# Section 5.
# White dwarf

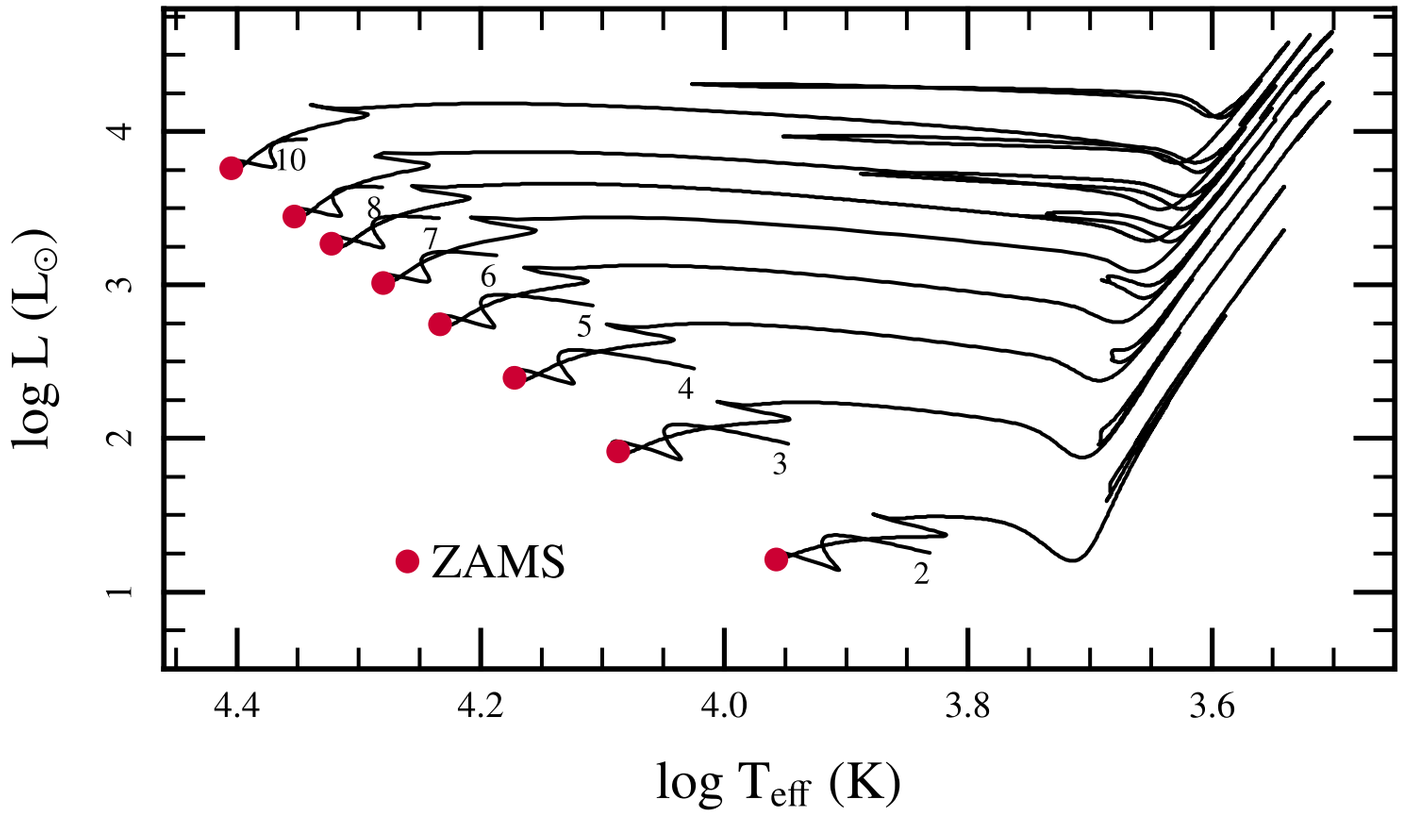
## 5.1 Stellar evolution calculations

## 5.2 White dwarf

## 5.3 Thermonuclear supernovae

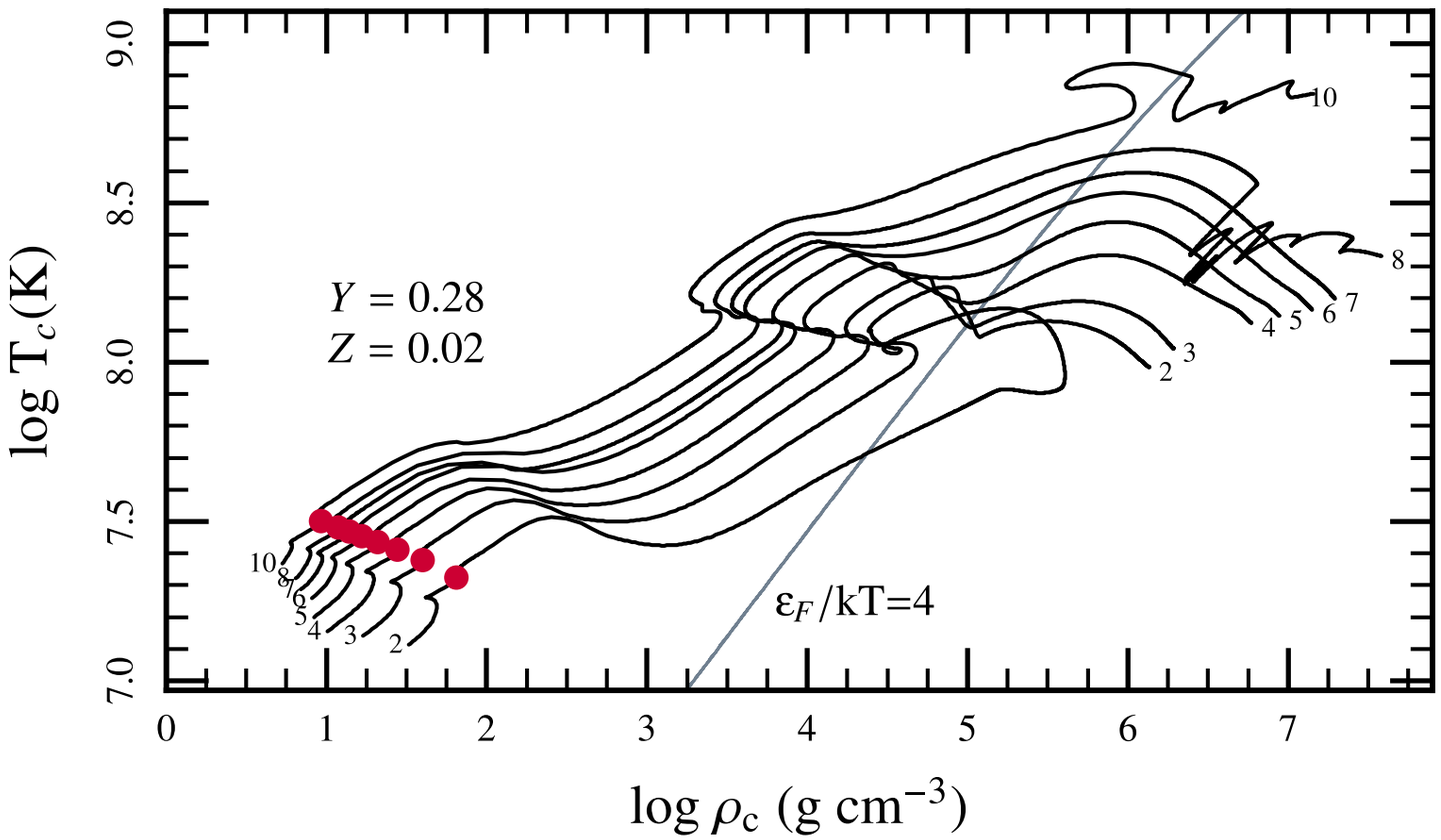
**Let's understand these questions with the words of physics**

- Why are stars so luminous?
- Why do stars show $L \sim M^4$?
- 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?
- …

