# Nuclear burning stages

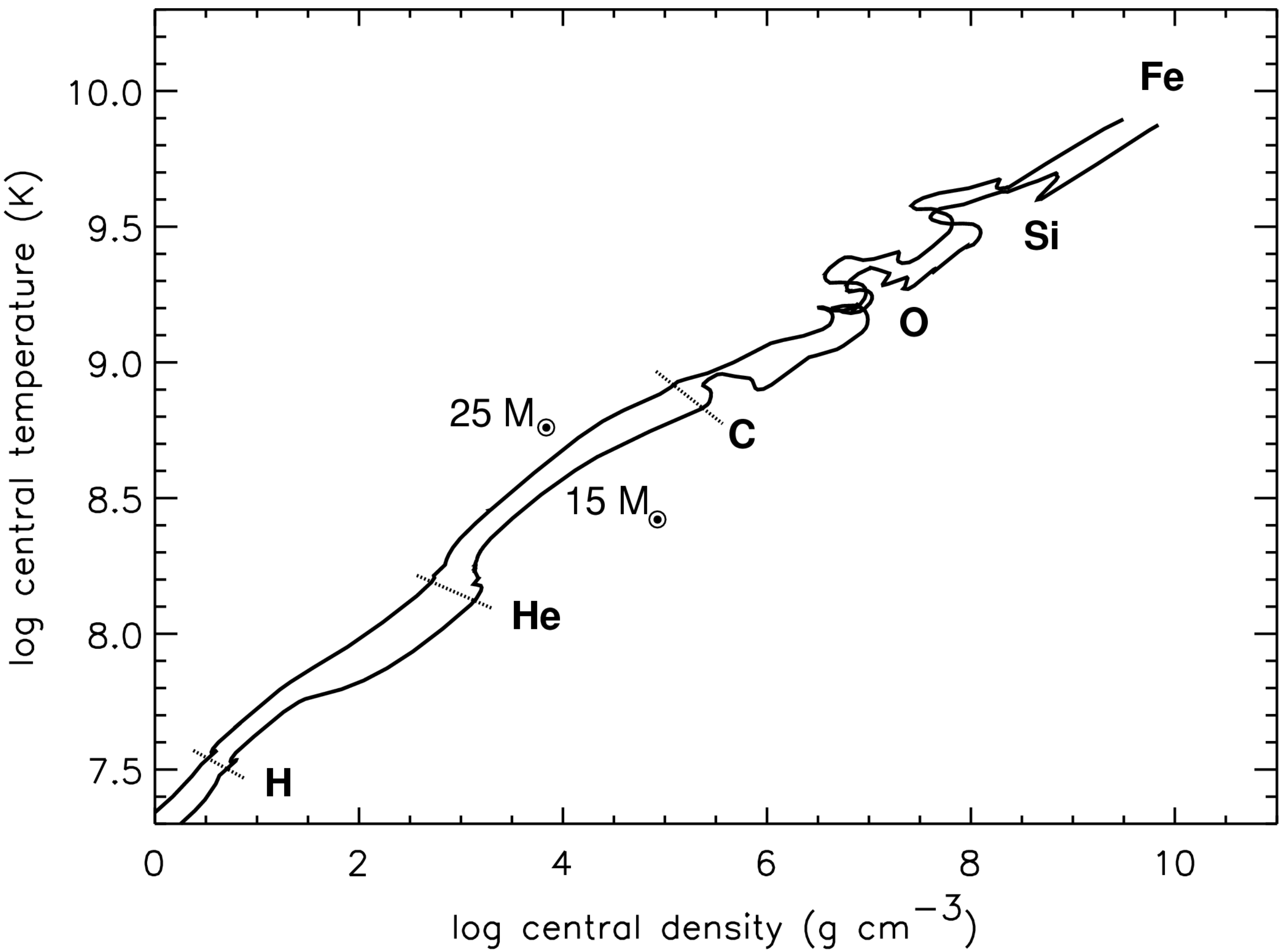
**($20\ M_\odot$ stars)**

| Fuel | Main Product | Secondary Product | T ($10^9$ K) | Time (yr) | Main Reaction |
|---|---|---|---|---|---|
| **H** | **He** | **$^{14}N$** | **0.02** | **$10^7$** | **$4\ H \xrightarrow{CNO} {}^4He$** |
| **He** | **O, C** | **$^{18}O$, $^{22}Ne$ s-process** | **0.2** | **$10^6$** | **$3\ He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$** |
