Observations of s-process elements in stars

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Outline:

1. **The s-process**

2. **Observational constraints from stars**
   - **intrinsic stars: AGBs, post-AGBs & PNe**
   - **extrinsic stars: Ba, CH & CEMP stars**

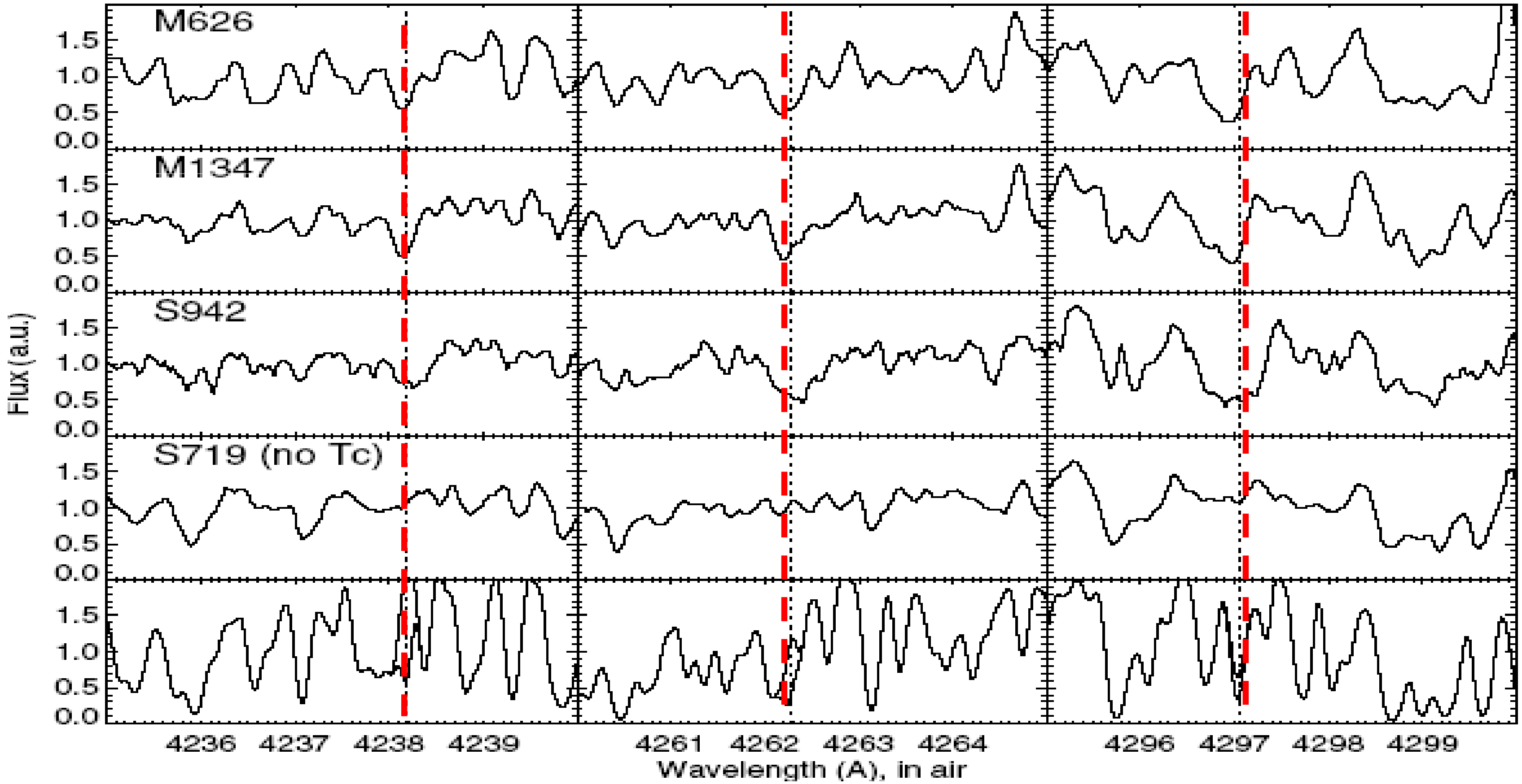
3. **Open problems & summary**

The s-process

- ✓ Responsible for ~ 50% of the elements beyond Fe-peak
- ✓ $\tau(n,\gamma) \gg \tau(\beta)$
- ✓ "Secondary" nature: needs seed nuclei (^{56}Fe) already present in the star
- ✓ $N_n \sim 10^7$-10^{11} cm^{-3}

In-situ production in stars: ^{99}Tc ($\tau_{1/2} \sim 2 \cdot 10^5$ yr)

Merrill (1952)



The neutron source(s) & the site(s)

- $^{13}C(\alpha,n)^{16}O$, and alternatively $^{22}Ne(\alpha,n)^{25}Mg$, Cameron (1955)

- Superposition of neutron exposures needed to fit the SS pattern Clayton (1961)
  - weak component A < 90 (Fe - Sr)
  - main component 90 ≤ A ≤ 204 (Sr - Ba)
  - strong component A > 204 (Pb, Bi)

$$\boxed{\tau = \int N_n v_{th} dt}$$

- Schwarzchild & Harm (1967): Thermally pulsing AGB stars ($1 \leq M/M_{\odot} \leq 8$)

  (main & strong components)

- Cauch et al. (1974): core He- & shell C-burning in massive stars ($M > 8\ M_{\odot}$)

  (weak component)

Later on, a huge THEORETICAL and OBSERVATIONAL effort has been made to confirm (discard) these ideas or/and to identify alternatives (Kappeler et al. 2011)

Observational tests to the s-process theory

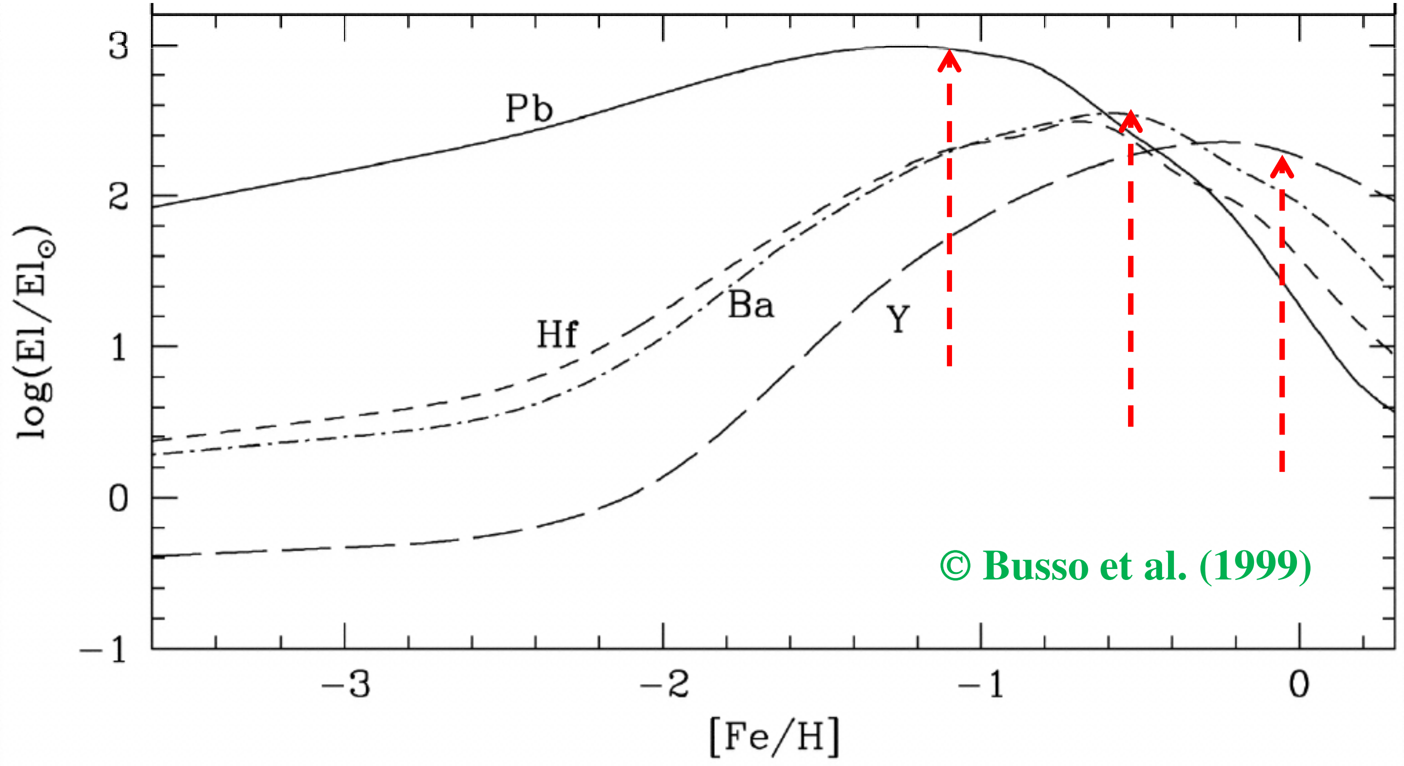
✓ **Abundance patterns: neutron source(s)?** **" ^{13}C-pocket" size & mass ; stellar mass**

