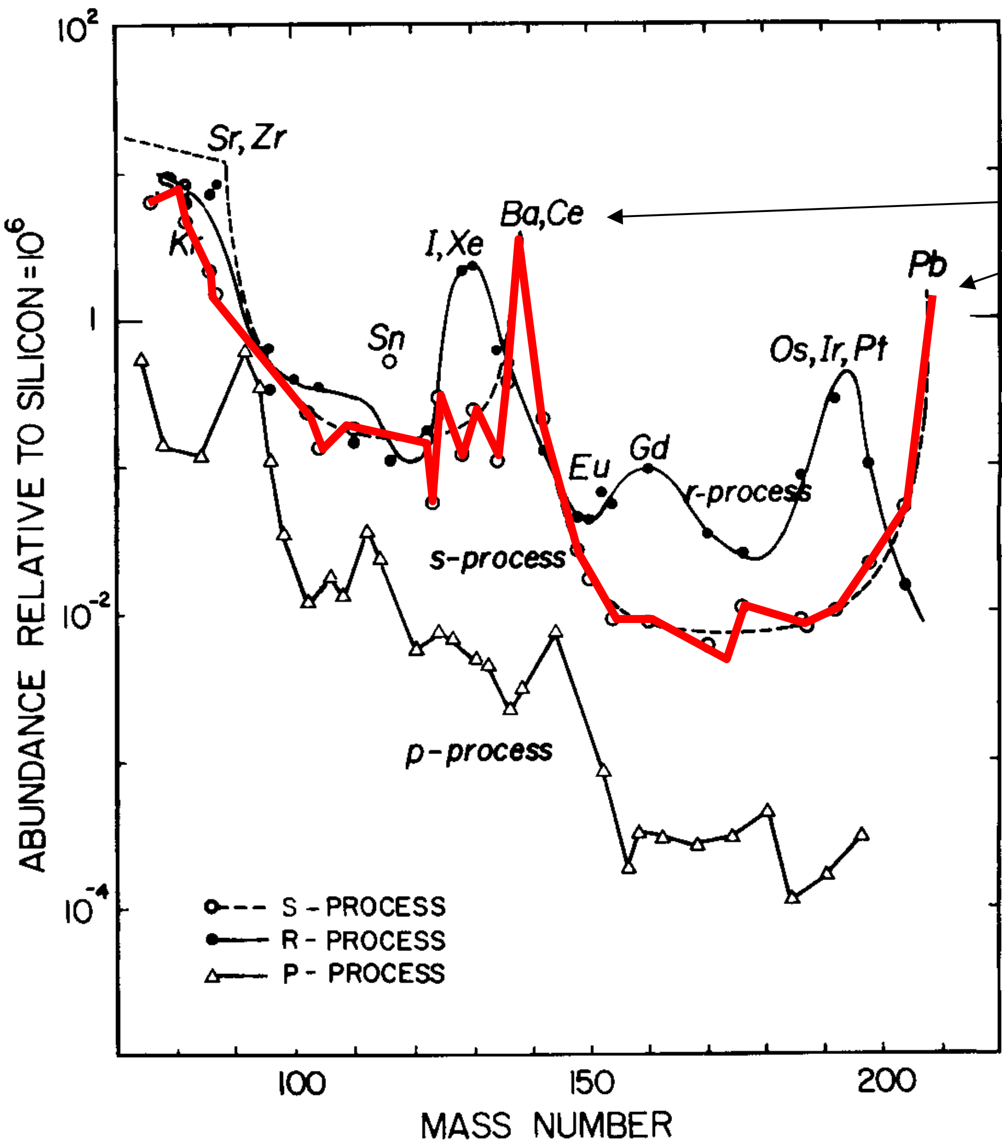
The origin of heavy elements in the solar system



(Pagel, Fig 6.8)

Location of peaks indicates n-capture along valley of stability → s-process

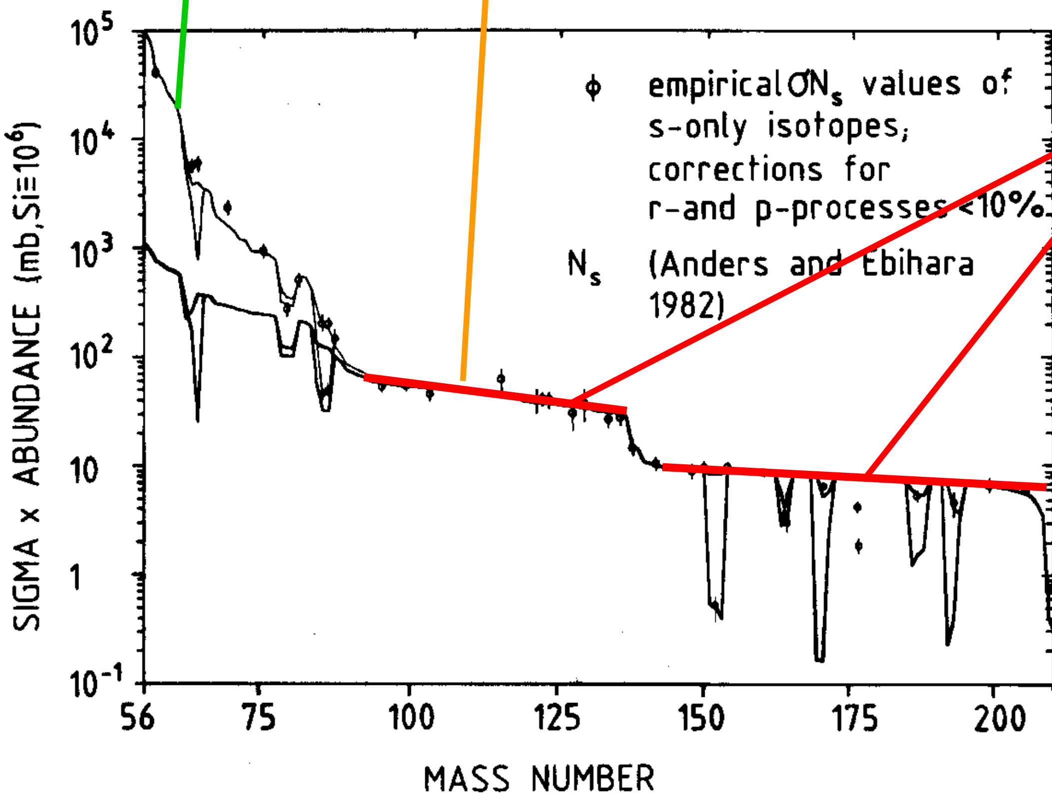
s-only isotopes are above p-process level → s-process

each process contribution is a mix of many events !

