Section 4.
Stellar evolution (I)

4.1 Virial theorem

4.2 Evolution of density and temperature

4.3 Burning stages

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

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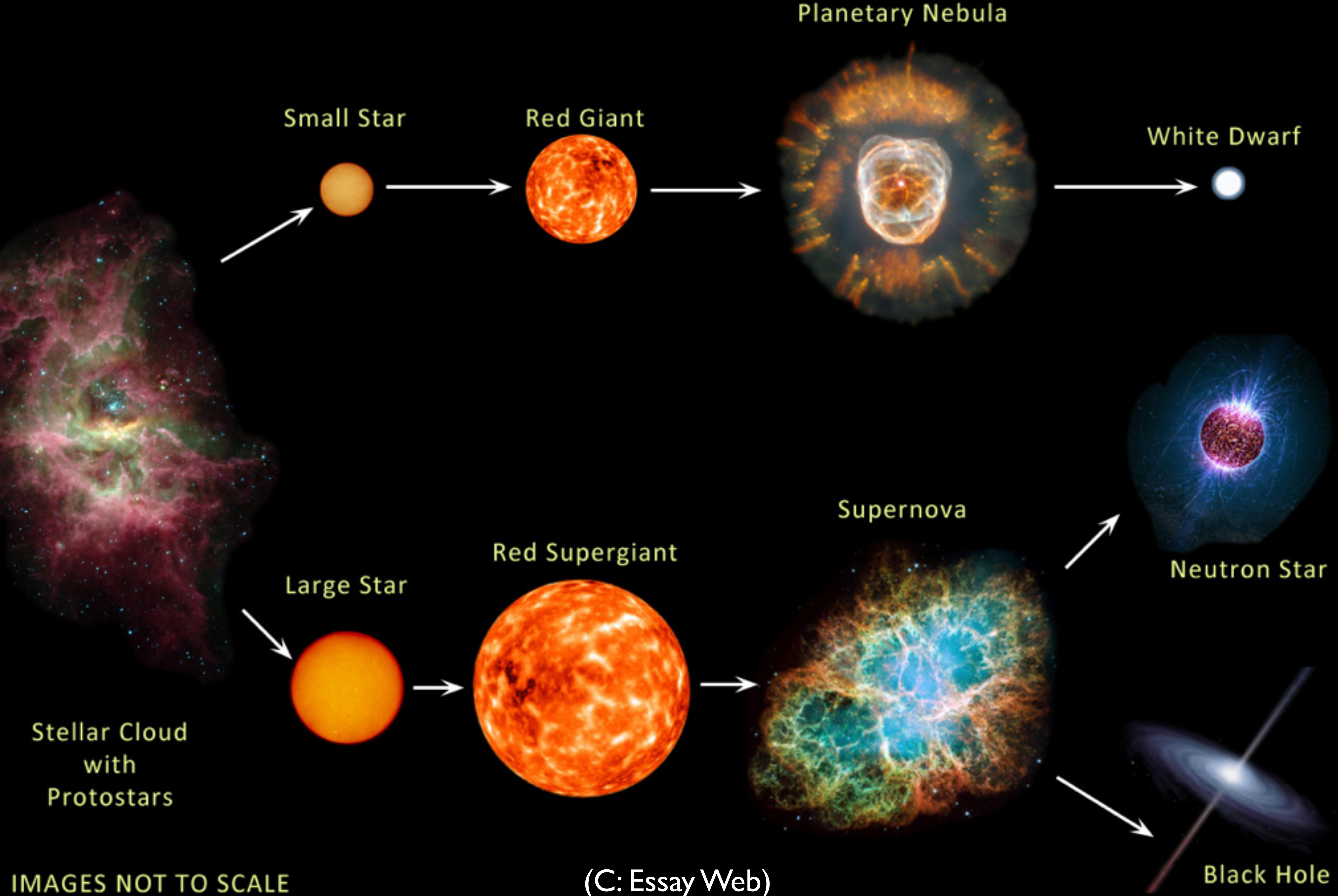
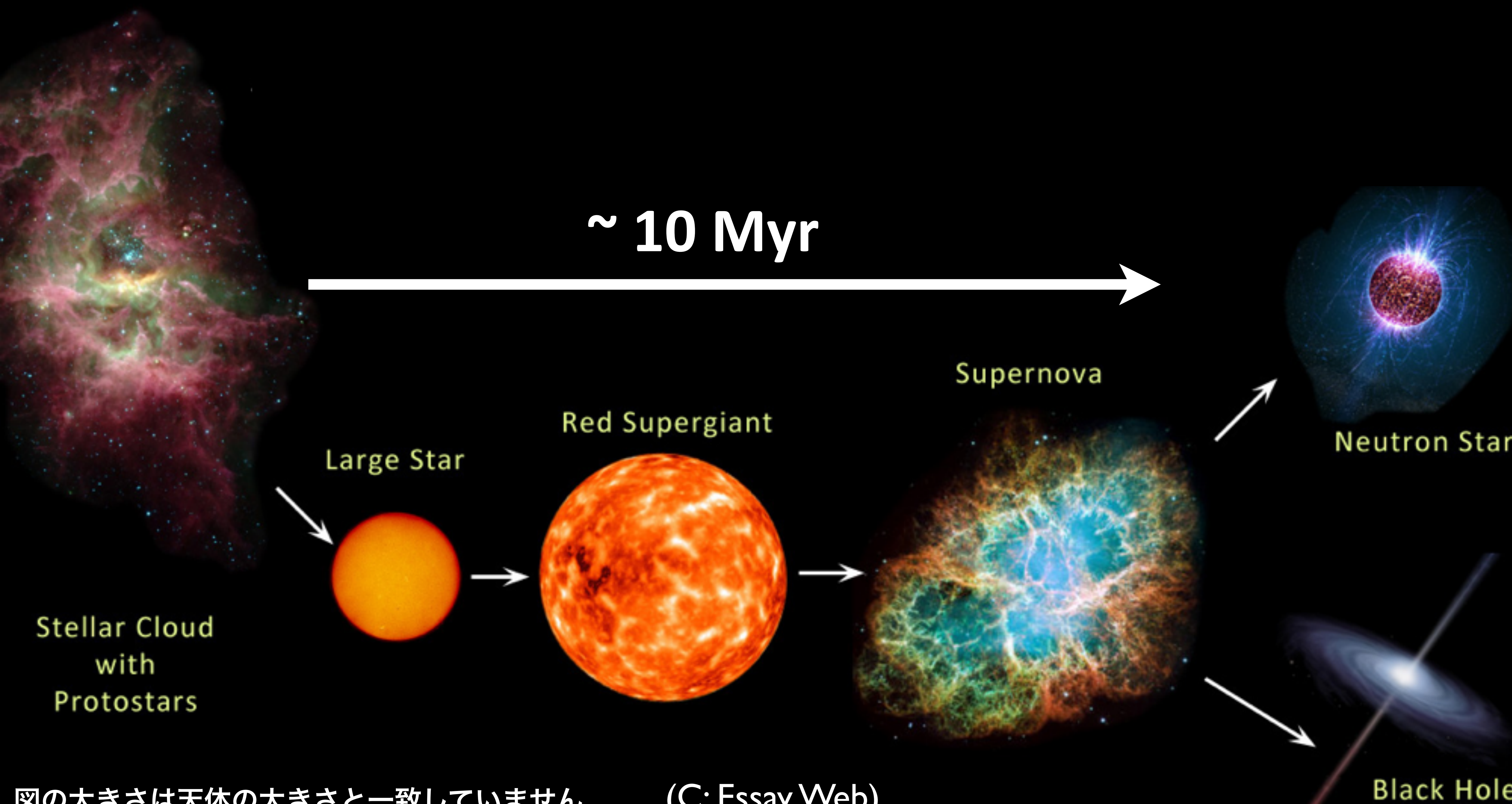
Stellar life



