Primer: Nuclear reactions in Stellar Burning

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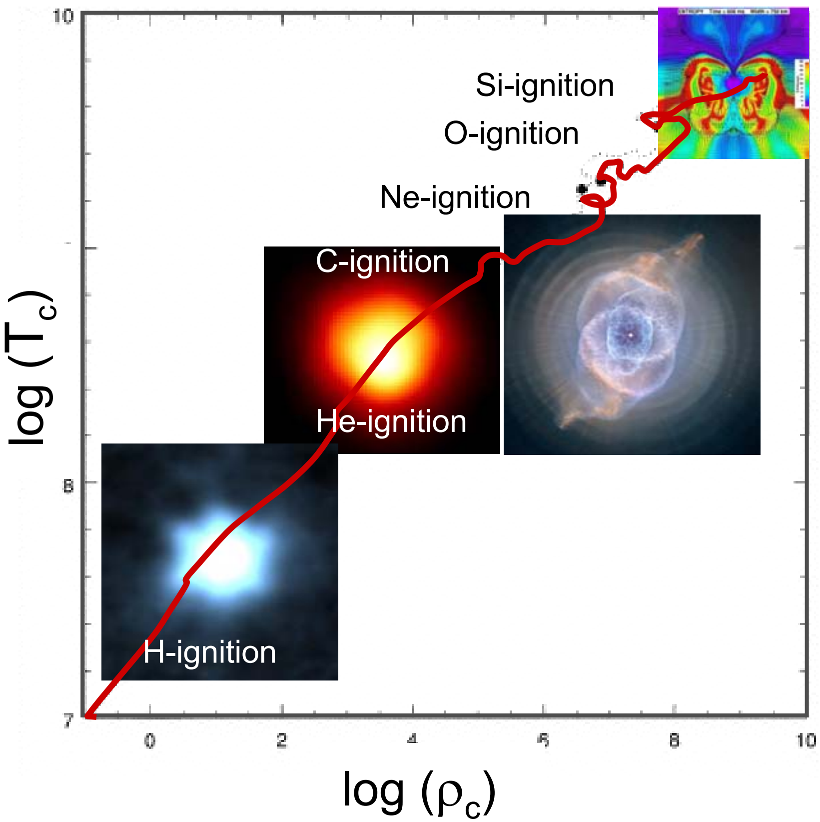
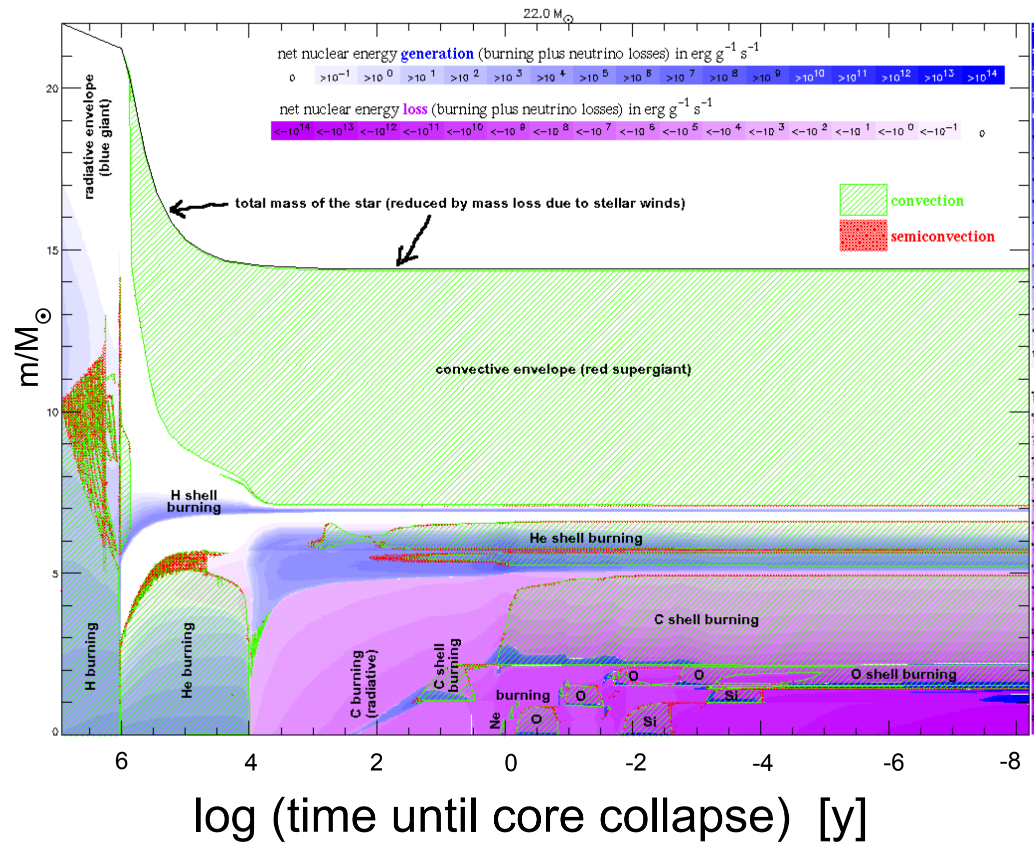
- The difficulty with low temperature reaction rates
- CNO reactions in massive main sequence stars
- He burning reactions in RGB stars, energy & neutron sources
- Questions in Carbon burning, $^{12}C+^{12}C$ revisited
- Reactions in the final days of burning

Nuclear burning & stellar evolution





Each burning phase is determined by nuclear reactions in terms of

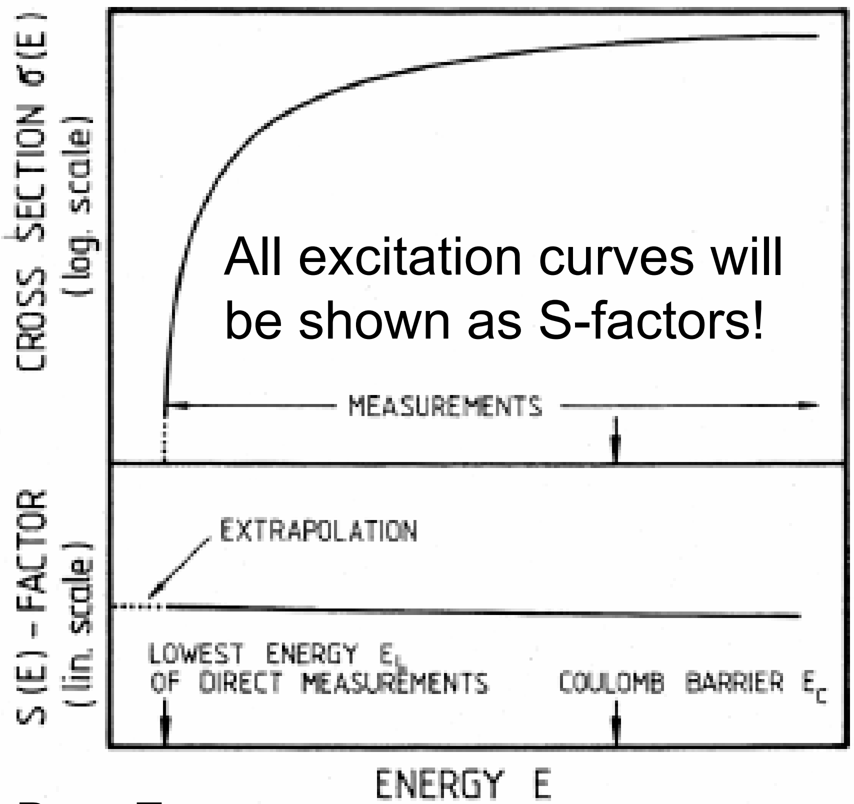
- energy generation,
- time scale
- nucleosynthesis

REACTION-RATE & S-FACTOR

$$N_A\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\cdot\mu}}\cdot(kT)^{-3/2}\cdot\int_0^\infty E\cdot\sigma(E)\cdot\exp\left(-\frac{E}{kT}\right)dE$$

Factorization of cross section into Coulomb part & “nuclear” component

$$\sigma(E) = \frac{S(E)}{E}\ \exp(-2\pi\eta)$$



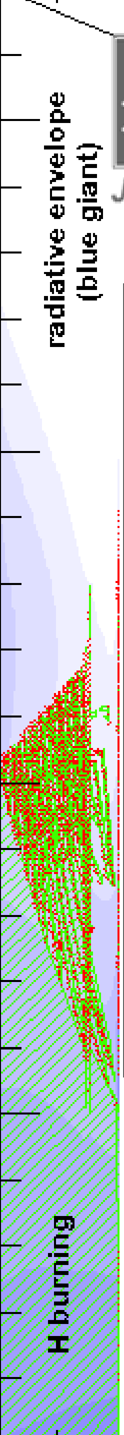
All excitation curves will be shown as S-factors!

Three techniques are typically used for the extrapolation to stellar energy range with a resonance density of $\rho=1/D$ MeV^{-1}

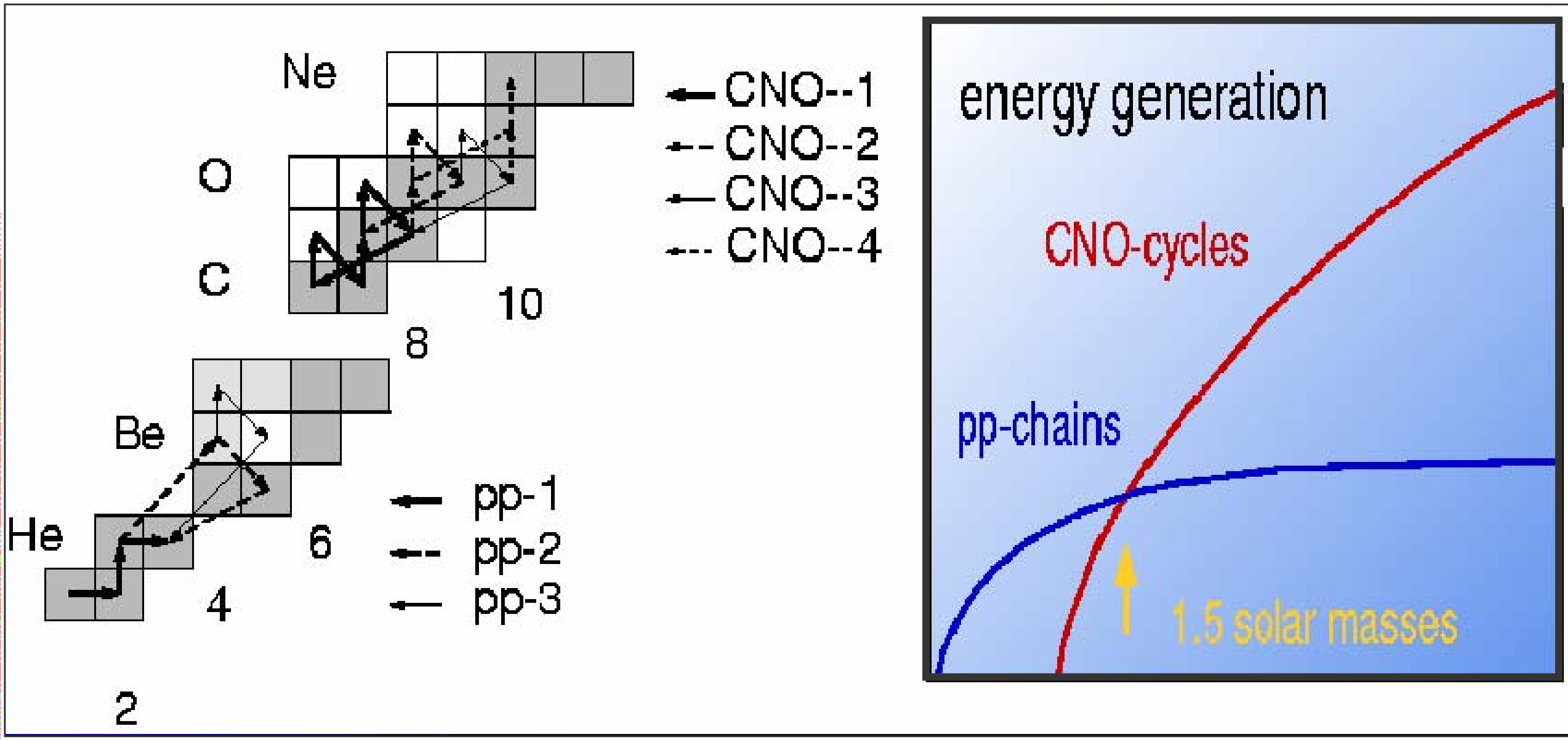
Single resonance Breit Wigner approach: $D \geq \Delta E_G \geq \Gamma$

Multi resonance R-matrix technique: $D \geq \Gamma \geq \Delta E_G$

Statistical Hauser Feshbach technique: $D \leq \Gamma \leq \Delta E_G$



Reactions in Stellar Hydrogen Burning



- CNO burning dominates in massive main sequence stars
- CNO time scale is determined by S-factor in $^{14}N(p,\gamma)^{15}O$
- CNO abundance distribution depends on CNO reaction rates and is correlated with the $^{15}N(p,\gamma/\alpha)^{16}O$ branch

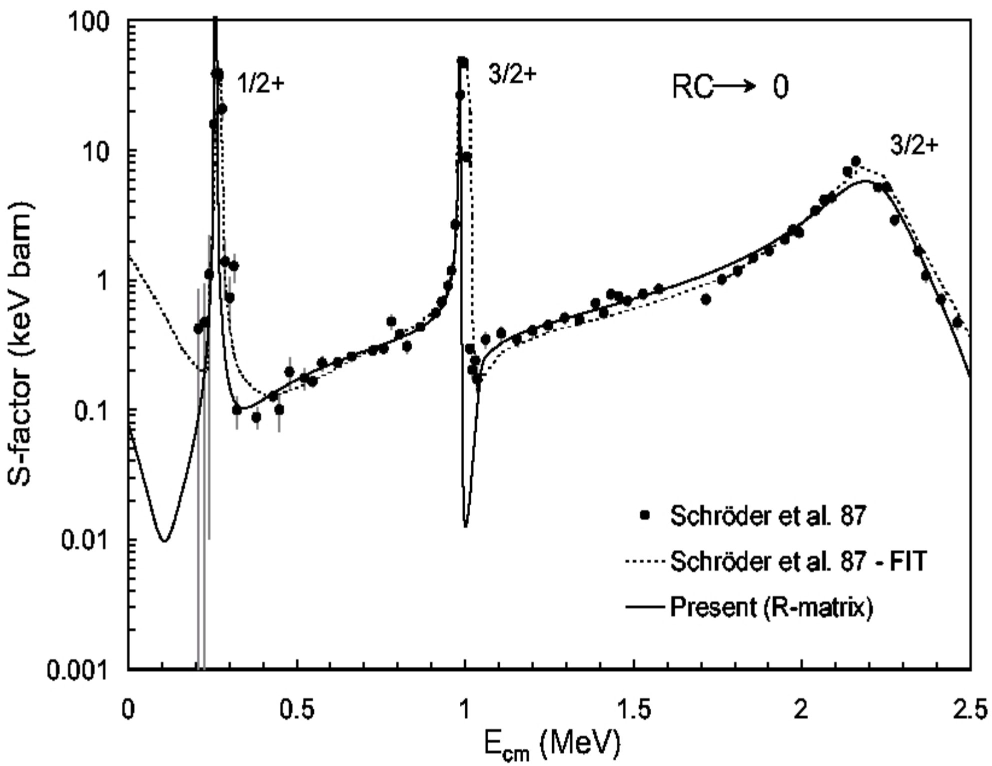
CNO example: The problem with extrapolation

Straight forward extrapolations may lead to substantial deviations in the S-factor! Particle threshold effects may change the predictions by orders of magnitude !

