AGB Stars and s process: a Laboratory for Nuclear Astrophysics

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Ambizione grant - SNSF

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A. Koloczek, **B. Thomas**, R. Reifarth

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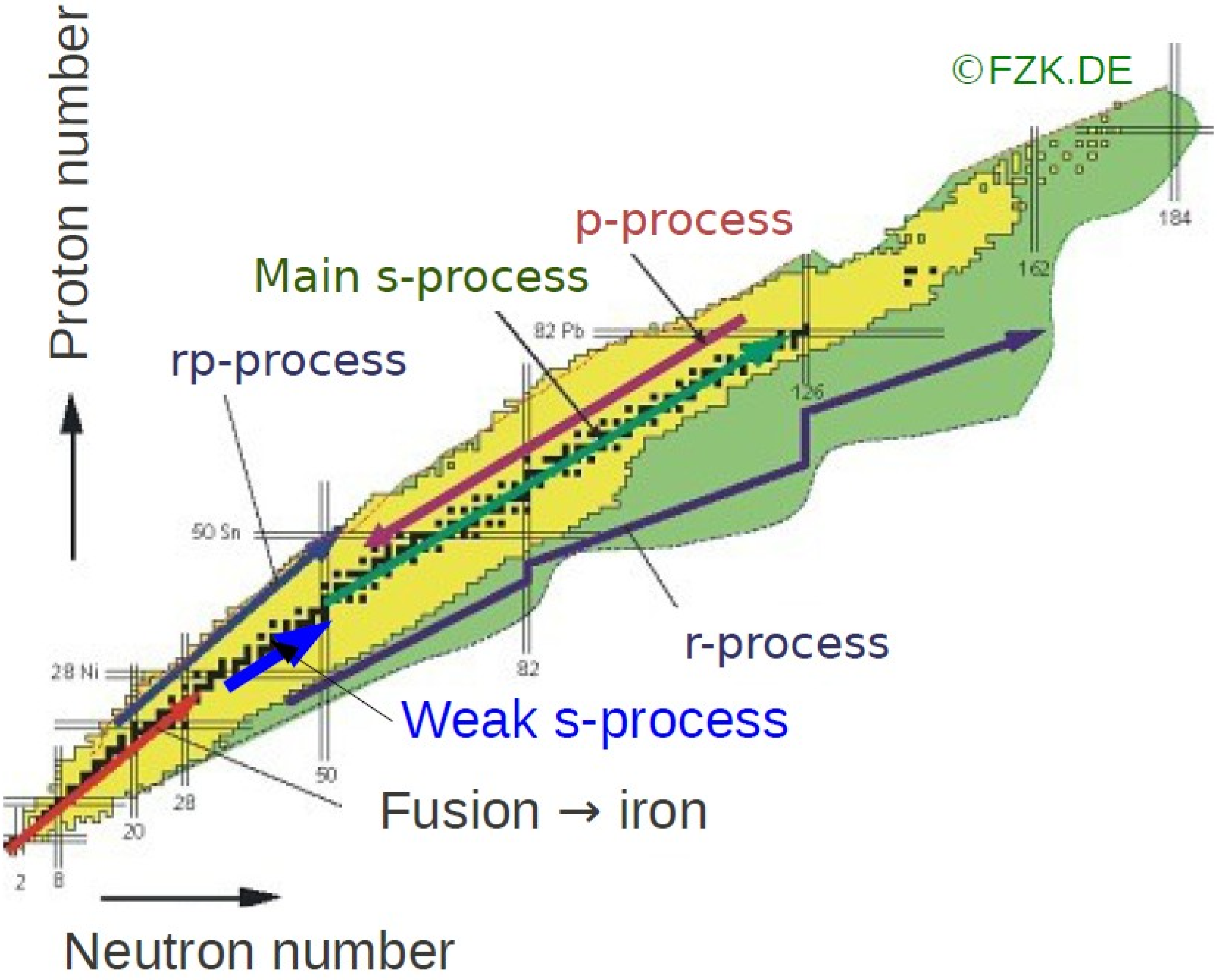
What is the Origin of the Elements?



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p-process

Main s-process

rp-process

r-process

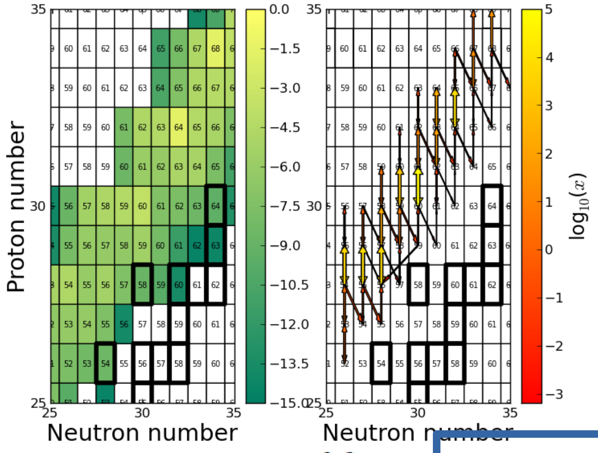
Weak s-process

Fusion → iron

Proton number

Neutron number

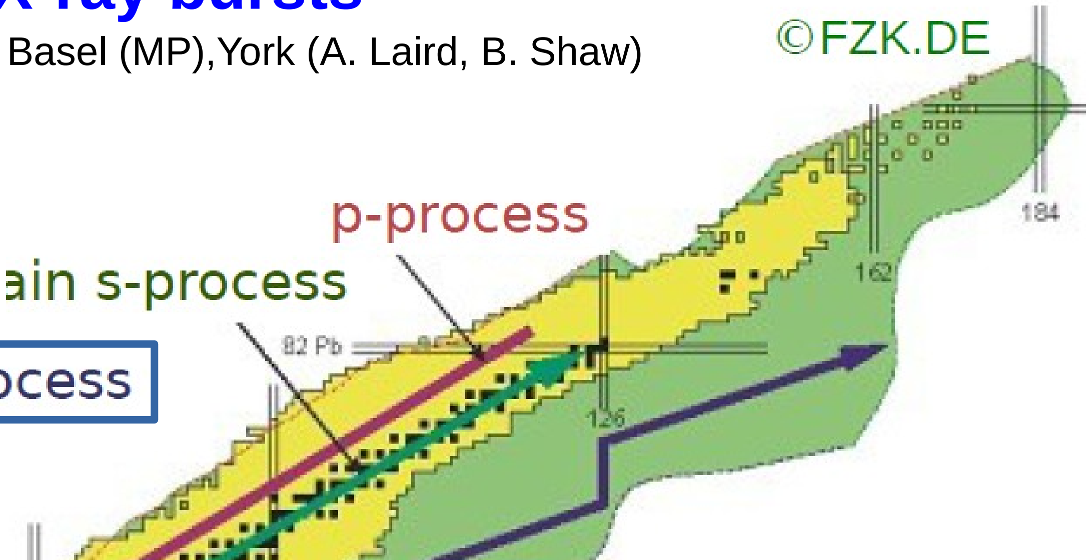
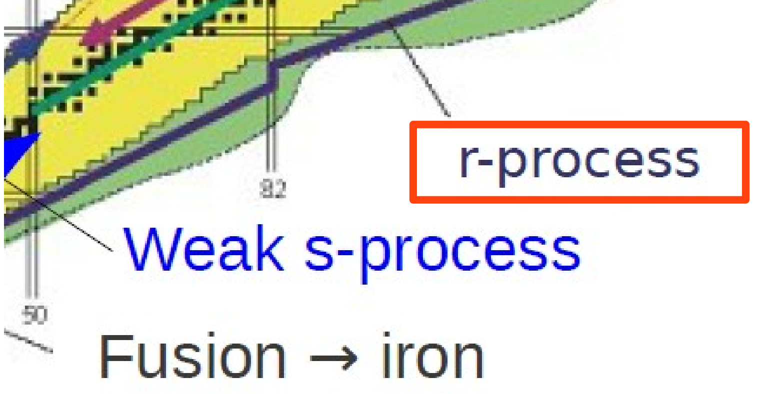
What is the Origin of the Elements?



X-ray bursts

Basel (MP),York (A. Laird, B. Shaw)

rp-process

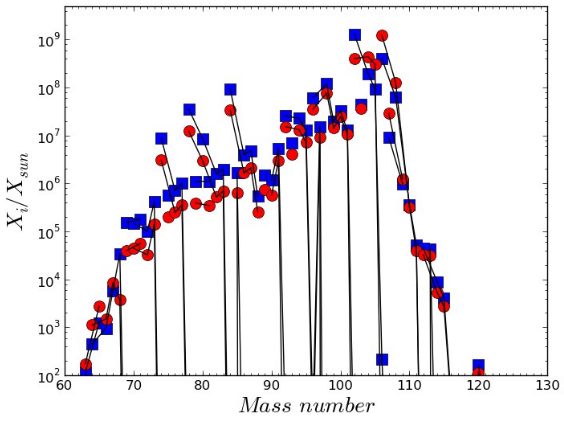
p-process

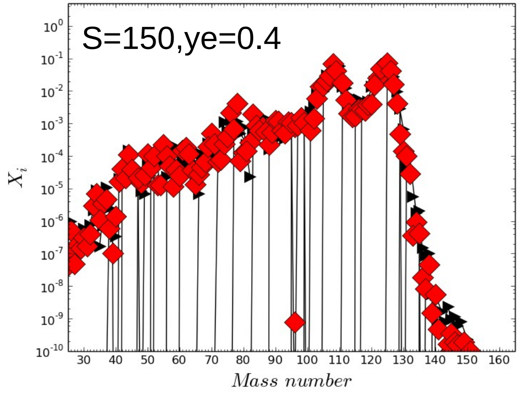
r-process

Weak s-process

Fusion → iron

Neutron number



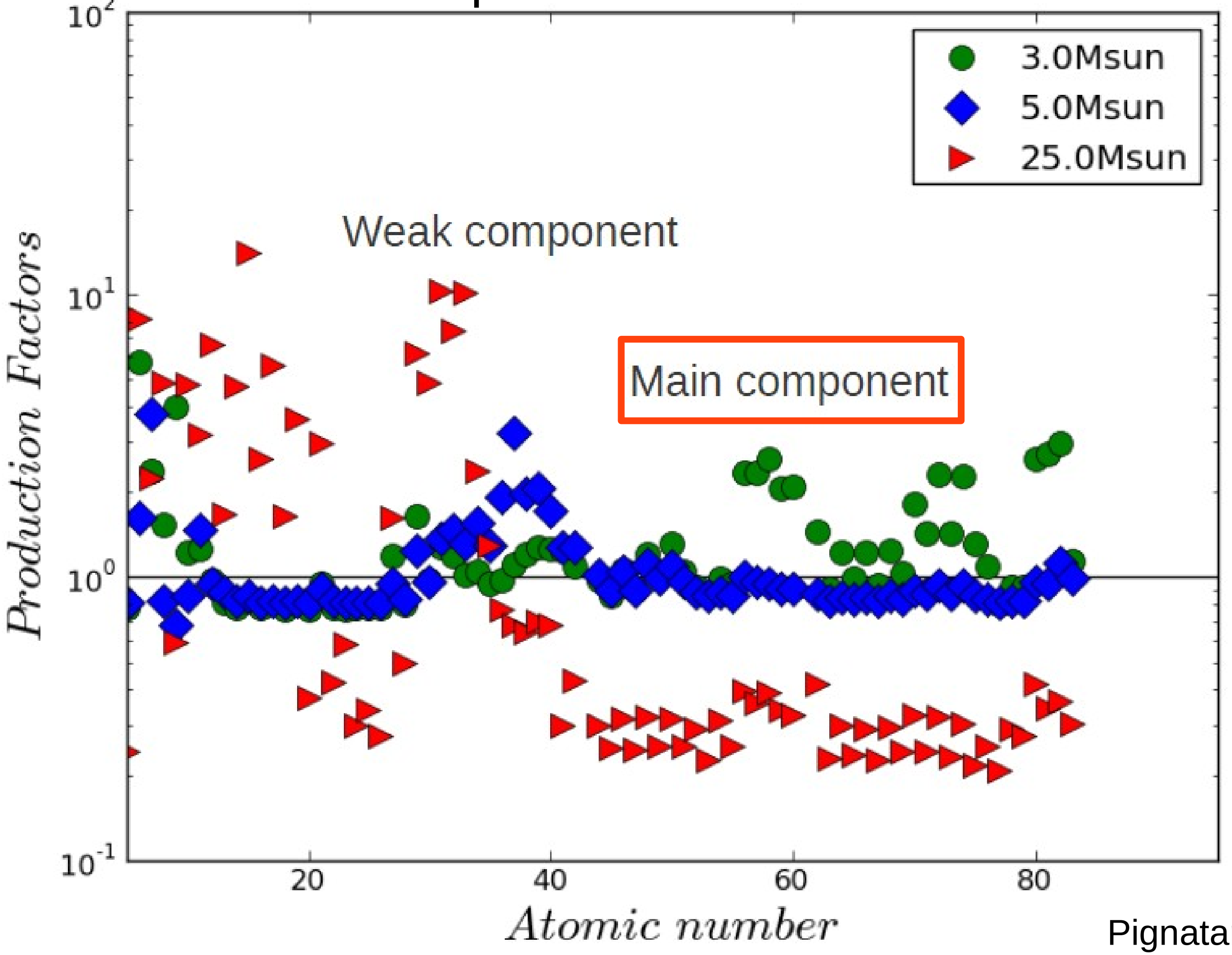


Basel (MP),Keele (N. Nishimura),
Livermore (M. Bertolli)

V&V ongoing

Recent Review from the nuclear astrophysics point of view:

