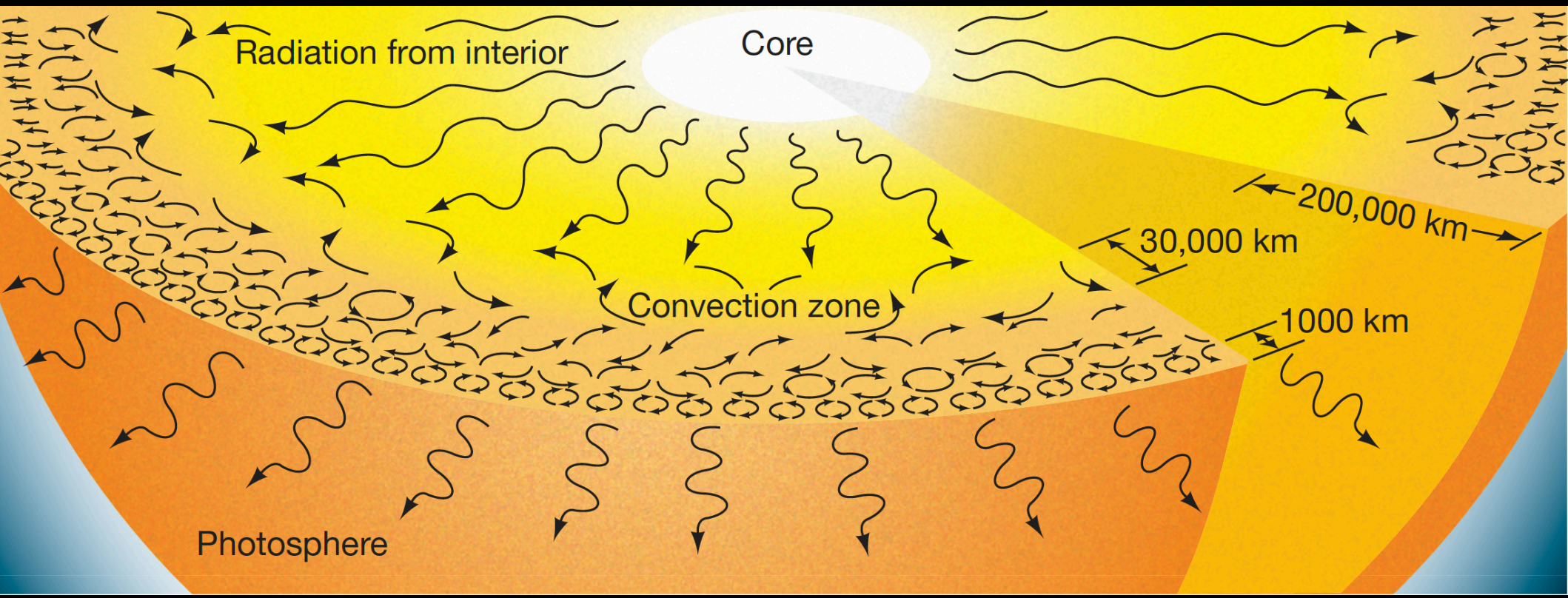
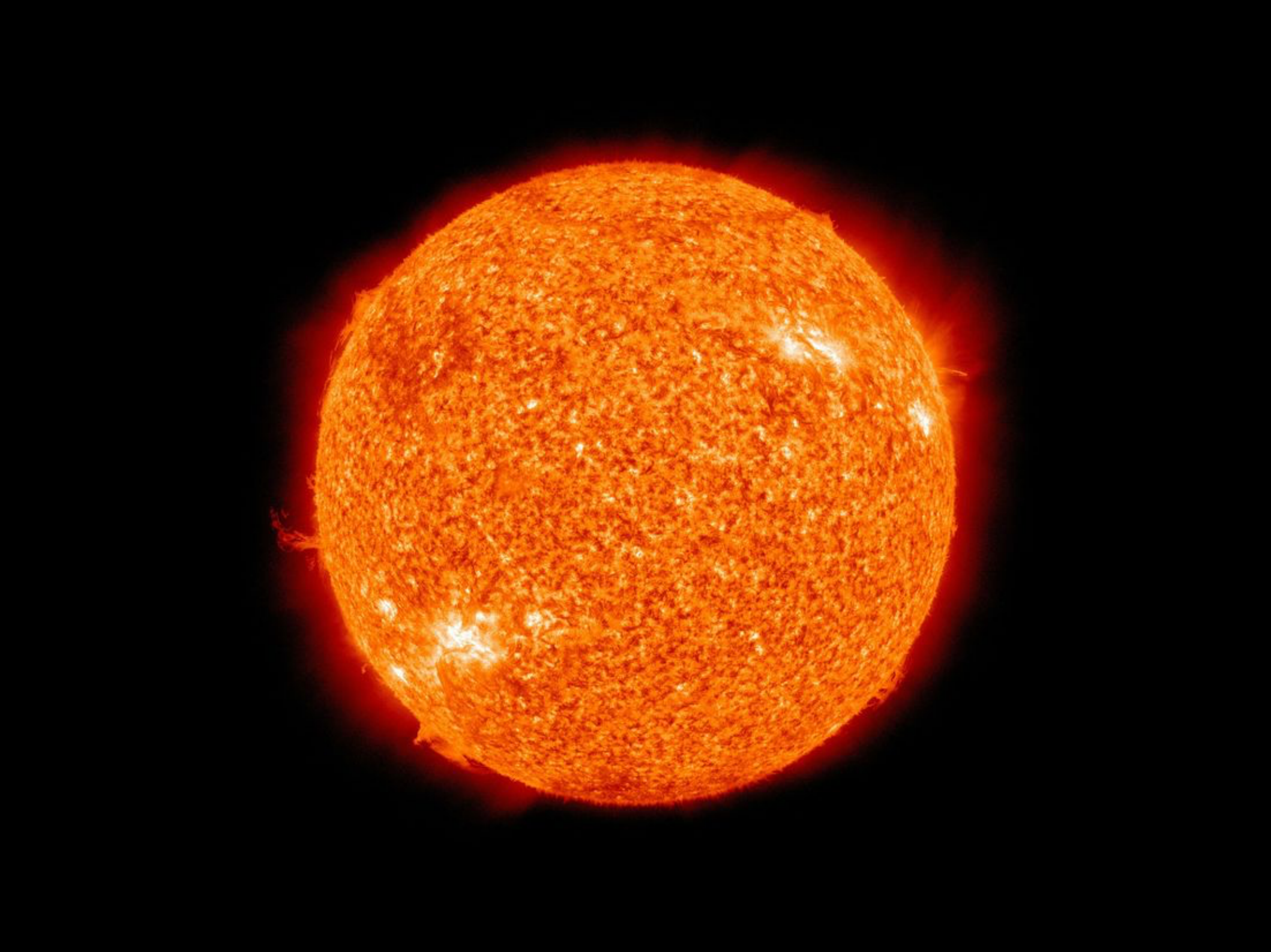
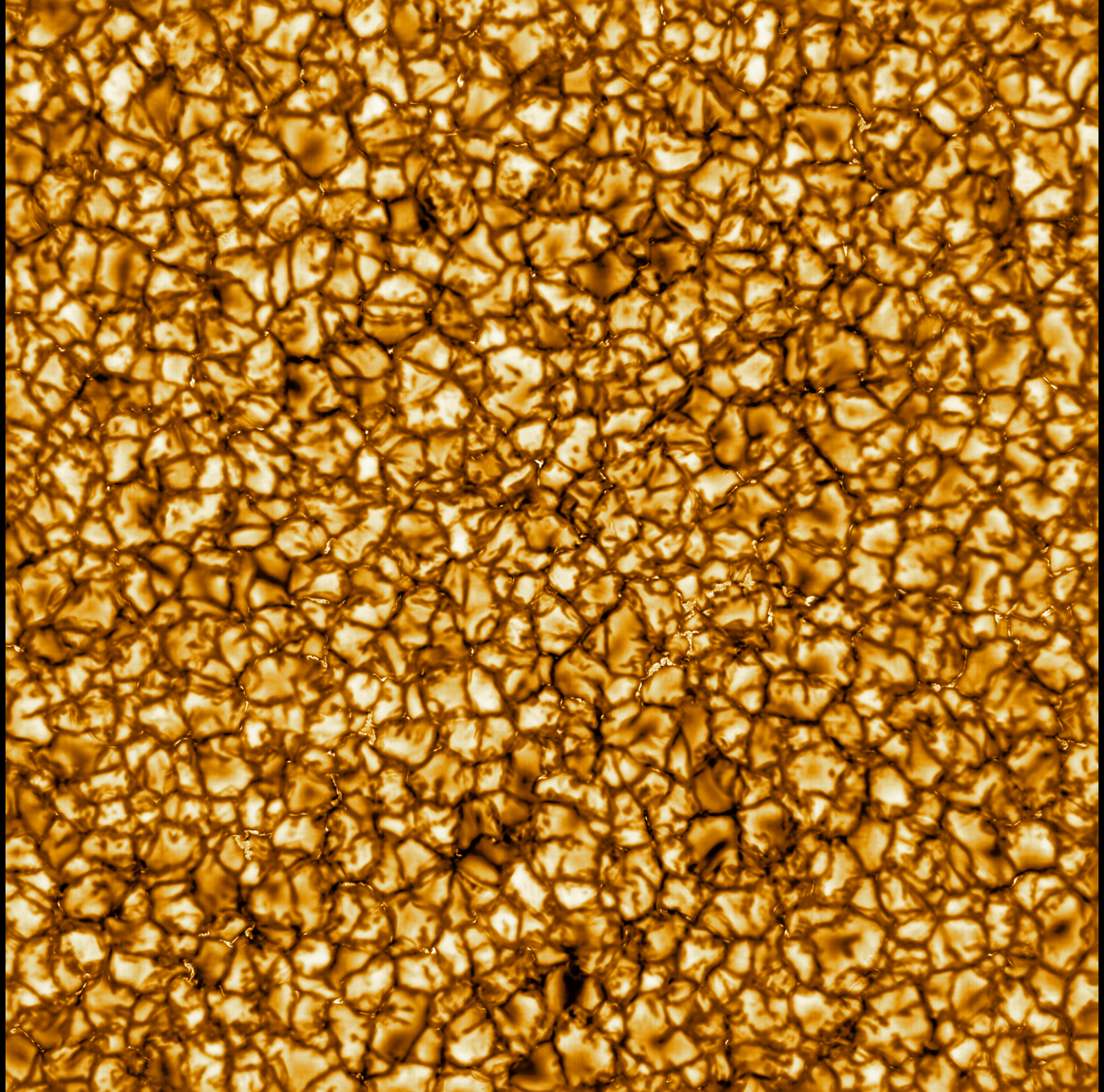