Schröder et al. 1987
Angulo et al. 2001

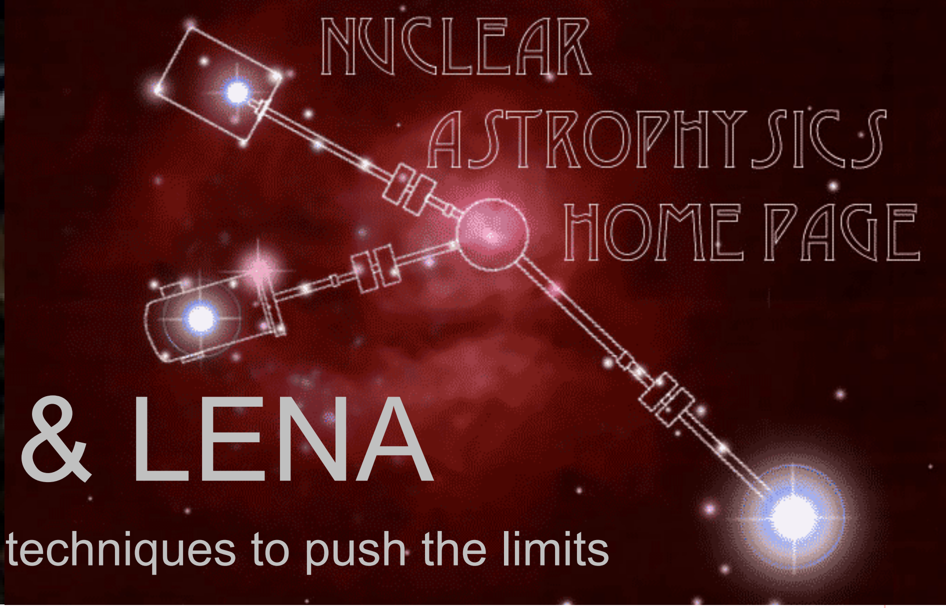
We need to account for all reaction contributions to extrapolate reliably:

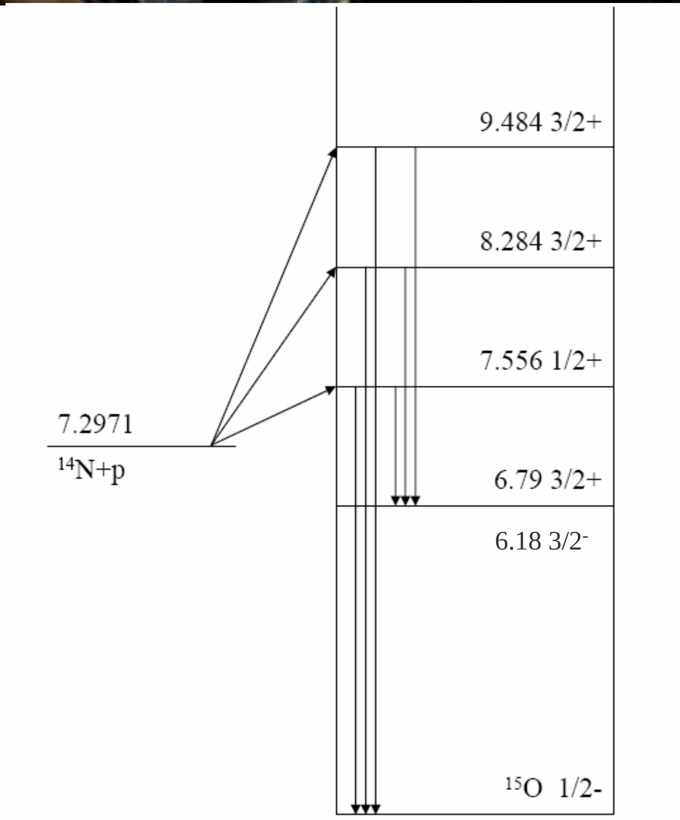
- direct component,
- resonance components
- interference structures
- all orbital momentum contributions
- all coupled channel contributions

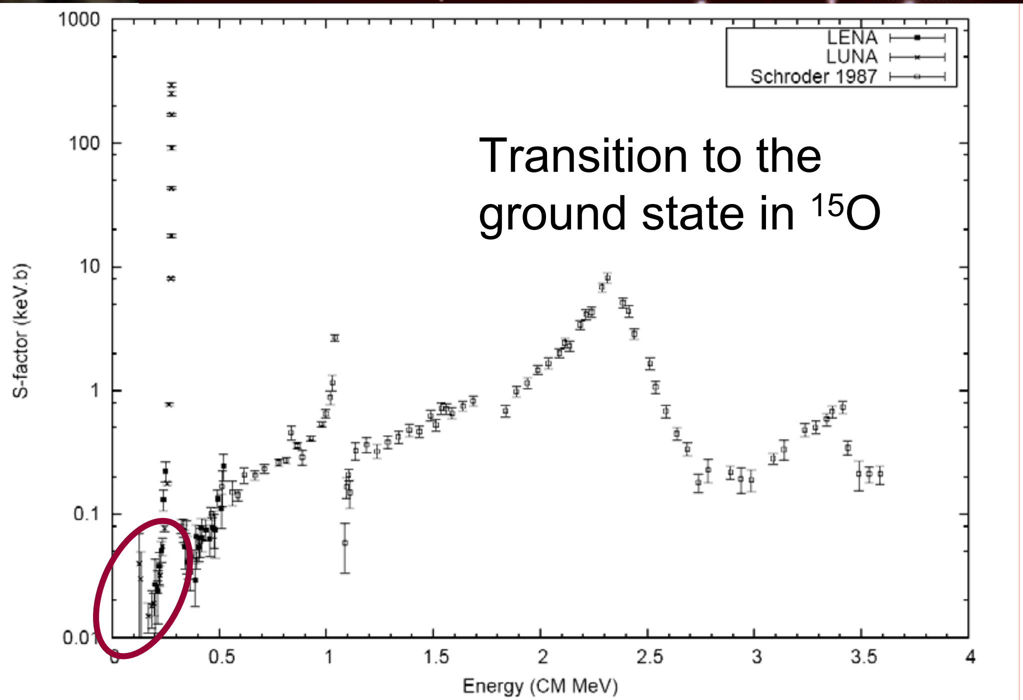


LUNA & LENA

new measurements & techniques to push the limits

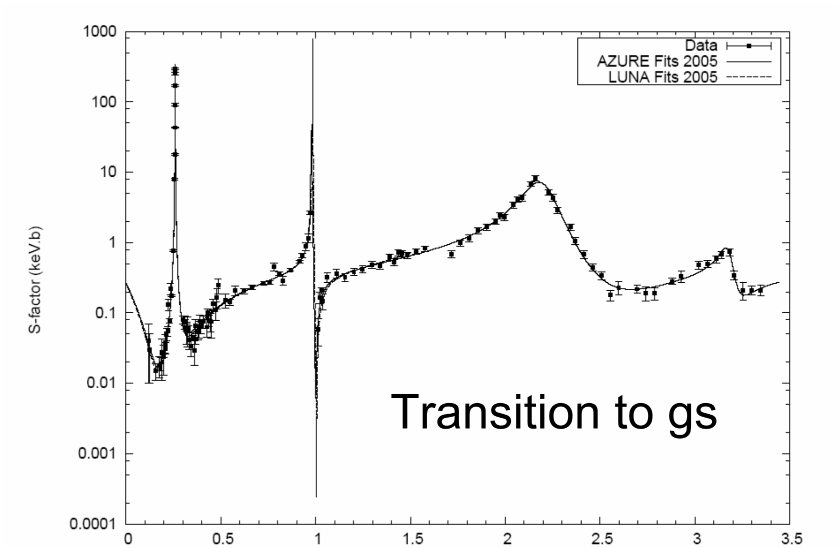


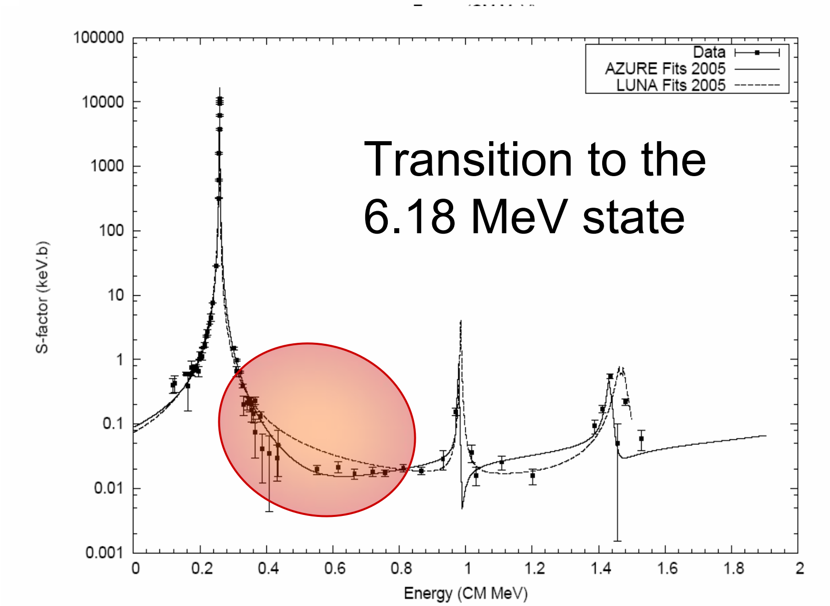




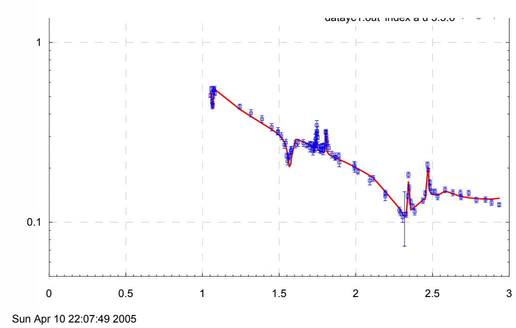
New data at low energy using passive and active background shielding techniques!

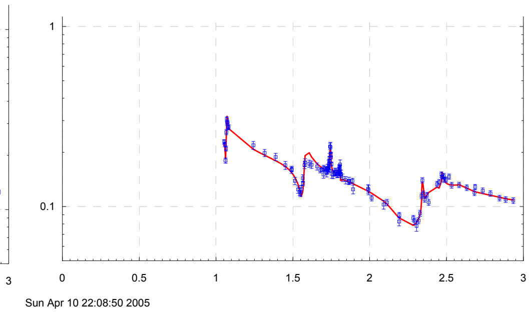
R-MATRIX FITS



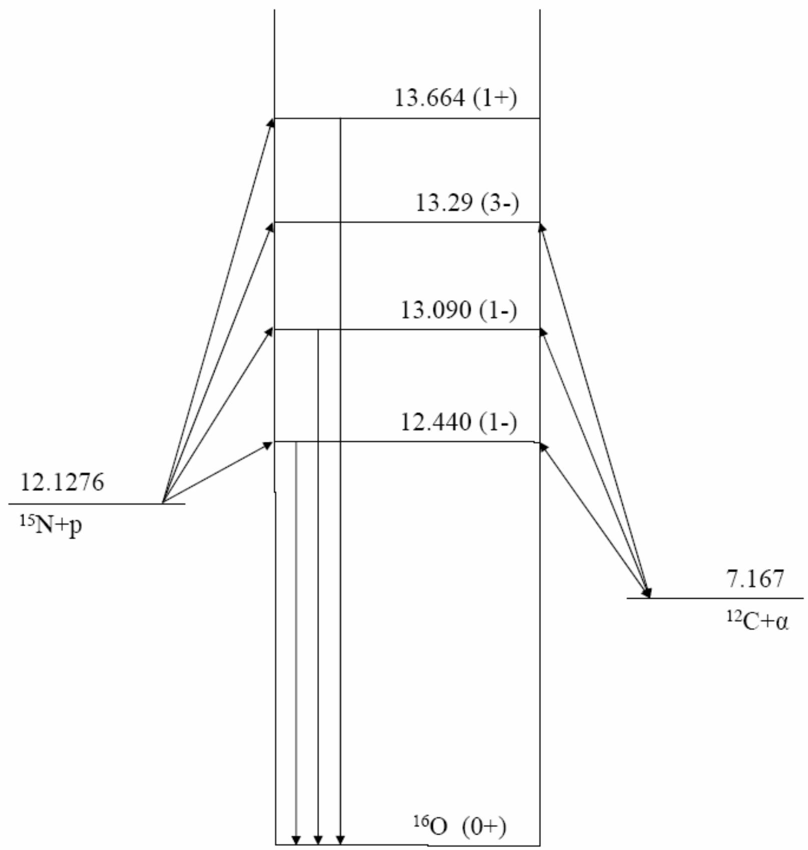


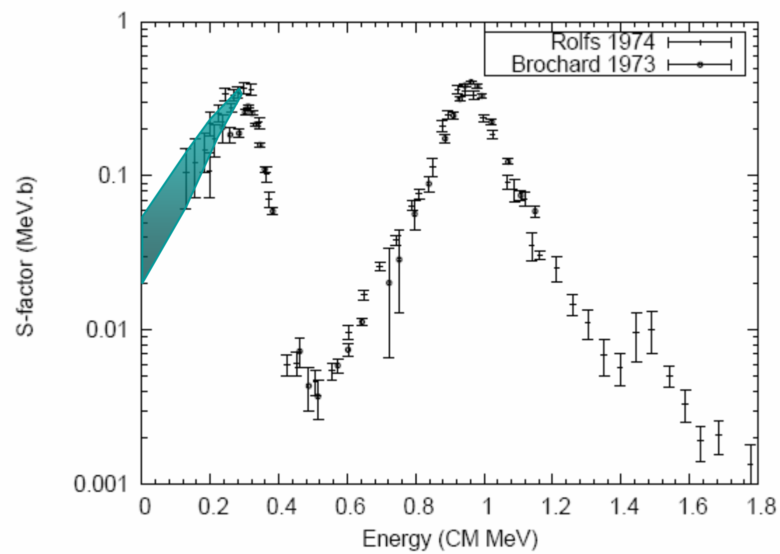
New developed multi-channel R-matrix code AZURE. The resulting S-factor is much higher (~3) than predicted by the r-matrix fit of Angulo et al. 2001, but it is lower (~1/3) than the NACRE value based on the results by Schröder et al. 1987! Agreement with the results by Imbriani et al. 2005.