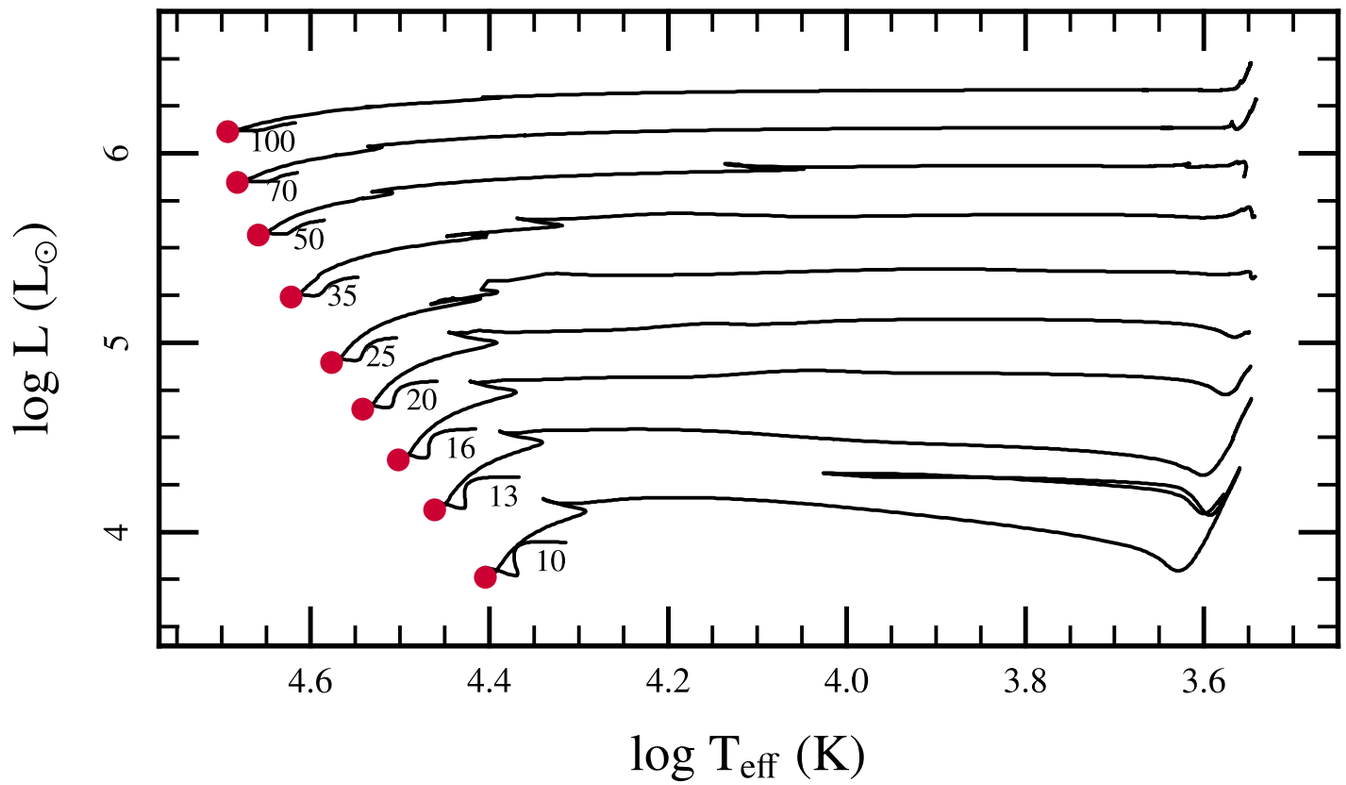



# Low/intermediate mass stars

**Core contraction**
**=> Expansion of the envelope**
**=> Red giant**

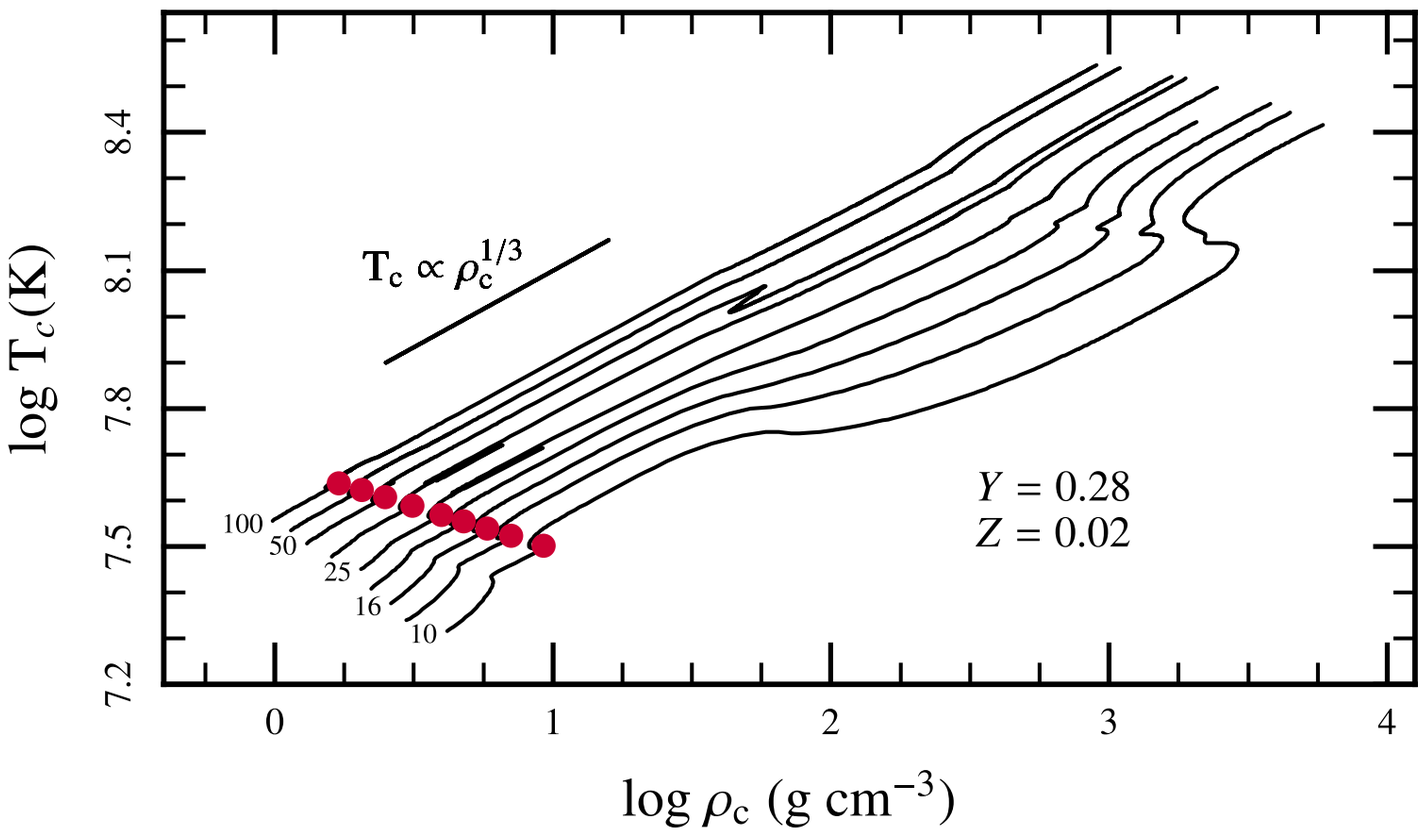



Paxton et al. 2011



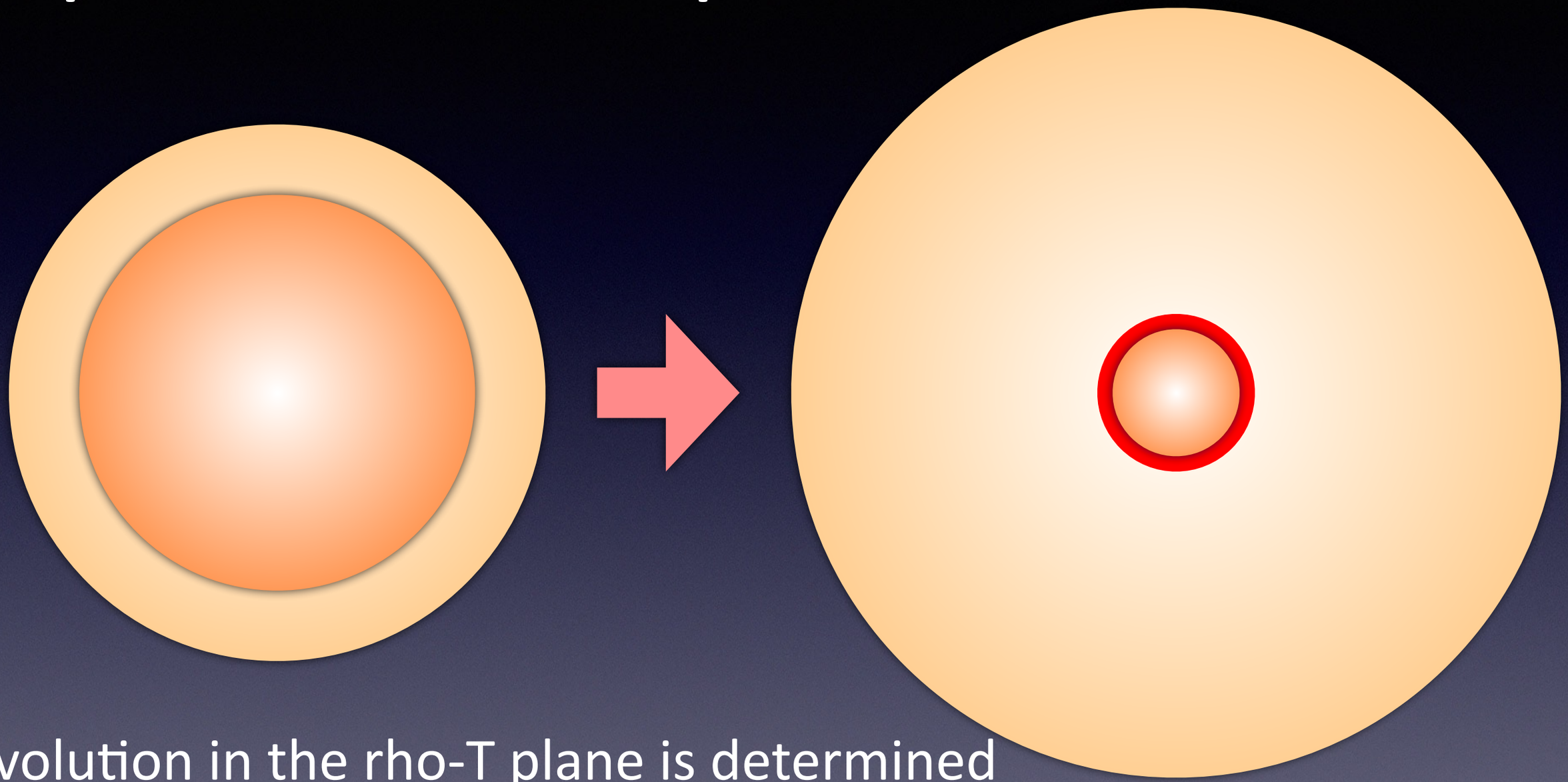

# Massive stars (until He-burning)

**Core contraction**
**=> Expansion of the envelope**
**=> Red super giant**




Paxton et al. 2011

# Contraction of the core
# = Expansion of the envelope



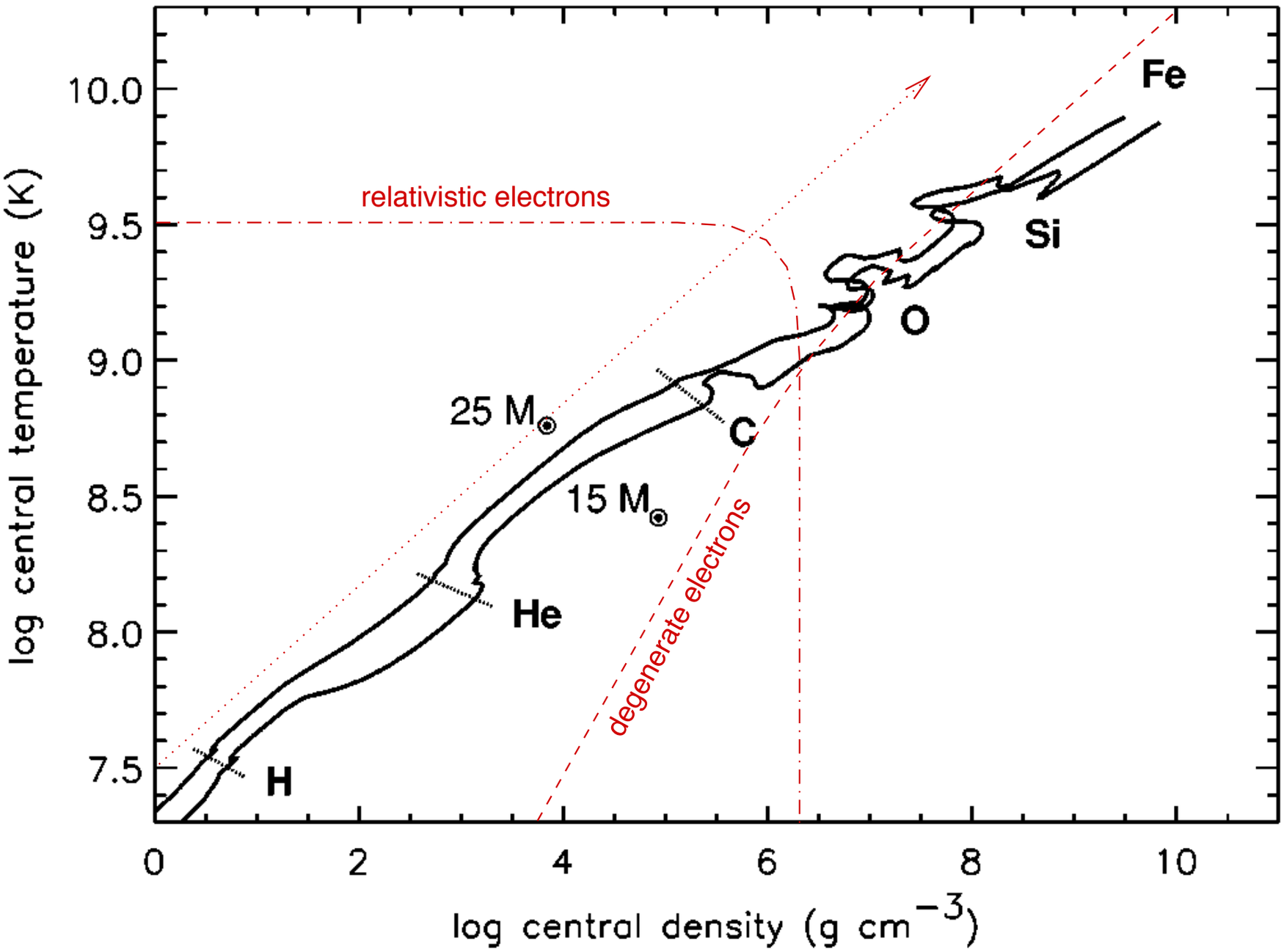
Evolution in the rho-T plane is determined
by the properties of the core

