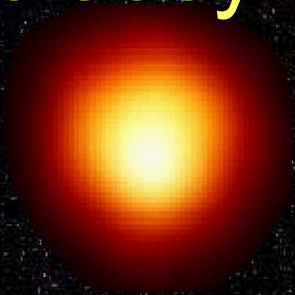
Nucleosynthesis in Late Stellar Burning

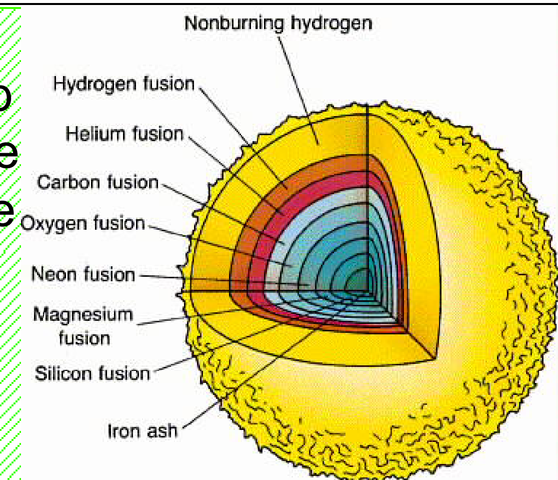


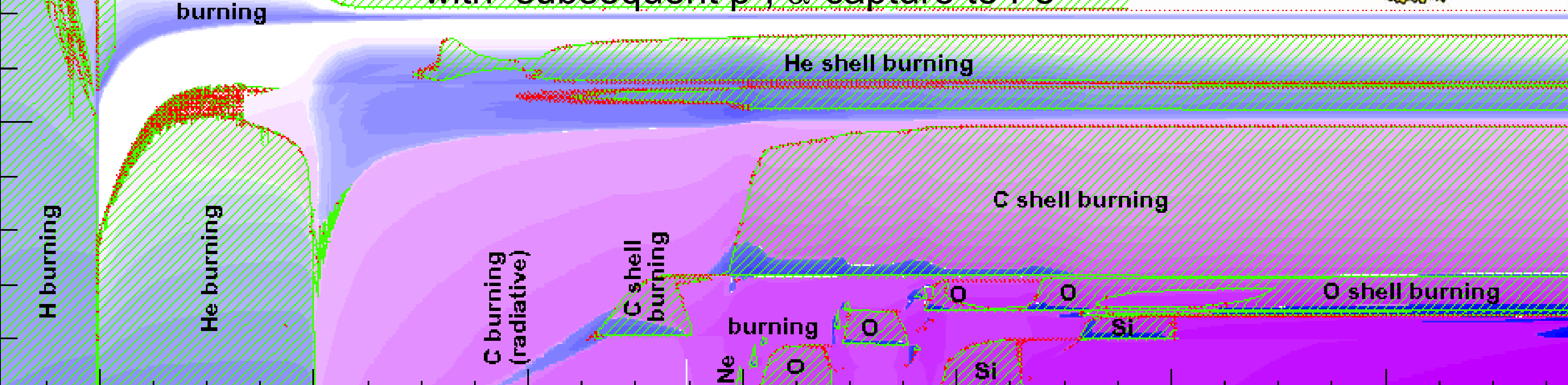
- post helium burning
- ignition of stellar carbon and oxygen burning
- nucleosynthesis in shell carbon burning
- from neon to silicon burning

Post-helium burning sequences

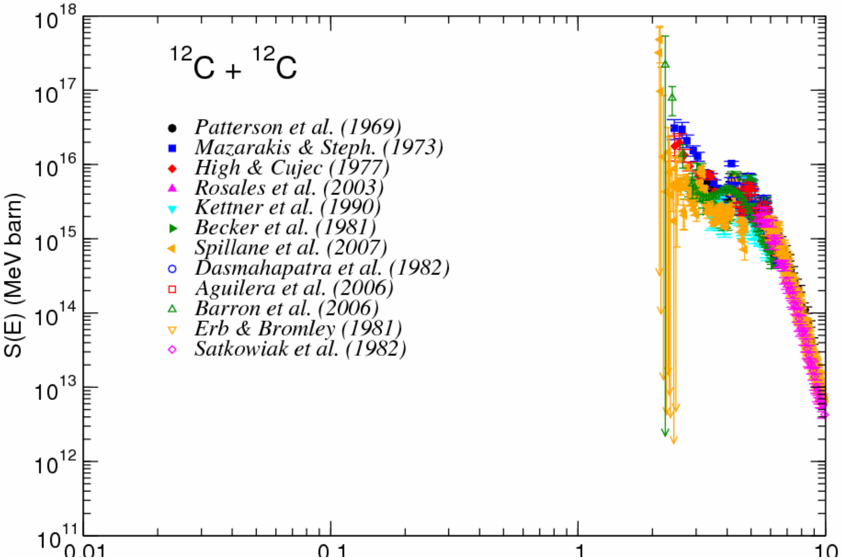
Takes place in environment of increasing density

Carbon burning:	heavy ion burning $^{12}C+^{12}C \Rightarrow ^{24}Mg$ $\Rightarrow ^{20}Ne+\alpha$ and $^{23}Na+p$
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 $^{16}O+^{16}O \Rightarrow ^{28}Si$ $\Rightarrow ^{24}Mg+\alpha$ and $^{27}Al+p$
Silicon burning:	photodissociation of weakly bound ^{28}Si with subsequent p-, α-capture to Fe





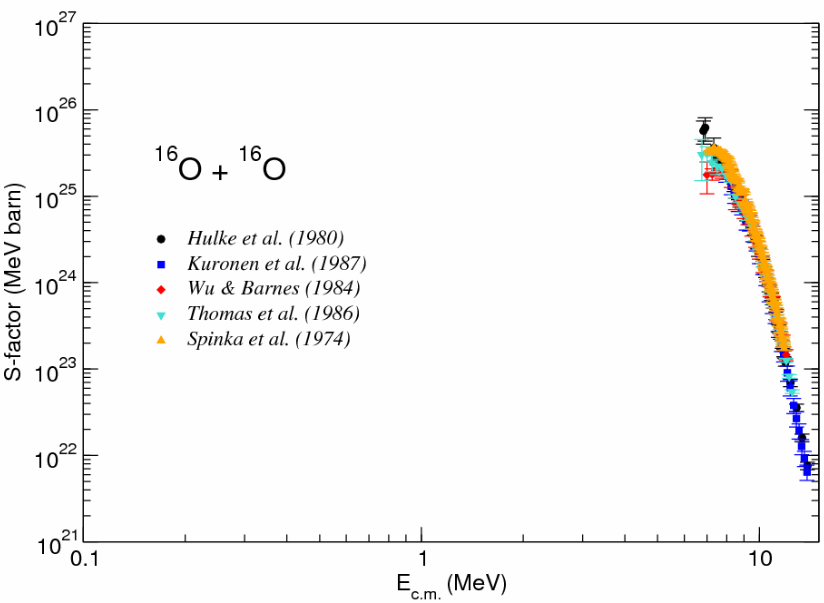
Problems of heavy ion burning



How to extrapolate, what are branchings

$$^{12}C+^{12}C \Rightarrow \begin{cases} ^{20}Ne+\alpha \\ ^{23}Na+p \\ ^{23}Mg+n \end{cases}$$

$$^{16}O+^{16}O \Rightarrow \begin{cases} ^{28}Si+\alpha \\ ^{31}P+p \\ ^{31}S+n \end{cases}$$



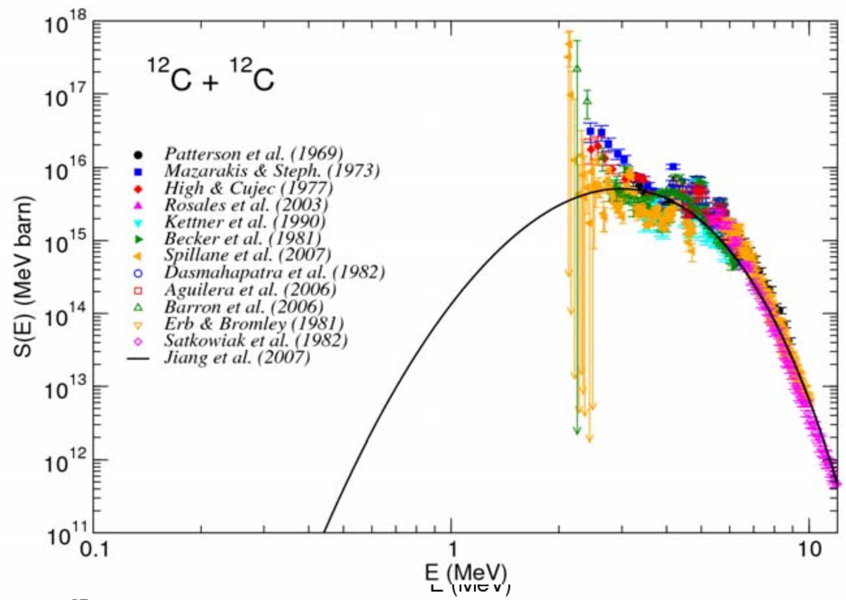
- Times scale for stellar C, O burning
- Neutron production in C-burning & weak s-process nucleosynthesis
- White dwarf abundance distribution & nucleosynthesis in Ne-novae
- Ignition conditions for type I SN
- Ignition condition for Superbursts

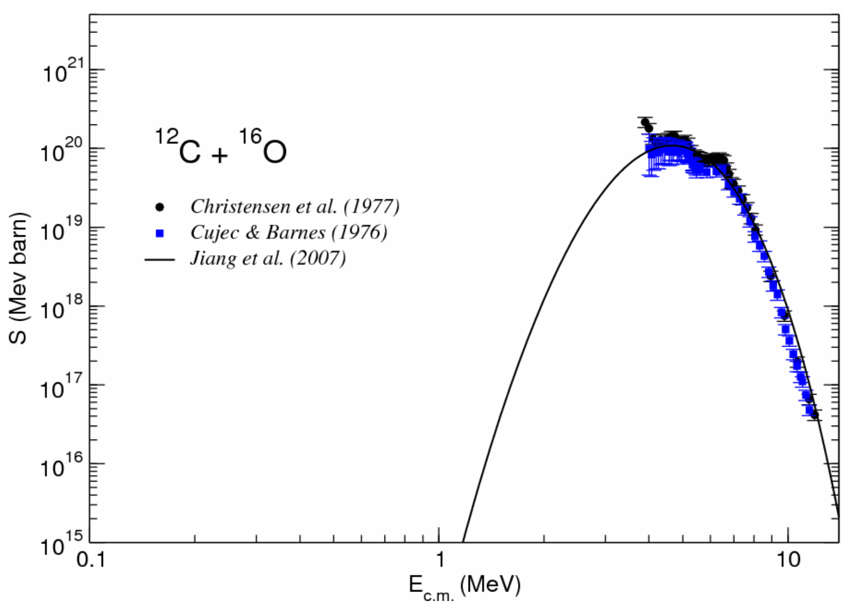
What potential model is appropriate?

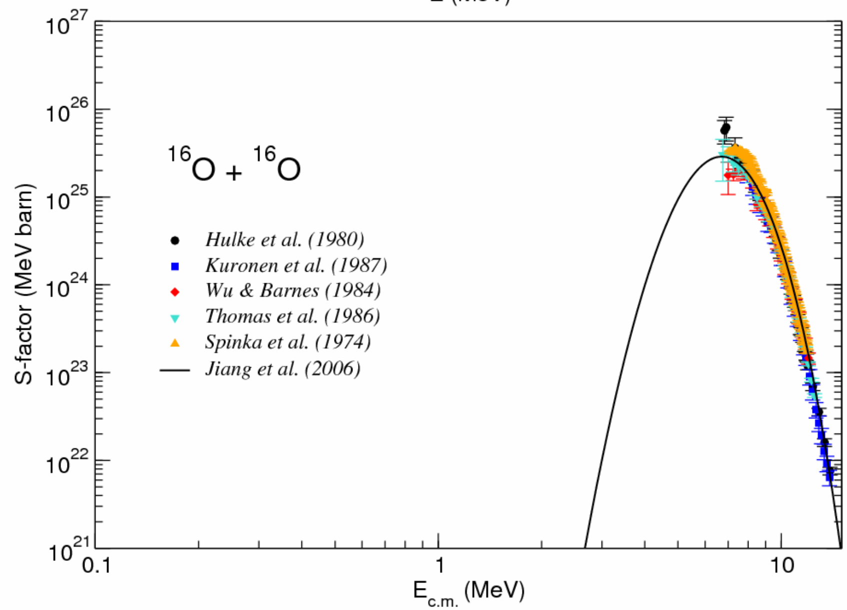
Different potential models leads to different extrapolation of low energy cross section (S-factor). Extreme case,

- standard potential model
- hindrance potential model

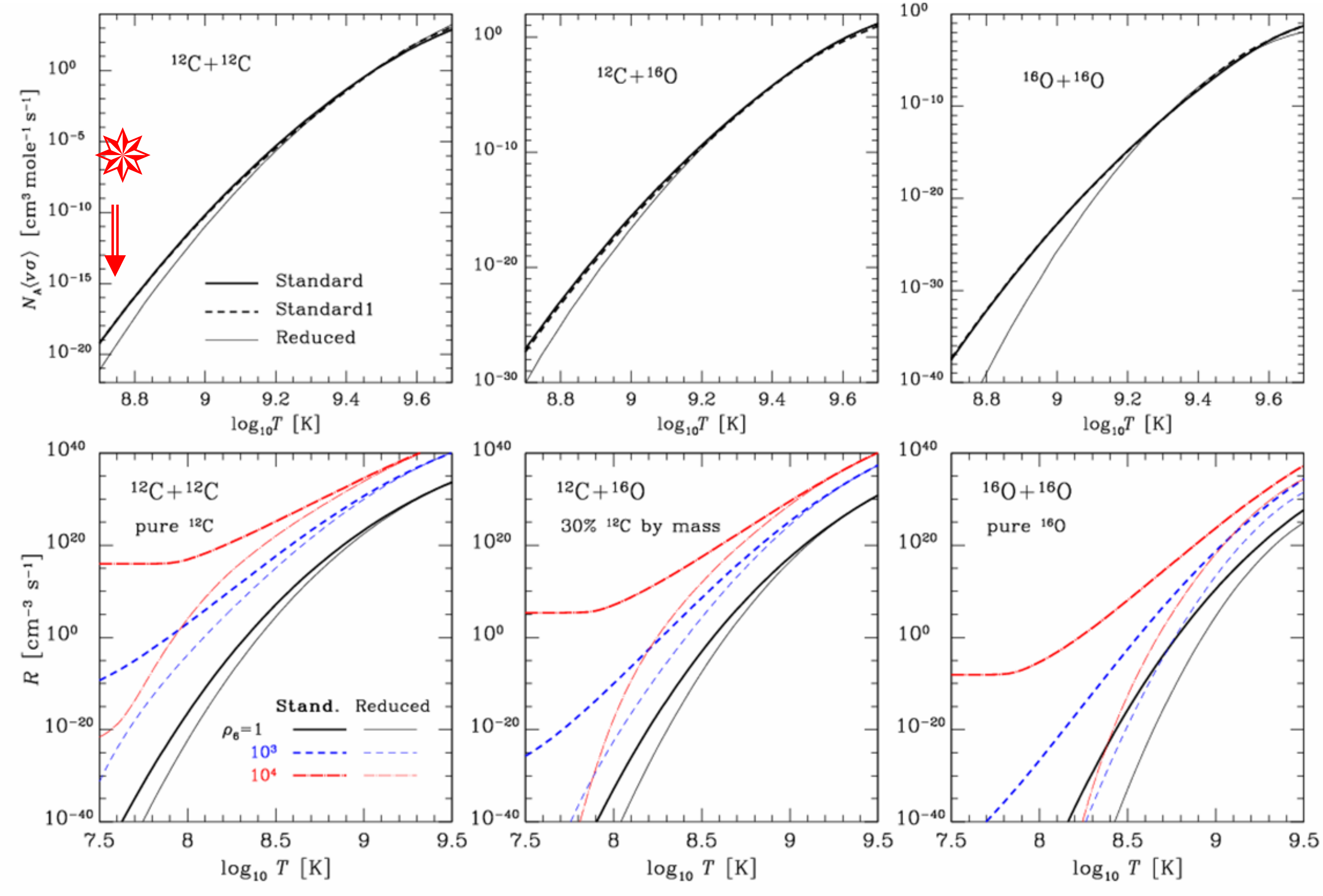
Caughlan & Fowler 1988
Gasques et al. 2005
Yakovlev et al. 2006
Jiang et al. 2007





