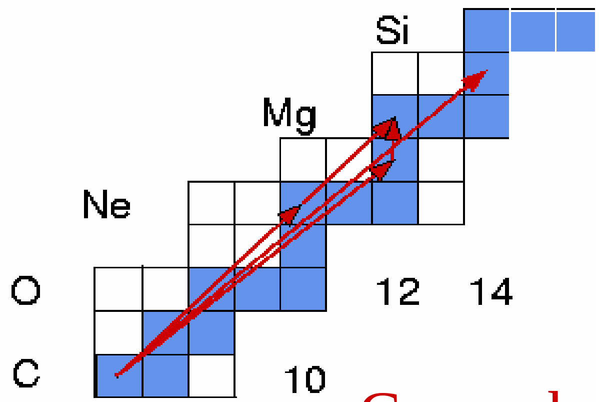
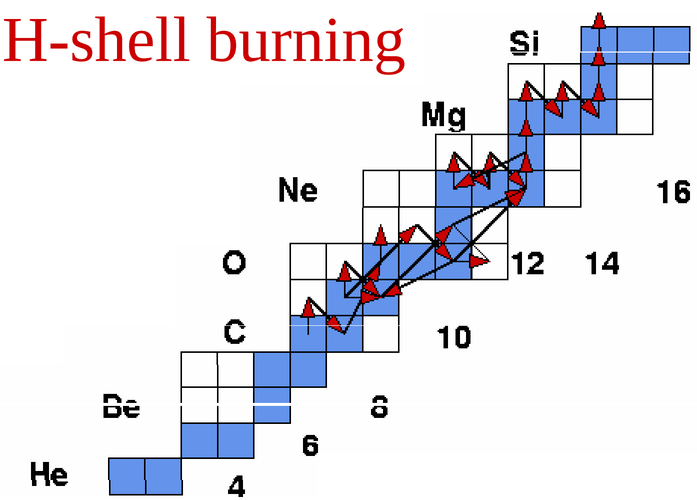
Carbon Burning and late stellar evolution (AGB stars)



C-core burning

H-shell burning



- Dredge-up to the surface
- mass loss by solar wind

nucleosynthesis contribution?

Carbon Burning

Conversion of ^{4}He into ^{12}C and ^{16}O
depending on the $^{12}C(\alpha,\gamma)^{16}O$ reaction

$$^{12}C(^{12}C,p)^{23}Na \quad Q = 2.240\,MeV$$

$$^{12}C(^{12}C,\alpha)^{20}Ne \quad Q = 4.617\,MeV$$

$$^{12}C(^{12}C,p)^{23}Na \quad Q = -2.598\,MeV$$

$$^{16}O(^{16}O,p)^{31}P \quad Q = 7.628\,MeV$$

$$^{16}O(^{16}O,\alpha)^{28}Si \quad Q = 9.594\,MeV$$

$$^{16}O(^{16}O,n)^{31}S \quad Q = 1.499\,MeV$$

$$^{16}O(^{12}C,p)^{27}Al \quad Q = 7.170\,MeV$$

$$^{16}O(^{12}C,\alpha)^{24}Mg \quad Q = 6.771\,MeV$$

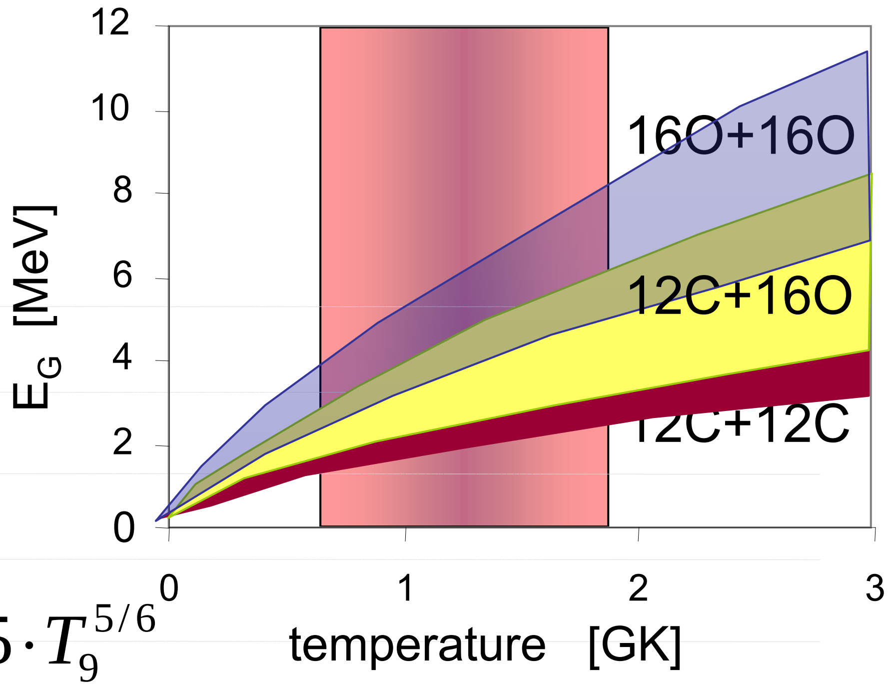
$$^{16}O(^{12}C,n)^{27}Si \quad Q = -0.424\,MeV$$

Wide range of possible
heavy ion
reactions at low energies

The Gamow window for heavy ion reactions

$$E_G = 0.122 \cdot \left(Z_1^2 \cdot Z_1^2 \cdot \mu \cdot T_9^2\right)^{1/3} \; [MeV]$$

$$\Delta E_G = 0.236 \cdot \left(Z_1^2 \cdot Z_1^2 \cdot \mu \cdot T_9^5\right)^{1/6} \; [MeV]$$

