The effect of rotation and non-canonical mixing on CEMP stars surface distributions

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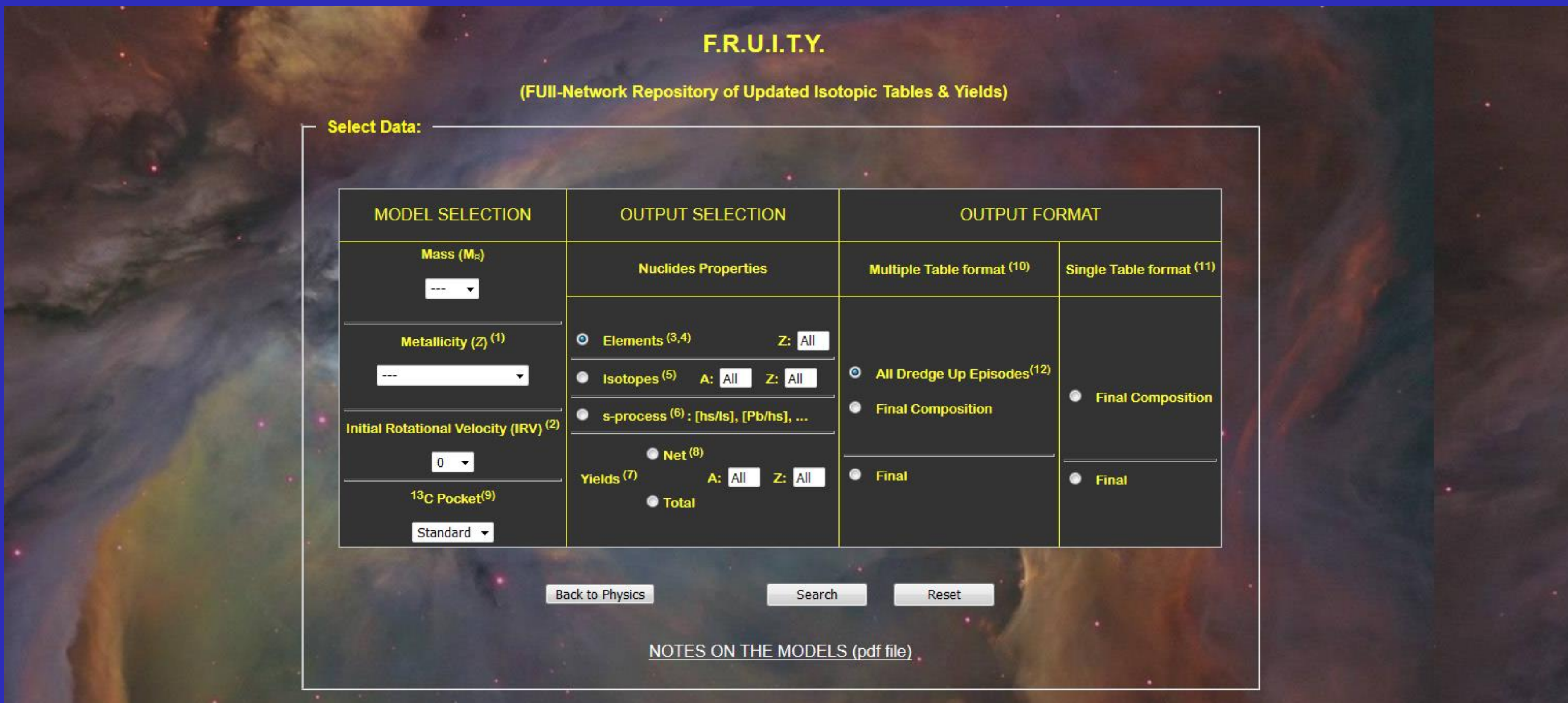
Summary

- An overview on the mechanisms at the origin of the ^{13}C pocket (major neutron source in low-mass AGBs);
- Models vs. Observations at low metallicities;
- The effects induced by rotation at low metallicities;
- The occurrence of the i-process at low metallicities;
- Alternative solutions

F.R.U.I.T.Y.

FUll-Network Repository of Updated Isotopic Tables & Yields



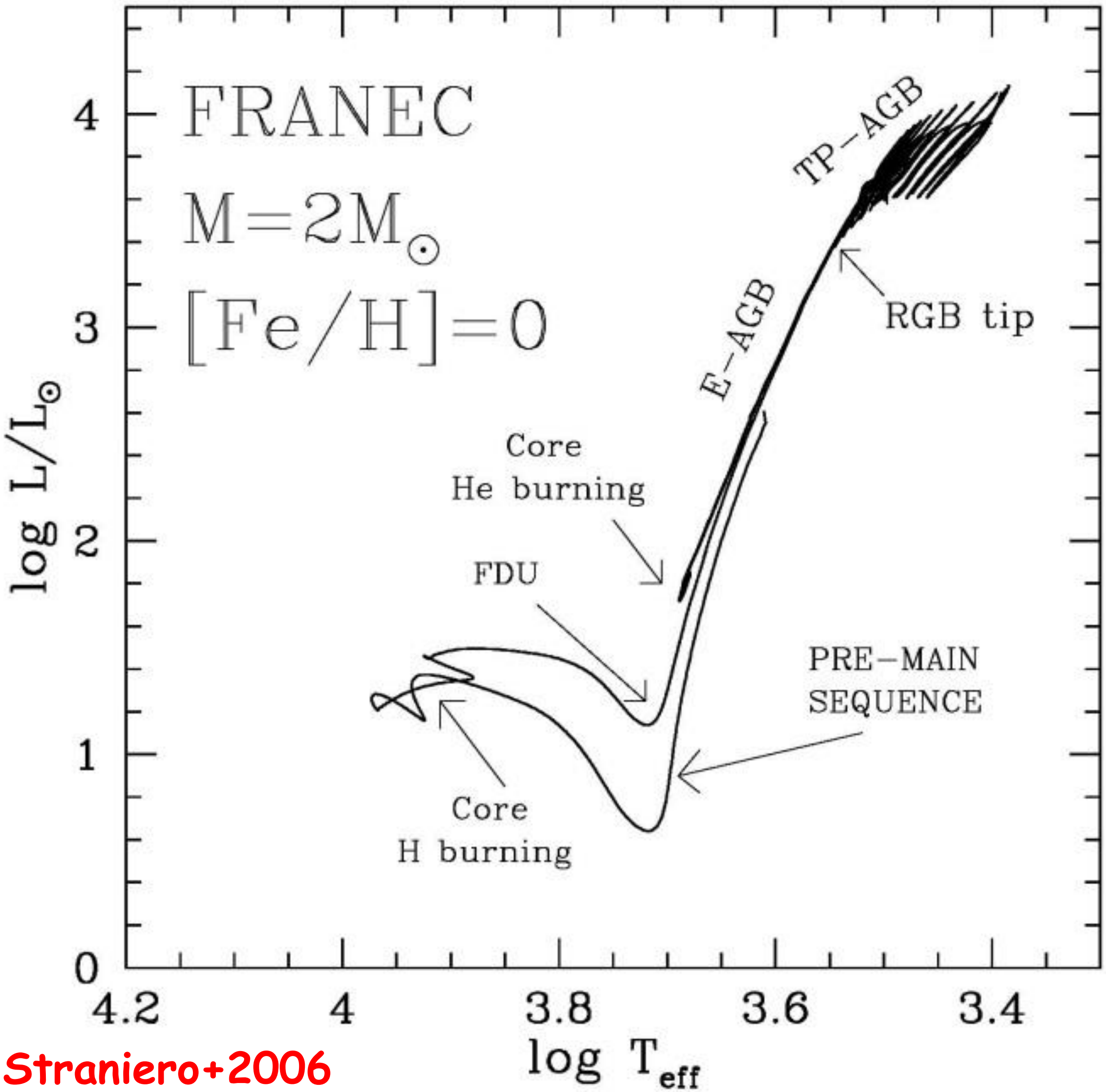
SC+ 2011,2015

fruity.oa-abruzzo.inaf.it

$-2.85 \leq [Fe/H] \leq +0.15$

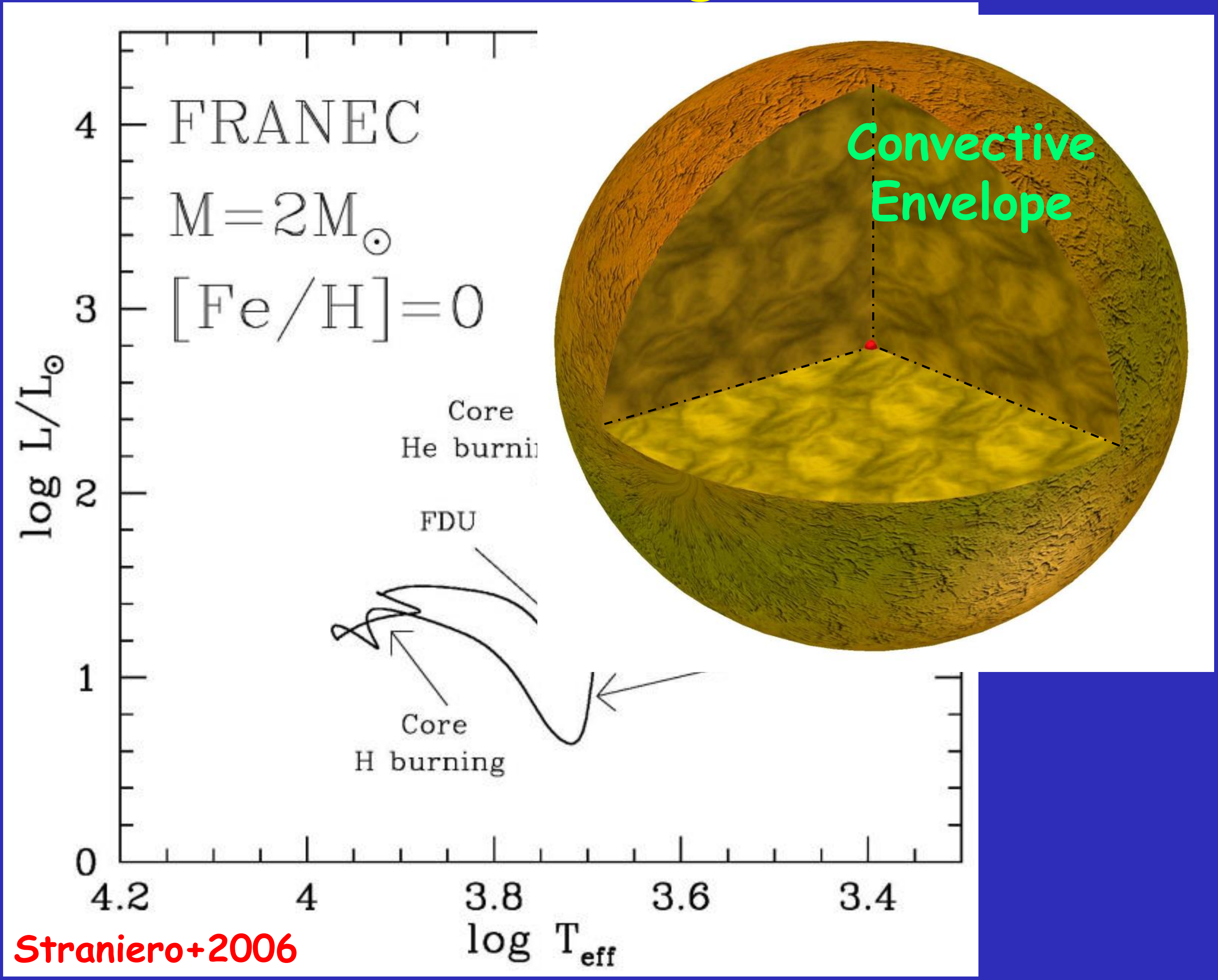
$1.3 \leq M/M_{sun} \leq 6.0$

Theoretical HR diagram



Straniero+2006

Theoretical HR diagram



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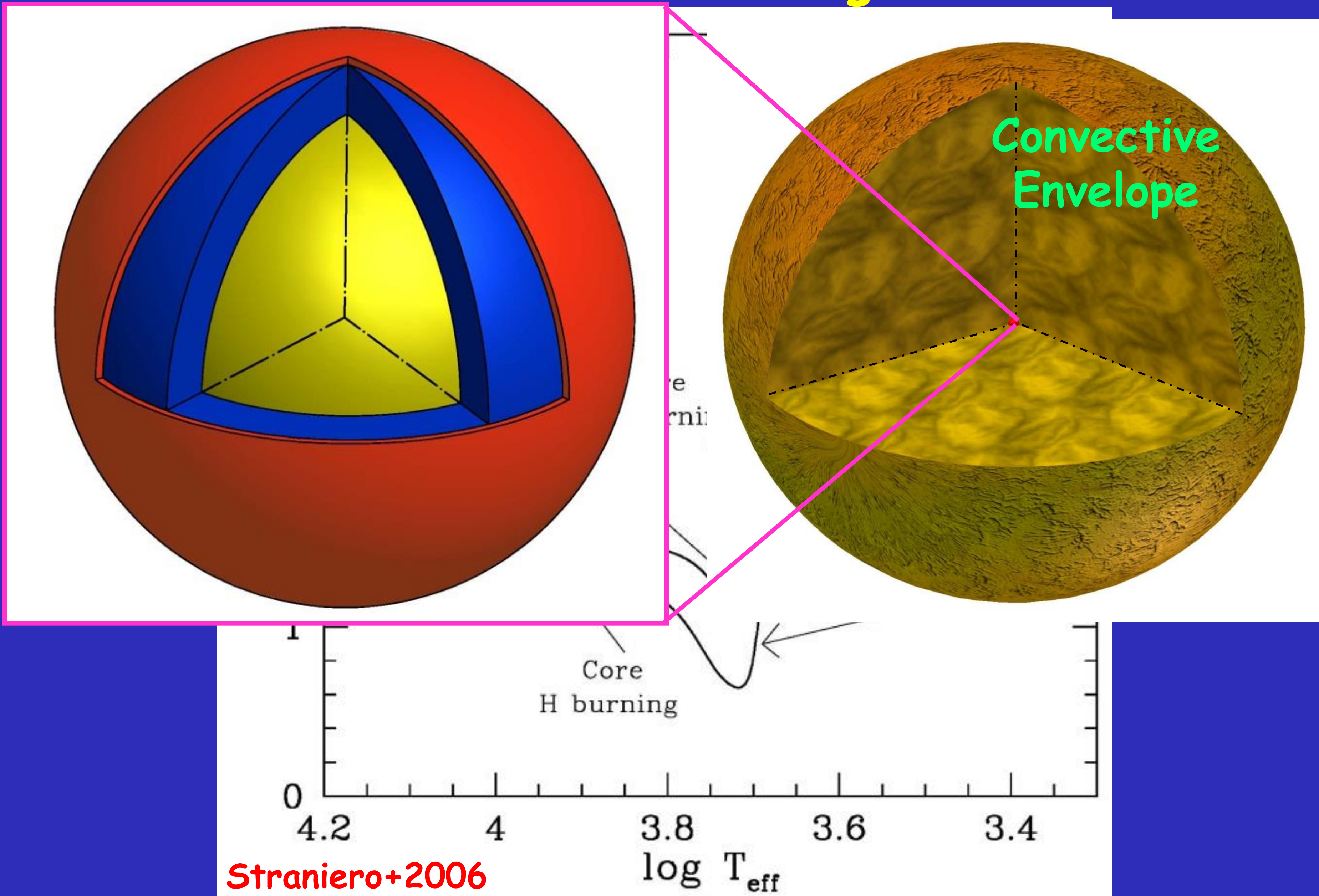

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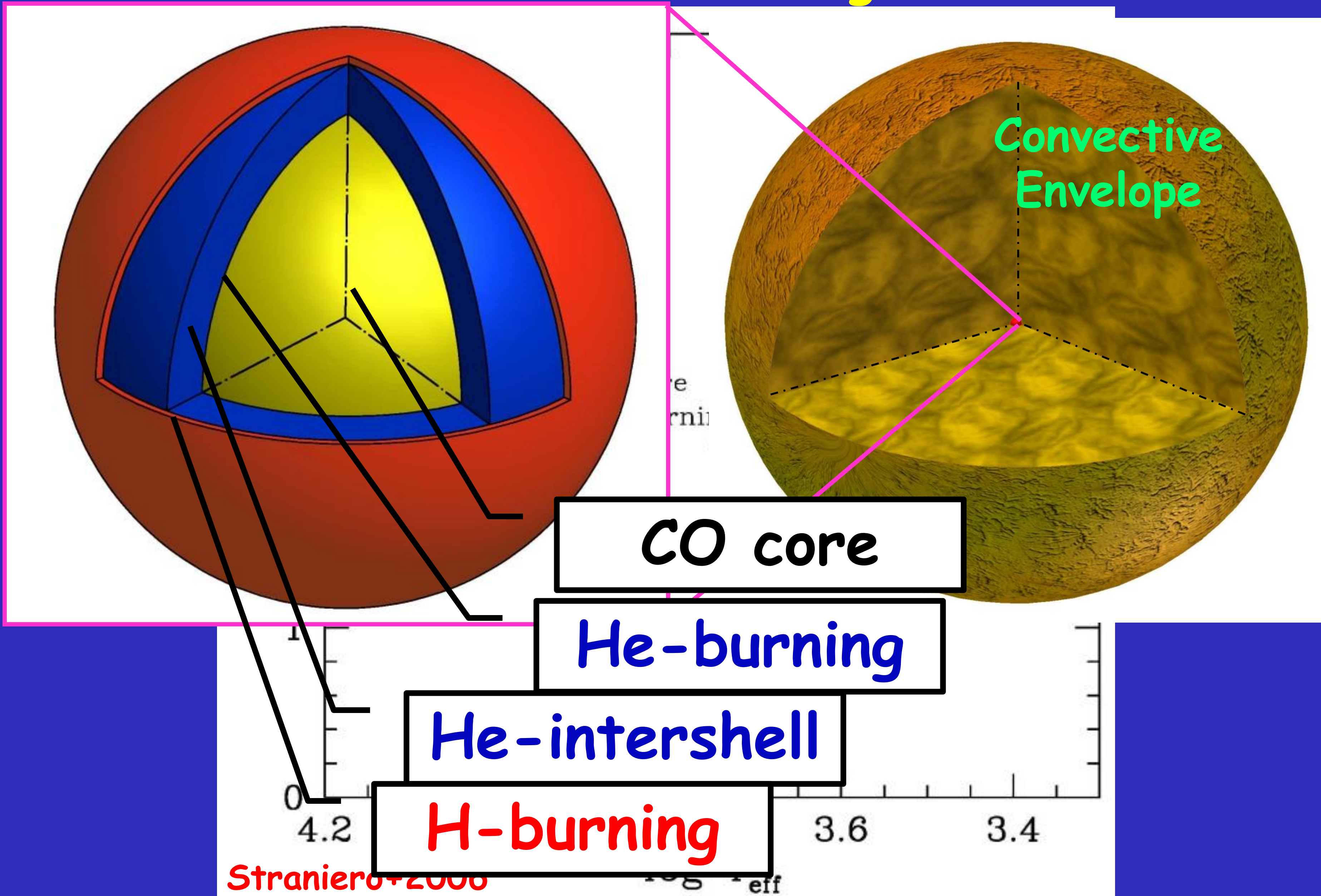
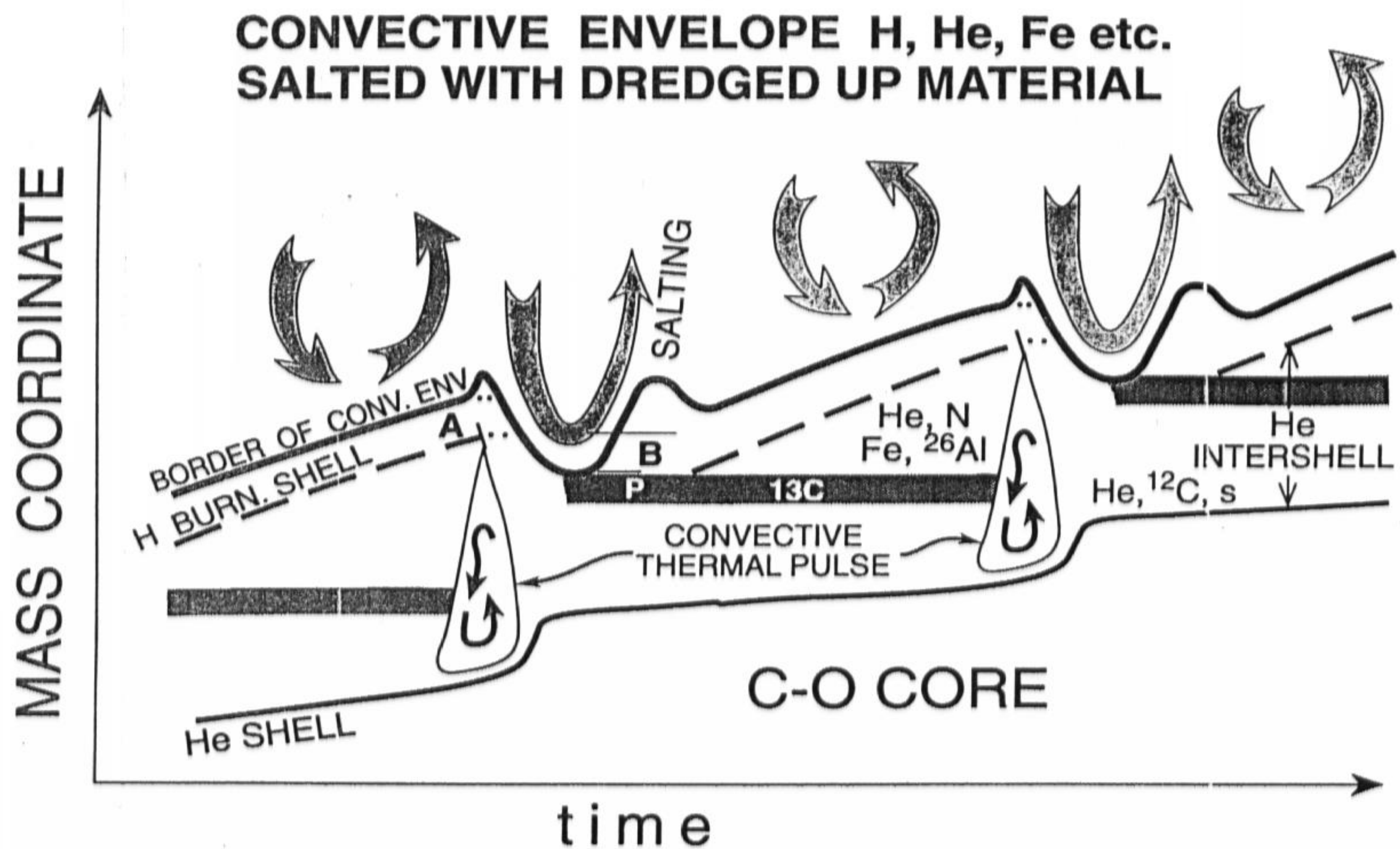
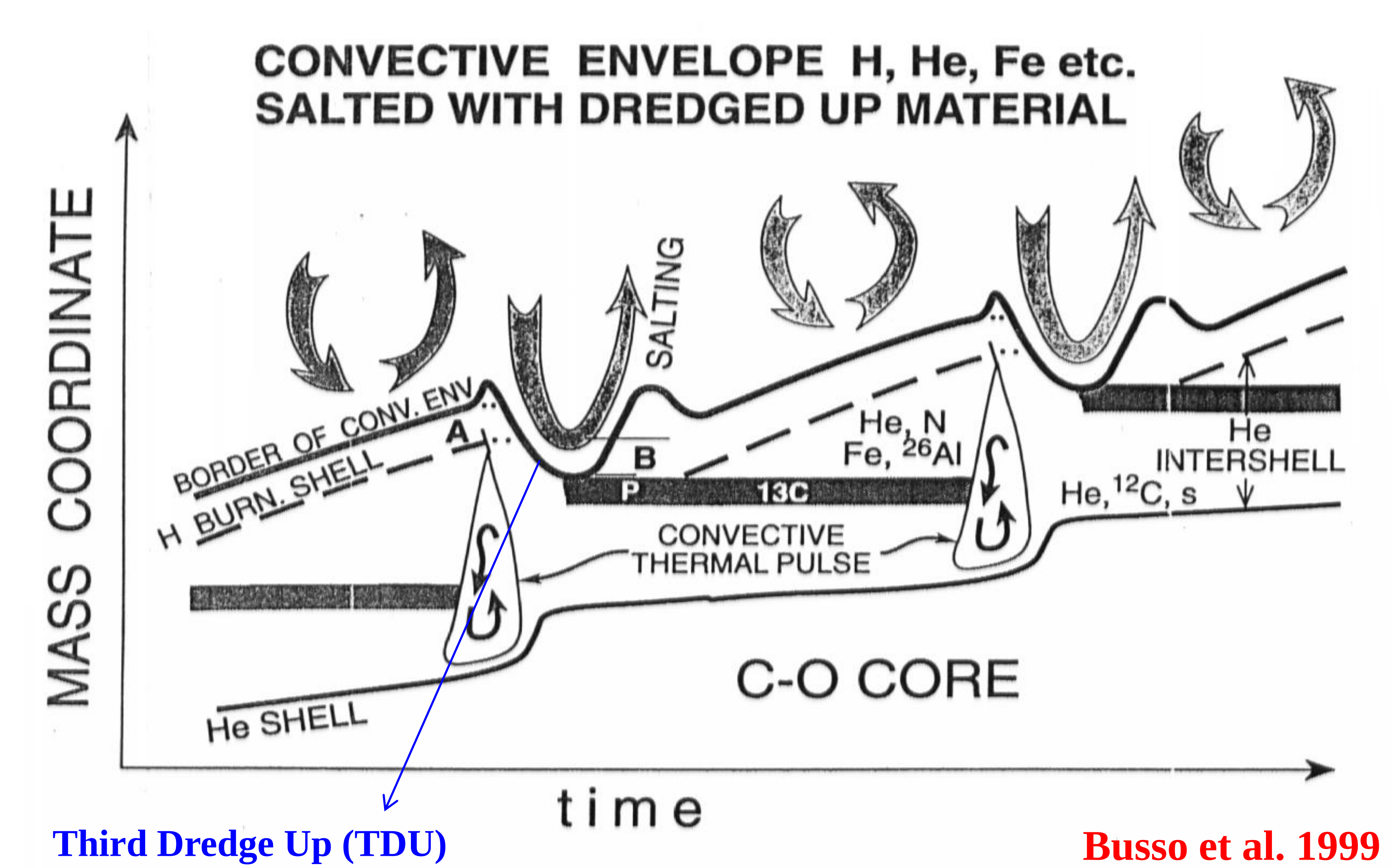