The sites of the s-process

weak s-process: **core He/ shell C burning in massive stars**

main s-process: **He shell flashes in low mass TP-AGB stars**



approx. steady flow

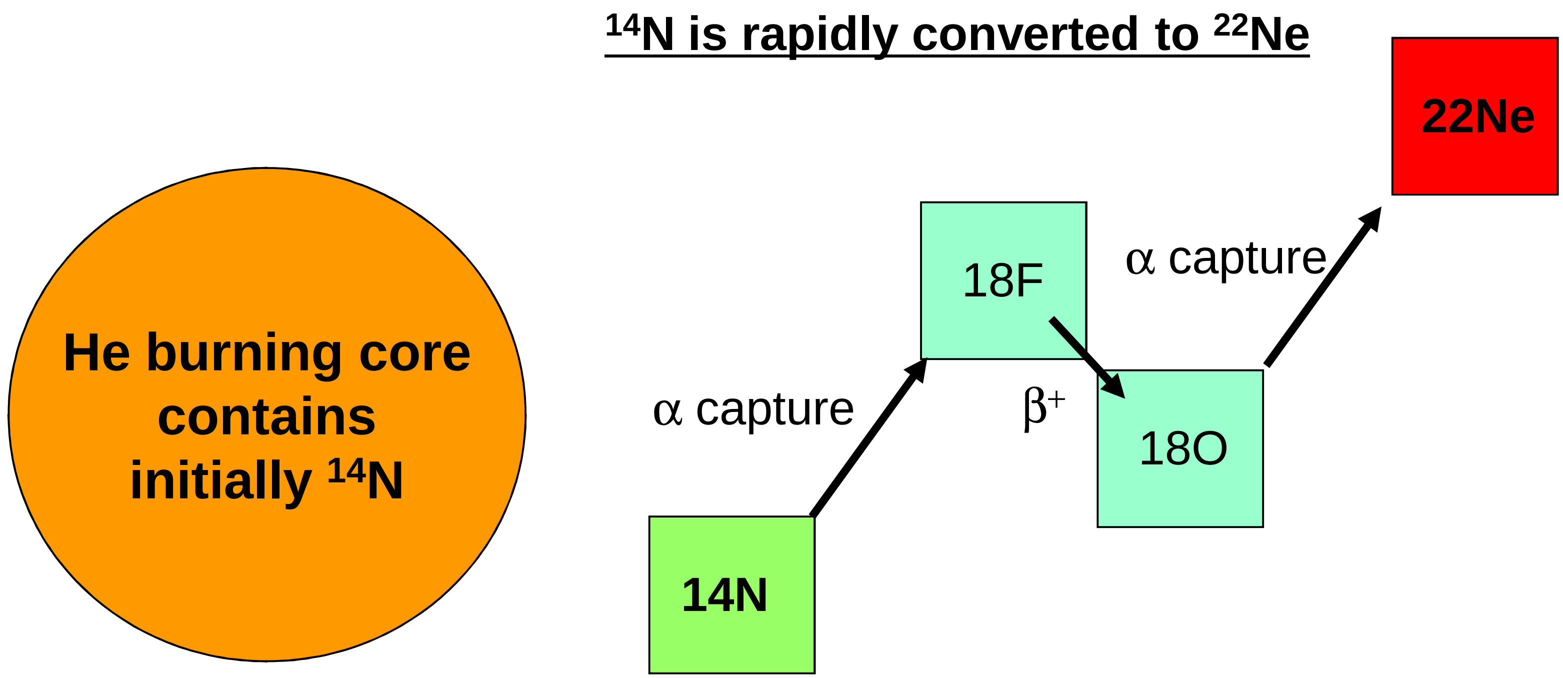
$$Y\lambda \propto Y\sigma_{(n,\gamma)} \approx \text{const}$$

↓

can easily interpolate
s-contribution for s+r-nuclei
if neutron capture cross sections are known

The weak s-process

Site: Core He burning (and shell C-burning) in massive stars (e.g. 25 solar masses)

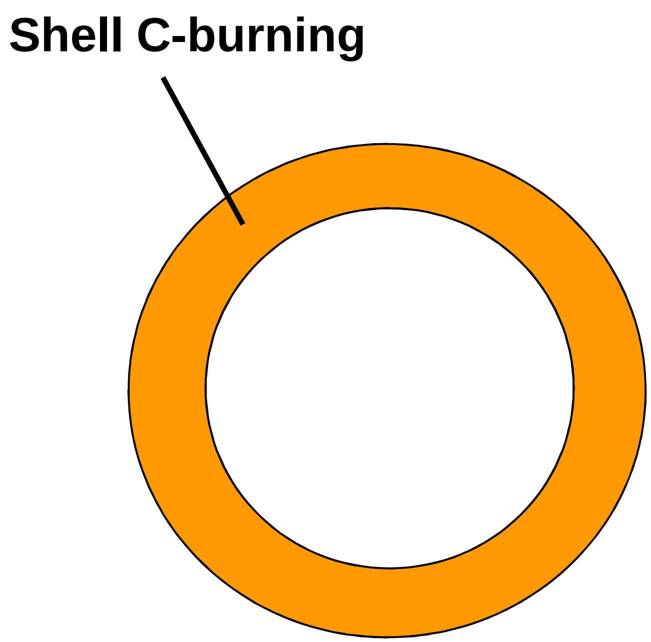


Towards the end of He burning T~3e8 K: ^{22}**Ne(α,n)** provides a neutron source

→ preexisting Fe (and other nuclei) serve as seed for a (secondary) s-process

The weak s-process (A < 90)

Site: Core He burning (and shell C-burning) in massive stars (e.g. 25 solar masses)



- **Not all ^{22}Ne consumed during He burning**
- **^{22}Ne(α,n) reactivated during C-shell burning**

  $^{12}C+^{12}C \rightarrow ^{20}Ne + ^{4}He$

→ About equal contribution to weak s-process from core He and shell C burning

What about core C burning?