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

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

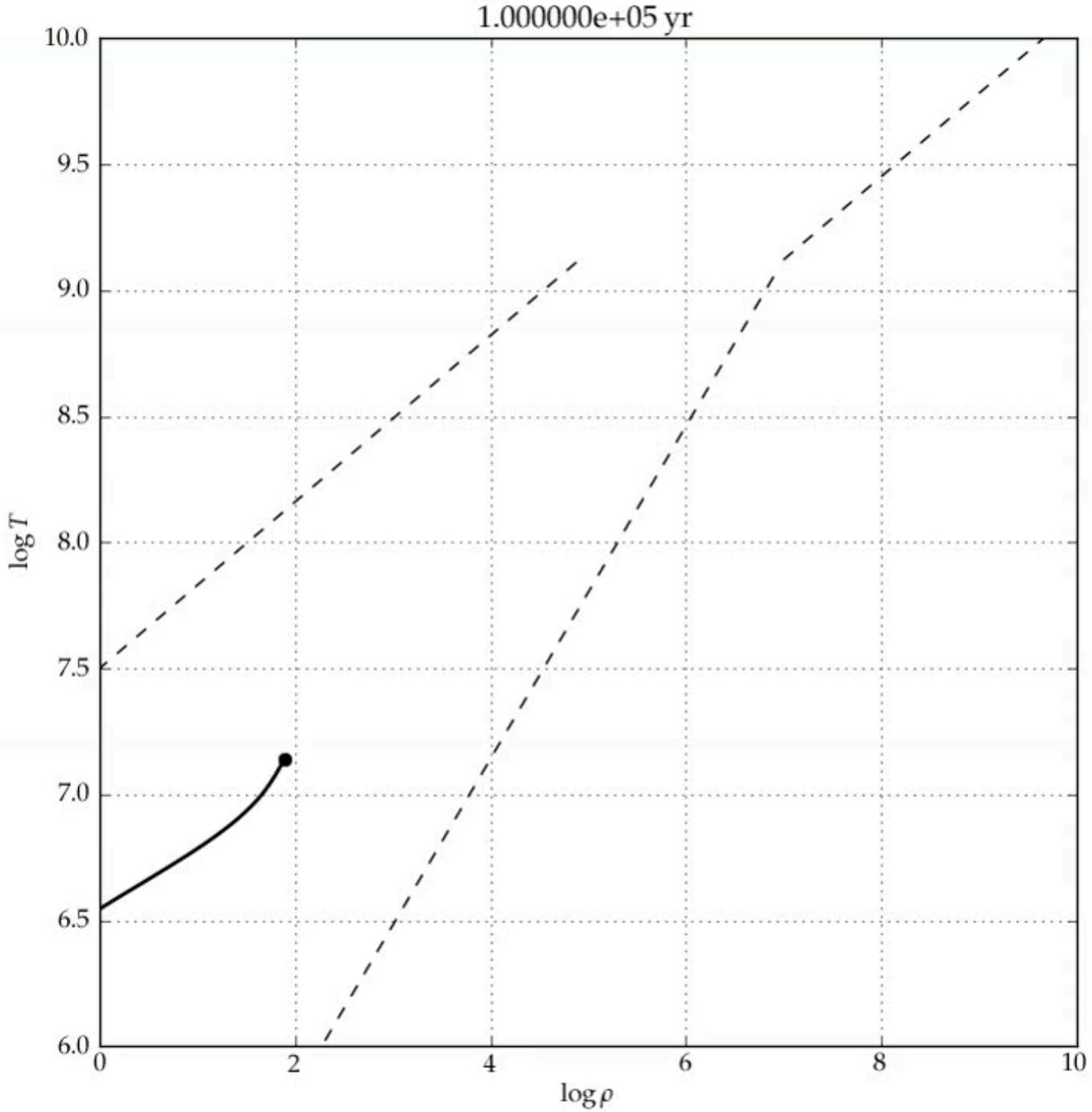
Stellar evolution calculations remain a basic tool of broad impact for astrophysics. New observations constantly test the models, even in 1D. The continued demand requires the construction of a general, modern stellar evolution code that combines the following advantages:

- **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

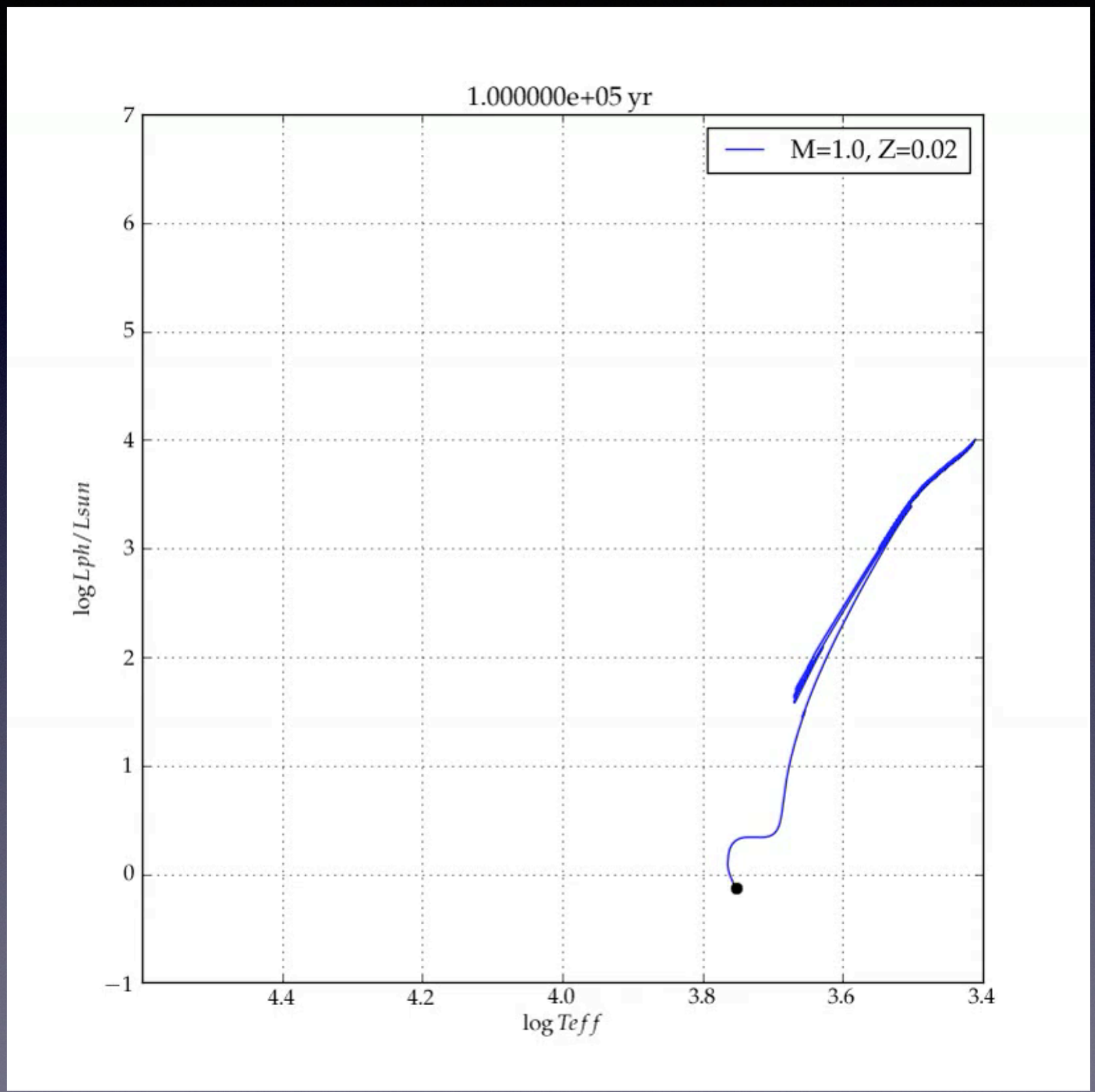
## Latest News

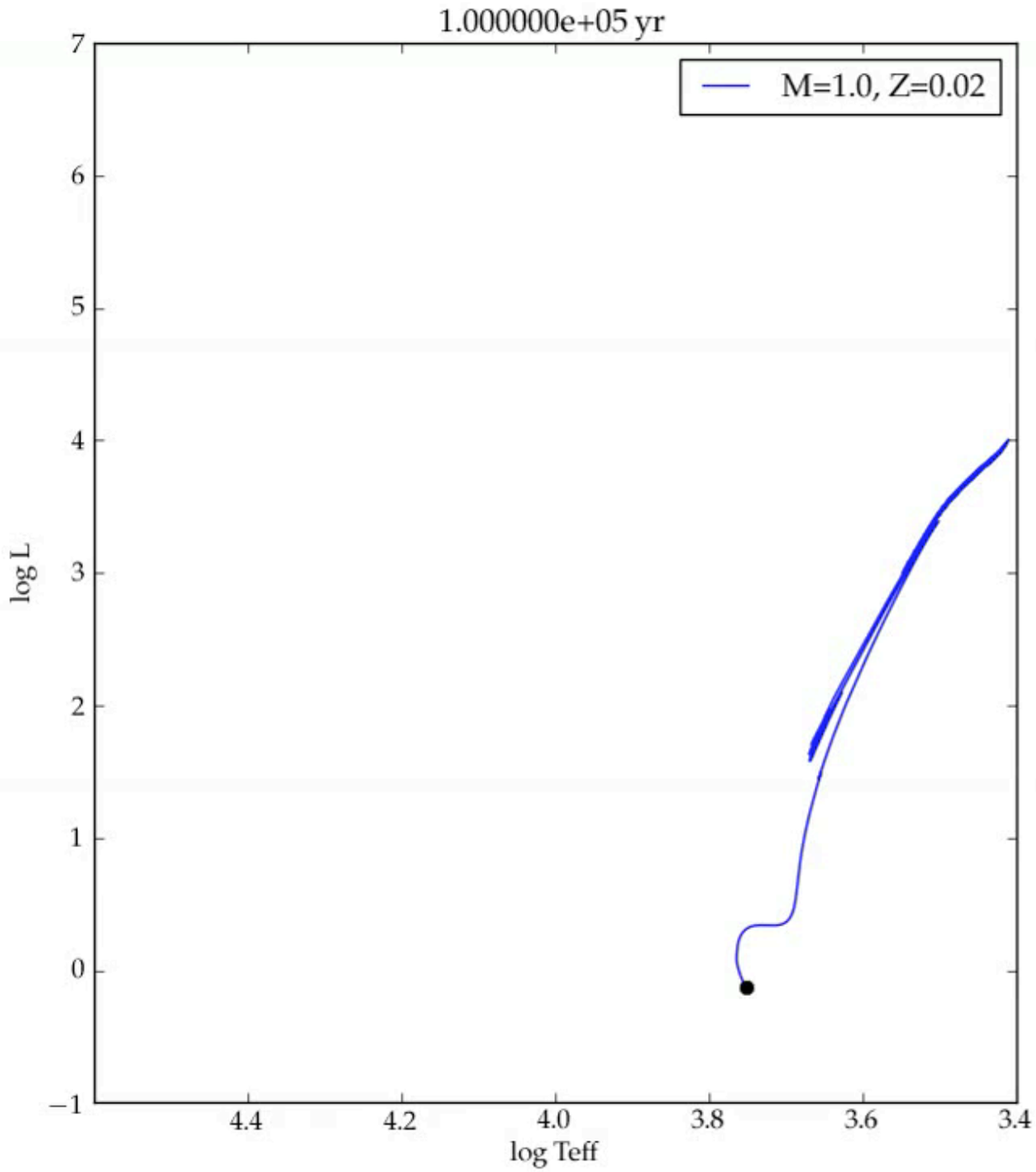
- 10 Aug 2016
  » **Documentation Archive**
- 19 Jun 2016
  » **Release 8845**
- 03 Feb 2016
  » **Release 8118**
- 29 Jan 2016
  » **New MESA SDK Version**
- 10 Jan 2016
  » **Summer School 2016**
- 27 Sep 2015
  » **Instrument Paper 3**
- 14 Sep 2015
  » **MESA-Web Updates**
- 08 Sep 2015
  » **New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