| **C** | **Ne, Mg** | **Na** | **0.8** | **$10^3$** | **$^{12}C + {}^{12}C$** |
| **Ne** | **O, Mg** | **Al, P** | **1.5** | **3** | **$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$** |
| **O** | **Si, S** | **Cl, Ar, K, Ca** | **2.0** | **0.8** | **$^{16}O + {}^{16}O$** |
| **Si,S** | **Fe** | **Ti, V, Cr, Mn, Co, Ni** | **3.5** | **0.02** | **$^{28}Si(\gamma,\alpha)$…** |

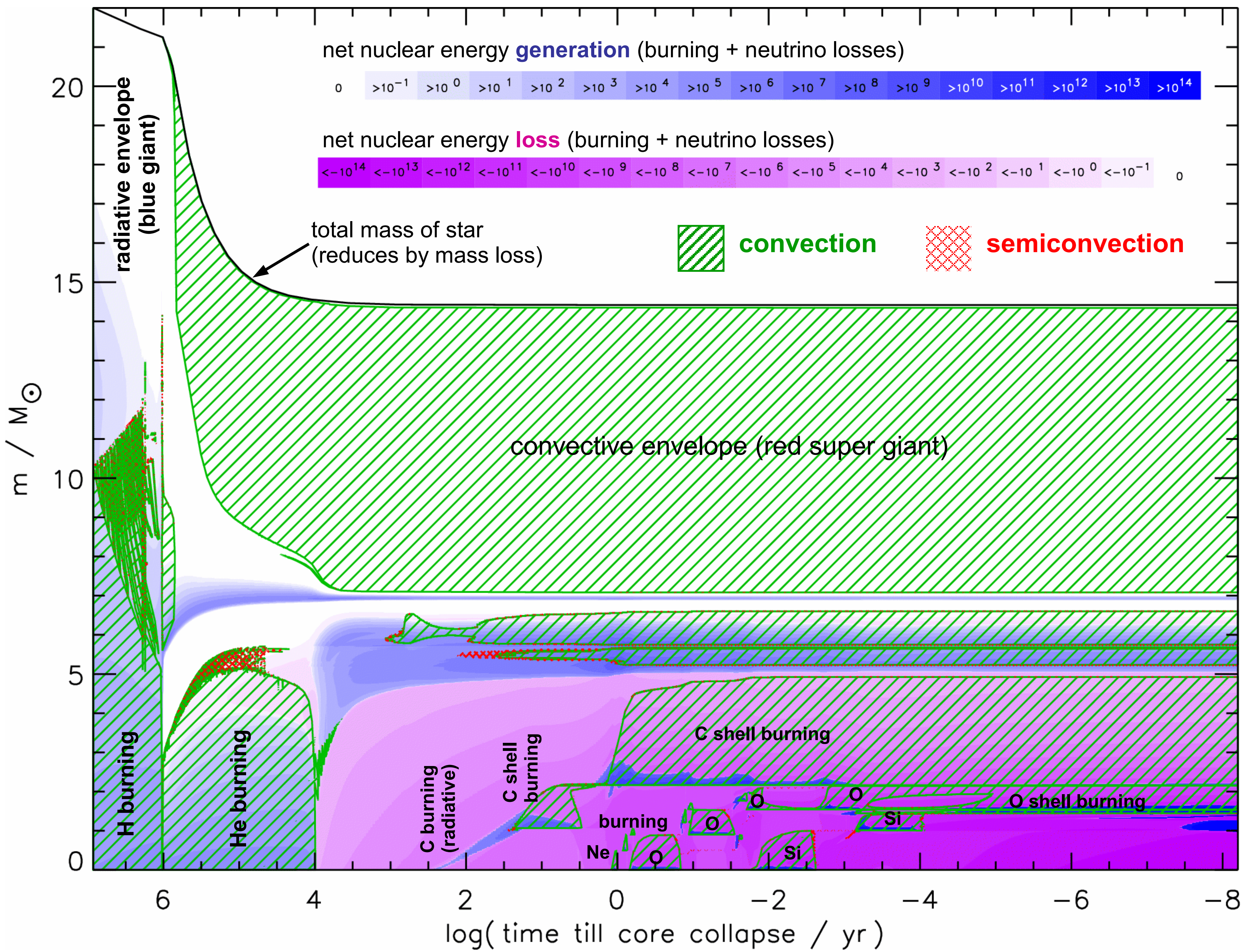
**Once formed, the evolution of a star is governed by gravity:**