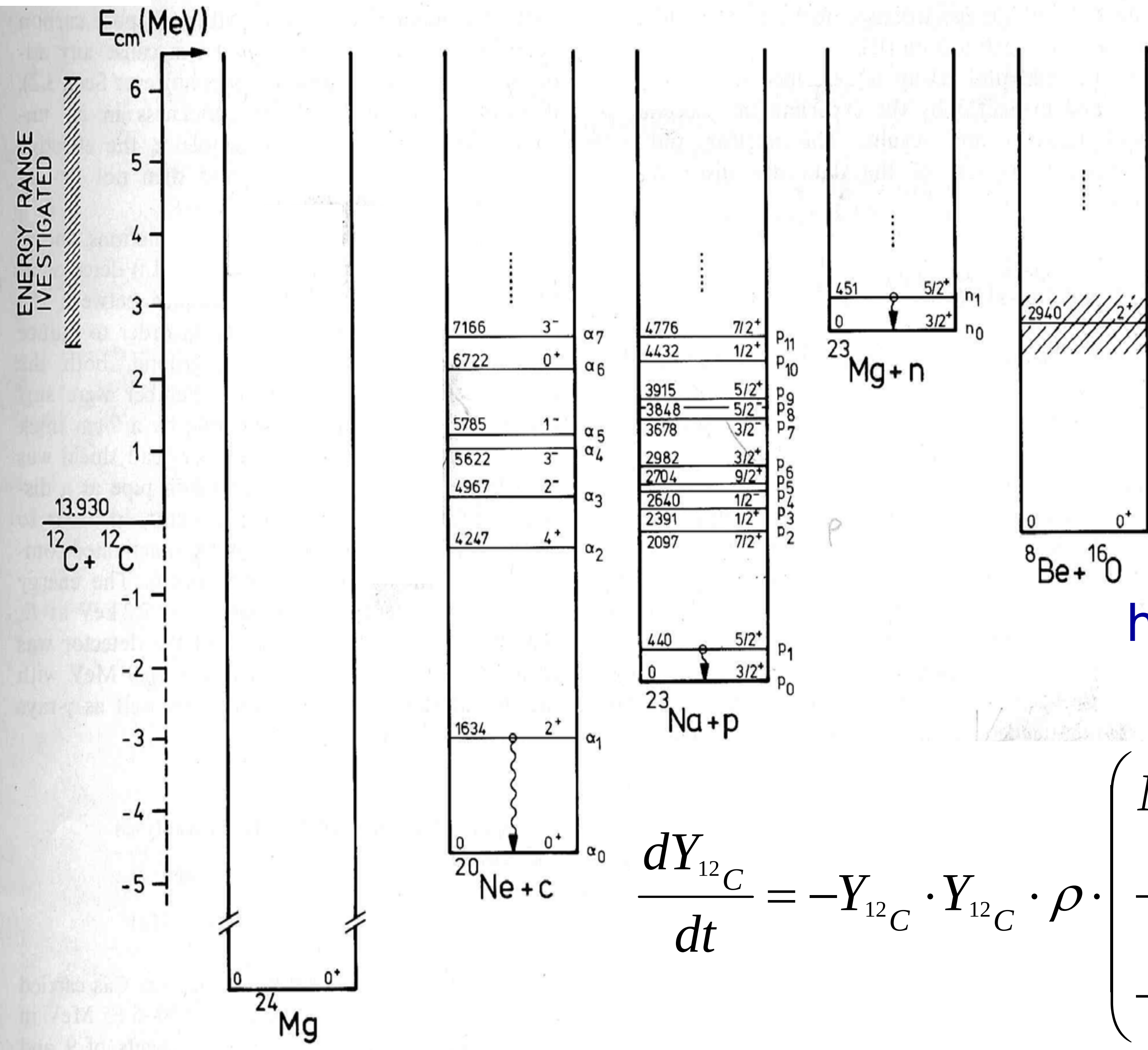


$$^{12}C + ^{12}C: \quad E_G = 2.42 \cdot T_9^{2/3} \pm 0.75 \cdot T_9^{5/6}$$

$$^{16}O + ^{12}C: \quad E_G = 3.06 \cdot T_9^{2/3} \pm 0.86 \cdot T_9^{5/6}$$

$$^{16}O + ^{16}O: \quad E_G = 3.90 \cdot T_9^{2/3} \pm 1.34 \cdot T_9^{5/6}$$

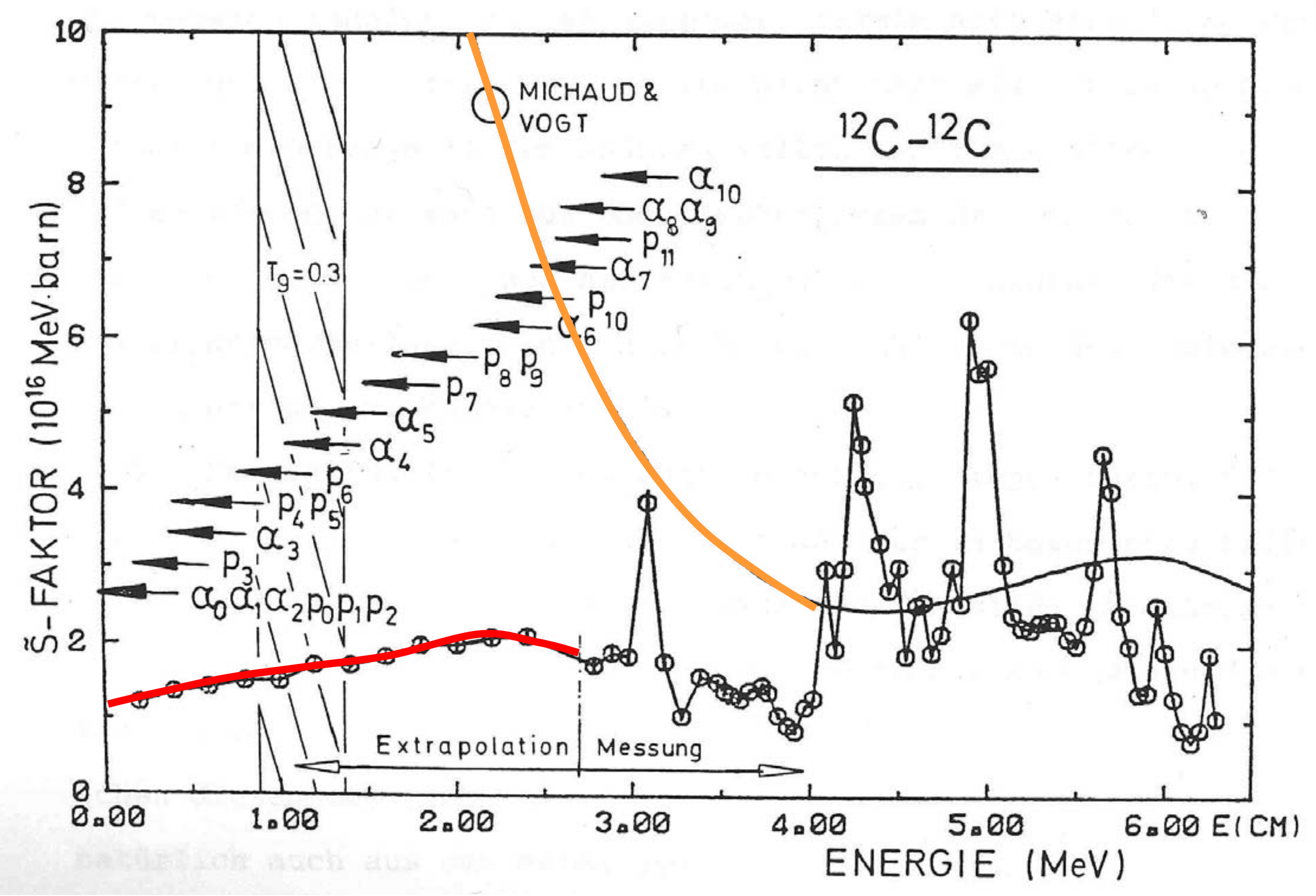
$^{12}C+^{12}C$



different reaction channels open at higher temperature

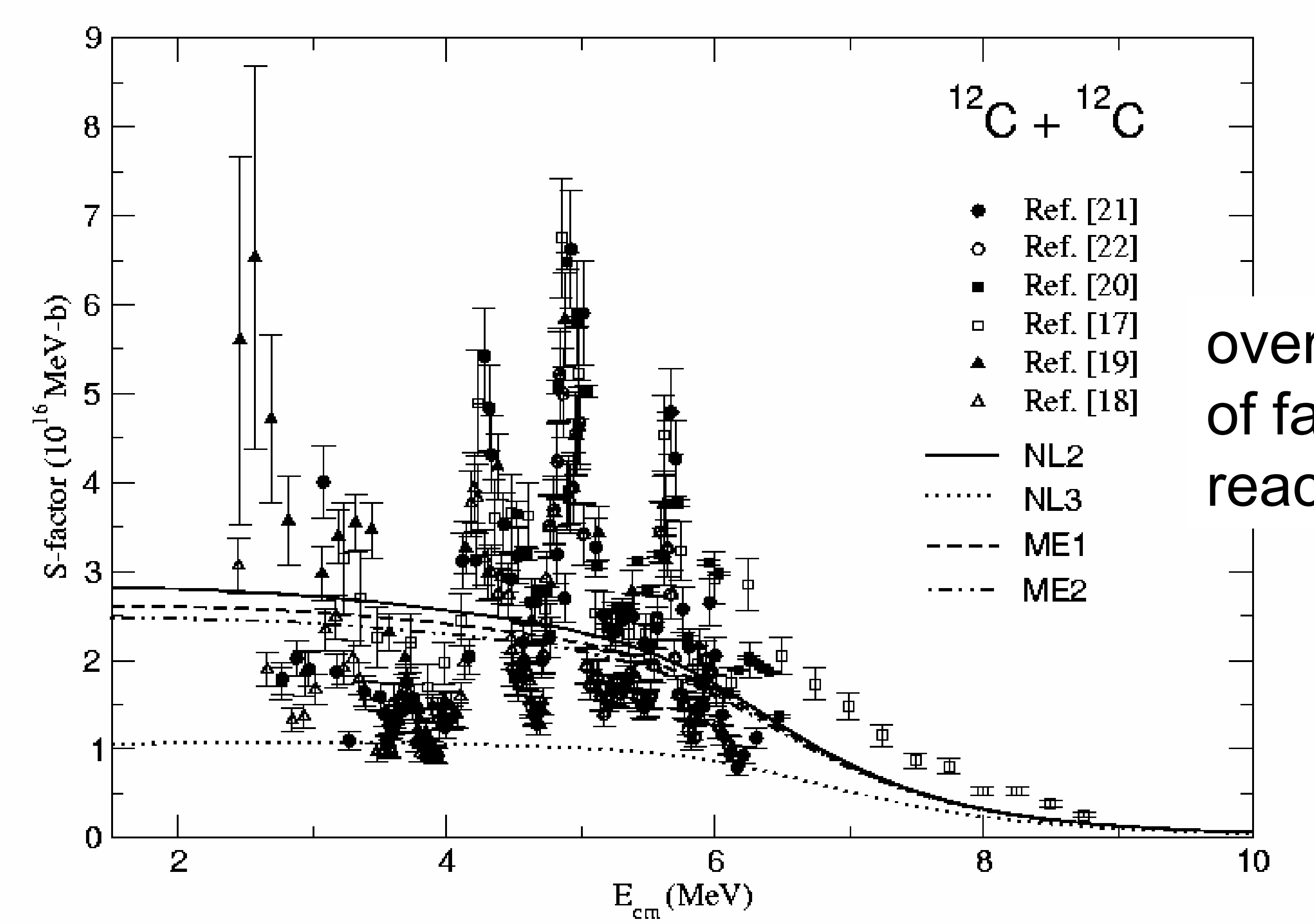
