The s process in AGB stars

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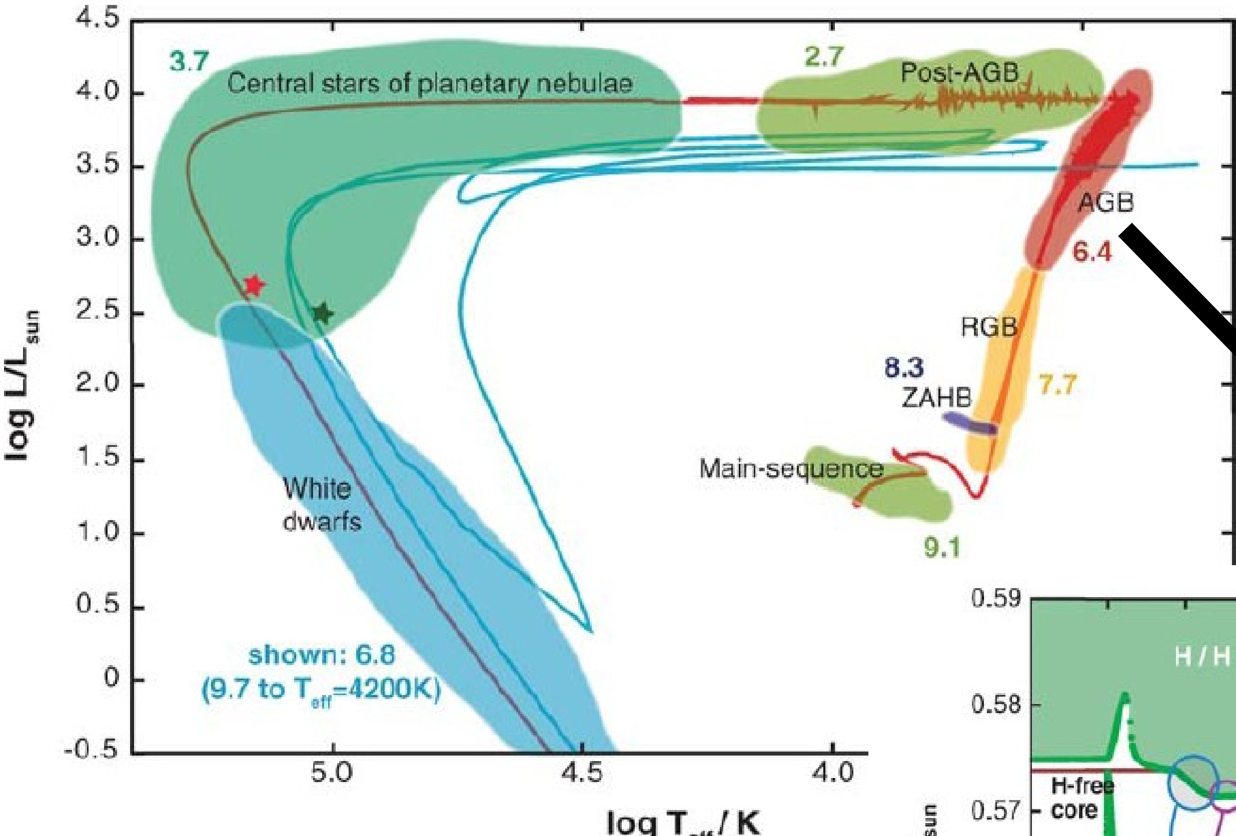
AGB stars



Herwig 2005, ARAA 43

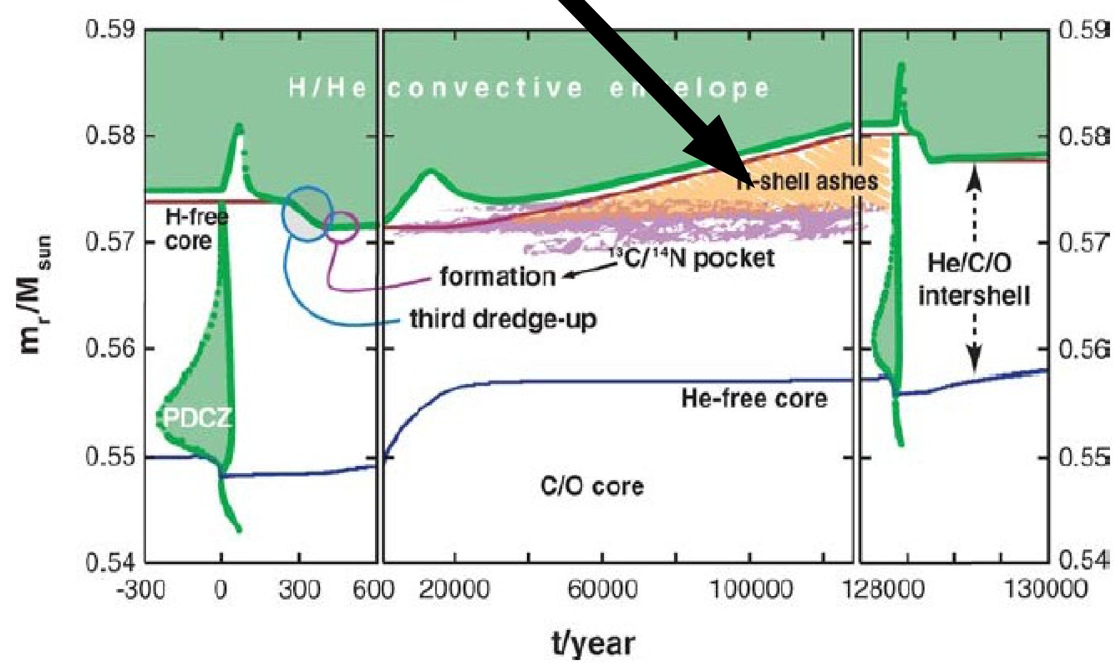
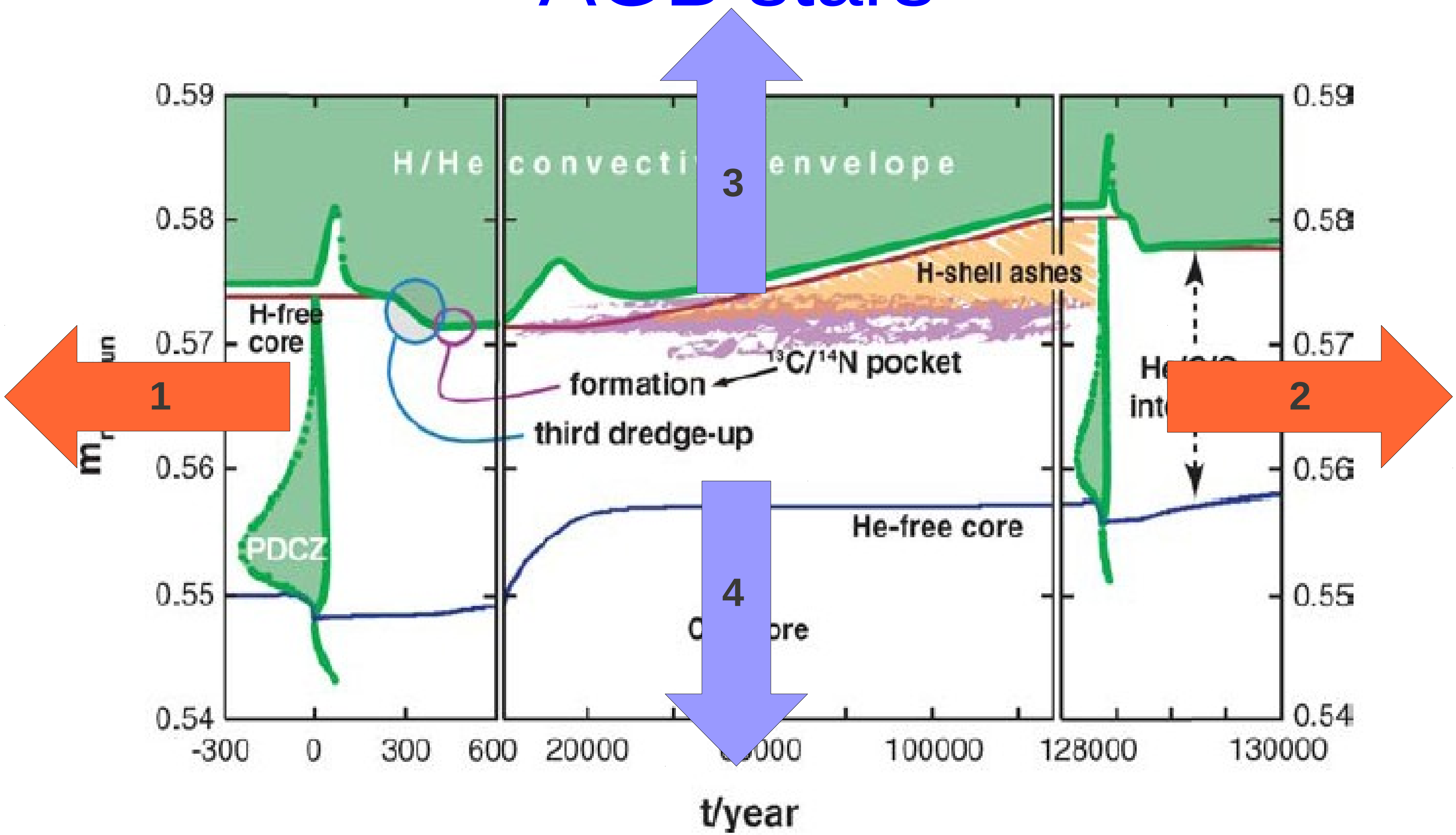


