Uncertainties in Helium Burning Rates and Nucleosynthesis

The helium burning reaction rates are not well known experimentally

Triple Alpha—Rate	$R_{3\alpha}$	±12%	Few studies
$^{12}C(\alpha,\gamma)^{16}O$ –Rate	$R_{\alpha 12}$	±25%	Significant attention

Investigated sensitivity of nucleosynthesis to variations of $\pm 2\sigma$ in $R_{3\alpha}$ and $R_{\alpha 12}$

For low mass (2 M_{sun} Z=0.01) AGB stars
Herwig, Austin, Latanzio: Ap. J. Lett., **613**, L73 (2004); PRC **73,** 025802 (2006)

For massive (15, 20, 25 M_{sun}) stars undergoing core collapse and a SN explosion
Tur, Heger, Austin: ApJ **671**, 821(2007); **702**, 1068 (2009); submitted

The SN sensitivities are the main subject for today.

NSCL JINA

NSF PHY0606007 & PHY0822648 (JINA)

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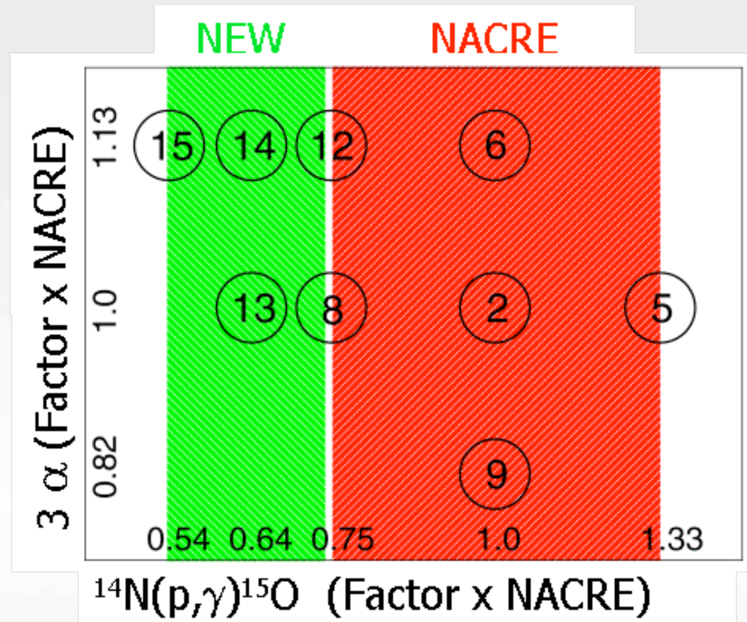
Results for Low-Mass AGB Stars

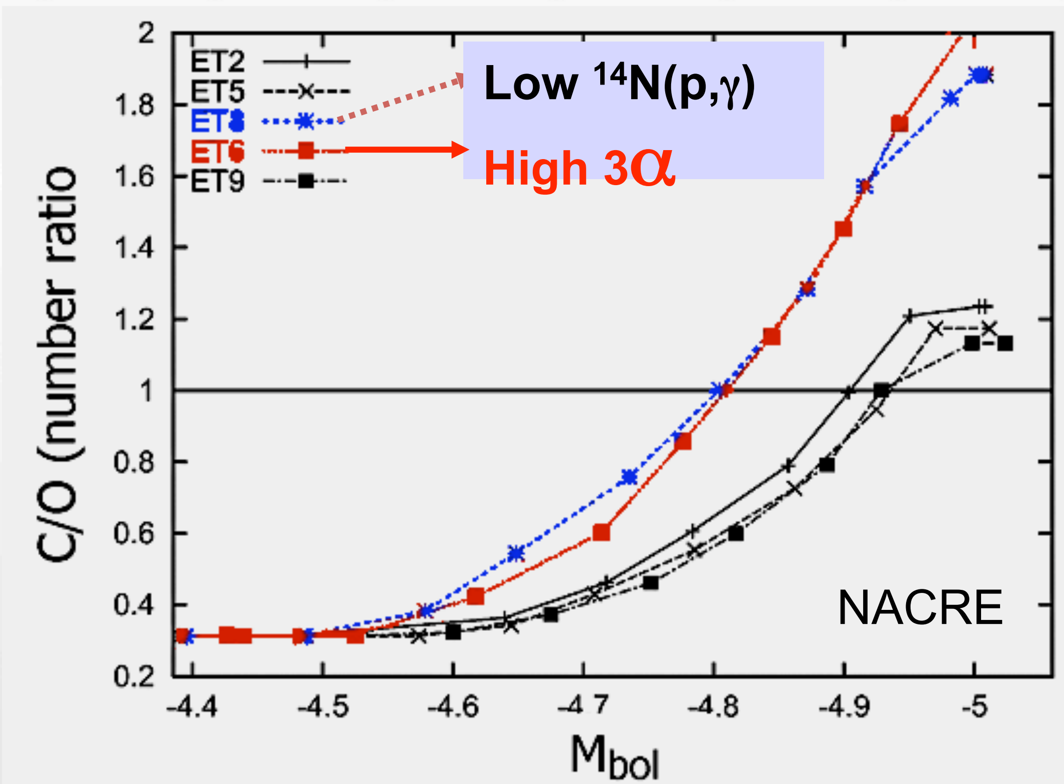
Motivation: Do low mass AGB stars become Carbon Stars?

Use code EVOL

Changes in $^{12}C(\alpha,\gamma)$ have weak effects

Rates: 2 (recommended), 5,6,8,9





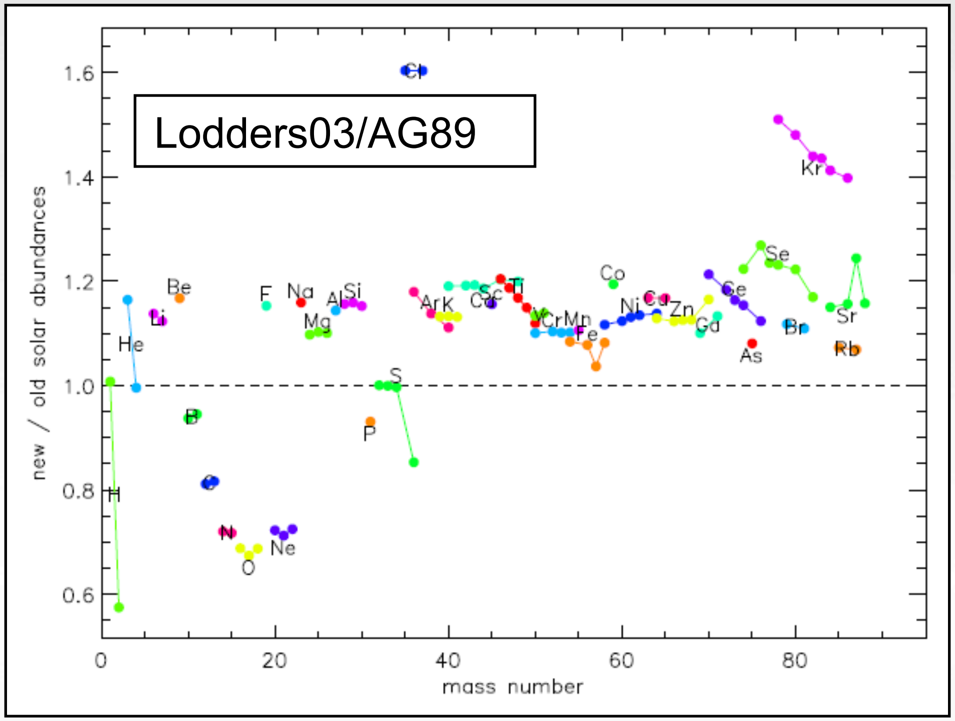
Higher R_{3a} (by $+1\sigma$) increases C/O by a factor of two over NACRE rates.

