Effects of Rotation on the s-process Nucleosynthesis in low-mass AGB Stars

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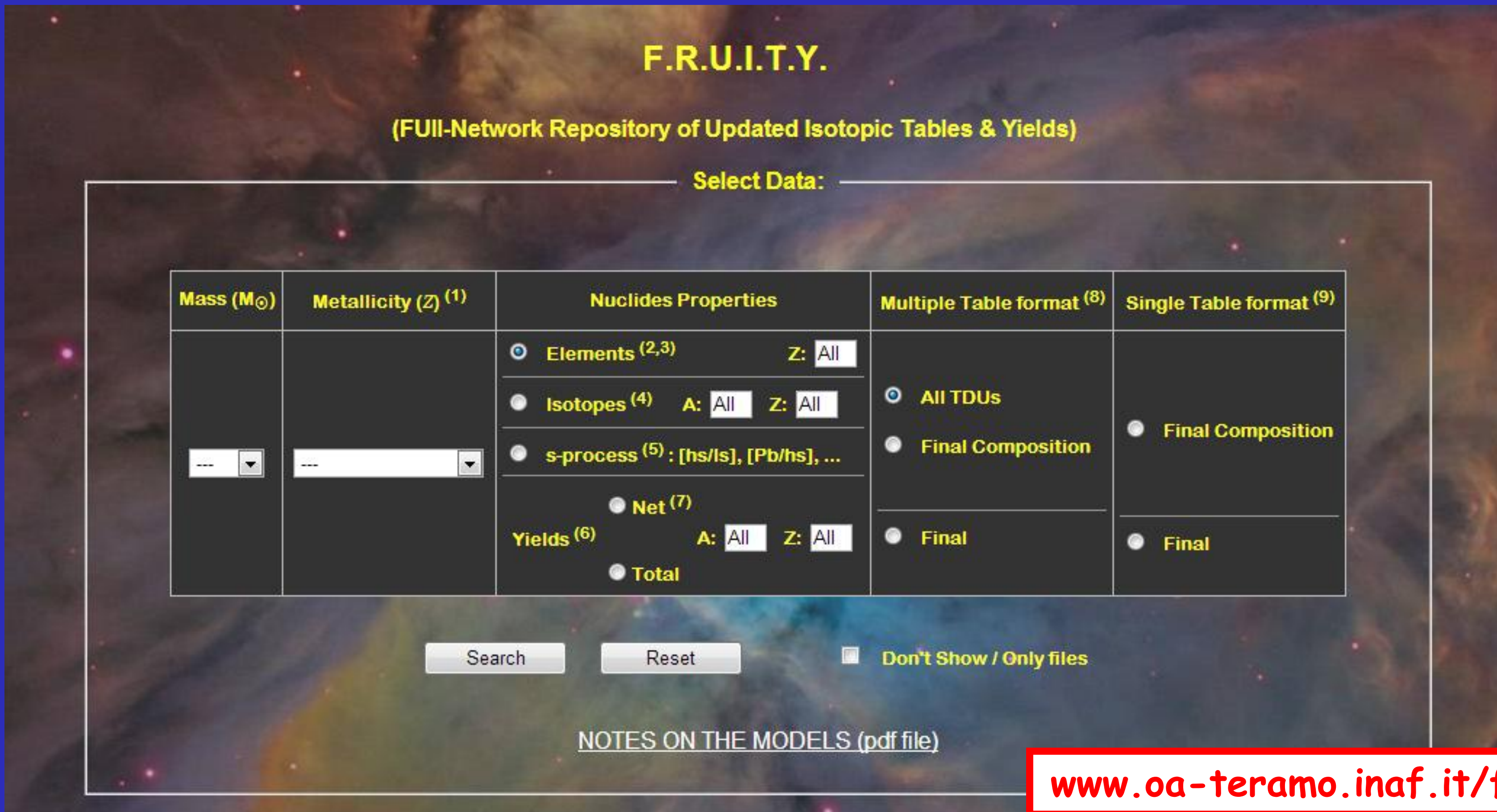
Partial financial support from the MIUR (FIRB2008)

