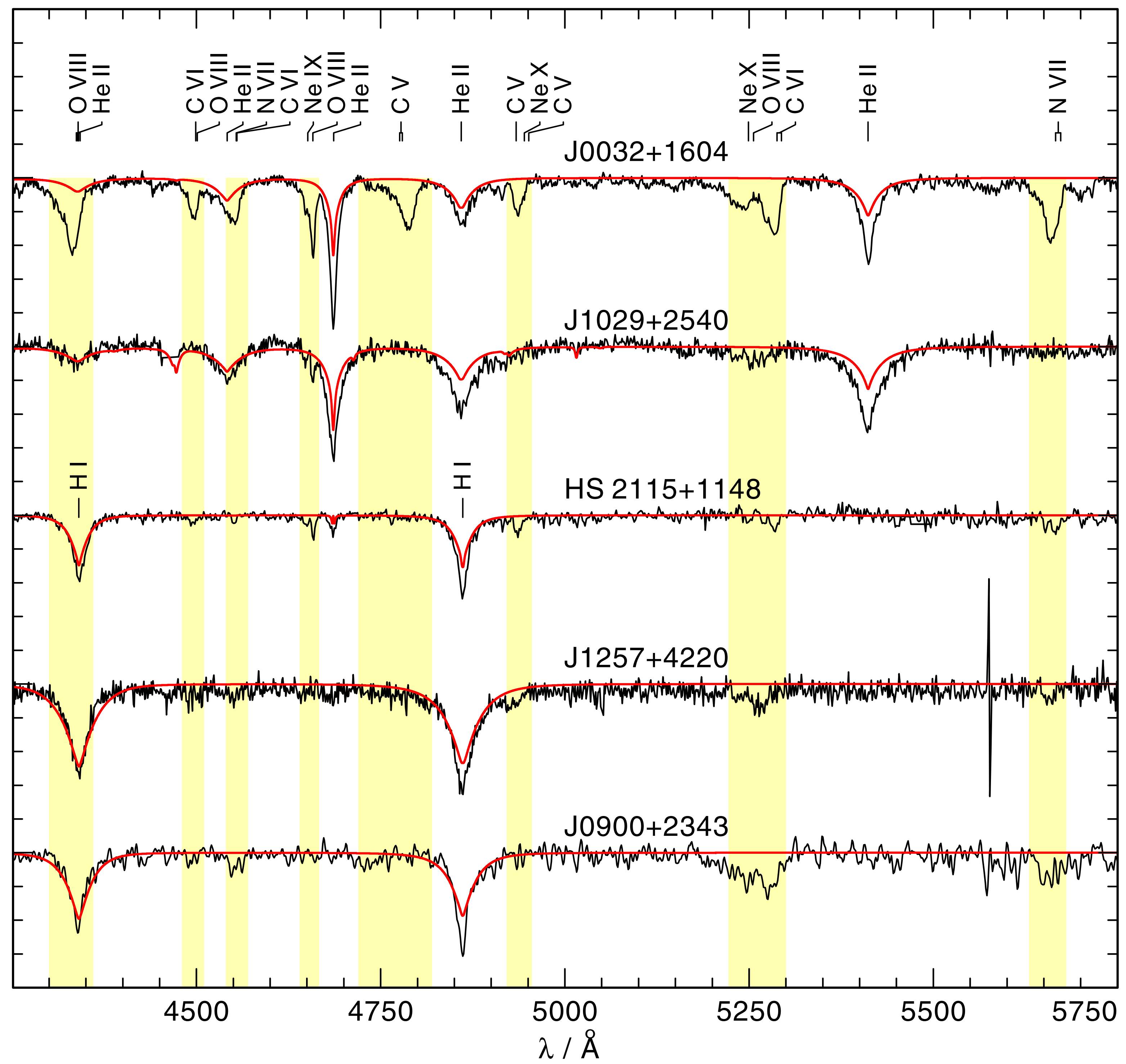
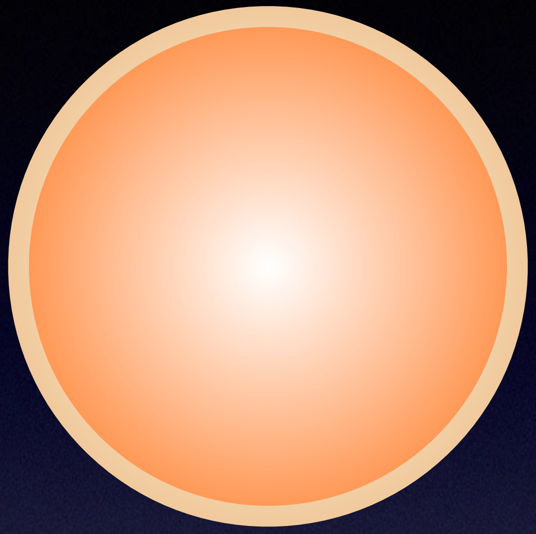
Section 7.
Supernova explosions