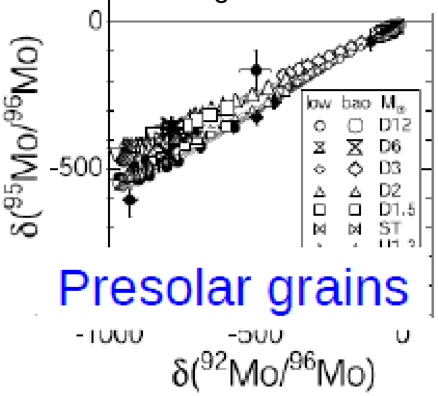
Kaeppeler et al. 2011
Rev Mod Phys 83



Pignatari et al. 2013 arXiv

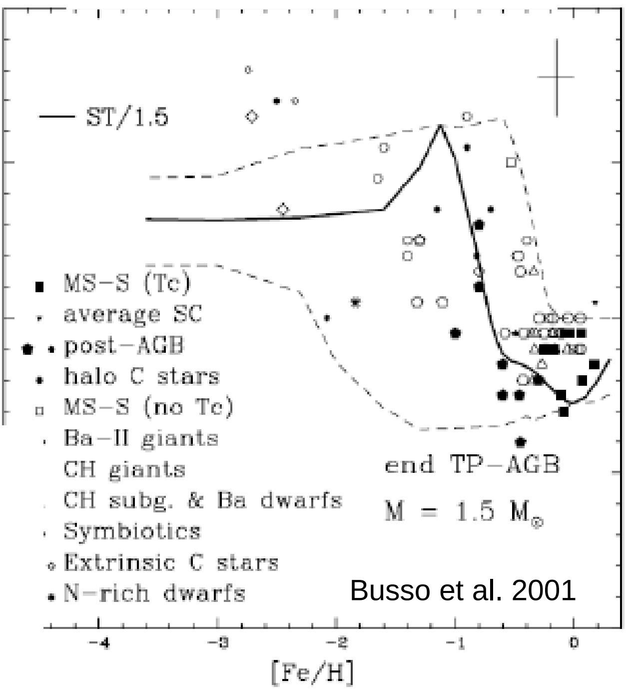
Elemental production factors for a low mass AGB star, a massive AGB stars, and a massive star (Z=0.01).

Lugaro et al. 2003

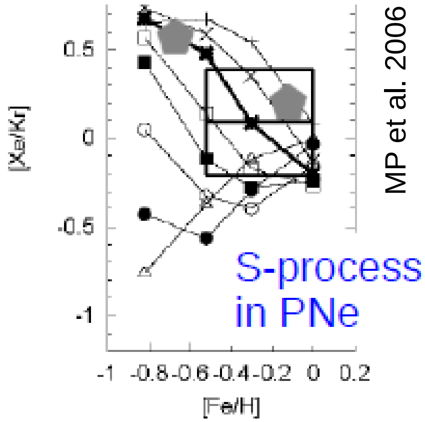


Presolar grains

Ba stars, MS-S stars, post-AGB stars...



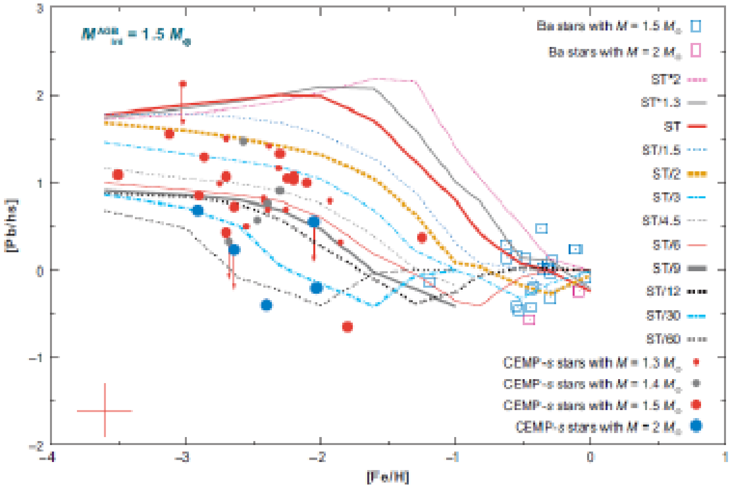
Busso et al. 2001



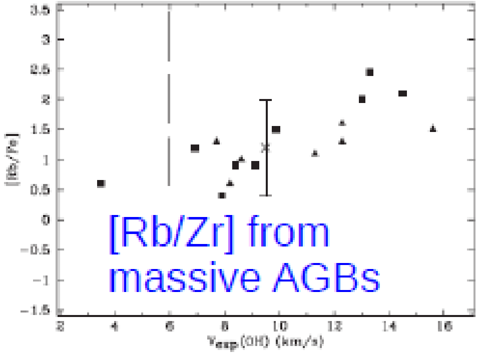
MP et al. 2006

S-process in PNe

CEMP-s stars

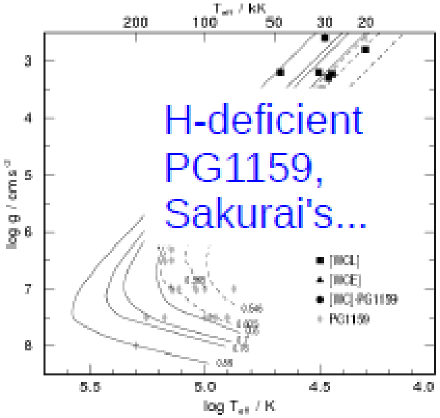


Sneden et al. 2008



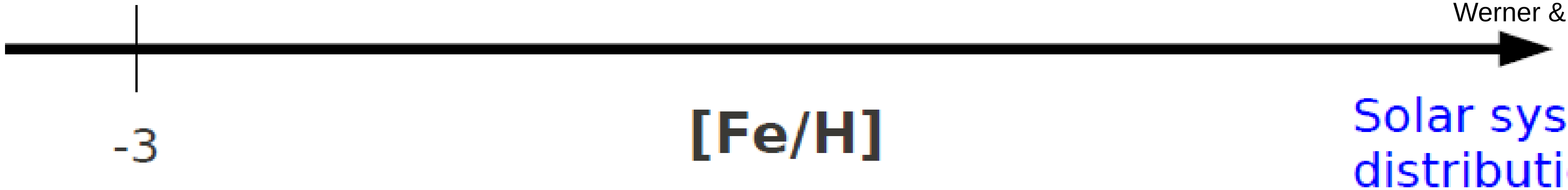
[Rb/Zr] from massive AGBs

Garcia-Hernandez et al. 2006



H-deficient PG1159, Sakurai's...

Werner & Herwig 2006



[Fe/H]

Solar system distribution

e.g., Bisterzo et al. 2014

Herwig ARAA 2005

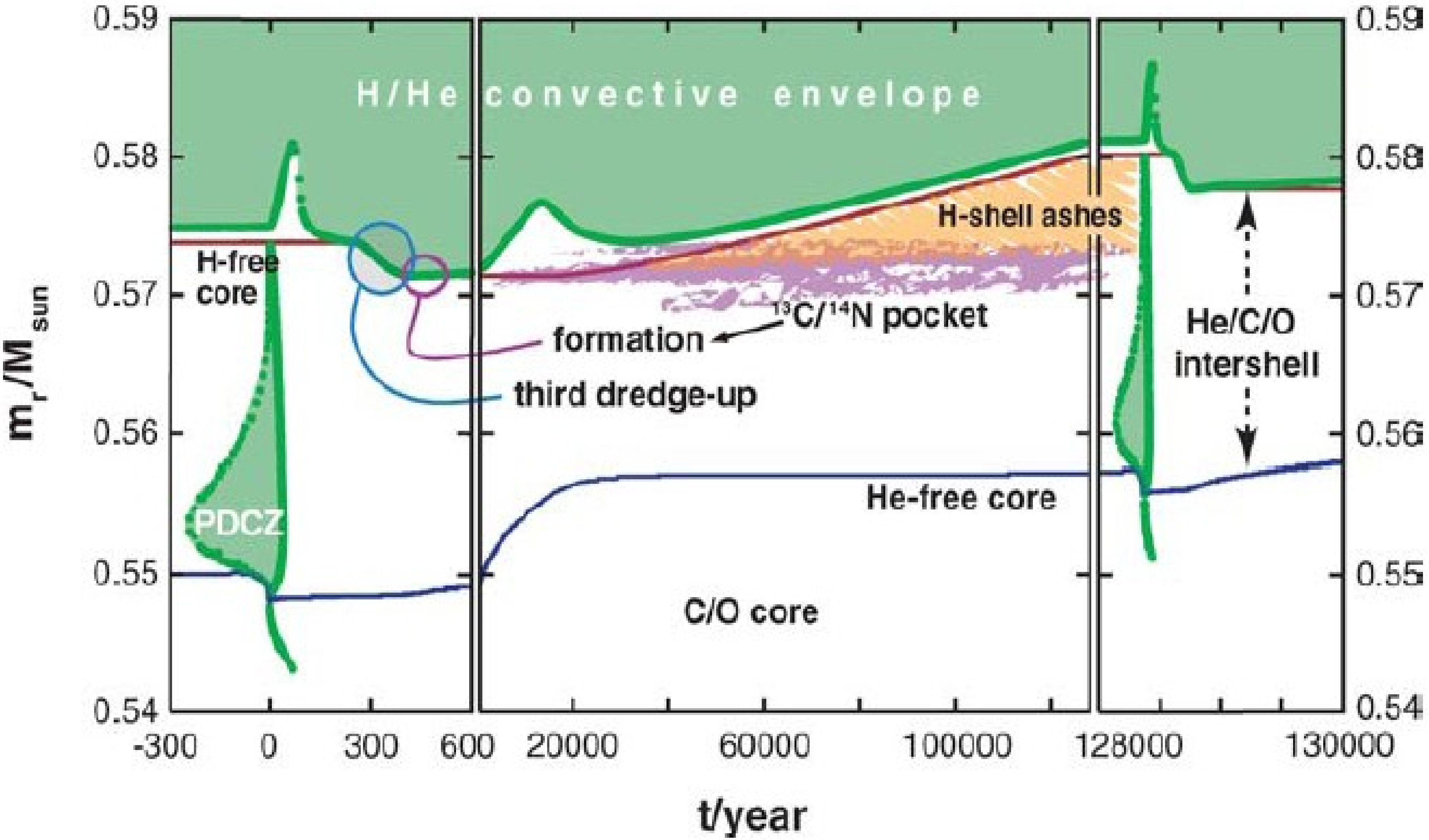


Figure 3 Thermal pulse 14, the subsequent interpulse phase and thermal pulse 15 of 2 $M_\odot$, $Z = 0.01$ sequence ET2 of Herwig & Austin (2004). The timescale is different in each panel.

Herwig ARAA 2005

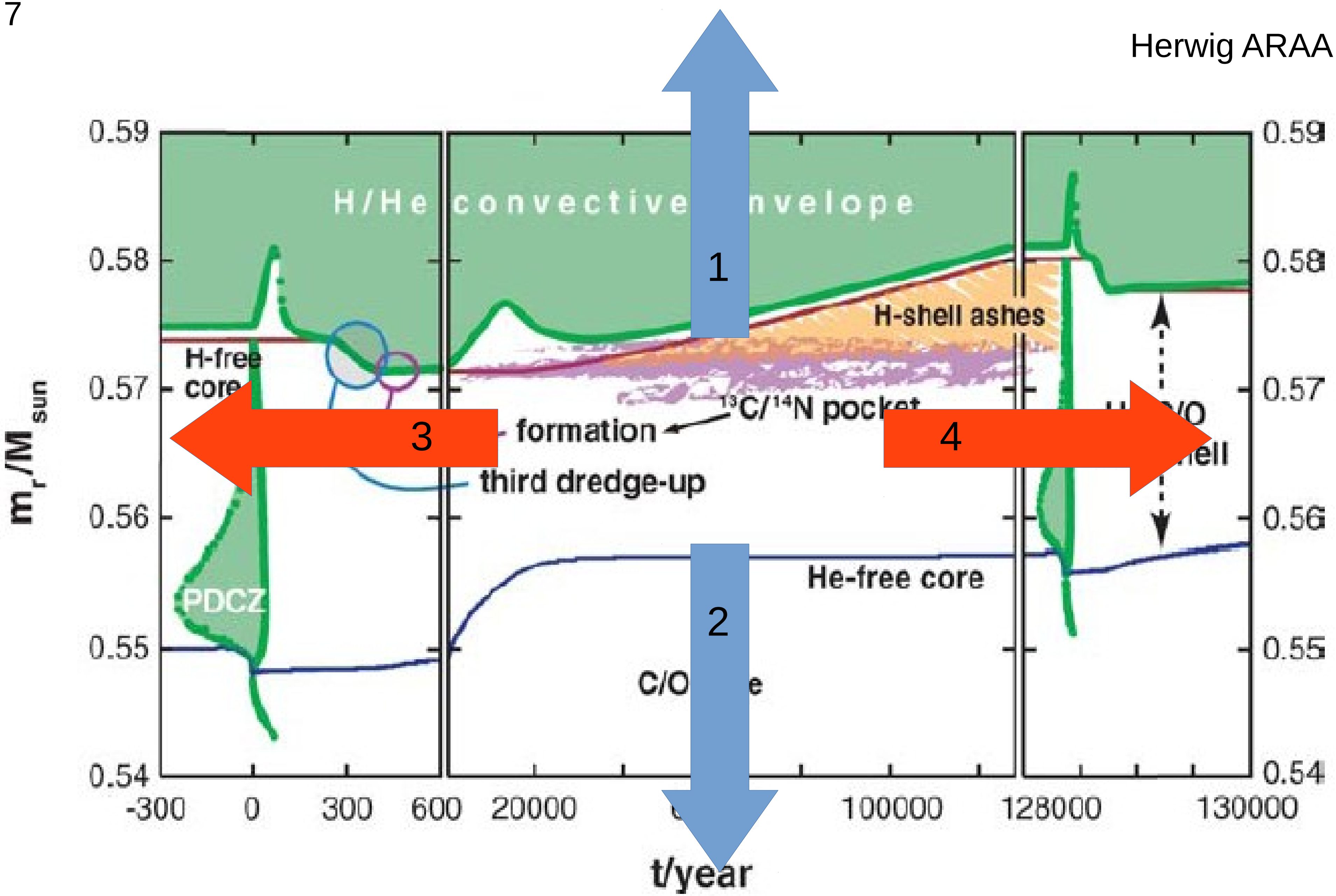
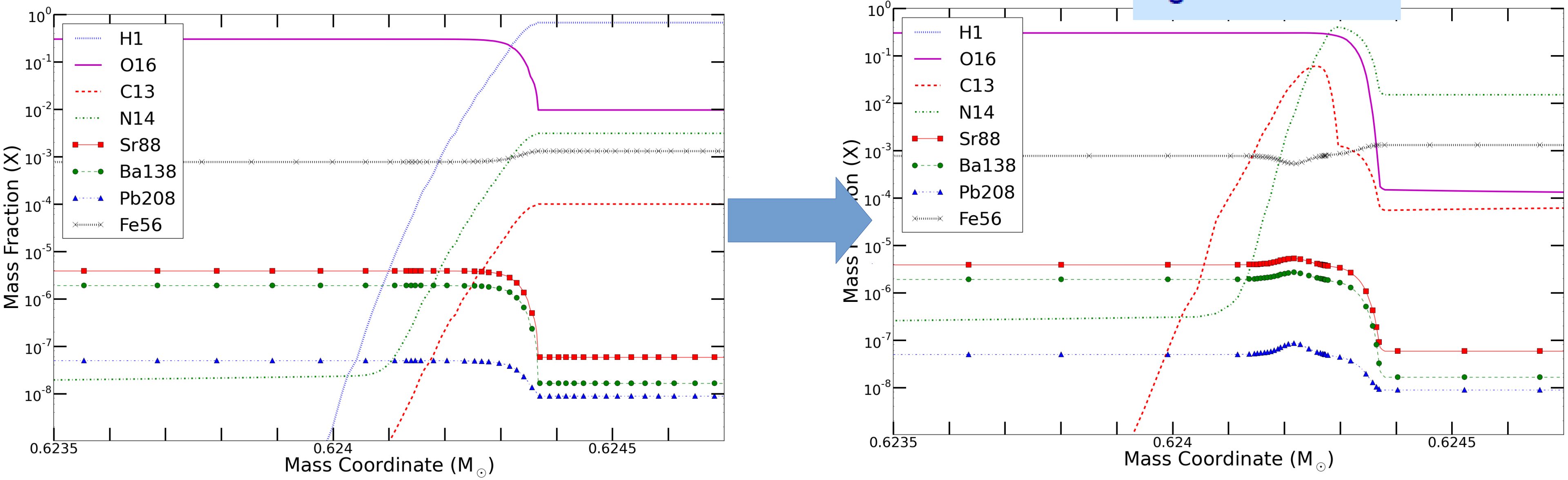