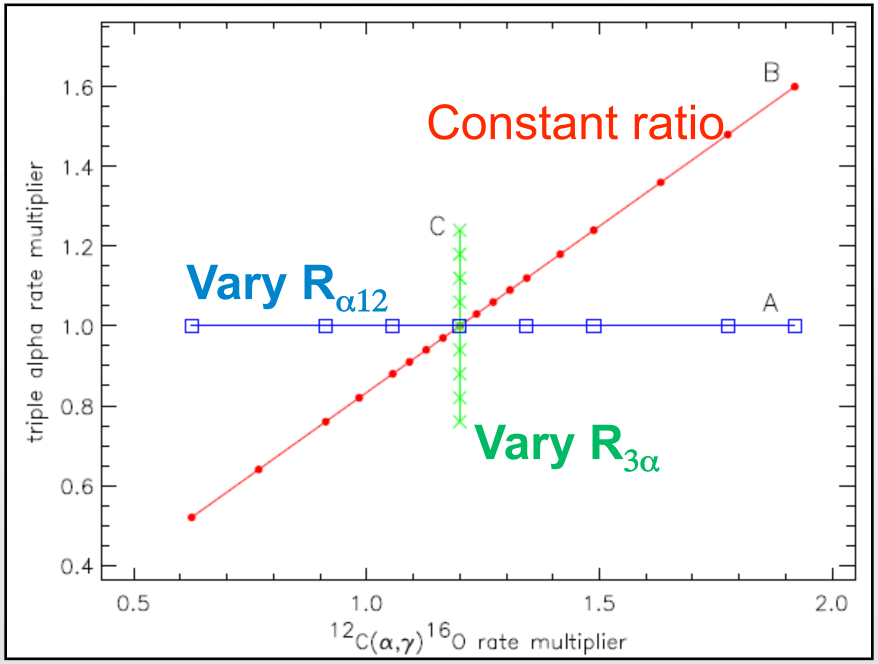
High R_{3a} ➔ Carbon Star

Calculations for Massive Stars

For 15, 20, 25 M_{sun} stars
Evolve to core collapse-KEPLER
Simulate ensuing explosion by a piston at the base of the O-burning shell (S=4k/Byon) that imparted 1.2 Bethe to the explosion products

Reaction rates (Vary by ± 2σ)

