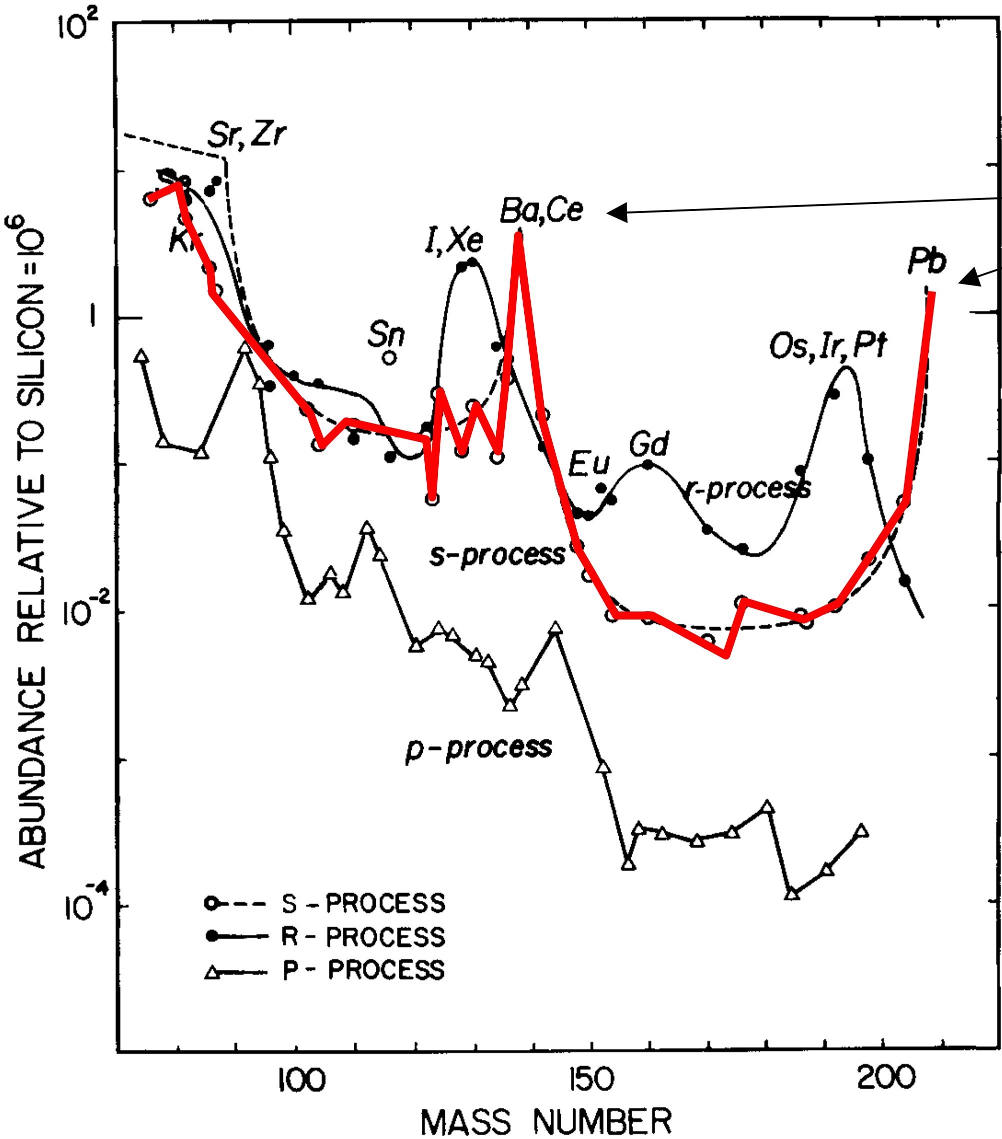
The origin of heavy elements in the solar system



(Pagel, Fig 6.8)

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

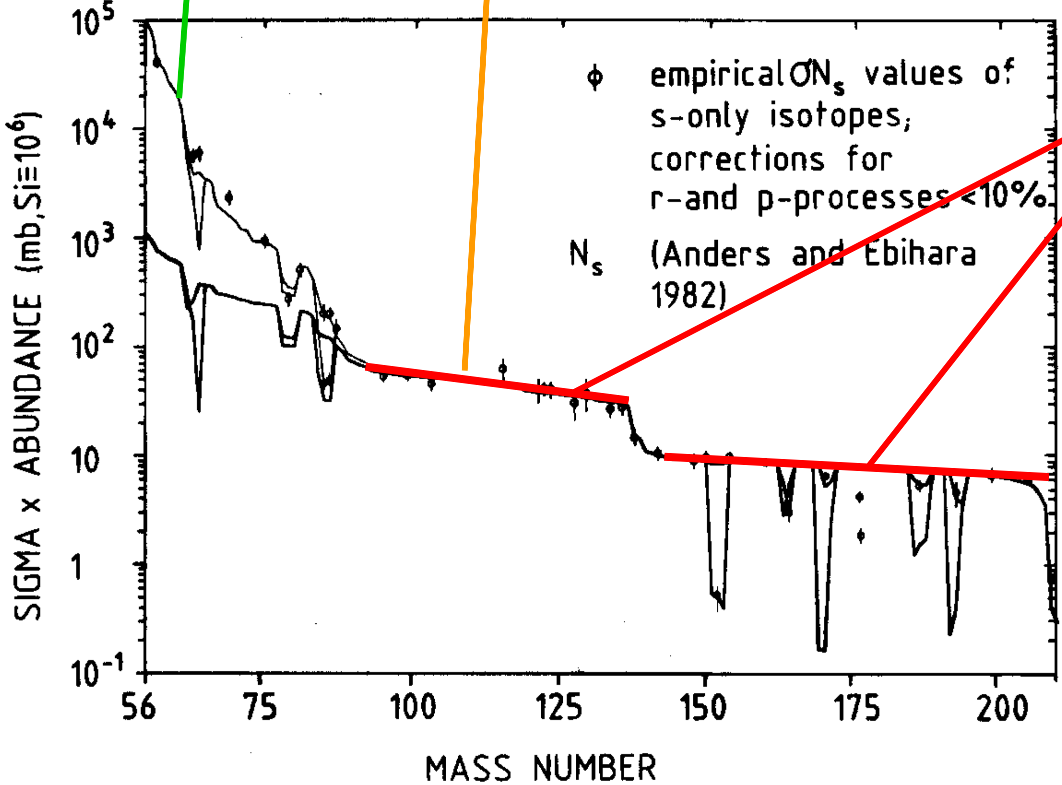
s-only isotopes are above p-process level → s-process