Figure 3 Thermal pulse 14, the subsequent interpulse phase and thermal pulse 15 of 2 $M_{\odot}$, $Z = 0.01$ sequence ET2 of Herwig & Austin (2004). The timescale is different in each panel.

$T_8 \sim 0.9\text{-}1$

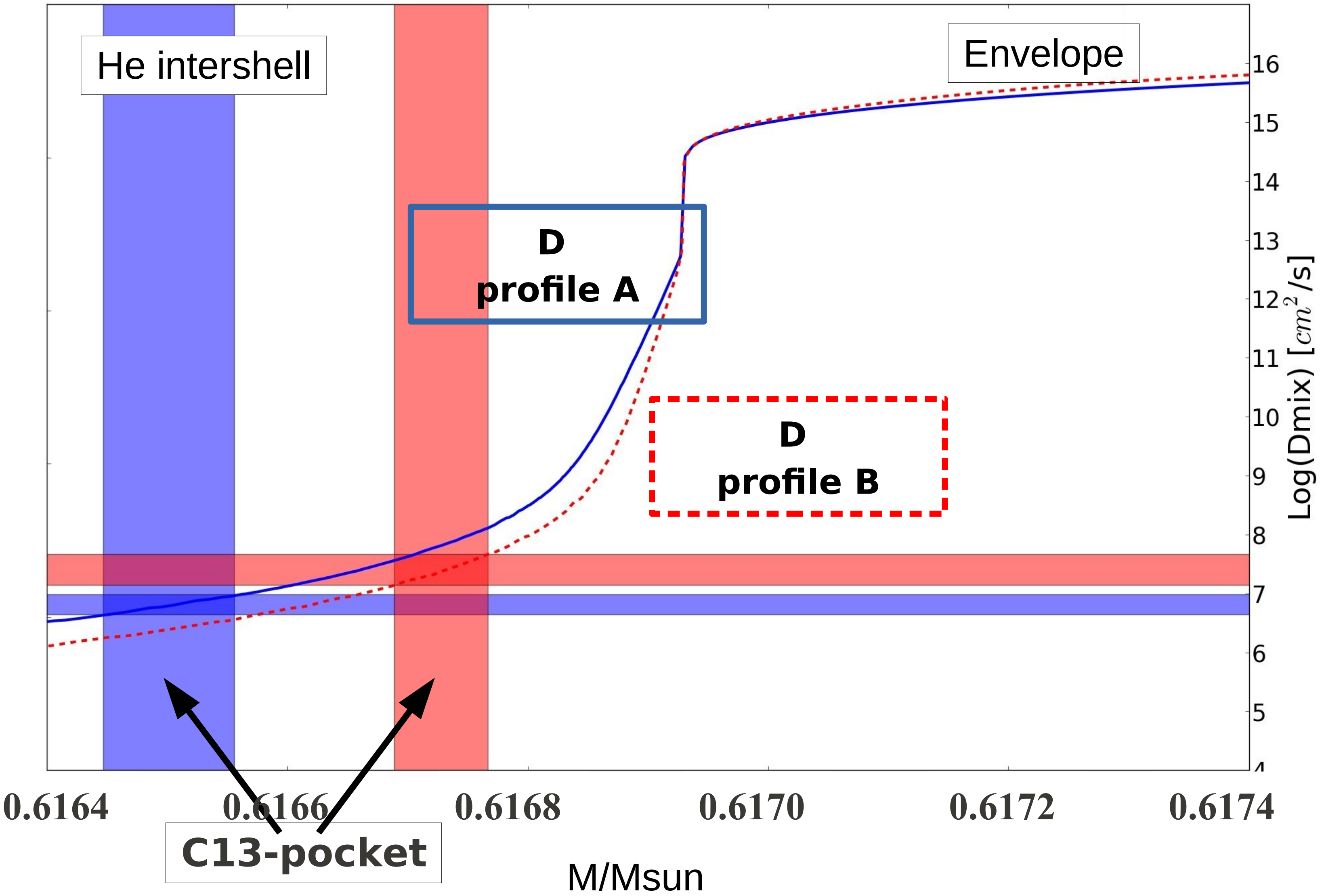


$^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C(\alpha,n)^{16}O$

10^{7} n/cm^{3}

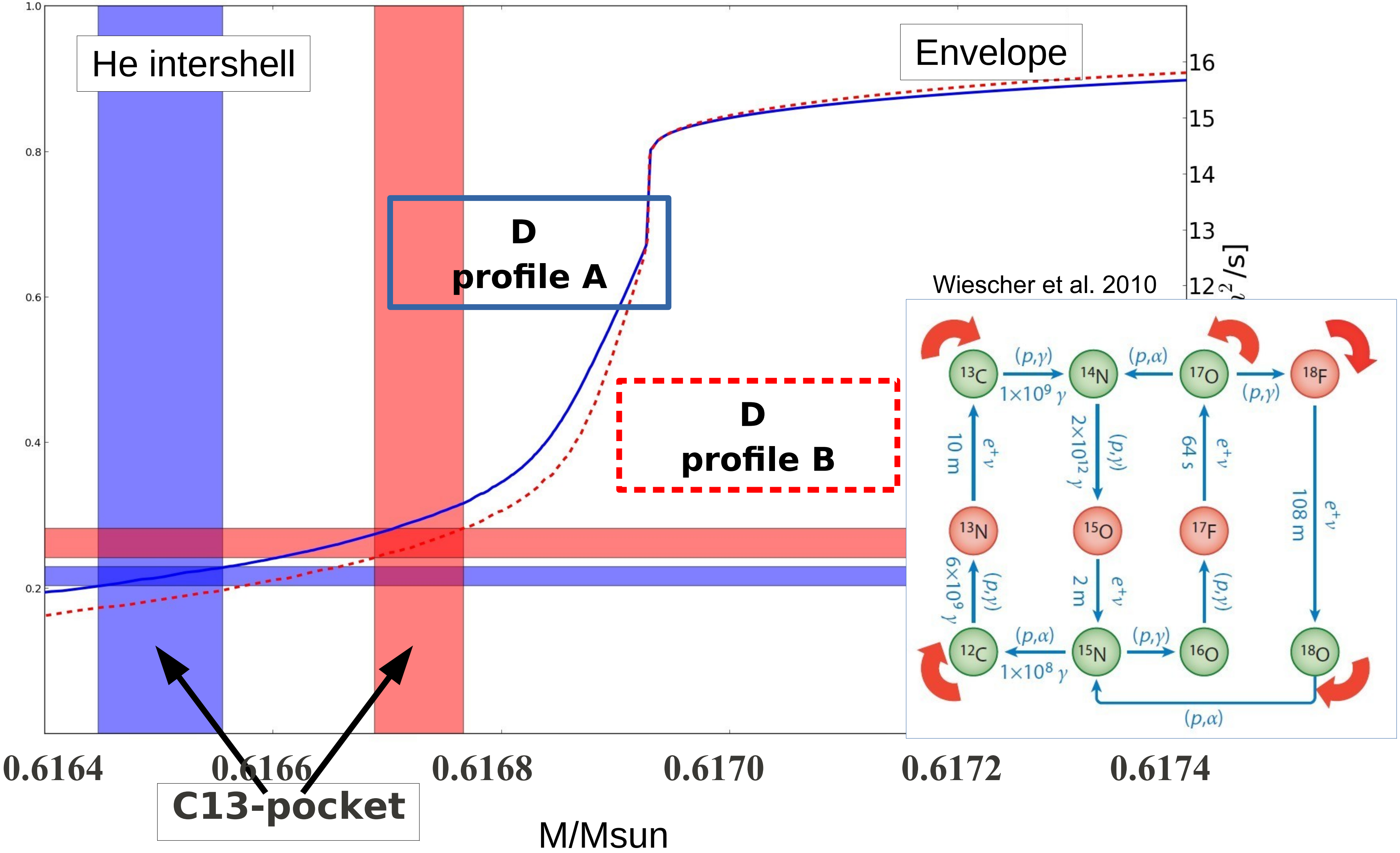
What is (are) the physics mechanism(s) driving the formation of the C13-pocket ?

Battino et al. 2014, in prep.



C13-pocket formed within a range of D (~ 10^{6-8} cm^2s^{-1}) and H/C12 (< 0.3-0.5). E.g., Lugaro et al. 2003 and Goriely & Siess 2004. See also discussion in Straniero et al. 2009, Cristallo et al. 2009.

Battino et al. 2014, in prep.