Radiation from interior
Core
200,000 km
30,000 km
Convection zone
1000 km
Photosphere





Main Sequence nuclear reactions

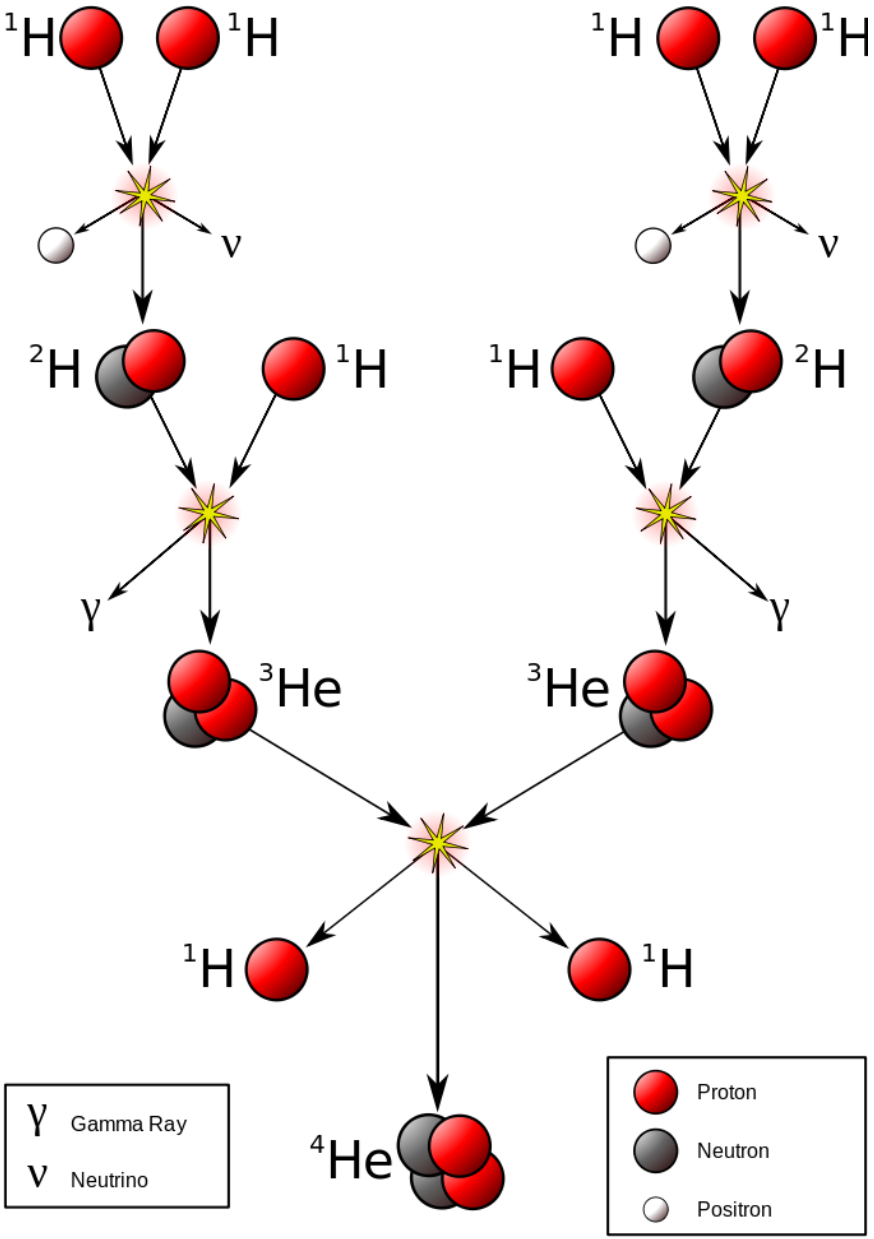
Proton-proton chain

$^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{2}He \rightarrow {}^{2}_{1}H + e^{+} + \nu_e$

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

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

$4\,(^{1}_{1}H) \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_e + 24\ \text{MeV}$



Proton-proton chain

$$4\mathrm{p} \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 2\gamma + KE$$

total energy released = 26.73 MeV
total local heating = 26.21 MeV

total mass of hydrogen = $4\,m_H = 6.68 \times 10^{-27}$ kg
total mass lost = 4.58×10^{-29} kg (0.7%)
total local heating = 4.20×10^{-12} J

energy/mass = 6.28×10^{14} J/kg

Main Sequence nuclear reactions

CNO cycle

$^{12}_{6}C + {}^{1}_{1}H \rightarrow {}^{13}_{7}N + \gamma$

$^{13}_{7}N \rightarrow {}^{13}_{6}C + e^{+} + \nu_e$

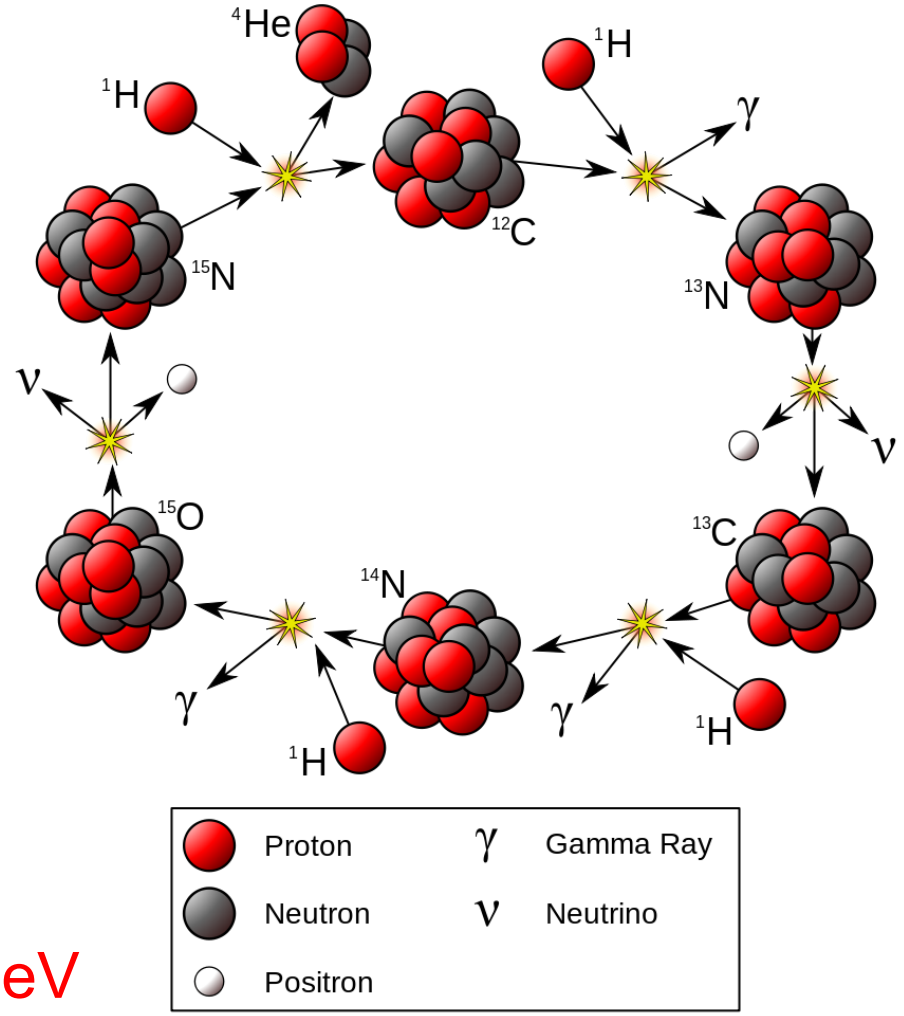
$^{13}_{6}C + {}^{1}_{1}H \rightarrow {}^{14}_{7}N + \gamma$

