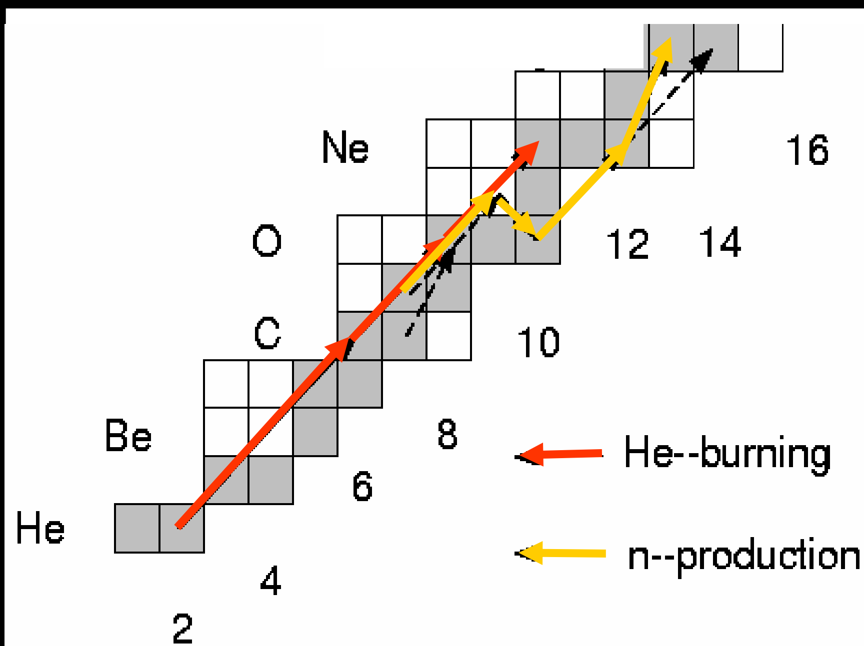
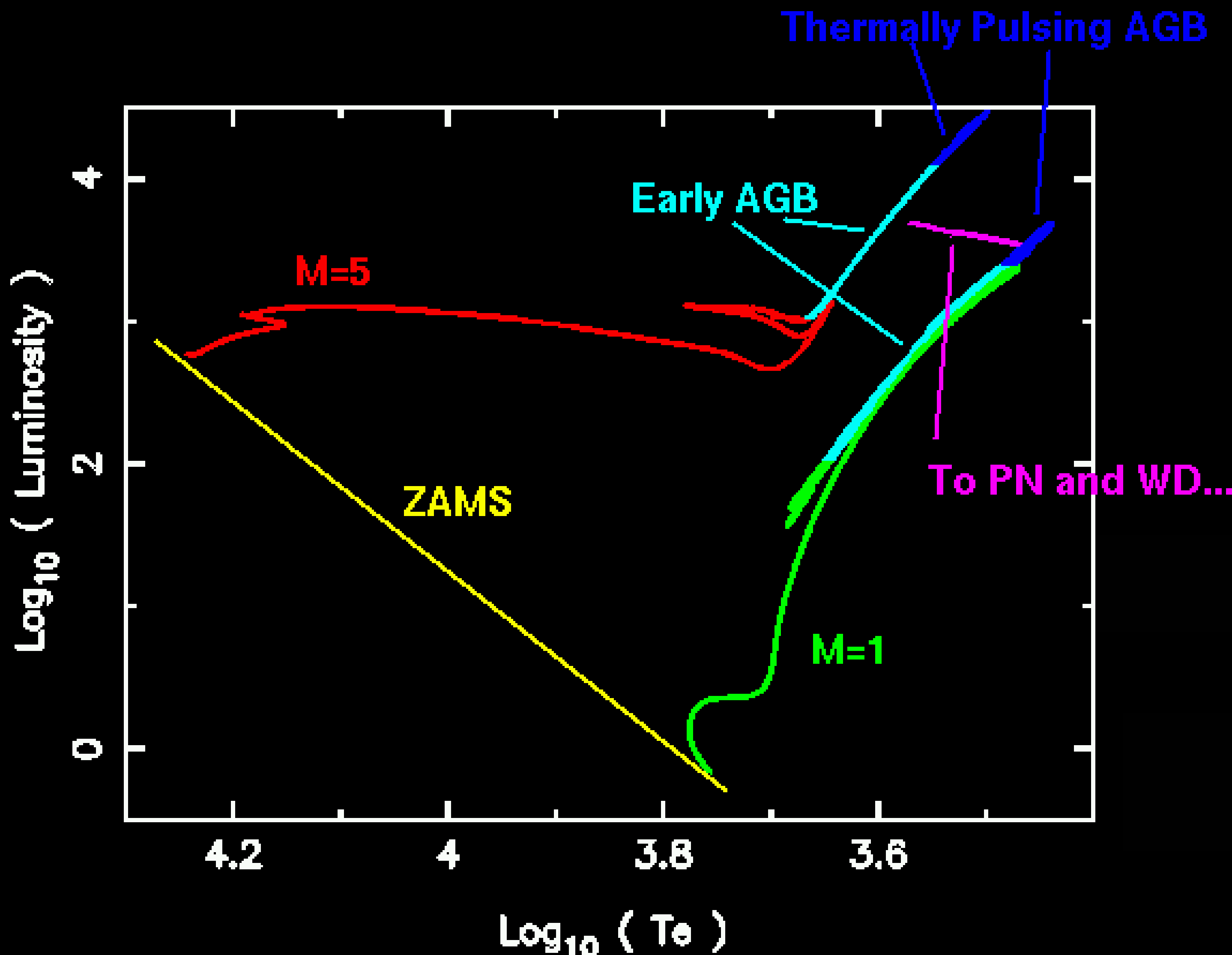
He-Burning in massive Stars

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



Most important reaction
-triple alpha process –
$3\alpha \Rightarrow {}^{12}C + 7.96$ MeV

Red Giant Evolution in HR diagram



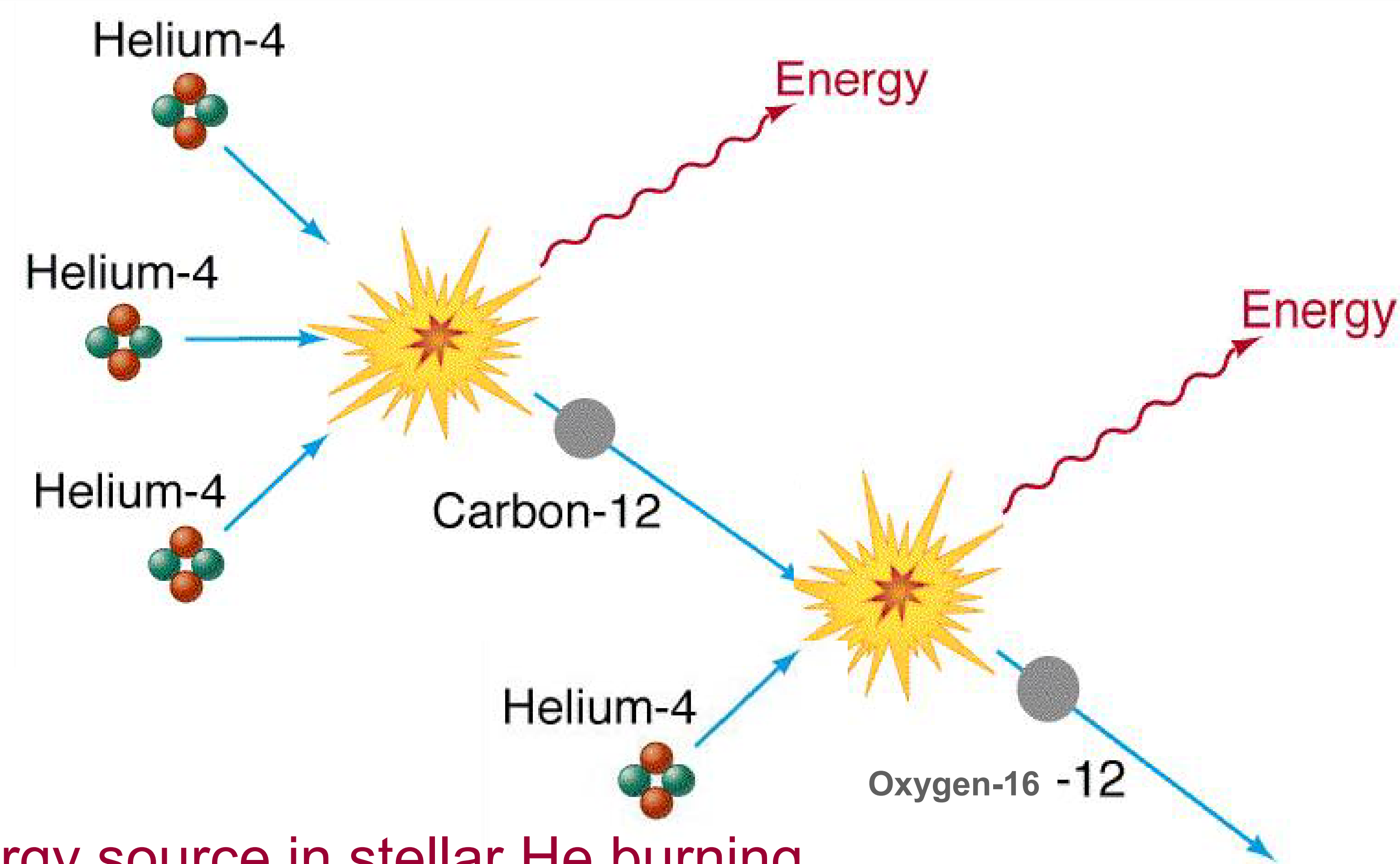
H+HRDhmovie.gif

Hemovie.gif

H+HRDhmovie.gif

CNOmovie.gif

Critical Reactions in He-burning



Energy source in stellar He burning
Energy release determined by associated reaction rates

