BRANCHINGS, NEUTRON SOURCES AND POISONS: EVIDENCE FOR STELLAR NUCLEOSYNTHESIS

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STRUCTURE OF THE TALK

1. Evidence for neutron sources in AGB stars. What are these stars? Which neutron sources?

2. Recent precise observational constraints on neutron captures on heavy elements from meteoritic SiC grains from AGB stars. Relevant examples: ^{95}Mo/^{96}Mo, Ru, Pd, ^{80,86}Kr/^{82}Kr.

3. Neutron captures and the light elements: Neutron Poisons. Examples ^{14}N(n,p)^{14}C and light elements in meteoritic grains, e.g. Mg, Si, Ti, Ca,…,: Galactic Chemical Evolution and the AGB component.

4. Summary and Conclusions

FIRST EVIDENCE OF STELLAR NUCLEOSYNTHESIS (1950S) :
The presence of Tc in the envelopes of some red giant stars.

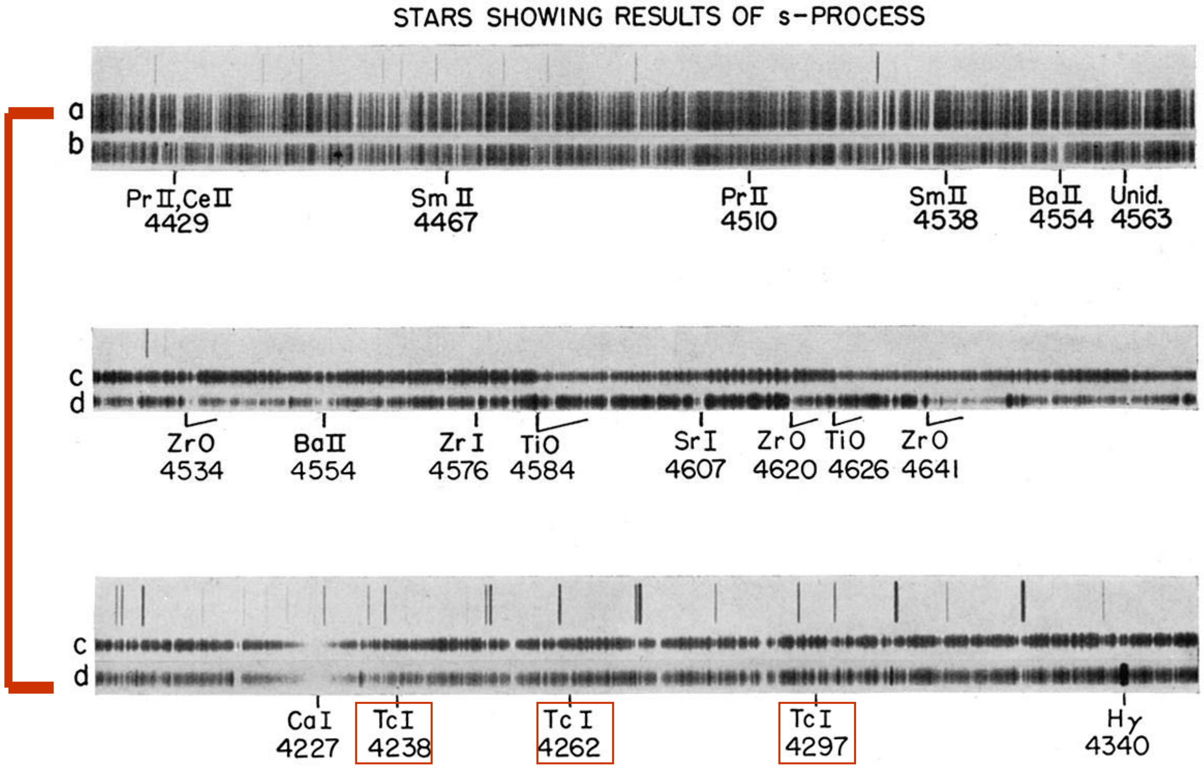


PLATE 3.

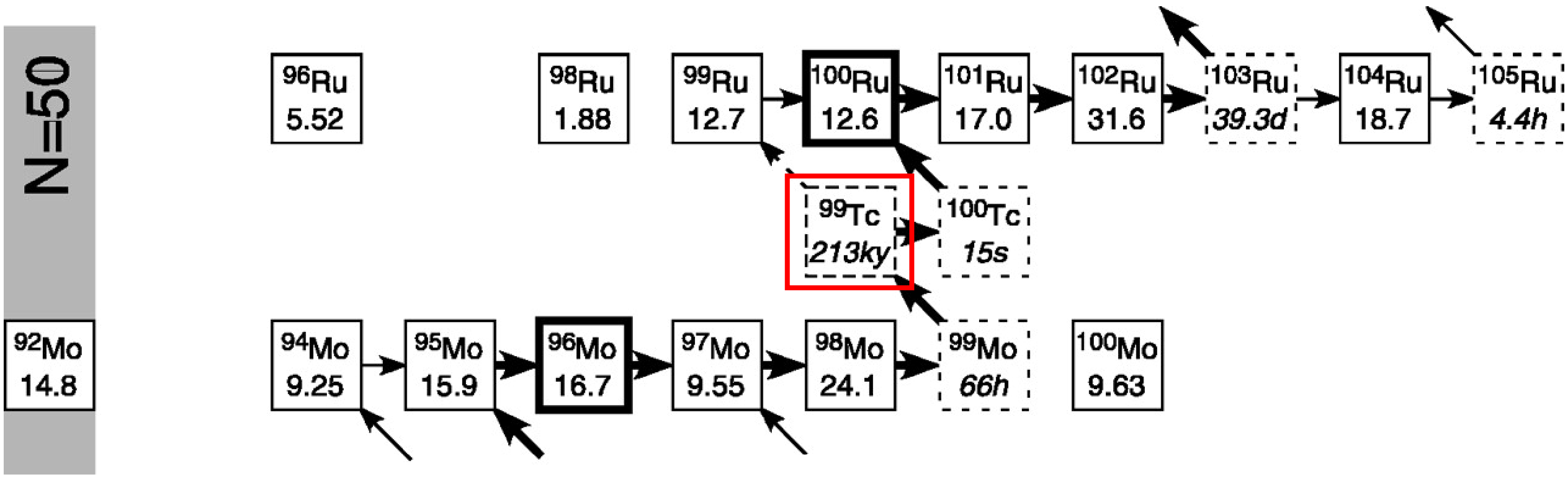
PLATE 3. Portions of the spectra of stars showing the results of the *s* process. Upper: (a) Normal *G*-type star, κ Geminorum. (b) Ba II star, HD 46407, showing the strengthening of the lines due to the *s*-process elements barium and some rare earths. Middle: (c) *M*-type star, 56 Leonis, showing TiO bands at λλ 4584 and 4626. (d) *S*-type star, R Andromedae, showing ZrO bands which replace the TiO bands. Lines due to Sr I, Zr I, and Ba II are all strengthened. Lower: (c) Another spectral region of the *M*-type star, 56 Leonis; note that Tc I lines are weak or absent. (d) R Andromedae; note the strong lines of Tc I. The spectrum of R Andromedae was obtained by P. W. Merrill, and the upper two spectra by E. M. and G. R. Burbidge.

Burbidge, Burbidge, Fowler & Hoyle (1957)