7.1 Thermonuclear supernova

7.2 Core-collapse supernova

Spectra of white dwarf

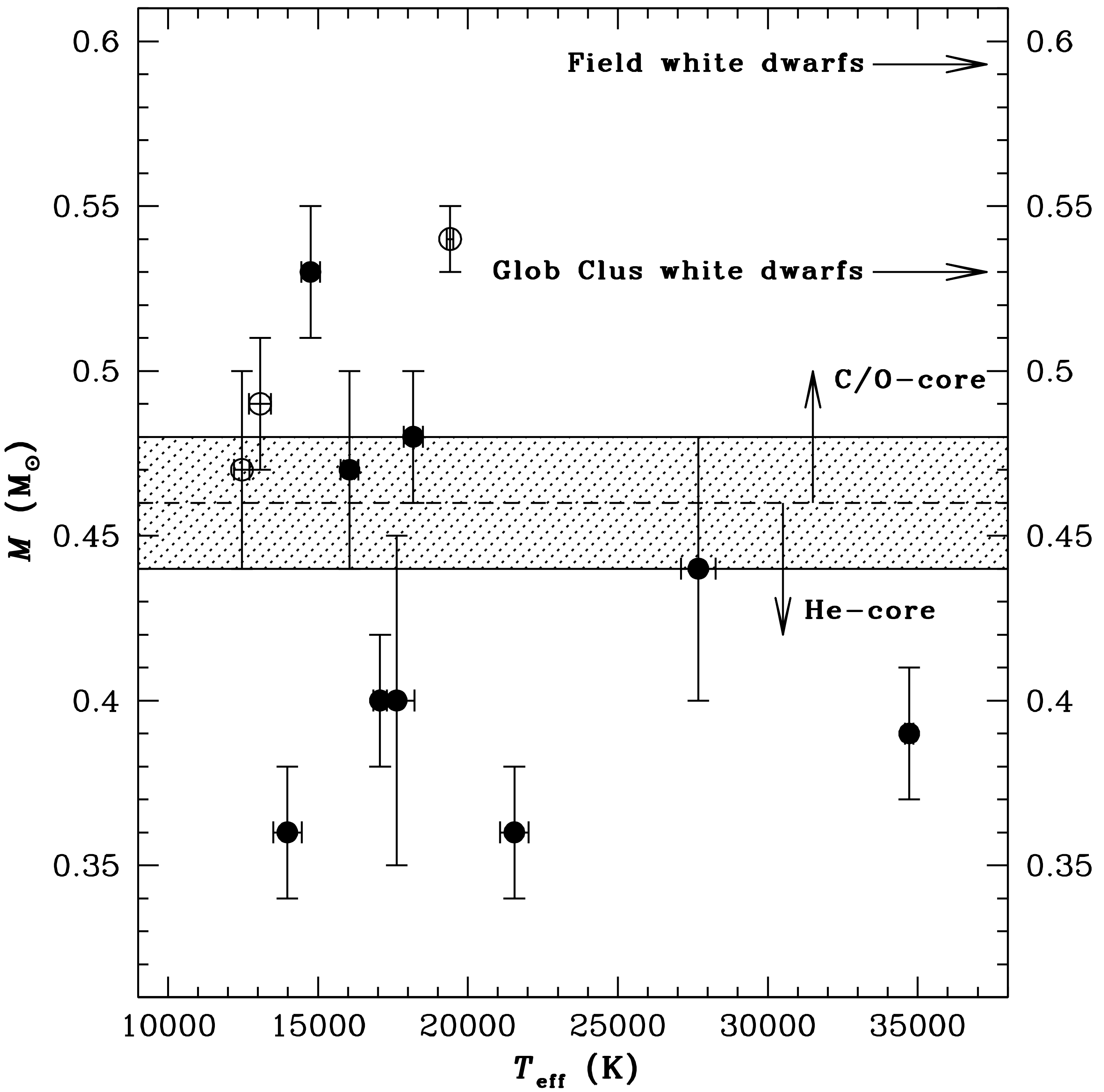




Pressure broadening (Stark effect) => good measure of gravity

Kepler et al. 2019

C+O and He white dwarfs



C+O

He

$L = 4\pi R^2 \sigma T^4$

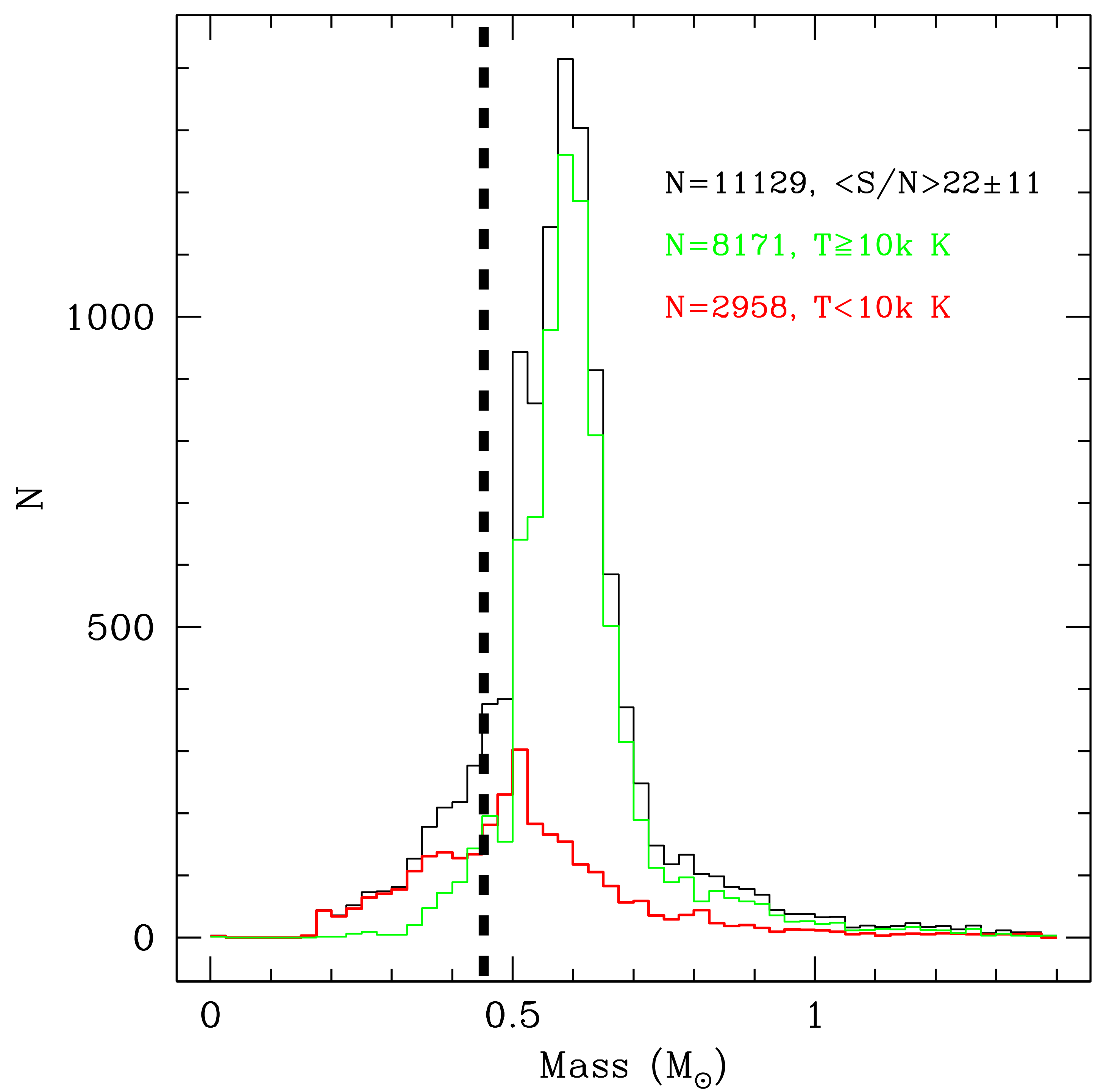
$g = GM/R^2$

if distance is known (cluster or parallax)

M ~ 0.45 Msun for He ignition

Kalirai et al. 2007

Mass distribution of WDs (with H)

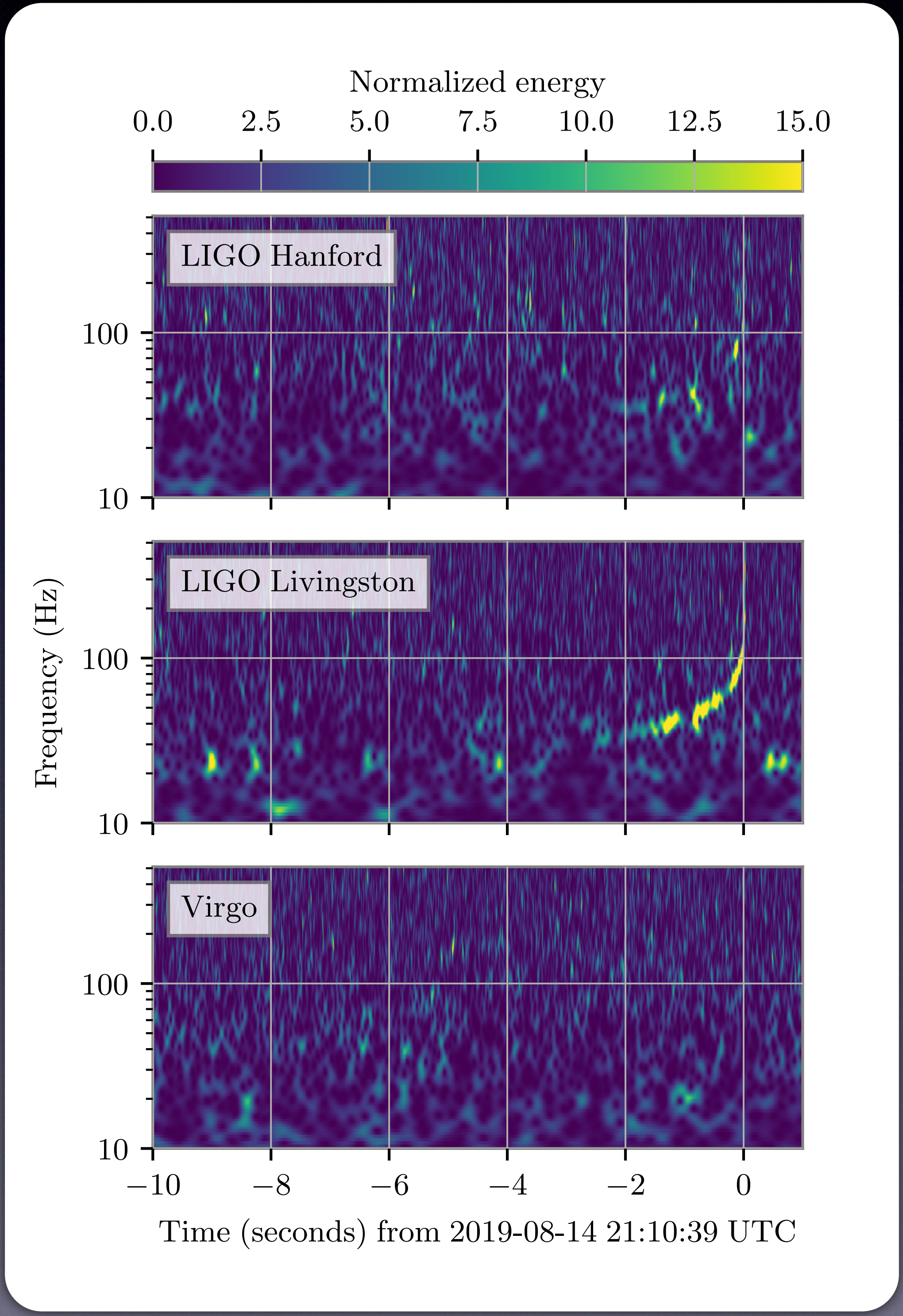


Kepler et al. 2019

Goals of this lecture

