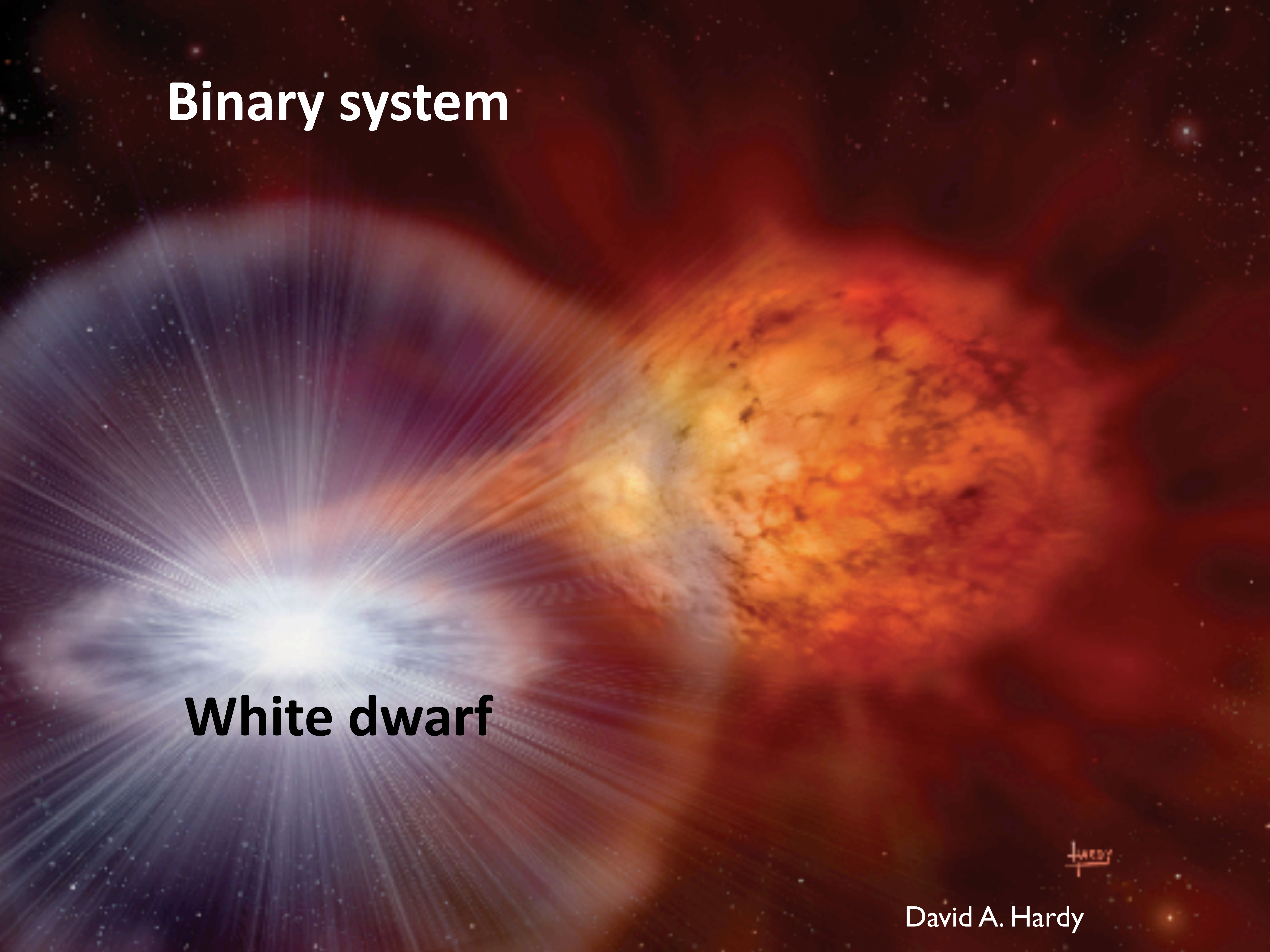
Section 9.
Stellar stability and supernovae