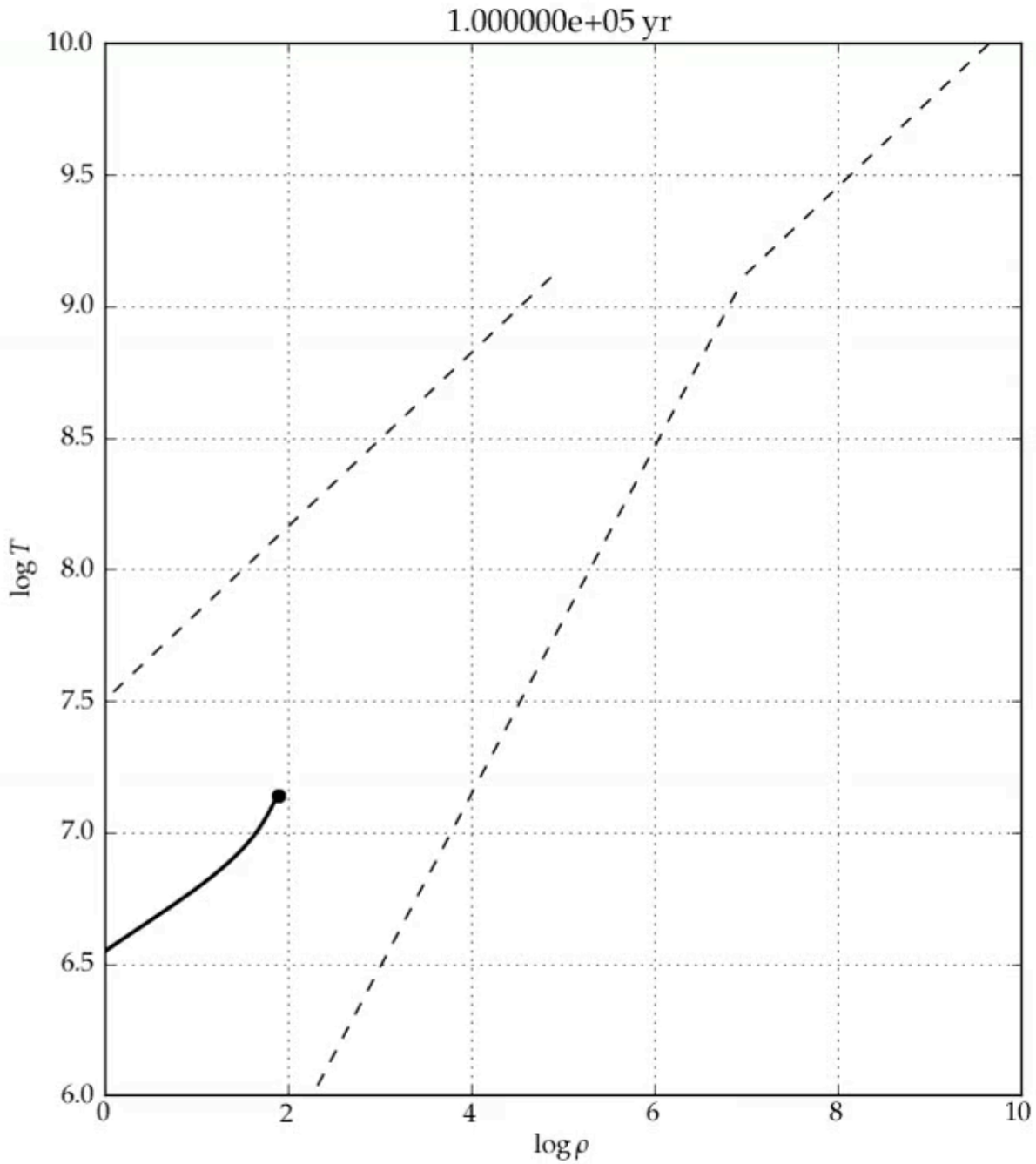
# 1 Msun (ρ-T)



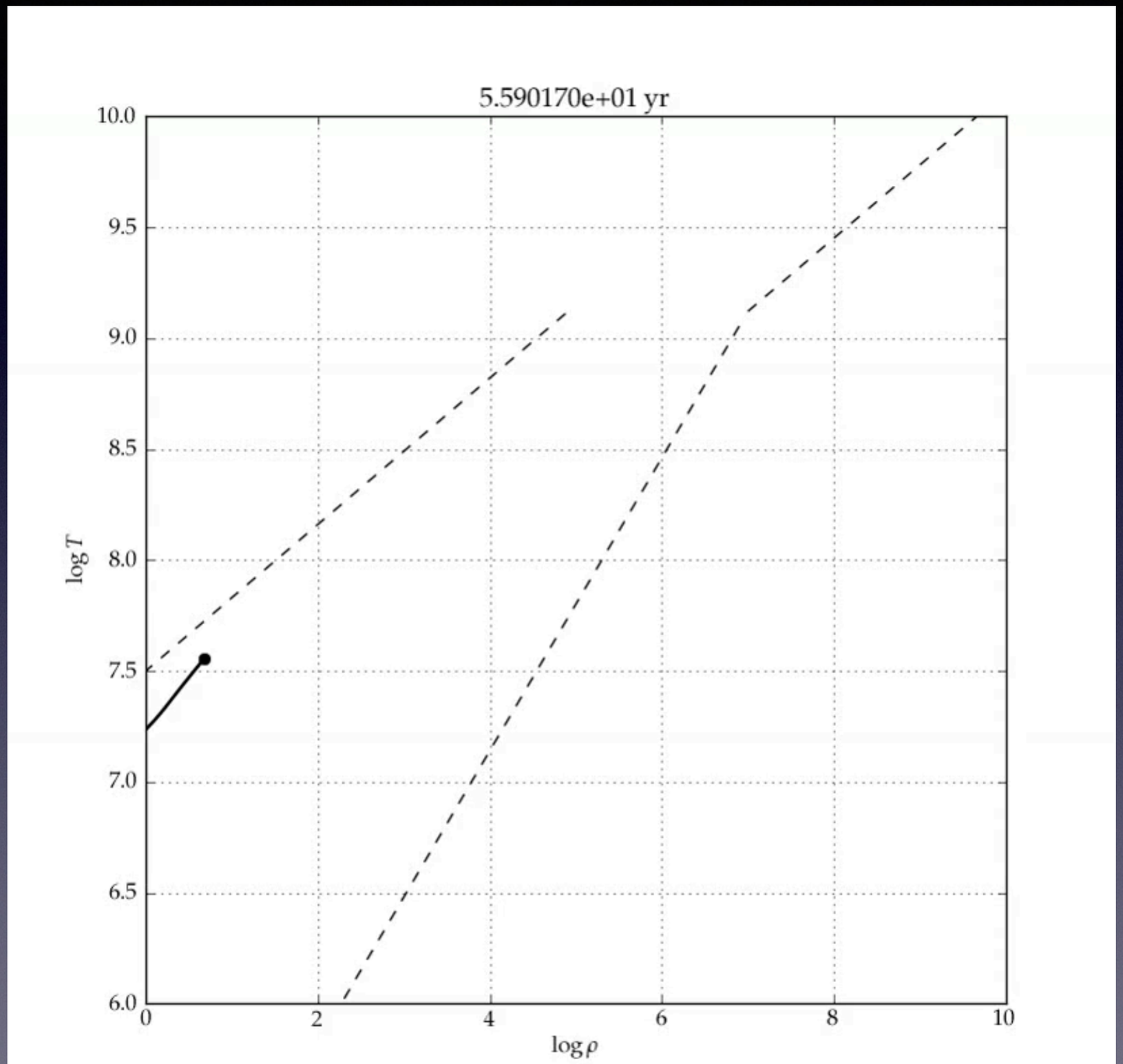
# 1 Msun (HR diagram)



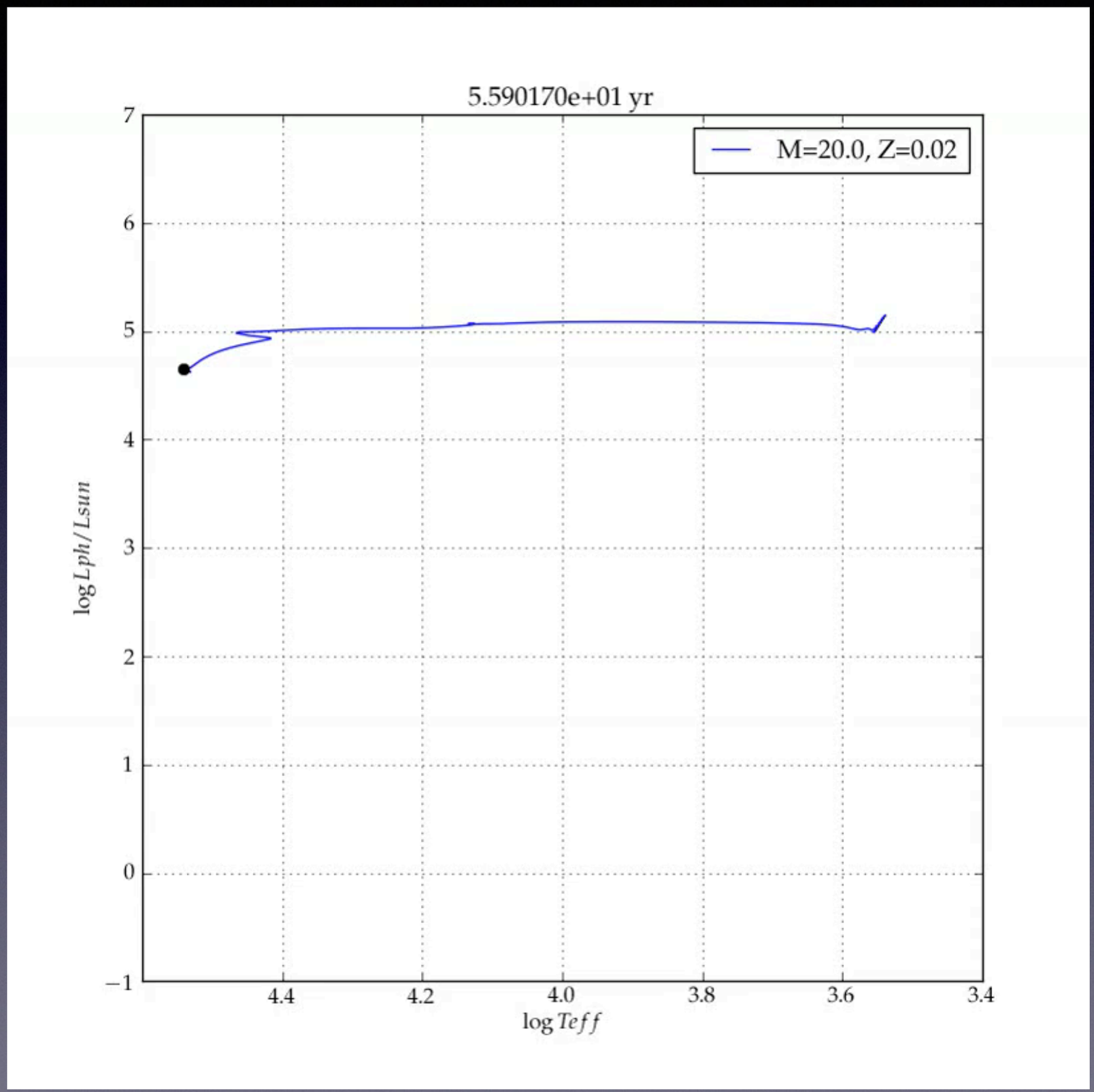

1.000000e+05 yr
M=1.0, Z=0.02
log L
log Teff
7
6
5
4
3
2
1
0
−1
4.4
4.2
4.0
3.8
3.6
3.4