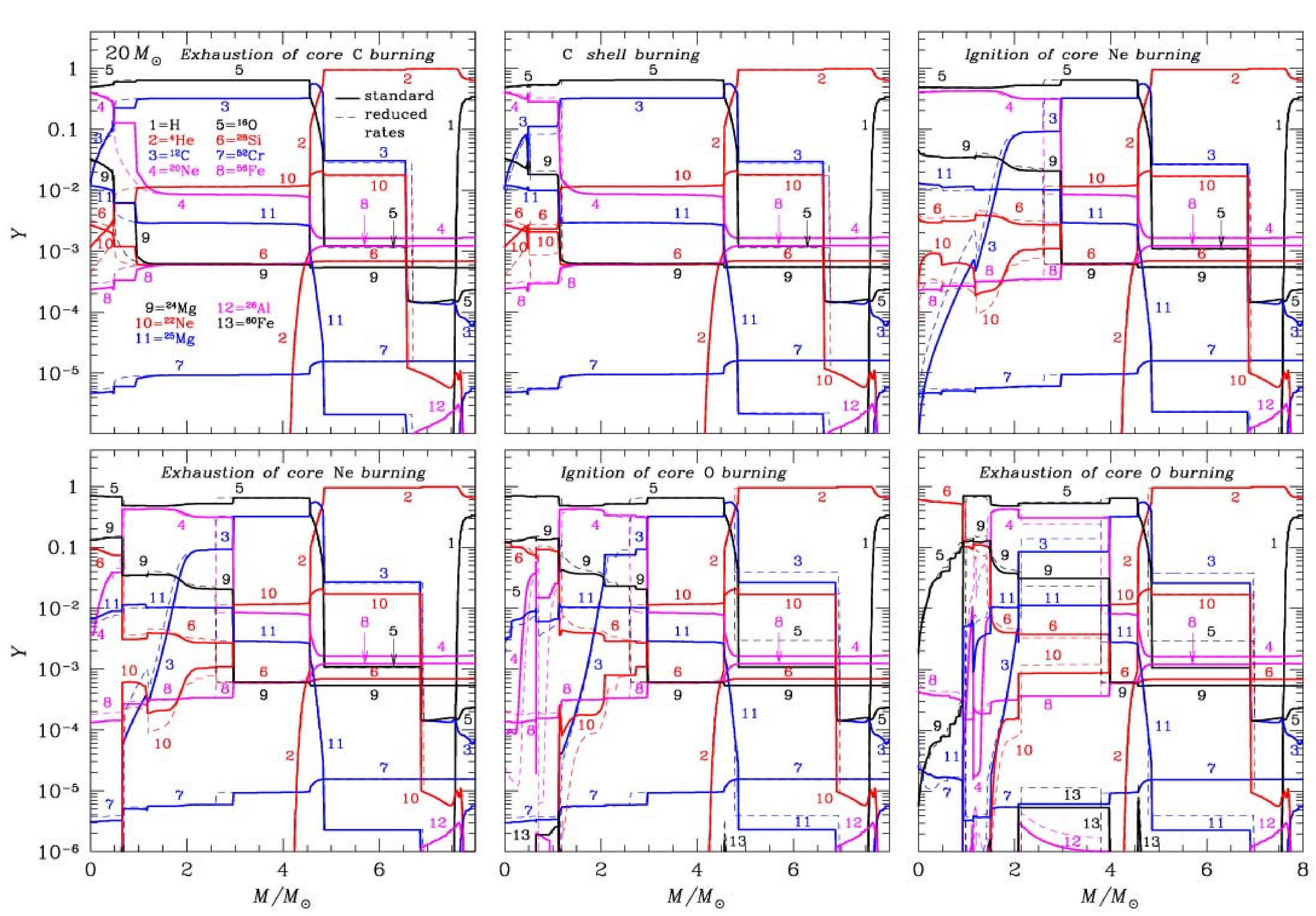


Density & Screening Dependence of Fusion

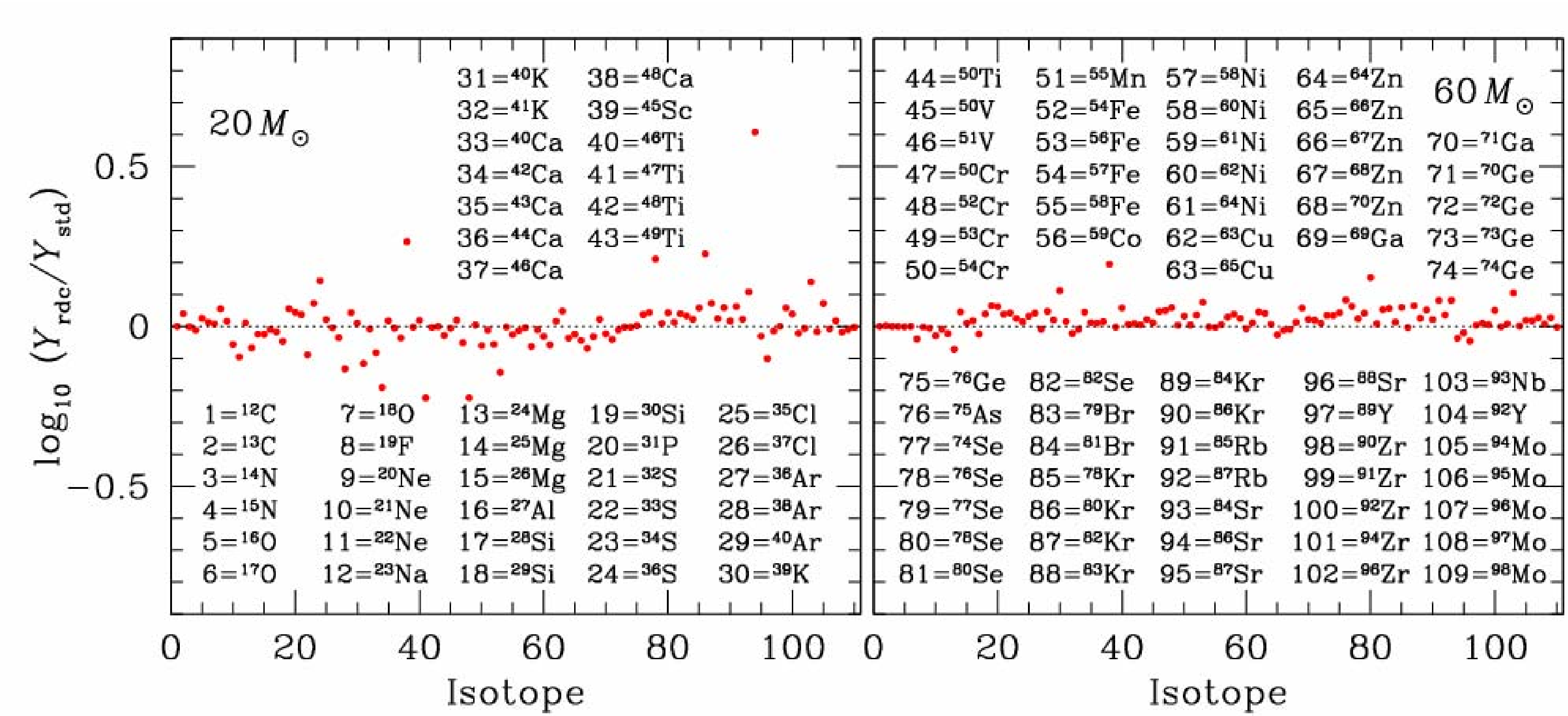


Towards higher densities there is an increase in the rate due to electron screening effects. The free electrons reduce the deflective Coulomb potential between the two fusioning ions.

Abundance evolution in late stellar burning

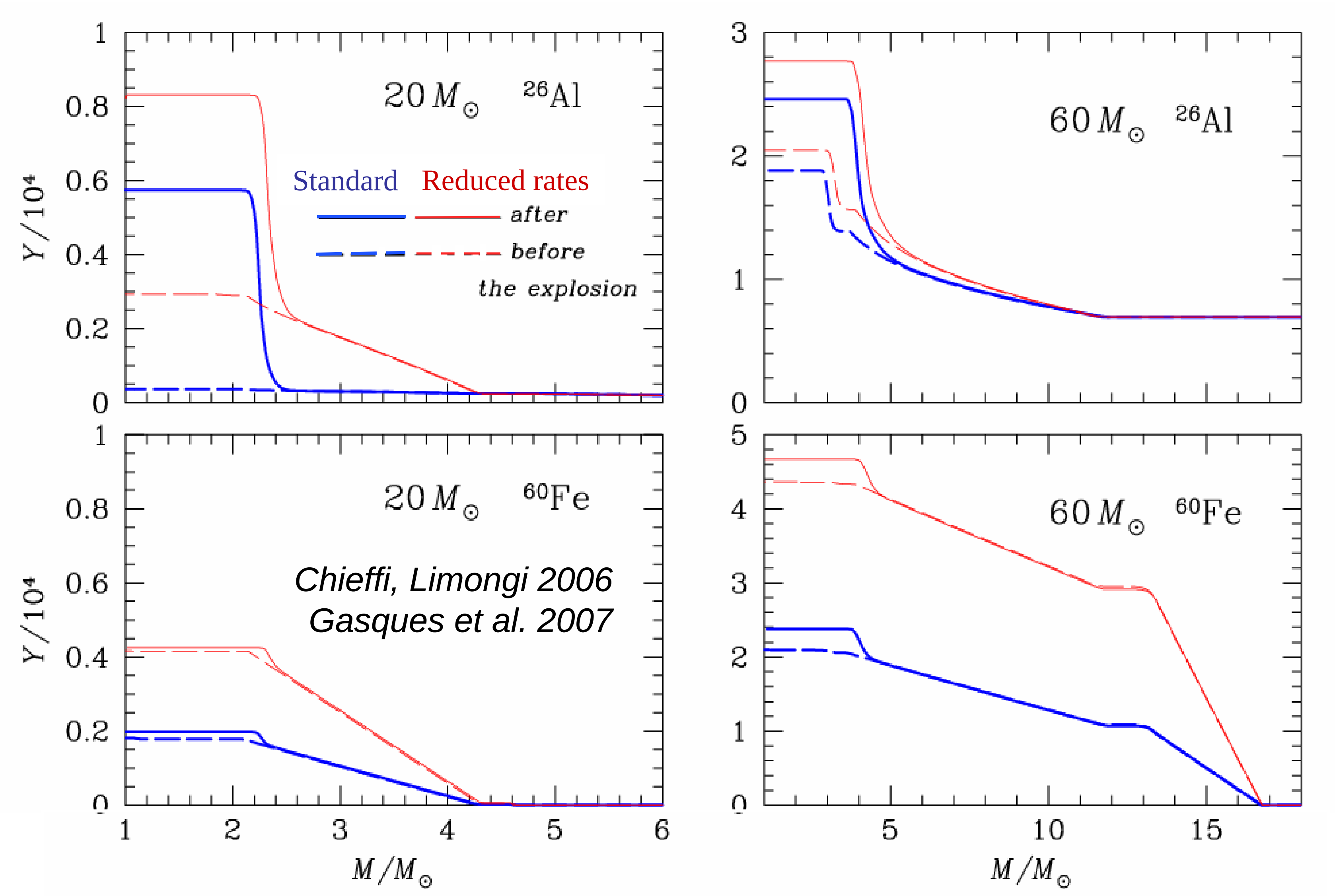


Consequences for late stellar burning



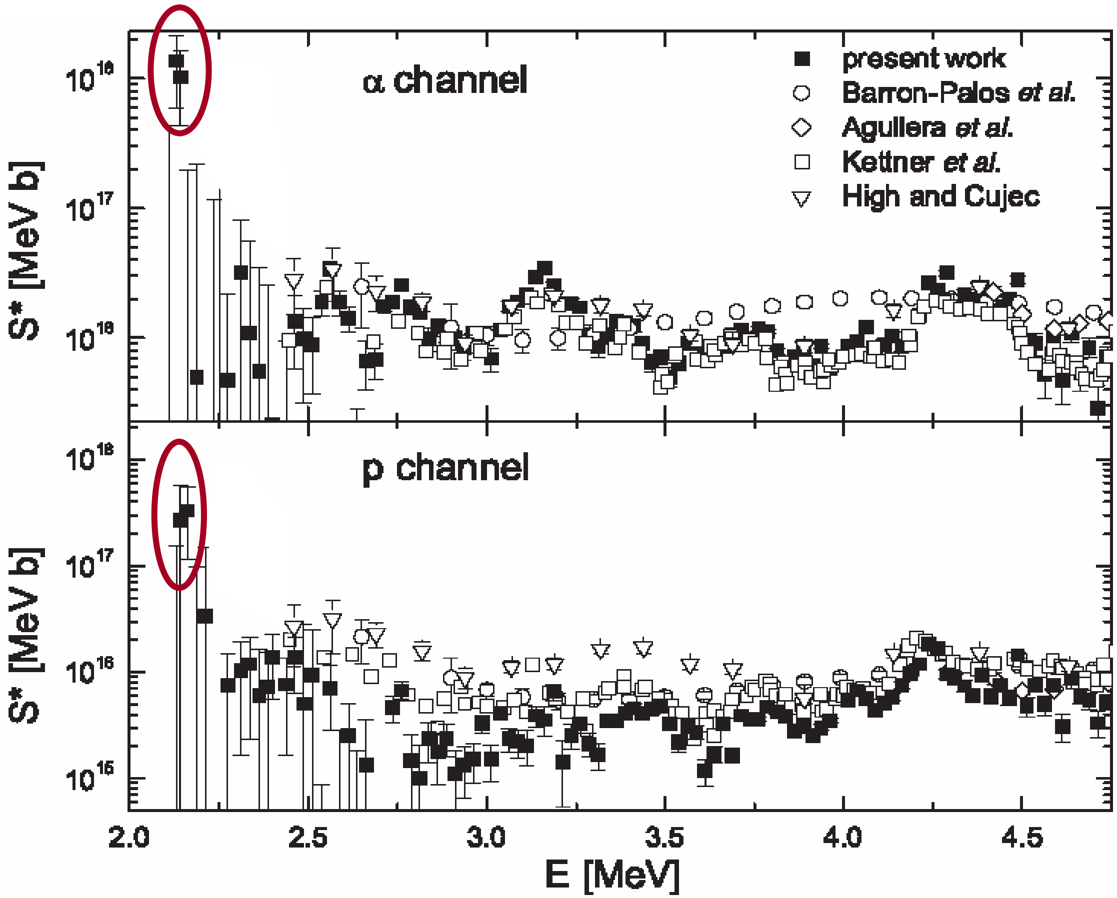
Simulations performed for 20 and 60 $M_\odot$ stars, no major differences for nucleosynthesis except a significant increase in abundance for the long-lived radioactive isotopes ^{26}Al and ^{60}Fe and some s-process nuclei. This suggests impact on n production. That needs further investigation.

Production of Galactic Radioactivity?



Gasques et al. PRC 2007

Resonance Structures in $^{12}C+^{12}C$

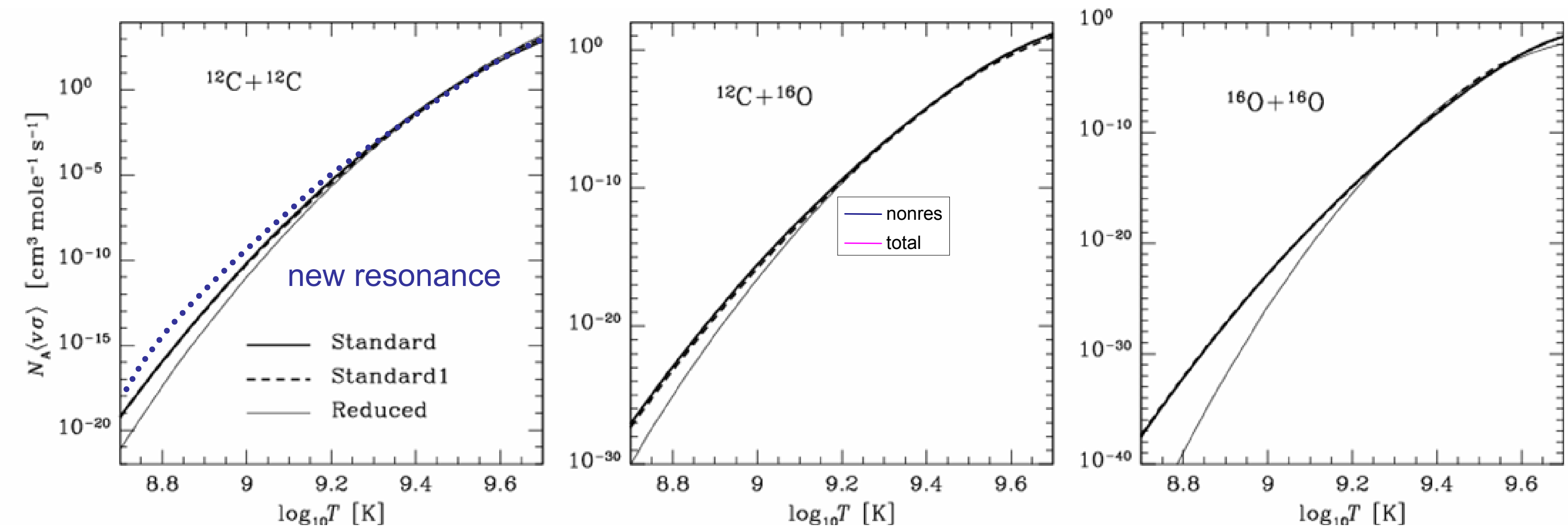


Recent data suggest strong but narrow resonance structures in the $^{12}C+^{12}C$ reaction system. The data point towards a ^{12}C configuration without a specific preference for the subsequent proton or alpha decay! The branching ratio is very uncertain.