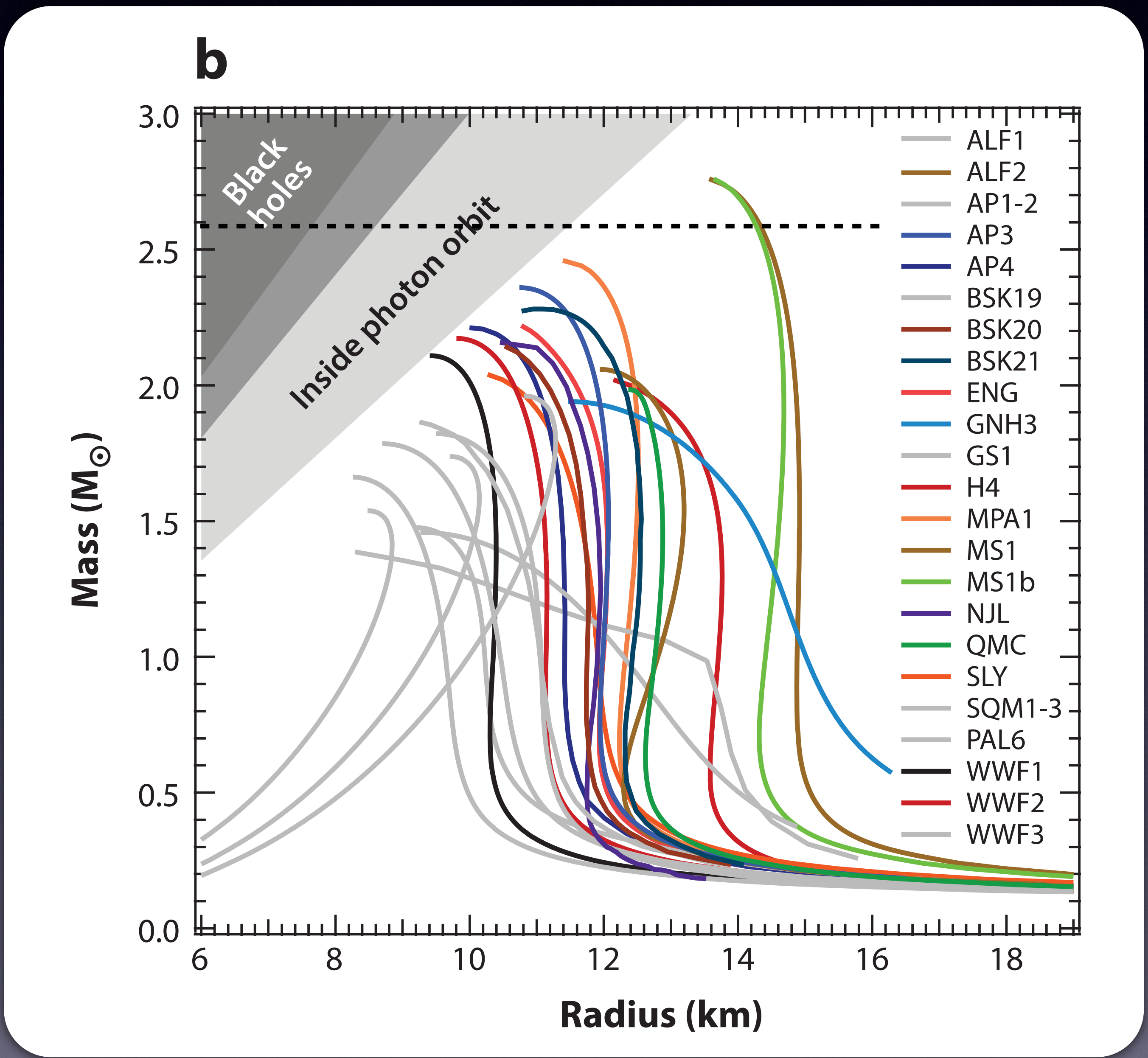
- Standard properties of stars
  - Stellar structure and properties
  - Stellar evolution
- Origin of the elements in the Universe
  - Nucleosynthesis in stars and supernovae
  - Explosion mechanism of supernovae
- Topics in time-domain astronomy
  - Radiation from explosive phenomena
  - Multi-messenger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

Gravitational waves from
23 Msun black hole + 2.6 Msun object!



arXiv: 2006.12611

Is 2.6 Msun object black hole or neutron star?