Figure 3 Thermal pulse 14, the subsequent interpulse phase and thermal pulse 15 of 2 $M_\odot$, $Z = 0.01$ sequence ET2 of Herwig & Austin (2004). The timescale is different in each panel.

AGB stars



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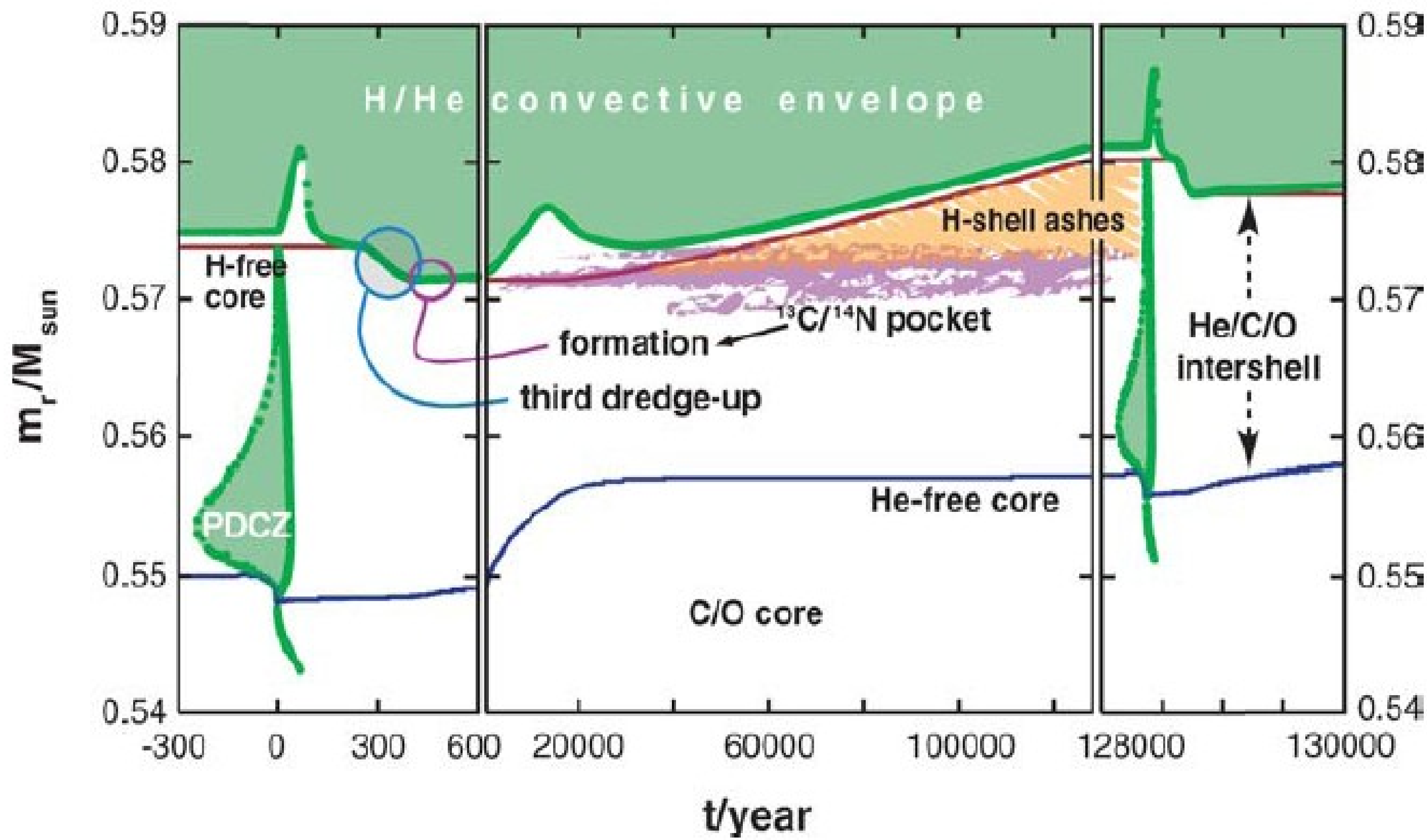
AGB stars