Spillane et al. PRL 2007

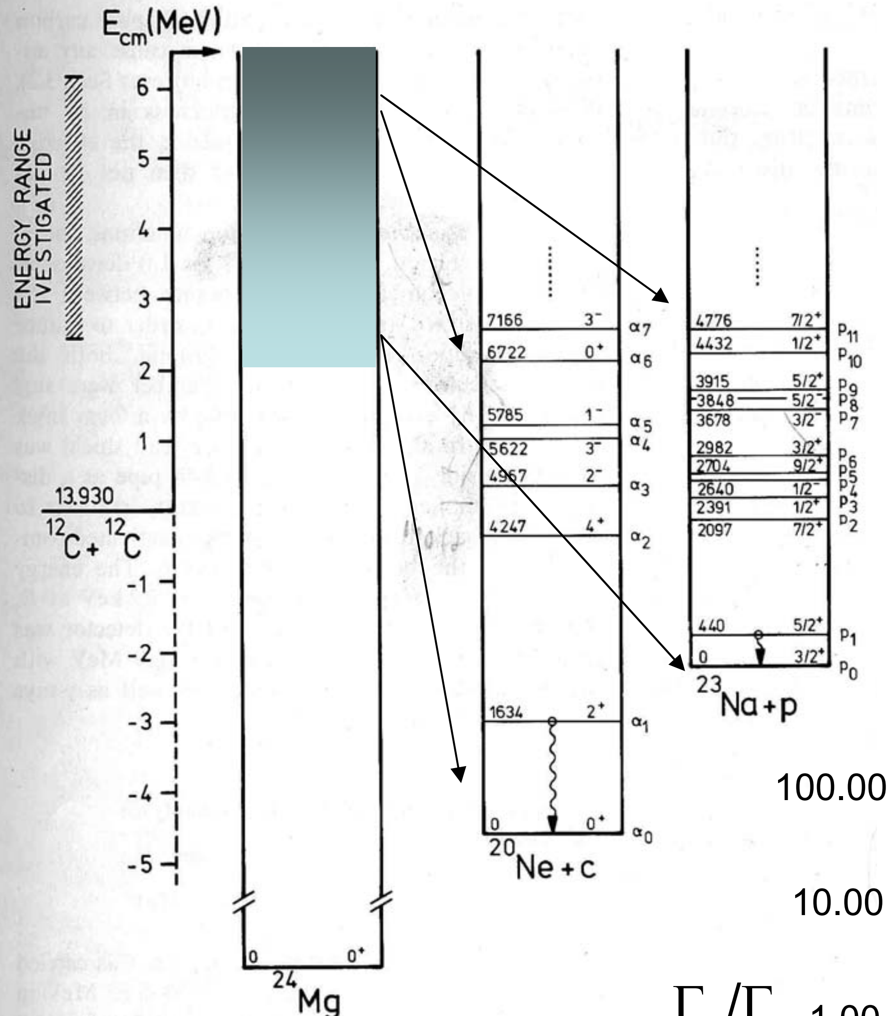
Reaction rate formalism

$$N_A\langle\sigma\upsilon\rangle = N_A \cdot f_{screen} \cdot \sqrt{\frac{2}{\mu}} \cdot \frac{\Delta E_G}{(kT)^{3/2}} \cdot S_{ij} \cdot e^{\left(-\frac{3E_G}{kT}\right)}$$

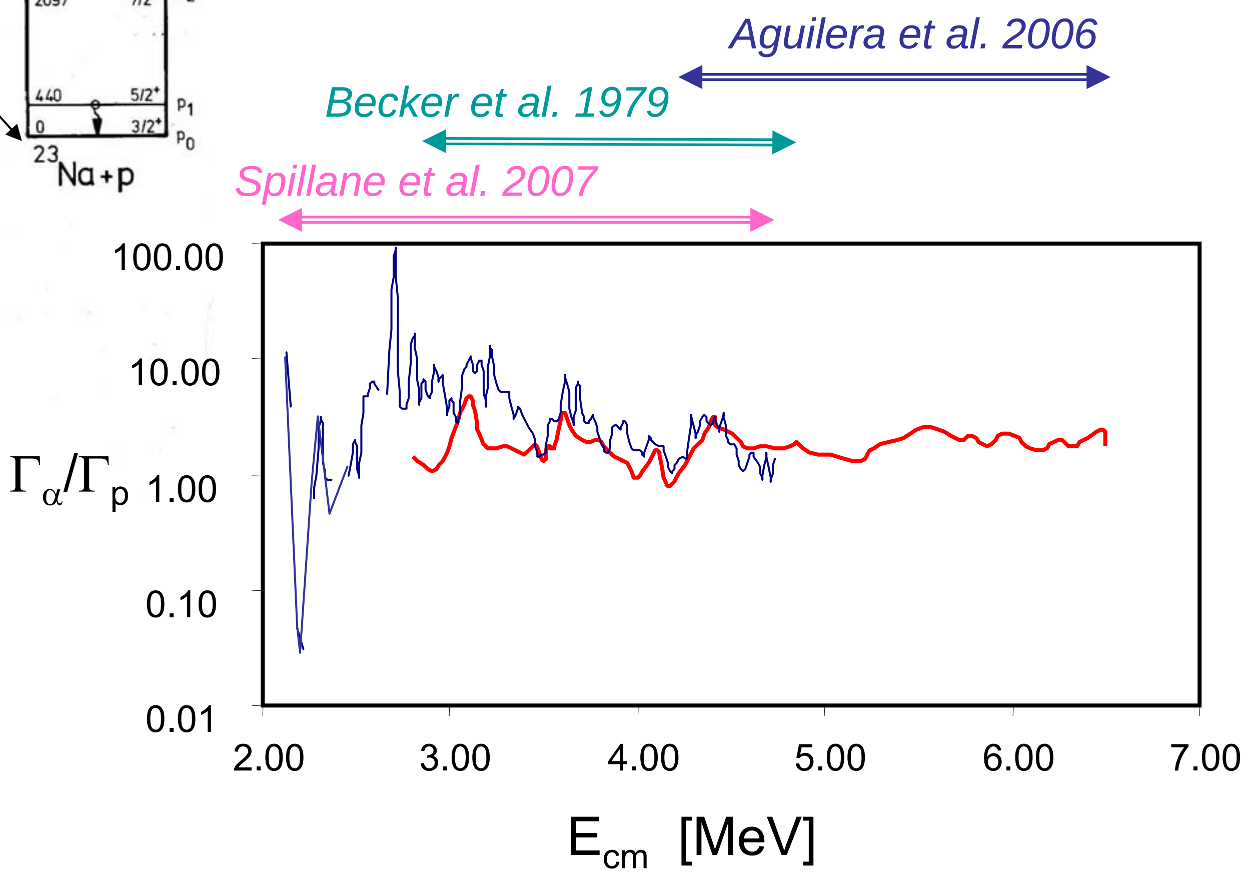


Additional resonance causes significant enhancement of low temperature rate, more resonances could contribute more strongly.

PROTON-ALPHA BRANCHING

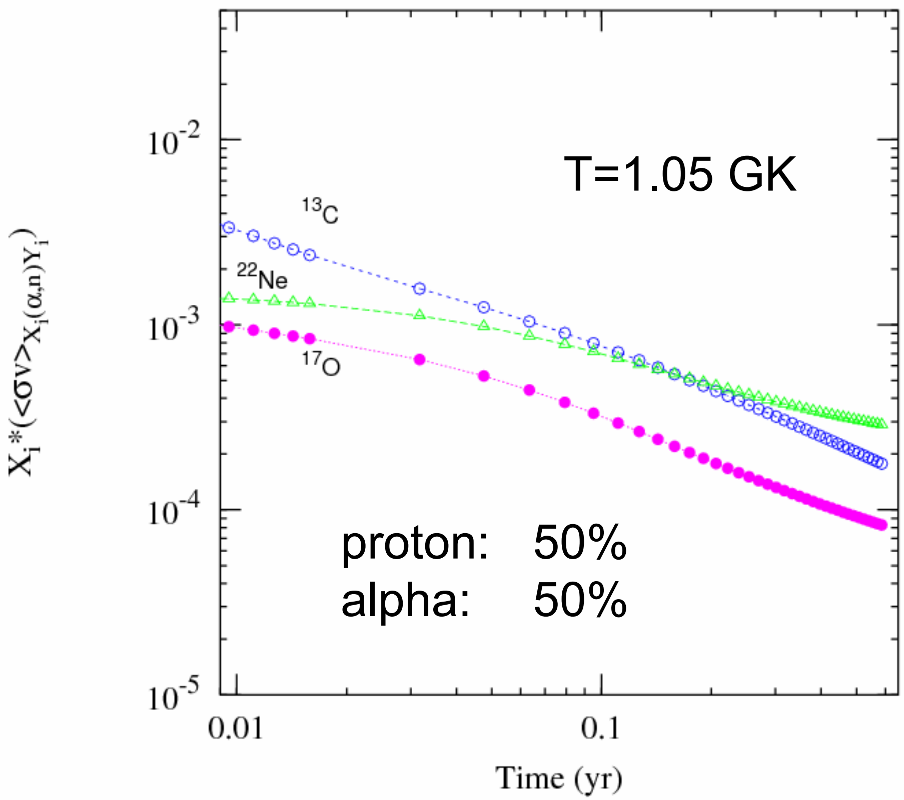


Pronounced alpha and single particle level structure at lower energies expected!



On average $\Gamma_\alpha/\Gamma_p \approx 1.8$!
But indication for α-cluster structure in ^{24}Mg is visible in resonance structure!

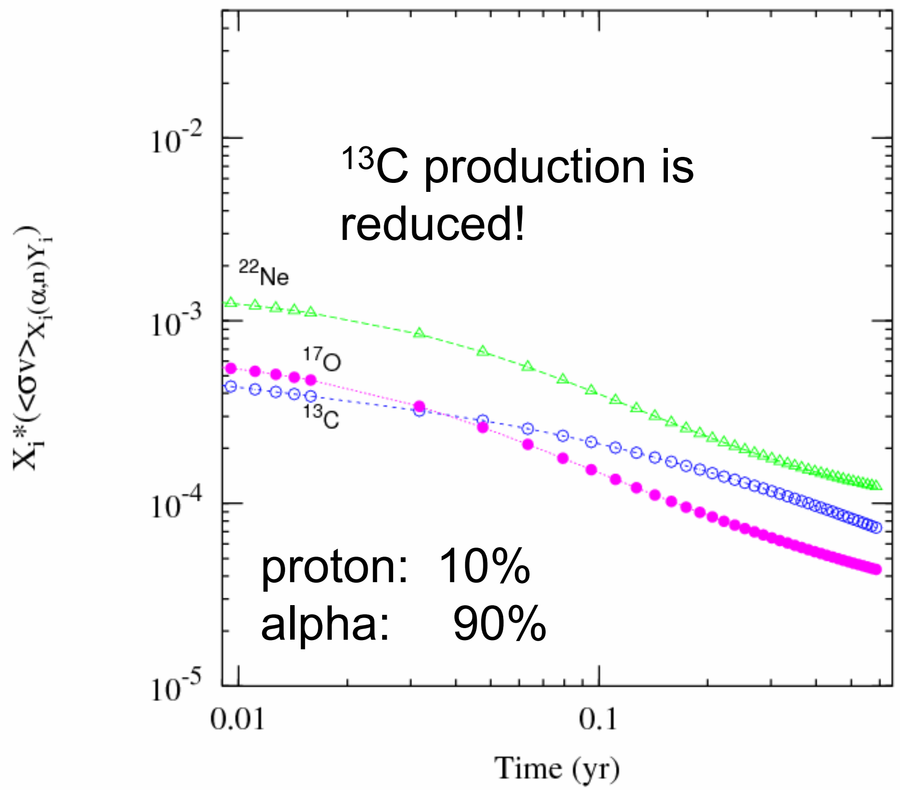
Consequences for Neutron Sources



^{13}C(α,n)

^{13}C originates through ^{12}C(p,γ)^{13}N(β+)^{13}C

Pignatari et al. 2008 in preparation



^{17}O(α,n) & ^{22}Ne(α,n)

^{22}Ne left from preceding He-burning

^{17}O originates through ^{16}O(n,γ)

Subsequent light ion reactions in carbon burning environment

Release of protons and alphas during carbon burning:

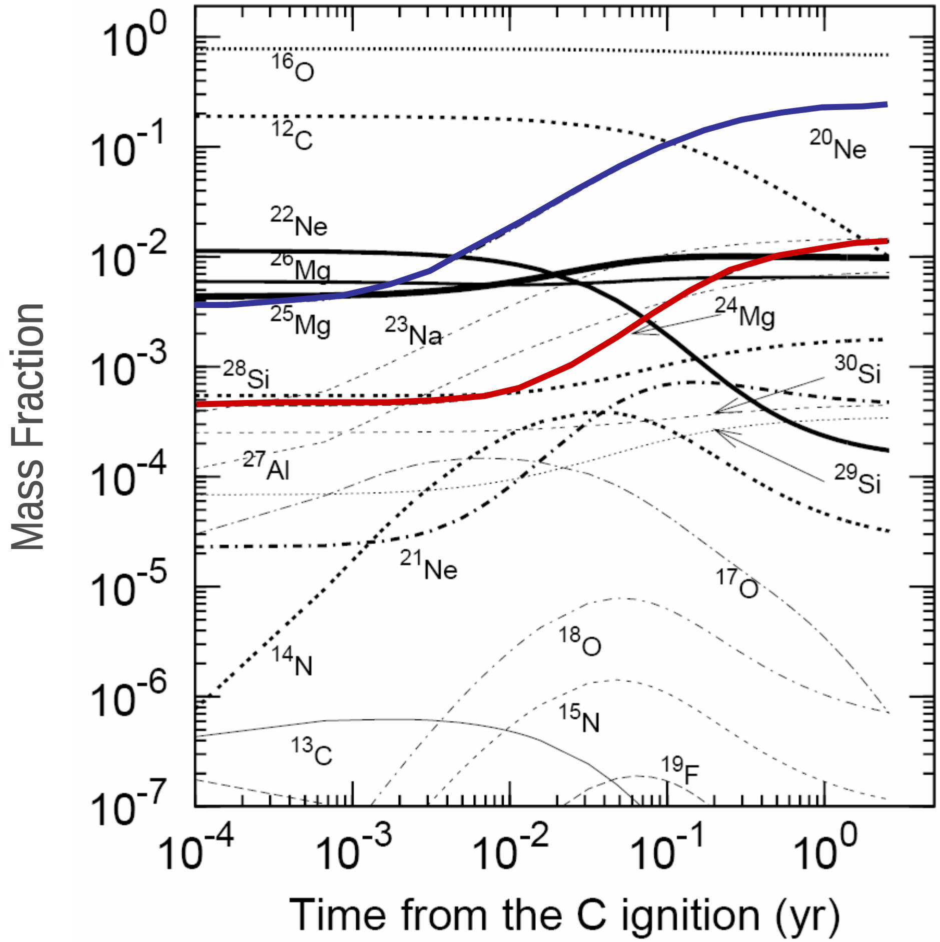
$$^{12}C(p,\gamma)^{13}N \qquad ^{12}C(\alpha,\gamma)^{16}O$$

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

$$^{23}Na(p,\alpha)^{20}Ne \qquad ^{24}Mg(\alpha,\gamma)^{28}Si$$

$$^{17}O(\alpha,n)^{20}Ne \qquad ^{22}Ne(\alpha,n)^{25}Mg$$

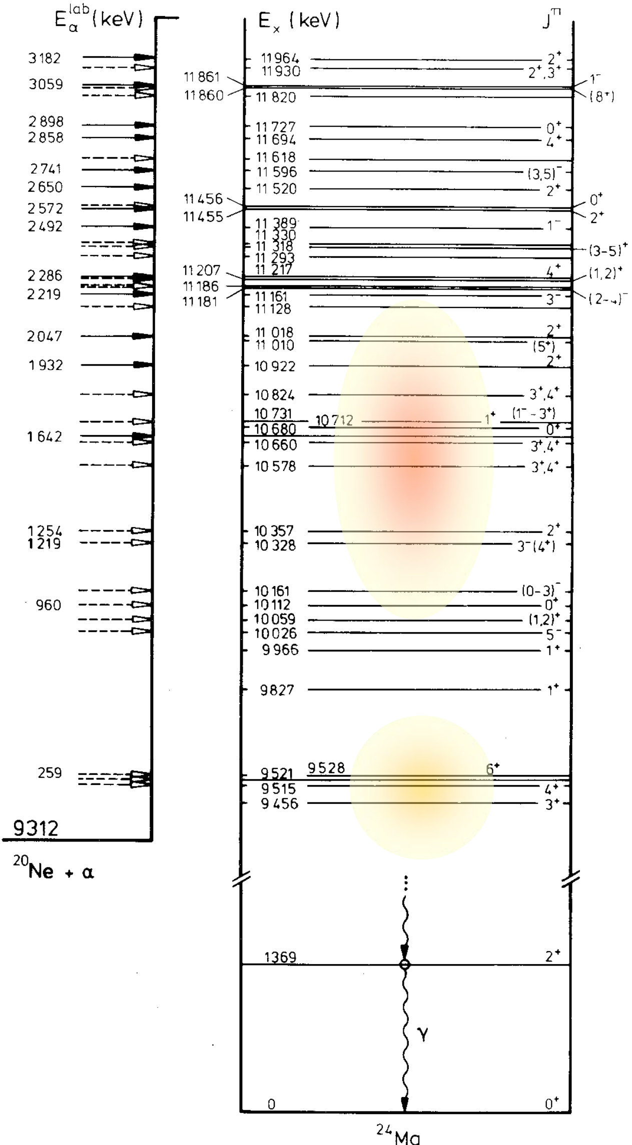
Alpha capture reactions are considerably weaker than proton capture! Subsequent nucleosynthesis depends critically on proton alpha emission associated with single particle/alpha cluster configuration of ^{24}Mg above the ^{12}C+^{12}C threshold.