Typical conditions (Raiteri et al. ApJ367 (1991) 228 and ApJ371(1991)665:

Temperature	2.2 - 3.5 e8 K
Density	1 - 3e3 g/cm^3
Average neutron density	7e5 cm^{-3}
Peak neutron density	2e7 cm^{-3}
Neutron exposure τ *)	0.206 / mb

*) time integrated neutron flux

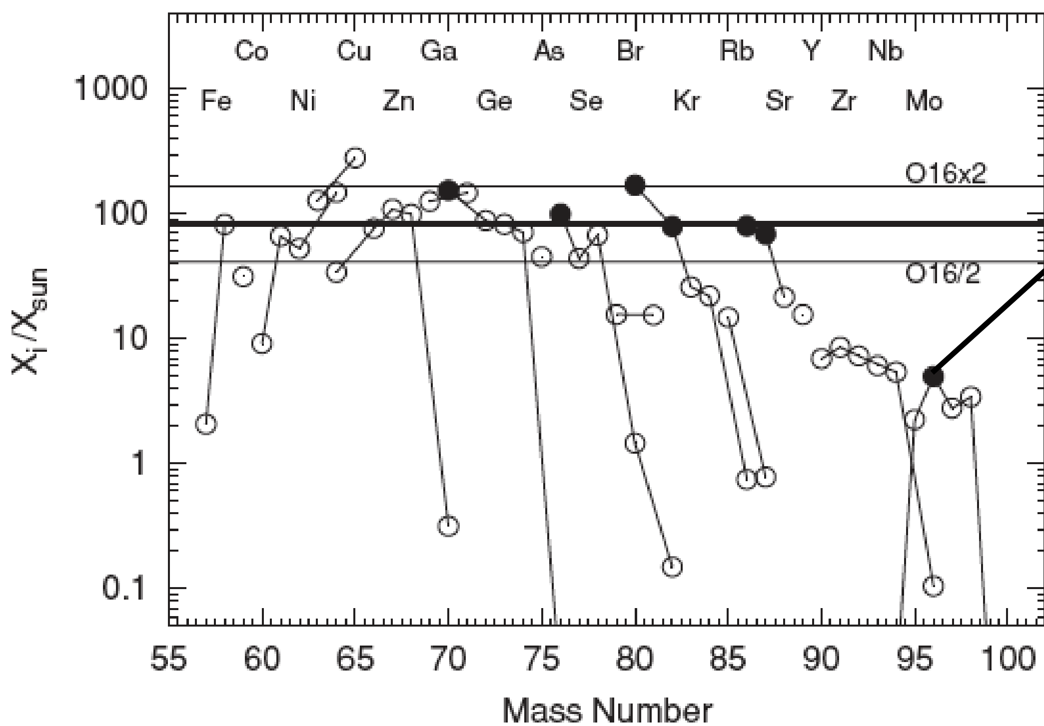
$$\tau = \int j_n(t)dt$$

Results:

At end of He burning

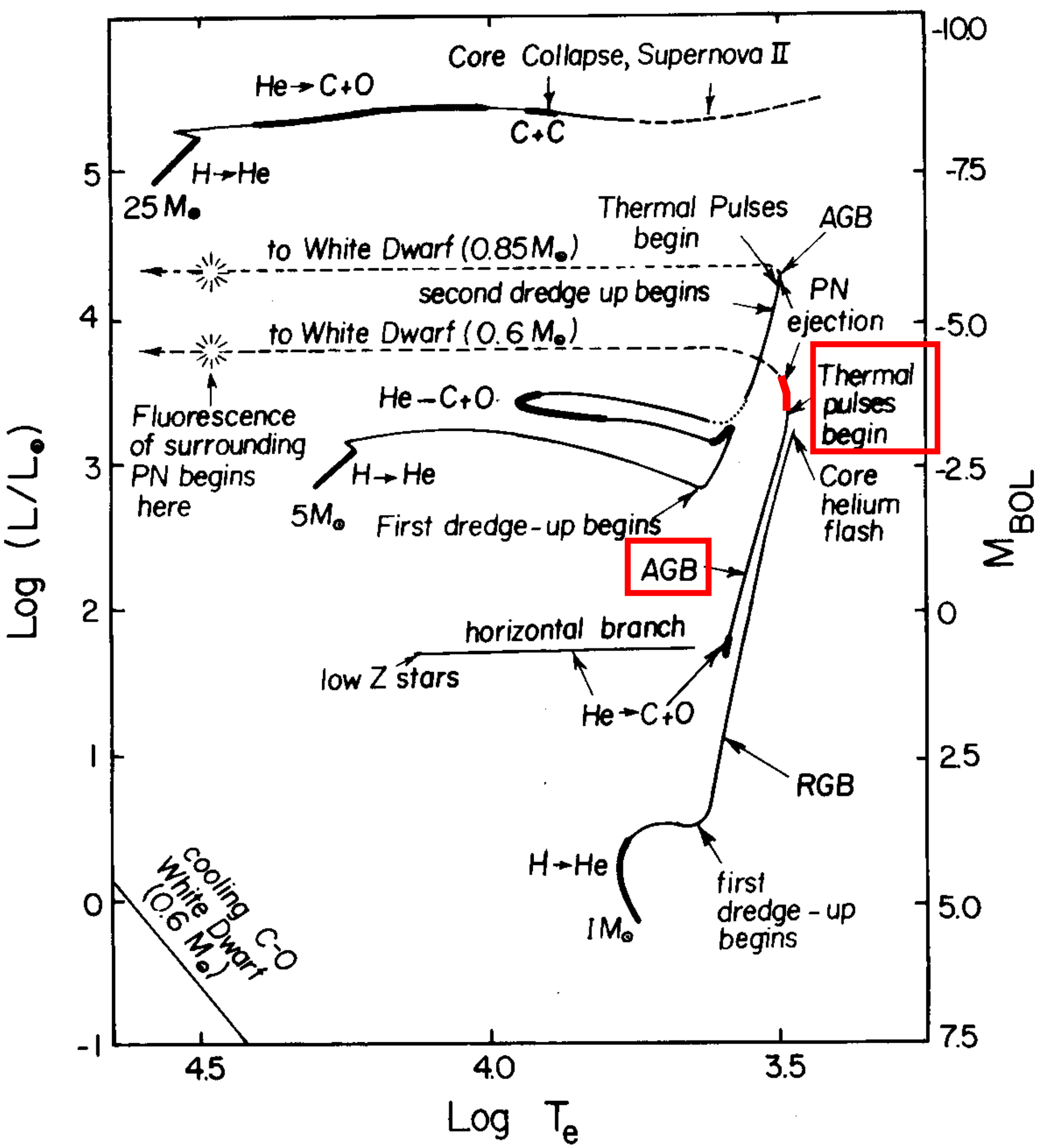
(Pignatari et al. 2010)

produced abundance/solar



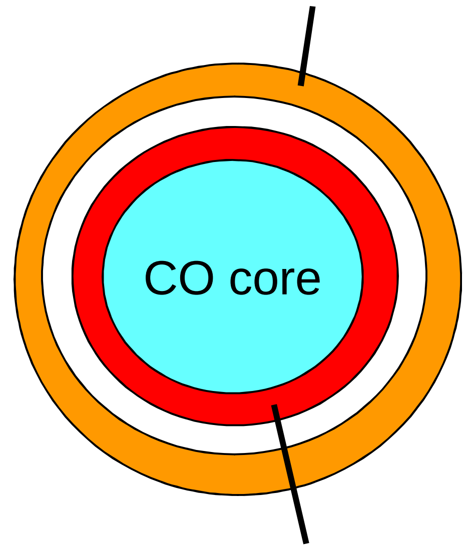
s-only

The main s-process (A>90)