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

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

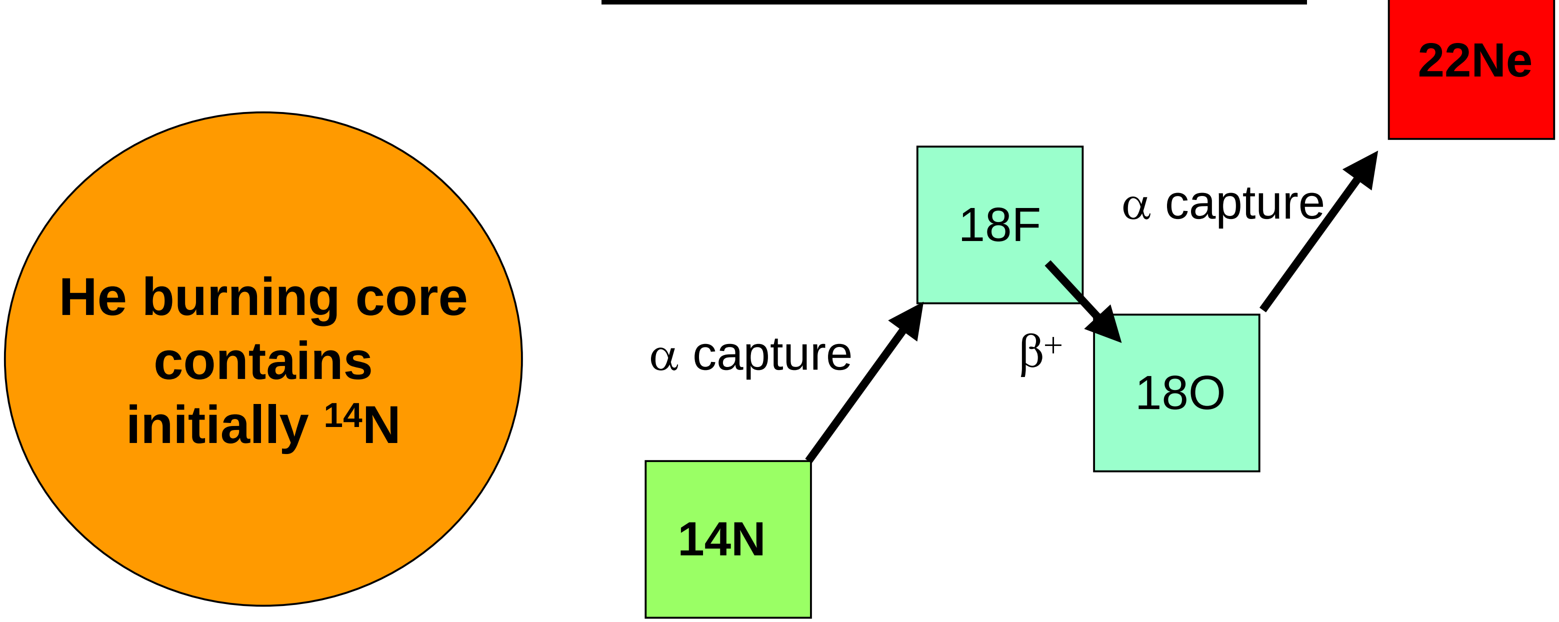
↓

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)

<u>**^{14}N is rapidly converted to ^{22}Ne**</u>



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

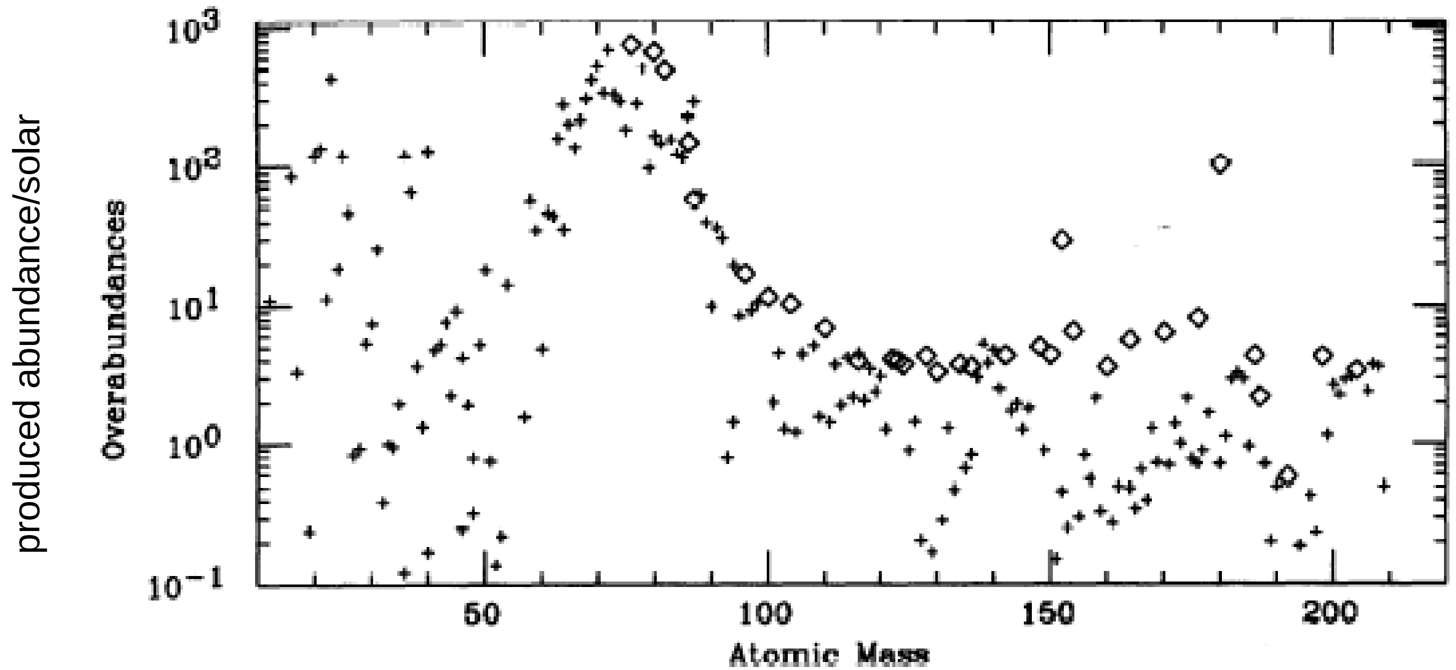
Typical conditions (Raiteri et al. ApJ367 (1991) 228 and ApJ371(1991)665:

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

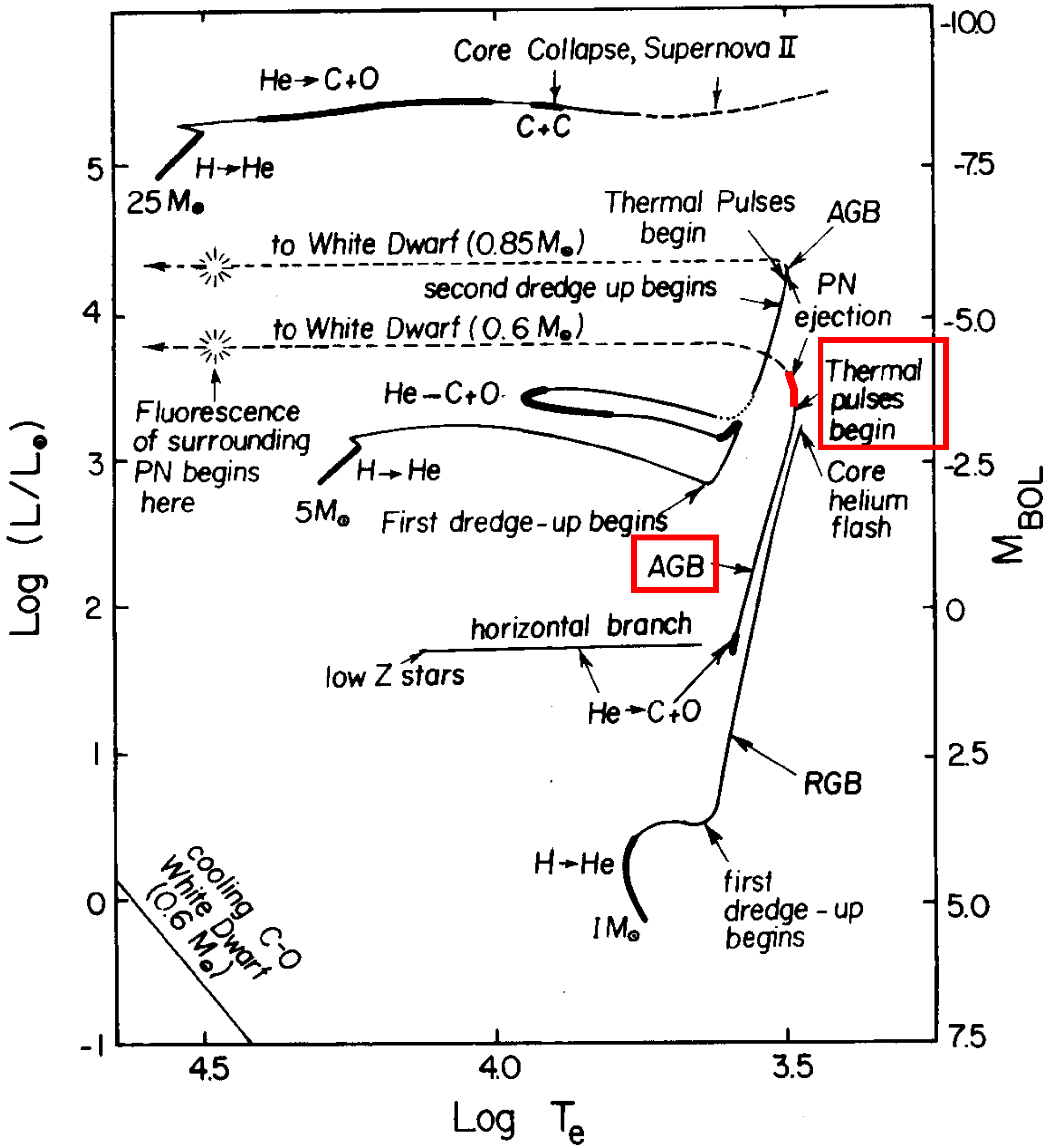
*) time integrated neutron flux

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

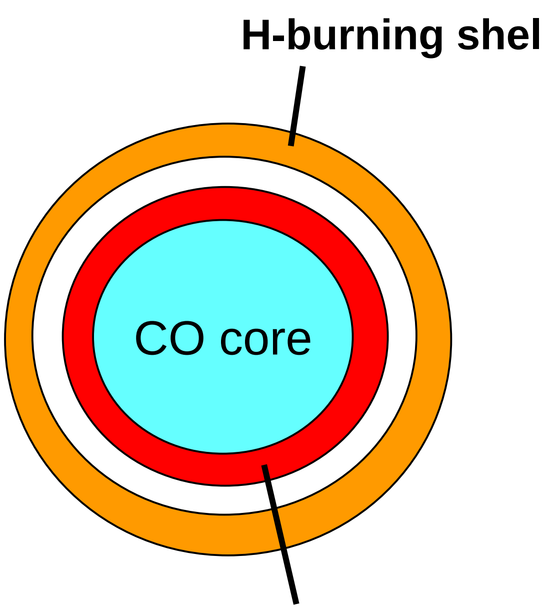
Results:



The main s-process

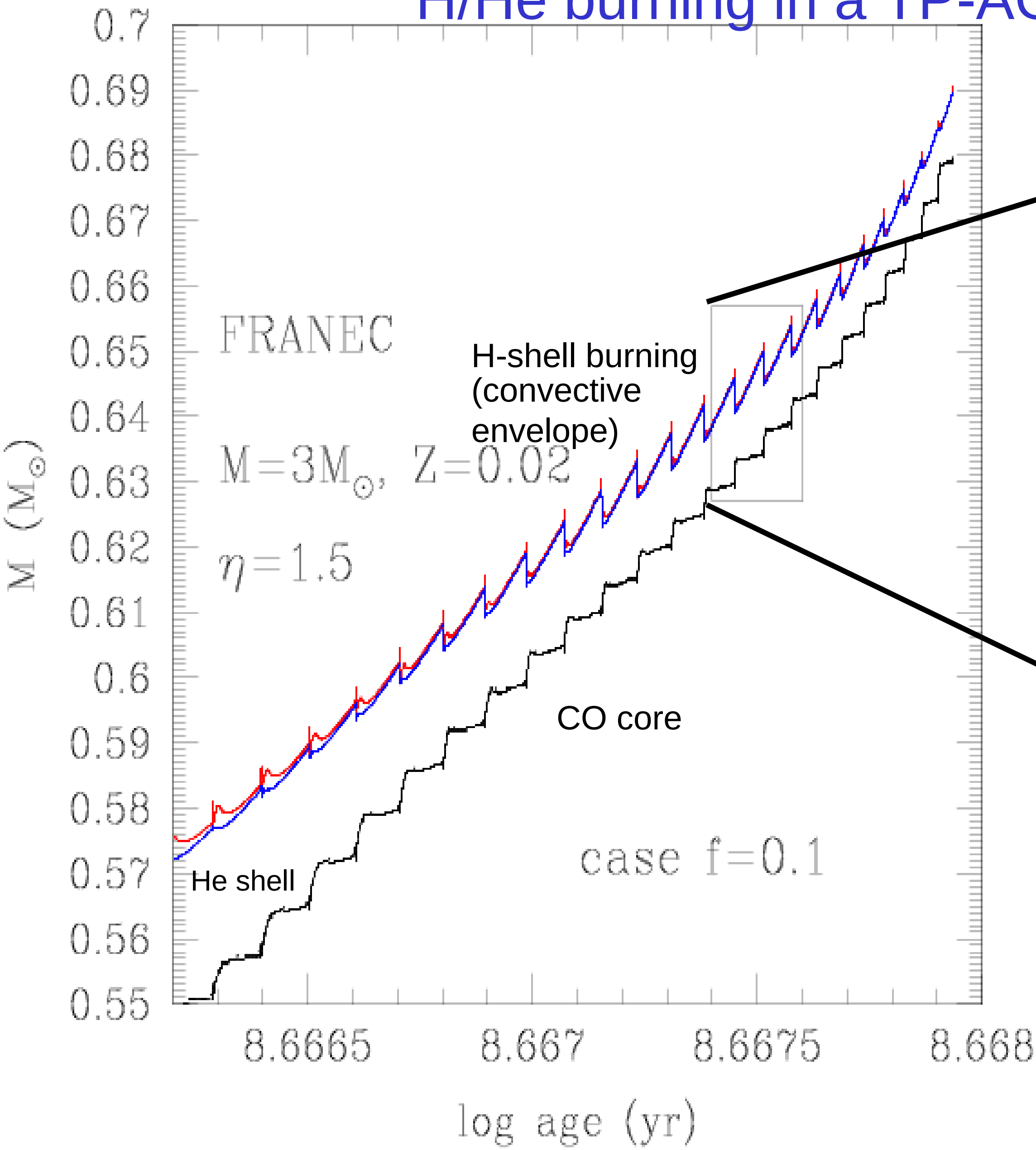


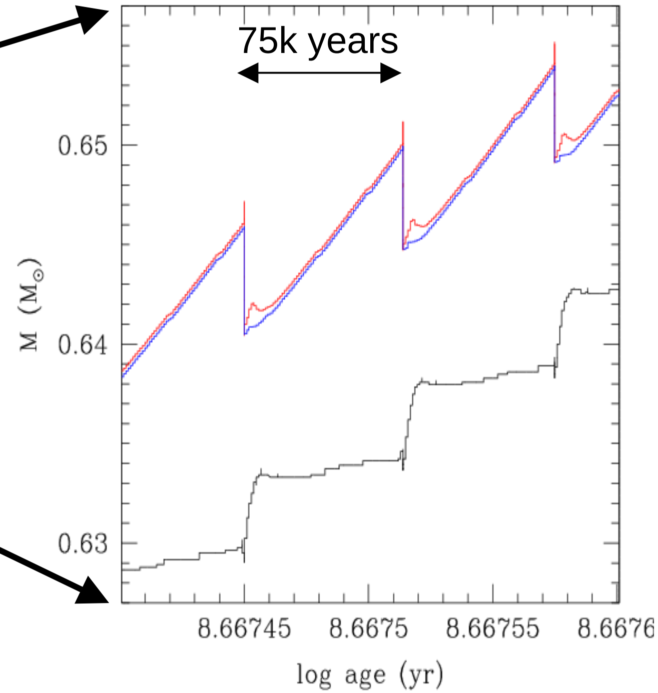
Site: low mass TP-AGB stars
(thermally pulsing stars
on the asymptotic giant
branch in the HR diagram,
1.5 - 3 solar masses)



