# Sensitivity of $^{26}$Al, $^{44}$Ti, and $^{60}$Fe production in SNII To triple-alpha and $^{12}C(\alpha, \gamma)^{16}O$ reaction rates

C. Tur, A. Heger, **S M. Austin**

Motivation--The helium burning reaction rates are not well known experimentally

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

QUESTION- sensitivity of AGB, SN II nucleosynthesis to $R_{3\alpha}$ and $R_{\alpha 12}$

For low mass (2 $M_{sun}$ Z=0.01) AGB stars—$^{12}$C production

Herwig, Austin, Latanzio: Ap. J. Lett., **613**, L73 (2004); PRC **73,** 025802 (2006)

Strong sensitivity to $R_{3\alpha}$ Little to $R_{\alpha 12}$

For massive (15, 20, 25 $M_{sun}$) stars undergoing core collapse and a SN explosion

Tur, Heger, Austin: ApJ **671**, 821(2007); ApJ **702**, 1068 (2009); ApJ **718**, 357 (2010)

$12 < A < 40$ weak S $^{26}$Al, $^{44}$Ti, $^{60}$Fe

Strong sensitivity to $R_{\alpha 12}$ AND $R_{3\alpha}$

The $^{26}$Al, $^{44}$Ti, $^{60}$Fe results are the subject for today.

NSF PHY0606007 & PHY0822648 (JINA)

# Preview of the results

| Rate | $^{26}$Al(1$\sigma$) | $^{44}$Ti(1$\sigma$) | $^{60}$Fe(1$\sigma$) | $^{26}$Al(2$\sigma$) | $^{44}$Ti(2$\sigma$) | $^{60}$Fe (2$\sigma$) |
|---|---|---|---|---|---|---|
| $R_{3\alpha}$ | 1.5 | 1.2 | 5.0 | 2.8 | 1.6 | 7.8 |
| $R_{\alpha 12}$ | 2.3 | 1.3 | 4.4 | 2.6 | 2.2 | 7.4 |
| $\Sigma$ | 2.7 | 1.8 | 6.6 | 3.8 | 2.7 | 10.7 |

Yield uncertain by factors of 2-6 for $\pm 1\sigma$ variation of rates, larger for $\pm 2\sigma$
$R_{\alpha 12}$ and $R_{3\alpha}$ contribute similarly to uncertainty

Observations yield accurate gamma-ray intensities for these nuclei. Provide, in principle:

Test of SN models.
Estimate of SN rate.

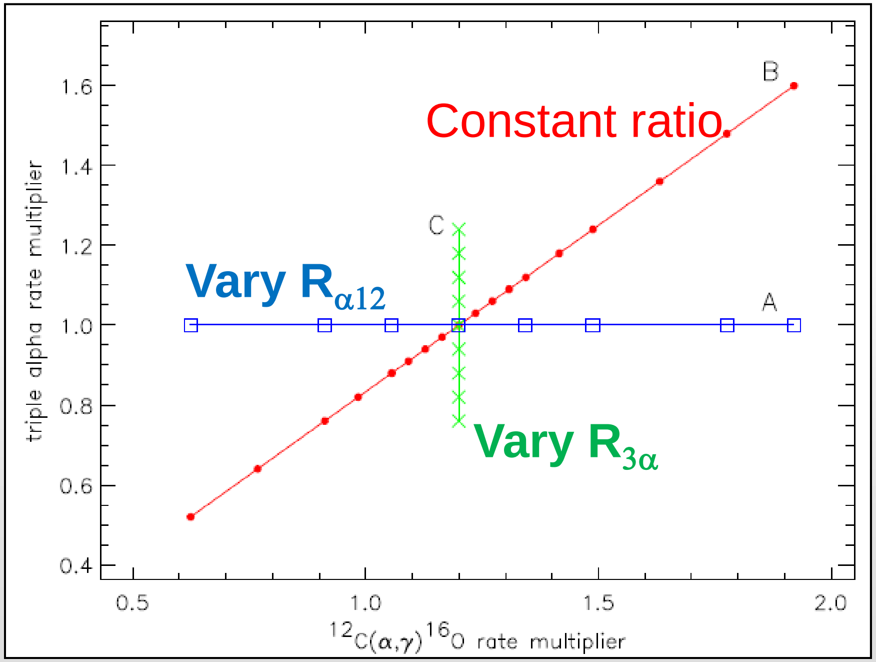
**Our question**: Are $R_{\alpha 12}$ and $R_{3\alpha}$ well enough known to provide rigorous interpretation?