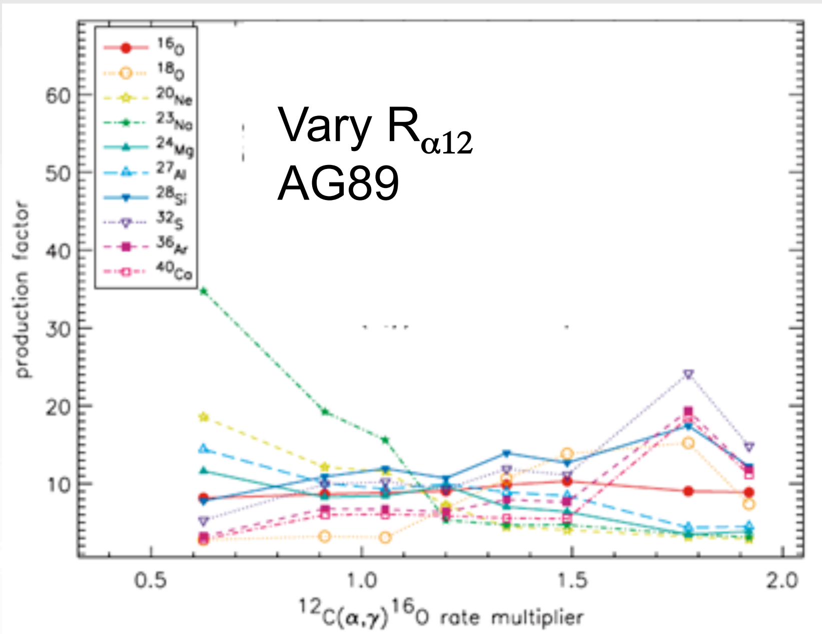


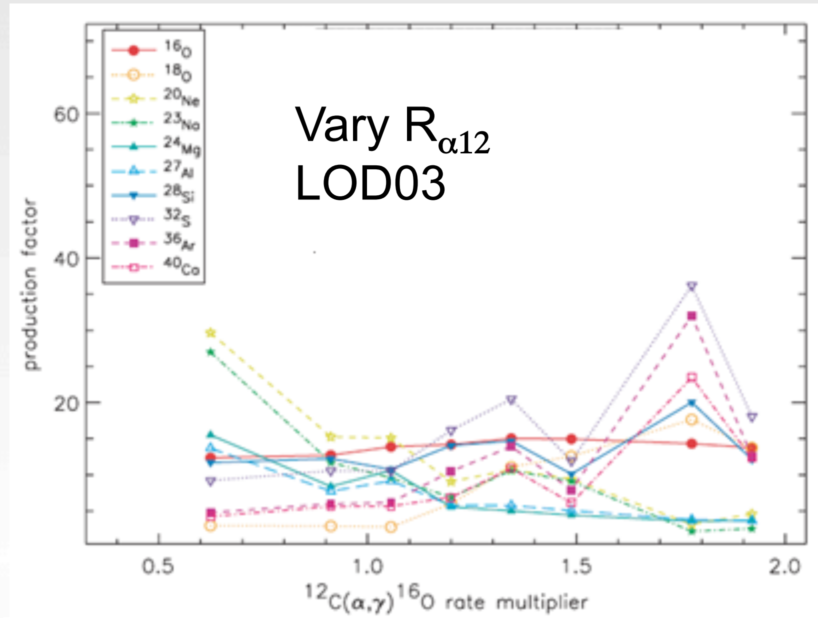


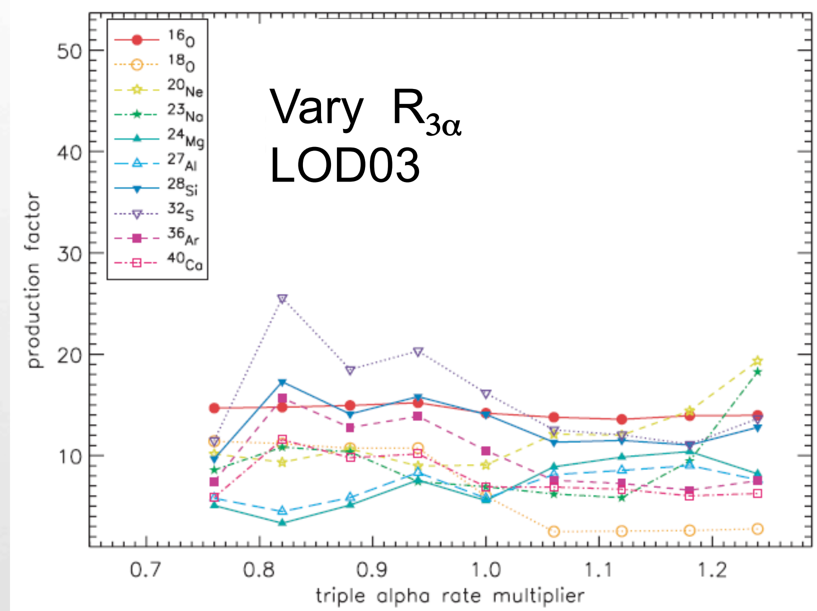
Calculate for both Ander-Grevasse (89) and Lodders(03 abundances.

Major difference: Lodders has ≈30% lower CNONe abundances—most other abundances are roughly15% higher

Nucleosynthesis for Massive Stars



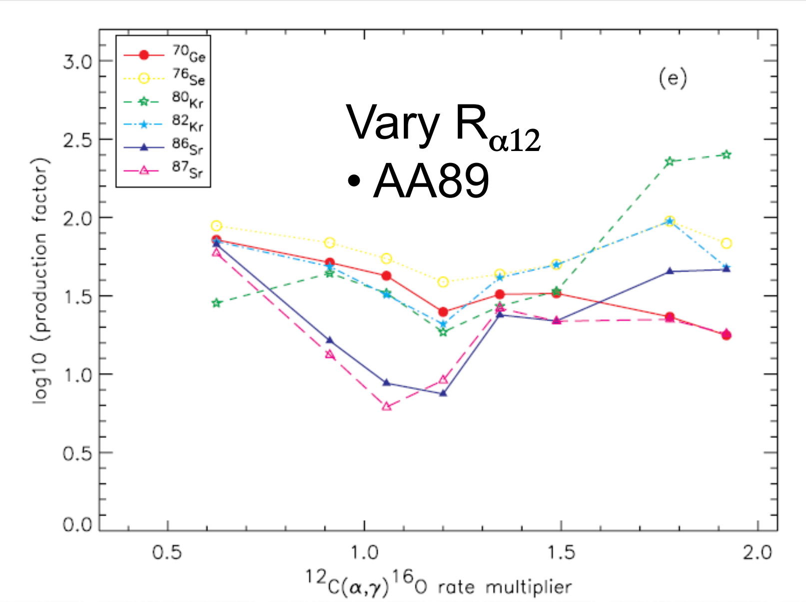


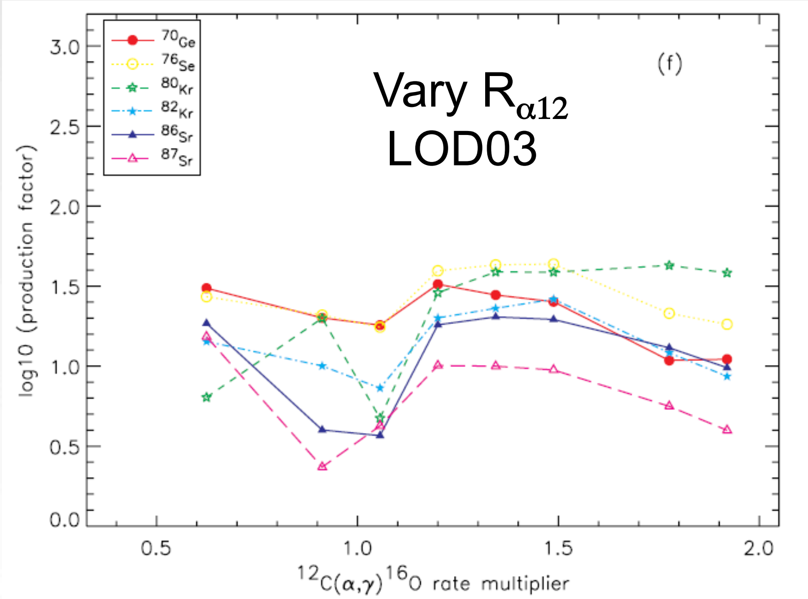


Significant variation of Production Factors for changes in either rate —factors of 5 to 10 occur.

Different for AA89 and LOD03 abundances.

More nucleosynthesis—S-Only Nuclei

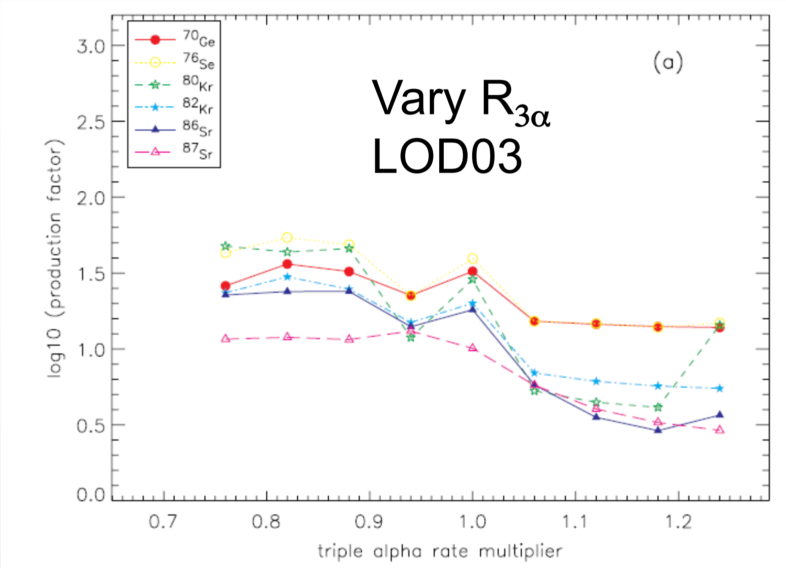




Note Log scale. Again significant variations for different abundances and for $R_{3\alpha}$ and $R_{\alpha 12}$