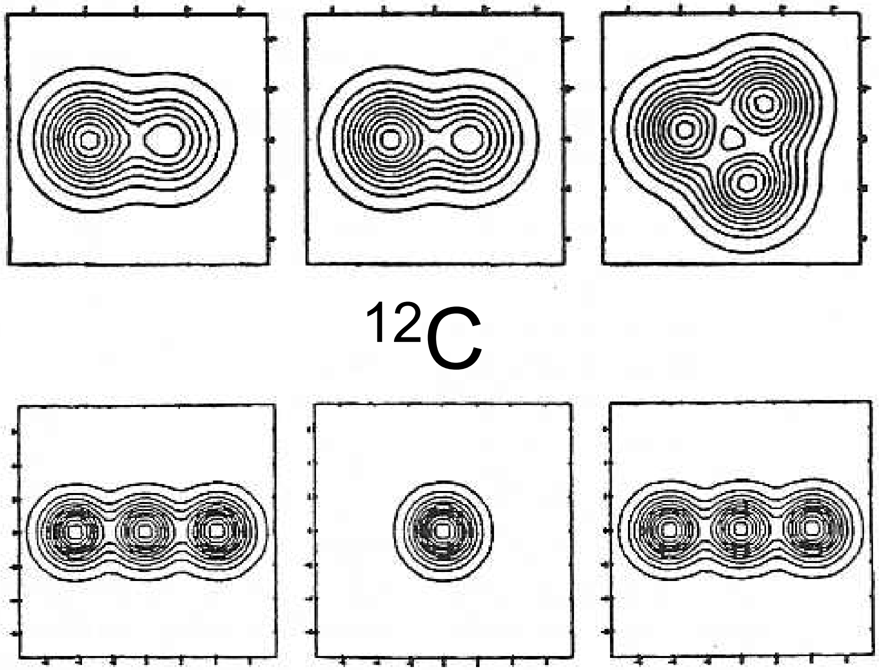
Nuclear Structure Aspects for evaluating and interpreting α capture reaction rates

hydrogen burning depends on capture probability of a proton
$\Longleftrightarrow$ single particle configuration of final state

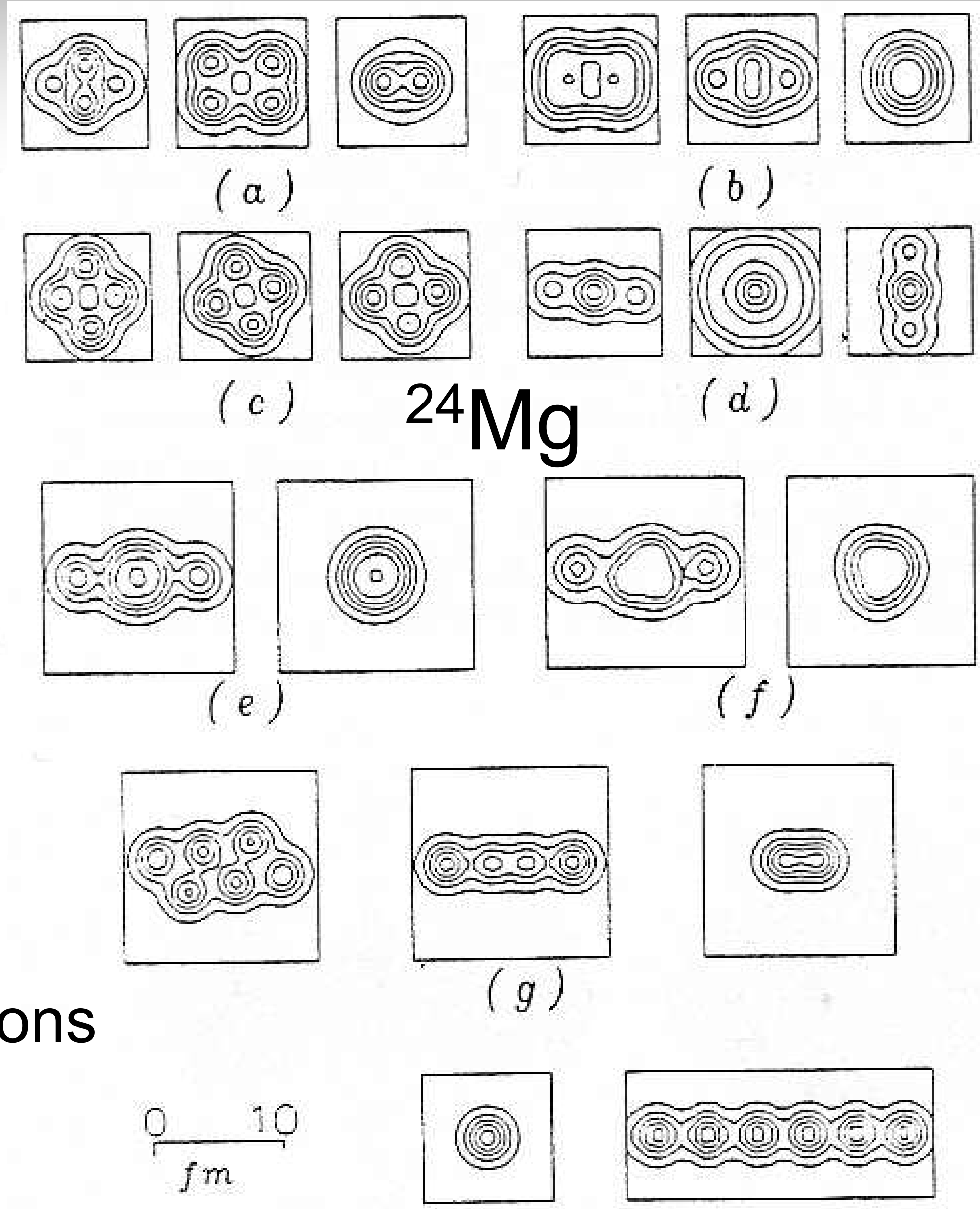
$$\sigma(E) \propto \left| \left\langle \psi_f \middle| H \middle| \psi_t + \psi_p \right\rangle \right|^2 \propto \Theta_p$$

helium burning depends on capture probability of an α particle
$\Longleftrightarrow$ α-cluster configuration of final state