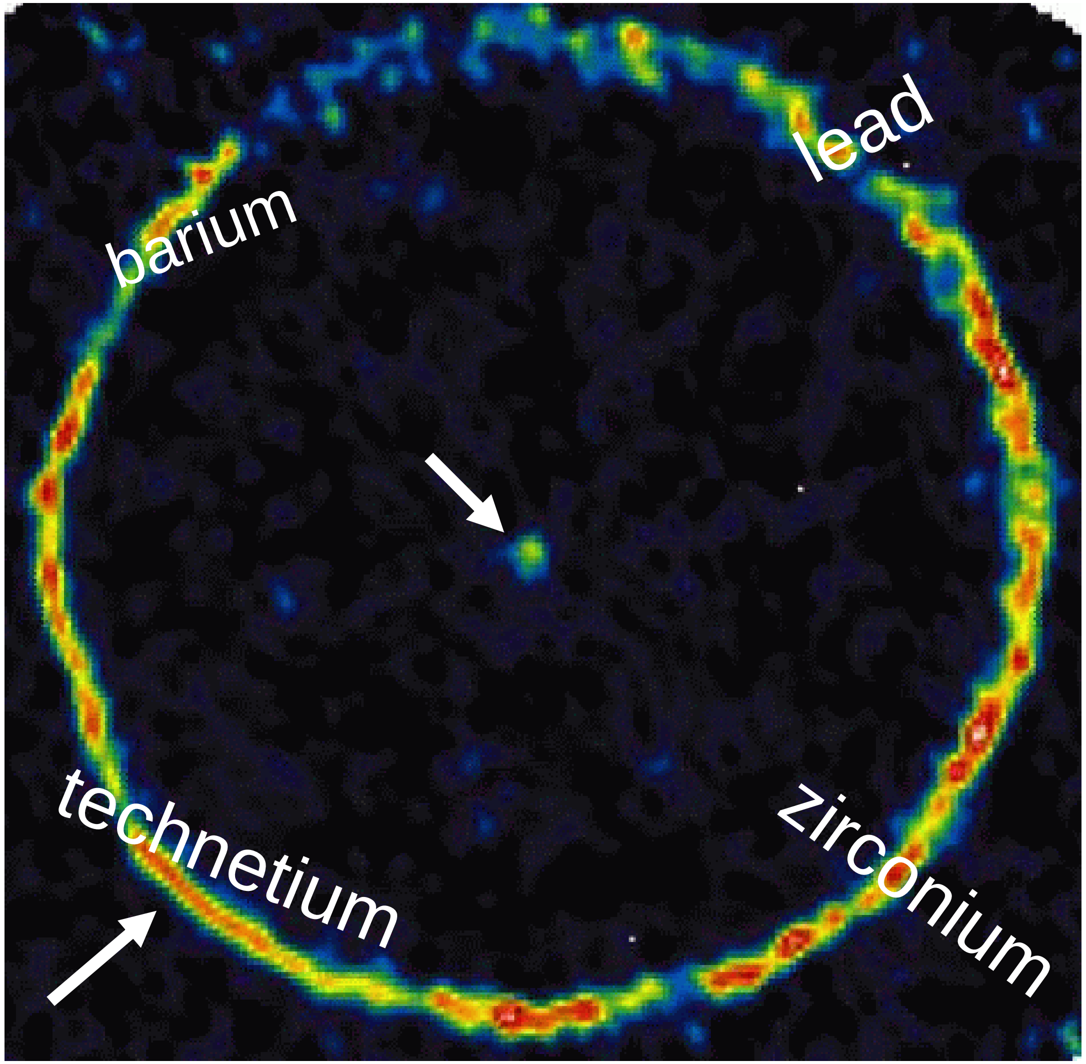
Technetium is a heavy radioactive element.

It can be produced only if neutrons are present and the *slow* neutron capture process, *s* process, occurs!

Section of the nuclide chart displaying the *s*-process path from Mo to Ru



The carbon star **TT Cygni**: a cool red giant with a wind.



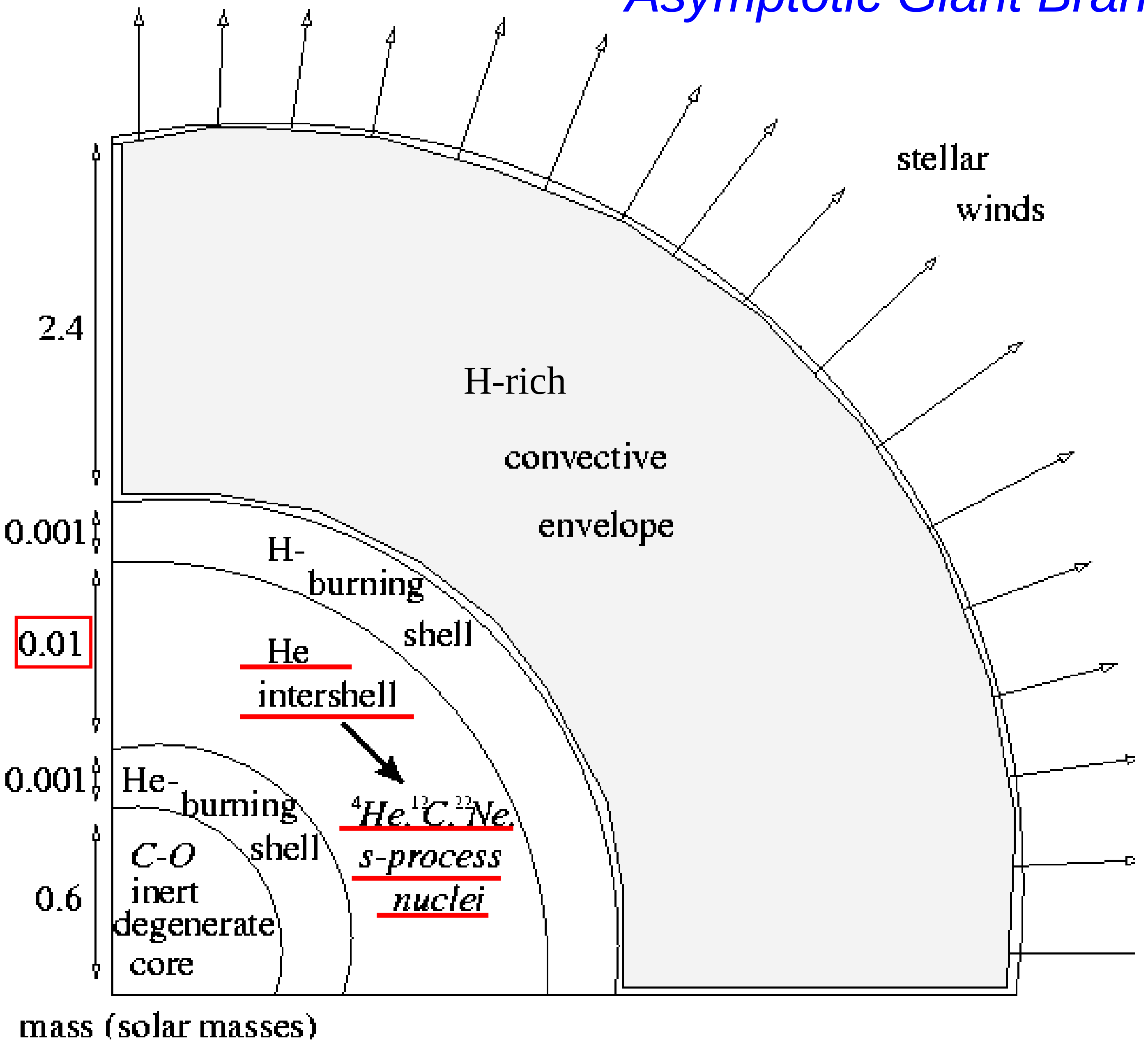
False-colour picture showing radio emission from carbon monoxide (CO) molecules.

The central emission is from material blown off the red giant over a few hundred years.

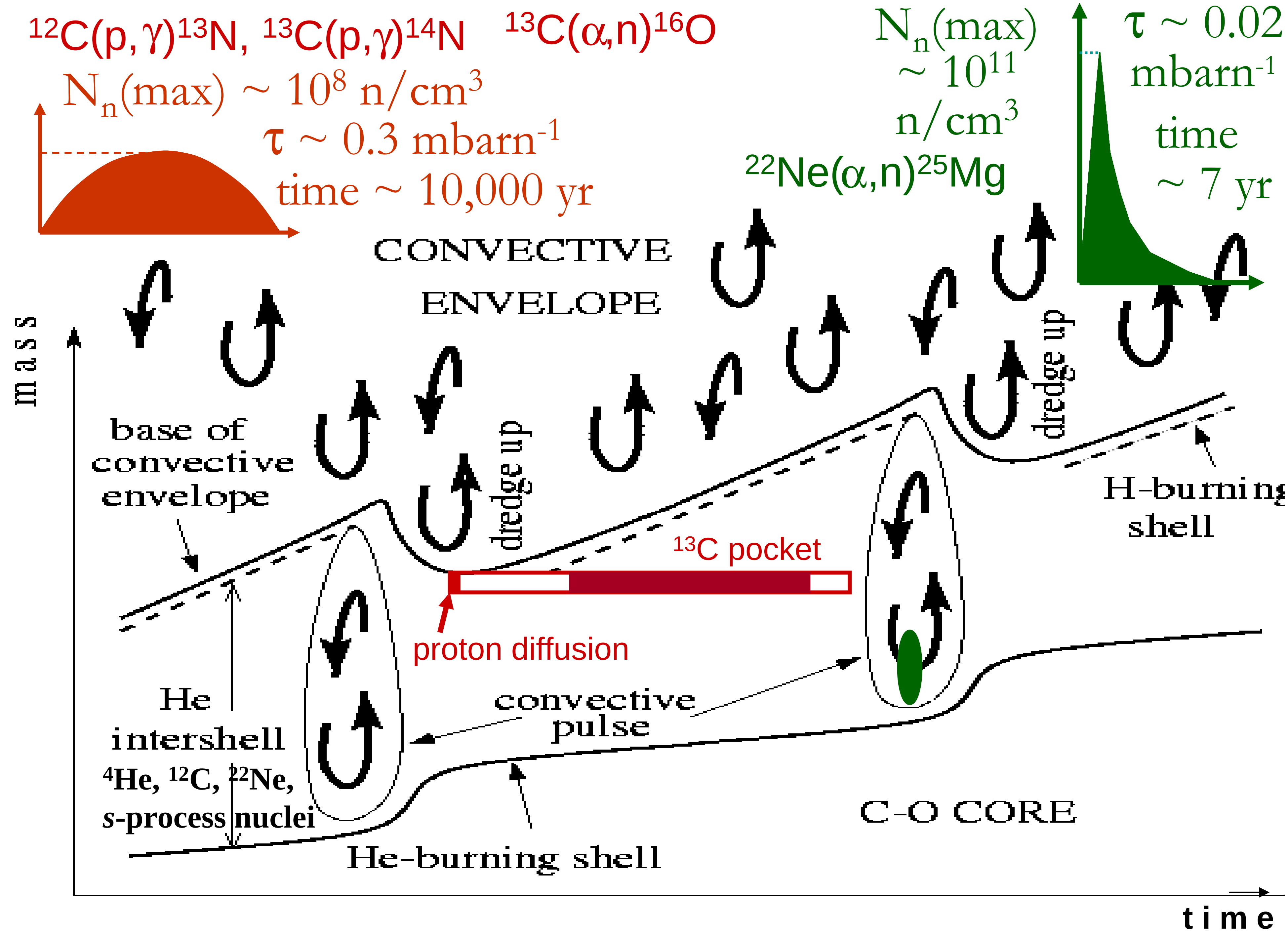
The thin ring represents a shell of gas expanding outward for 6,000 yr.