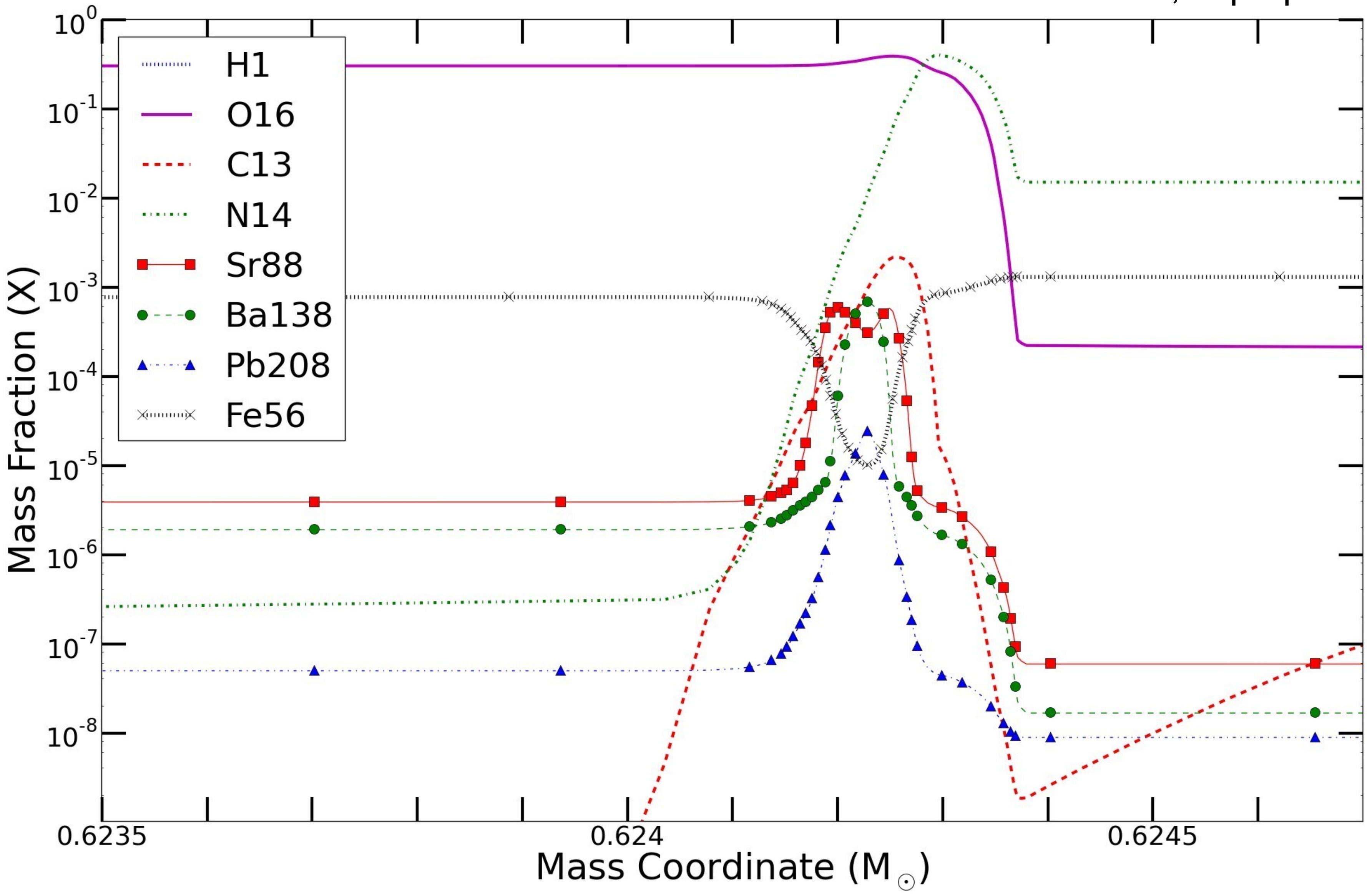


Wiescher et al. 2010

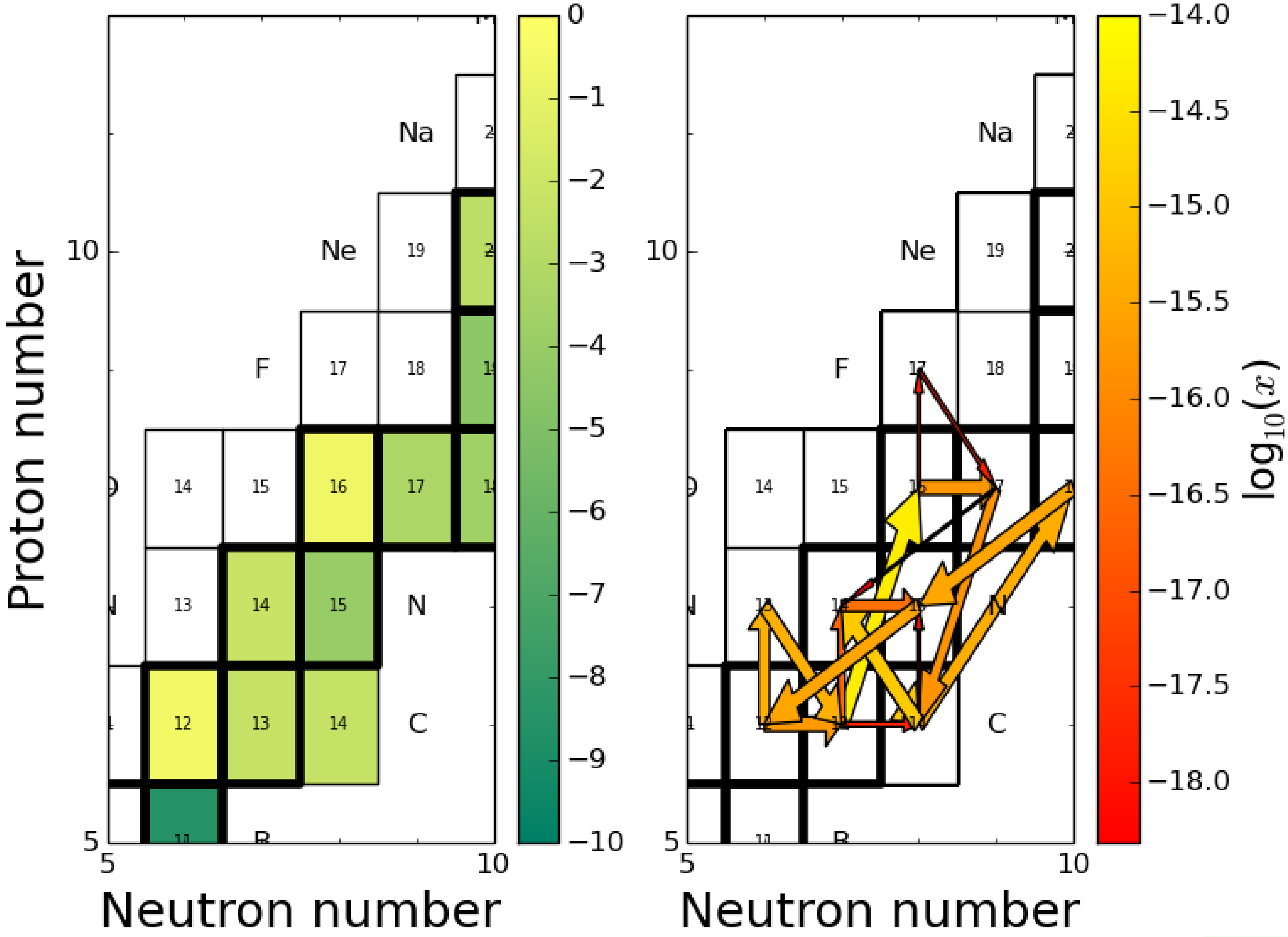
C13-pocket formed within a range of D (~ 10^{6-8} cm^{2}s^{-1}) and H/C12 (< 0.3-0.5). E.g., Lugaro et al. 2003 and Goriely & Siess 2004. See also discussion in Straniero et al. 2009, Cristallo et al. 2009.

Snapshot of the s-process products at the end of the C13-pocket

Battino et al. 2014, in prep.



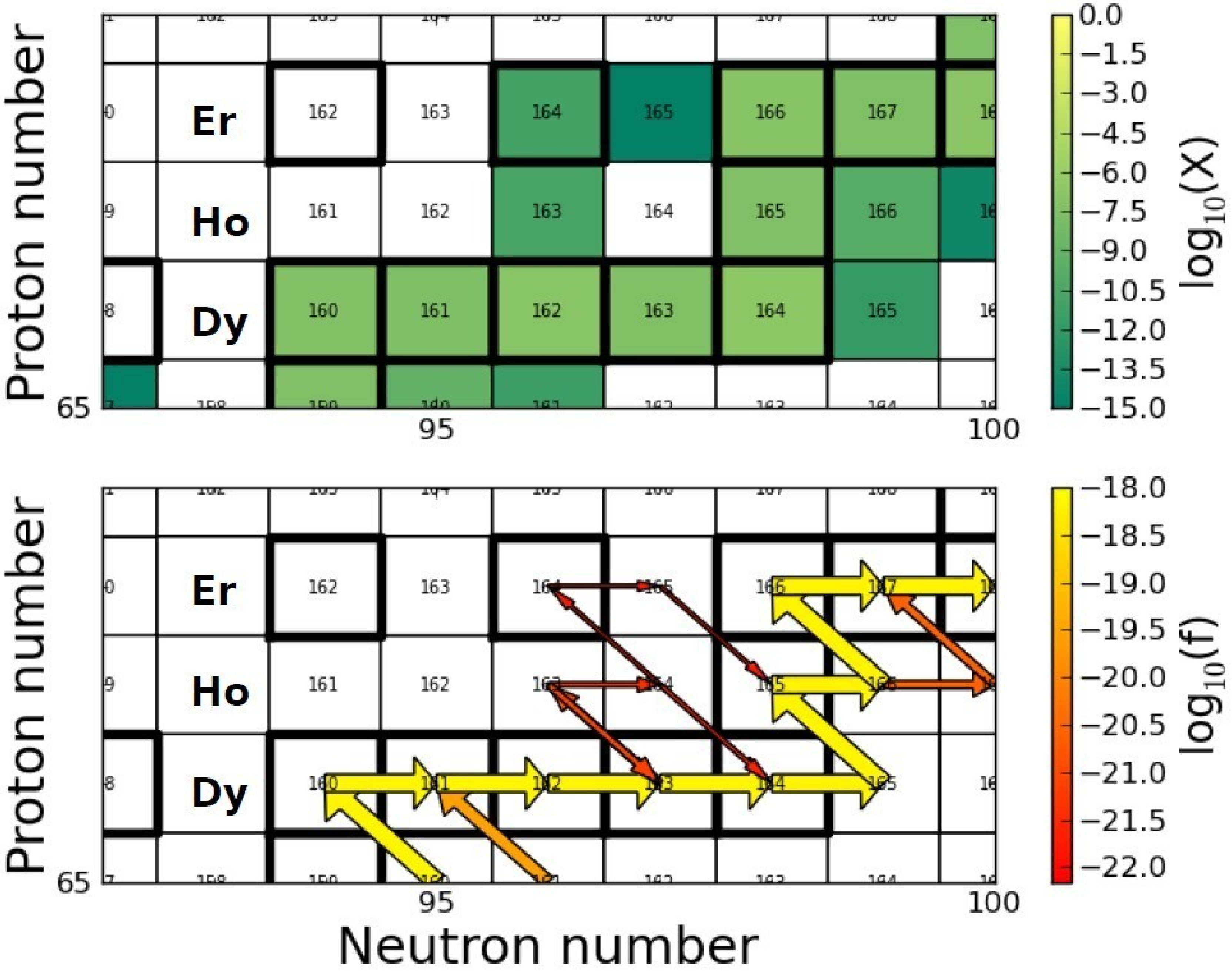
Some more details about the nucleosynthesis in the C13-pocket:



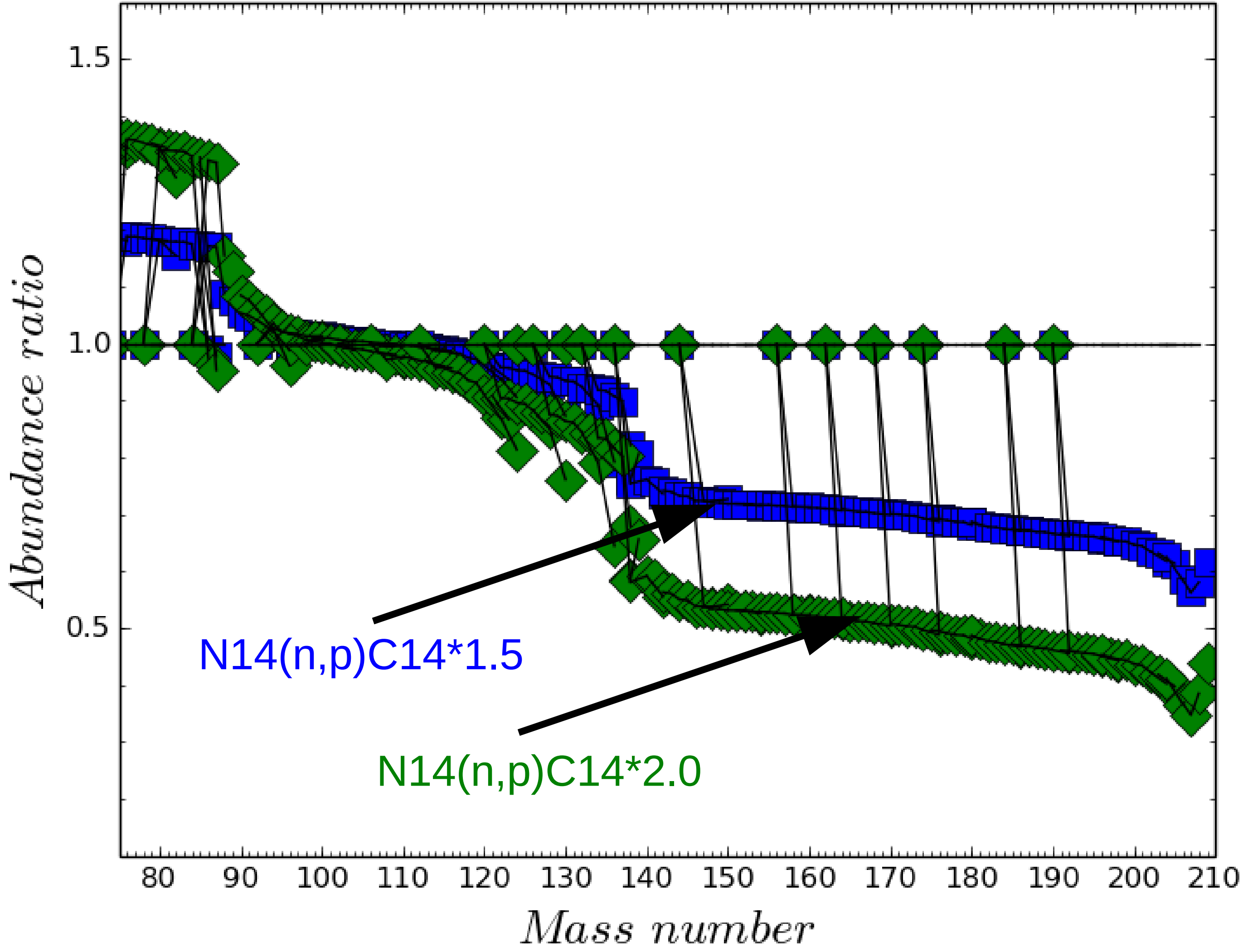
Fluxes integrated over the all life of a C13-pocket trajectory extracted from the full AGB model (A. Koloczek)

Initial abundances:
C12=0.30
C13=0.03
N14=0.01
...