✓**s-process enhancements: efficiency of the 3rd dredge-up and mixing in stars**

$$[s/Fe] \propto 1/ Z$$

✓**Dependence on metallicity: the neutron exposure**

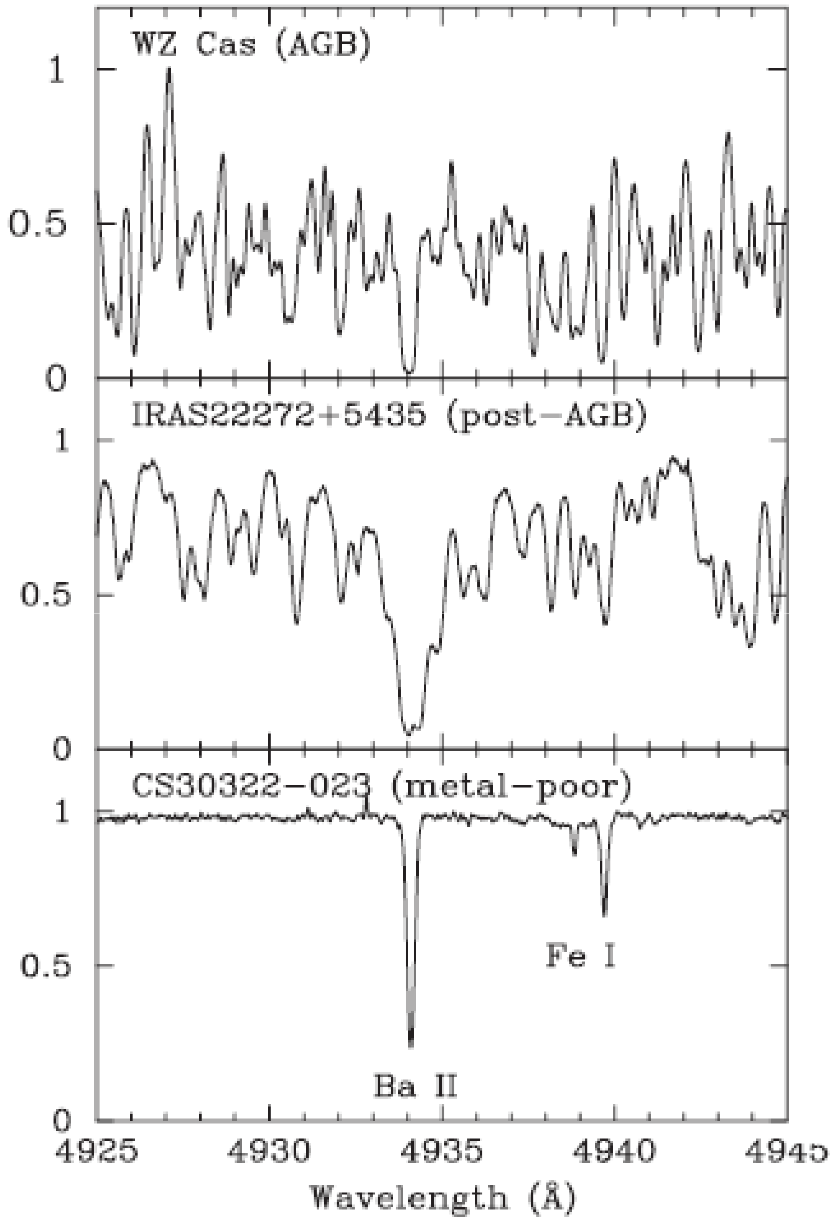
The abundance ratio between heavy-s (Ba,La,Ce…) and light-s (Sr,Y,Zr) elements [hs/ls], depends on the stellar metallicity



Chemical analysis: pros (+) & cons (-)

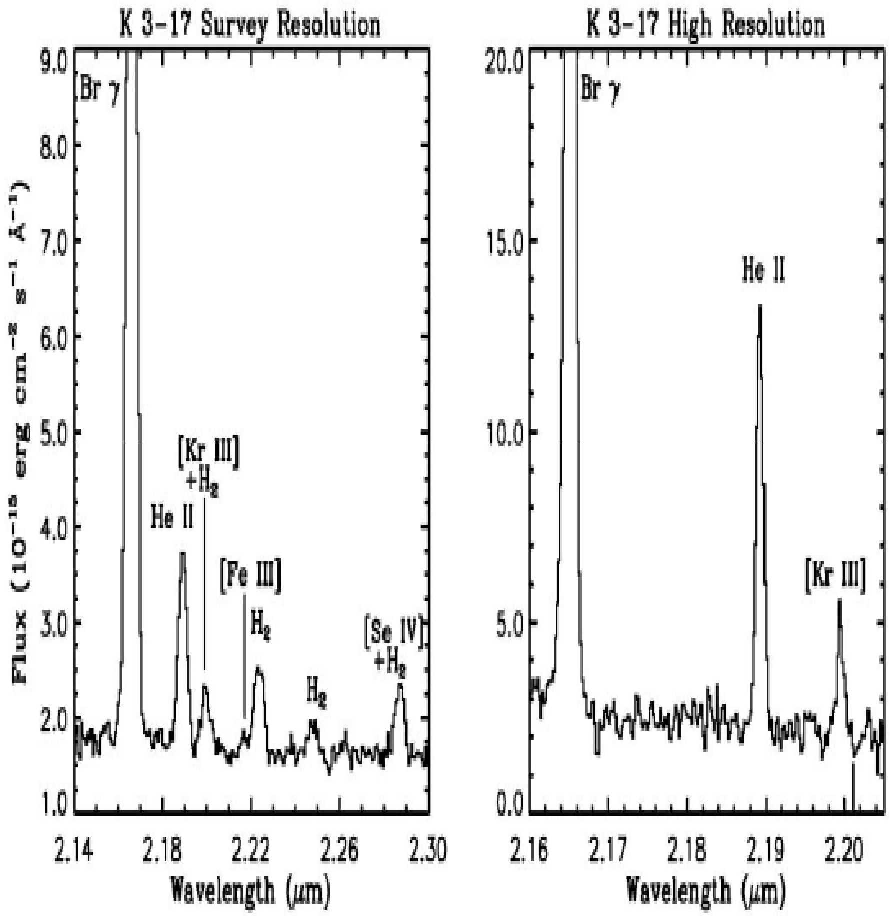
- ✓ **AGB stars:**
  - \- Cool: molecular & dust opacities, C/O ??
  - \- Variable stars: shock waves, dynamical atmospheres
  - \- Very crowded/blended spectra
  - \+ Bright (extragalactic), numerous
  - \+ Intrinsic objects (Tc)
- ✓ **Post AGB stars**
  - \+ Warm atmospheres: no molecules in the spectrum
  - \- Short life-times: very few objects (difficult to identify)
- ✓ **PNe**
  - \- Very weak emission s-element lines: ionization corrections
  - \- Lack of spectroscopy data
  - \+ Promising...
- ✓ **Ba- stars, CH-stars, CEMP-s...**
  - \- Extrinsic objects (no Tc): dilution effects, initial abundances...?
  - \+ Accurate atmosphere parameters
  - \+ Easy analysis

Samples of spectra



© Kappeler et al. (2011)