9.1 Thermonuclear supernova

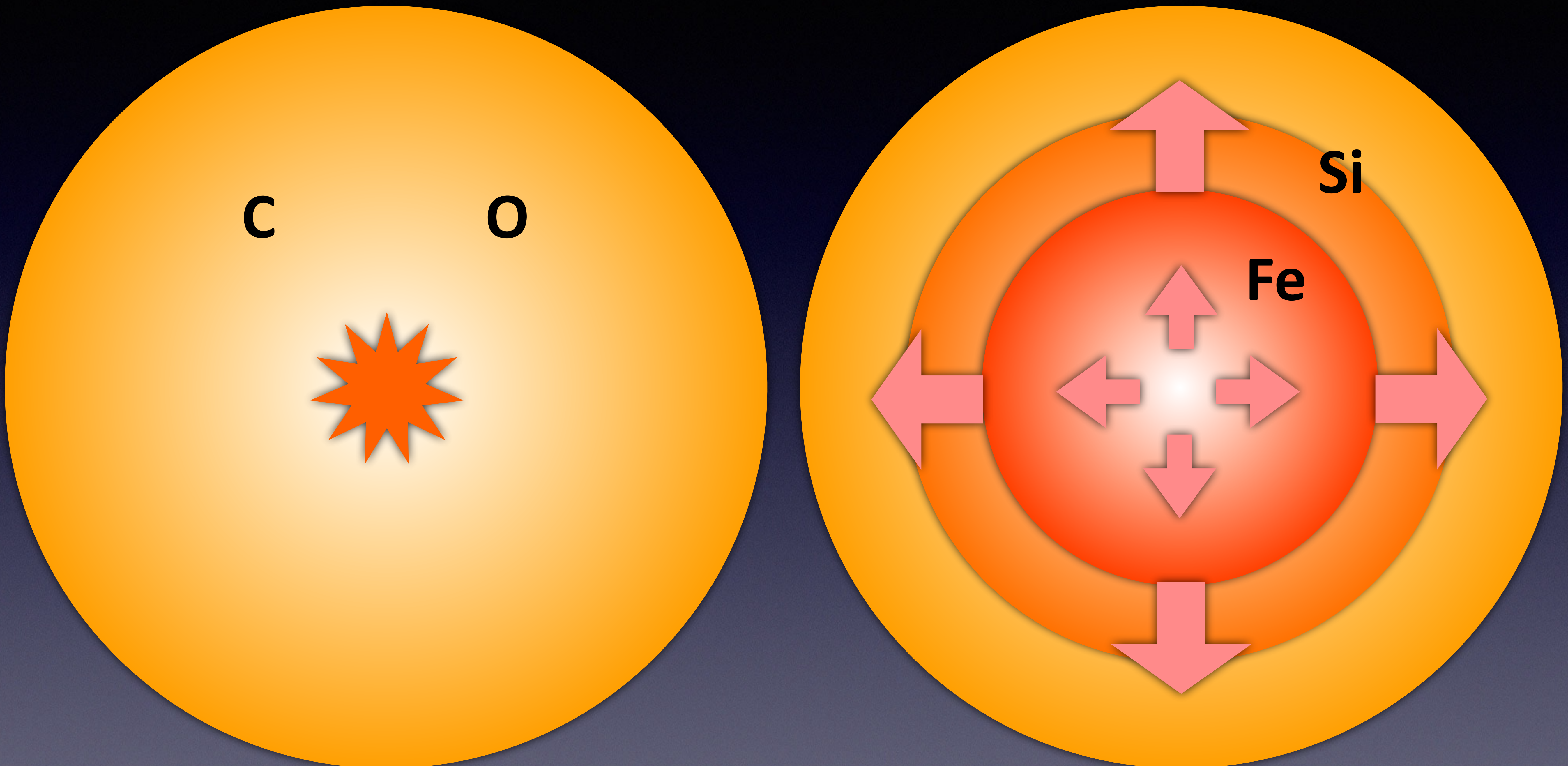
9.2 Core-collapse supernova

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?
- …

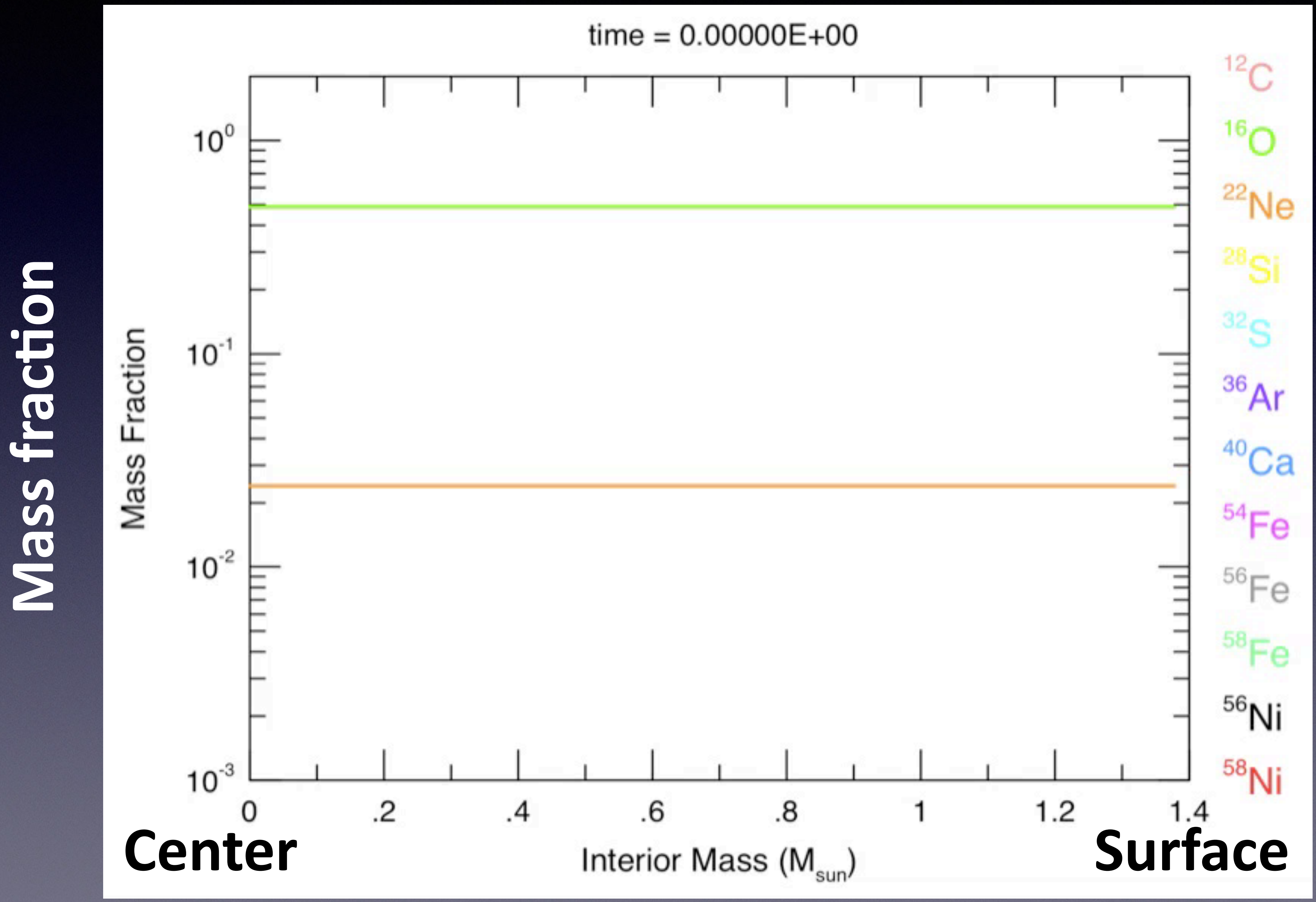

Binary system
White dwarf
David A. Hardy

Thermonuclear explosion

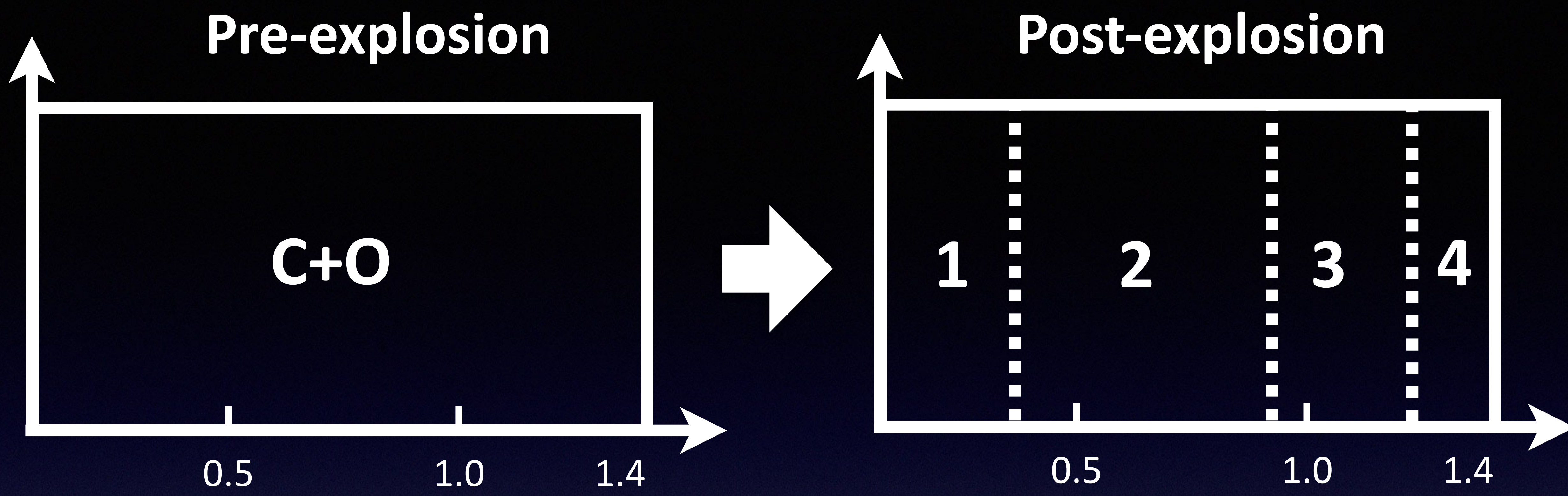


Supernova!