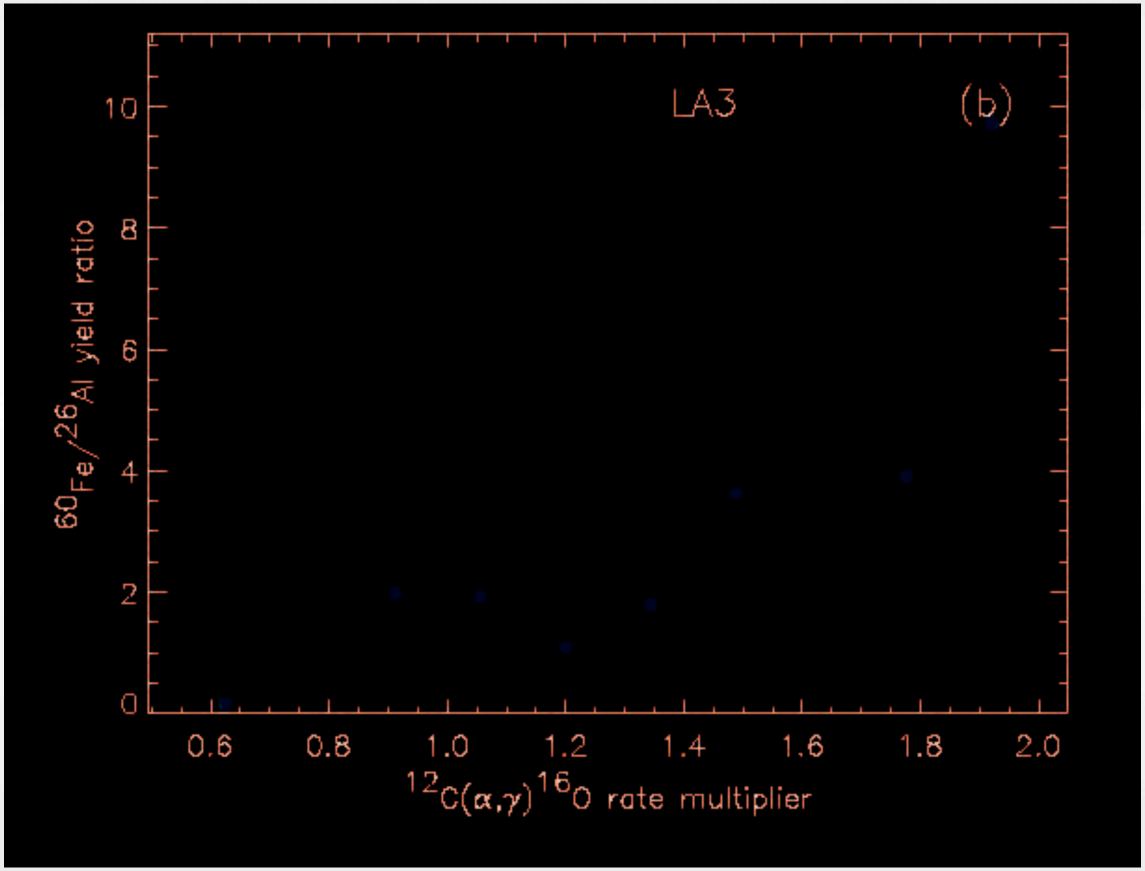
Side remark—still larger differences for the gamma emitters ^{26}Al, ^{60}Fe

Roughly factor 2 differences for neutrino production of ^{11}B, ^{19}F, ^{138}La, ^{180}Ta

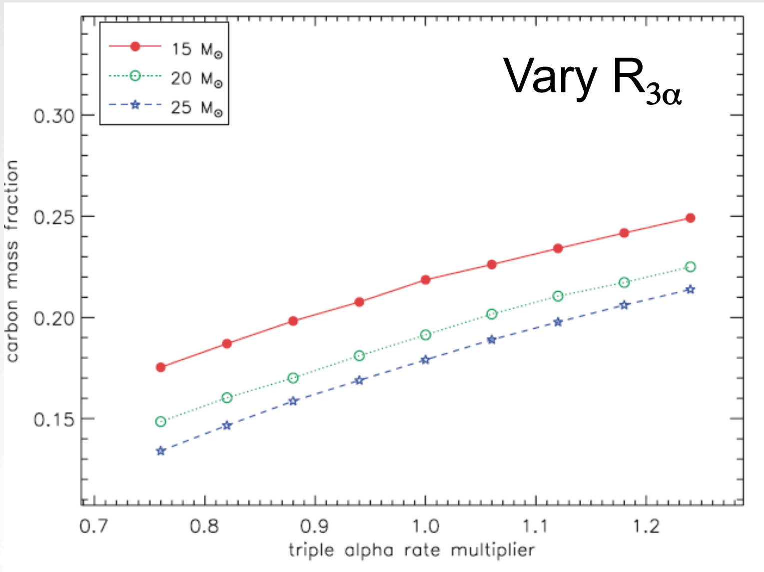


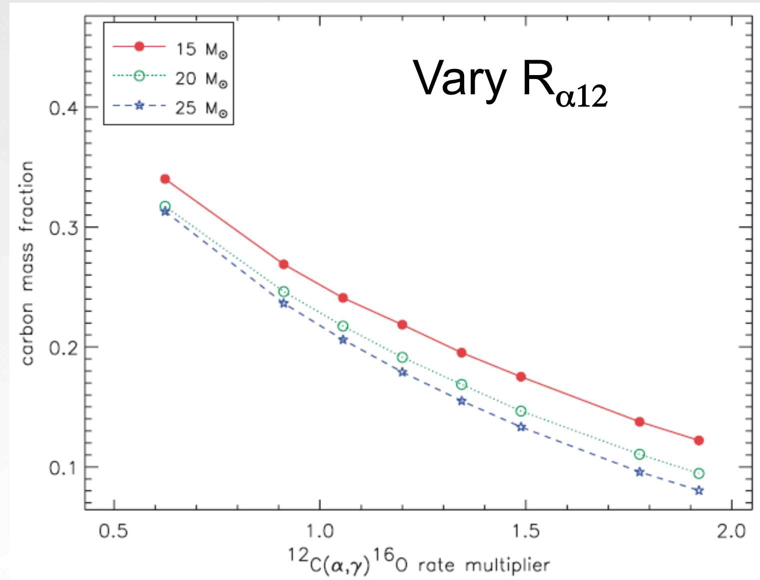
The Radioactive Nuclei

60Fe/26Al ratio is uncertain at the x10 level



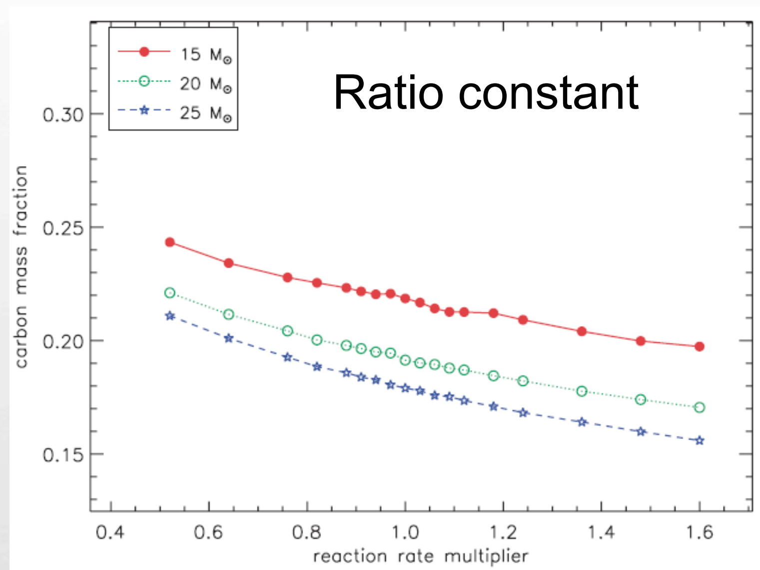
Central Carbon Mass Fraction at C ignition



