Section 5.
Stellar evolution (II)

5.1 Equation of state

5.2 Evolutionary track

Goals of this lecture

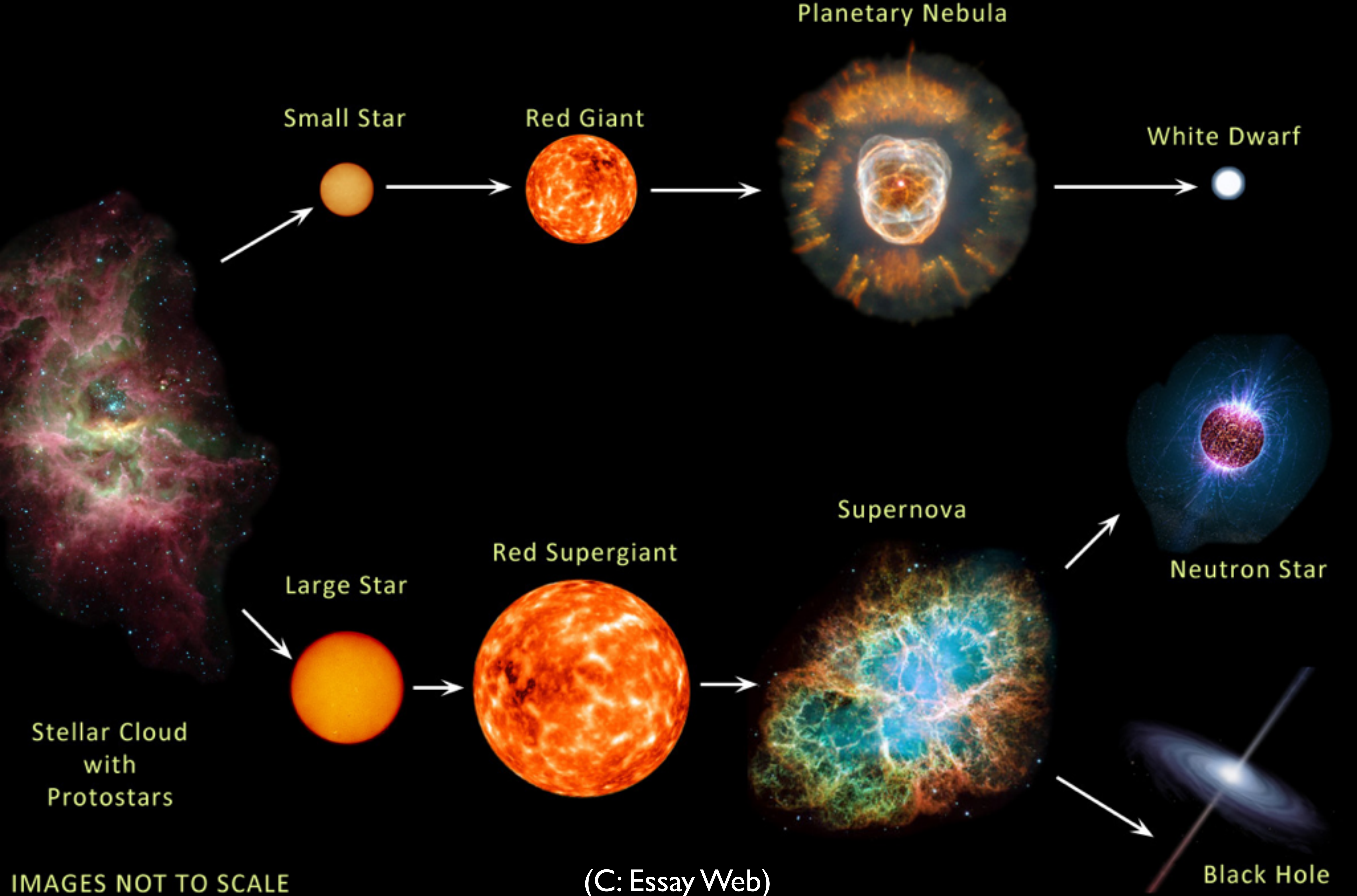
- Standard properties of stars
  - Stellar structure and properties
  - Stellar evolution
- Origin of the elements in the Universe
  - Nucleosynthesis in stars and supernovae
  - Explosion mechanism of supernovae
- Topics in time-domain astronomy
  - Radiation from explosive phenomena
  - Multi-messenger astronomy

Section 5.
Stellar evolution (II)

5.1 Equation of state

5.2 Evolutionary track

Stellar life



(C: Essay Web)

Why does the destiny of the stars depend on the mass?

Microscopic properties of the gas play important roles

Assignment 2

2a. Derive pressure of ideal gas from the Maxwell distribution

2b. Derive pressure of degenerate electrons
(both for non-relativistic case and relativistic case)

2c. Derive radiation pressure from Planck function

2d. Draw the regions where

- ideal gas pressure

- degenerate pressure of non-relativistic electrons

- degenerate pressure of relativistic electrons

- radiation pressure

become dominant in the rho-T diagram.