K13-17, PN

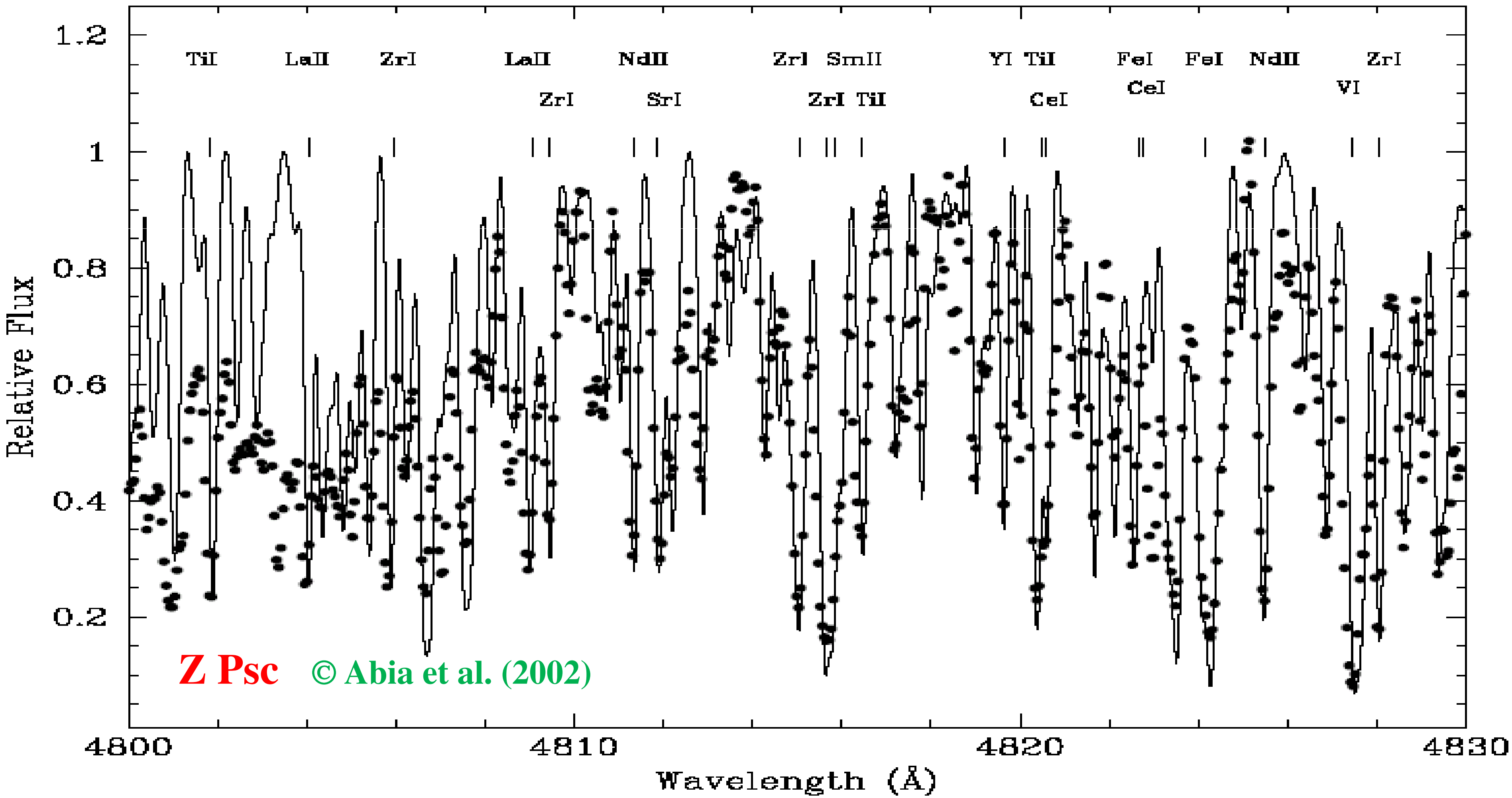


© Sterling & Dinerstein (2008)

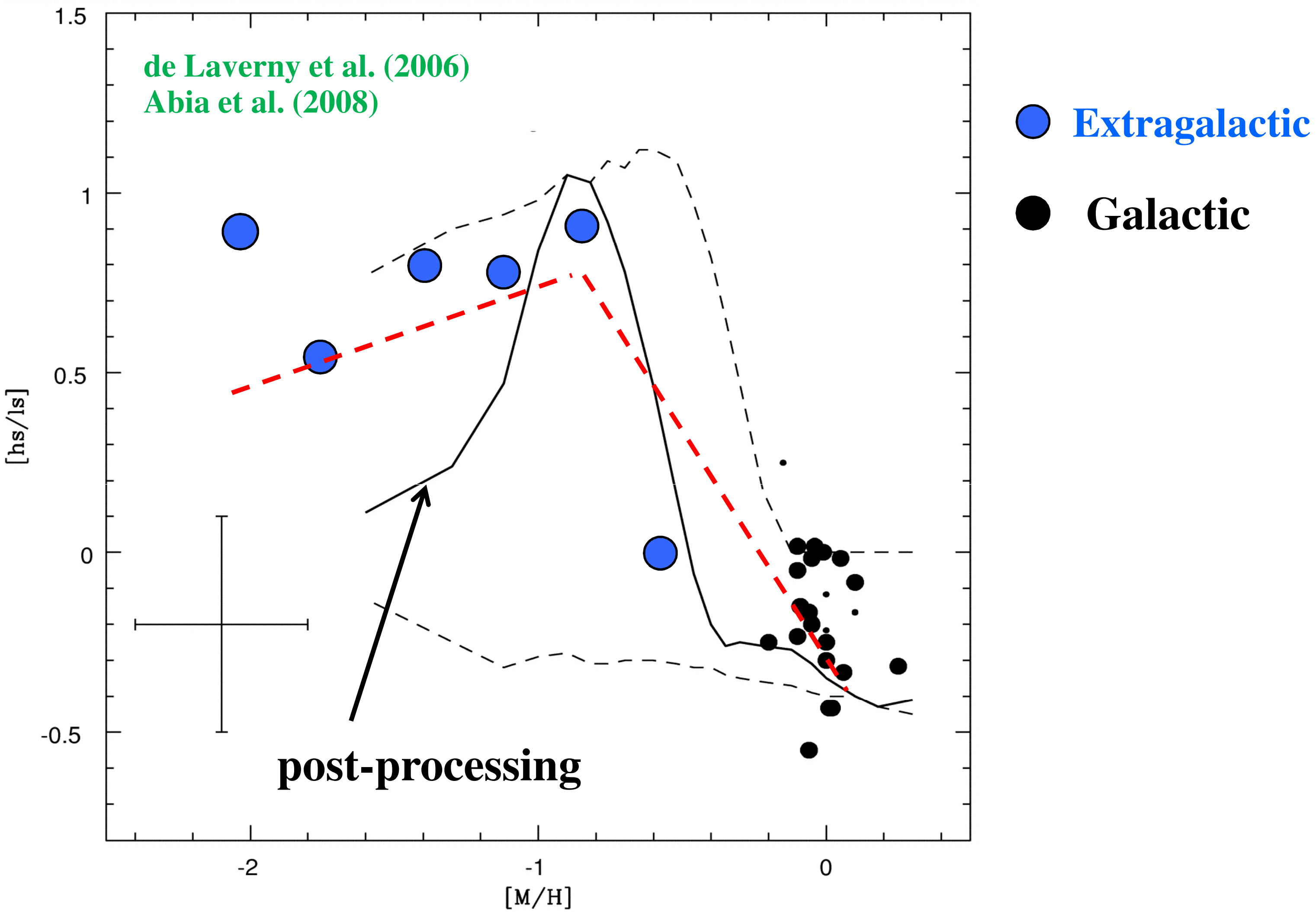
AGB stars: Utsumi (1985)

- Galactic O- & C-rich ([Fe/H]~0) AGBs show enhancements [s/Fe] ~ +0.5
- Metal-poor AGBs in satellite galaxies show larger enhancements [s/Fe] ~ 1-2

$$[s/Fe] \propto 1/Z \quad \text{ok!!}$$



The neutron exposure: [hs/ls] vs. [Fe/H] in AGB C-stars

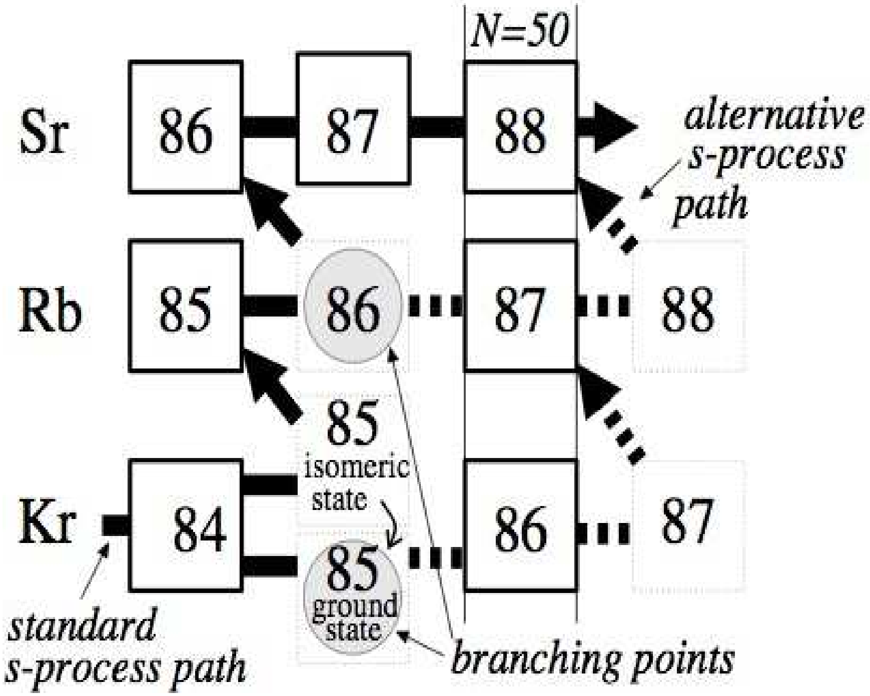


In O-rich AGB stars, similar agreement with theoretical models is found

Smith & Lambert (1990) etc..