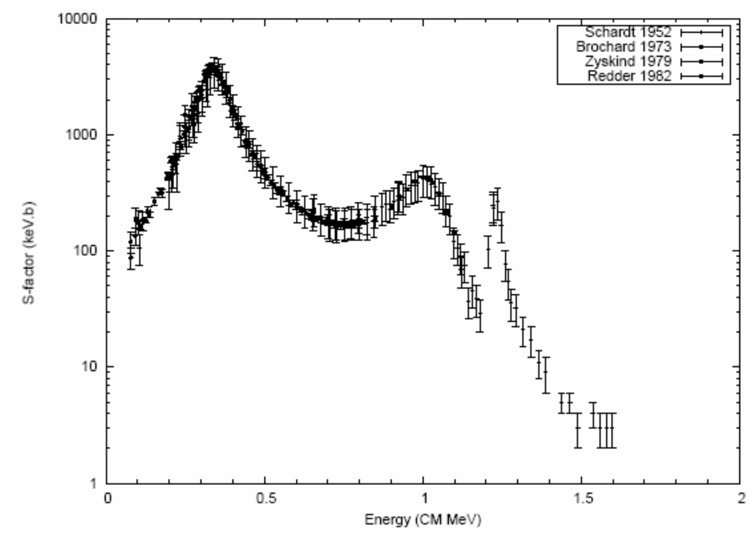




$^{15}N(p,\alpha)^{12}C$ & $^{15}N(p,\gamma)^{16}O$

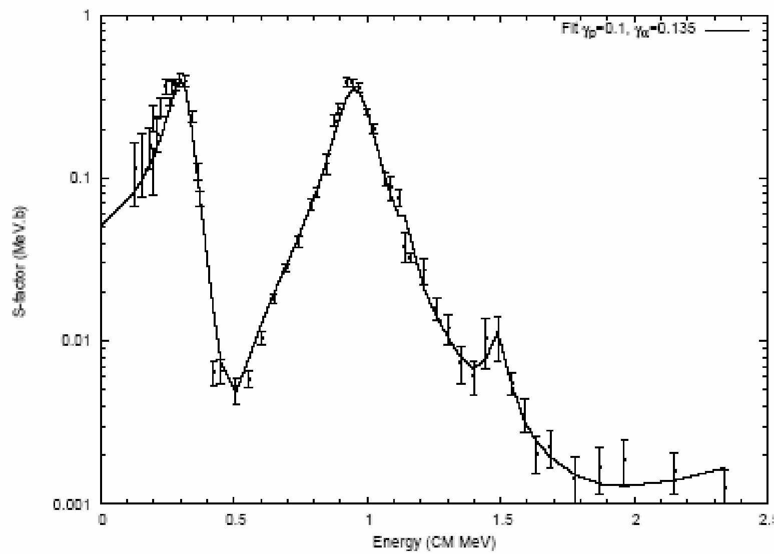


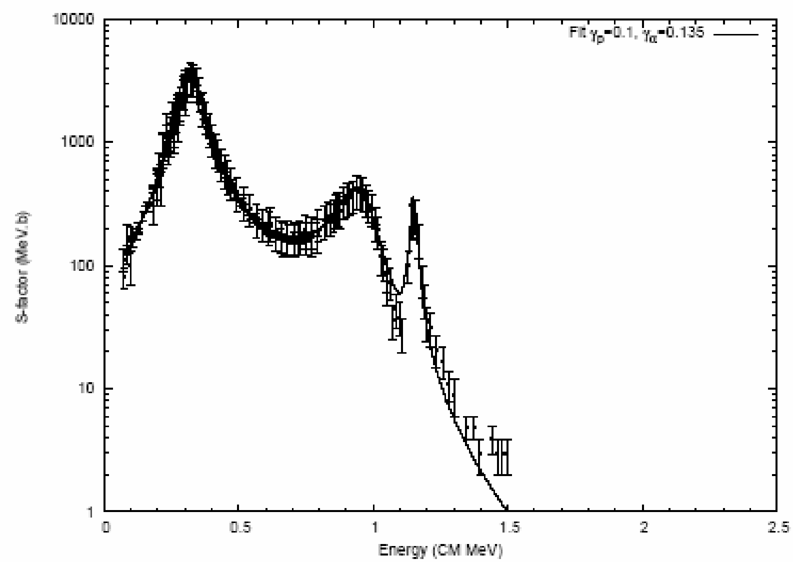




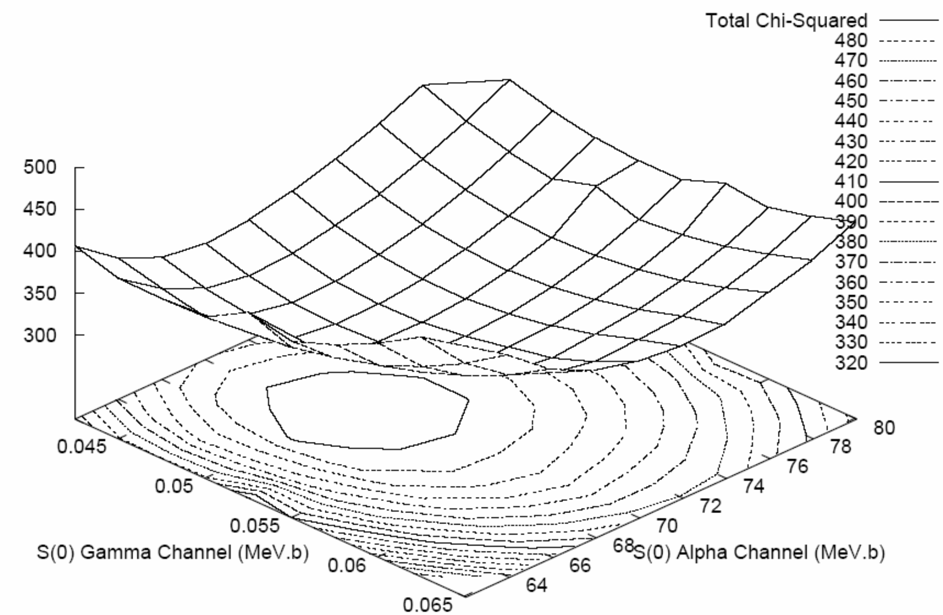
The data are good, but extrapolation still carry substantial uncertainties!

NEW FITS with AZURE





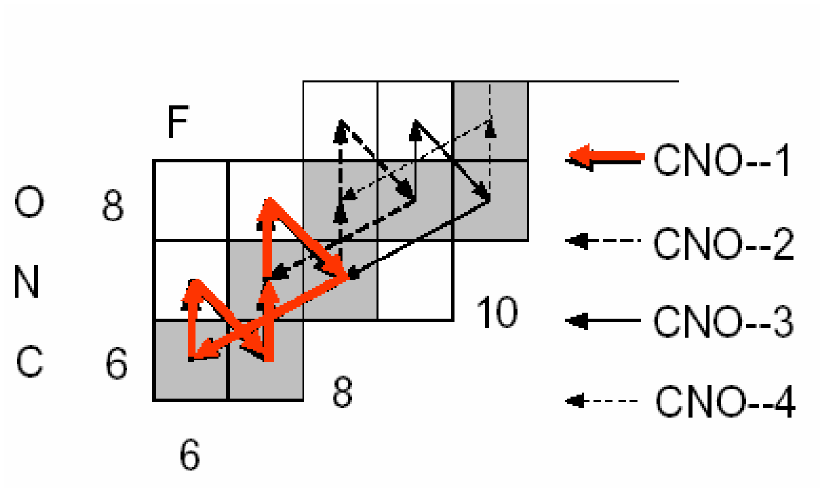
Fits include also consideration of the $^{15}N(p,p)$ and the $^{12}C(\alpha,\alpha)$ elastic scattering channels!

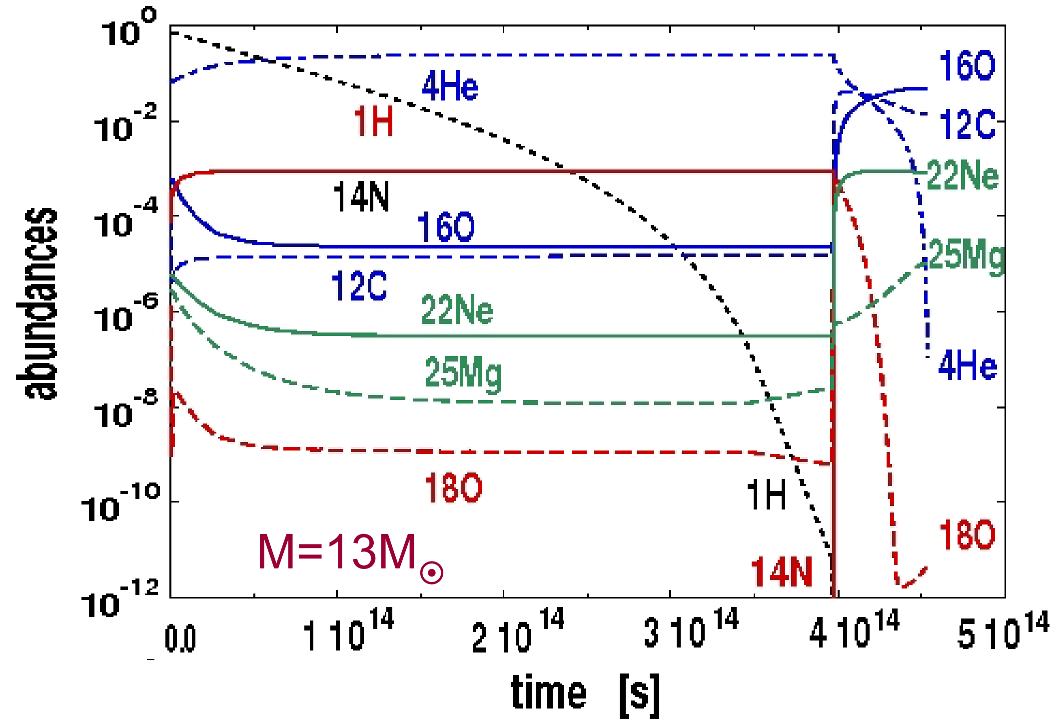


Reaction	present	NACRE
$^{15}N(p,\gamma)^{16}O$	51 keV-b	64±6 keV-b
$^{15}N(p,\alpha)^{12}C$	69 MeV-b	65±7 MeV-b

The (p,γ) channel is weaker than previously extrapolated on the one-channel basis only.

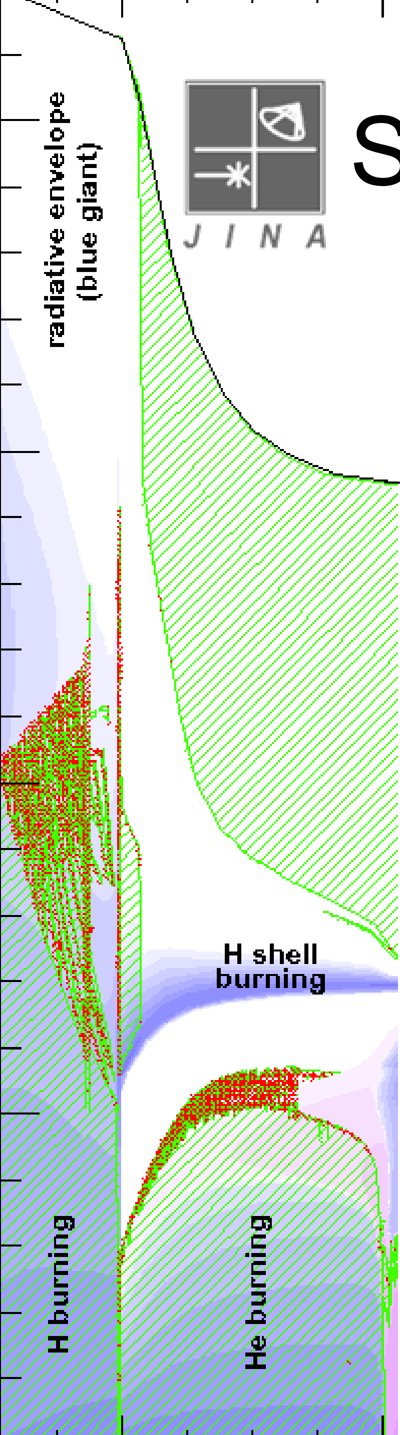
CNO nucleosynthesis

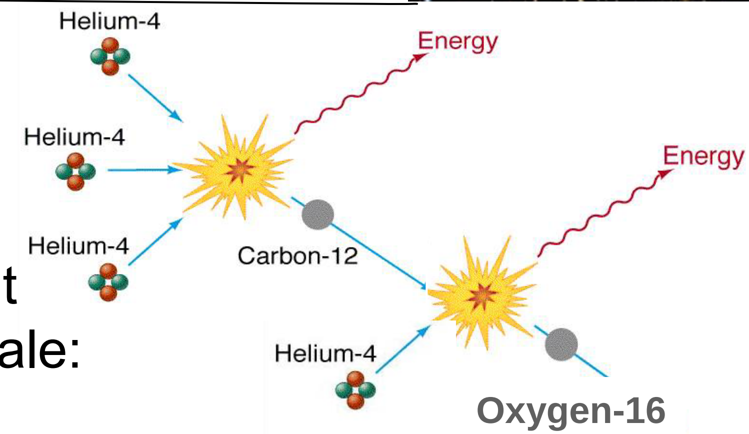




$^{14}N(p,\gamma)^{15}O$ is the slowest reaction in the CN cycle
Loss by $^{15}N(p,\gamma)^{16}O$ is negligible $\Rightarrow$ enrichment in ^{14}N