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

H/He burning in a TP-AGB star





From R. Gallino

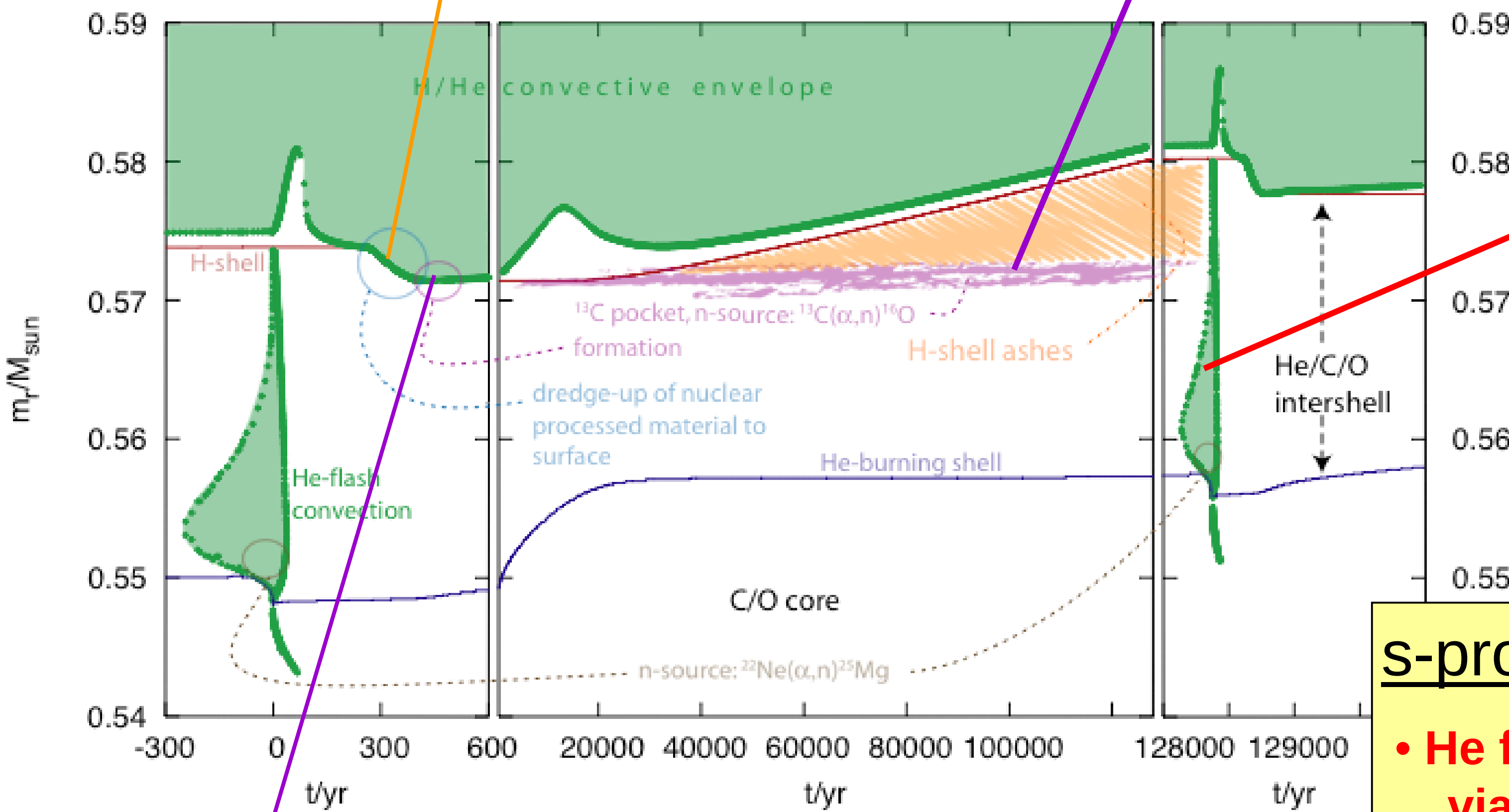
H/He burning in a TP-AGB star

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

Transport of s-process products to the surface

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

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



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

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

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

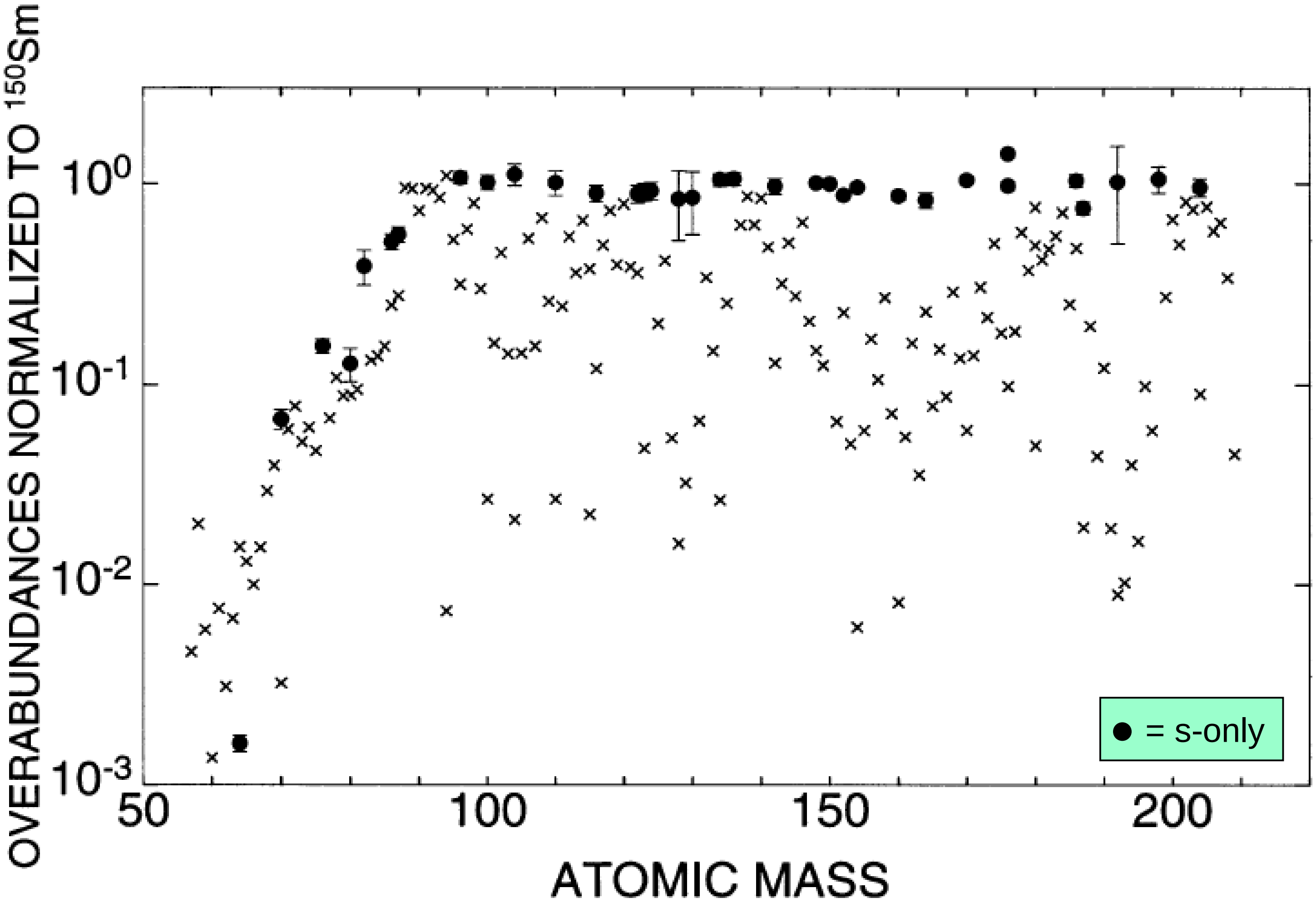
Conditions during the main s-process

	$^{13}C(\alpha,n)$ **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)