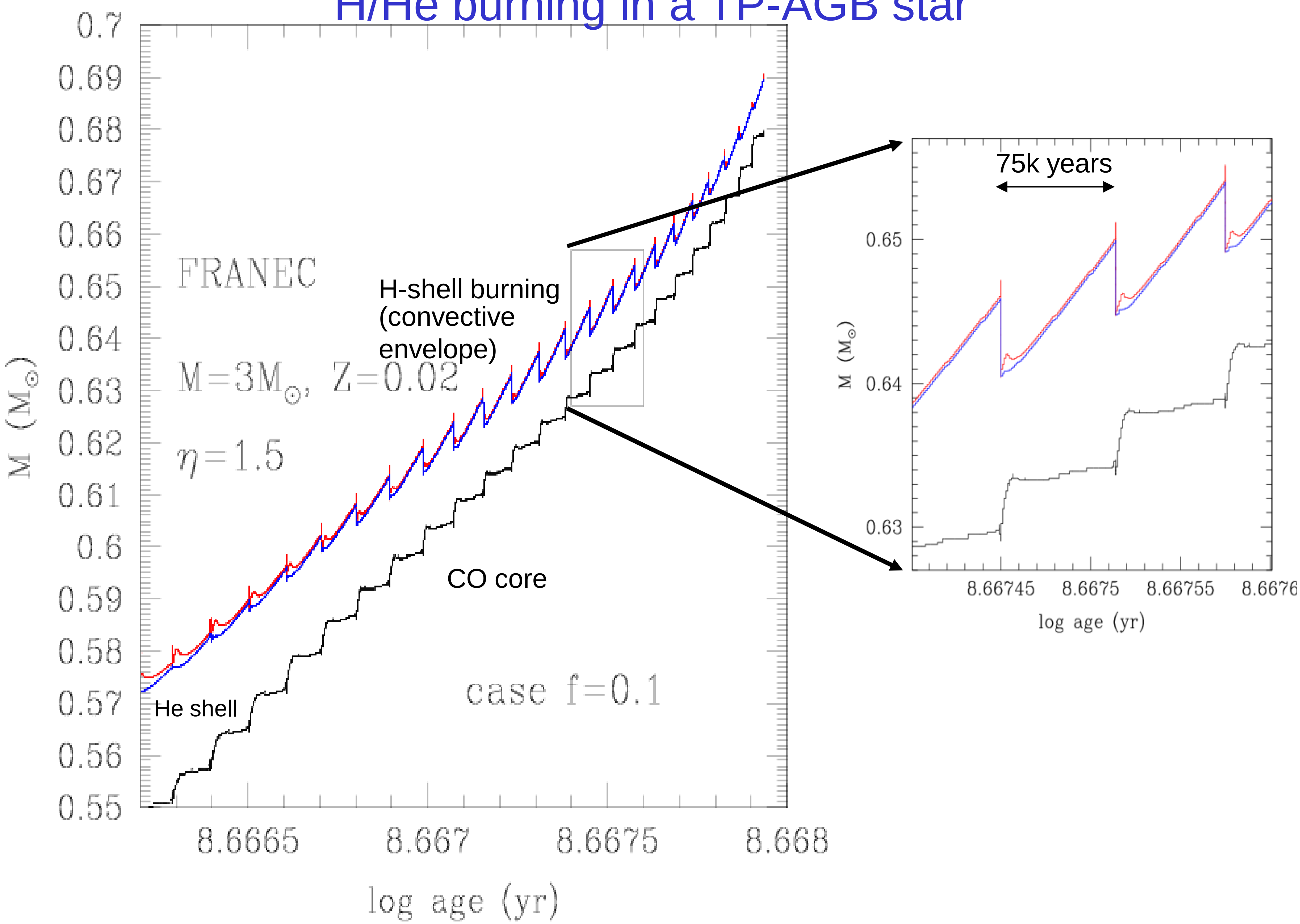
Site: low mass TP-AGB stars
(thermally pulsing stars
on the asymptotic giant
branch in the HR diagram,
1.5 - 3 solar masses)

H-burning shell



He-burning shell
unstable - burns in flashes
(thin shell instability)

