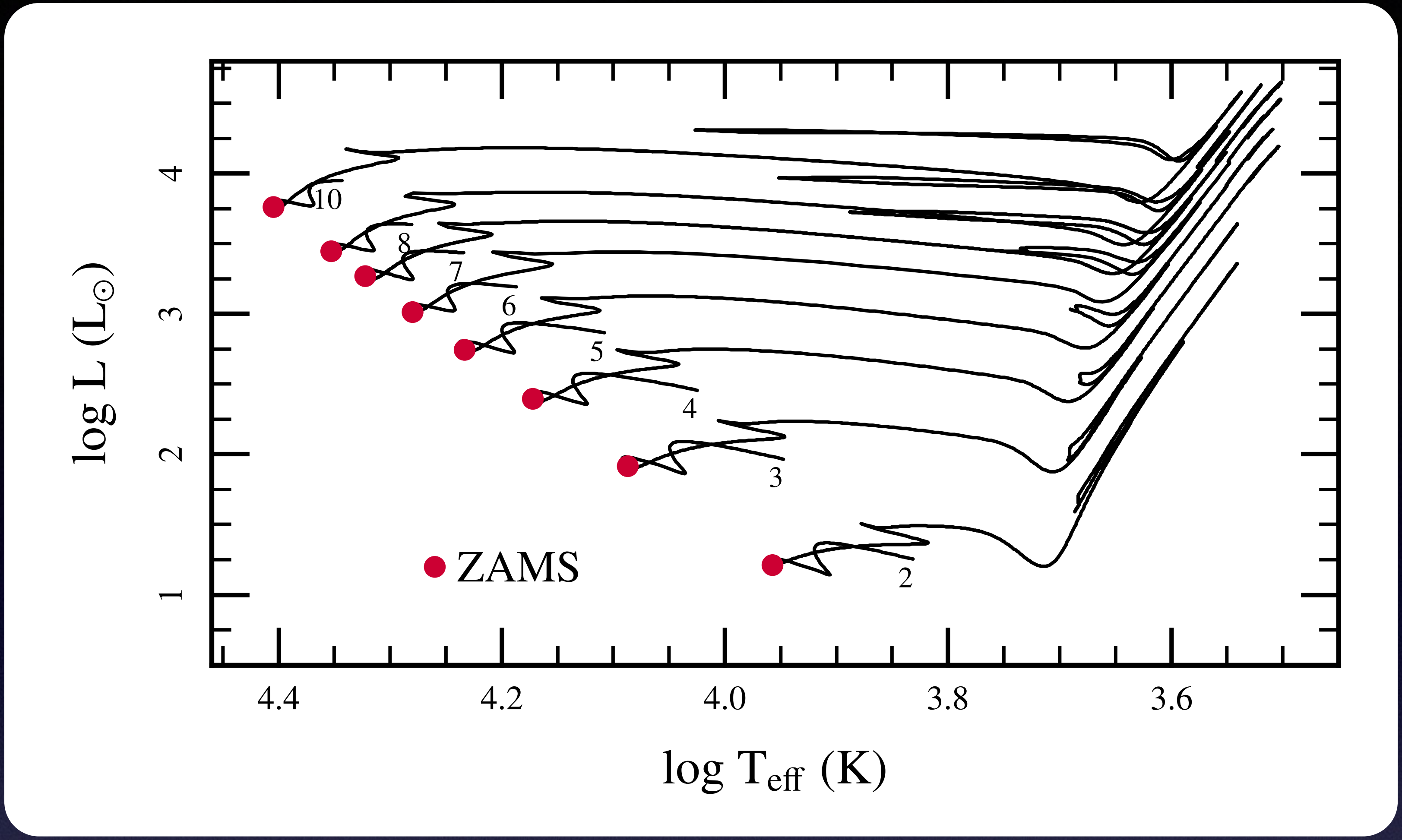
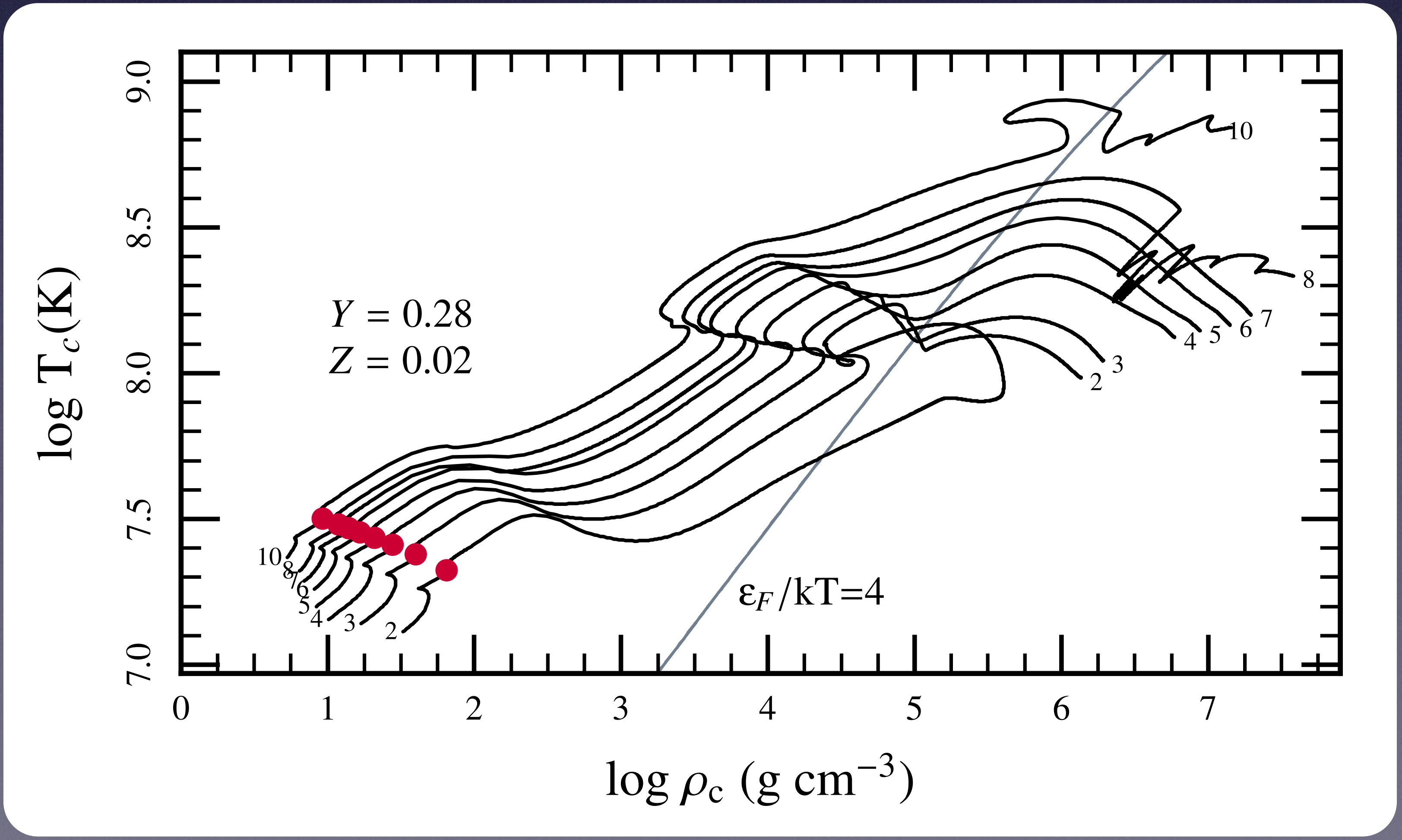
Section 5.
White dwarf

Let's understand these questions with the words of physics

- Why are stars so luminous?
- Why do stars show L ~ M^4?
- Why do stars evolve?
- Why does the destiny of stars depend on the mass?
- Why do some stars explode?
- Why don't normal star explode?
- Why does stellar core collapses?
- Why is the energy of supernova so huge?
- …