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

FUll-Network Repository of Updated Isotopic Tables & Yields

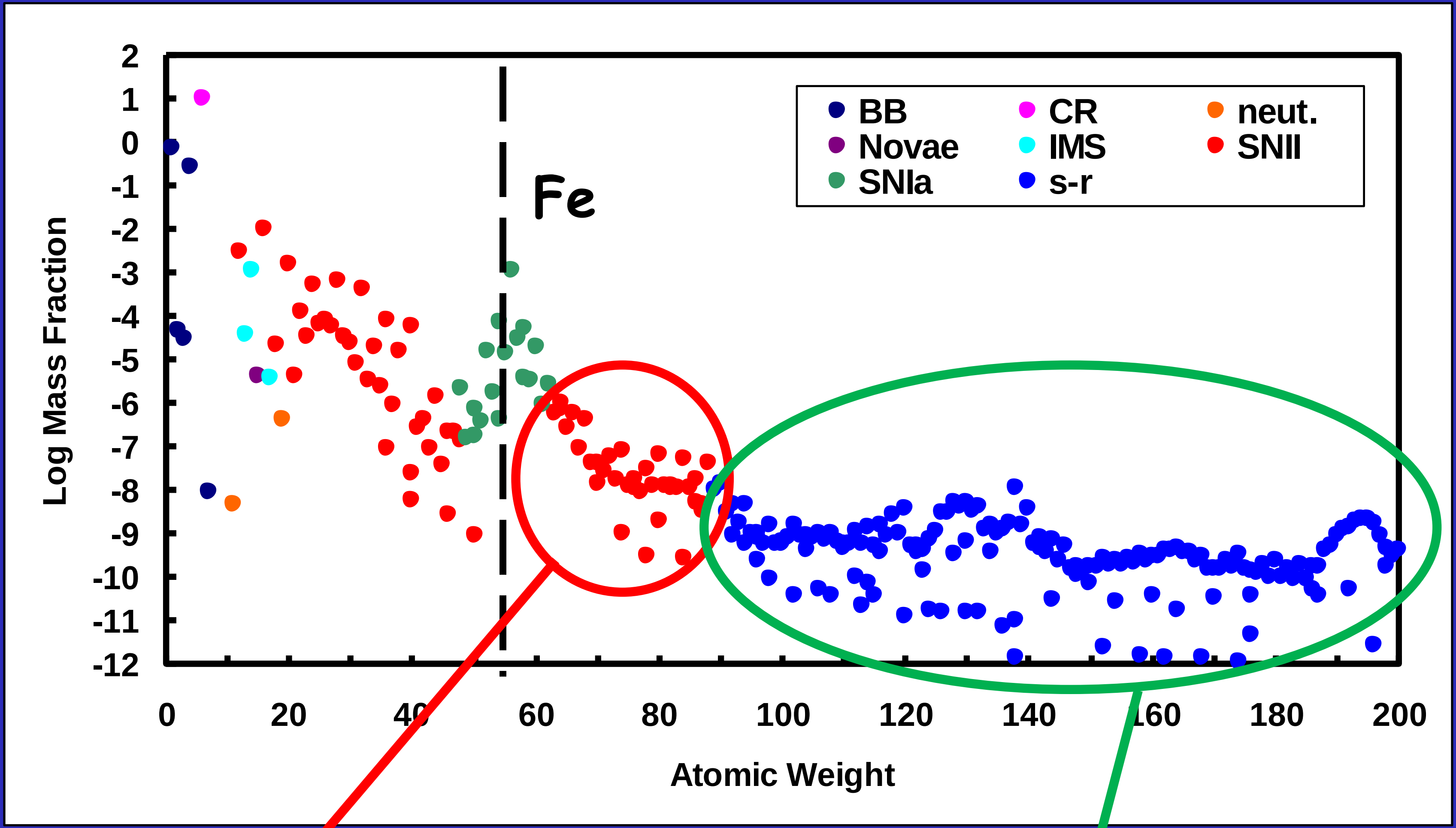


www.oa-teramo.inaf.it/fruity

$10^{-4} \leq Z \leq Z_{sun}$

$1.3 \leq M/M_{sun} \leq 3.0$

Origin of the elements



Weak Component: A<90

Main Component: 90<A<204

Massive Stars

AGB Stars

A bit of history …

1868: Father A. Secchi observed "Red Carbon Stars" in the Galactic Disk

C stars have C/O > 1

Evolved low mass giant stars (AGB Stars)