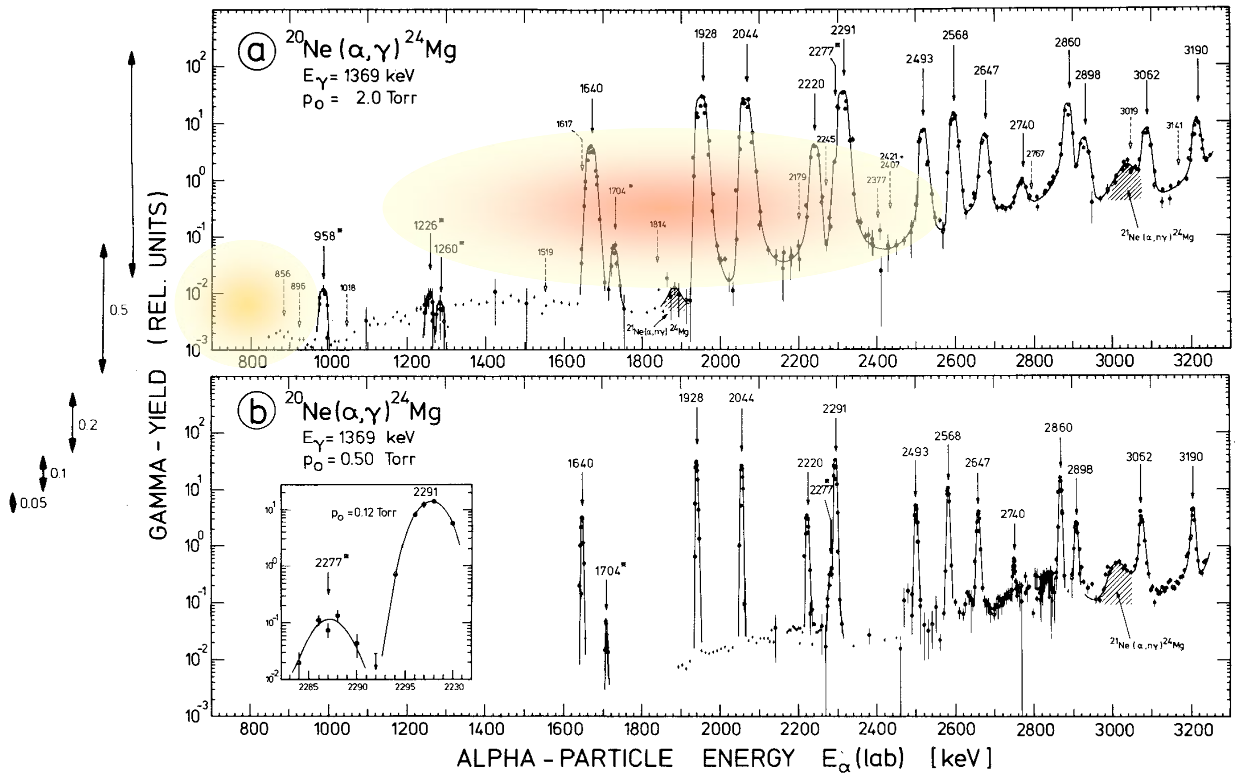


The ^{20}Ne(α,γ)^{24}Mg reaction

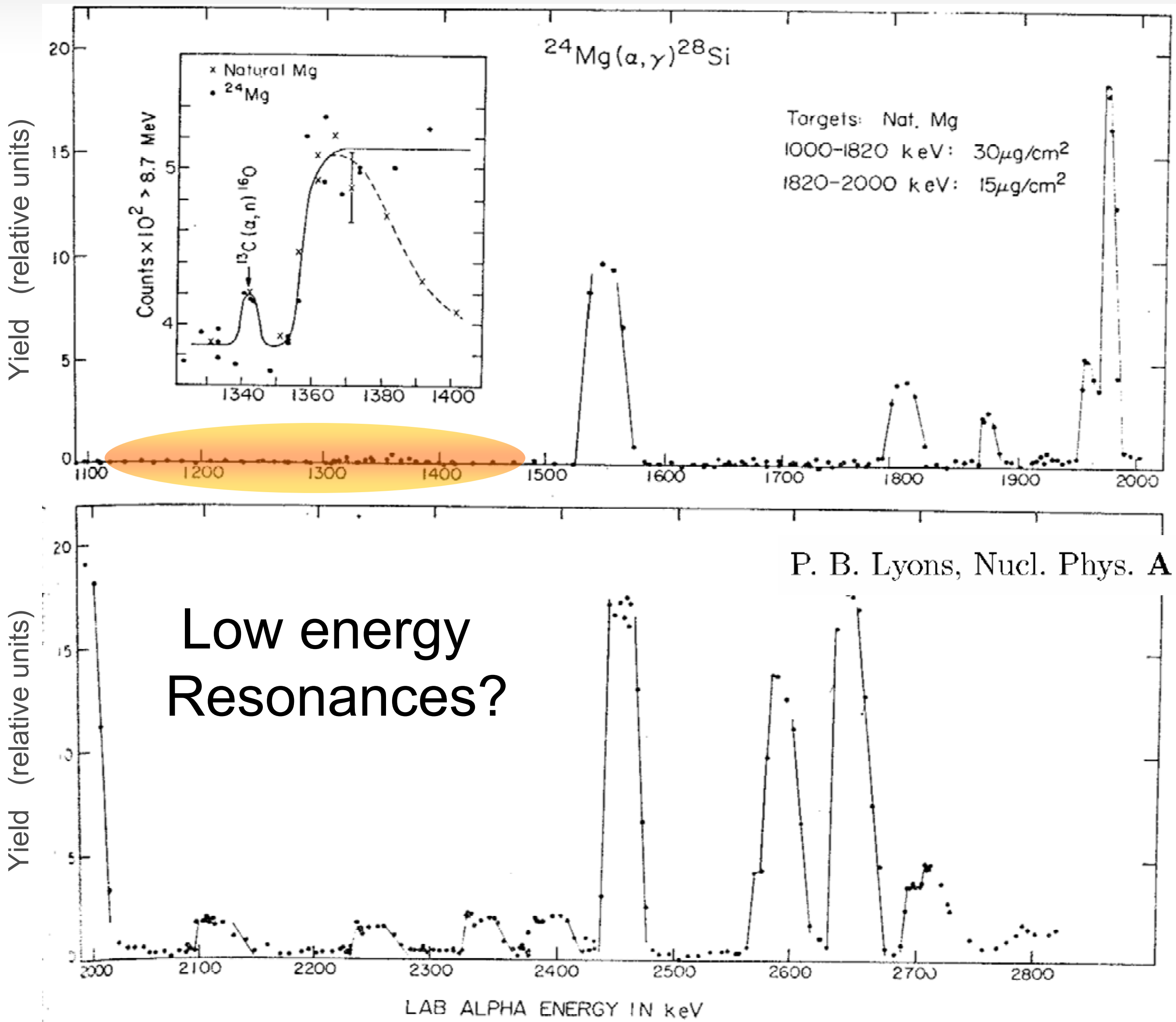
$$E_G = 0.122 \cdot \left(Z_1^2 \cdot Z_1^2 \cdot \mu \cdot T_9^2\right)^{1/3} \left[MeV\right]$$

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



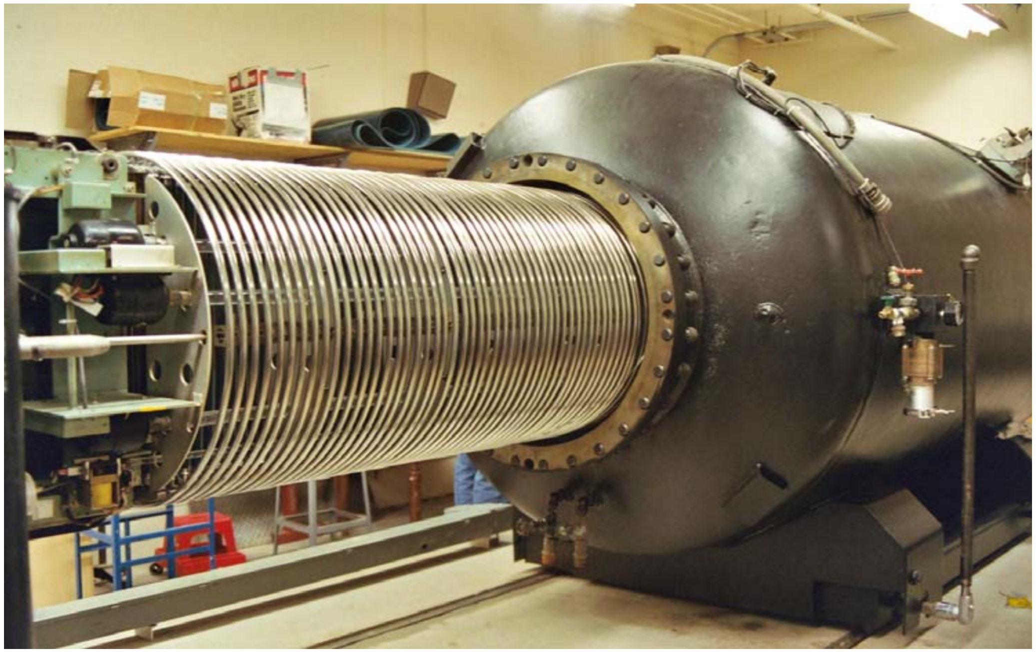


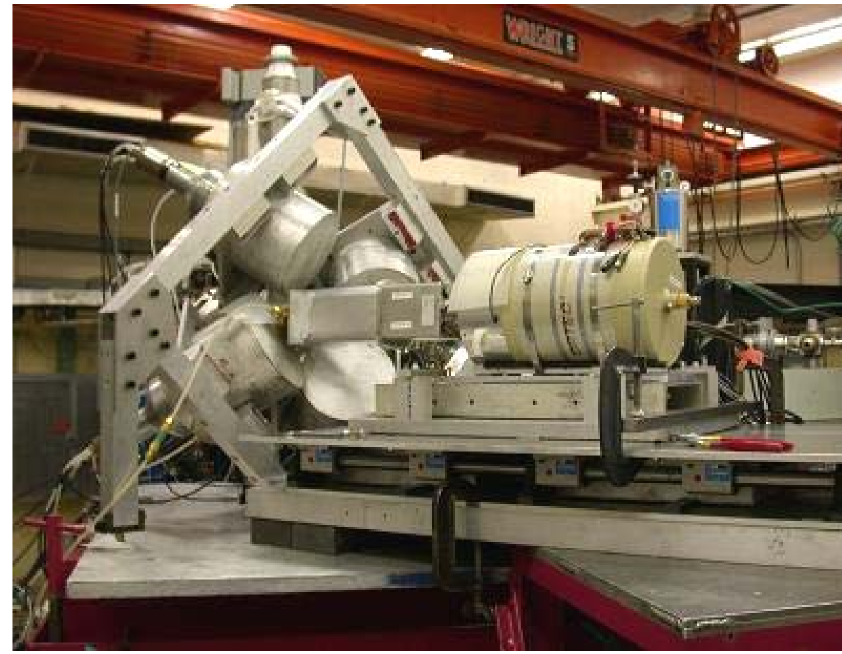
The $^{24}Mg(\alpha,\gamma)^{28}Si$ reaction



P. B. Lyons, Nucl. Phys. **A130**, 25 (1969)

$^{24}Mg(\alpha,\gamma)^{28}Si$ at Notre Dame



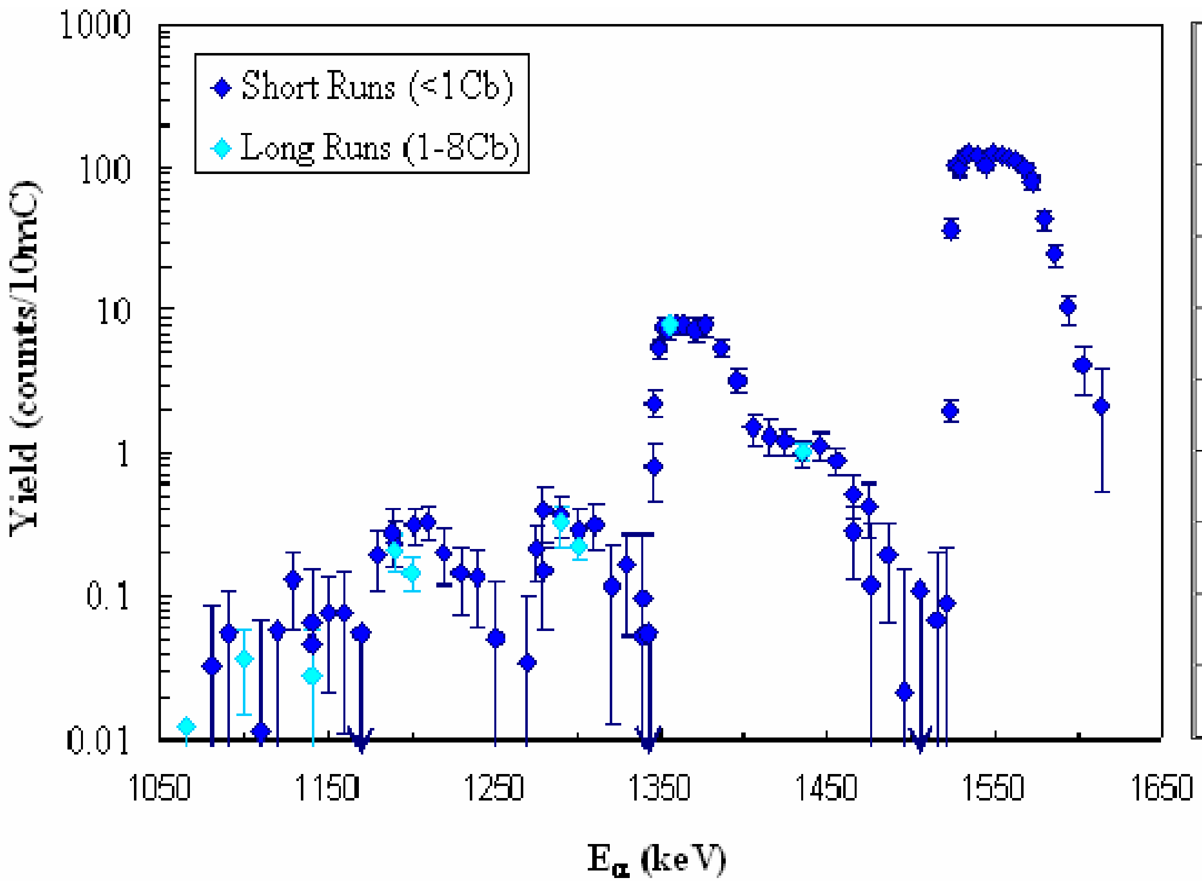


3.5 MV KN VdG accelerator
Beam of 50-150 μA on target

Natural Mg evaporated on Cu backing.
Long runs, with up to 20Cb charge accumulation at low energies

NaI-Ge-Clover array. Active shielding by coincidence requirement between 1.779 MeV ground state transition of 1st excited state in ^{28}Si (Ge) and the primary resonance decays with $E_{\gamma}>2.4$ MeV.

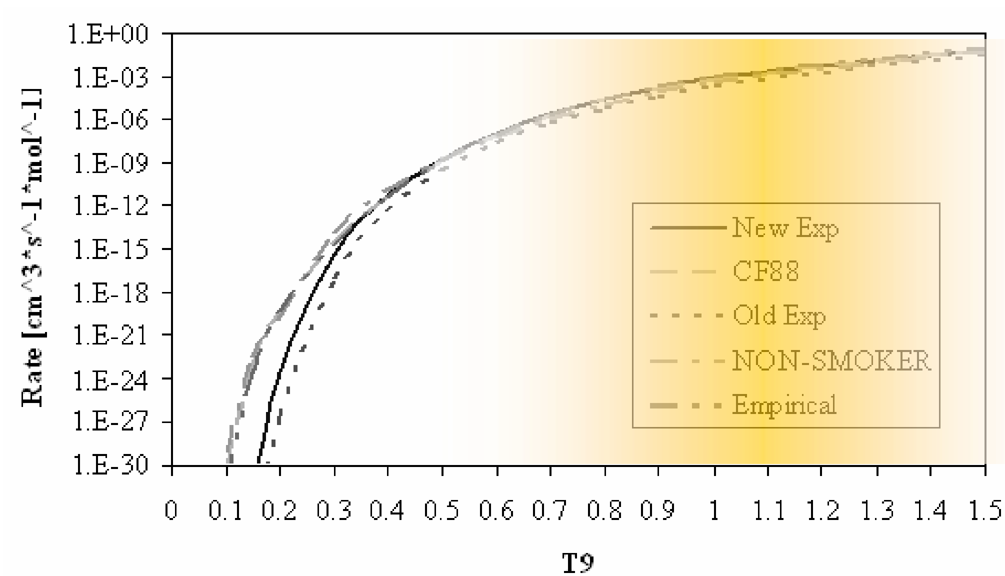
Thick Target Yield and Resonance Strength



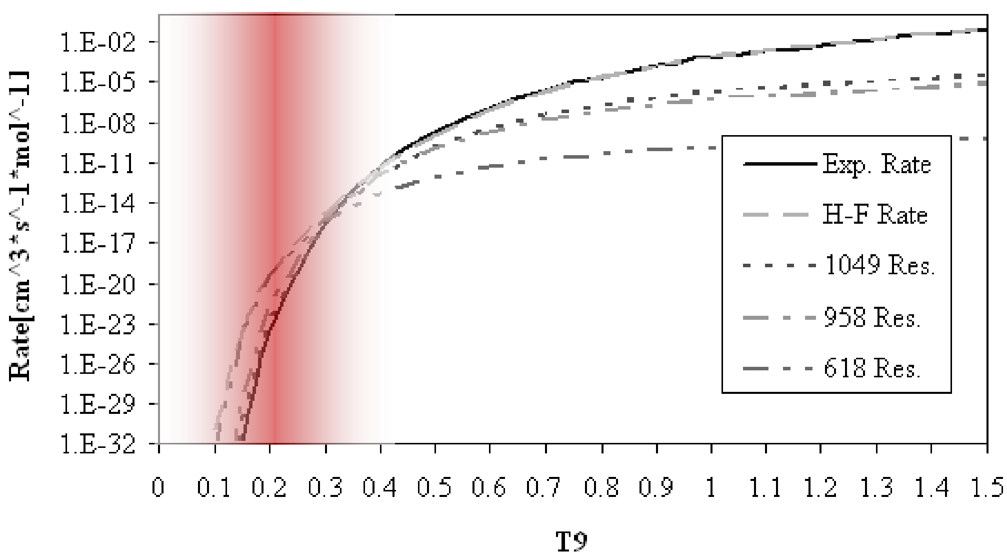
E_R (keV)	$\omega\gamma$–this experiment (meV)	$\omega\gamma$–previous value (meV)
1530	94 ± 14	110 ± 20
1413	0.21 ± 0.04	—
1351	1.9 ± 0.3	1.9 ± 0.6
1277	0.058 ± 0.011	—
1178	0.22 ± 0.06	—
1120/1130	<0.016	—
1087	<0.014	—
<1060	<0.002	—

New low energy resonances found, but considerable uncertainties remain!