Er164 = s-process contribution (Roberto's talk)
e.g., Bisterzo et al. 2011



Neutron poison in the C13-pocket: N14(n,p)C14



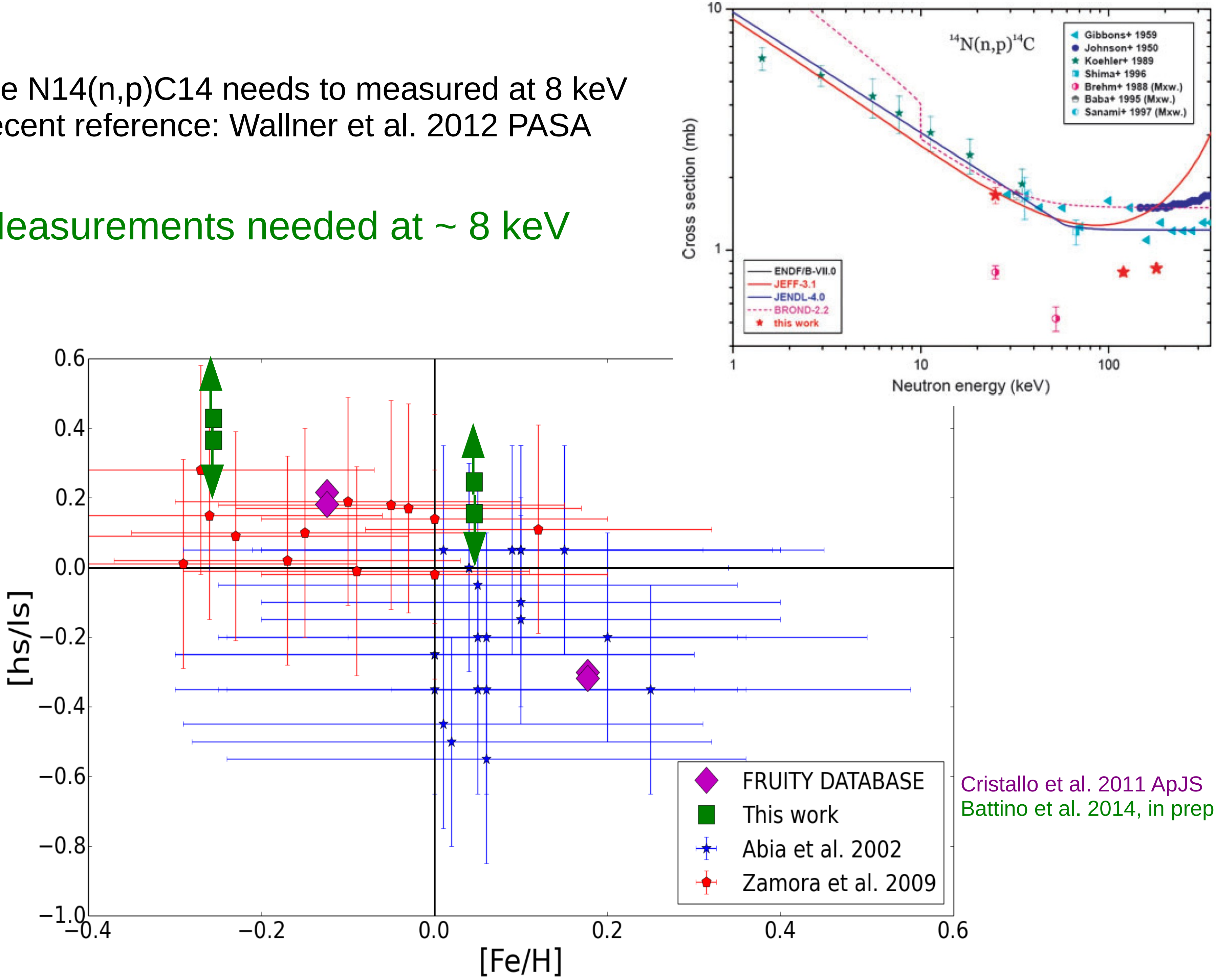
N14(n,p)C14*1.5

N14(n,p)C14*2.0

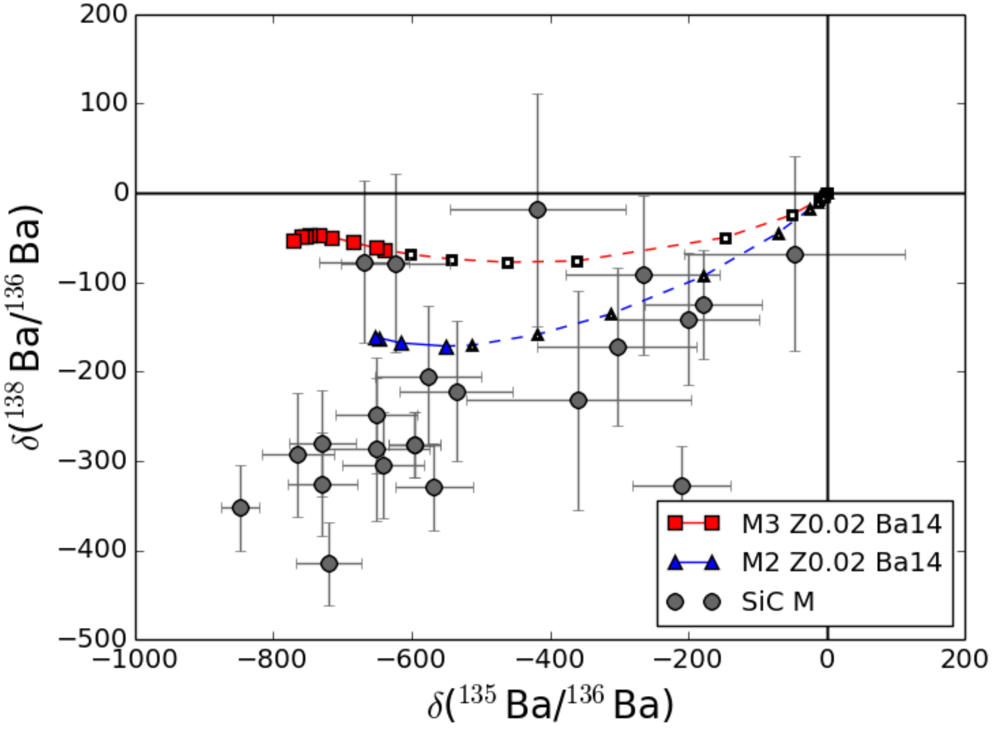
N14(n,p)*1.5 --> [hs/ls] - 0.1 dex
N14(n,p)*2.0 --> [hs/ls] - 0.2 dex

The N14(n,p)C14 needs to measured at 8 keV
Recent reference: Wallner et al. 2012 PASA

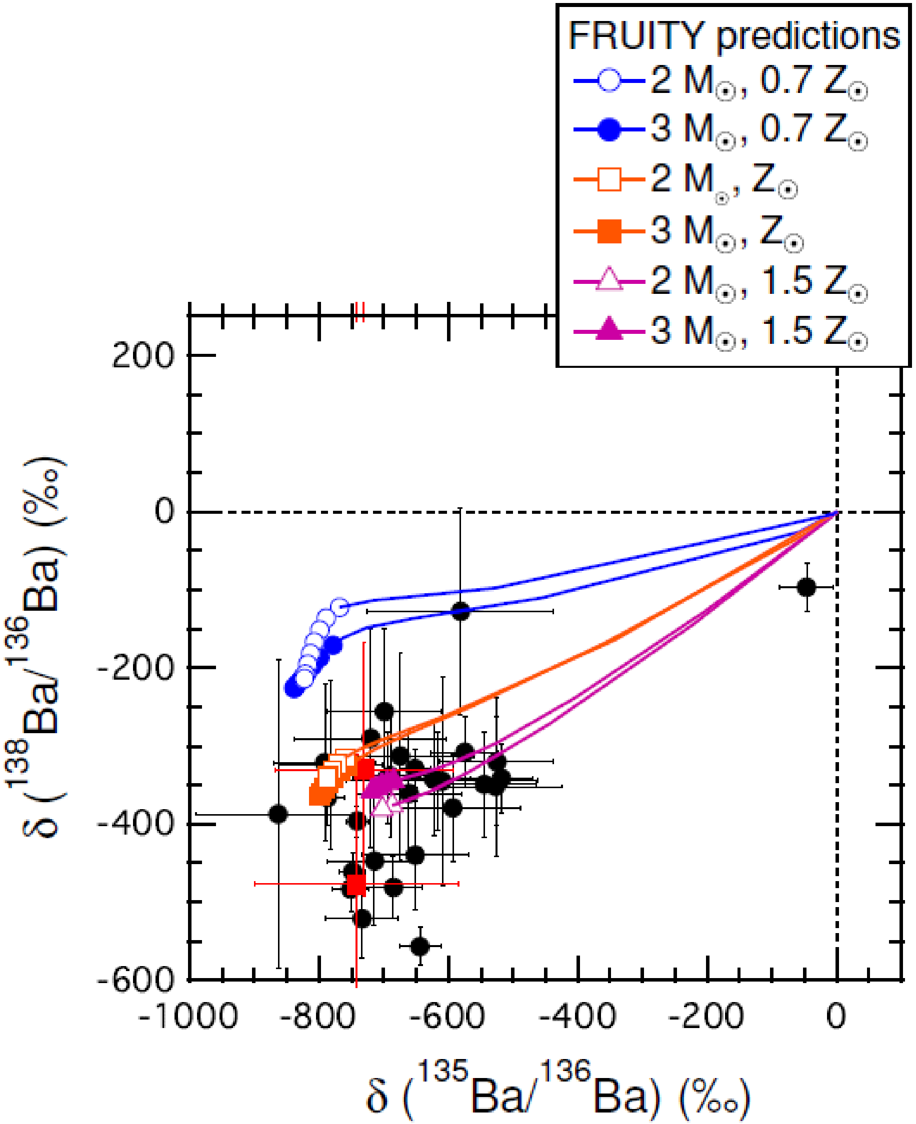
Measurements needed at ~ 8 keV



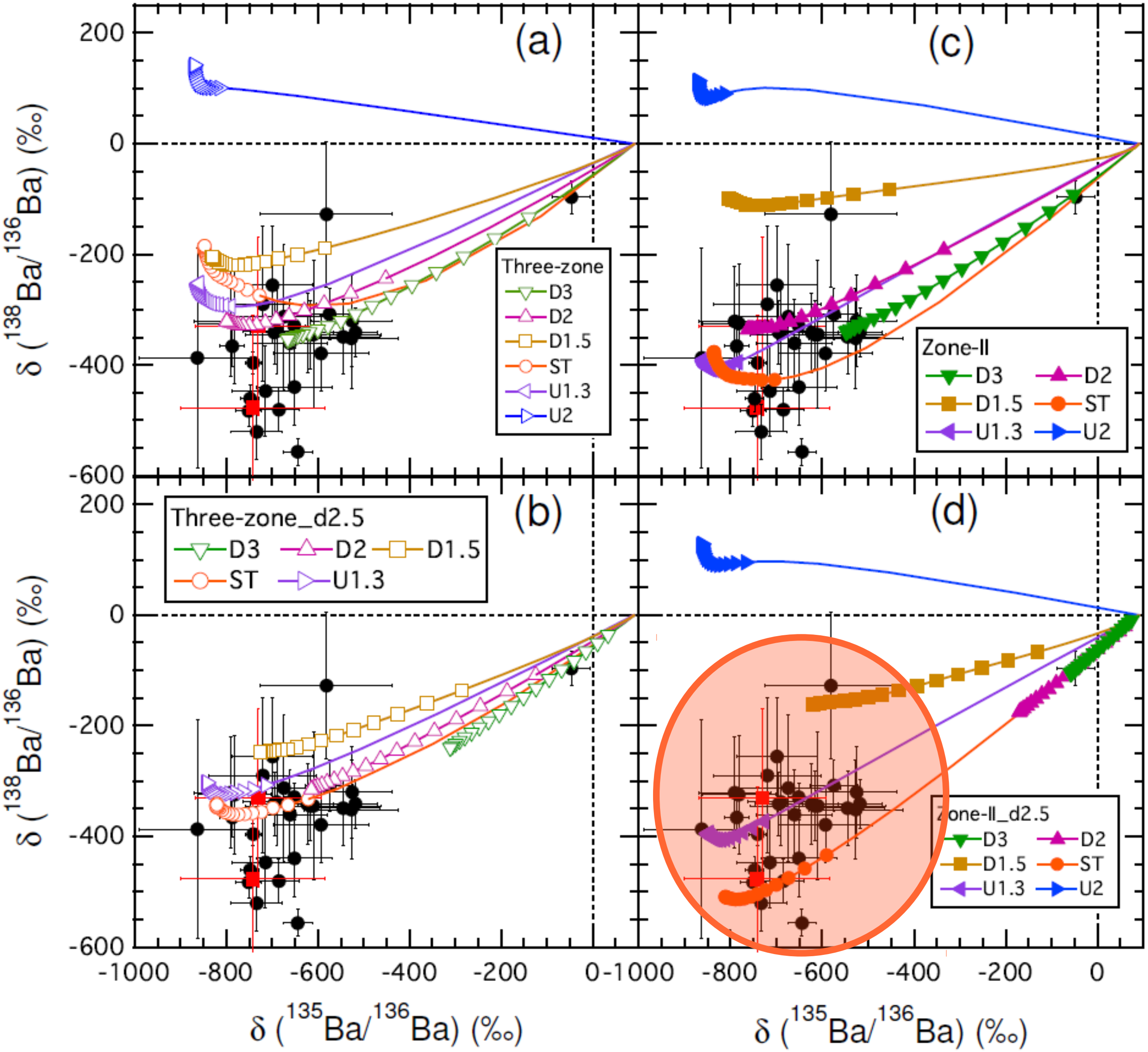
Cristallo et al. 2011 ApJS
Battino et al. 2014, in prep.