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

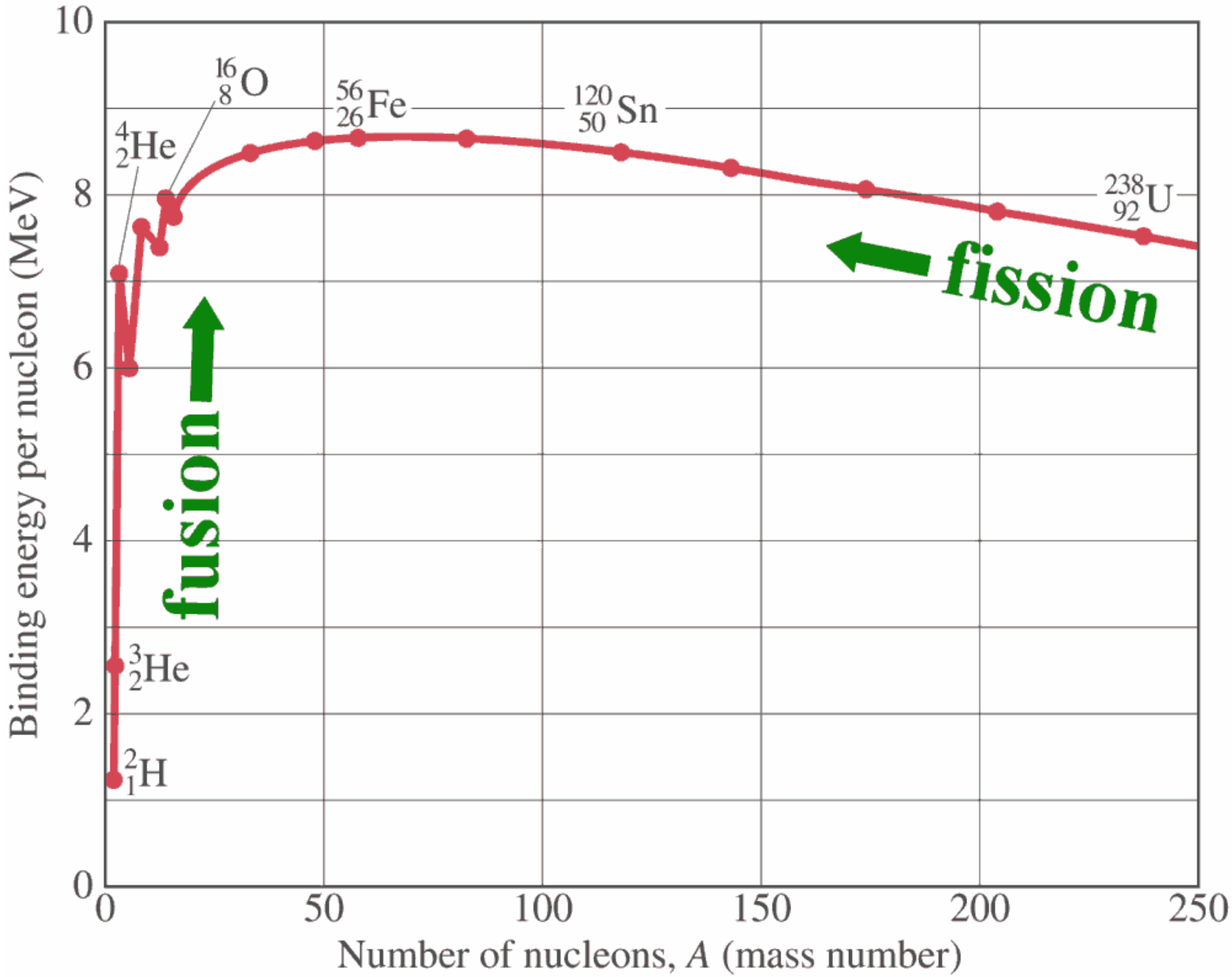
Thermonuclear supernovae

Normal stars are stable with nuclear burning

Why do white dwarfs explode by nuclear burning?

Type Ia SN

Sun



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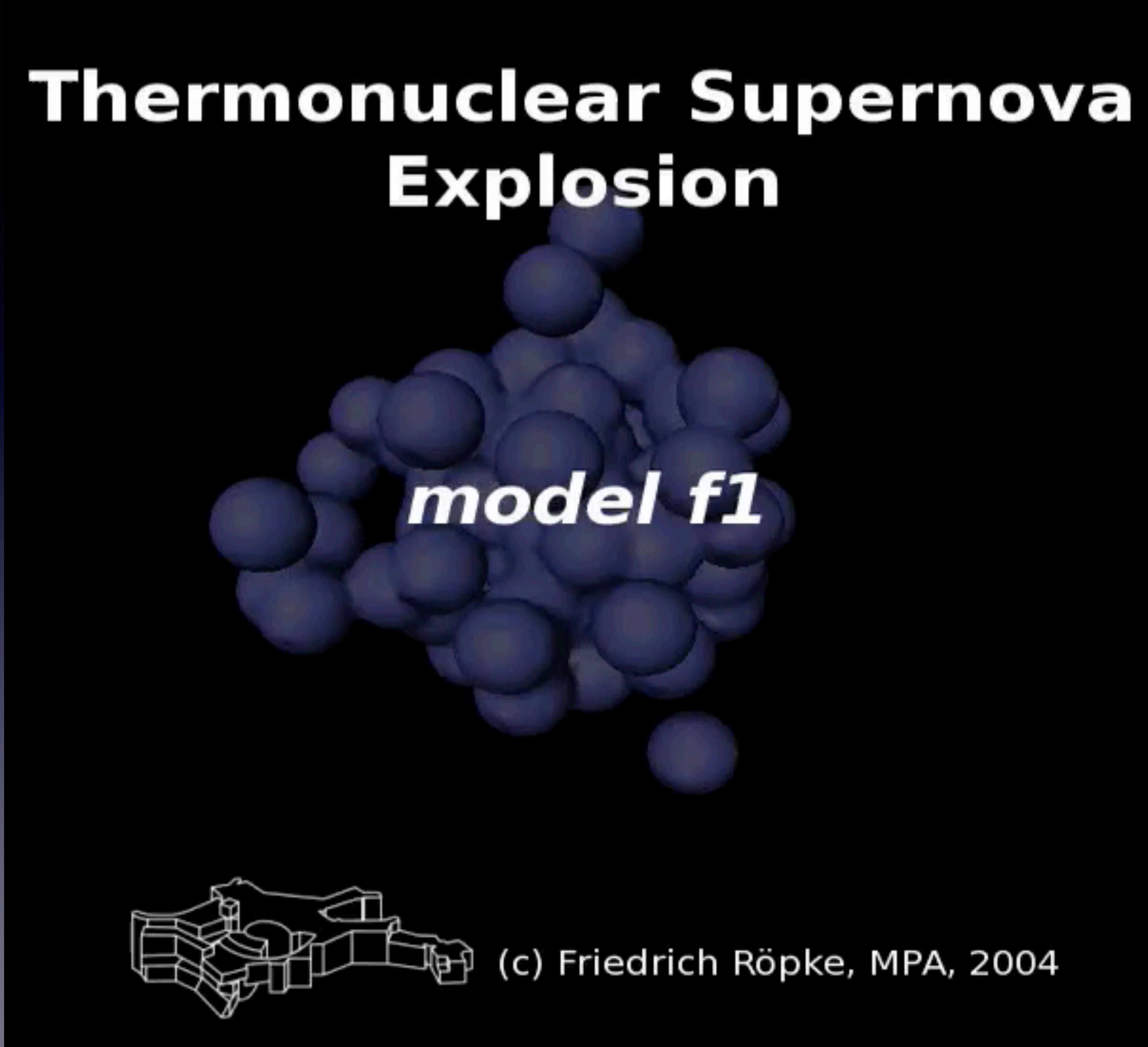
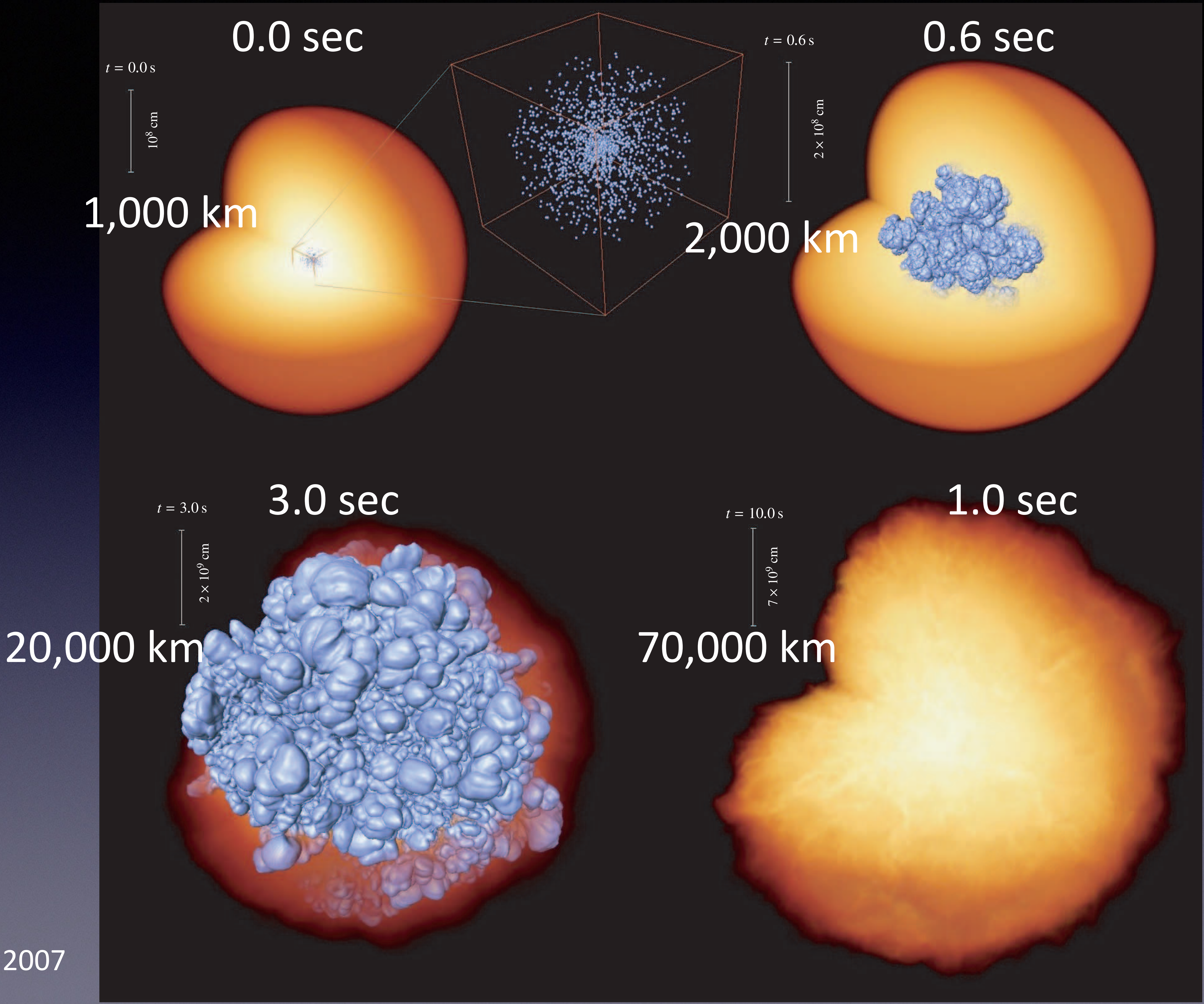