Stellar He-burning in massive Stars





Two questions remain relevant
Energy production and timescale:

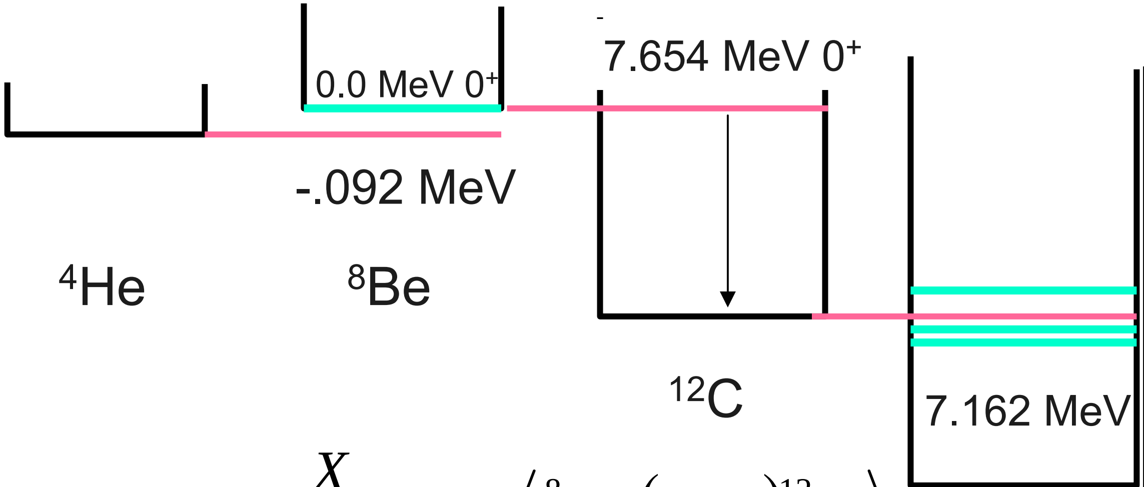
$^{4}He(2\alpha,\gamma)^{12}C(\alpha,\gamma)^{16}O(\alpha,\gamma)^{20}Ne$

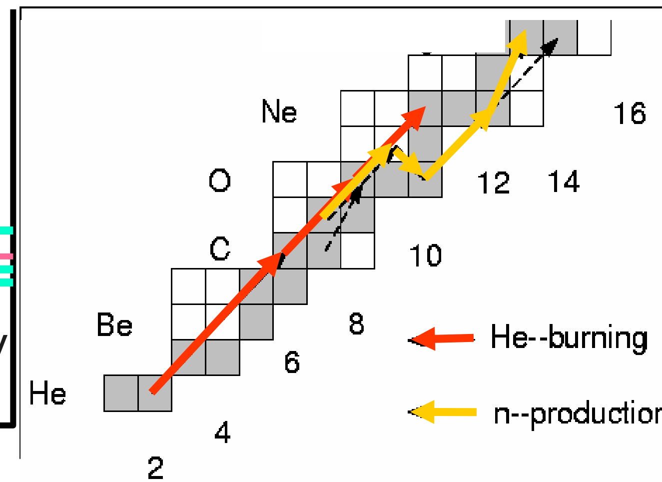
Neutron production for weak s-process:

$^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)$

$^{22}Ne(\alpha,\gamma)$

The 3α ⇒ ^{12}C reaction





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

Step 1

Step 2

$$N\left({}^8Be\right) = 6 \cdot 10^{-35} \cdot N_\alpha^2 \cdot T_9^{-3/2} \cdot e^{\left(-\frac{11.64 \cdot Q_\alpha}{T_9}\right)}$$

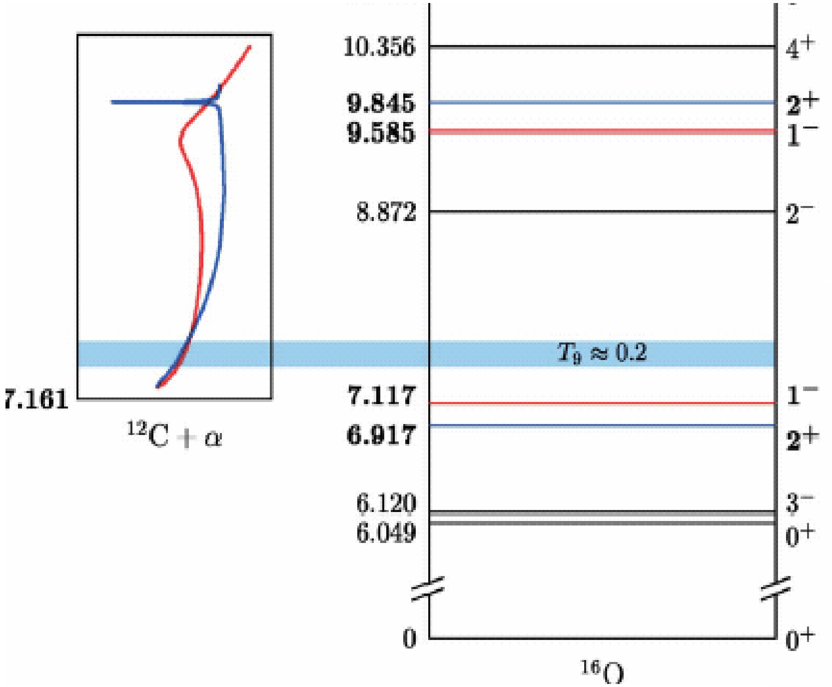
Present uncertainties are associated with nuclear masses and in the decay widths of the “Hoyle” resonance

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

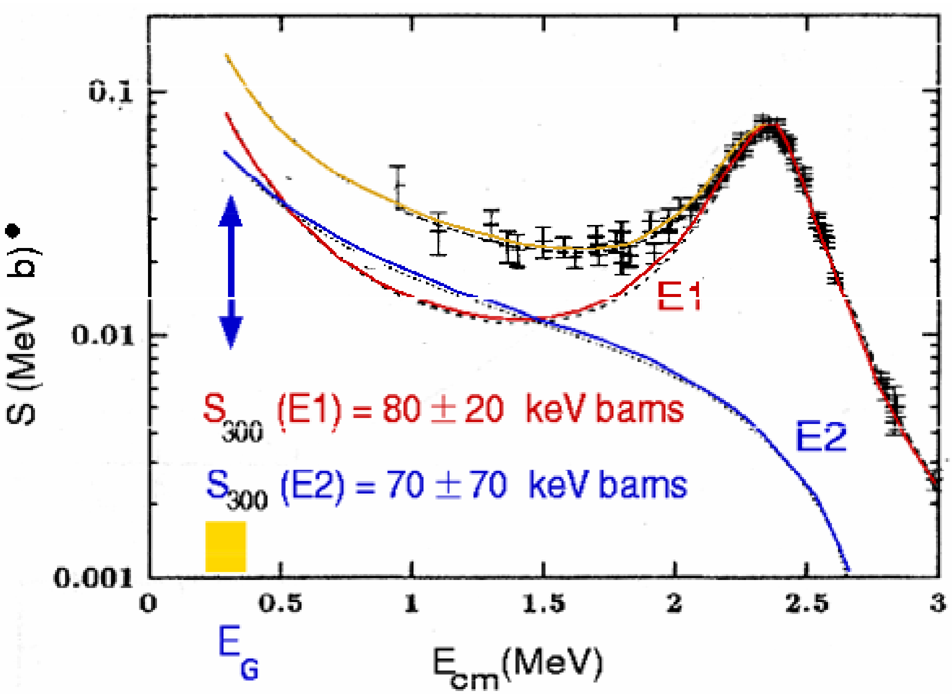
$$\omega\gamma = (2J+1) \cdot \frac{\Gamma_\alpha \left(\Gamma_\gamma + \Gamma_\pi\right)}{\Gamma_{tot}}$$

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

Level and Interference Structure



Uncertainty in low energy extrapolation



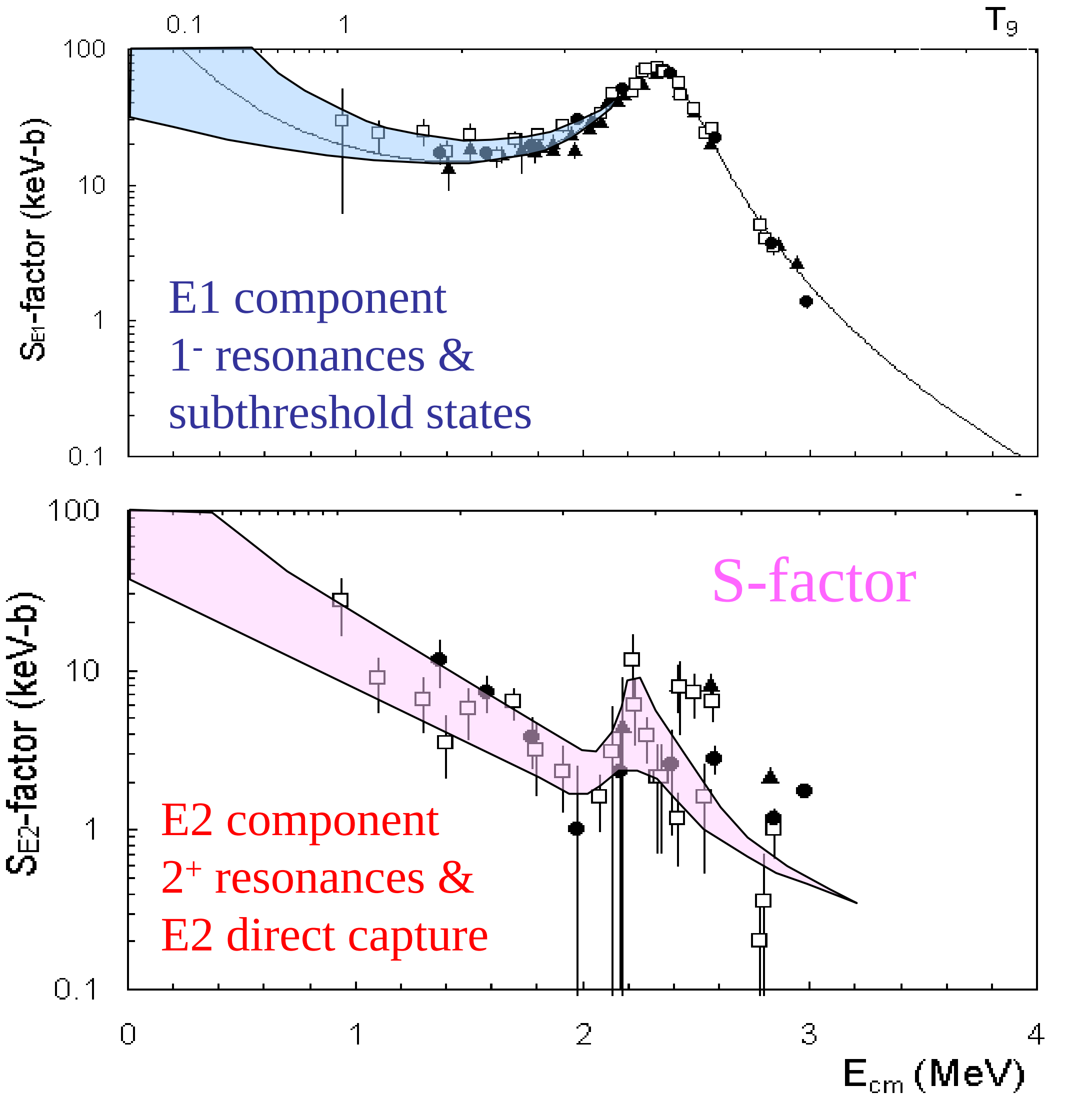
$$N_A\langle\sigma\upsilon\rangle = 6.9\cdot 10^8 \cdot T_9^{-2/3}\cdot S_{eff}\left[MeV - barn\right]\cdot e^{-\frac{32.11}{T_9^{1/3}}} \quad \left[\frac{cm^3}{s}\right]$$

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

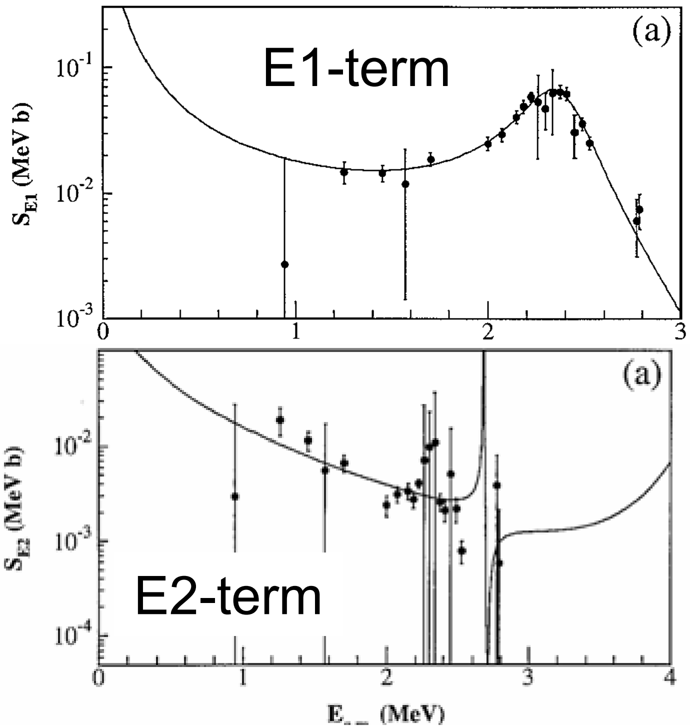
Complex resonance structure, interfering broad resonances causes difficulties in the reliability of low energy extrapolation on the basis of capture data only!