α-cluster configurations in ^{12}C and ^{24}Mg



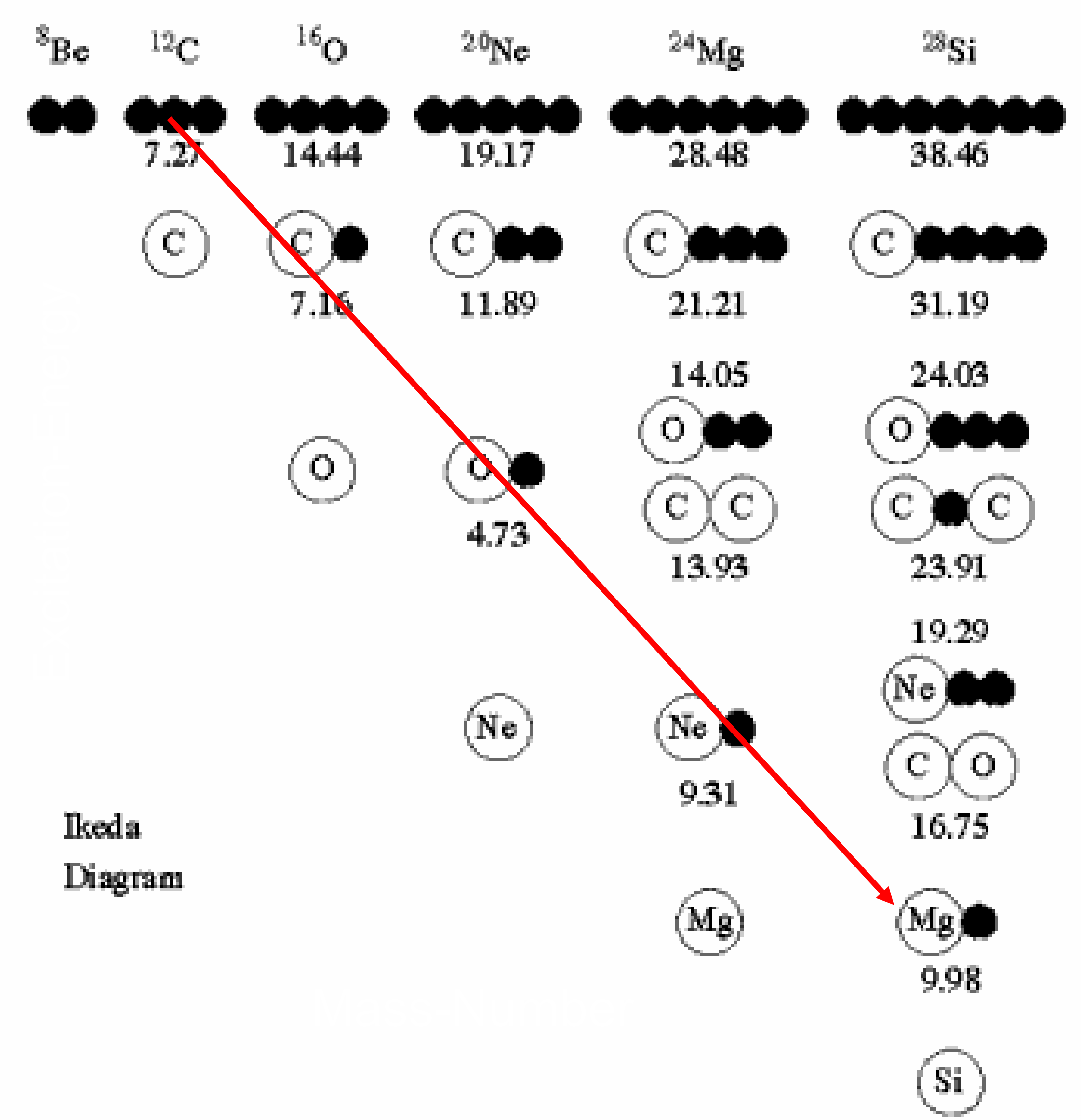
^{12}C



^{24}Mg

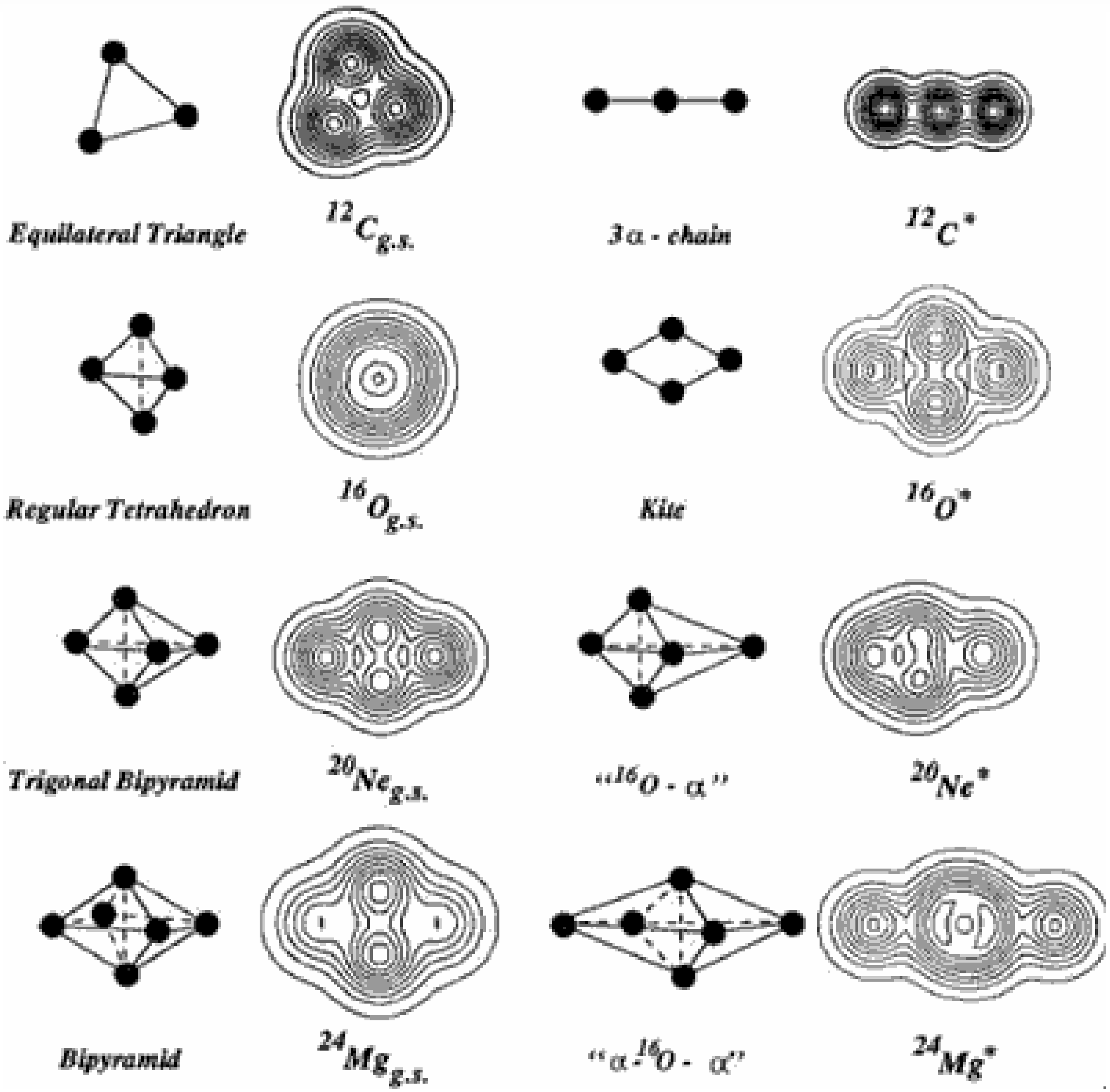
Cluster model predictions for
Cluster and shape configurations
For ^{12}C and ^{24}Mg T=0 nuclei

Alpha Cluster Structure in T=0,1 nuclei



Pronounced
α clustering
In T=0 nuclei
near α threshold
θ_α^2 **> 0.1**

Geometry of cluster configurations



Resonant Reaction Rate

$$N_A\langle\sigma v\rangle = 1.54\cdot 10^{11}\cdot\omega\gamma\,[MeV]\cdot\left(\frac{1}{\mu\cdot T_9}\right)^{3/2}\cdot e^{-\left(\frac{11.605\cdot E_R[MeV]}{T_9}\right)}$$

$$\omega\gamma = \frac{(2J+1)}{(2j_p+1)\cdot(2j_T+1)}\cdot\frac{\Gamma_{in}\cdot\Gamma_{out}}{\Gamma_{tot}} \qquad \Gamma_{tot} = \sum_i \Gamma_i$$

at low energy astrophysical conditions: $\Gamma_{\text{in}} << \Gamma_{\text{out}} \approx \Gamma_{\text{tot}}$

$$\Gamma_{in} = \Gamma_\alpha = T_{V_c,V_\ell}\cdot\Theta_\alpha$$

Network for stellar Helium burning

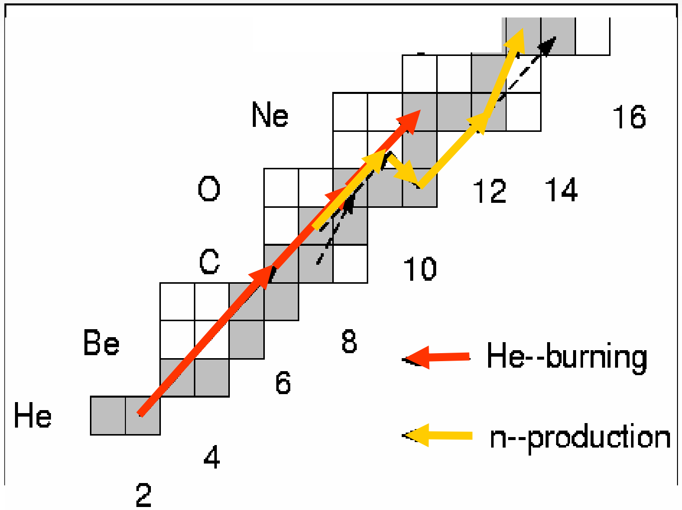
$$\frac{dY_{^4He}}{dt} = -Y_{^4He}^3 \cdot \rho^2 \cdot N_A \langle \sigma \upsilon \rangle_{3\alpha} - Y_{^{12}C} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(\alpha,\gamma)}$$
$$- Y_{^{16}O} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{16}O(\alpha,\gamma)} - Y_{^{14}N} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(\alpha,\gamma)}$$
$$\left(- Y_{^{18}O} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{18}O(\alpha,\gamma)} - Y_{^{22}Ne} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{22}Ne(\alpha,n)} \right)$$

$$\frac{dY_{^{12}C}}{dt} = -Y_{^{12}C} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(\alpha,\gamma)} + Y_{^4He}^3 \cdot \rho^2 \cdot N_A \langle \sigma \upsilon \rangle_{3\alpha}$$

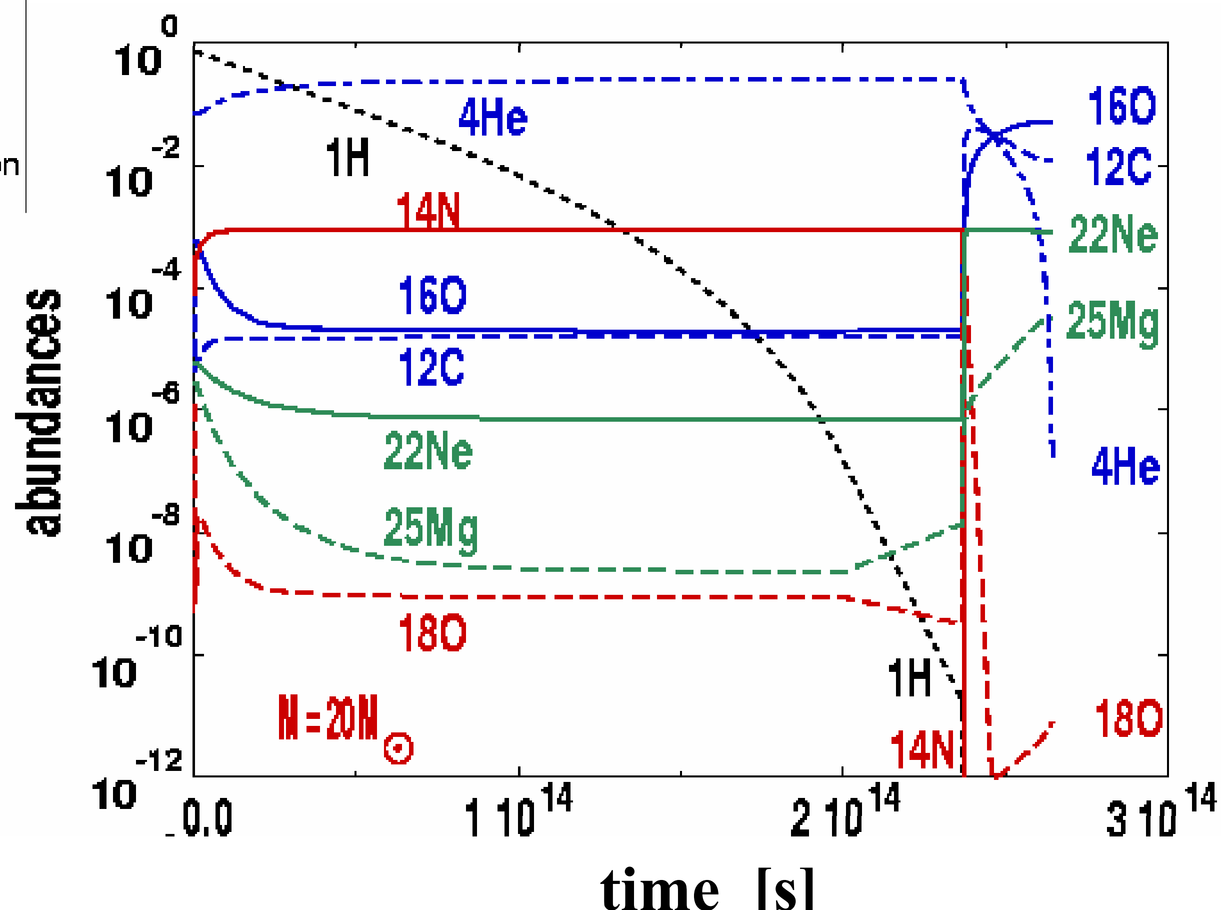
$$\frac{dY_{^{16}O}}{dt} = -Y_{^{16}O} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{16}O(\alpha,\gamma)} + Y_{^{12}C} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(\alpha,\gamma)}$$

$$\frac{dY_{^{14}N}}{dt} = -Y_{^{14}N} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{14}N(\alpha,\gamma)}$$