Thermonuclear Supernova
Explosion
model f1
(c) Friedrich Röpke, MPA, 2004


0.0 sec
t = 0.0 s
10⁸ cm
1,000 km
t = 0.6 s
0.6 sec
2 × 10⁸ cm
2,000 km
t = 3.0 s
3.0 sec
2 × 10⁹ cm
20,000 km
t = 10.0 s
1.0 sec
7 × 10⁹ cm
70,000 km

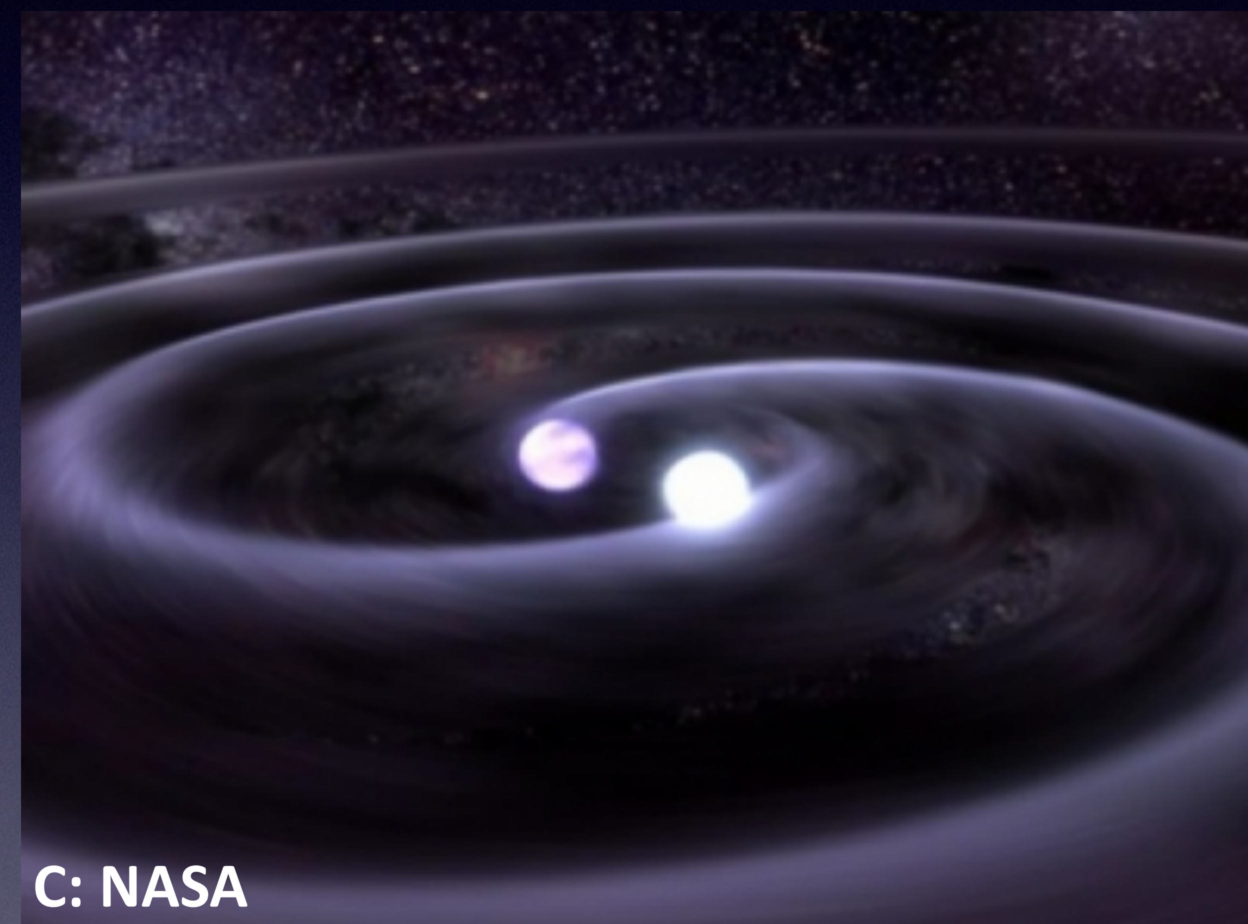
Roepke 2007

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: Thermonuclear supernovae

- **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)
- **Progenitor scenario**
  - Single degenerate or double degenerate
  - Not yet solved