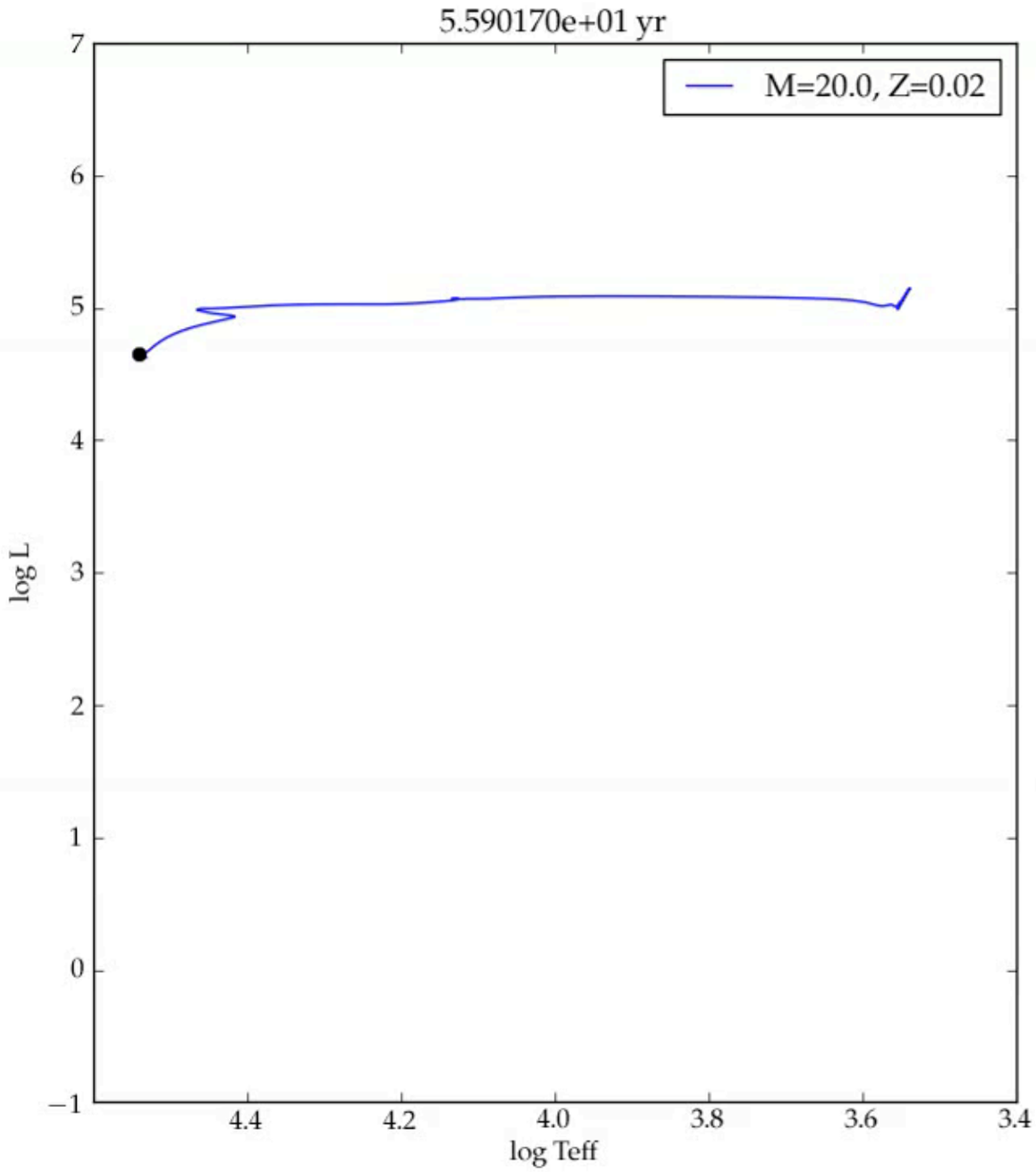

1.000000e+05 yr
log T
log ρ
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
0
2
4
6
8
10

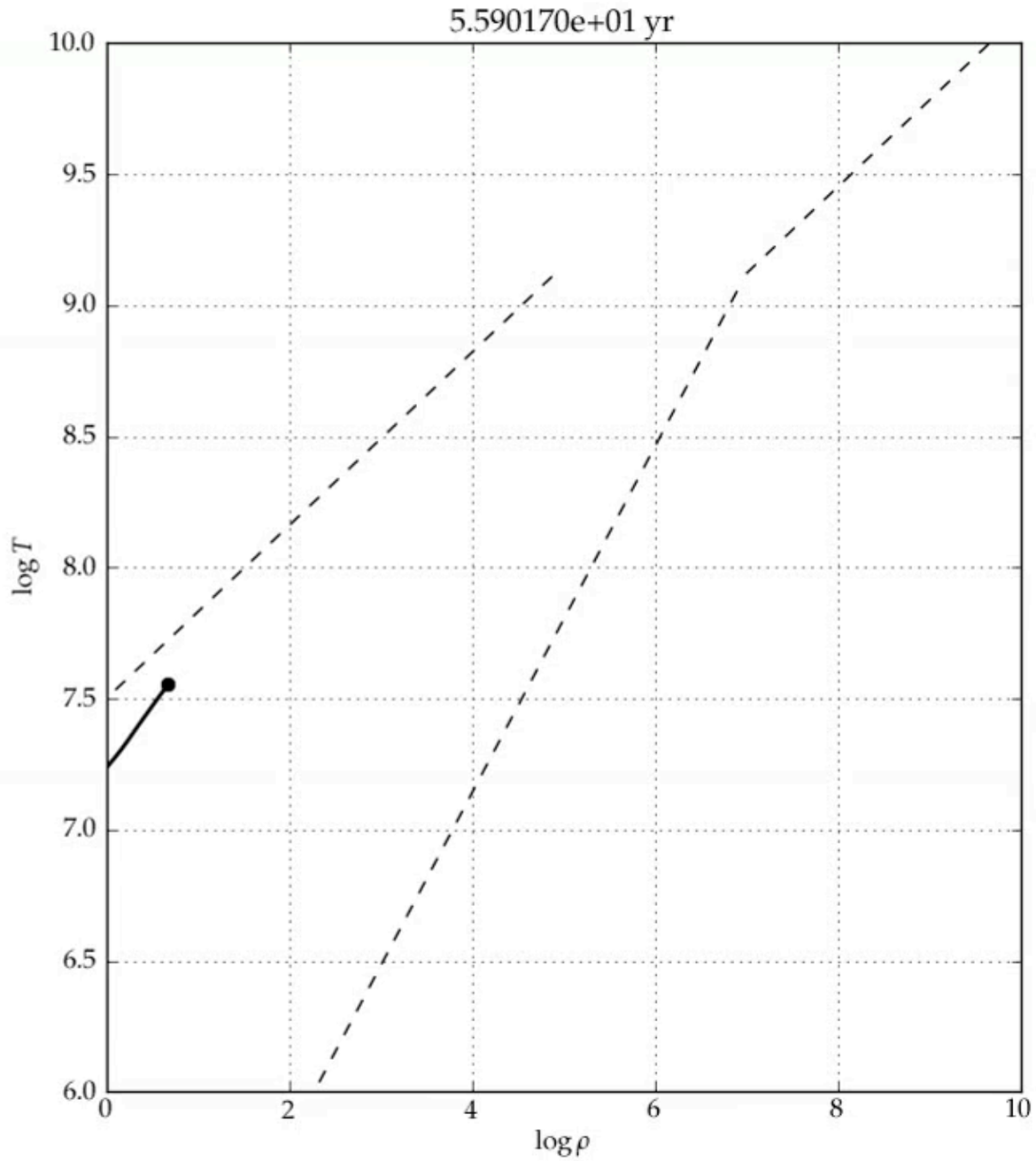
# 20 Msun (ρ-T)



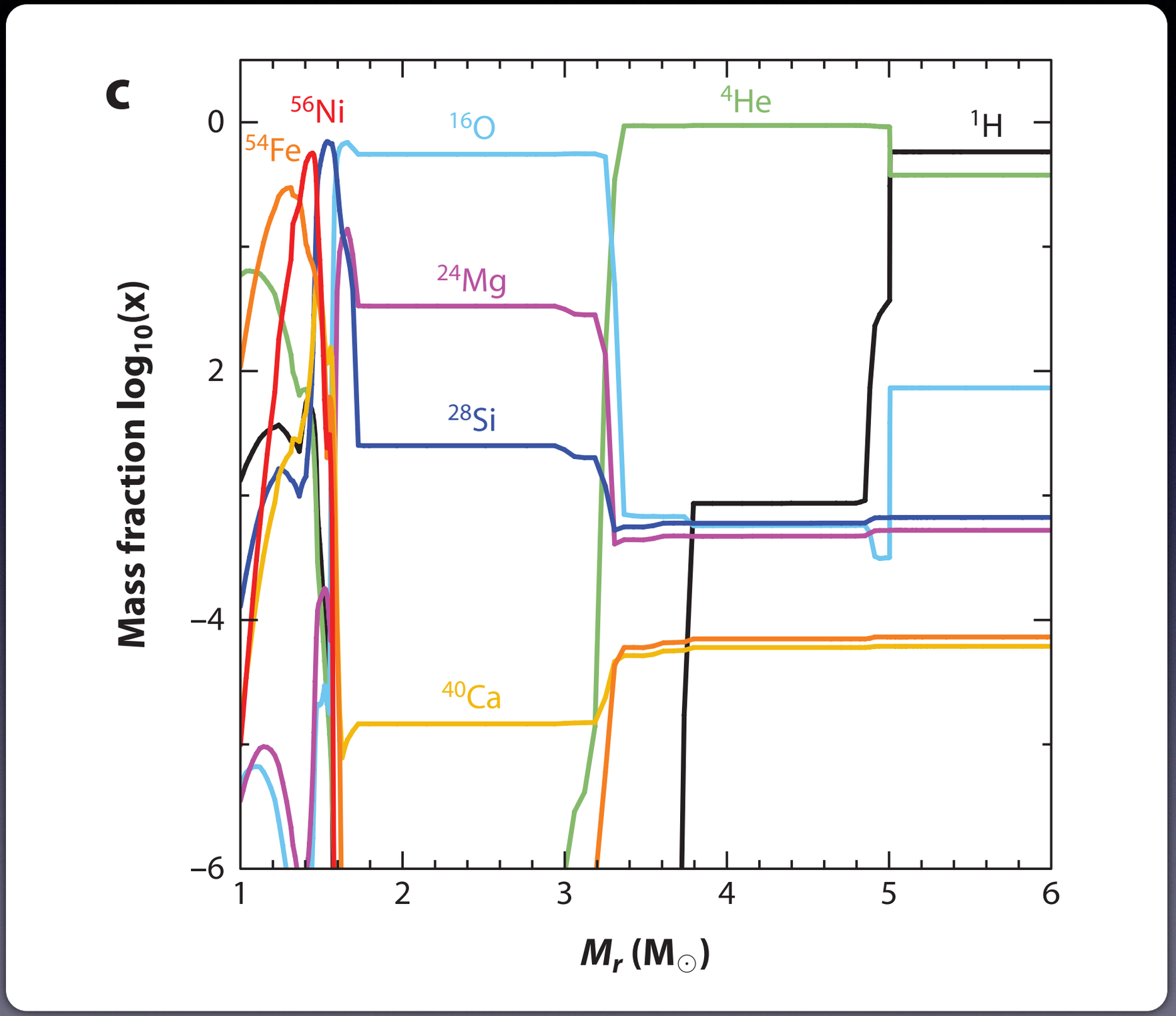
# 20 Msun (HR diagram)