St. Louis Presolar Grains database:
Hynes & Gyngard 2009 LPIS 40
(grains from Barzyk et al. 2007)



Liu et al. 2014, ApJ 786

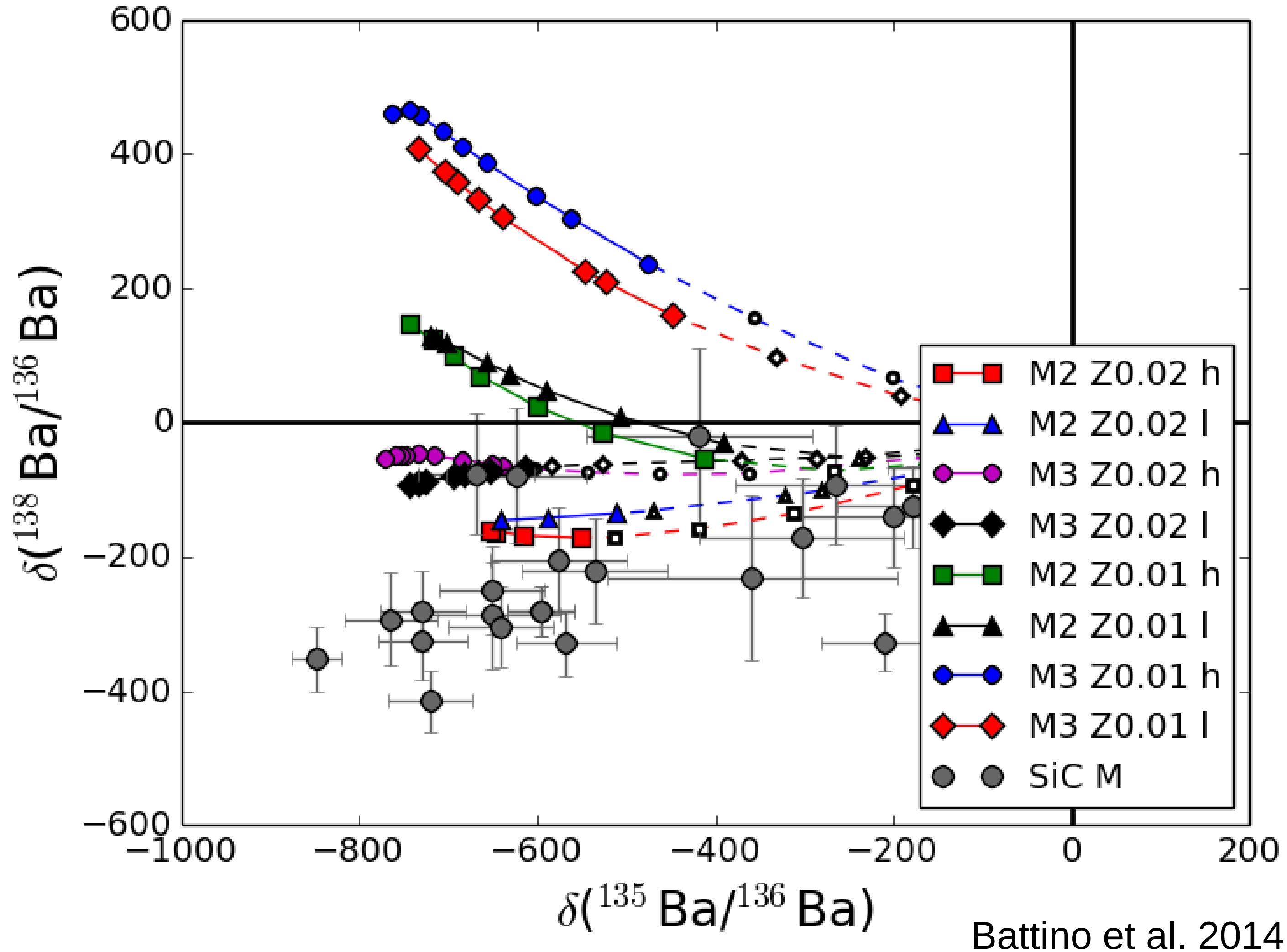


Comparison of grains data with the predictions from the Torino models (e.g., Bisterzo et al. 2014)

This corresponds to a range of [hs/ls] of the parent stars

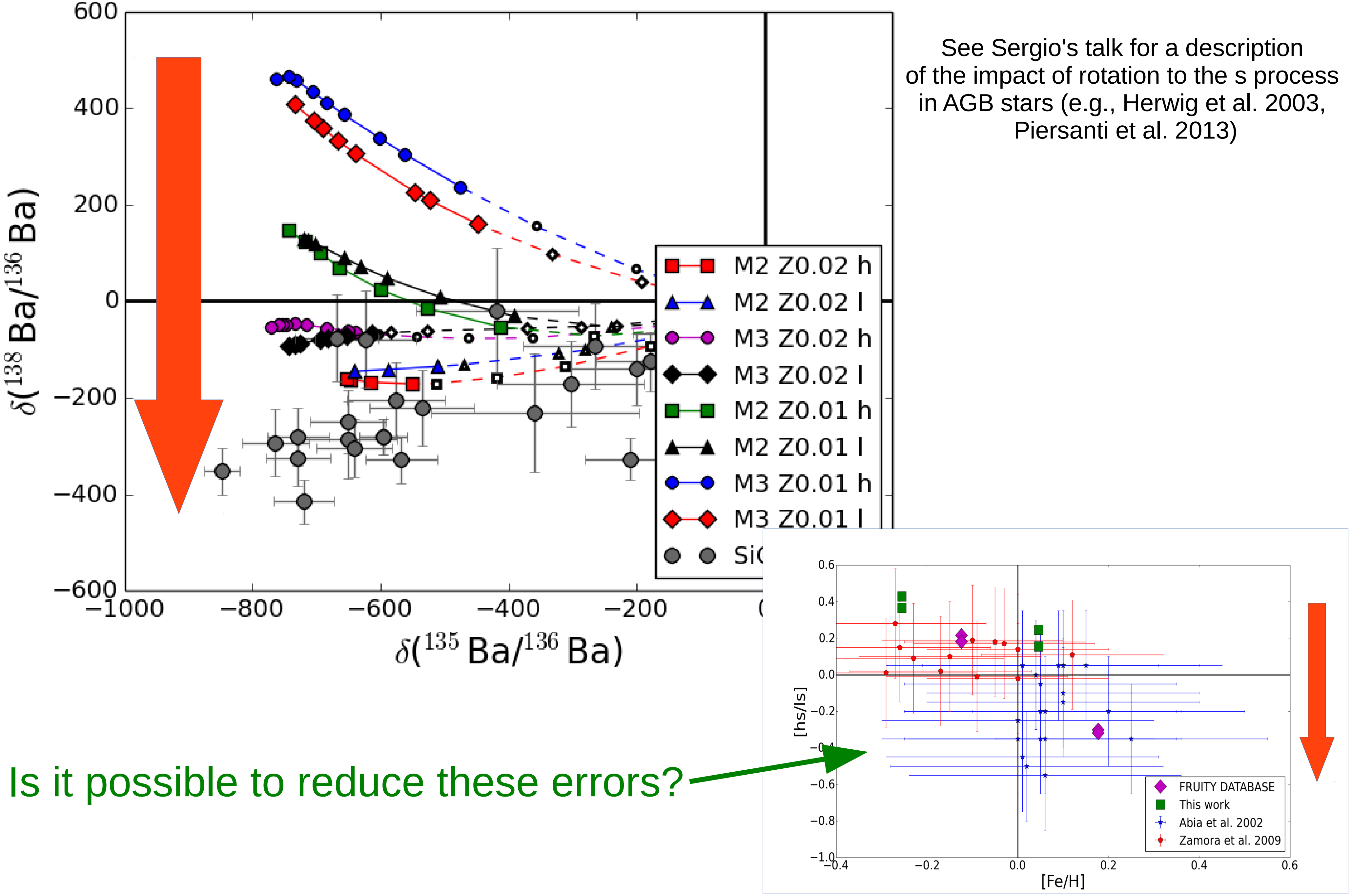
Liu et al. 2014, ApJ 786

Impact of the CBM below convective TPs, and of mass and metallicity



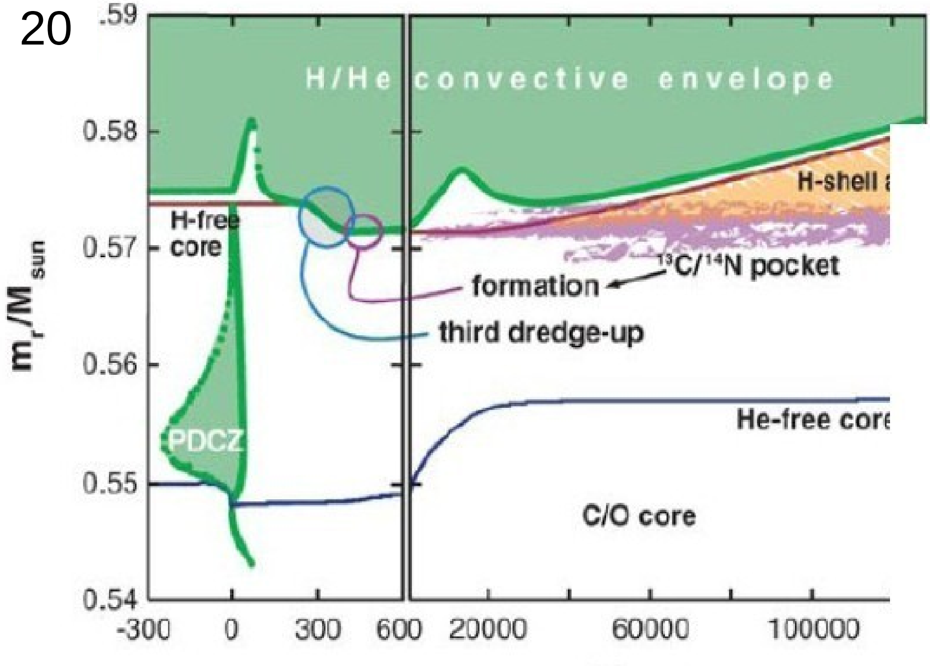
Battino et al. 2014, in prep.

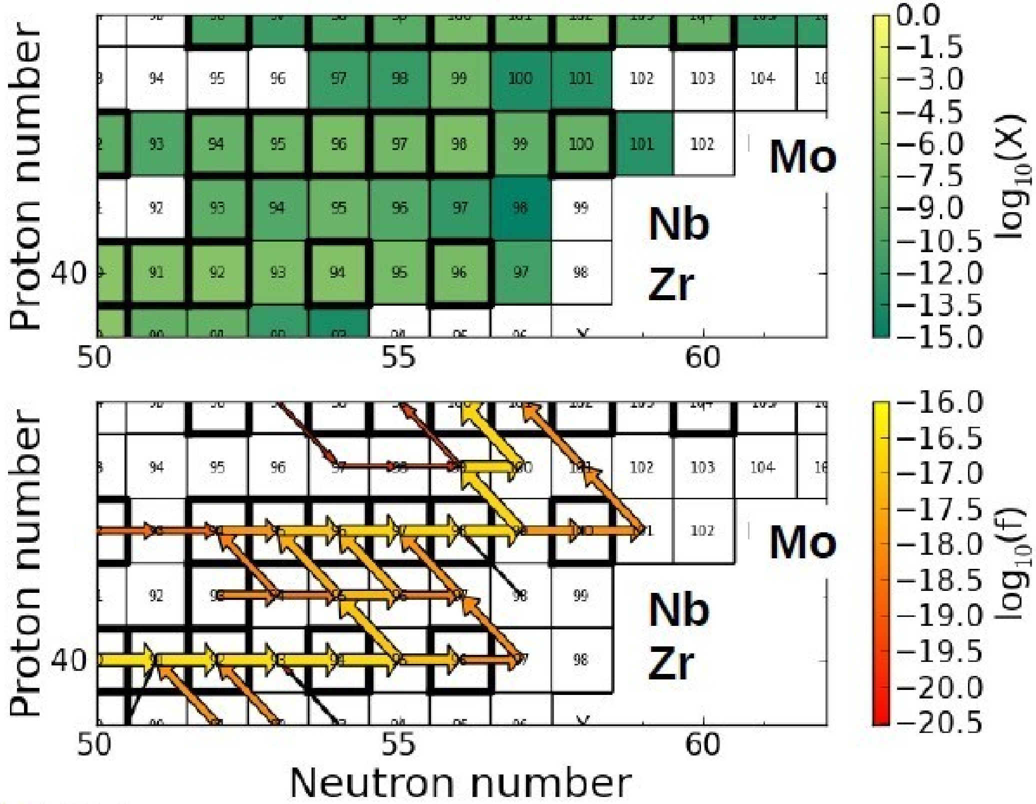
Potential solution from the next generation of these AGB models is to include feedback from rotation and magnetic field (poster by J. den Hartogh)

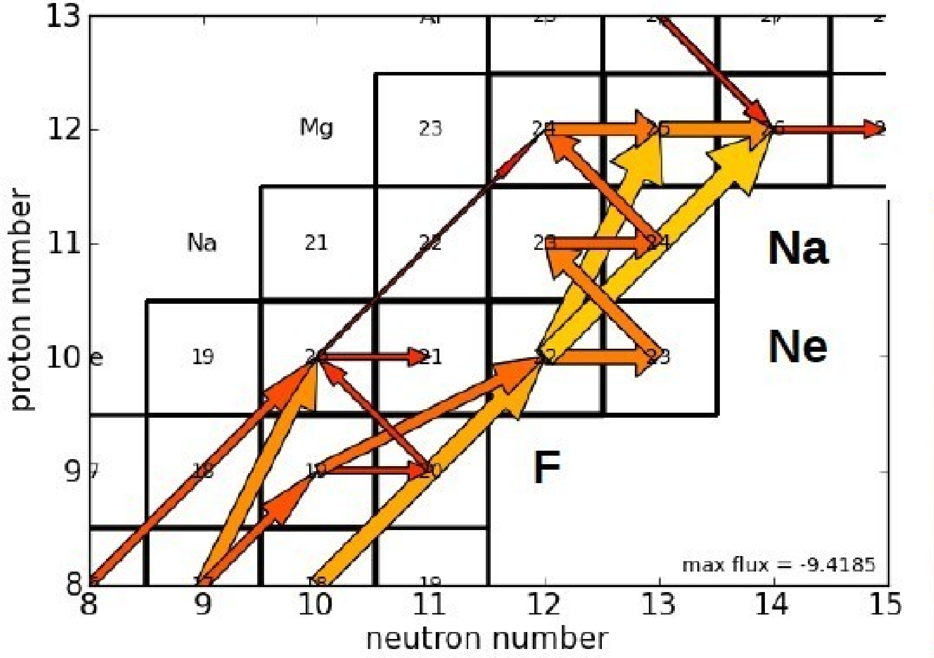


See Sergio's talk for a description of the impact of rotation to the s process in AGB stars (e.g., Herwig et al. 2003, Piersanti et al. 2013)

Is it possible to reduce these errors?