Section 9.
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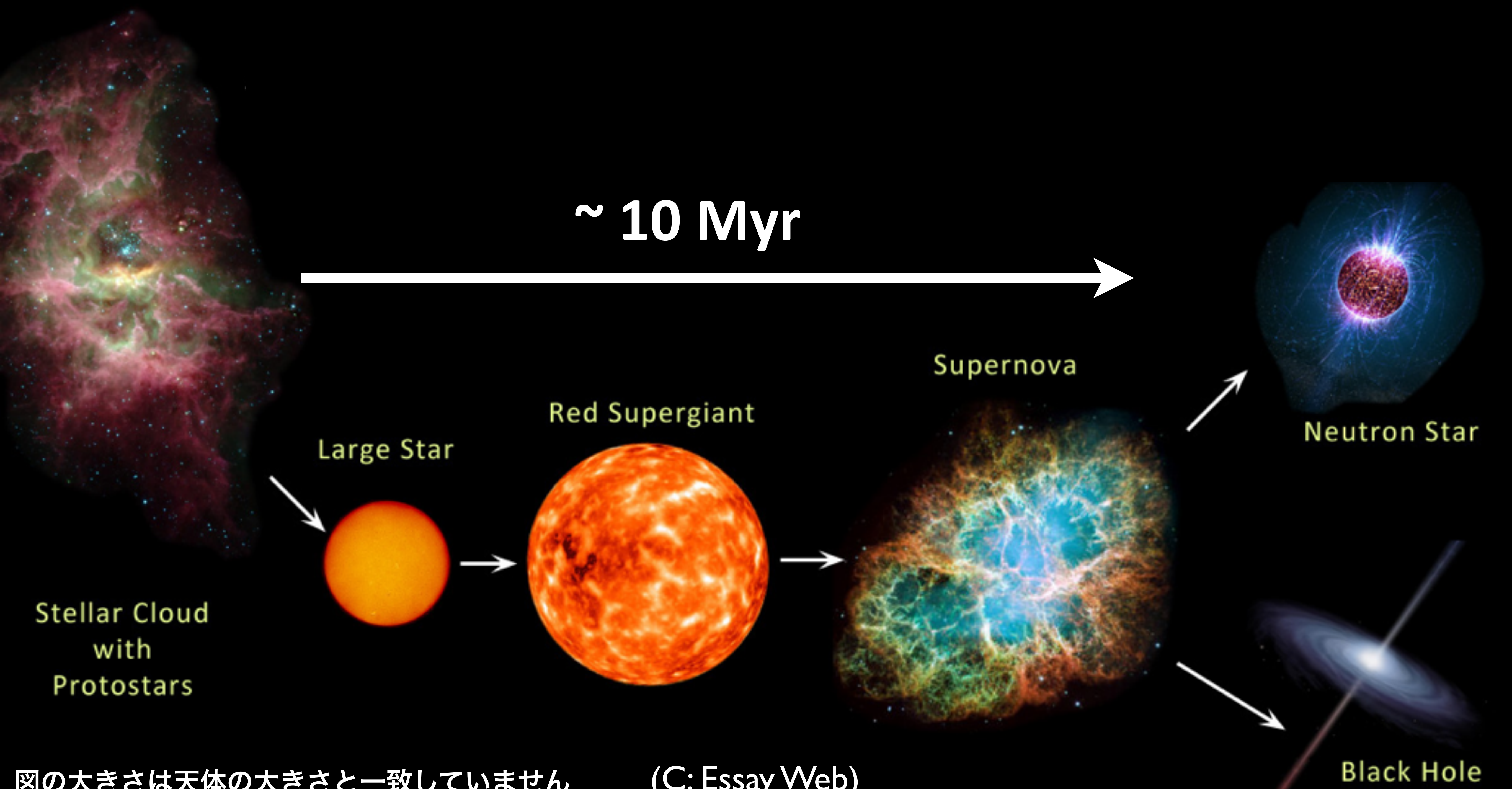
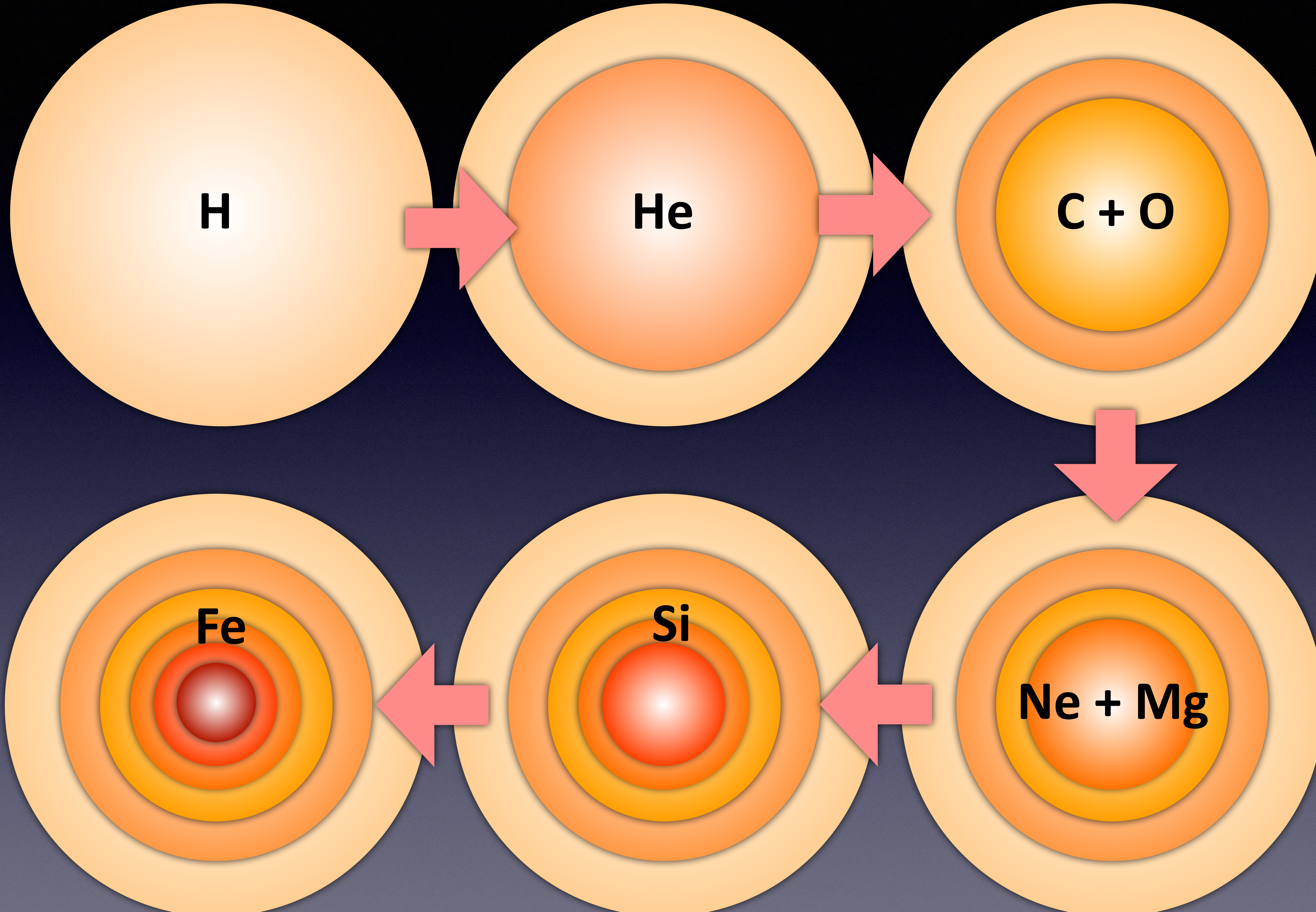
1. Massive stars