(Olofsson, H.,
Stockholm observatory)

Theoretically, such stars are known as *Asymptotic Giant Branch (AGB) stars*.



Schematic out-of-scale picture of the structure of an of and AGB star of typical mass of 3 solar masses.



$^{12}C(p,\gamma)^{13}N$, $^{13}C(p,\gamma)^{14}N$ $^{13}C(\alpha,n)^{16}O$

$N_n(max) \sim 10^8$ n/cm^3

$\tau \sim 0.3$ mbarn^{-1}

time ~ 10,000 yr

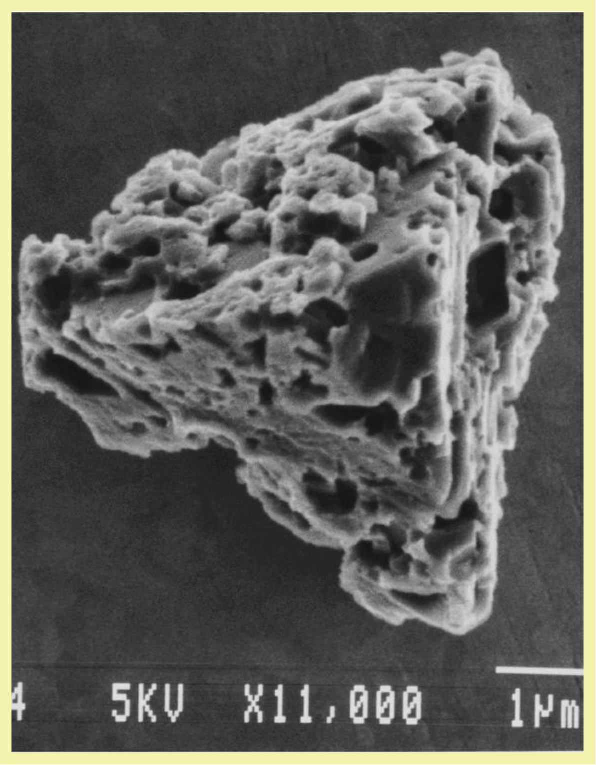
$N_n(max) \sim 10^{11}$ n/cm^3

$^{22}Ne(\alpha,n)^{25}Mg$

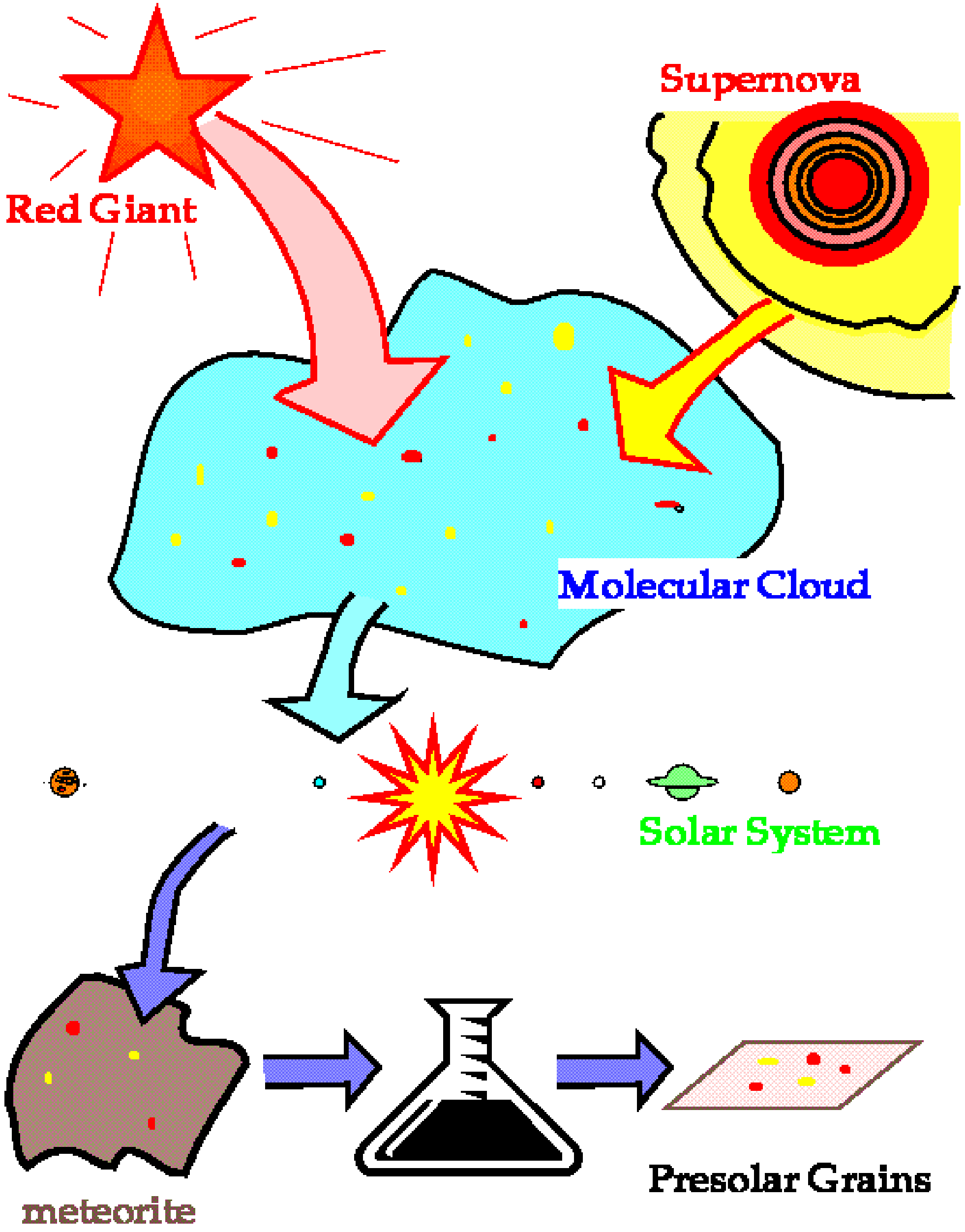
$\tau \sim 0.02$ mbarn^{-1}

time ~ 7 yr

New constraints on the *s* process in AGB stars come from meteoritic silicon carbide (SiC) grains that formed in the expanding envelopes of carbon stars and contain trace amounts of heavy elements showing the signature of the *s* process.