H/He burning in a TP-AGB star



From R. Gallino

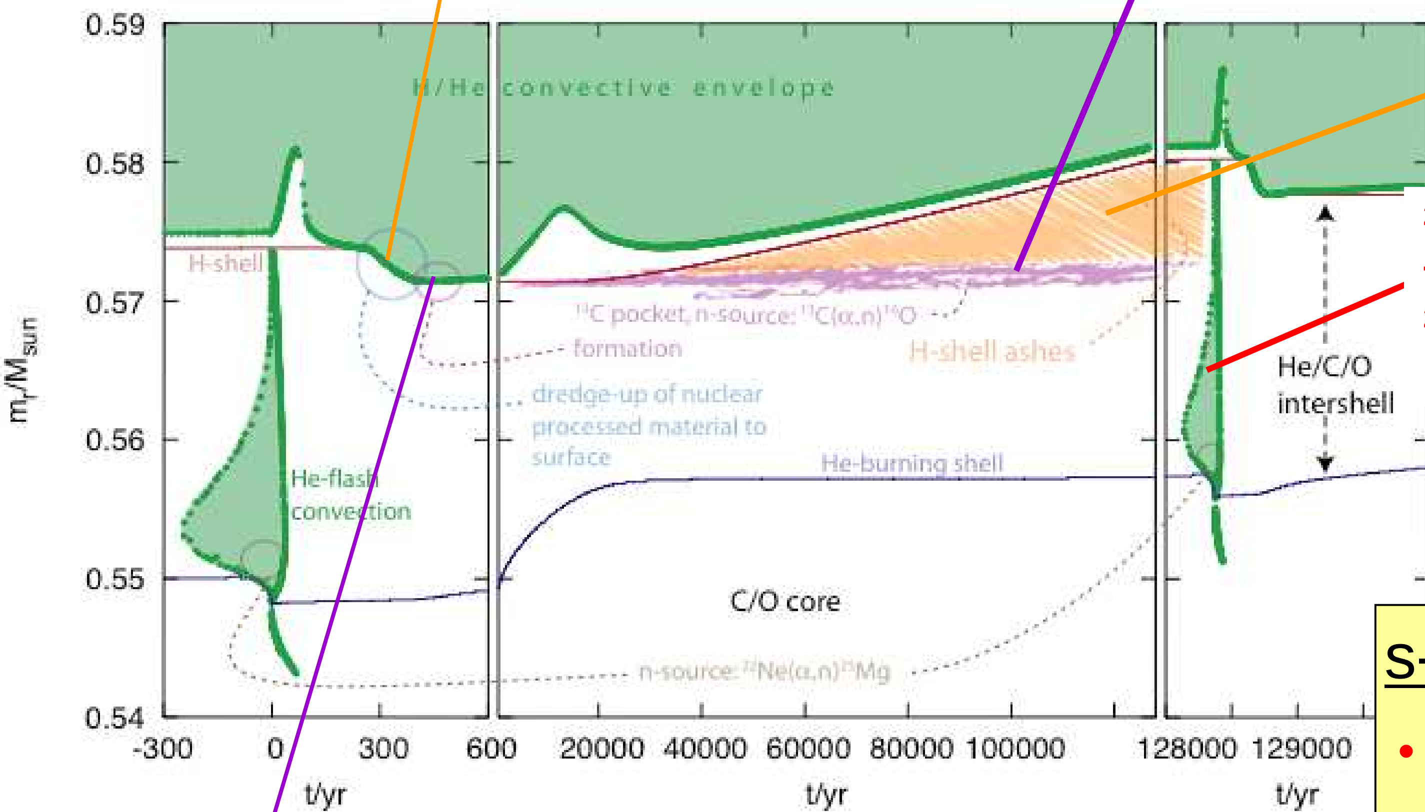
H/He burning in a TP-AGB star

- number of He flashes in stars life: few – 100
- period of flashes: 1000 – 100,000 years

Transport of s-process products to the surface

$^{13}C(\alpha,n)$ s-process

^{14}N production via CNO cycle



^{22}Ne production from ^{14}N then $^{22}Ne(\alpha,n)$ s-process

^{13}C pocket formation by mixing He burning products with H (ingestion) via $^{12}C + p \rightarrow {}^{13}N \ \beta^+ \rightarrow {}^{13}C$

<u>s-process in:</u>

- **He flash via $^{22}Ne(\alpha,n)$**
- **^{13}C pocket via $^{13}C(\alpha,n)$**

Main s-process in TP-AGB Stars step by step:

1.Convective He shell flash

1. Initiates He shell burning
2. Triggers convection zone that includes He and H shells
    1. Mixes He burning products (^{12}C) throughout the He burning shell
    2. Extinguishes H shell burning for brief period

2.3rd dredge up: After end of He flash and cooling, with H-shell extinguished, outer H-rich convection zone penetrates deeper than before

1. At boundary of H-envelope and He-burning shell ingestion of H into He-shell
2. $^{12}C+p \rightarrow {}^{13}N\ \beta+ \rightarrow {}^{13}C$ creates a ^{13}C pocket (extent of overlap of previous He convection zone and H convection zone, which then retracts again)

3.He-shell burning: s-process in ^{13}C pocket for 10,000 – 100,000 years

1. During He shell burning in hot He intershell, ^{13}C pocket produces s-process via $^{13}C(\alpha,n)$ neutron source

4.H-shell burning (re-starts a bit later than He-shell burning once envelope has retracted)

1. Produces ^{14}N via CNO cycle

5.Next He flash

1. Mixes s-process products, He burning products (^{12}C), and H-burning products (^{14}N)
2. ^{14}N is converted into ^{22}Ne (see weak s-process) and $^{22}Ne(\alpha,n)$ neutron source is briefly activated leading to some “touchup” of the s-process abundances especially at branchings