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

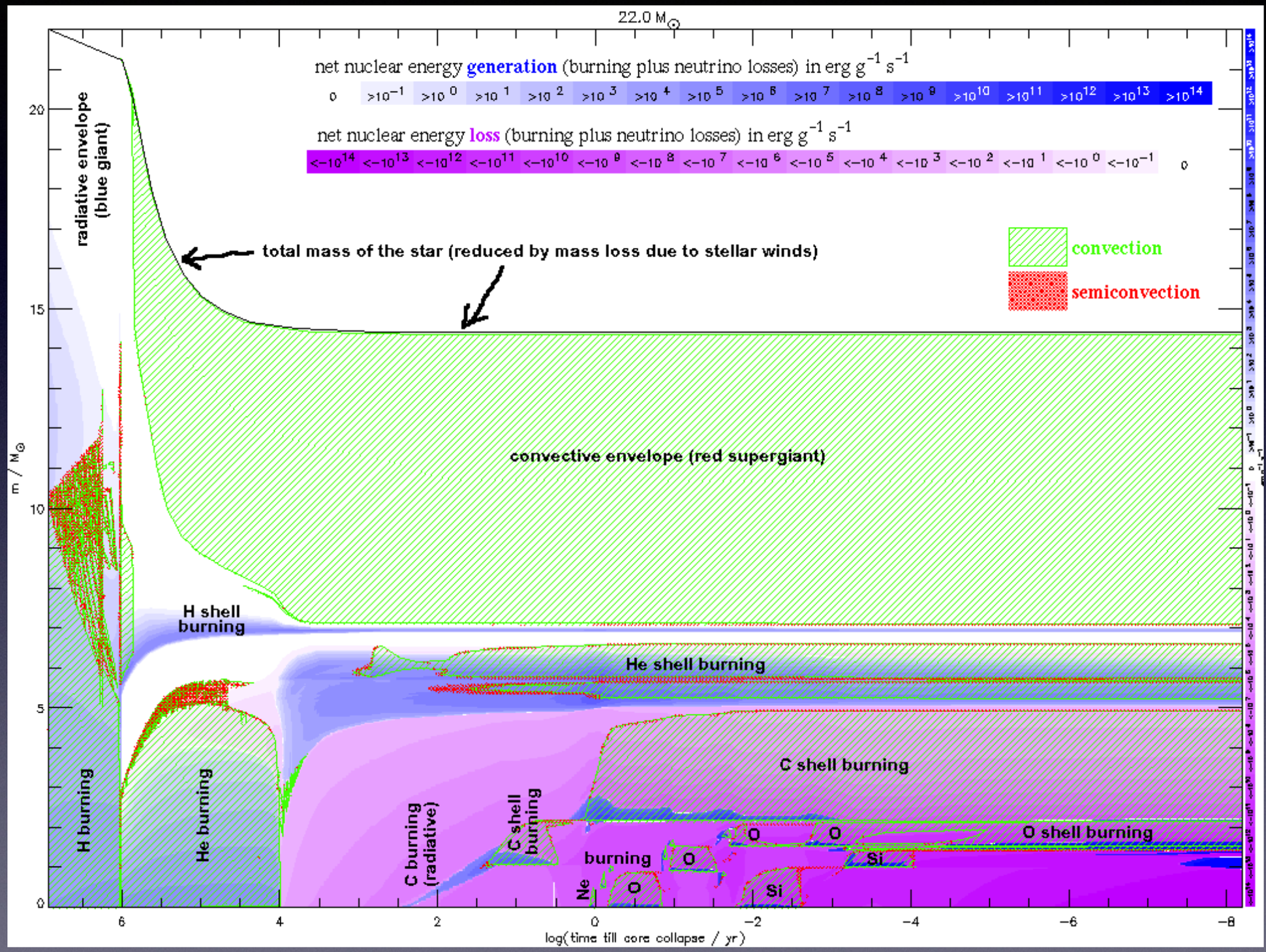

5.590170e+01 yr
log T
log ρ
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
0
2
4
6
8
10

# 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

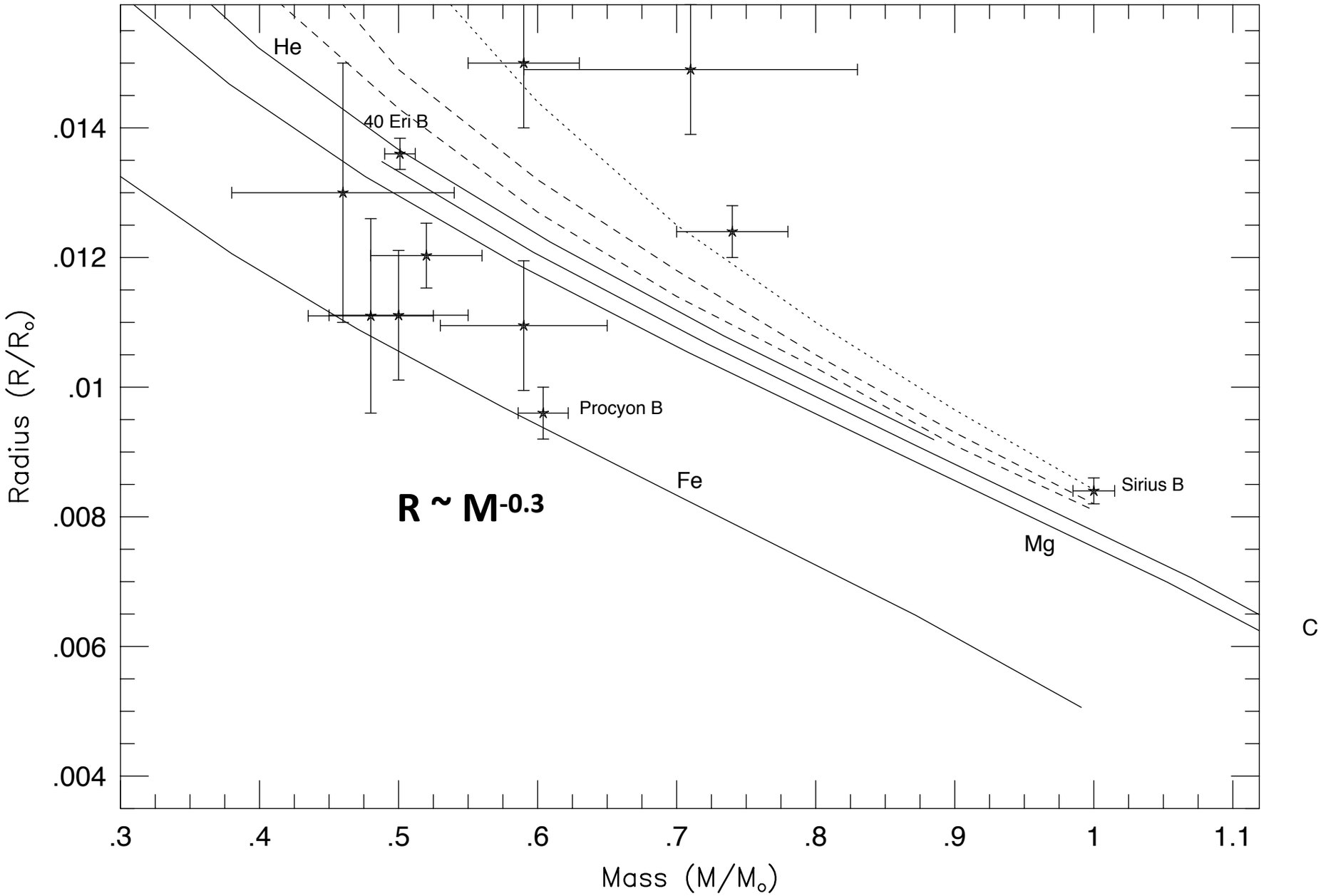
**Cat’s eye nebula**

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

**Helix nebula**

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

# Mass-radius relation for white dwarfs



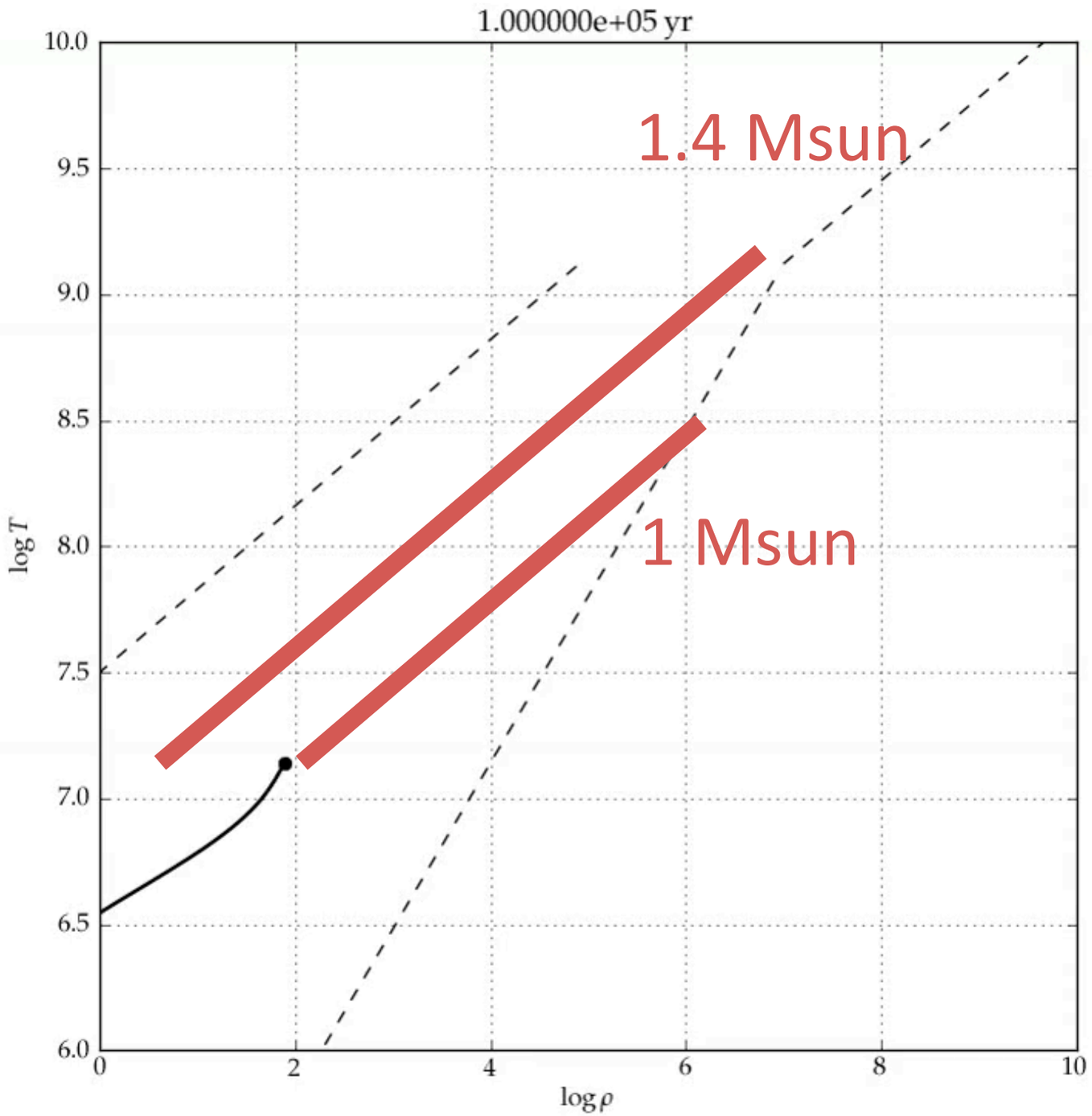

Provencal et al. 1998



**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 $\alpha_G$, 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 $\alpha_G$, 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