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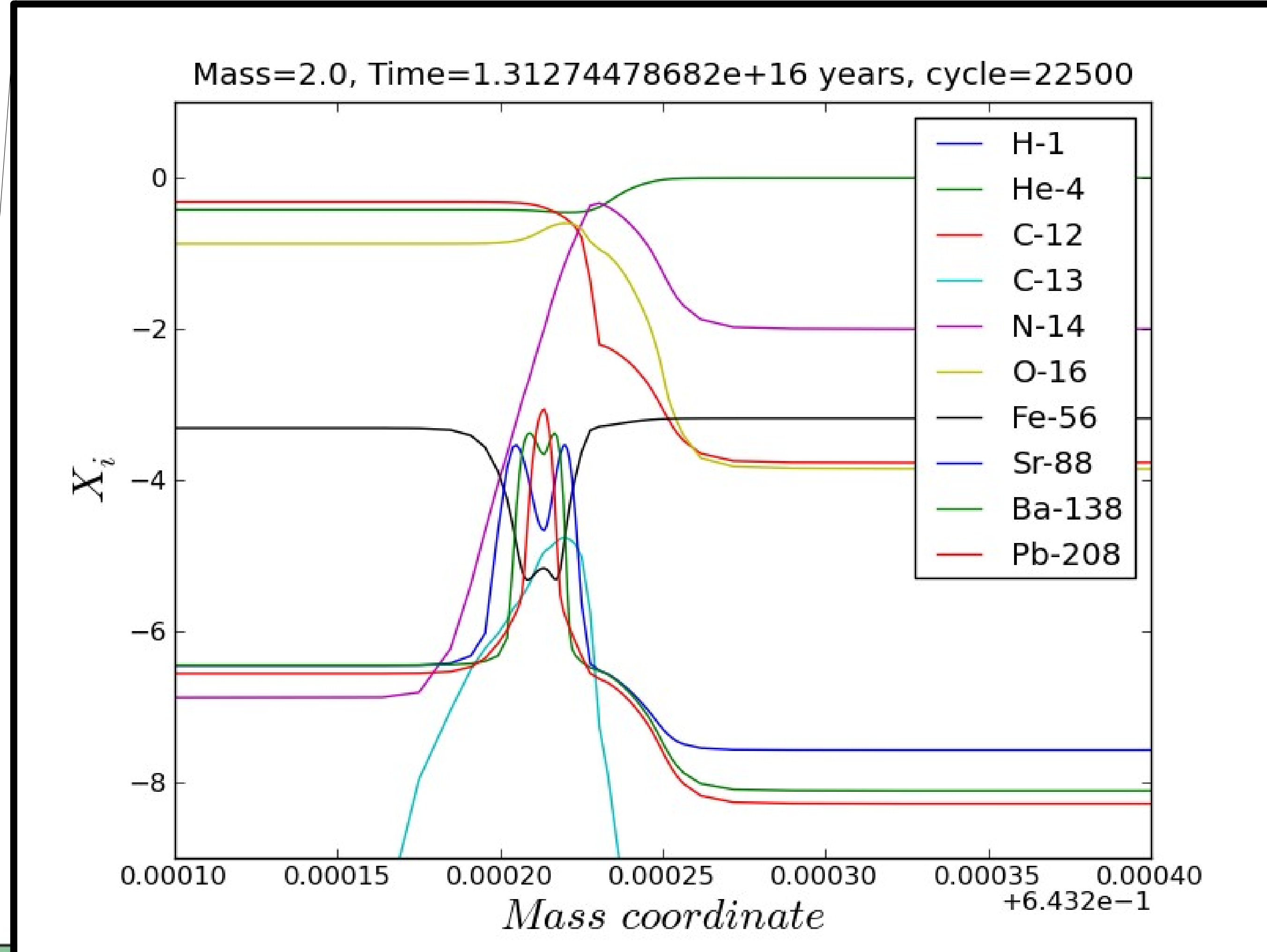

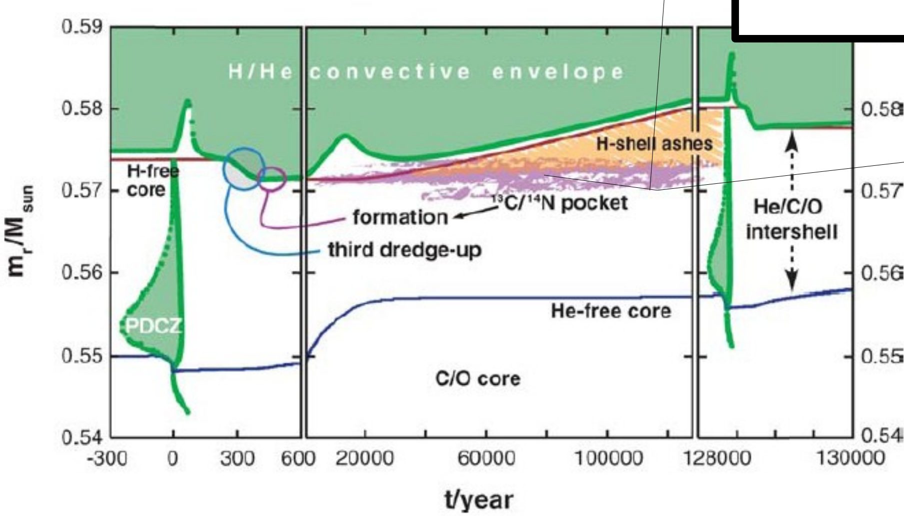

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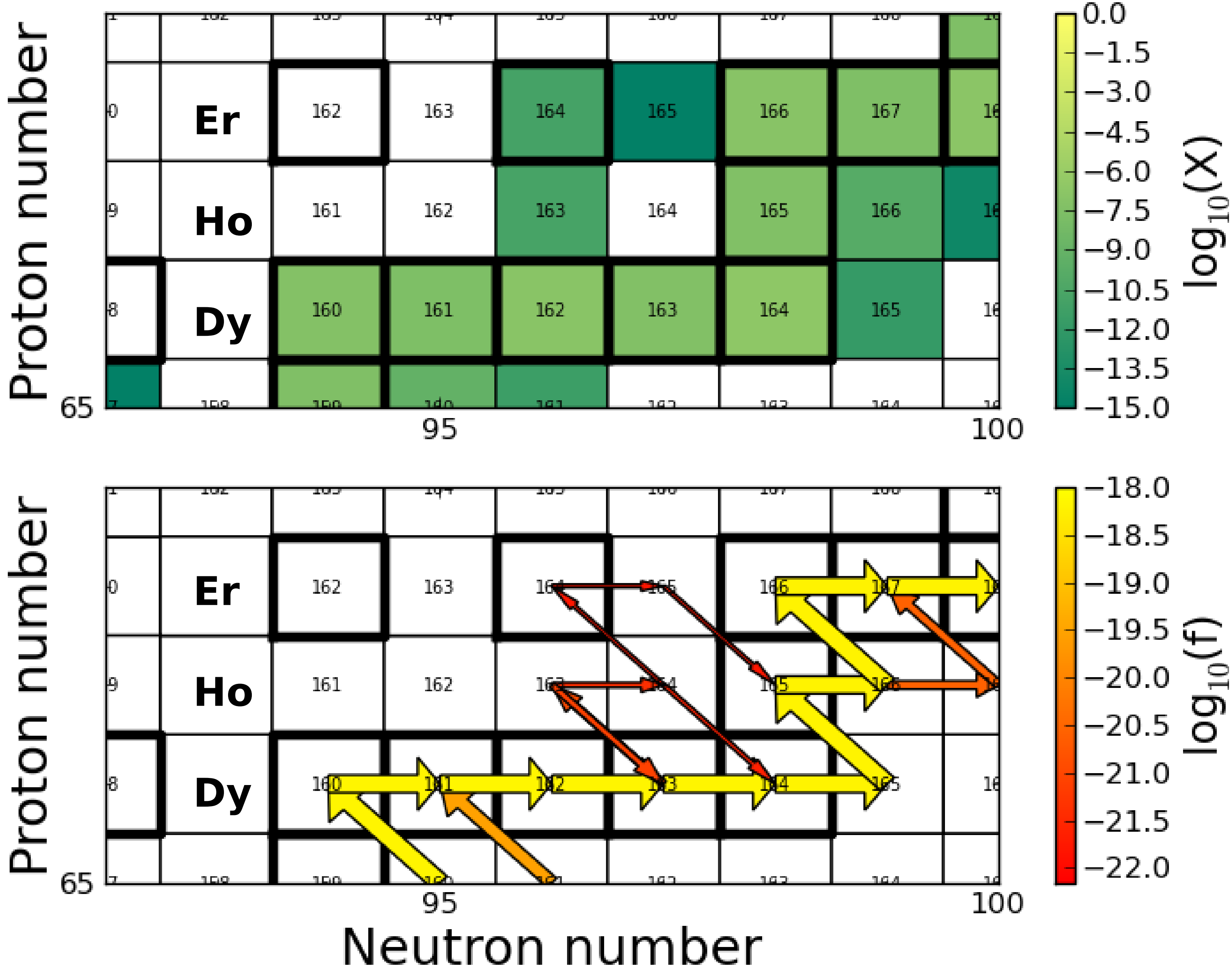
Once C13 is depleted by the (α,n), the C13-pocket layers are s-process rich.