Low/intermediate mass stars

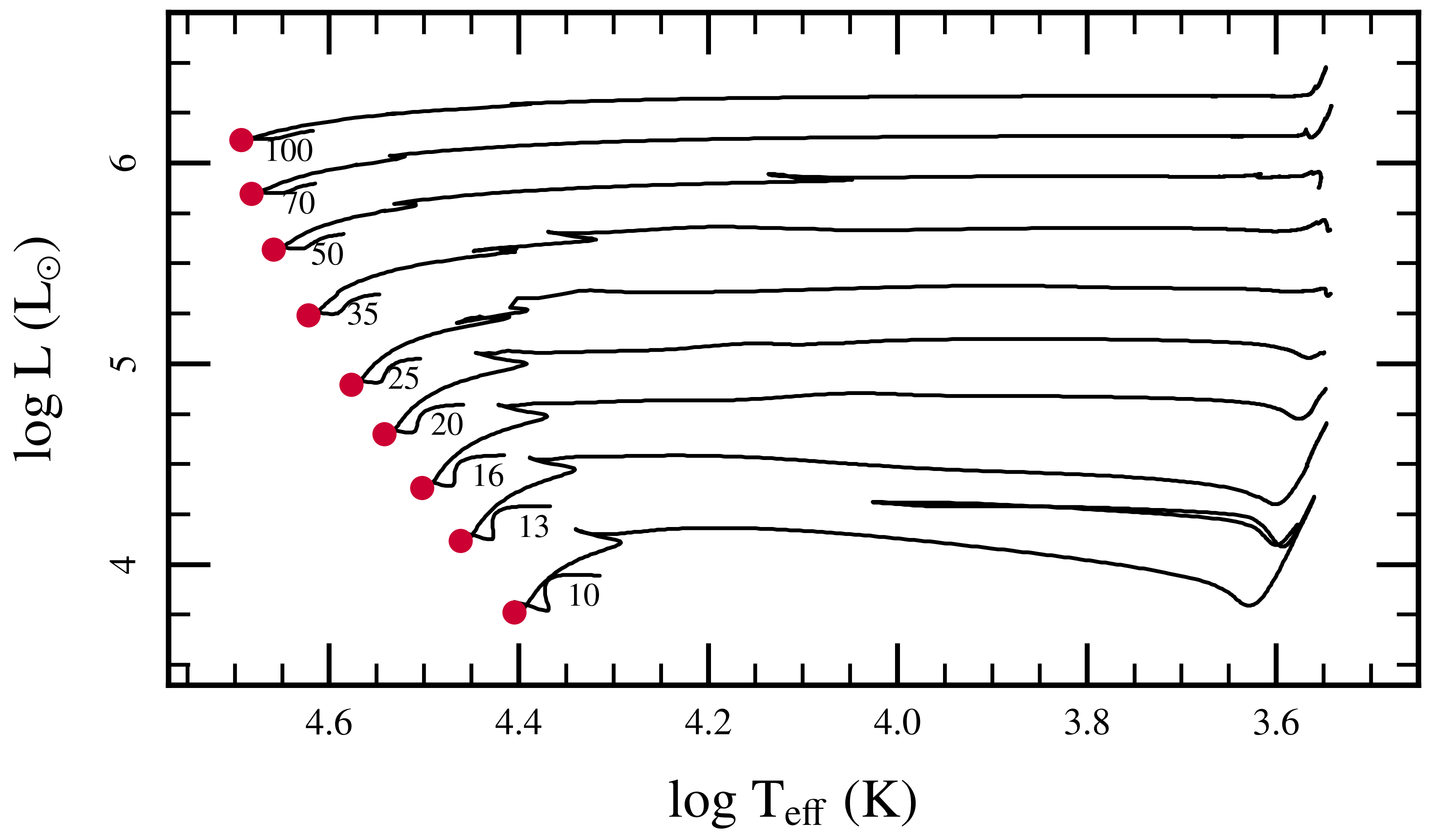
Core contraction

=> Expansion of the envelope

=> Red giant

Paxton et al. 2011

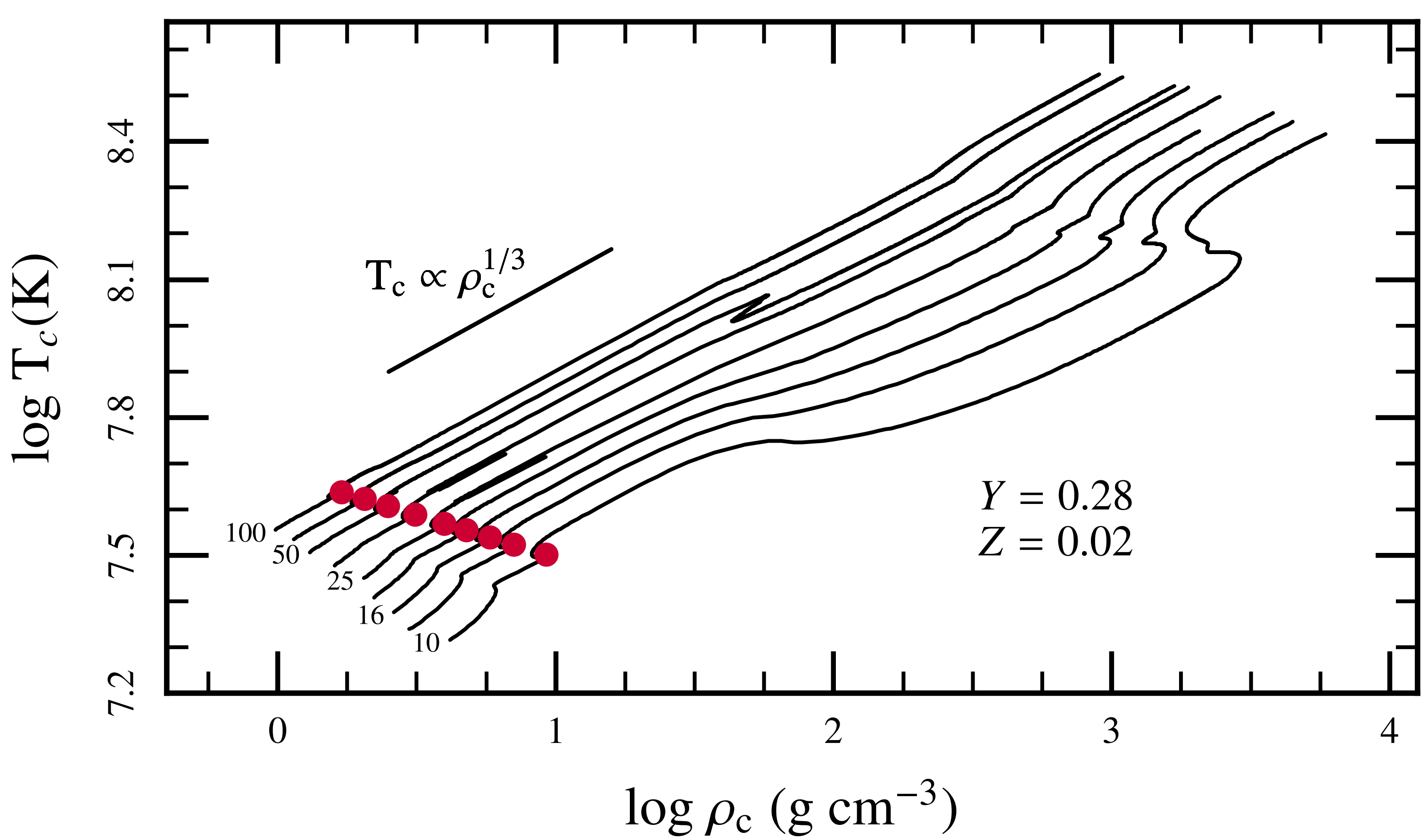
Massive stars
(until He-burning)



Core contraction

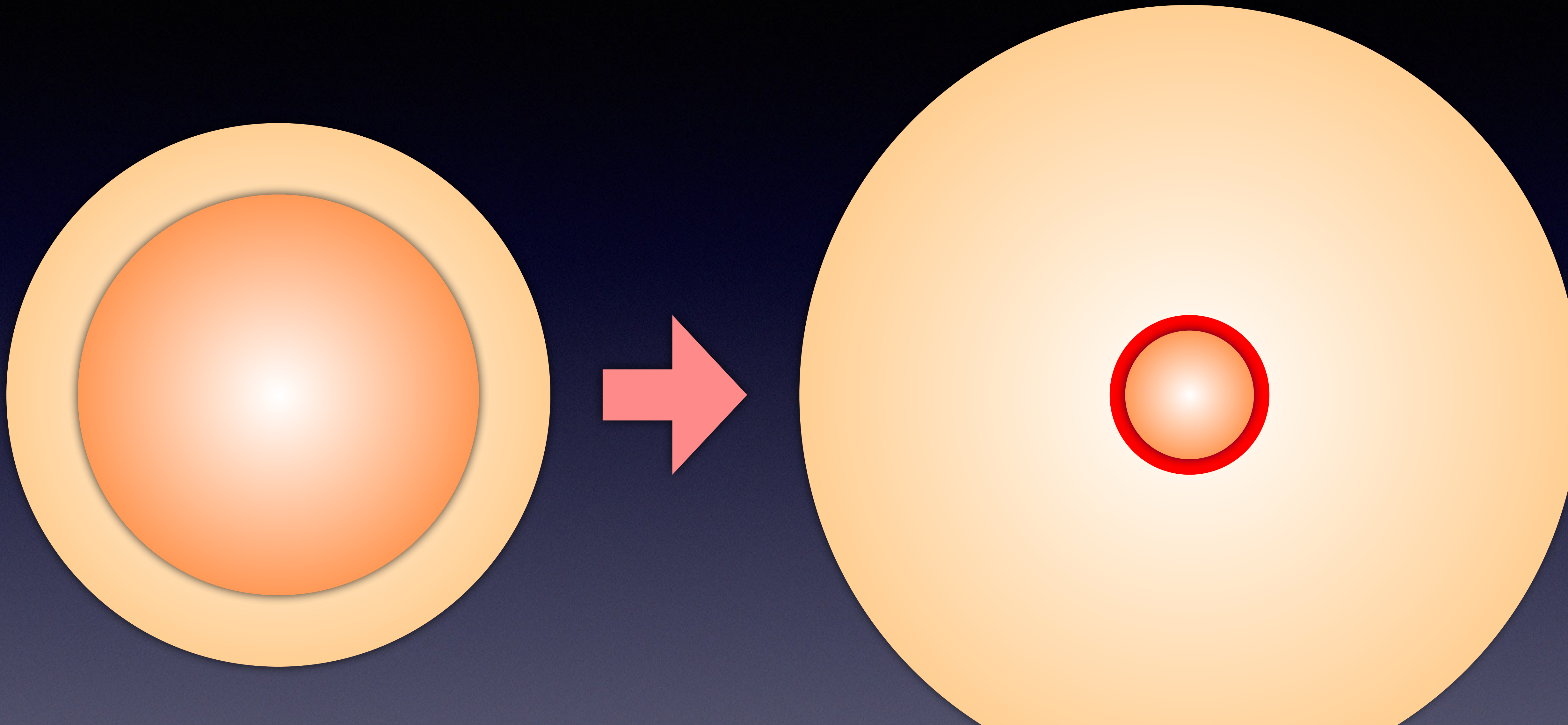
=> Expansion of the envelope

=> Red super giant



Paxton et al. 2011

Contraction of the core
= Expansion of the envelope



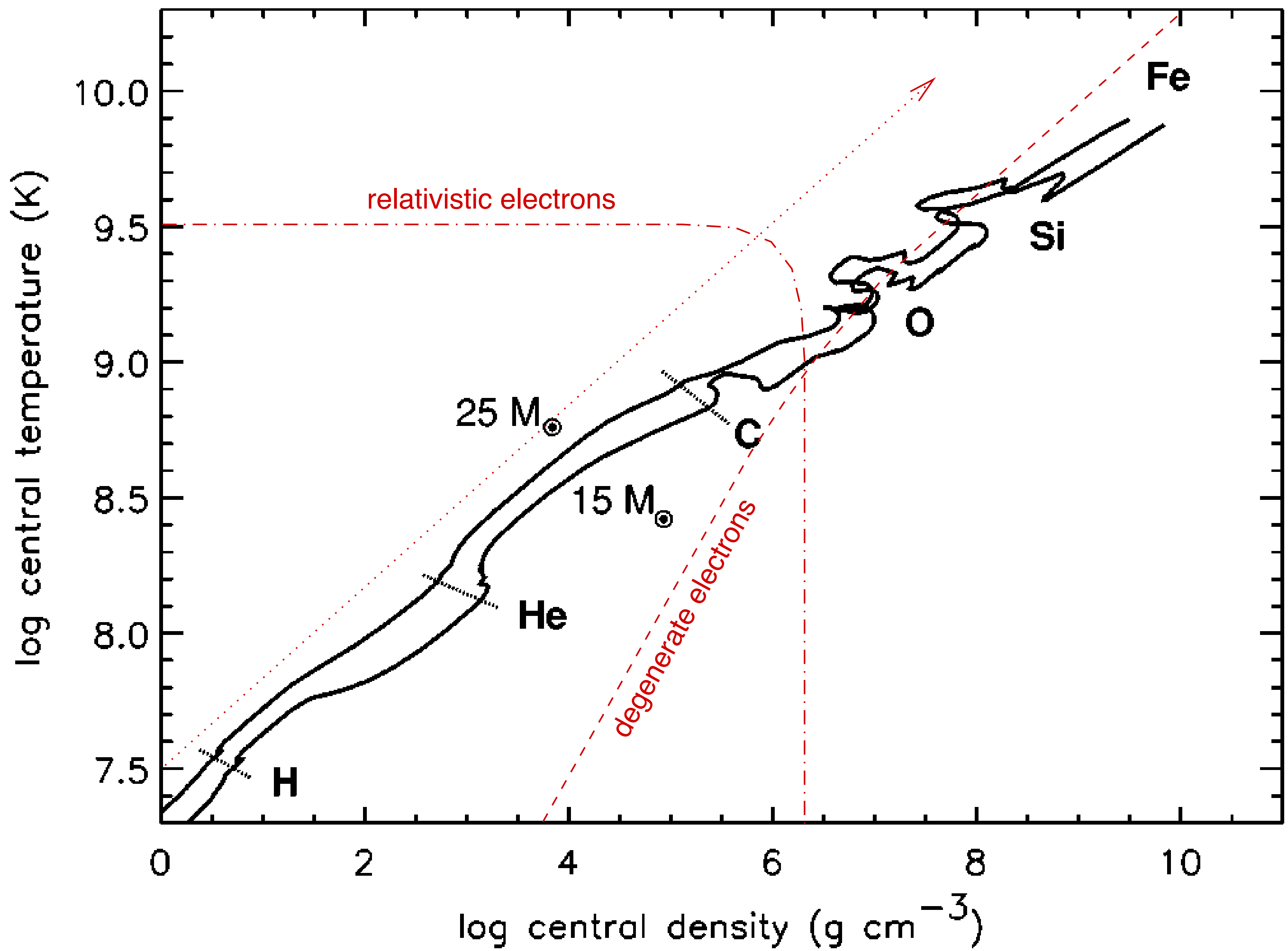
Evolution in the rho-T plane is determined
by the properties of the core

$T \sim M^{2/3} \rho^{1/3}$

M decreases => Lower part of the ρ-T plane

Massive stars
(until Si burning)

Finally degeneracy pressure becomes important



textbook by Pols

MESA code

http://mesa.sourceforge.net/index.html

MESA
Modules for Experiments in Stellar Astrophysics

MESA home
code capabilities
prereqs & installation
getting started
using pgstar
using MESA output
beyond inlists (extending MESA)
troubleshooting
FAQ
star_job defaults
controls defaults
pgstar defaults
binary_controls defaults
news archive
documentation archive

MESA

*You may also want to visit **the MESA community portal**, where users share the inlists from their published results, tools & utilities, and teaching materials.*

Why a new 1D stellar evolution code?