Reaction Rate

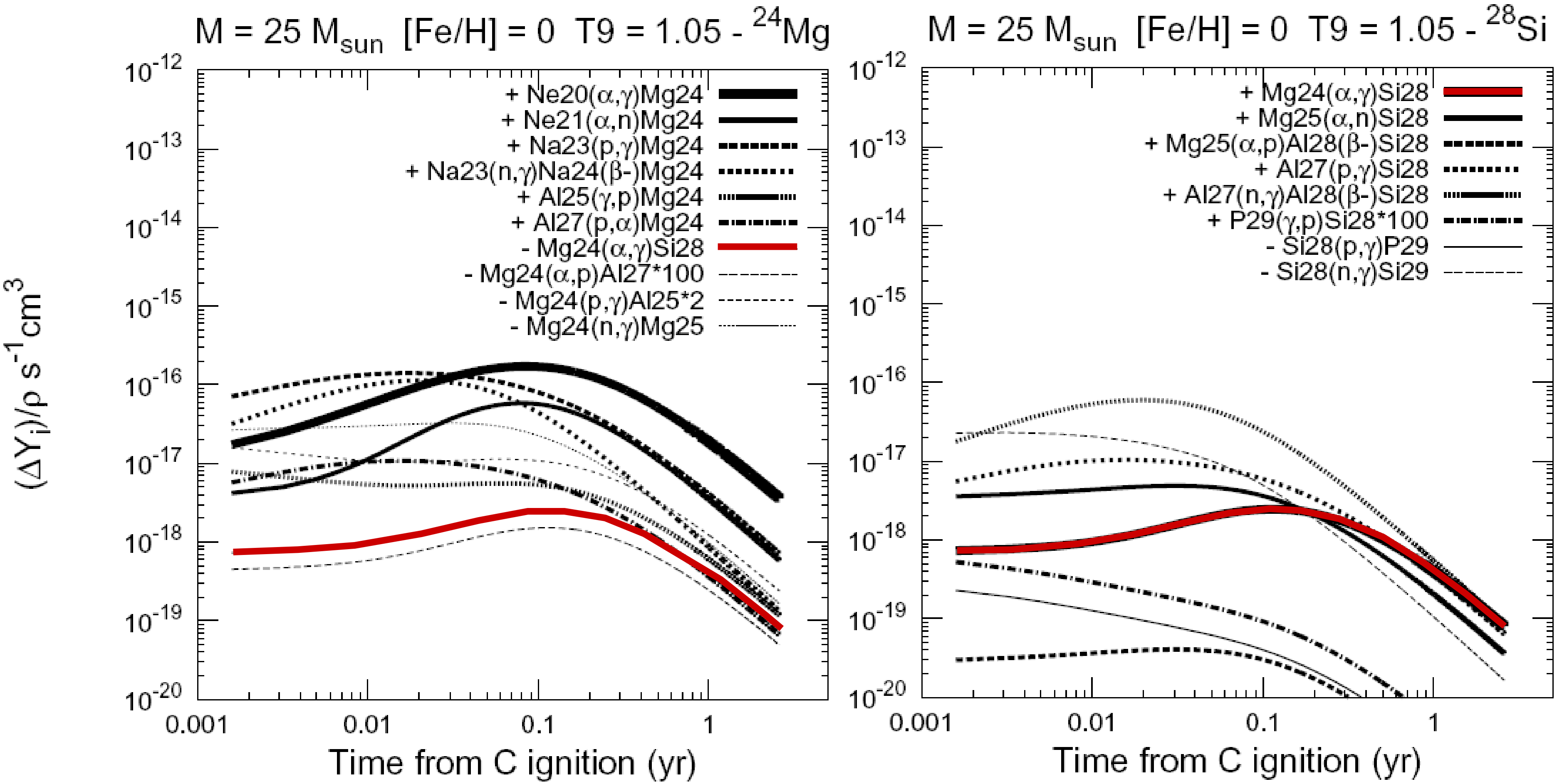


Experimental results indicate a slight enhancement of the rate in the temperature range of stellar carbon burning of ~0.8-1.5GK.



Estimated contributions of lower energy resonances (based on known natural parity states in ^{28}Si) indicate an enhancement of the rate in comparison to Hauser-Feshbach predictions at typical temperatures of stellar He burning.

Total flux for reactions forming or depleting ^{24}Mg, forming ^{28}Si in shell carbon burning

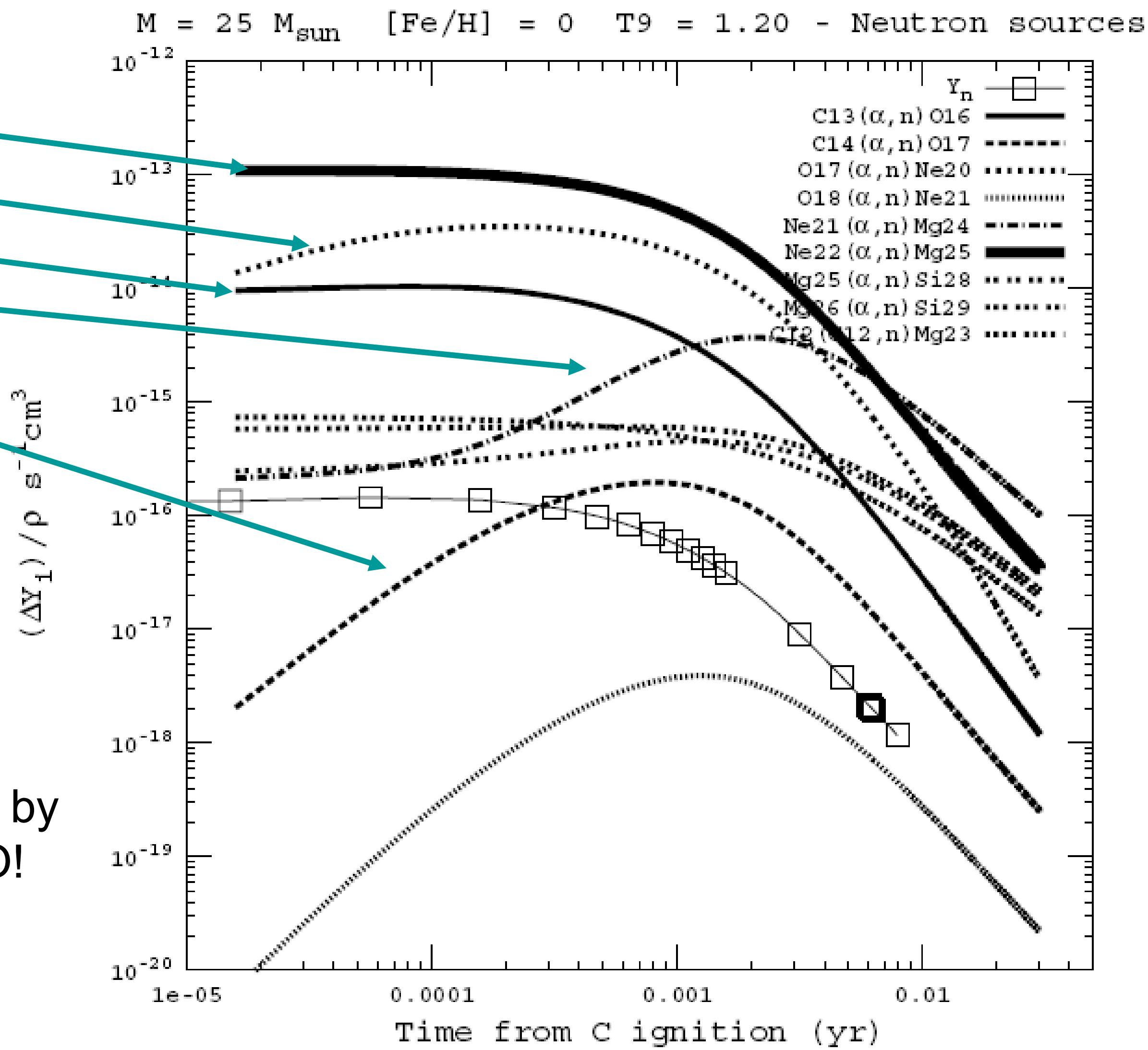


Strongest ^{24}Mg depletion reaction is ^{24}Mg(n,γ)^{25}Mg

Strongest ^{28}Si production is ^{24}Mg(α,γ) & ^{25}Mg(α,n)^{28}Si

On-site neutron production by (α,n) reactions

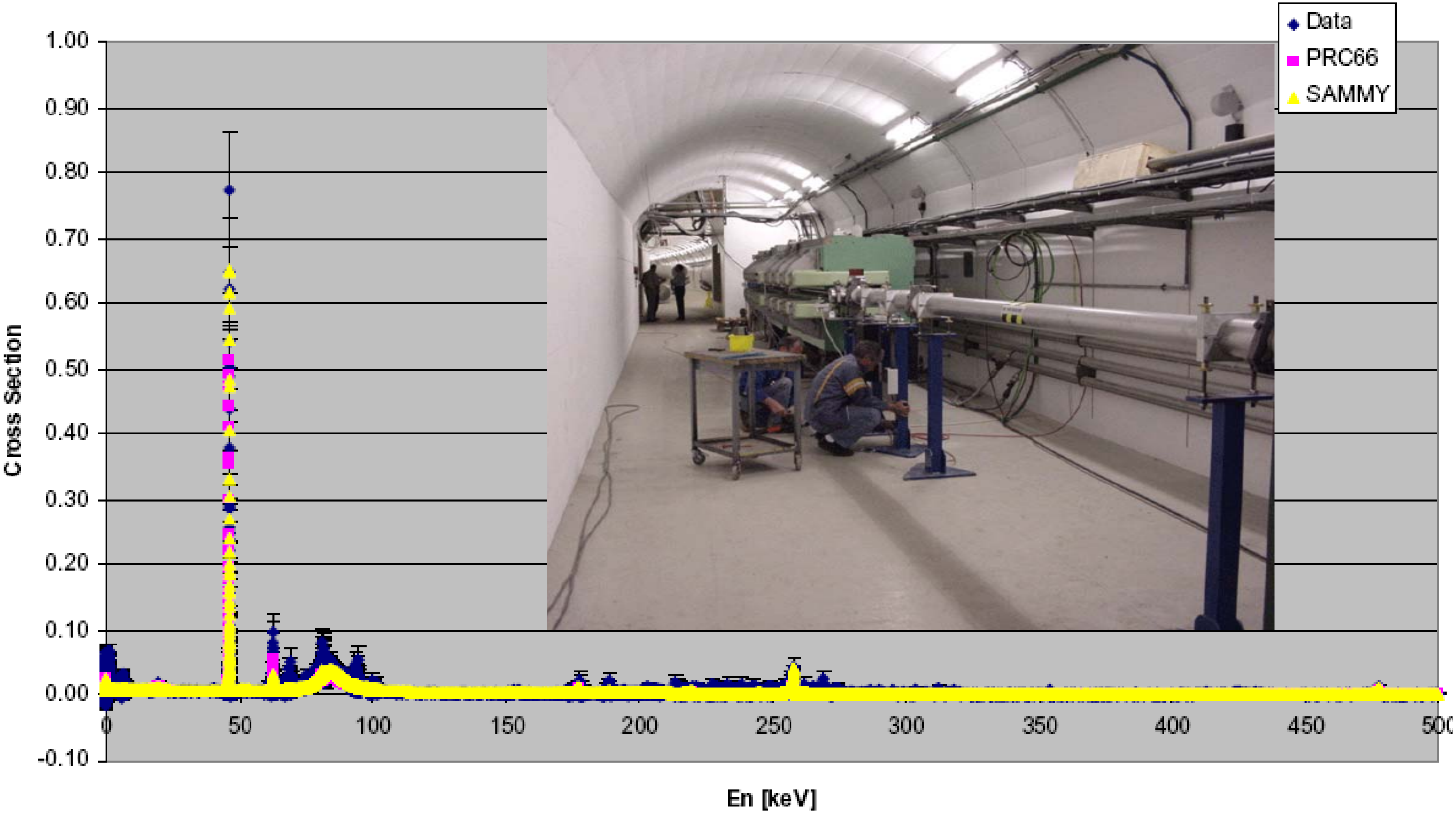
^{22}Ne(α,n)
^{17}O(α,n)
^{13}C(α,n)
^{21}Ne(α,n)
^{14}C(α,n)



^{13}C, ^{17}O, ^{21}Ne, ^{22}Ne are the main neutron sources!

- ^{22}Ne is left over from preceding He burning!
- ^{13}C, ^{17}O are produced on site by proton capture on ^{12}C and ^{16}O!
- ^{21}Ne is produced by alpha capture sequence on ^{14}N

$^{24}Mg(n,\gamma)^{25}Mg$ branch

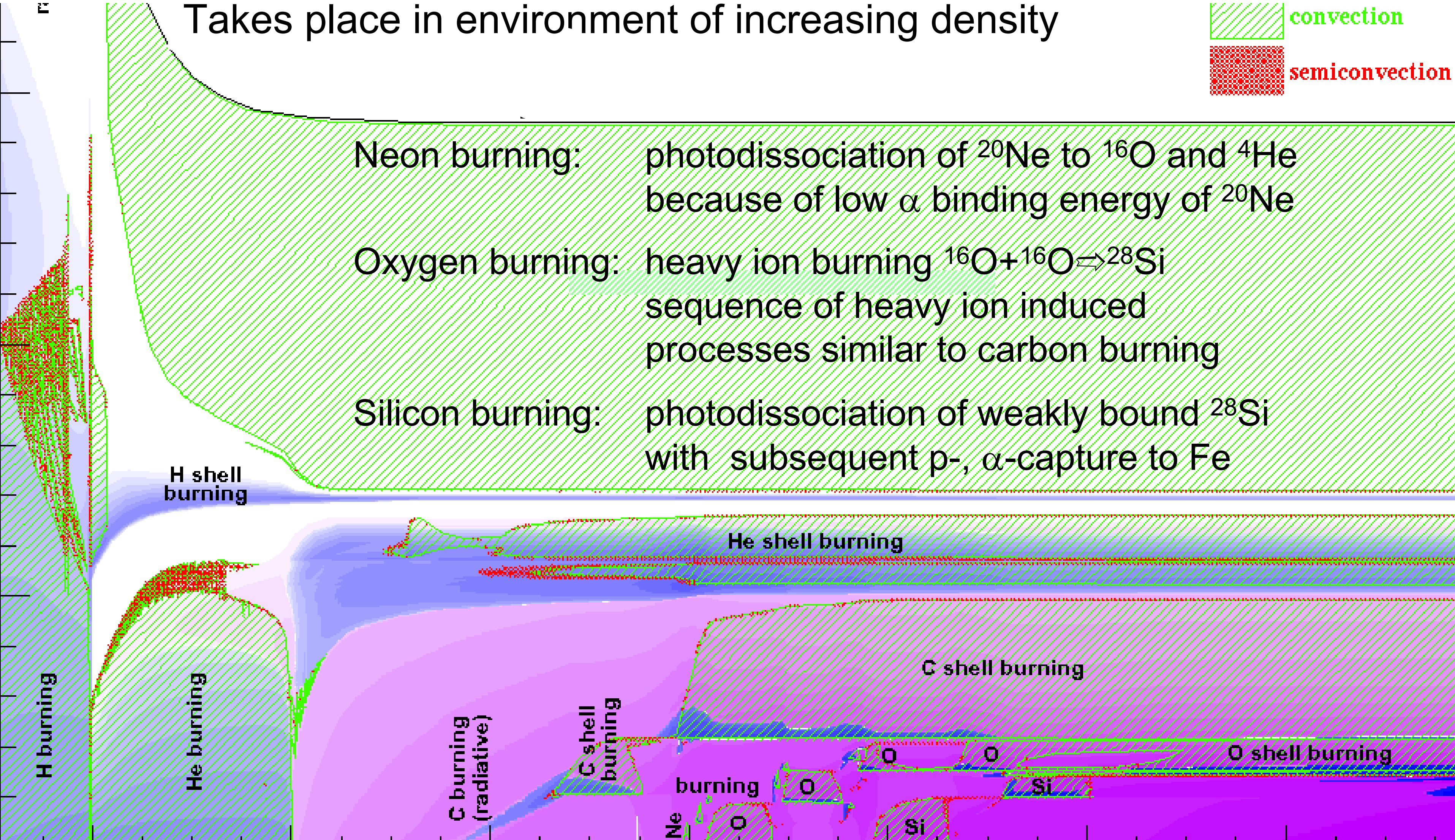


Recent n_ToF experiment yielded higher resonance strength.