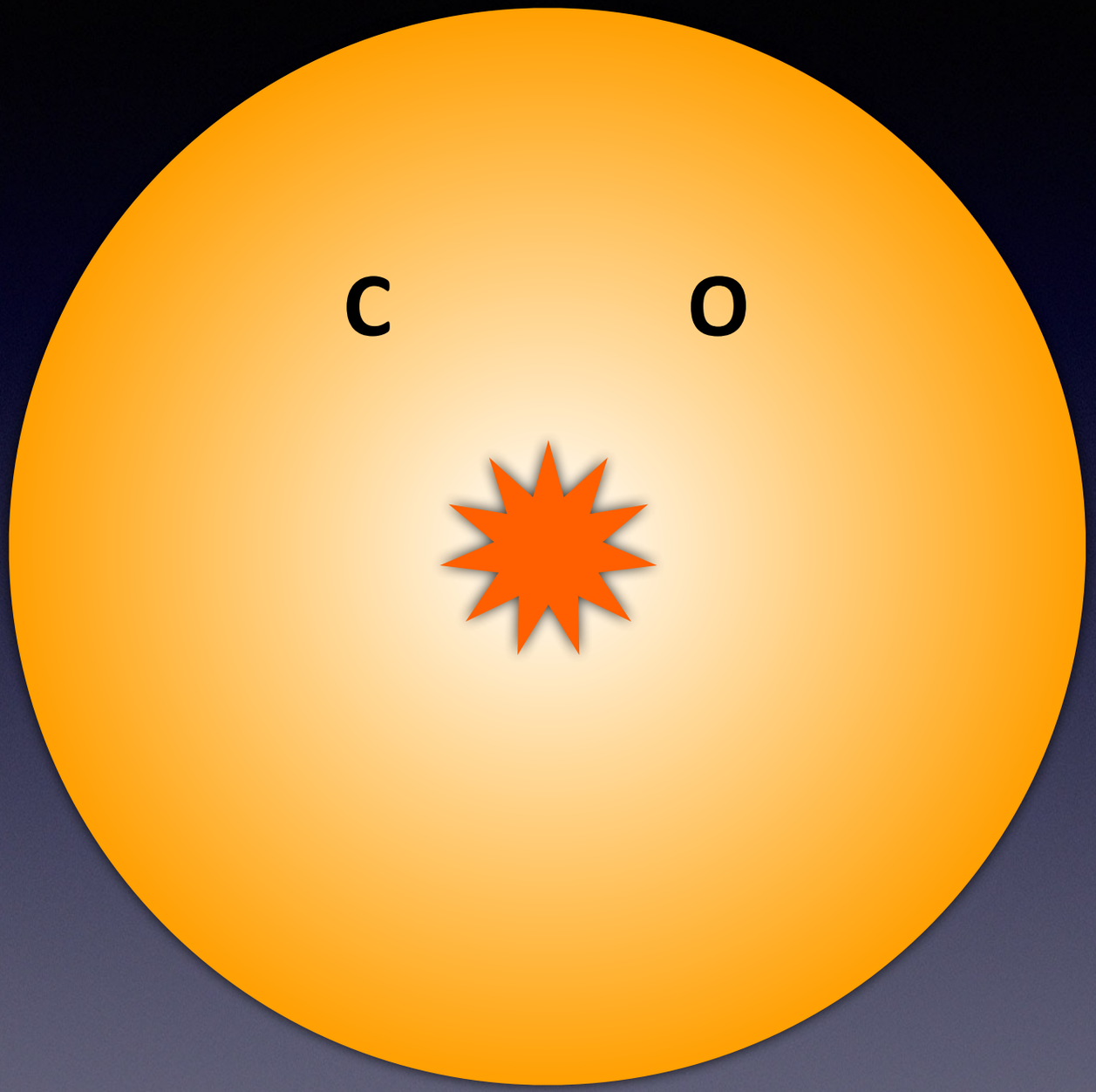
## 5.3 Thermonuclear supernovae

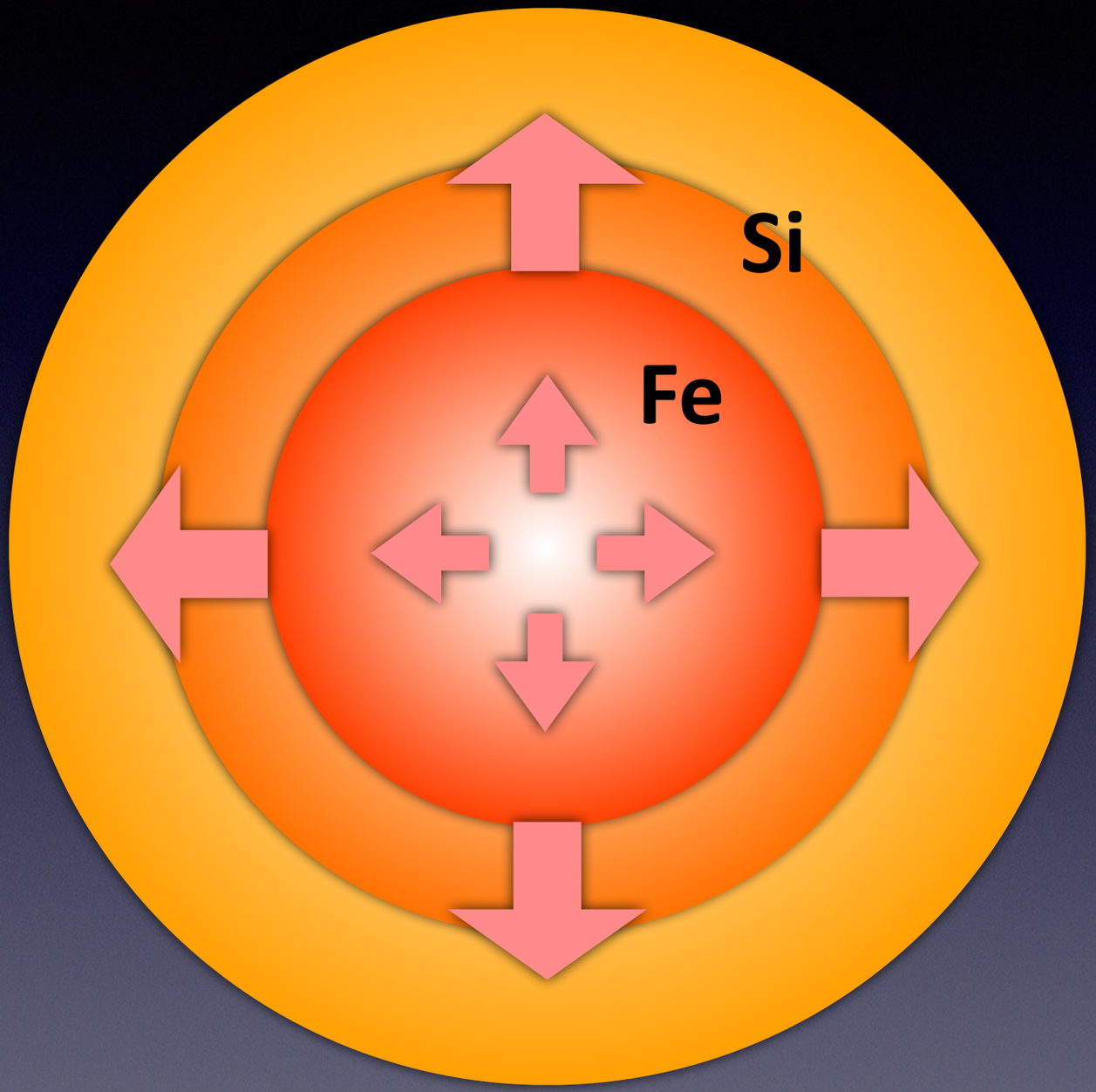
# Binary system

# White dwarf

David A. Hardy

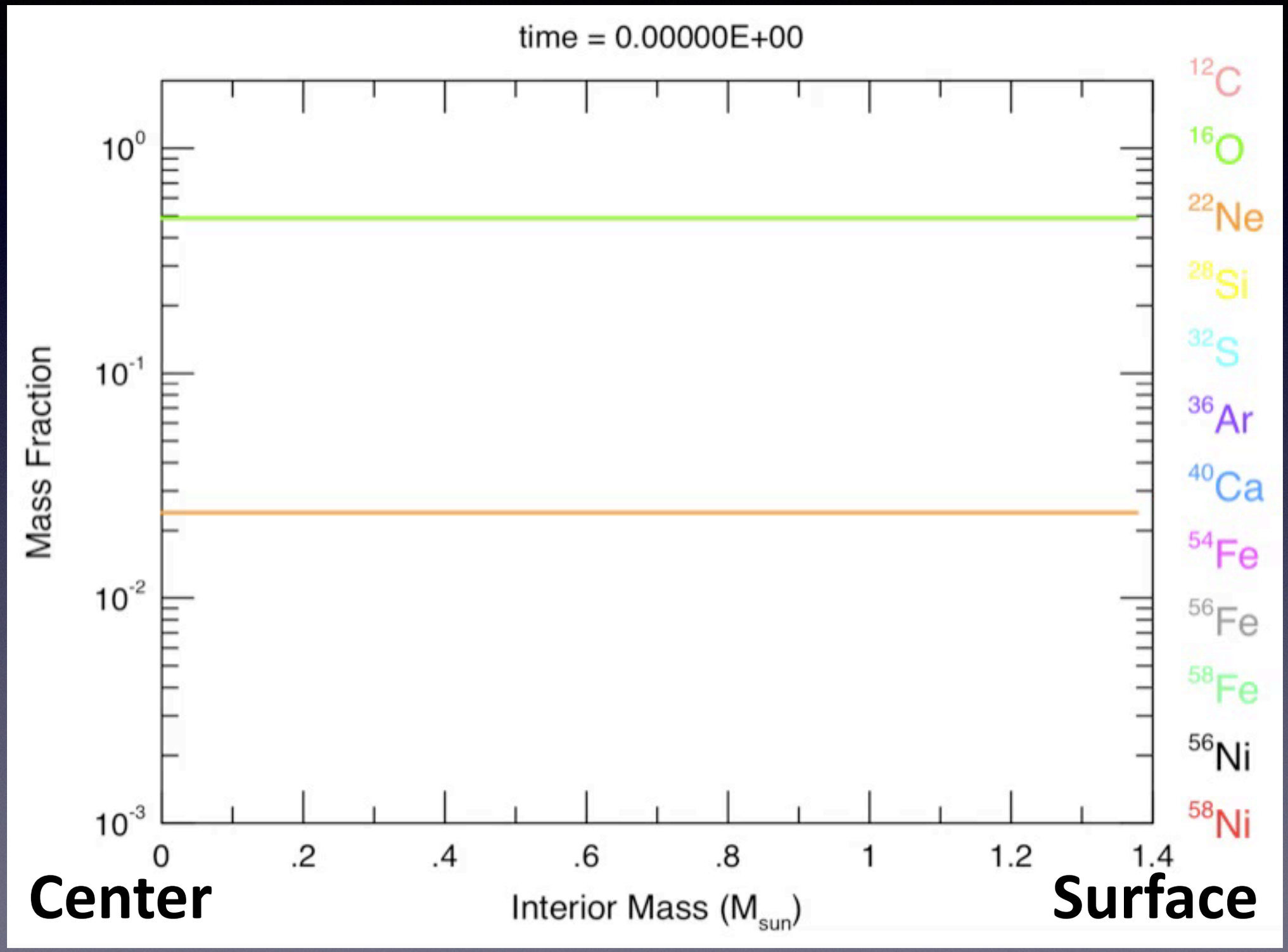
# Thermonuclear explosion




**Supernova!**

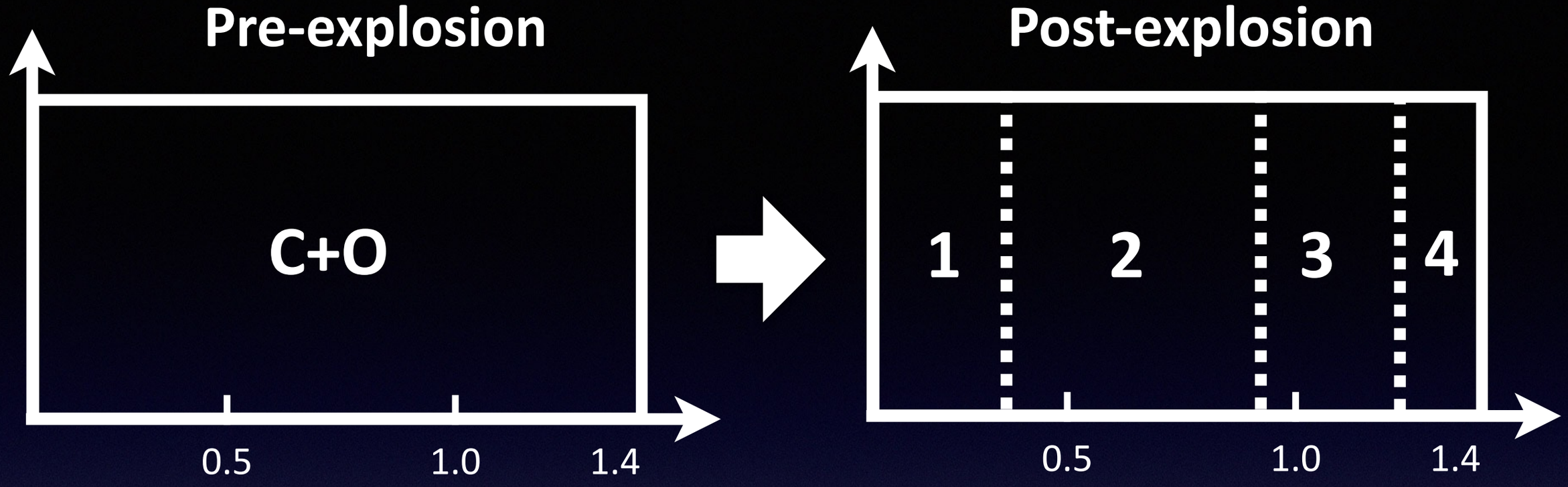
# Explosion of white dwarf




Mass fraction

**Center** **Surface**

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 |

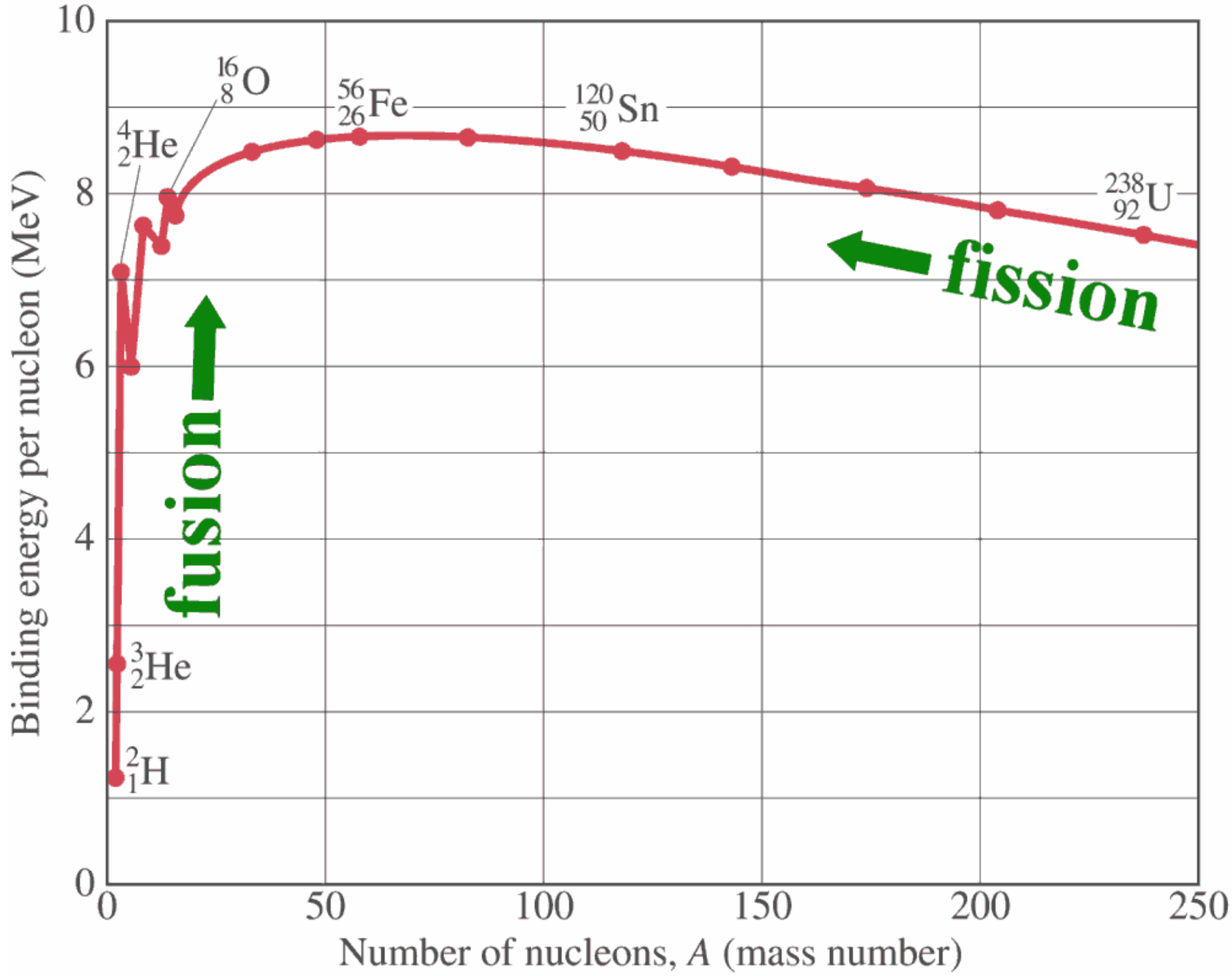