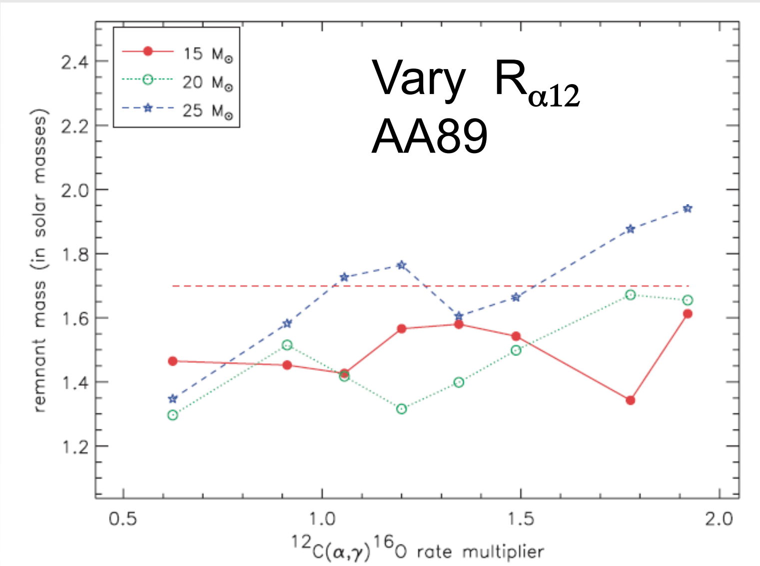


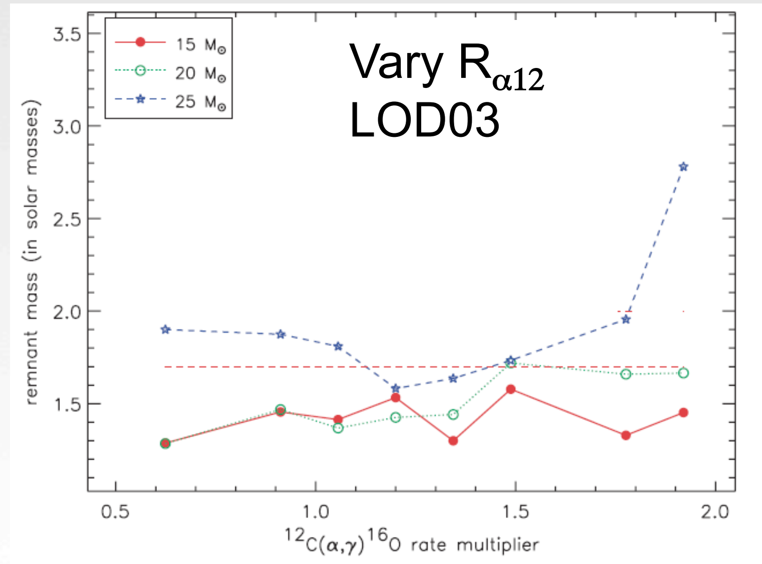
Significant variations of central C mass fraction with both $R_{3\alpha}$ and $R_{\alpha12}$ Similar for AA89 and LOD03 abundances—shown for LOD 03

Smaller but significant variation if the ratio of $R_{3\alpha}$ and $R_{\alpha12}$ is kept at its central value, but both rates are increased or decreased.



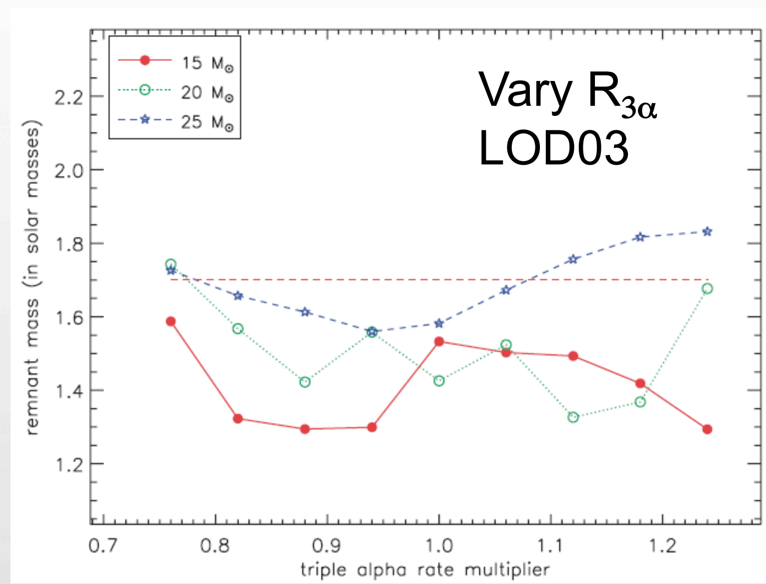
Remnant Mass





Significant non-monotonic changes in remnant mass (corrected for gravitational binding) for changes in $R_{3\alpha}$ or $R_{\alpha 12}$