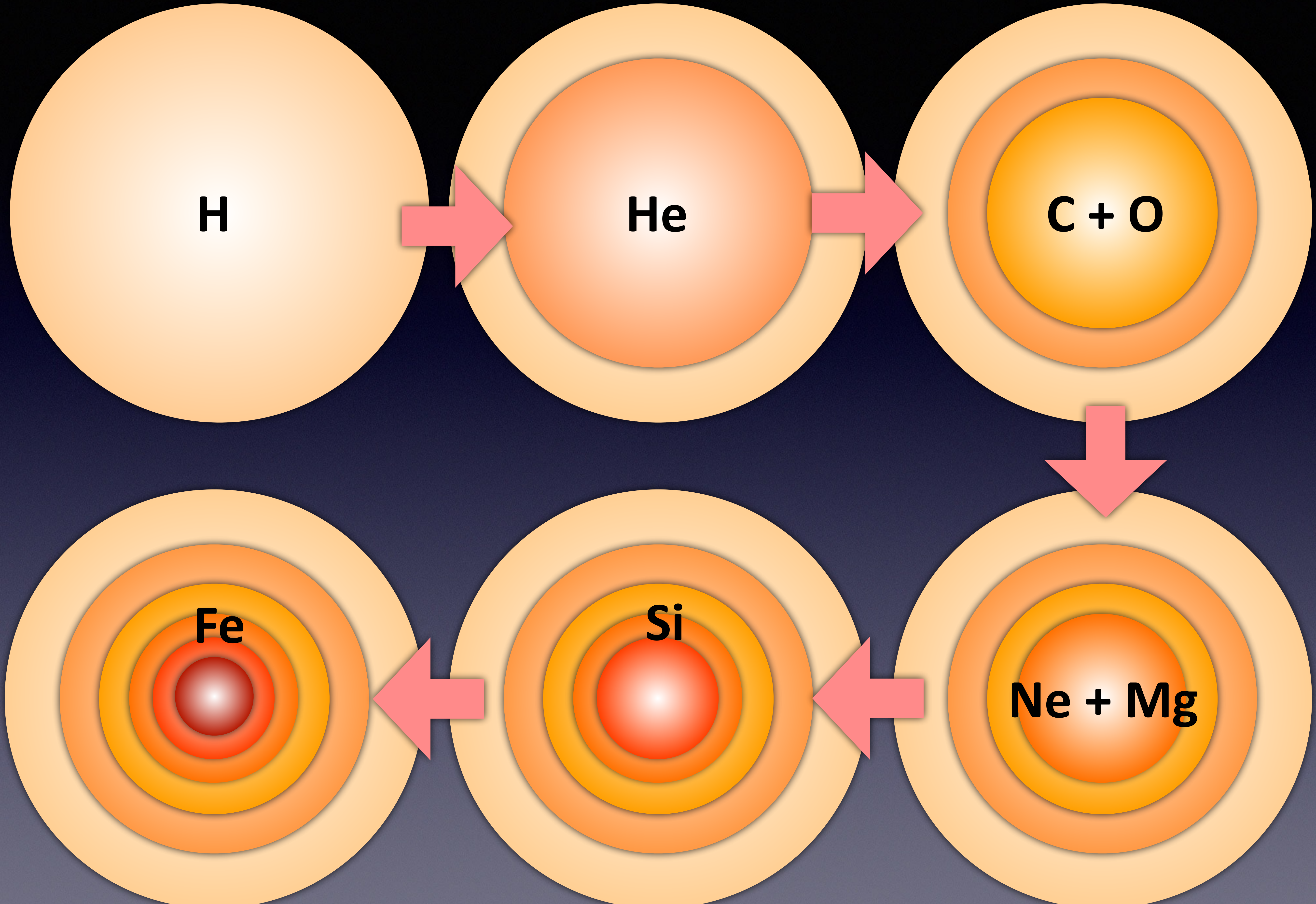
(C: Essay Web)