M > 10 Msun



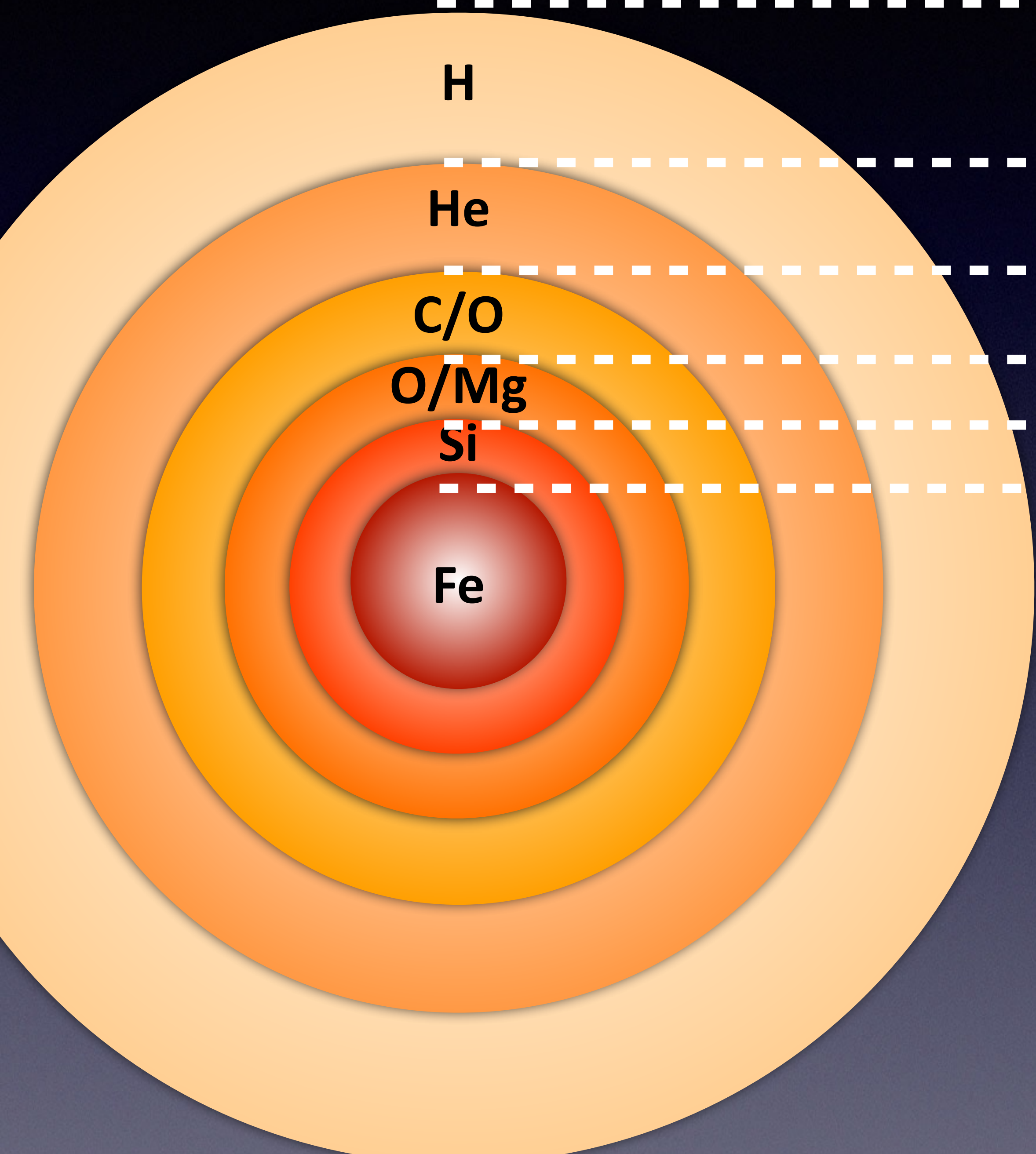
図の大きさは天体の大きさと一致していません　(C: Essay Web)



Images are not to scale

20 Msun star

(~16 Msun before the collapse)

