Outline: Helium burning

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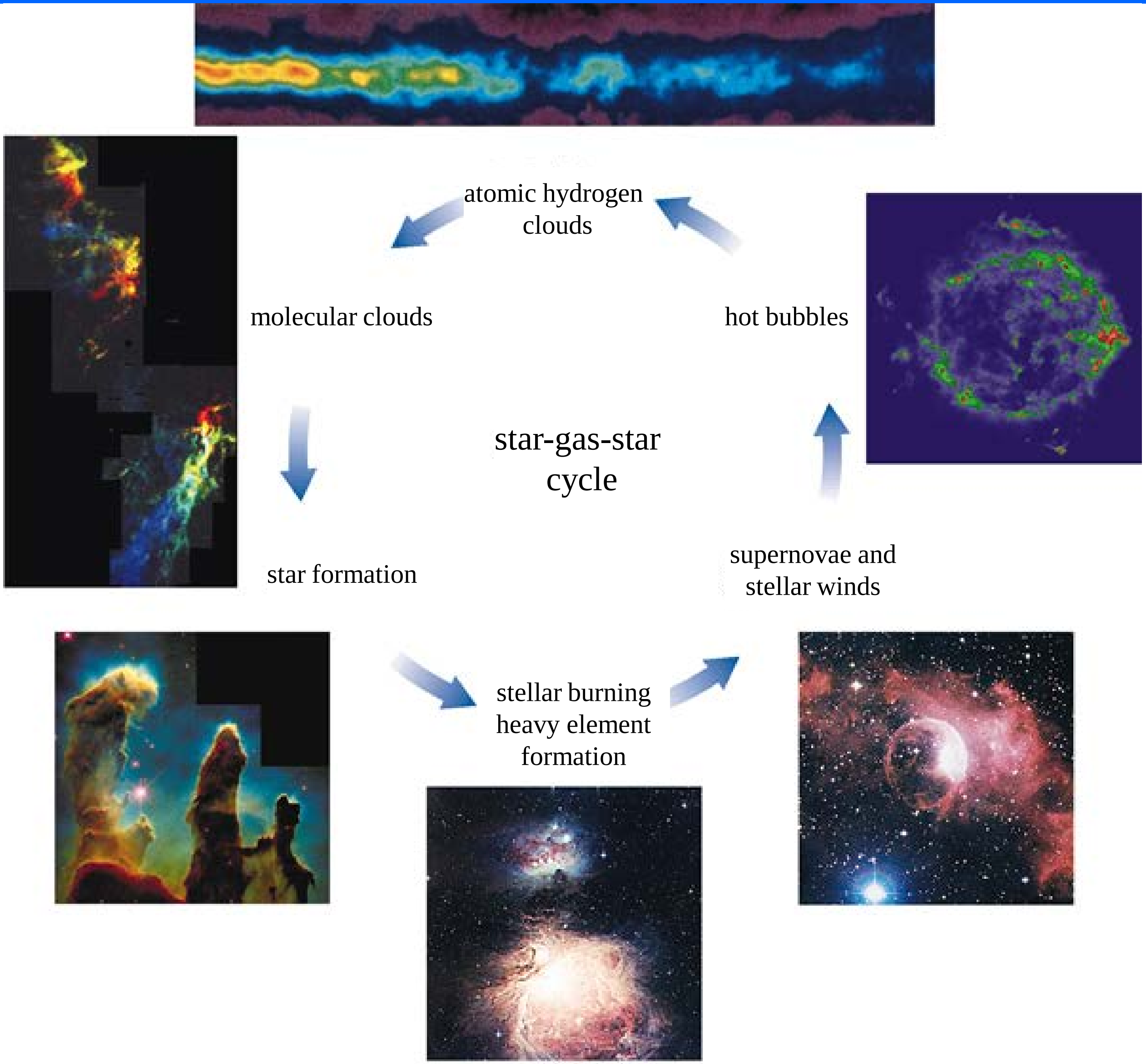
1. critical reactions in He-burning
2. the 3α reaction as two step process
3. $^{12}C(\alpha,\gamma)^{16}O$ reaction

The star-gas-star cycle



star-gas-star
cycle

atomic hydrogen
clouds

molecular clouds

star formation

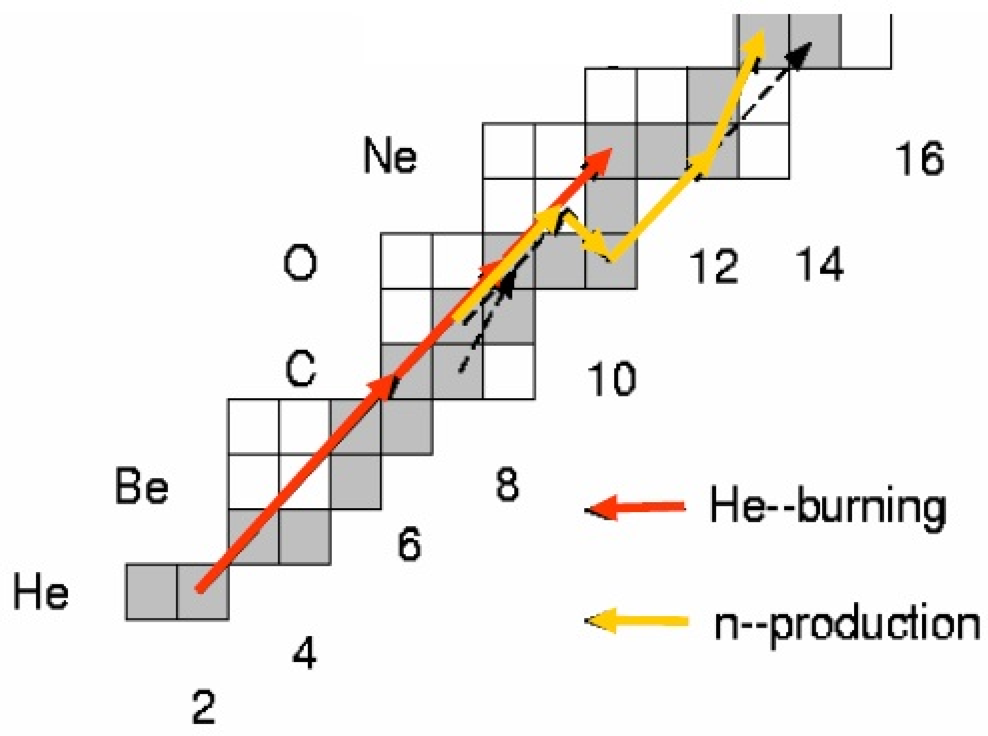
stellar burning
heavy element
formation

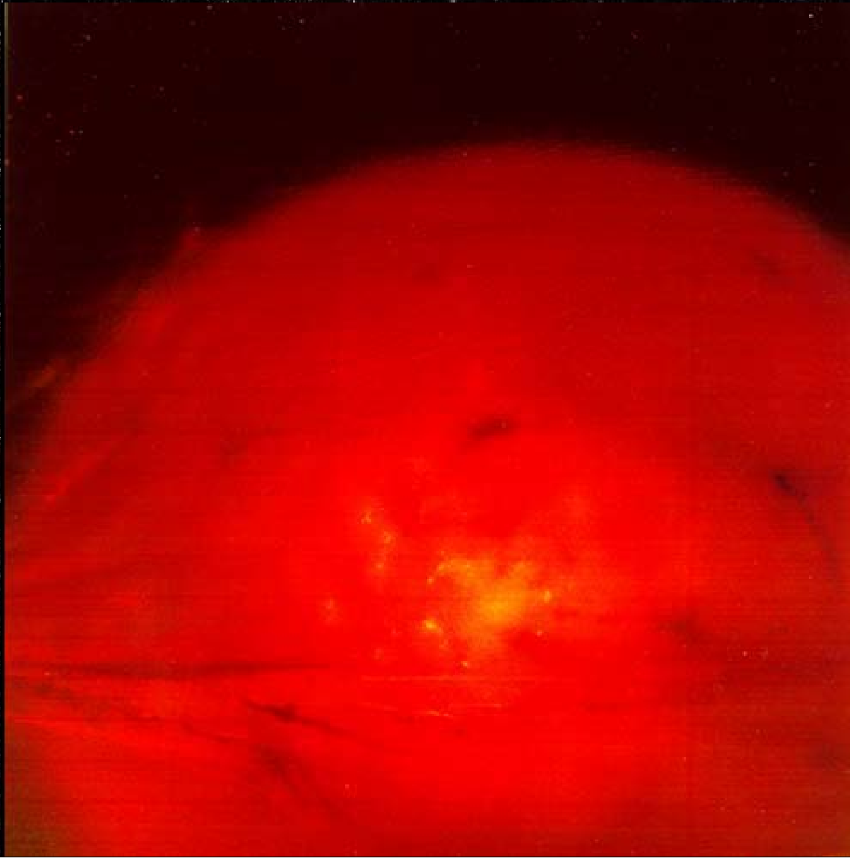
supernovae and
stellar winds

hot bubbles

He-burning in massive stars

He-burning is ignited on the ^4He and ^{14}N ashes of the preceding hydrogen burning phase!