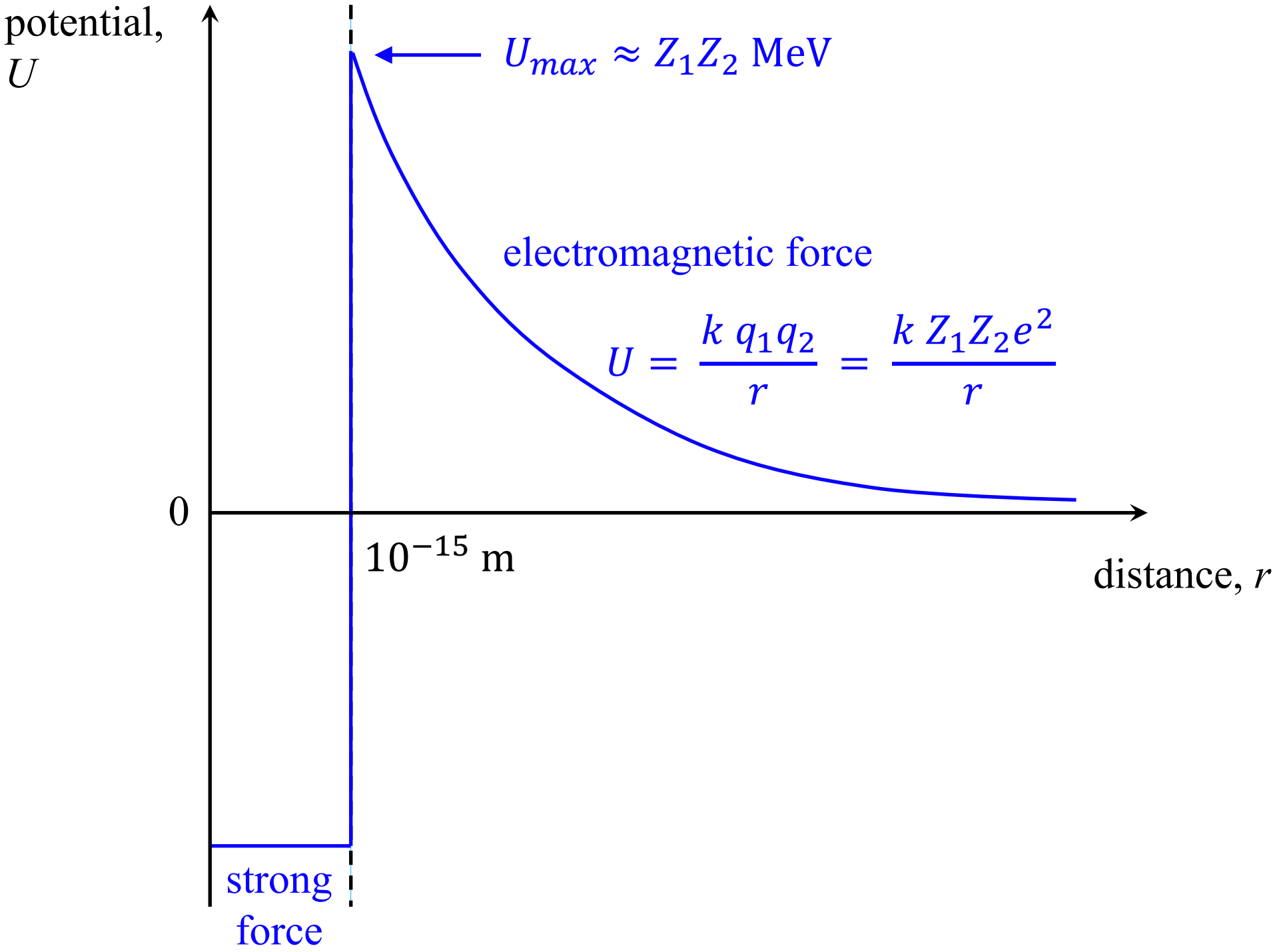
$^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + \gamma$

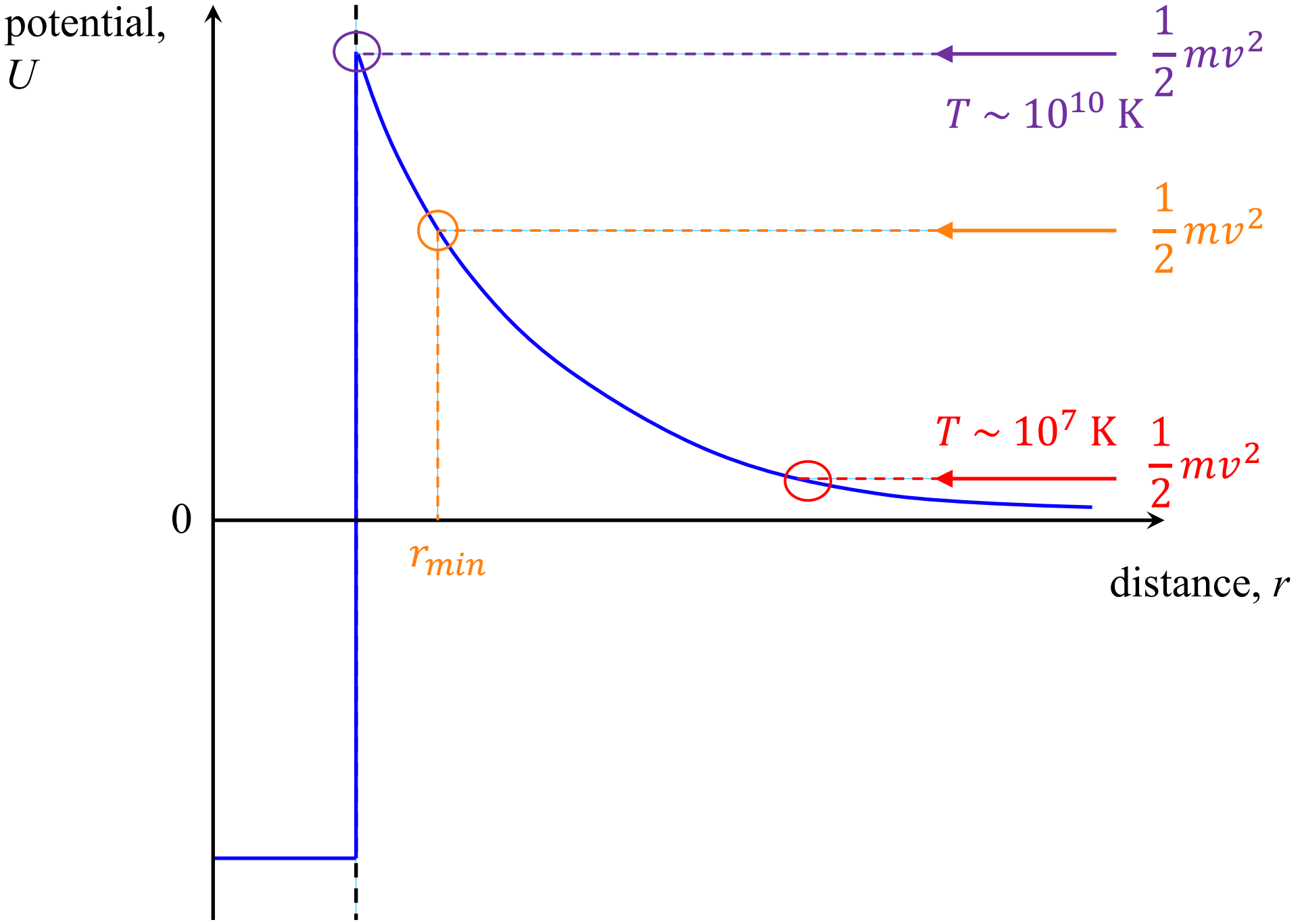
$^{15}_{8}O \rightarrow {}^{15}_{7}N + e^{+} + \nu_e$

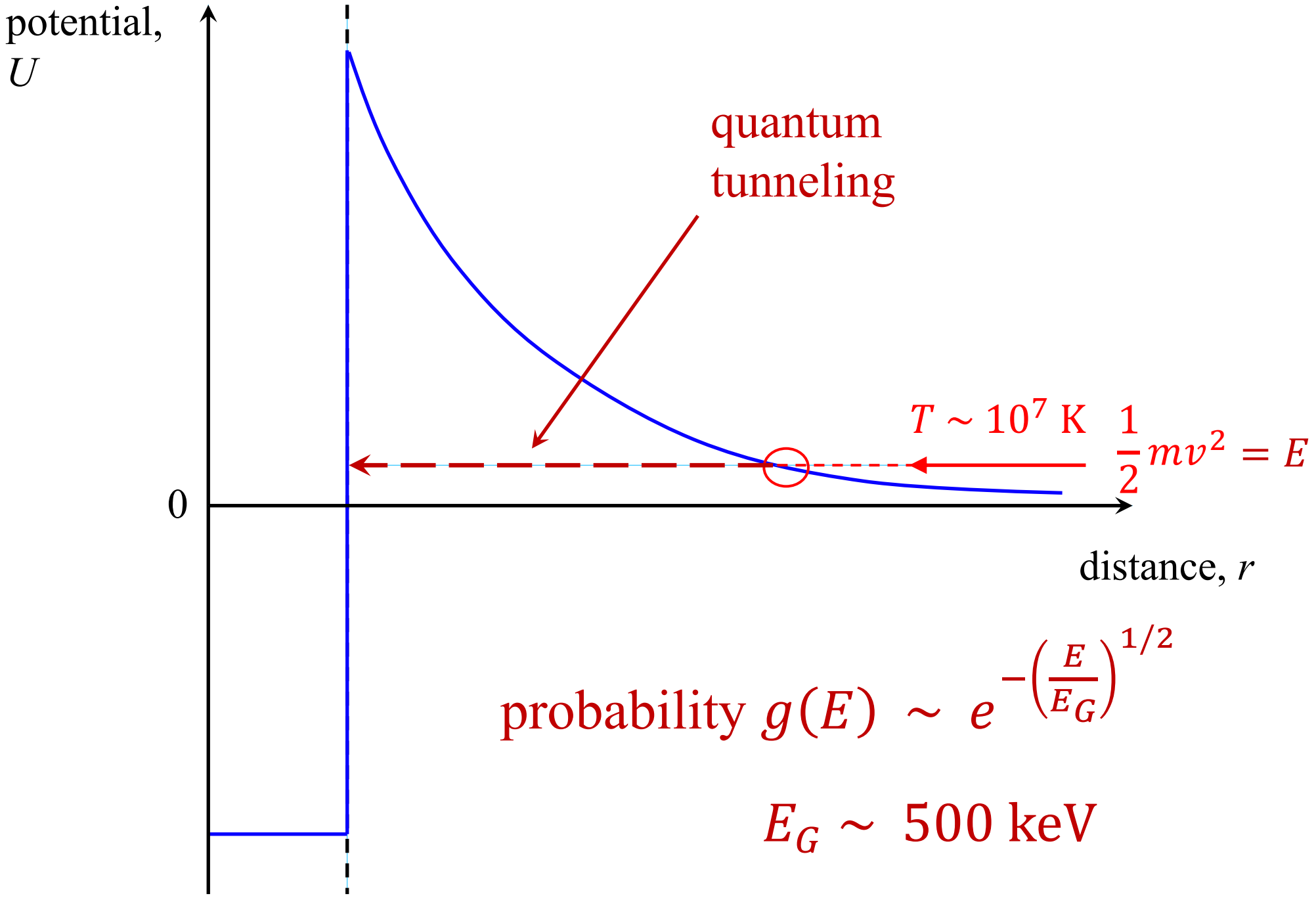
$^{15}_{7}N + {}^{1}_{1}H \rightarrow {}^{12}_{6}C + {}^{4}_{2}He$