*continuing contraction*

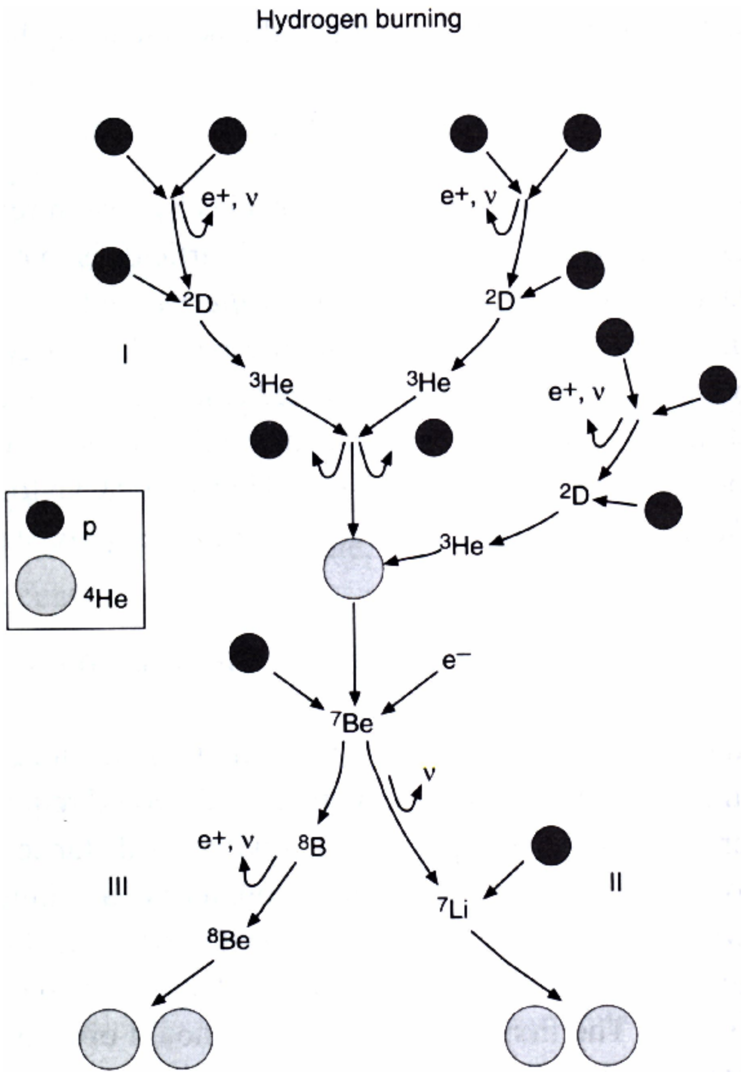
to higher central densities and temperatures




Evolution of central density and temperature of 15 $M_\odot$ and 25 $M_\odot$ stars


net nuclear energy generation (burning + neutrino losses)
0
>10^−1
>10^0
>10^1
>10^2
>10^3
>10^4
>10^5
>10^6
>10^7
>10^8
>10^9
>10^10
>10^11
>10^12
>10^13
>10^14
net nuclear energy loss (burning + neutrino losses)
<−10^14
<−10^13
<−10^12
<−10^11
<−10^10
<−10^9
<−10^8
<−10^7
<−10^6
<−10^5
<−10^4
<−10^3
<−10^2
<−10^1
<−10^0
<−10^−1
0
convection
semiconvection
total mass of star
(reduces by mass loss)
radiative envelope
(blue giant)
convective envelope (red super giant)
H burning
He burning
C burning
(radiative)
C shell
burning
C shell burning
burning
Ne
O
O
O
O
O shell burning
Si
Si
m / M⊙
log( time till core collapse / yr )
0
5
10
15
20
6
4
2
0
−2
−4
−6
−8