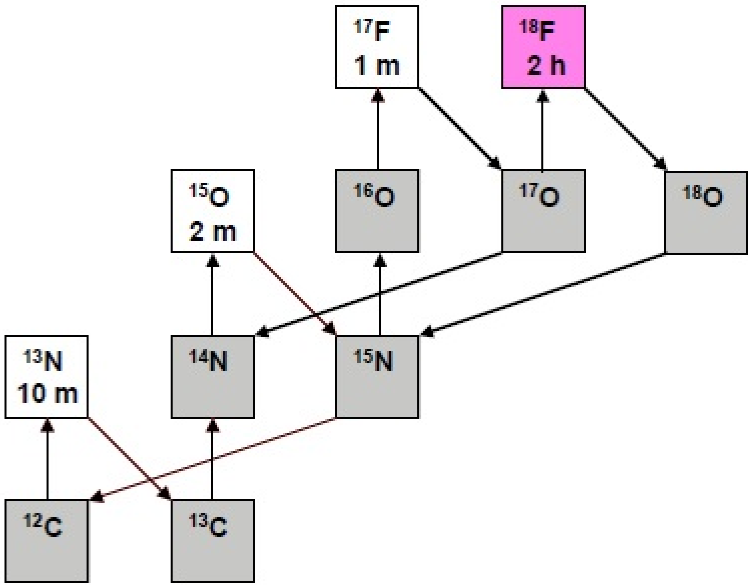


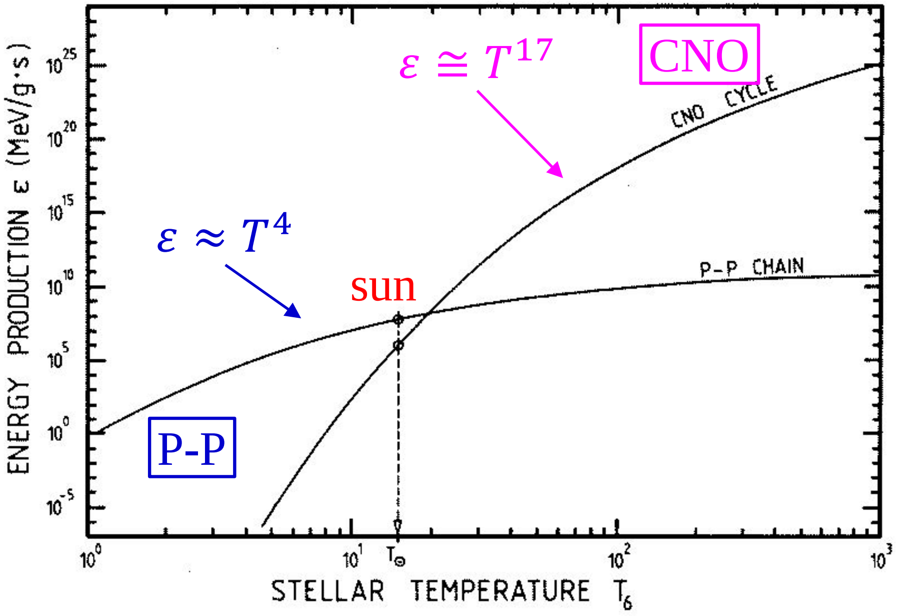


Most important reaction
– triple alpha process -
$3\alpha \rightarrow 12C + 7.96\ MeV$

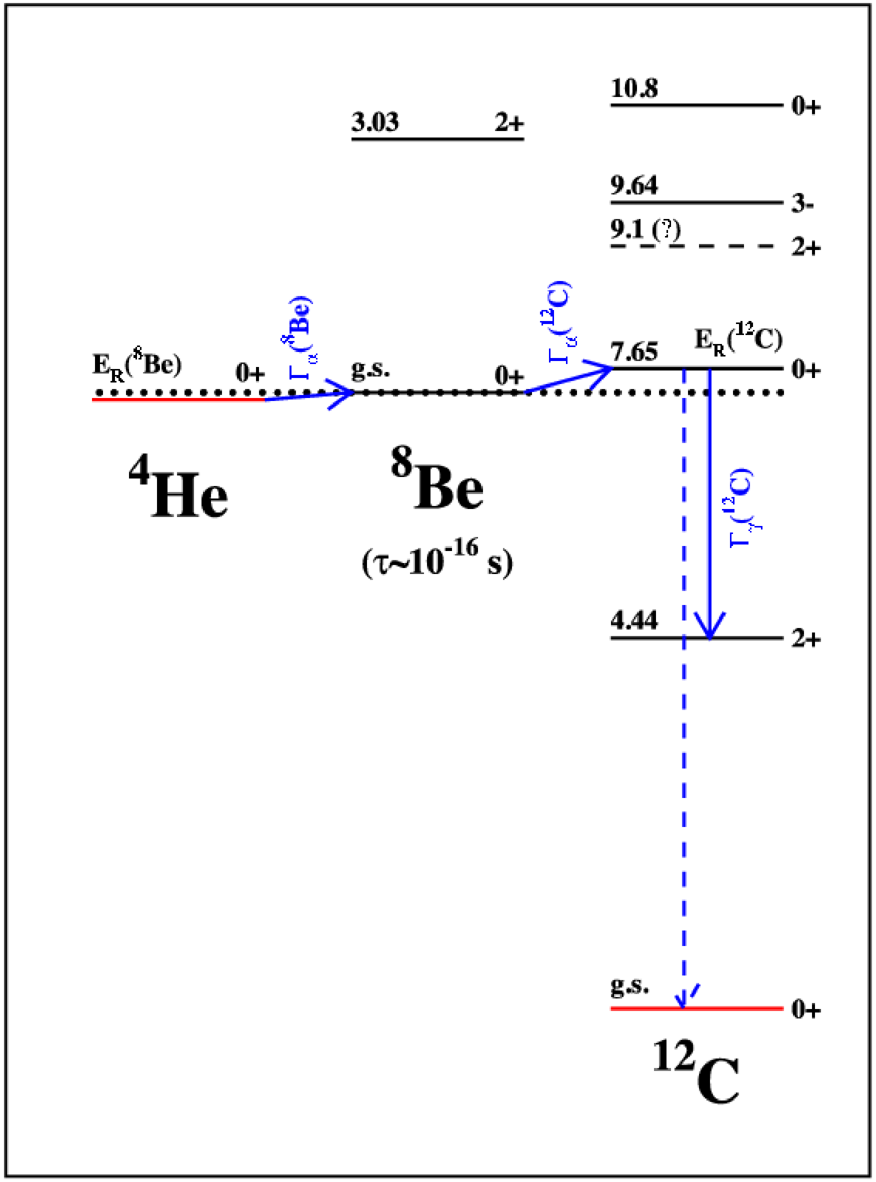
CNO-cycle

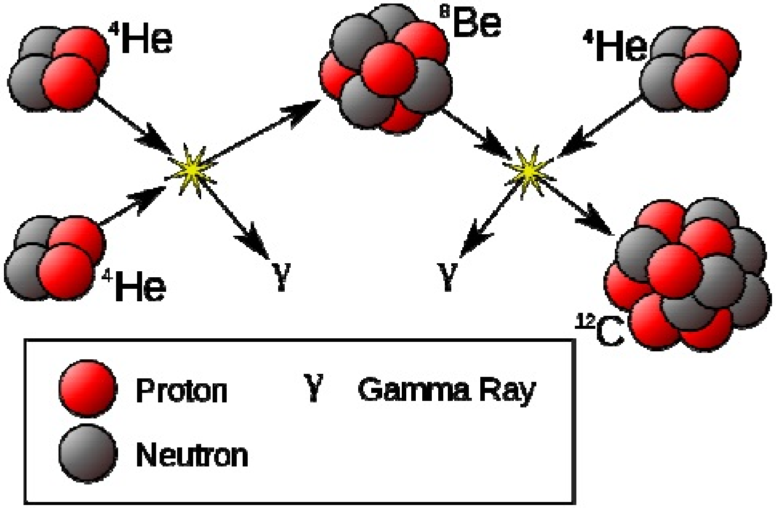
- Dominant source of energy generation in stars heavier than the sun
- What is CNO contribution to energy production in the sun? few %?
- CNO abundances in sun certain
- Stellar photospheric metallicity disagrees with helioseismology





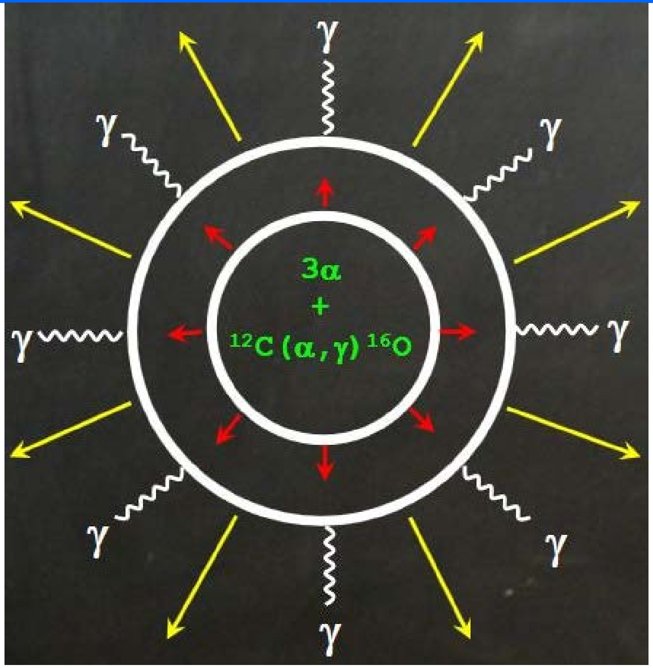
Critical reactions in He-burning





Resonance in Gamow window
- C is made !

He burning



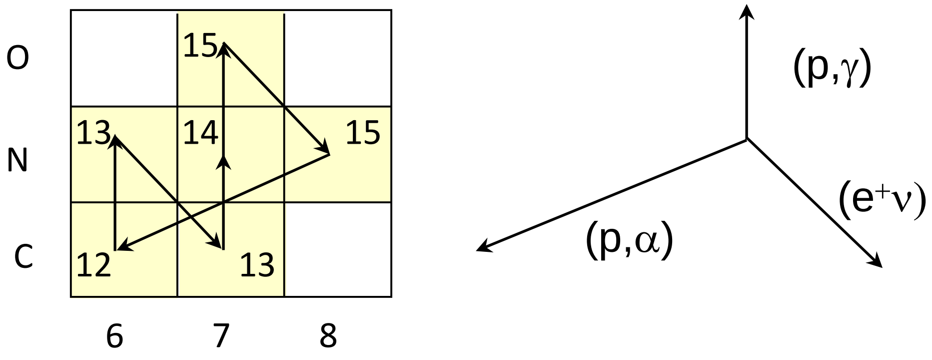
- Typical conditions:
  - Temperature: (1-2) 10^8 K
  - Density: a few $10^2 - 10^4$ g/cm^3

- Net reaction: $^4He\ (2\alpha,\gamma)\ ^{12}C$
- fuel: helium
- main products: carbon, oxygen
- $^4He + {}^4He \leftrightarrow {}^8Be + \gamma$
  $^8Be + {}^4He \leftrightarrow {}^{12}C + \gamma$
- and $^{12}C + {}^4He \rightarrow {}^{16}O + \gamma$
- difficulty: lifetime of $^8Be \sim 10^{-16}$ s
  → Hoyle state (resonance in ^{12}C at E=7.68 MeV)
- Other products: $^{21,22}Ne$, $^{25,26}Mg$, ^{36}S, ^{37}Cl, ^{40}K, ^{40}Ar
- $^{14}N\ (\alpha,\gamma)\ ^{18}F\ (e^+,\nu)\ ^{18}O\ (\alpha,\gamma)\ ^{22}Ne\ (\alpha,n)\ ^{25}Mg$