The MESA Manifesto discusses the motivation for the MESA project, outlines a MESA code of conduct, and describes the establishment of a MESA Council. Before using MESA, you should read the **manifesto document**. Here's a brief extract of some of the key points

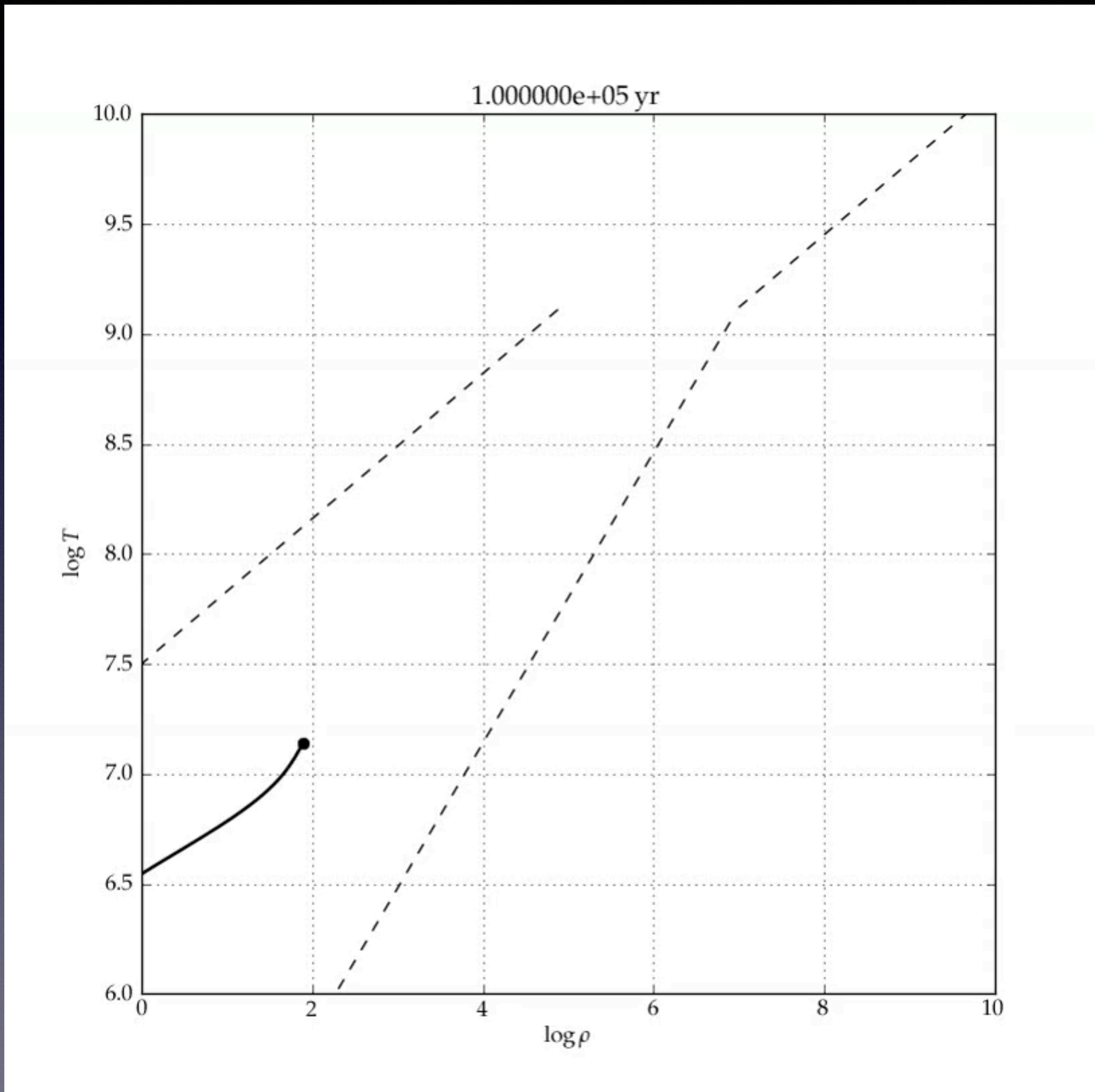
Stellar evolution calculations remain a basic tool of broad impact for astrophysics. New observations constantly test the models, even in 1D. The continued demand requires the construction of a general, modern stellar evolution code that combines the following advantages:

- **Openness**: anyone can download sources from the website.
- **Modularity**: independent modules for physics and for numerical algorithms; the parts can be used stand-alone.
- **Wide Applicability**: capable of calculating the evolution of stars in a wide range of environments.
- **Modern Techniques**: advanced AMR, fully coupled solution for composition and abundances, mass loss and gain, etc.
- **Comprehensive Microphysics**: up-to-date, wide-ranging, flexible, and

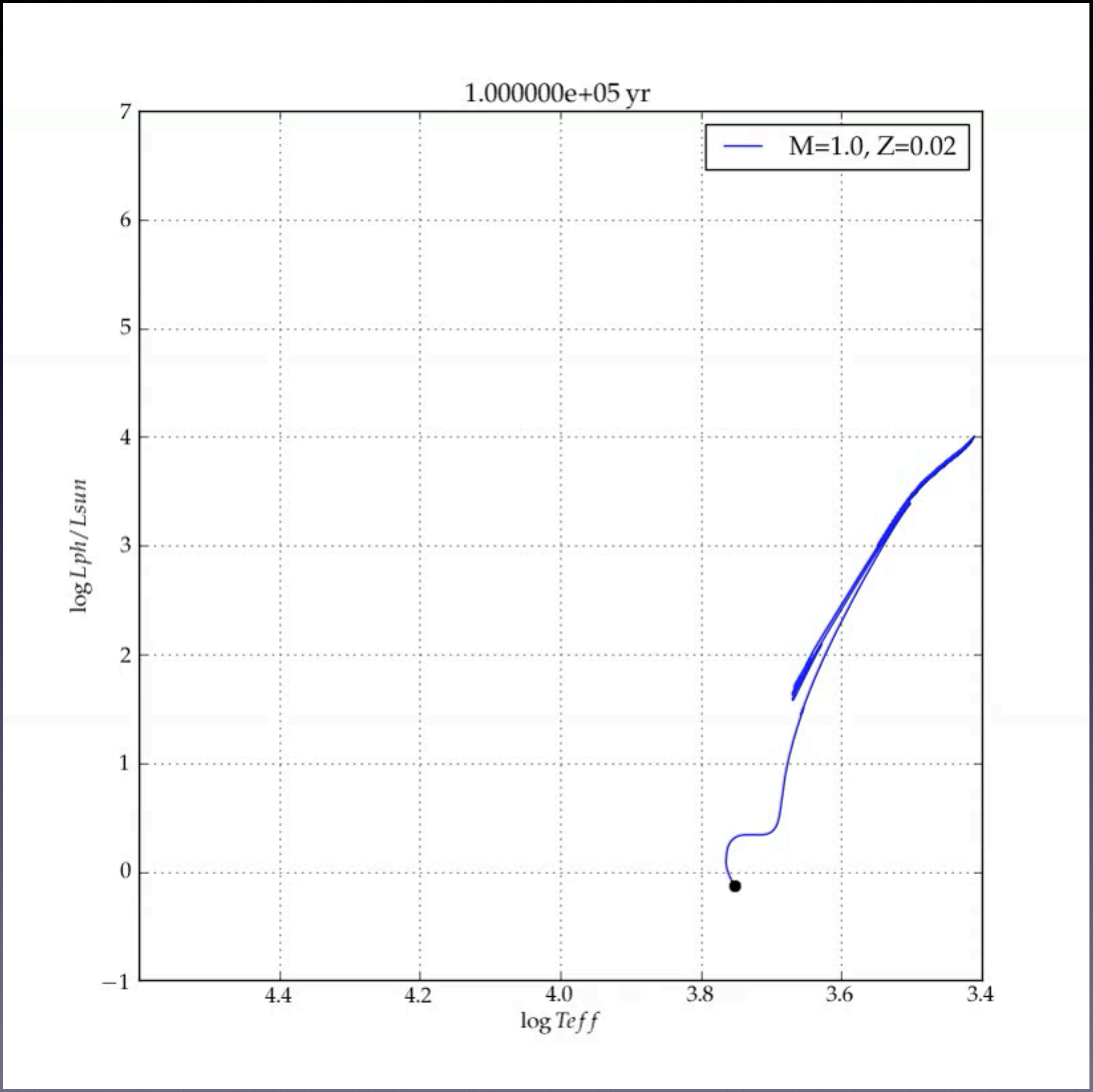
Latest News

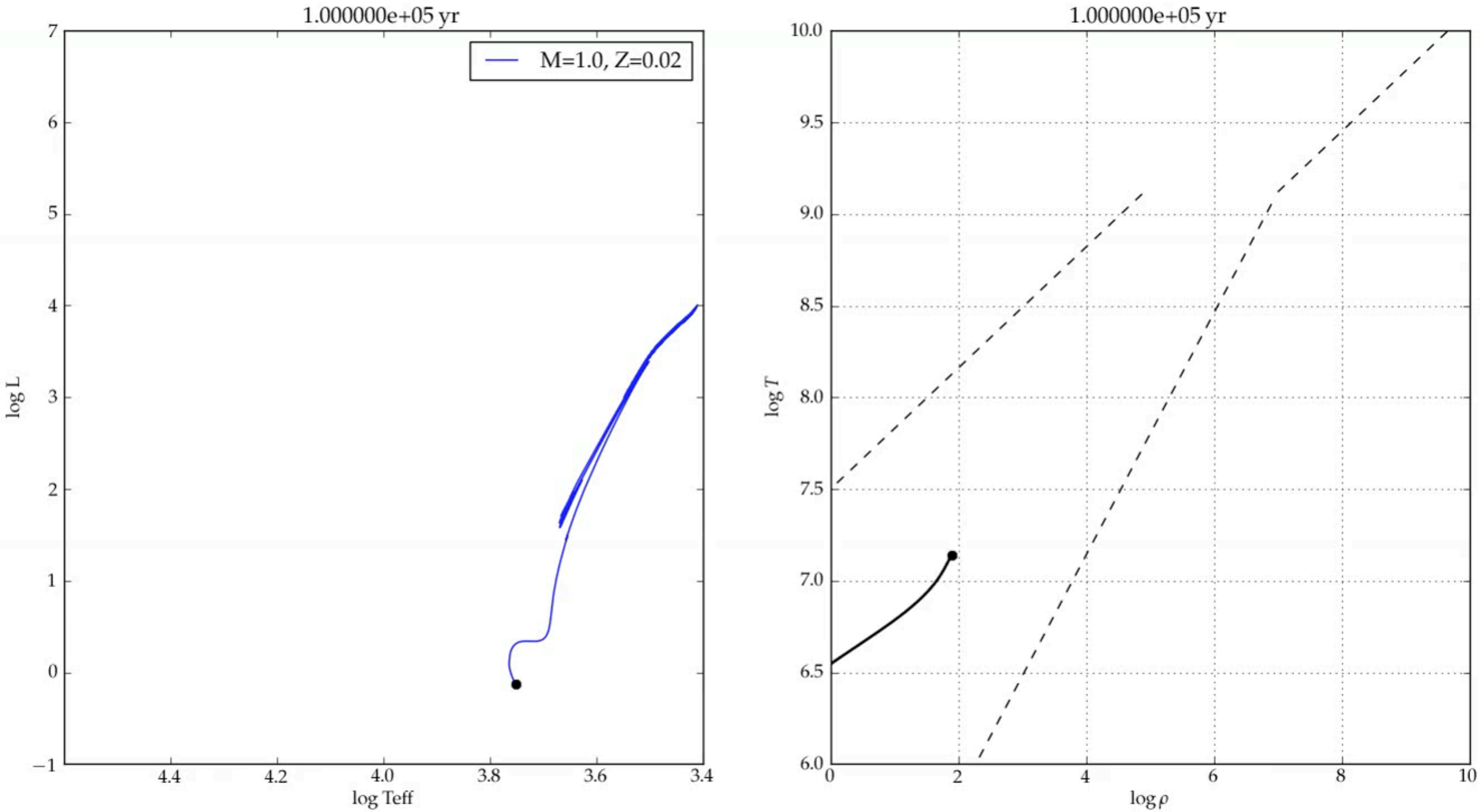
- 10 Aug 2016
  » **Documentation Archive**
- 19 Jun 2016
  » **Release 8845**
- 03 Feb 2016
  » **Release 8118**
- 29 Jan 2016
  » **New MESA SDK Version**
- 10 Jan 2016
  » **Summer School 2016**
- 27 Sep 2015
  » **Instrument Paper 3**
- 14 Sep 2015
  » **MESA-Web Updates**
- 08 Sep 2015
  » **New MESA SDK Version**
- 03 Sep 2015
  » **Updated MESA Maps**
- 27 Aug 2015
  » **Summer School Success!**