Note: Takes 1 Bethe to dissociate 0.1 M_{sun}



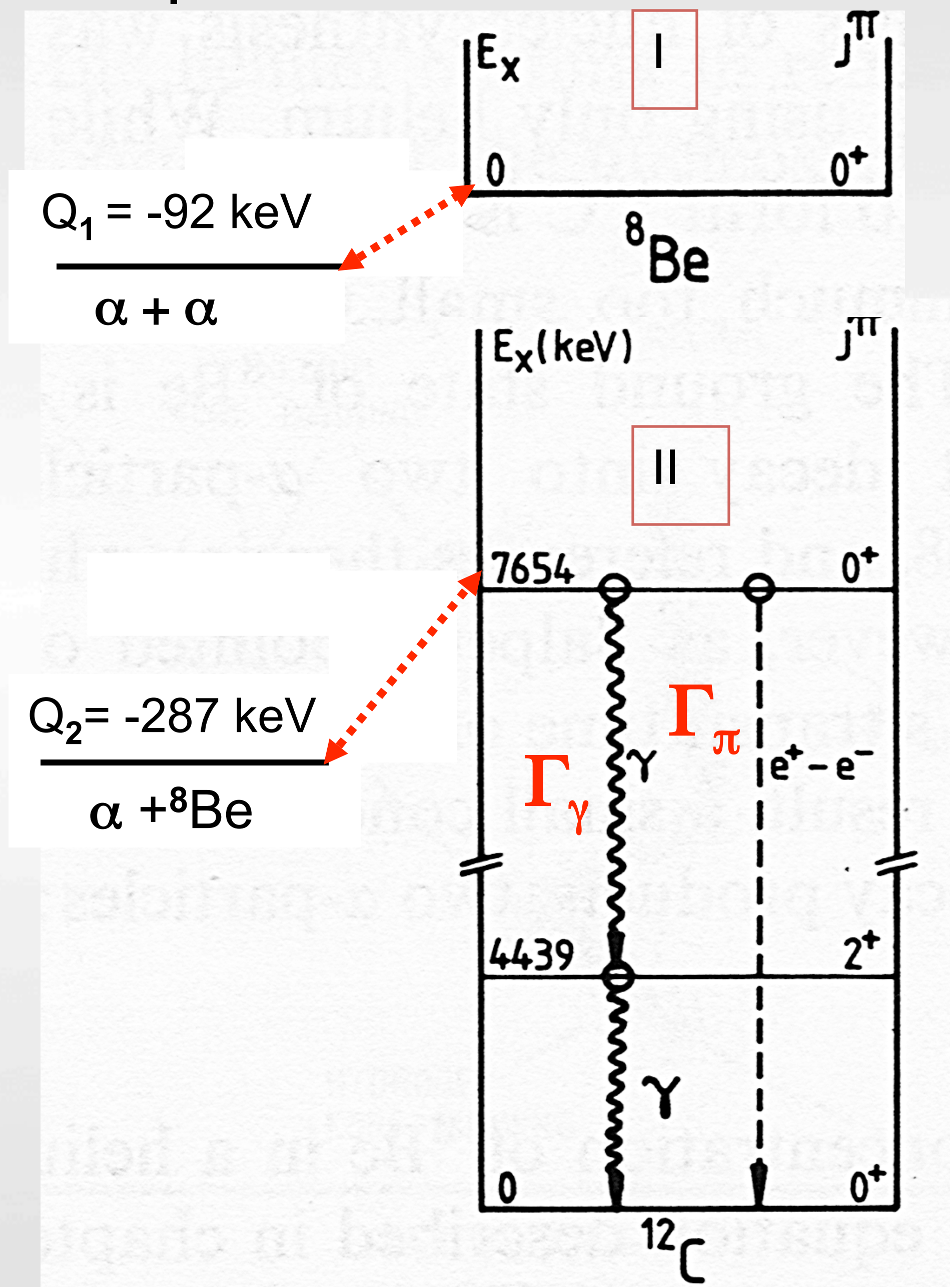
Improving the The Triple Alpha Reaction Rate

Step I: $\alpha+\alpha \Leftrightarrow {}^{8}Be$

Resonant process

Form equilibrium abundance of ^{8}Be

Step II: $^{8}Be + \alpha \Leftrightarrow {}^{12}C(7.65)$



If resonant as in core helium burning:

$$r_{3\alpha} \propto \Gamma_{rad}(7.65)e^{-Q/kt}$$

$$\Gamma_{rad} = \Gamma_{\gamma}+\Gamma_{\pi}\ ,\ Q = Q_1+Q_2$$

If non-resonant:

At very low or high T

Much more complex

Prospects for Improved *Resonant* $R_{3\alpha}$

$$\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{(\Gamma_\gamma + \Gamma_\pi)}{\Gamma} \frac{\Gamma}{\Gamma_\pi} \Gamma_\pi \qquad Q_{3\alpha} = E_r - 3M\alpha^2$$

Each arrow
a measurement

	Γ	Γ/Γ_π	Γ_π	$Q_{3\alpha}$
Experiments	≈8	3	2	6
Excluded results	1	0	0	0
Precision	2.7%	9.2%	6.4%	1.2%
Improvements possible?		4%	3.2%	

4% → WMU+MSU+ANL (to do)

3.2% → Darmstadt(in press)

If the improvements happen (likely?) then the uncertainty will be reduced from about **12% to about 6%.** Certainly there will be some improvement

Triple-alpha At Low T

Triple alpha is non-resonant process at sufficiently low T

Ogata et al. 2009, Progr. Theor. Phys., 122, 1055

CDCC calculations include non-resonant effects

At $T = 10^7$ $R_{3\alpha}$ is 10^{26} x NACRE

$T = 10^8$, 1.5×10^6 x NACRE

$T = 2 \times 10^8$, 1.9 x NACRE

At higher $T > 2.5 \times 10^8$, same as NACRE

Dotter and Paxton, A&A 507, 1617-1619 (2009) show that
Ogata rate results in stellar behavior that deviates from the observation of extended red giant branches for helium burning stars in old systems.

Is the rate calculation right?

Is screening dealt with appropriately?

An unresolved issue

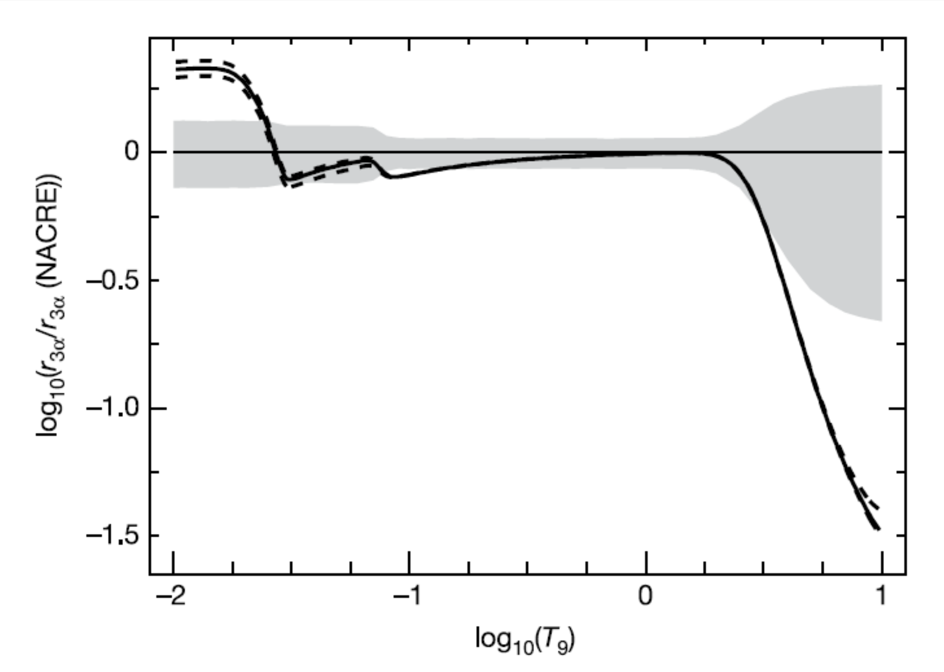
Triple Alpha at High T

Is there a $J^{\pi}=2^+$ resonance near 10 MeV in ^{12}C?

Predicted by cluster models

Not seen in β decay, claimed in (p,p') and (α,α')

Diget, et al Nature **433**, 136 (2005) show effect of 2^+ state near 10 MeV employed in NACRE rates—increases rate above 2 x 10^9 K:



Evidence for 2^+(inconclusive?):

(α,α): M. Itoh, Mod. Phys. Lett. A **21,**2359 (2006)

(p,p'): M. Freer, PRC **80**, 041303 (2009)

Detailed discussion: S. Hyldegaard, PRC **81**, 024303 (2020)

Another unresolved issue

Triple Alpha at High T, Density

An old/new issue: In matter the de-excitation of the Hoyle state can be enhanced by interaction with particles or electrons.