レポート課題 2

2a. マクスウェル分布から
　理想気体の圧力の式を導け

2b. 電子が非相対論的、超相対論的なときの
　縮退圧の式を導き、実際に数字を入れて計算せよ

2c. プランク関数から輻射圧の式を導け

2d. 密度 - 温度平面で

- 理想気体のガス圧

- 電子の縮退圧（非相対論的）

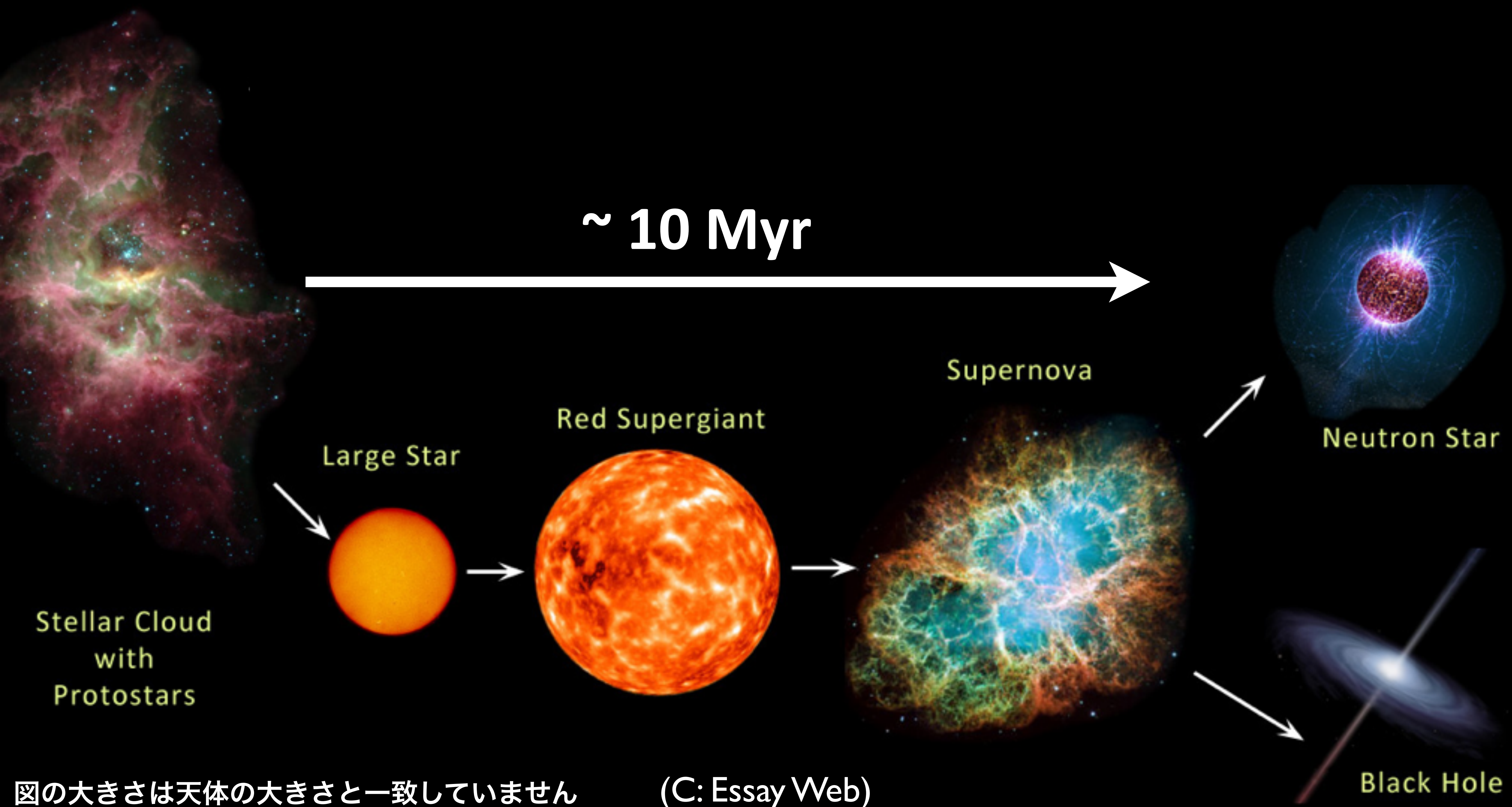
- 電子の縮退圧（超相対論的）

- 輻射圧

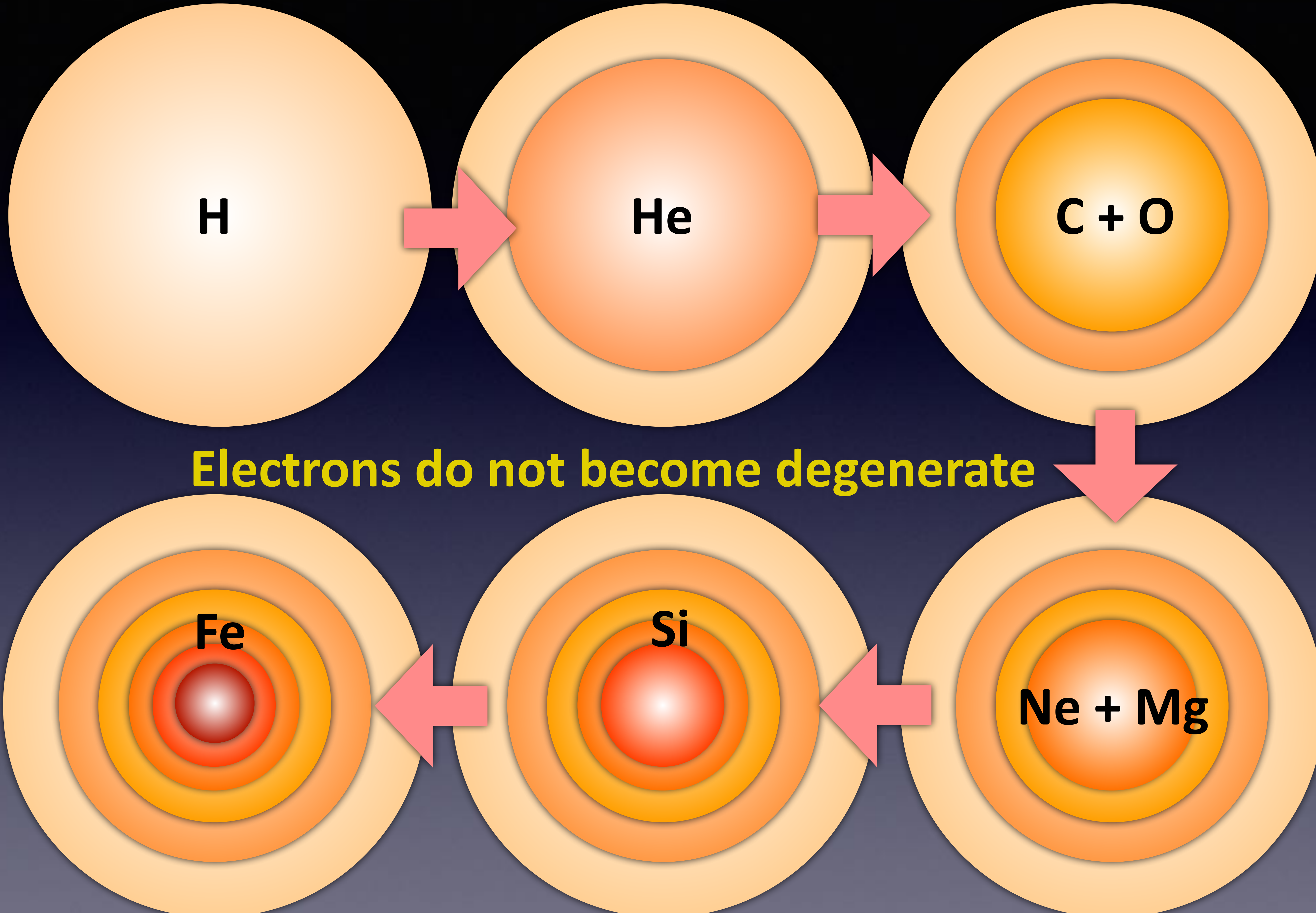
がそれぞれ支配的になる境界を求め、図示せよ

1. Massive stars

M > 10 Msun



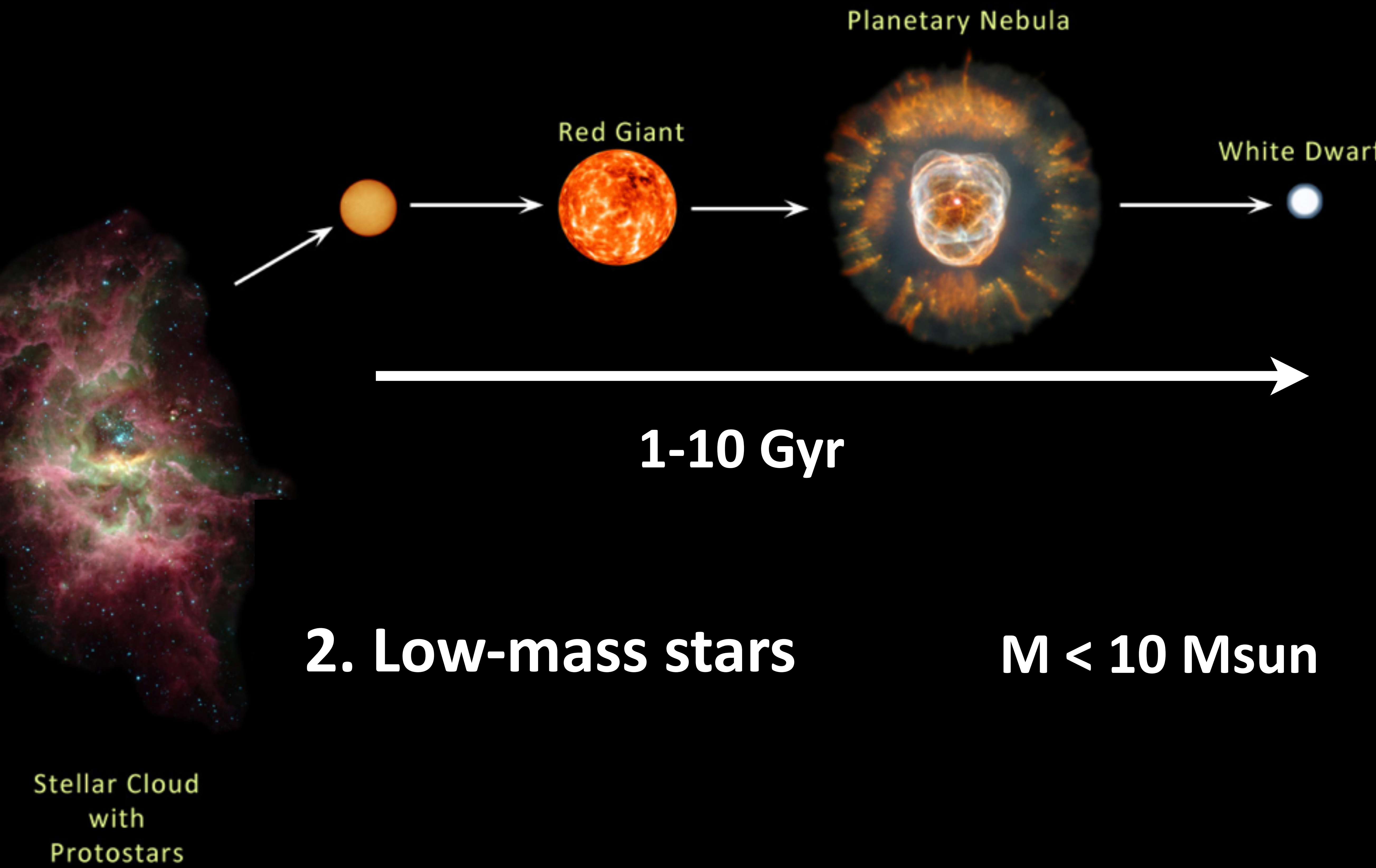
図の大きさは天体の大きさと一致していません　(C: Essay Web)



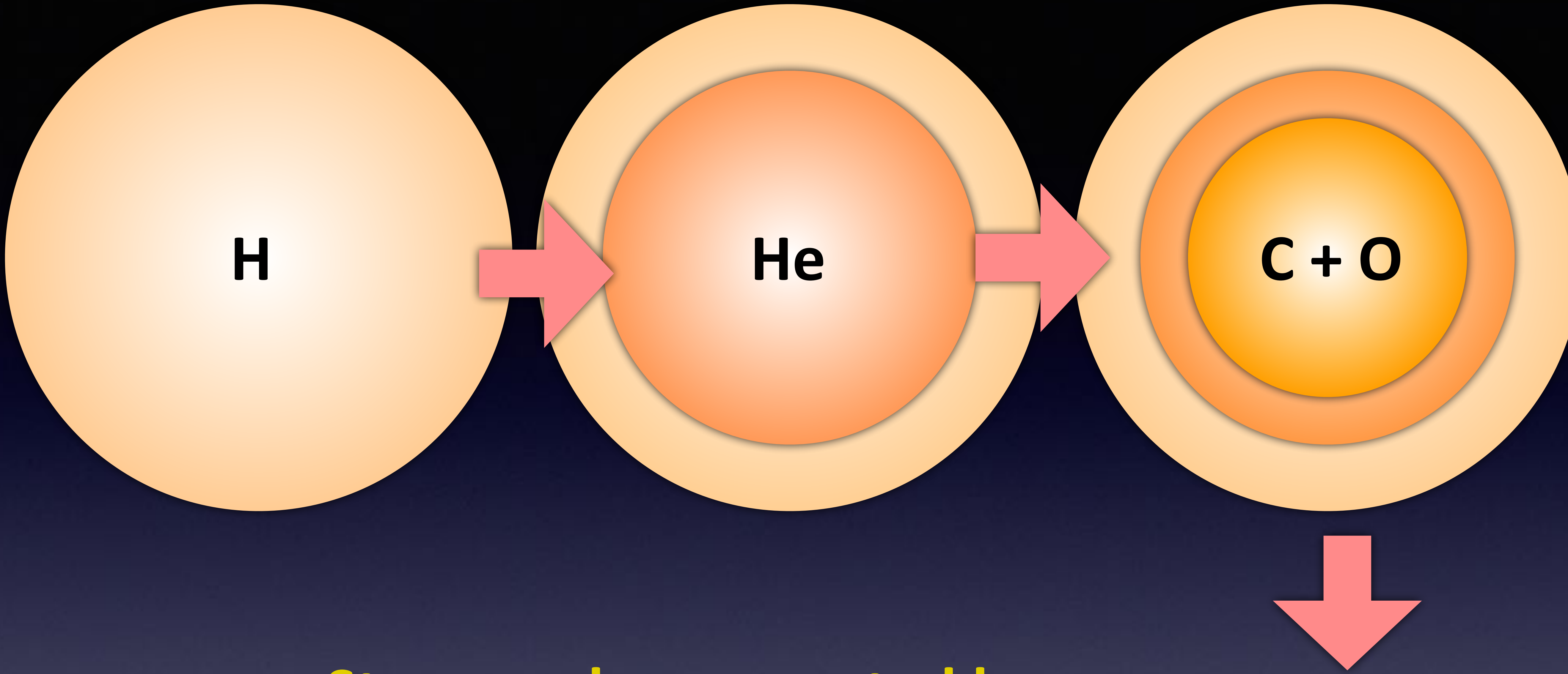
Images are not to scale

2. Low-mass stars

M < 10 Msun

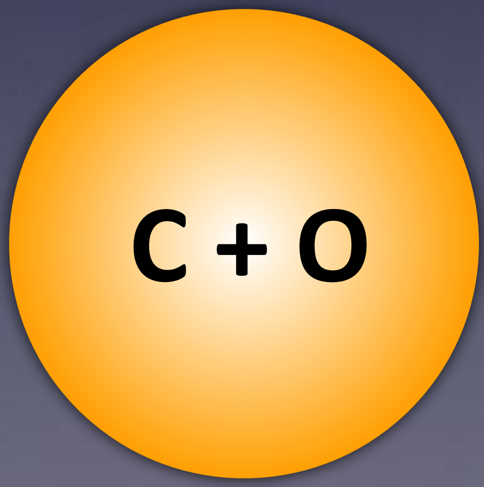


図の大きさは天体の大きさと一致していません　(C: Essay Web)