Abundance evolution in stellar core

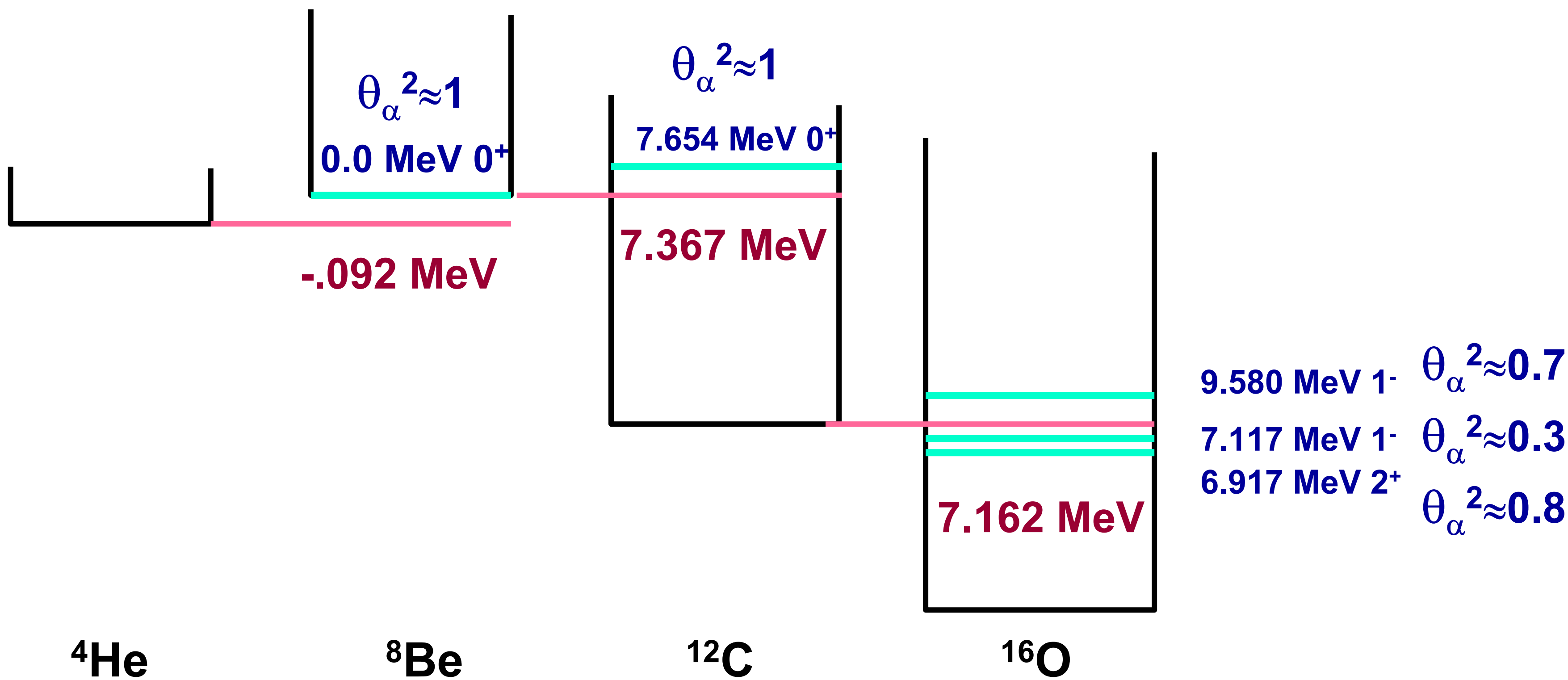


Decline of ^{4}He (time-scale)
increase in ^{12}C, ^{16}O
$\Rightarrow$equilibrium $^{12}C/^{16}O$
Rapid decline in ^{14}N.



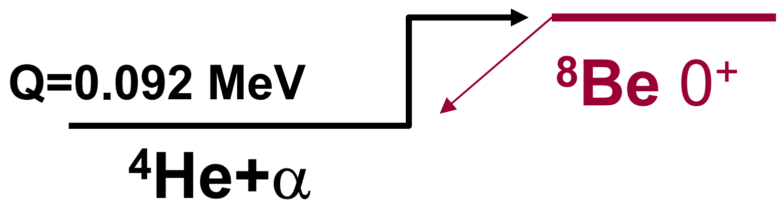
The case of: 3-α and $^{12}C(\alpha,\gamma)^{16}O$

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



The (ααα) Reaction as two step process

first step!



$T_{1/2}(^{8}Be) = 9.7\cdot10^{-17}$ s
Γ_{α}=6.8 eV
pure α cluster configuration

fast capture ⇒ equilibrium between capture and decay

Interaction time: $t \approx \frac{2R_{\alpha}}{v_{\alpha}} = \frac{2\cdot1.3\cdot A^{1/3}}{\sqrt{\frac{2E_{\alpha}^{cm}}{\mu}}} \approx \frac{4.17\ fm}{3.8\cdot10^{24}\ fm/s} \approx 10^{-24}\ s << \tau(^{8}Be)$

Application of Saha Equation
For calculating ^{8}Be equilibrium:

$$N(^{8}Be) = N_{\alpha}^{2}\cdot\hbar^{3}\cdot\left(\frac{2\pi}{\mu\cdot kT}\right)^{3/2}\cdot e^{\left(-\frac{Q}{kT}\right)}$$

Example for ^{8}Be equilibrium abundance:

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

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

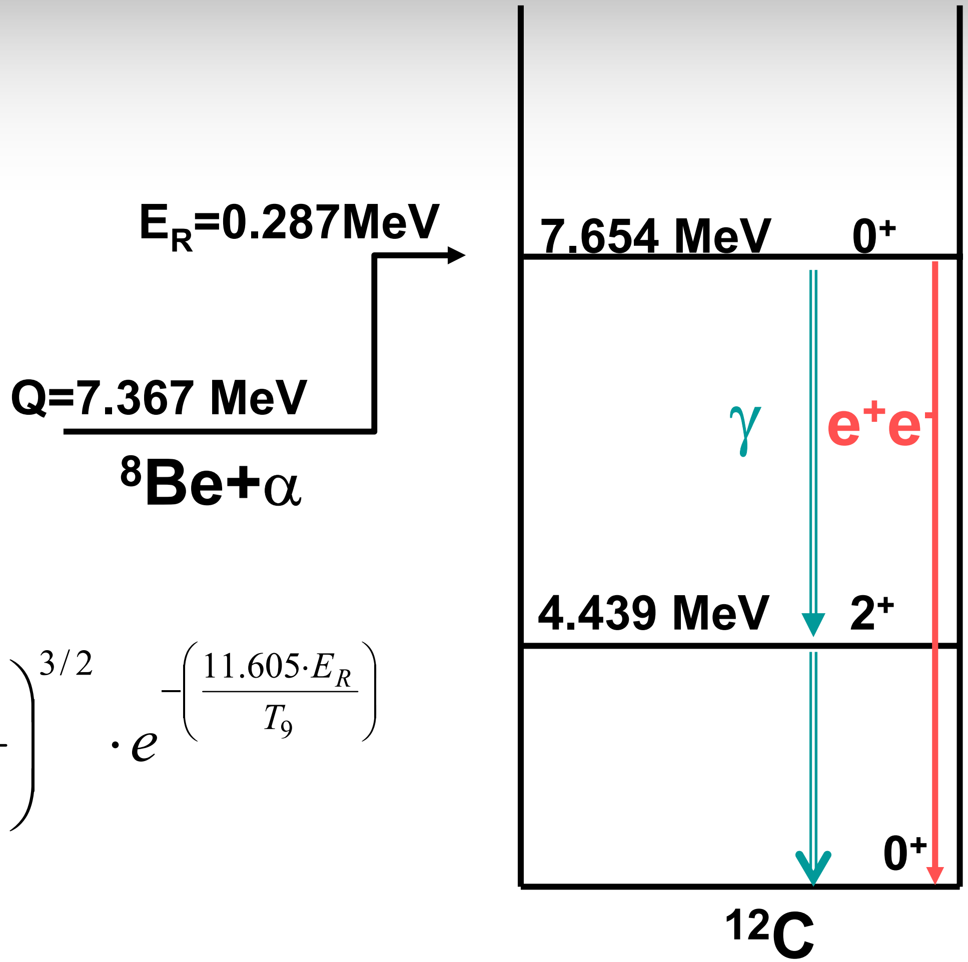
$$N\left({}^8Be\right) \approx 4.4\cdot 10^{-38}\cdot N_\alpha^2$$

$$N = \rho\cdot N_A \cdot \frac{X_i}{A_i} \quad \Rightarrow \quad \frac{X\left({}^8Be\right)}{X_\alpha^2} \approx 1.3\cdot 10^{-9}$$

~ one ^{8}Be nucleus
for 10^9 α particles

Resonant capture on ^{8}Be

The Hoyle resonance!



$$N_A\langle\sigma v\rangle = 1.54\cdot 10^{11}\cdot\omega\gamma\cdot\left(\frac{1}{\mu\cdot T_9}\right)^{3/2}\cdot e^{-\left(\frac{11.605\cdot E_R}{T_9}\right)}$$