Shaw and Clayton(1967); Truran and Kozlovsky (1969); Morgan and Wisser (1970); Davids and Bonner (1971)

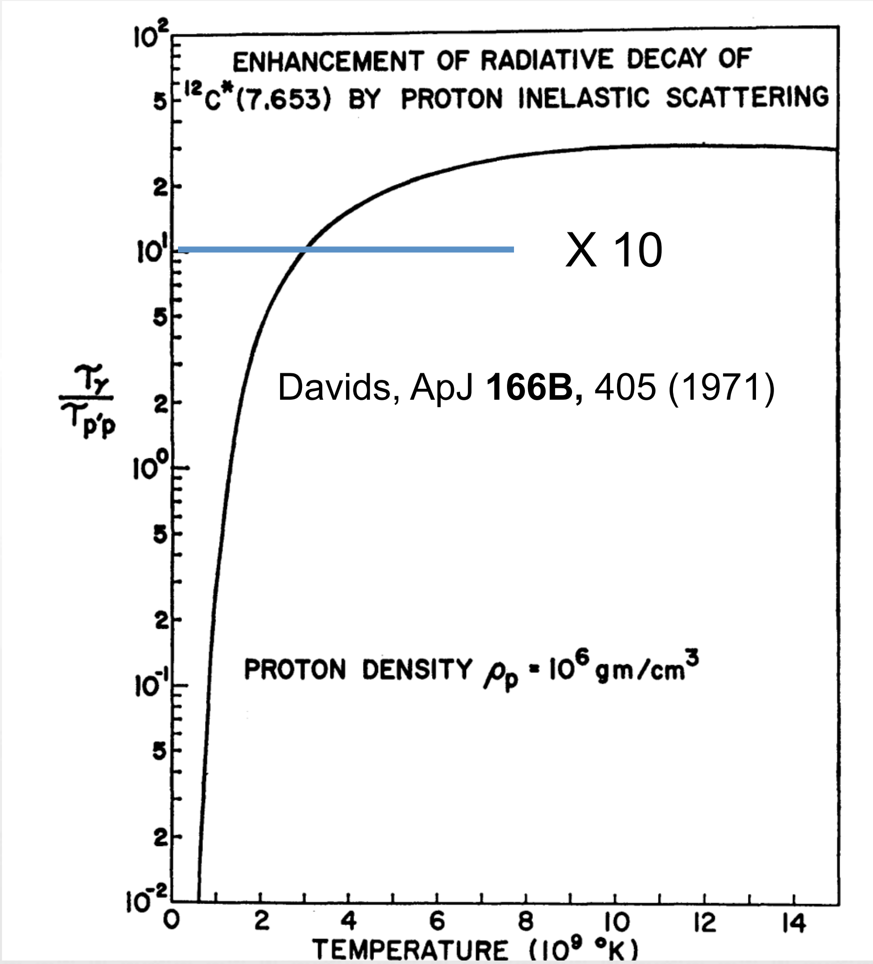
This will affect (increase) **any** reaction rate that depends on Γ_{rad}

The enhancement shown here is an **underestimate**. Doesn't include:

- De-excitation to the 4.44 MeV state
- Alpha particle scattering
- Neutron scattering

Important in x-ray bursters?

Important for (n,γ) reactions?



Prospects for Improved $R_{\alpha 12}$

To quote Woosley, et al. 2003: The major nuclear uncertainty afflicting modern studies of massive stellar evolution and nucleosynthesis continues to be $R_{\alpha 12}$

Similar statements have motivated MANY experiments and continue to do so. Yet the rate uncertainty remains large and there is no assurance that it will significantly decrease in the near future

The great majority of model studies use a specific rate, unpublished, but quoted, for example, by Woosley, et al. 2003.

Next we discuss how this determination was made.

The Boyes Determination

Evolve 15, 20, 25 M_{sun} stars, average

KEPLER

Anders & Grevasse (1989) abundances

Range of $R_{\alpha,12}$

No explosive processing

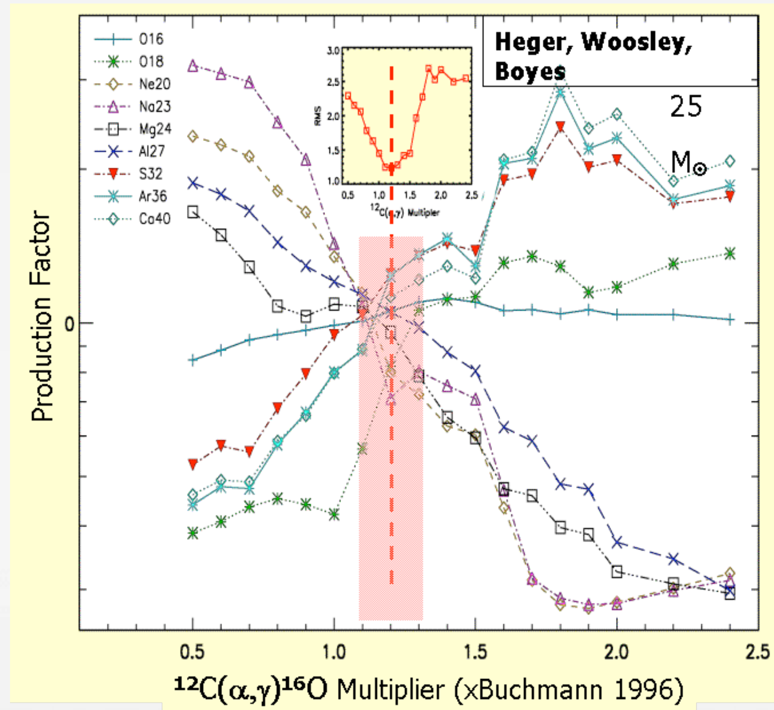
Find value of $R_{\alpha,12}$ that minimizes spread in Production Factors = **1.1 ± 0.1 x Buchmann,** Widely used as standard rate

Need to check. Why?