6.Next 3rd dredge up

1. Mixes s-process products to the surface

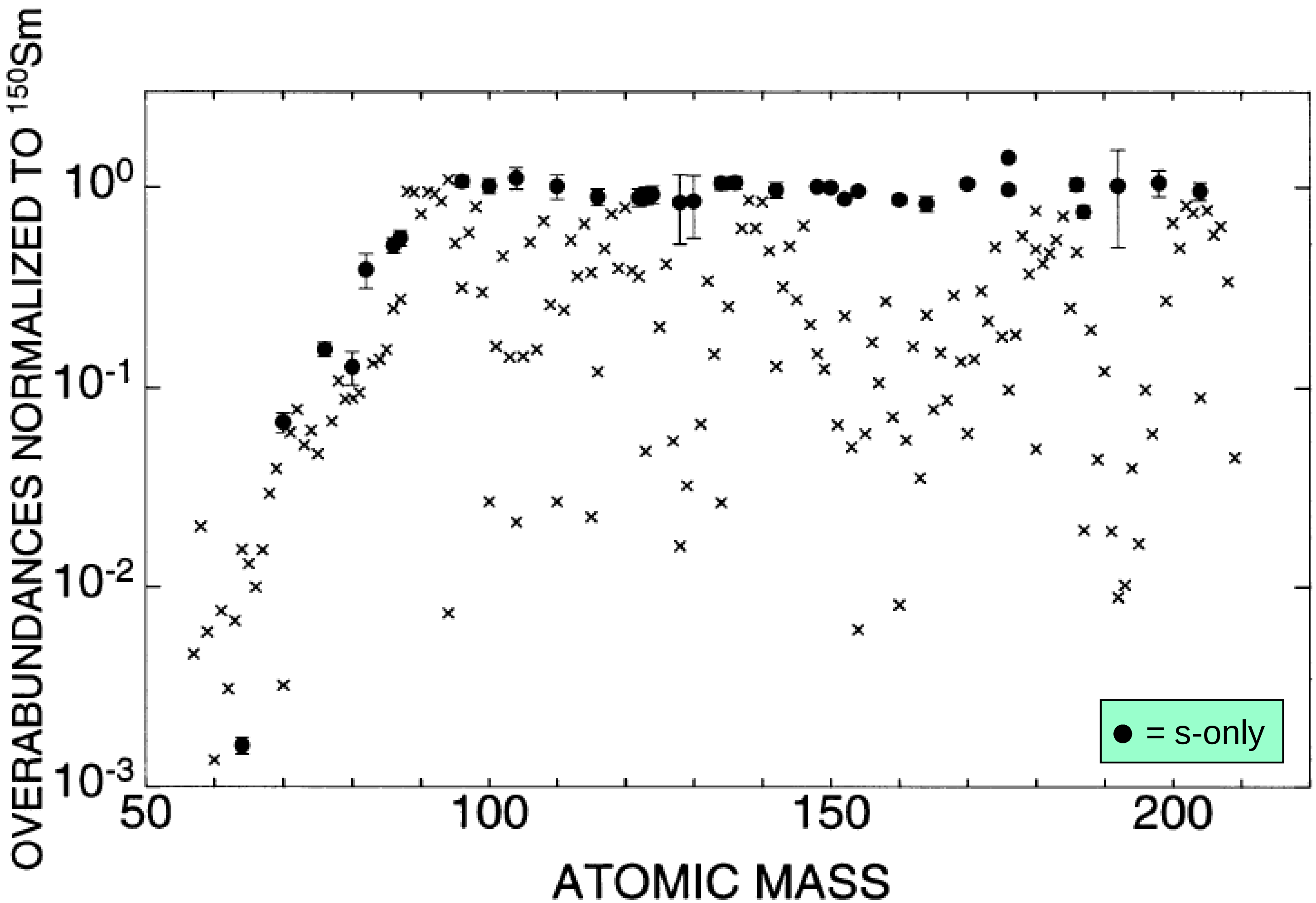
Conditions during the main s-process

	$^{13}C(\alpha,n)$ in pocket	$^{22}Ne(\alpha,n)$ in He flash
Temperature	0.9×10^8 K	2.7×10^8 K
Neutron density	7×10^7 cm^{-3}	10^{10} cm^{-3}
Duration	20,000 yr	few years
Neutron exposure τ *)	0.1 / mb	0.01 / mb

weaker but longer
main contribution
(90% of exposure)

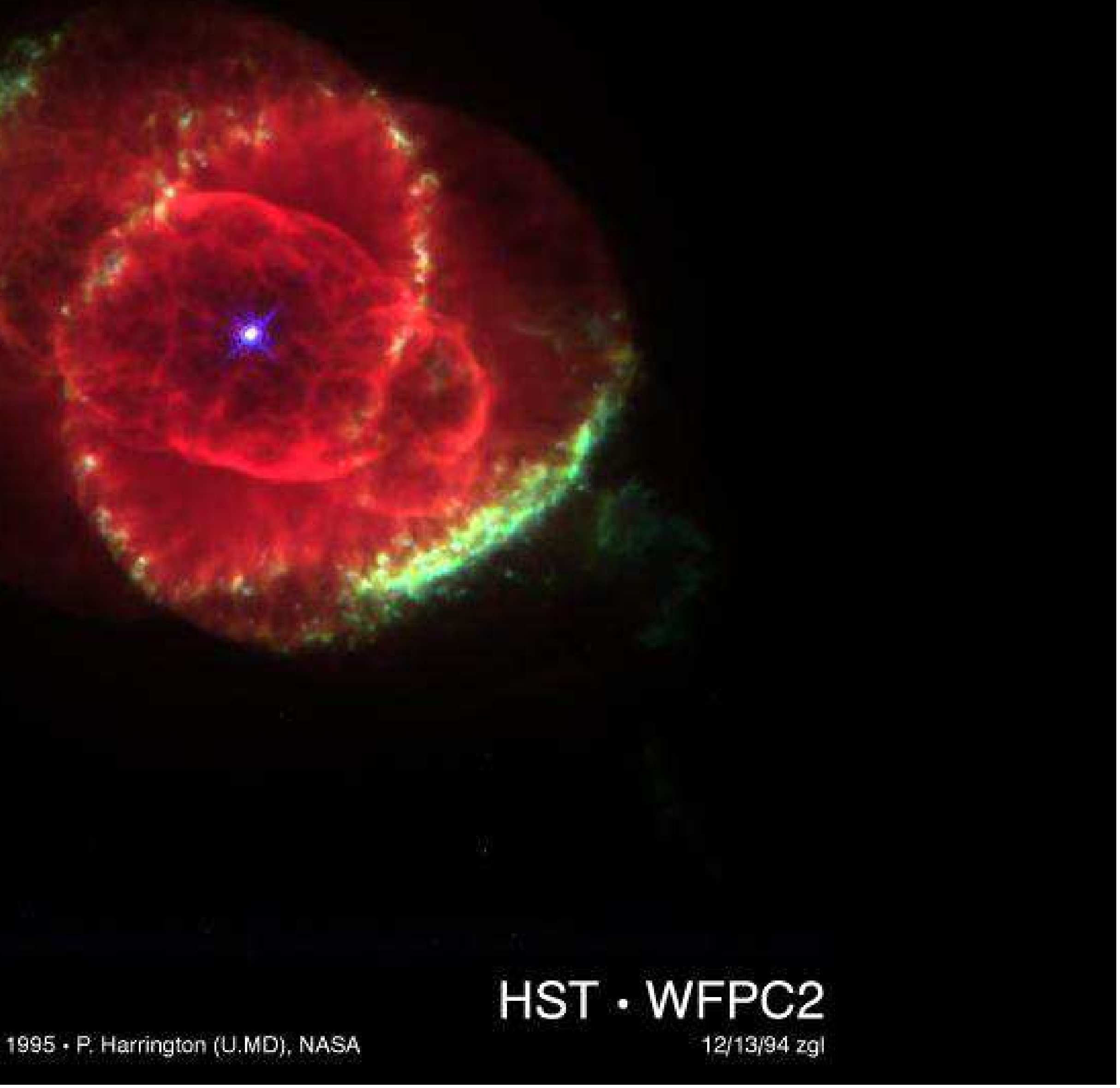
short, intense burst
slight modification
of abundances
(branchings !)