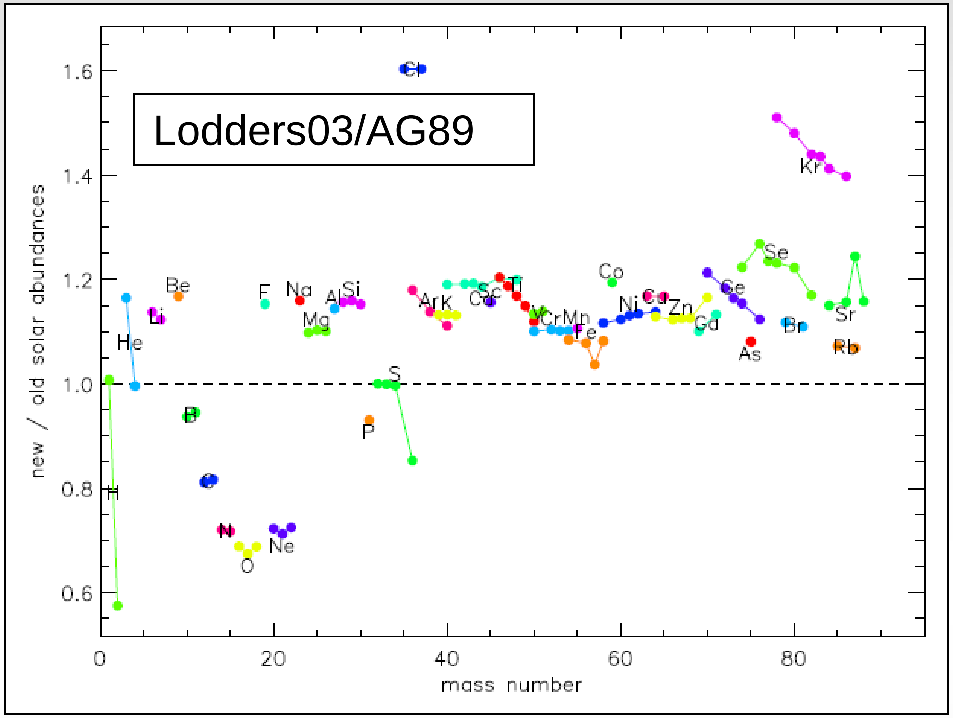
**Answer**: Probably not. Table shows
(maximum yield)/(minimum yield)
$\pm 1\sigma$ and $\pm 2\sigma$ ranges of rates

# SNII Calculations

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/Baryon) that imparts 1.2 Bethe to the explosion products