# Hydrogen-Burning: pp Chains




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

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

(*pp*1)

$$^3He + {}^4He \rightarrow {}^7Be + \gamma \qquad (18.62)$$

$$^7Be + e^- \rightarrow {}^7Li + \nu$$
$$^7Li + {}^1H \rightarrow {}^4He + {}^4He$$

(*pp*2)

$$^7Be + {}^1H \rightarrow {}^8B + \gamma$$
$$^8B \rightarrow {}^8Be + e^+ + \nu$$
$$^8Be \rightarrow {}^4He + {}^4He$$

(*pp*3)

Energy release:

$Q(pp1) = 26.20 MeV$

$Q(pp2) = 25.67 MeV$

$Q(pp3) = 19.20 MeV$

Reaction rate: $\langle \sigma v \rangle \propto T^4$

# Hydrogen Burning: CNO Bi-Cycle

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

Energy release:
$Q(CNO) = 24.97 MeV$

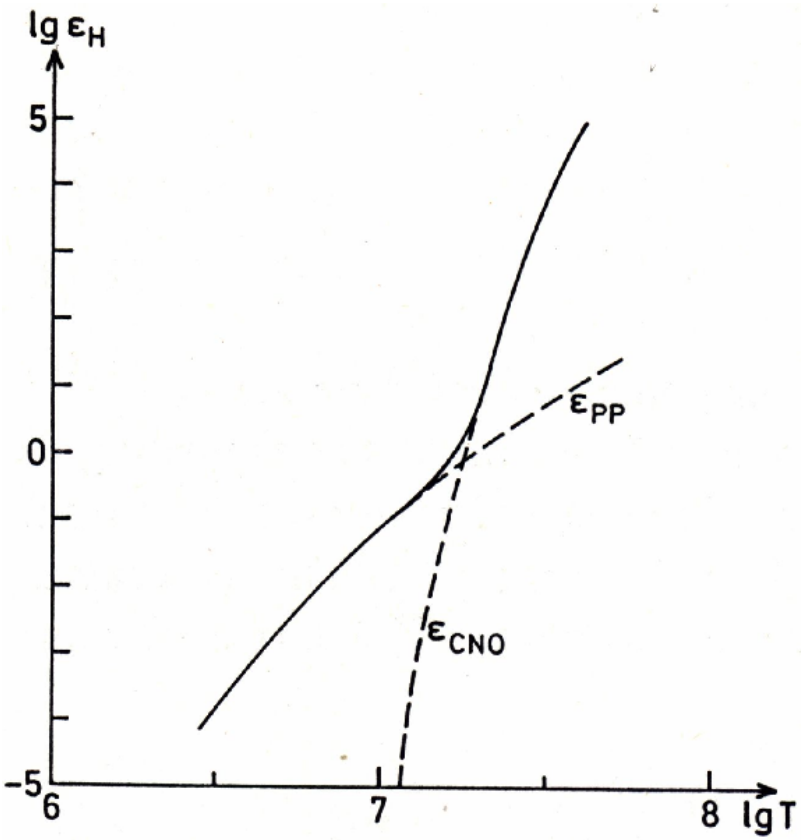
Reaction rate: $\langle \sigma v \rangle \propto T^{16}$