The s-process in AGB stars



Busso et al. 1999

The s-process in AGB stars

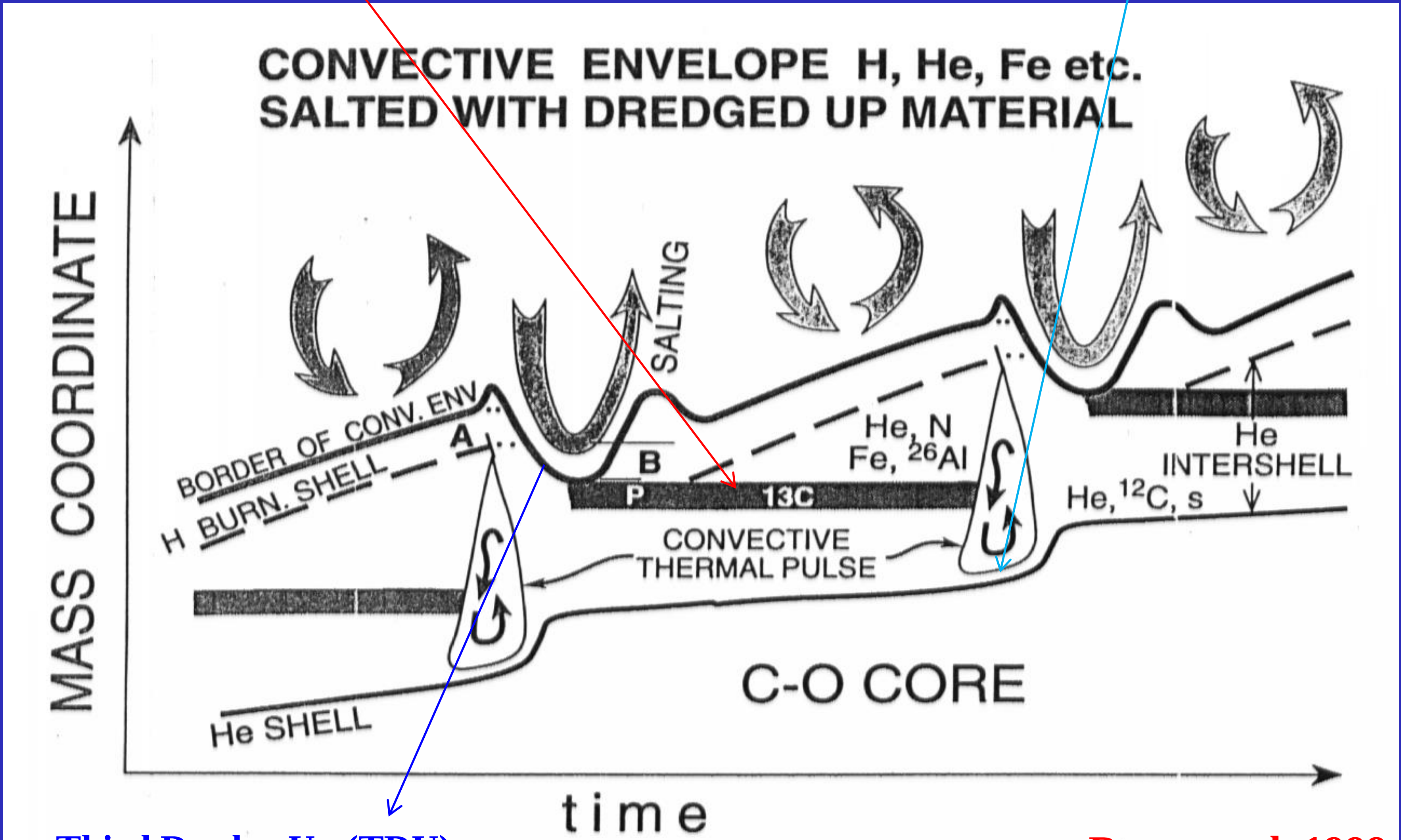


Busso et al. 1999

The s-process in AGB stars

$^{13}C(\alpha,n)^{16}O$ reaction

$^{22}Ne(\alpha,n)^{25}Mg$ reaction



Third Dredge Up (TDU)

Busso et al. 1999

The ^{13}C pocket in stellar evolutionary models

- ✓ **Opacity induced overshoot (SC+…)**
- ✓ **Convective Boundary Mixing + Gravity Waves (Battino+ 2017)**

The ^{13}C pockets in post-process calculations:

- ✓ **n-zones profile (Gallino+…)**
- ✓ **Exponential hydrogen profile (Lugaro+…)**
- ✓ **Magnetic-induced mixing (Trippella+ 2014)**

How does the ^{13}C pocket change?

- ✓ **Rotation-induced mixing (Herwig+ 2003; Siess+ 2004; Piersanti+ 2013)**

Opacity induced overshoot: a ballistic approach

Let's assume that the deceleration is proportional to the square of the velocity, as it happens to a body moving in a sufficiently dense fluid:

Viscosity

$$\ddot{r} \propto -kv^{-2}$$

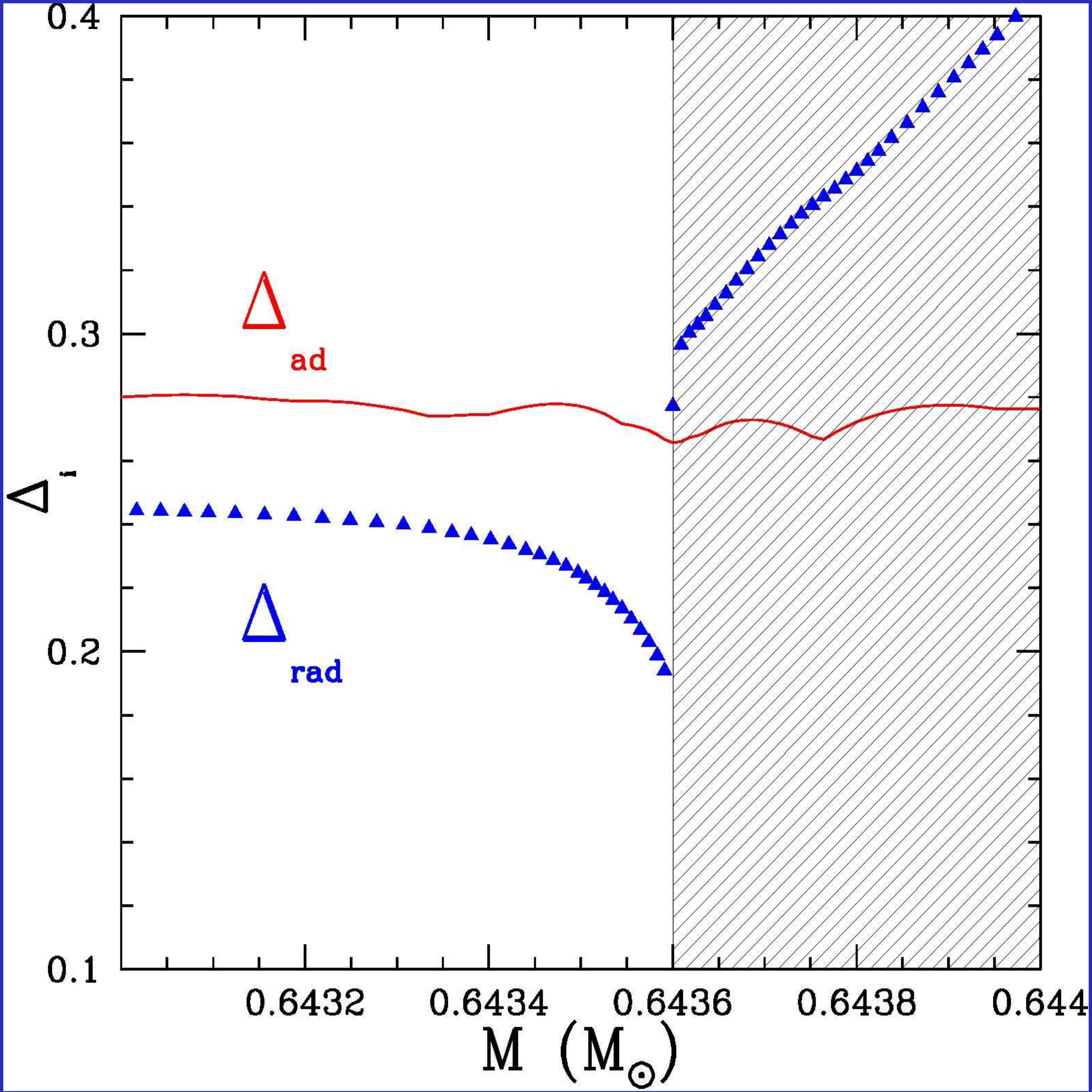
$$v = v_0 \mathbf{exp[-k(r-r_0)]}$$

$$\mathbf{v = v_{bce} \cdot exp\,(-d/\beta\, H_p)}$$

- **V_{bce} is the convective velocity at the inner border of the convective envelope (*CE*)**
- **d is the distance from the *CE***
- **H_p is the scale pressure height**
- **β = 0.1**

Opacity induced overshoot

The formation of the ^{13}C pocket

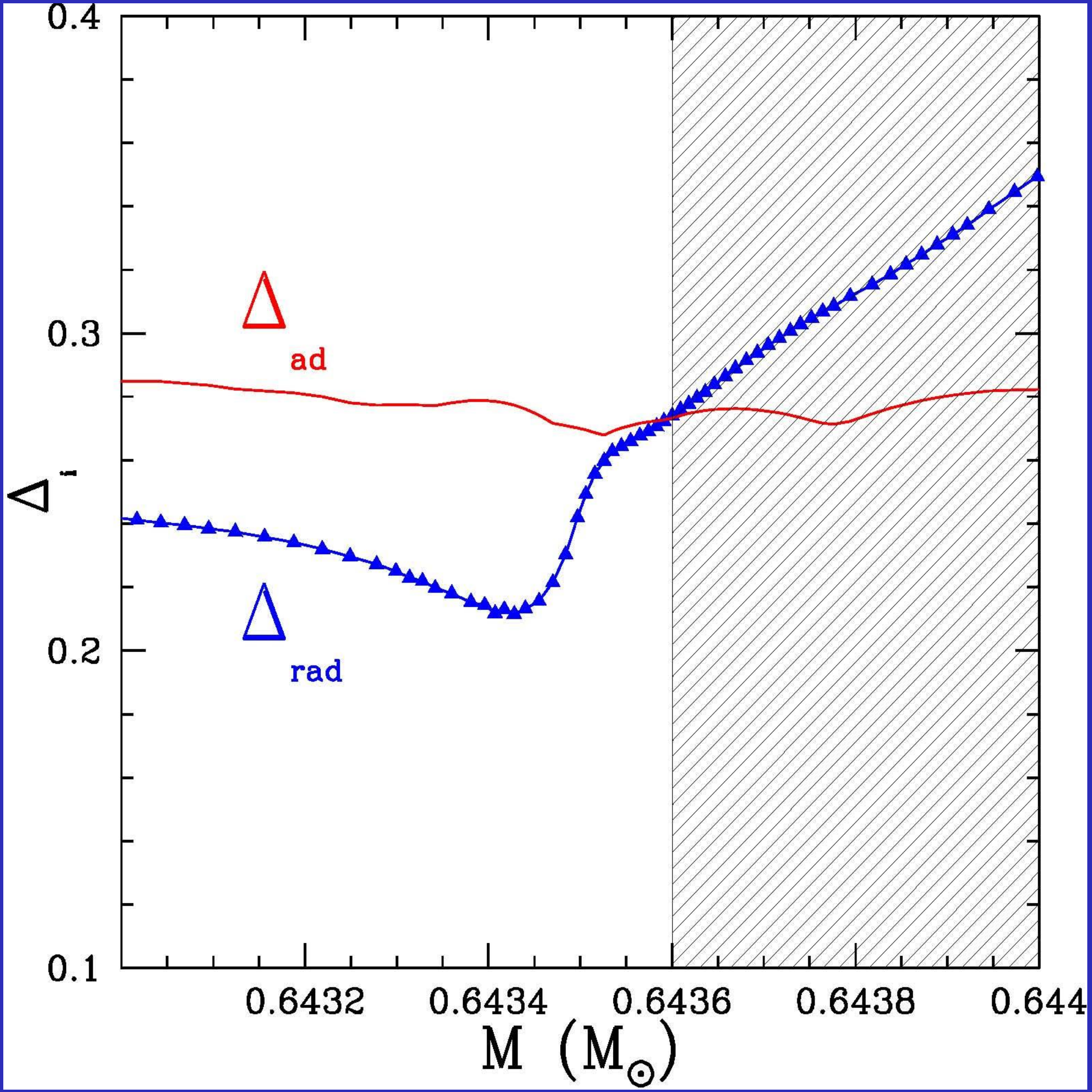


v=0 beyond SC

SC+2009

Opacity induced overshoot

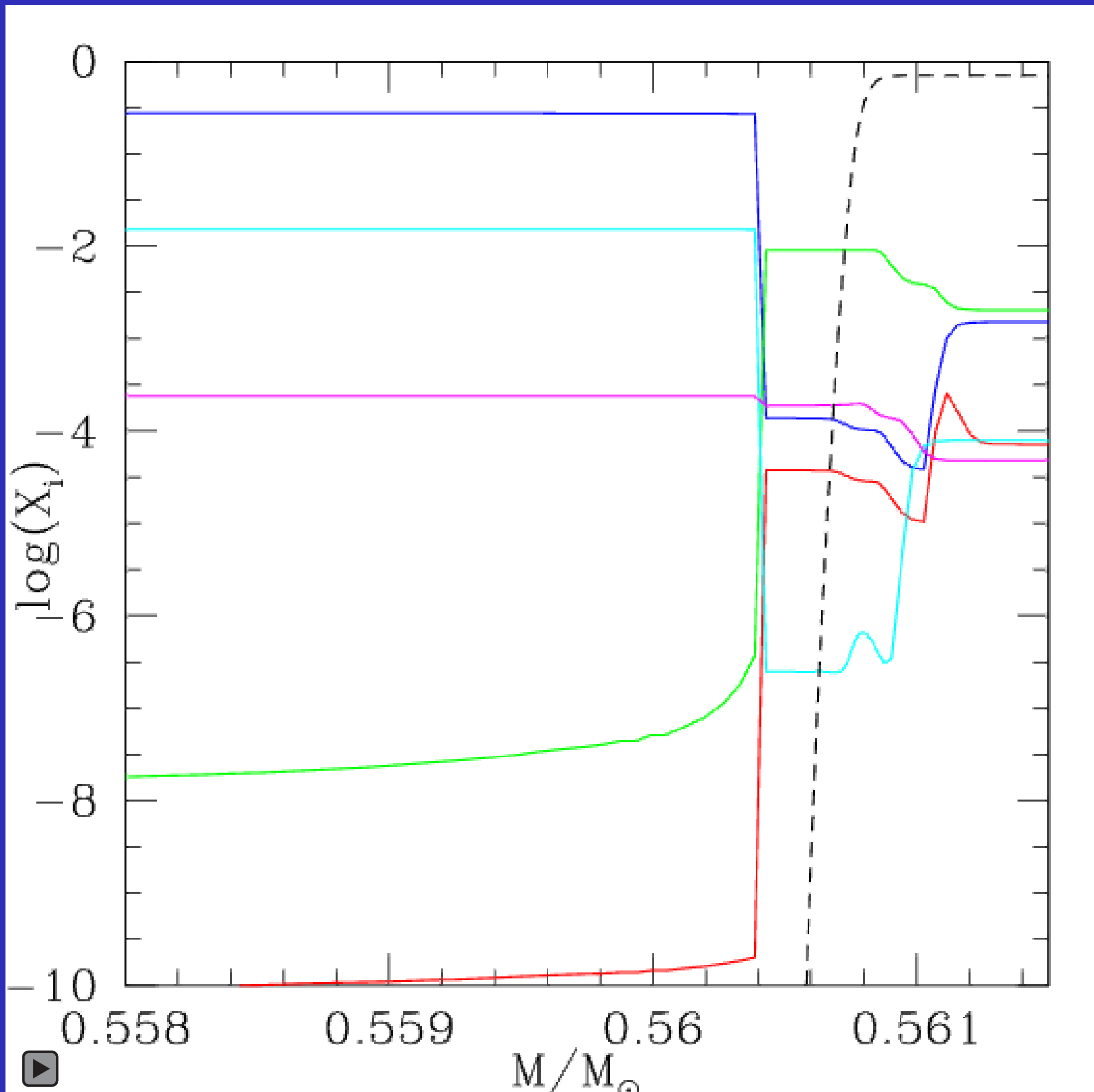
The formation of the ^{13}C pocket



$$v = v_{BCE}\, e^{-\frac{d}{\beta H_P}}$$

SC+2009

The formation of the ^{13}C pocket



^{12}C

^{13}C

^{14}N

^{22}Ne

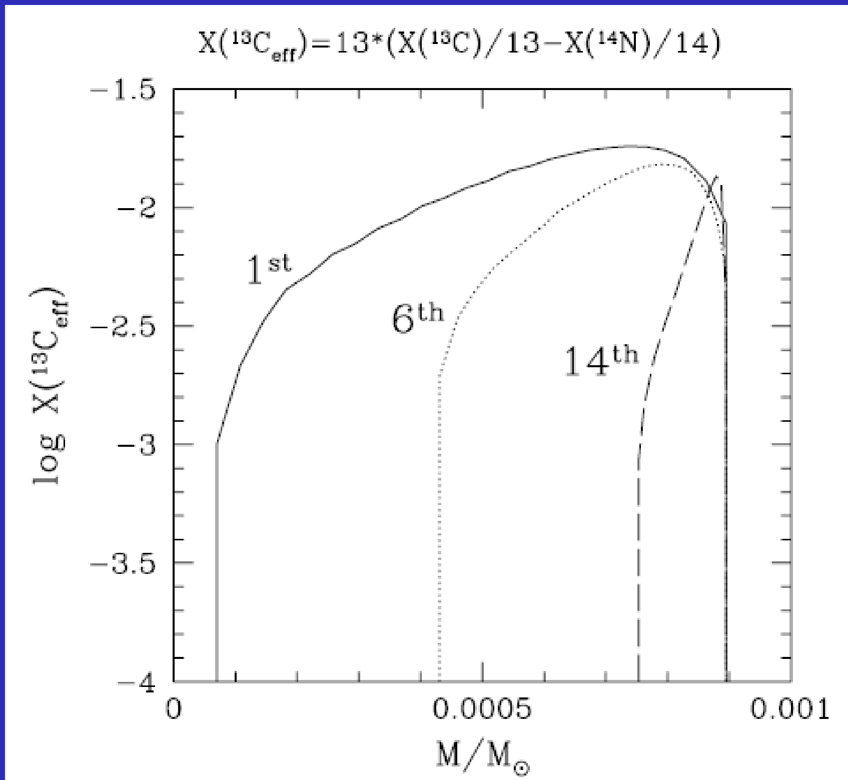
^{23}Na

H

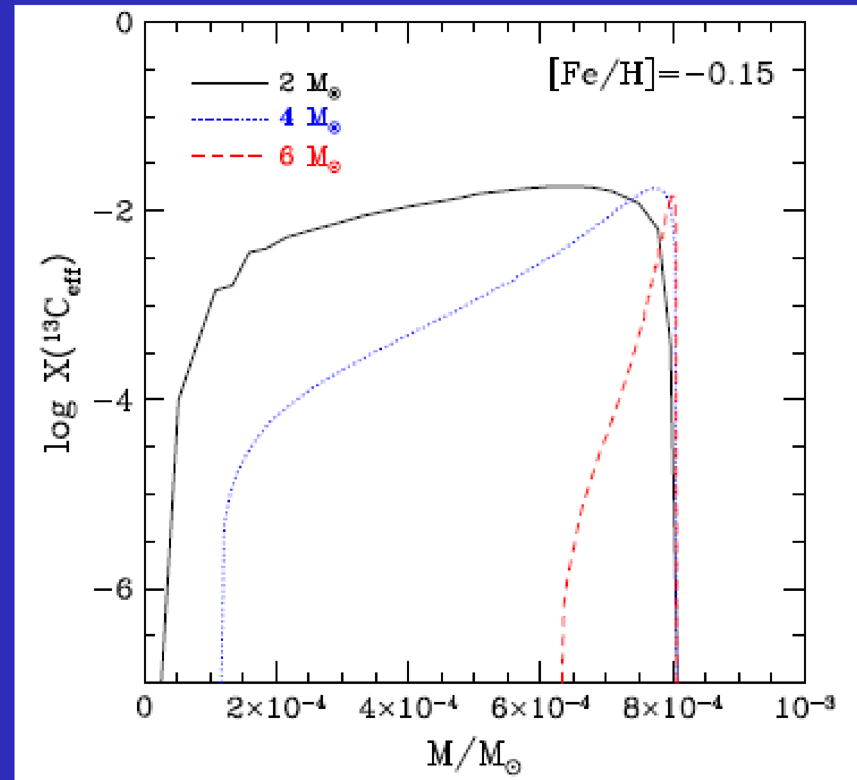
$M=2M_\odot$

$Z=Z_\odot$

Stellar model vs. post-process



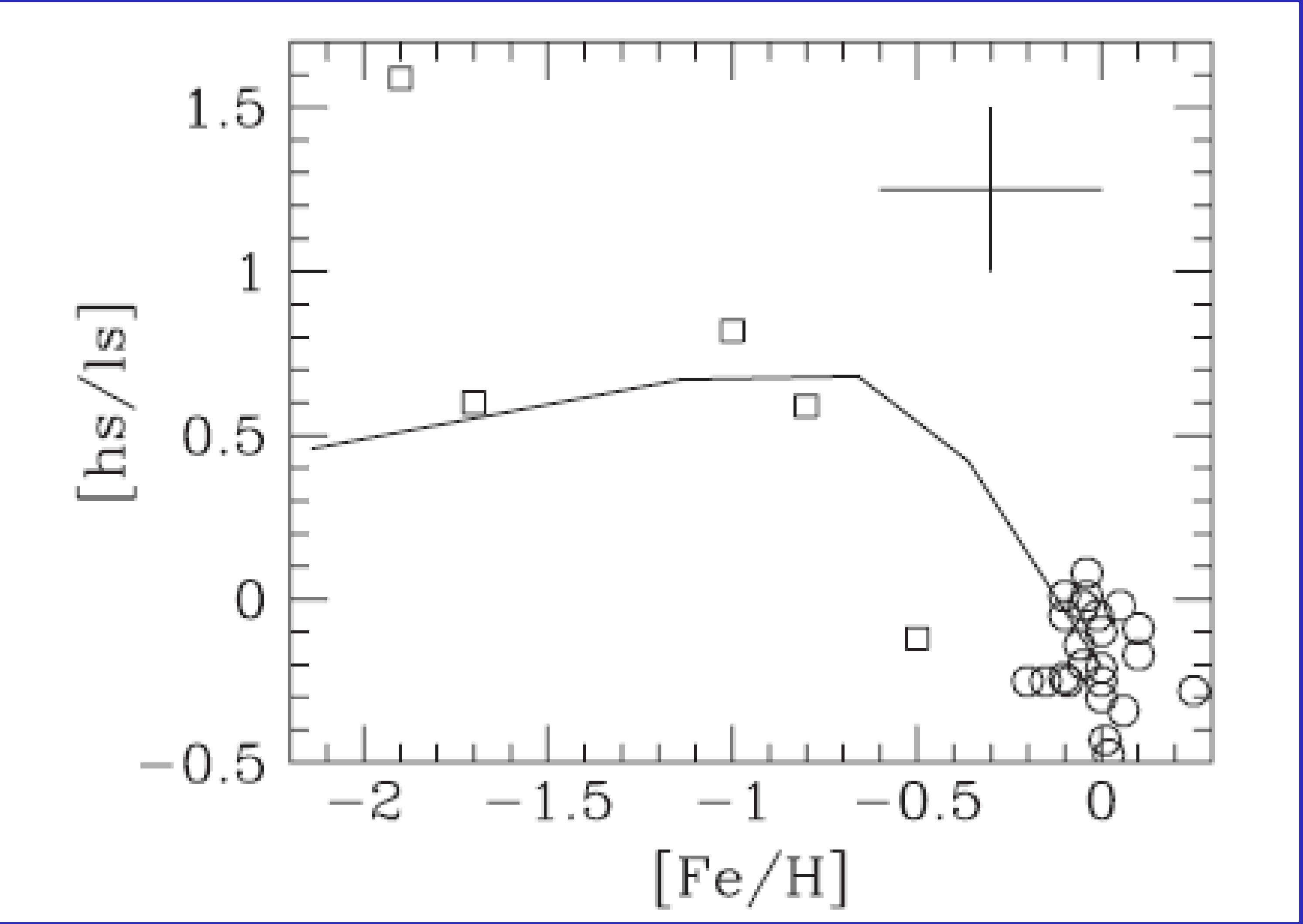
SC+2011



SC+2015

The pocket mass extension scales as the inverse of the core mass

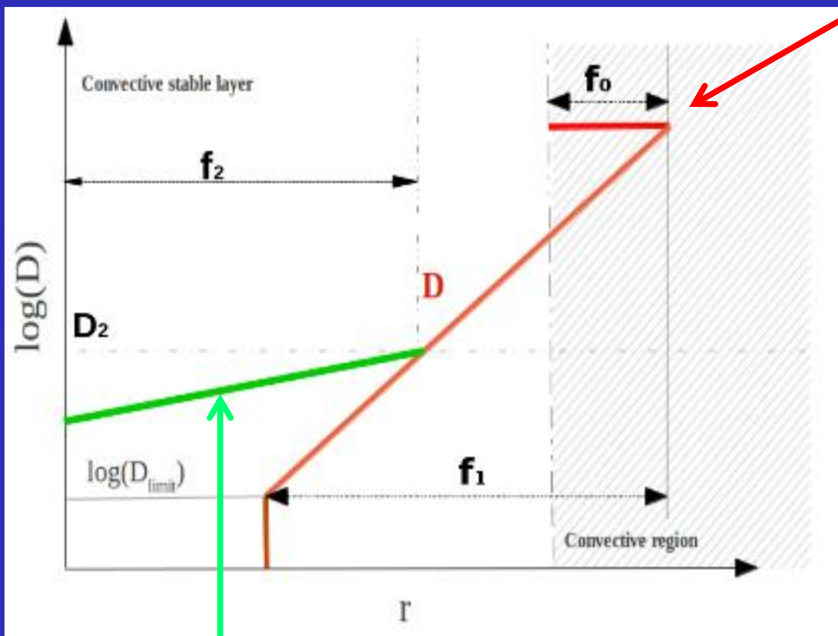
Comparison with observations



SC+2009

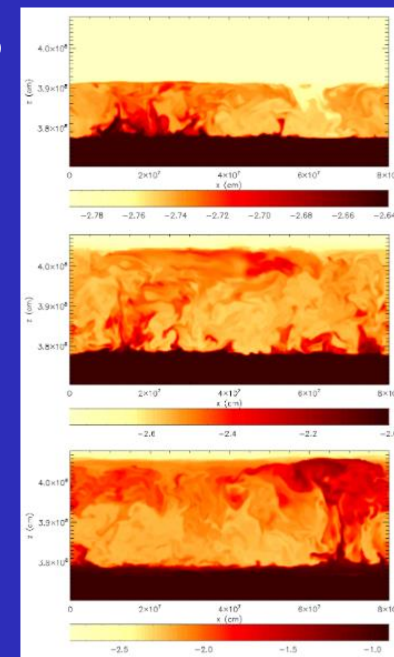
Convective Boundary Mixing + Gravity Waves