Discovery of the heaviest NS!?

- Large uncertainty in EOS for NS matter
- But difficult to support 2.6 Msun.

Discovery of lightest black hole!

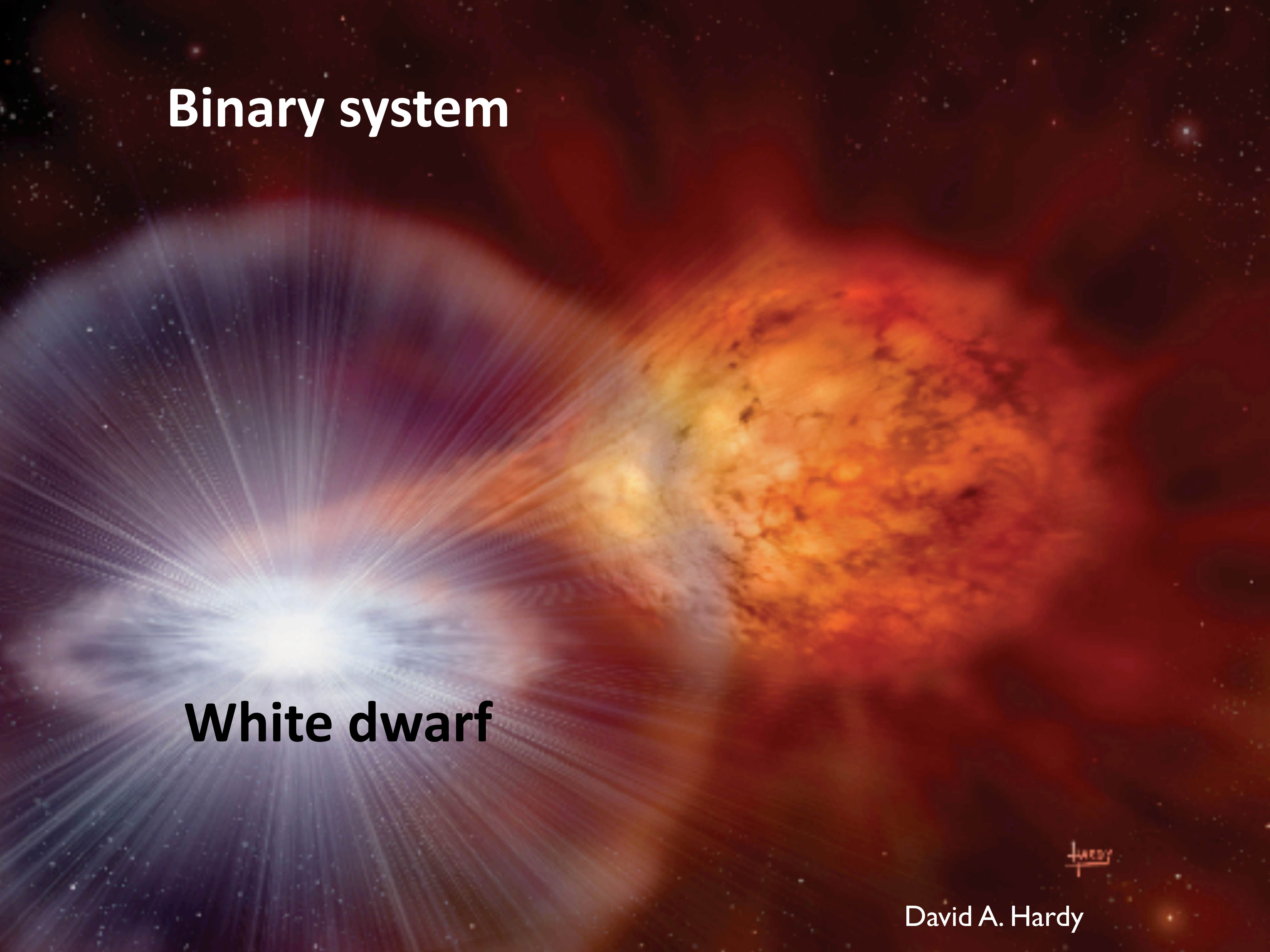
- Implications to supernova mechanism

Ozel 2016

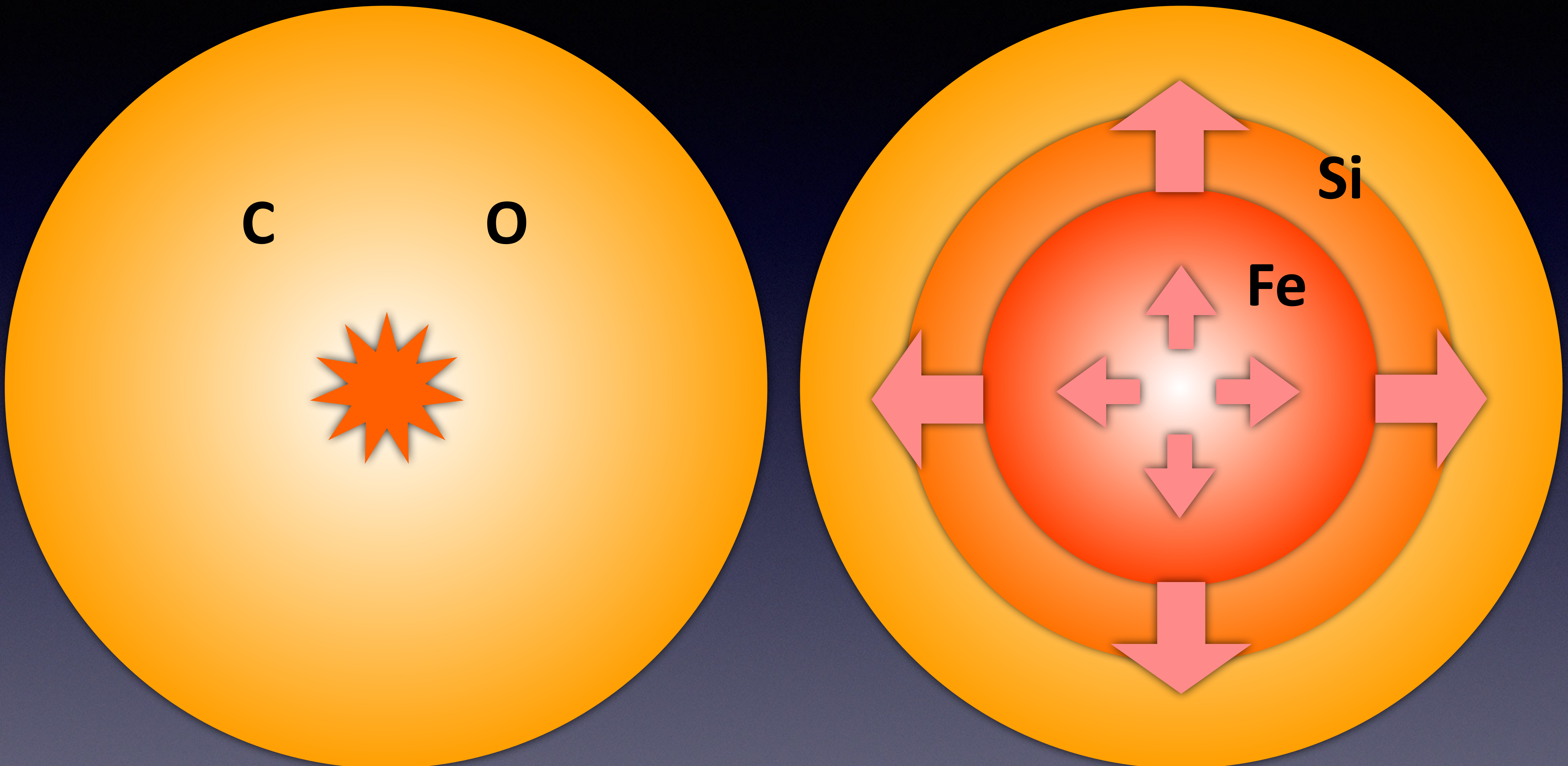
Section 7.
Supernova explosions

7.1 Thermonuclear supernova

7.2 Core-collapse supernova


Binary system
White dwarf
David A. Hardy

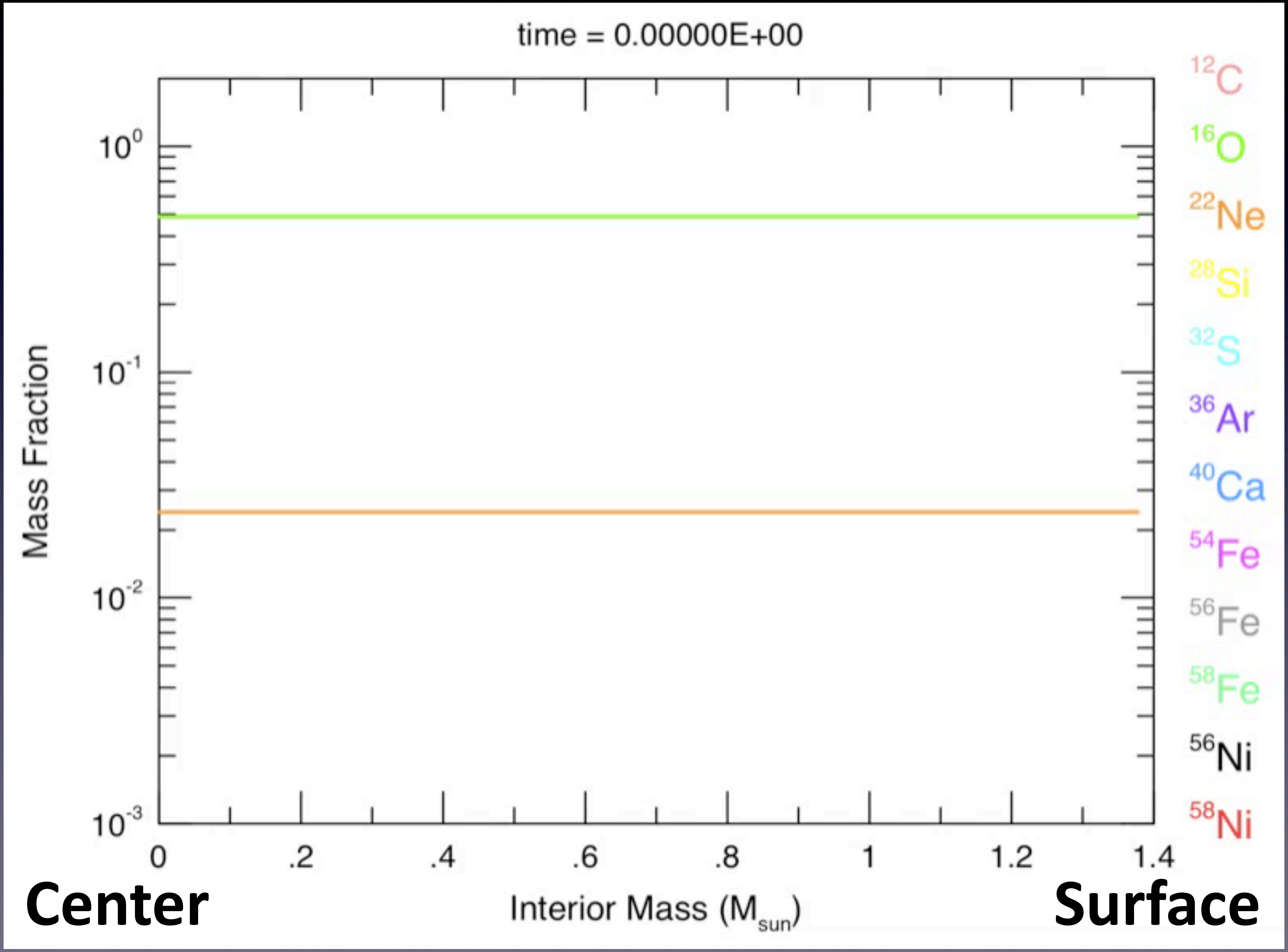
Thermonuclear explosion



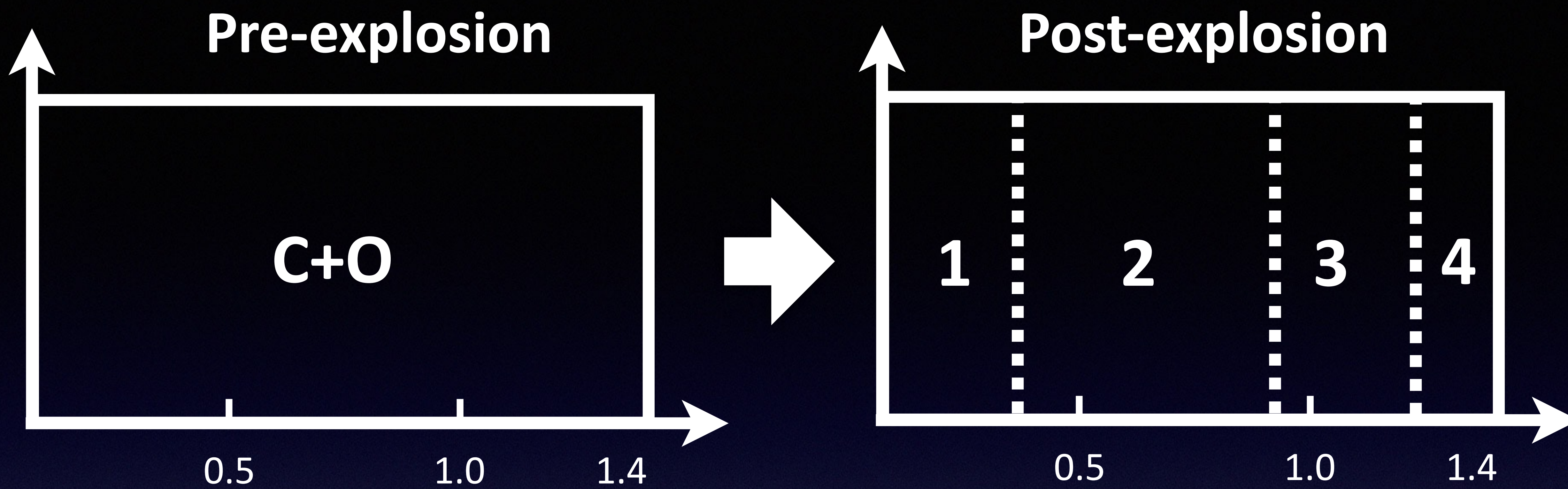
Supernova!