$$\frac{dY_{^{12}C}}{dt} = -Y_{^{12}C} \cdot Y_{^{12}C} \cdot \rho \cdot \left(\begin{array}{l} N_A \langle \sigma \upsilon \rangle_{^{12}C(^{12}C,\alpha)^{20}Ne} \\ + N_A \langle \sigma \upsilon \rangle_{^{12}C(^{12}C,p)^{23}Na} \\ + N_A \langle \sigma \upsilon \rangle_{^{12}C(^{12}C,n)^{23}Mg} \end{array} \right)$$

Experimental status and goals



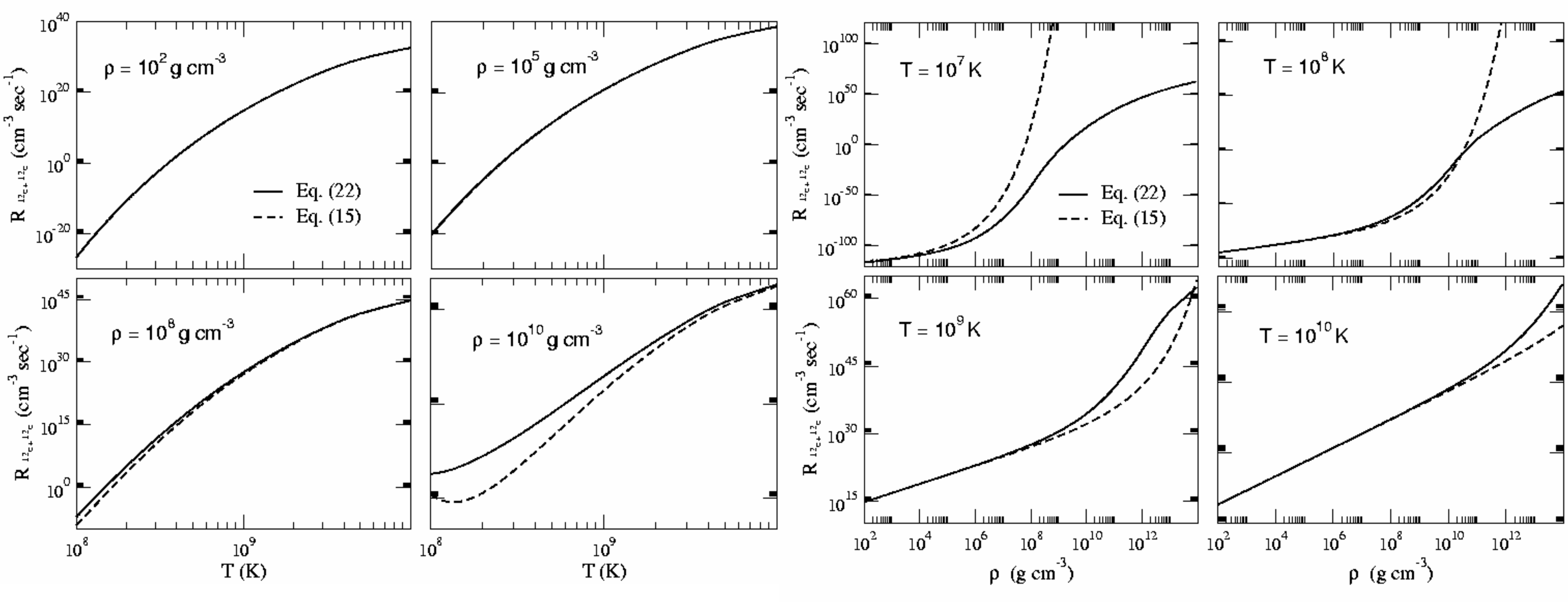
unknown S-factor towards lower energies!
new generation of initiatives has started!