$kT \sim 8.6 \times 10^{-8}\ T[K]$ keV

CNO-cycle

CNO cycle



$^{12}C(p,\gamma)^{13}N(e^{+}\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(e^{+}\nu)^{15}N(p,\alpha)^{12}C$

Cycle limited by β-decay of ^{13}N (t ~ 10 min) and ^{15}O (t ~ 2 min)

CNO isotopes act as catalysts

$\alpha+\alpha \rightleftarrows {}^{8}Be \qquad {}^{8}Be + \alpha \rightleftarrows {}^{12}C^{*}(7.7\ MeV)$

nucleosynthesis **energy production**

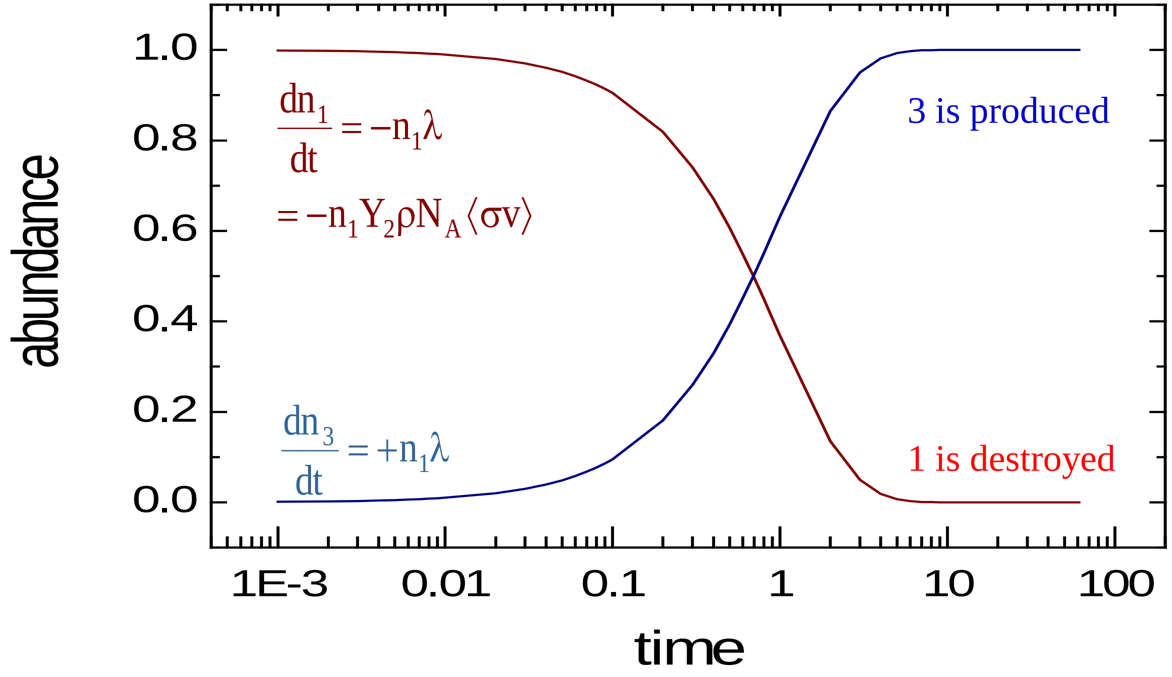
changes in stellar conditions ⇒ changes in energy production and nucleosynthesis

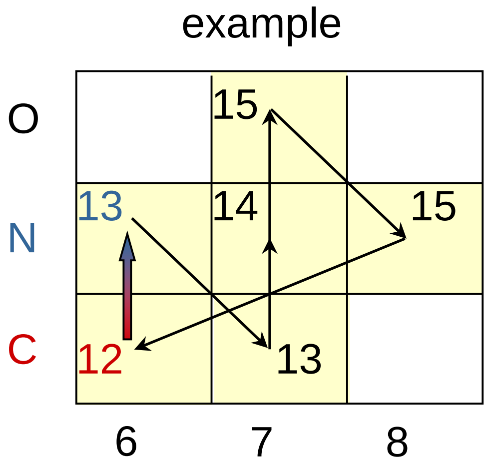
need to know REACTION RATE at all temperatures to determine ENERGY PRODUCTION

Abundance change and lifetimes

consider reaction **1+2 → 3**

where **1** is destroyed through capture of **2** and **3** is produced





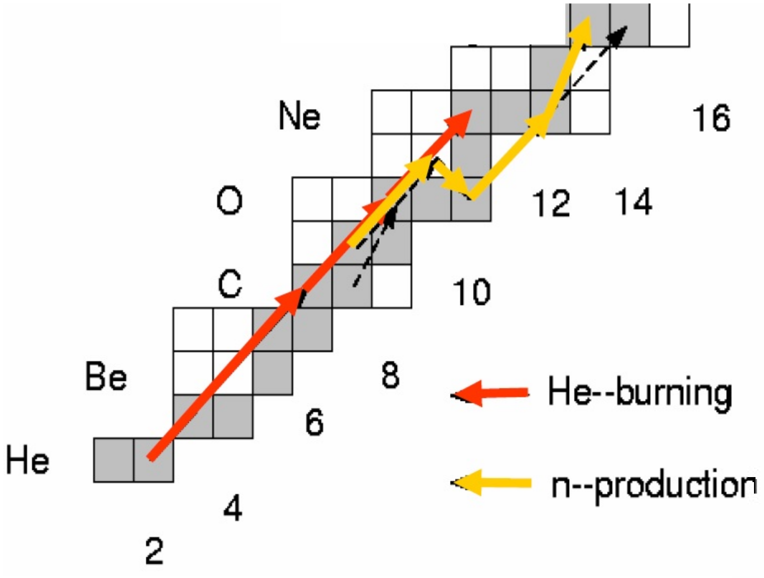
define:

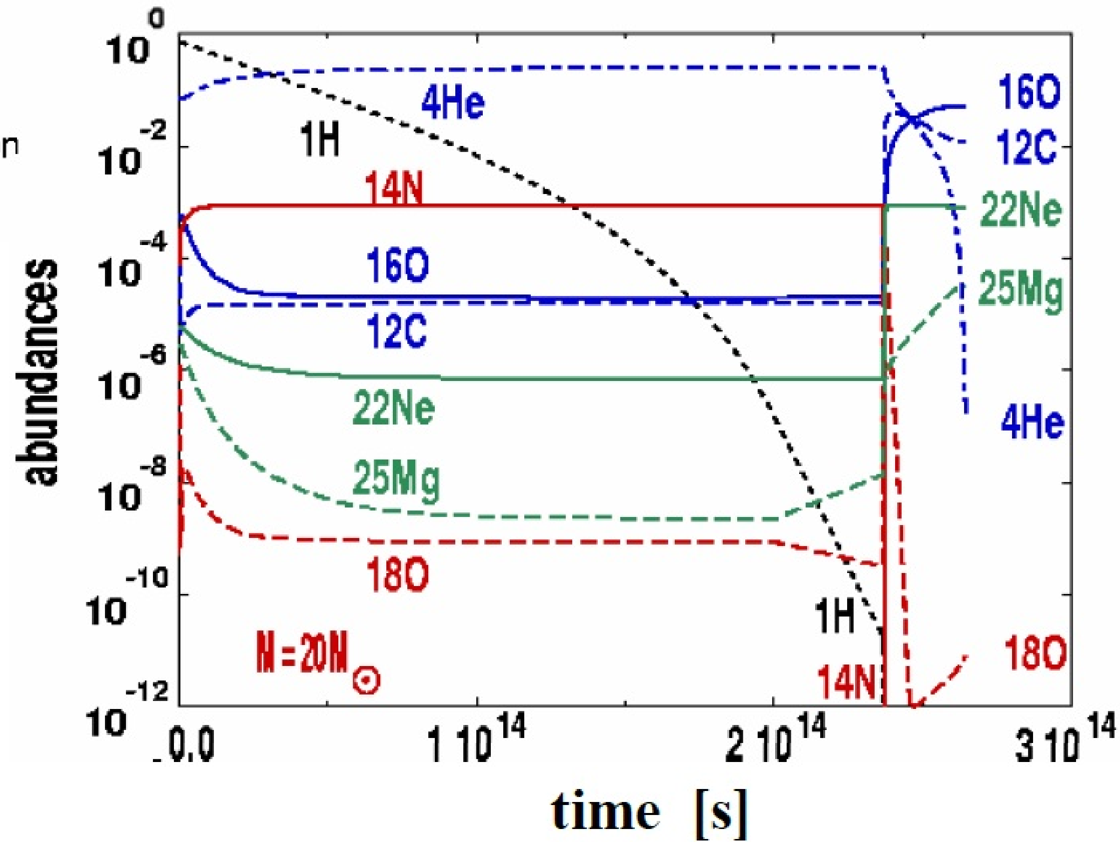
lifetime of 1 against destruction by with 2:

$$\tau = \frac{1}{\lambda} = \frac{1}{Y_1 \rho N_A \langle\sigma v\rangle}$$

need to know REACTION RATE at all temperatures to determine NUCLEOSYNTHESIS

Abundance evolution in stellar core

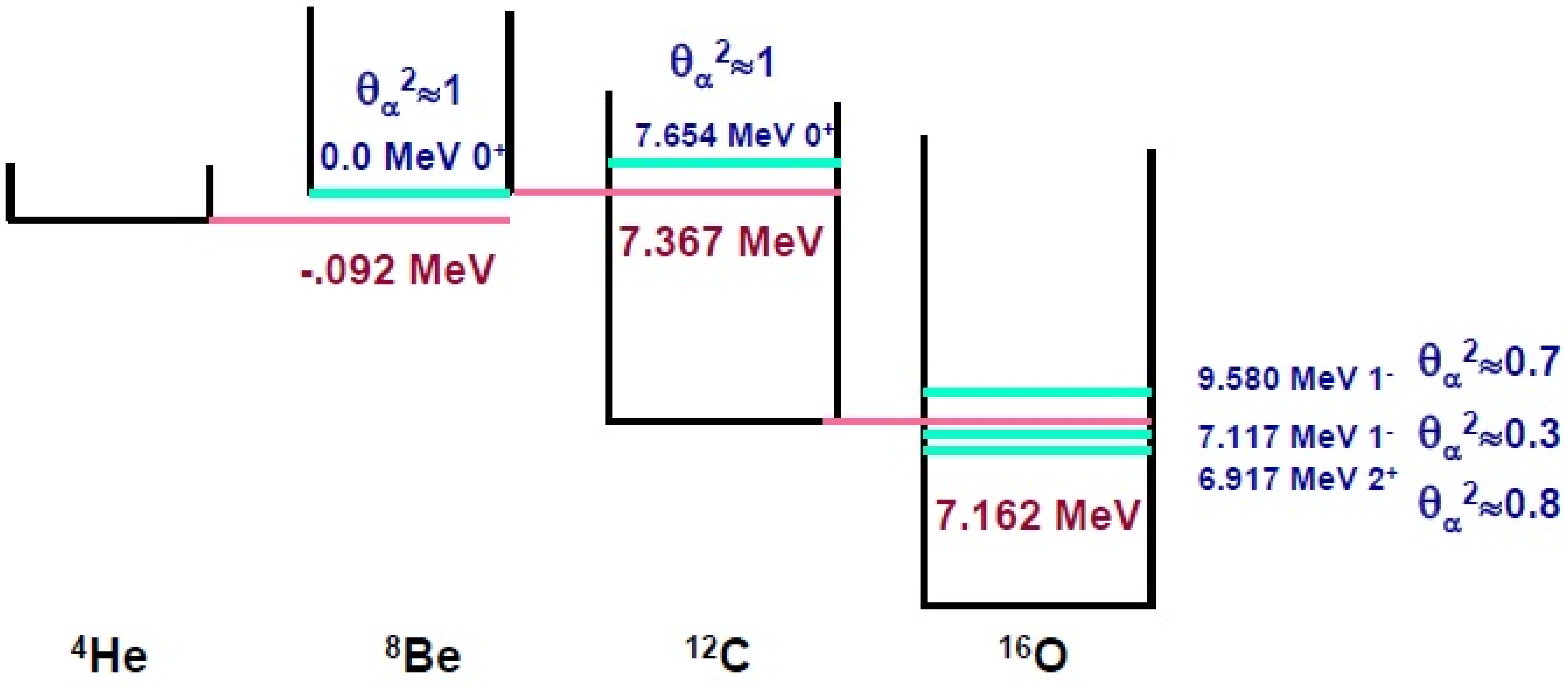




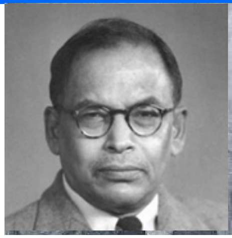
Decline of ^{4}He (time scale)
increase in ^{12}C, ^{16}O
→ equilibrium ^{12}C/^{16}O
rapid decline in ^{14}N

The case of 3α and $^{12}C(\alpha,\gamma)^{16}O$

Reaction rates determined by
α cluster state configurations
providing strong resonances!

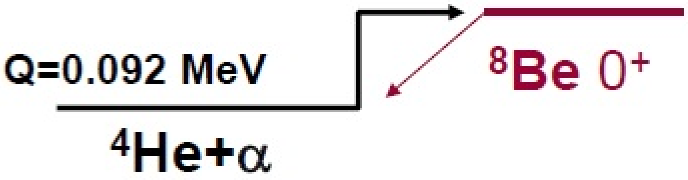


The (ααα) reaction as two step process



Meghnad Saha

first step!



Q=0.092 MeV

^{4}He+α

^{8}Be 0^+

$T_{1/2}(^{8}\mathrm{Be}) = 9.7 \cdot 10^{-17}$ s

$\Gamma_\alpha = 6.8$ eV

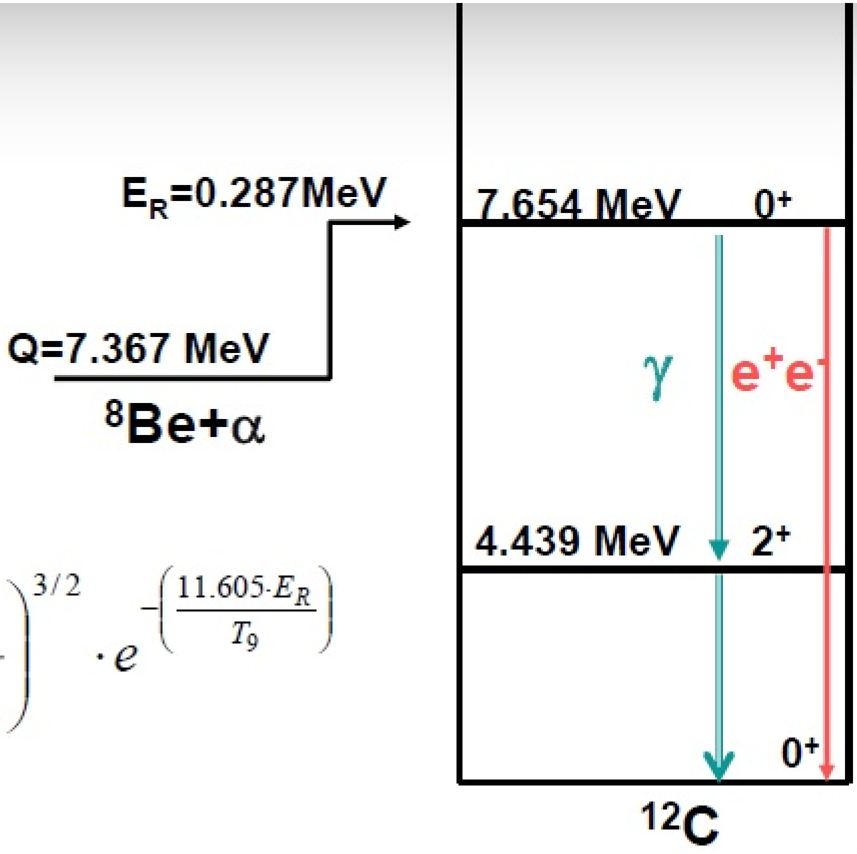
pure α cluster configuration

Example for ^{8}Be equilibrium abundance:

Case of typical He-burning: T=0.1GK ⇒ $T_9=0.1$; $\rho=10^5$ g/cm^3

Resonant capture on ^{8}Be

The Hoyle resonance!



$$N_A\langle\sigma v\rangle = 1.54\cdot10^{11}\cdot\omega\gamma\cdot\left(\frac{1}{\mu\cdot T_9}\right)^{3/2}\cdot e^{-\left(\frac{11.605\cdot E_R}{T_9}\right)}$$

$$\omega\gamma = (2J+1)\cdot\frac{\Gamma_{in}\cdot\Gamma_{out}}{\Gamma_{tot}}$$

Decay by sequential E2 γ transitions or internal e^+ e^- pair conversion

The resonance strength

$$\omega\gamma = \frac{\Gamma_\alpha \cdot \left(\Gamma_\gamma + \Gamma_{e^+e^-}\right)}{\Gamma_\alpha + \Gamma_\gamma + \Gamma_{e^+e^-}}$$

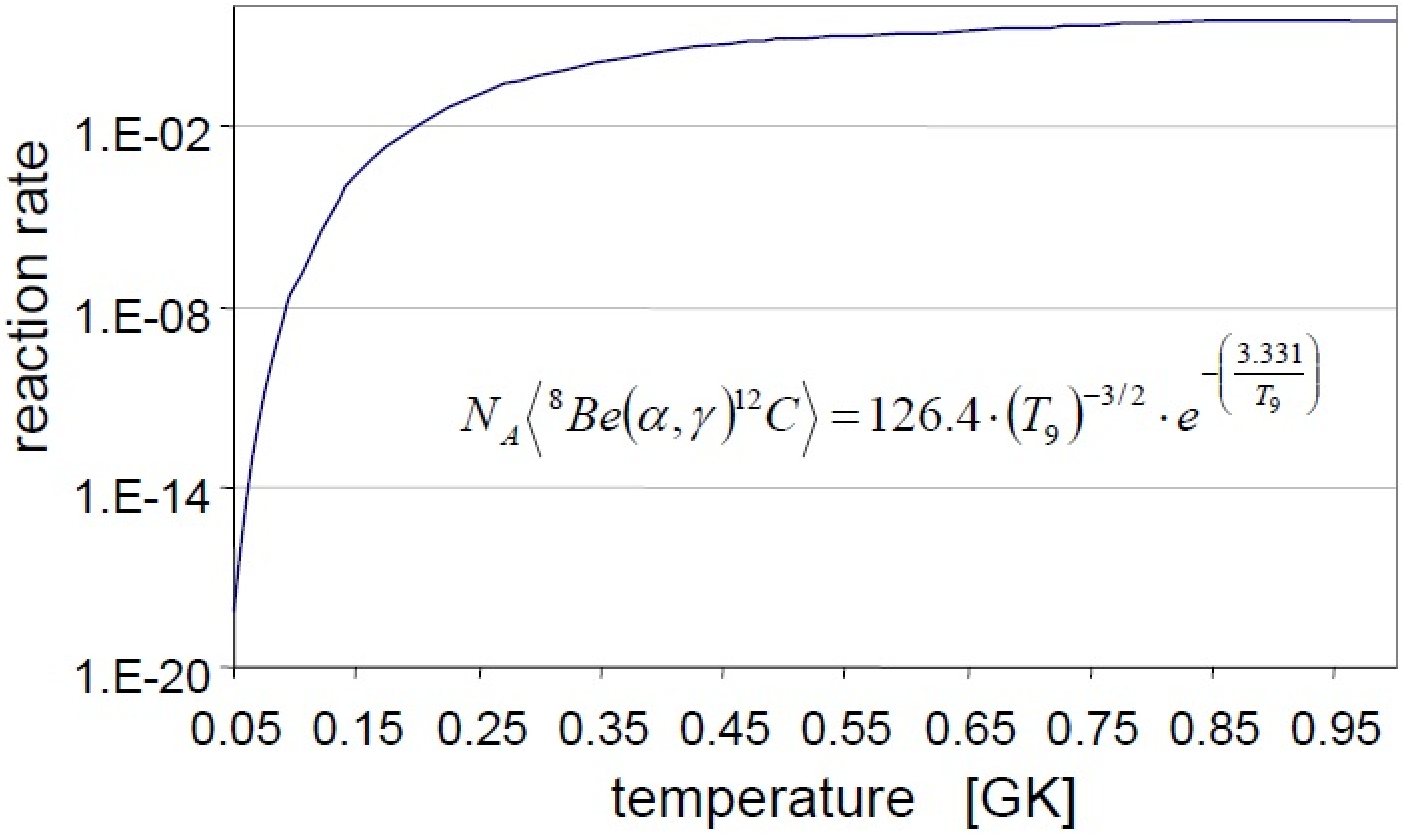
$$\Gamma_\alpha = 8.09 \pm 1.08\, eV$$

$$\Gamma_\gamma = 3.58 \pm 0.5\, meV \qquad \frac{\Gamma_{rad}}{\Gamma_{tot}} = 4.12 \cdot 10^{-4}$$

$$\Gamma_{e^+e^-} = 60.6 \pm 3.9\, \mu eV$$

$$\boxed{\omega\gamma = 3.58 \cdot 10^{-9}\ MeV \quad \pm 12\%}$$

The ^{8}Be+α reaction rate



$$N_A\langle {}^8Be(\alpha,\gamma)^{12}C\rangle = 126.4\cdot(T_9)^{-3/2}\cdot e^{-\left(\frac{3.331}{T_9}\right)}$$

How did they do the experiment?