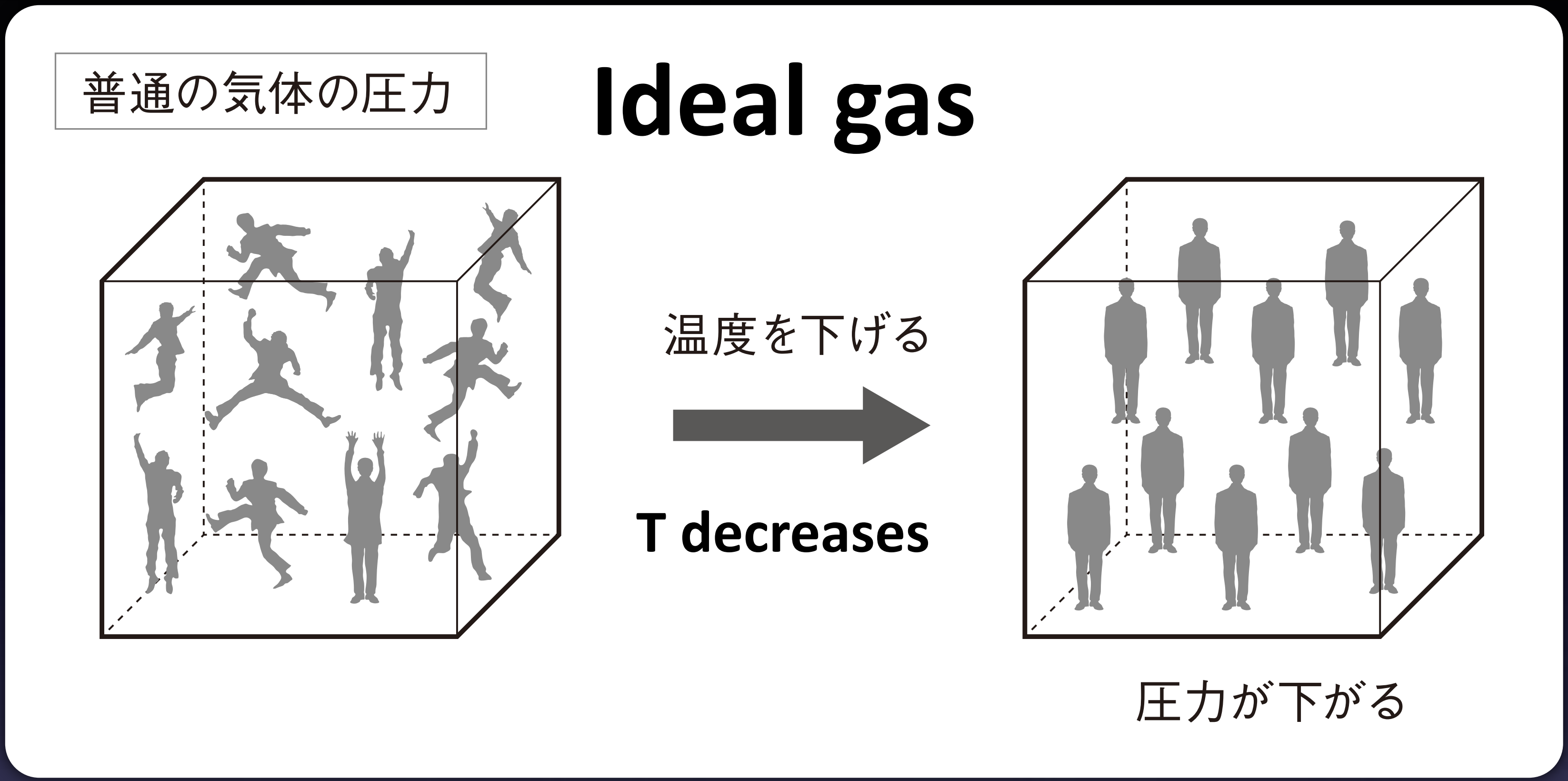
Stars can be supported by electron degeneracy pressure