S-factor extrapolations for different nuclear models



overall uncertainty of factor 2-5 in the reaction rate

Temperature and density impact on heavy ion reaction rate



Depending on matter conditions, ideal gas, fluid, solid crystal

Reaction rate formalism

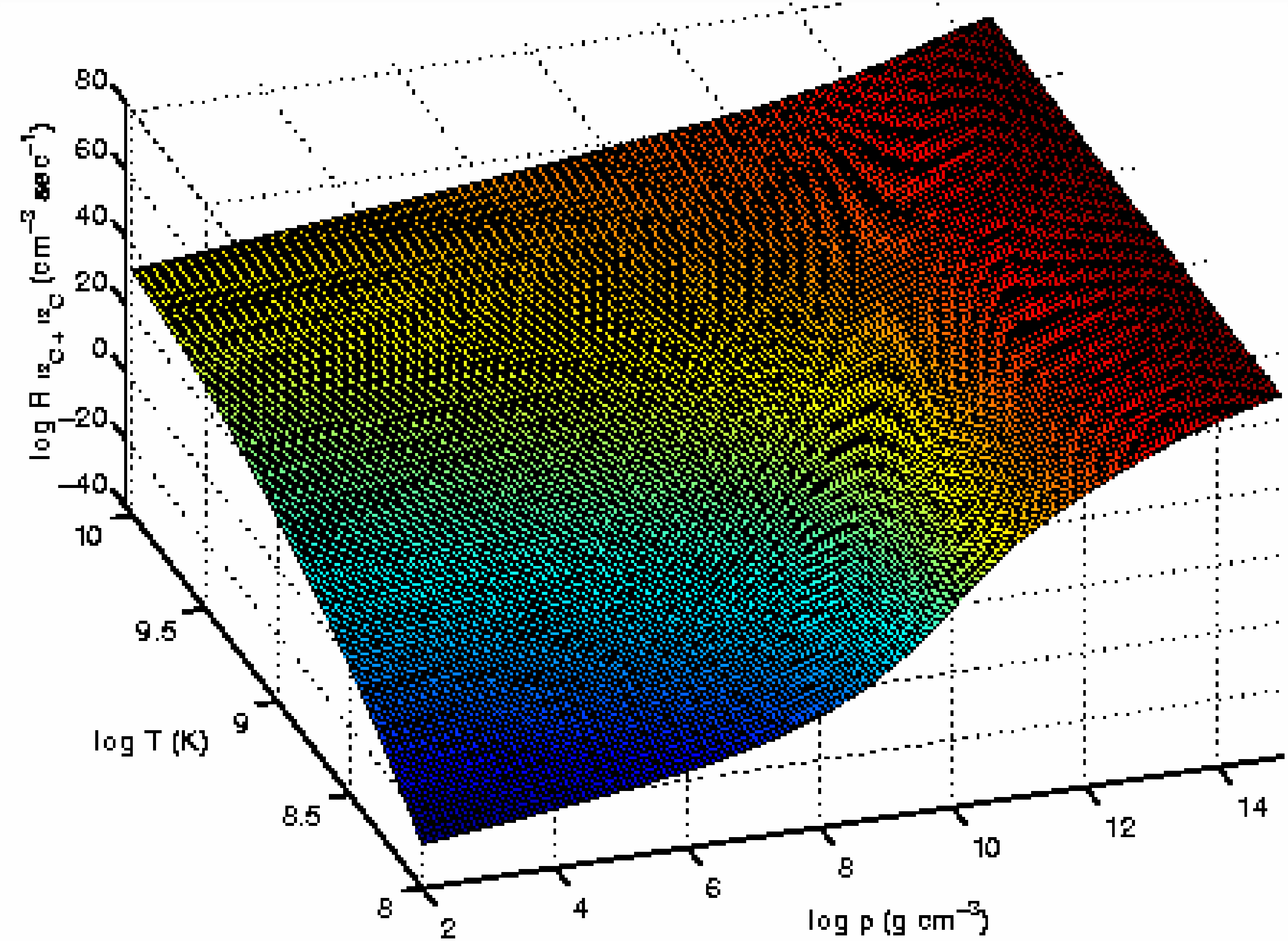
$$N_A < \sigma v >= N_A \cdot f \cdot \left(\frac{2}{\mu}\right)^{1/2} \frac{\Delta E_G}{(kT)^{3/2}} \cdot S_{ij} \cdot exp\left(-\frac{3E_G}{kT}\right)$$

$$R_{ij}\ [cm^{-3} s^{-1}] = \frac{1}{1+\delta_{ij}} \frac{X_i X_j (A_i + A_j)}{Z_i Z_j (A_i A_j)^2}\ \rho^2\ S_{ij}(E_{eff})\ R_0$$