Explosion of white dwarf

Mass fraction



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

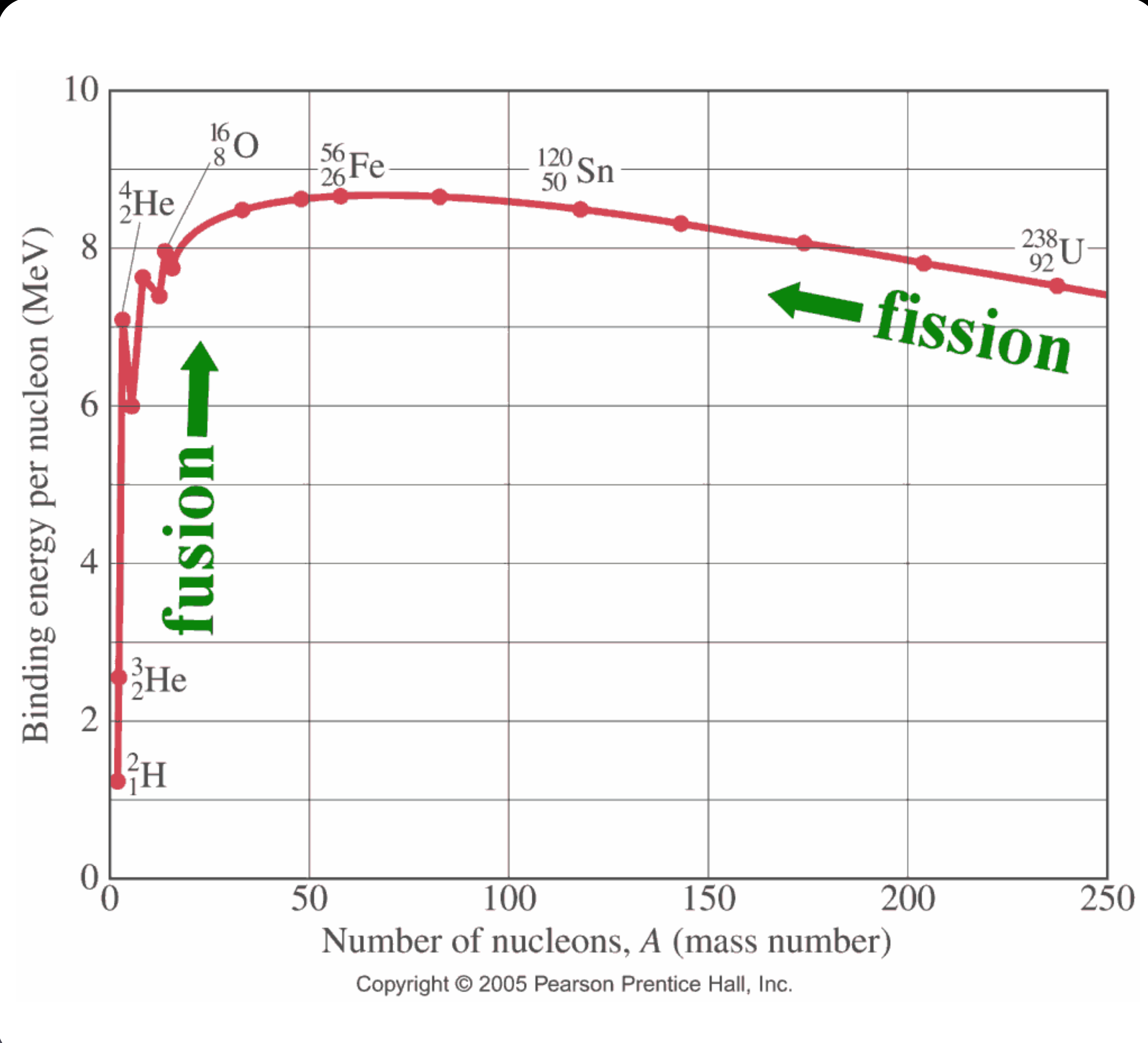
Thermonuclear supernovae

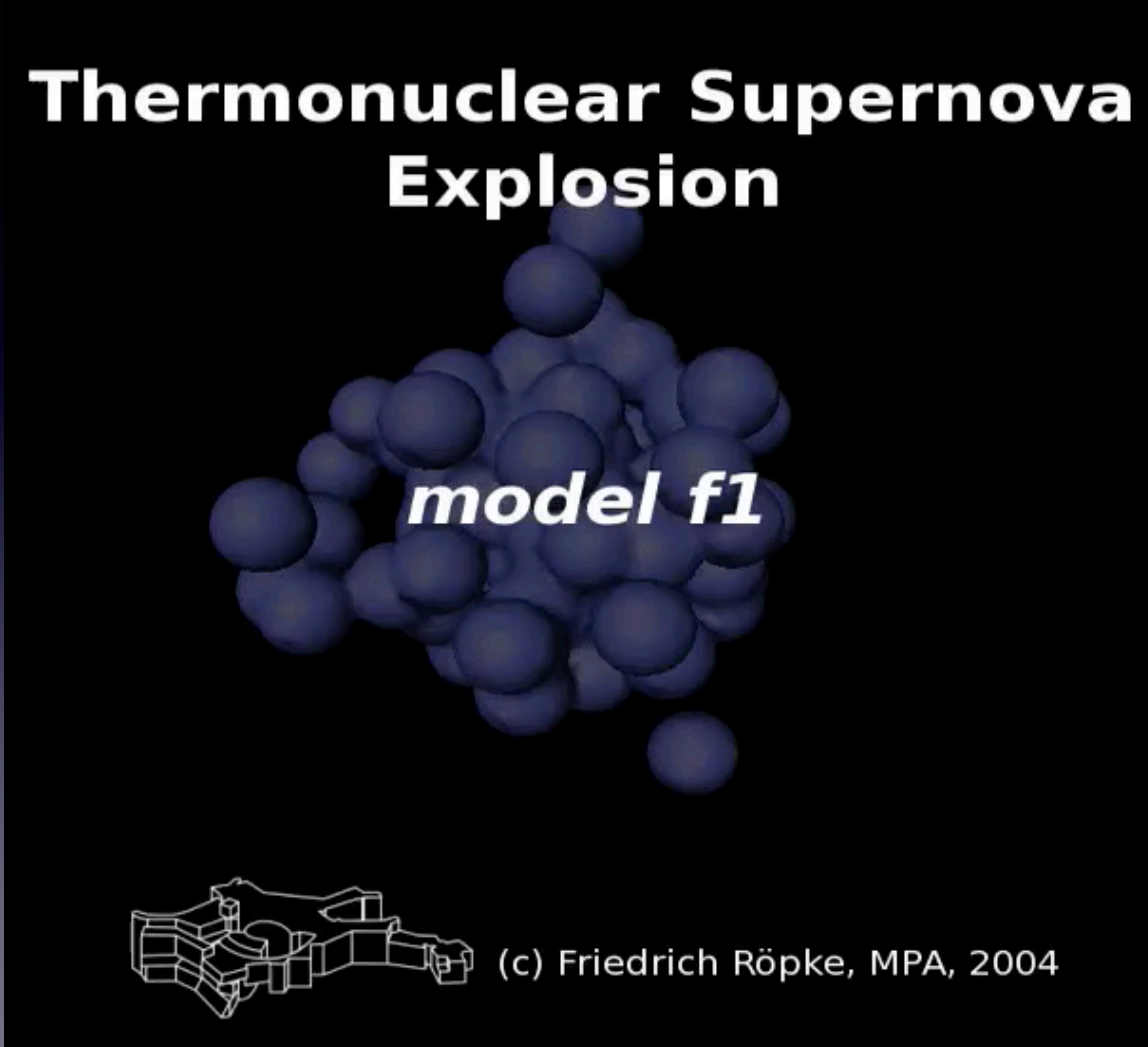
Normal stars are stable with nuclear burning

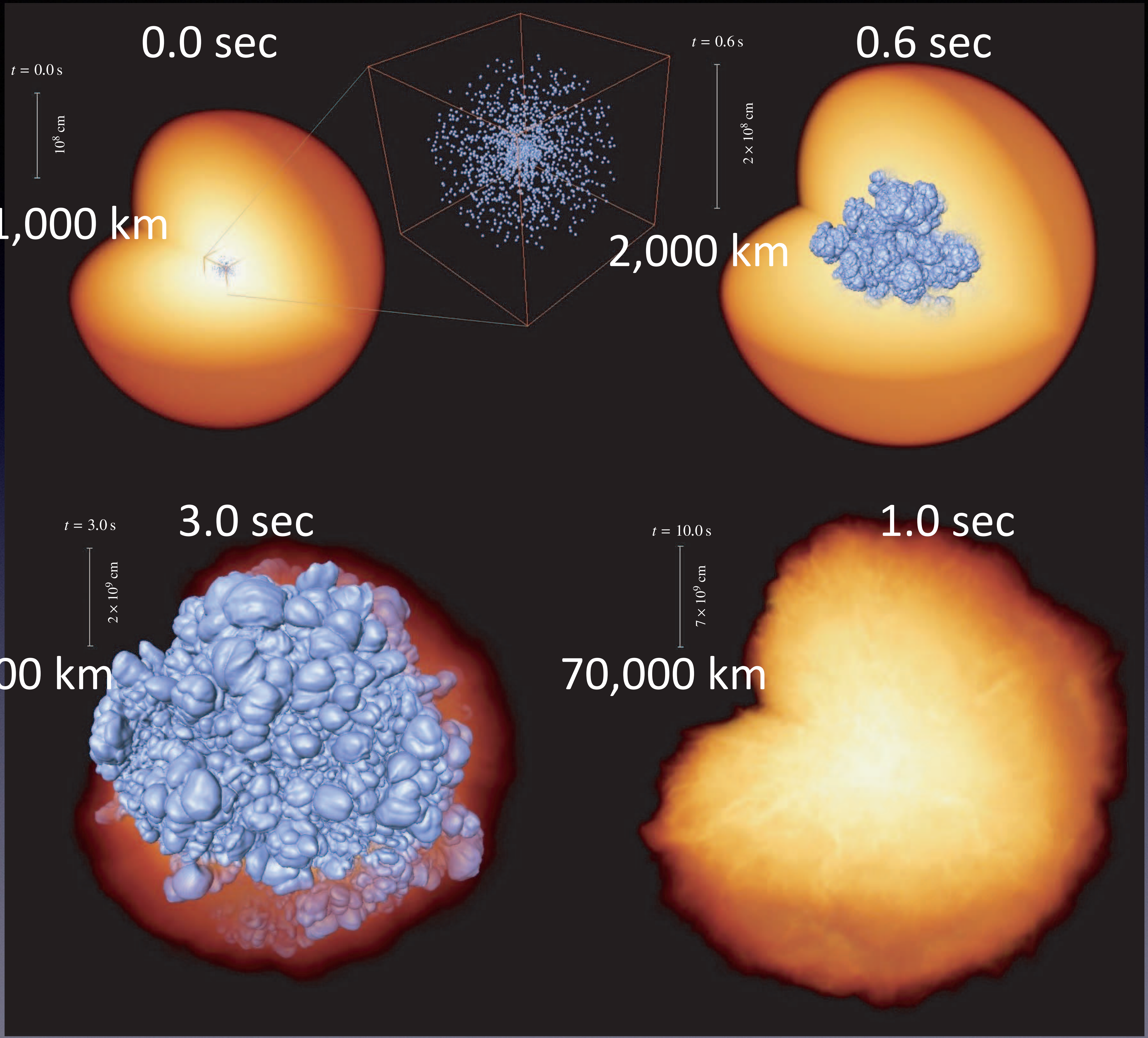
Why do white dwarfs explode by nuclear burning?

Type Ia SN

Sun




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


0.0 sec
t = 0.0 s
10^8 cm
1,000 km
t = 0.6 s
2 × 10^8 cm
0.6 sec
2,000 km
t = 3.0 s
3.0 sec
2 × 10^9 cm
20,000 km
t = 10.0 s
1.0 sec
7 × 10^9 cm
70,000 km