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 ^{20}Ne ((α,γ)-(γ,α)-equilibrium?) and subsequent α capture induced nucleosynthesis along the T=0 line. (α-cluster structure effects)

Oxygen burning

temperature at T ≈ 2 GK; Gamow range at $E_G \approx 6\pm2$ MeV

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

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

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

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

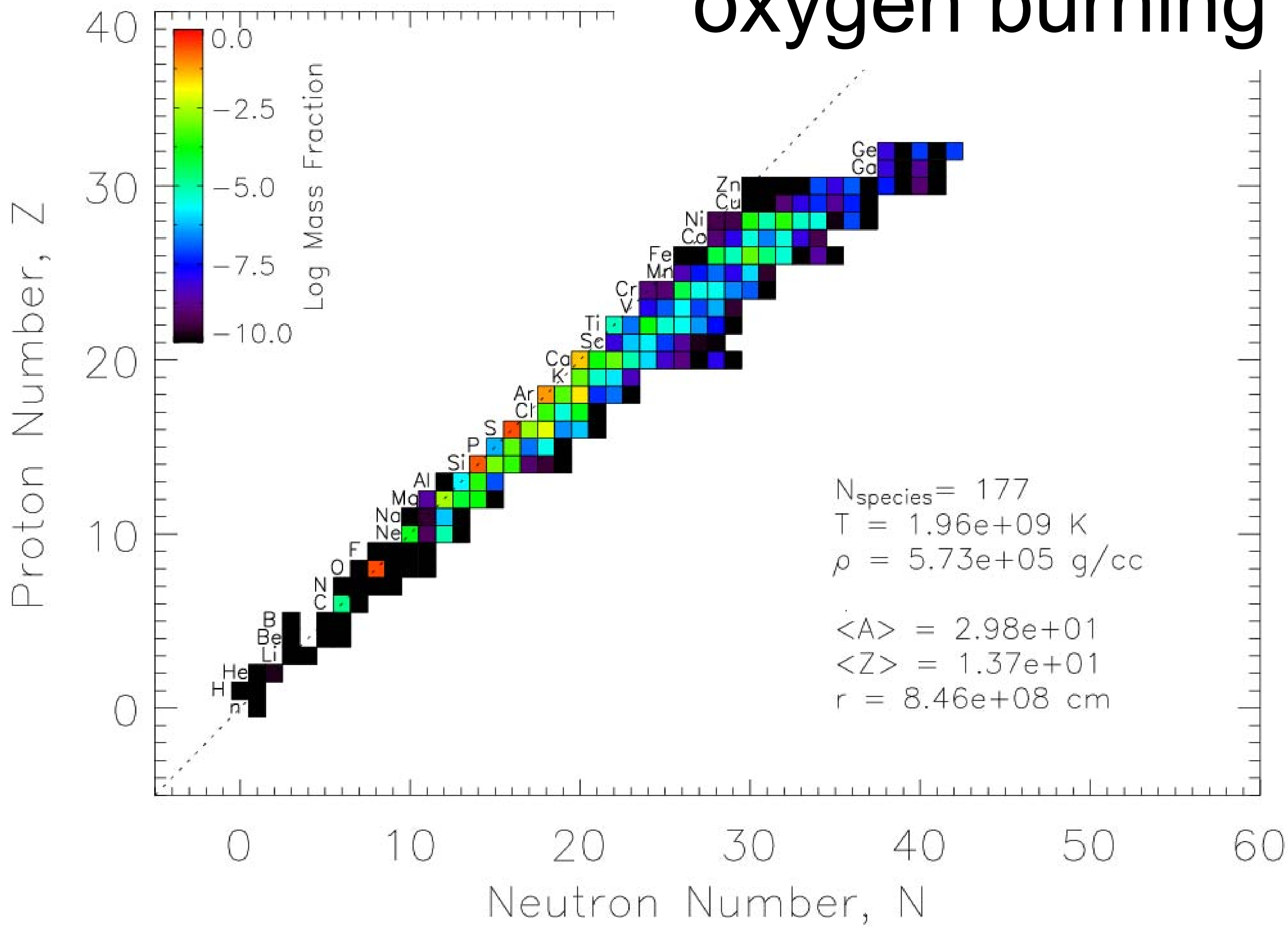
$$^{28}Si(\alpha,\gamma)^{32}S \quad Q = 6.771\,MeV$$

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

$$^{28}Si(n,\gamma)^{29}Si \quad Q = 8.641\,MeV$$

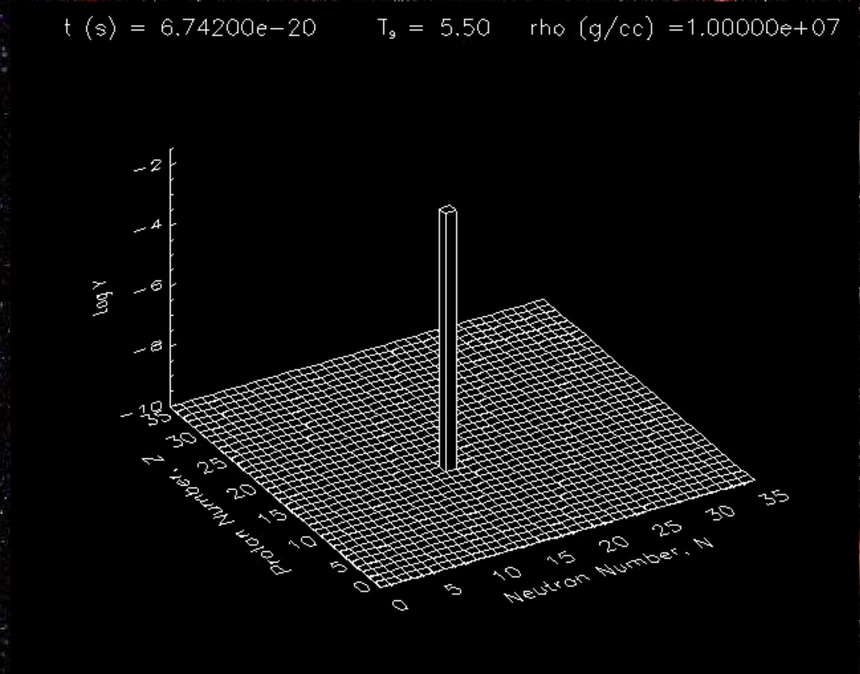
Like in carbon burning, release on protons, alphas, and neutrons which change abundance conditions through subsequent capture processes at high energies ⇨ enrichment in ^{28}Si because of a presumably weak $^{28}Si(\alpha,\gamma)^{32}S$ reaction rate.

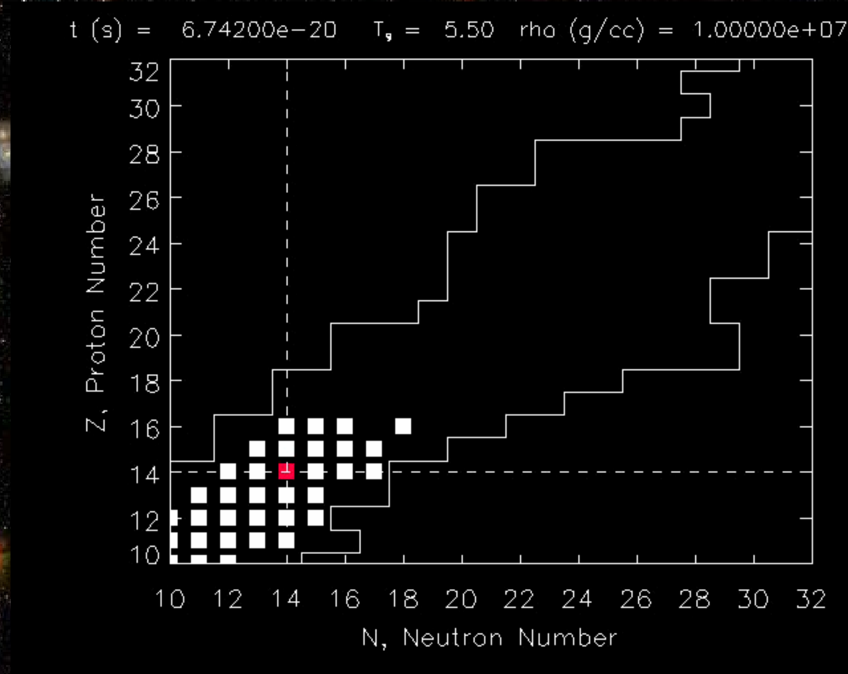
Abundance distribution after stellar oxygen burning



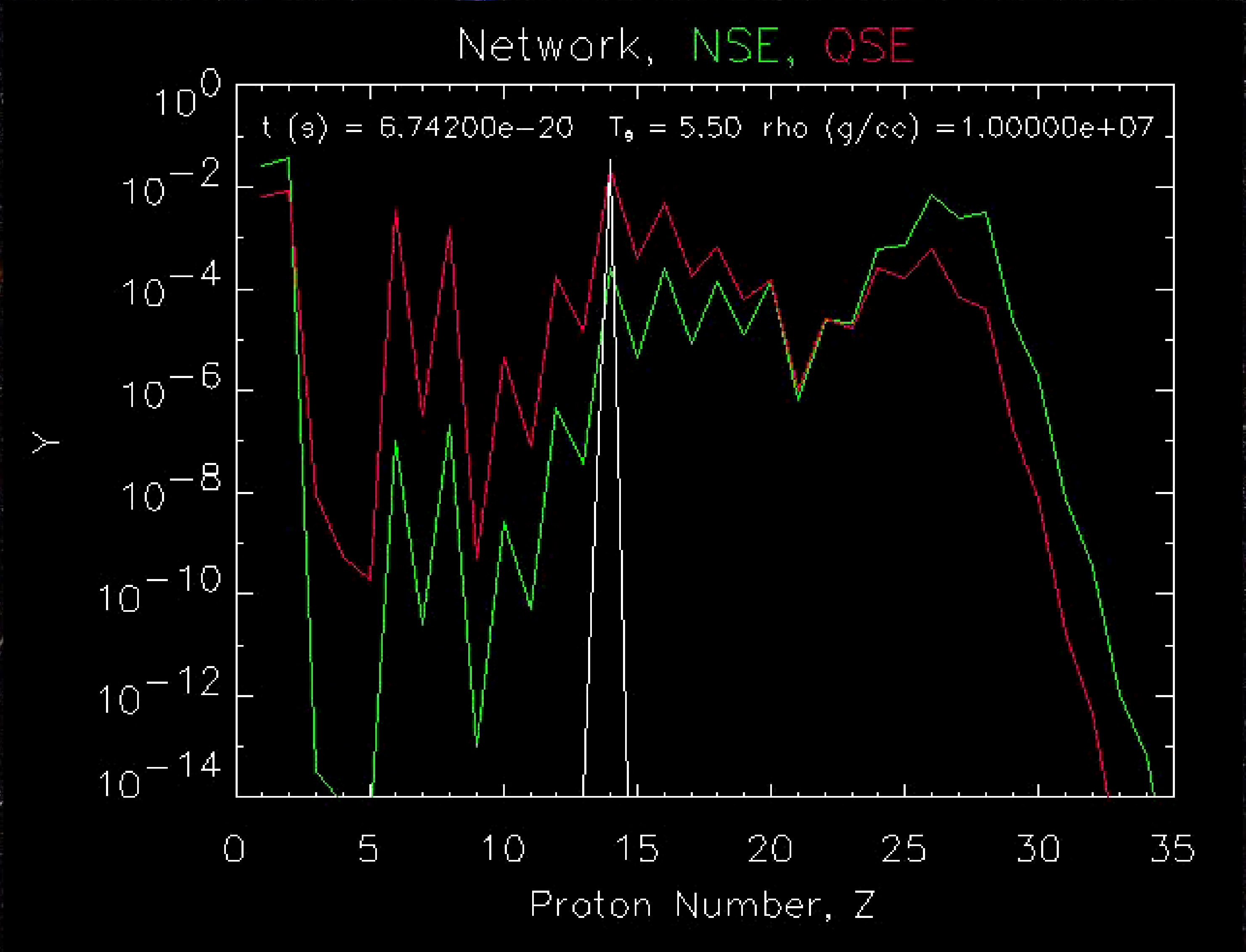
Si-burning

Photodissociation of ^{28}Si with subsequent build-up of heavy elements up to iron in statistical equilibrium
All reactions are balanced and the rates cancel out!