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

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

The Resonance Strength

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

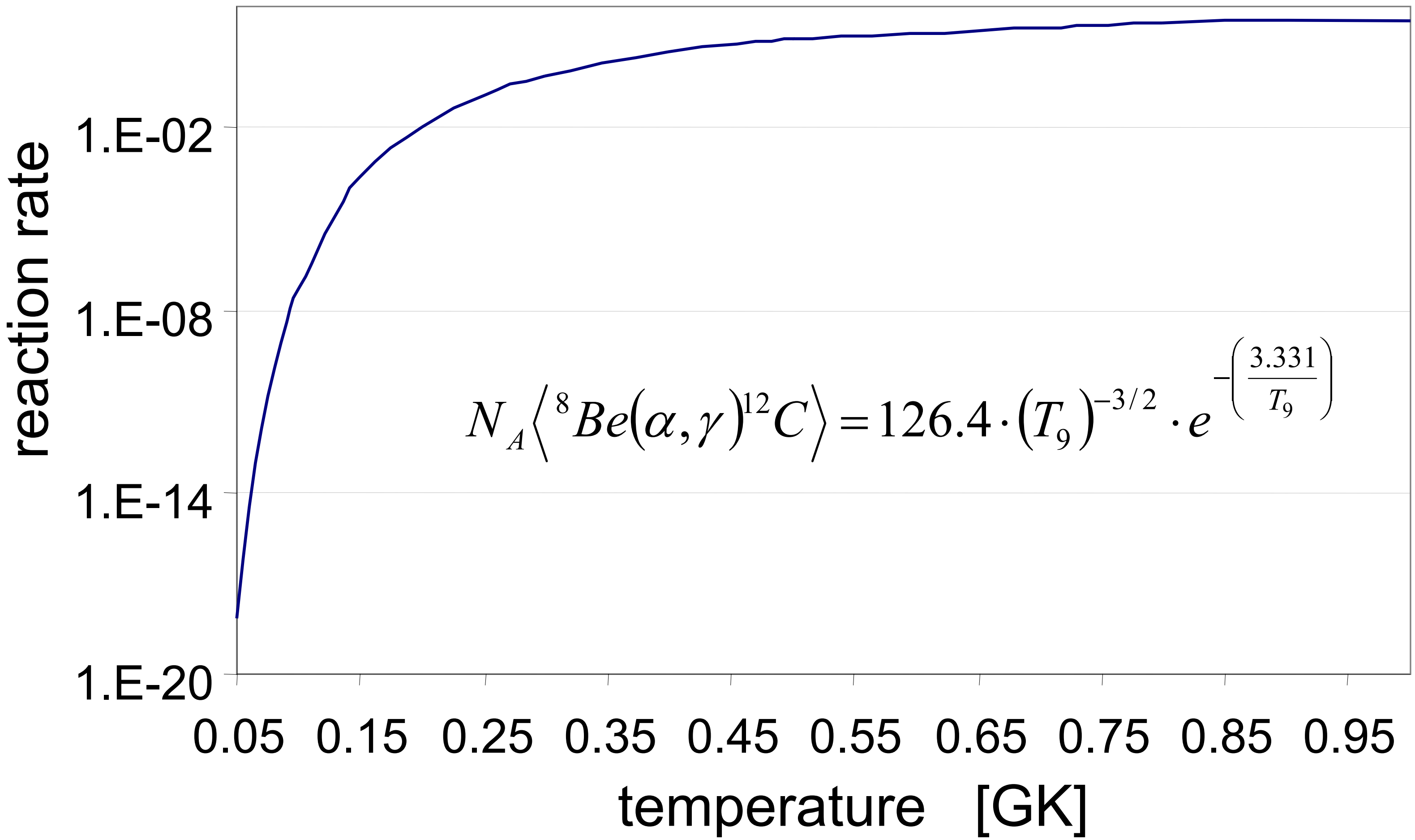
$$\Gamma_\alpha = 8.09 \pm 1.08\, eV$$

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

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

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

The $^8Be+\alpha$ reaction rate



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

The total <αααα> 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

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

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

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

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

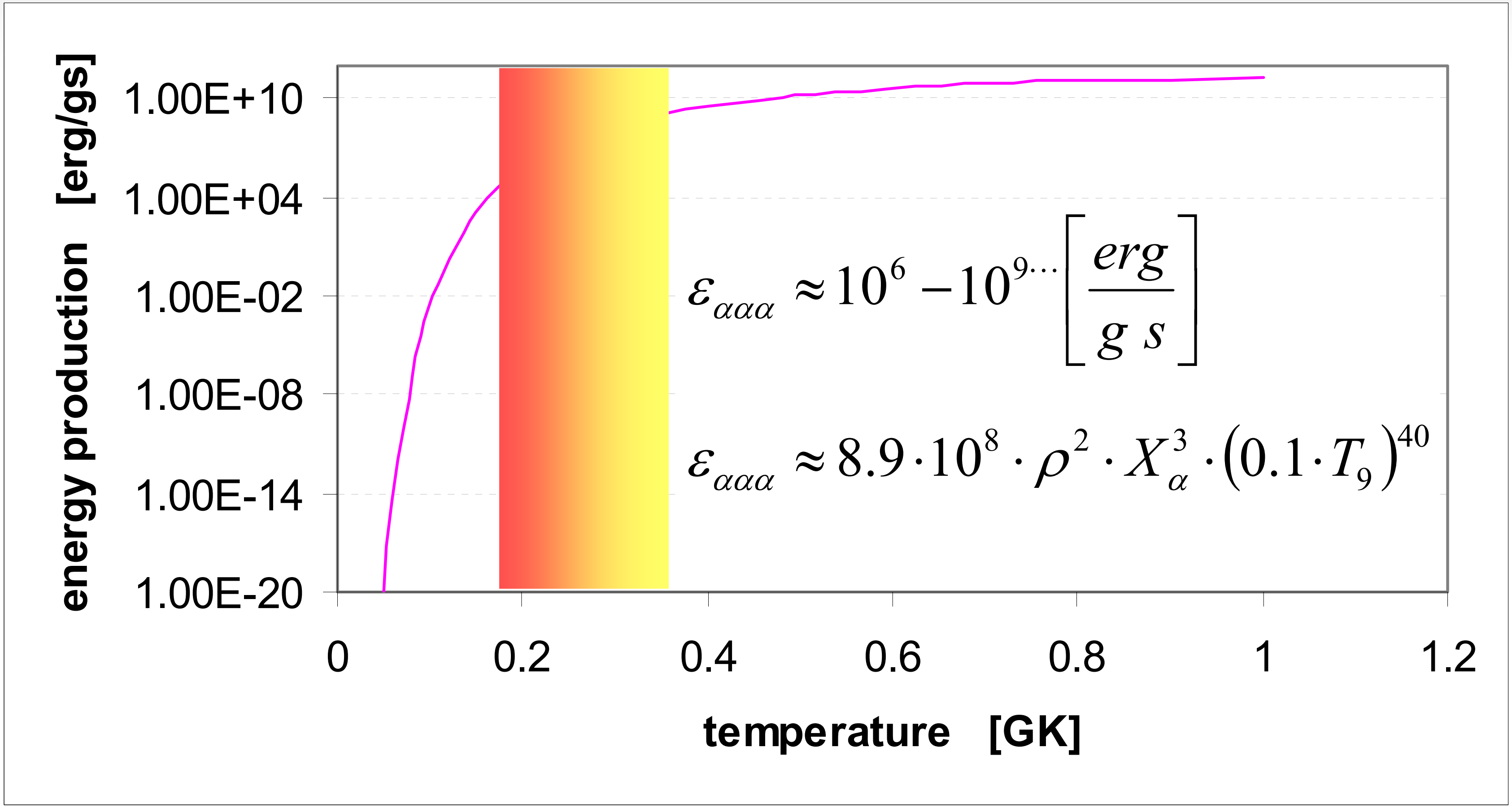
Energy production in He burning

$$\varepsilon_{\alpha\alpha\alpha} = Q_{\alpha\alpha\alpha \Rightarrow {}^{12}C} \cdot \frac{r_{\alpha\alpha\alpha}}{\rho}$$

$$Q_{\alpha\alpha\alpha \Rightarrow {}^{12}C} = 7.274\ MeV = 1.16 \cdot 10^{-5}\ erg$$

$$\varepsilon_{\alpha\alpha\alpha} = 2.5 \cdot 10^{8} \cdot \rho^{2} \cdot X_{\alpha}{}^{3} \cdot T_9^{-3} \cdot e^{-\frac{4.294}{T_9}} \quad \left[\frac{erg}{g\ s}\right]$$