1 Msun (ρ-T)

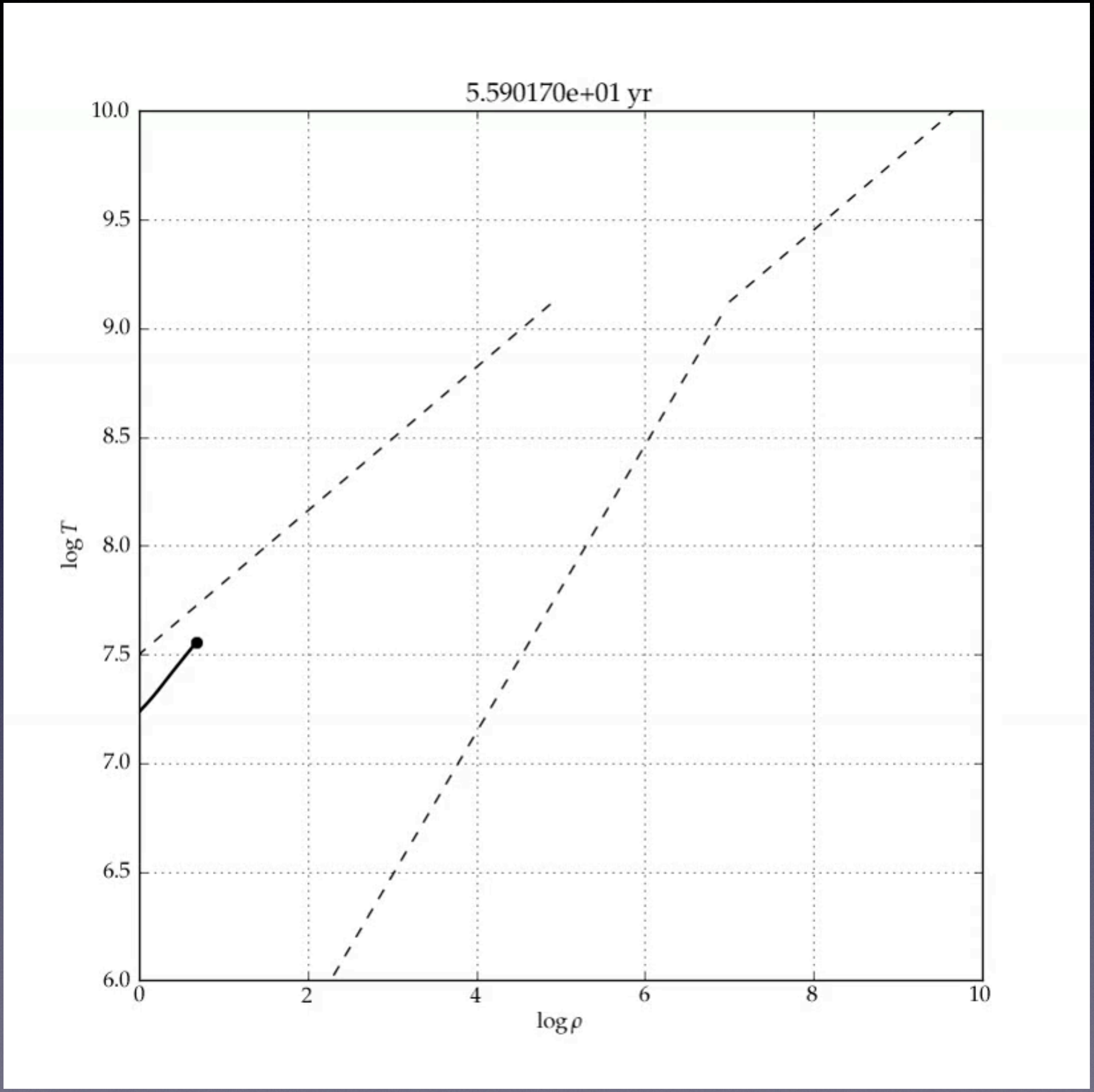


1 Msun (HR diagram)

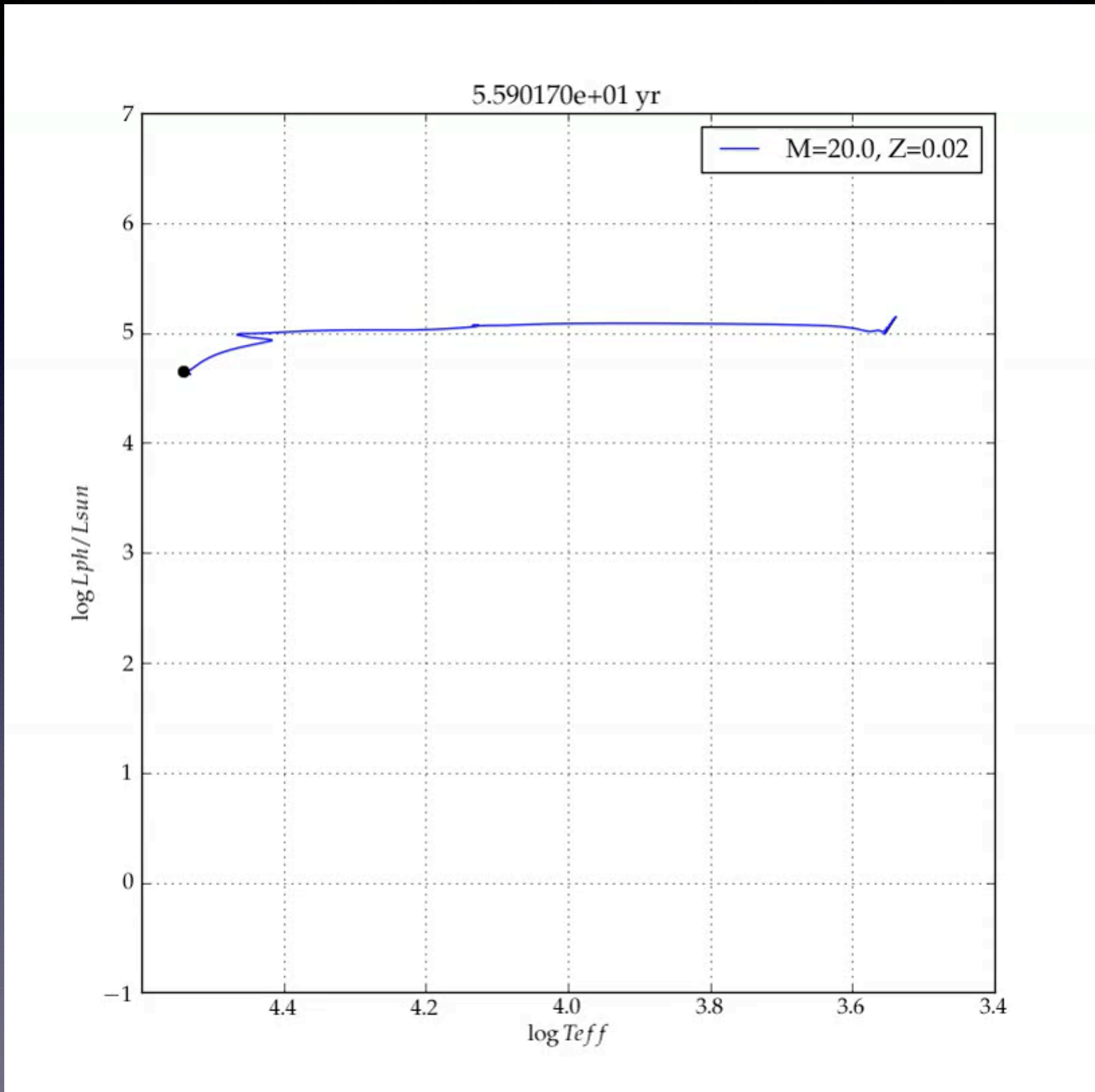


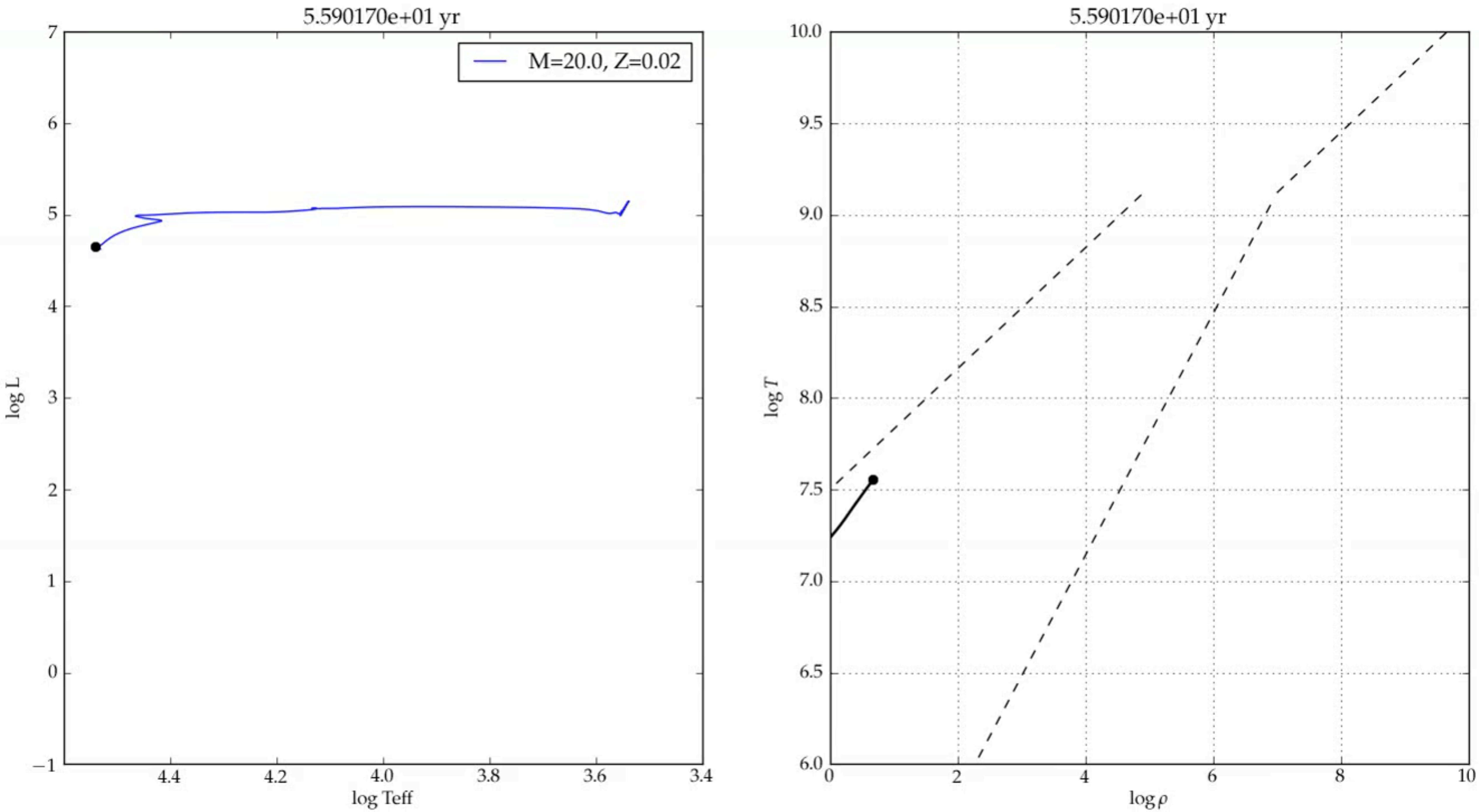

1.000000e+05 yr
M=1.0, Z=0.02
log L
log Teff
7
6
5
4
3
2
1
0
−1
4.4
4.2
4.0
3.8
3.6
3.4
1.000000e+05 yr
log T
log ρ
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
0
2
4
6
8
10

20 Msun (ρ-T)