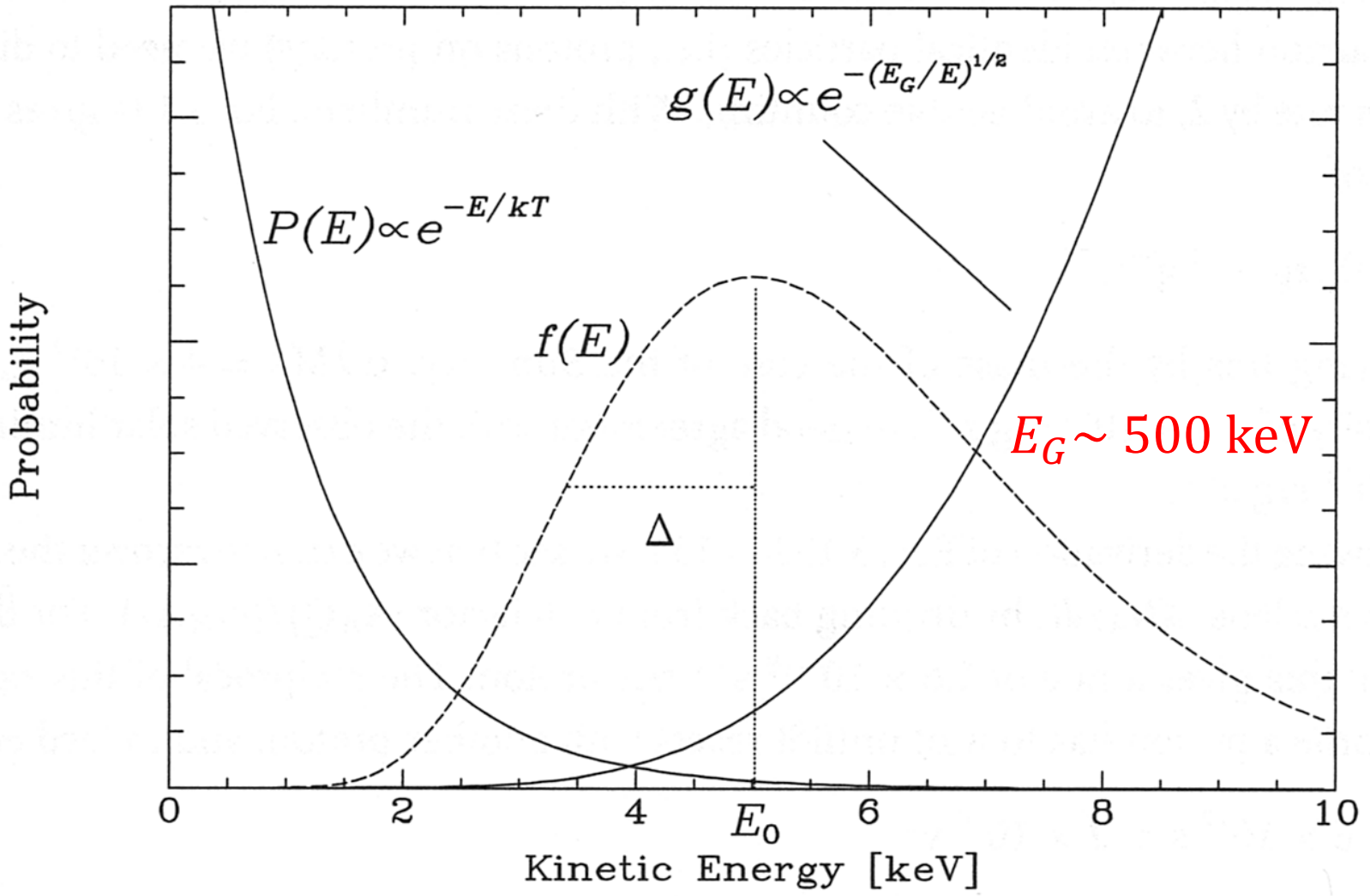
$4\,({}^{1}_{1}H) \rightarrow {}^{4}_{2}He + 2\,e^{+} + 2\nu_e + 24\ \text{MeV}$