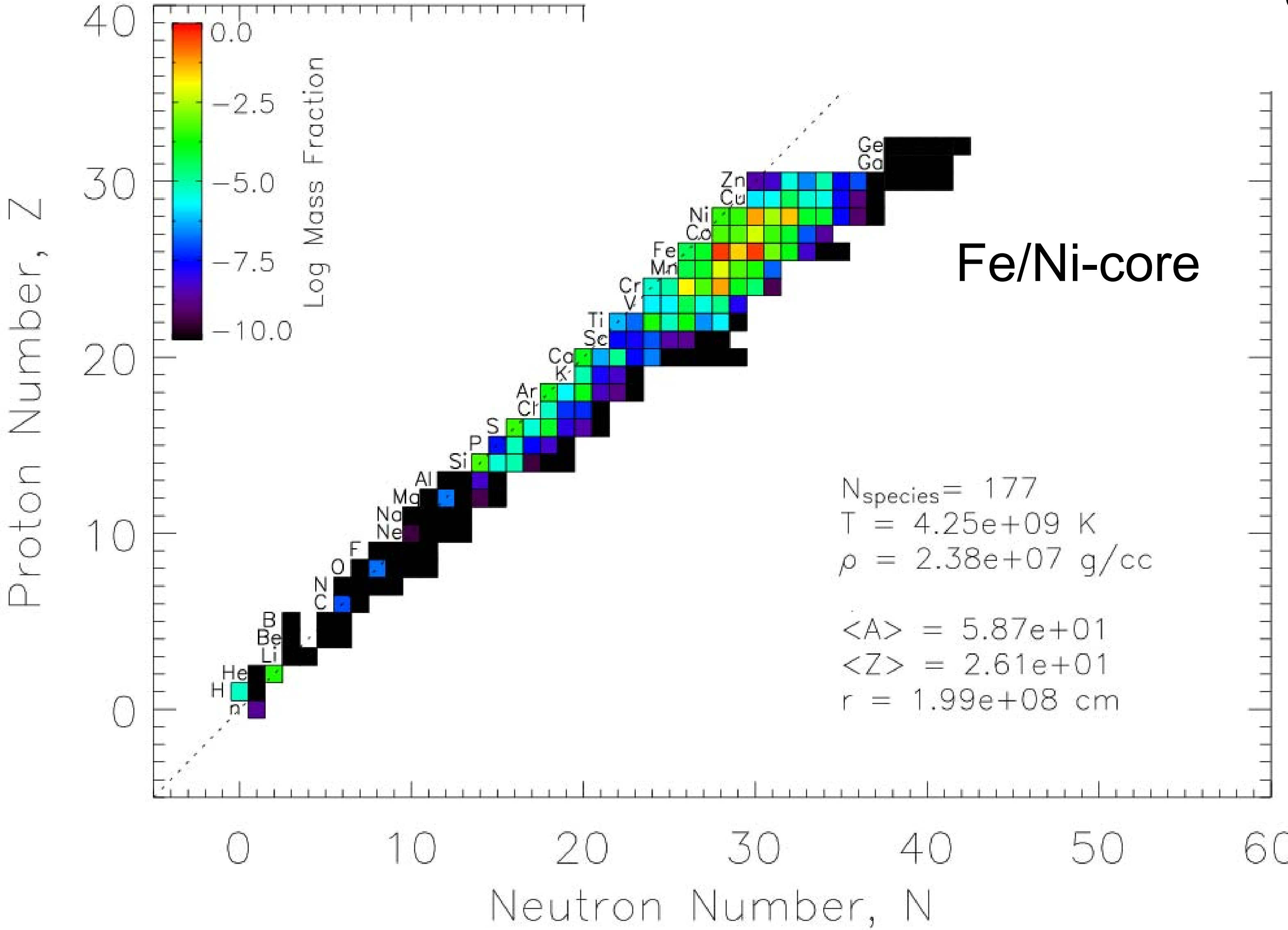




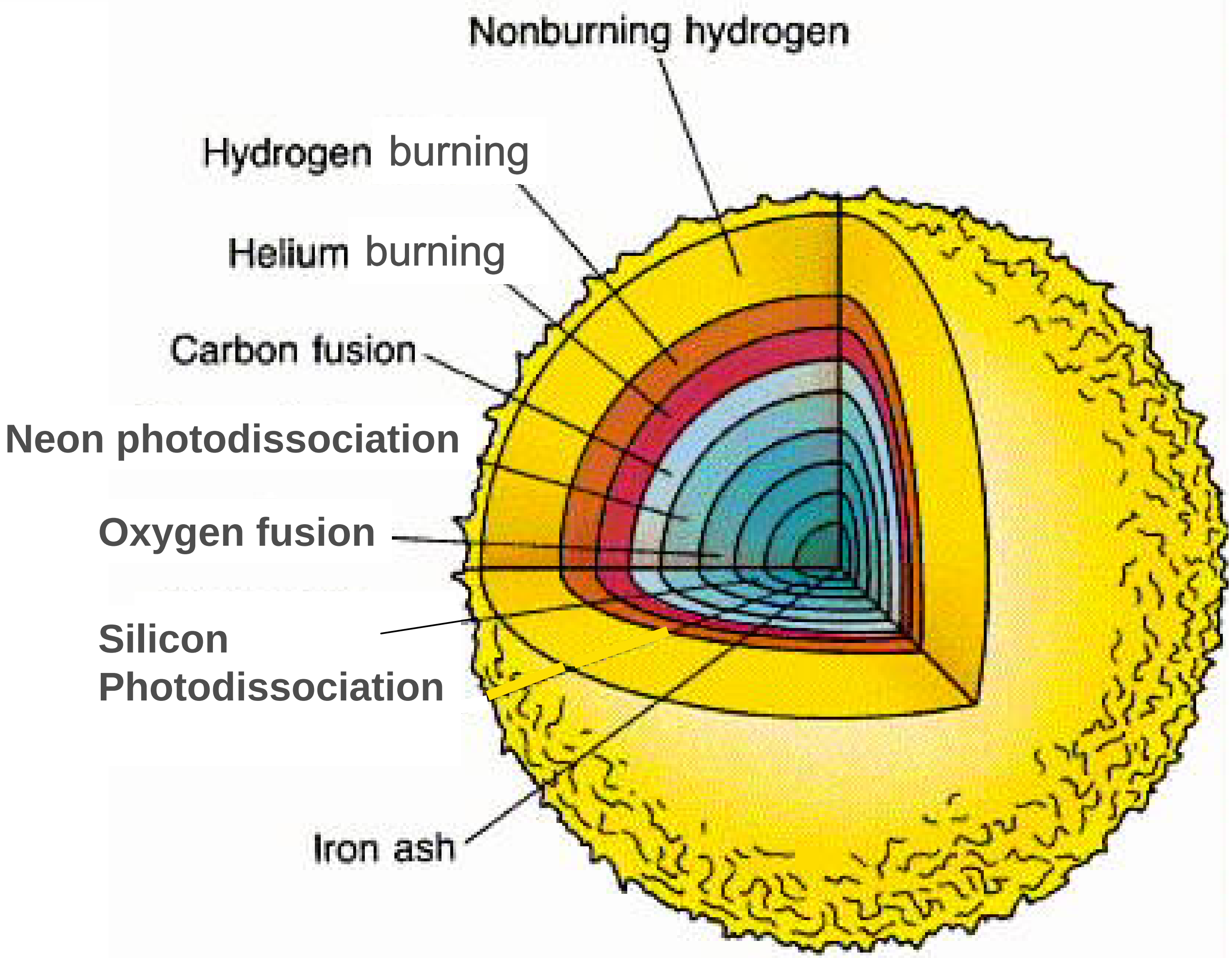
Si burning abundance evolution



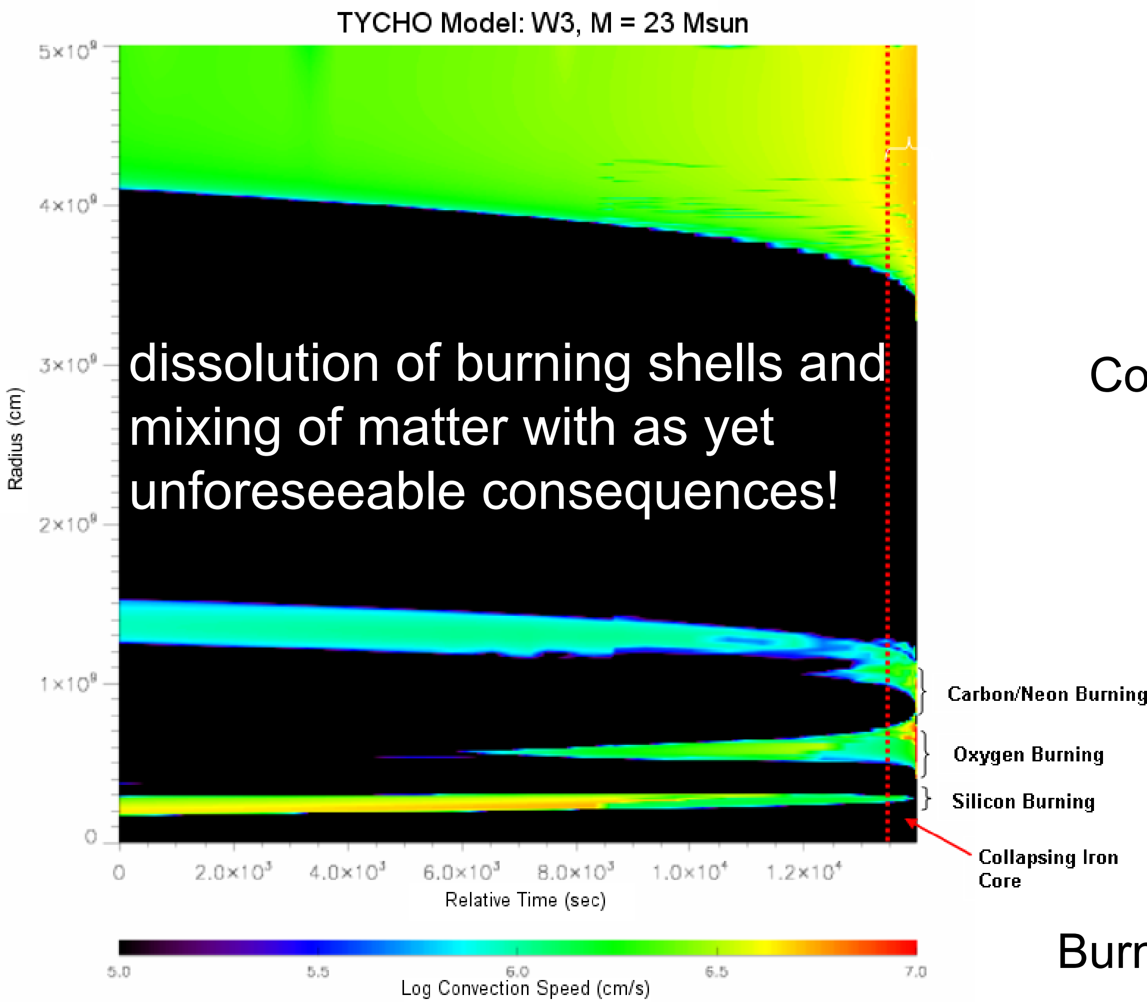
Abundance distribution in core after stellar Si-burning

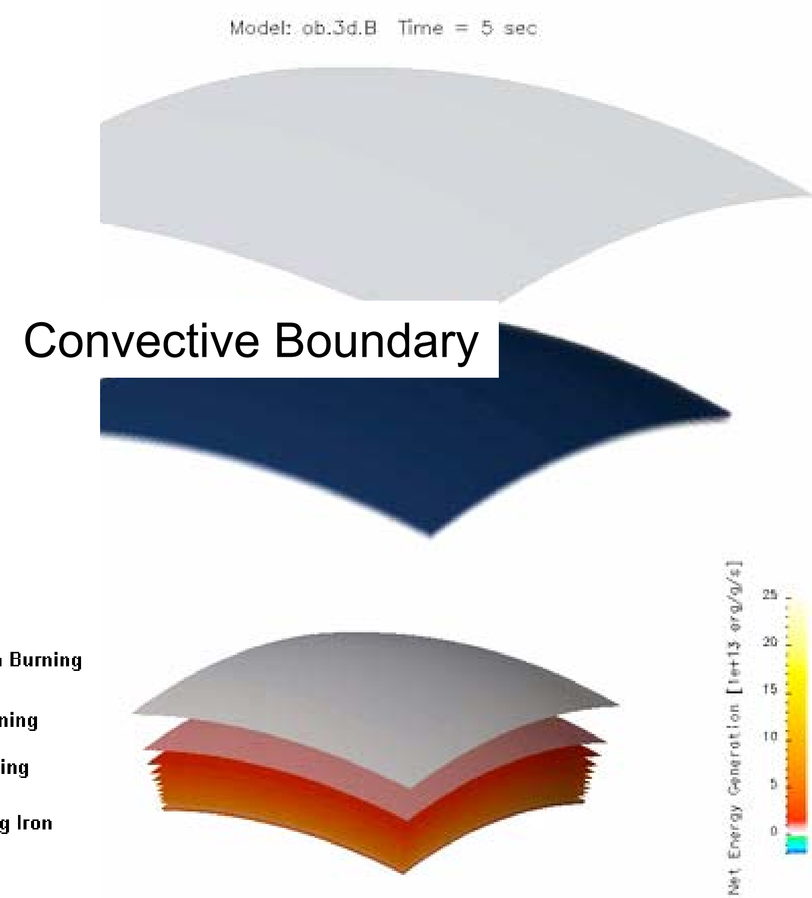


The stellar Onion Model



The last Days of Stellar Burning

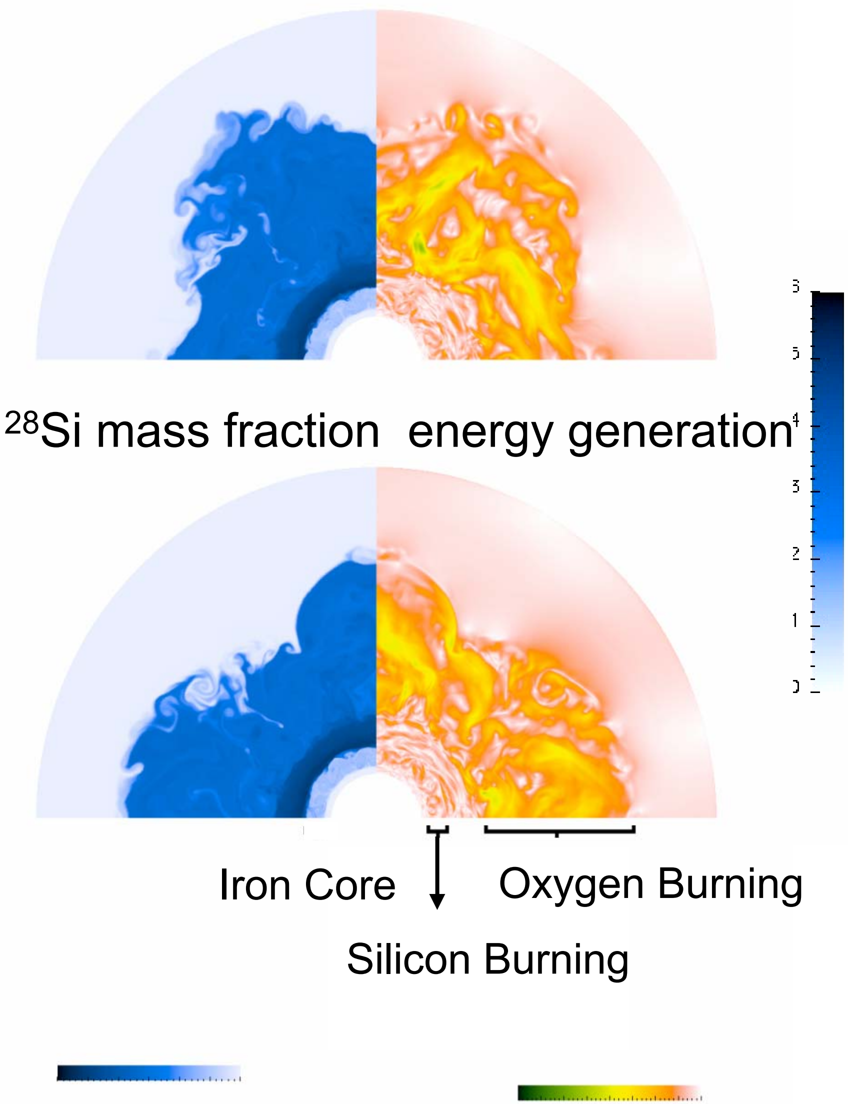




Burning Zones

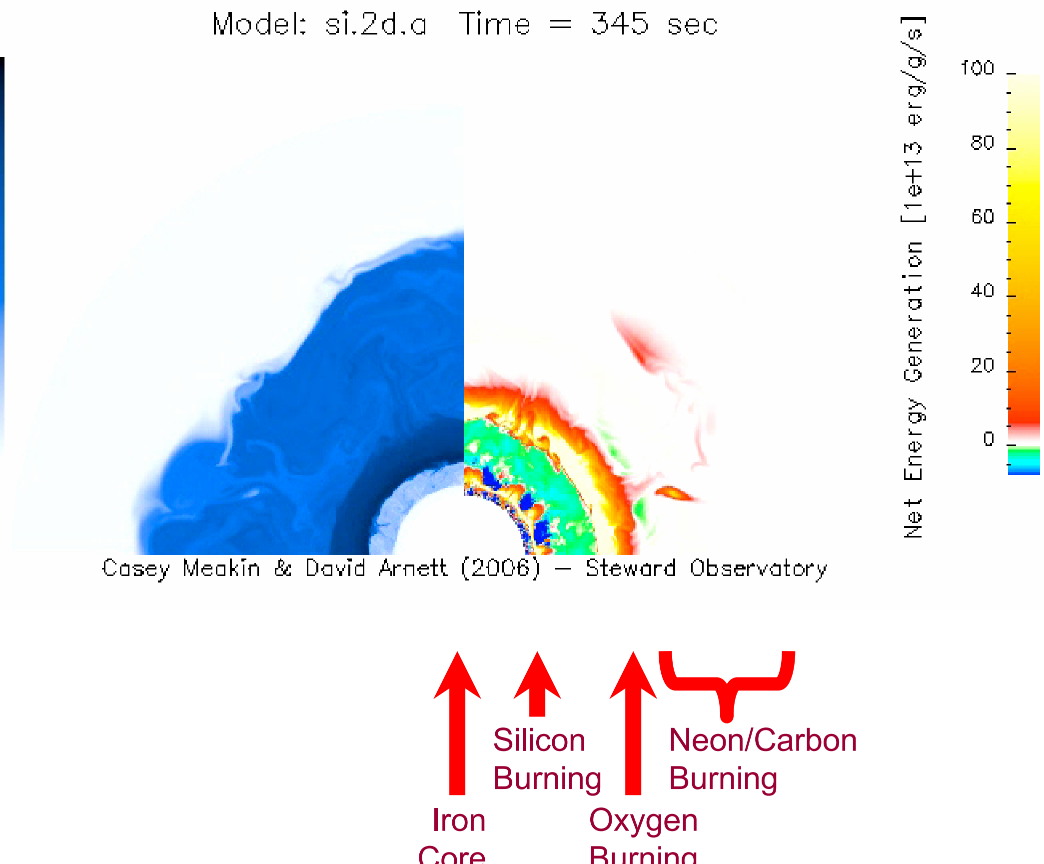
Dave Arnett; Santa Barbara, “The last Days of Burning”
http://www.jinaweb.org/events/ucsb06/talks_SB06.html

Shell Burning and Shell Mixing

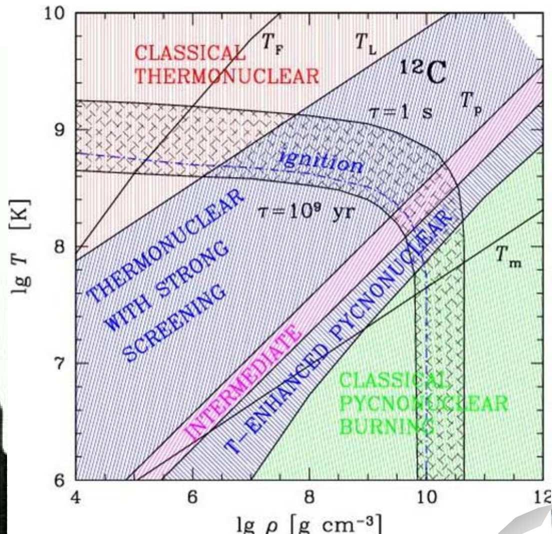


Casey Meakin & David Arnett (2006)

Shell burning takes places in moving blobs of material, rather than in well defined shells.



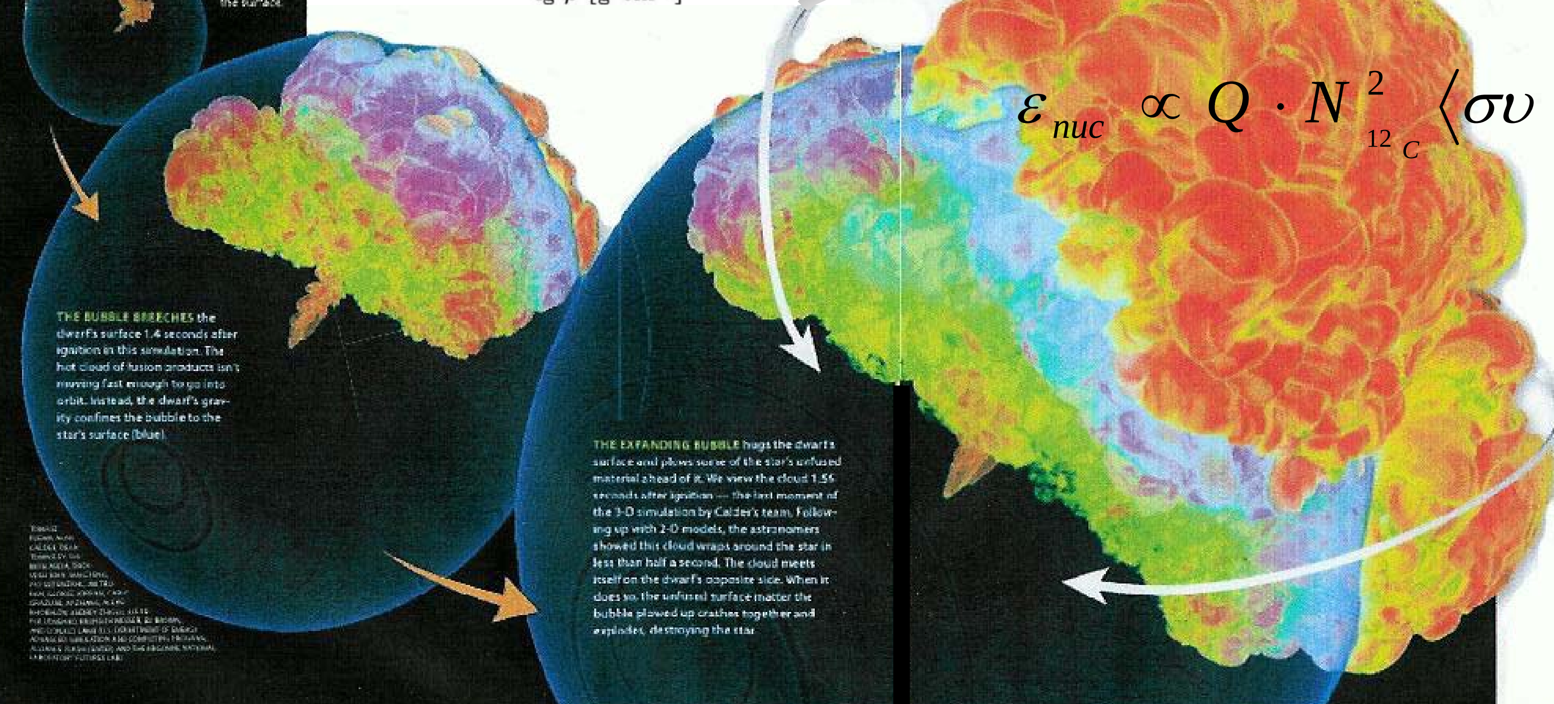
White Dwarf Matter and Type I SN Ignition