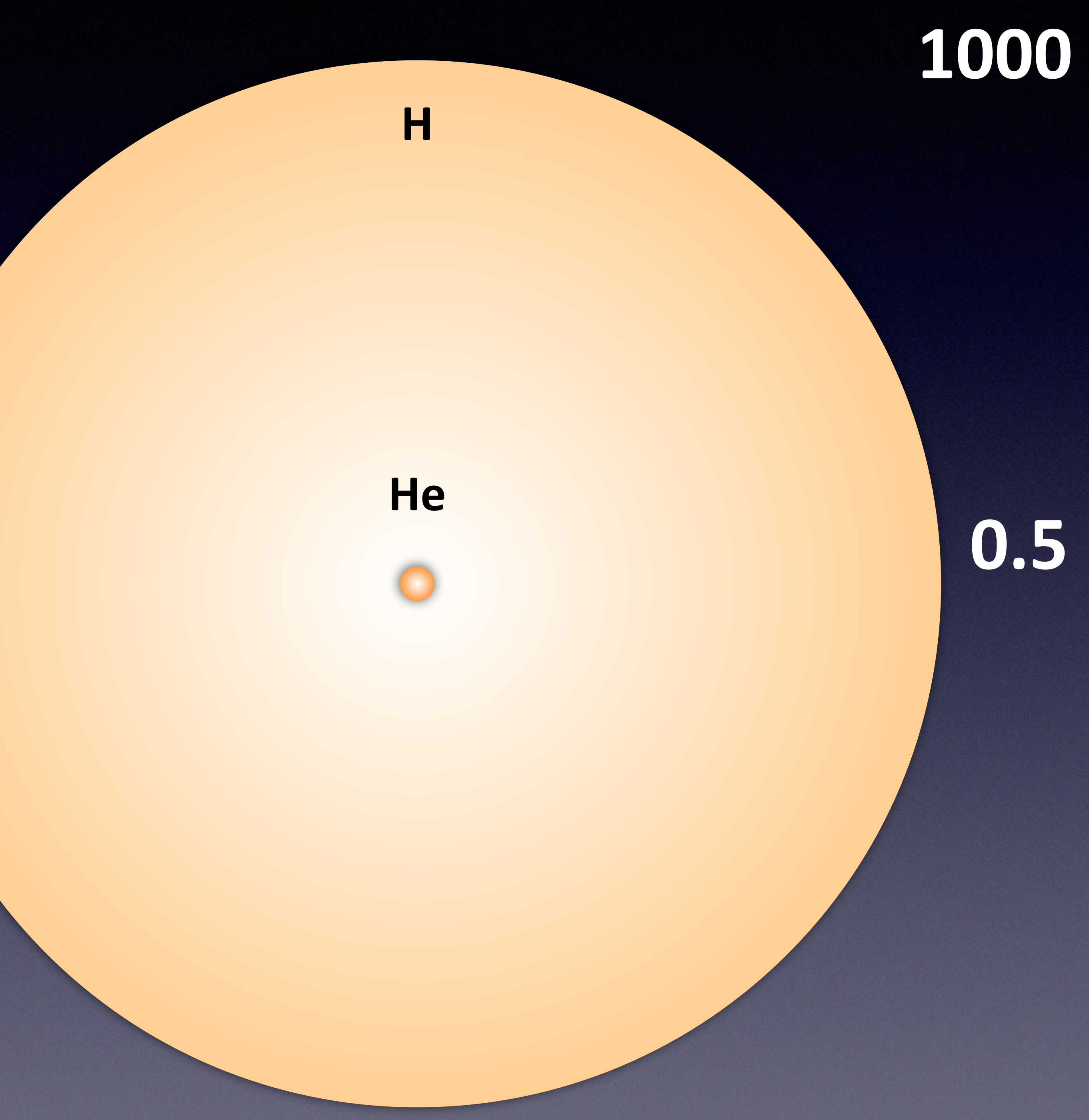


Mass (Msun)	R (Rsun)	Free-fall time (s)
16	1000	3×10^7 (1yr)
6	0.5	300
5	0.2	50
4	0.08	20
2	0.005	1
1.5	0.003	0.1