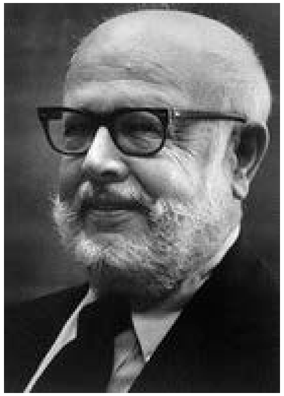
- Used a deuterium beam on a ^{11}B target to produce ^{12}B via a (d,p) reaction.
- ^{12}B β-decays within 20 ms into the second excited state in ^{12}C
- This state then immediately decays under alpha emission into ^{8}Be
- Which immediately decays into 2 alpha particles

So they saw after the delay of the β-decay 3 alpha particles coming from their target after a few ms of irradiation

This proved that the state can also be formed by the 3 alpha process …

→ removed the major roadblock for the theory that elements are made in stars

→ Nobel Prize in Physics 1983 for Willy Fowler (alone !)



The total <ααα> rate

$$r_{\alpha\alpha\alpha} = N_{^8Be} \cdot \rho \cdot \frac{X_\alpha}{A_\alpha} \cdot N_A \left\langle {}^8Be(\alpha,\gamma)^{12}C \right\rangle$$

Step 1

Step 2

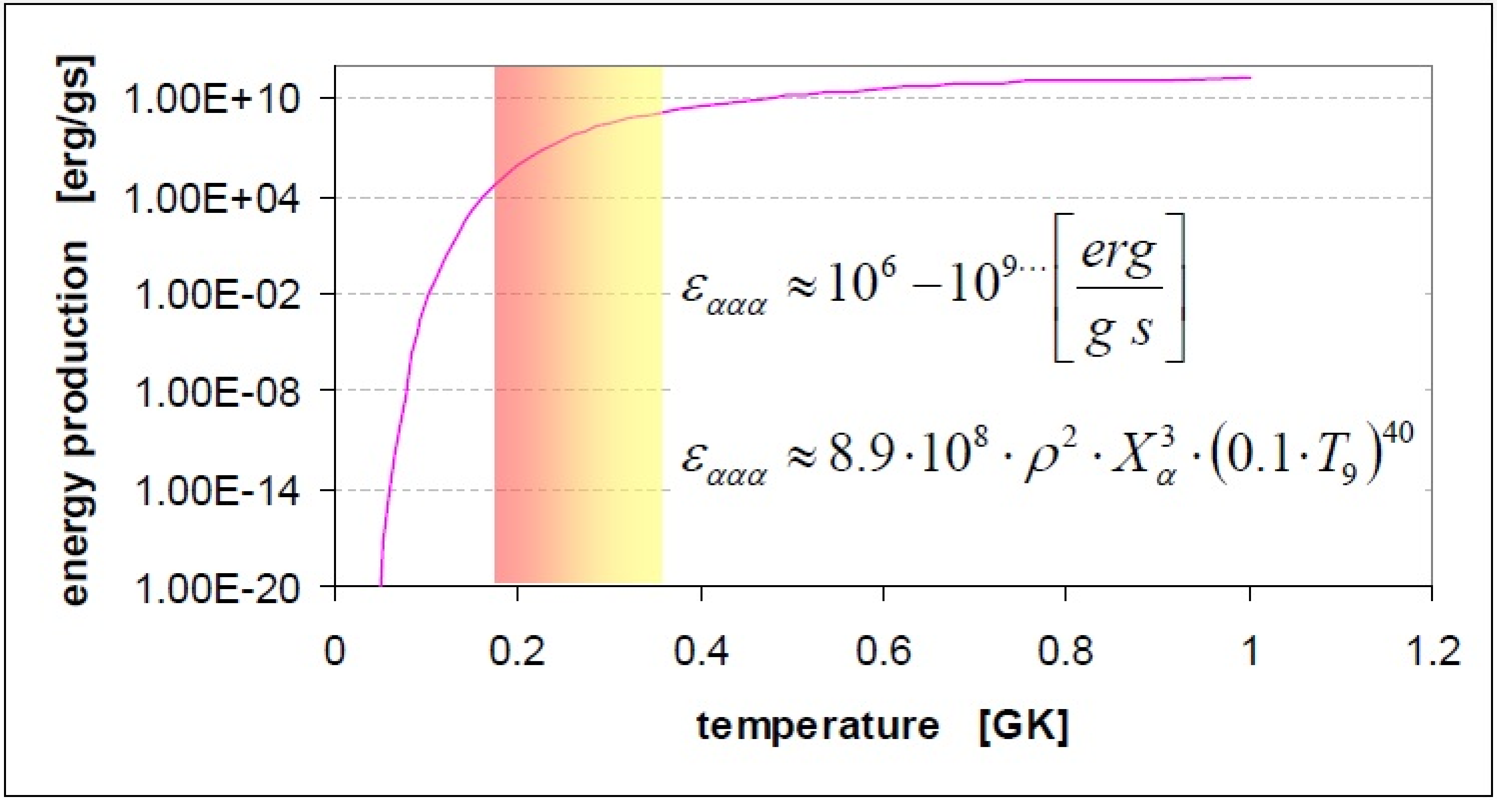
$$N\left({}^8Be\right) = 6\cdot 10^{-35}\cdot N_\alpha^2 \cdot T_9^{-3/2}\cdot e^{\left(-\frac{1.068}{T_9}\right)}$$

$$N_A\left\langle {}^8Be(\alpha,\gamma)^{12}C\right\rangle = 126.4\cdot (T_9)^{-3/2}\cdot e^{-\left(\frac{3.331}{T_9}\right)}$$

$$r_{\alpha\alpha\alpha} = \frac{1.26\cdot 10^{-56}}{1+\delta_{\alpha\alpha}}\cdot N_\alpha^3\cdot T_9^{-3}\cdot e^{\left(-\frac{11.605\cdot(0.092+0.278)}{T_9}\right)}$$

$$r_{\alpha\alpha\alpha} = 1.38\cdot 10^{15}\cdot\rho^3\cdot\left(\frac{X_\alpha}{4}\right)^3\cdot T_9^{-3}\cdot e^{\left(-\frac{4.294}{T_9}\right)} \quad \left[cm^{-3}s^{-1}\right]$$

Example: $\rho = 10^5$ g/cm^3



$$\varepsilon_{\alpha\alpha\alpha} \approx 10^6 - 10^{9\cdots} \left[\frac{erg}{g\ s}\right]$$

$$\varepsilon_{\alpha\alpha\alpha} \approx 8.9 \cdot 10^8 \cdot \rho^2 \cdot X_\alpha^3 \cdot (0.1 \cdot T_9)^{40}$$

T-dependent main energy source for stellar He-burning

C-burning

- Typical conditions:
  - Temperature: (6-8) 10^8 K
  - Density: 10^5 g/cm^3

- Net reaction: $^{12}C + ^{12}C$
- fuel: carbon
- main products: neon, magnesium, oxygen
- $^{12}C + ^{12}C \rightarrow \alpha + ^{20}Ne$ (Q = 4.62 MeV)
- $^{12}C + ^{12}C \rightarrow p + ^{23}Na$ (Q = 2.24 MeV)
- other reactions: $^{23}Na + p \rightarrow \alpha + ^{20}Ne$

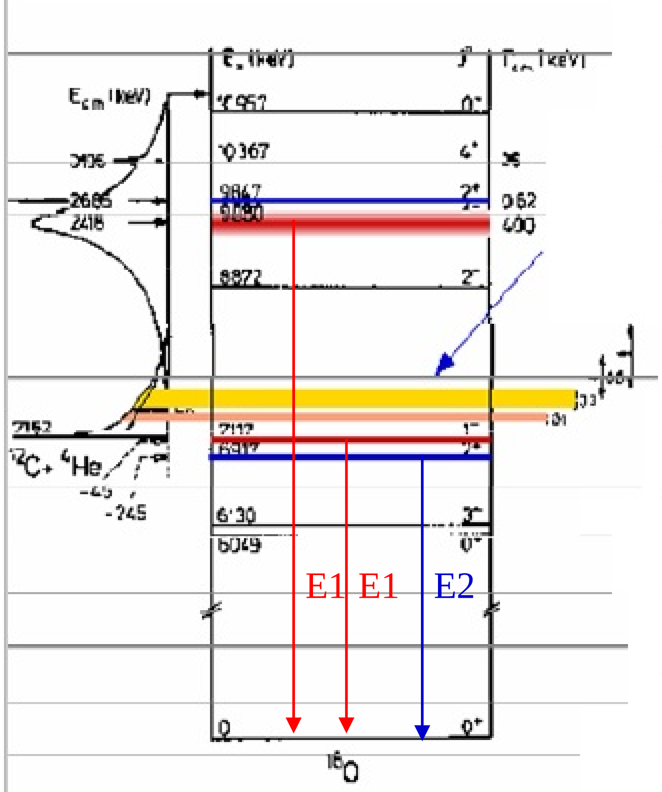
  $^{20}Ne + \alpha \rightarrow ^{24}Mg$
- **$^{12}C + \alpha \rightarrow ^{16}O + \gamma$**