Carbon ignition occurs when fusion induced energy production becomes larger than neutrino cooling.

$$\left(\frac{\partial \varepsilon_{nuc}}{\partial T}\right)_P - \left(\frac{\partial \varepsilon_{cool}}{\partial T}\right)_P \geq 0$$

$$\varepsilon_{nuc} \propto Q \cdot N^2_{^{12}C} \langle \sigma \upsilon \rangle \qquad \varepsilon_{cool} \approx \varepsilon_\nu$$

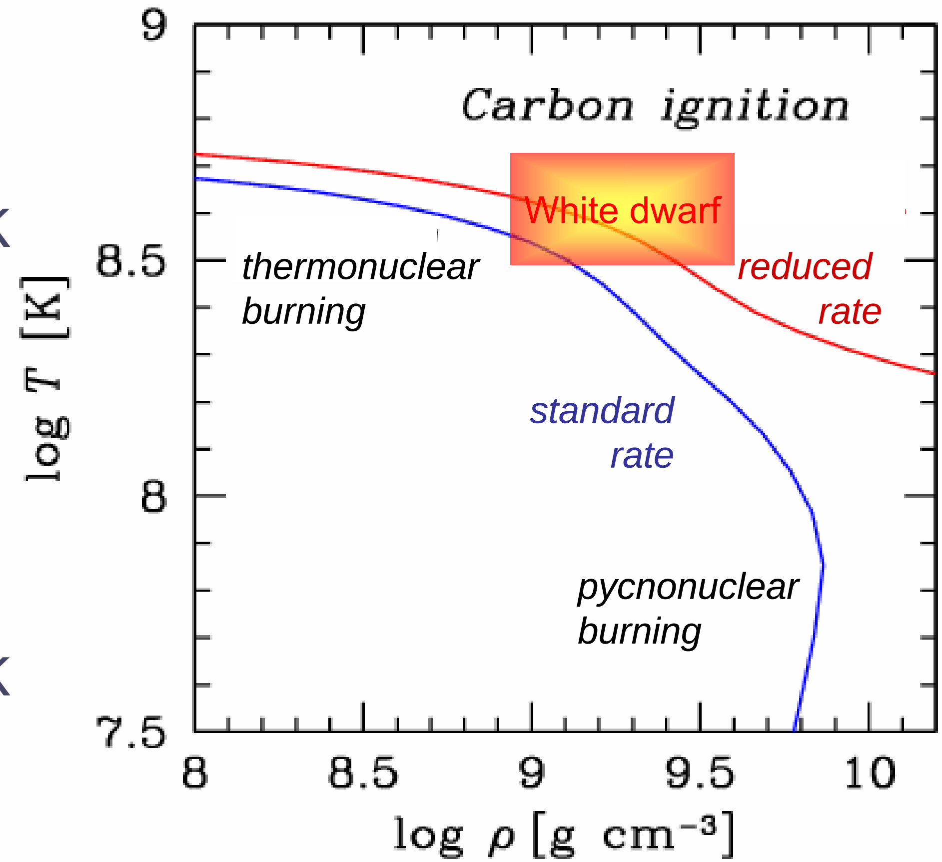
Gasques et al.
PRC 2007 in print

Consequences for type I SN ignition

ignition conditions in white dwarfs based on the $^{12}C+^{12}C$ "standard" rate are:
$\rho \approx 2\cdot10^9$ g/cm^3 and $T \approx 3\cdot10^8$ K

Reduction in rate reduces energy production ε_{nuc}

$\Rightarrow$higher temperature and/or density for ignition:
$\rho \approx 2\cdot10^9$ g/cm^3 and $T \approx 4\cdot10^8$ K



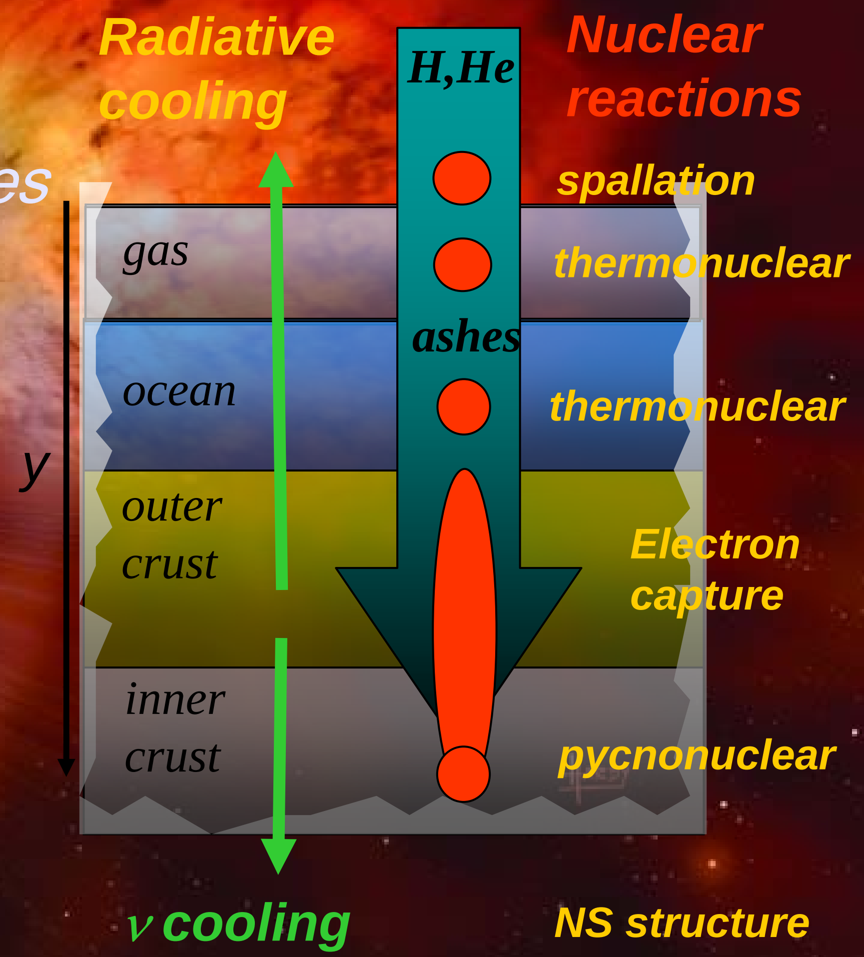
More realistic model simulations required!

Gasques et al. PRC 2007 in print

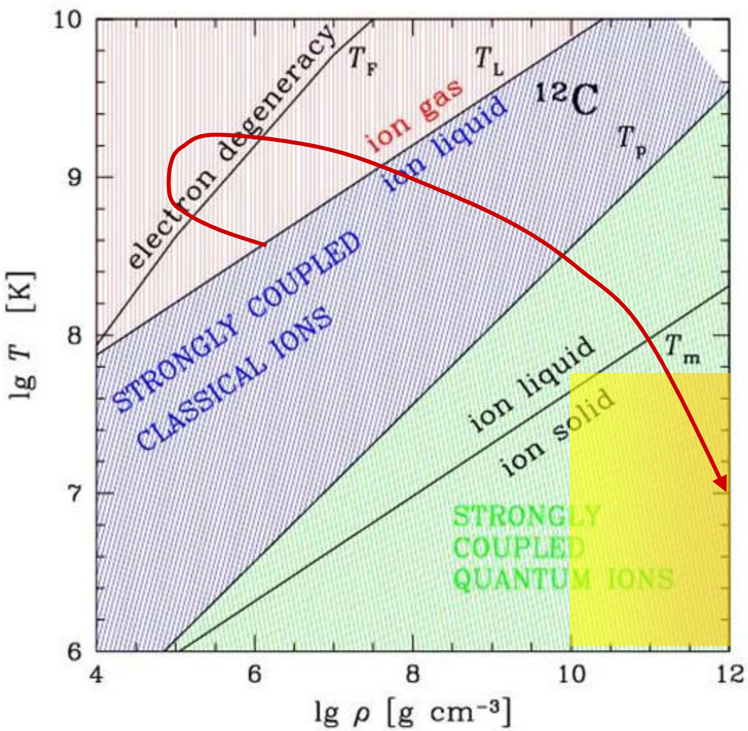
Accretion induced Reactions

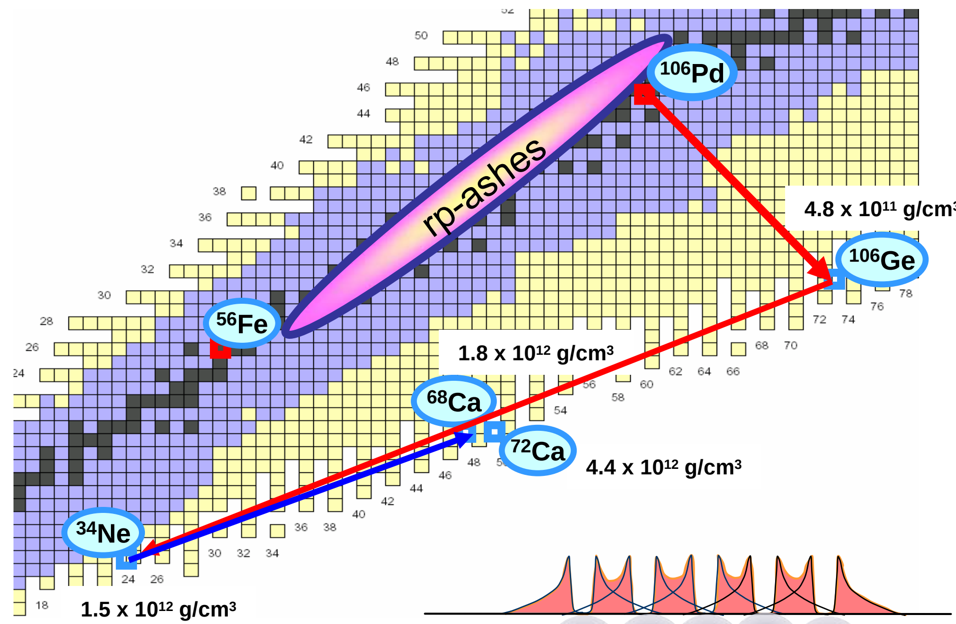
Nuclear fuel feeding into a hot & dense stellar environment

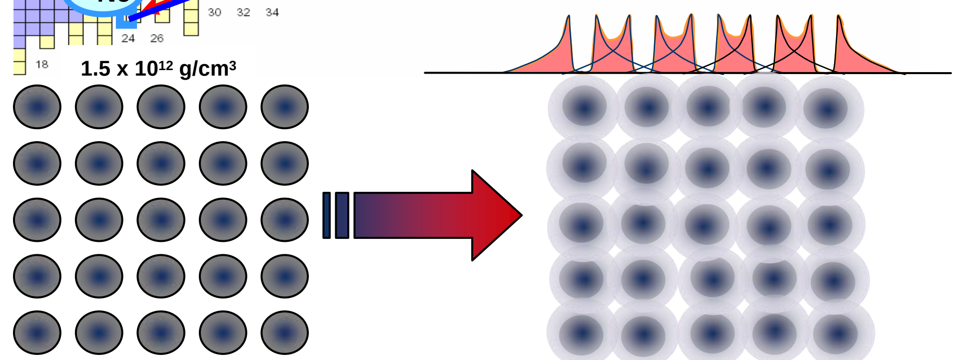
⇒ ignition conditions as function of energy production & energy loss rates



Pycnonuclear Burning





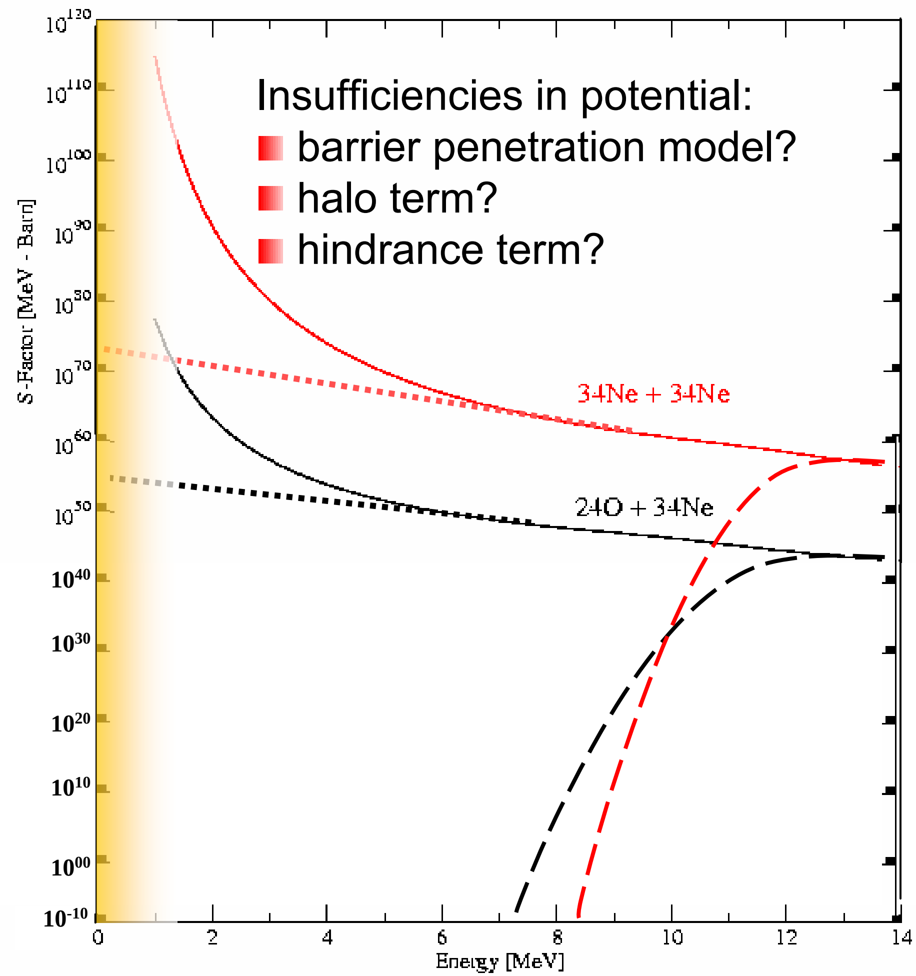


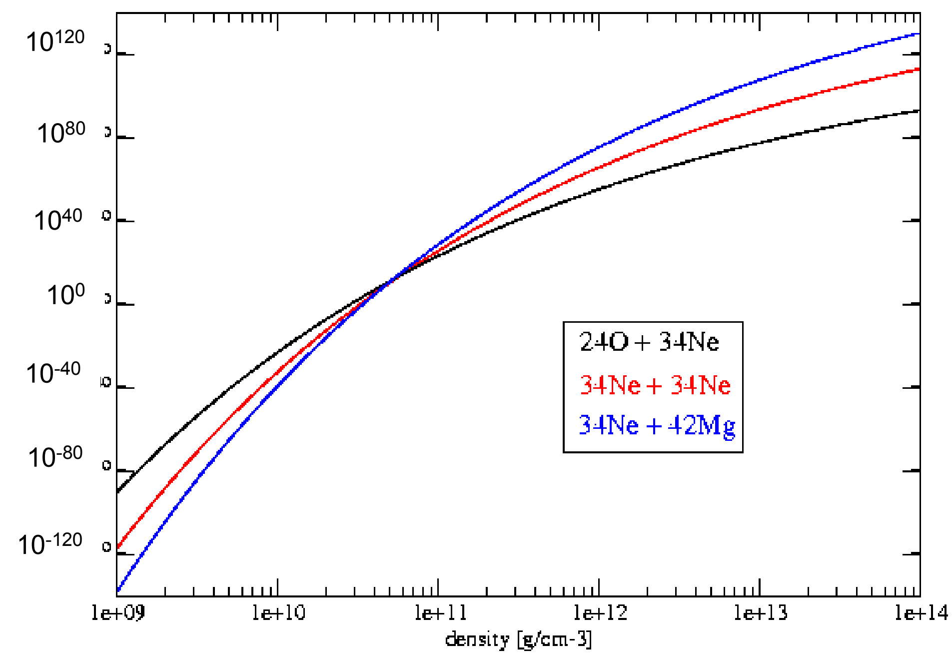
$$R_{pycno} = \left(\frac{\rho}{A}\right) \cdot A^2 \cdot Z^4 \cdot S \;\; [MeV \cdot b] \cdot 4.76 \cdot 10^{46} \cdot \lambda^{7/4} \cdot e^{-2.52/\sqrt{\lambda}} \qquad [s^{-1} cm^{-3}]$$

$$\lambda \equiv \textit{length parameter:} \quad \lambda = \frac{1.95 \cdot 10^{-4} \cdot \rho^{1/3}}{A^{4/3} \cdot Z^2}$$

Cameron 1959
Salpeter & de Haan 1969
Schramm & Koonin 1990
Ichimaru & Kitamura 1999
Haensel & Zdunik 2003

S-factor & Rate Predictions





Hindrance factor would cause a rapid reduction in the S-factor towards low T!

$\Rightarrow$ no pycnonuclear fusion burning!?

Gasques et al. PRC 2007

Neff et al. PRC 2007

Diaz-Torres et al. PL 2007