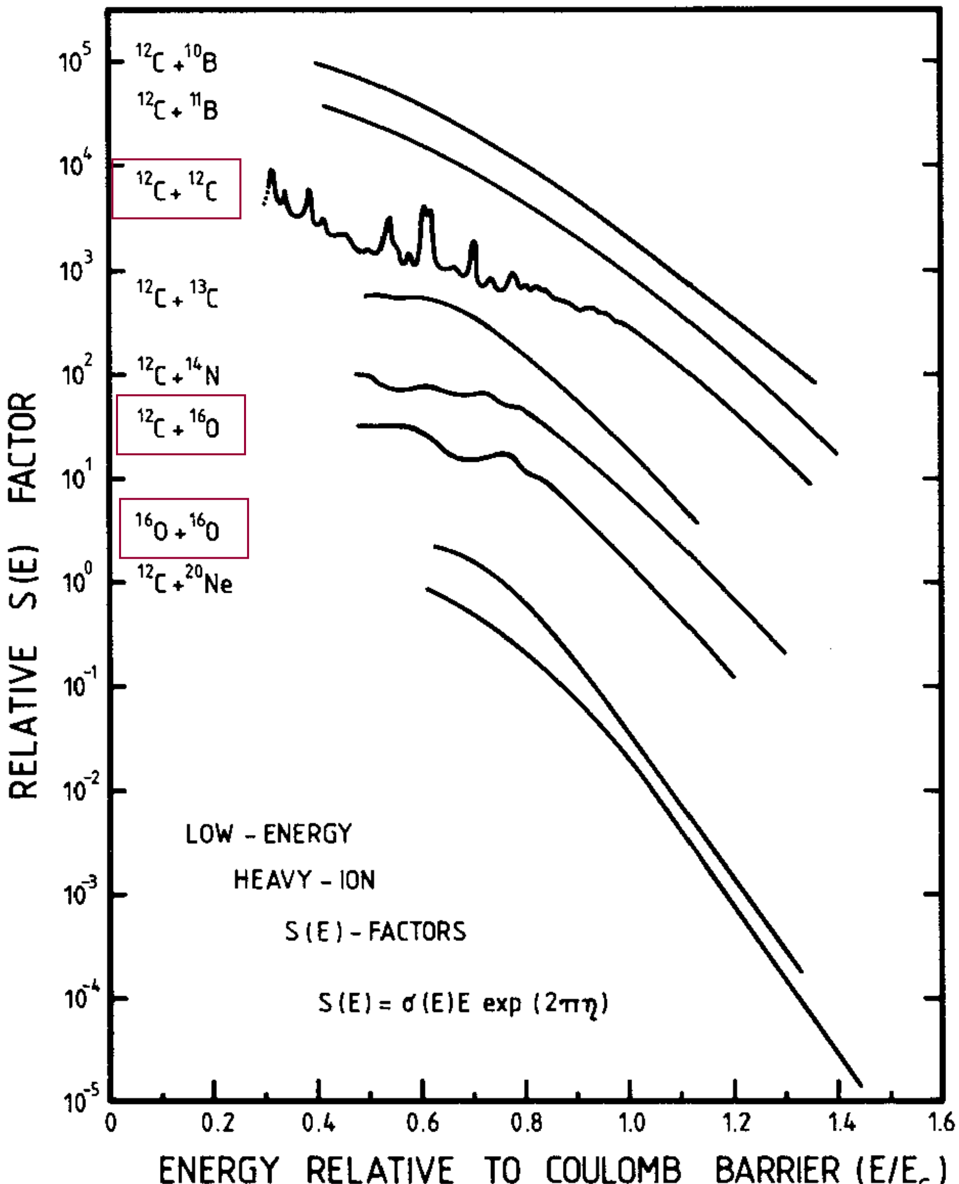
with

$$R_0 = \begin{cases} 2.613 \times 10^{32}\ r_{ij}^{2} \sqrt{1 - \left[tanh\left(\frac{T_n}{T}\right)^8\right]^{1/12}}\ \times exp\left(-\alpha_{ij}\pi\sqrt{\frac{D_n}{r_{ij}^{T}}} + \xi_{ij}\right) & \text{for } T \geq T_n \\ 1.600 \times 10^{33}\ \left(\frac{D_n}{r_{ij}^{T}}\right)^{1/2} \left\{1 + \left[0.543\left(\frac{D_n}{r_{ij}^{T}}\right)^{1/2} - 1\right]\left(\frac{T}{T_n}\right)^3\right\} \times \\ \times exp\left(-\alpha_{ij}\pi\sqrt{\frac{D_n}{r_{ij}^{T}}} + \xi_{ij}\right) & \text{for } T < T_n \end{cases}$$

Temperature & density dependence of $^{12}C+^{12}C$ rate



S-factors for other possible heavy ion reaction processes



12C+12C clearly dominates carbon burning by several orders of magnitude, only with large 16O abundances alternative reaction branches may open.

Subsequent light ion reactions in carbon burning environment

Release of protons and alphas during carbon burning:

$$^{12}C(p,\gamma)^{13}N \qquad ^{12}C(\alpha,\gamma)^{16}O$$

$$^{20}Ne(p,\gamma)^{21}Na \qquad ^{20}Ne(\alpha,\gamma)^{24}Mg$$

$$^{23}Na(p,\alpha)^{20}Ne$$

Alpha capture reactions considerably weaker than proton capture!

Subsequent burning sequences

Takes place in environment of increasing density

Neon burning: photodissociation of ^{20}Ne to ^{16}O and ^{4}He because of low α binding energy of ^{20}Ne

Oxygen burning: heavy ion burning $^{16}O+^{16}O \Rightarrow ^{28}Si$ sequence of heavy ion induced processes similar to carbon burning

Silicon burning: photodissociation of weakly bound ^{28}Si with subsequent p-, α-capture to Fe

Neon burning

$$^{20}Ne(\gamma,\alpha)^{16}O \quad Q = -4.73\,MeV$$

$$^{16}O(\alpha,\gamma)^{20}Ne \quad Q = 4.730\,MeV$$

$$^{20}Ne(\alpha,\gamma)^{24}Mg \quad Q = 9.316\,MeV$$

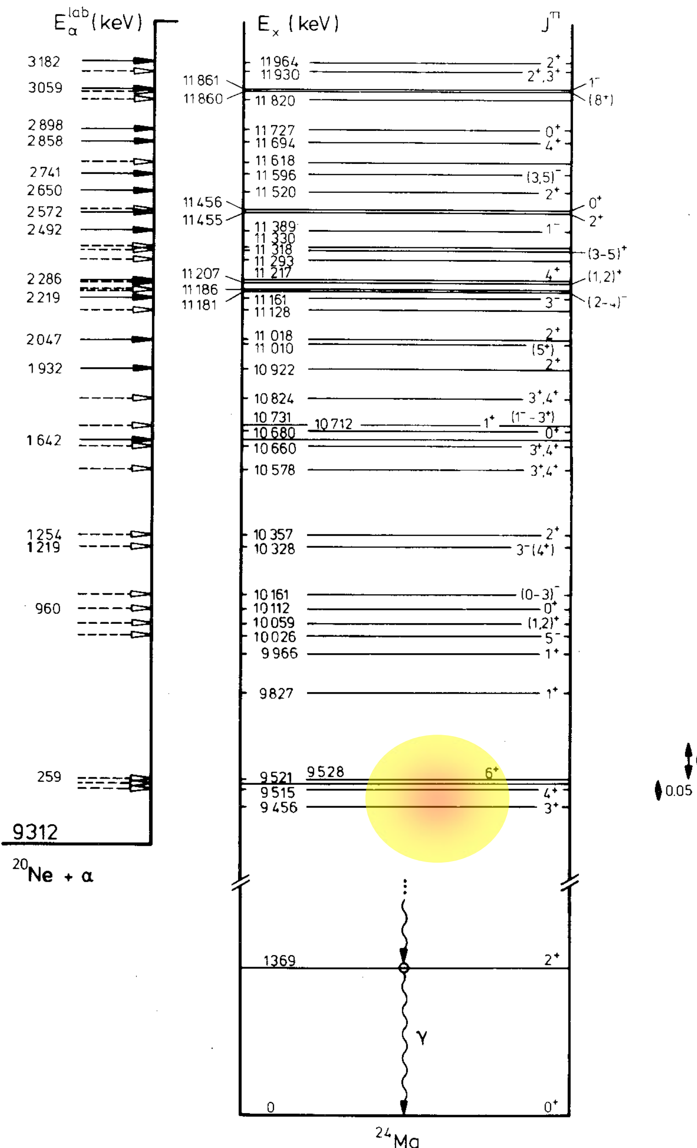
$$^{24}Mg(\alpha,\gamma)^{28}Si \quad Q = 9.984\,MeV$$

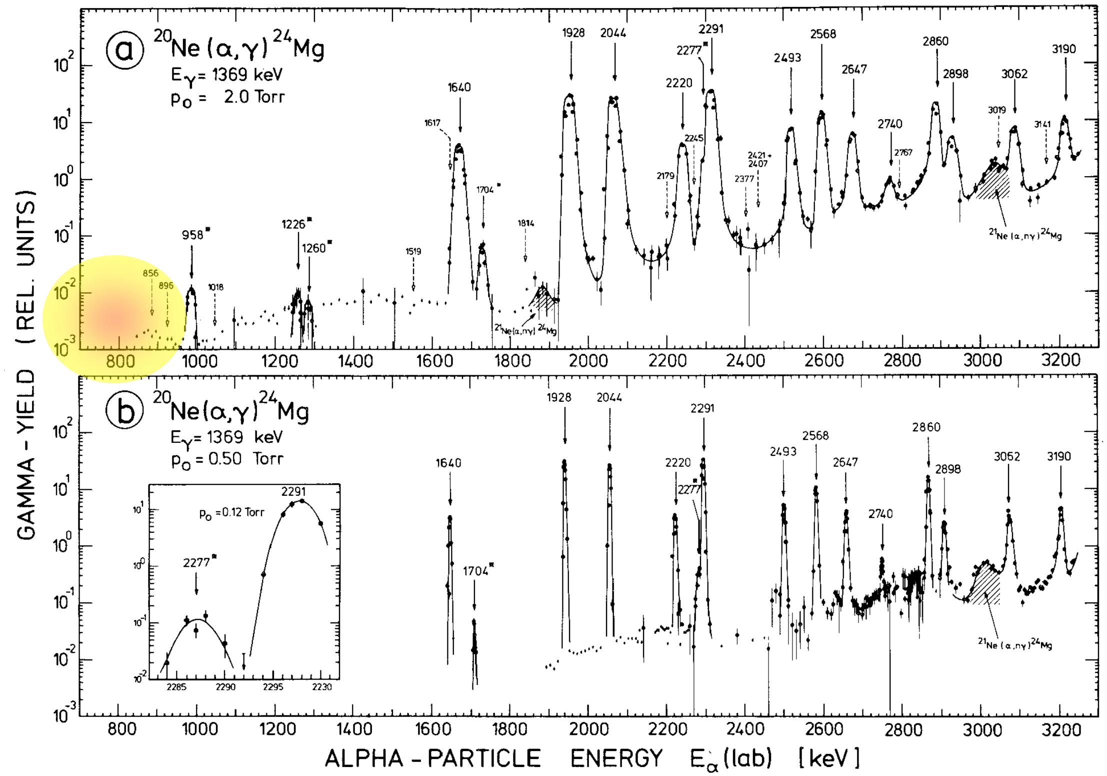
Release of α particles through photodissociation of weakly bound 20Ne ((α,γ)-(γ,α)-equilibrium?) and subsequent α capture induced nucleosynthesis along the T=0 line. (α-cluster structure effects)