Proton number
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−4.5
−6.0
−7.5
−9.0
−10.5
−12.0
−13.5
−15.0
log10(X)
Proton number
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Ho
Dy
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95
100
Neutron number
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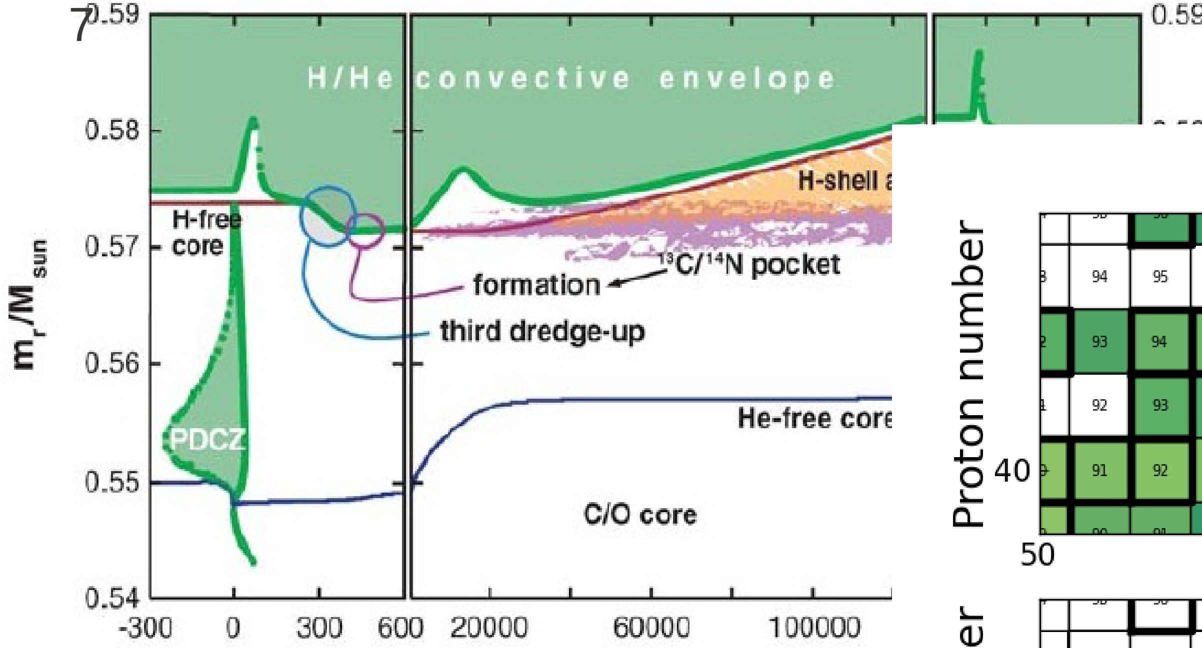
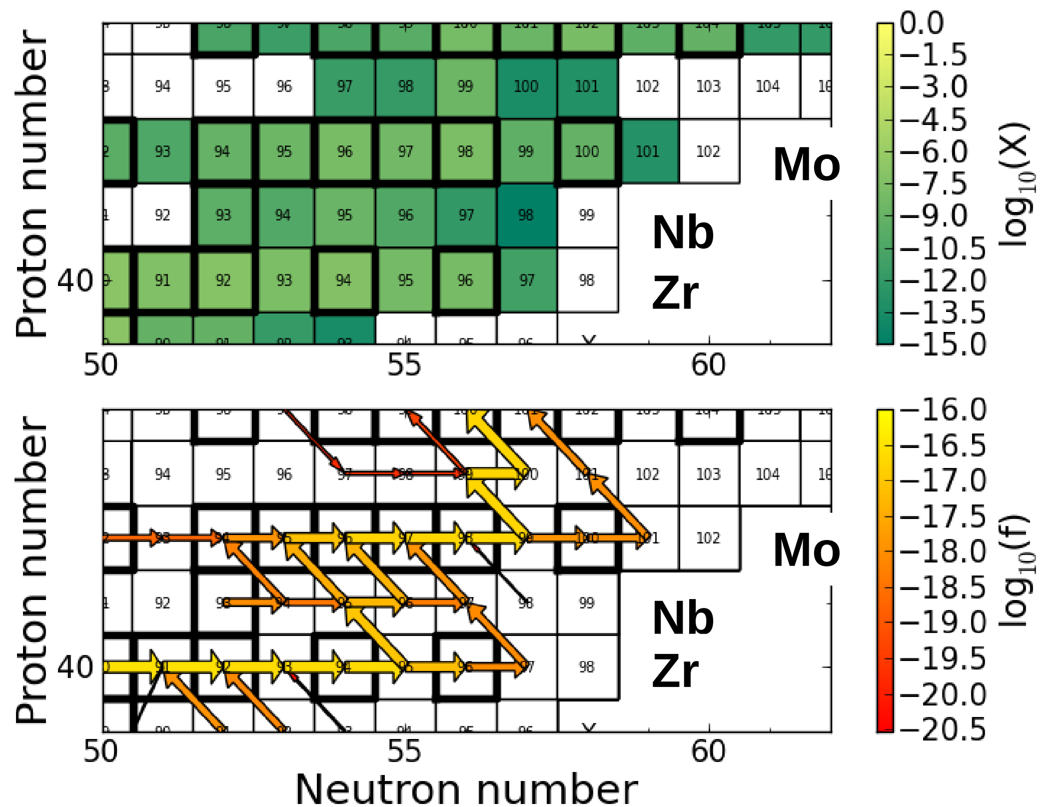
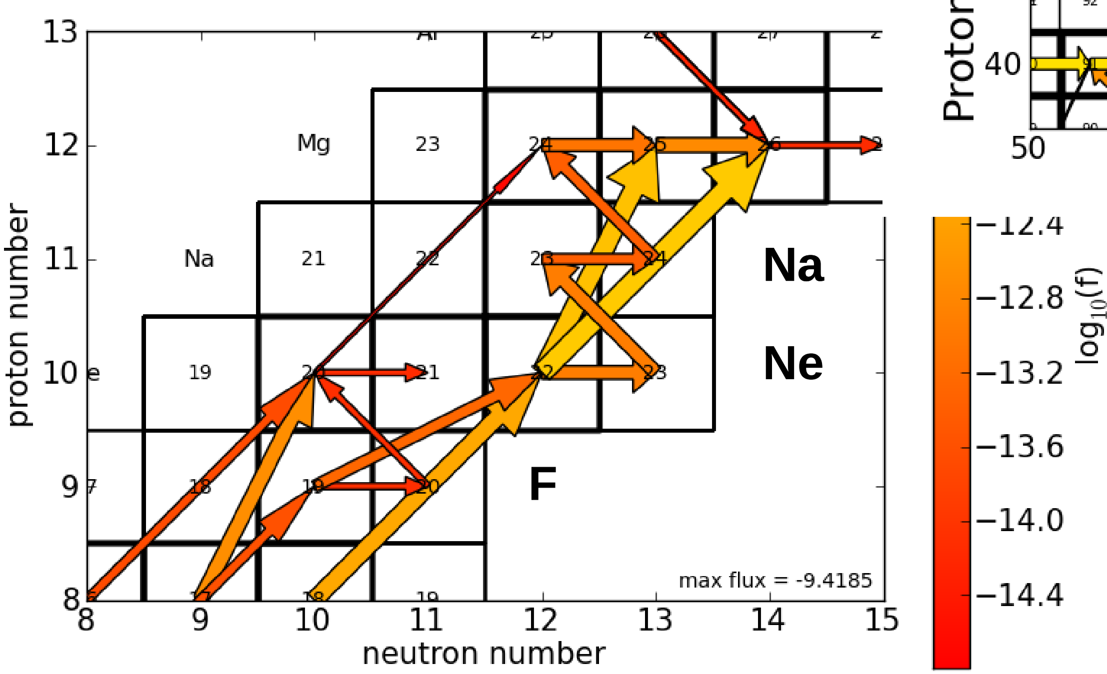
−20.0
−20.5
−21.0
−21.5
−22.0
log10(f)







s-process during
the Thermal Pulse
Ne22(a,n)Mg25 activation -
Competition (a,n)/(a,g)
T ~ 2.5 – 3 * 10^8 K