Battino+ 2016



Kelvin-Helmholtz (shear) instability

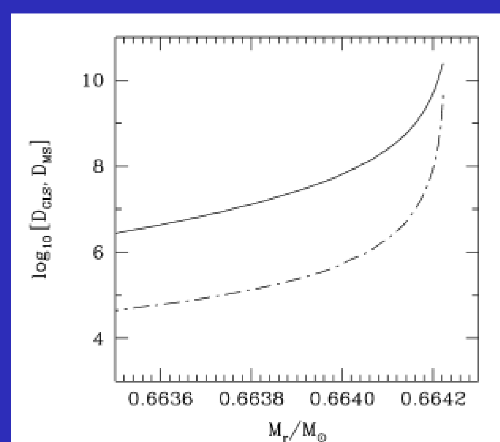
Casanova+ 2016



Depending on the velocity difference across the interface, K-H instability may induce mixing if:

$N^2/(dv/dr)^2 < 0.25$

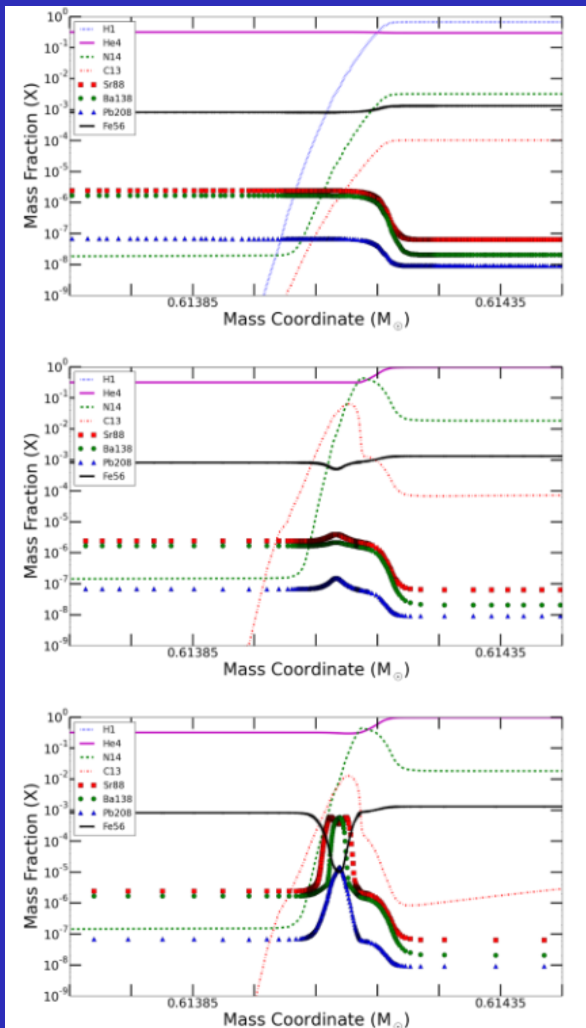
Gravity waves

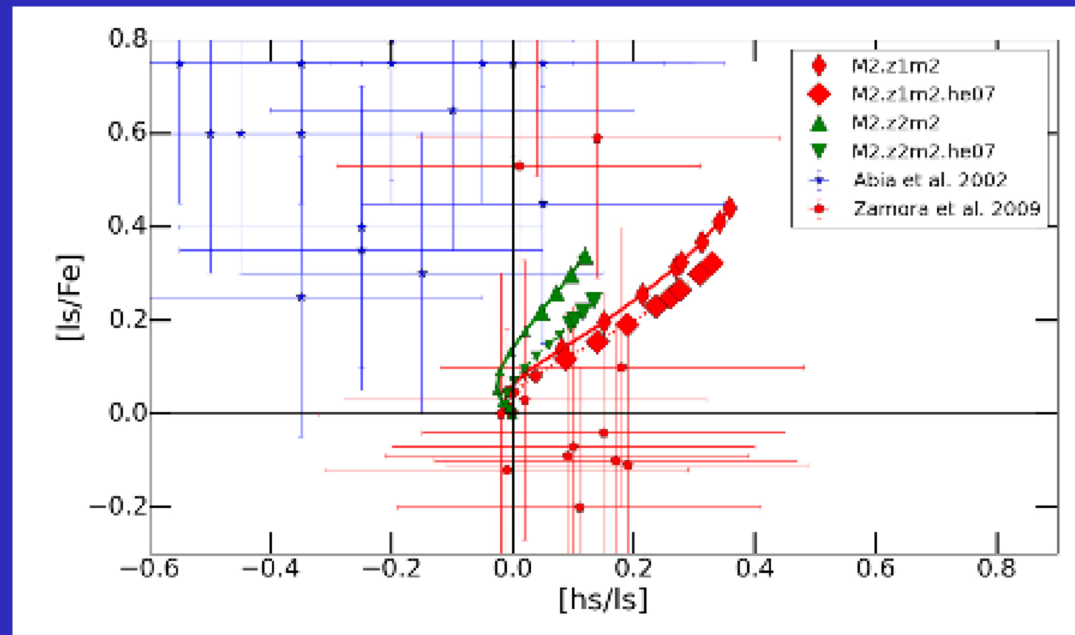


Denissenkov & Tout 2003

Comparison with observations

Battino+ 2016





In agreement with observations, but pockets are very small

Post-processes

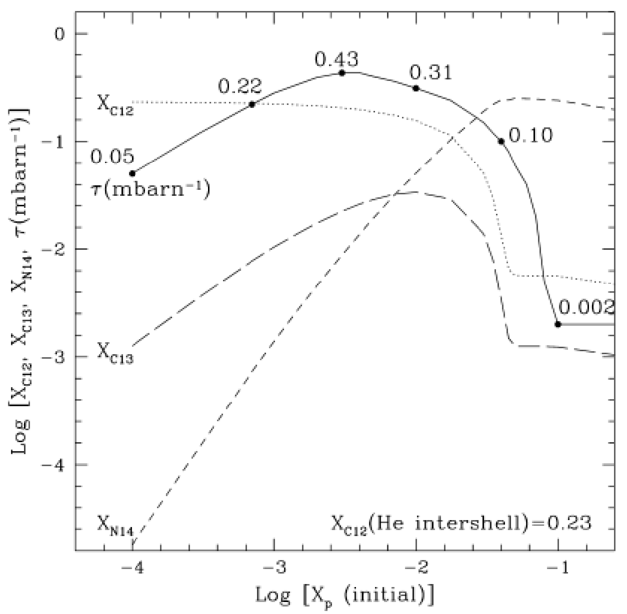


FIG. 4.—Resulting mass fractions of ^{12}C, ^{13}C, and ^{14}N as functions of the initial mass fraction of protons introduced below the H/He discontinuity during the simulations performed with the Monash nucleosynthesis code. The protons are introduced after the 10th TDU episode of the 3 $M_{\odot}$ star of solar metallicity computed with the MSSSP code. Also plotted is the corresponding neutron exposure at the end of the interpulse period after all the ^{13}C has burnt.

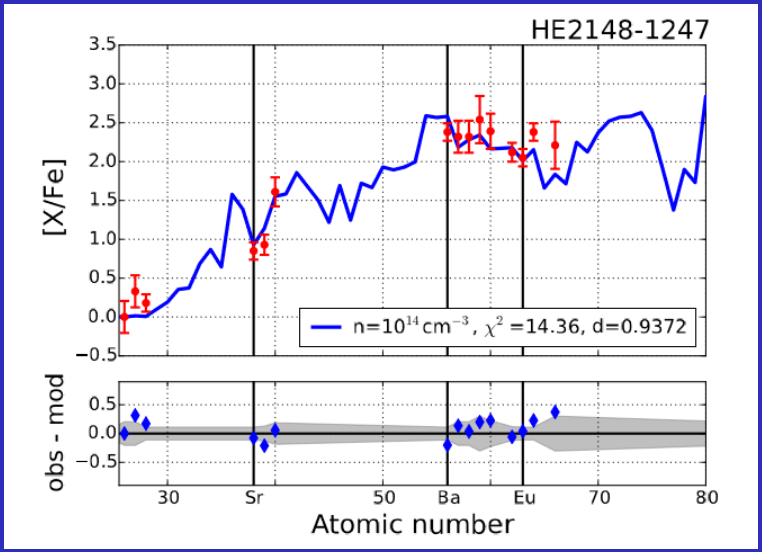
Lugaro+ 2003

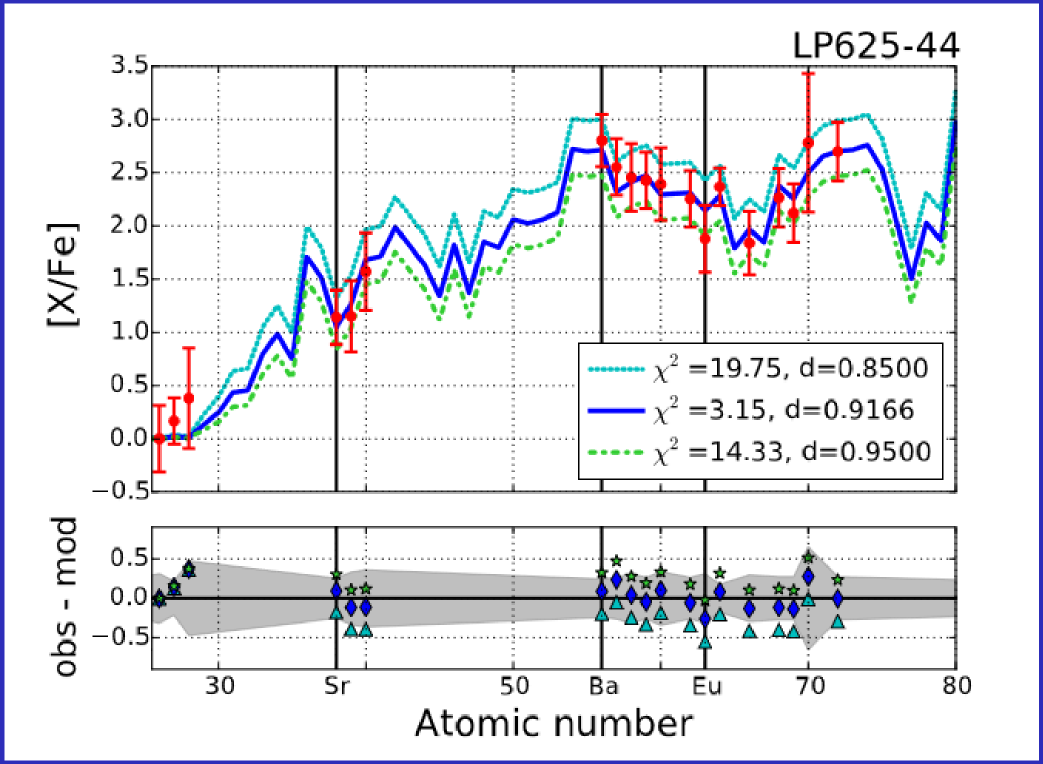
Artificially introduced an exponentially decaying profile of protons in Monash models (Karakas+…)

Similar to SC+2009, but they do not feed the change of physics quantities along the AGB.

Post-processes

For CEMP stars analysis (i-process): Hempel+2016





See also Abate & Stancliffe 2016

Post-processes

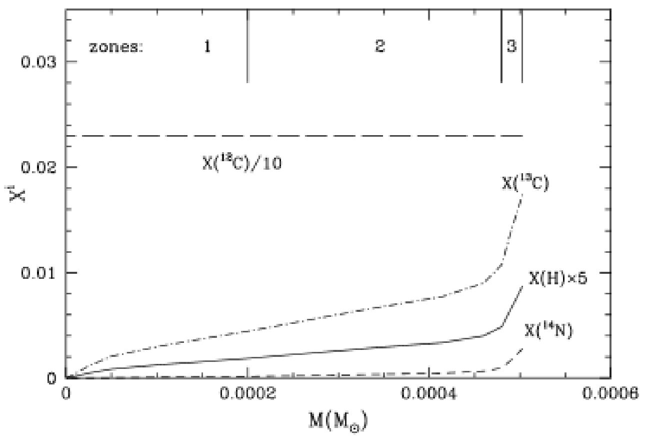
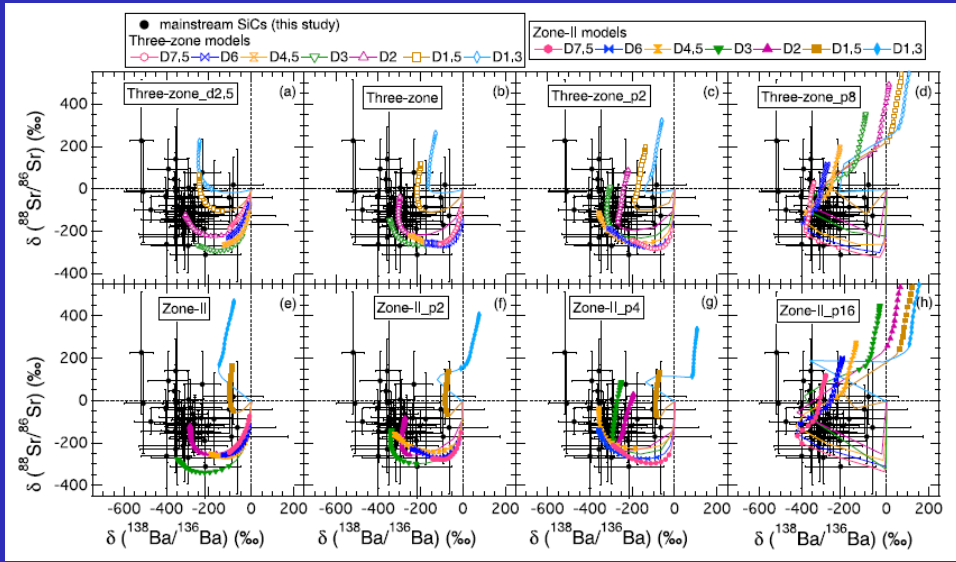


FIG. 1.—The adopted distribution in the mass of hydrogen introduced in the ^{12}C-rich intershell, and of the resulting ^{13}C and ^{14}N profiles at H-shell reignition, as discussed in the text.

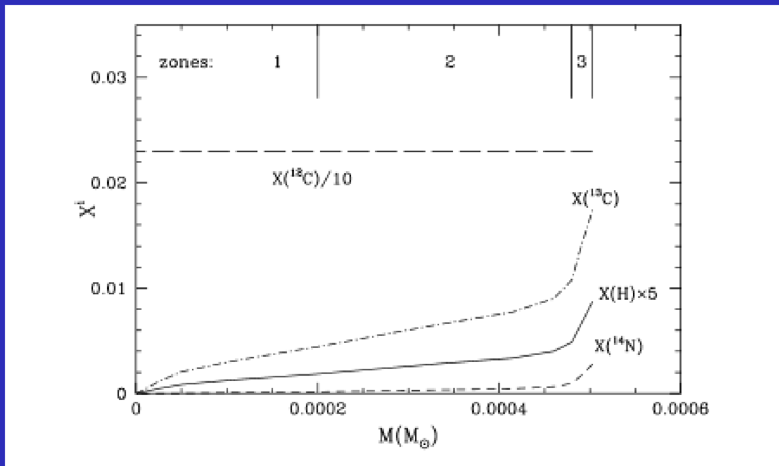
Gallino+ 1998



Liu+ 2015

Strong points: versatility and speed

Torino Post-process



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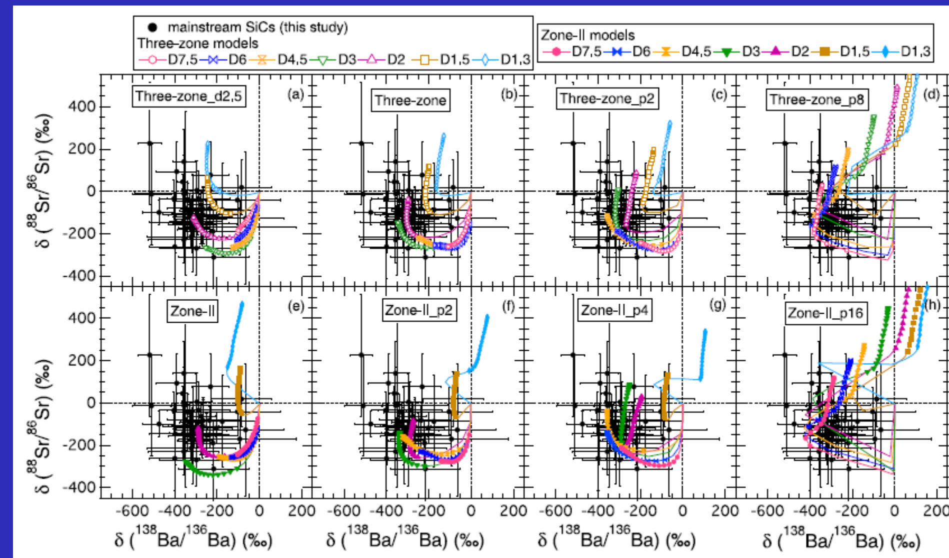
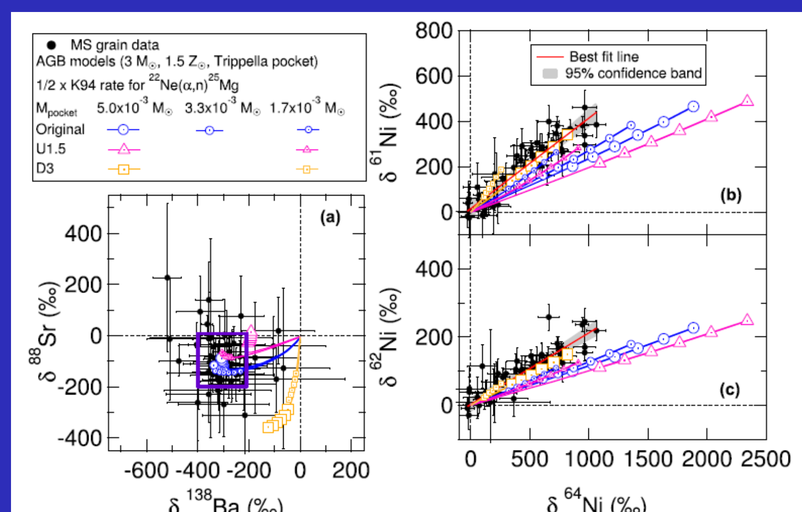


Liu+ 2015

However, ...



Liu+ 2018

Magnetic induced mixing

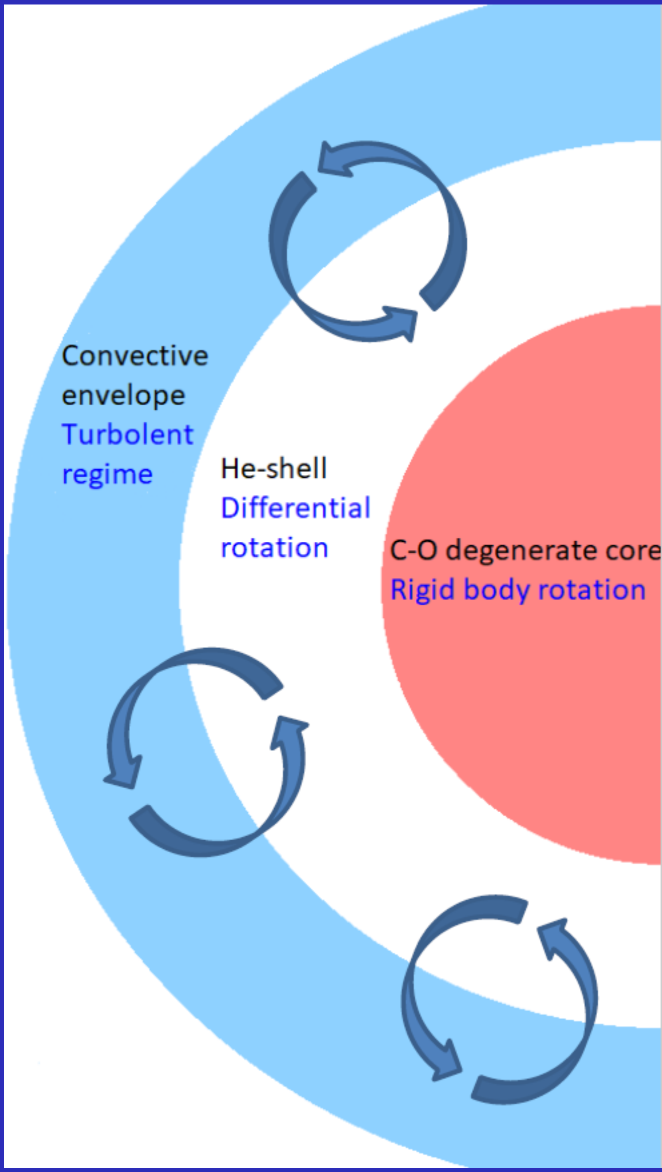
Nucci & Busso 2014

$$v_r = \frac{dw(t)}{dt} r^{-(k+1)}$$

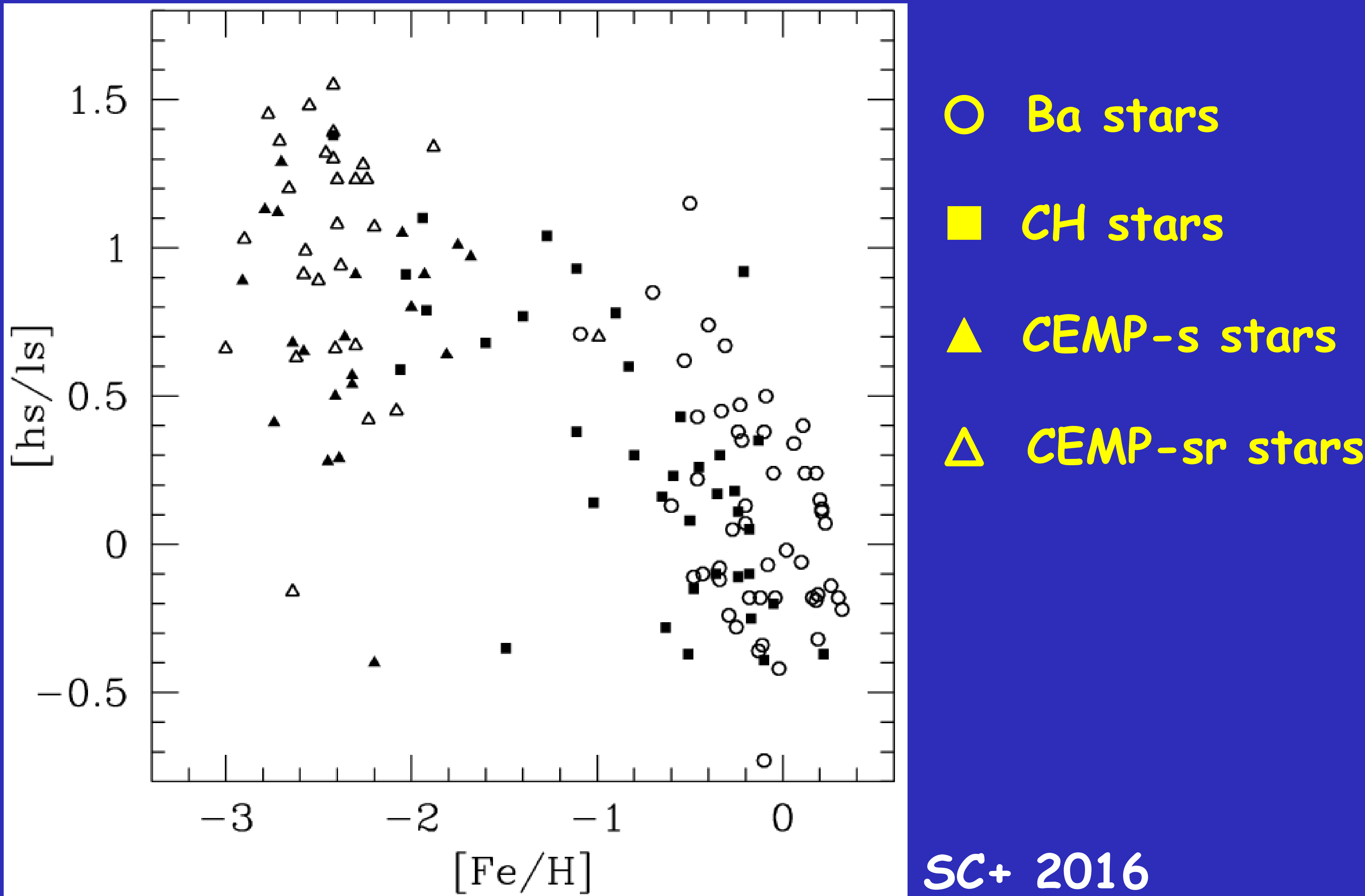
$$B_\varphi = \Phi(\xi) r^{k+1}, \quad [\xi = -(k+2)w(t) + r^{k+2}].$$

This morning: talk by D. Vescovi

$$v_{down}(r) = v(r_p)\frac{\rho(r_p)}{\rho(r_{h+1})}\left(\frac{r_h}{r_p}\right)^{k+2}\left(\frac{r_h}{r}\right)^{k+1}$$