Vary Helium burning rates by ± 2σ

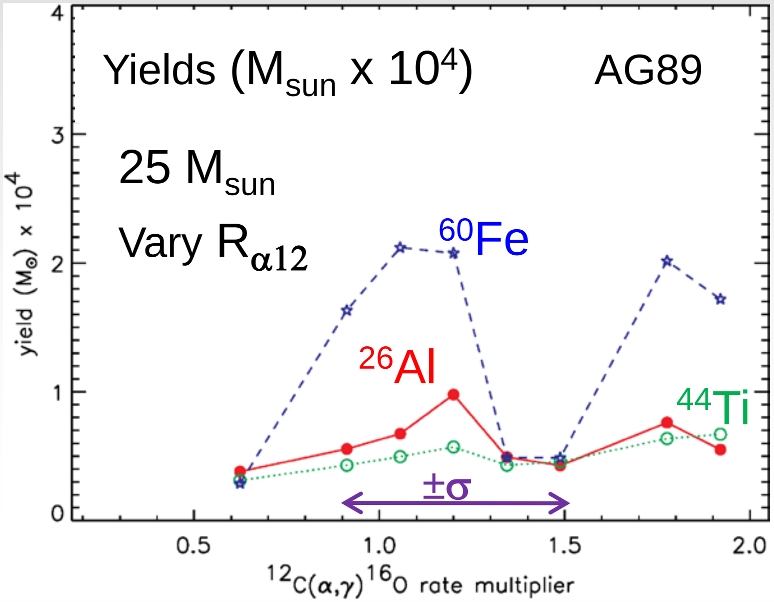


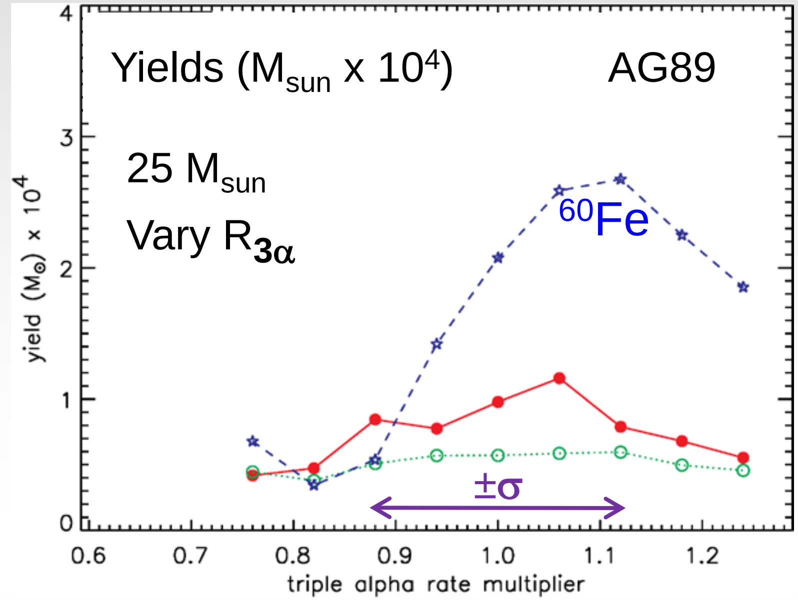



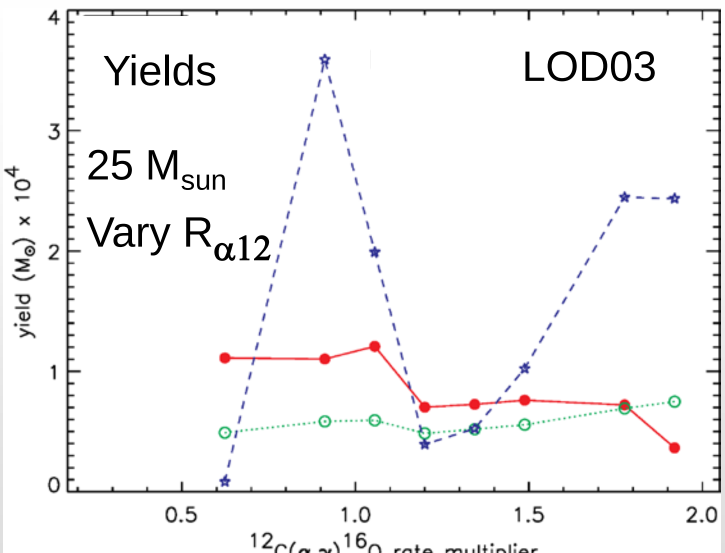

Calculate for both **Anders-Grevasse** AG(89) and Lodders(03) abundances.

Major difference: Lodders has ≈ 20-30% lower CNONe abundances—most other abundances are roughly15% higher.