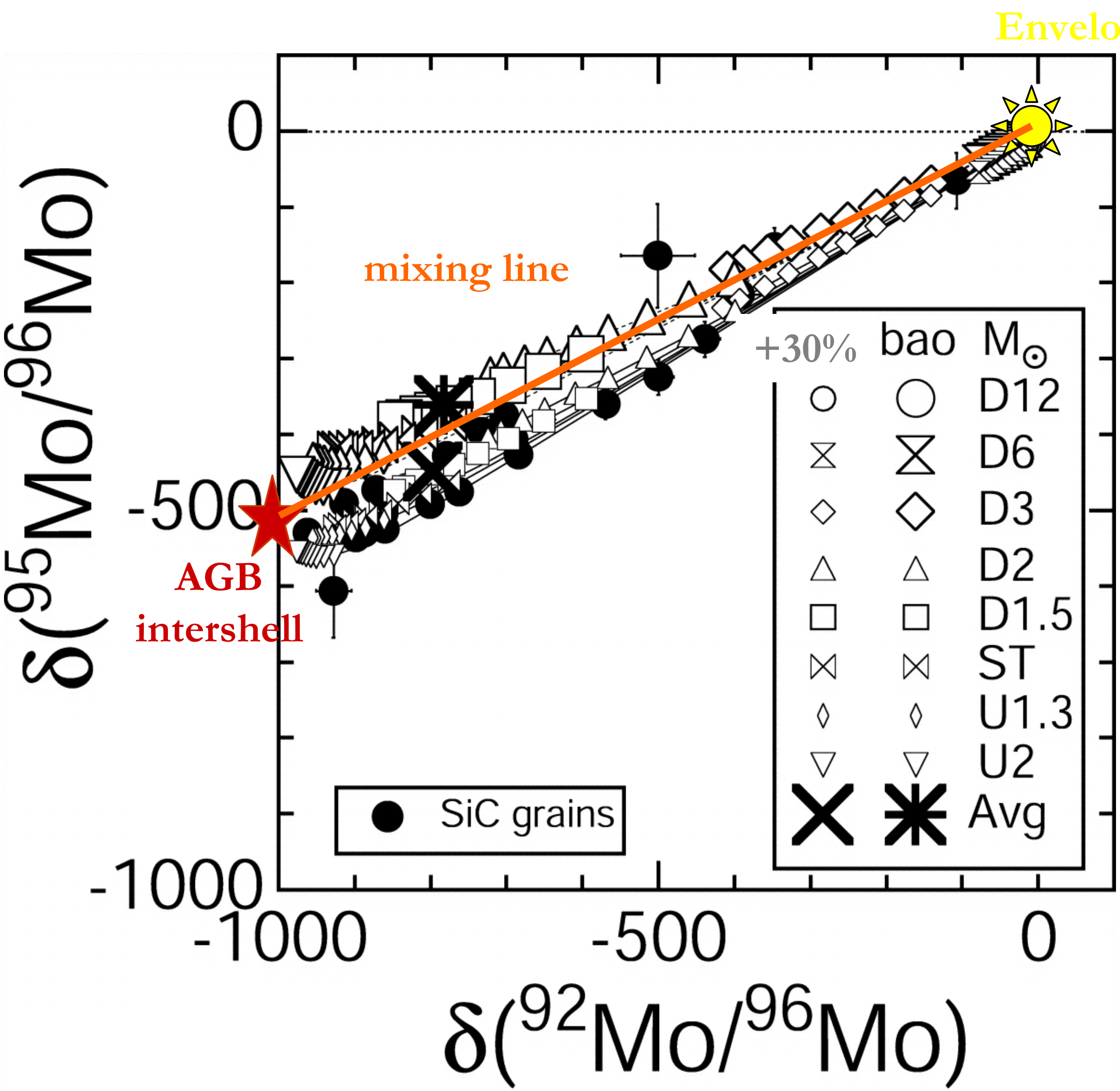


High-sensitivity laboratory measurements of the isotopic composition of trace heavy element in single SiC of the size of micrometers provide constraints of precision never achieved before.



Presolar stellar grains journey from their site of formation around stars to our laboratories.

Mo composition of single SiC grains

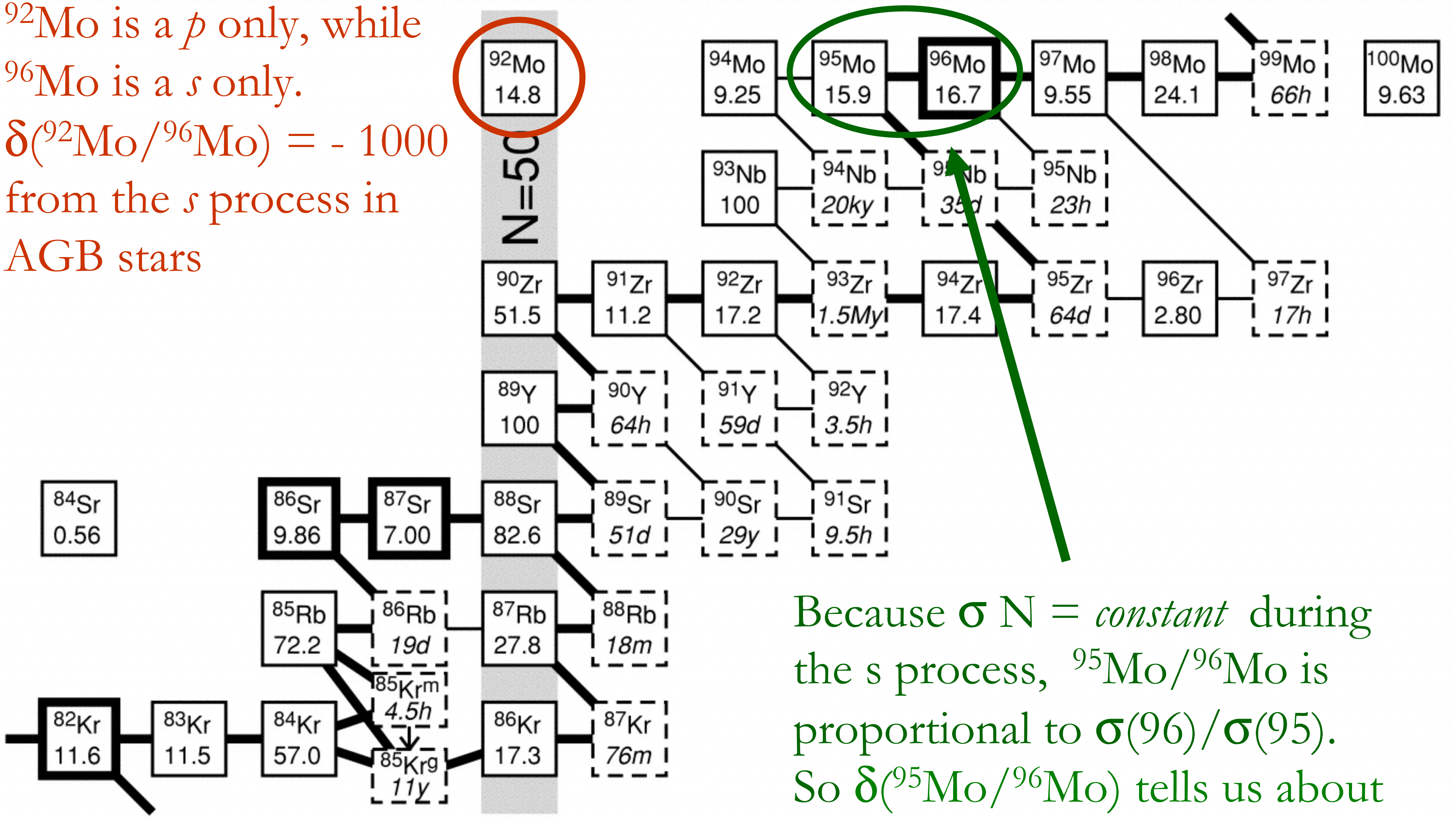


Three-isotope plots are very useful because the composition of material produced by mixing of two components lies on the line that connects the two component.