^{85}Kr-branching ($\tau_n \sim \tau_\beta$) reveals the astrophs. scenario: neutron source

Lambert et al. (1995)
Abia et al. (2001)



^{85}Rb, σ = 240 mb (30 keV)

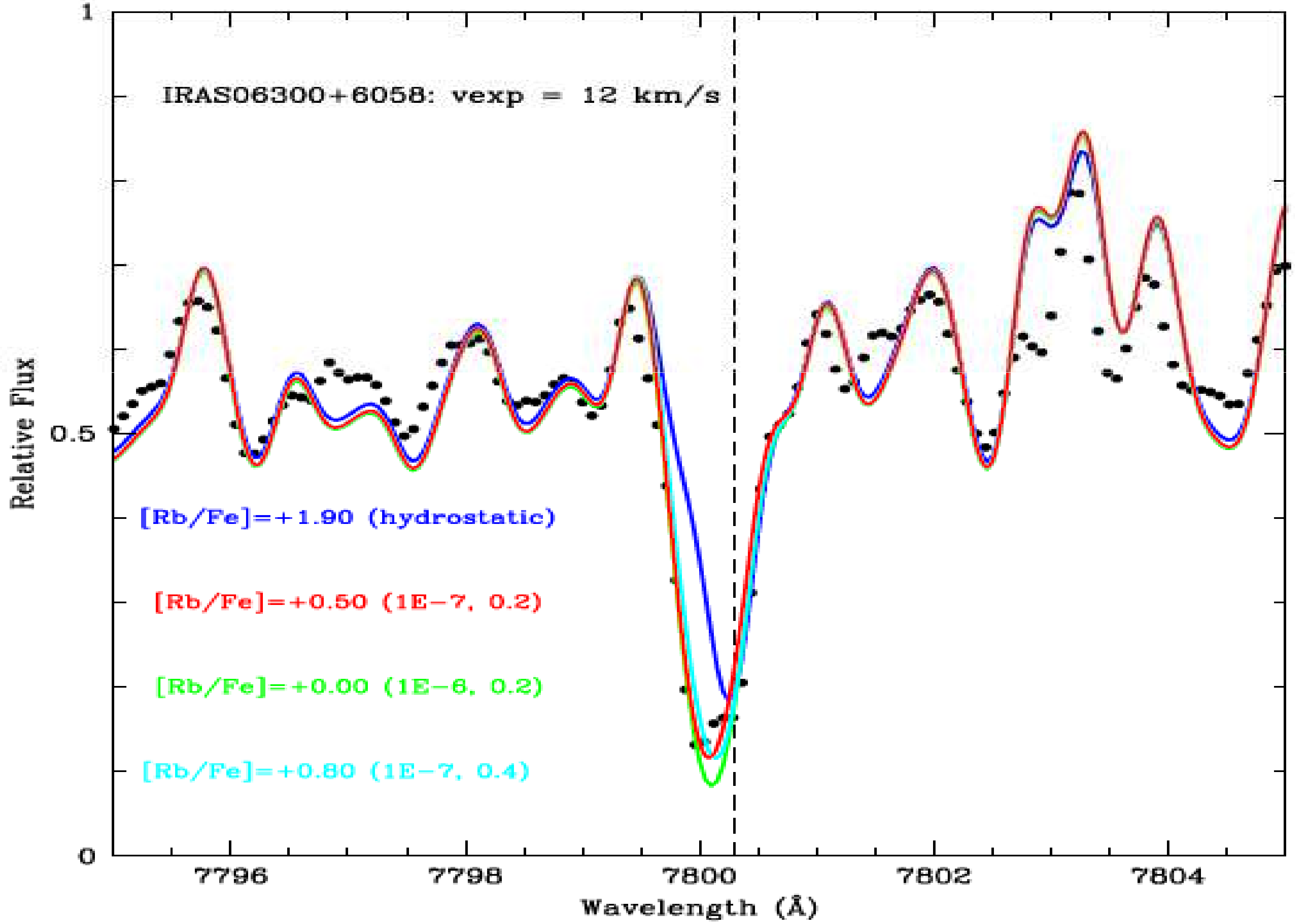
^{87}Rb, σ = 15 mb (30 keV)

$N_n \sim 10^8$ cm^{-3}, radiative ^{13}C(α,n)^{16}O → low [Rb/Sr,Y,Zr]

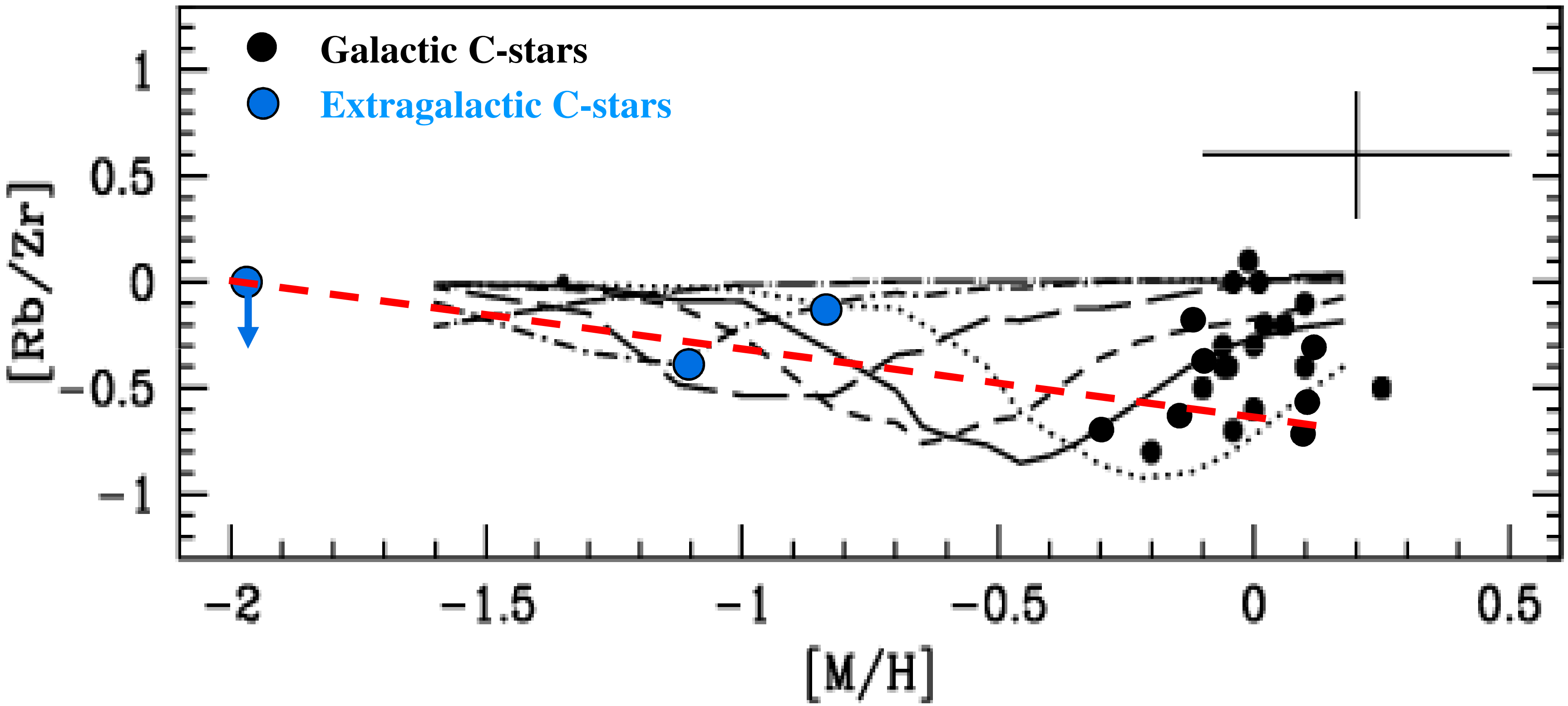
$N_n \sim 10^{11}$ cm^{-3}, convective ^{22}Ne(α,n)^{25}Mg → high [Rb/Sr,Y,Zr]

Fit to the Rb line in a O-rich AGB star using dynamical model atmospheres

© Perez-Mesa et al. (2017)



The low [Rb/Zr] ratios in AGB C-stars supports the $^{13}C(\alpha,n)^{16}O$ as the main neutron source in low mass stars, $M < 3\ M_\odot$