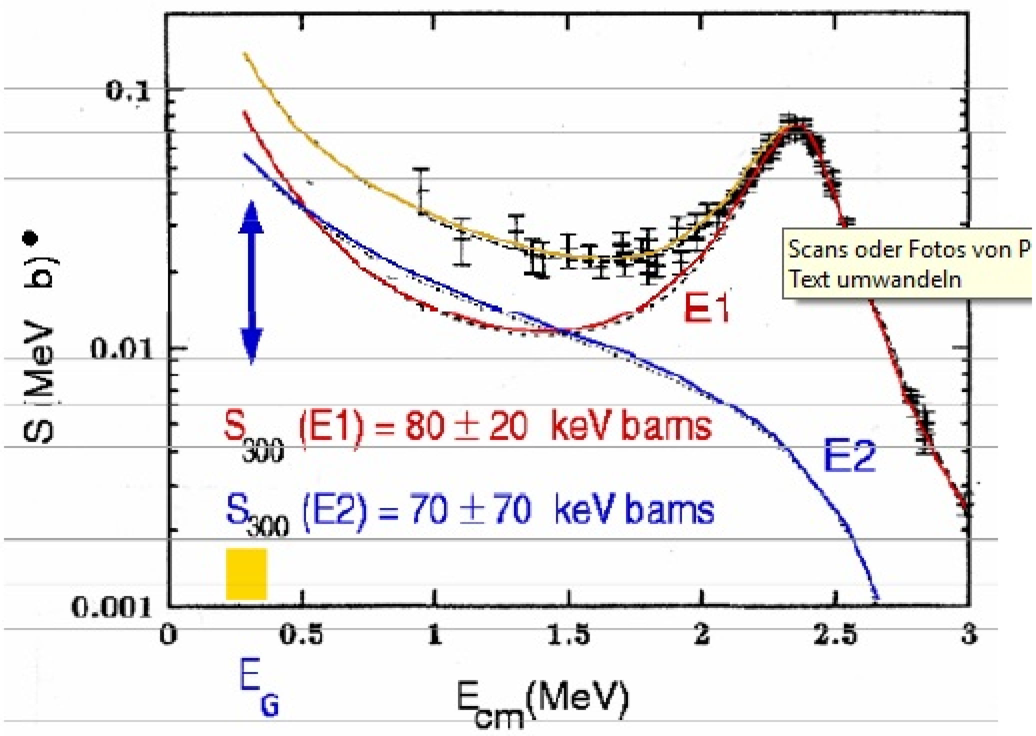
conversion of ^4He into ^{12}C and ^{16}O

$kT \sim 8.6 \times 10^{-8}\ T[K]$ keV

$^{12}C(\alpha,\gamma)^{16}O$, the Holy Grail

Level and Interference Structure between 1^- levels (E1) and 2^+ states (E2).

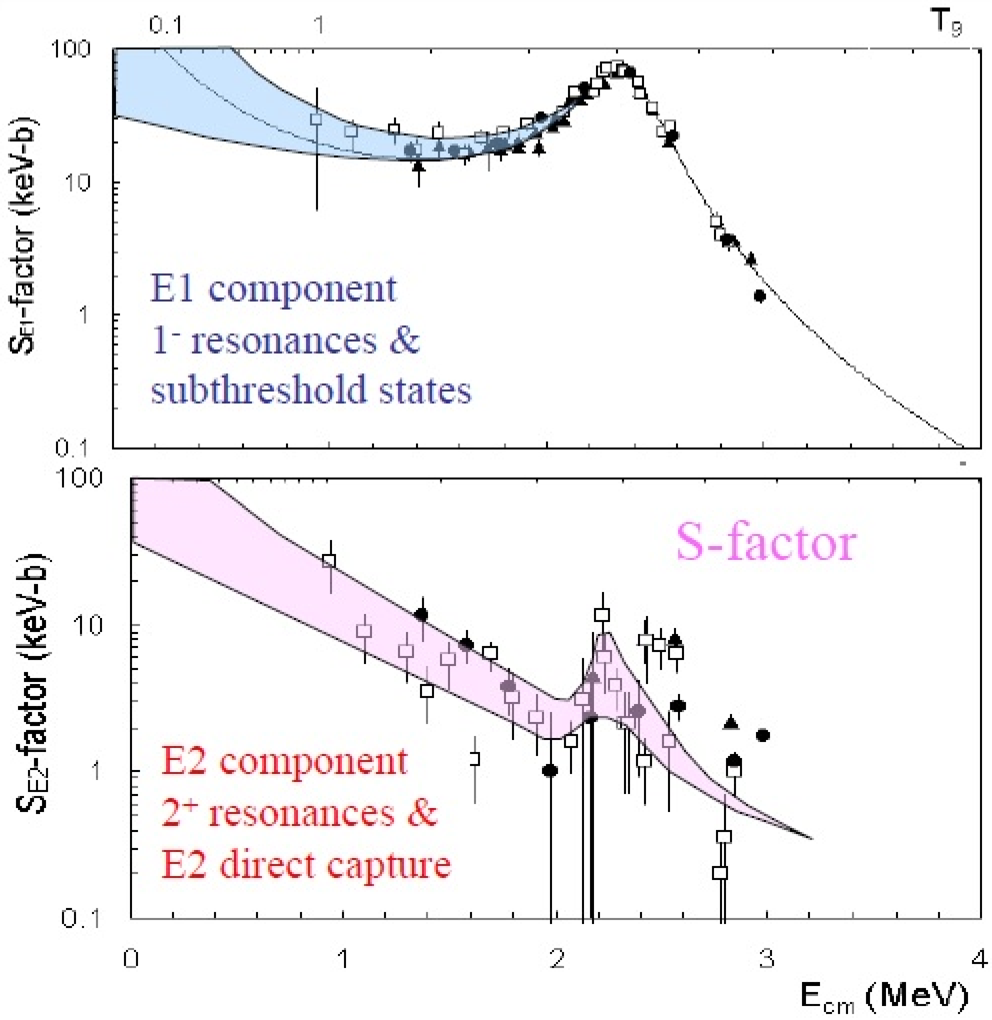




Uncertainty in low energy extrapolation

Reaction contributions in $^{12}C(\alpha,\gamma)^{16}O$

Difficulty in the reliability of low energy extrapolation



$^{12}C(\alpha,\gamma)^{16}O$ reaction rate

$$N_A\langle\sigma\upsilon\rangle = 6.9\cdot 10^8 \cdot T_9^{-2/3} \cdot S_{eff}\left[MeV-b\right]\cdot e^{-\frac{32.11}{T_9^{1/3}}} \quad \left[\frac{cm^3}{s}\right]$$

$$S_{eff} \approx 0.17\left[MeV-b\right]$$

$$N_A\langle\sigma\upsilon\rangle \approx 1.2\cdot 10^8 \cdot T_9^{-2/3} \cdot e^{-\frac{32.11}{T_9^{1/3}}} \quad \left[\frac{cm^3}{s}\right]$$

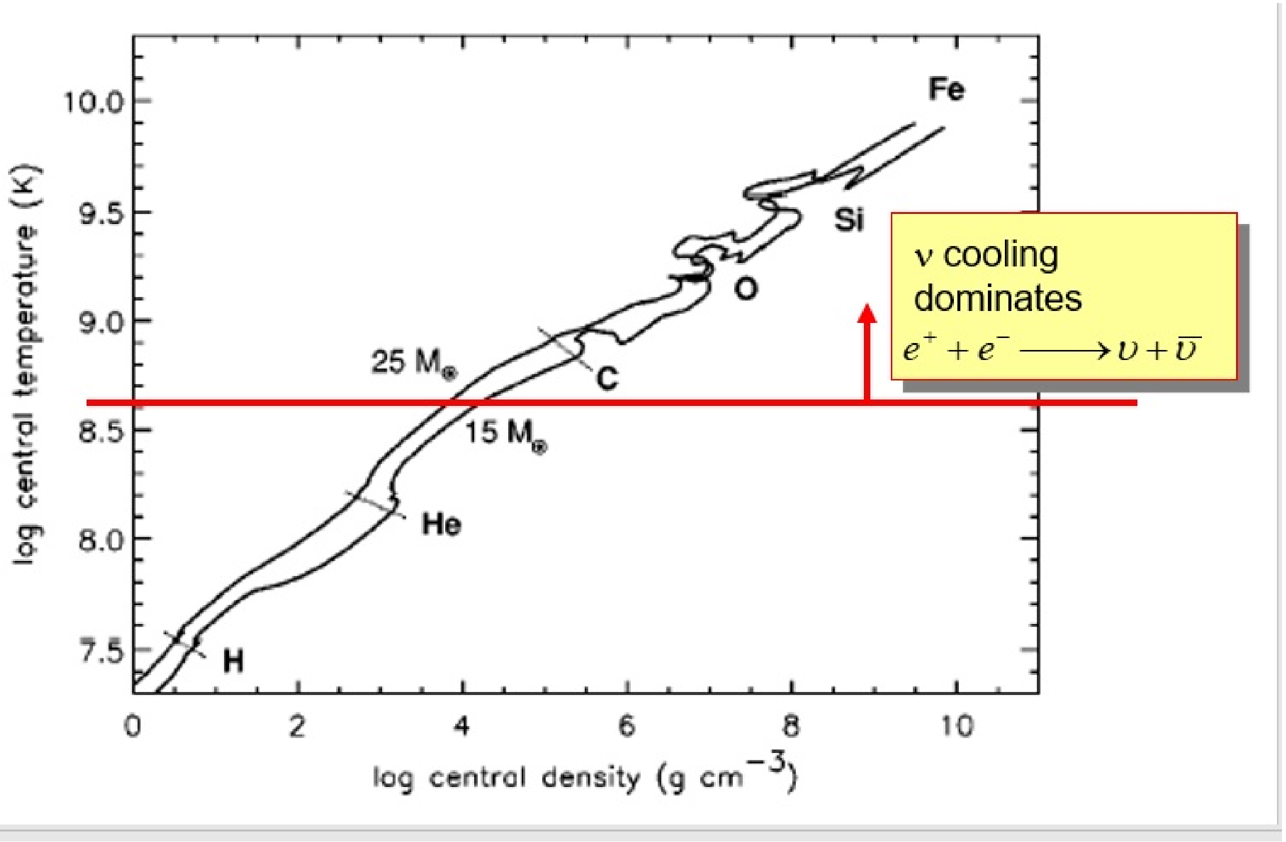
Only very crude estimate!
E-T dependency needs to be considered!