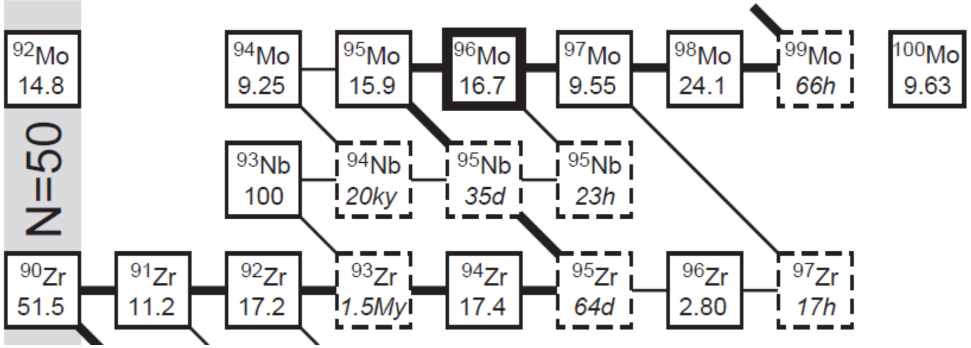




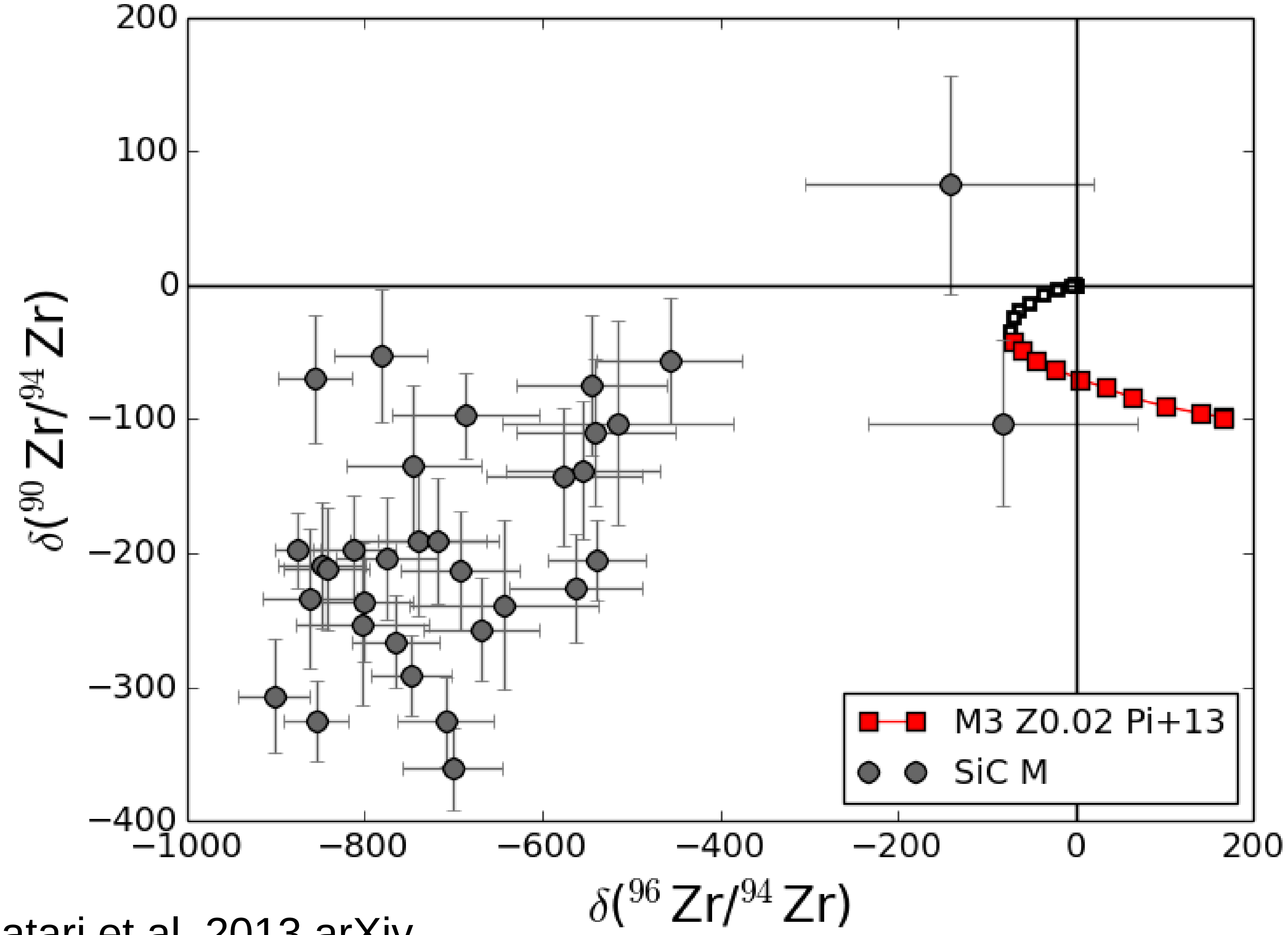
s-process during
the Thermal Pulse
Ne22(a,n)Mg25 activation -

N_n peak > 10^{10} cm^{-3}

Lugaro et al. 2003 ApJ



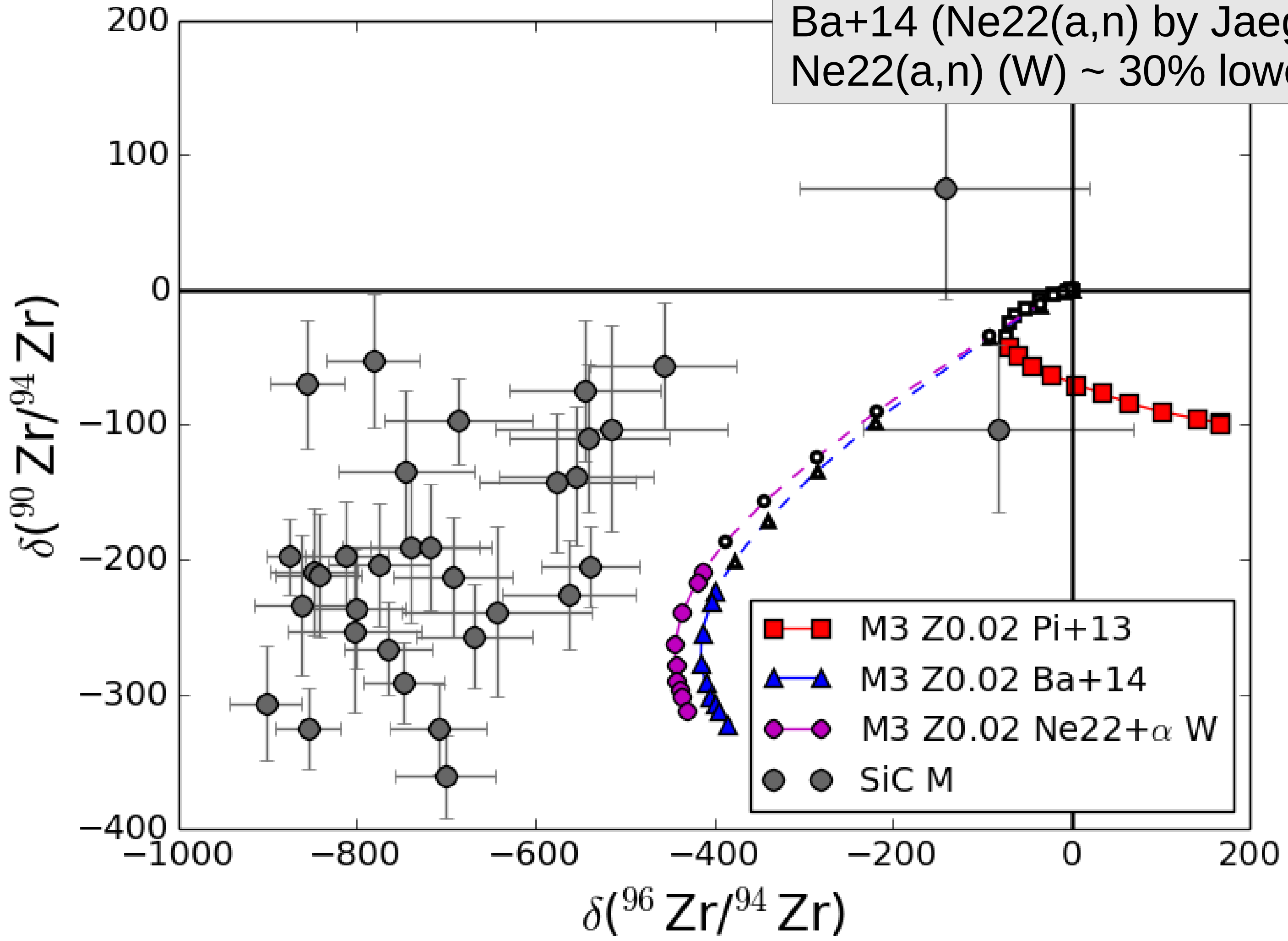
Starting point:



Pi+13: Pignatari et al. 2013 arXiv

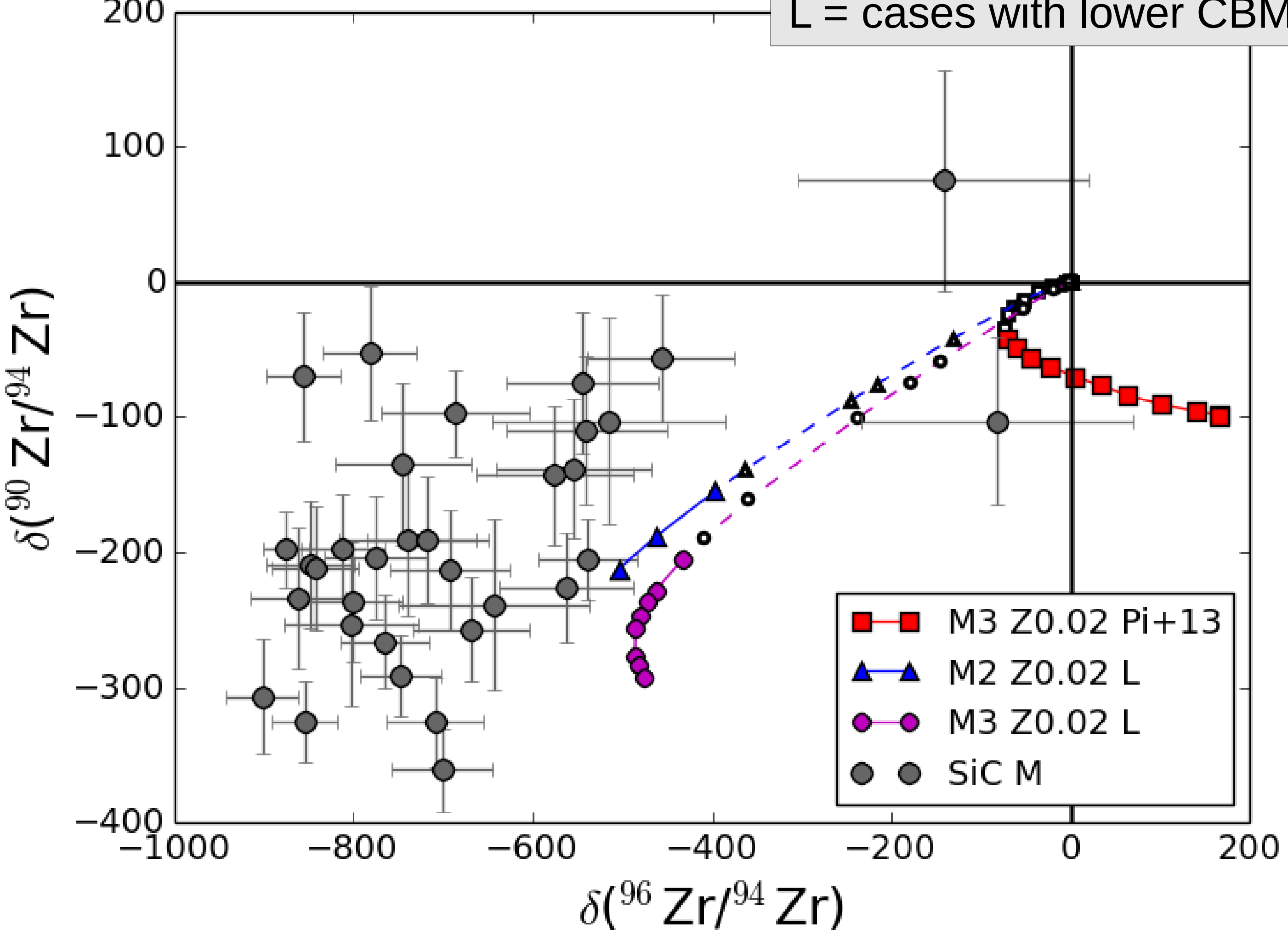
- New set of models: Umberto's talk on Monday
- New Zr95(n,γ)Zr96 MACS Lugaro et al. 2014 ApJ

Pi+13 (Ne22(a,n) by Jaeger et al. 2001)
Ba+14 (Ne22(a,n) by Jaeger et al. 2001)
Ne22(a,n) (W) ~ 30% lower than Jaeger+



Ne22(a,n) (W): M. Wiescher, G. Imbriani
and J. Gorres, priv. comm.