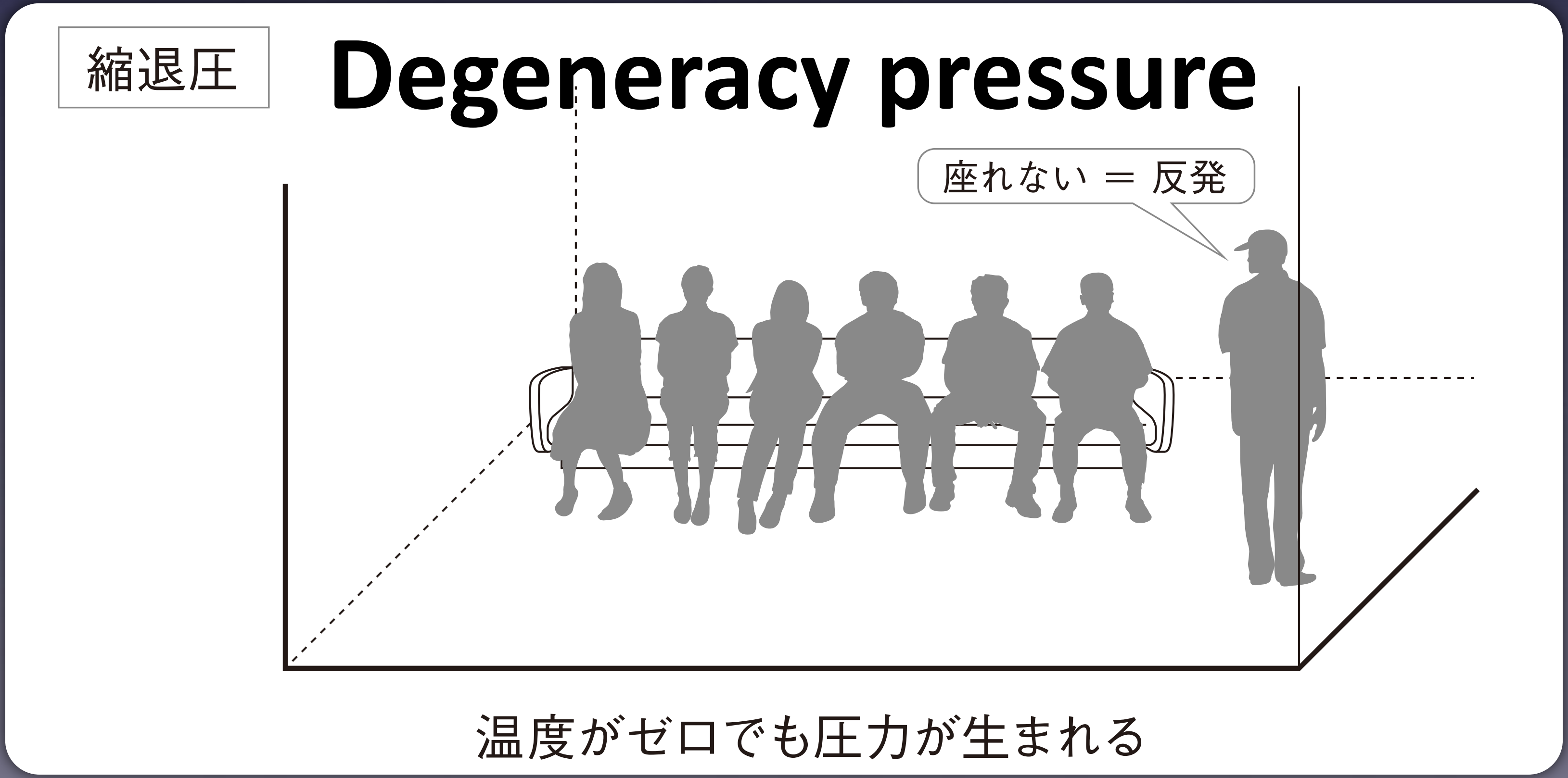
White dwarf



Images are not to scale

White dwarf: supported degeneracy pressure





P is non-zero even at T=0

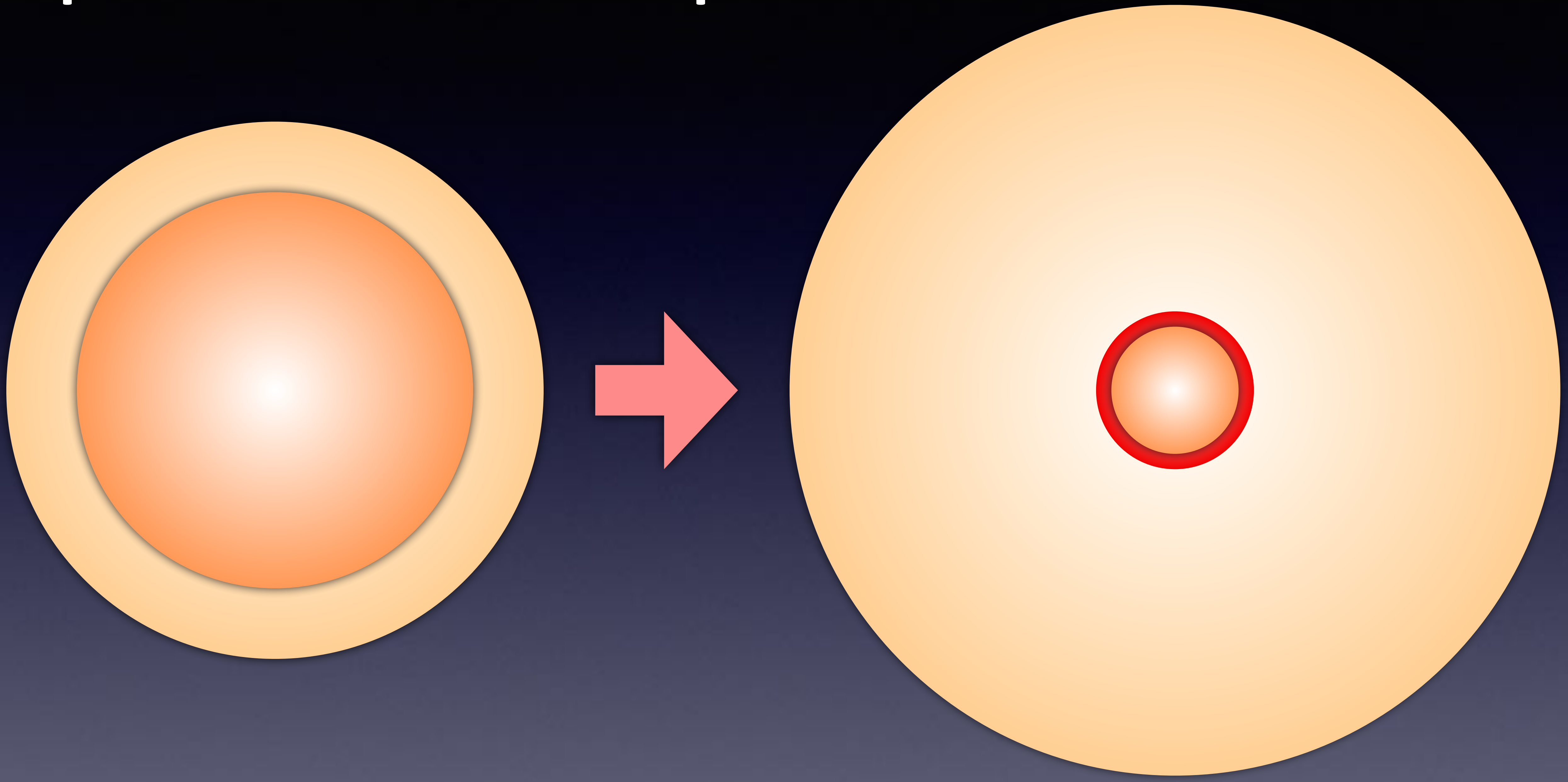
星が「死ぬ」とはどういうことか
（ベレ出版）

Section 5.
Stellar evolution (II)

5.1 Equation of state

5.2 Evolutionary track

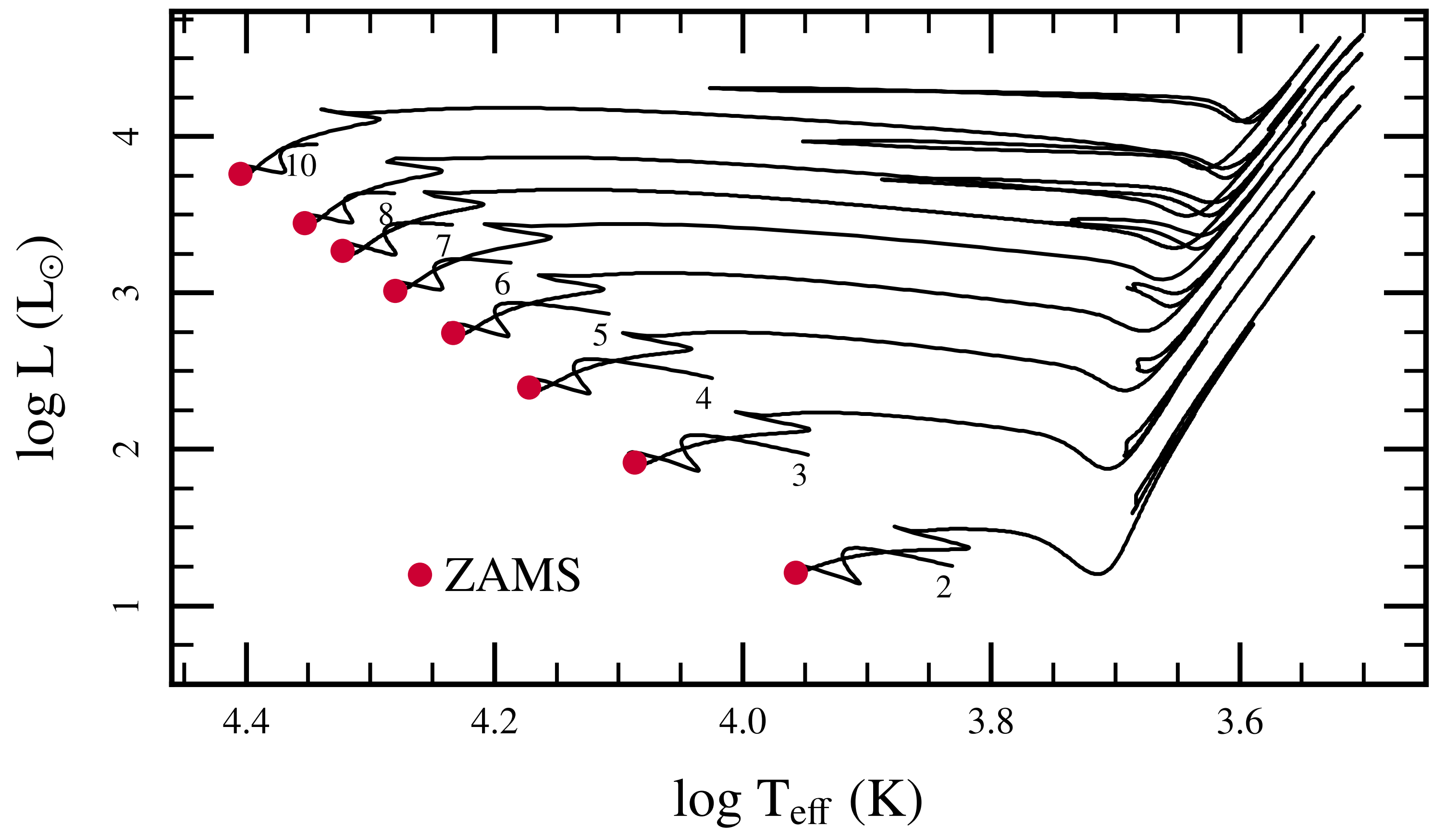
Contraction of the core
= Expansion of the envelope



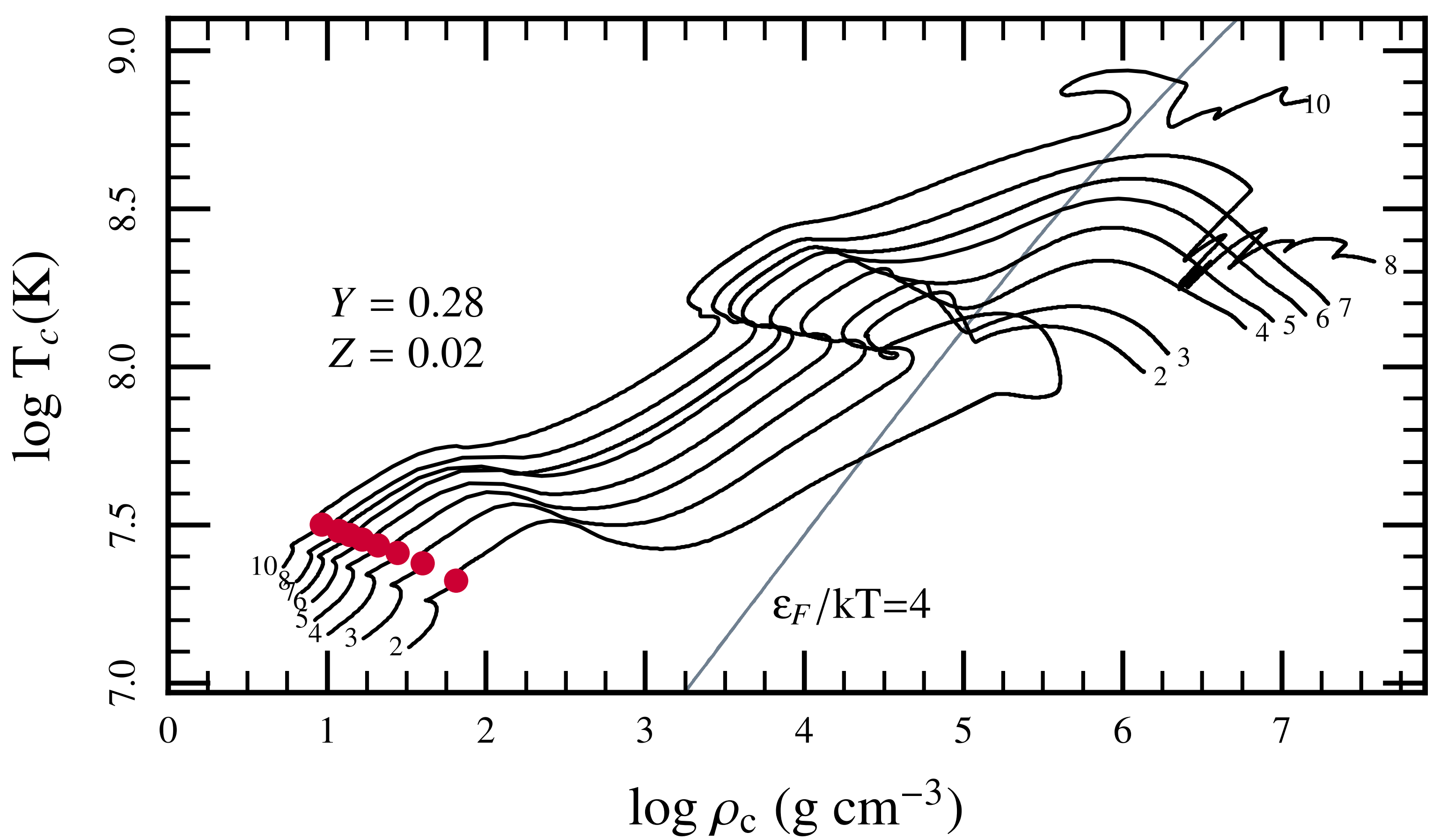
Shell burning => energy generation

(more than required to support the envelope)