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

Why do stars evolve??

"Evolution" = Changes in the state with time

What happens when there is no more fuel for nuclear burning

E_{tot}: Total energy

Ω: Gravitational energy

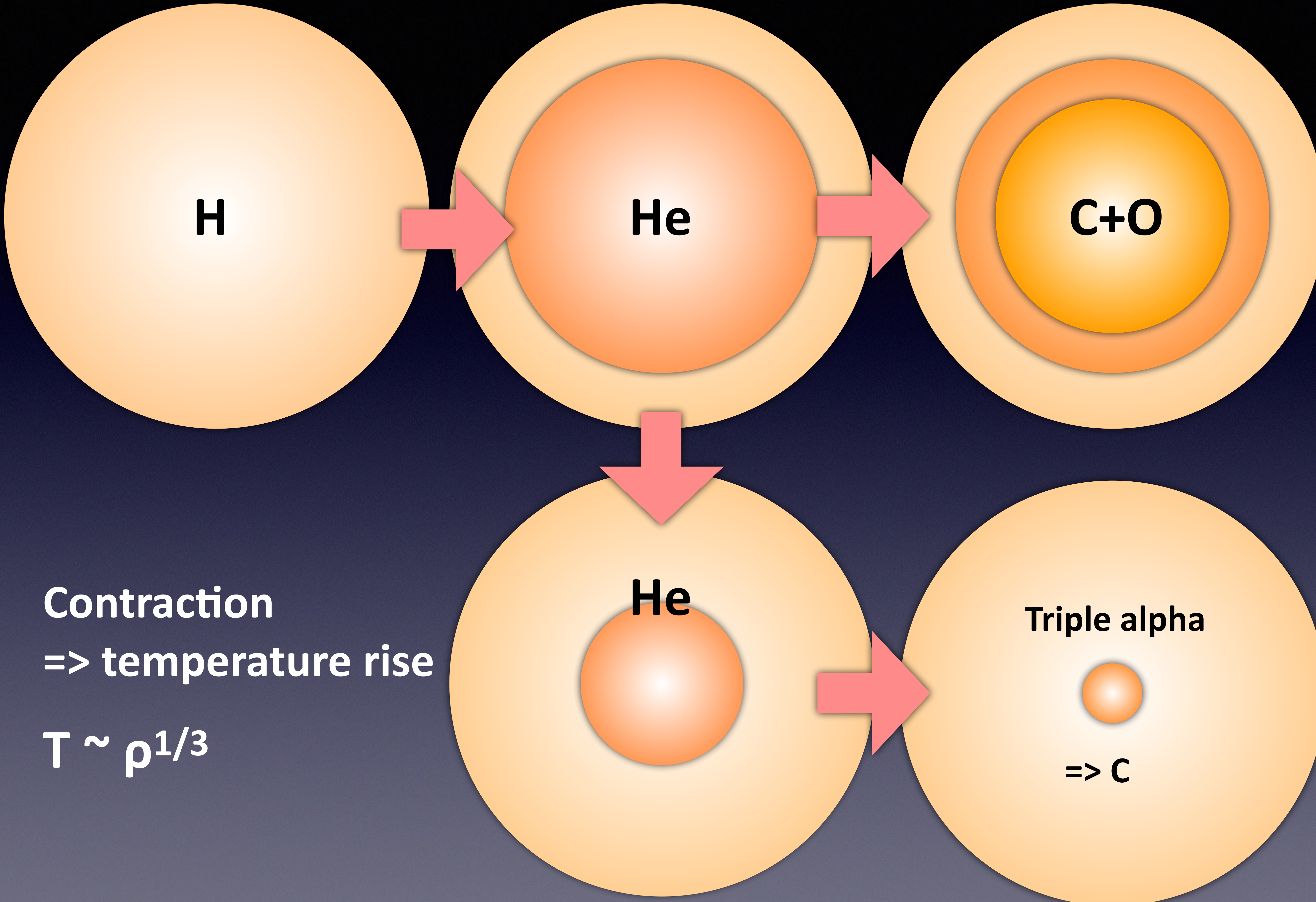
U: Internal energy

$$U = -\frac{1}{2}\Omega$$

$$E_{\rm tot} = U + \Omega = \frac{1}{2}\Omega = -U$$

No nuclear burning

- Total energy decreases
- Contraction (gravitational energy decreases)
- Temperature rises