δ = Permil variation with respect to solar composition

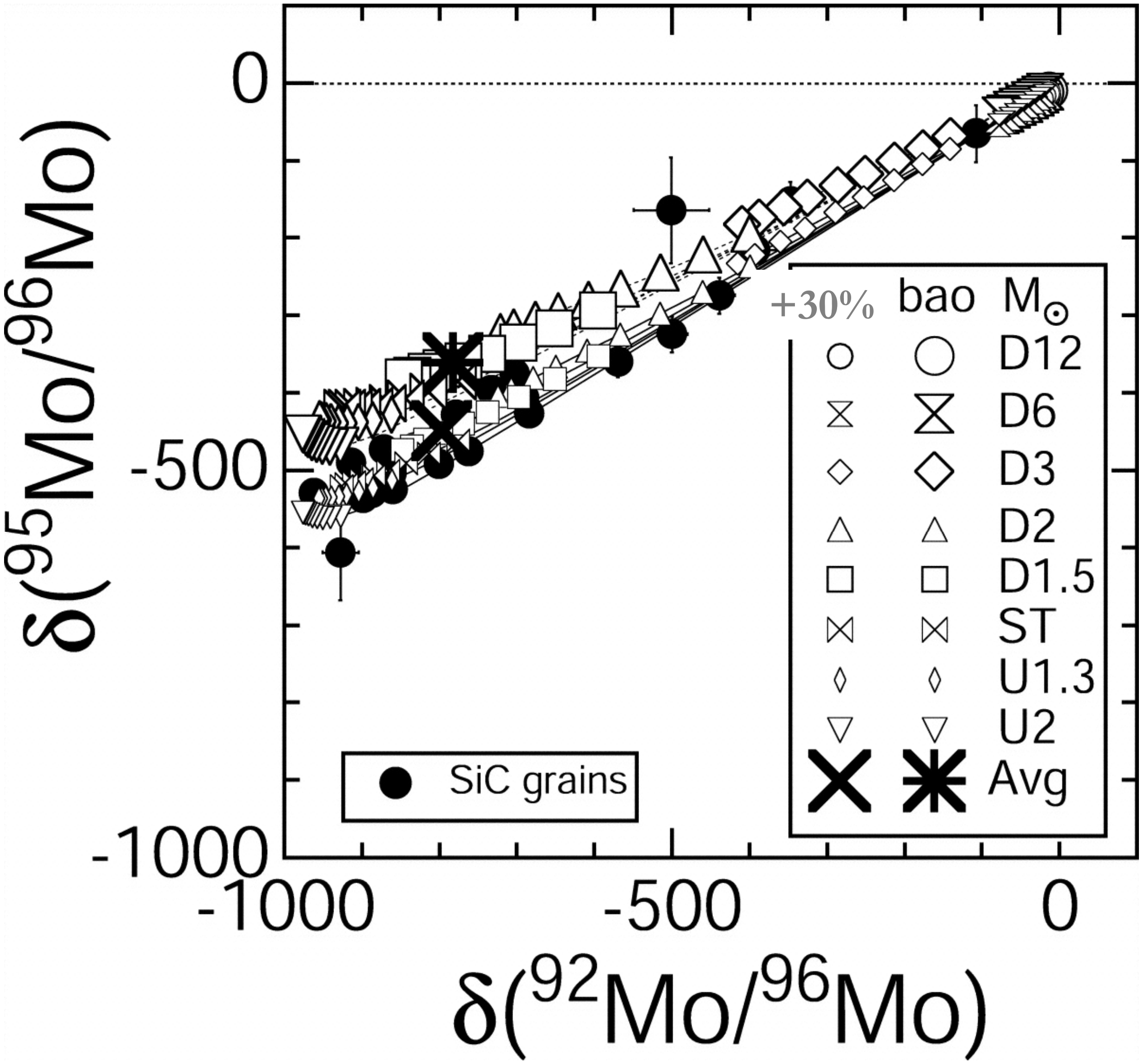
Mo composition

^{92}Mo is a *p* only, while
^{96}Mo is a *s* only.
$\delta(^{92}\mathrm{Mo}/^{96}\mathrm{Mo}) = -1000$
from the *s* process in
AGB stars



Because σ N = *constant* during the s process, ^{95}Mo/^{96}Mo is proportional to $\sigma(96)/\sigma(95)$. So $\delta(^{95}\mathrm{Mo}/^{96}\mathrm{Mo})$ tells us about the neutron capture cross sections of these isotopes.

Mo composition of single SiC grains



An increase of 30% in the σ(95) reproduces the measurements.

Bao et al. recommended:
292 +/- 12
Winters & Macklin (1987)

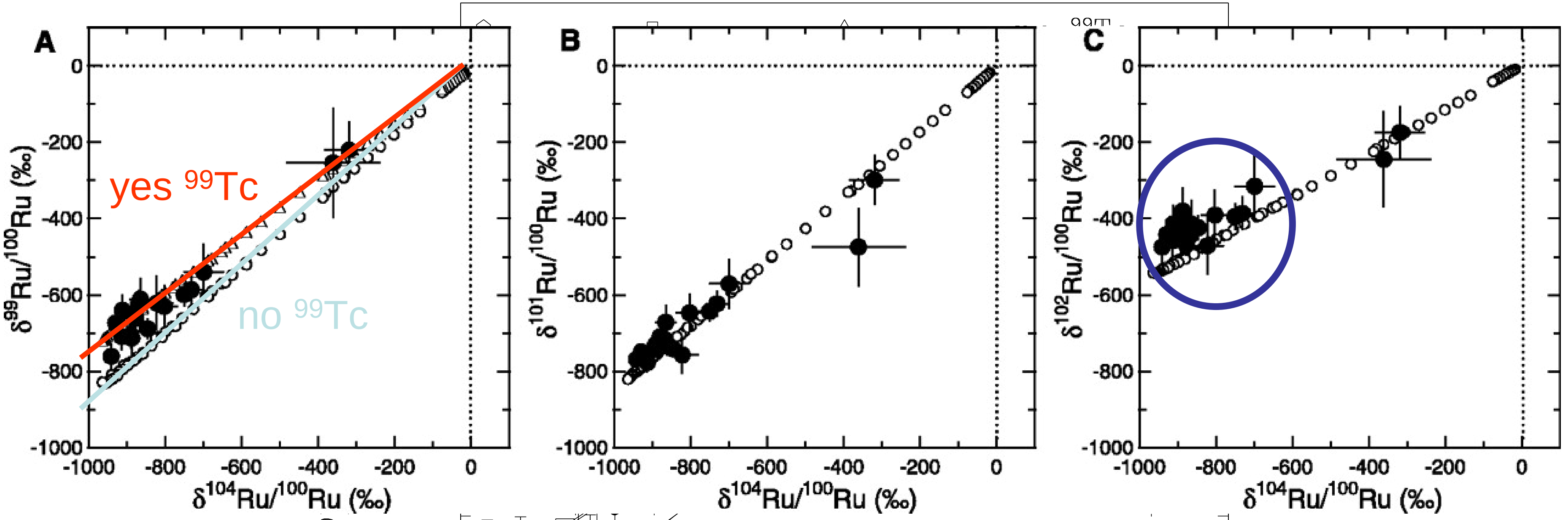
374 +/- 50 = 1.28 * Bao
Musgrove et al. (1976)

384 = 1.31 * Bao
Kikuchi et al. (1981)

430 +/- 50 = 1.47 * Bao
Allen et al. (1971)

Lugaro et al. 2003, ApJ, 593, 486

Ru composition of single SiC grains



A=99 in SiC grains includes ^{99}Ru and possibly also decayed ^{99}Tc!

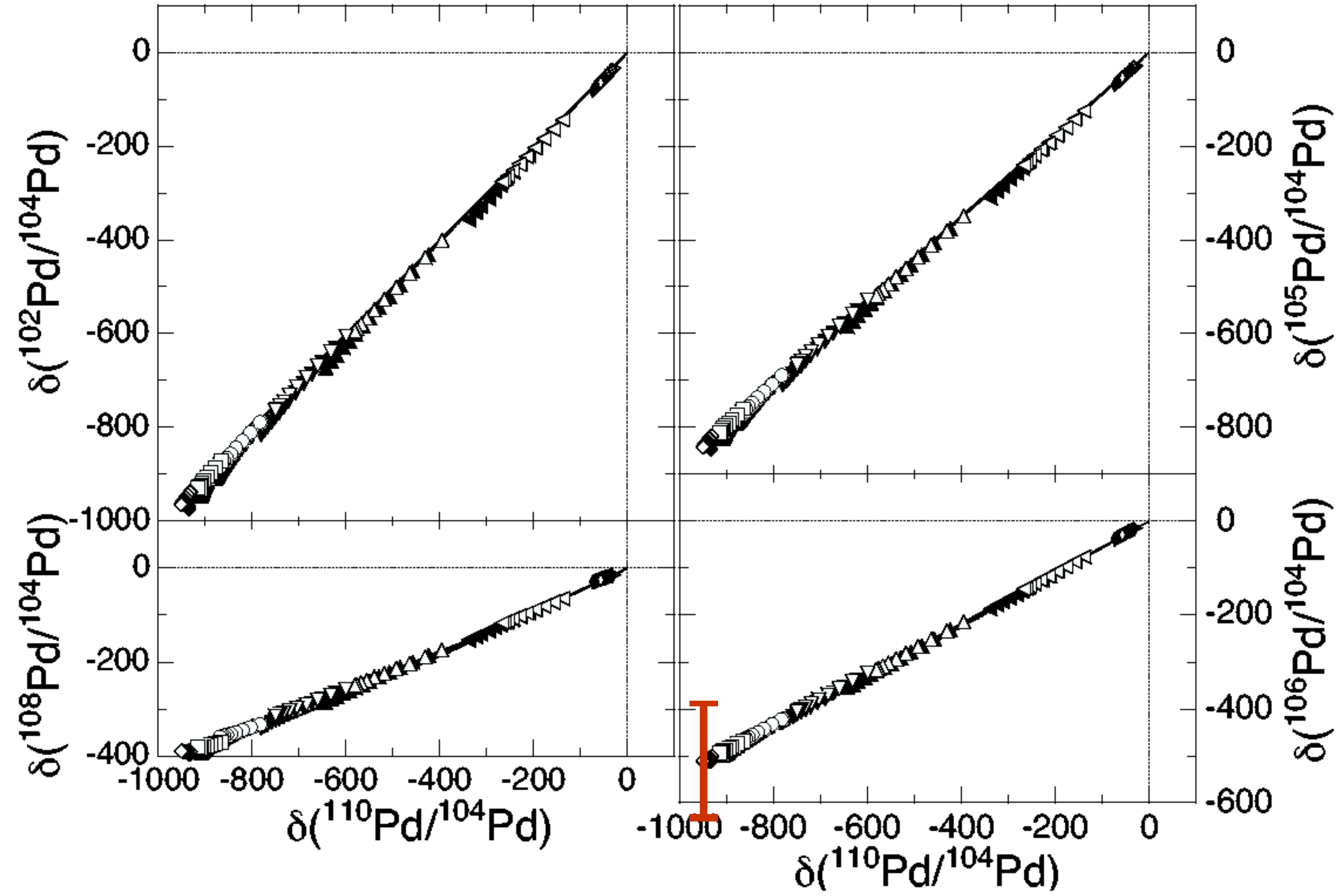
SiC data show that also Tc was included in the grains.
(Savina et al. 2004, Science, 303, 649)

The neutron capture cross sections of Ru isotopes still suffer from uncertainties of the order of 5%.