Low/intermediate mass stars

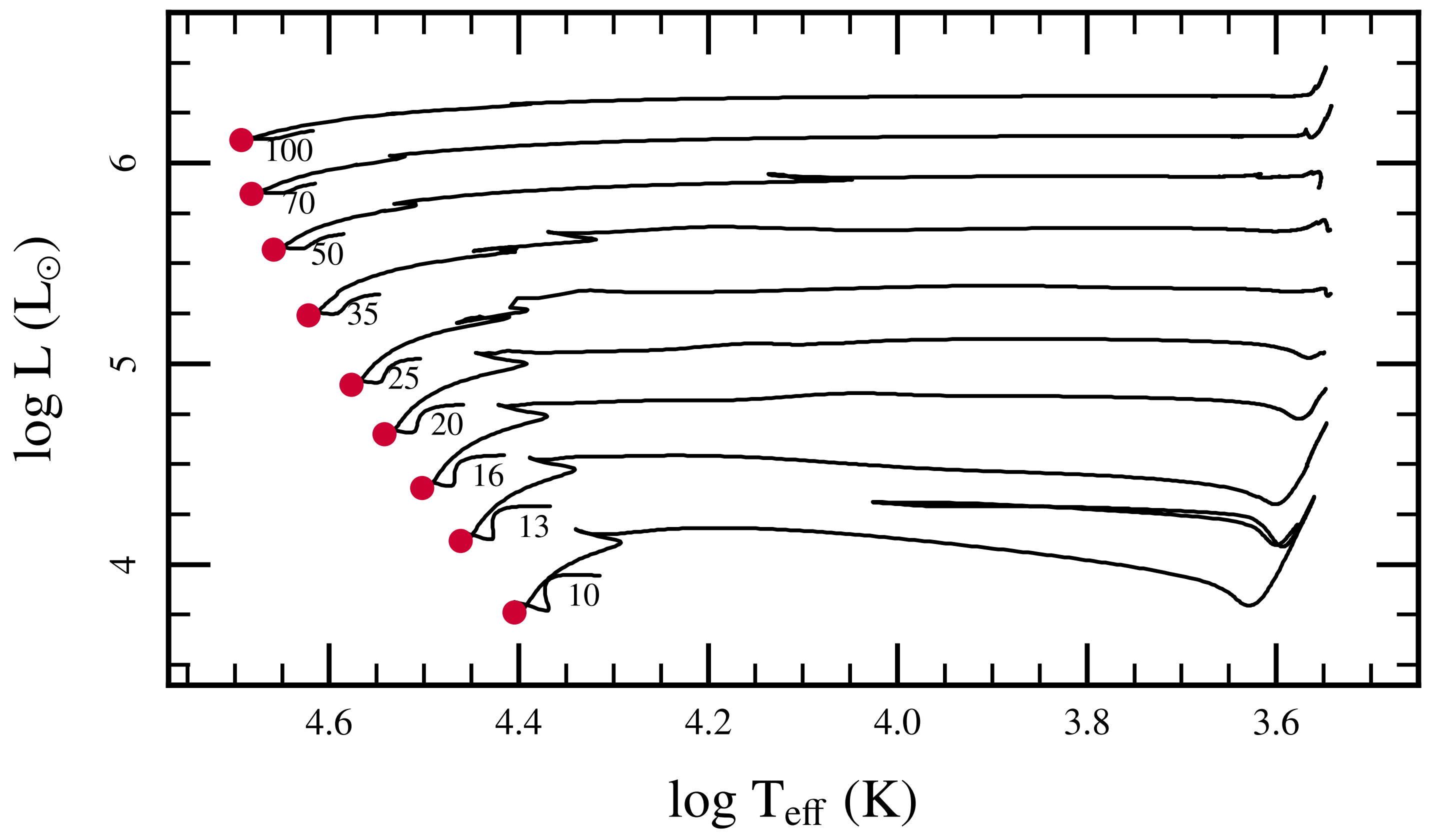


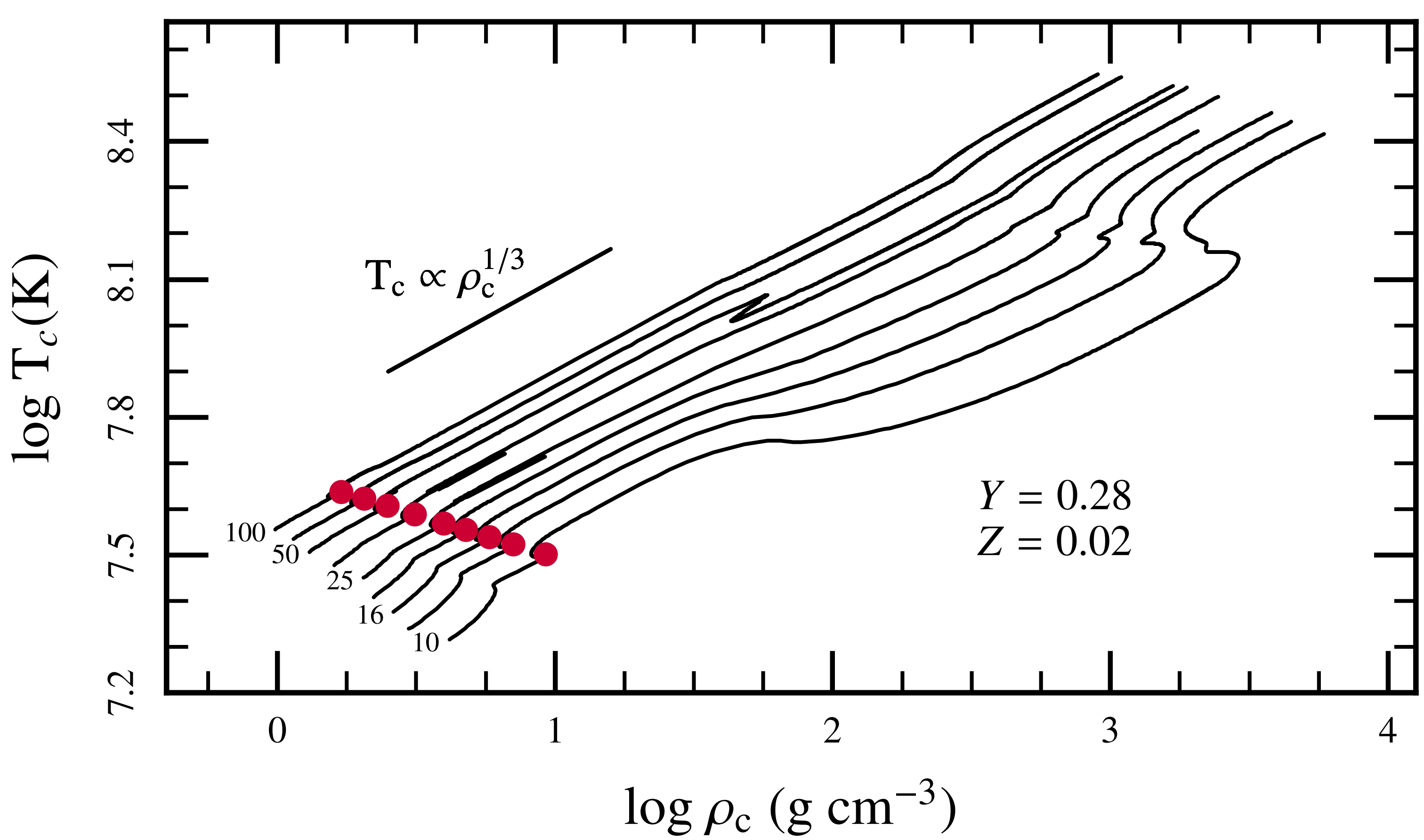
Core contraction
=> Expansion of the envelope
=> Red giant



Paxton et al. 2011

Massive stars (until He-burning)