- New set of models: Umberto's talk on Monday
- New Zr95(n,γ)Zr96 MACS Lugaro et al. 2014 ApJ



Ba+14 (Ne22(a,n) by Jaeger et al. 2001)
L = cases with lower CBM

- New set of models: Umberto's talk on Monday
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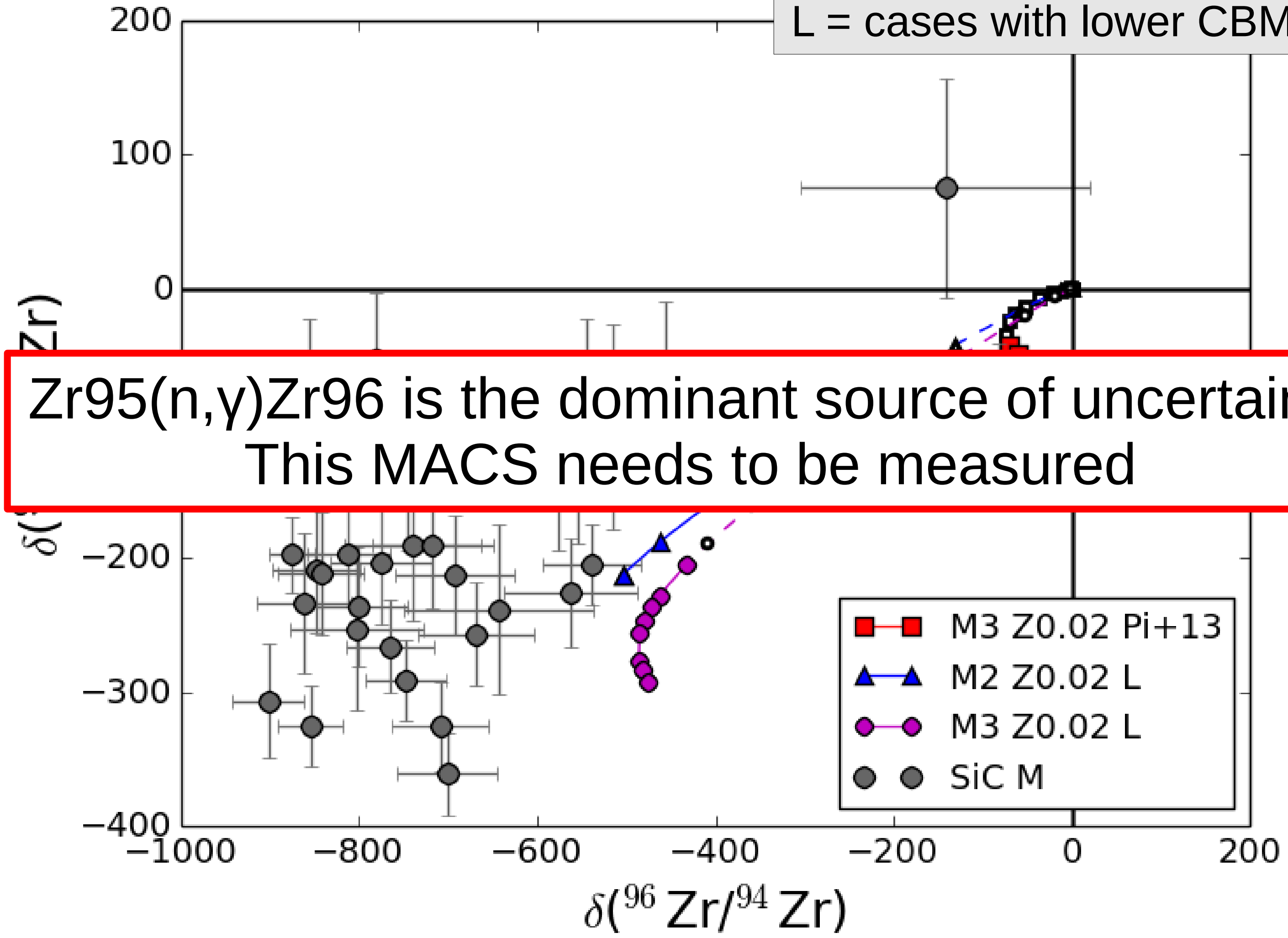
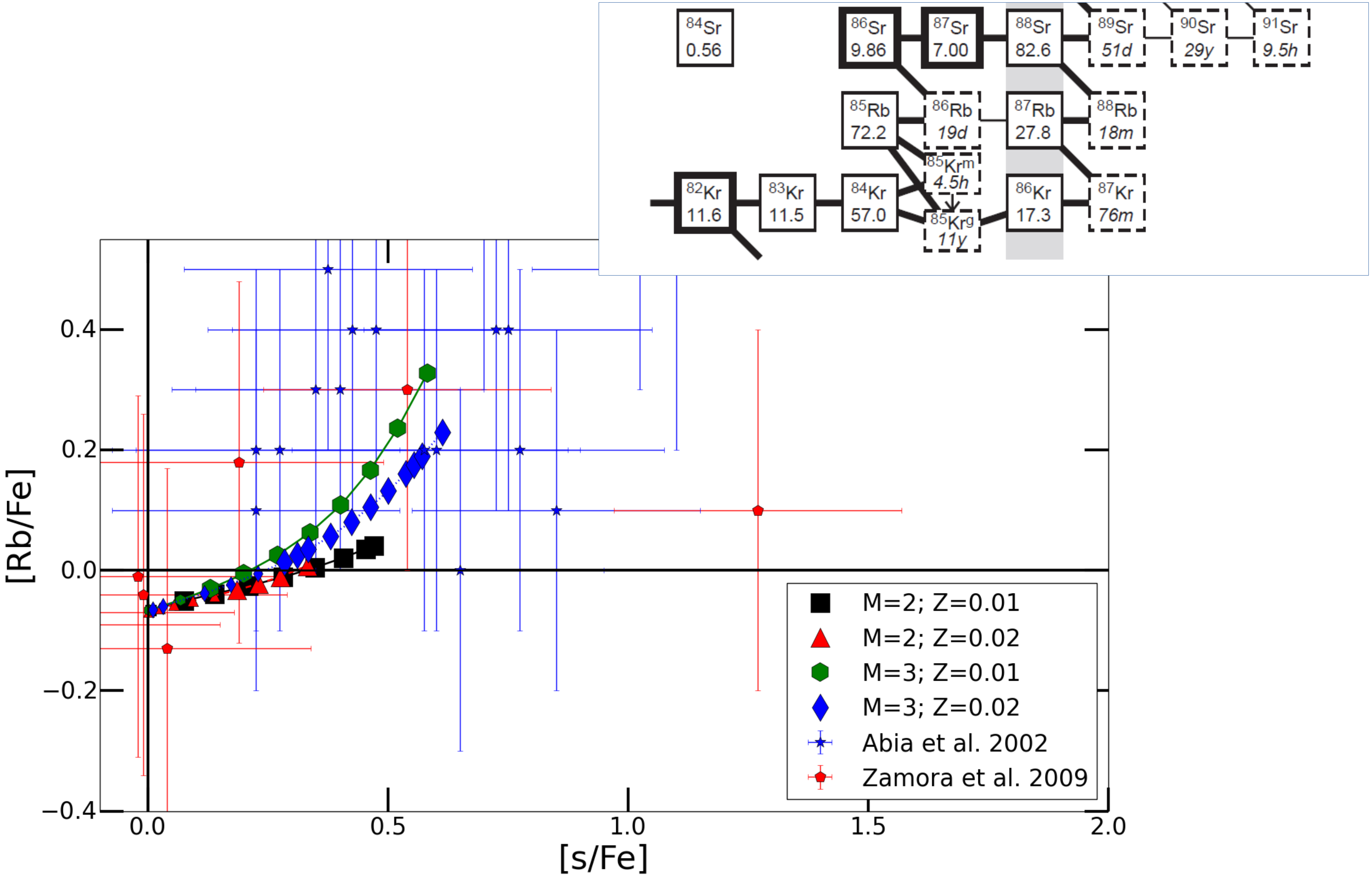


Ba+14 (Ne22(a,n) by Jaeger et al. 2001)
L = cases with lower CBM

Zr95(n,γ)Zr96 is the dominant source of uncertainty.
This MACS needs to be measured



- The [Rb/Fe] dependends on: (1) CBM below the TP; (2) Ne22(a,n); (3) Kr85(n,y)
- The [s/Fe] depends on: (1) the production efficiency of the C13-pocket (2) mass loss; ...

BETTER OBSERVATIONS NEEDED TO CONSTRAIN THE MODELS!

Sensitivity study for the s process: application for the Kr branching point in AGB stars

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B. Thomas[1]
C. Ritter[2]
R. Reifarth[1]
M. Pignatari[3]
((1)Frankfurt,(2)Victoria,(3)Basel)

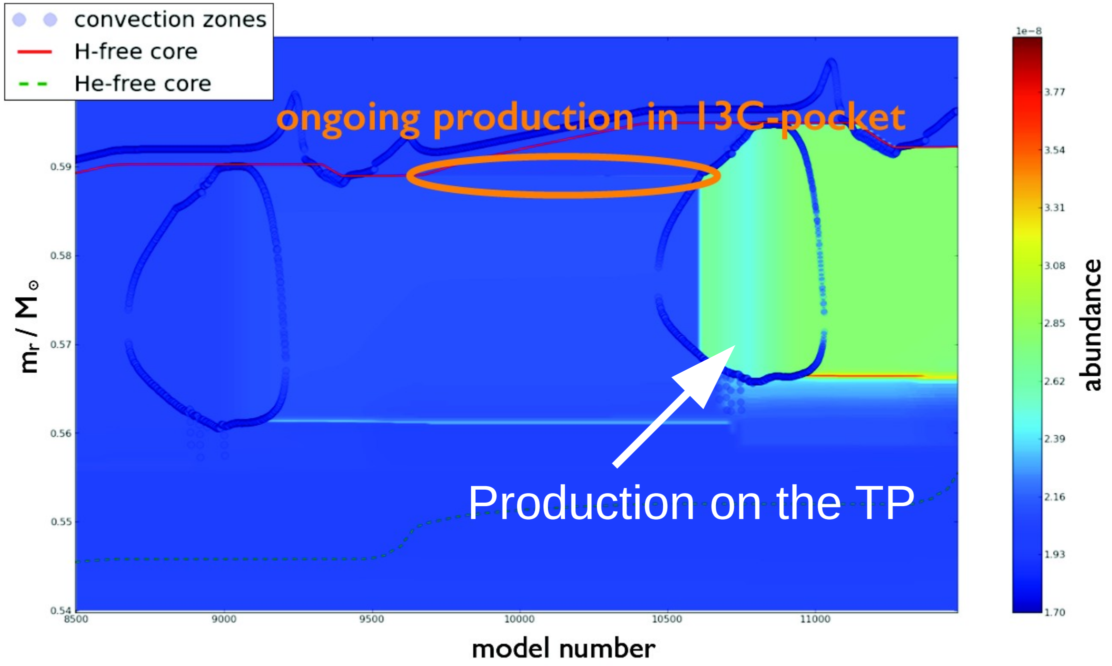
Error estimation resuluting from TP sensitivities and nuclear uncertainties for Kr isotopes

Isotope	ΔN	ΔN^{max}
^{80}Kr	35.2%	^{22}Ne(α,n) (24.2%)
^{82}Kr	37.5%	^{22}Ne(α,n) (33.0%)
^{83}Kr	37.5%	^{22}Ne(α,n) (32.9%)
^{84}Kr	27.9%	^{22}Ne(α,n) (25.0%)
^{86}Kr	85.4%	^{85}Kr(n,γ) (68.7%)

Error estimation resulting from ^{13}C-pocket sensitivities and nuclear uncertainties for Kr isotopes

Isotope	ΔN	ΔN^{max}
^{80}Kr	20.6%	^{79}Se(n,γ) (16.3%)
^{82}Kr	8.7%	^{82}Kr(n,γ) (6.9%)
^{83}Kr	8.2%	^{83}Kr(n,γ) (6.3%)
^{84}Kr	8.4%	^{84}Kr(n,γ) (6.4%)
^{86}Kr	77.8%	^{85}Kr(n,γ) (77.4%)

^{86}Kr production during ^{13}C-pocket and TPs



ongoing production in 13C-pocket

Production on the TP

Conclusions

- AGB stars are an ideal laboratory for nuclear astrophysics. The impact of nuclear reaction rate uncertainties can be disentangled from different sources of uncertainty;
- Whishlist of nuclear reaction rates: N14(n,p)C14, Zr95(n,g)Zr96, Kr85(n,g)Kr86, Si30(n,g)Si31;
- AGB models including CBM below the convective TP are more strongly affected from these nuclear uncertainties;
- Wishlist for spectroscopic observations: more observations and smaller errors for Rb, Sr-Y-Zr, Ba-La;
- Wishlist for Andy: go CHILI!
- Results published soon in Battino et al. 2014, in prep. and in Koloczek et al. 2014, in prep.

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NuGrid stats:

16 institutions
18 senior investigators
25 post-docs and students

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