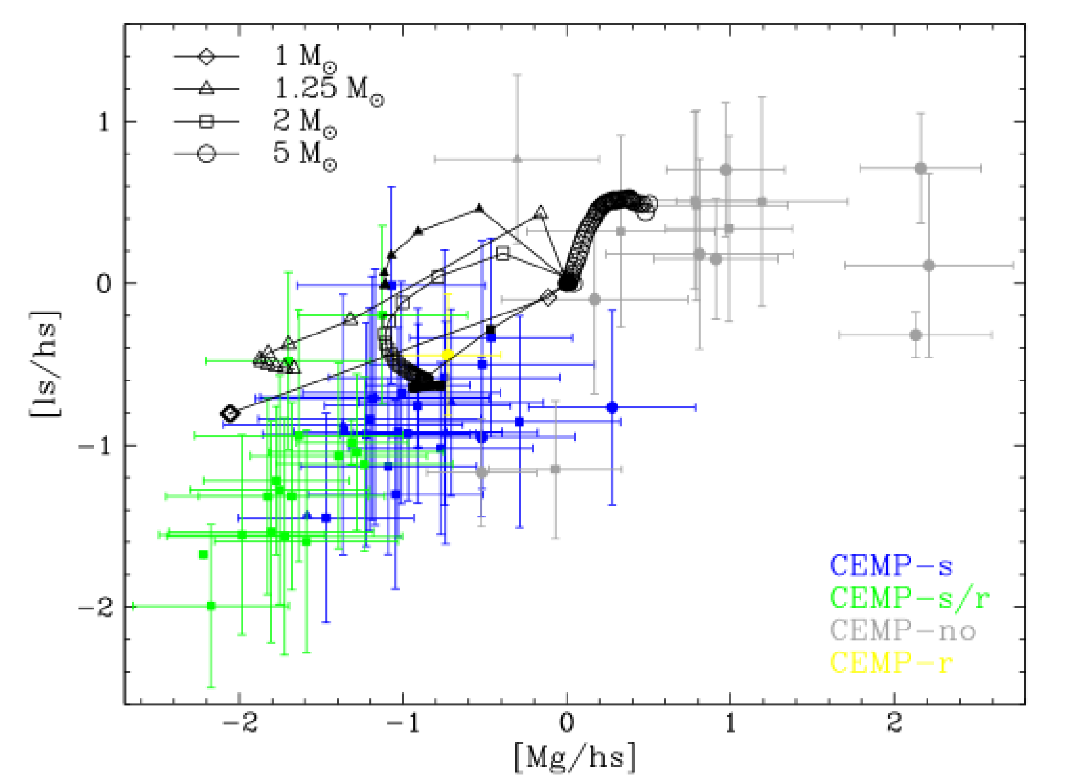
The s-process at low metallicities

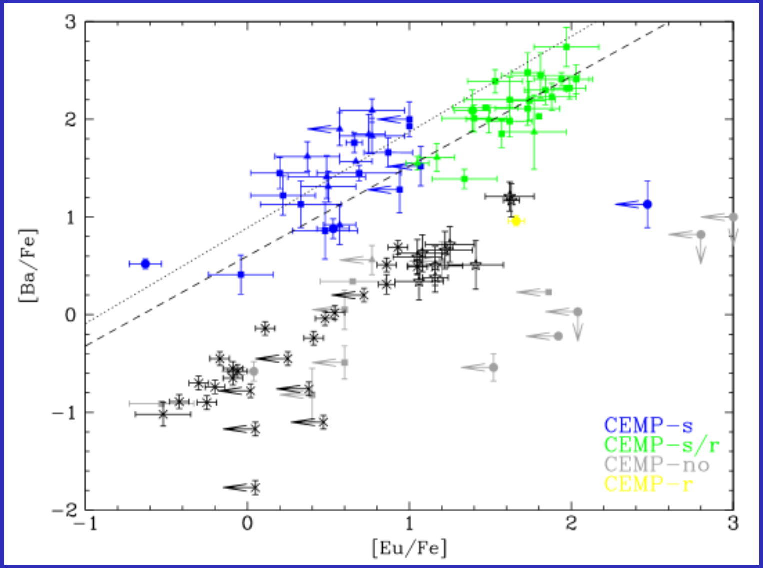


SC+ 2016

CEMP stars: nucleosynthesis features

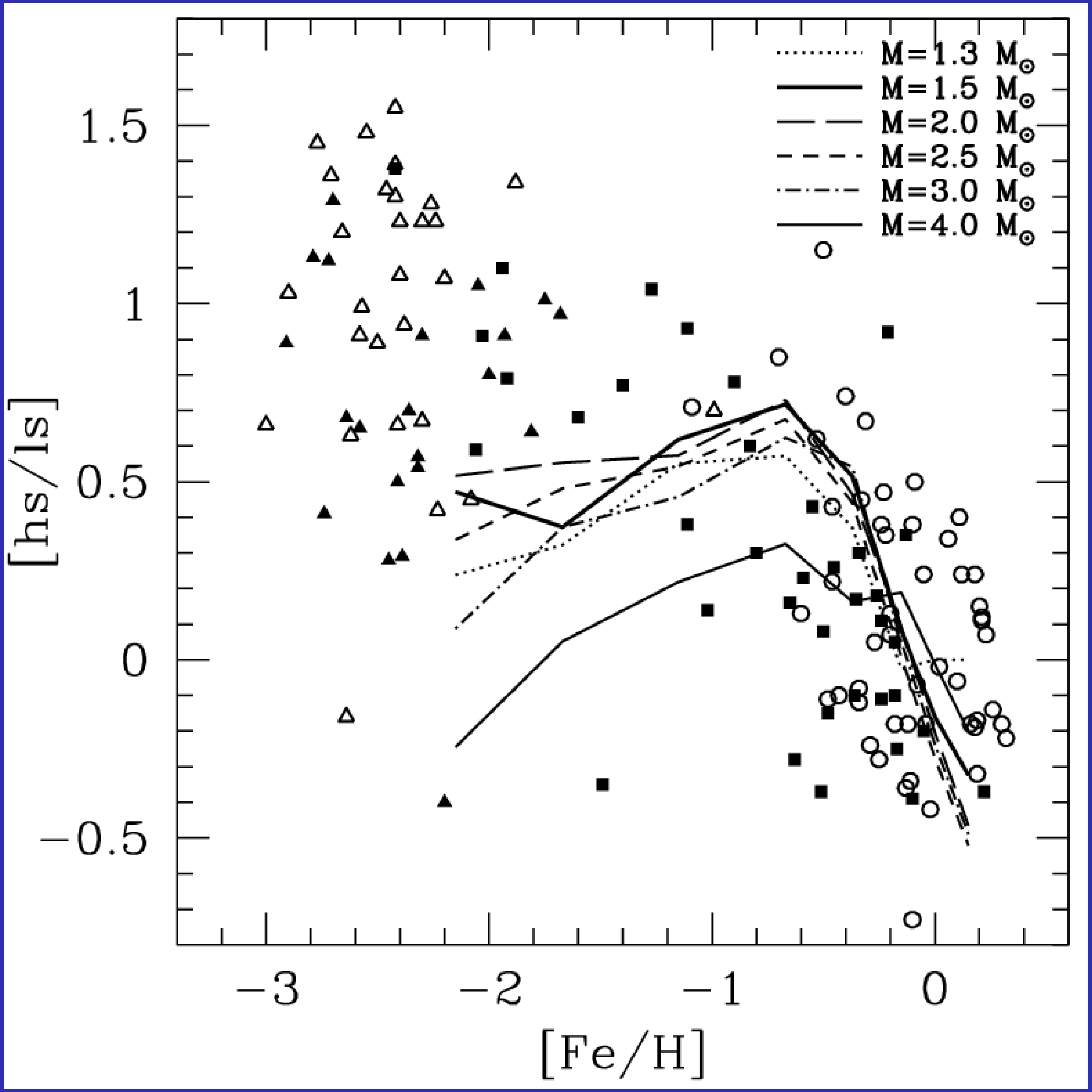
CEMP: Carbon Enhanced Metal poor stars
CEMP-s: CEMP stars enriched in s-process only
CEMP-r: CEMP stars enriched in r-process only
CEMP-s/r: CEMP stars enriched in both s- and r-processes





Lugaro+ 2012

Problems at low metallicities: the effect of initial mass



○ Ba stars

■ CH stars

▲ CEMP-s stars

△ CEMP-sr stars

SC+ 2016

The effects of rotation: I

Lifting + cylindrical simmetry

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

$$\frac{dL}{dm} = \varepsilon_{nuc} - \varepsilon_{\nu} + \varepsilon_g$$

$$\frac{dP}{dm} = -\frac{Gm_r}{4\pi r^4} \cdot f_P$$

$$\frac{dlnT}{dlnP} = \min\left[\nabla_{ad}, \nabla_{rad} \cdot \frac{f_T}{f_P}\right]$$

$$f_P = \frac{4\pi r_\psi^4}{m_\psi S_\psi} \langle g^{-1} \rangle^{-1}$$

$$f_T = \left(\frac{4\pi r_\psi^2}{S_\psi}\right)^2 \left(\langle g \rangle \langle g^{-1} \rangle\right)^{-1}$$

The effects of rotation: II

Transport of angular momentum & mixing

$$\frac{\partial \omega}{\partial t} = \frac{1}{i}\frac{\partial}{\partial m}\left[\left(4\pi r^2 \rho\right)^2 i D_J \left(\frac{\partial \omega}{\partial m}\right)\right]$$

$$D_J = D_{conv} + f_\omega (D_{ES} + D_{GSF} + D_{SS} + D_{DS} + D_{SH})$$

$$\frac{\partial X_k}{\partial t} = \frac{\partial}{\partial m}\left[\left(4\pi r^2 \rho\right)^2 i D_C \left(\frac{\partial X_k}{\partial m}\right)\right]$$

$$D_J = D_{conv} + f_\omega f_c (D_{ES} + D_{GSF} + D_{SS} + D_{DS} + D_{SH})$$

The ES circulation velocity

$$v_{ES} = \frac{\nabla_{ad}}{\delta(\nabla_{ad} - \nabla_{rad})} \frac{\omega^2 r^3 L}{(Gm)^2} \left[\frac{2\varepsilon r^2}{L} - \frac{2r^2}{m} - \frac{3}{4\pi\rho r} \right]$$

$$v_{ES} \sim -\frac{\nabla_{ad}}{\delta(\nabla_{ad} - \nabla_{rad})} \frac{\omega^2 r^3 L}{(Gm)^2} \frac{3}{4\pi\rho r} = cost.\frac{j(r)^2}{\rho}$$

μ-gradient barrier

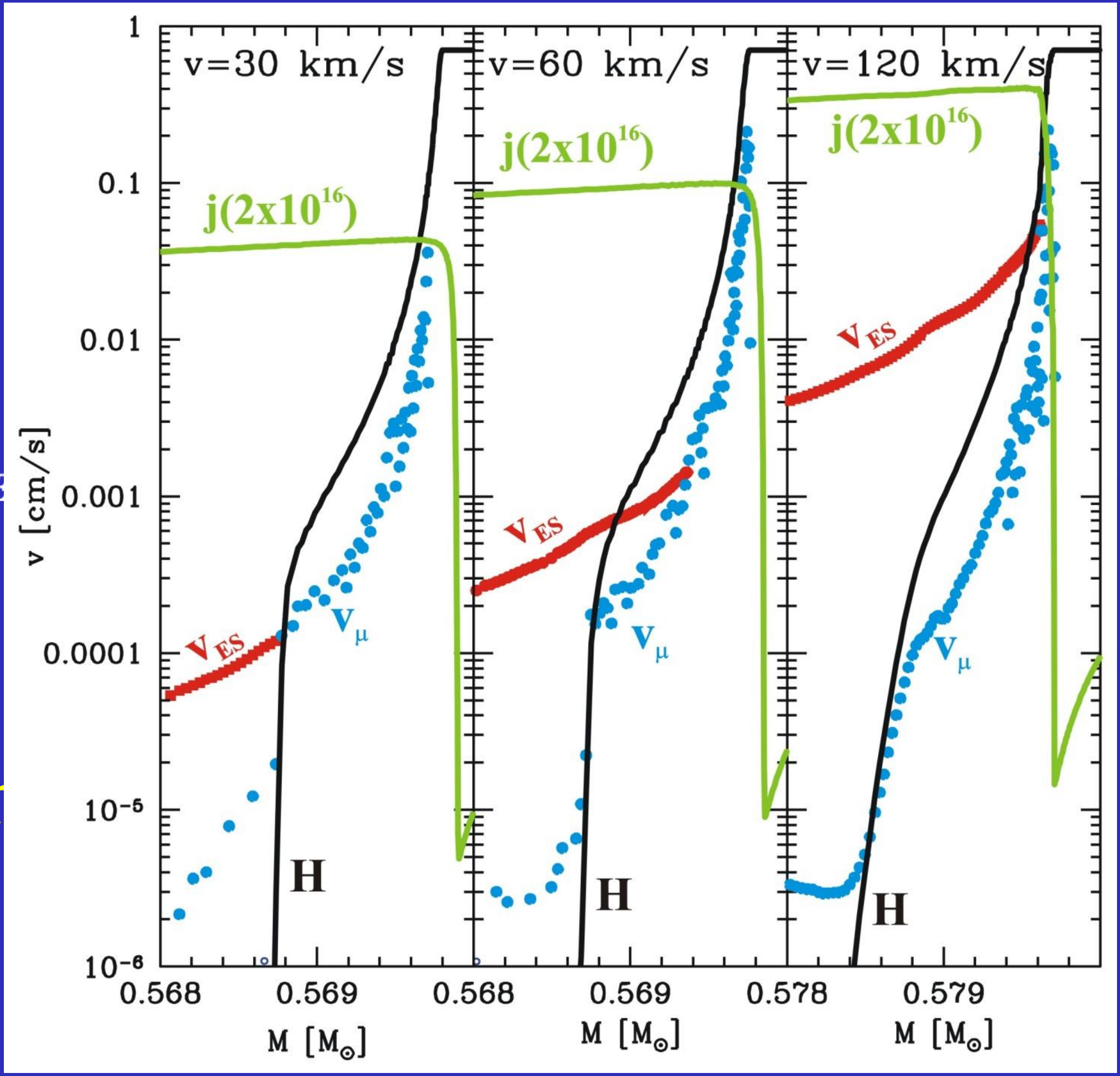
$$v_\mu = f_\mu \frac{H_P}{\tau_{\rm th}} \frac{\varphi \nabla_\mu}{\nabla - \nabla_{ad}}$$

The ES circulation velocity

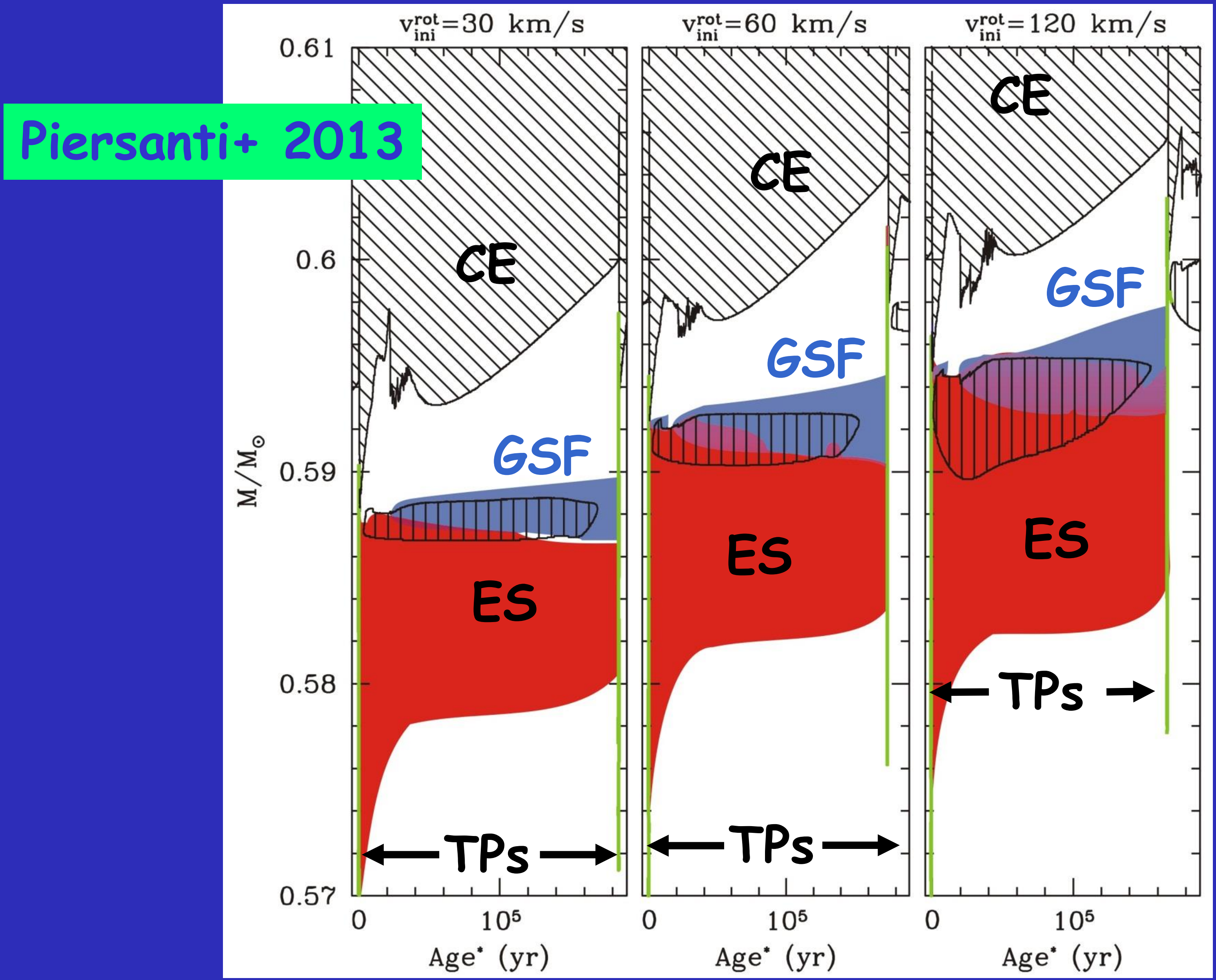
$v_{ES} =$

v_E

μ-gr

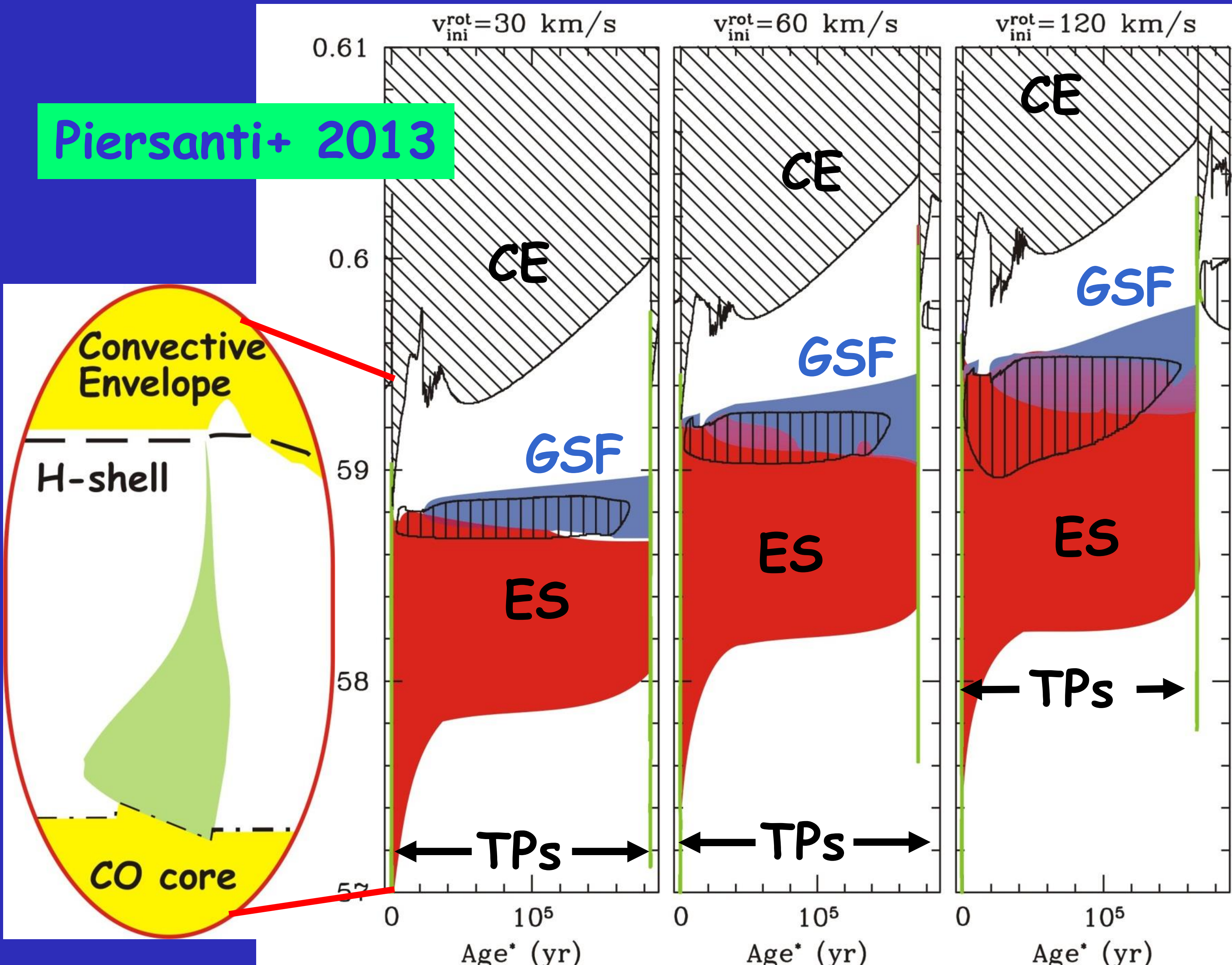


The AGB phase: the [Fe/H]=-1.7 case



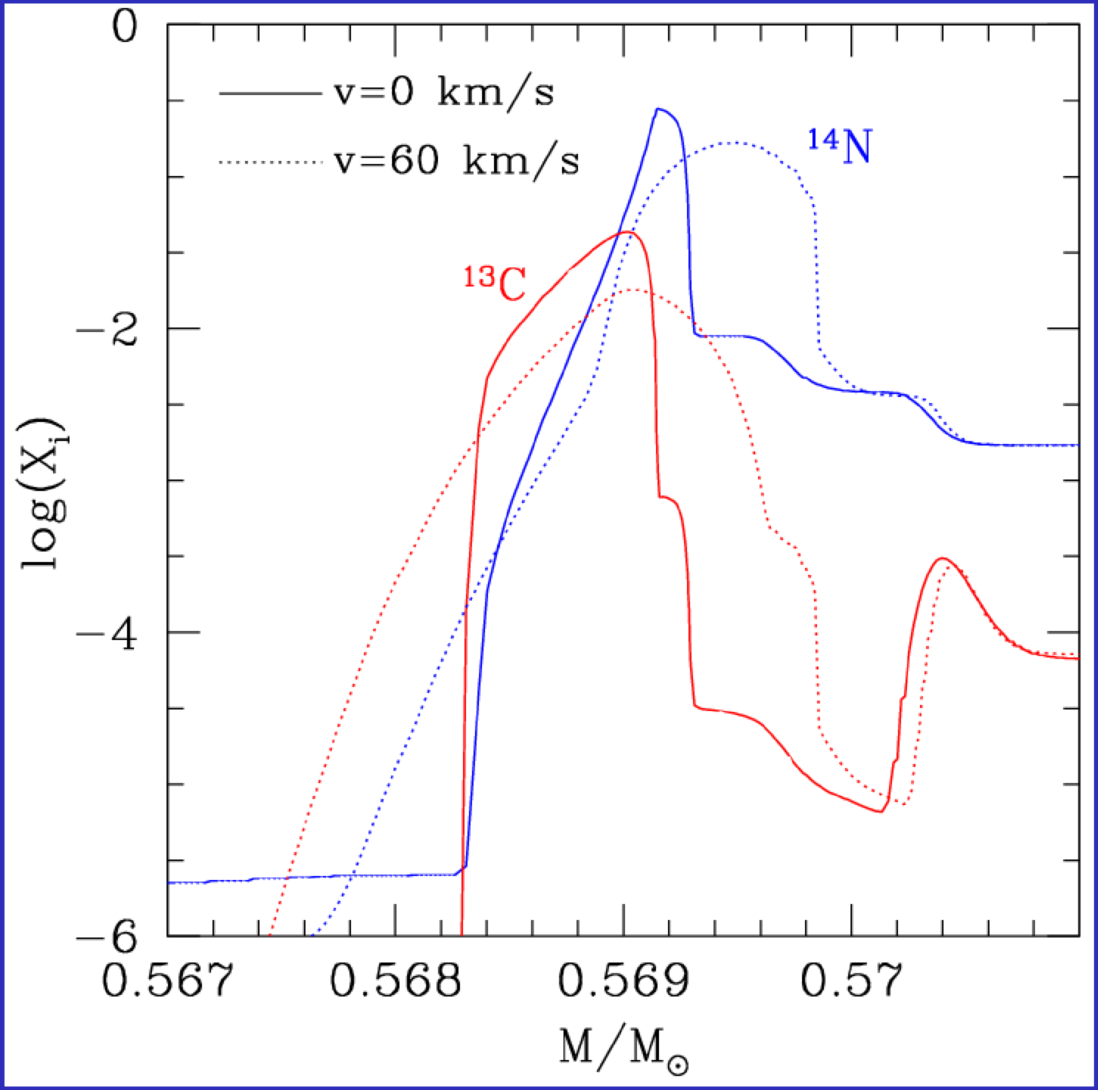
The AGB phase: the [Fe/H]=-1.7 case

Piersanti+ 2013



NET EFFECT:

It mixes ^{14}N in ^{13}C-rich layers (and viceversa), thus implying a decrease of the local neutron density and an increase of the iron seeds. As a consequence, the surface s-process distributions change.



The AGB phase: the [Fe/H]=-1.7 case

Without rotation …

The Fe abundance is low

The neutrons-to-seeds ratio is very high

The s-process produces large amount a Pb

Rotation reduces neutrons-to-seeds ratio

The Pb production is reduced

The abundances of hs and ls increase!!!