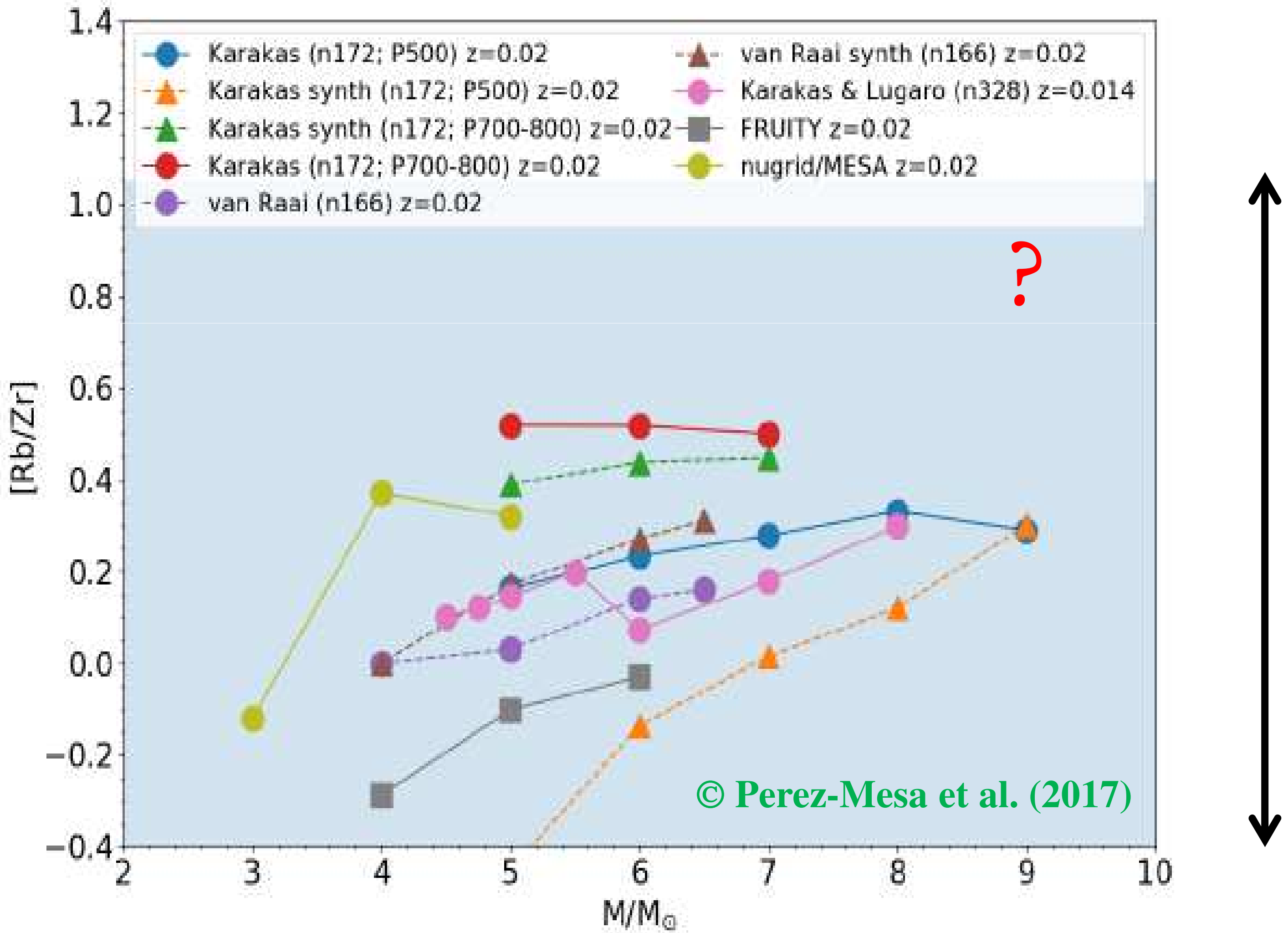
Black lines: Post-processing 1.5 $M_\odot$ model for different ^{13}C-pockets, Gallino et al. (1998)

Red-dashed line: 2 $M_\odot$, phys & chem. fully coupled after 10th TP, Cristallo et al. (2011)

Other calculations obtain very similar results (Monash, Brussels...)!!

instead... the high [Rb/Zr] found in massive ($M > 4\ M_{\odot}$) AGB stars, favours the $^{22}Ne(\alpha,n)^{25}Mg$ reaction in these stars

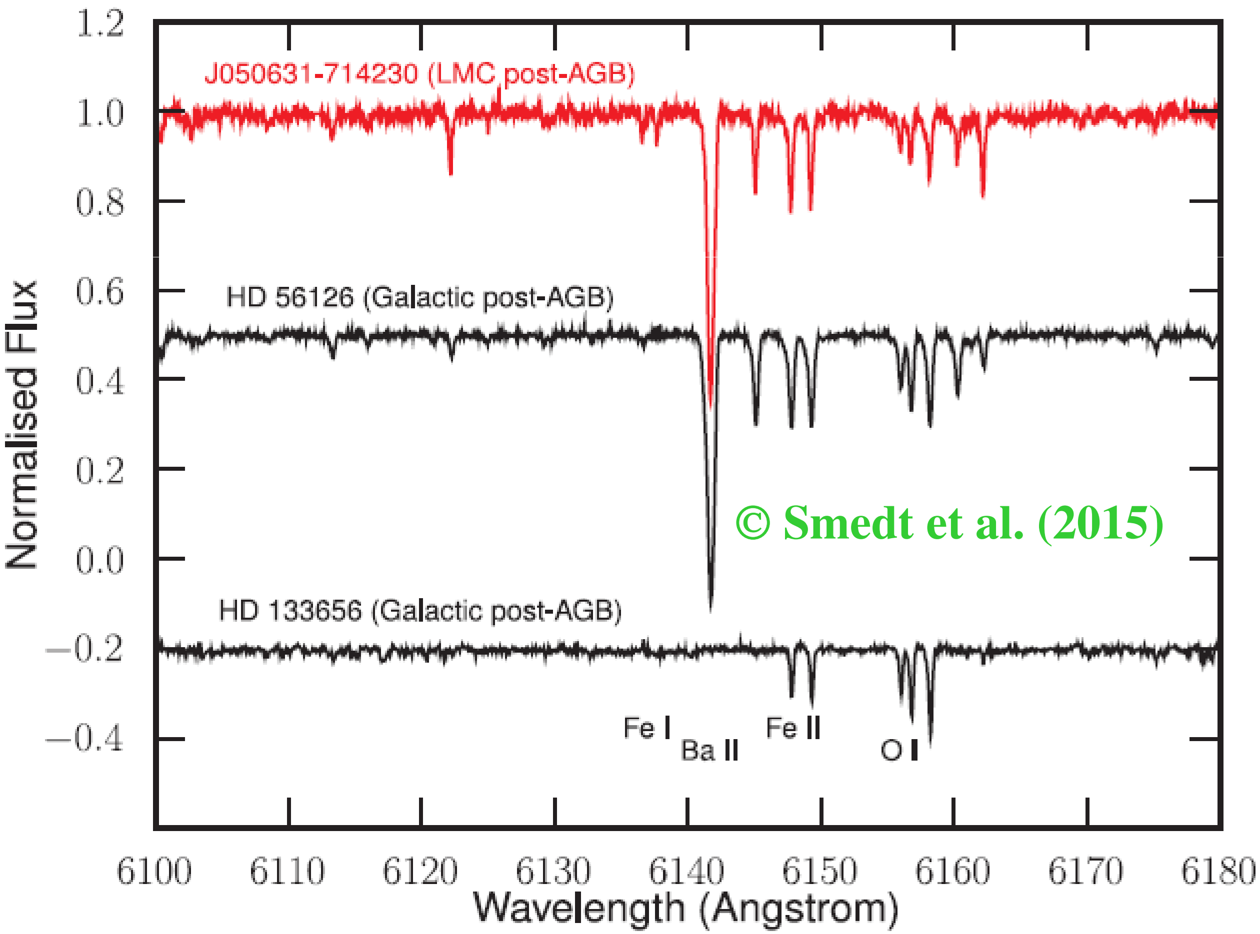
García-Hernández et al. (2007)
Zamora et al. (2014)



Post AGB-stars
Van Winckel et al.

Tracers of the s-process at the end of the AGB phase → [s/Fe] >>1

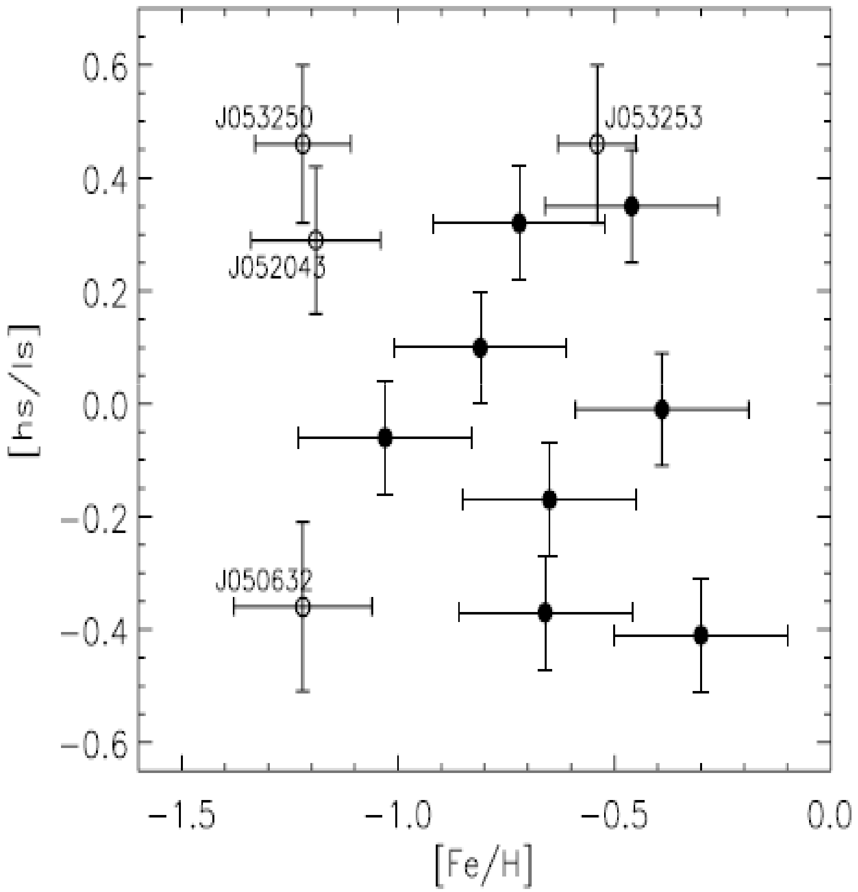
- Large diversity in [s/Fe] in Galactic and LMC post-AGB at a given Z (mass)
- Many do not show s-element enhancements:
  mixing in AGBs (TDU) vs. mass, [Fe/H] etc ??