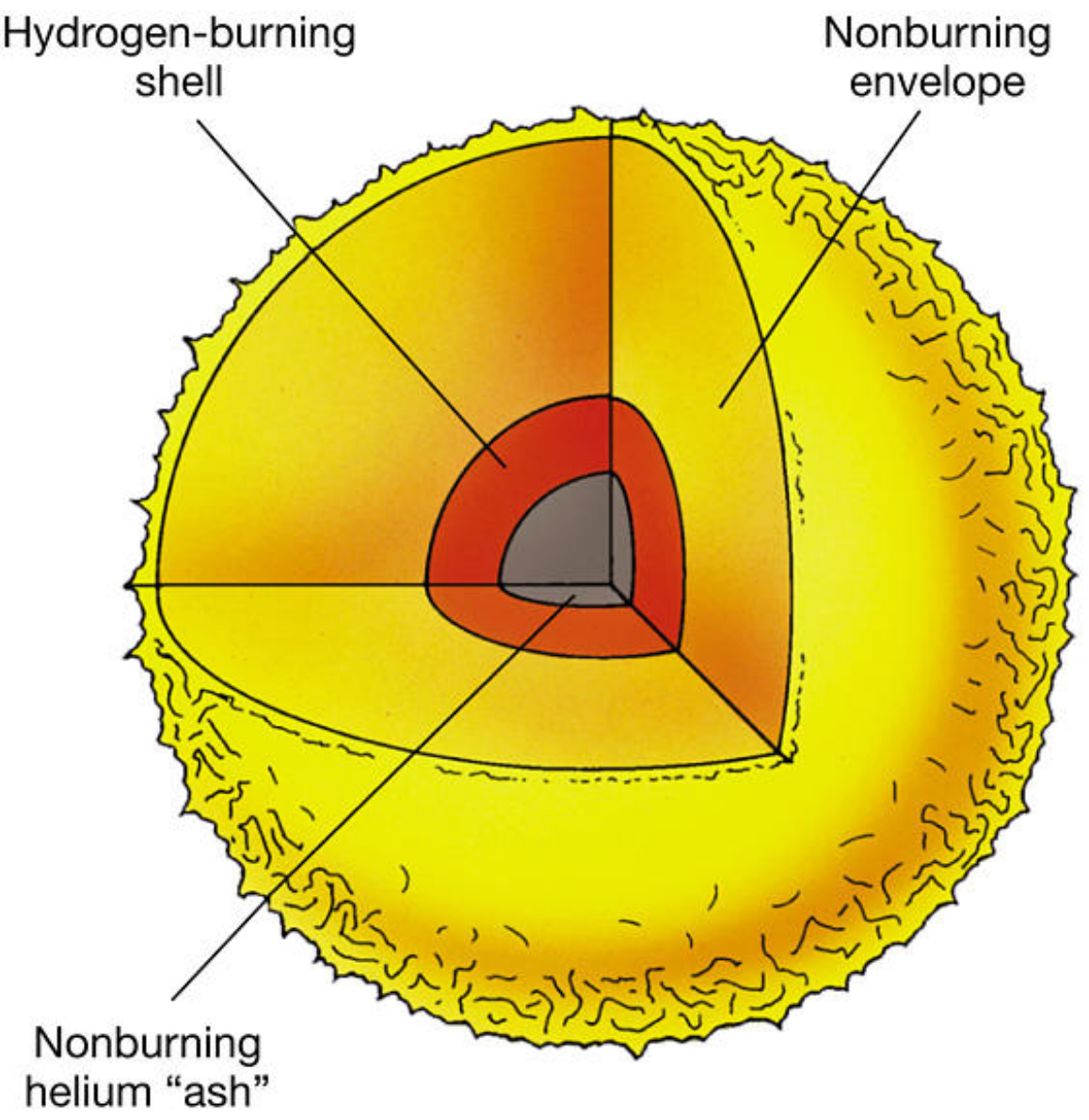


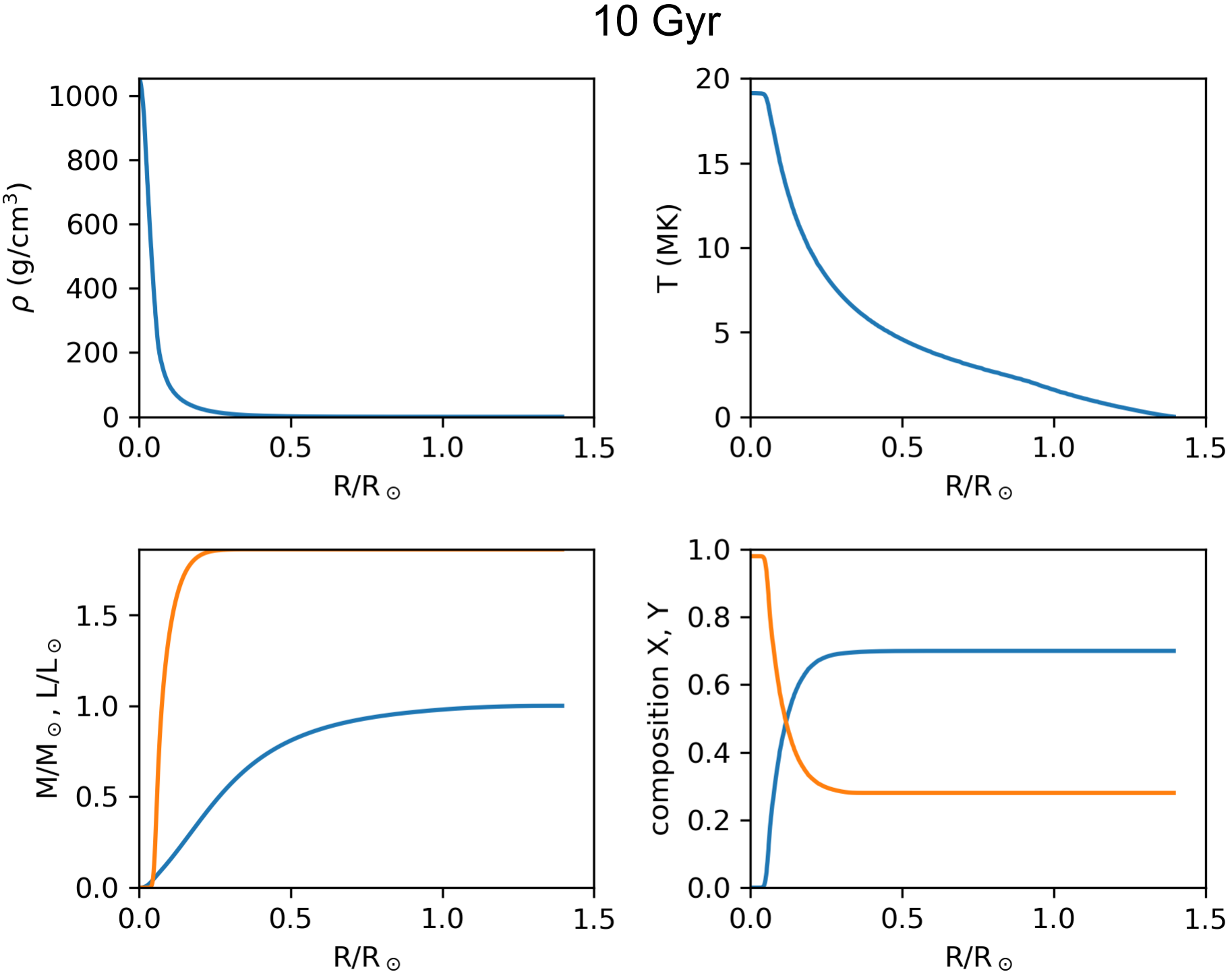

potential,
U
$U_{max} \approx Z_1 Z_2$ MeV
electromagnetic force
$U = \frac{k\, q_1 q_2}{r} = \frac{k\, Z_1 Z_2 e^2}{r}$
0
10^{-15} m
distance, r
strong
force


potential,
U
$\frac{1}{2}mv^2$
$T \sim 10^{10}$ K
$\frac{1}{2}mv^2$
$T \sim 10^7$ K
$\frac{1}{2}mv^2$
0
r_{min}
distance, r

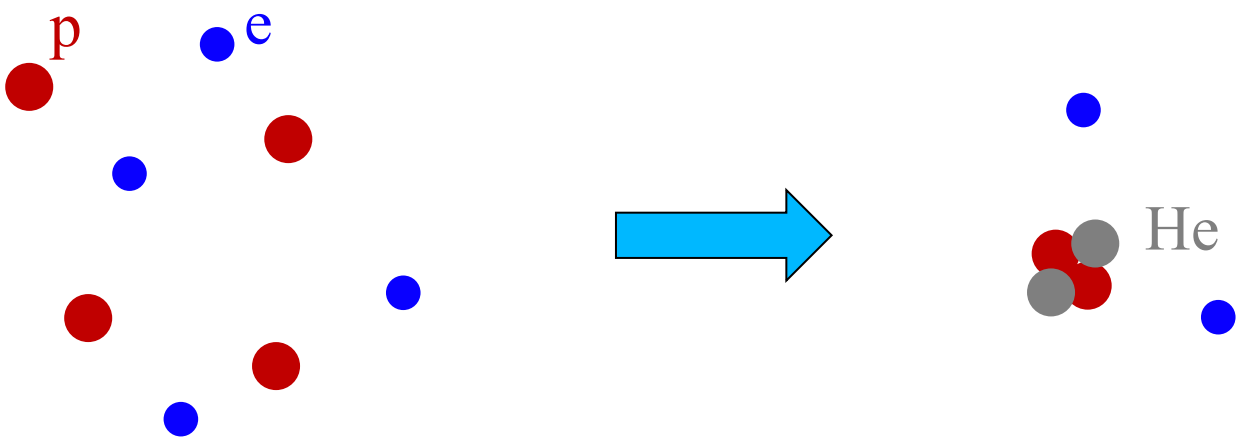

potential,
U
quantum
tunneling
$T \sim 10^7$ K
$\frac{1}{2}mv^2 = E$
0
distance, r
probability $g(E) \sim e^{-\left(\frac{E}{E_G}\right)^{1/2}}$
$E_G \sim$ 500 keV


Probability
$g(E) \propto e^{-(E_G/E)^{1/2}}$
$P(E) \propto e^{-E/kT}$
$f(E)$
Δ
$E_G \sim 500$ keV
0
2
4
E_0
6
8
10
Kinetic Energy [keV]

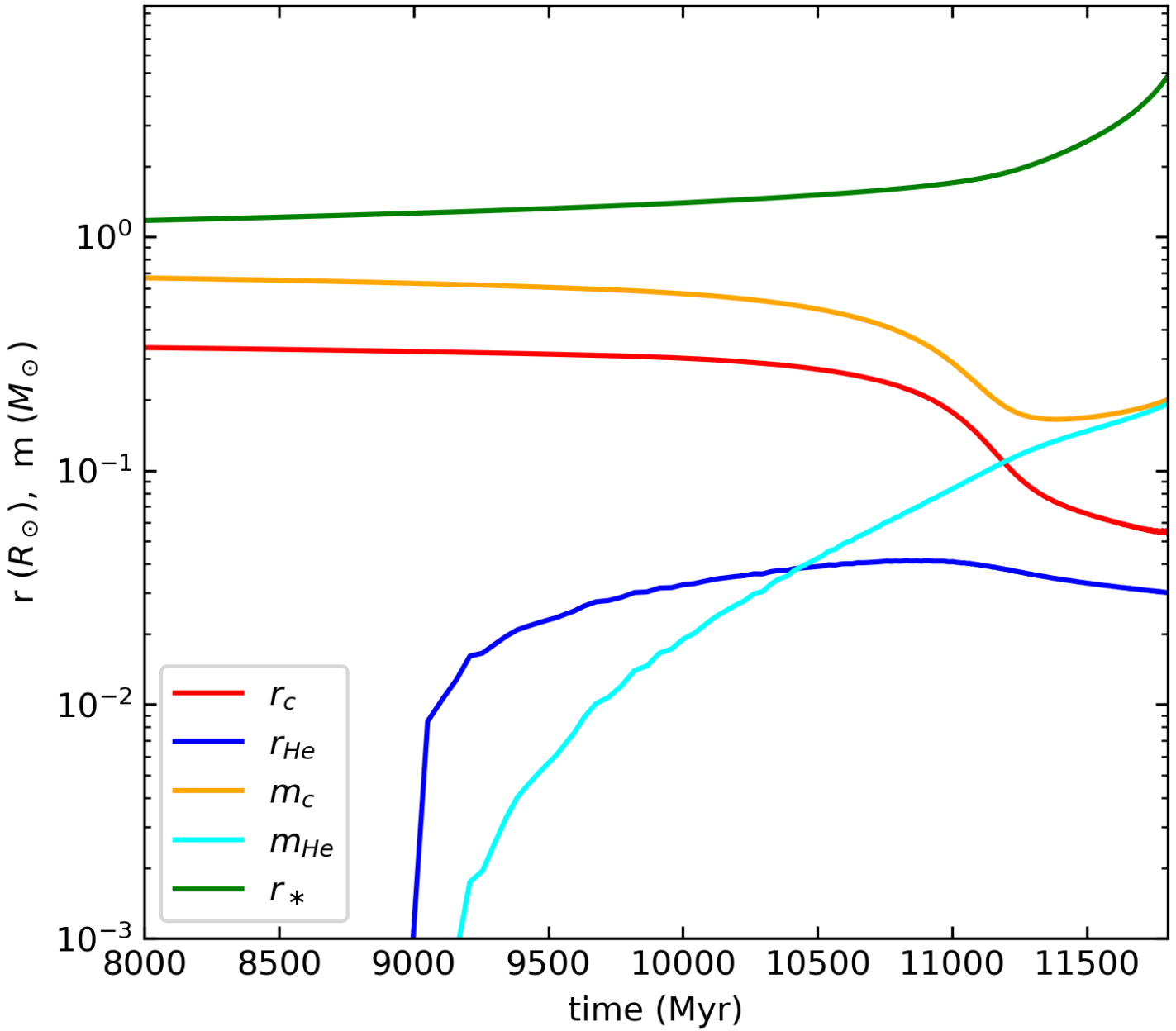

Hydrogen-burning shell
Nonburning envelope
Nonburning helium “ash”