Within these uncertainties the ^{102}Ru/^{100}Ru ratio measured in SiC grains are not matched.

e.g.: Pd composition

In view of possible future measurements in SiC grains we also have predictions for many other selected heavy elements.



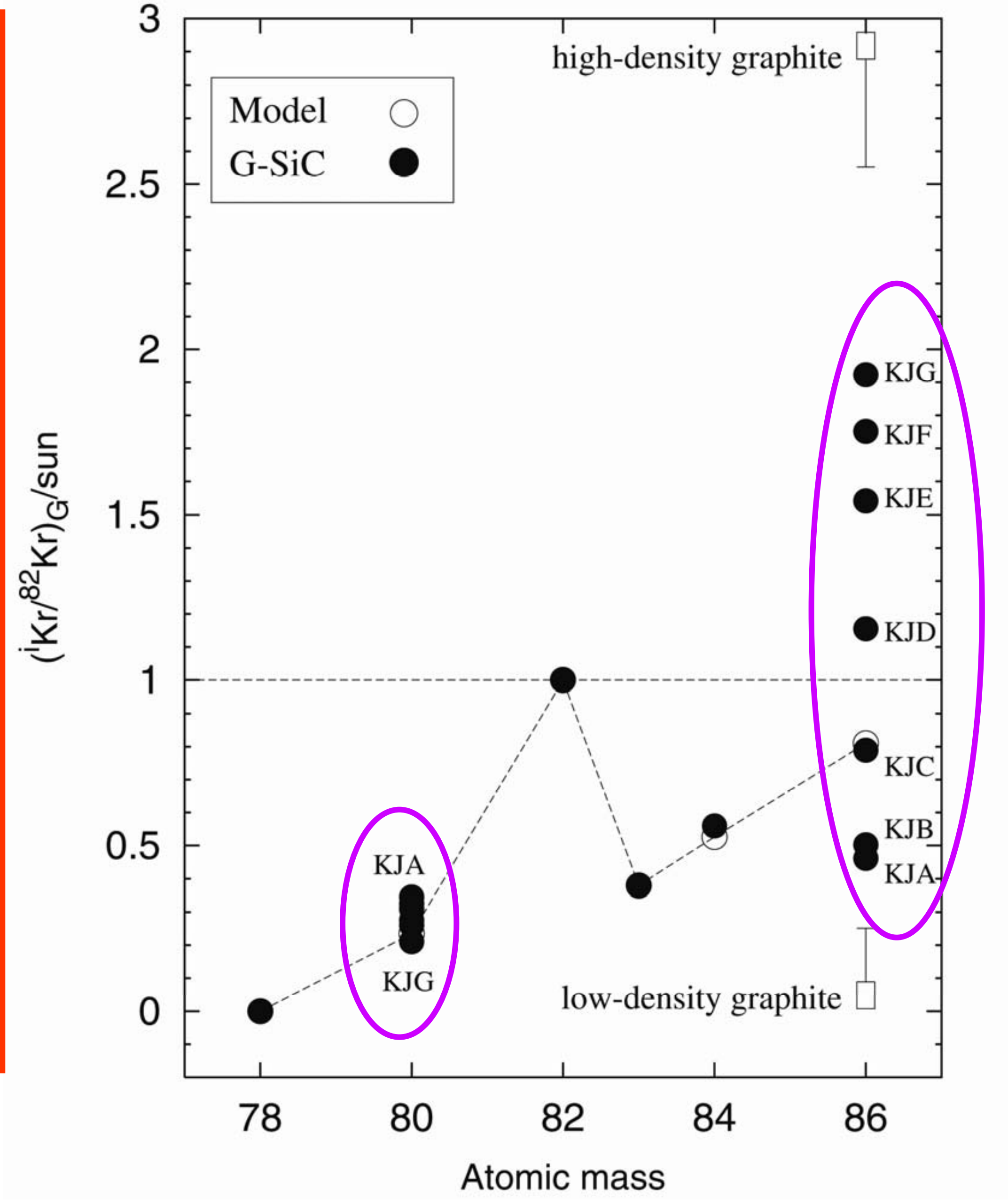
The neutron capture cross sections of the Pd isotopes have uncertainties ~ 10%!

This produces uncertainties in the predictions, for example in the ^{106}Pd/^{104}Pd ratio.

It will be of much interest to perform a consistency check having available high-precision data both on cross sections and on the composition in SiC grains.

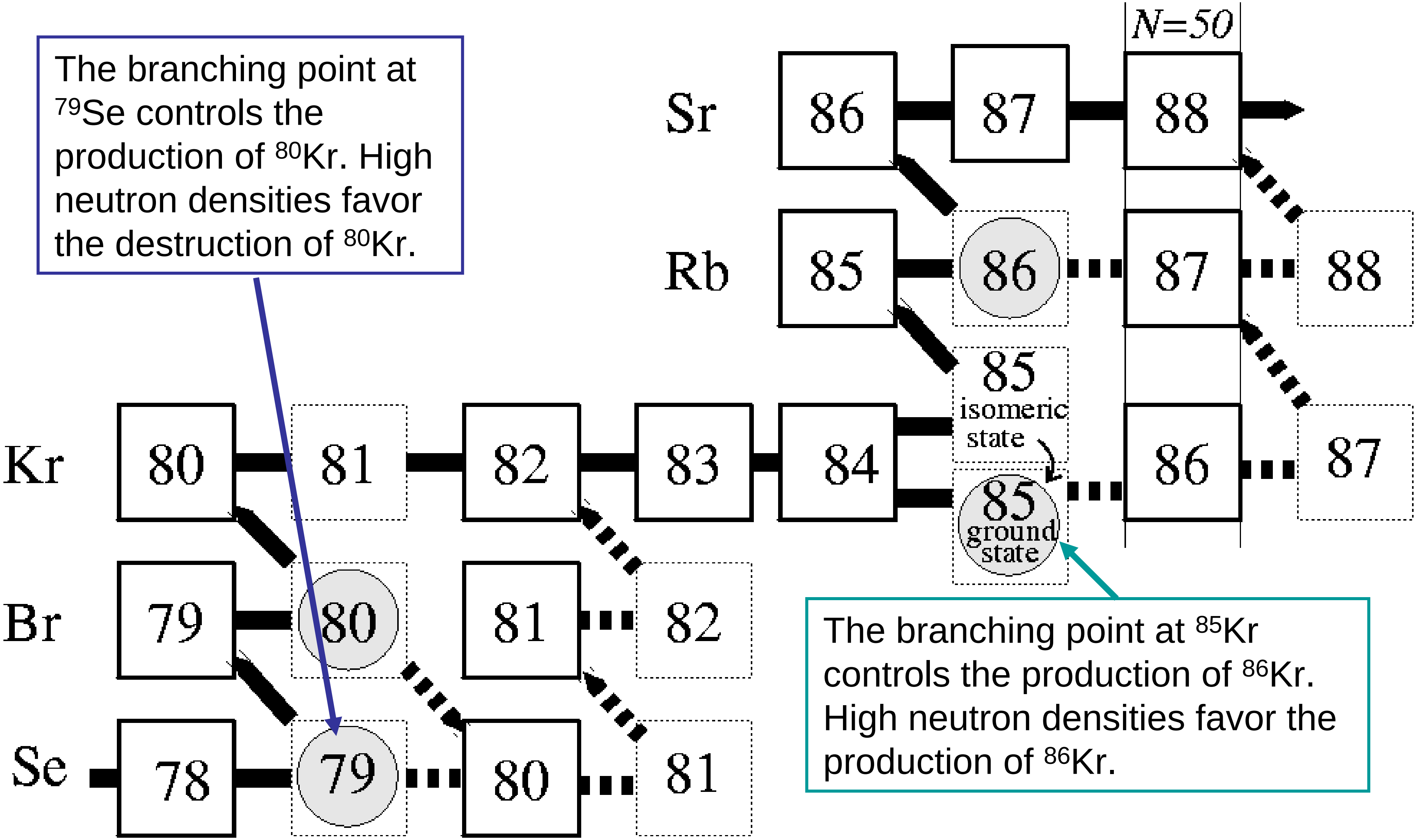
Kr composition of bulk SiC grains

Kr is a noble gas and thus was *implanted* in SiC grains. Only a small fraction of SiC grains contain noble gases, and data are only available for large collections (~millions) of grains measured at the same time.