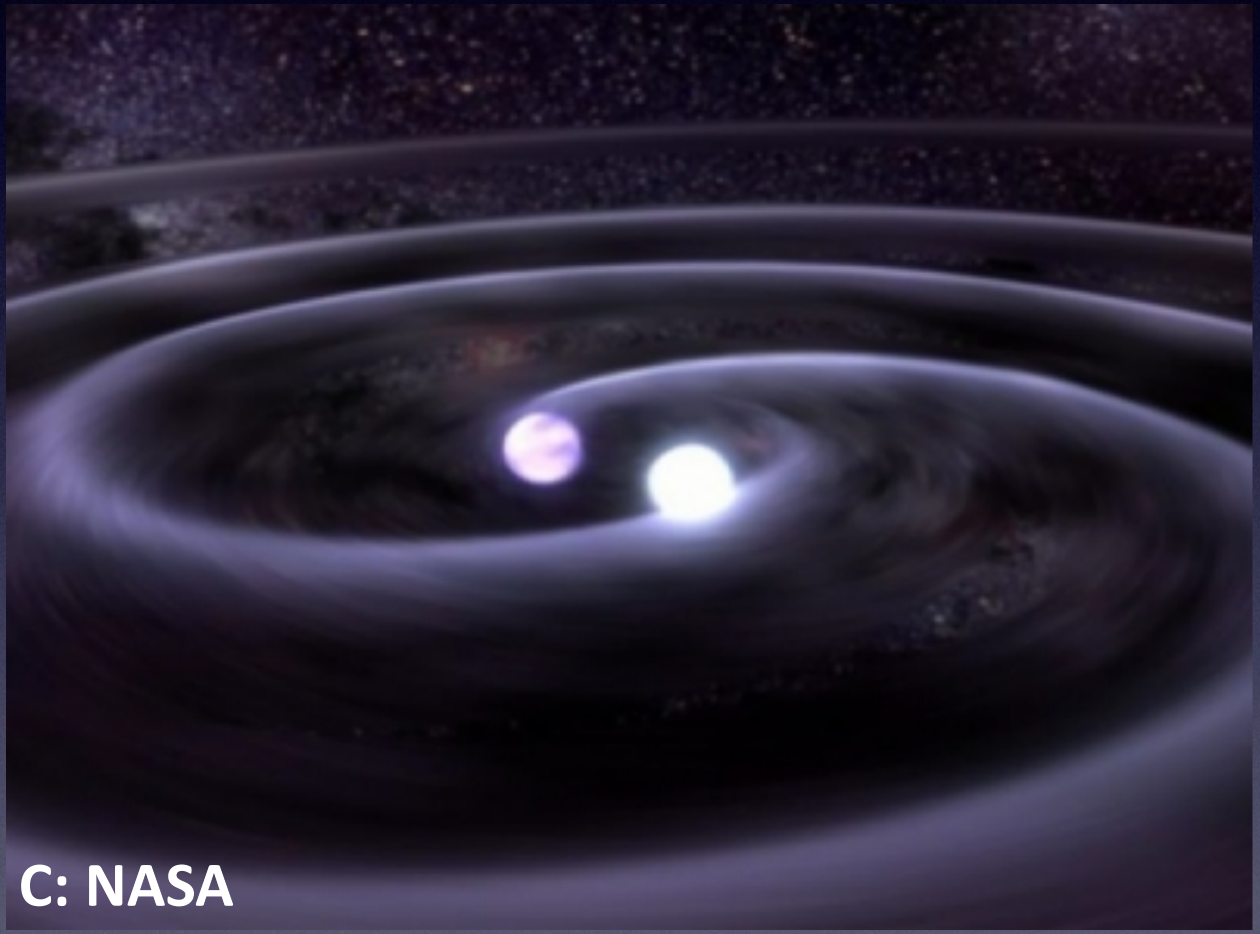
Roepke 2007

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

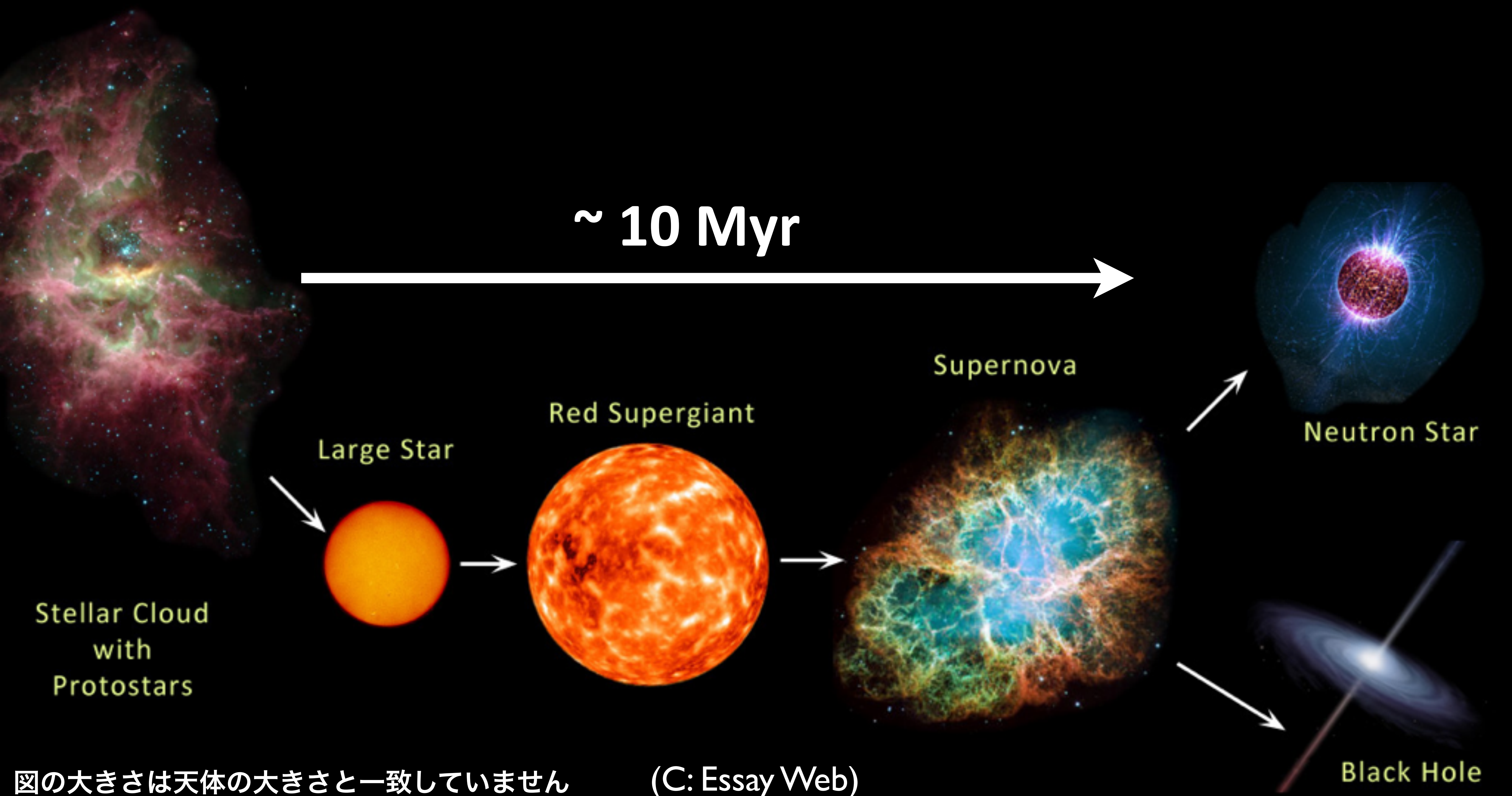
Section 7.
Supernova explosions

7.1 Thermonuclear supernova

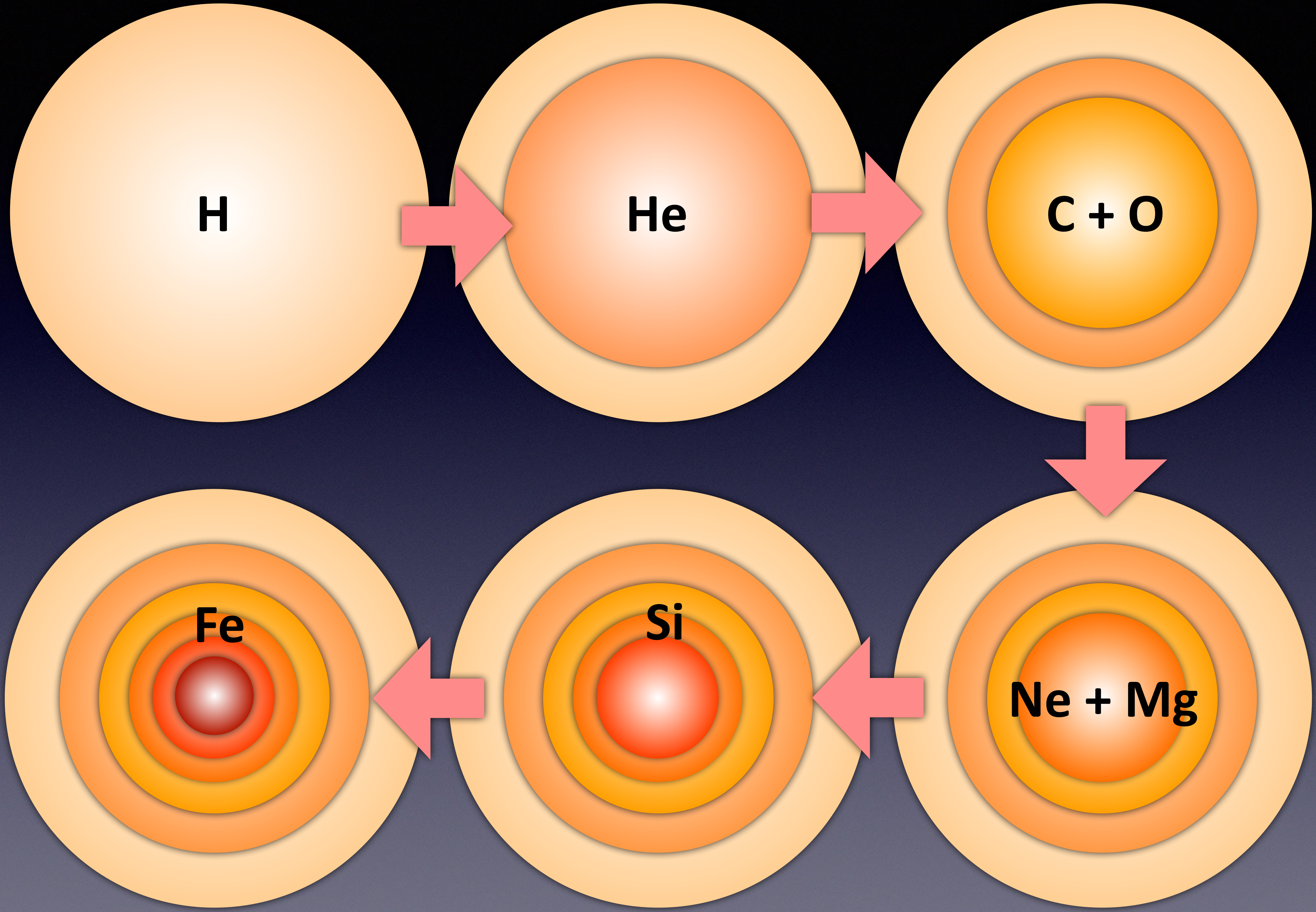
7.2 Core-collapse supernova

1. Massive stars

M > 10 Msun