Contraction

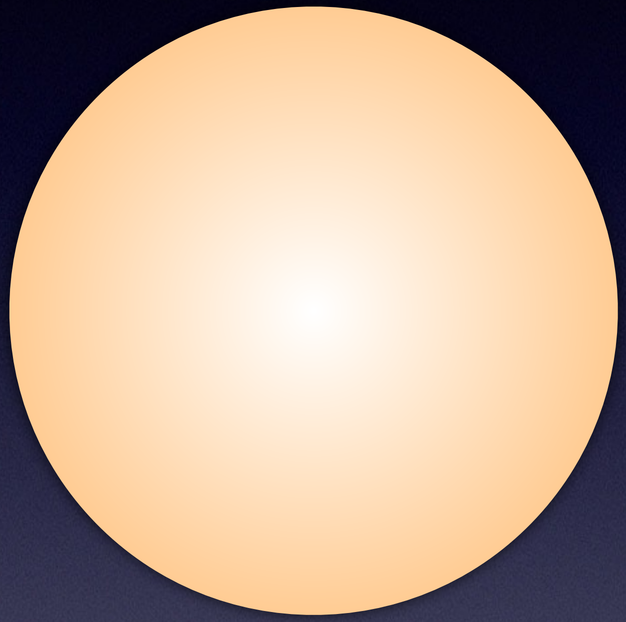
=> temperature rise

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

Images are not to scale

Heated iron

stars



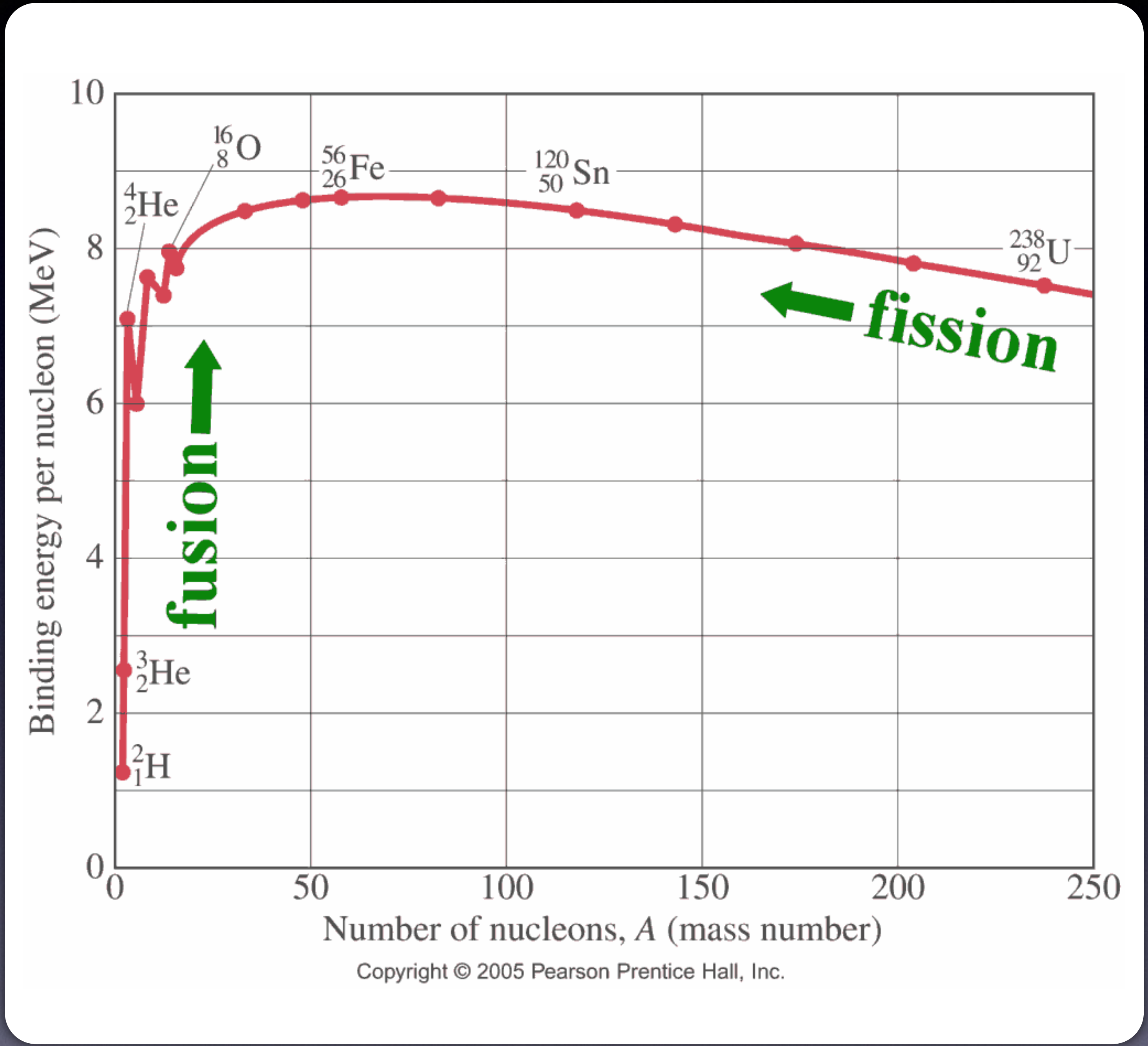
Gets colder

Gets hotter

Section 4.
Stellar evolution (I)

Nuclear binding energy

$$Eb = [Nm_N + Zm_p - m_i]\, c^2 > 0$$



Larger binding energy
= more stable

Fe has the largest
Eb/nucleon

Then, all the stars produce Fe? => No
Stellar material does not always behave as ideal gas

Phase 燃焼段階	Main reactions おもな反応	Products おもな生成物	T 温度 (10^8 K)
H	pp チェイン CNO サイクル	^{4}He ^{14}N	0.15-0.2
He	$3\,^{4}He \longrightarrow {}^{12}C$ $^{12}C + {}^{4}He \longrightarrow {}^{16}O + \gamma$	^{12}C ^{16}O	1.5
C	$^{12}C + {}^{12}C \longrightarrow \begin{cases} ^{23}Na + p \\ ^{20}Ne + \alpha \end{cases}$	Ne,Na Mg,Al	7
Ne	$^{20}Ne + \gamma \longrightarrow {}^{16}O + \alpha$ $^{20}Ne + \alpha \longrightarrow {}^{24}Mg + \gamma$	O Mg	15
O	$^{16}O + {}^{16}O \longrightarrow \begin{cases} ^{28}Si + \alpha \\ ^{31}P + p \end{cases}$	Si,P,S, Cl,Ar,Ca	30
Si	$^{28}Si + \gamma \longrightarrow {}^{24}Mg + \alpha$ $^{24}Mg + \gamma \longrightarrow \begin{cases} ^{23}Na + p \\ ^{20}Ne + \alpha \end{cases}$ 多くの反応 ⟶ 統計平衡	Cr,Mn, Fe,Co, Ni,Cu	40

Nuclear statistical equilibrium

元素はいかにつくられたか（岩波書店）

ρ-T plane
密度 - 温度平面

Summary: Stellar evolution (I)

- Virial theorem (for ideal gas case)
  - Internal energy always relates with gravitational energy
  - When stars lose energy, they contract
  - Temperature rises ("negative heat capacity")
- Evolution of density and temperature
  - Rise in temperature due to contraction $T \sim \rho^{1/3}$
  - Next burning stages => Onion-like structure
  - Do all the stars produce Fe?? => No.
    Equation of states plays an important role

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

Appendix

1a. H-burning (pp chain)

$$4\,{}^{1}H \rightarrow {}^{4}He + 2\,e^{+} + 2\,\nu$$

$${}^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$$

$${}^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$$

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H$$

pp1

$${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$

$${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$$

$${}^{7}Li + {}^{1}H \rightarrow {}^{4}He + {}^{4}He$$

pp2

$${}^{7}Be + {}^{1}H \rightarrow {}^{8}B + \gamma$$

$${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$$

$${}^{8}Be \rightarrow {}^{4}He + {}^{4}He$$

pp3

Textbook by Pols

Energy production rate (per gram)