A most striking feature is the different ratios of $^{80}Kr/^{82}Kr$ and $^{86}Kr/^{82}Kr$ observed in bulk grains of different sizes!

The production of ^{86}Kr and ^{80}Kr depends on the activation of branchings on the s-process path:



The branching point at ^{79}Se controls the production of ^{80}Kr. High neutron densities favor the destruction of ^{80}Kr.

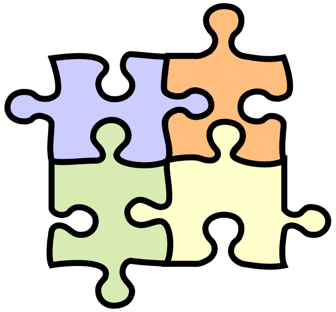
The branching point at ^{85}Kr controls the production of ^{86}Kr. High neutron densities favor the production of ^{86}Kr.

The variations in the Kr isotopic composition with the grain size is related to the operation of branching in different conditions of neutron densities. They can be used as tests for nucleosynthesis conditions during the *s* process.

The variations in the Kr isotopic composition with the grain size is also possibly related to the presence of two Kr components:

- one (small grains) implanted by the low-energy stellar winds present during the AGB phase, and
- one (large grains) implanted by the high-energy stellar winds (*superwind*) during the post-AGB phase, when a planetary nebula is formed.

(Verchovsky et al. 2004, ApJ, 607, 611)



Future developments could aim at relating nucleosynthesis processes inside AGB and post-AGB stars to the energy of the corresponding stellar winds!

However, there are still too many nuclear uncertainties related to cross sections of stable and unstable isotopes, and decay rates of unstable isotopes involved in the operation of these branching points.

Neutron *poisons* are elements lighter than Fe:

They steal neutrons to the production of heavy elements,
BUT they produce interesting nucleosynthesis themselves!

Example: the ^{14}N(n,p)^{14}C reaction is a strong neutron poison. ^{14}N is produced by proton captures together with ^{13}C and its presence can even completely inhibit the production of heavy element!

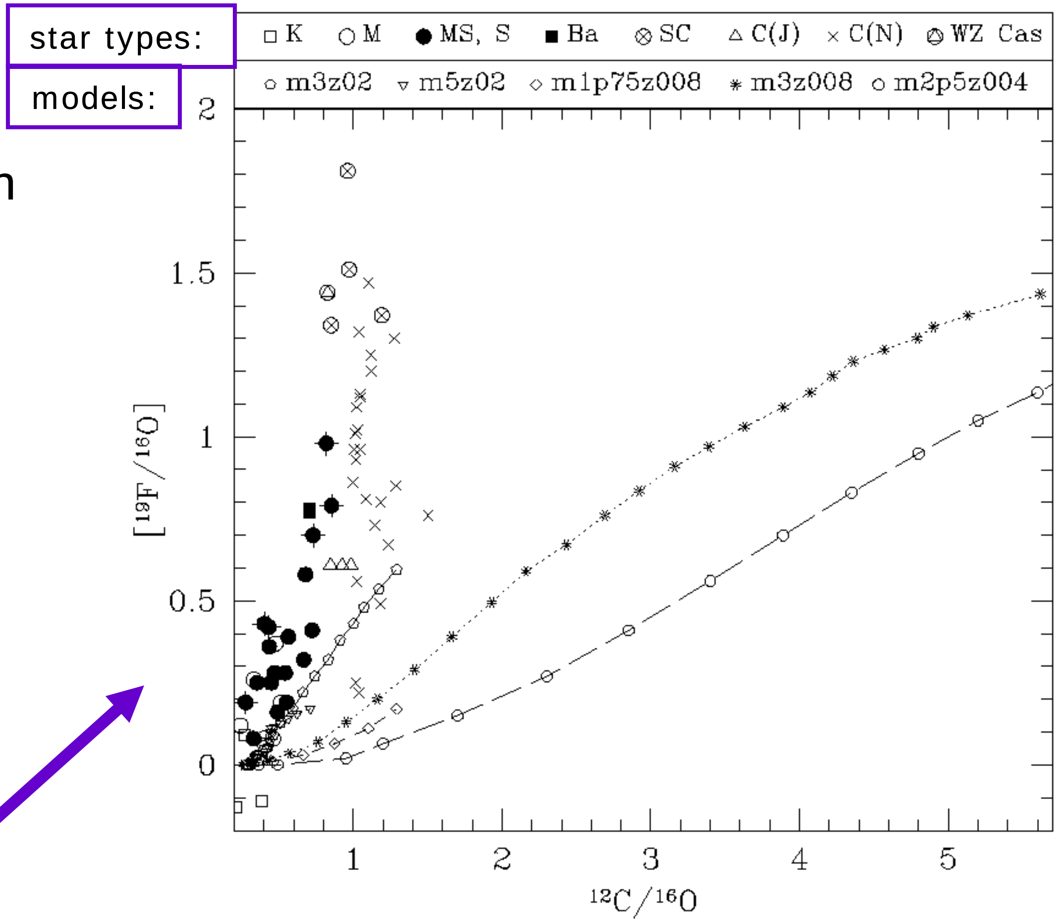
BUT

it leads to the production of fluorine:

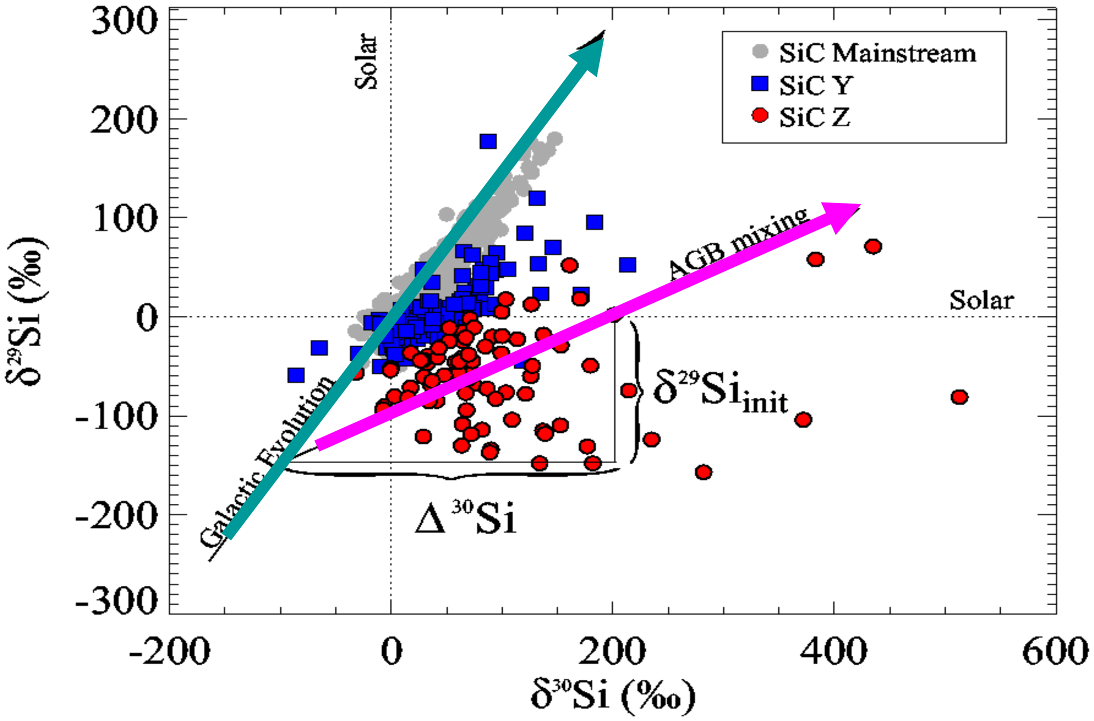
^{14}N(n,p)^{14}C ^{14}N(a,g)^{18}O
^{14}C(a,g)^{18}O
^{18}O(p,a)^{15}N(a,g)^{19}F

Destruction channels:
^{19}F(a,p)^{22}Ne and ^{19}F(n,g)^{20}F

Fluorine is observed to be enhanced in AGB stars up to 30 times the solar value.



Many light elements neutron poisons, such as Mg, Si, Ti, Ca, …, are present in SiC grains. Let us take as an example the Si composition of different SiC populations. Its isotopic composition is determined both by:



The initial composition of the parent star produced by Galactic Chemical Evolution effects, which are still very uncertain.

The occurrence of neutron captures in the parent star:

^{28}Si(n,γ)^{29}Si(n,γ)^{30}Si(n,γ)

^{32}S(n,γ)^{33}S(n,α)^{30}Si

Combining SiC data and theoretical predictions for light element isotopic abundances in AGB stars we can obtain information on the evolution of isotopic abundances in the Galaxy.