Results for main s-process model



(Arlandini et al. ApJ525 (1999) 886)

Grains from AGB stars



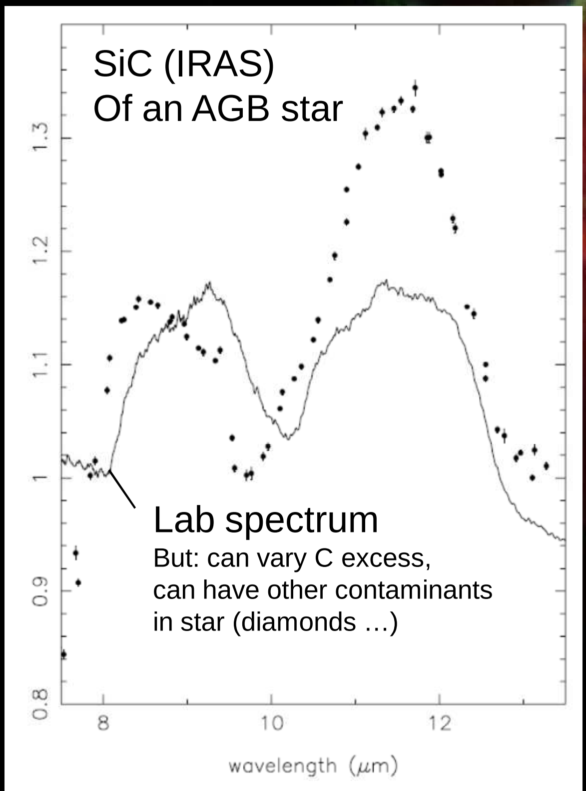
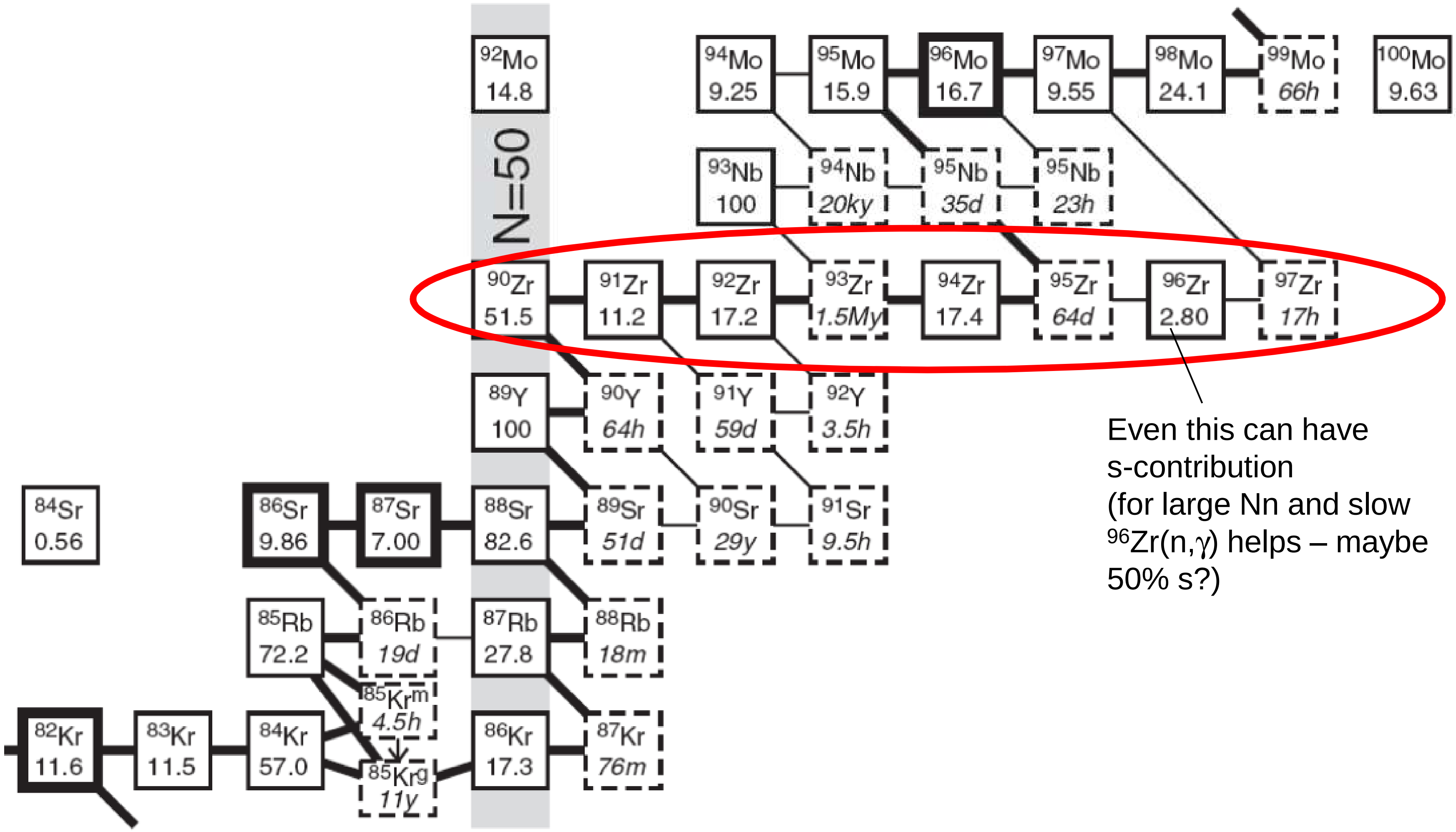