# Yields for 25 $M_{sun}$ Star



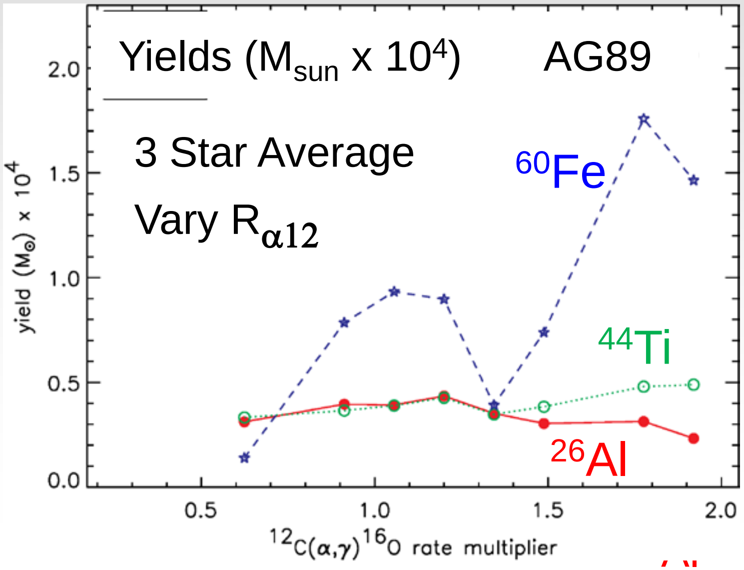



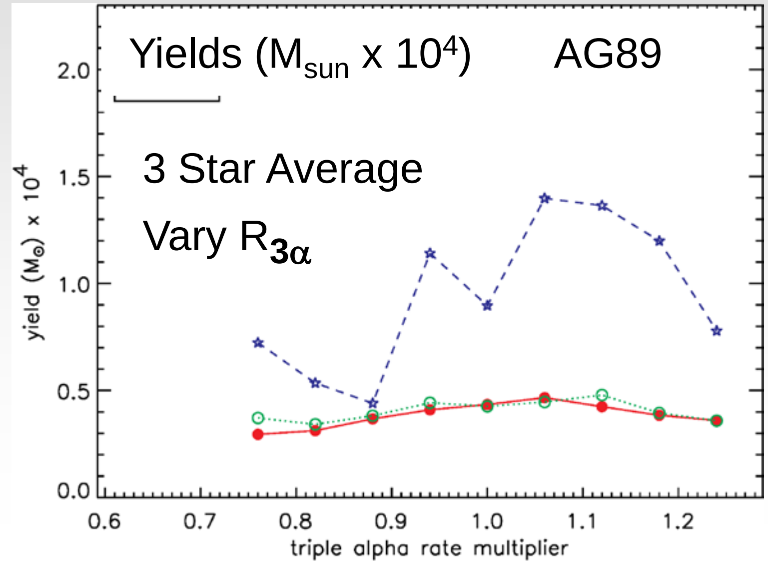

Large variations within $\pm\sigma$, sometimes very rapid

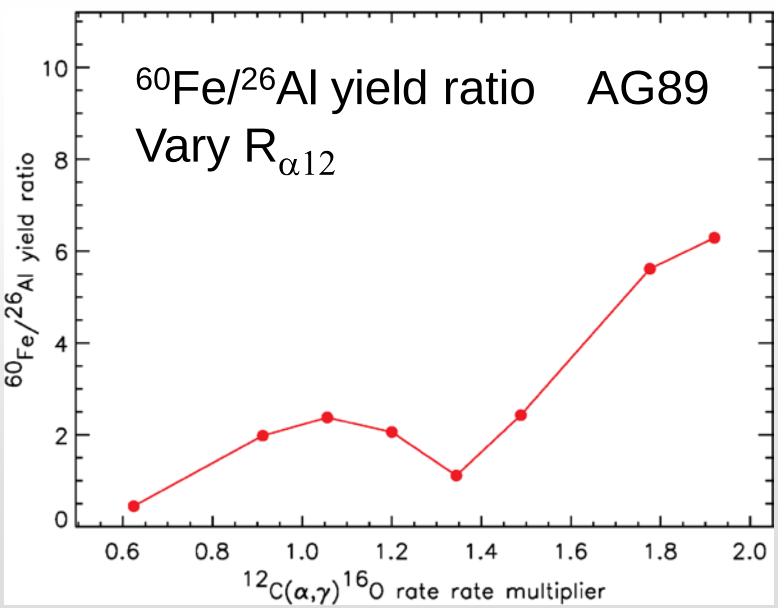
Uncertainties in $R_{3\alpha}$ as important as those in $R_{\alpha 12}$