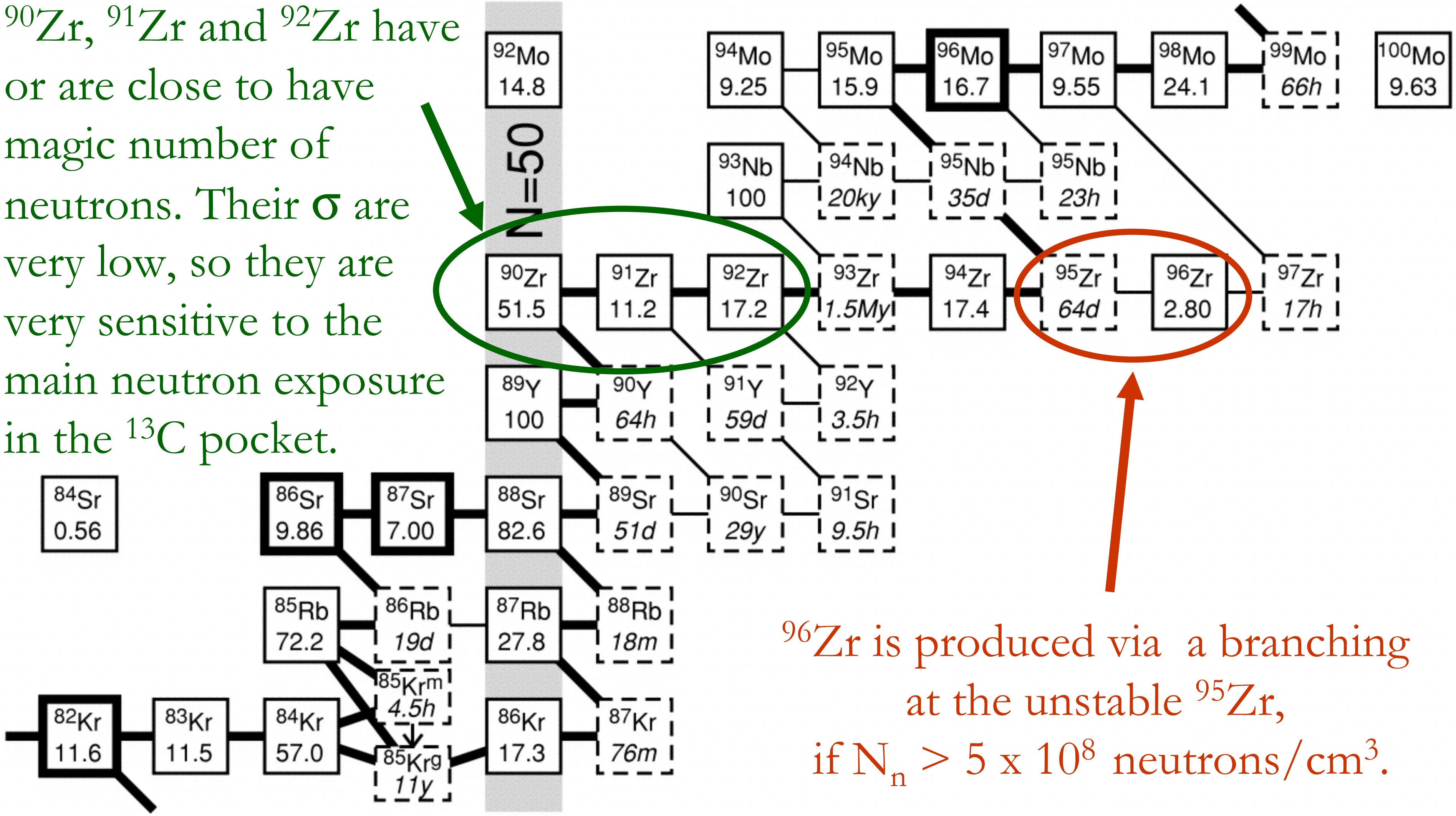
SUMMARY AND CONCLUSIONS

1. AGB stars are the site of the *s* process. In the current models the neutron sources are: ^{13}C, responsible for producing the bulk of heavy elements, and ^{22}Ne, only marginally activated and responsible for the activation of branching points along the *s*-process path.

2. SiC grains give detailed constraints to be matched by theoretical models, they yield important information on stellar models. Precise information on cross sections (and decay rates) are needed.

3. Neutron poisons also produce interesting nucleosynthesis effects, whose evidence is testified by stellar observations and SiC grains. The latter can be used to probe the Galactic chemical evolution of isotopes.

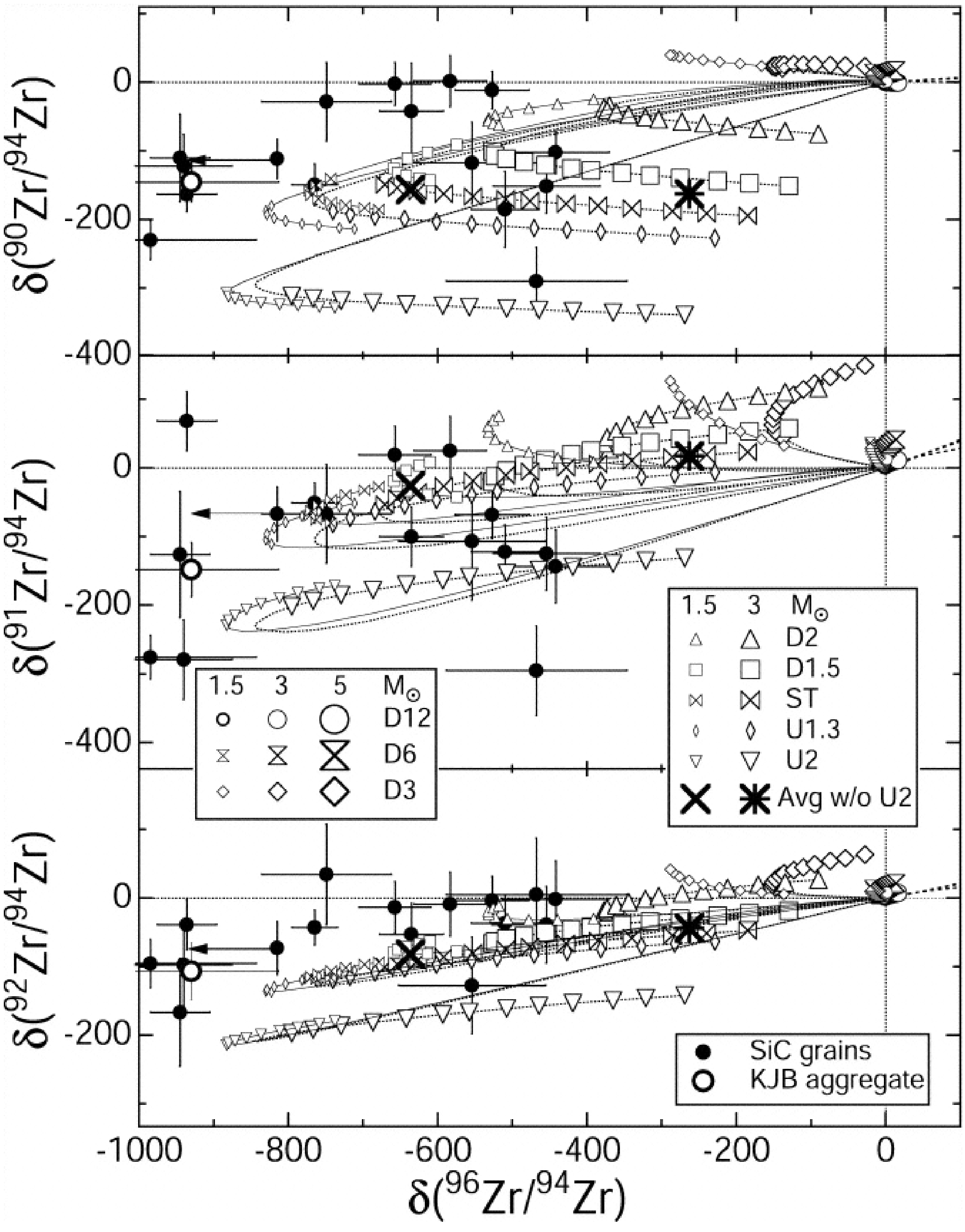
Zr composition



^{90}Zr, ^{91}Zr and ^{92}Zr have or are close to have magic number of neutrons. Their σ are very low, so they are very sensitive to the main neutron exposure in the ^{13}C pocket.

^{96}Zr is produced via a branching at the unstable ^{95}Zr, if $N_n > 5 \times 10^8$ neutrons/cm^3.

Zr composition of single SiC



$^{96}Zr/^{94}Zr$ ratios point to a marginal activation of ^{22}Ne neutron source

$^{90,91,92}Zr/^{94}Zr$ ratios indicate a spread of efficiencies in the ^{13}C neutron source

Also information on neutron capture cross sections.

Lugaro et al. 2003