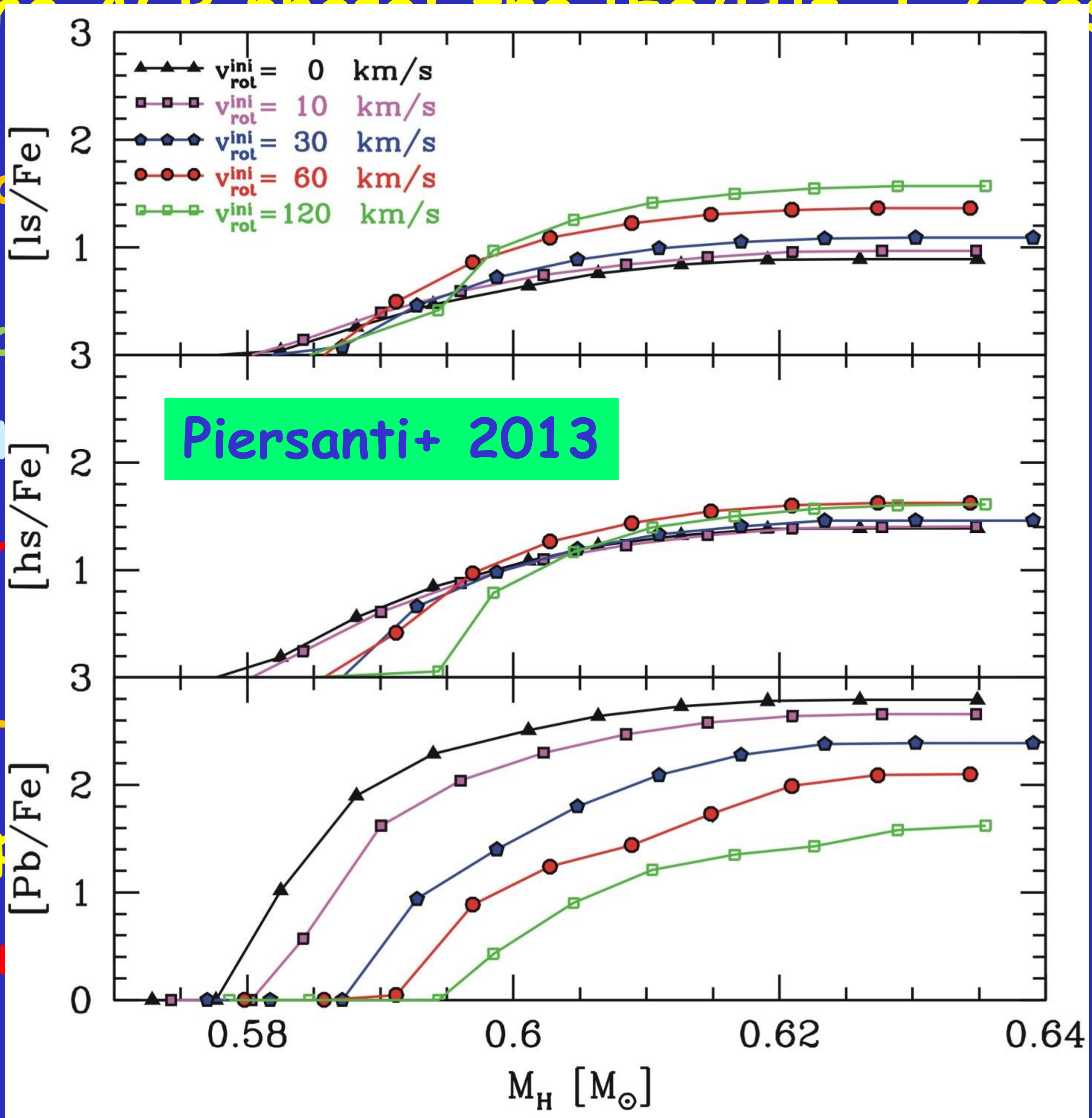
The AGB phase: the [Fe/H]=-1.7 case

Witho

The Fe c

The neut

The s-pr

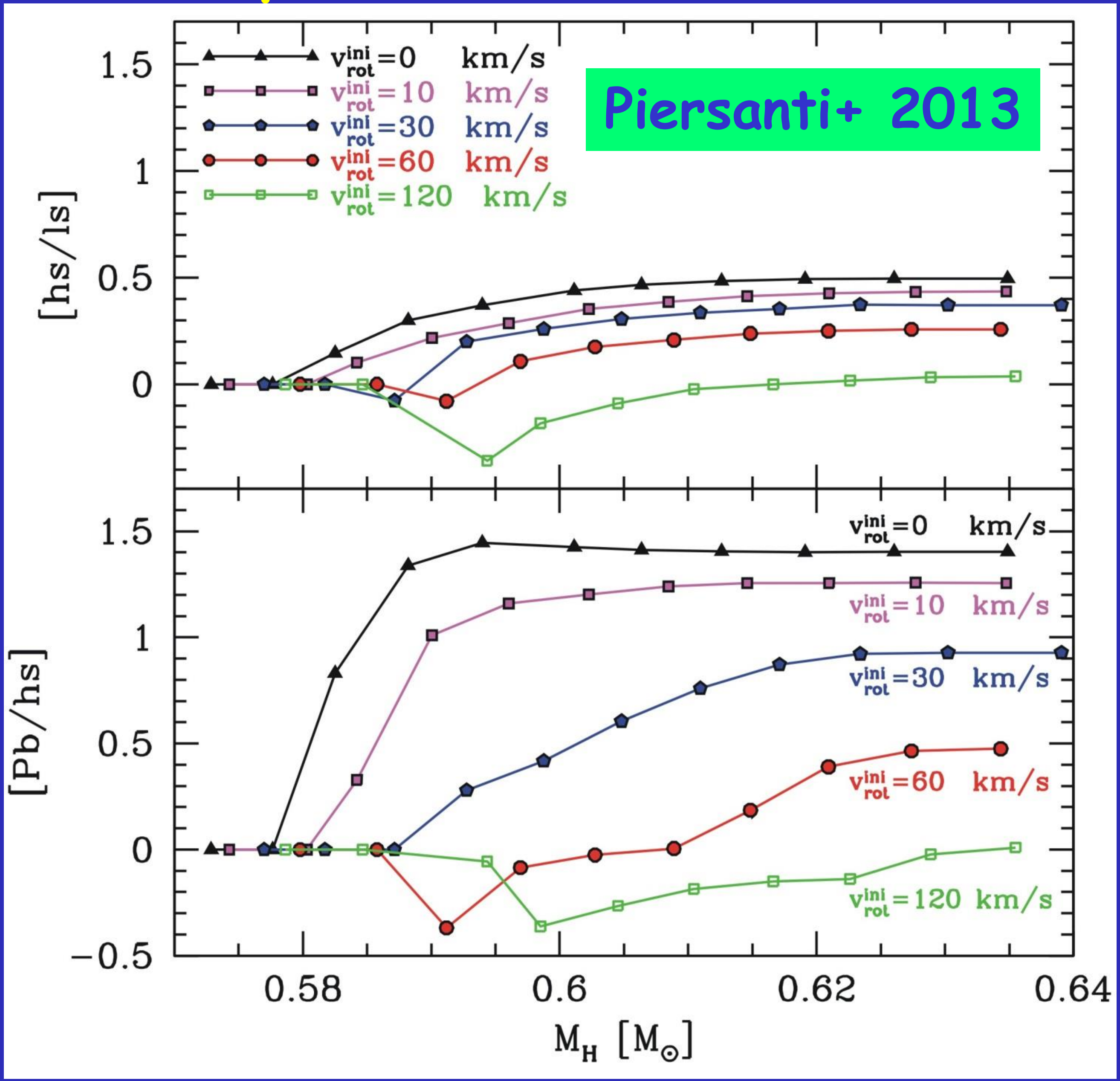


Rotat

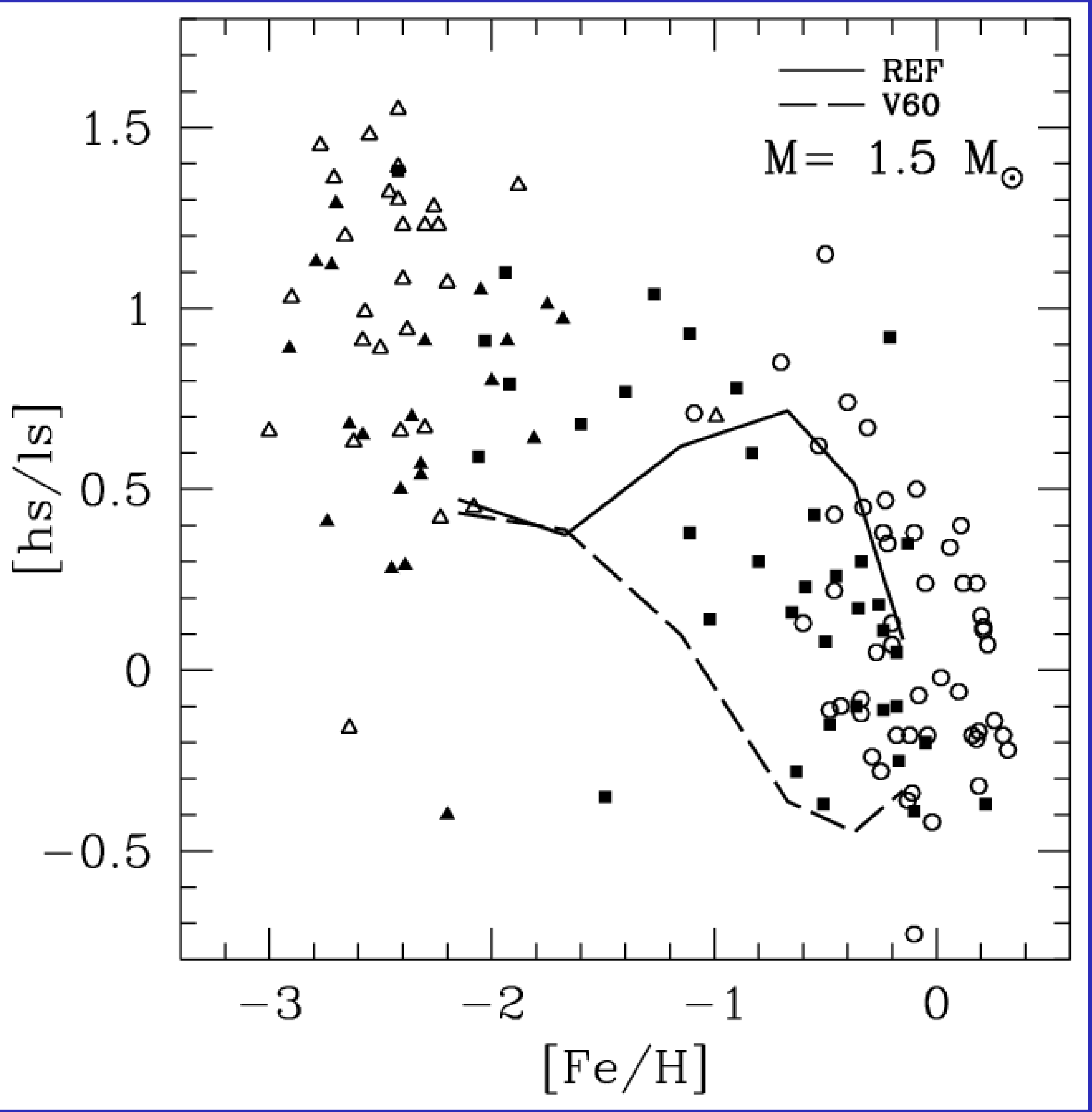
The Pb p

The abu

The AGB phase: the [Fe/H]=-1.7 case



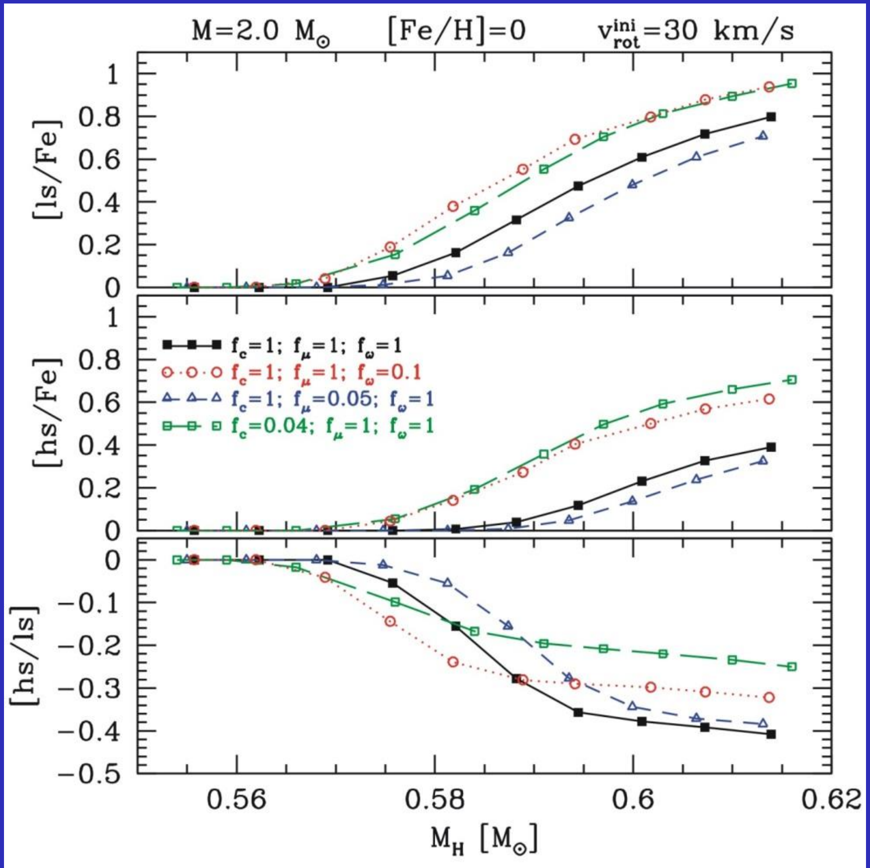
Problems at low metallicities: the effect of rotation

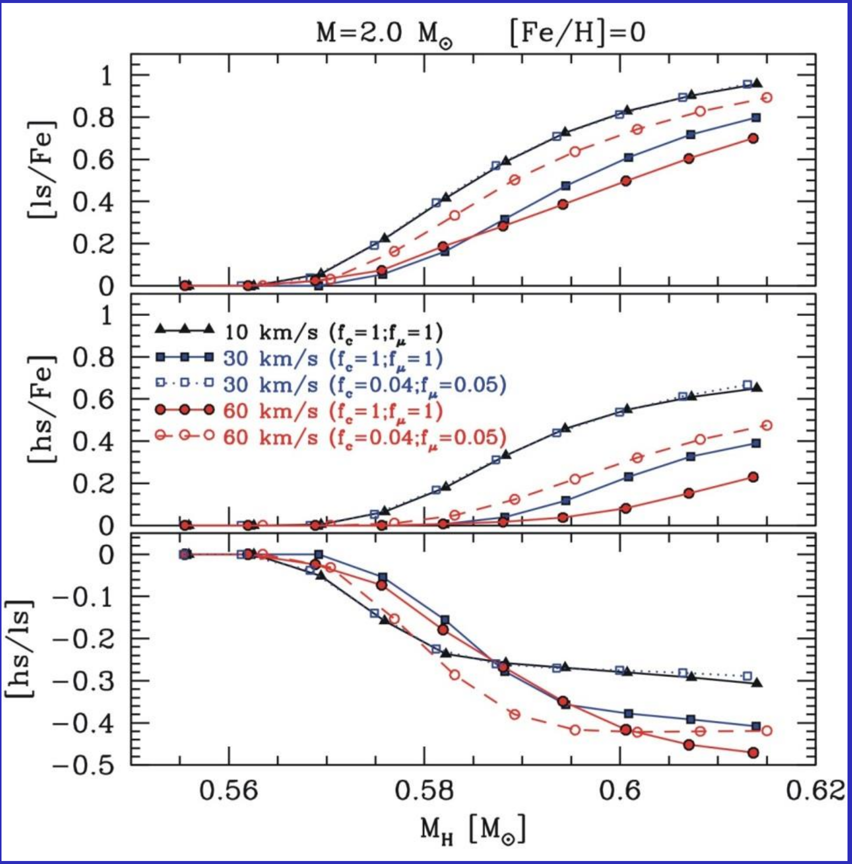


- ○ Ba stars
- ■ CH stars
- ▲ CEMP-s stars
- △ CEMP-sr stars

SC+ 2016

Uncertainties: efficiency of mixing



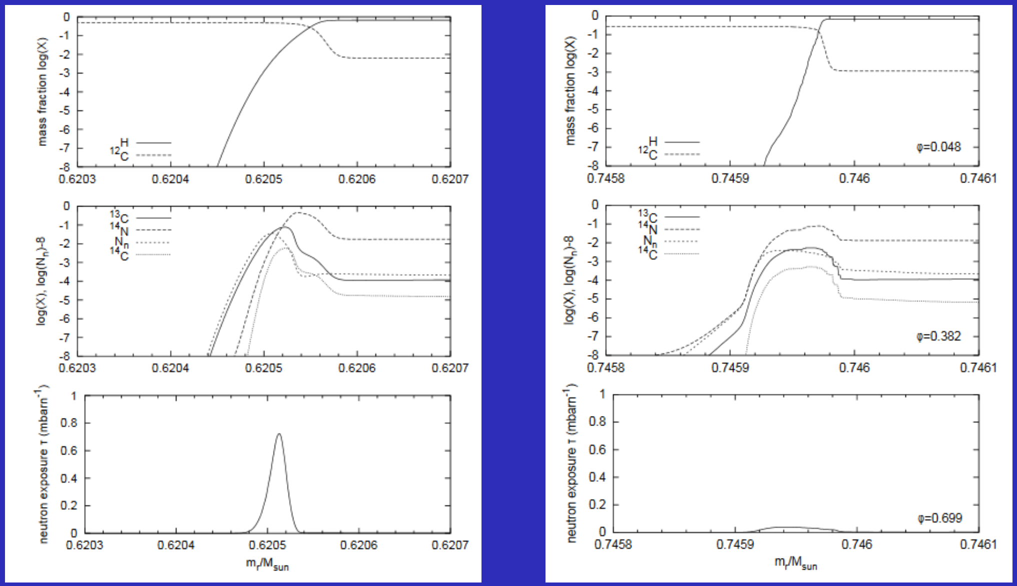


Piersanti+ 2013

Rotation-induced mixing: other studies

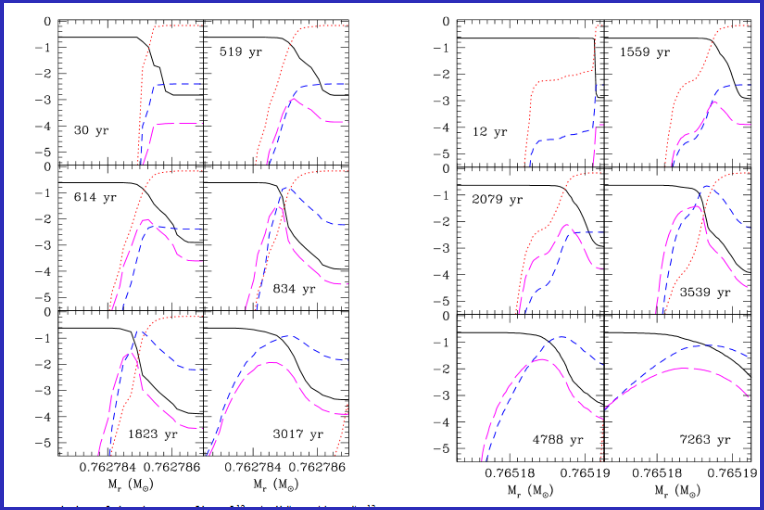
Overshoot

Overshoot+rotation



Herwig+ 2003

Siess+ 2004



Without μ barrier   With μ barrier

See also Langer+1999

Asteroseismology constraints

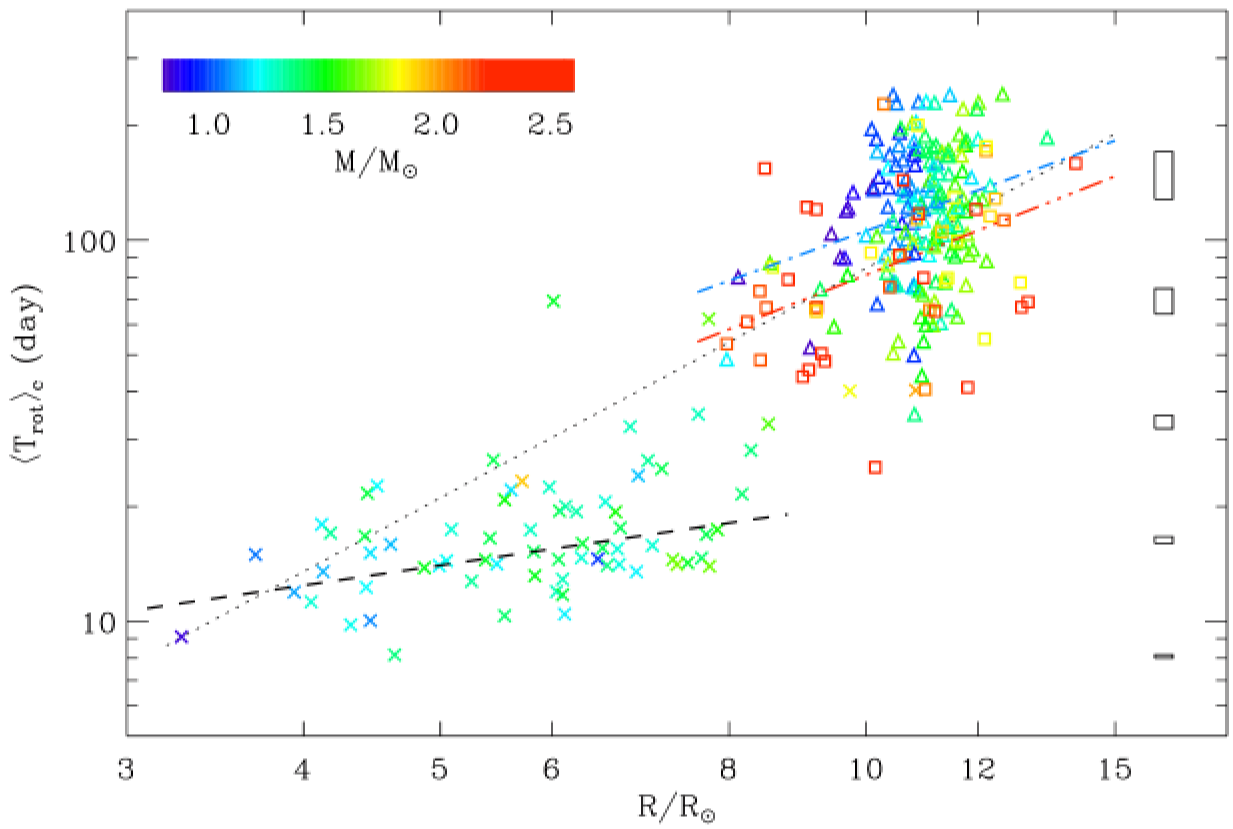
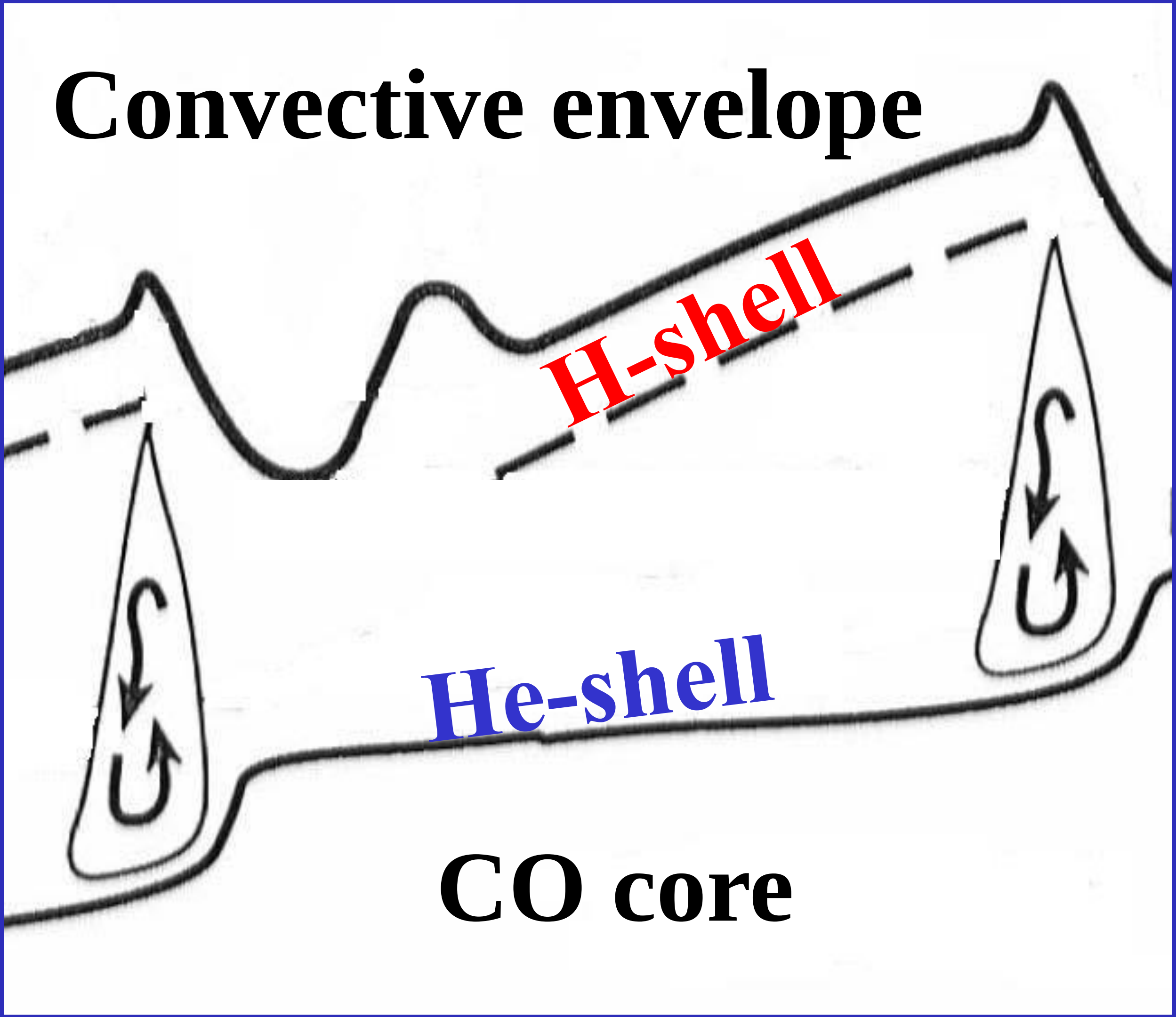