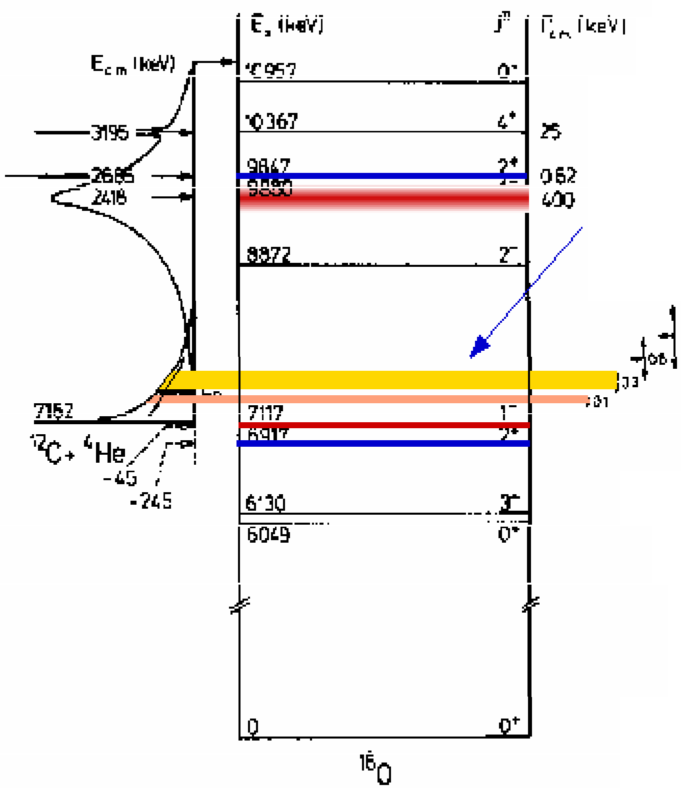
Example: ρ=10⁵ g/cm³

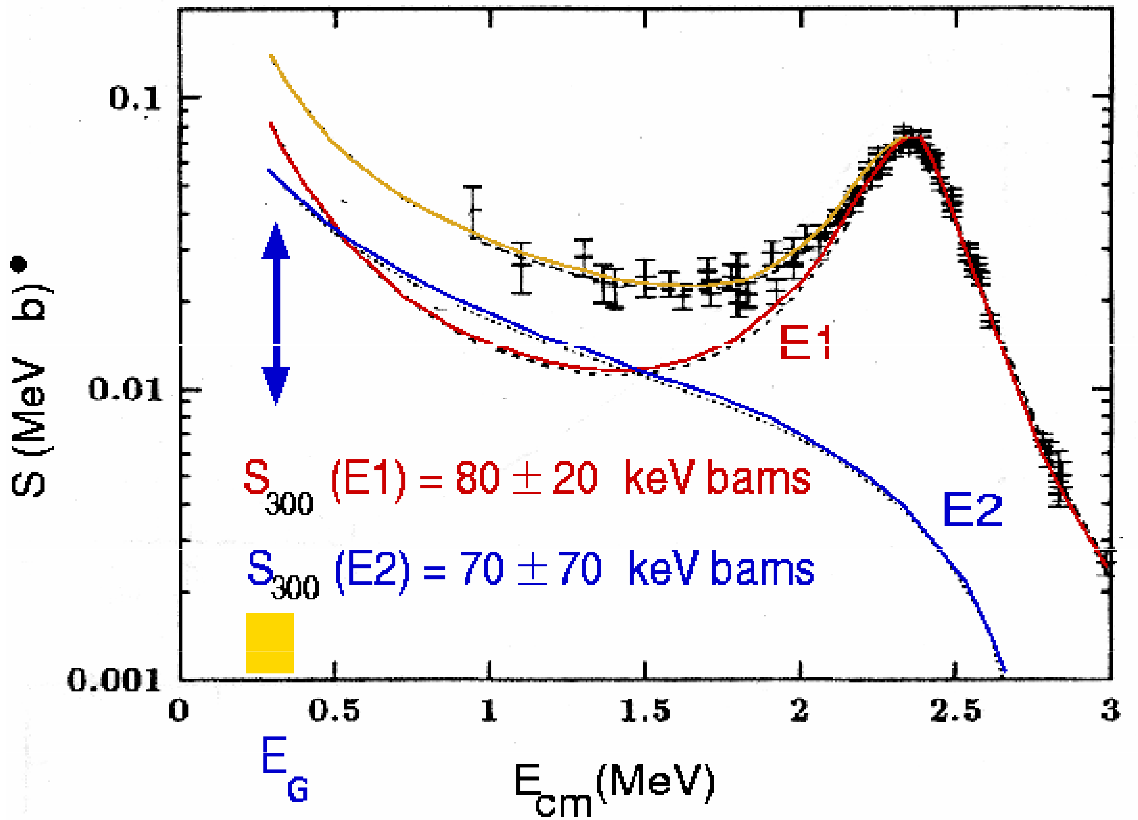


T-dependent main energy source for stellar He-burning

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

Level and Interference Structure

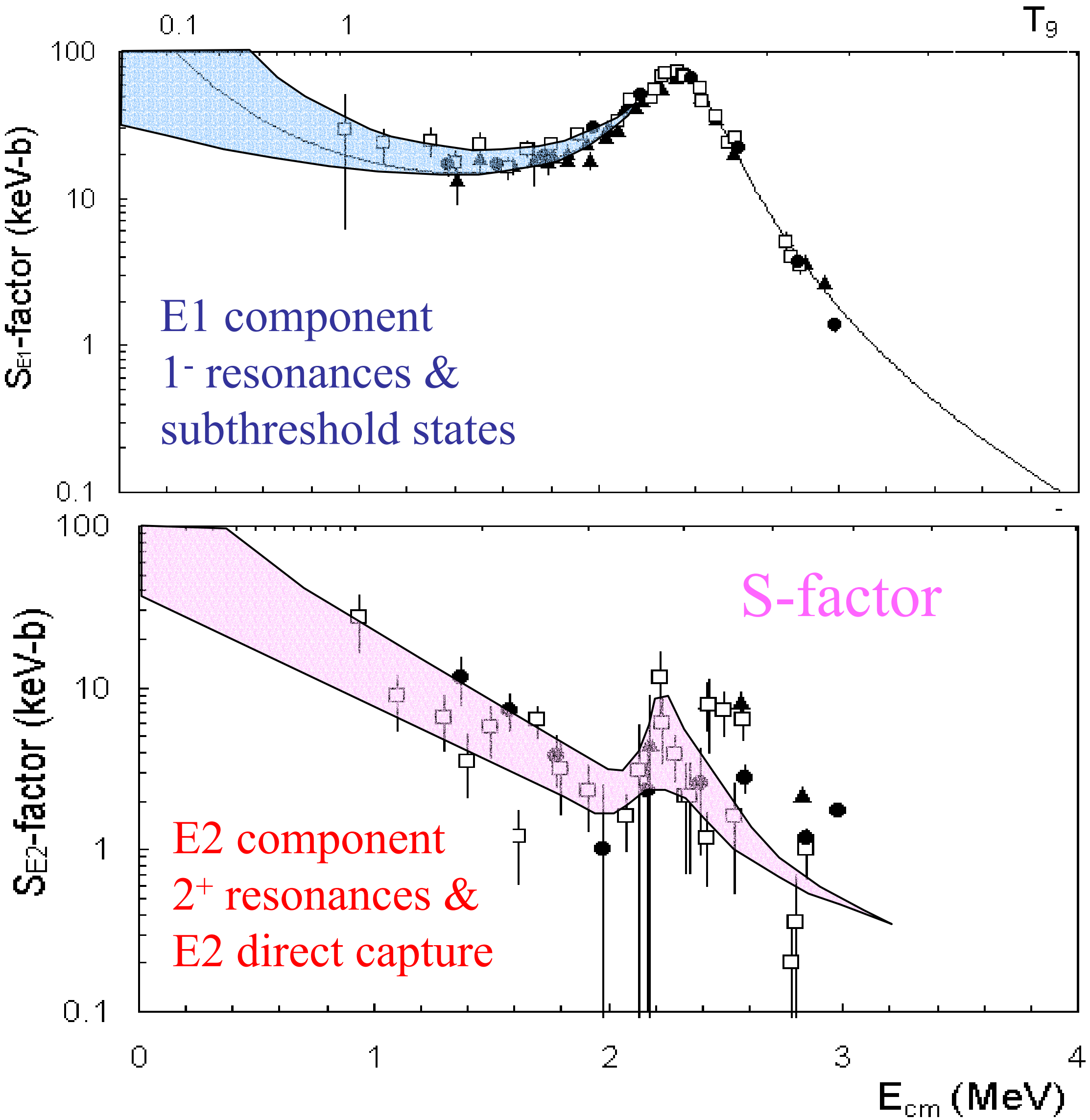




Uncertainty in low energy extrapolation

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

Difficulty in the reliability of low energy extrapolation



R-matrix analysis

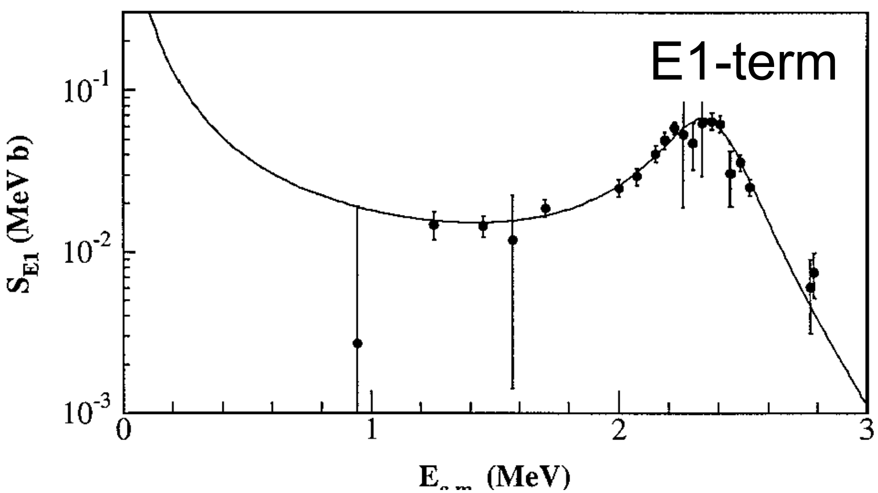
Complex resonance structure, interfering broad resonances

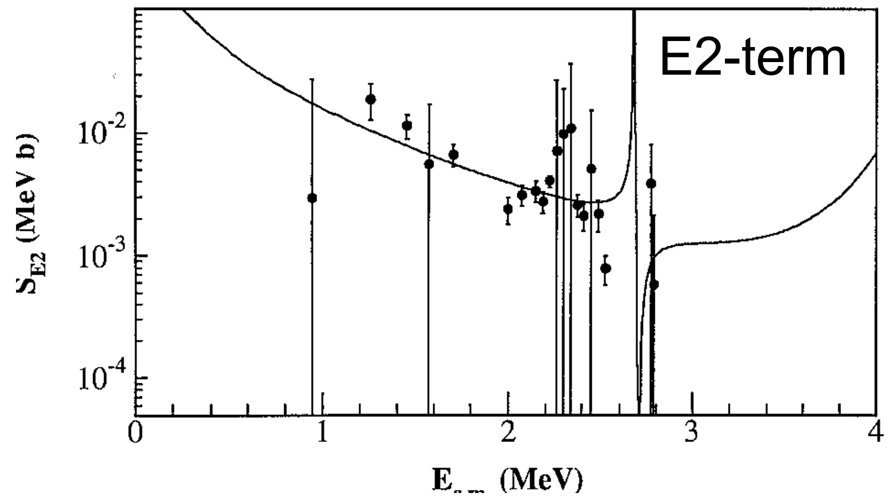
R-matrix analysis $\Rightarrow$ R-matrix school

Parameters from probing ^{16}O compound nucleus through

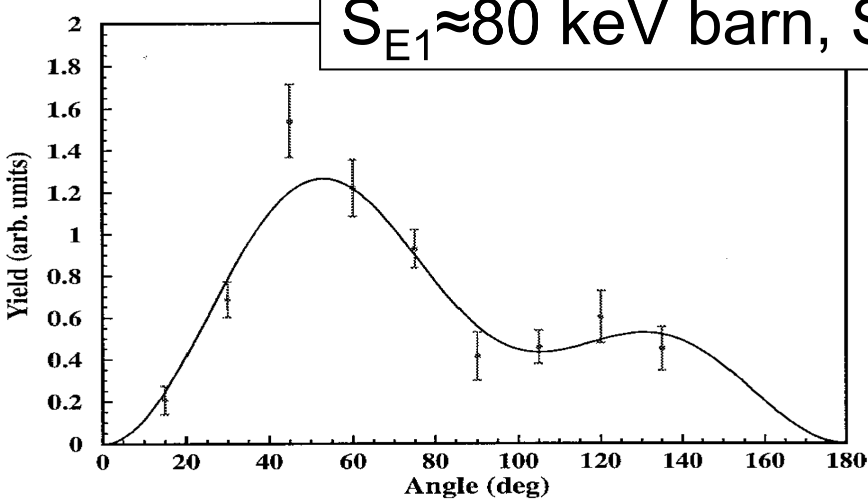
• elastic scattering	$^{12}C(\alpha,\alpha)^{12}C$
• β-delayed α-decay	$^{16}N(\beta,\alpha)^{12}C$
• resonant α capture	$^{12}C(\alpha,\gamma)^{16}O$
• α-transfer reaction	$^{12}C(^{7}Li,t)^{16}O$

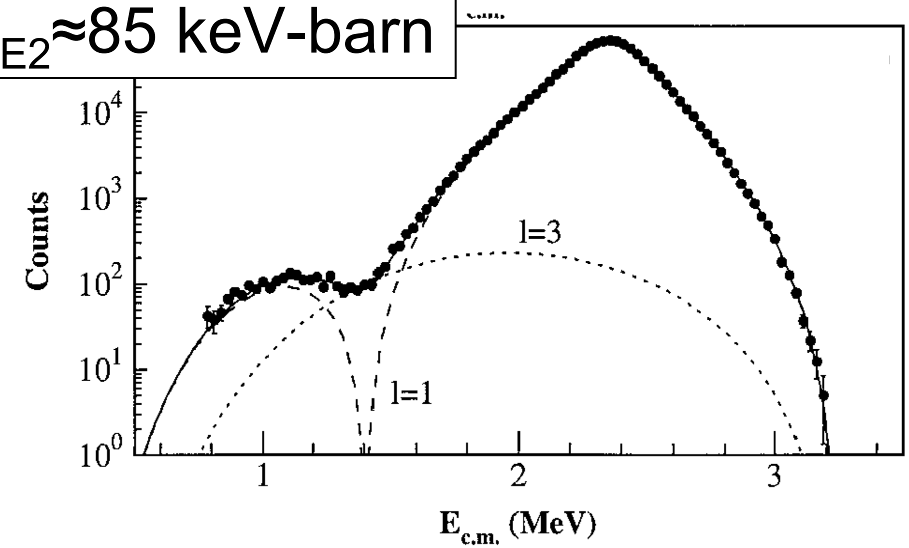
R-matrix fit examples





S_{E1}≈80 keV barn, S_{E2}≈85 keV-barn





From Kunz et al. PRL 86 (2004)