MESA models, Paxton et al. 2011,2013
Pignatari et al. 2013, arXiv

Radiative C13-pocket:

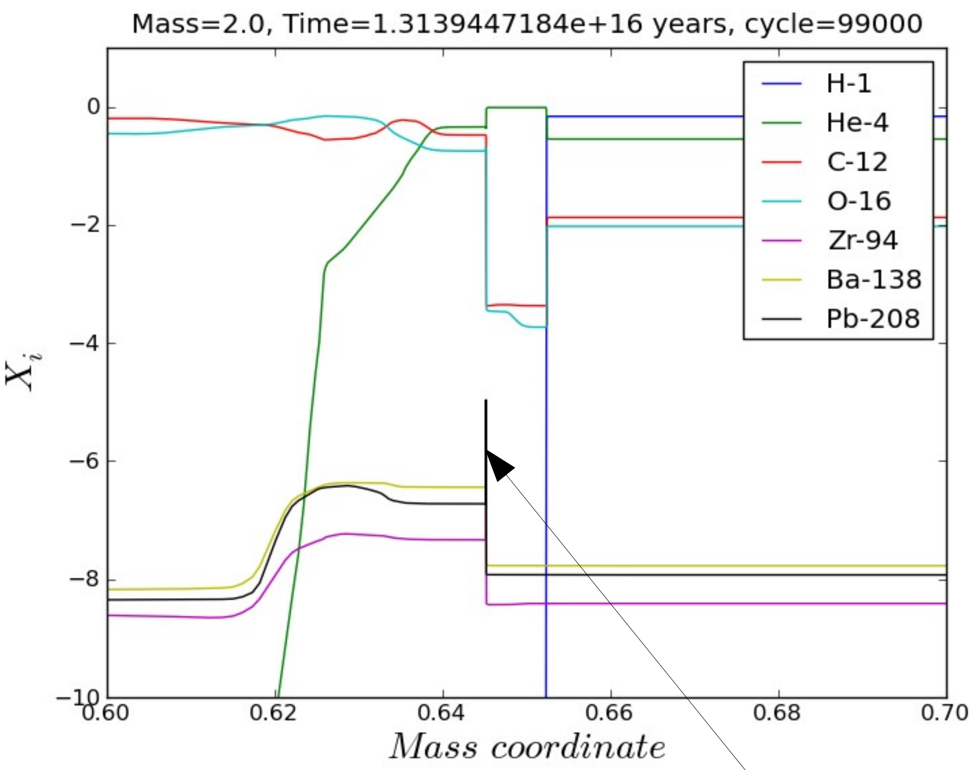
Major Neutron source:
$^{12}C(p,\gamma)^{13}N(\beta^{+})^{13}C(\alpha,n)^{16}O$.

Type: primary

When: interpulse T_8 ~ 0.9-1

Where: He-intershell zone

Neutron Density: 10^7 n/cm^3

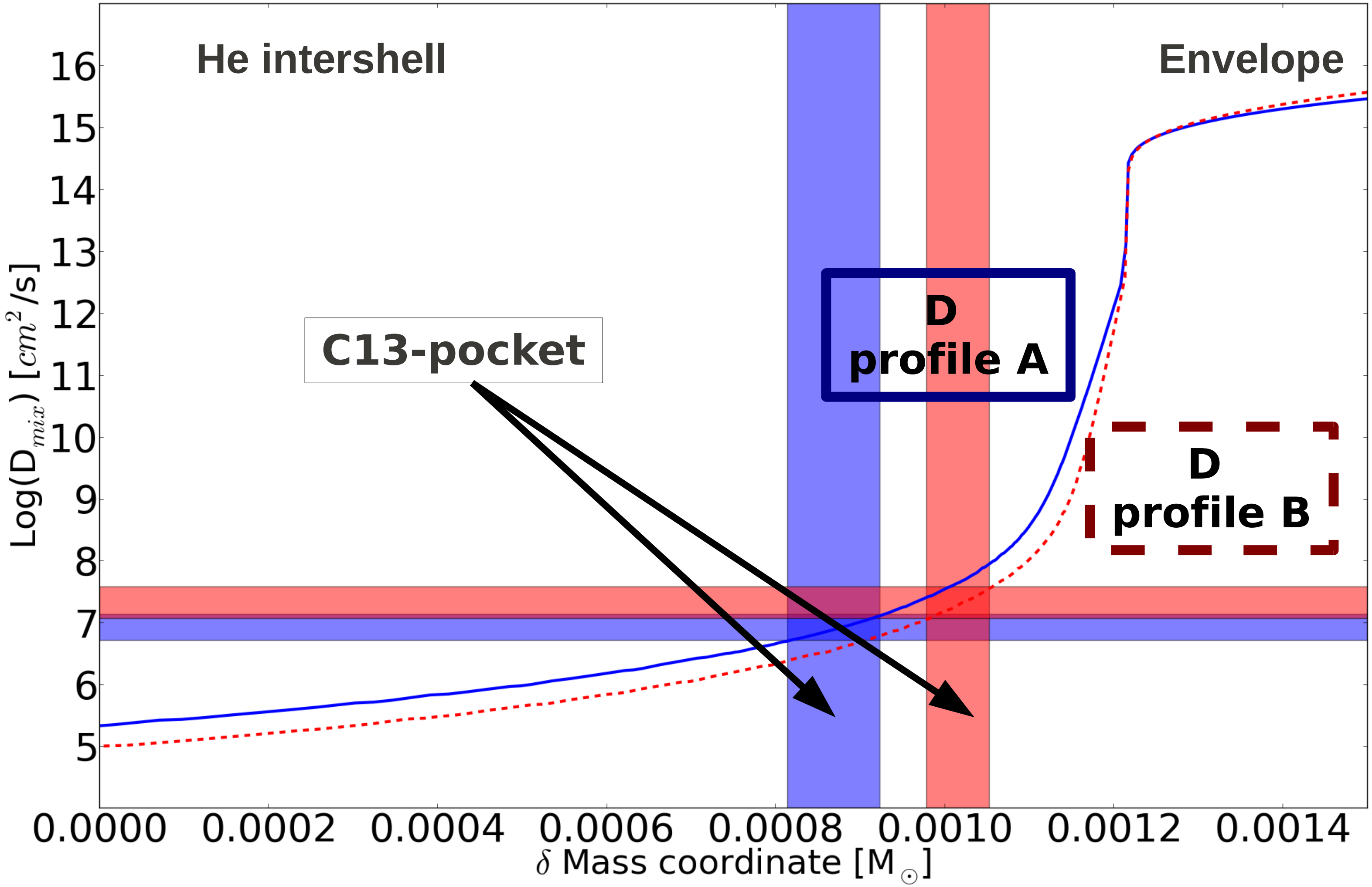


C13-pocket - size ≥ 10^{-4} Msun
≥ 10^2 Km (!)