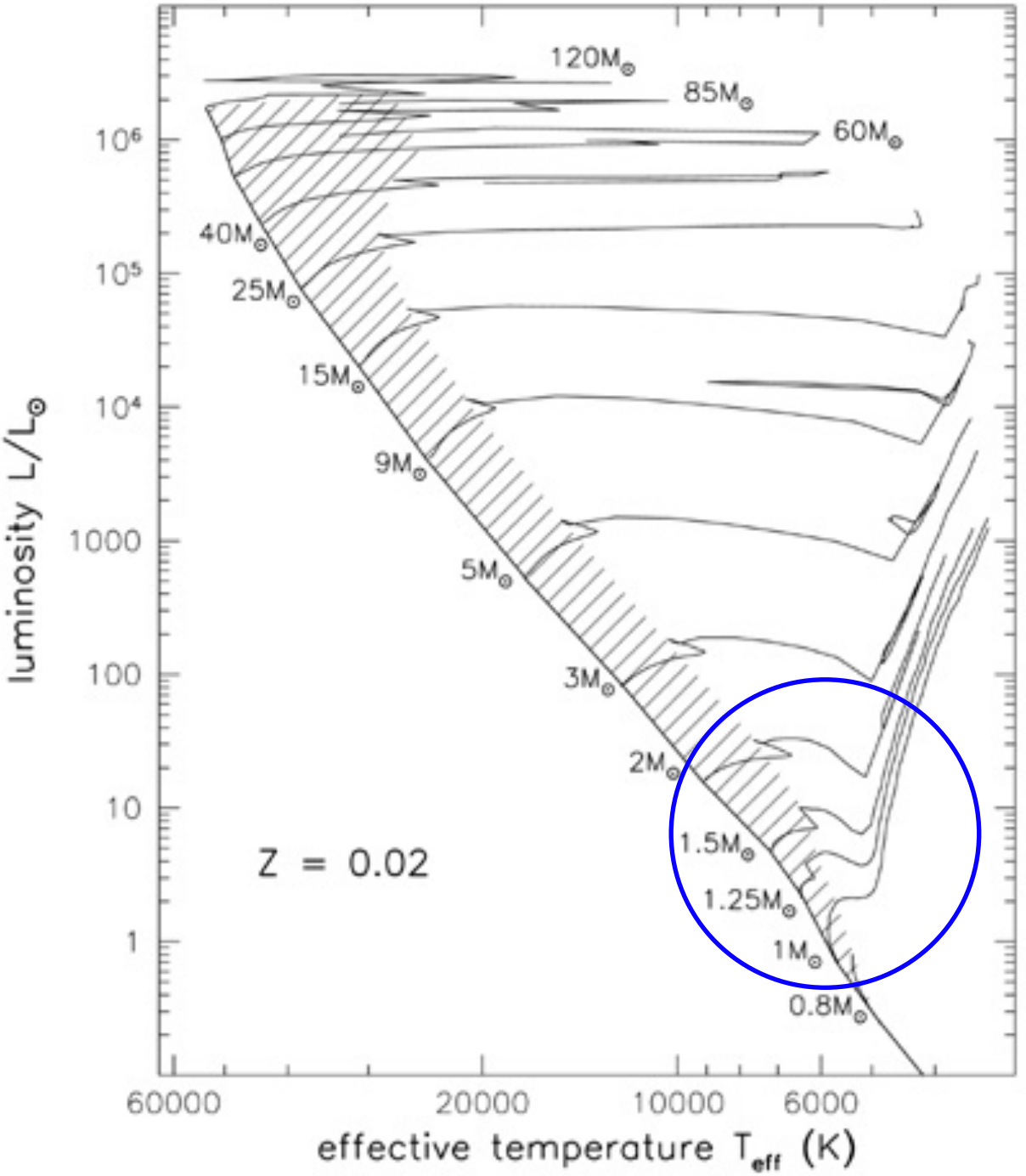

10 Gyr
ρ (g/cm³)
1000
800
600
400
200
0
0.0
0.5
1.0
1.5
R/R ⊙
T (MK)
20
15
10
5
0
M/M ⊙, L/L ⊙
composition X, Y
1.0
0.8
0.6
0.4
0.2
0.0

$$P = n\,k\,T$$



$n = 8$ $\qquad\qquad$ $n = 3$


r ($R_\odot$), m ($M_\odot$)
10^0
10^{-1}
10^{-2}
10^{-3}
8000
8500
9000
9500
10000
10500
11000
11500
time (Myr)
r_c
r_{He}
m_c
m_{He}
r_*

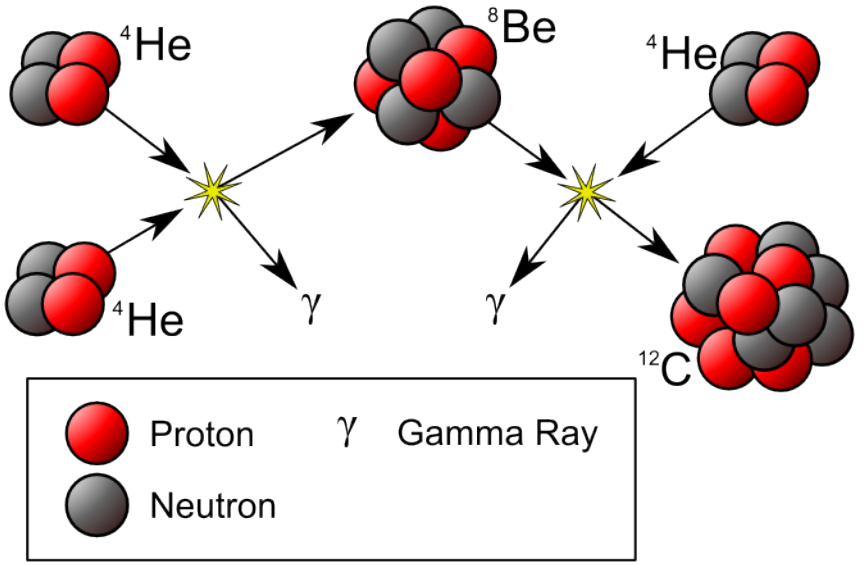

120M⊙
85M⊙
60M⊙
40M⊙
25M⊙
15M⊙
9M⊙
5M⊙
3M⊙
2M⊙
1.5M⊙
1.25M⊙
1M⊙
0.8M⊙
Z = 0.02
luminosity L/L⊙
10⁶
10⁵
10⁴
1000
100
10
1
60000
20000
10000
6000
effective temperature T_eff (K)