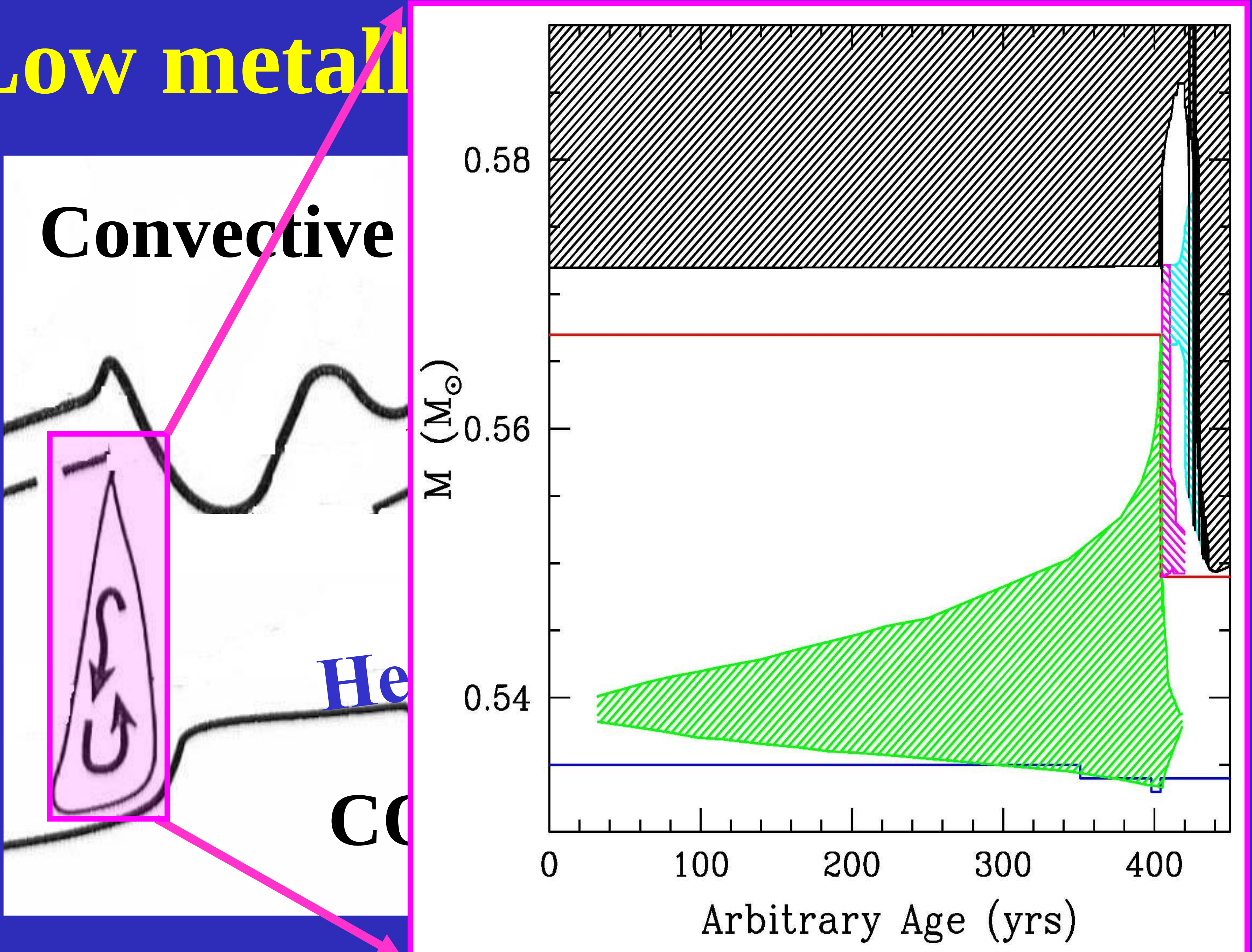
Fig. 9. Mean period of core rotation as a function of the asteroseismic stellar radius, in log-log scale. Same symbols and color code as in Fig. 6. The dotted line indicates a rotation period varying as R^2. The dashed (dot-dashed, triple-dot-dashed) line indicates the fit of RGB (clump, secondary clump) core rotation period. The rectangles in the right side indicate the typical error boxes, as a function of the rotation period.

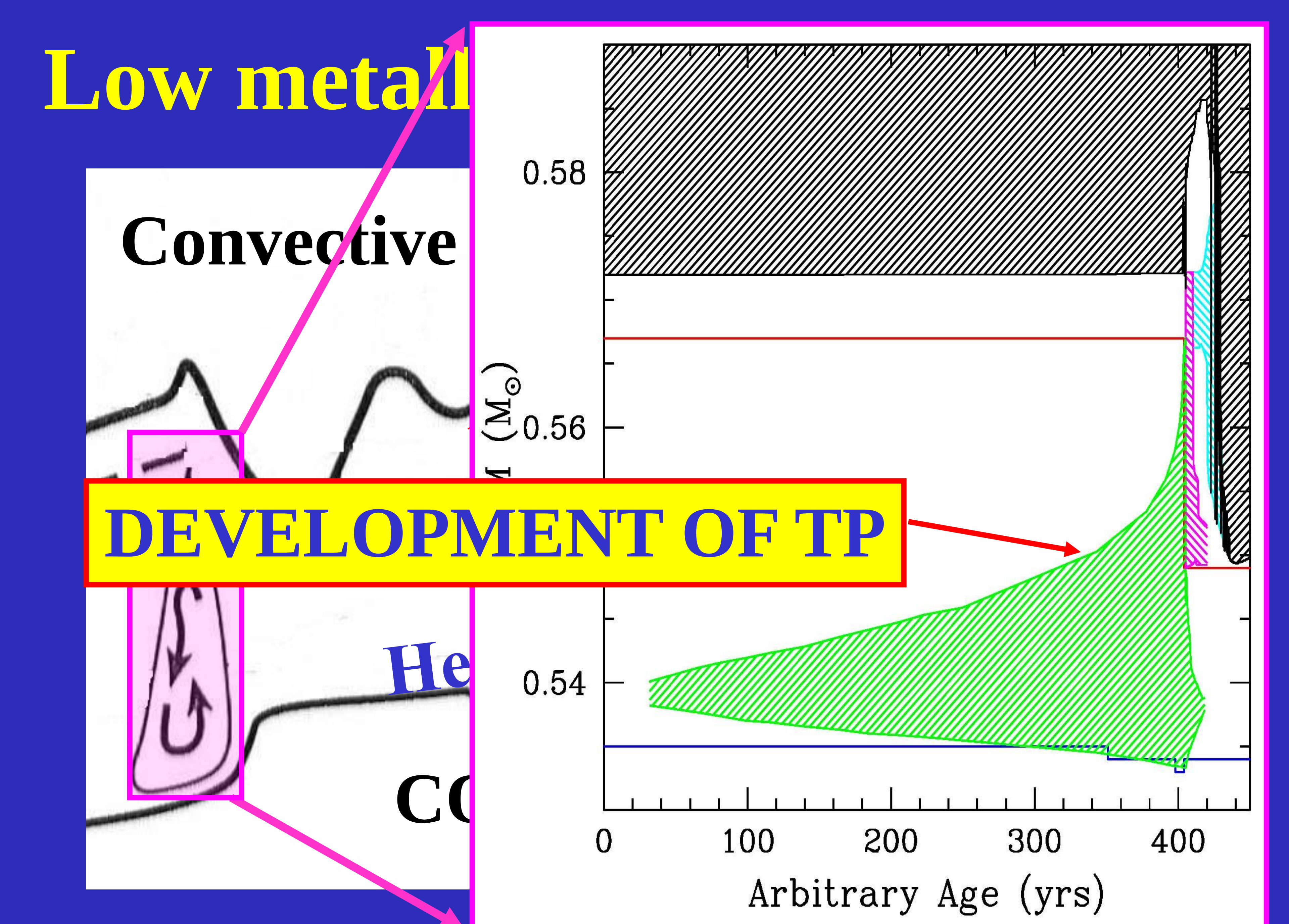
Mosser+ 2012

Low metallicity low mass AGBs



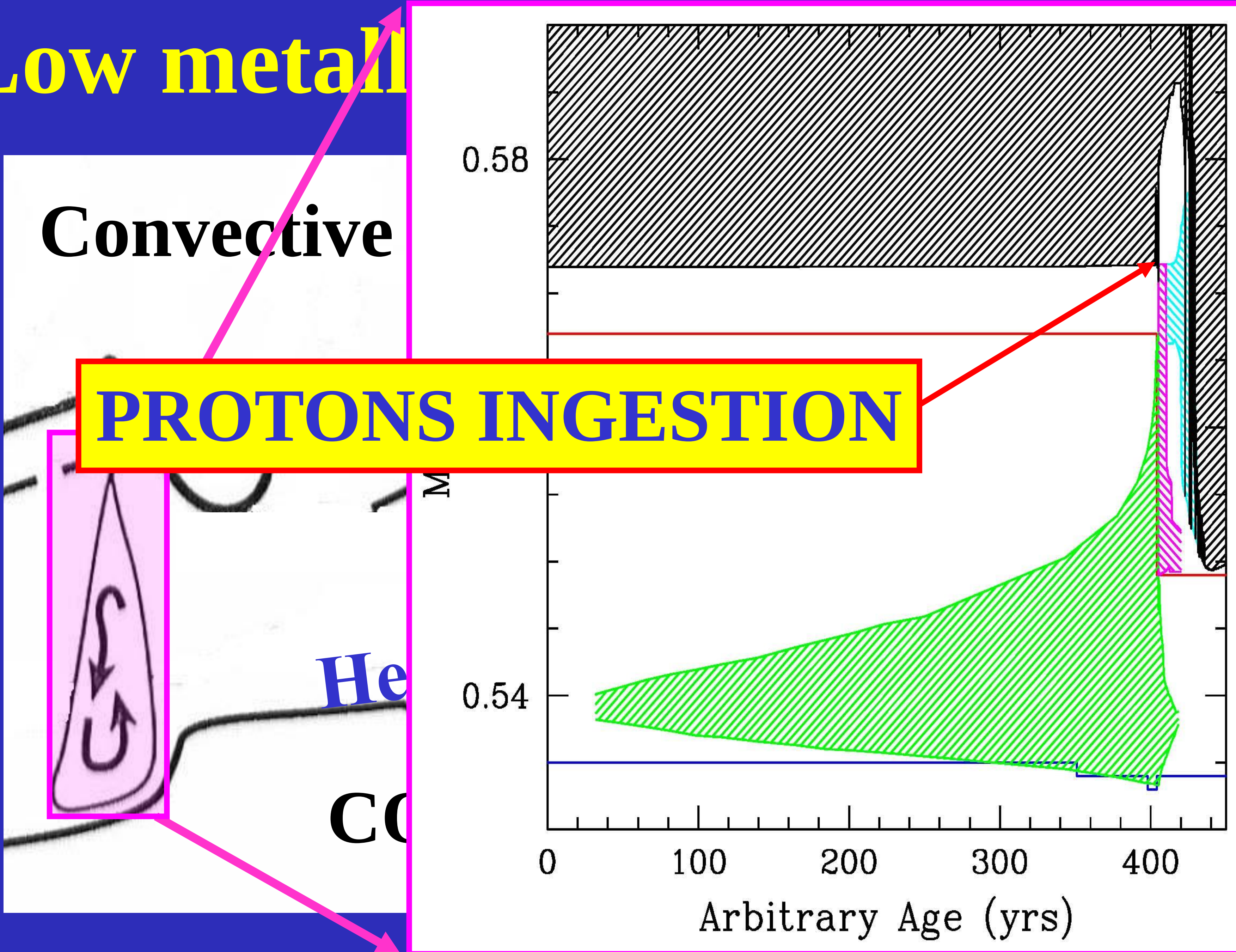
Low metall


Convective
He
CO
0.58
0.56
0.54
M (M$_\odot$)
0
100
200
300
400
Arbitrary Age (yrs)

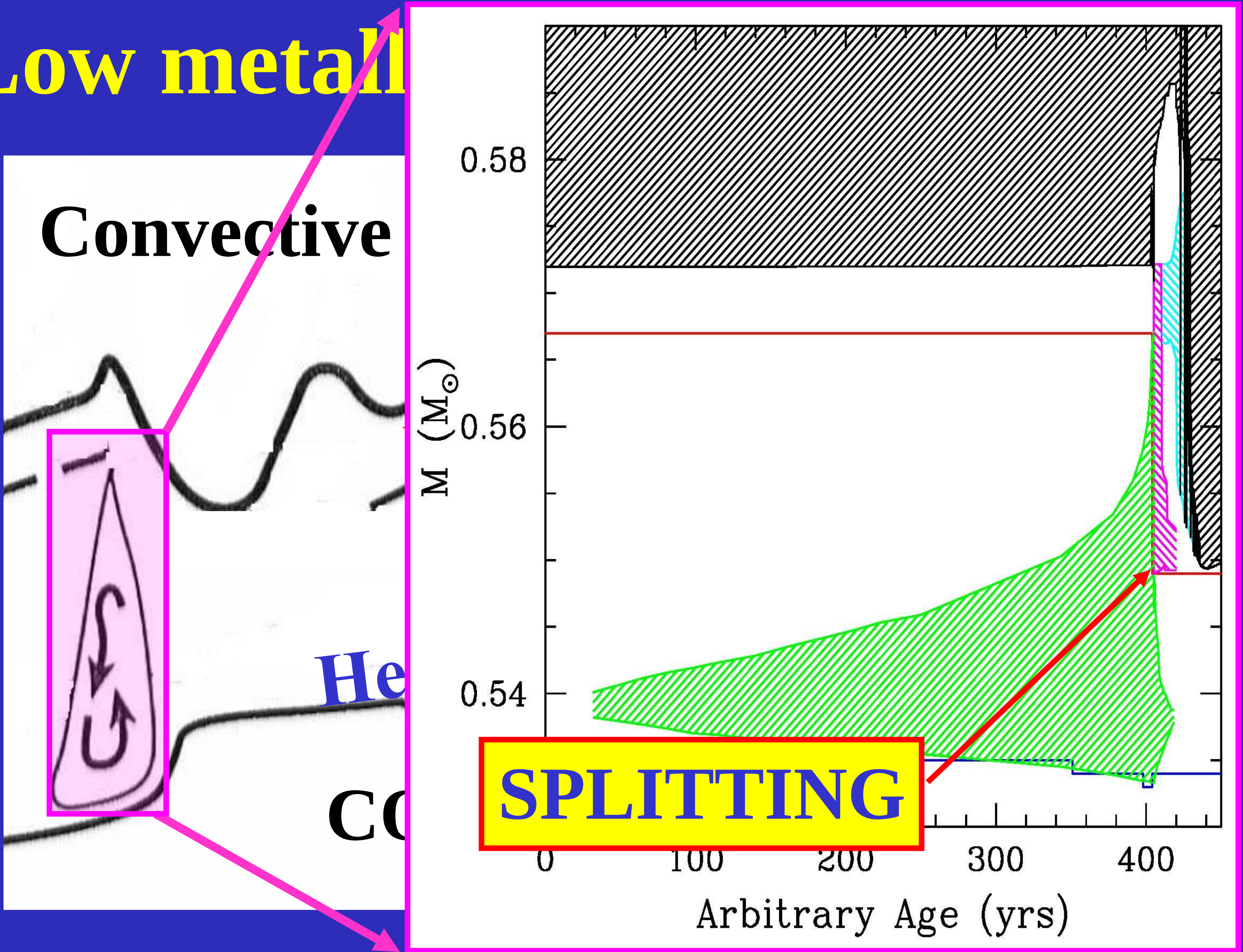


Low metall
Convective
He
CC
0.58
0.56
0.54
M (M⊙)
0
100
200
300
400
Arbitrary Age (yrs)
DEVELOPMENT OF TP

Low metall

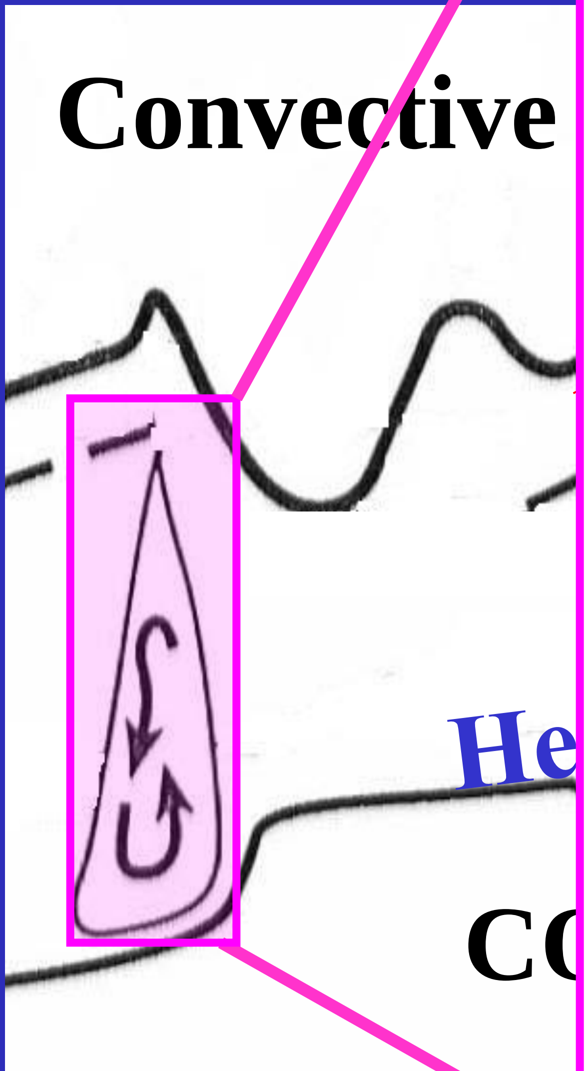

Convective
He
CO
PROTONS INGESTION
M
0.58
0.54
0
100
200
300
400
Arbitrary Age (yrs)

Low metall

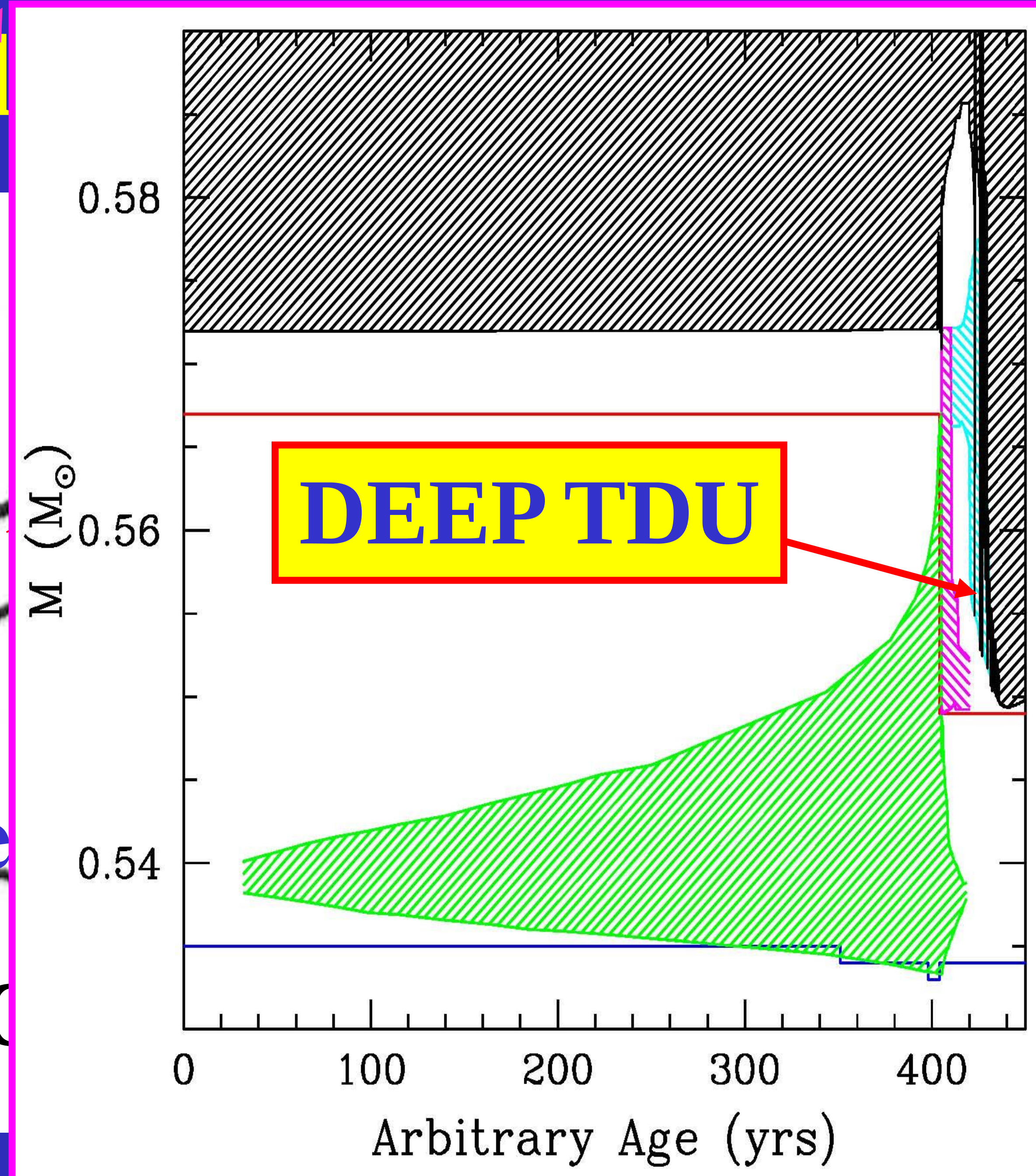


Convective
He
CO
0.58
0.56
0.54
M (M$_\odot$)
0
100
200
300
400
Arbitrary Age (yrs)
SPLITTING

Low metall



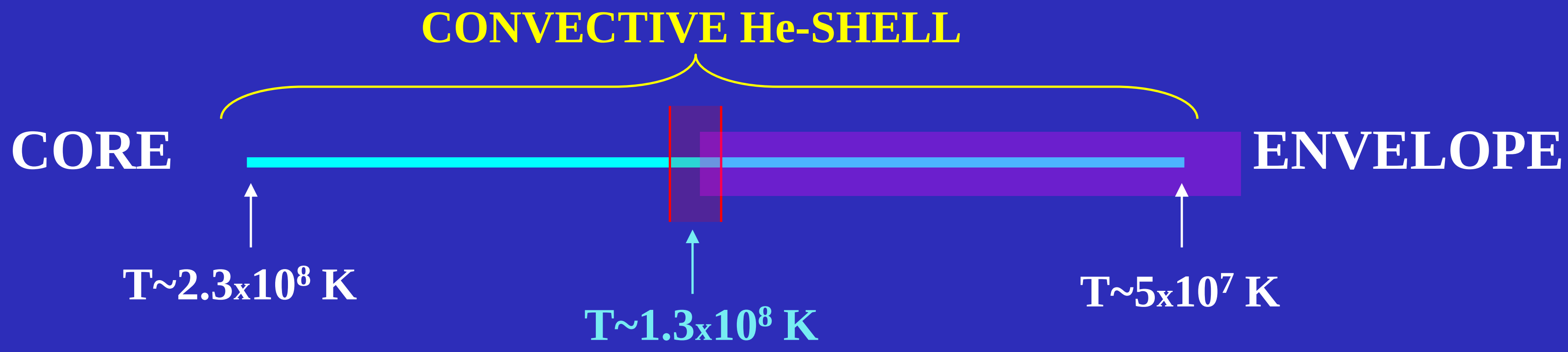
Convective
He
CO



0.58
0.56
0.54
M $(M_\odot)$
DEEP TDU
0
100
200
300
400
Arbitrary Age (yrs)

Proton Ingestion Episode (PIE)

- Low time steps → Time dependent mixing
- Rapid structure reaction → Coupling between phisical and chemical evolution
- Large neutron densities ($n_n > 10^{15}$ cm^{-3}) → 700 isotopes & 1000 reactions