$q \sim \rho T^4$

$T \sim 4 \times 10^6$ K

$^1H + {^1H} \rightarrow {^2H} + e^+ + \nu$

$^2H + {^1H} \rightarrow {^3He} + \gamma$

$^3He + {^3He} \rightarrow {^4He} + 2\,{^1H}$

pp1

$^3He + {^4He} \rightarrow {^7Be} + \gamma$

$^7Be + e^- \rightarrow {^7Li} + \nu$

$^7Li + {^1H} \rightarrow {^4He} + {^4He}$

pp2

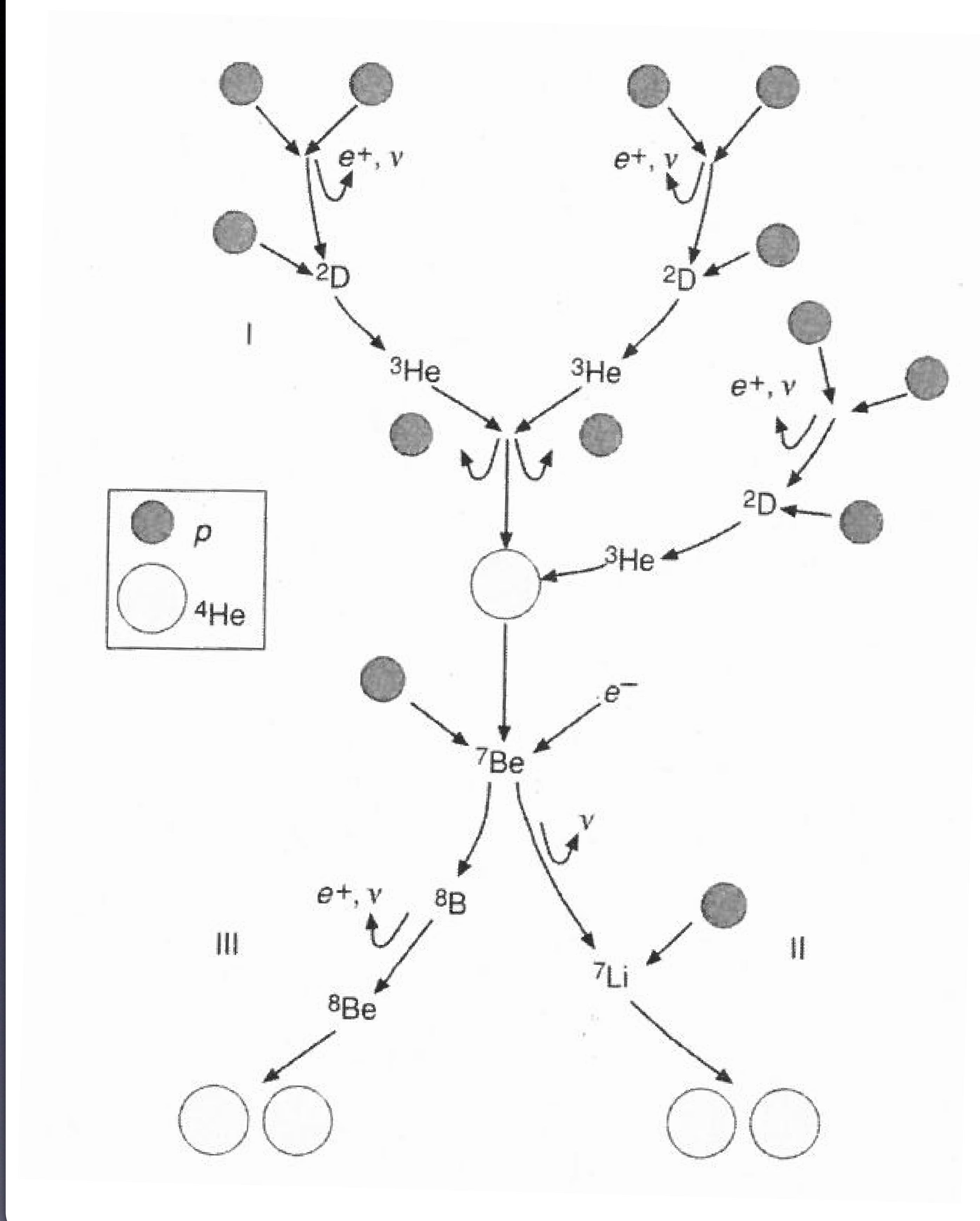
$^7Be + {^1H} \rightarrow {^8B} + \gamma$

$^8B \rightarrow {^8Be} + e^+ + \nu$

$^8Be \rightarrow {^4He} + {^4He}$

pp3

Textbook by Pols



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1b. H burning (CNO cycle)

E production rate q ~ ρT^{16}

T ~ 1.5×10^7 K

$$^{12}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{13}\mathrm{N} + \gamma$$
$$^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^+ + \nu$$
$$^{13}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{14}\mathrm{N} + \gamma$$
$$^{14}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{15}\mathrm{O} + \gamma$$
$$^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^+ + \nu$$
$$^{15}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$$
$$\rightarrow {}^{16}\mathrm{O} + \gamma$$
$$^{16}\mathrm{O} + {}^{1}\mathrm{H} \rightarrow {}^{17}\mathrm{F} + \gamma$$
$$^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^+ + \nu$$
$$^{17}\mathrm{O} + {}^{1}\mathrm{H} \rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$$