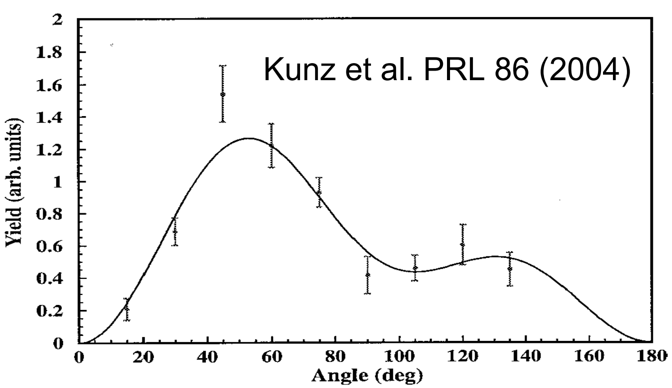
R-matrix analysis of multiple reaction channels

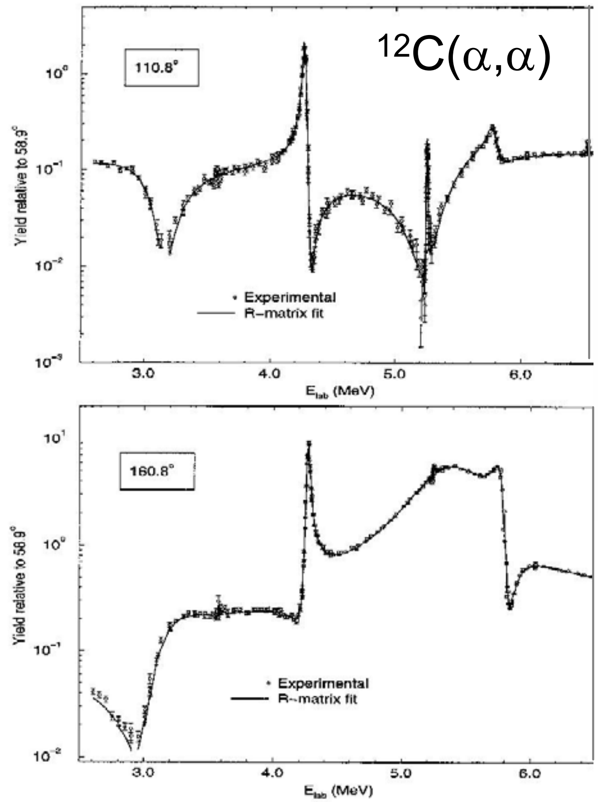
- elastic scattering $^{12}C(\alpha,\alpha)^{12}C$
- β-delayed α-decay $^{16}N(\beta,\alpha)^{12}C$
- resonant α capture $^{12}C(\alpha,\gamma)^{16}O$
- α-transfer reaction $^{12}C(^{7}Li,t)^{16}O$

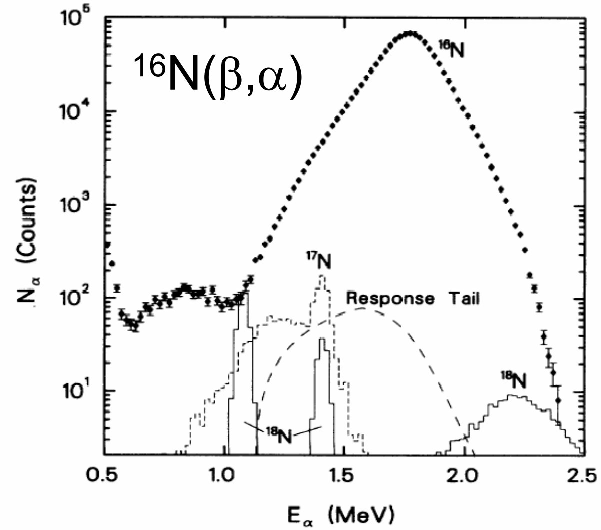


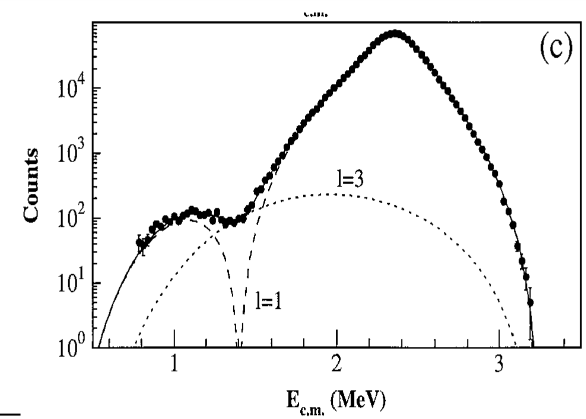
R-matrix fit examples





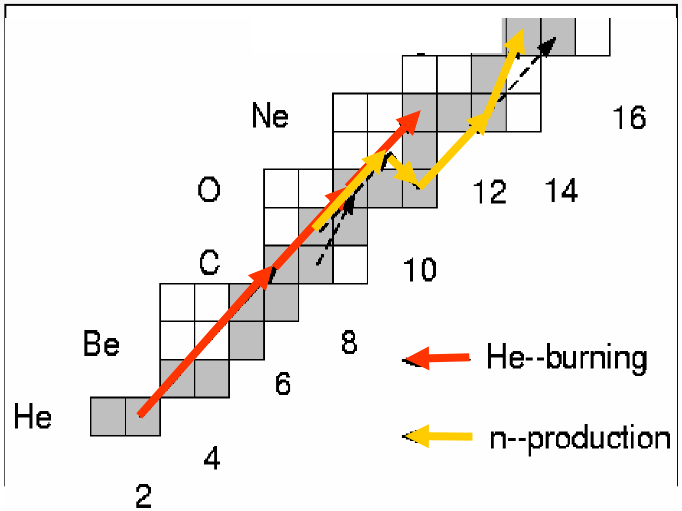




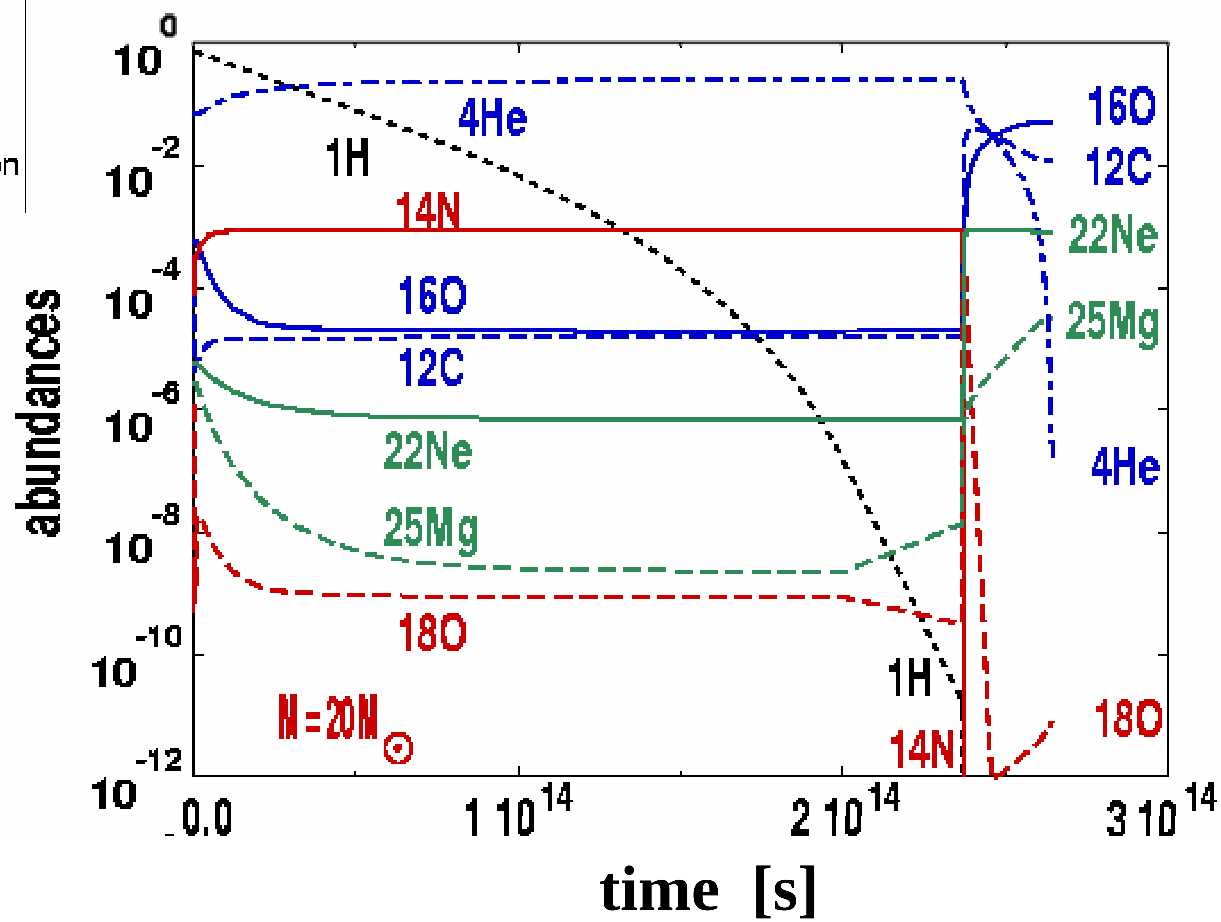


Arguments & experiments are continuing!!!
But, consistent multi-channel R-matrix fits are necessary for reliable extrapolation!!!

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 & conversion to ^{22}Ne.



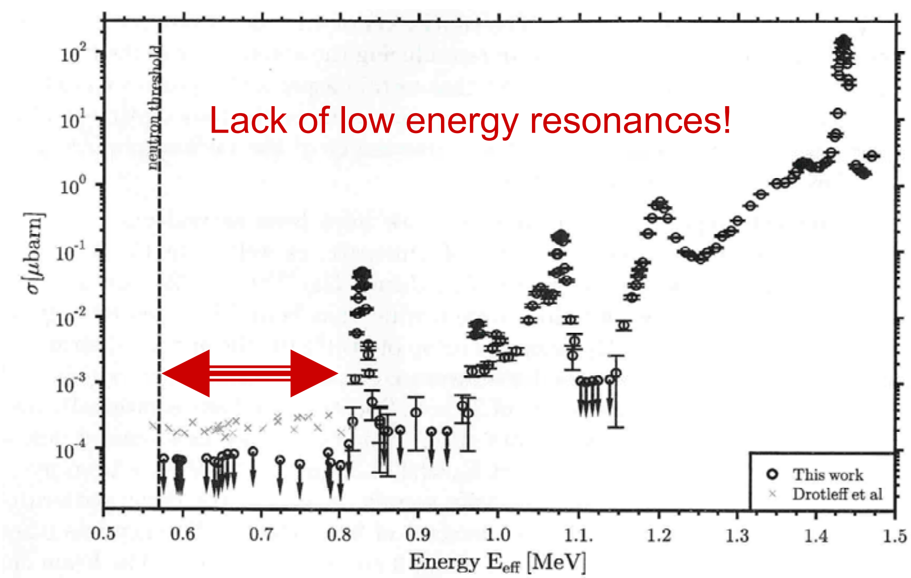
$^{22}Ne(\alpha,n)$ IN STELLAR He BURNING

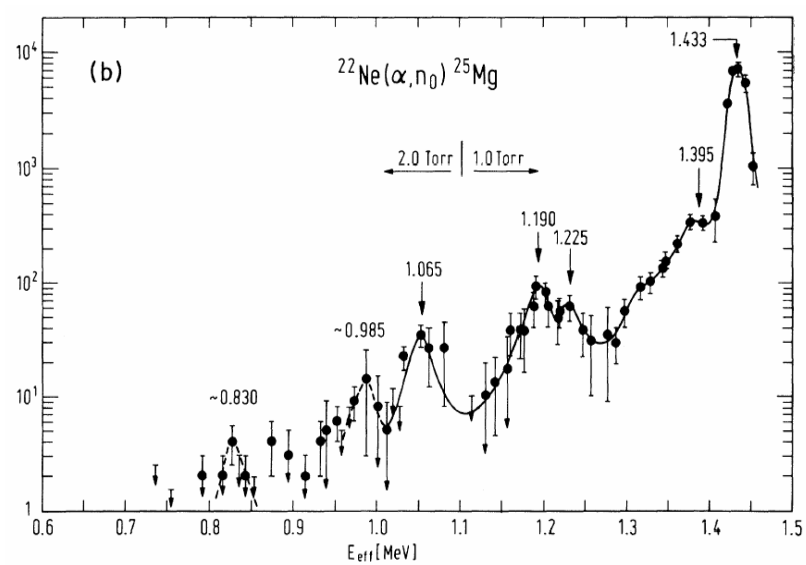
J I N A

Production from the ^{14}N ashes of CNO burning

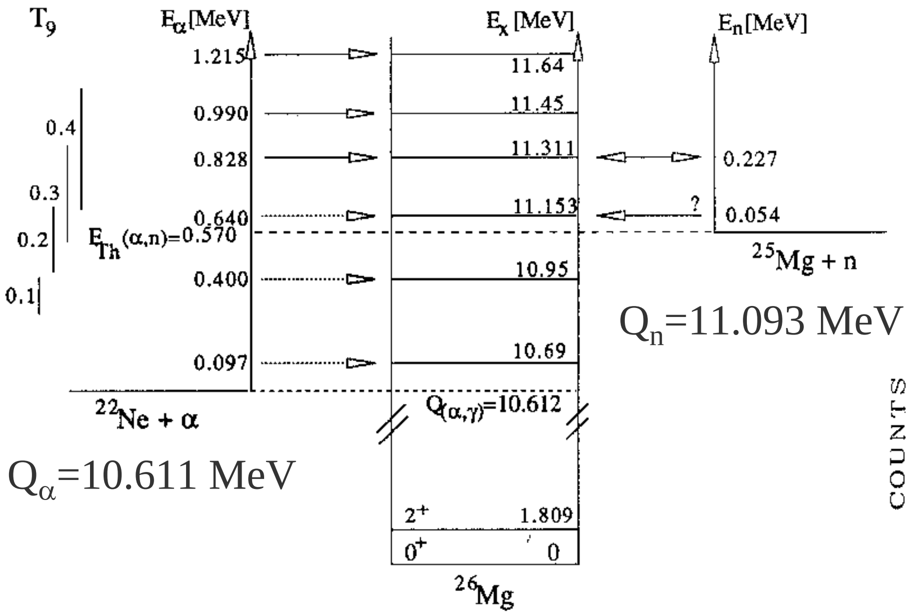
Production sequence $^{14}N(\alpha,\gamma)^{18}F(\beta^+\nu)^{18}O(\alpha,\gamma)^{22}Ne$ triggering: $^{22}Ne(\alpha,\gamma)^{26}Mg$, $^{22}Ne(\alpha,n)^{25}Mg$