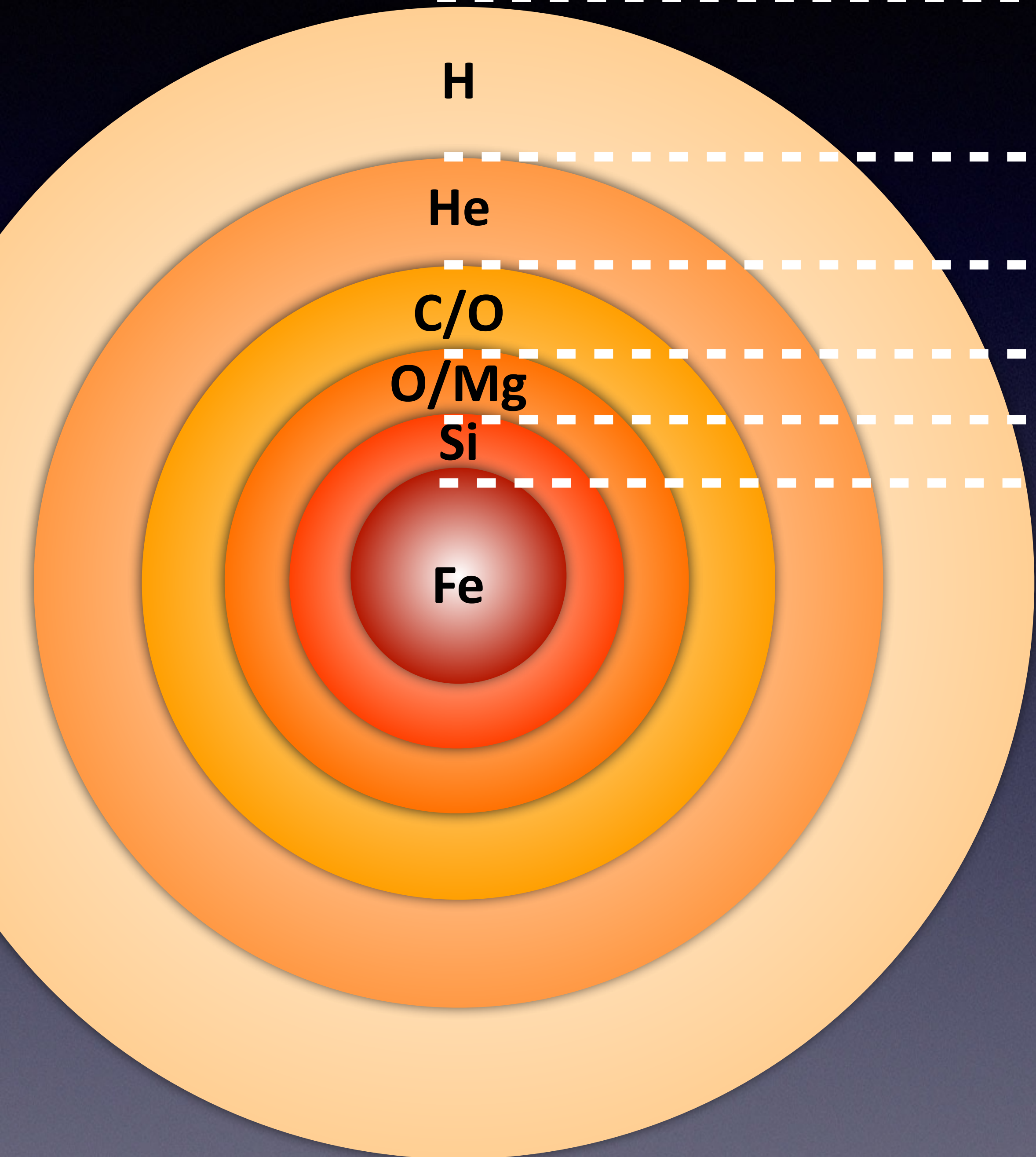
図の大きさは天体の大きさと一致していません (C: Essay Web)



Images are not to scale

20 Msun star

(~16 Msun before the collapse)

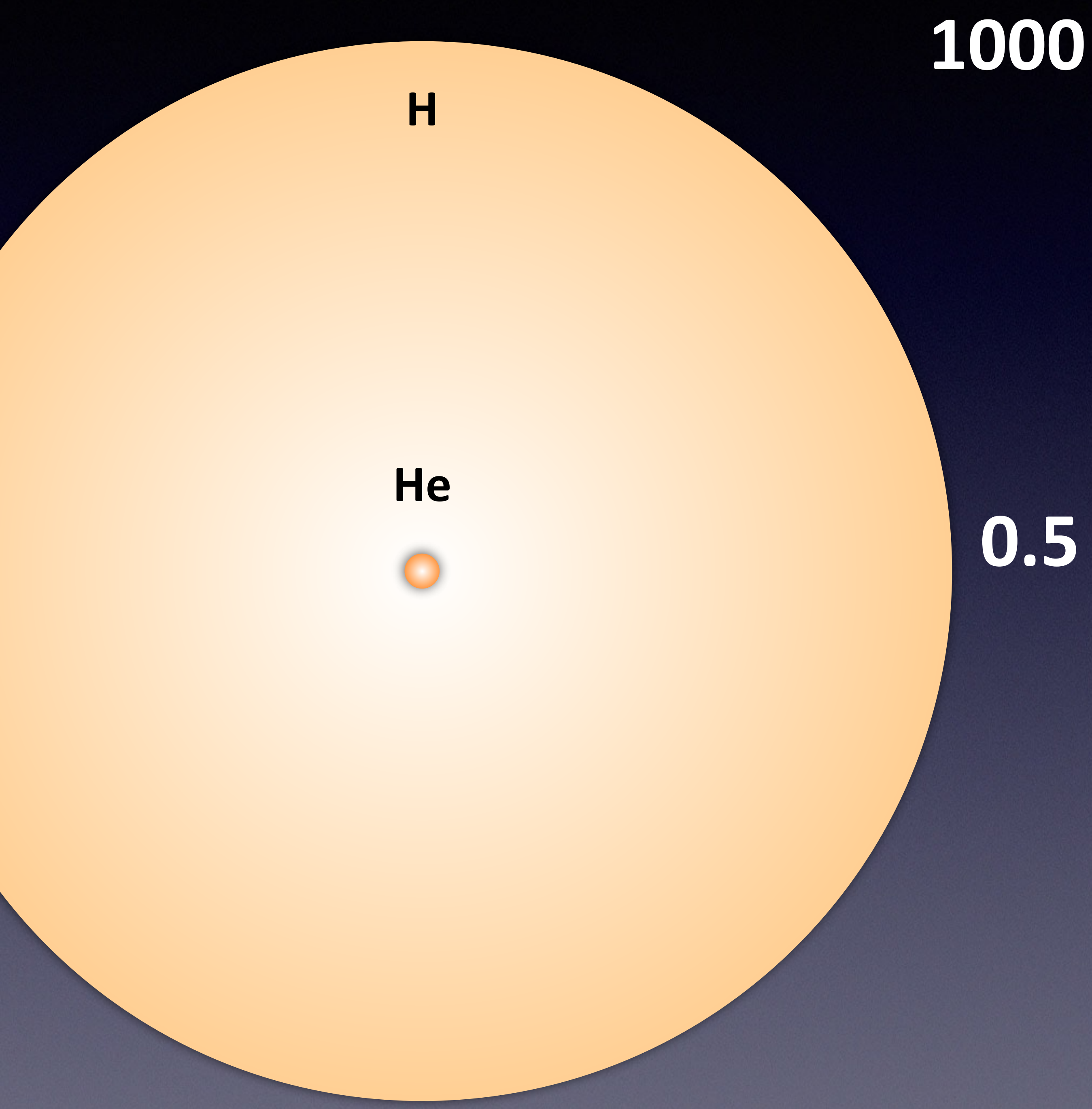


Mass (Msun)	R (Rsun)	Free-fall time (s)
16	1000	3×10^7 (1yr)
6	0.5	300
5	0.2	50
4	0.08	20
2	0.005	1
1.5	0.003	0.1