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

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

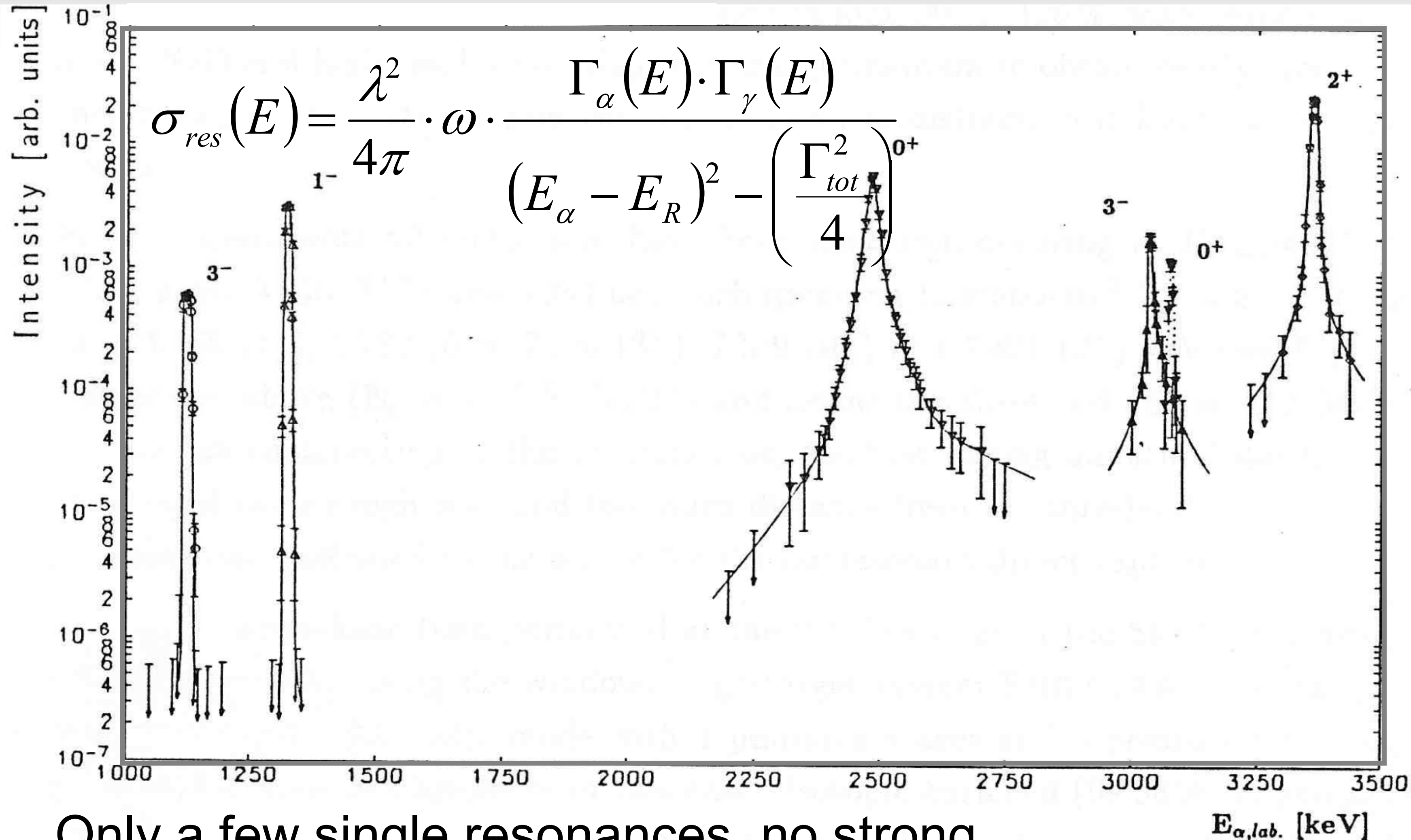
$$S_{eff}\approx 0.17\left[MeV-b\right]$$

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

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

The $^{16}O(\alpha,\gamma)^{20}Ne$ reaction mechanism

$$\sigma_{res}(E) = \frac{\lambda^2}{4\pi} \cdot \omega \cdot \frac{\Gamma_\alpha(E) \cdot \Gamma_\gamma(E)}{(E_\alpha - E_R)^2 - \left(\frac{\Gamma_{tot}^2}{4}\right)}$$



Only a few single resonances, no strong non-resonant term observed in the excitation curve!

Direct capture contributions to the cross section of $^{16}O(\alpha,\gamma)^{20}Ne$

$$\sigma_{dc}(E1) \propto \mu^2 \cdot \left(\frac{Z_1}{M_1} - \frac{Z_2}{M_2} \right)^2 \frac{1}{\sqrt{\mu}} \frac{E_\gamma^3}{E_\alpha^{3/2}} \cdot \frac{(2J_f+1)(2\ell_i+1)}{(2J_t+1)(2\ell_f+1)} \cdot$$

$$(\ell_i 010 \mid \ell_{f0})^2 \int_0^\infty u_c(r) \cdot \Omega_{E1}(r) \cdot u_b(r) \cdot r^2 \, dr$$

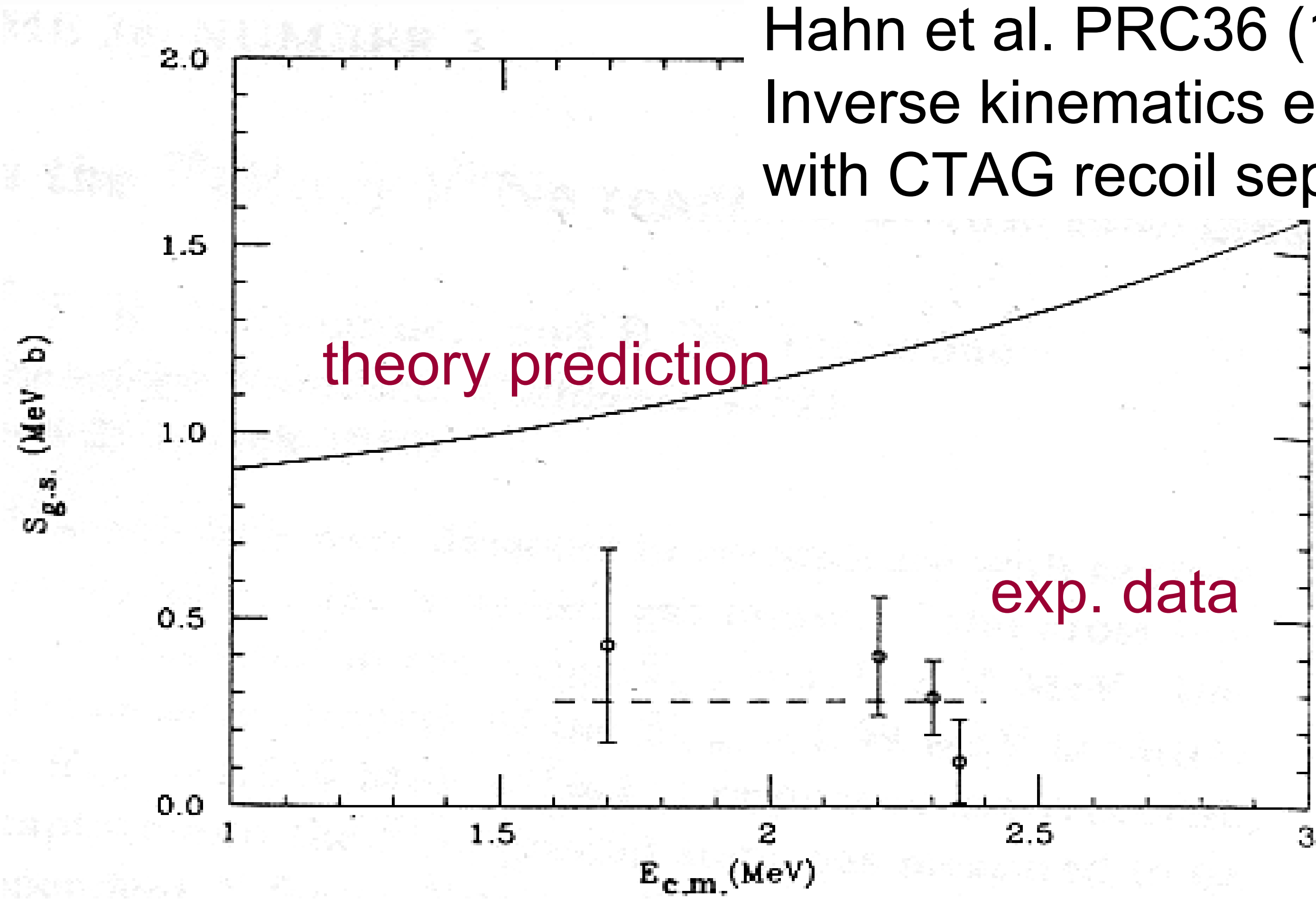
For $^{16}O+\alpha$ $\quad \frac{Z_1}{M_1} - \frac{Z_2}{M_2} = \frac{2}{4} - \frac{8}{16} = 0$ No E1 dc-term

$$\sigma_{dc}(E2) \propto \mu^4 \cdot \left(\frac{Z_1}{M_1^2} + \frac{Z_2}{M_2^2} \right)^2 \frac{1}{\sqrt{\mu}} \frac{E_\gamma^5}{E_\alpha^{3/2}} \cdot \frac{(2J_f+1)(2\ell_i+1)}{(2J_t+1)(2\ell_f+1)} \cdot$$

$$(\ell_i 010 \mid \ell_{f0})^2 \int_0^\infty u_c(r) \cdot \Omega_{E1}(r) \cdot u_b(r) \cdot r^2 \, dr$$