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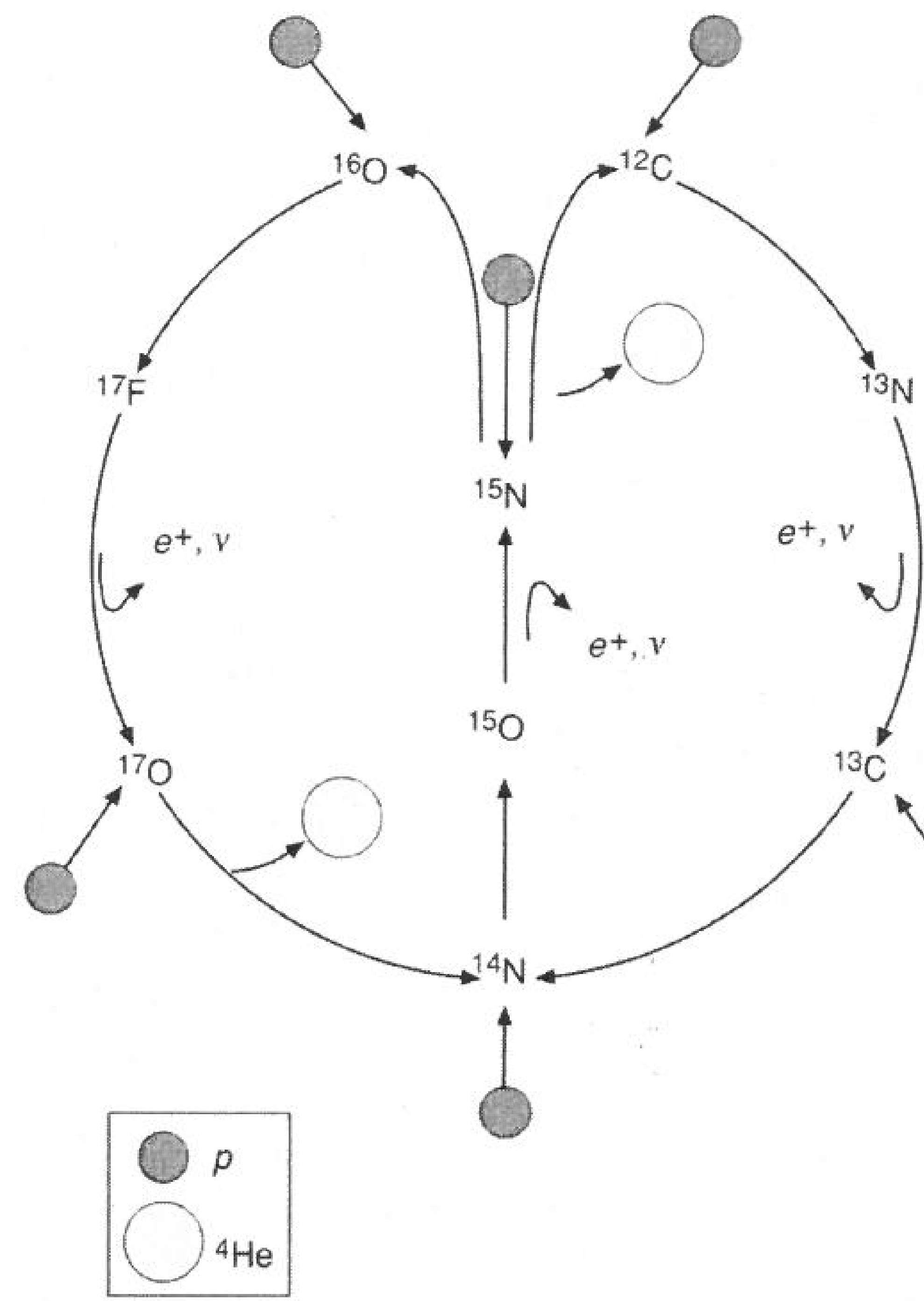

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2. He-burning (triple alpha)