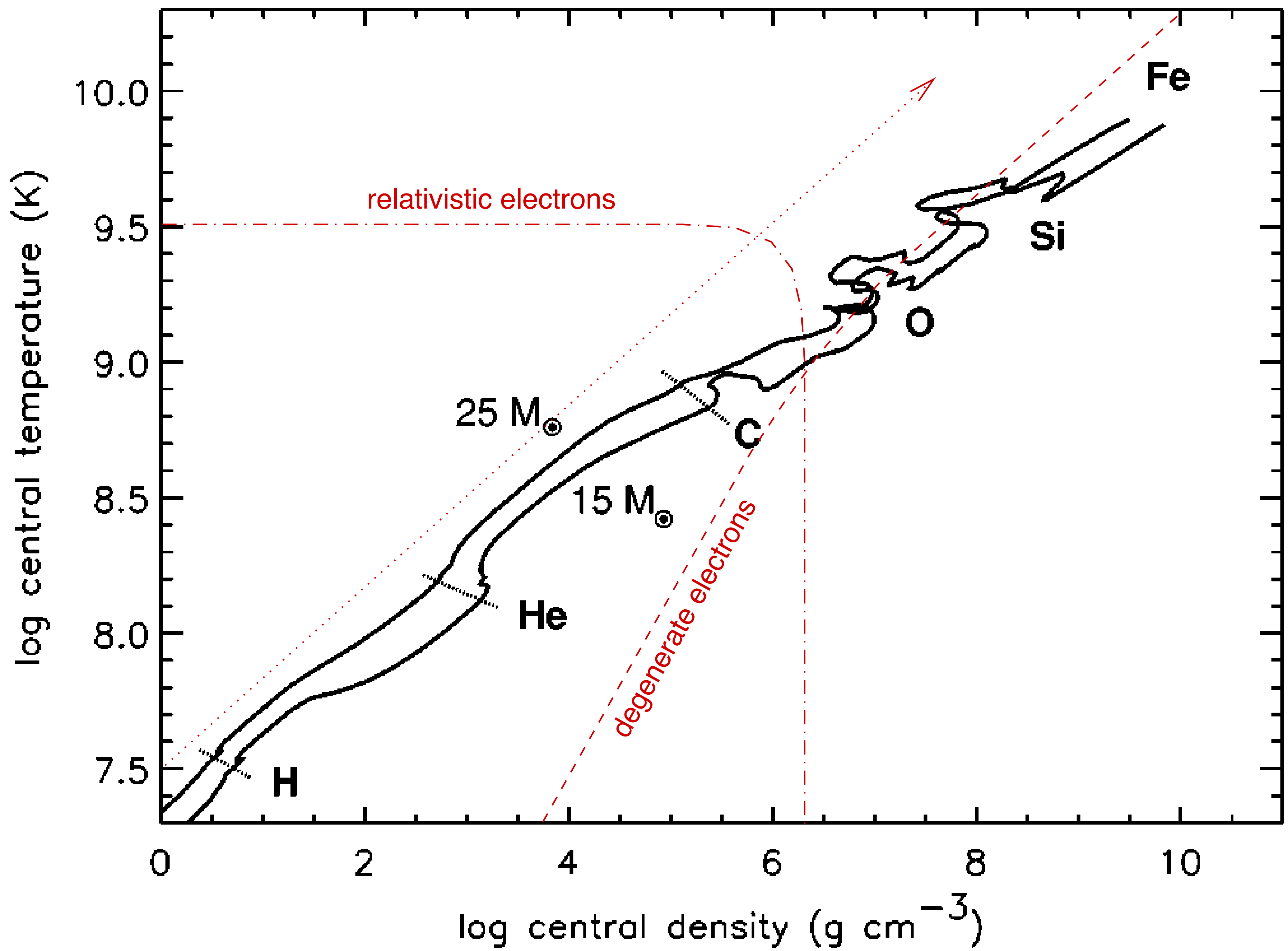
Rsun = 7×10^{10} cm

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

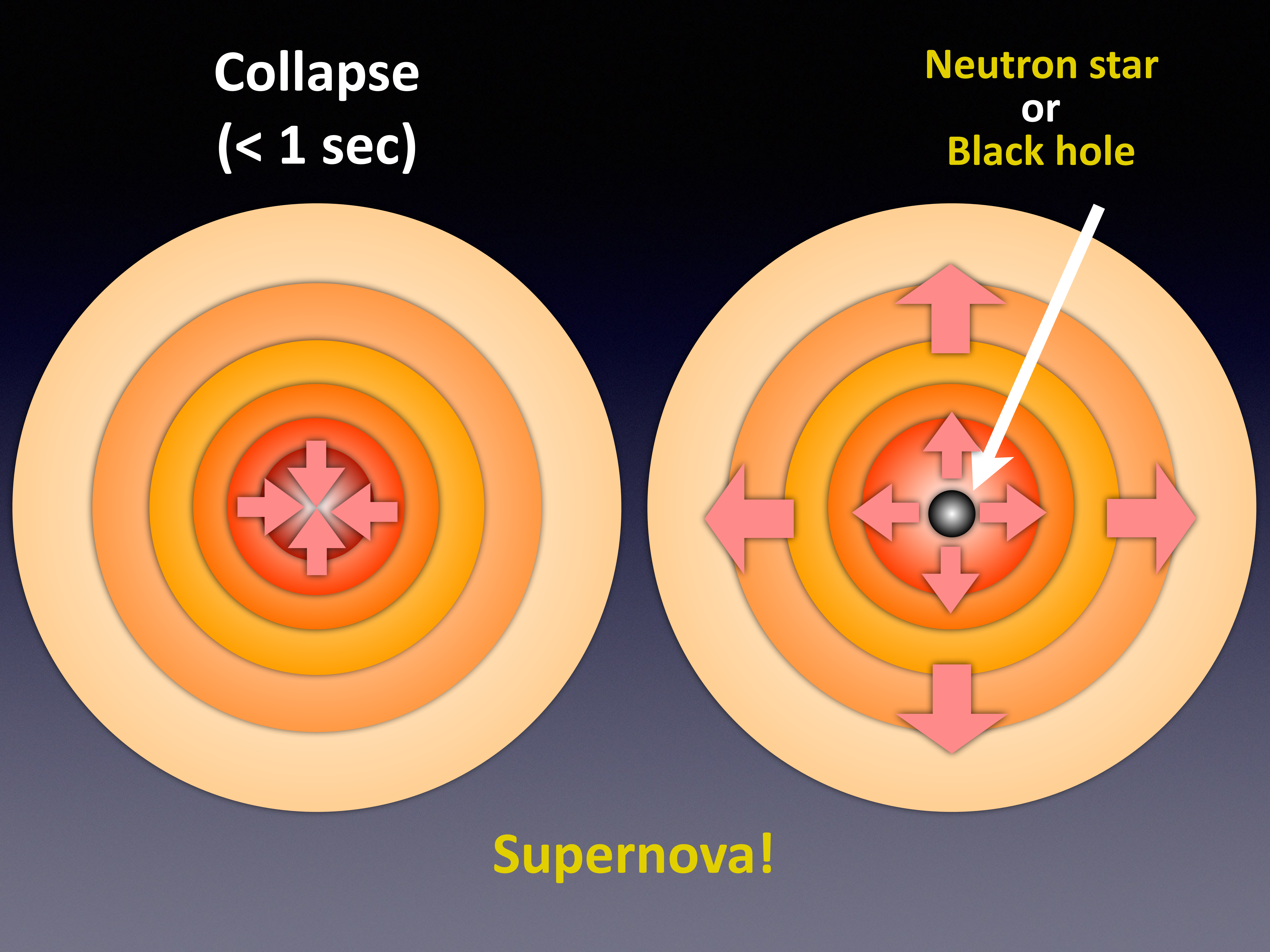


textbook by Pols

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?

Assignment 3 / レポート課題 3

Consider gas consisting of
- non-relativistic (NR) particles (e.g., NR ideal gas, NR degenerate gas) and
- extremely-relativistic (ER) particles (e.g., ER degenerate gas, photons)

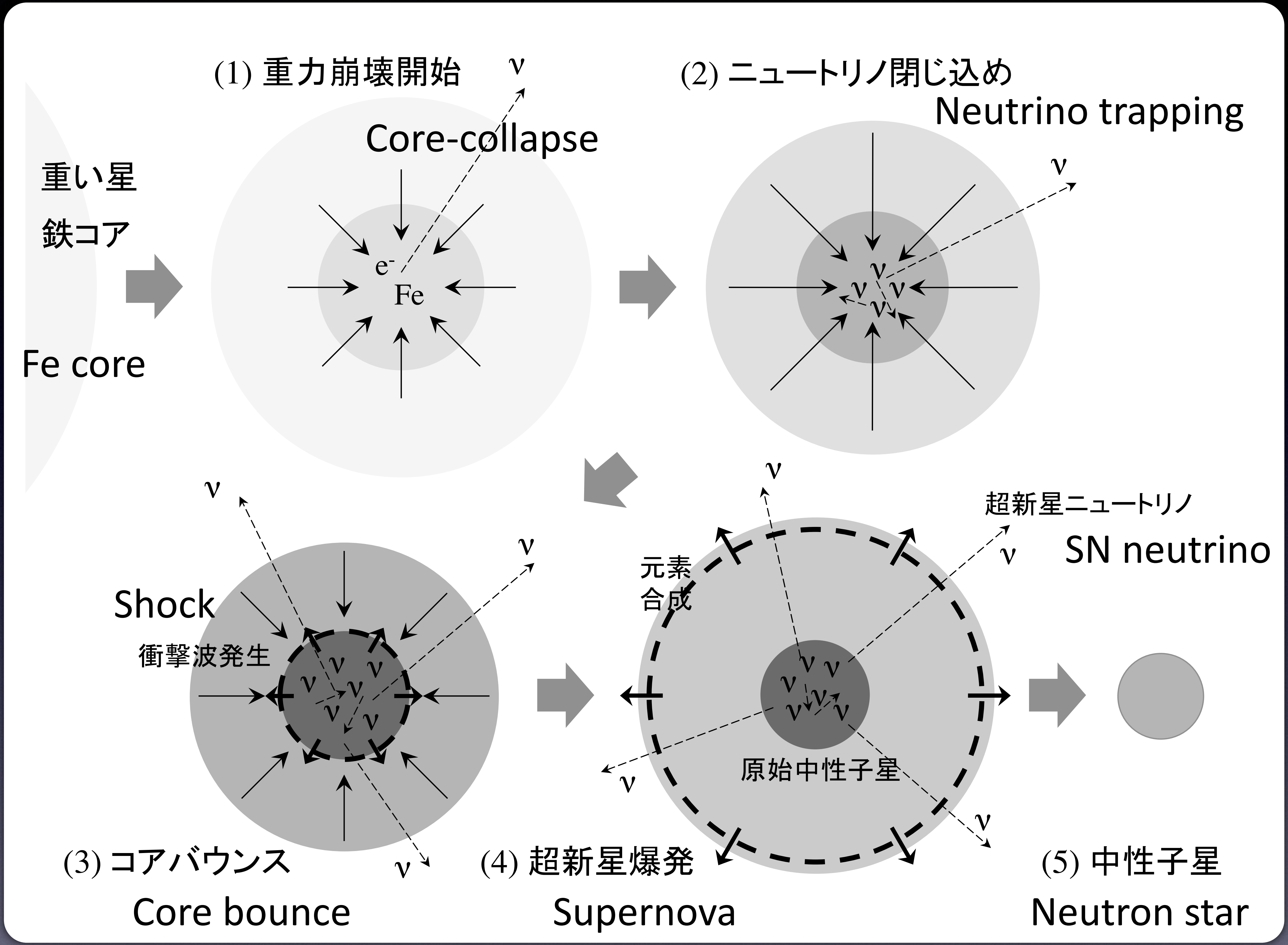
非相対論的(NR)/超相対論的(ER)粒子からなるガスを考える

(3a) Show the following relations
between pressure (P) and energy density (ε)
圧力 (P) とエネルギー密度 (ε) の間に、
以下の関係が成り立つことを示せ

* $P = (2/3)\,\varepsilon$ for NR particles
* $P = (1/3)\,\varepsilon$ for ER particles

(3b) Show adiabatic index (γ) are following
Adiabatic index (γ) が以下のようになることを示せ

* $\gamma = 5/3$ for NR particles
* $\gamma = 4/3$ for ER particles



(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