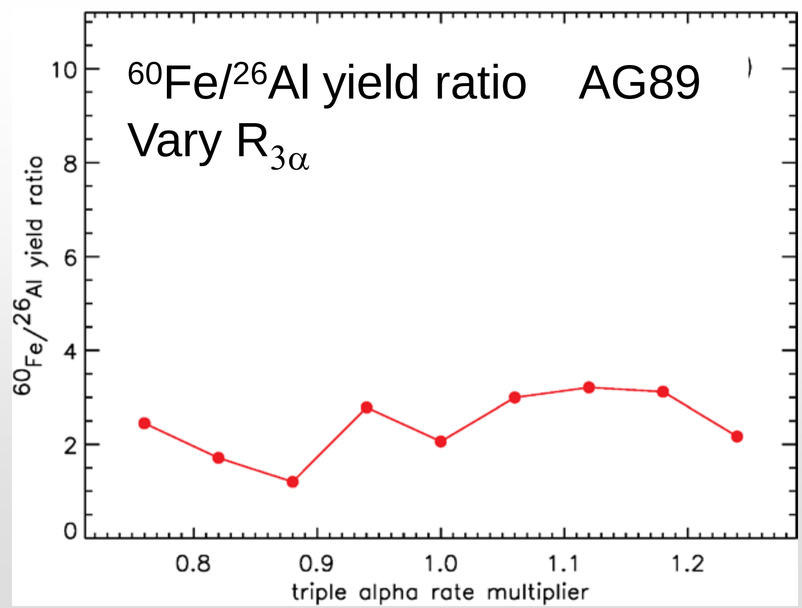
Some dependence on abundances--AG89 vs LOD03

# Three star average—Differences still large



# Why sensitive to helium burning rates?

Helium burning rates affect the convection structure of the star

Lifetimes of $^{26}Al$, $^{60}Fe$ depend strongly on temperature—From Limongi 2006

$^{60}Fe$: $t_{1/2}$ (lab) = 2.6 x $10^6$ yr, $t_{1/2}(10^9$ K) = 0.5 yr

$^{26}Al$: $t_{1/2}$ (lab) = 7.2 x $10^5$ yr, $t_{1/2}$ (2.5 x $10^8$ K)= 0.19 yr

If made in a hot region they will mainly be destroyed ***unless*** they are convected to a cooler region.

Convection can bring reactants to a hot region where reaction rates are larger

An example: Compare yield of $^{60}Fe$, 25 $M_{\mathbf{sun}}$ star, in two cases

$R_{\alpha 12}$ ($R_{3\alpha}$) = standard (standard)--Convective O shell mixes with $^{12}C$ layer

above, much $^{60}Fe$ destroyed

$R_{\alpha 12}$($R_{3\alpha}$) = (standard, standard + 18%) No mixing. Yield of $^{60}Fe$ is 5.5 times larger

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

$$R_{3\alpha} \propto \quad \Gamma_{rad}^{\text{Hoyle}} = \frac{\left(\Gamma_\gamma + \Gamma_\pi\right)}{\Gamma} \frac{\Gamma}{\Gamma_\pi} \; \Gamma_\pi$$

$$\Uparrow \qquad \Uparrow \qquad \Uparrow$$

Each arrow
a measurement

| | | | |
|---|---|---|---|
| Experiments | ≈8 | 3 | 2 |
| Excluded results | 1 | 0 | 0 |
| Precision | 2.7% | 9.2% | 6.4% |
| Improvements possible? | | 4% | 3.2% |

WMU+MSU+ANL (to do)

Darmstadt(PRL)
Chernykh, et al.

The Darmstadt results reduce the uncertainty from about 12% to10.2%. If the pair branch can be measured to 4%, the overall all uncertainty will be about 6%.

# Comments on the $^{12}C(\alpha,\gamma)^{16}O$ rate

Many experiments, but the normalization and energy dependence of $R_{\alpha 12}$ remains poorly known—experimentally it is a daunting challenge.

Many model studies use the Boyes' rate, unpublished, but often quoted, for example, in Woosley & Heger, Phys. Rep. 442, 269 (2007).