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

Straniero et al. 1995, Herwig et al. 1997, Gallino et. al. 1998, Goriely & Molawi 2000, Denissennkov & Tout 2003, Goriely & Siess 2004, Cristallo et al. 2009, Karakas et al. 2010, Bisterzo et al. 2010, Lugaro et al. 2012, Maiorca et al. 2012...

Battino et al. 2013, in preparation.

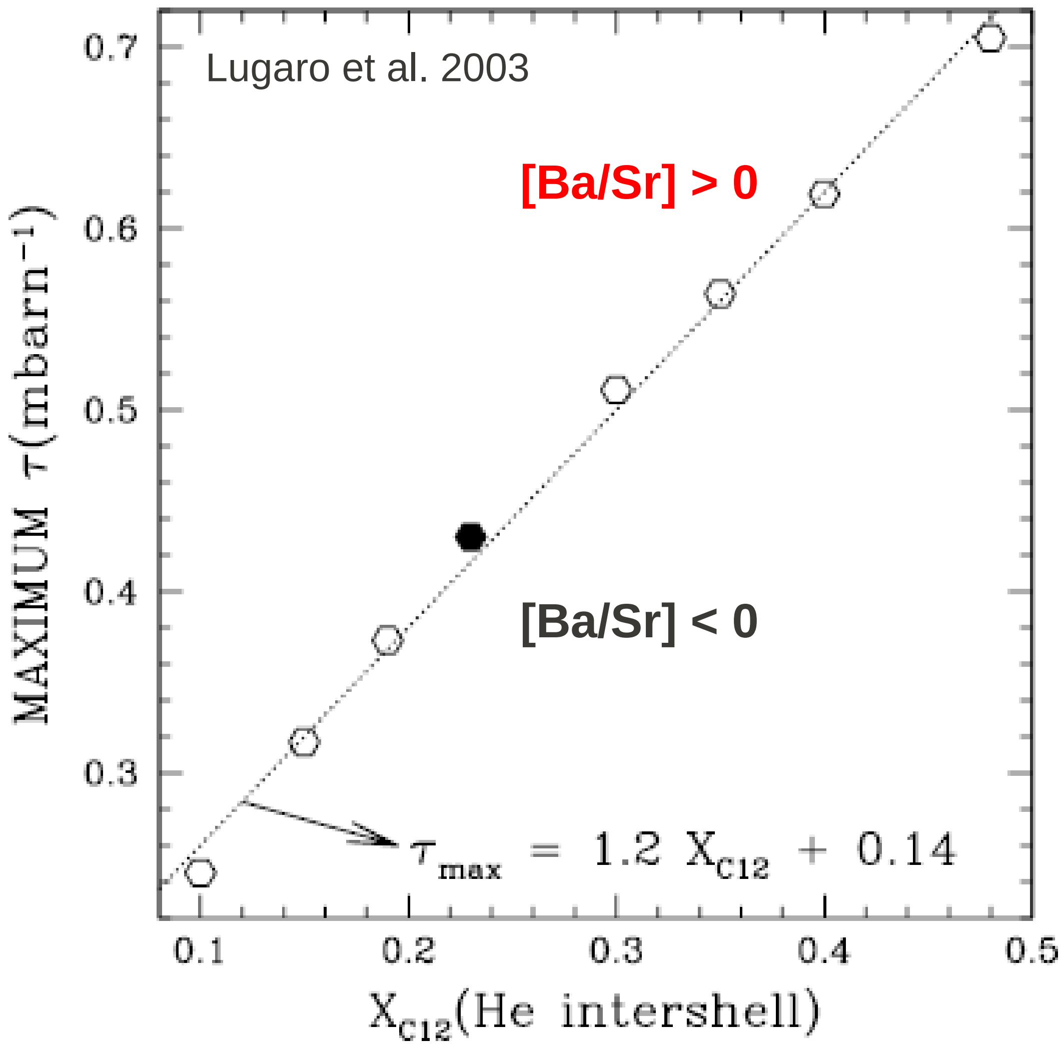


C13-pocket formed within a range of D_{coeff} (~ 10^6-10^8 cm^2/s) and H/C12 (see e.g., Lugaro et al. 2003 and Goriely & Siess 2004)

H/C12 < 0.3-0.5 → C13 > N14

This depends on the abundances in the He intershell, and on the nuclear reaction rates used.

The convective boundary mixing (CBM) below the TDU affects *how much* s-process material is made. The CBM below the He intershell during the TPs affects all the He-intershell composition, and therefore the observed s-process distribution.

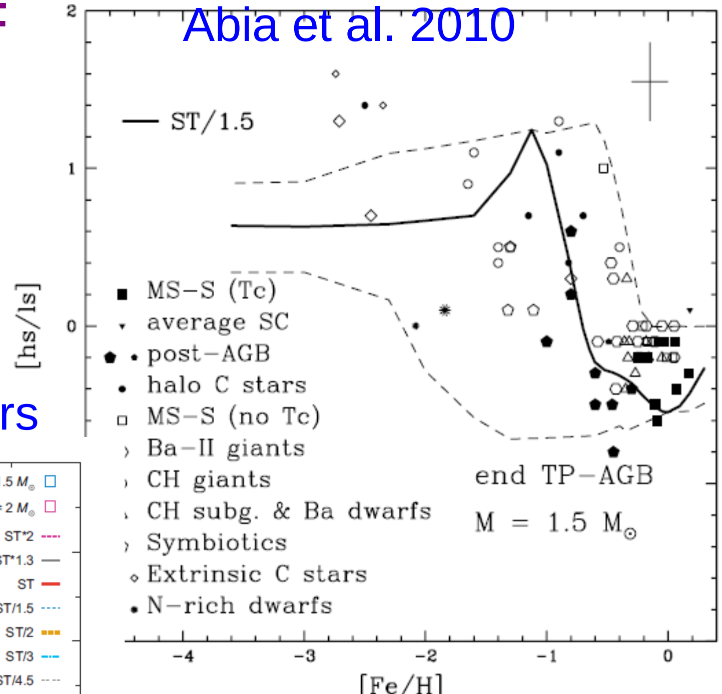


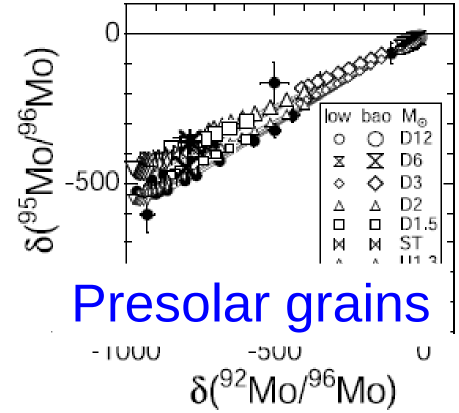
Therefore, a second fundamental question for the s process in AGB stars is:

(2) What is(are) the physics mechanism(s) driving the CBM below the convective TPs?

- Large sample of different observations available to test AGB stars s-process and nucleosynthesis.