The role of neutrino-losses

- At temperatures above ~10^9 K: pair-production

$$\gamma \leftrightarrow e^+ + e^- \leftrightarrow \nu_e + \bar{\nu}_e$$

- Luminosity of photons and neutrinos



ν cooling dominates

$$e^+ + e^- \longrightarrow \upsilon + \overline{\upsilon}$$

Ne-burning

- Typical conditions:
  - Temperature: (1-2) 10^9 K
  - Density: 10^6 g/cm^3

- Reactions: $^{20}Ne + ^{20}Ne \rightarrow ^{16}O + ^{24}Mg$ +4.59 MeV
- fuel: neon
- main products: oxygen, silicon
- $^{20}Ne\ (\gamma,\alpha)\ ^{16}O$
- other reactions:

$^{20}Ne\ (\alpha,\gamma)\ ^{24}Mg\ (\alpha,\gamma)\ ^{28}Si\ (\alpha,\gamma)\ ^{32}S$
$^{21}Ne\ (\alpha,n)\ ^{24}Mg\ (n,\gamma)\ ^{25}Mg\ (\alpha,n)\ ^{28}Si$
$^{23}Na\ (\alpha,p)\ ^{25}Mg\ (\alpha,n)\ ^{28}Si$
$^{25}Mg\ (p,\gamma)\ ^{25}Al$
$^{23}Na\ (p,\alpha)\ ^{20}Ne$

Why would neon burn before oxygen?

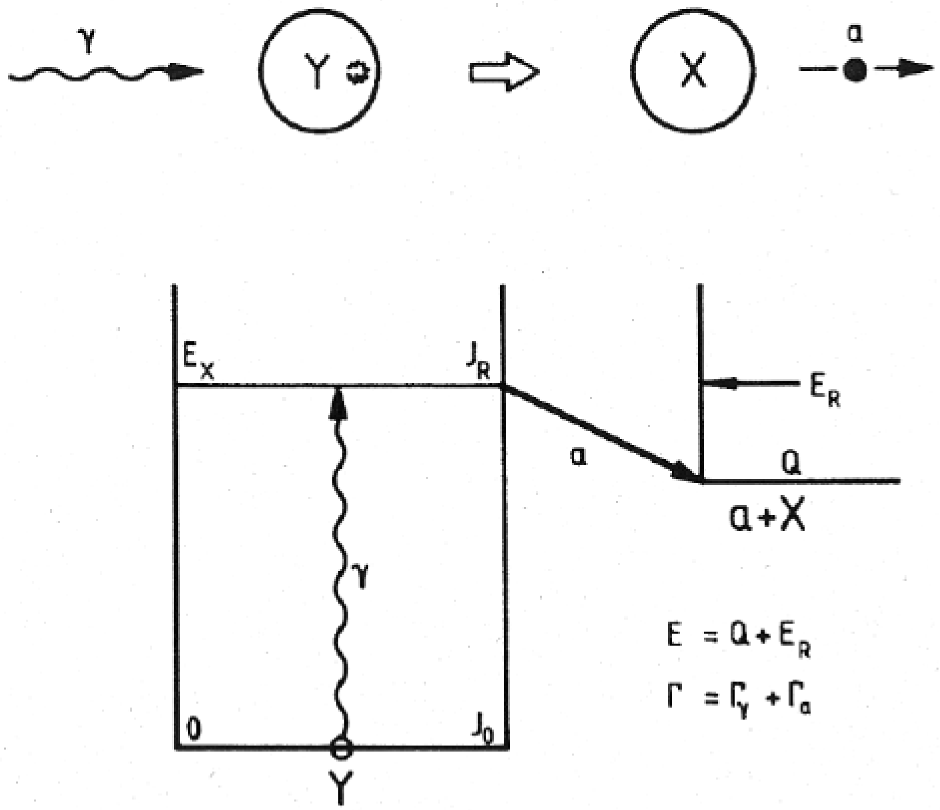
Temperatures are sufficiently high to initiate photodisintegration of ^{20}Ne

$$\left.\begin{aligned} {}^{20}Ne + \gamma &\rightarrow 16O + \alpha \\ {}^{16}O + \alpha &\rightarrow 20Ne + \gamma \end{aligned}\right\} \quad equilibrium\ is\ established$$

$$\boxed{kT \sim 8.6 \times 10^{-8}\ T[K]\ \ keV}$$

Photodisintegration

PHOTODISINTEGRATION Y(γ, a) X



$E = Q + E_R$

$\Gamma = \Gamma_\gamma + \Gamma_a$

O-burning

- Typical conditions:
  - Temperature: (1.5-2.2) 10^9 K
  - Density: 10^7 g/cm^3

- Reactions:
- fuel: oxygen
- main products: silicon, sulfur (90%)
- $^{16}O + ^{16}O \rightarrow ^{32}S^* \rightarrow p + ^{31}P$ (56%, Q = 7.676 MeV)
- $^{16}O + ^{16}O \rightarrow ^{32}S^* \rightarrow \alpha + ^{28}Si$ (34%, Q = 9.593 MeV)
- $^{16}O + ^{16}O \rightarrow ^{32}S^* \rightarrow n + ^{31}S$ (5%, Q = 1.459 MeV)
- other reactions:

  $^{31}P\ (p,\alpha)\ ^{28}Si$
  $^{33}S\ (e^-,\nu)\ ^{33}P$
  $^{35}Cl\ (e^-,\nu)\ ^{35}P\ ^{25}Mg\ (p,\gamma)\ ^{25}Al$
  $^{23}Na\ (p,\alpha)\ ^{20}Ne$

$\boxed{kT \sim 8.6 \times 10^{-8}\ T[K]\ \ keV}$

Si-burning

- Typical conditions:
  - Temperature: (3-4) 10^9 K
  - Density: 10^9 g/cm^3

- Net reaction: $^{28}Si + ^{28}Si$
- fuel: silicon
- main products: Fe-group elements (A = 50-60 nuclei)
- other reactions: $^{28}Si + \gamma \rightarrow p + ^{27}Al$

  $^{28}Si + \gamma \rightarrow \alpha + ^{24}Mg$

  $^{28}Si + \gamma \rightarrow n + ^{27}Si$

- Balance between forward and reverse reactions for increasing number of processes: $a + b \leftrightarrow c + d$
  → Nuclear Statistical Equilibrium (NSE)

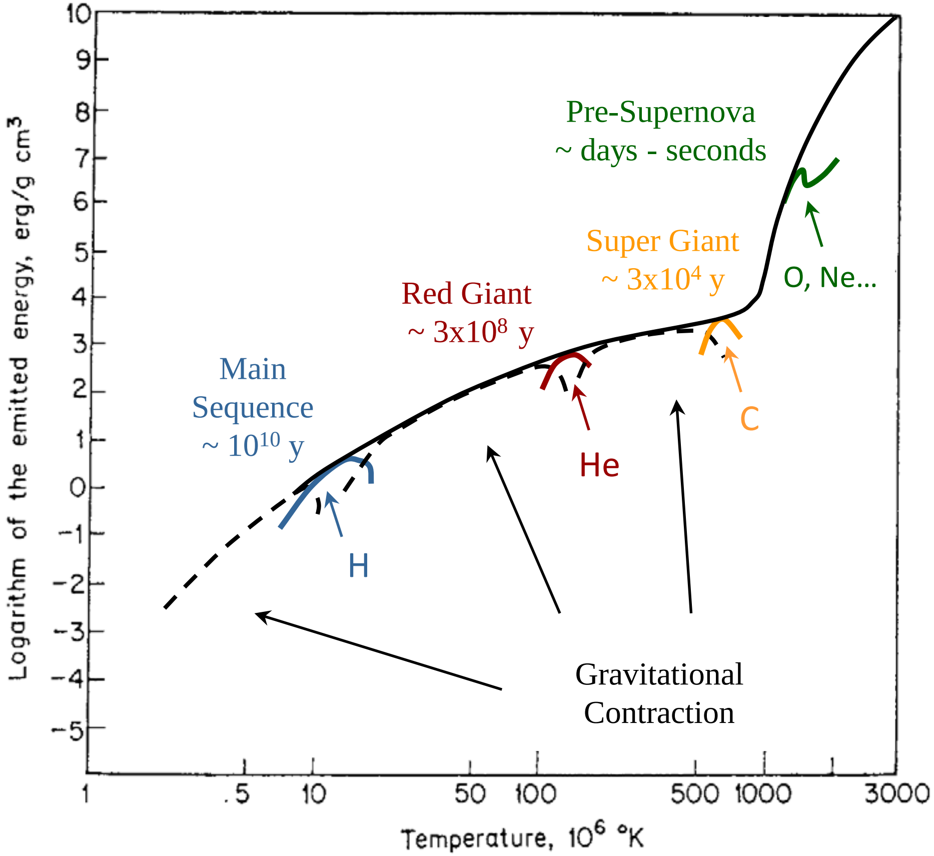
$\boxed{kT \sim 8.6 \times 10^{-8}\ T[K]\ \ keV}$

Stellar evolution

Main parameters governing evolution: initial mass & initial chemical composition

Example: evolution stages of a 25 $M_\odot$ star

Quiescent burning



Energy generation rate

$\varepsilon \sim T^n$

n ~ 4 (H-burning)

n ~ 30 (C-burning)