> Determined by finding the value of $R_{\alpha 12}$ that yields the minimum spread in SNII production factors for a set of light nuclei made in 15, 20, 25 $M_{sun}$ stars.

$R_{\alpha 12}$ is found to be1.2 ± 0.1 times the rate presented in Buchmann 96,97 Astrophys. J. Lett. 468, L127, 479, L153.

We now present, and criticize, an improvement of the Boyes' procedure

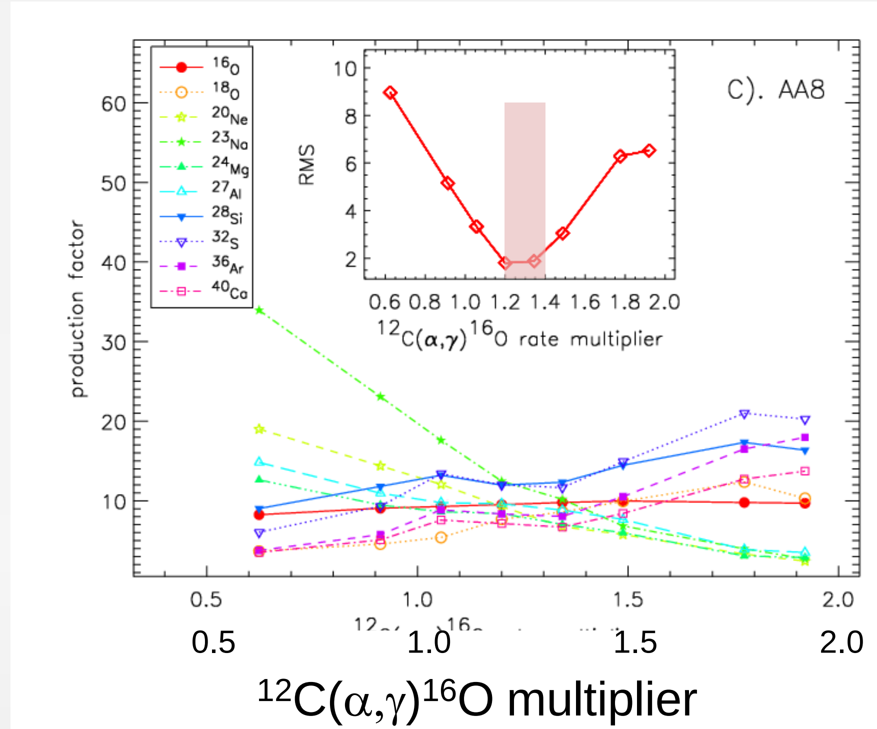
# Improvement on Boyes' Procedure

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

AG89 abundances

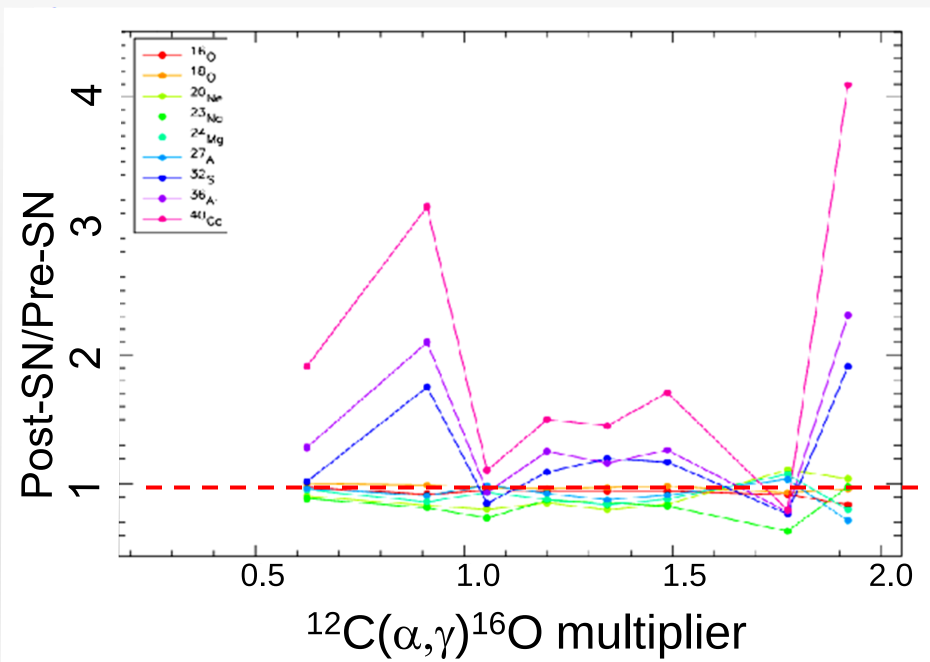
Include explosive processing—not done by Boyes—important (below).