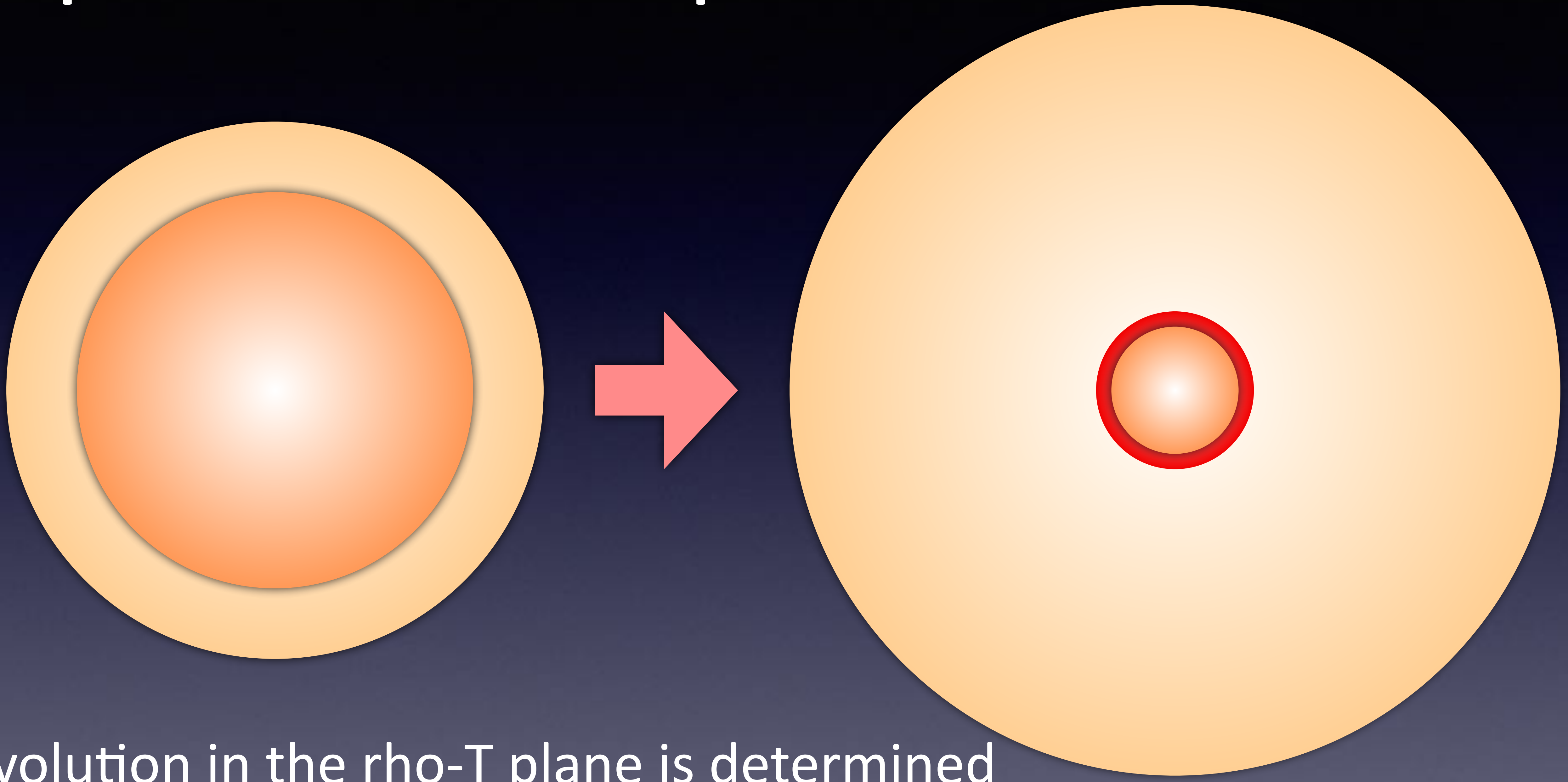




Core contraction
=> Expansion of the envelope
=> Red super giant

Paxton et al. 2011

Contraction of the core
= Expansion of the envelope



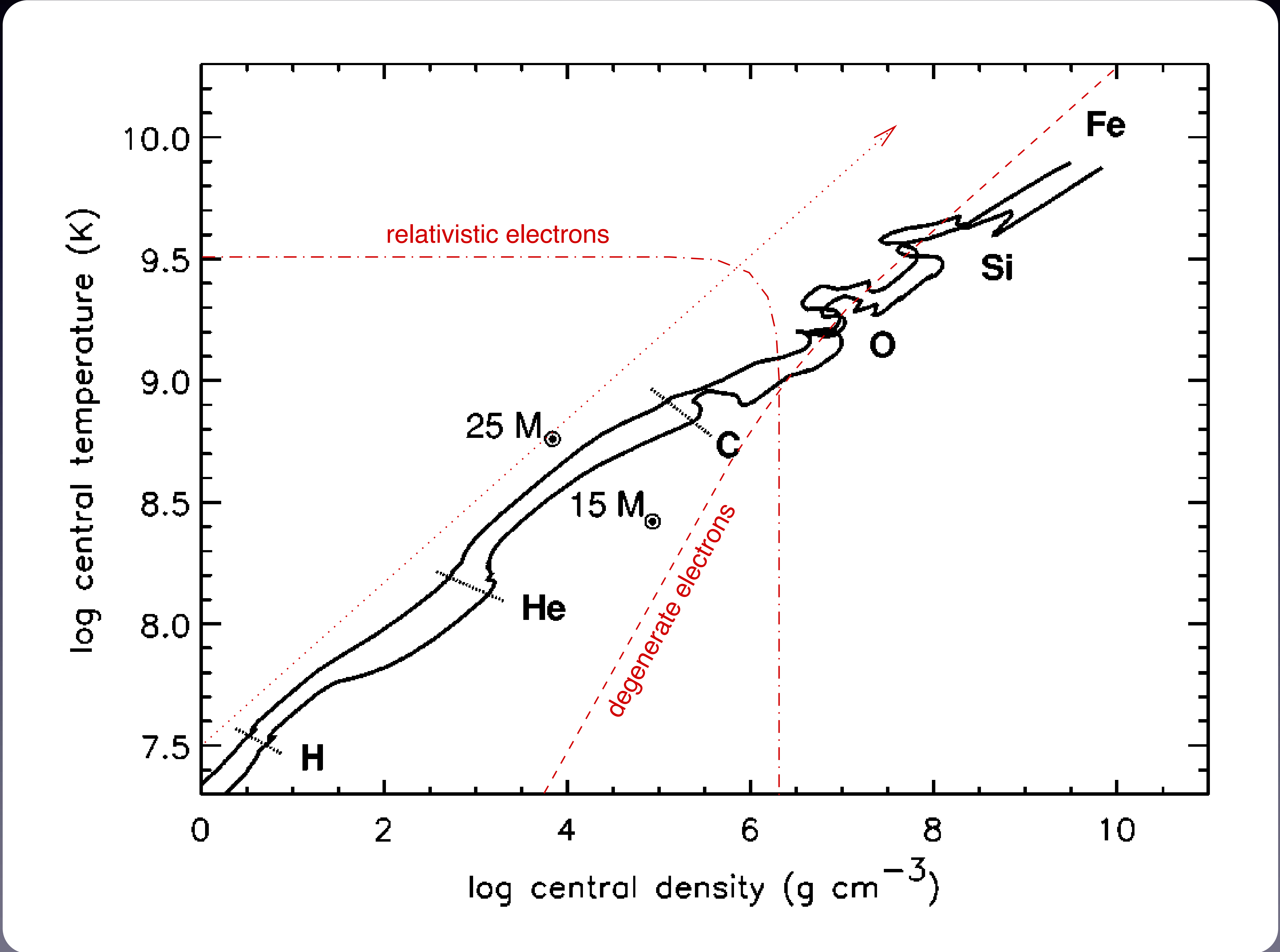
Evolution in the rho-T plane is determined by the properties of the core

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

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

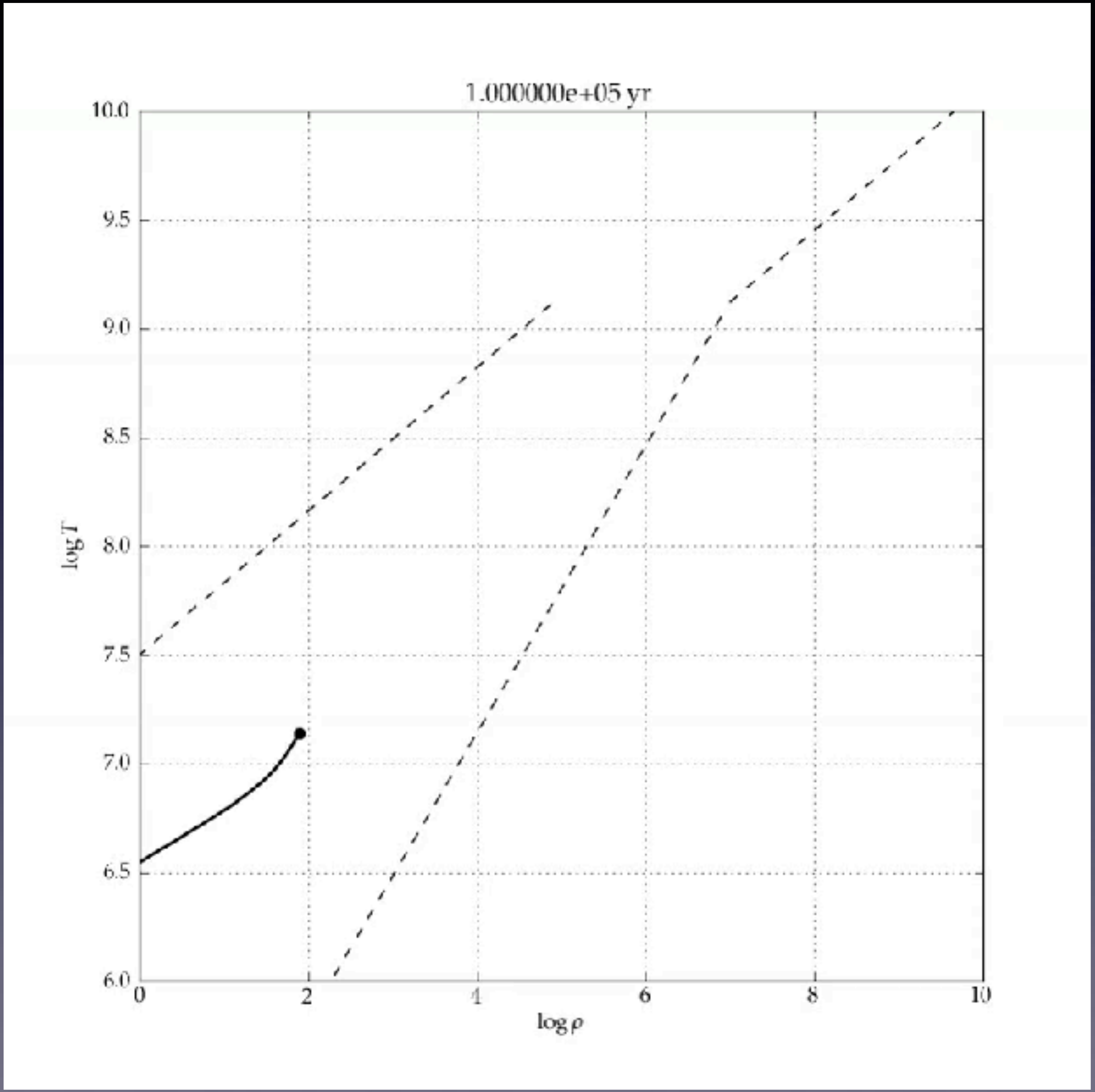
Stellar evolution calculations remain a basic tool of broad impact for astrophysics. New observations constantly test the models, even in 1D. The continued demand requires the construction of a general, modern stellar evolution code that combines the following advantages:

- **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

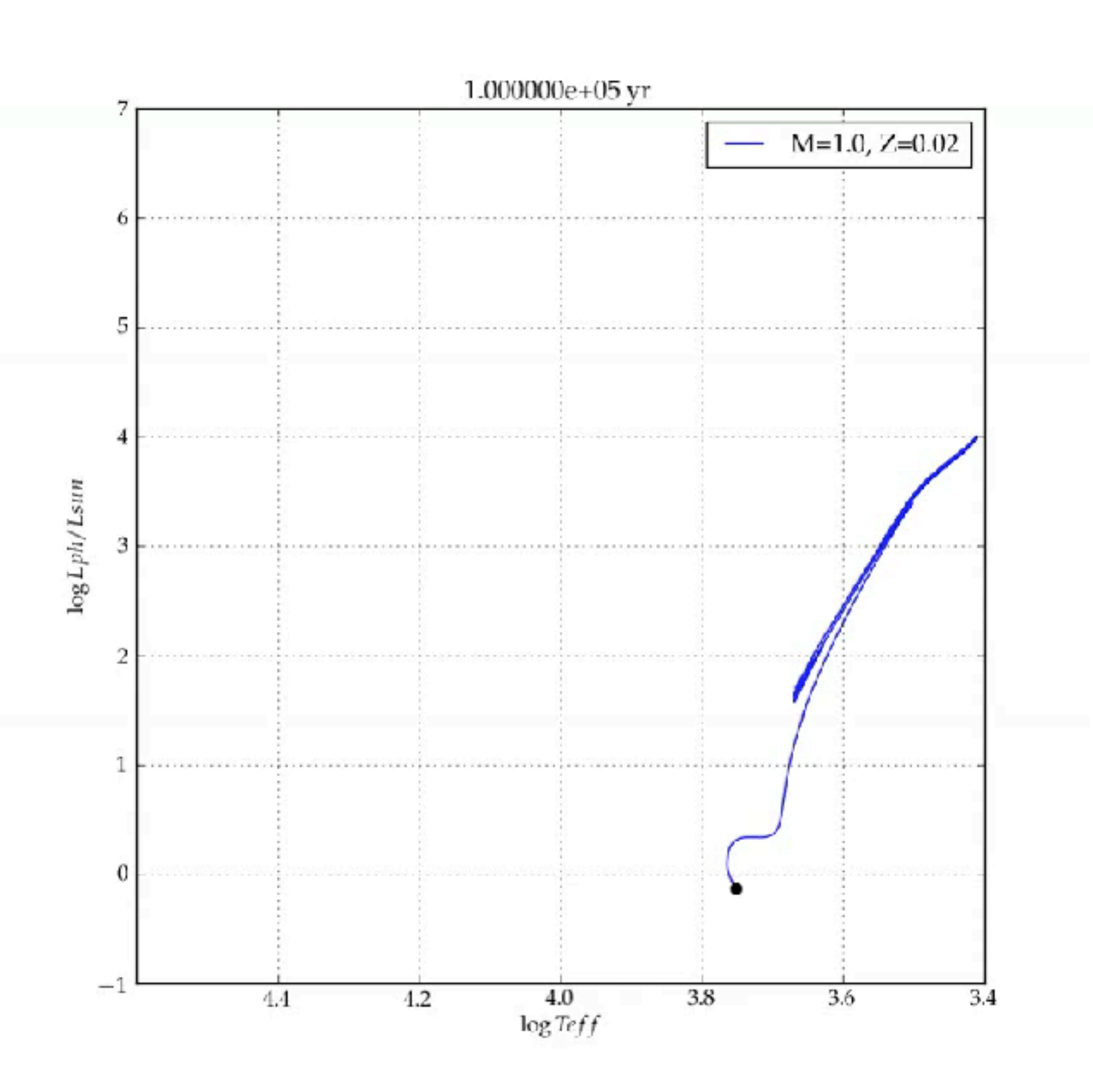
Latest News

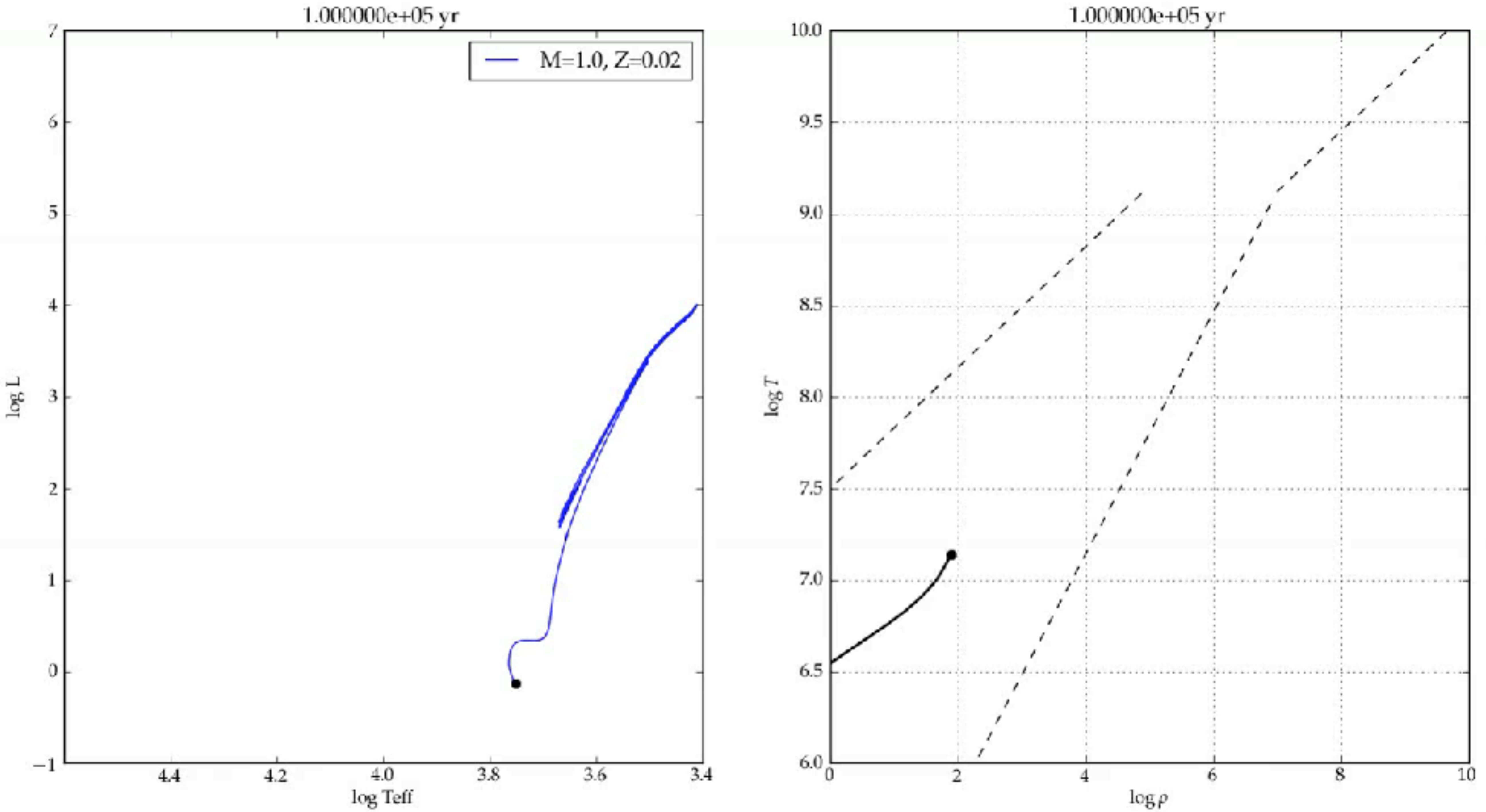
- 10 Aug 2016 » **Documentation Archive**
- 19 Jun 2016 » **Release 8845**
- 03 Feb 2016 » **Release 8118**
- 29 Jan 2016 » **New MESA SDK Version**
- 10 Jan 2016 » **Summer School 2016**
- 27 Sep 2015 » **Instrument Paper 3**
- 14 Sep 2015 » **MESA-Web Updates**
- 08 Sep 2015 » **New MESA SDK Version**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