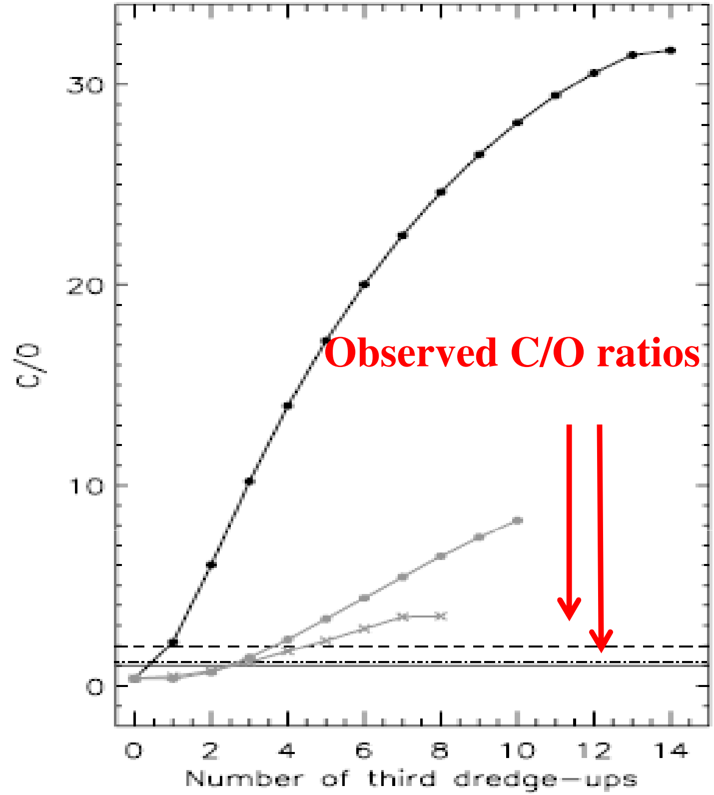


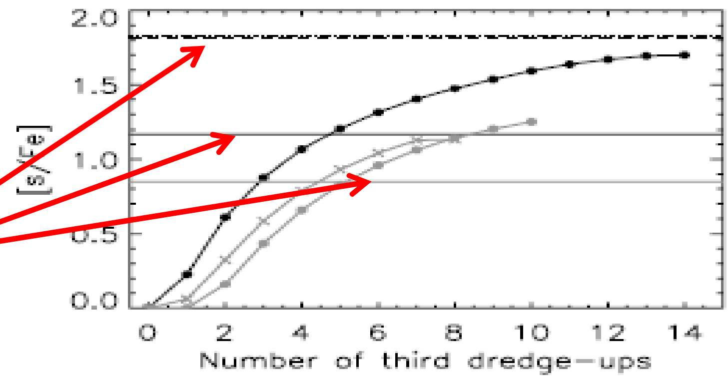
© Smedt et al. (2015)

Post-AGB stars do not show the expected correlation [hs/ls] vs. [Fe/H] ...nor the [s/Fe] vs. C/O !!!

© van Earle et al. (2013)



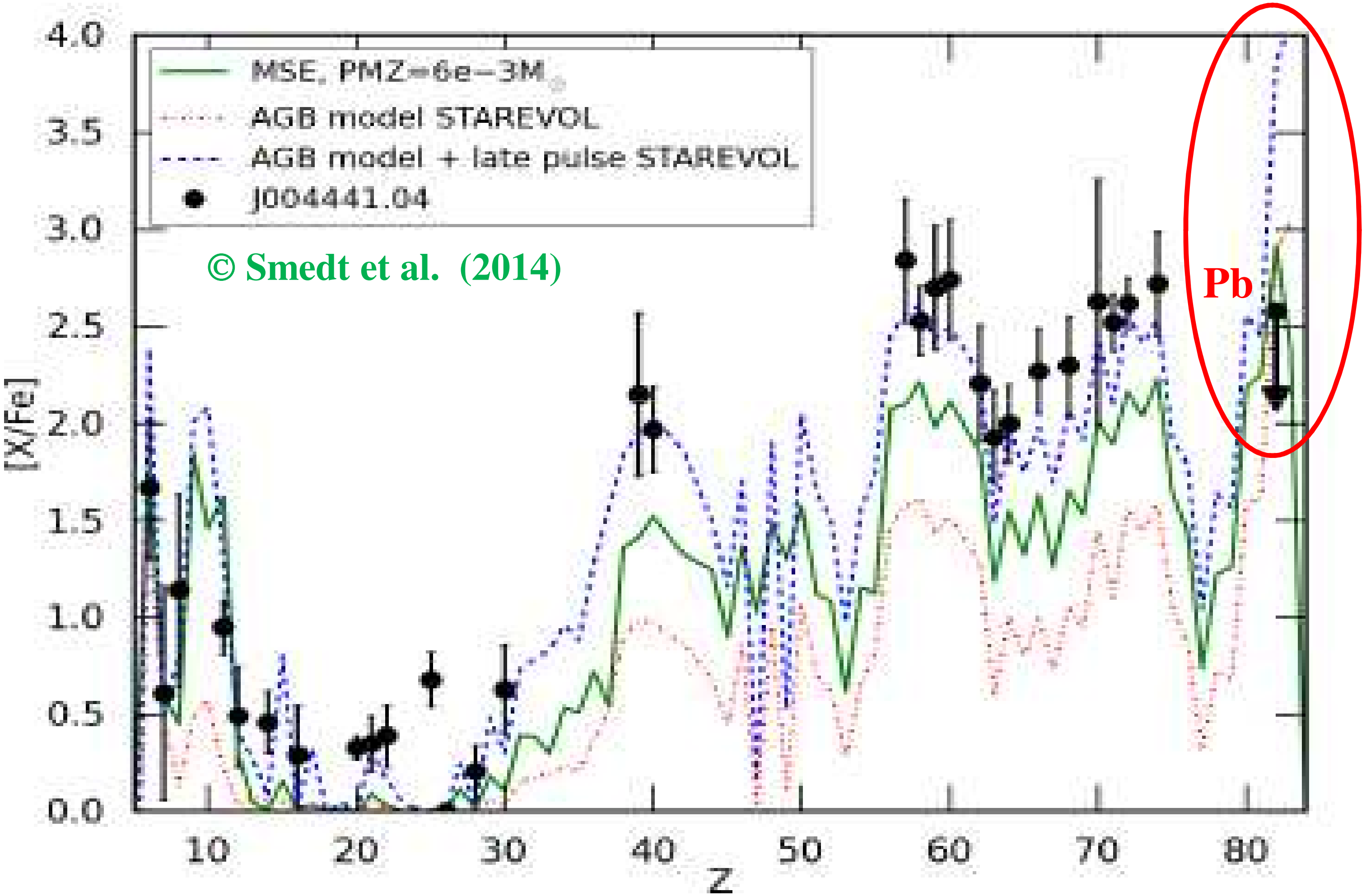




Observed s-element enhancements

The lead discrepancy

Some post-AGB stars show much lower [Pb/Fe] ratios than predicted

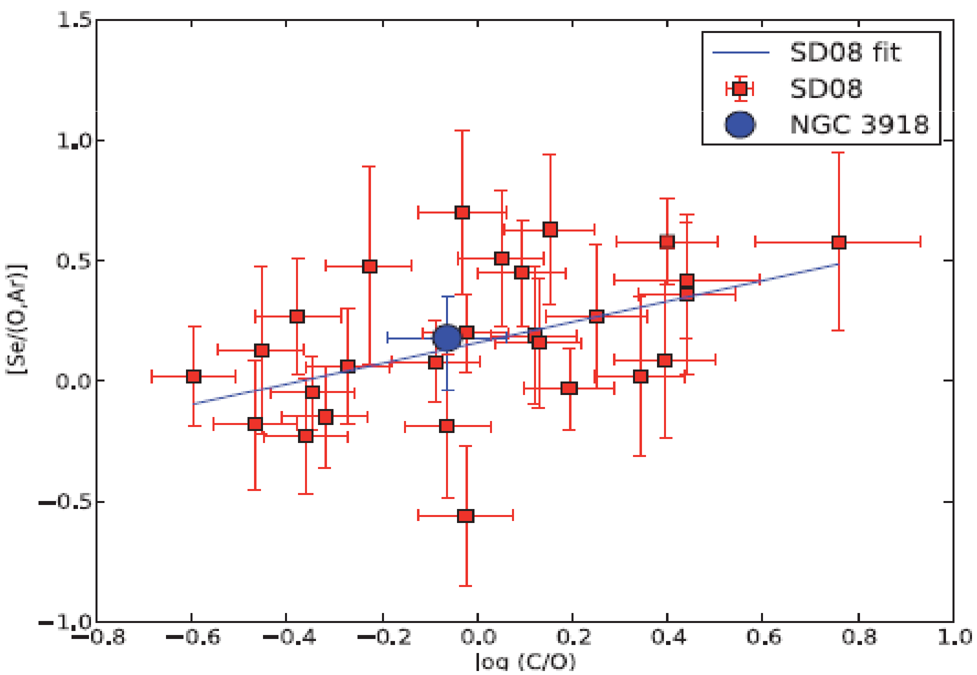


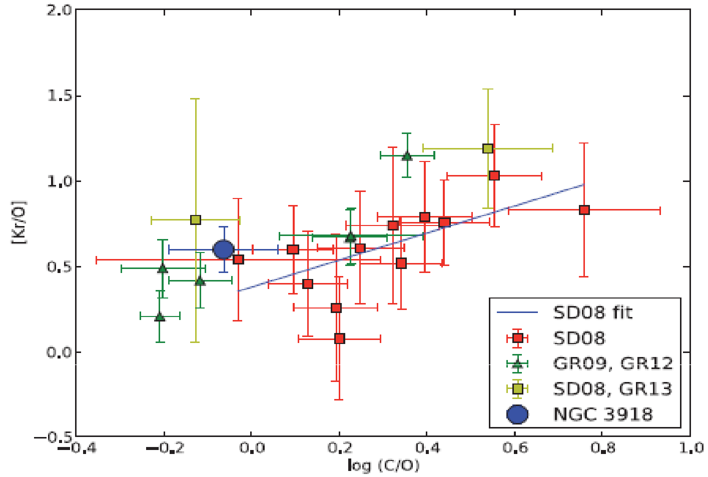
A neutron density in between the s- and the r-process: the "i"-process??