Post-Main-Sequence nuclear reactions

Triple-alpha process

$^{4}_{2}He + {}^{4}_{2}He \rightarrow {}^{8}_{4}Be - 94\ keV$

$^{8}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + 7.4\ MeV$

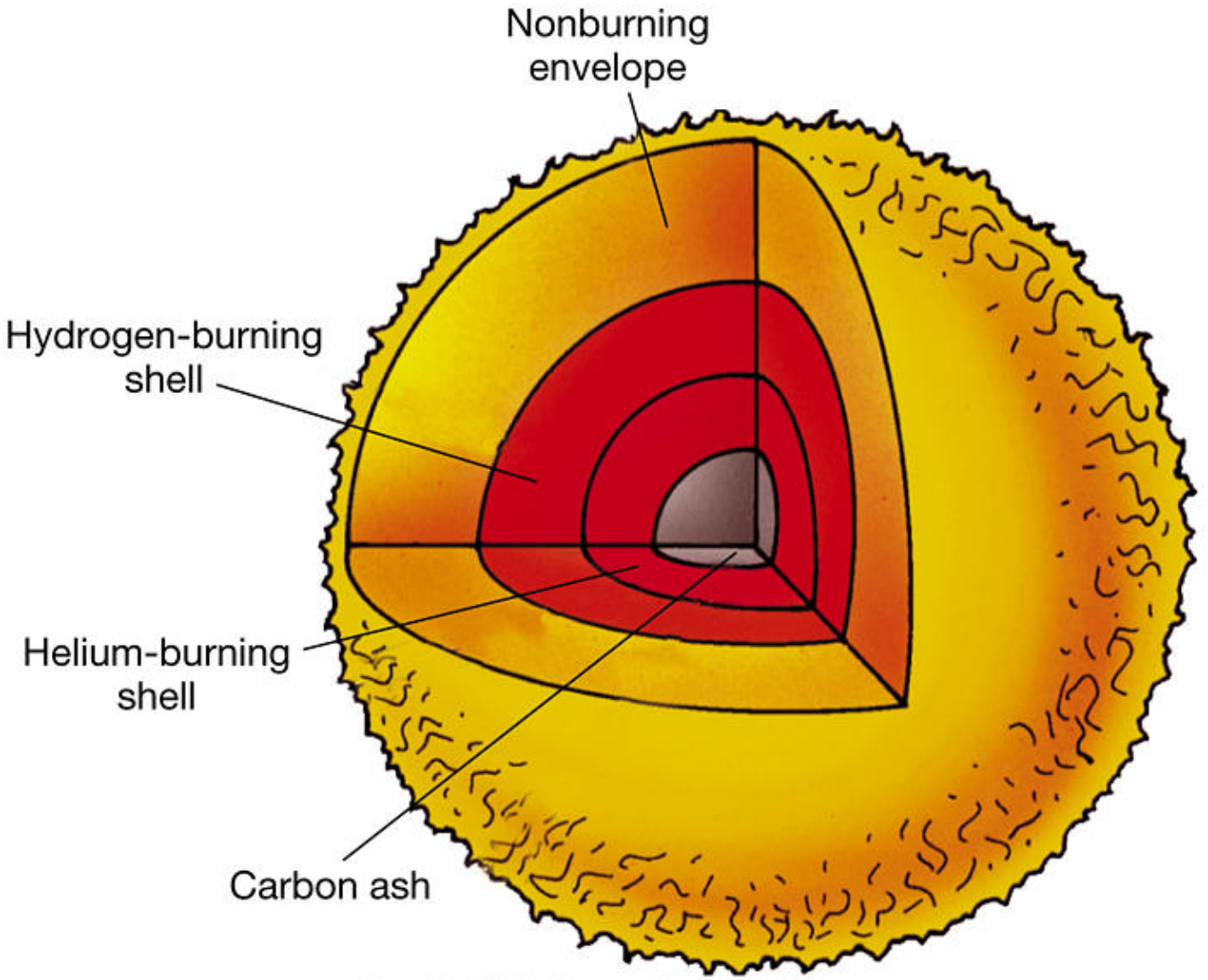


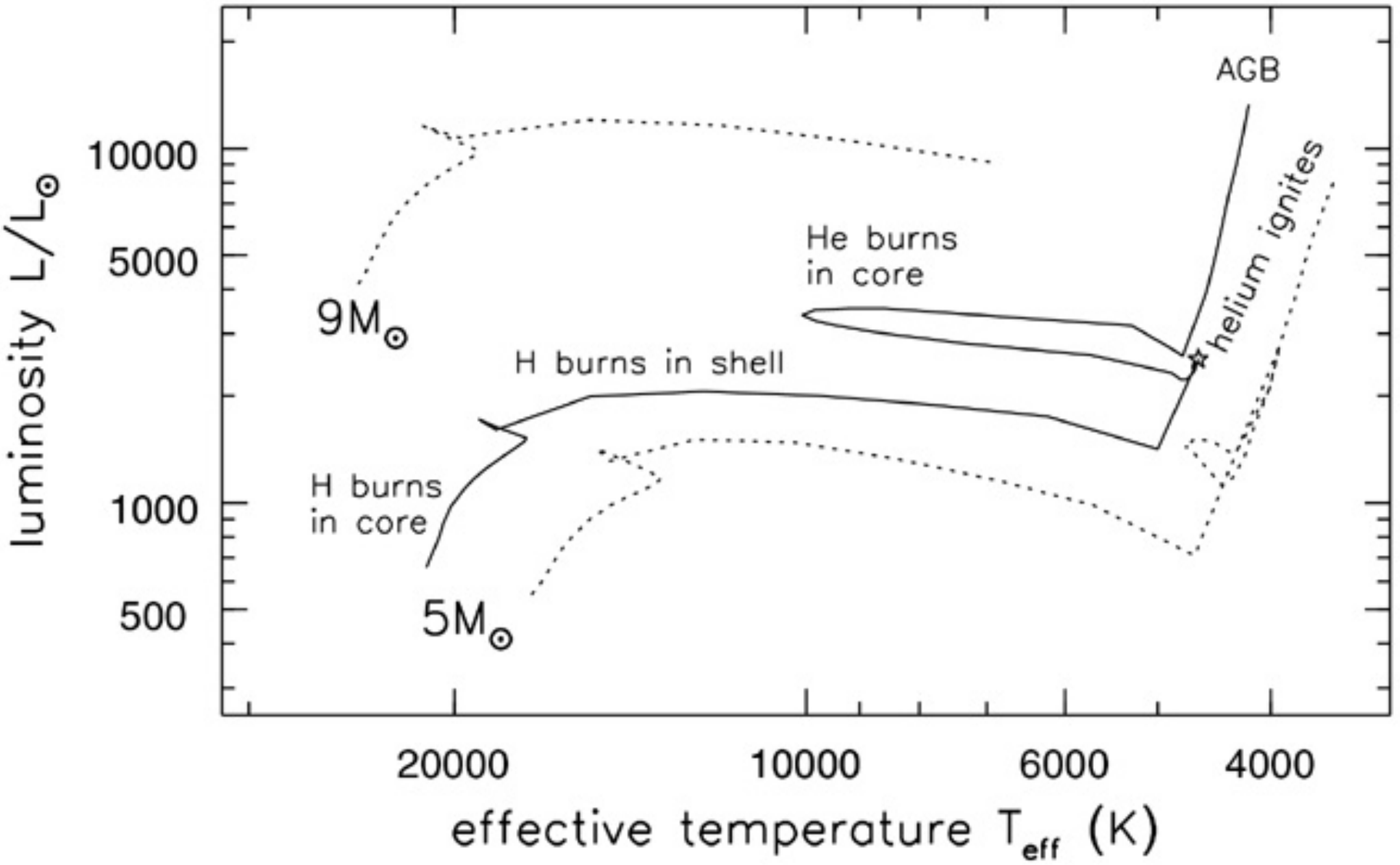
Alpha capture

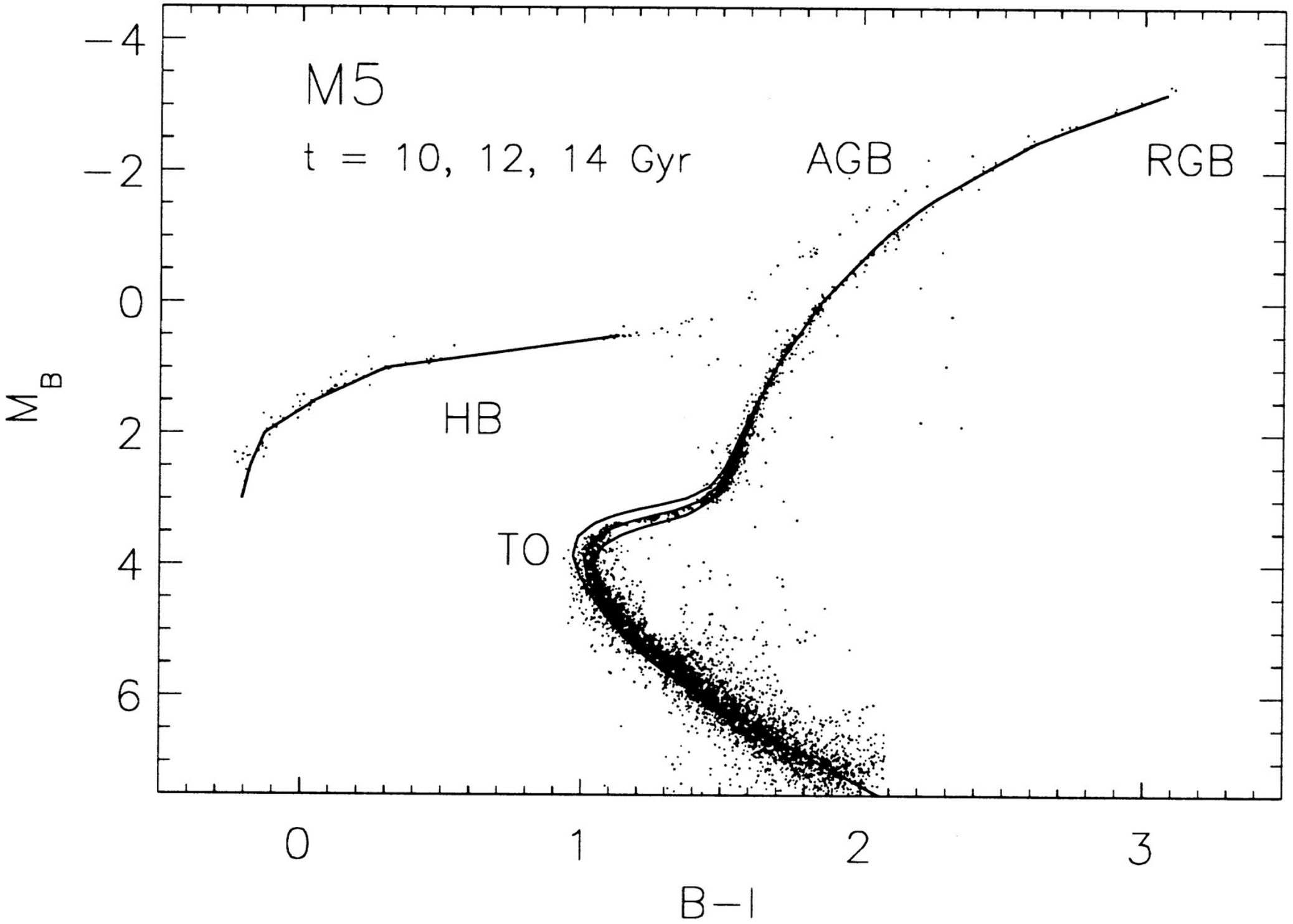
$^{12}_{6}C + {}^{4}_{2}He \rightarrow {}^{16}_{8}O + 7.2\ MeV$

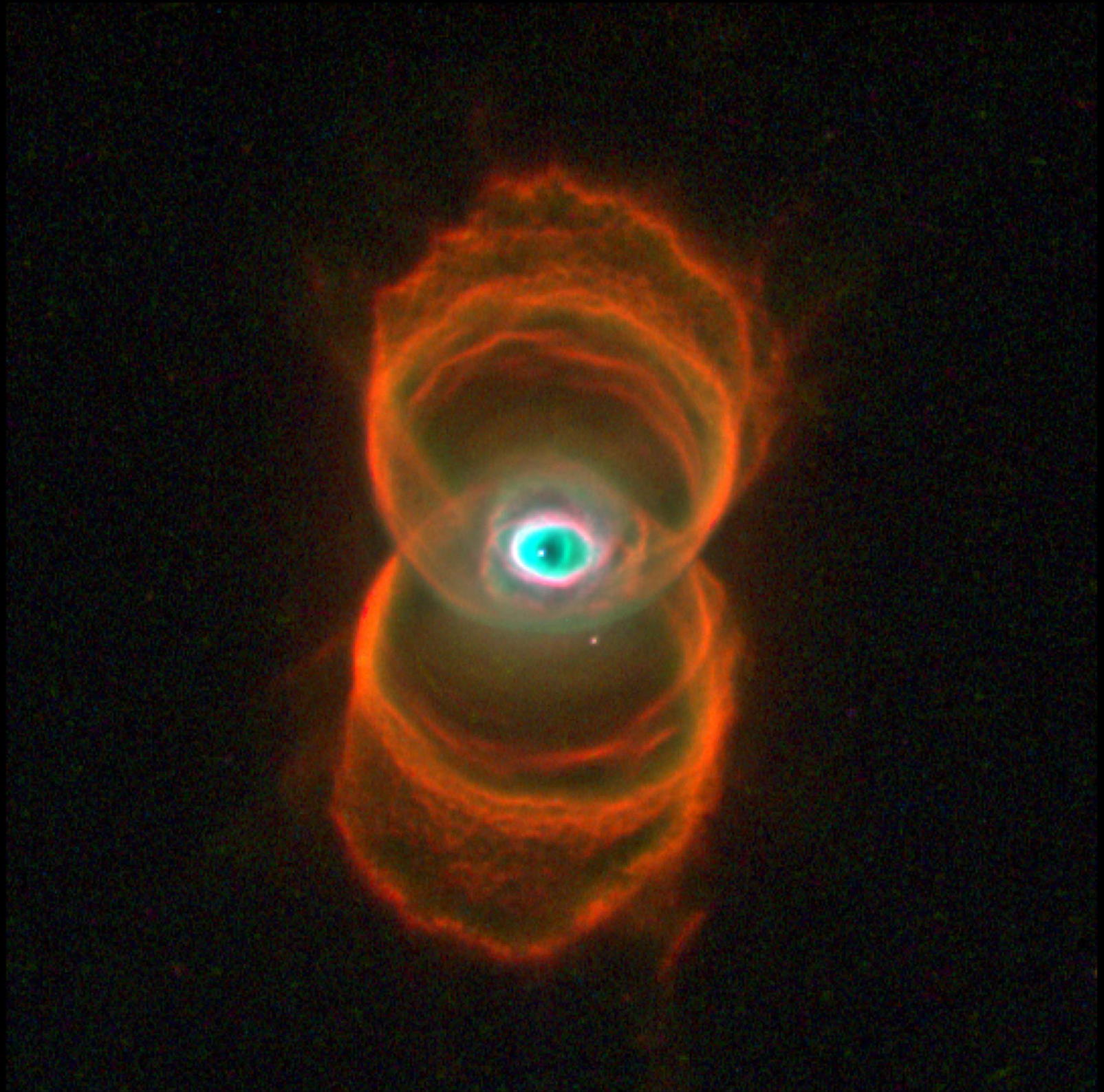
$^{16}_{8}O + {}^{4}_{2}He \rightarrow {}^{20}_{10}Ne + 4.7\ MeV$