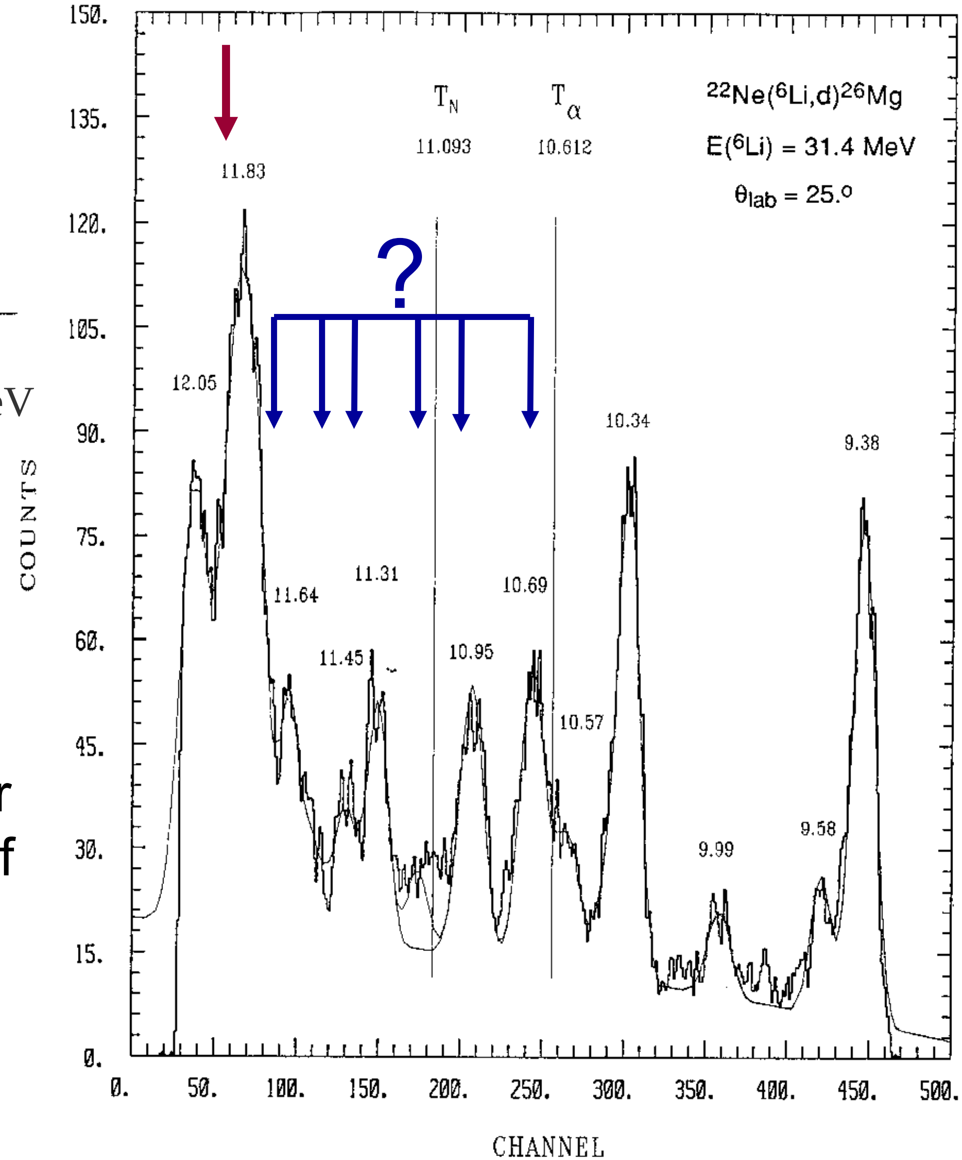
- Lowest resonance at $E_R \approx 830$keV, but more resonances anticipated;
- Do the two resonances correspond to the same state?
- Same strength suggests comparable rates, reduction in neutron production!





α-transfer studies in ^{26}Mg



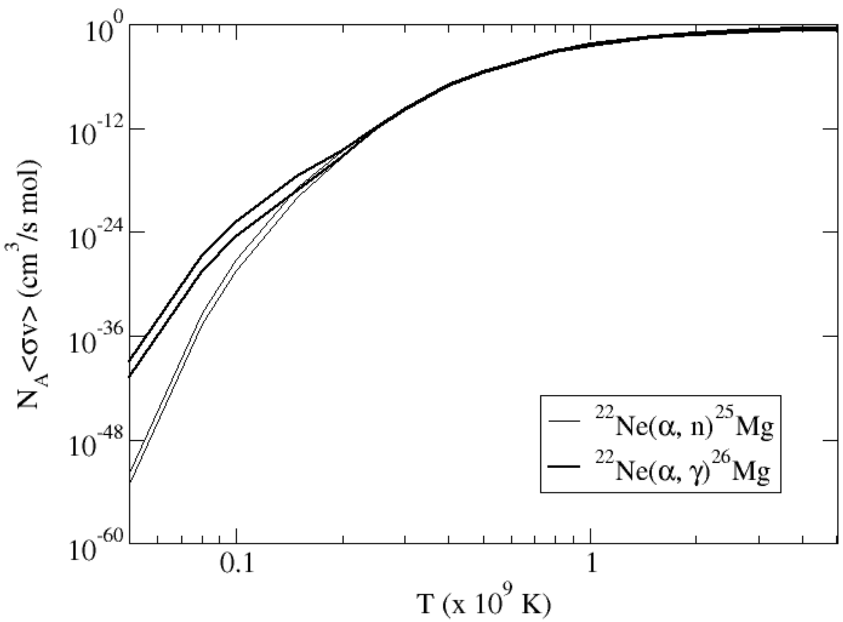


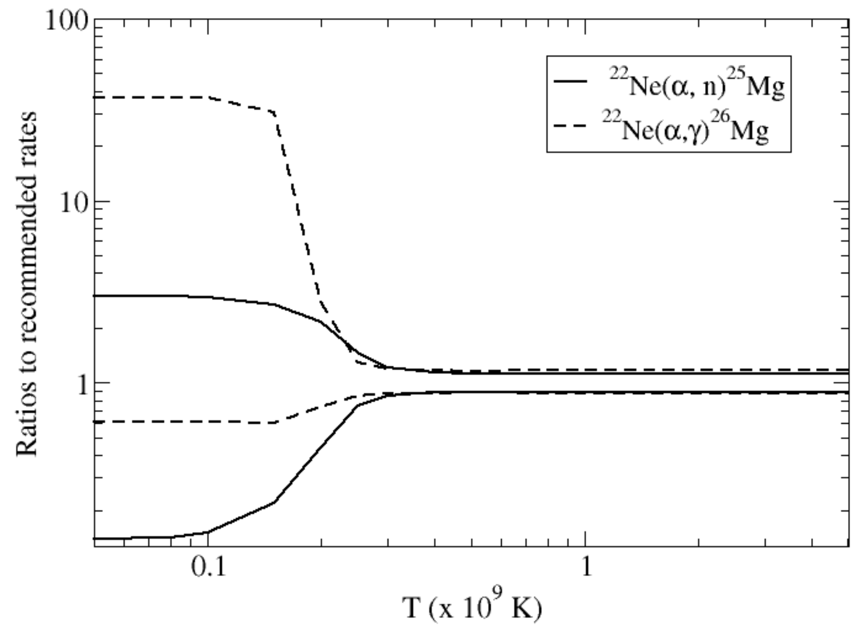
Observational evidence for α cluster configuration near the α threshold of ^{26}Mg at 10-12 MeV! Systematic studies with better resolution are necessary to verify the information!

Reaction Rate Estimates

Resonance parameters determined by

- ❑ Re-analysis of $^{25}Mg(n,\gamma)$ data by Koehler et al. 2000 (new n-ToF experiment)
- ❑ Analysis of $^{22}Ne(^{6}Li,d)$ transfer data
- ❑ Shell model calculations
- ❑ Cluster model calculations

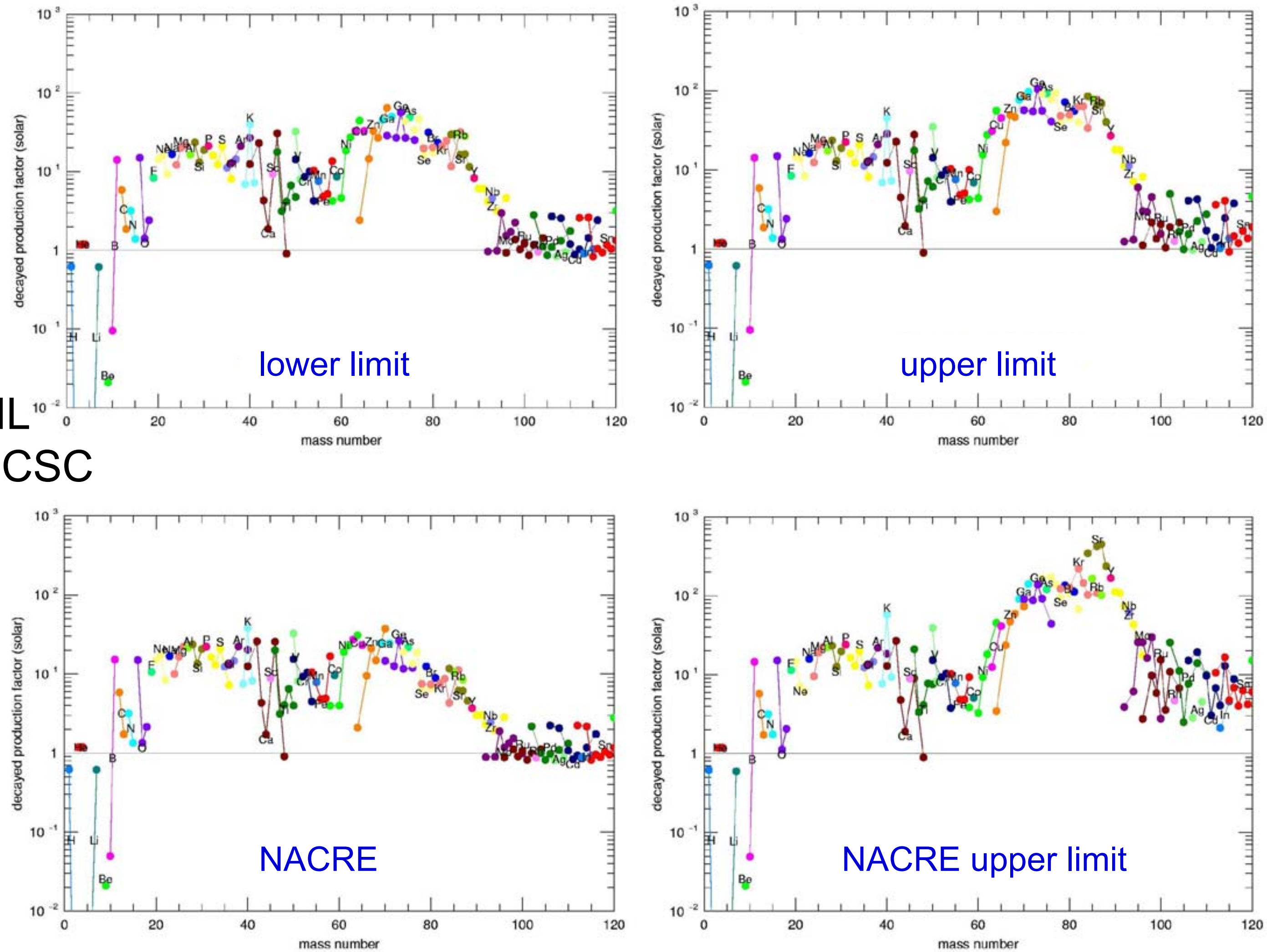




Low energy resonance contributions in the $^{22}Ne(\alpha,\gamma)^{26}Mg$ channel, the cross-over depends critically on resonances and resonance parameters within 500-800 keV. Considerable uncertainties remain, low energy measurements are still necessary!