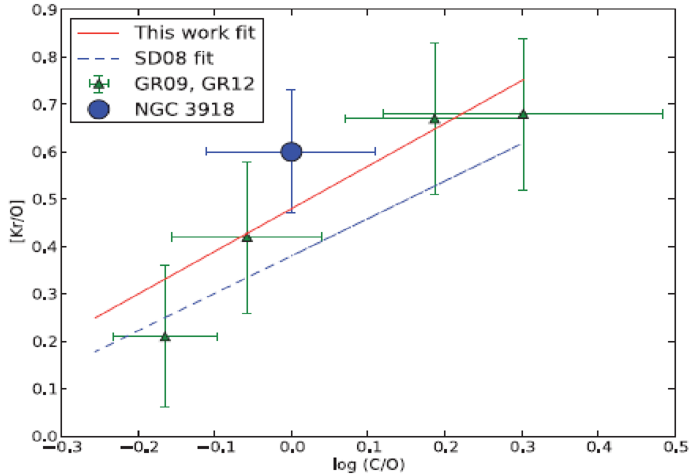
Lugaro et al. (2015)

Planetary nebulae

- [Ge,Se,Kr,Xe/O,Ar] ratios compatible with $^{13}C(\alpha,n)^{16}O$ as the neutron source
- Large spread in the s-element enhancements : $-0.6 \leq [s/O, Ar] \leq 2$
- Correlation with C/O ?







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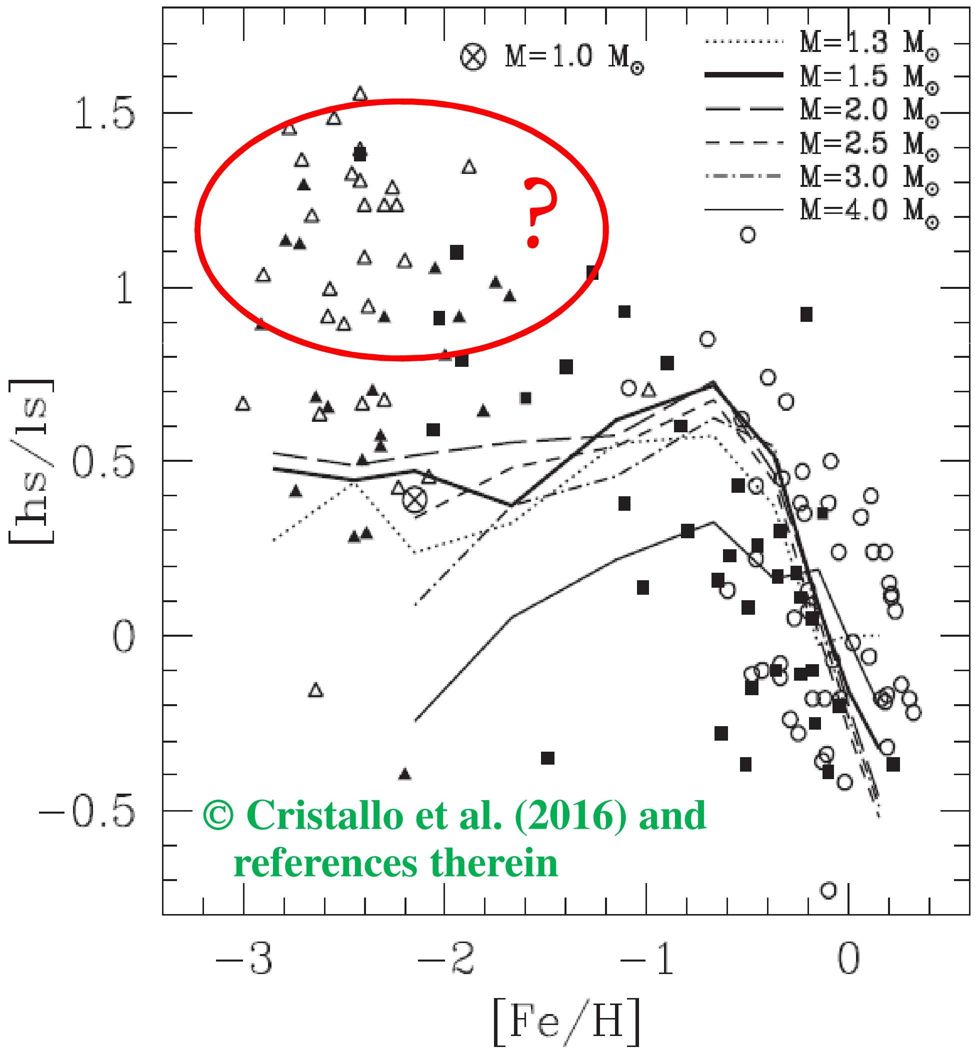
© García-Rojas et al. (2015)

Extrinsinc stars: Ba, CH, CEMP-s stars

✓ **Binary stars which accreted material from a former AGB star (WD); differences in [Fe/H] and C enhancement**

✓ **[s/Fe] ∝ 1/Z ...with a large dispersion**



© Cristallo et al. (2016) and references therein

○ **Ba-stars**

■ **CH-stars**

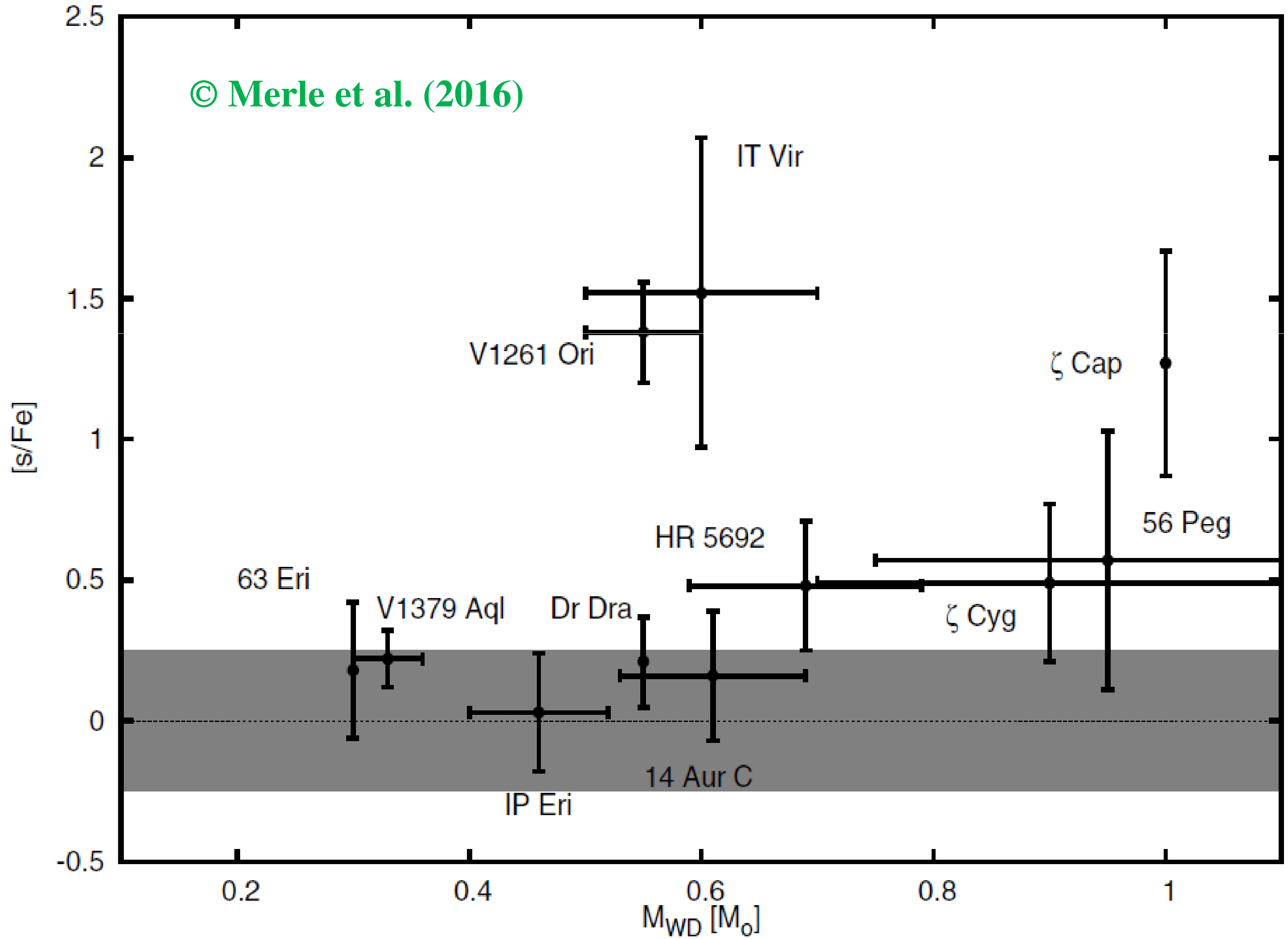
△ **CEMPs-stars**

➢ **Spread in the amount of ^{13}C burnt must exists !**

proposed by R. Gallino et al. (1998)!!!