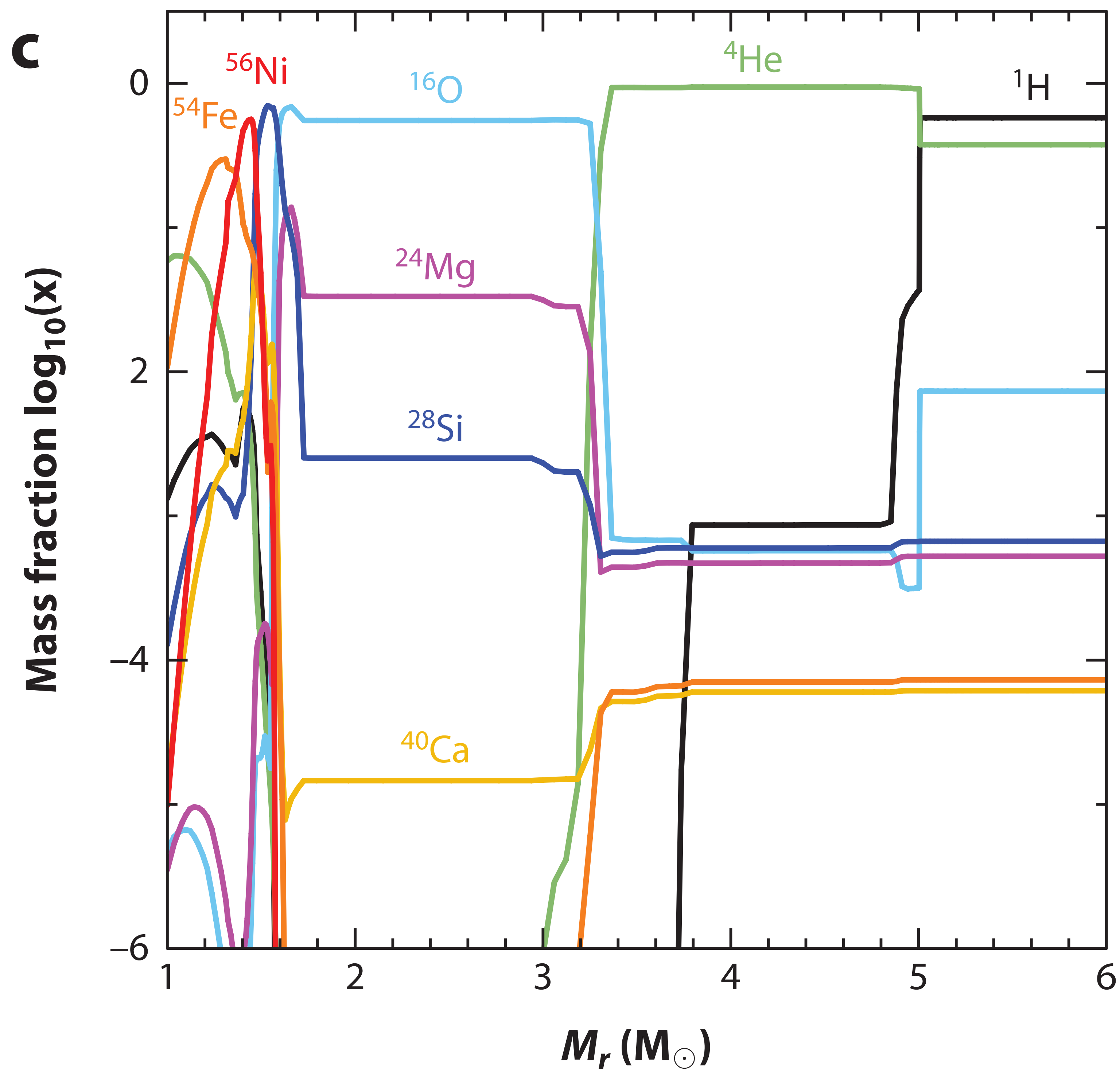


20 Msun (HR diagram)



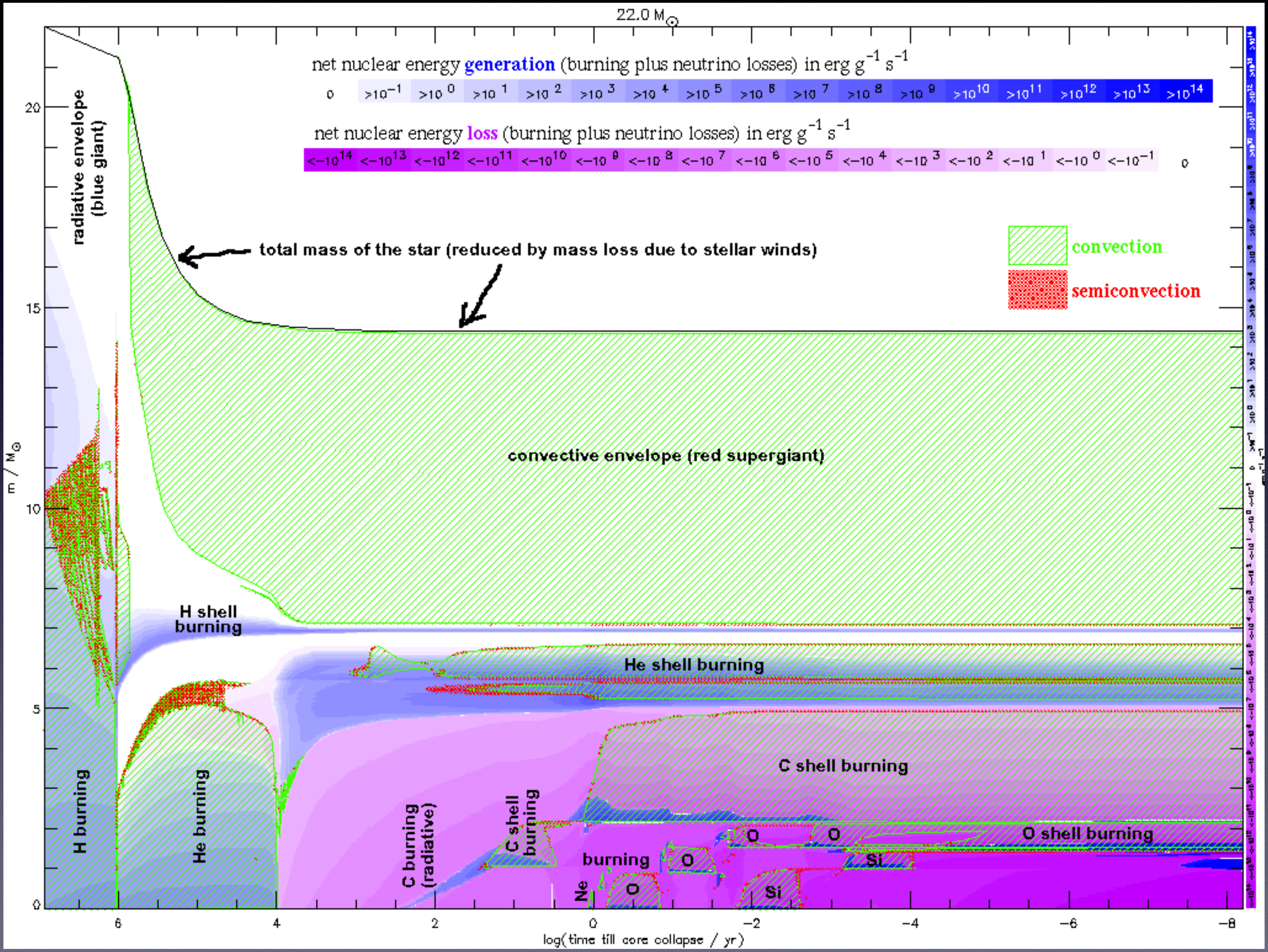

5.590170e+01 yr
M=20.0, Z=0.02
log L
log Teff
7
6
5
4
3
2
1
0
−1
4.4
4.2
4.0
3.8
3.6
3.4
5.590170e+01 yr
log T
log ρ
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
0
2
4
6
8
10

Elemental distribution before core-collapse SN



Nomoto+13

"Kippenhahn diagram"