The $^{20}Ne(\alpha,\gamma)^{24}Mg$ reaction

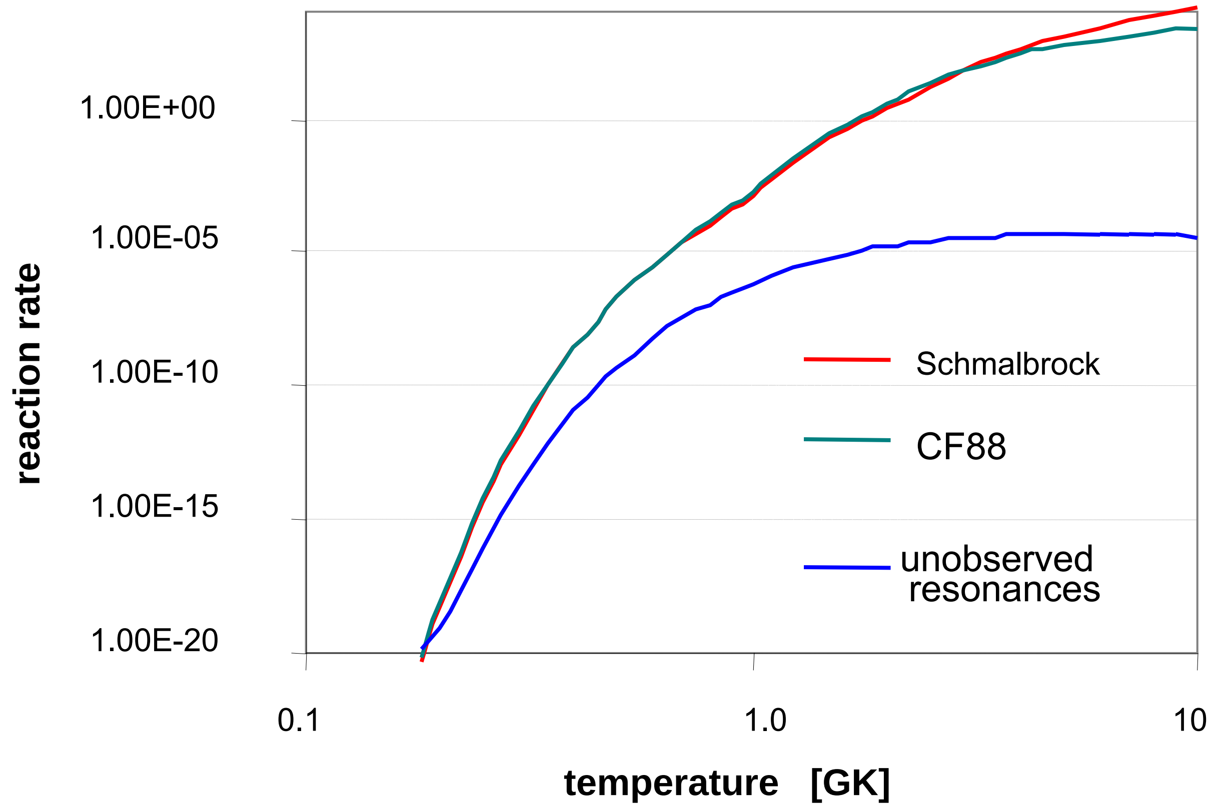
$$E_G = 0.122 \cdot \left(Z_1^2 \cdot Z_1^2 \cdot \mu \cdot T_9^2\right)^{1/3} \, [MeV]$$

$$\Delta E_G = 0.236 \cdot \left(Z_1^2 \cdot Z_1^2 \cdot \mu \cdot T_9^5\right)^{1/6} \, [MeV]$$