$$^4\text{He} + {}^4\text{He} \leftrightarrow {}^8\text{Be}$$

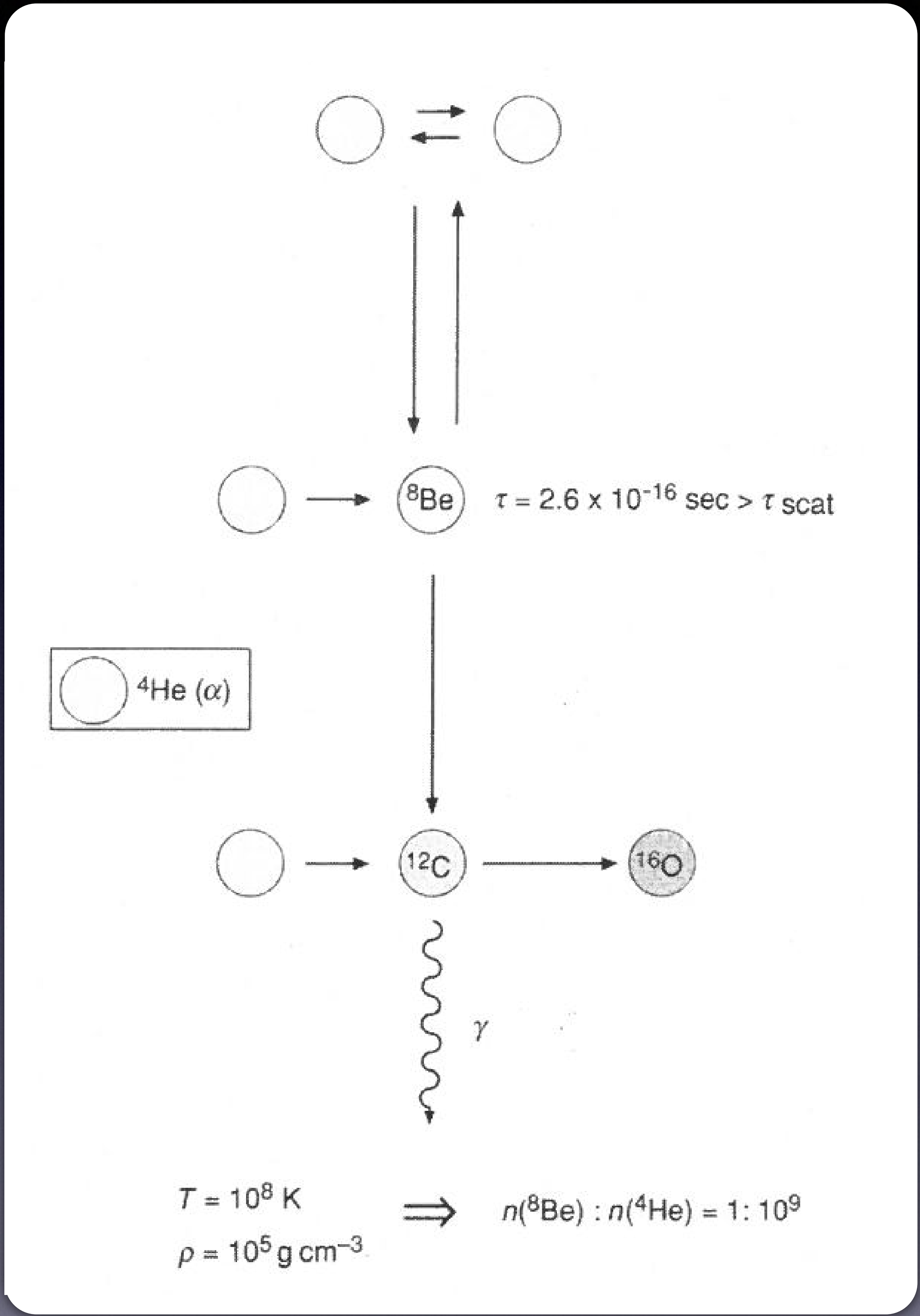
$$^8\text{Be} + {}^4\text{He} \rightarrow {}^{12}\text{C}^* \rightarrow {}^{12}\text{C} + \gamma$$

$$^{12}\text{C} + {}^4\text{He} \rightarrow {}^{16}\text{O} + \gamma,$$

Energy production rate (per gram)

$q \sim \rho^2 T^{40}$

$T \sim 1.5 \times 10^8$ K



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3. C-burning

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* \rightarrow {}^{20}\mathrm{Ne} + \alpha$$
$$\rightarrow {}^{23}\mathrm{Na} + \mathrm{p}$$

T ~ 7 x 10^8 K

4. Ne-burning

$$^{20}\mathrm{Ne} + \gamma \leftrightarrow {}^{16}\mathrm{O} + \alpha$$
$$^{20}\mathrm{Ne} + \alpha \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

T ~ 1.5 x 10^9 K

5. O-burning

$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{32}\mathrm{S}^* \rightarrow {}^{28}\mathrm{Si} + \alpha$$
$$\rightarrow {}^{31}\mathrm{P} + \mathrm{p}$$

T ~ 2-3 x 10^9 K

6. Si-burning（Nuclear statistical equilibrium）

T > 4 x 10^9 K

High temperature => photo-dissociation

$$^{28}\mathrm{Si}\,(\gamma,\alpha)\,^{24}\mathrm{Mg}\,(\gamma,\alpha)\,^{20}\mathrm{Ne}\,(\gamma,\alpha)\,^{16}\mathrm{O}\,(\gamma,\alpha)\,^{12}\mathrm{C}\,(\gamma,\alpha)\,2\alpha$$

He capture

$$^{28}\mathrm{Si}\,(\alpha,\gamma)\,^{32}\mathrm{S}\,(\alpha,\gamma)\,^{36}\mathrm{Ar}\,(\alpha,\gamma)\,^{40}\mathrm{Ca}\,(\alpha,\gamma)\,^{44}\mathrm{Ti}\,(\alpha,\gamma)\,\ldots\,^{56}\mathrm{Ni}$$

=> equilibrium of many reactions

(Ex.)

$$^{28}\mathrm{Si} + \gamma \leftrightarrow {}^{24}\mathrm{Mg} + \alpha,$$

Nuclei with high binding energy tend to be produced (Fe, Co, Ni)