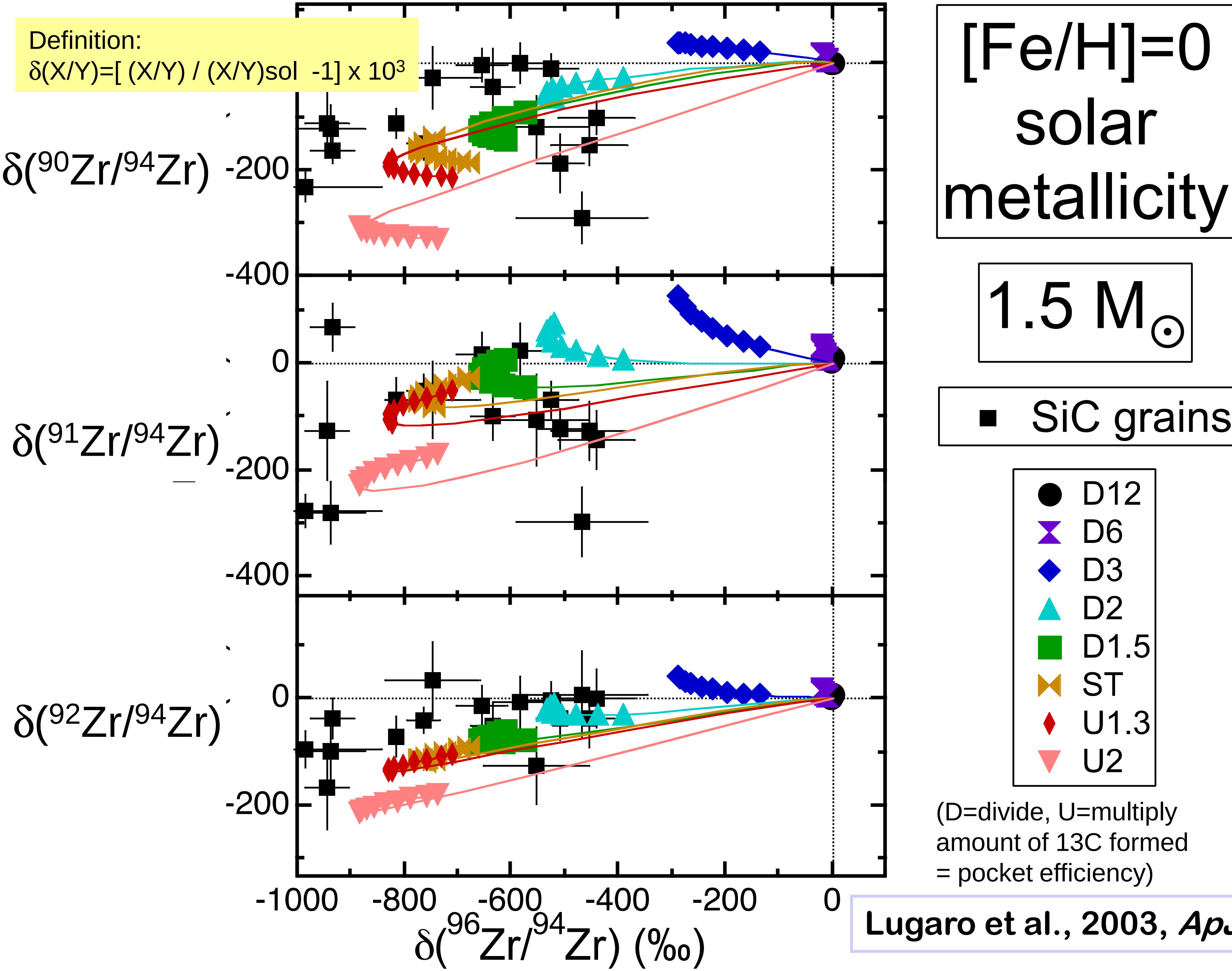
FIG. 3.—Comparison of double-peaked observed astronomical feature in the continuum-divided spectrum of Y CVn (*filled circles*) with laboratory spectrum of amorphous SiC (*solid line*).


Murchison CM chondrite

Zr in the s-process

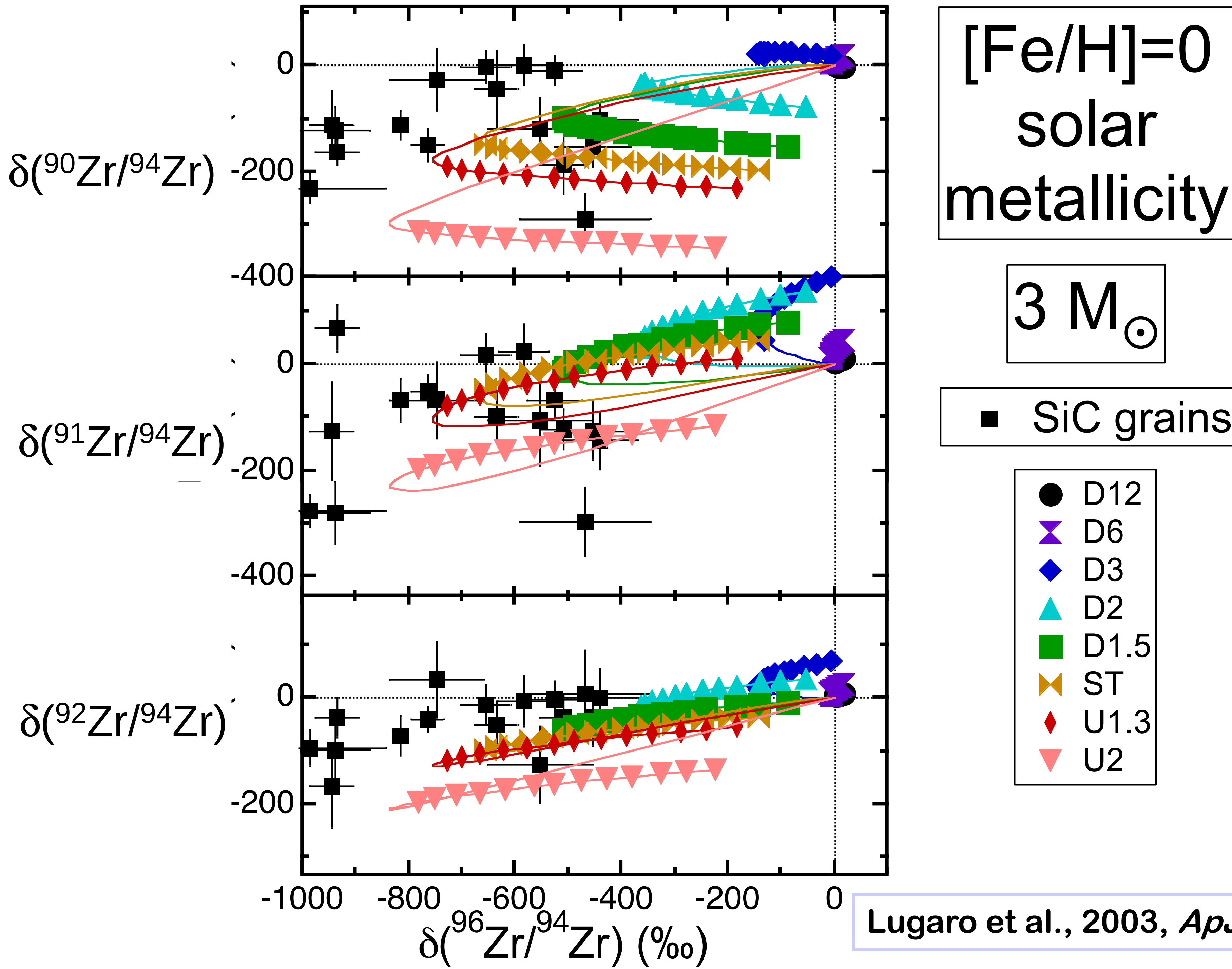


Even this can have s-contribution (for large Nn and slow ^{96}Zr(n,γ) helps – maybe 50% s?)



(D=divide, U=multiply amount of 13C formed = pocket efficiency)

Lugaro et al., 2003, *ApJ*



Lugaro et al., 2003, *ApJ*