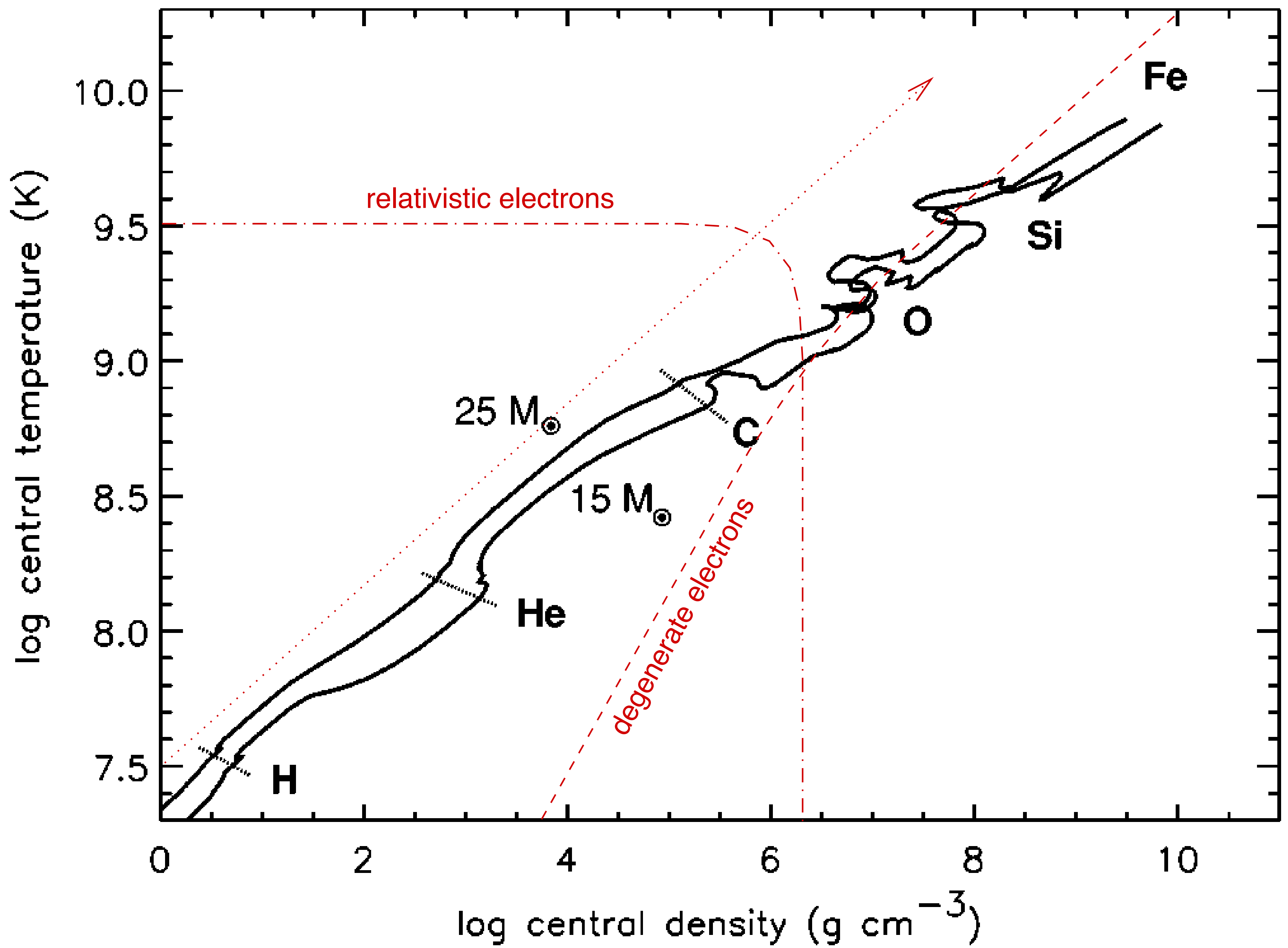
Rsun = 7×10^{10} cm

R(Fe core) ~ $0.003 \times 7 \times 10^{10}$ cm

~ 2×10^8 cm ~ 2,000 km


1000
H
He
0.5

Rho-T diagram

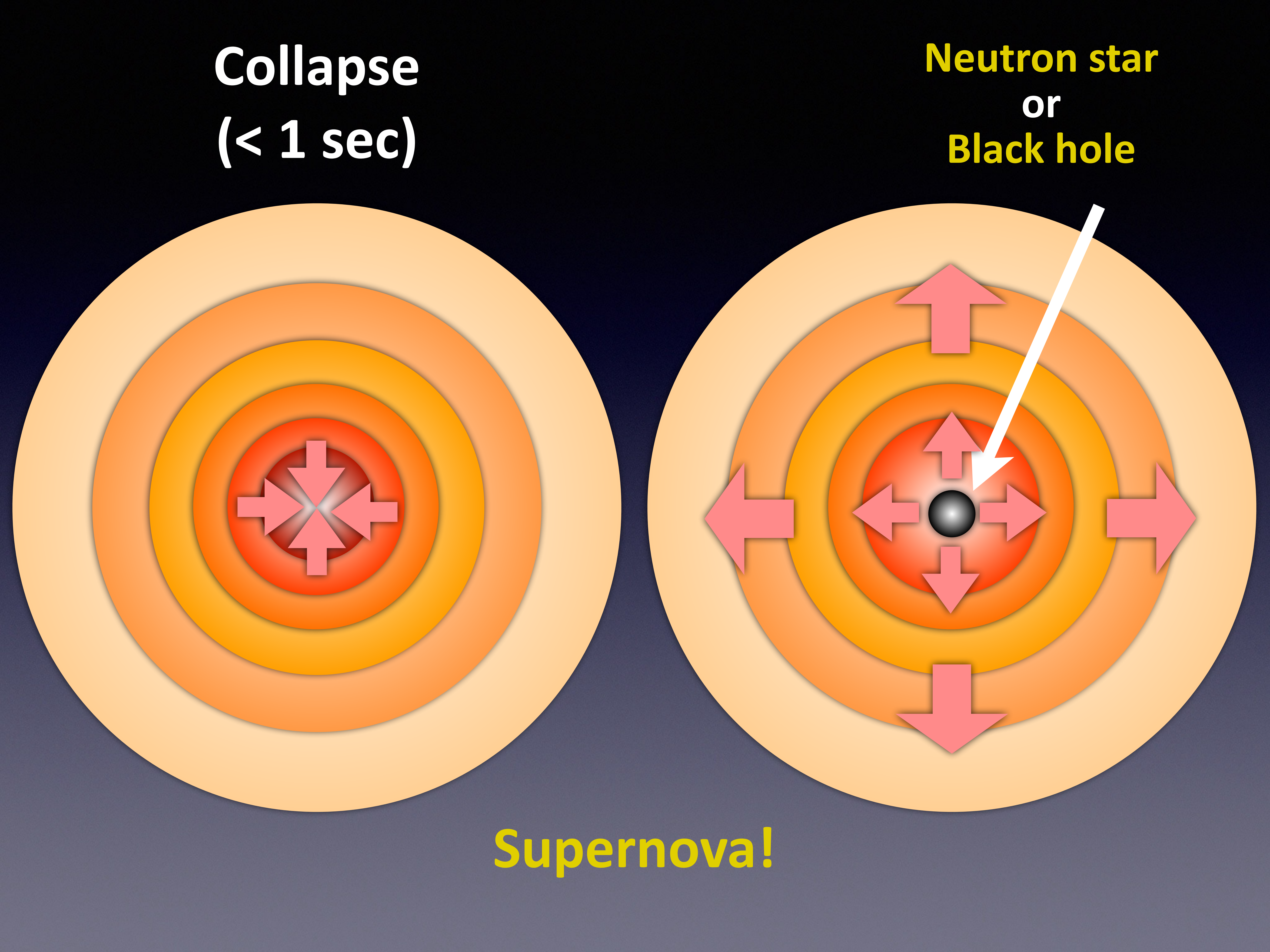


textbook by Pols

Timescales for nuclear burning stages

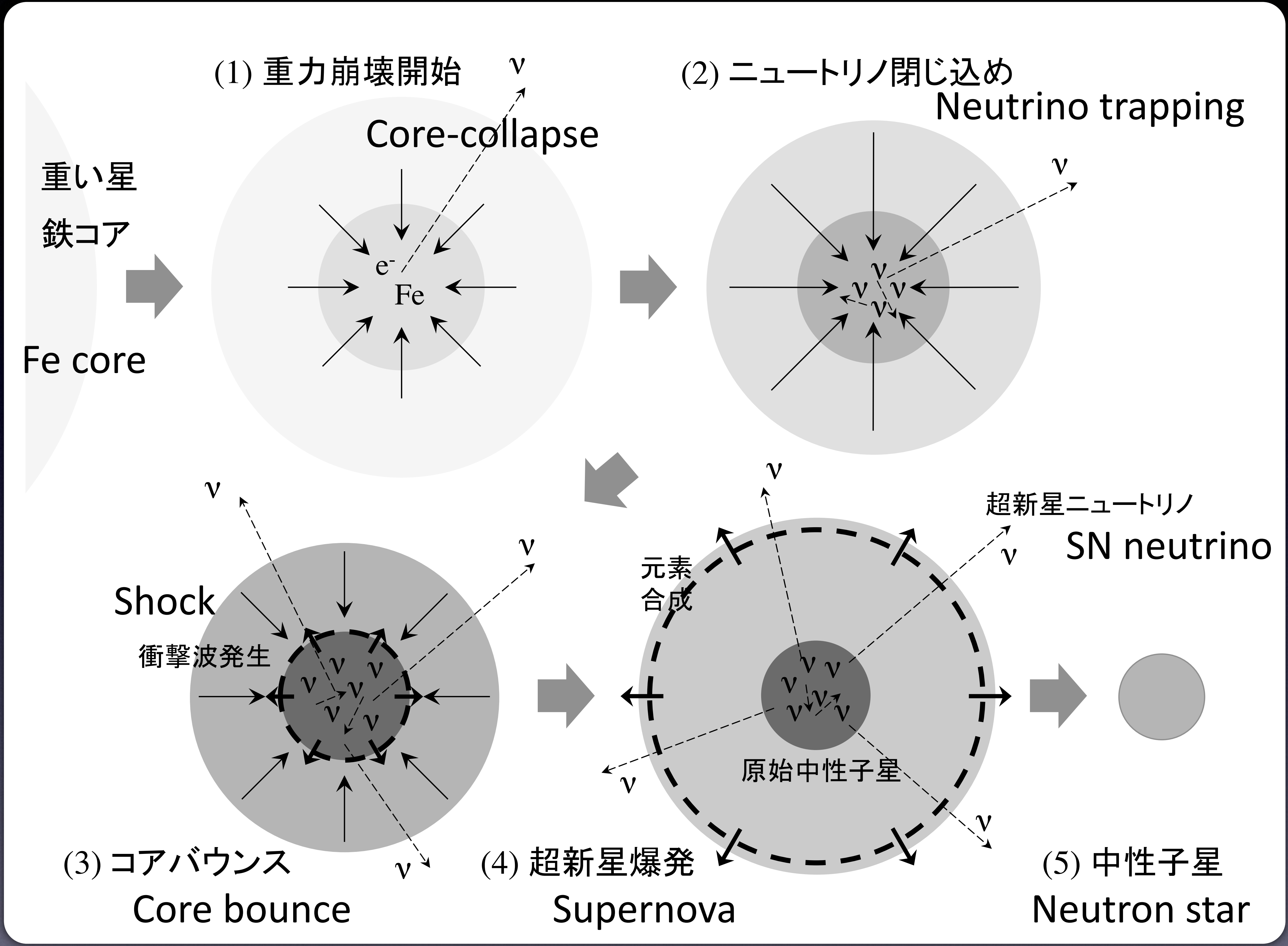
Table 12.1. Properties of nuclear burning stages in a 15 $M_\odot$ star (from Woosley et al. 2002).

burning stage	T (10^9 K)	ρ (g/cm^3)	fuel	main products	timescale
hydrogen	0.035	5.8	H	He	1.1×10^7 yr
helium	0.18	1.4×10^3	He	C, O	2.0×10^6 yr
carbon	0.83	2.4×10^5	C	O, Ne	2.0×10^3 yr
neon	1.6	7.2×10^6	Ne	O, Mg	0.7 yr
oxygen	1.9	6.7×10^6	O, Mg	Si, S	2.6 yr
silicon	3.3	4.3×10^7	Si, S	Fe, Ni	18 d


Collapse
(< 1 sec)
Neutron star
or
Black hole
Supernova!

Core-collapse supernovae

What happens to massive stars at the end of lives?
Where does huge energy come from?



(C) 原子核から読み解く超新星爆発の世界

住吉光介さん著 (Kosuke Sumiyoshi)

Summary: Core-collapse supernovae

- **Stability of star**
  - Dynamically unstable if adiabatic index $\gamma < 4/3$
  - Degenerate Fe core => unstable
  - What trigger the core-collapse?
- **Energy source**
  - Gravitational energy
  - Collapse of the core (~1 Msun) to ~10 km size => 10^{53} erg