# Thermonuclear supernovae

**Normal stars are stable with nuclear burning**

**Why do white dwarfs explode by nuclear burning?**

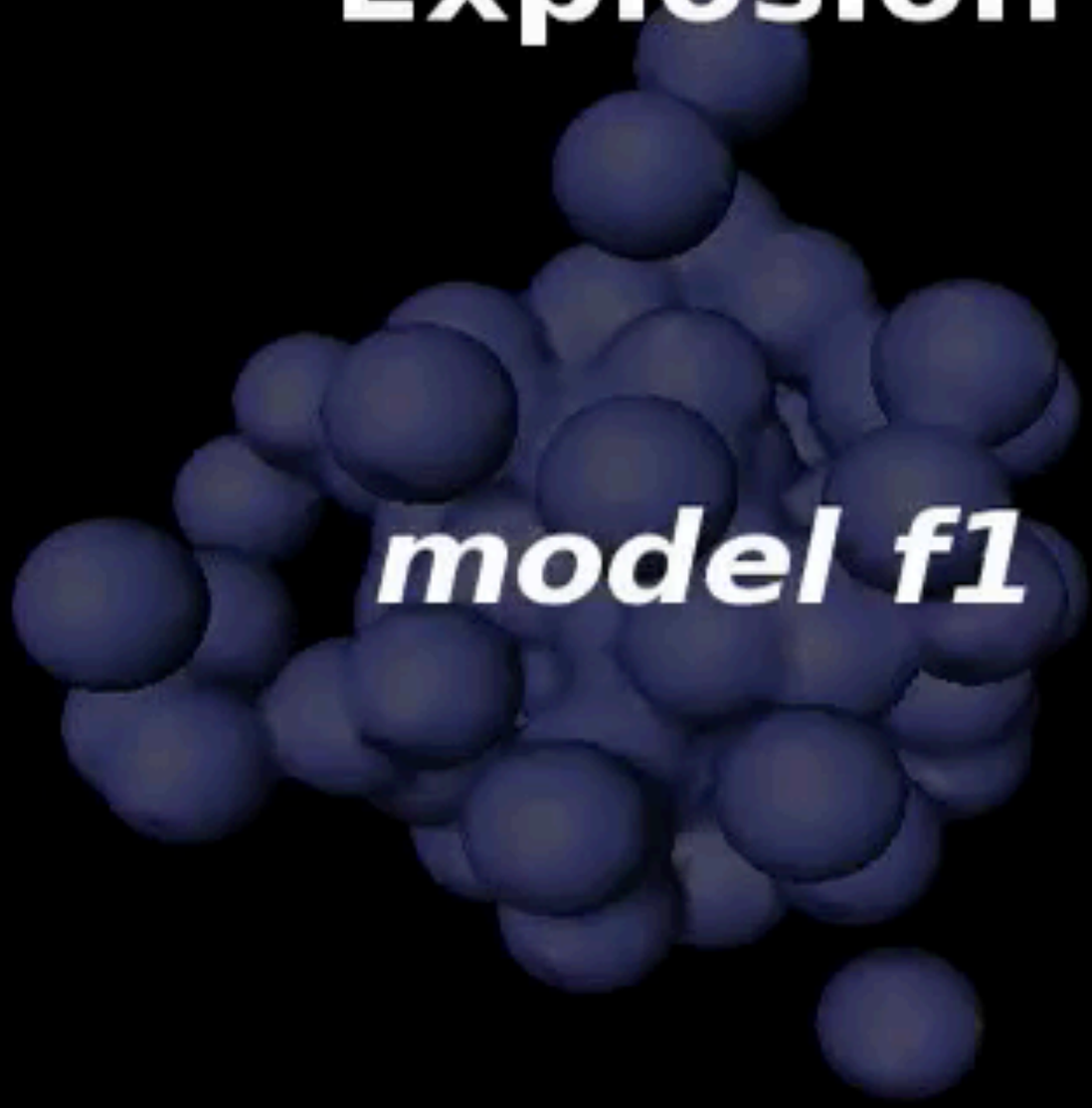
**Type Ia SN**

**Sun**




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# Thermonuclear Supernova Explosion



*model f1*



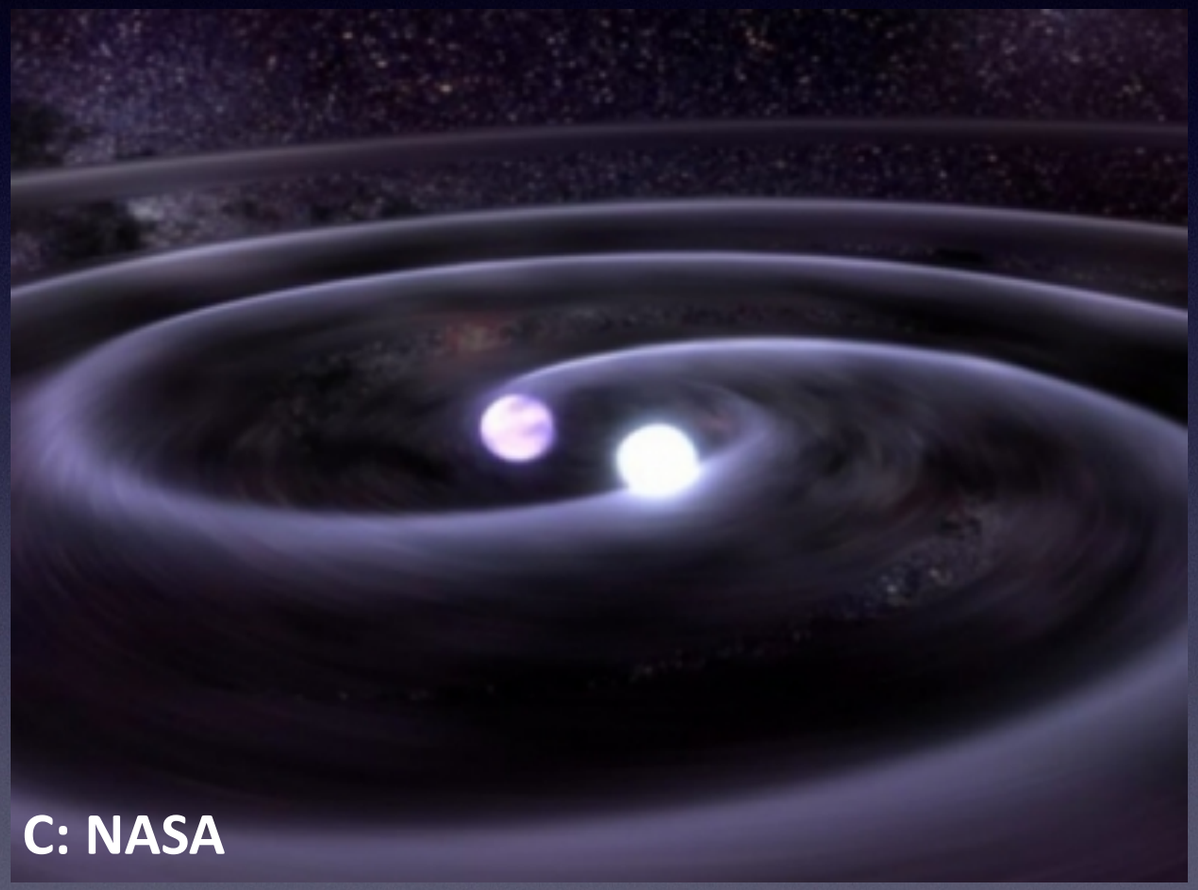
(c) Friedrich Röpke, MPA, 2004

# How to trigger explosion (progenitor scenarios)

## Accretion from non degenerate star




## Merger of two white dwarfs




single degenerate

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)