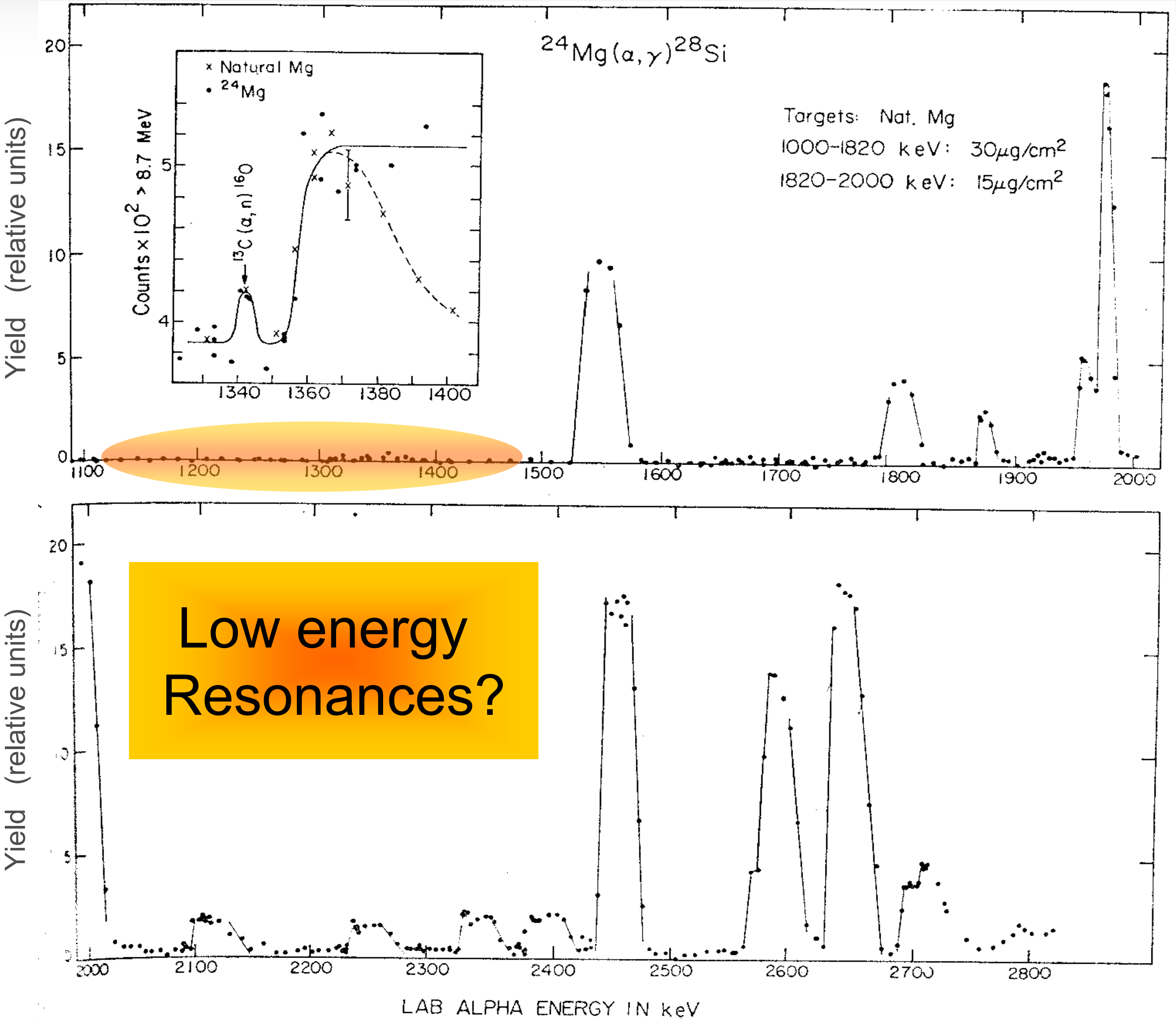


$^{20}Ne(\alpha,\gamma)$ reaction rate



Rate is fairly well known, lower resonance contributions are more less negligible for the T-range of Ne-burning T=1-2GK. Uncertainties in $^{24}Mg(\alpha,\gamma)^{28}Si$!

The $^{24}Mg(\alpha,\gamma)^{28}Si$ reaction



Oxygen burning

temperature at T ≈ 2 GK;   Gamow range at E_G ≈ 6±2 MeV

$$^{16}O(^{16}O,p)^{31}P \quad Q = 7.628\,MeV \qquad ^{31}P(p,\gamma)^{32}S \quad Q = 7.680\,MeV$$

$$^{31}P(p,\alpha)^{28}Si \quad Q = 1.916\,MeV$$

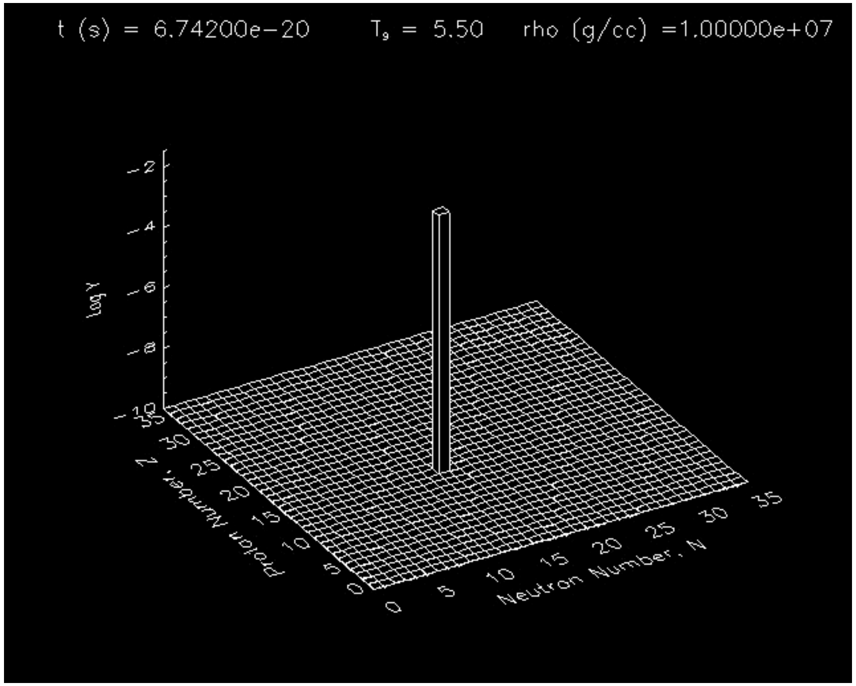
$$^{16}O(^{16}O,\alpha)^{28}Si \quad Q = 9.594\,MeV \qquad ^{28}Si(\alpha,\gamma)^{32}S \quad Q = 6.771\,MeV$$

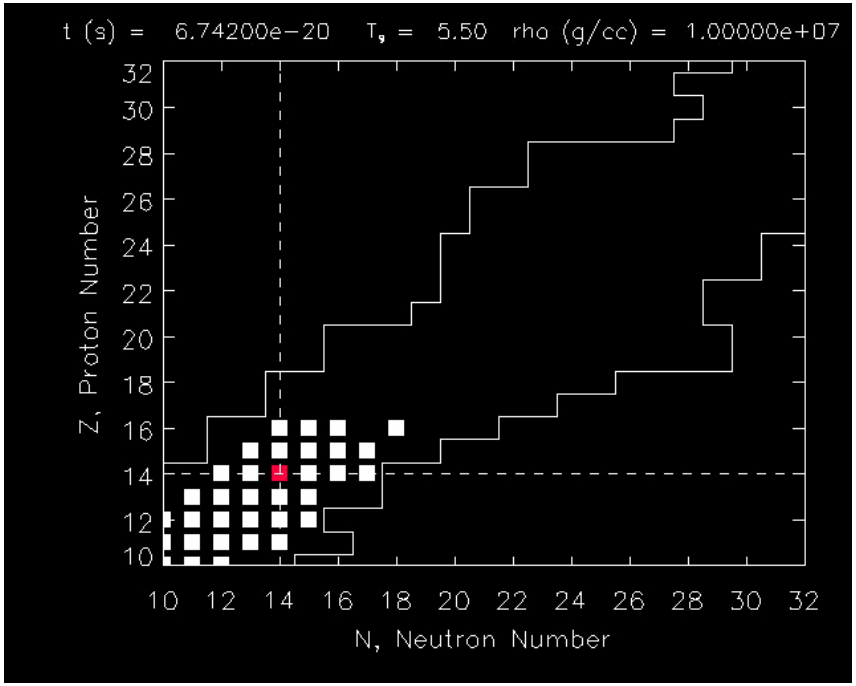
$$^{16}O(^{16}O,n)^{31}S \quad Q = 1.499\,MeV \qquad ^{28}Si(n,\gamma)^{29}Si \quad Q = 8.641\,MeV$$

Like in carbon burning, release on protons, alphas, and neutrons which change abundance conditions through subsequent capture processes at high energies ⇨ enrichment in ^{28}Si because of a presumably weak ^{28}Si(α,γ)^{32}S reaction rate.