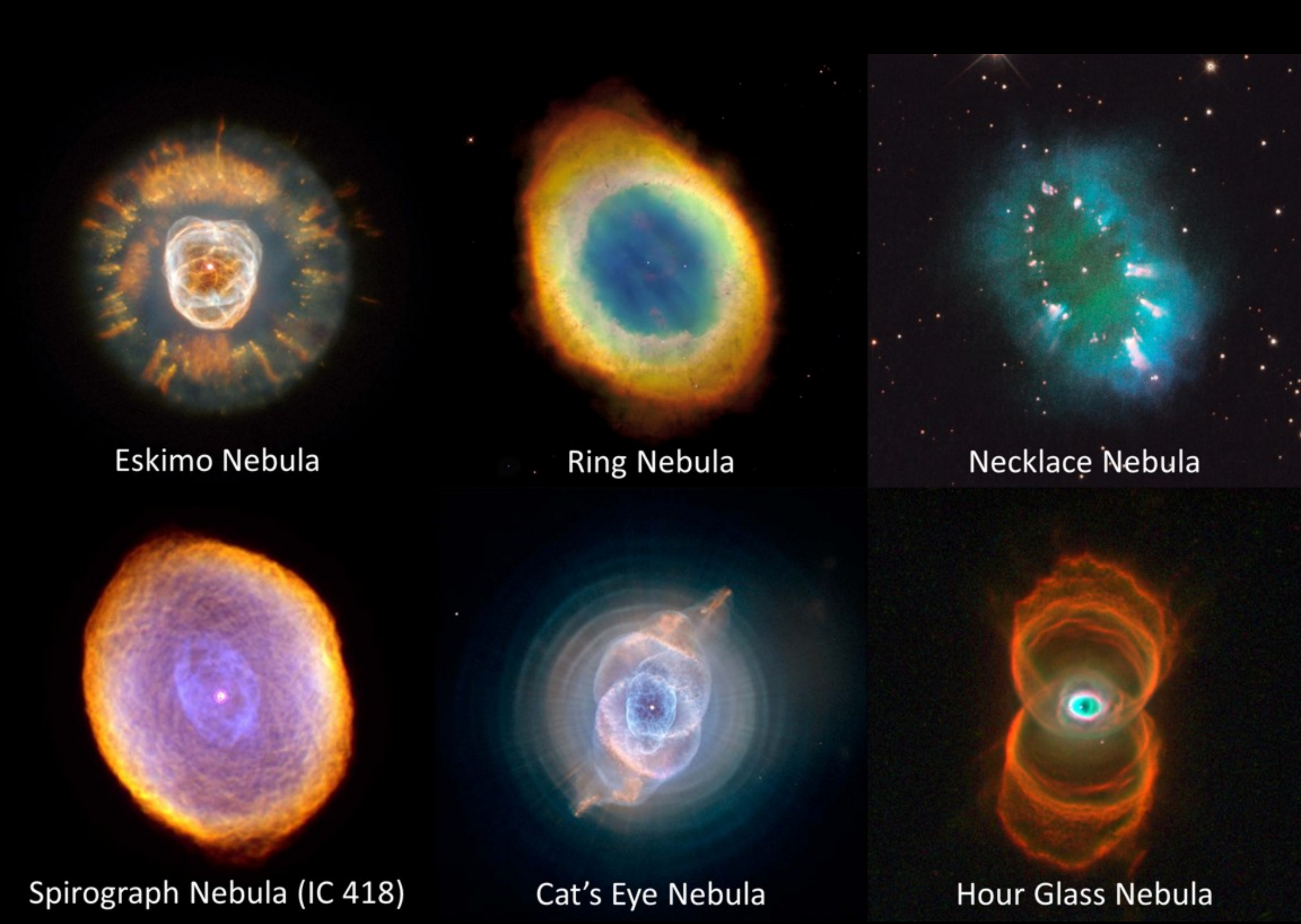
$^{20}_{10}Ne + {}^{4}_{2}He \rightarrow {}^{24}_{12}Mg + 9.3\ MeV$

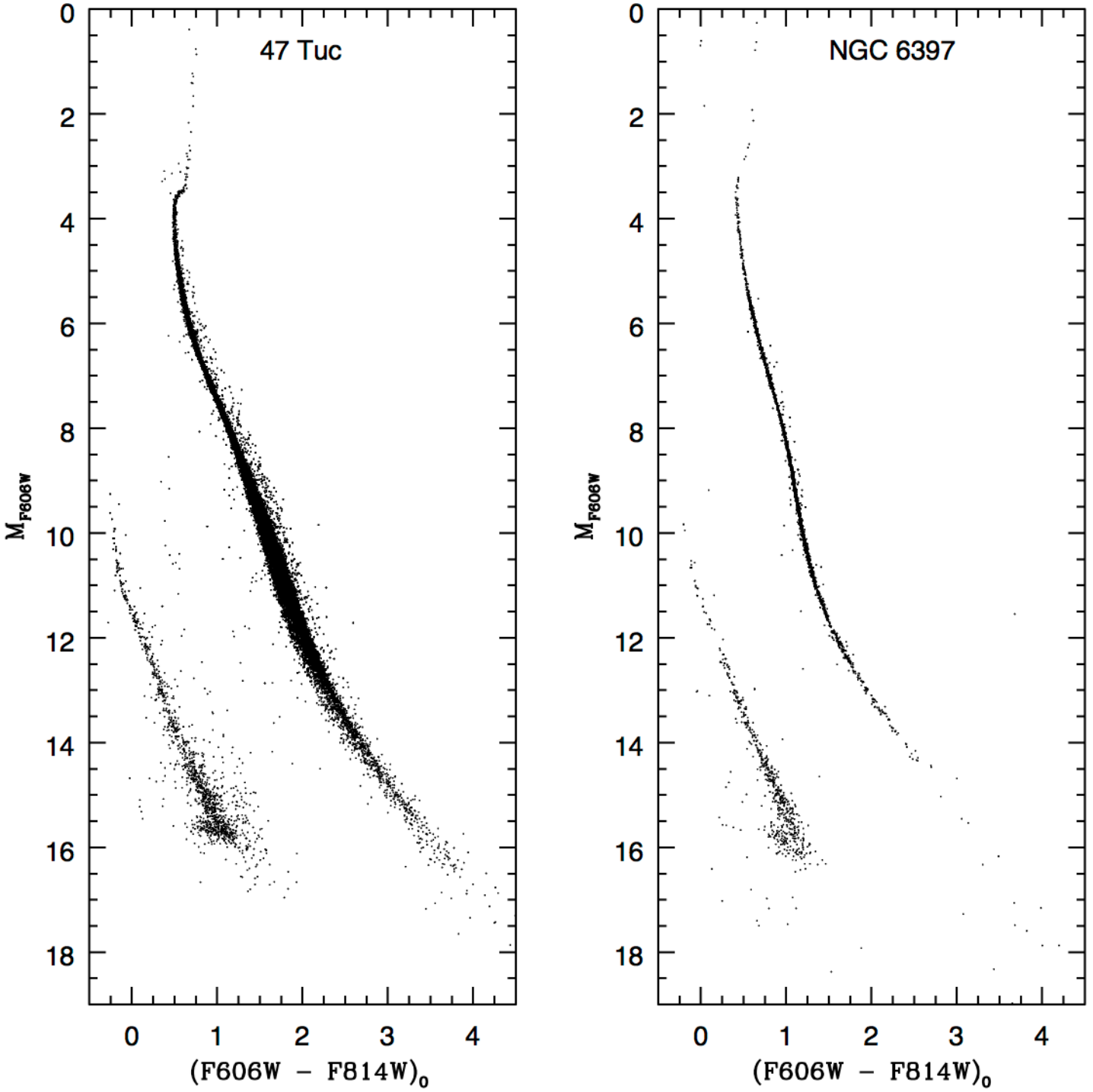

Nonburning
envelope
Hydrogen-burning
shell
Helium-burning
shell
Carbon ash


luminosity L/L⊙
10000
5000
1000
500
9M⊙
5M⊙
AGB
He burns
in core
helium ignites
H burns in shell
H burns
in core
20000
10000
6000
4000
effective temperature T_eff (K)


M5
t = 10, 12, 14 Gyr
AGB
RGB
HB
TO
−4
−2
0
2
4
6
M_B
0
1
2
3
B−I




Eskimo Nebula
Ring Nebula
Necklace Nebula
Spirograph Nebula (IC 418)
Cat’s Eye Nebula
Hour Glass Nebula


47 Tuc
NGC 6397
M_{F606W}
$(F606W - F814W)_0$
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4

Stellar Evolution Outcomes

$< 0.08\ M_\odot$	brown dwarf (degenerate H)	
$0.08-0.25\ M_\odot$	He white dwarf	$t \sim 10^{10}\ \text{yr}\ (M/M_\odot)^{-3}$
$0.25-8\ M_\odot$	CO white dwarf	
$8-12\ M_\odot$	NeO white dwarf	
$12-20\ M_\odot$	supernova/neutron star	$t \sim 3\text{-}5 \times 10^6\ \text{yr}$
$>20\ M_\odot$	supernova/black hole	

Quantum gas

de Broglie wavelength of an electron:

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}} = \frac{h}{\sqrt{3mkT}}$$

non-classical behavior when

$$n^{-1/3} < \lambda/2$$

$$\Rightarrow \quad \rho > \rho_q = \frac{8m_p}{h^3}(3m_e kT)^{3/2}$$

$$= 3.5\times10^5 \text{ kg m}^{-3} \left(\frac{T}{10^7\ K}\right)^{3/2}$$