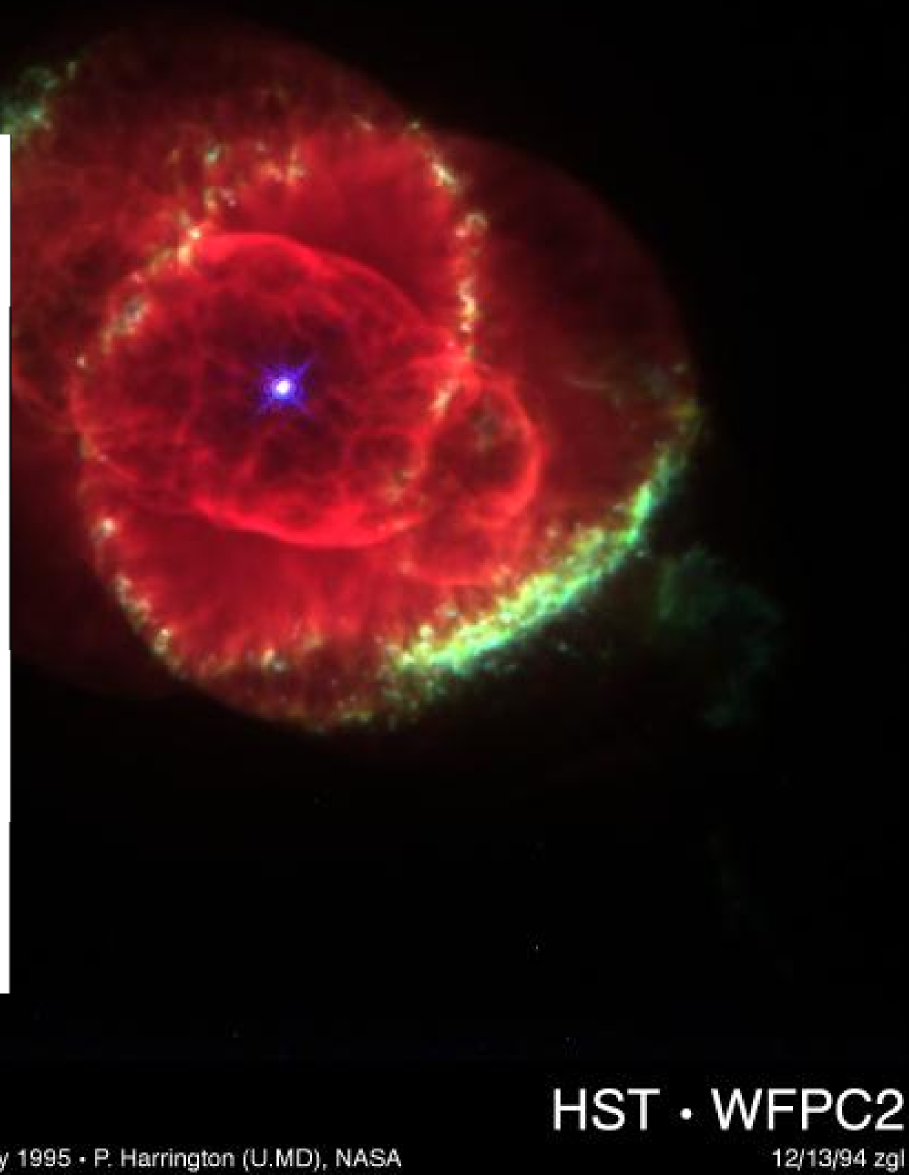
short, intense burst
slight modification
of abundances
(branchings !)

Results for main s-process model



(Arlandini et al. ApJ525 (1999) 886)

Grains from AGB stars



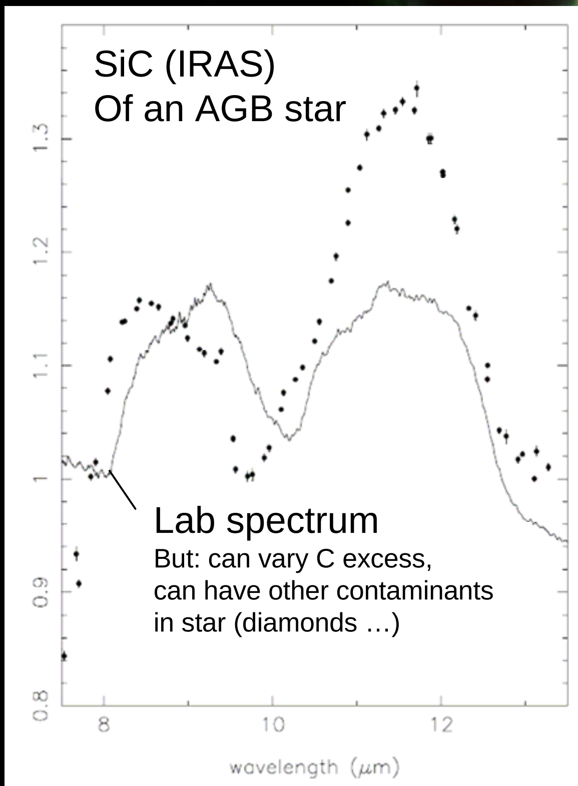


FIG. 3.—Comparison of double-peaked observed astronomical feature in the continuum-divided spectrum of Y CVn (*filled circles*) with laboratory spectrum of amorphous SiC (*solid line*).