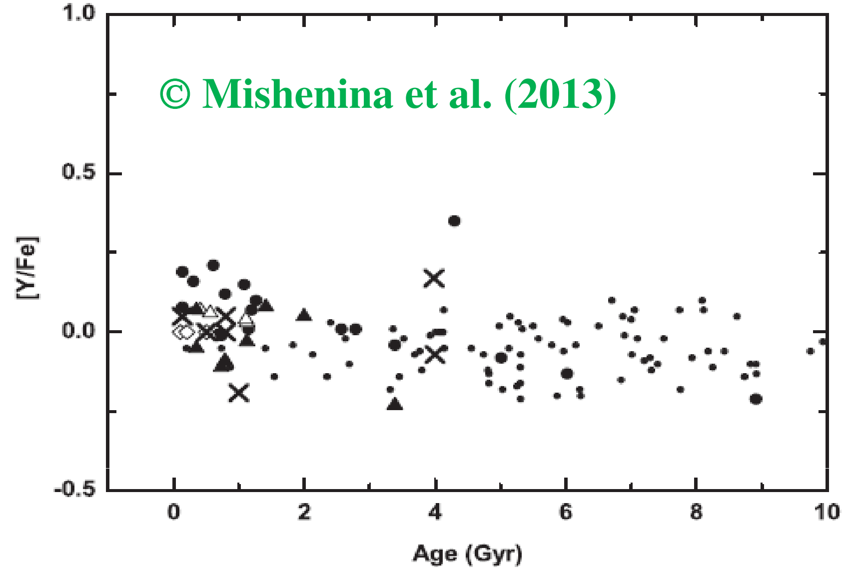
The extrinsic scenario and the mass of WDs

Stars producing WD < 0.5 $M_\odot$ never reached the AGB → never polluted their companions with s-elements



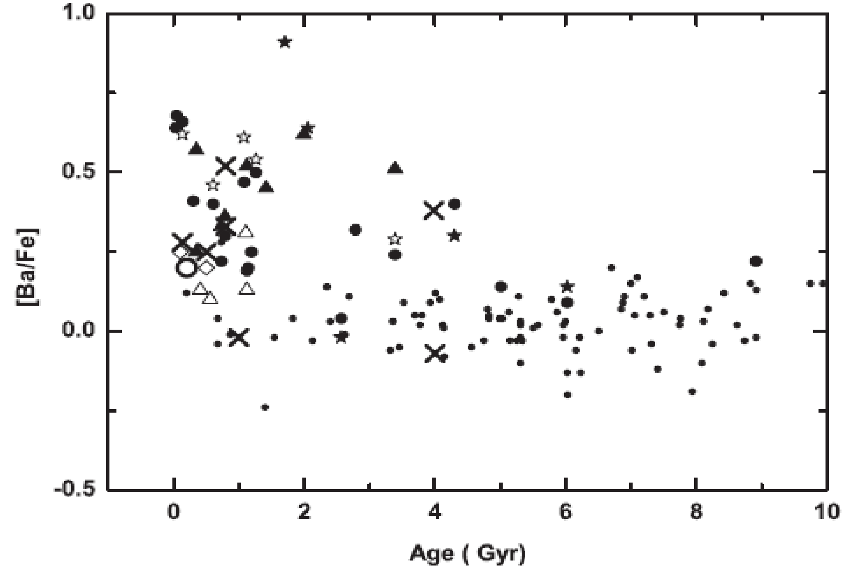
s-process and Open Clusters

[Ba/Fe] vs. Age in galactic OC,...not observed for any other s-element ??



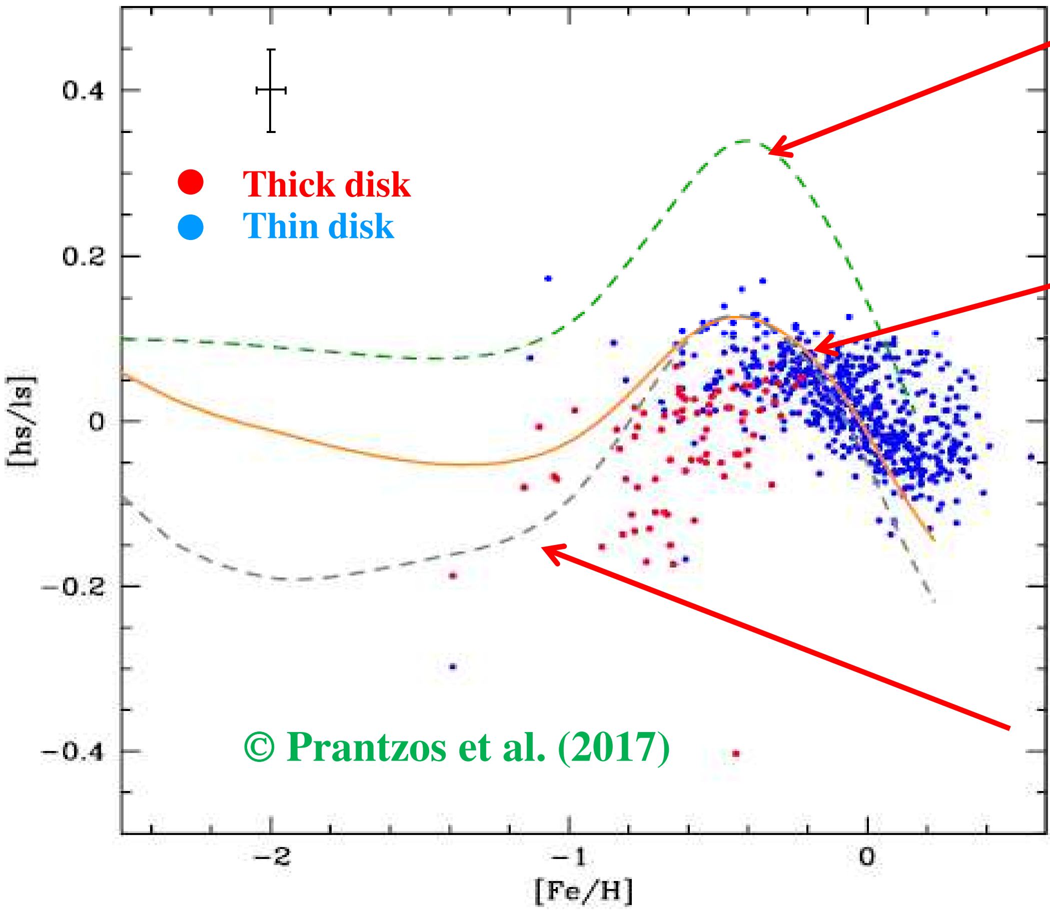
N-LTE analyses confirm the pattern

- ✓ **Another mechanism for Ba production?**
- ✓ **Origin of these Open Cluster ?**



s-elements and chemical evolution

The [hs/ls] ratio in unevolved stars (Delgado-Mena et al. 2017) **reveals the contribution of the different s-process sources**



AGBs + non-rotating massive stars

AGBs + rotating massive stars

Limongi & Chieffi (2017)
FRUITY

AGBs + rotating massive stars
+ no r-contribution

Rotating massive stars are necessary to explain [hs/ls] vs. [Fe/H] and the s-element abundances in the Solar System

Summary

- **Abundance determinations in stars show that the s-process is not unique, but depends on the initial mass, metallicity, size/mass ^{13}C-pocket, efficiency of TDU, mass loss ...**

- **More determinations of s-element abundances in massive AGB (PNe) stars are needed to quantify the role of the $^{22}Ne(\alpha,n)^{25}Mg$ neutron source.**

- **There are discrepancies between observed and predicted abundances of Pb, which require further theoretical and observational study**

- **Abundance uncertainties must be reduced: accurate spectroscopic data, dynamical atmosphere models, N-LTE...**

- **Existence of a "i"-process ? s-element abundances in young open clusters? Chemical evolution of s-elements?**

THANKS!!!!!

&

TANTI AUGURI !!!