Consequences for weak s-process

Heger, LANL
Woosley, UCSC



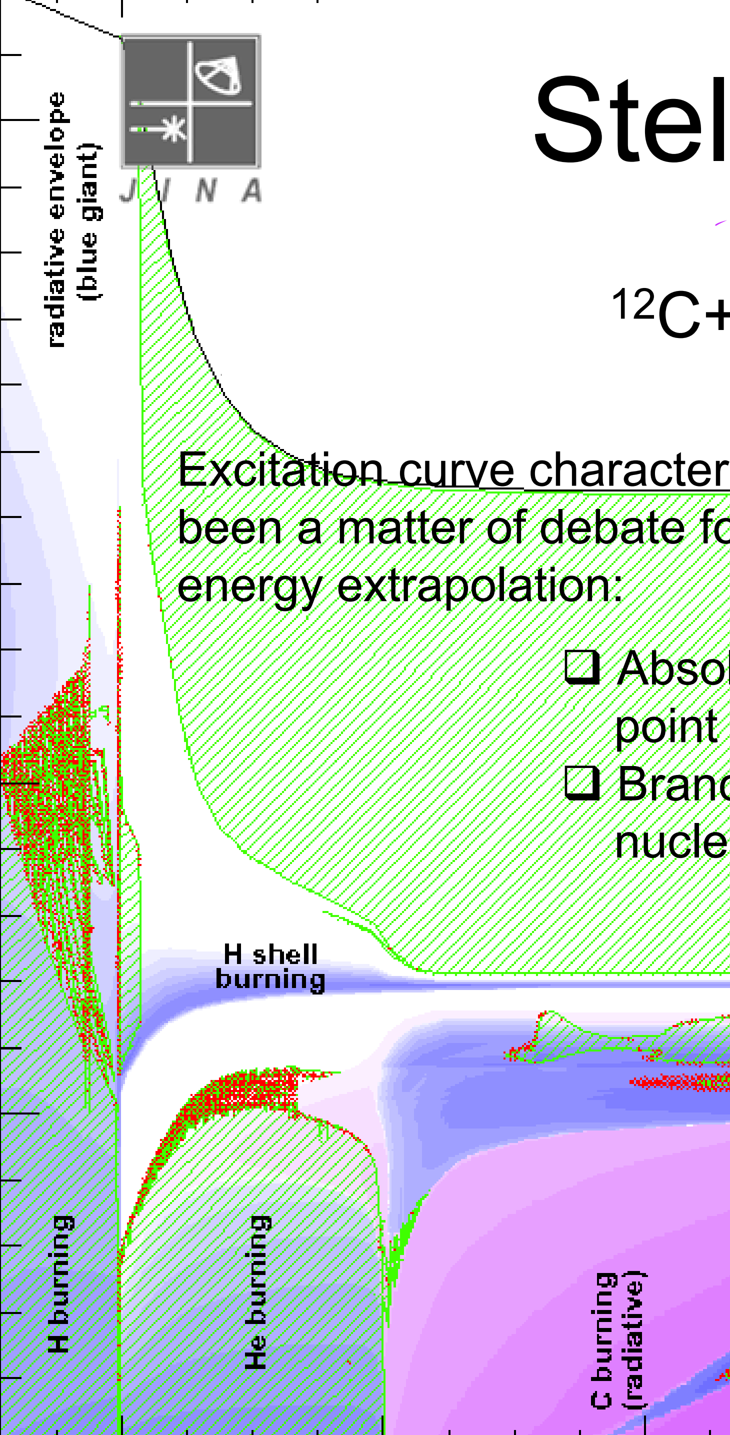
Variation between limits suggests considerable affect on weak s-process abundance distribution; severe consequences for p-process predictions!

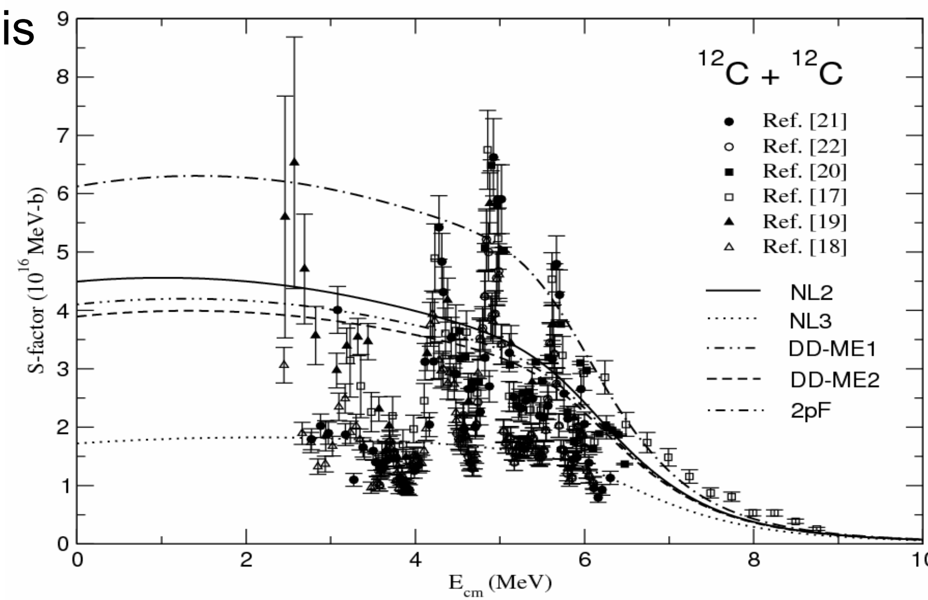
Stellar C Burning

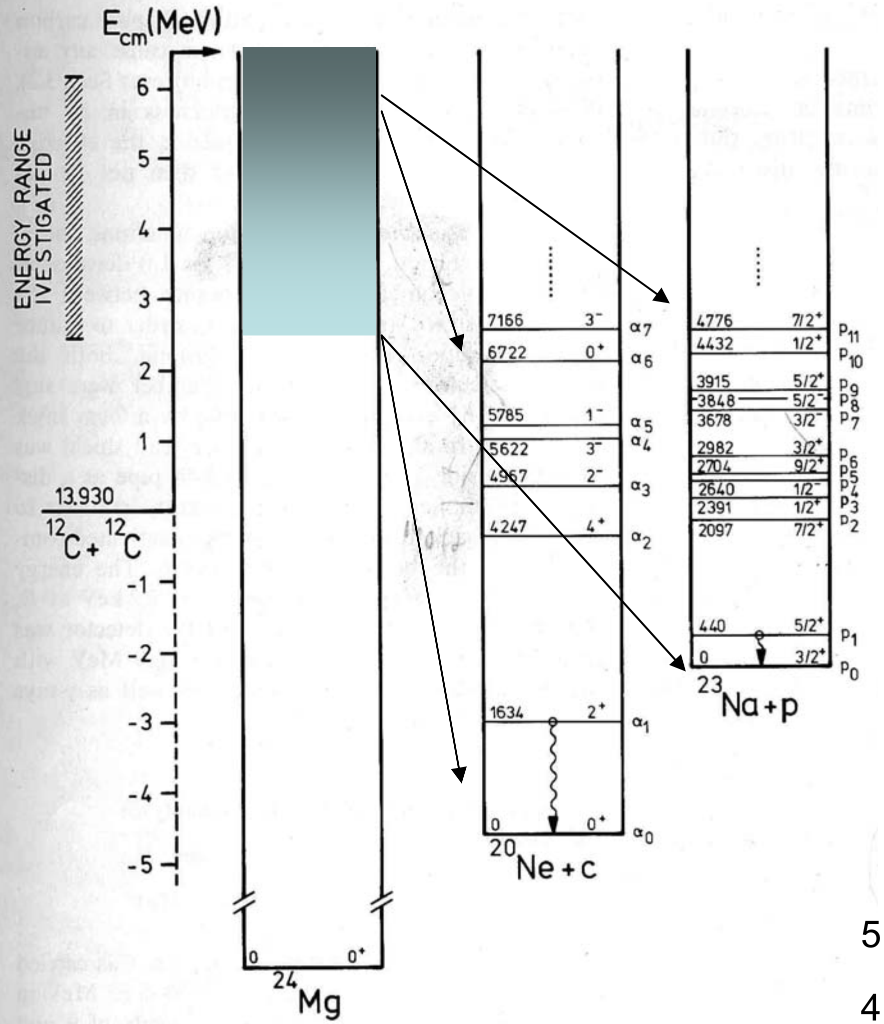
$^{12}C + ^{12}C \Rightarrow$
$^{24}Mg + \gamma$, Q=13.93 MeV
$^{23}Na + p$, Q= 2.24 MeV
$^{20}Ne + \alpha$, Q= 4.62 MeV

Excitation curve characterized by several low energy resonances which have been a matter of debate for quite some time. Two questions are important for low energy extrapolation:

- Absolute cross section to determine fusion ignition point conditions
- Branching in p, α channel to investigate subsequent nucleosynthesis





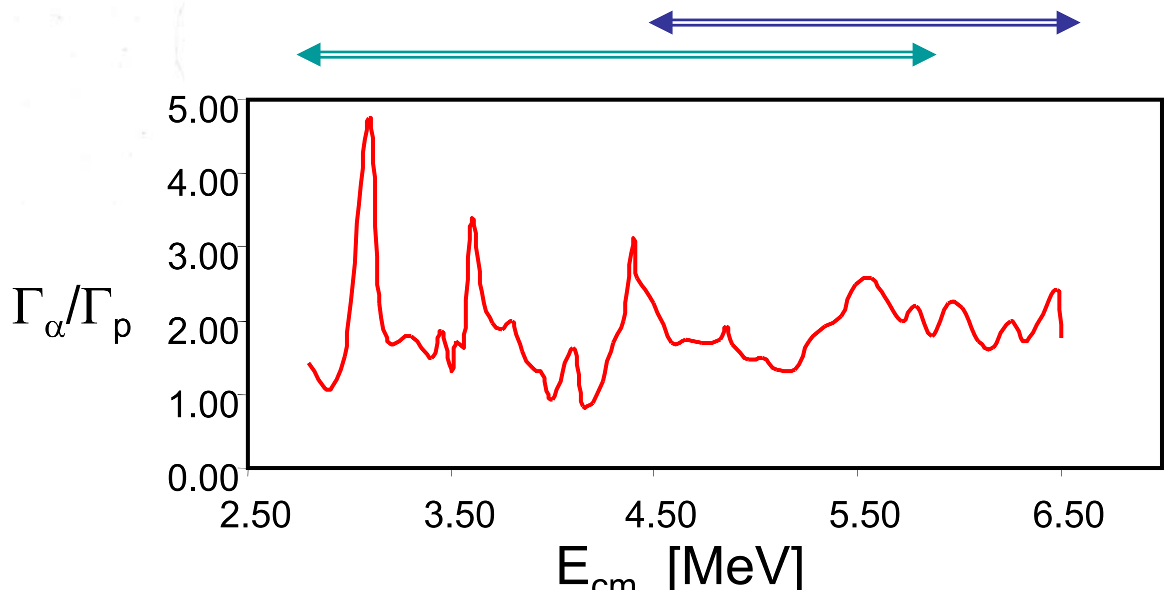


Low energy branching

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

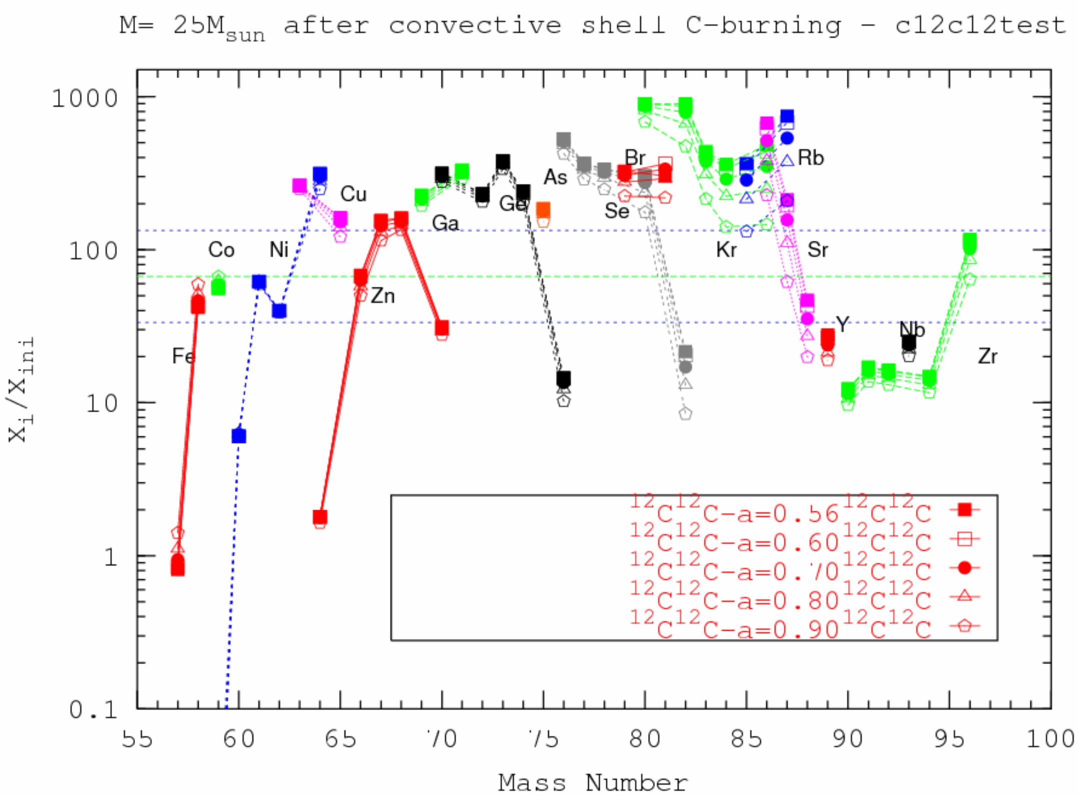
Question about s-process in C-burning
$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)$
Depends on p,α-production in $^{12}C+^{12}C$

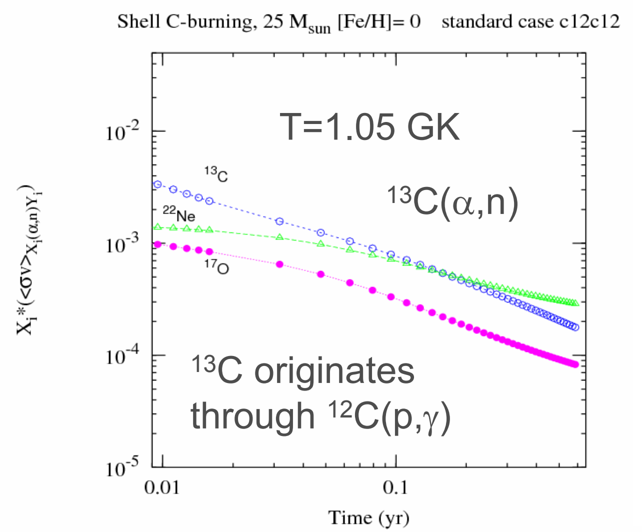
Becker et al. 1979 Aguilera et al. 2006

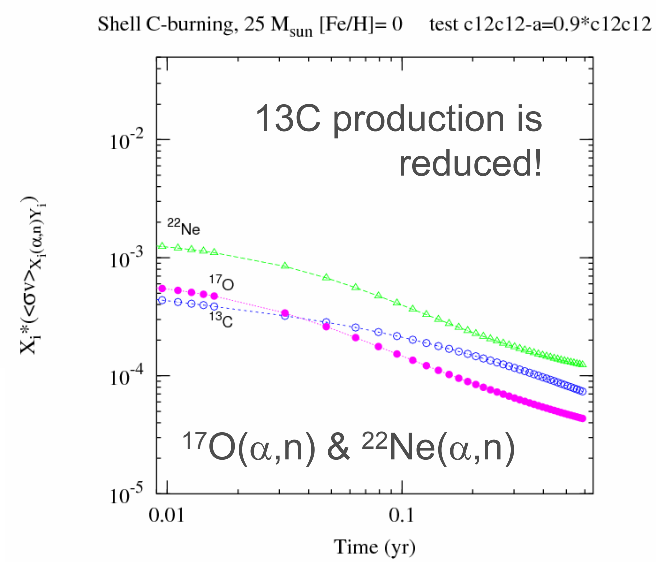


On average $\Gamma_\alpha/\Gamma_p \approx 1.8$!
But indication for α-cluster structure in ^{24}Mg is visible in resonance structure!