(C) A. Heger
https://2sn.org/stellarevolution/explain.gif

Section 5.
White dwarf

5.1 Stellar evolution calculations

5.2 White dwarf

5.3 Thermonuclear supernovae

https://kids.yahoo.co.jp/zukan/astro/winter/0001.html

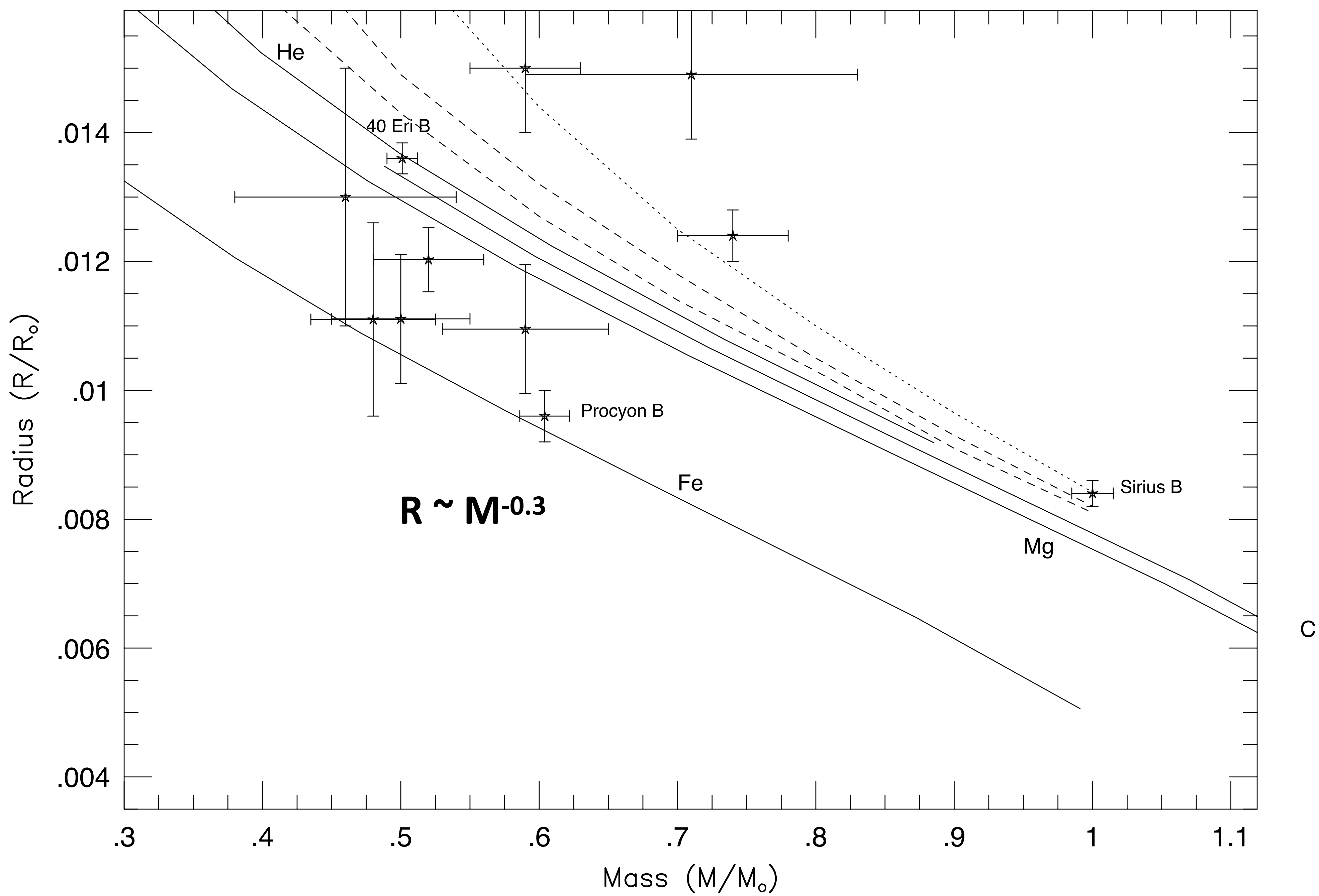
Cat’s eye nebula

(J.P. Harrington and K.J. Borkowski, and NASA)

Helix nebula

(NASA, ESA, and C.R. O'Dell)

Mass-radius relation for white dwarfs

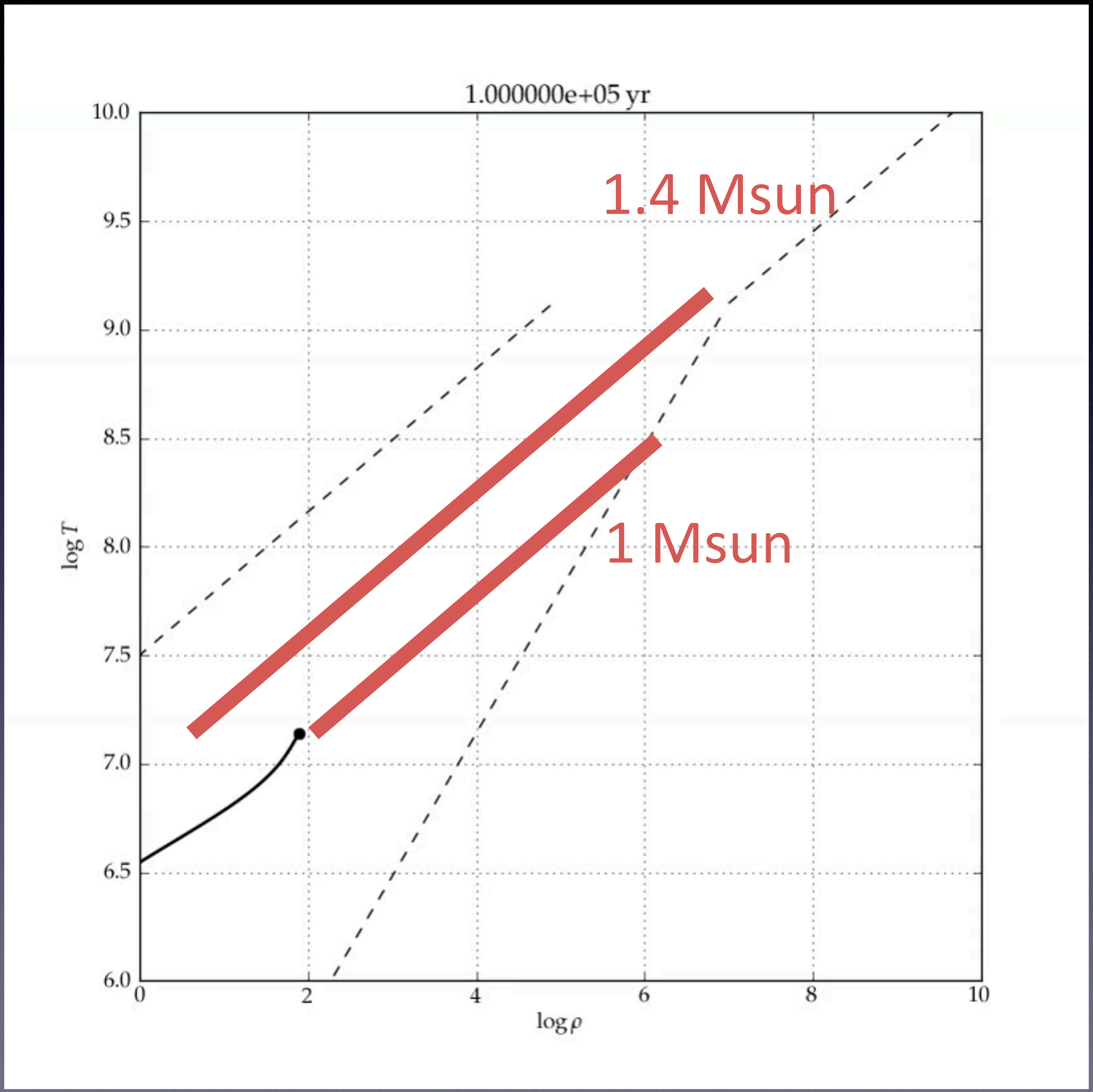


Provencal et al. 1998

More massive white dwarfs are smaller
Opposite to the main sequence stars

Why??

1 Msun (ρ-T)



$T \sim M^{2/3} \rho^{1/3}$

Assignment 3 / レポート課題3

(3a) By assuming the polytrope EOS, derive Lane-Emden equation.
(3b) By using the properties of the solution,
show that Chandrasekhar mass can be expressed only by
- mean molecular weight μ
- gravitational fine structure constant α_G, and
- mass of the proton m_p
(3c) Derive Chandrasekhar mass for C+O white dwarf

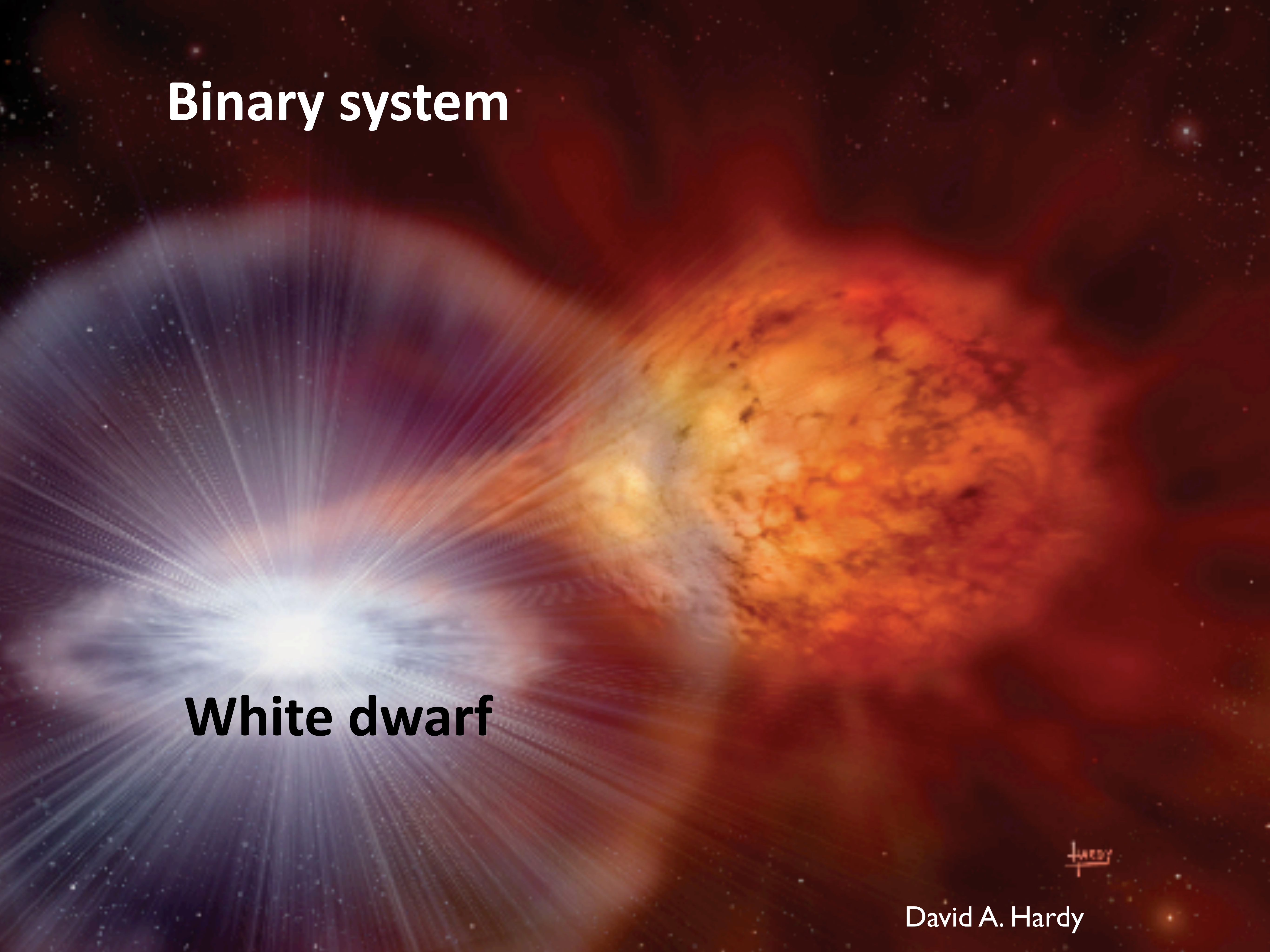
(3a) ポリトロープ状態方程式を仮定することで
Lane-Emden equationを導出せよ。
(3b) Lane-Emden equationの解の性質を用いて,
チャンドラセカール質量が以下の3つの量のみで表せられることを示せ。
- mean molecular weight μ
- gravitational fine structure constant α_G, and
- mass of the proton m_p
(3c) C+O white dwarfのチャンドラセカール質量を求めよ。