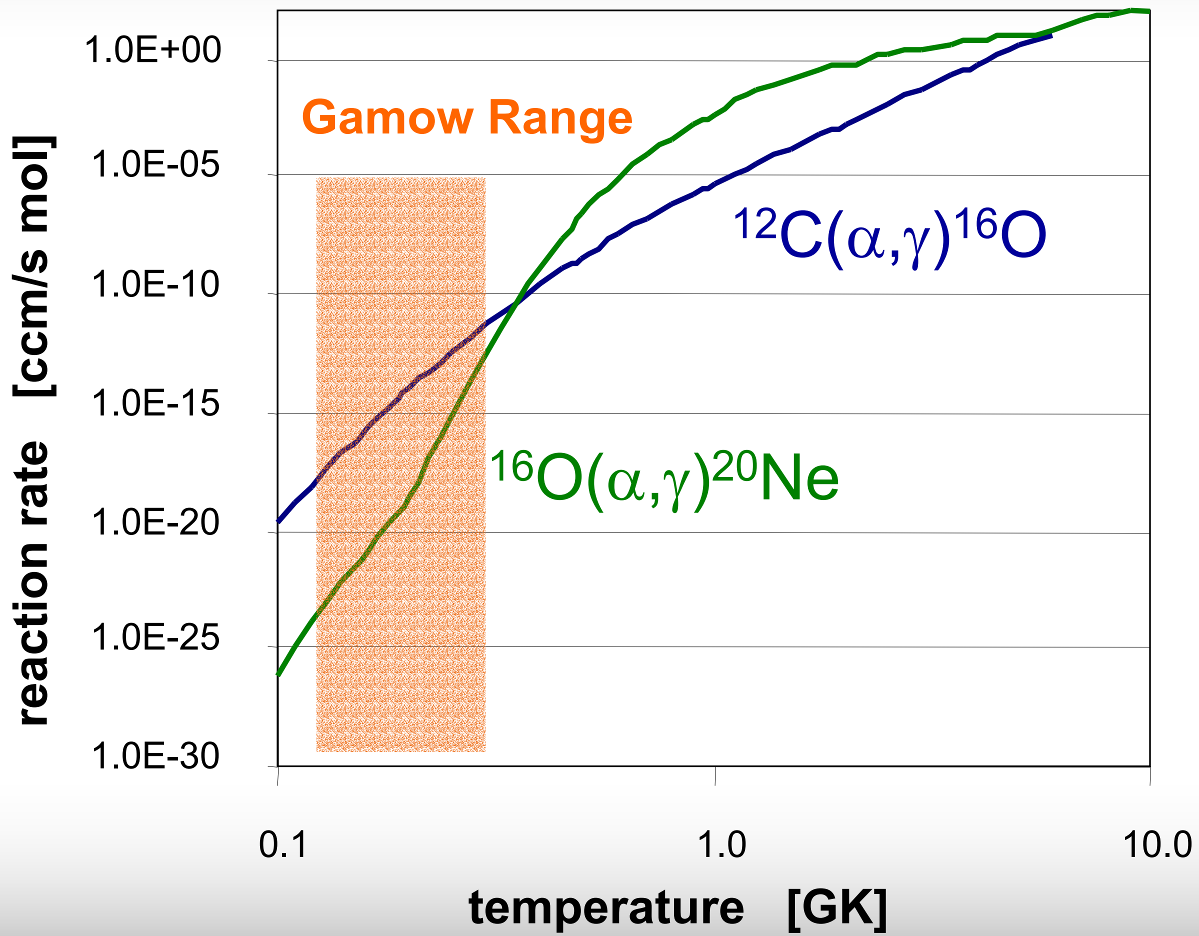
E2-dc S-factor term

Hahn et al. PRC36 (1987)
Inverse kinematics experiment with CTAG recoil separator



No strong direct capture in E1 and E2 observed!

Impact of the ^{12}C,$^{16}O(\alpha,\gamma)$ rates

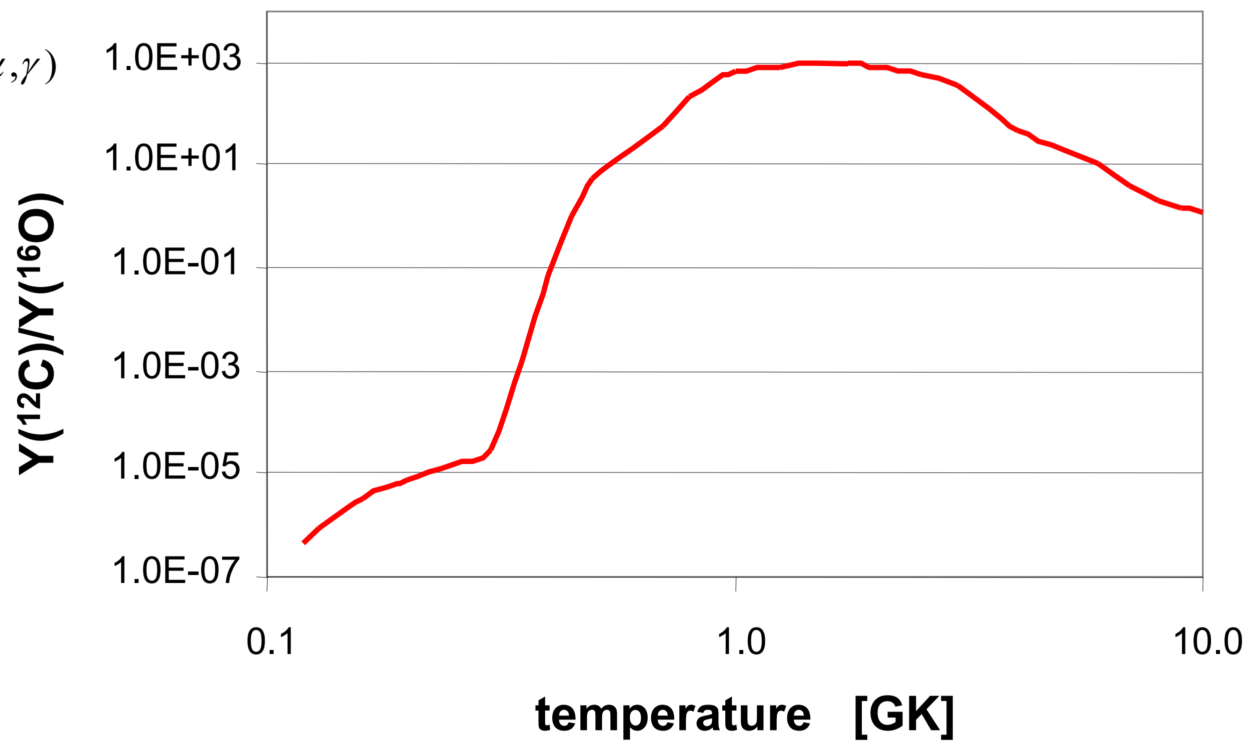


$^{12}C(\alpha,\gamma)$ rate dominates over the $^{16}O(\alpha,\gamma)$ rate at typical He-burning temperatures T~0.1-0.3 GK.

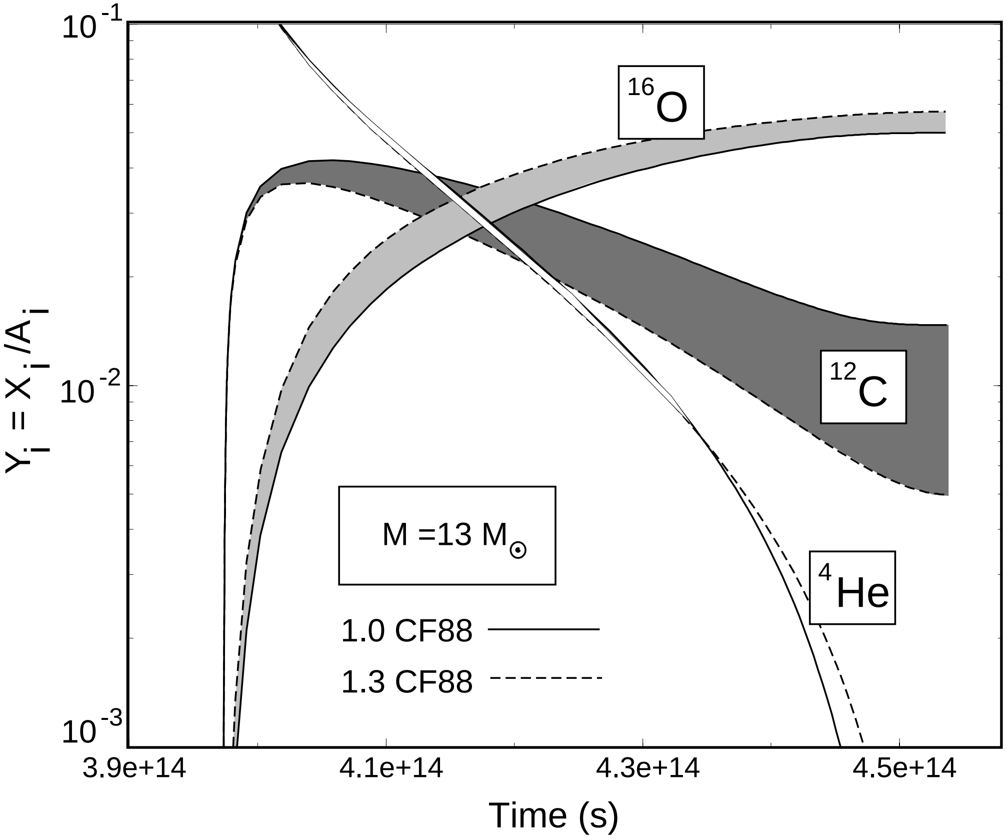
… the $^{16}O/^{12}C$ ratio in steady state

$$\frac{dY_{^{16}O}}{dt} = -Y_{^{16}O} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{16}O(\alpha,\gamma)} + Y_{^{12}C} \cdot Y_{^4He} \cdot \rho \cdot N_A \langle \sigma \upsilon \rangle_{^{12}C(\alpha,\gamma)} = 0$$

$$\frac{Y_{^{12}C}}{Y_{^{16}O}} = \frac{N_A \langle \sigma \upsilon \rangle_{^{16}O(\alpha,\gamma)}}{N_A \langle \sigma \upsilon \rangle_{^{12}C(\alpha,\gamma)}}$$



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



- Late Stellar Evolution
  determines Carbon and/or Oxygen phase
- Type Ia Supernova
  central carbon burning of C/O white dwarf
- Type II Supernova
  shock-front nucleosynthesis in C and He shells of pre-supernova star

Summary

Several important experiments are being discussed

- ❑ Possible improvement in the accuracy of the 7.654 0^+ decay channel

- ❑ Improved low energy data (yield and angular distribution) for $^{12}C(\alpha,\gamma)^{16}O$ R-matrix analysis

- ❑ Alternative approaches like $^{16}O(\gamma,\alpha)^{12}C$ to broaden data set and statistics for R-matrix analysis

- ❑ New resonance and E2 direct capture study for $^{16}O(\alpha,\gamma)^{20}Ne$