Murchison CM chondrite

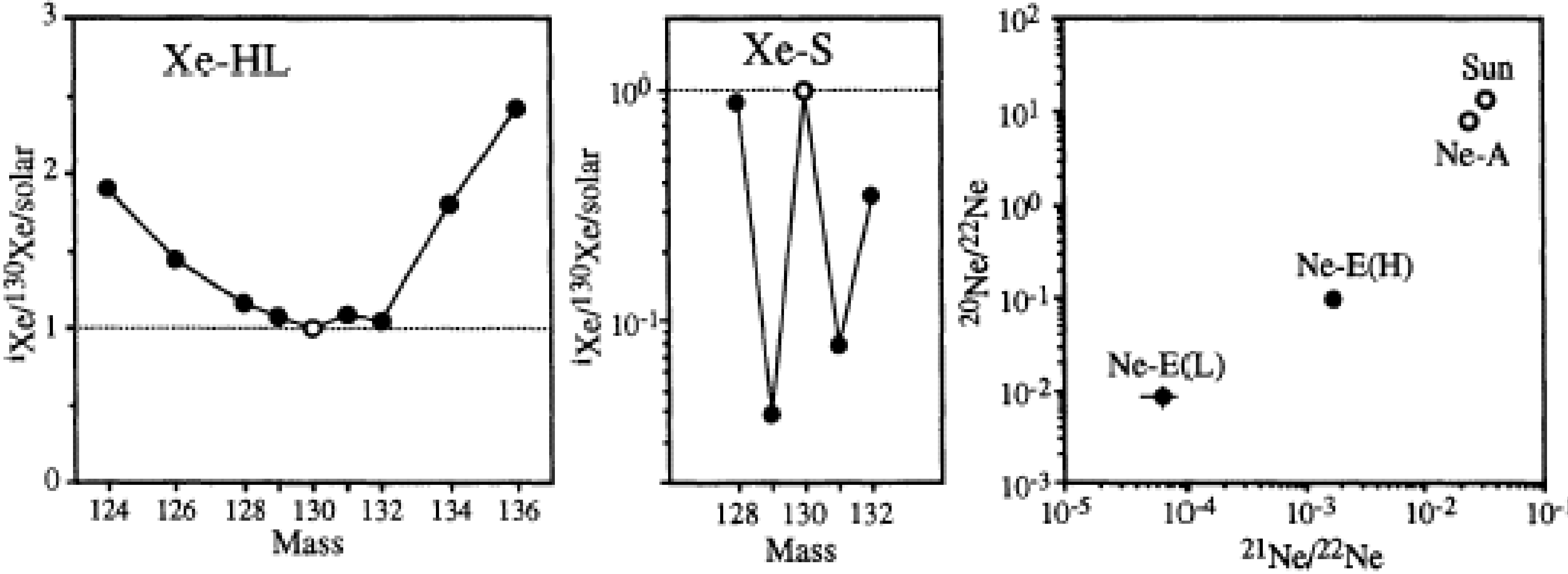
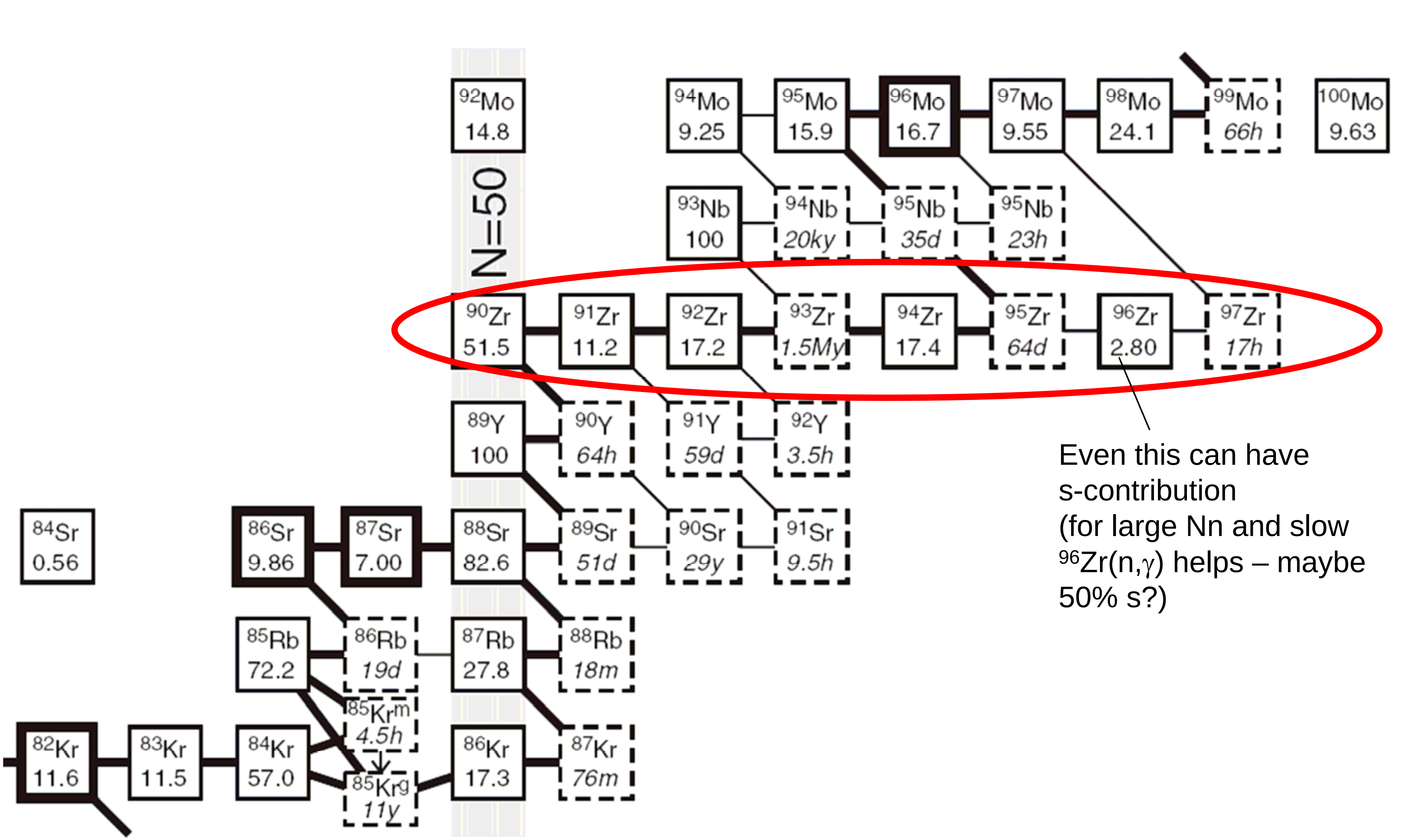
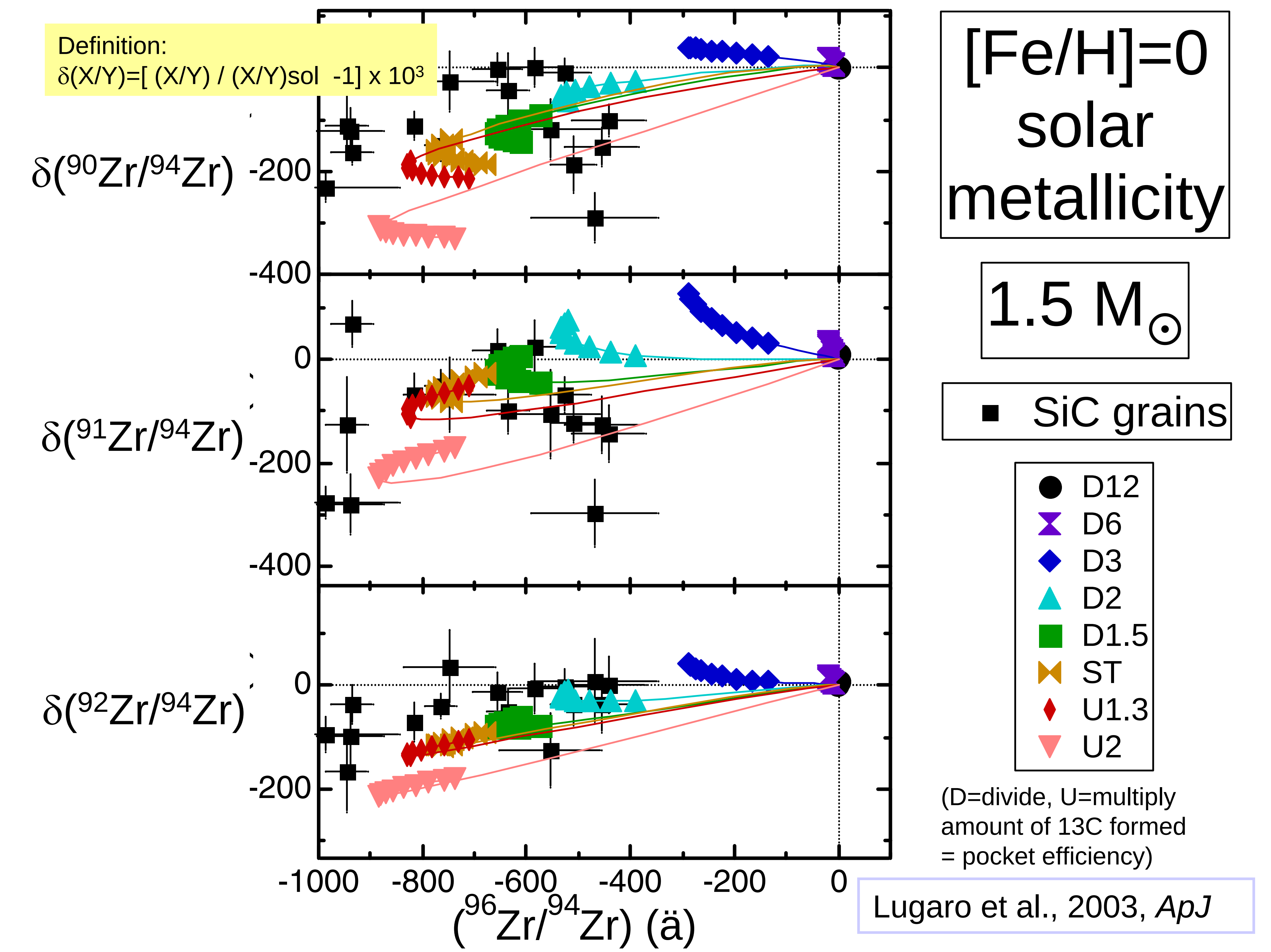
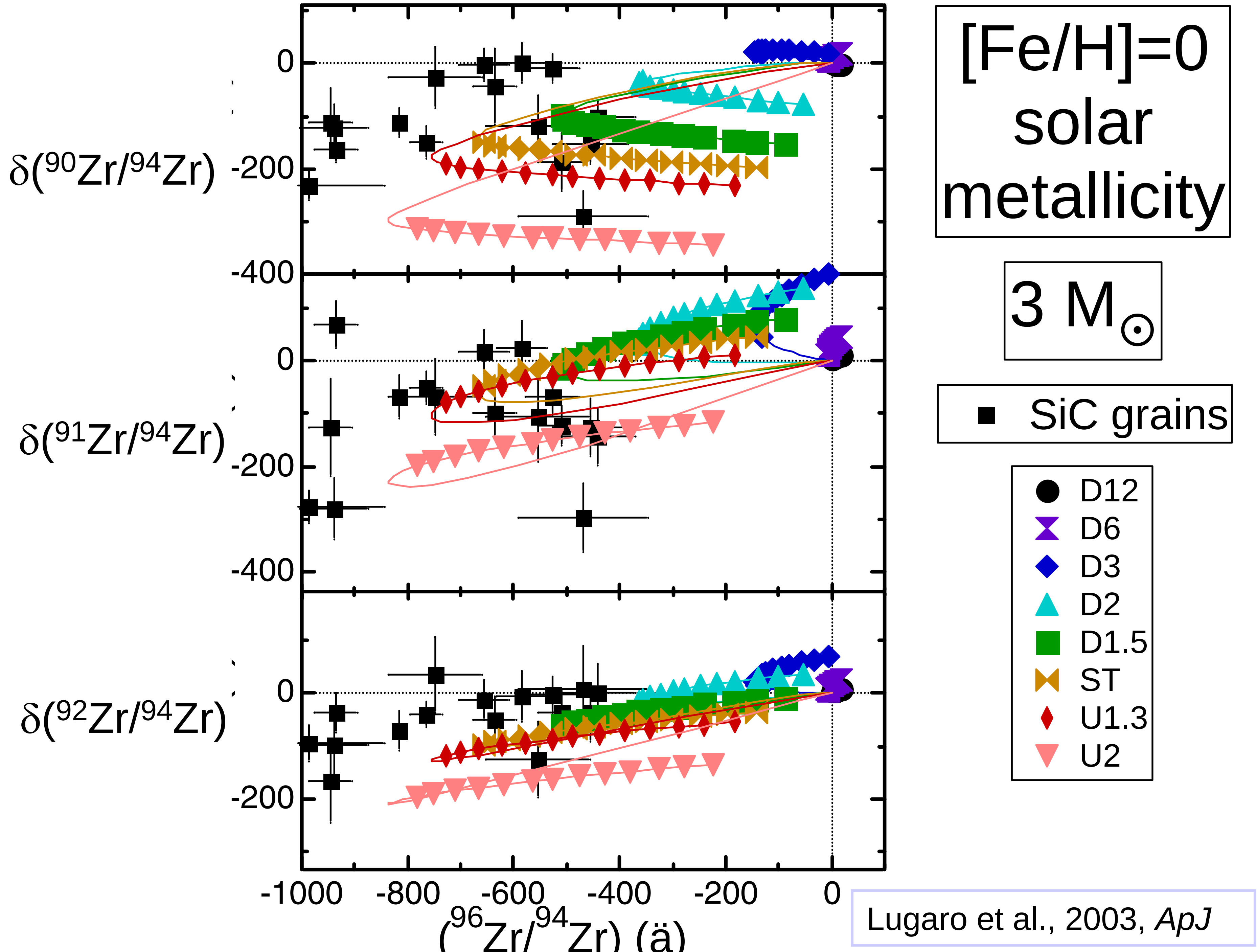