Consequences for neutron production and s-process







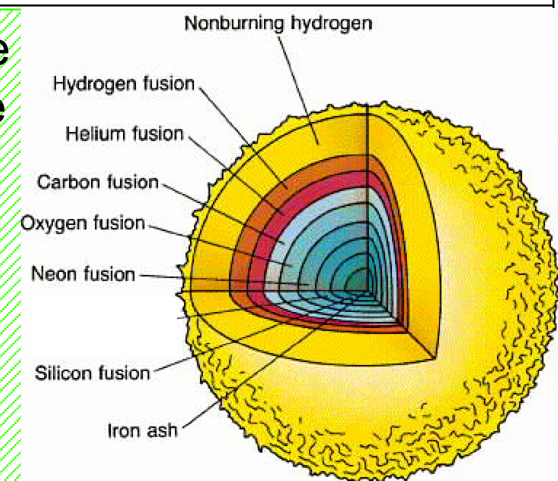
New and different neutron sources!!!

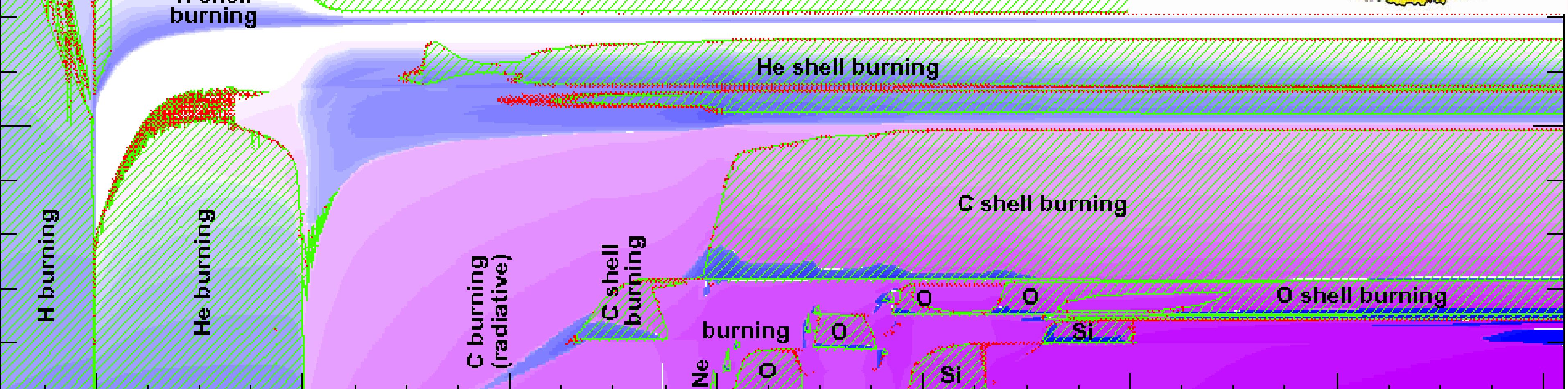
Project by Pignatari et al. (Torino-LANL-ND)

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

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

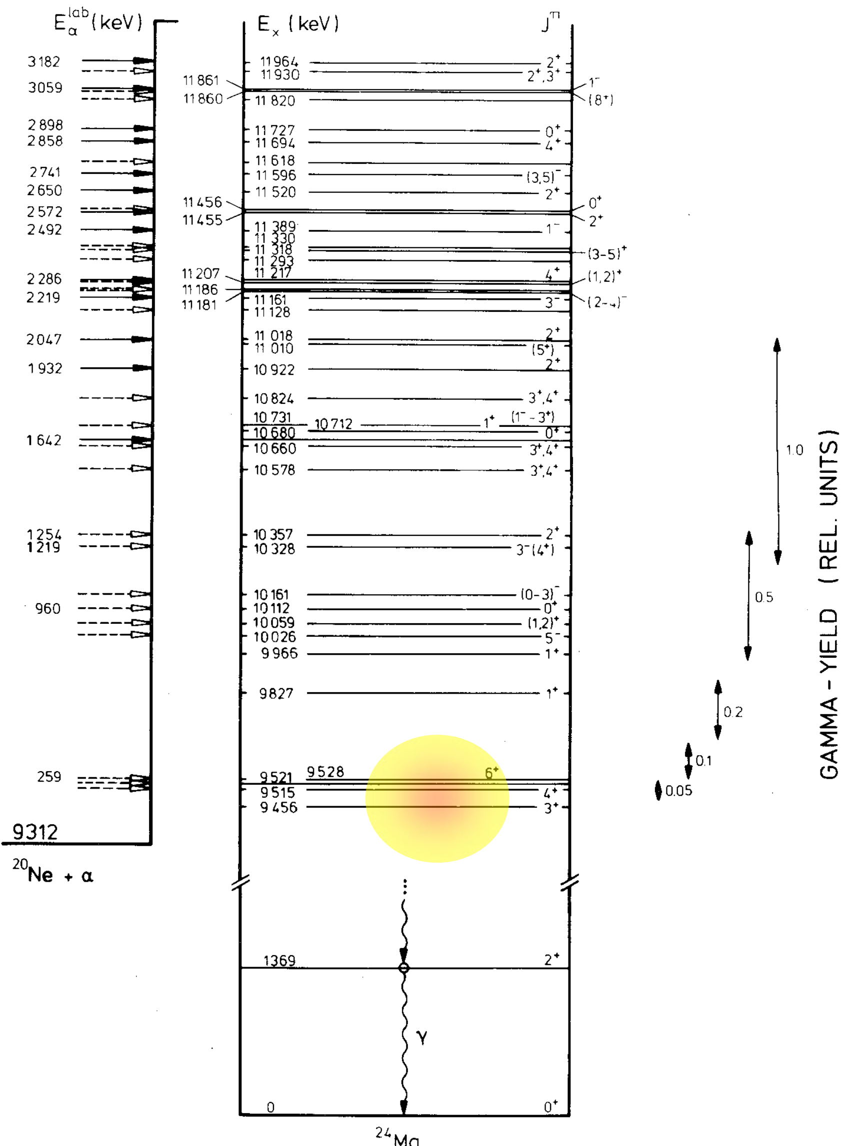
$$^{16}O(\alpha,\gamma)^{20}Ne \quad Q=4.730\,MeV$$

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

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

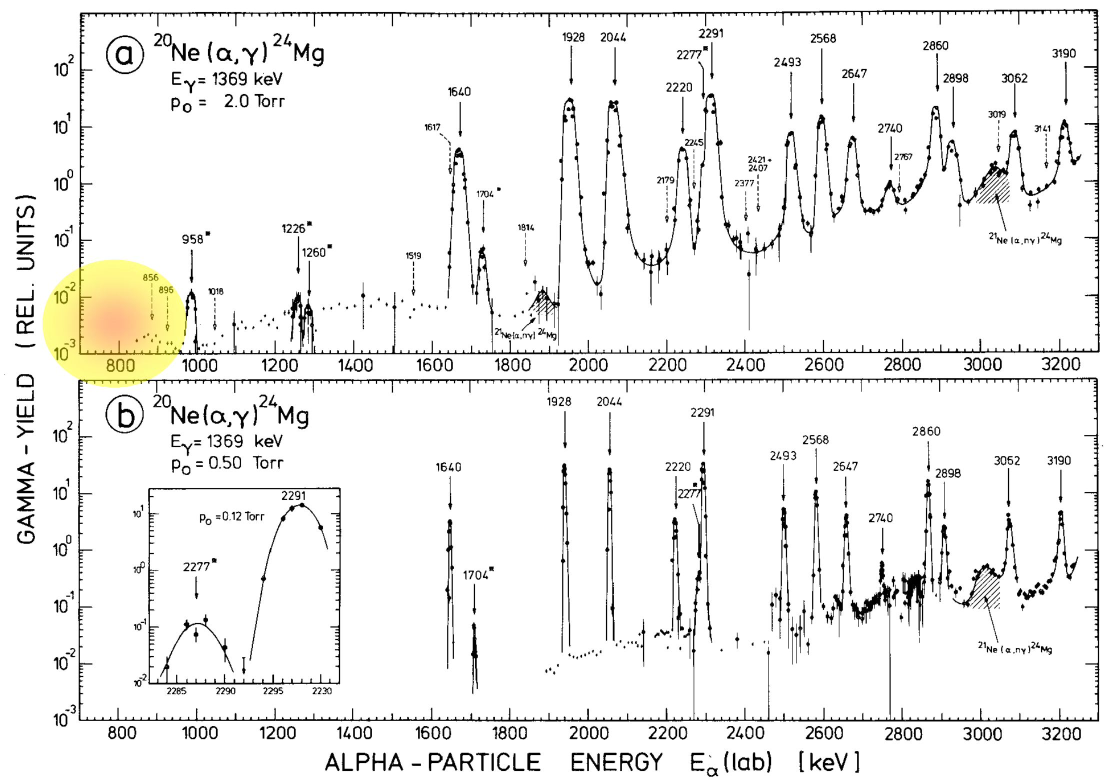
Release of α particles through photodissociation of weakly bound ^{20}Ne ((α,γ)-(γ,α)-equilibrium?) and subsequent α capture induced nucleosynthesis along the T=0 line. (α-cluster structure effects)

The ^{20}Ne(α,γ)^{24}Mg reaction

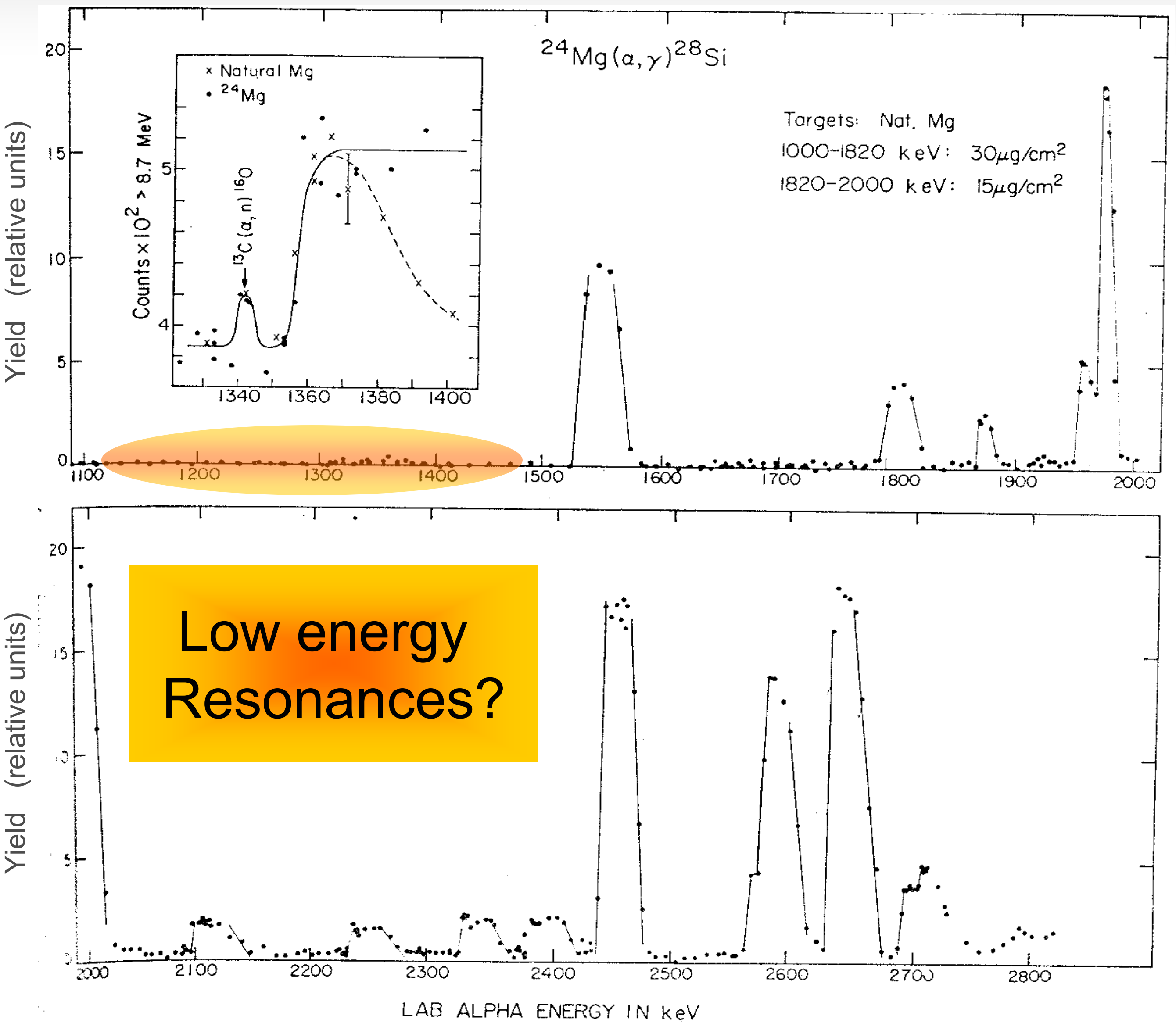


$$E_G = 0.122 \cdot \left(Z_1^2 \cdot Z_1^2 \cdot \mu \cdot T_9^2\right)^{1/3}\ [MeV]$$

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



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



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.

Summary & Conclusion

- Low energy cross section extrapolations still carry substantial uncertainties; besides improved experimental techniques (background reduction, detection efficiency) better theoretical tools are required.

- Multi-channel R-matrix is a powerful tool for low energy extrapolation taking into account “known” level structure as well as interference and coupling effects!

- He/C burning reactions are not sufficiently known! R-matrix approach limited ($^{12}C(\alpha,\gamma)$ & $^{13}C(\alpha,n)$) due to lack of low energy resonance data. Cluster model calculations may provide complementary tool!

- Uncertainties in reactions at later burning stages, mainly associated with secondary, convection driven processes