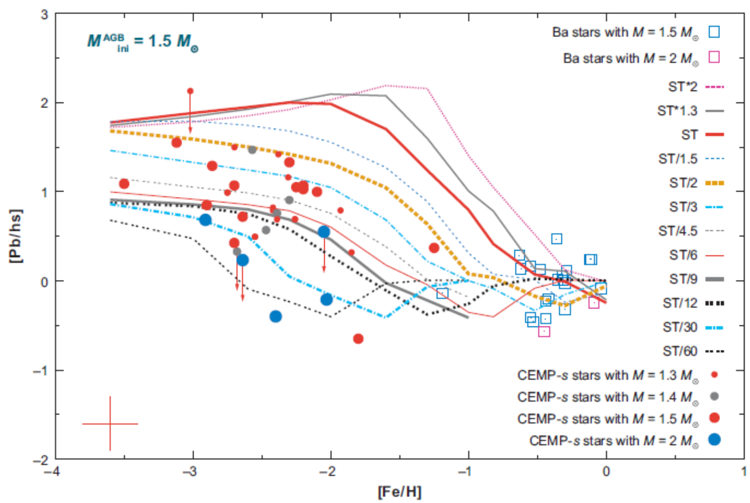
Ba stars, MS-S stars...
e.g.,Busso et. Al 2001,
Abia et al. 2010

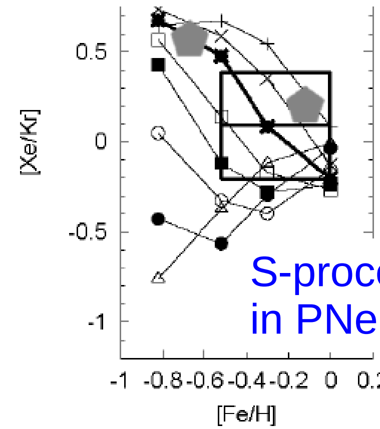




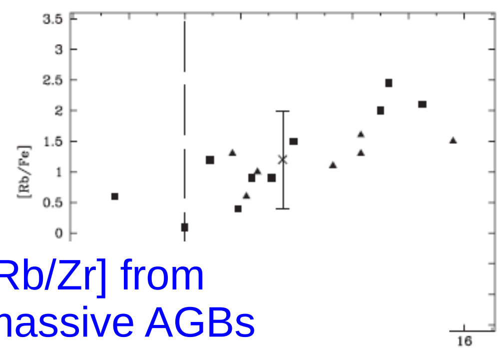
Presolar grains

Sneden et al. 2008: CEMP stars

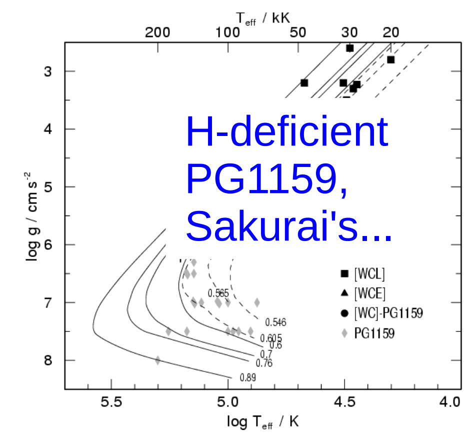




S-process
in PNe



[Rb/Zr] from
massive AGBs
Garcia-Hernandez et al.



H-deficient
PG1159,
Sakurai's...

-3

[Fe/H]

Solar system
distribution

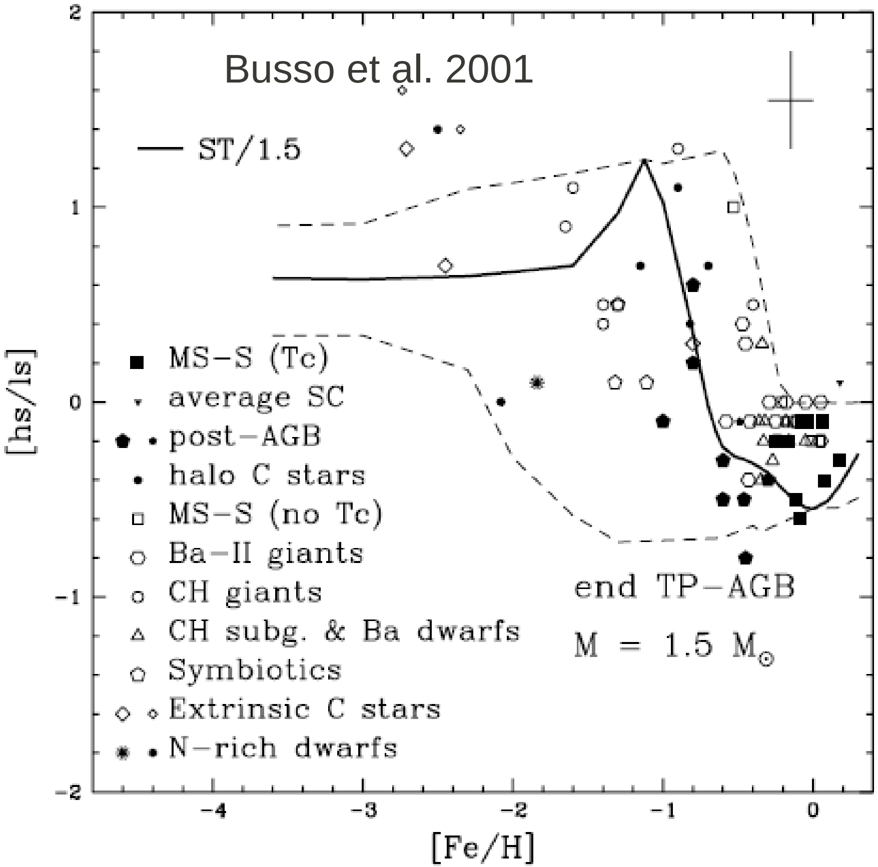
The AGB models that fit better the s-process observations consider negligible the effect of CBM below the He intershell. The observation of H-deficient stars (20% of post-AGB stars) allows to observe He-intershell abundances directly. A large variety of conditions are observed.

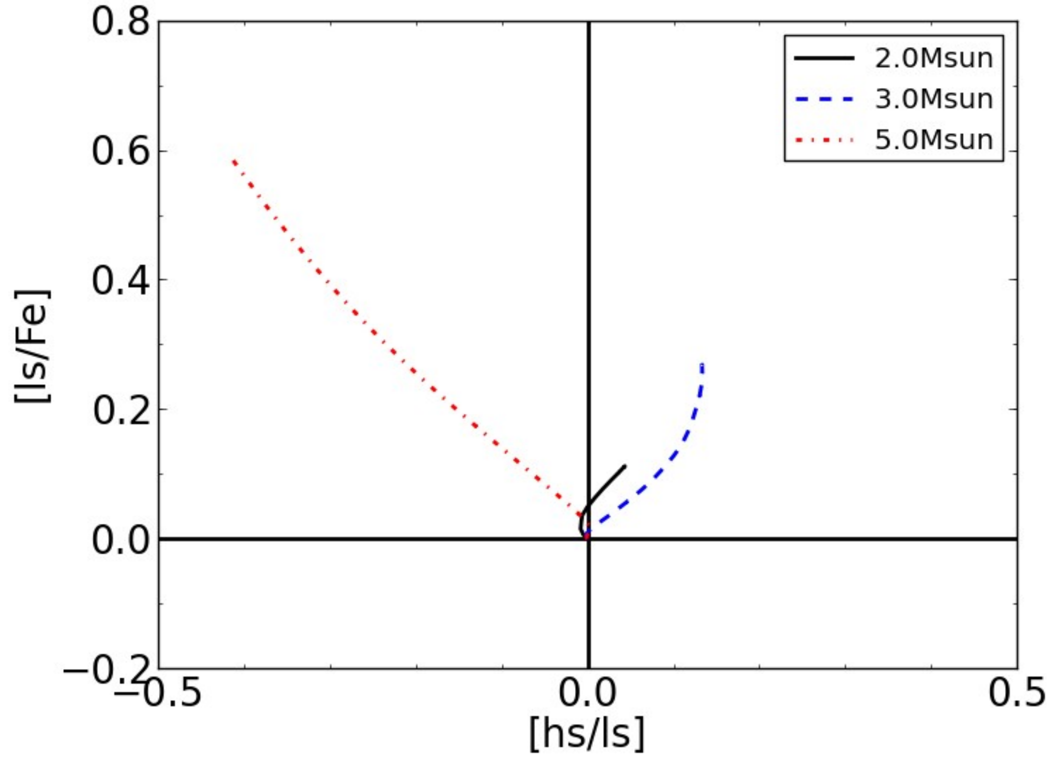
What is the impact on the s process?