Explosive processing changes abundances

20 M_{sun} stars have anomalous nucleosynthesis—average over more stars

Come back to other issues



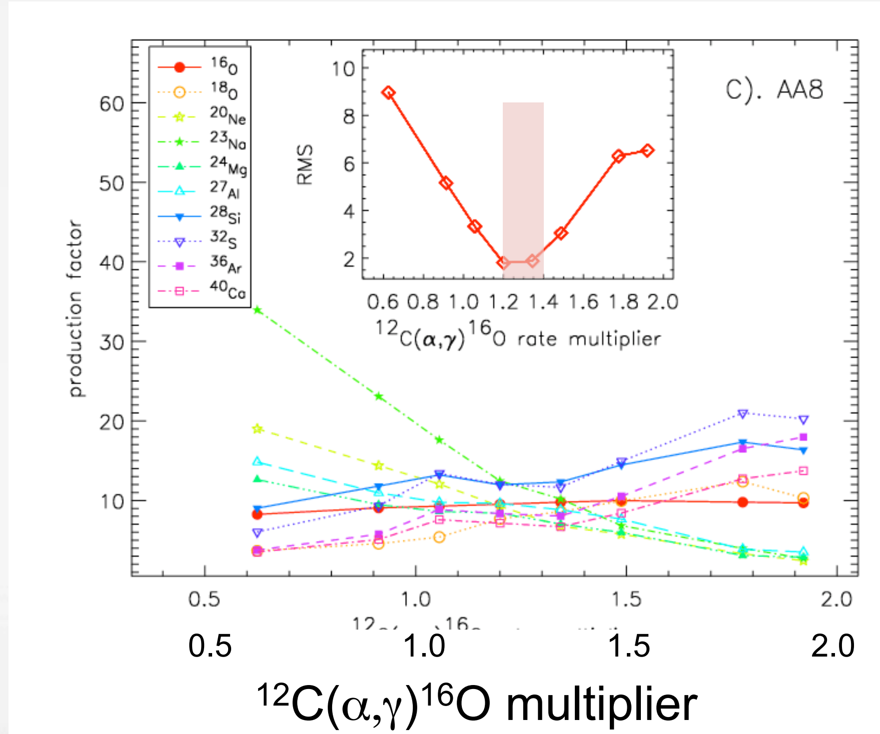
Check on Boyes

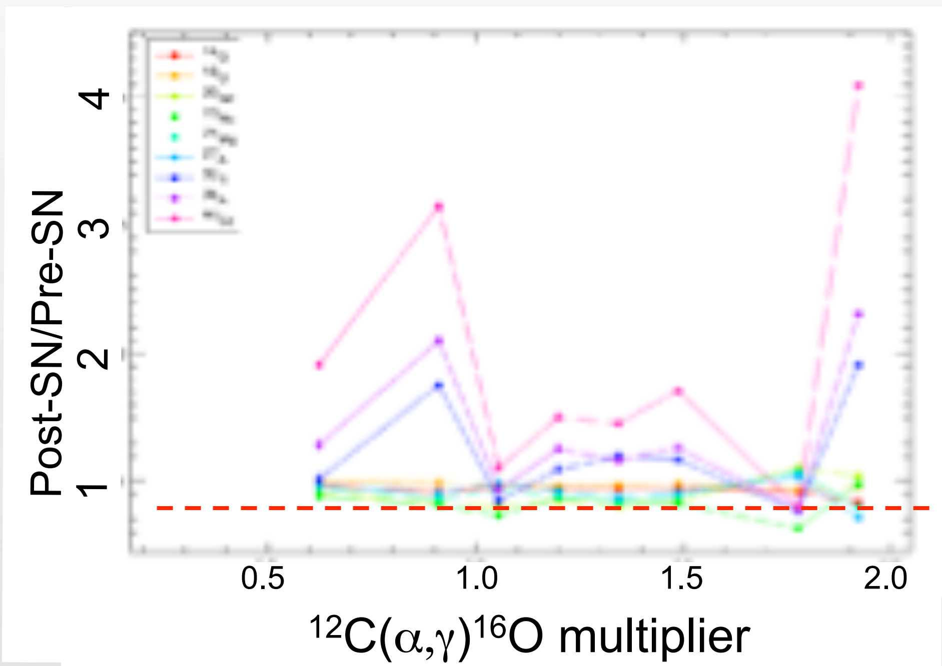
Large star set: 13, 15, 17, 19, 21, 23, 25, 27 M_{sun}

AG89 abundances

Include explosive processing

Reasonable agreement in minimum (1.3 vs 1.2) and rms scatter at minimum. ± 0.1 seems too accurate





Somewhat surprising, since explosion changes abundances by >x2 for A>30

Issues Not Resolved

PROBLEM: Rate derived for a specific case, but used in many situations

Does not always work

For LOD03 RMS minimum is poorly defined

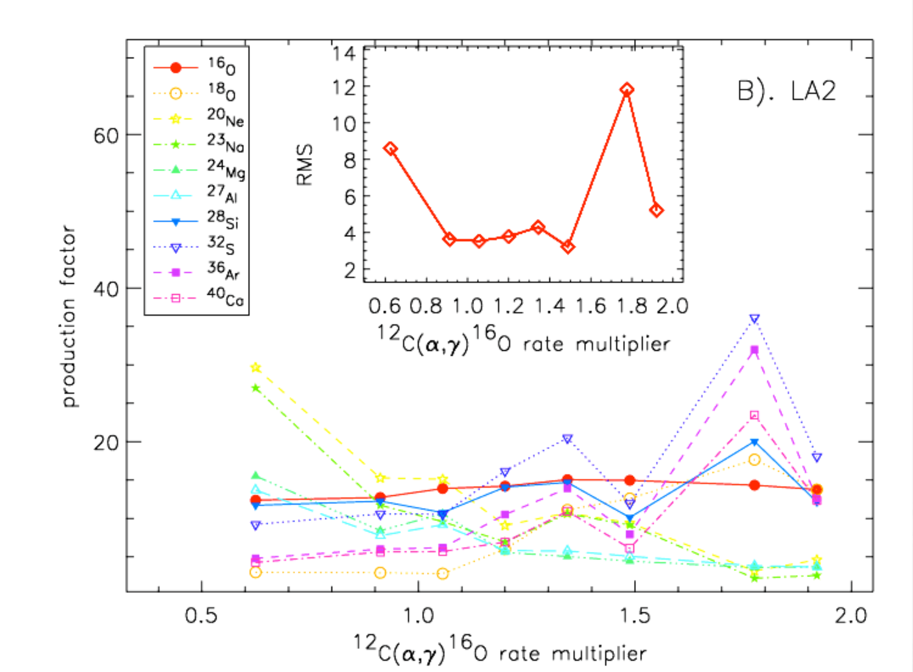
Other things not considered in detail

Different models, convection, etc.

$R_{3\alpha}$ uncertain

Changes with metallicity

· Changes with mass



An Effective Reaction Rate

A safer point of view: Define an "Effective Reaction Rate" with application limited to a specific code.

Determine dependence of interaction on

- Metallicity
- Mass
- Range of nuclei described
- $R_{3\alpha}$ --When $R_{3\alpha}$ is better known, can avoid latter dependence—until then it's an uncertainty.

Parameterize dependence of these quantities

Compare results for different codes.

A lot of work

Some Directions

Need to understand the uncertainties in the simulation codes so we can understand the reliability of our simulations and whether any discrepancies with observation are real.

Specific needs for SNII:

Compare the results of extant codes for some benchmark cases.

Develop an open source SN code, with open source rates.

Incorporate insights from multi-D calculations: convection issues, explosion issues

Evaluate of effects of uncertainties in input abundances and reaction rates

Well predicted abundances

Some abundances are more sensitive to uncertainties than others.

Perhaps one should concentrate, as far as possible, on those isotopes/ elements that are less sensitive to the nuclear physics uncertainties