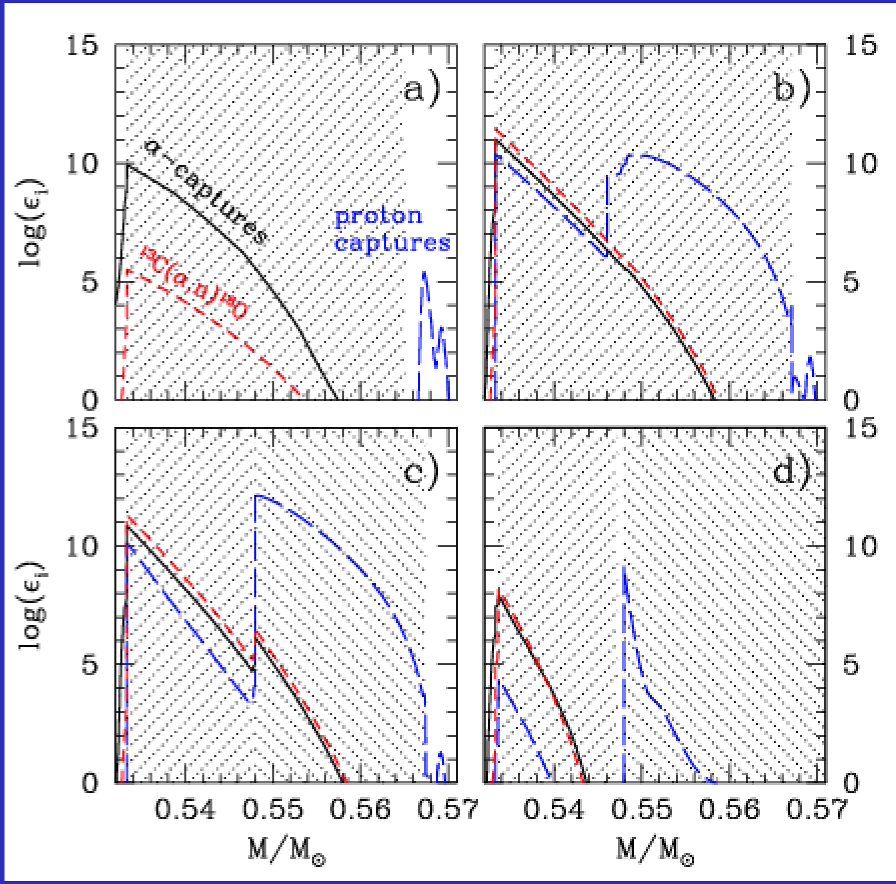


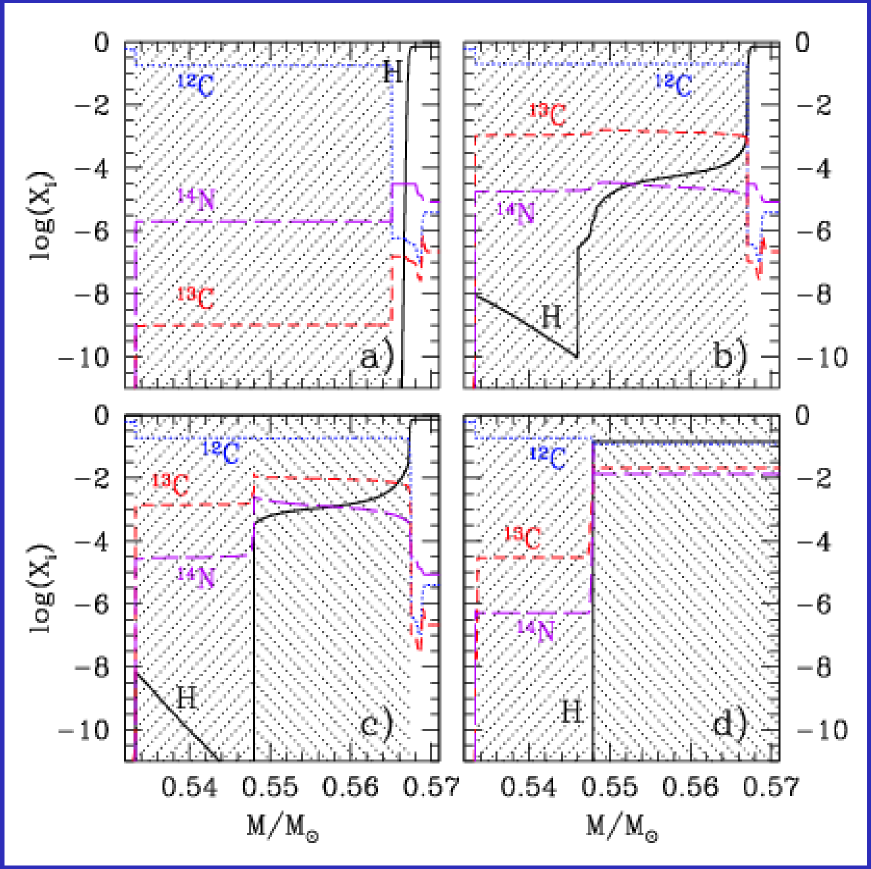
We limit proton ingestion up to the mesh where $\tau_{CNO} = 1/3\ \Delta t$

Temporal step of the model (Δt) is limited to $1/2\ \tau_{mix}$

Energy

a) Δt=0
b) Δt=1.6457 yrs
c) Δt=1.6468 yrs
d) Δt=2.1843 yrs





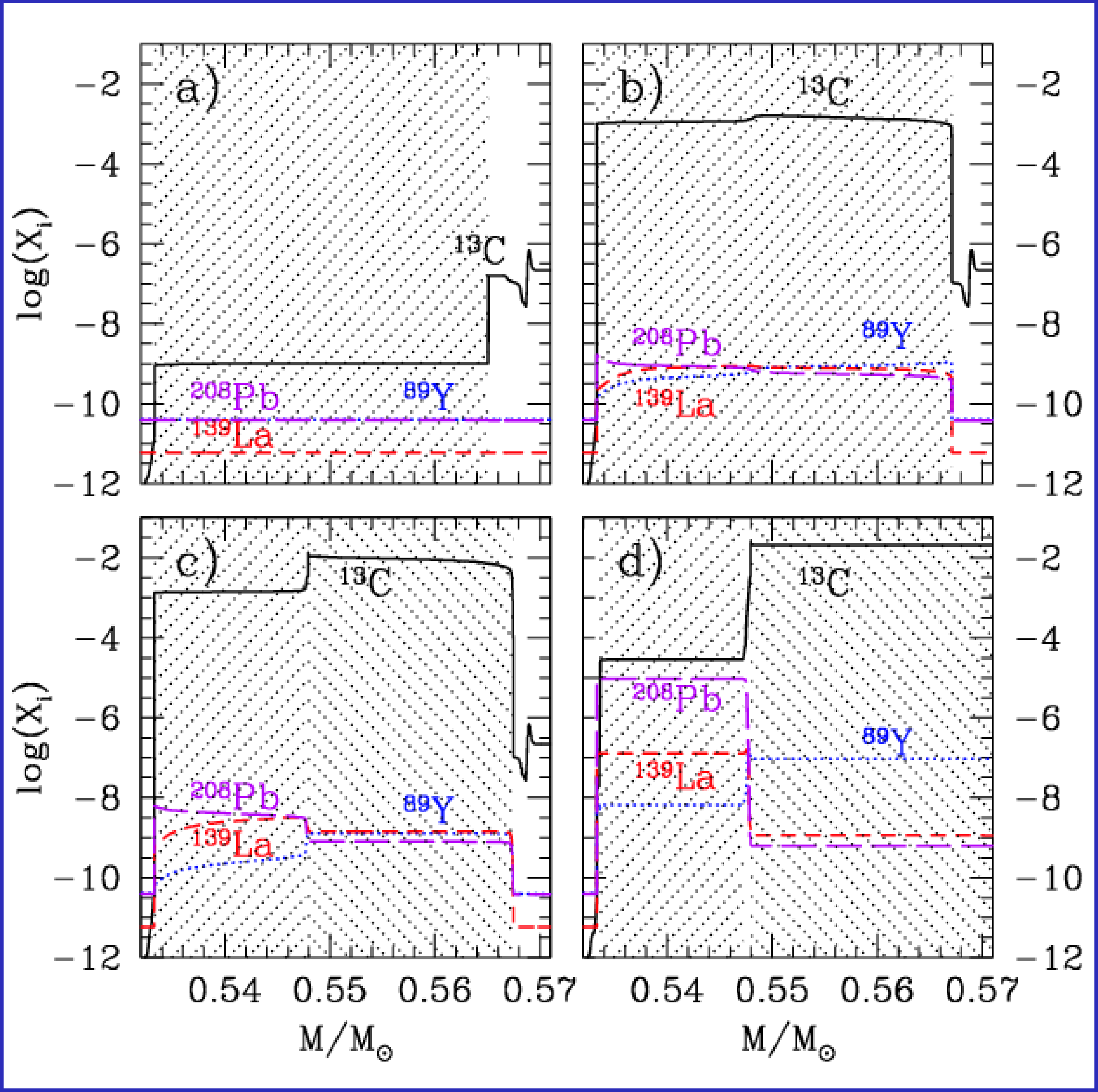
SC+ 2009b

M= 1.5 $M_\odot$, [Fe/H]= -2.45

Light elements

Heavy elements

SC+ 2009b



M= 1.5 $M_\odot$
[Fe/H]= -2.45

Nuclear Network of 700 isotopes coupled with the physics

The importance of nuclear cross sections

—— Normal s-process (main path)

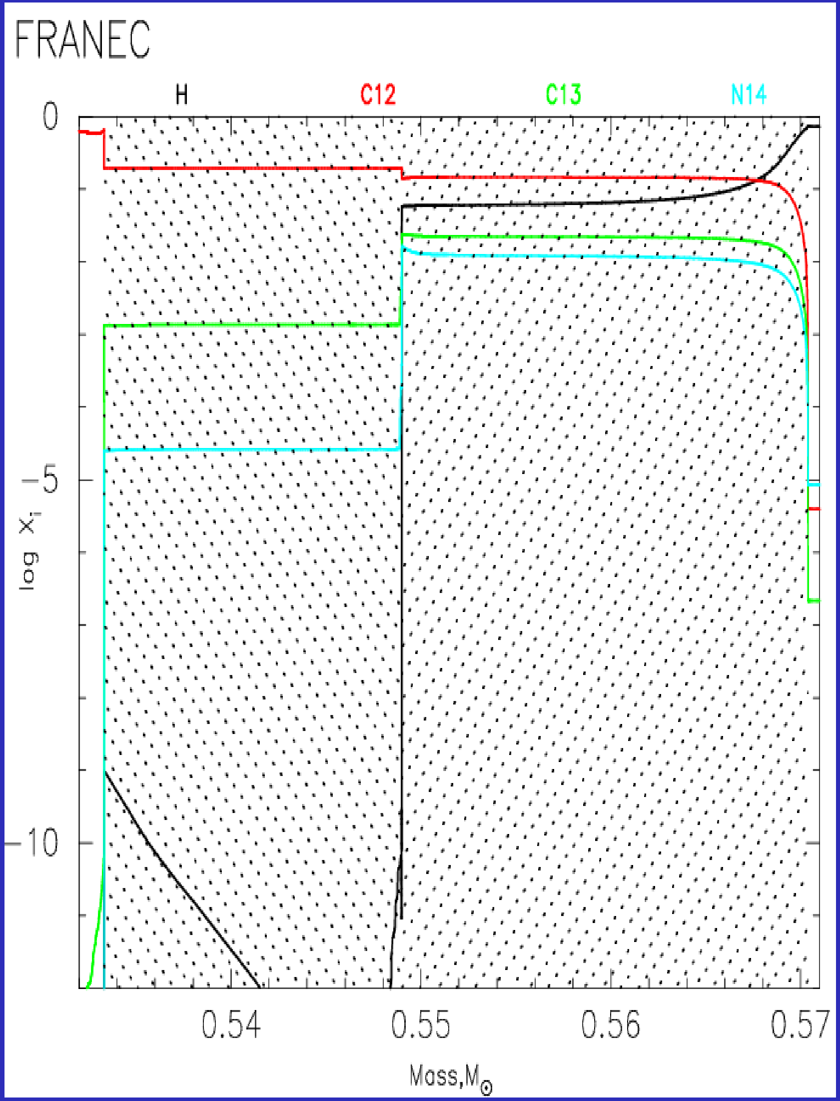
—— Proton ingestion

$n_n^{max} > 10^{14}$ cm^{-3}

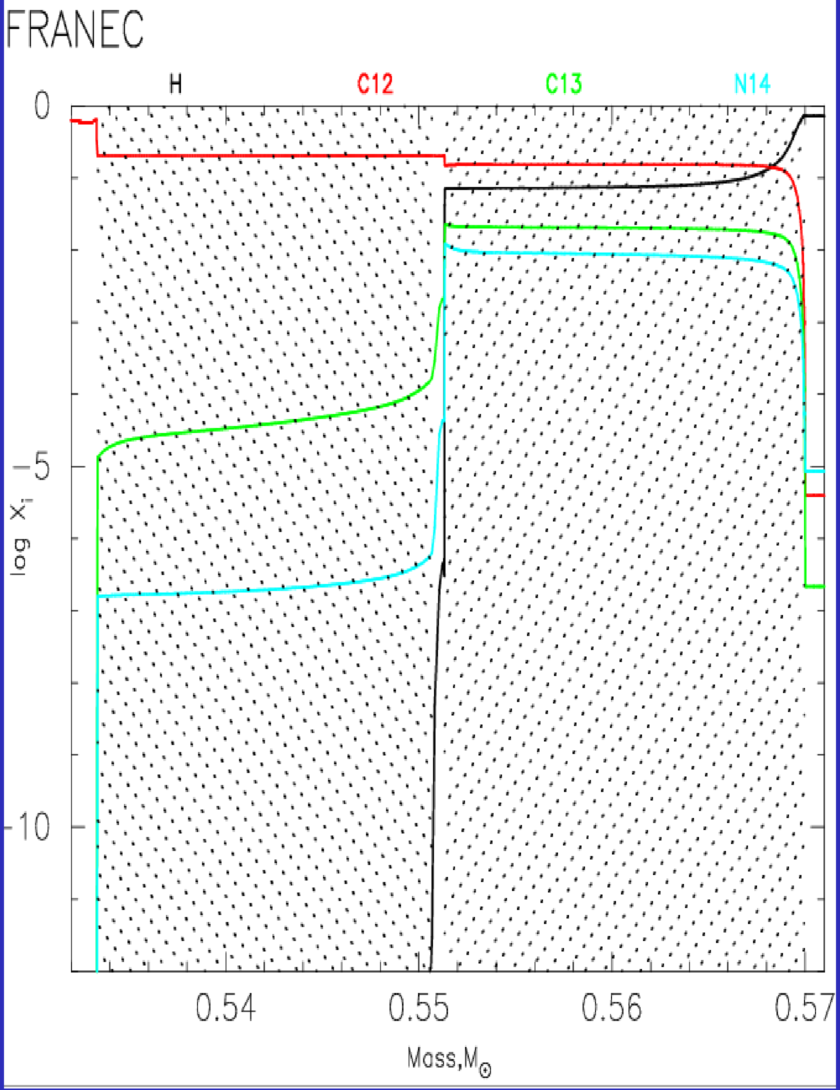
$\sigma(^{135}I)_{30\ Kev} \sim 1/20\ \sigma(^{138}Ba)_{30\ Kev}$

from Rauscher&Thielemann 2000

The importance of the network

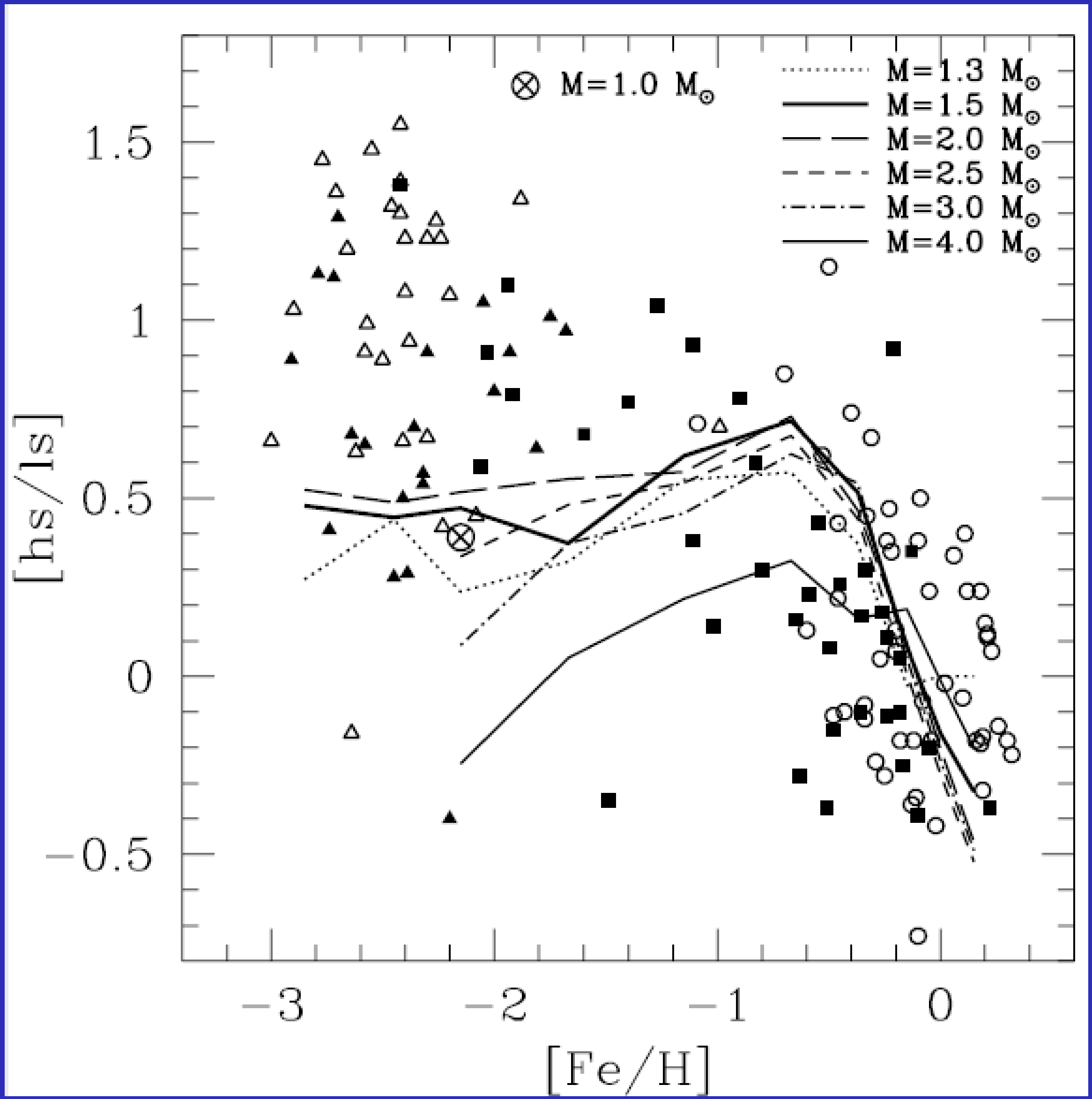


Complete network



Reduced network

Problems at low metallicities: the effect of PIEs



○ Ba stars

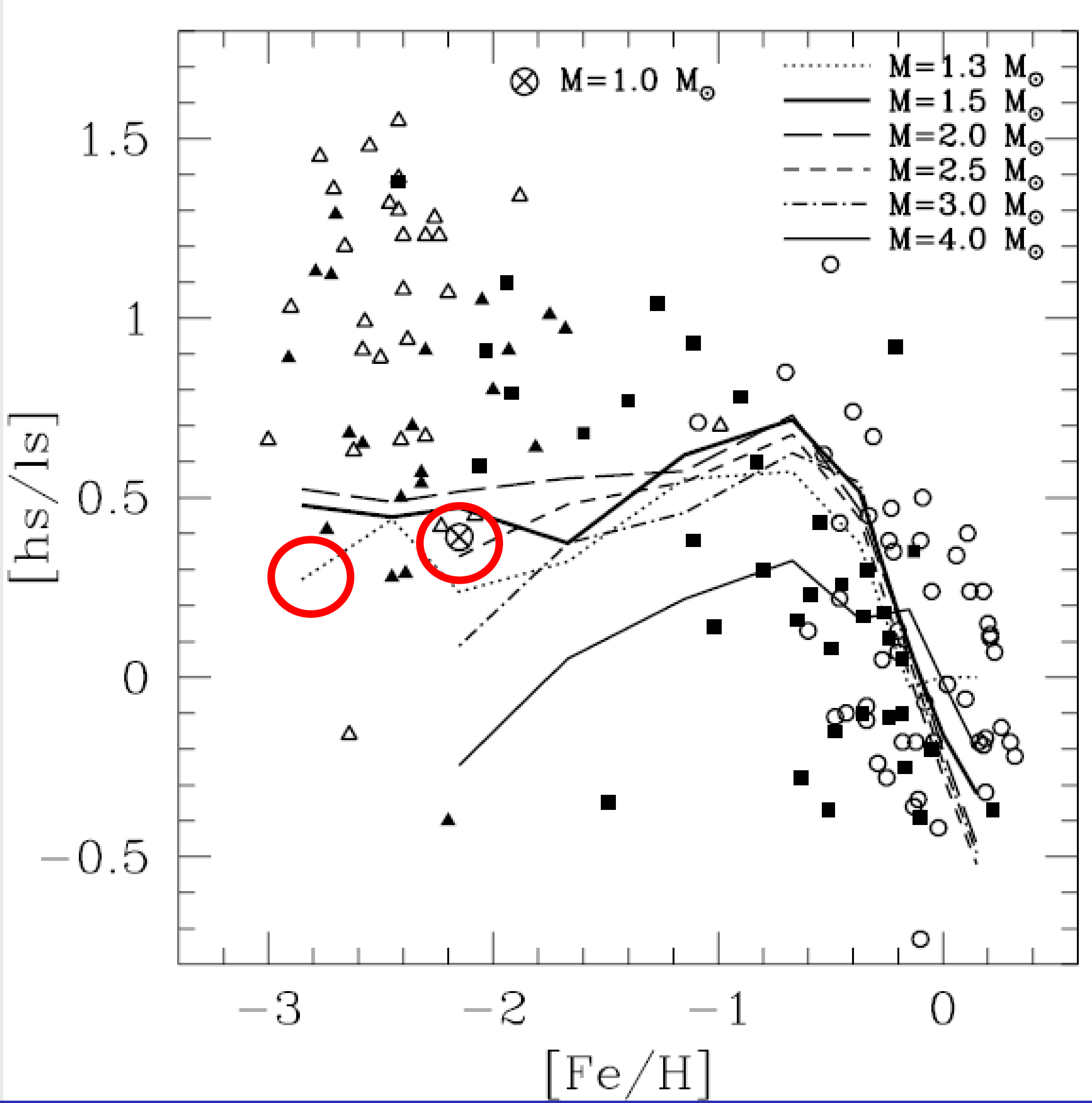
■ CH stars

▲ CEMP-s stars

△ CEMP-sr stars

SC+ 2016

Problems at low metallicities: the effect of PIEs



- ○ Ba stars
- ■ CH stars
- ▲ CEMP-s stars
- △ CEMP-sr stars

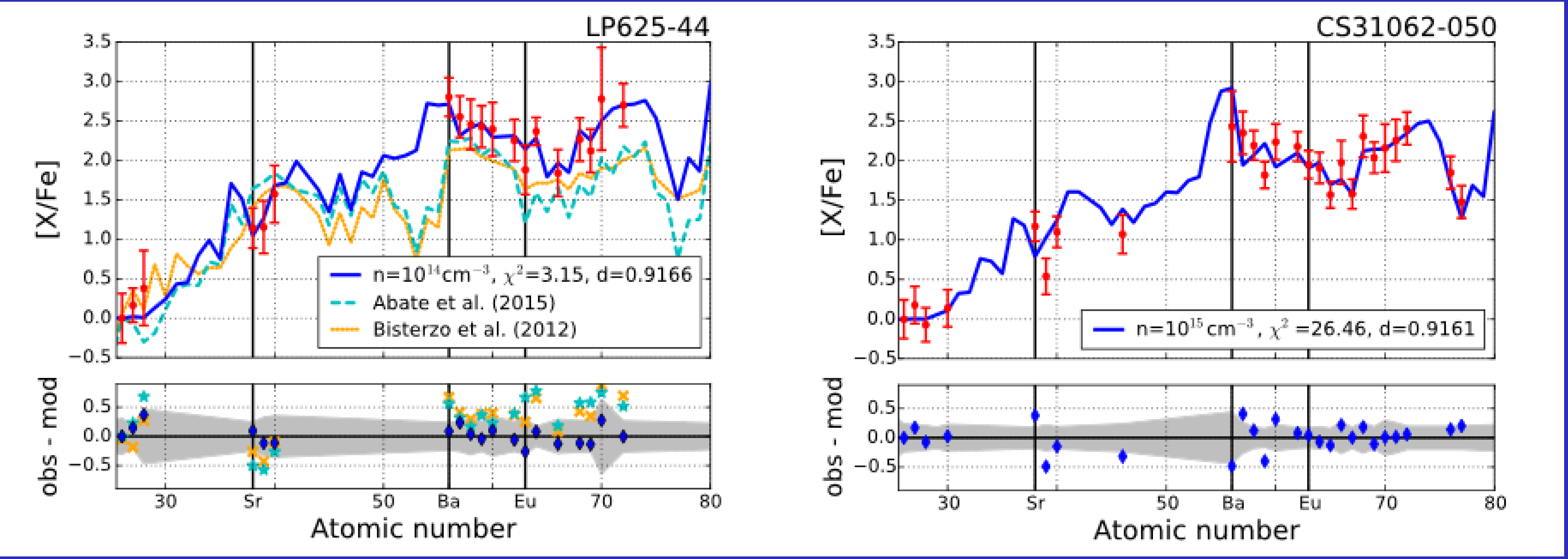
SC+ 2016

PIEs:
transient phase or destructive episode?

Dardelet+ 2015

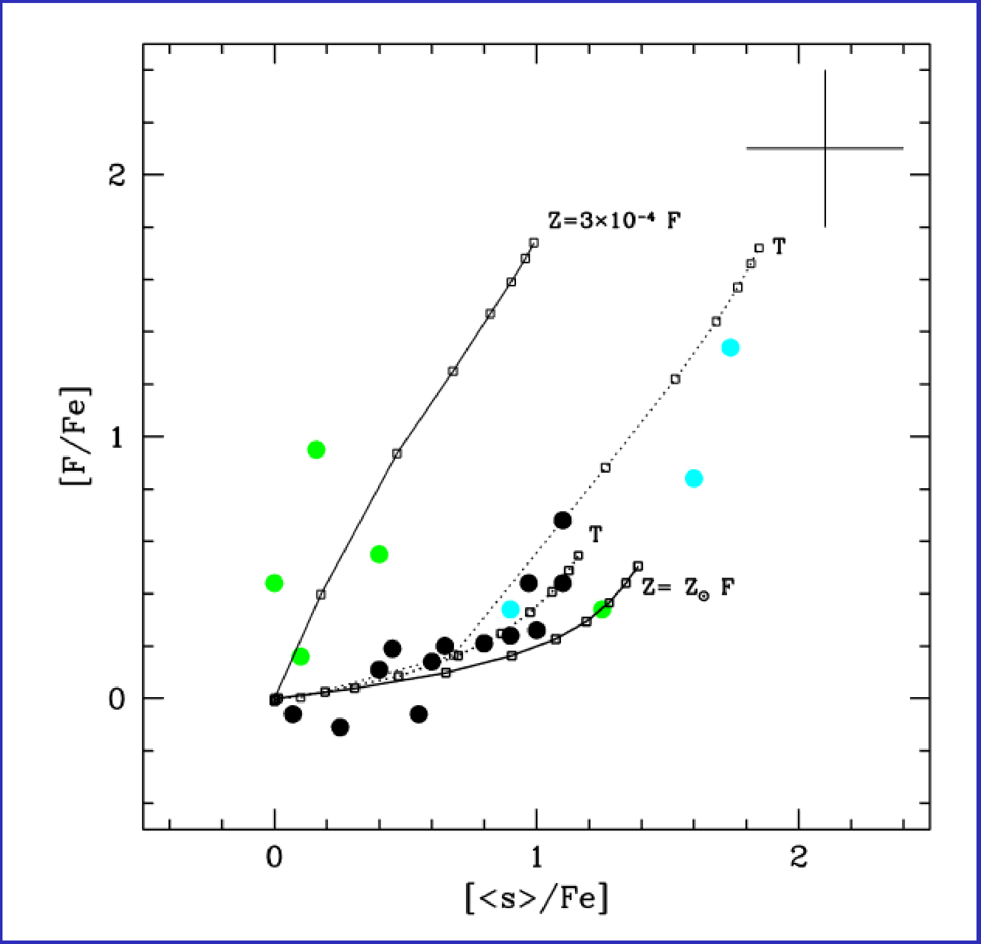
Hampel+ 2016

Observed [hs/ls] ratios can be matched with very high neutron densities ($n_n > 10^{15}$ cm^{-3}) lasting for about 0.1 yr.