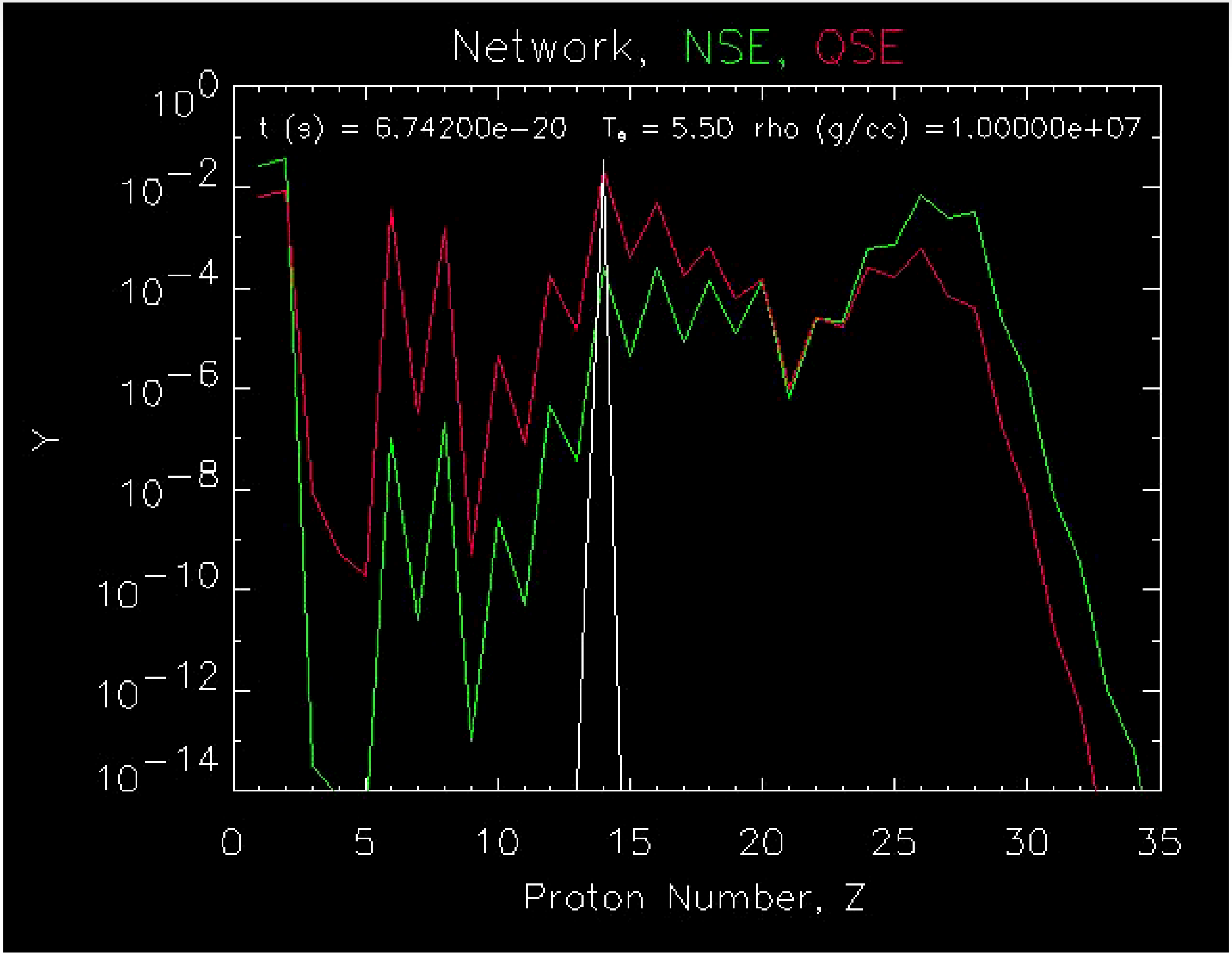
Si-burning

Photodissociation of ^{28}Si with subsequent build-up of heavy elements up to iron in statistical equilibrium

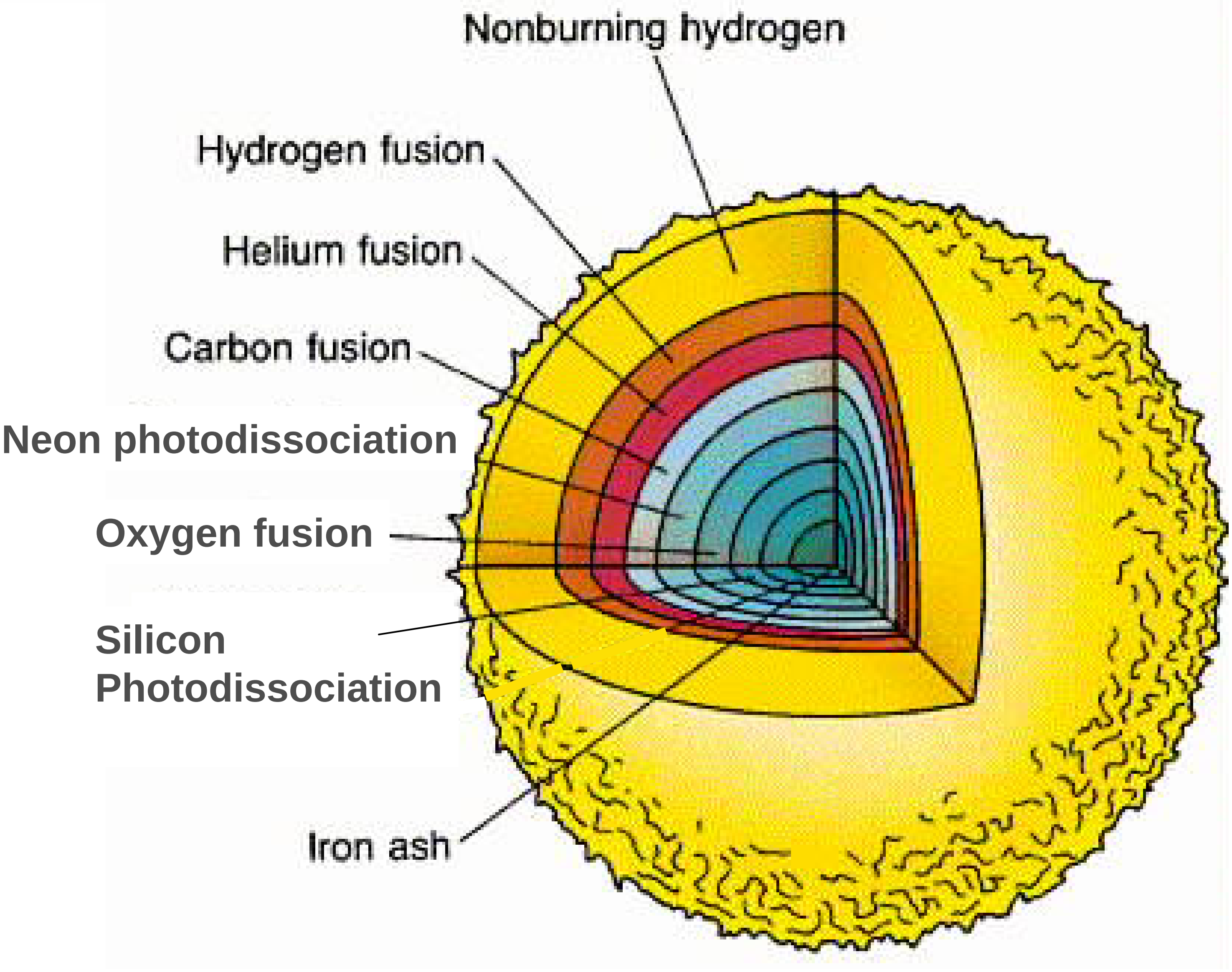




Si burning abundance evolution



The stellar Onion Model



Multitude of open questions!

- heavy ion reactions at sub-threshold energies
- search for cluster and molecular configurations