FIG. 1. Exotic noble-gas components in interstellar grains have highly anomalous isotopic patterns. The Xe-S pattern is the *extrapolated* end member, corrected for accompanying normal gases (Lewis *et al.*, 1993). The remaining patterns are the most extreme *actual* compositions measured.

Zr in the s-process




Definition:
δ(X/Y)=[(X/Y) / (X/Y)sol -1] x 10³
δ(⁹⁰Zr/⁹⁴Zr)
δ(⁹¹Zr/⁹⁴Zr)
δ(⁹²Zr/⁹⁴Zr)
-200
-400
0
-1000
-800
-600
-400
-200
(⁹⁶Zr/⁹⁴Zr) (ä)
[Fe/H]=0
solar
metallicity
1.5 M☉
SiC grains
D12
D6
D3
D2
D1.5
ST
U1.3
U2
(D=divide, U=multiply
amount of 13C formed
= pocket efficiency)
Lugaro et al., 2003, ApJ



[Fe/H]=0
solar
metallicity
3 M⊙
SiC grains
D12
D6
D3
D2
D1.5
ST
U1.3
U2
δ(90Zr/94Zr)
δ(91Zr/94Zr)
δ(92Zr/94Zr)
(96Zr/94Zr) (ä)
0
-200
-400
-1000
-800
-600
-400
-200
0
Lugaro et al., 2003, ApJ