1 Msun (ρ-T)

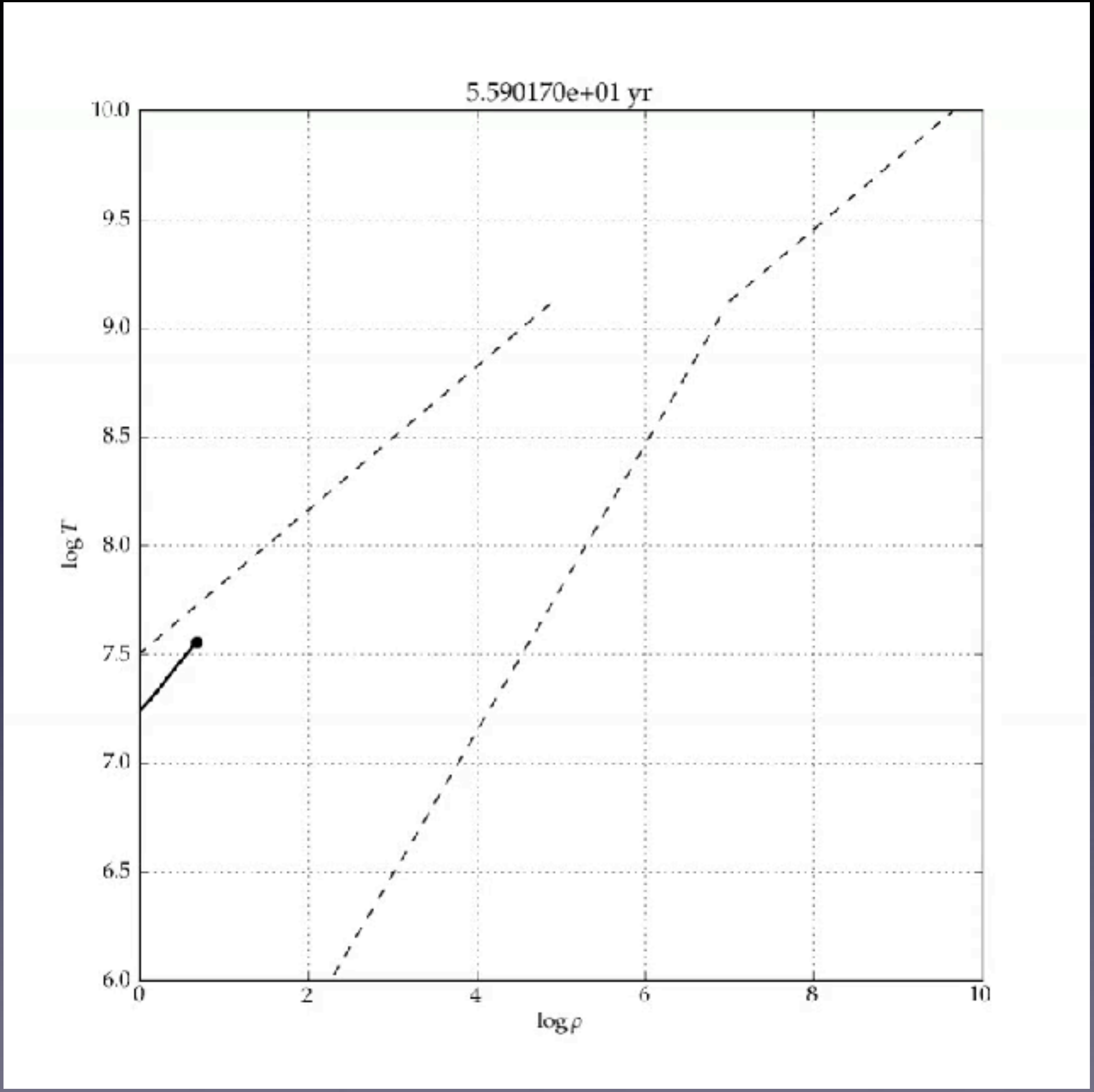


1 Msun (HR diagram)

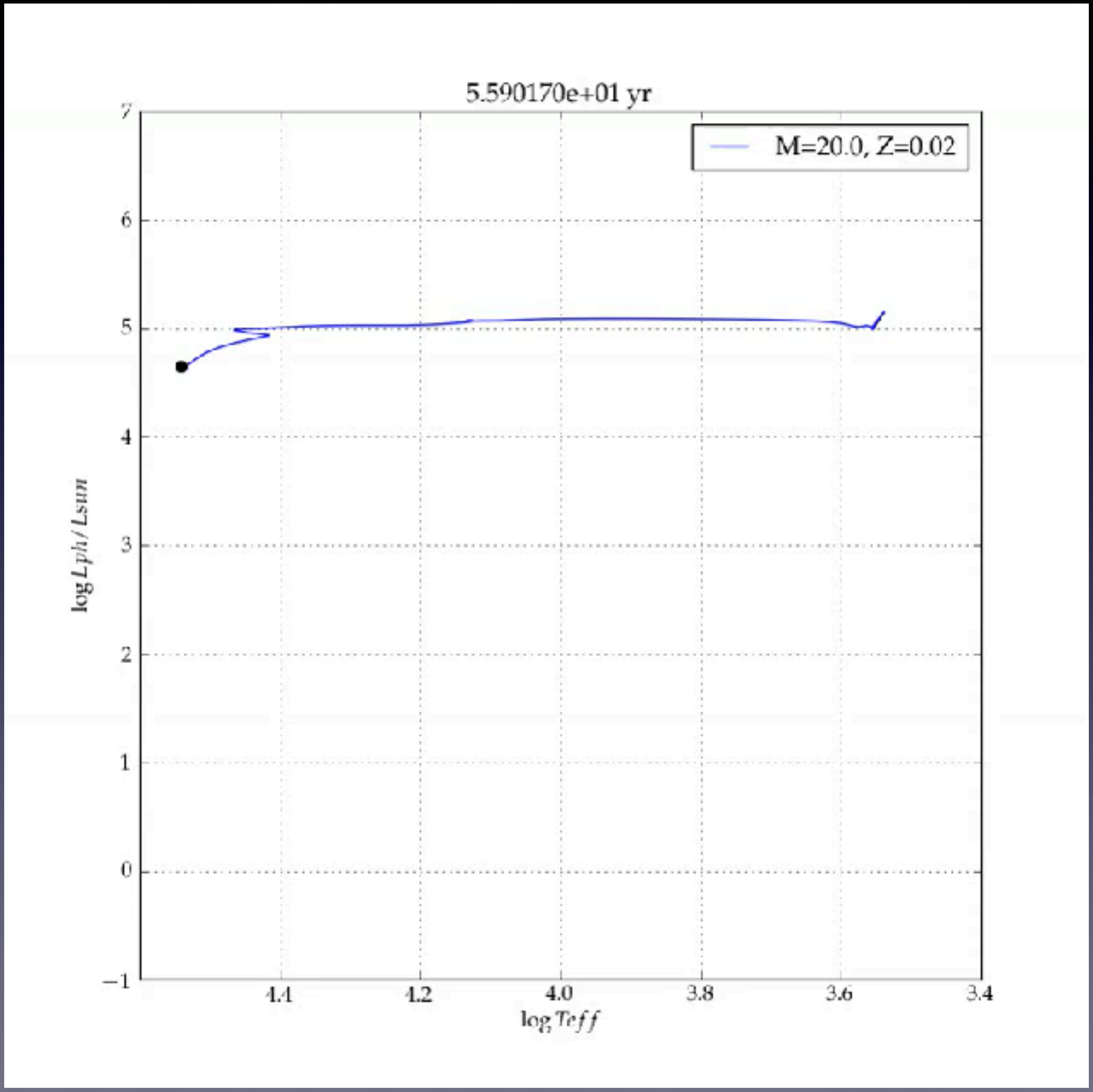


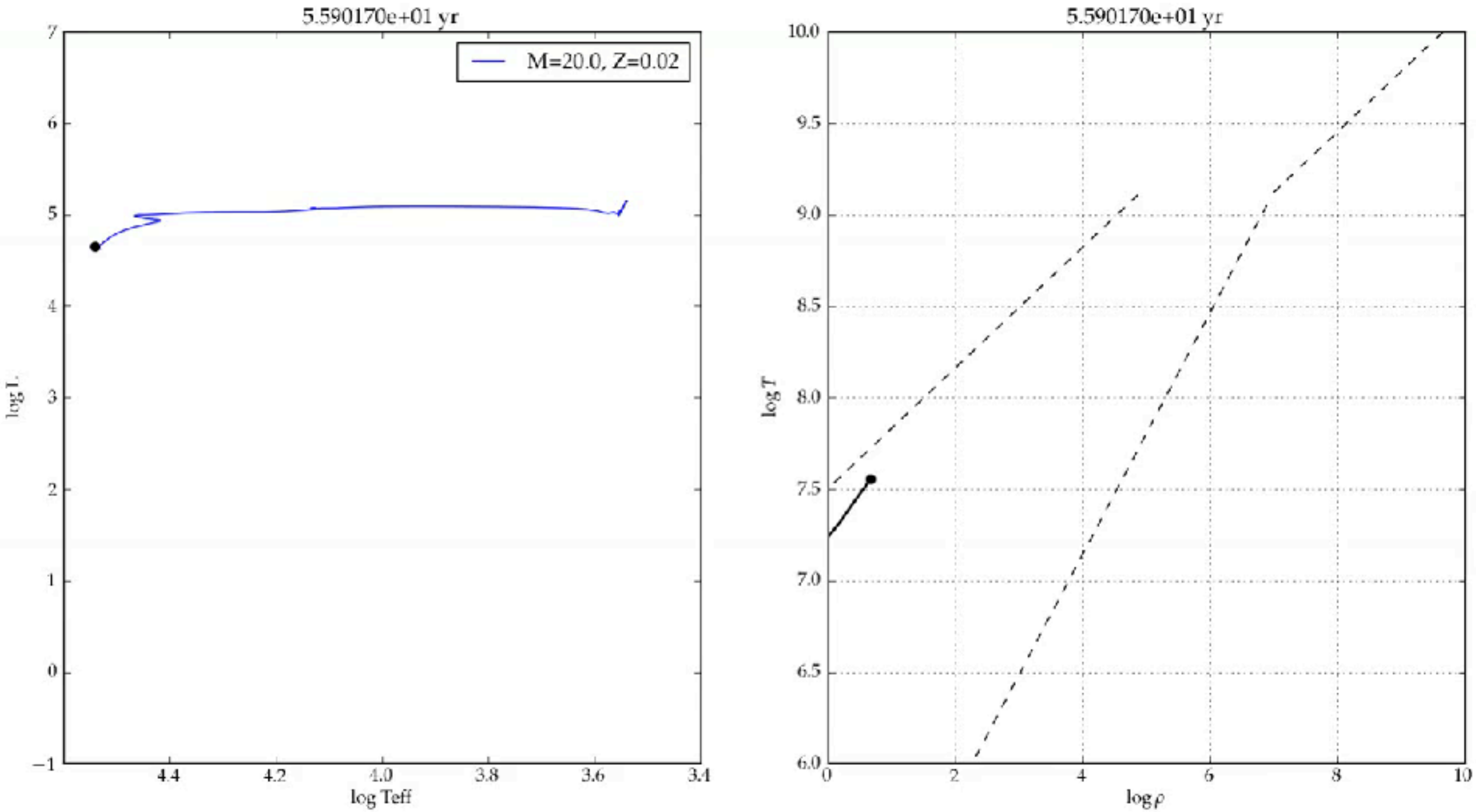

1.000000e+05 yr
M=1.0, Z=0.02
log L
log Teff
1.000000e+05 yr
log T
log ρ

20 Msun (ρ-T)



20 Msun (HR diagram)




5.590170e+01 yr
M=20.0, Z=0.02
log L
log Teff
5.590170e+01 yr
log T
log ρ

Summary: stellar evolution (II)

- **Properties of gas (microscopic)**
  ==> properties of stars (macroscopic)
- **Equation of states**
  - Ideal gas $P \sim \rho T$
  - Degeneracy pressure $P \sim \rho^{5/3}$ (non-rel)、 $P \sim \rho^{4/3}$ (rel)
  - Radiation pressure $P \sim T^4$

  => Important in different areas in the rho-T diagram
- **Stellar evolution**
  - Stars stop contraction when supported by degeneracy pressure
    => No temperature rise => End of nuclear burning
  - The core of low mass stars become generate

Let's understand these questions with the word of physics

Knowing ≒ Understanding

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

Thermodynamics

Electromagnetism

Classical mechanics

Statistical mechanics

Astrophysics

Hydrodynamics

Quantum mechanics

Relativity

Nuclear physics