⬇

innermost regions only contribute to nuclear burning

e.g. 1/10 M for H-burning
less for subsequent stages

⬇

H-burning ≡ MAIN SEQUENCE
longest stage of star's lifetime

Summary stellar burning

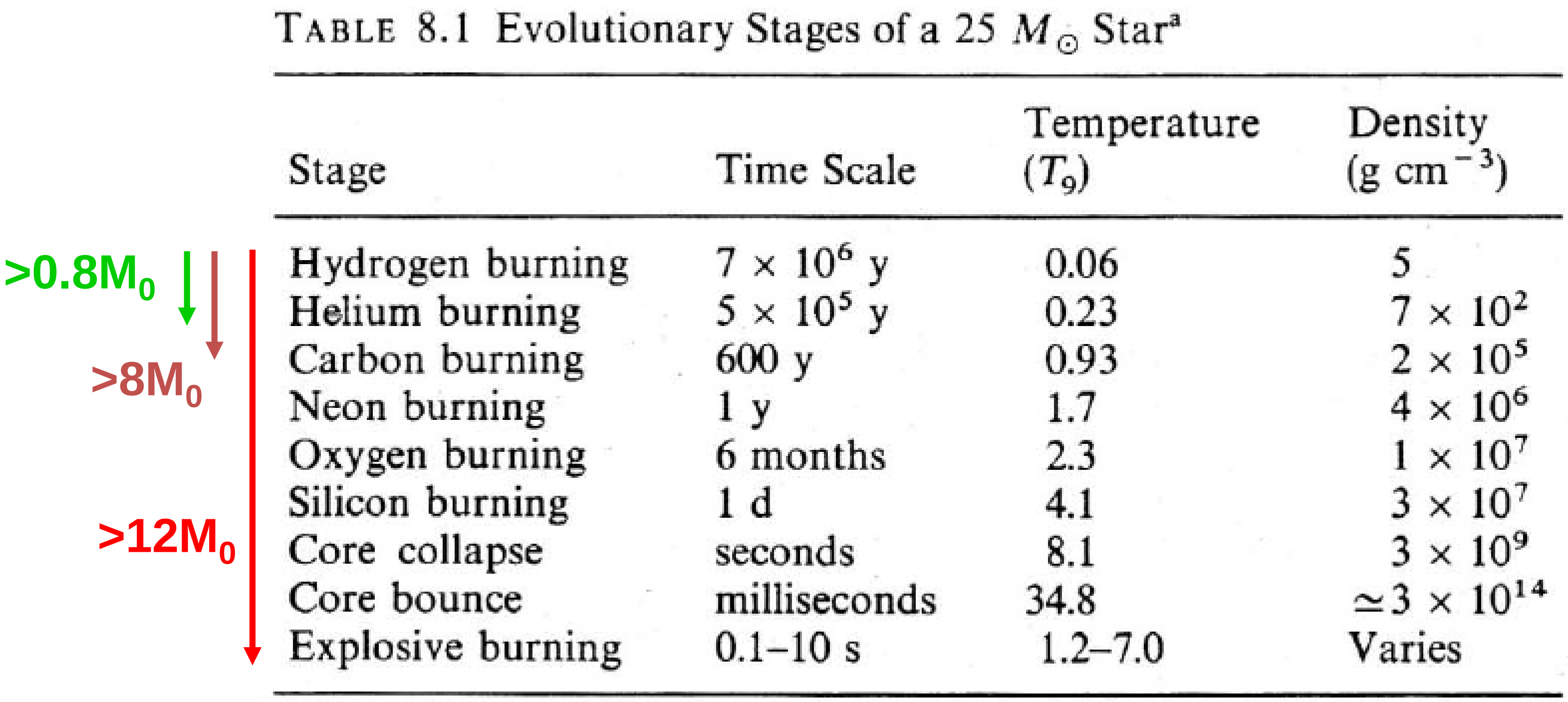


TABLE 8.1 Evolutionary Stages of a 25 $M_\odot$ Star[a]

Stage	Time Scale	Temperature (T_9)	Density (g cm^{-3})
Hydrogen burning	7×10^6 y	0.06	5
Helium burning	5×10^5 y	0.23	7×10^2
Carbon burning	600 y	0.93	2×10^5
Neon burning	1 y	1.7	4×10^6
Oxygen burning	6 months	2.3	1×10^7
Silicon burning	1 d	4.1	3×10^7
Core collapse	seconds	8.1	3×10^9
Core bounce	milliseconds	34.8	$\simeq 3 \times 10^{14}$
Explosive burning	0.1–10 s	1.2–7.0	Varies

Why do timescales get smaller ?

Note: Kelvin-Helmholtz timescale for red supergiant ~10,000 years,
so for massive stars, no surface temperature - luminosity change for C-burning and beyond

… and nucleosynthesis

nucleosynthesis energy

HYDROGEN BURNING (1st equilibrium) $4p \rightarrow {}^{4}He + 2\beta^{+} + 2\nu$ + 26 MeV

HELIUM BURNING (2nd equilibrium)

$3\alpha \rightarrow {}^{12}C$

${}^{12}C(\alpha,\gamma){}^{16}O$

+ 8 MeV

${}^{12}C/{}^{16}O$ BURNING

… ${}^{12}C$ ashes = Ne, Na, Mg

… ${}^{16}O$ ashes = Al, … Si

${}^{28}Si$ MELTING

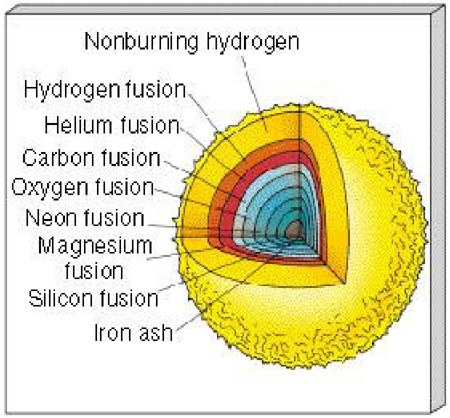
major ash = ${}^{56}Fe$

… A = 40-65

further reactions endothermic gravitational collapse

The Stellar Onion

T, ρ

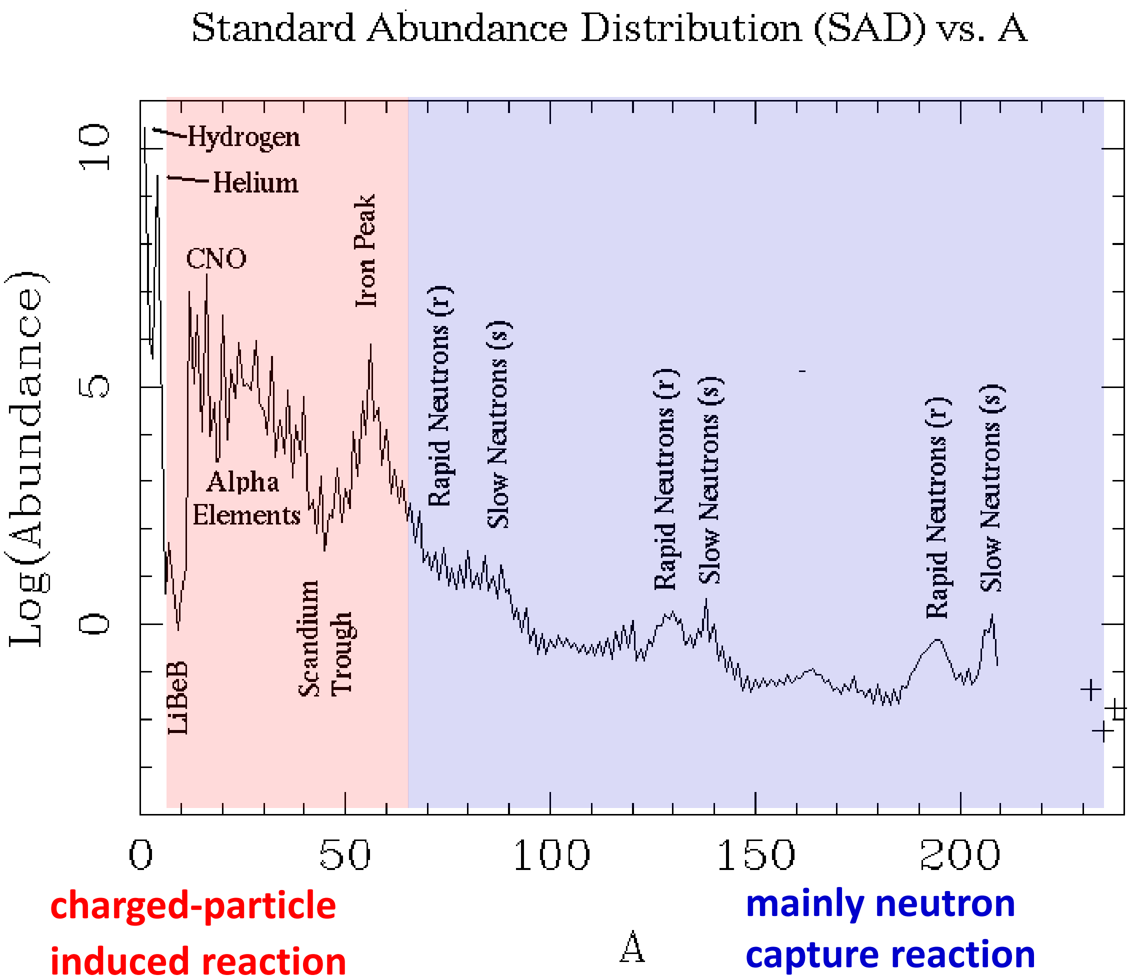


SUPERNOVA EXPLOSION

neutron star

black hole

Nuclear processes in stars



charged-particle induced reaction

during quiescent stages of stellar evolution

mainly neutron capture reaction

mainly during explosive stages of stellar evolution

involve mainly STABLE NUCLEI

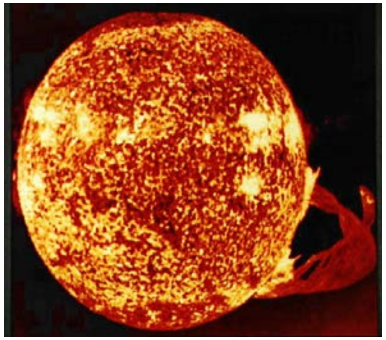
involve mainly UNSTABLE NUCLEI

Interstellar gas

BIRTH

gravitational contraction

Stars

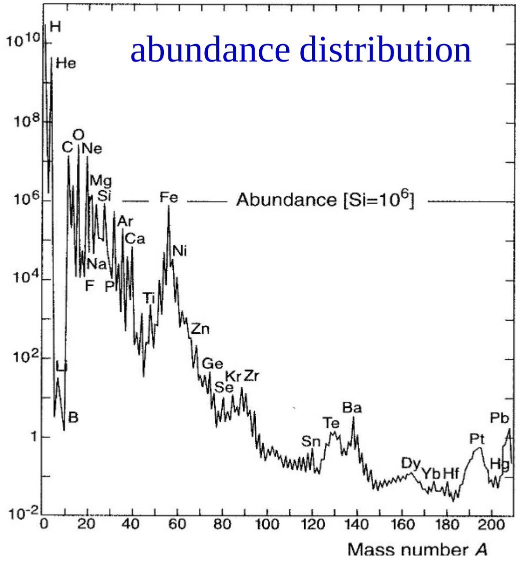


explosion ejection

DEATH

mixing of interstellar gas

thermonuclear reactions



abundance distribution

- ➢ energy production
- ➢ stability against collapse
- ➢ synthesis of “metals”