Assume Buchmann (96, 97) energy dependence




Reasonable agreement in minimum (1.3 vs 1.2) and rms scatter at minimum. Somewhat surprising, since explosion changes abundances by >x2 for A>30

Uncertainty of ± 0.1, as shown, appears too small in light of large rms.



# 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

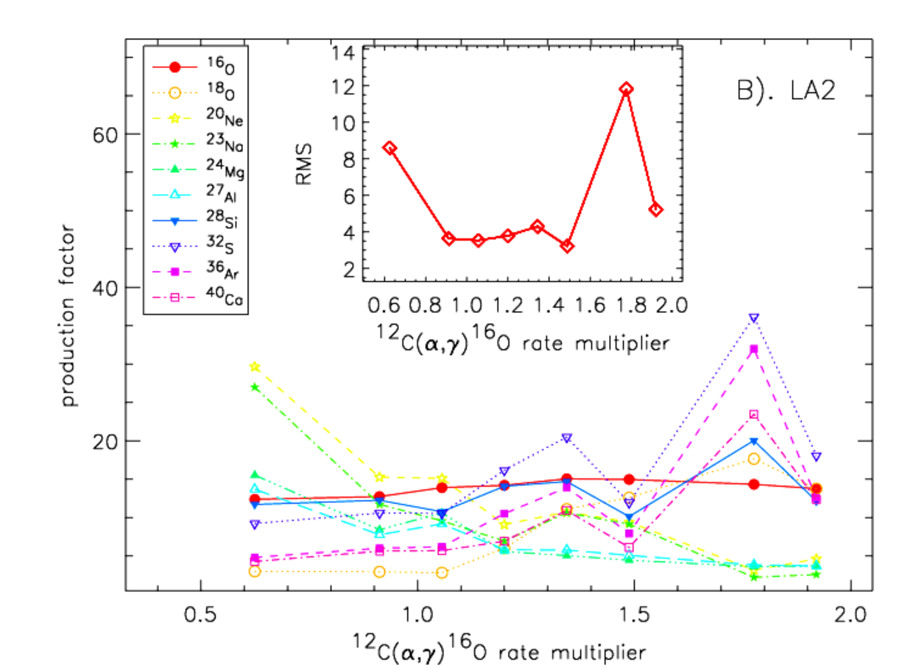
$R_{3\alpha}$ uncertain

Different models, convection, etc.

Changes with metallicity

Changes with mass

An effective rate, only valid for the situation for which it was obtained



# Summary

Simulations of SNII find large changes in the yields of $^{60}Fe$, $^{26}Al$ and (to a lesser extent) $^{44}Ti$ as $R_{3\alpha}$ and $R_{\alpha 12}$ are varied within their experimental limits.

Uncertainties in other rates and in model (e.g. convection) and calculational details will further increase uncertainties.

Comparisons to observed gamma intensities

Diehl et al. Nature 439, 45 (2006) argue that the $^{26}Al$ gamma flux corresponds to 1.9 ± 1.1 SN events/century. Uncertainty will be larger.

Wang et al. A&A 469, 1005 (2007) determined that the yield ratio $^{60}Fe/^{26}Al = (60/26)(0.15 \pm 0.06)$. Comparisons with SN model calculations will be unconvincing because of the large rate uncertainties

Improvements in helium burning rates

Reasonable prospects for decreasing uncertainty in $R_{3\alpha}$ to ± 6%

Situation for $R_{\alpha 12}$ is less clear, but there will be progress in the long run.

The widely used Boyes' $R_{\alpha 12}$ rate is weakly justified, and as a minimum should be revised.