Branching:
CNO-1 : CNO-2 $\sim$ 10,000 : 1

# Hydrogen Burning: CNO Bi-Cycle

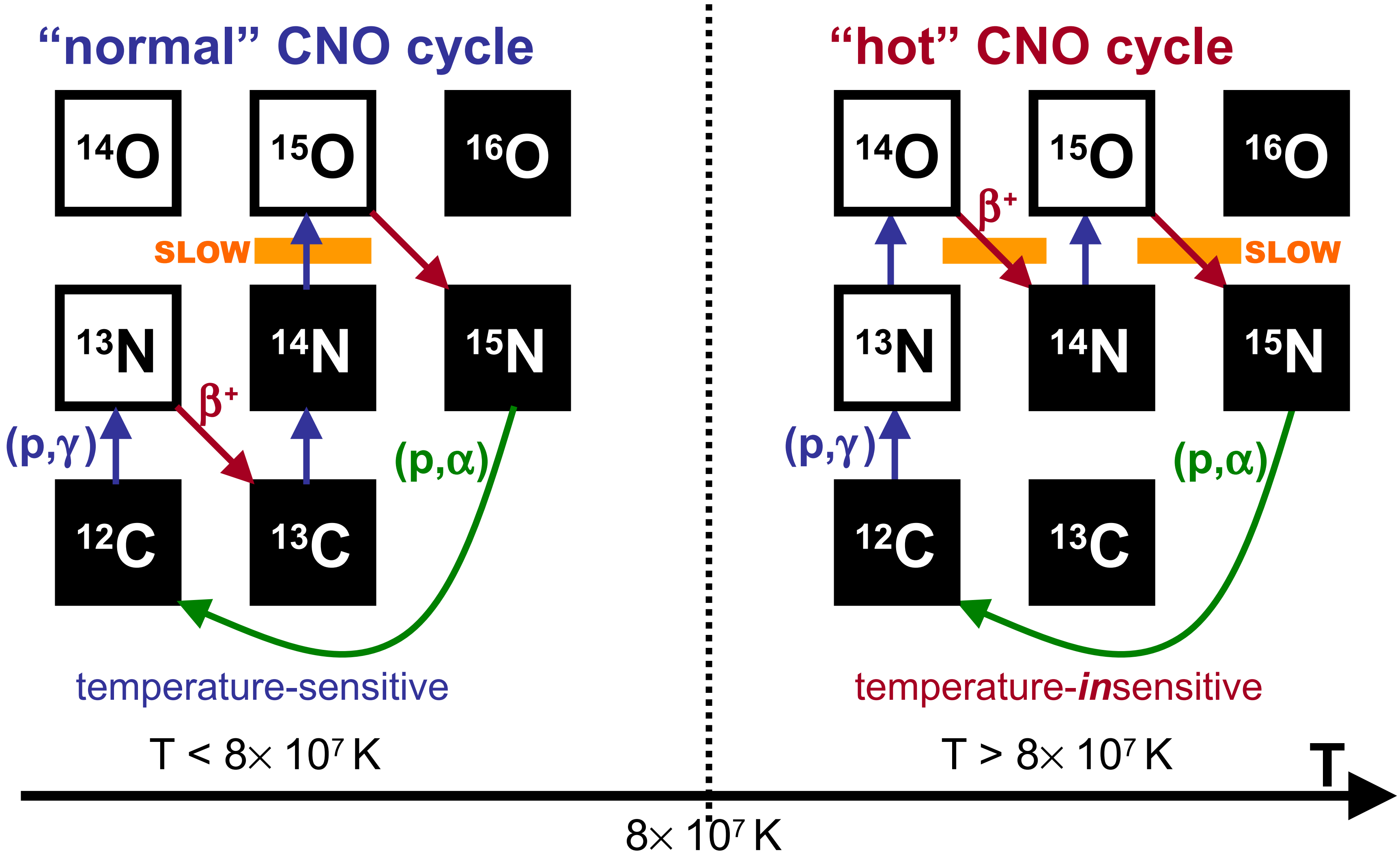
- Usually the beta-decays are fast compared to the capture reactions, (p,$\gamma$).
- $^{14}$O: $\tau_{1/2} = 70$ sec
  $^{15}$O: $\tau_{1/2} = 122$ sec
  $^{13}$N: $\tau_{1/2} = 10\,\mathrm{min}$
  $^{17}$F: $\tau_{1/2} = 64$ sec
  $^{18}$O: $\tau_{1/2} = 110\,\mathrm{min}$
- $^{14}$N(p,$\gamma$)$^{15}$O usually is the slowest “bottleneck” reaction.
- CNO cycle burning converts most CNO isotopes into $^{14}$N.

# Competition of Hydrogen-Burning Modes




Transition from pp-chains in low-mass stars (low $T$) to CNO chains in high-mass stars (high $T$)

# Hydrogen Burning by CNO Cycle




time for an eddy to burn its hydrogen content by **hot** CNO cycle $\tau_H = 11\ \mathrm{h} \left(\frac{0.02}{Z}\right)\left(\frac{X_0}{0.7}\right)$