Fluorine production at low metallicity

Abia+2015



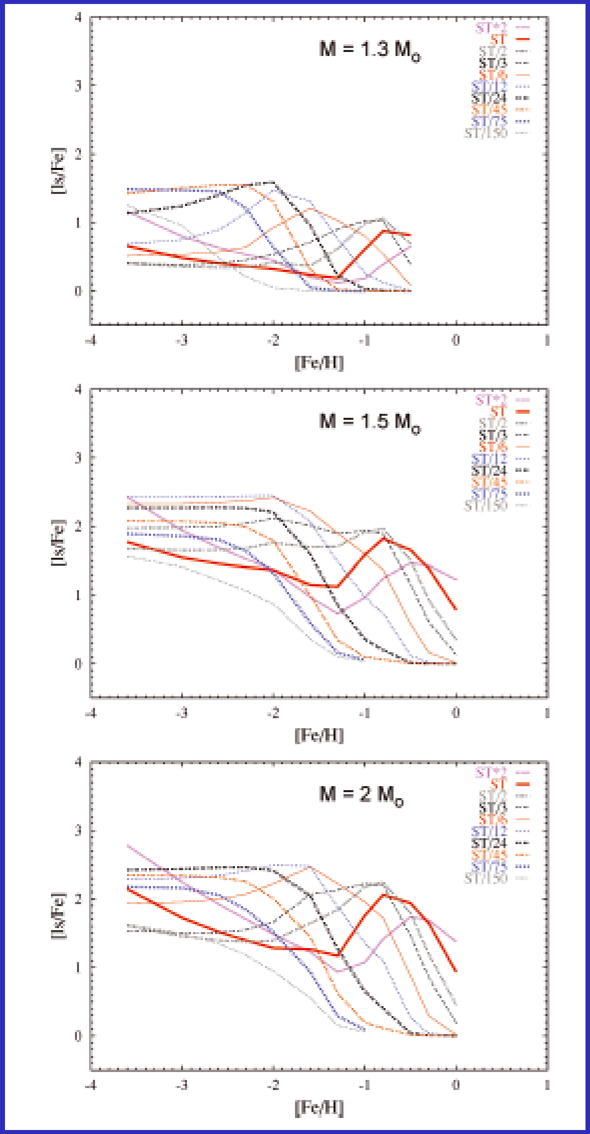
It's not just a problem of relative values, but also of absolute ones!



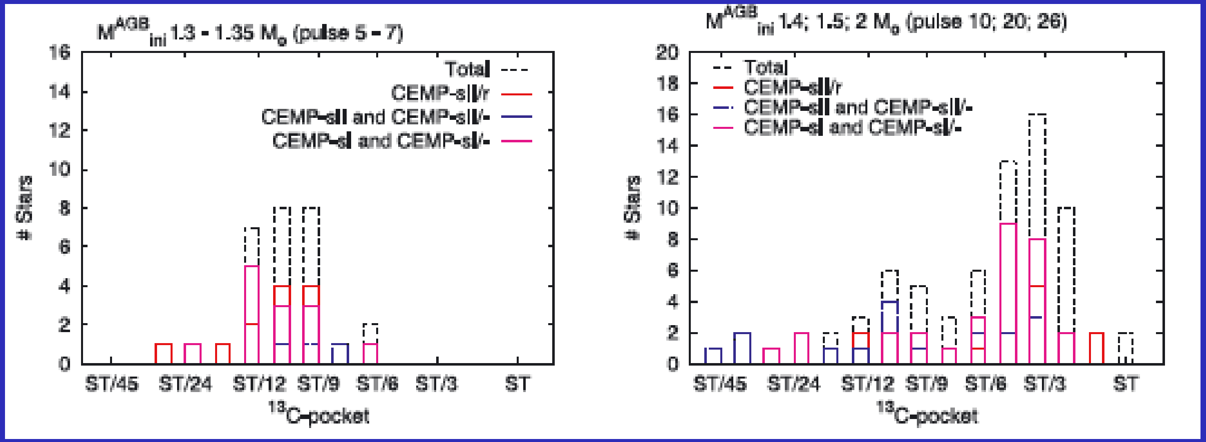




HINTS from POST_PROCESSES

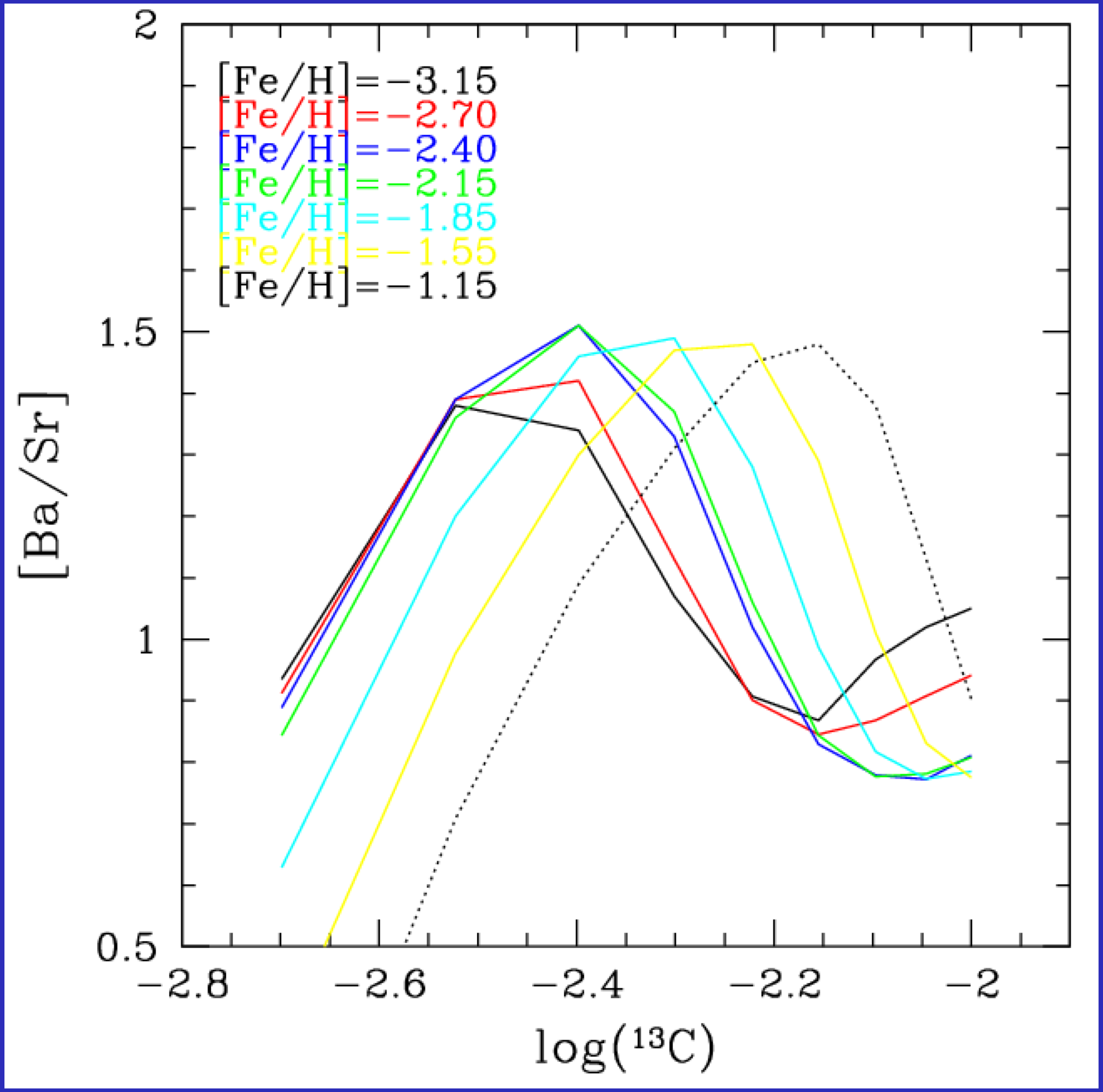


Bisterzo+ 2010



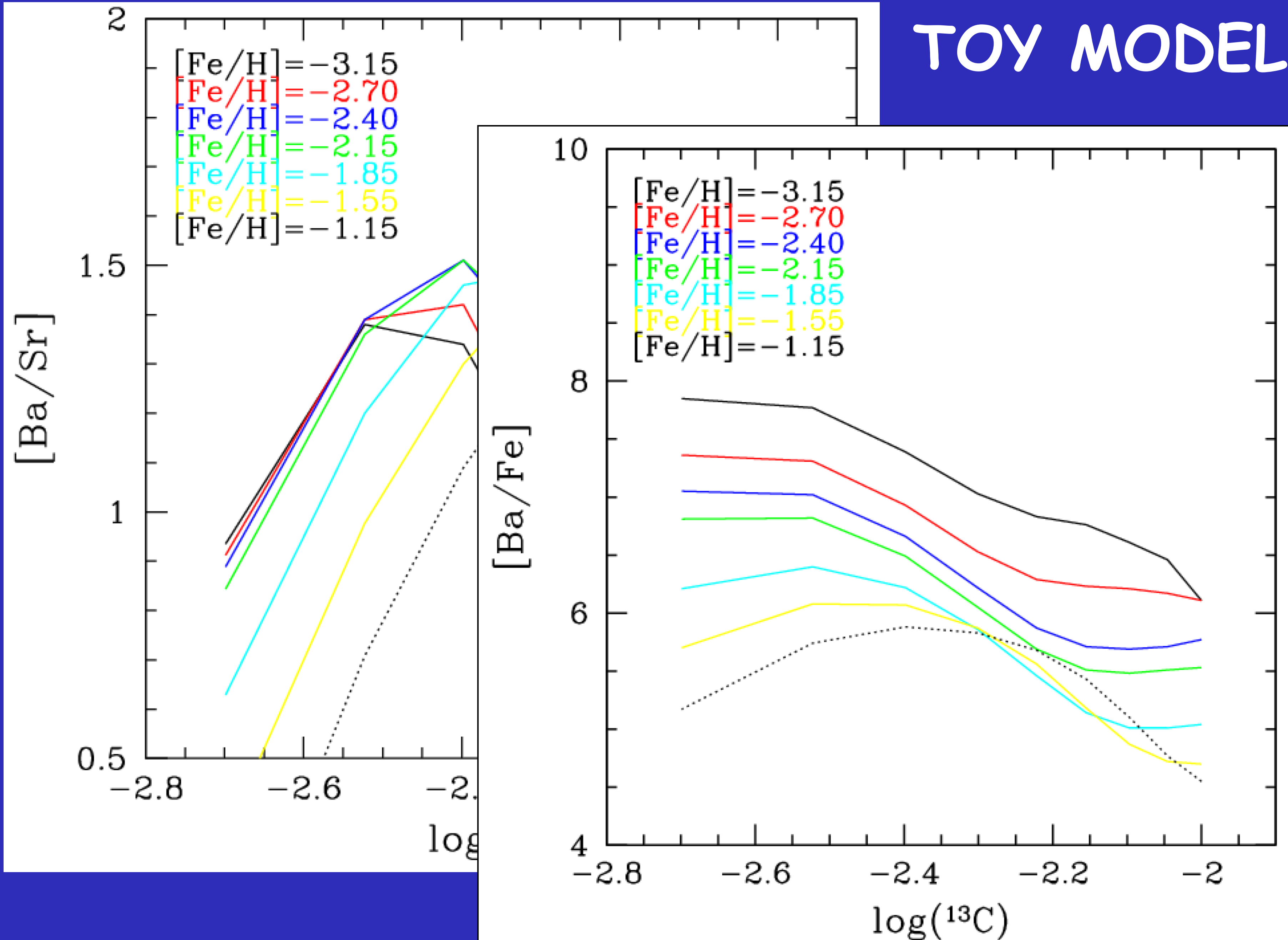
Bisterzo+ 2011

TOY MODEL



[Fe/H]=−3.15
[Fe/H]=−2.70
[Fe/H]=−2.40
[Fe/H]=−2.15
[Fe/H]=−1.85
[Fe/H]=−1.55
[Fe/H]=−1.15
2
1.5
1
0.5
−2.8
−2.6
−2.4
−2.2
−2
[Ba/Sr]
log(13C)

TOY MODEL



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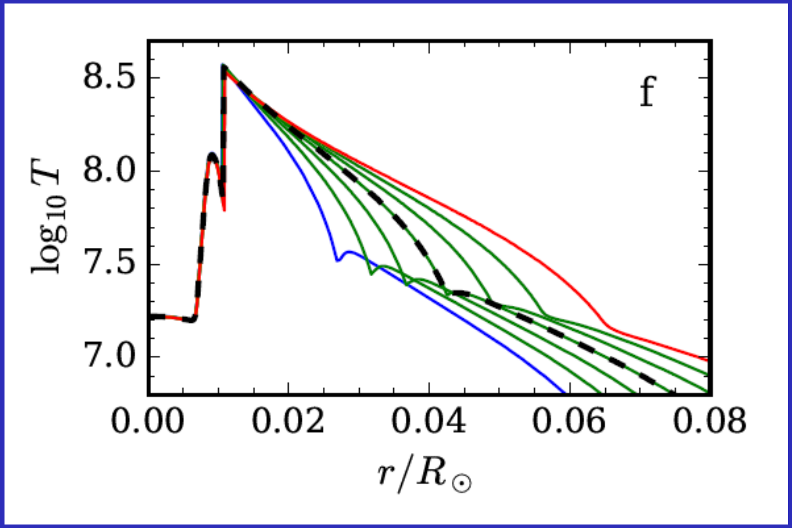
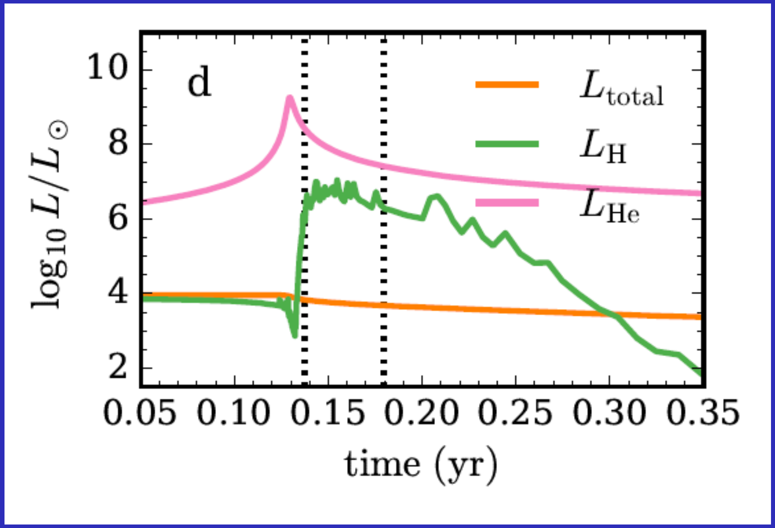
[Fe/H]=−1.55
[Fe/H]=−1.15
[Ba/Fe]
10
8
6
4
−2.8
−2.6
−2.4
−2.2
−2
log(¹³C)

ALTERNATIVE SOLUTIONS?

H-ingestion in rapidly accreting WDs (talk by F. Herwig)

Activation of the intermediate neutron-capture process (i process), as the dominant process for the production of heavy elements beyond Fe.





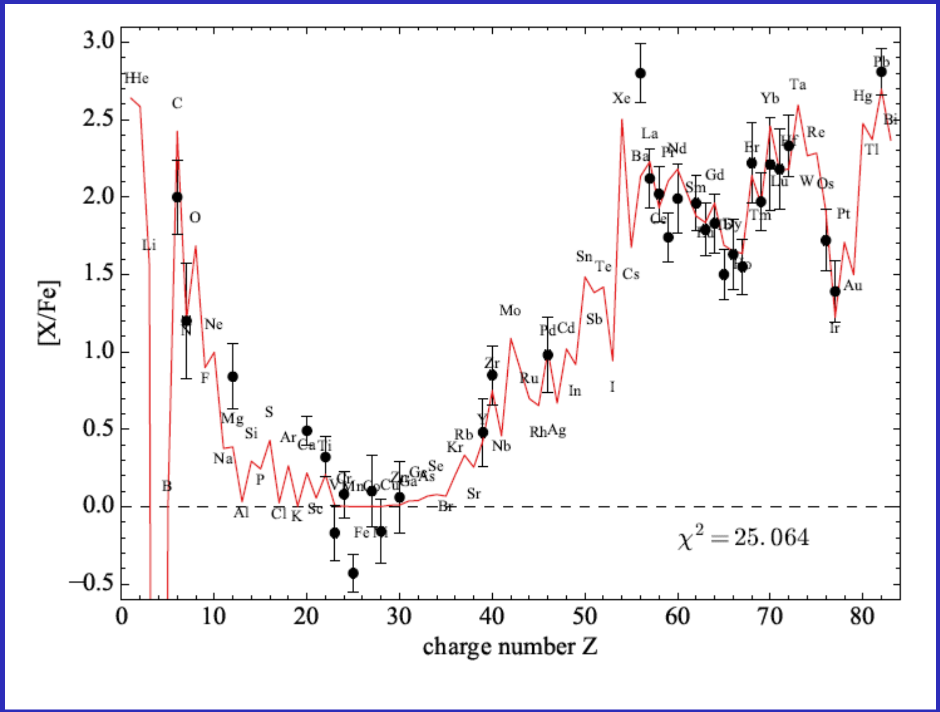
Denissenkonv+ 2018

Higher temperature at the base of the convective shell

NO SPLITTING of the shell

ALTERNATIVE SOLUTIONS?

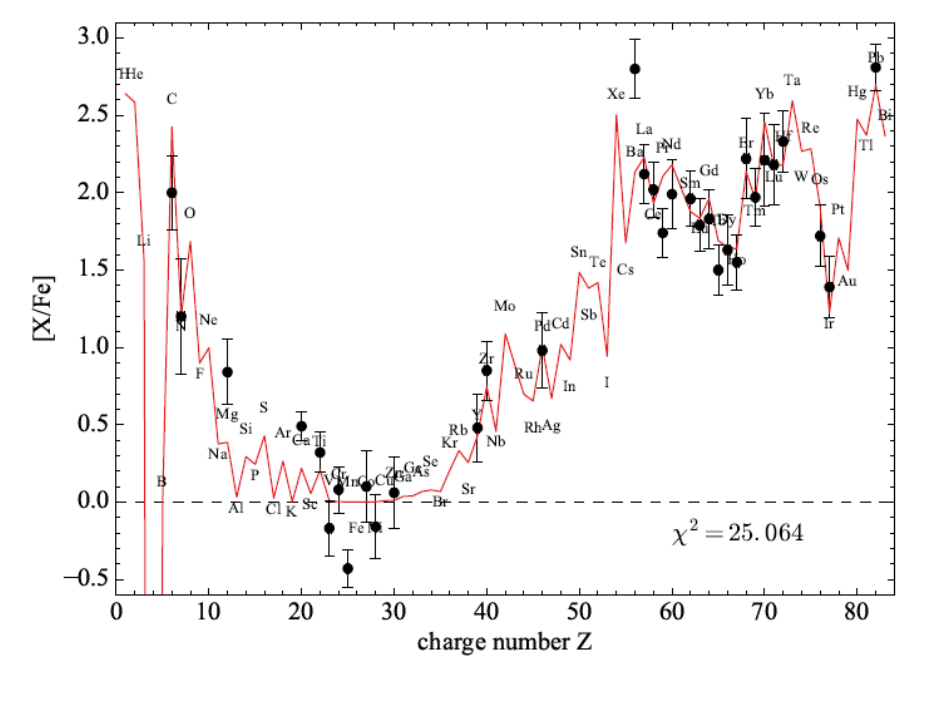
H-ingestion in rapidly accreting WDs (RAWD)



Denissenkonv+ 2018

ALTERNATIVE SOLUTIONS?

H-ingestion in rapidly accreting WDs (RAWD)



Denissenkonv+ 2018

PROBLEMS

- Statistics: how many triple systems in the halo? Binarity of CEMP s/r stars? (talk by Abate & Stancliffe)

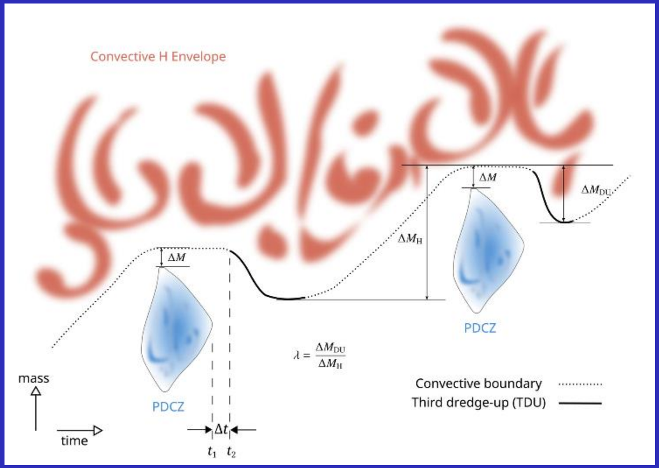
ALTERNATIVE SOLUTIONS?

Massive AGBs stars at low Z

Jones+ 2016 suggest that PIEs occurring in massive Agbs could lead to the obnserved [hs/ls] ratios. However, no s-process calculation has been performed yet (?)

Complex interaction between dredge-up and dredge-out events.

Next talk by C. Doherty



Jones+ 2016

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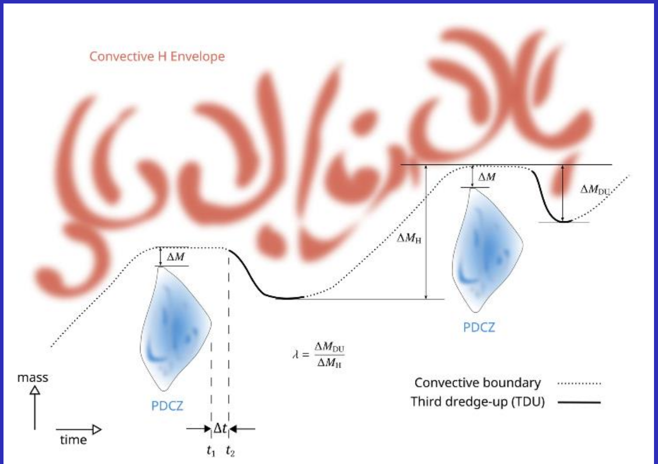


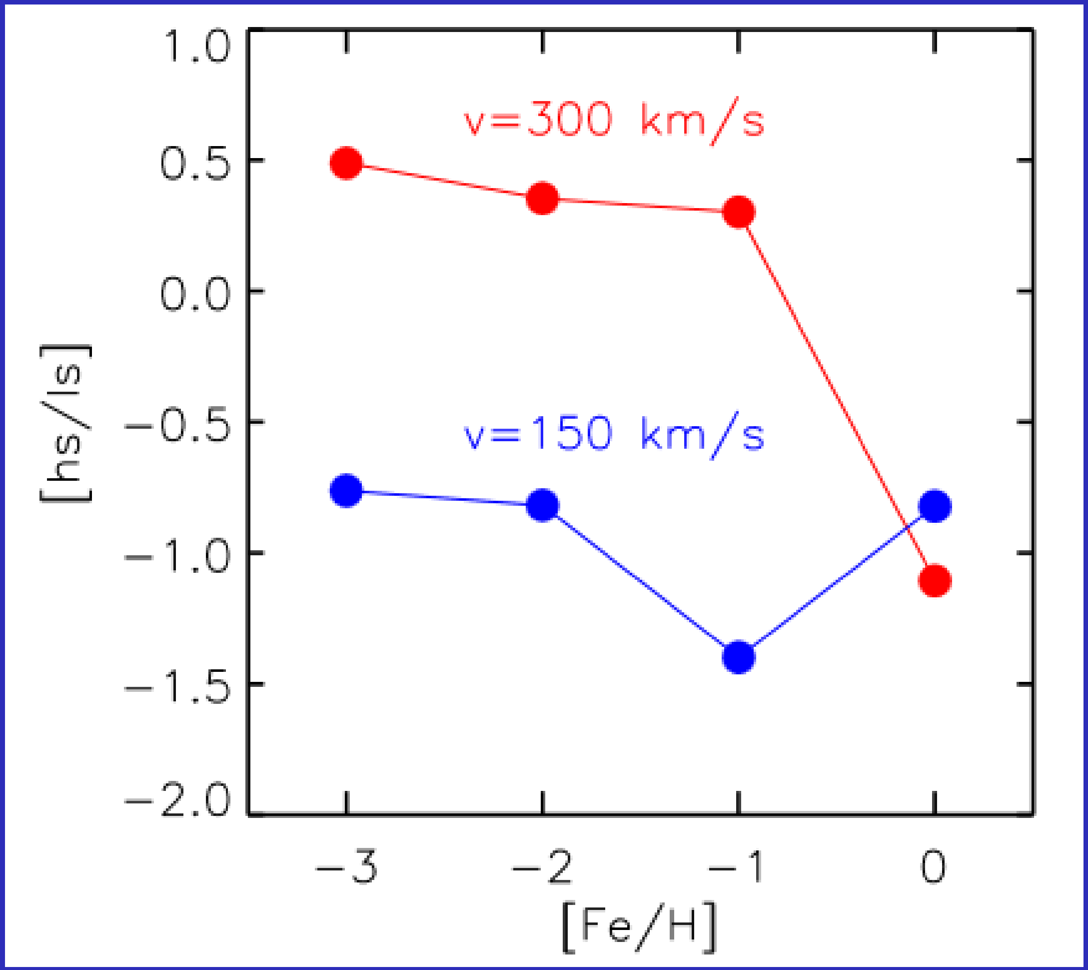
Jones+ 2016

PROBLEMS

- Statistics
- Very high temperature (see Goriely & Siess 2004)

ALTERNATIVE SOLUTIONS?

Rotating massive stars at low Z



Limongi & Chieffi 2018

See also Frischknecht+ 2016

Talk by G. Meynet

Take home message

1. Mechanism at the origin of the ^{13}C pocket still not unequivocally identified;
2. Only post-processes are able to fit observed disributions;
3. Rotation cannot help improving the situation;
4. PIEs (i-process) could be a viable solution, but AGB stellar models are not yet able to reproduce observed distributions
5. Magnetic induced mixing: to be studied yet!
6. Alternative solutions (RAWD)? To be verified!