Section 5.
White dwarf

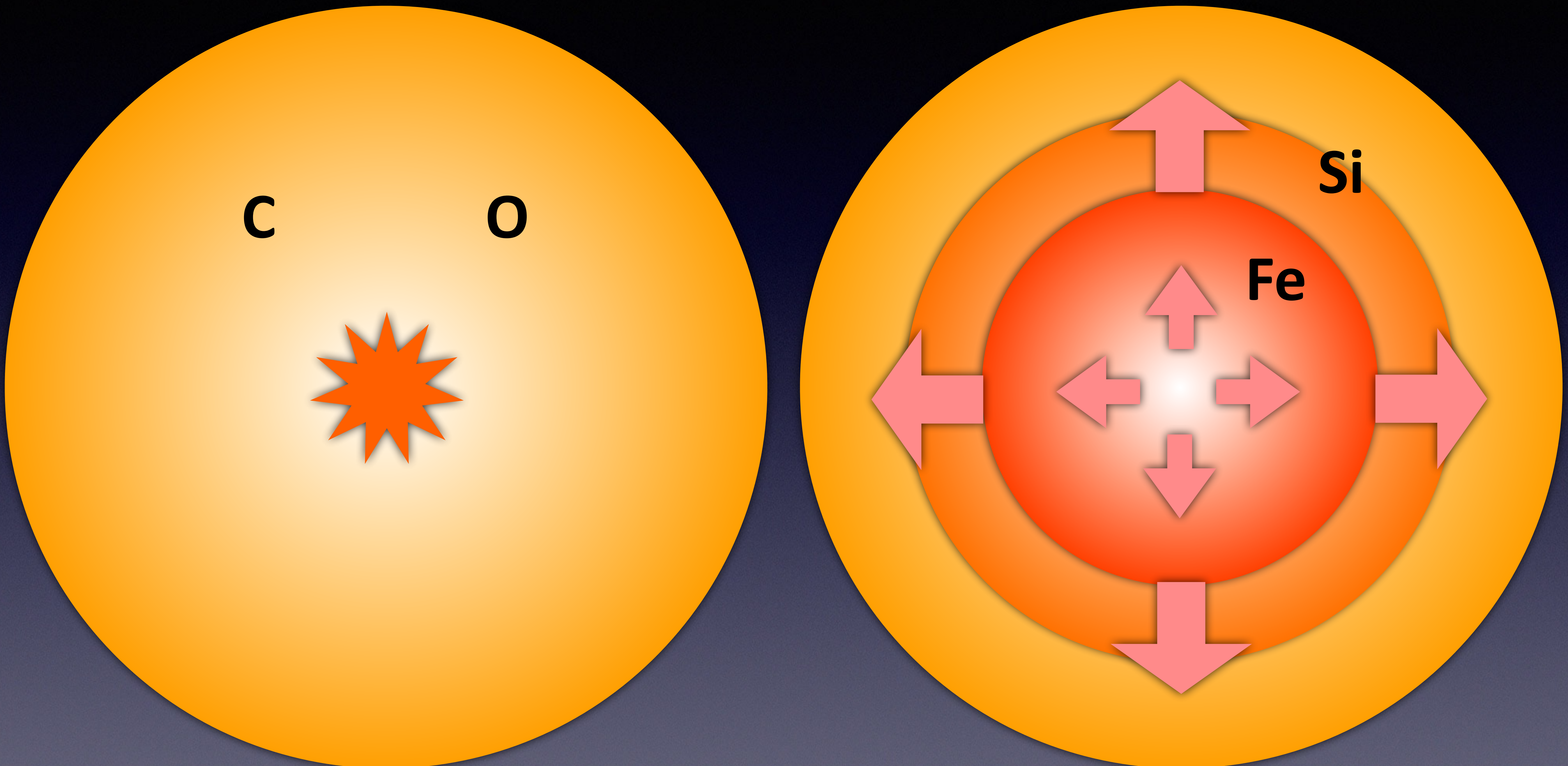
5.1 Stellar evolution calculations

5.2 White dwarf

5.3 Thermonuclear supernovae

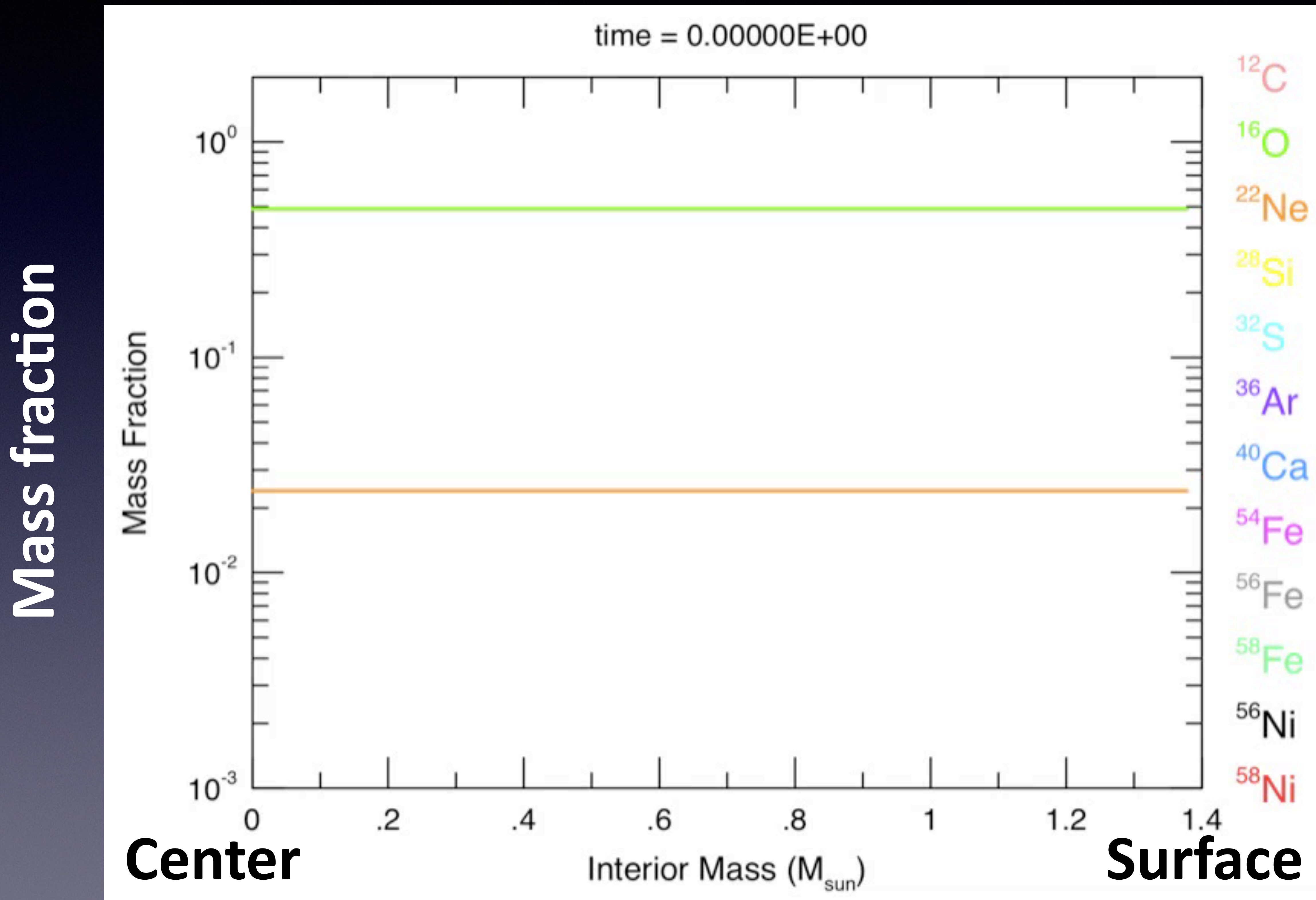

Binary system
White dwarf
HARDY
David A. Hardy

Thermonuclear explosion

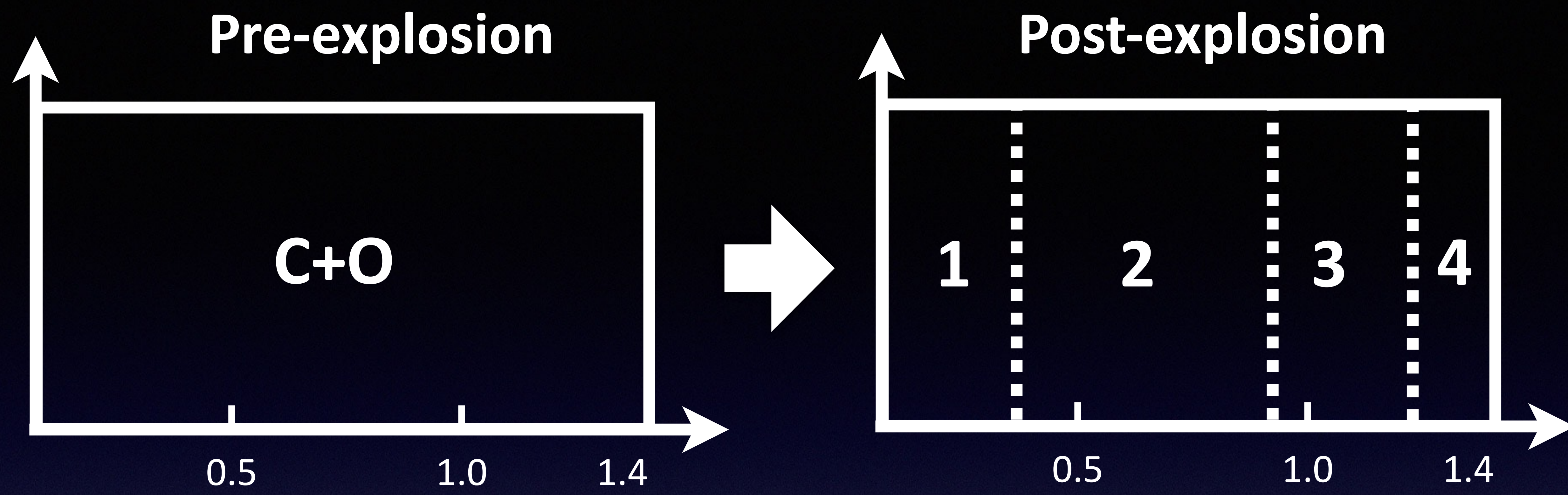


Supernova!