PG1159	C	N	O
HS 1517+7403 ..	0.13	$<3 \times 10^{-5}$	0.02
HS 2324+3944 ..	0.42	<0.0003[a]	0.06
PG 1159−035 ...	0.48	0.001	0.17
PG 1144+005 ...	0.57	0.015	0.016

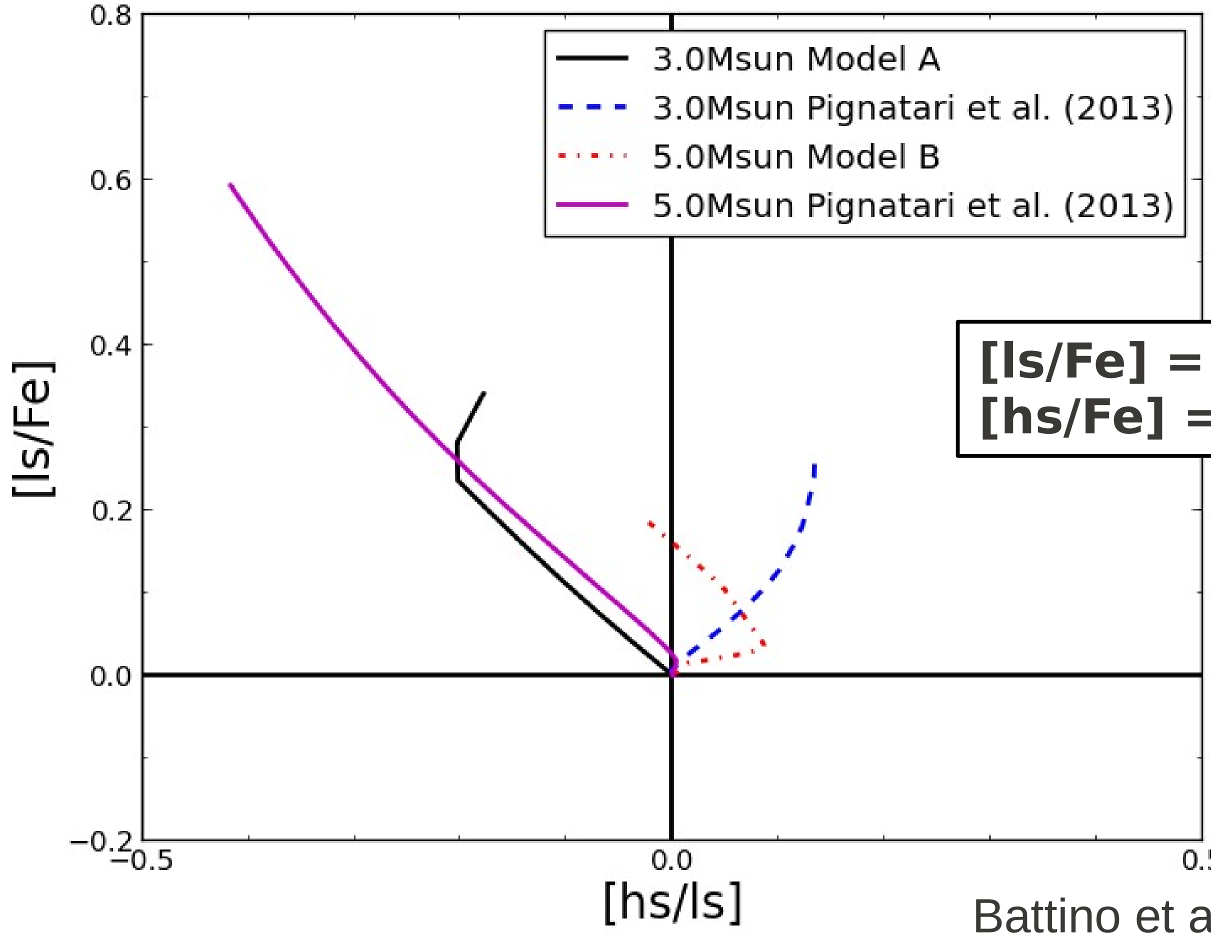
Werner & Herwig 2006

[ls/Fe] = [Sr,Y,Zr/Fe]
[hs/Fe] = [Ba,La,Nd,Sm/Fe]





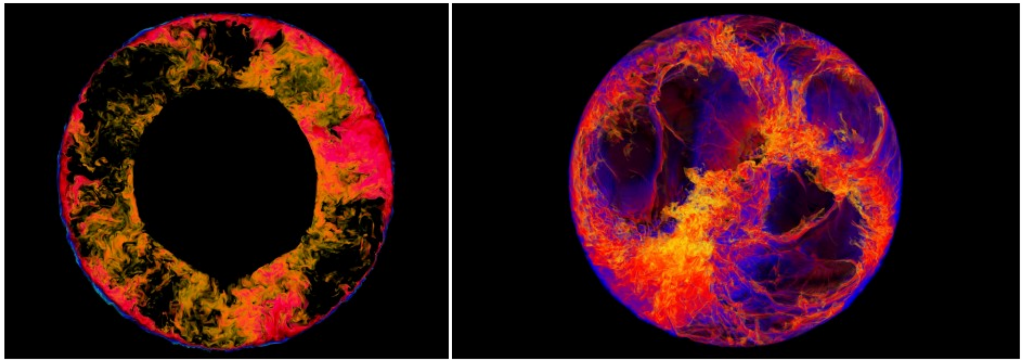
With an He-intershell composition typical of PG1159 stars, for Z = 0.02 the C13-pocket material has [hs/ls] > 0, against most of the observations.



[ls/Fe] = [Sr,Y,Zr/Fe]
[hs/Fe] = [Ba,La,Nd,Sm/Fe]

Battino et al. 2013, in preparation. (CBM based on Herwig et al. 2007, Woodward et al. 2009, 2013, and Denissenkov & Tout 2001)

[hs/ls] depends on:
- **C12 concentration in the He intershell (i.e., CBM below the He intershell);**
- amount of the total neutrons made by the C13(a,n) compared to the Ne22(a,n)



Woodward et al. 2009

Final remarks

- In the next ~ 2-3 years we can obtain more robust s-process predictions for AGB stars, guided by multi-D hydrodynamic simulations and observations. Only a multi-disciplinary effort can solve AGB star nucleosynthesis puzzles (NuGrid high priority goal: **www.nugridstars.org**).

- The spread of C, O and C/O abundances in the He intershell observed in H-deficient Post-AGB stars need to be considered while producing s-process yields.
The no-CBM option that is mostly adopted reproduce the s-process observations (C12 ~ 20-25%, O16 $\leq$ 2%), but it is clearly not a common case in the zoo of H deficient stars.

- Between the observation of 5 new CEMP-s/rs stars and 1 new PG1159 star, I would definitely consider more constraining for AGB stellar models the second option.
It would be also extremely useful to re-analyze again the measurements of available WCL, WCE and PG1159 stars, to better constrain the absolute abundances of available elements, and their ratio.

- Short-term goals – (Basel, 2014):
* production of the first set of AGB models able to explain at least qualitatively **all** the observations at metallicities typical of the galactic disk.
* test of the new models at metallicities typical of the halo.
- Needs from observations:
* more and better observations of post-AGB H-deficient stars
* more and better observations from young open clusters and solar and super-solar AGB stars.