Explosion of white dwarf



Nomoto+84, Timmes+



*NSE = nuclear statistical equilibrium (核統計平衡)

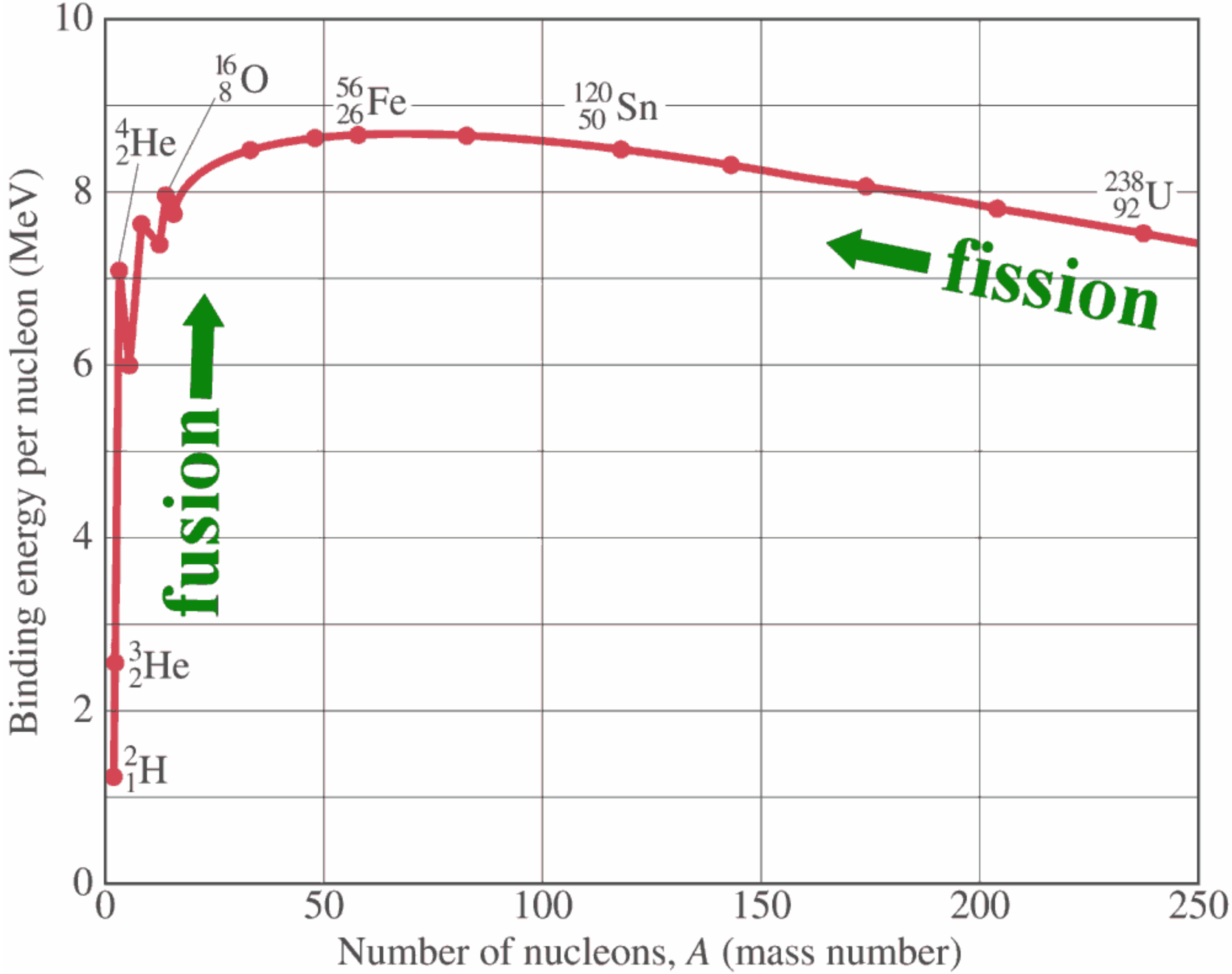
zone	T (K)	P (g cm^{-3})		Elements
1	(7-9) x 10^9	10^{8-9}	NSE + e-capture	^{56}Fe, ^{54}Fe, ^{58}Ni
2	(5-7) x 10^9	10^{7-8}	NSE	^{56}Ni
3	(4-5) x 10^9	<10^7	Incomplete Si burning	^{28}Si, ^{32}S, ^{40}Ca
4	< 4 x 10^9	<10^7	Incomplete O burning	^{16}O, ^{24}Mg

Thermonuclear supernovae

Normal stars are stable with nuclear burning

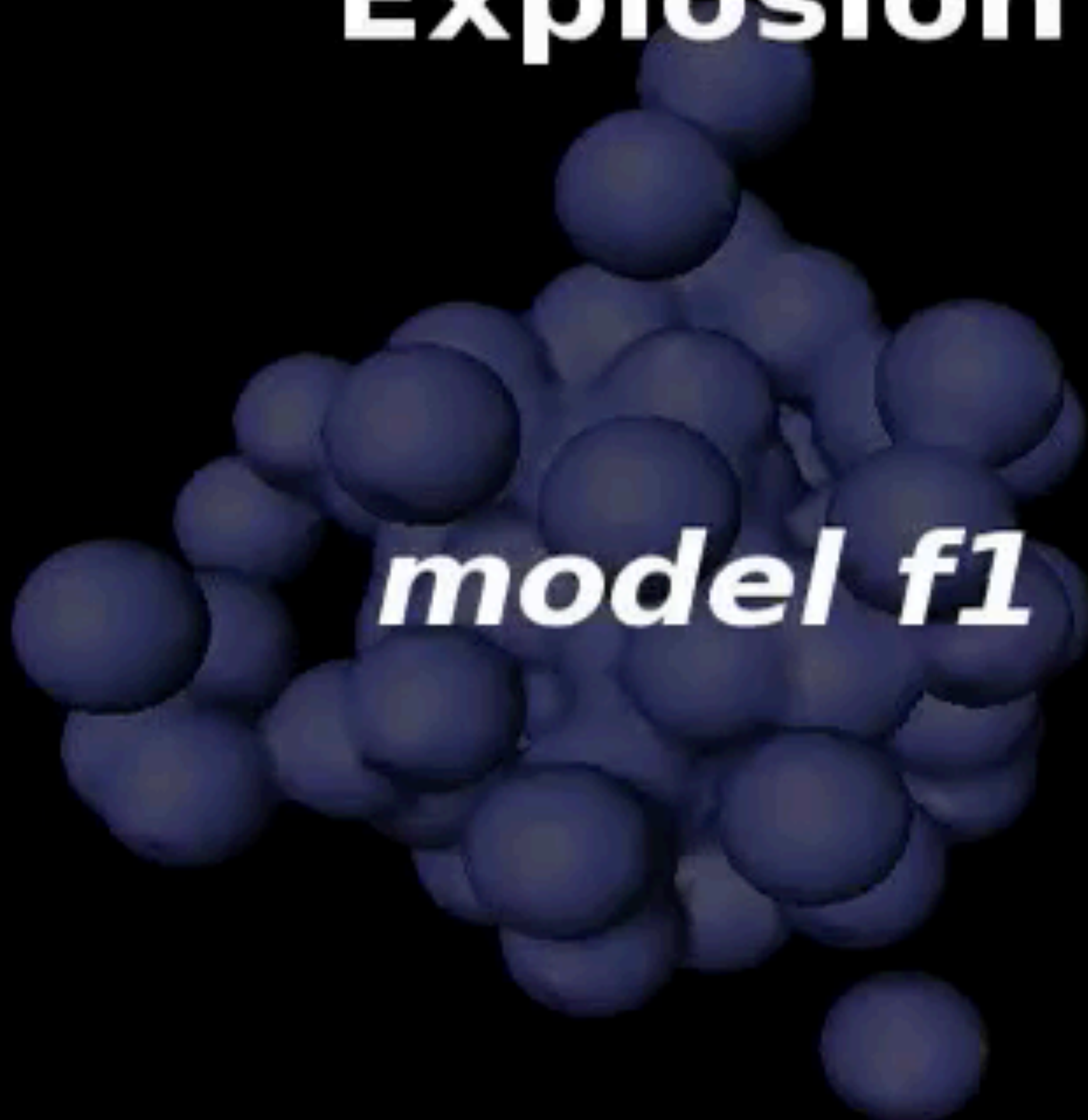
Why do white dwarfs explode by nuclear burning?

Type Ia SN



Sun

Thermonuclear Supernova Explosion

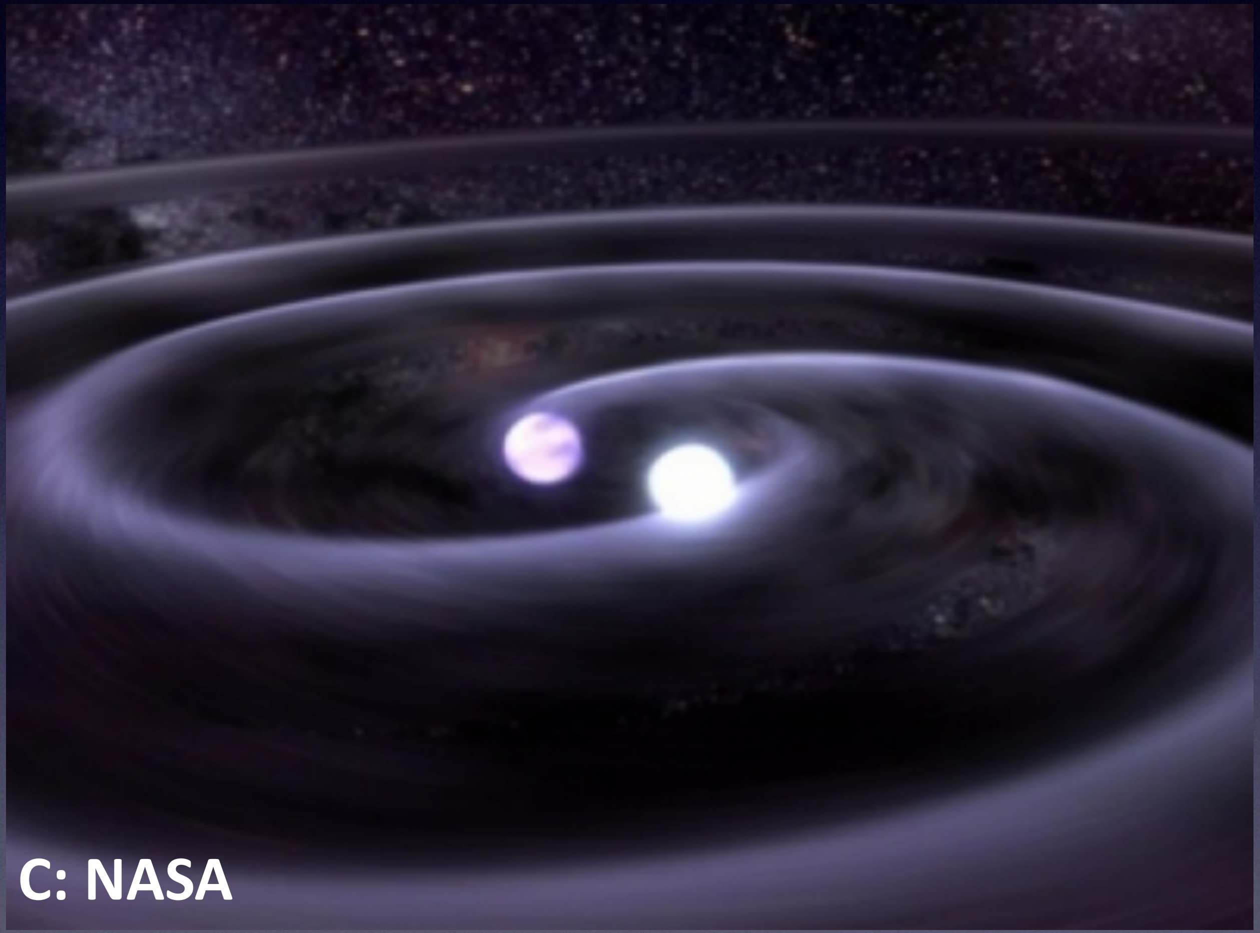


How to trigger explosion (progenitor scenarios)

Accretion from
non degenerate star

single degenerate

Merger of two white dwarfs



double degenerate

Which is correct or dominant? Not yet understood

Summary: white dwarf

- **White dwarf**
  - Supported by electron degeneracy pressure
    => Stellar equations become independent on temperature
  - More massive stars have smaller radius
    $R \sim M^{-1/3}$ (non-relativistic)
  - Limit of relativistic electrons
    M = constant (Chandrasekhar limit) ~ 1.4 Msun
- **Thermonuclear explosion**
  - Explosion of white dwarf close to Mch
  - Nuclear burning => runaway under degenerate condition
  - Explosive nucleosynthesis
    - About 0.8 Msun of Fe-group elements (^{56}Ni & ^{56}Fe, ^{54}Fe, ^{58}Ni)
      > Core-collapse SNe
    - About 0.4 Msun of intermediate mass elements (^{28}Si, ^{32}S, ^{40}Ca)