They go through the M, MS, S, C(N) stage

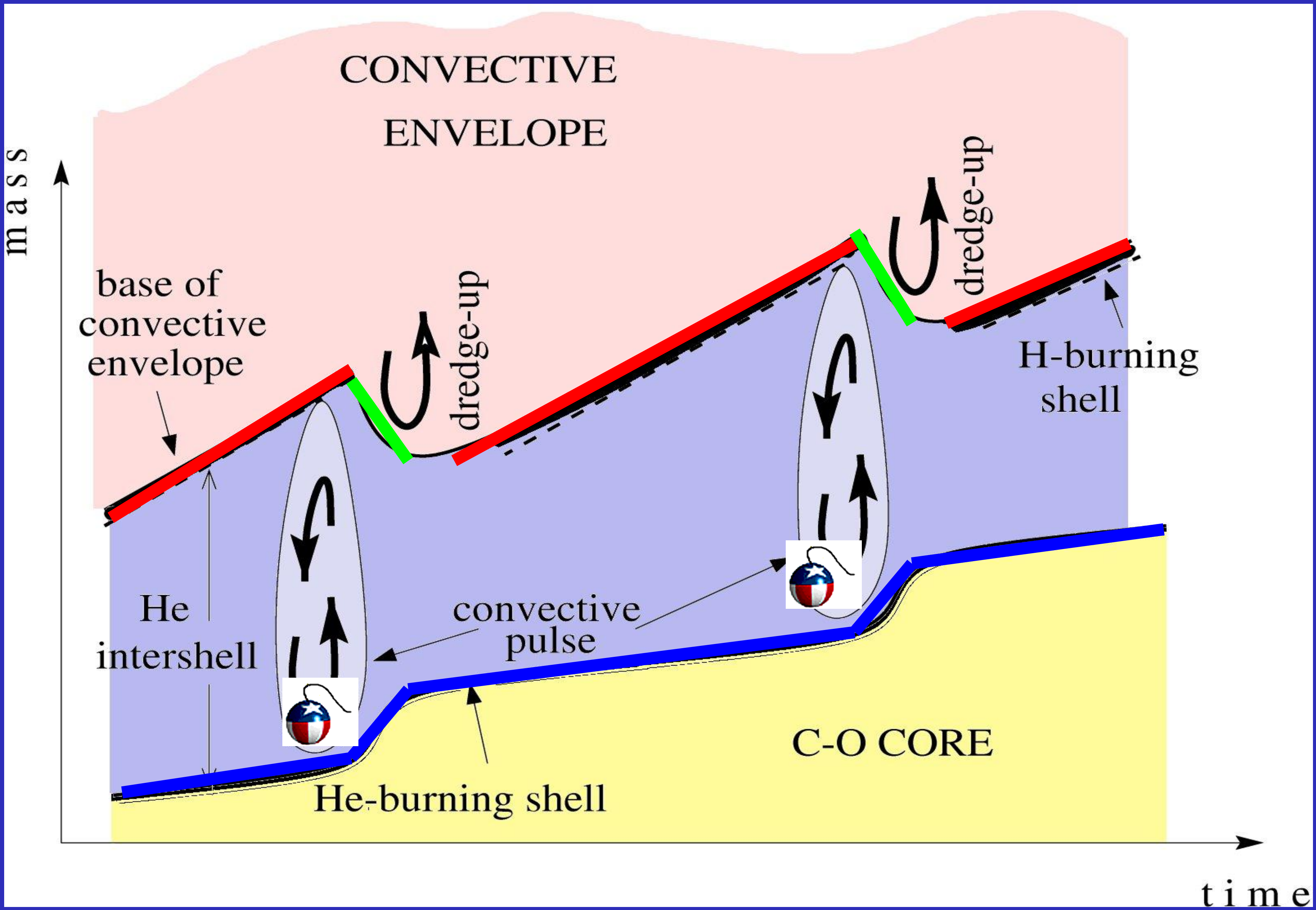
Enhancement of s-elements (both light-s and heavy-s)

Detection of ^{99}Tc $\tau_{hl} \sim 10^5$ yr

⬇

The enrichment in s-elements and carbon has to occur during the AGB phase!

The Third Dredge-Up



The neutrons source

In principles all reactions producing neutrons

(p,n),(α,n),(γ,n),...

- Actually, there are only two efficient reactions:

$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$
?	$^{14}N(\alpha,\gamma)^{18}F(\beta^{-}\nu)^{18}O\ (\alpha,\gamma)^{22}Ne$
It works for $T\sim 9\cdot 10^7$ K	It works for $T>3\cdot 10^8$ K
	This occurs in AGBs with $M>3M_{sun}$
	Lack of C-enhancement

The formation of ^{13}C pocket

A bit of history

Iben 1982

Atomic diffusion driven by the sharp chemical discontinuity.

Herwig et al. 1997

Convective overshoot.

Langer et al. 1999

Rotation-induced mixing.

Denissenkov & Tout 2003

Gravity waves.

Busso et al. 2004

Circulation induced by magnetic field.

The formation of ^{13}C pocket

Becker & Iben 1979

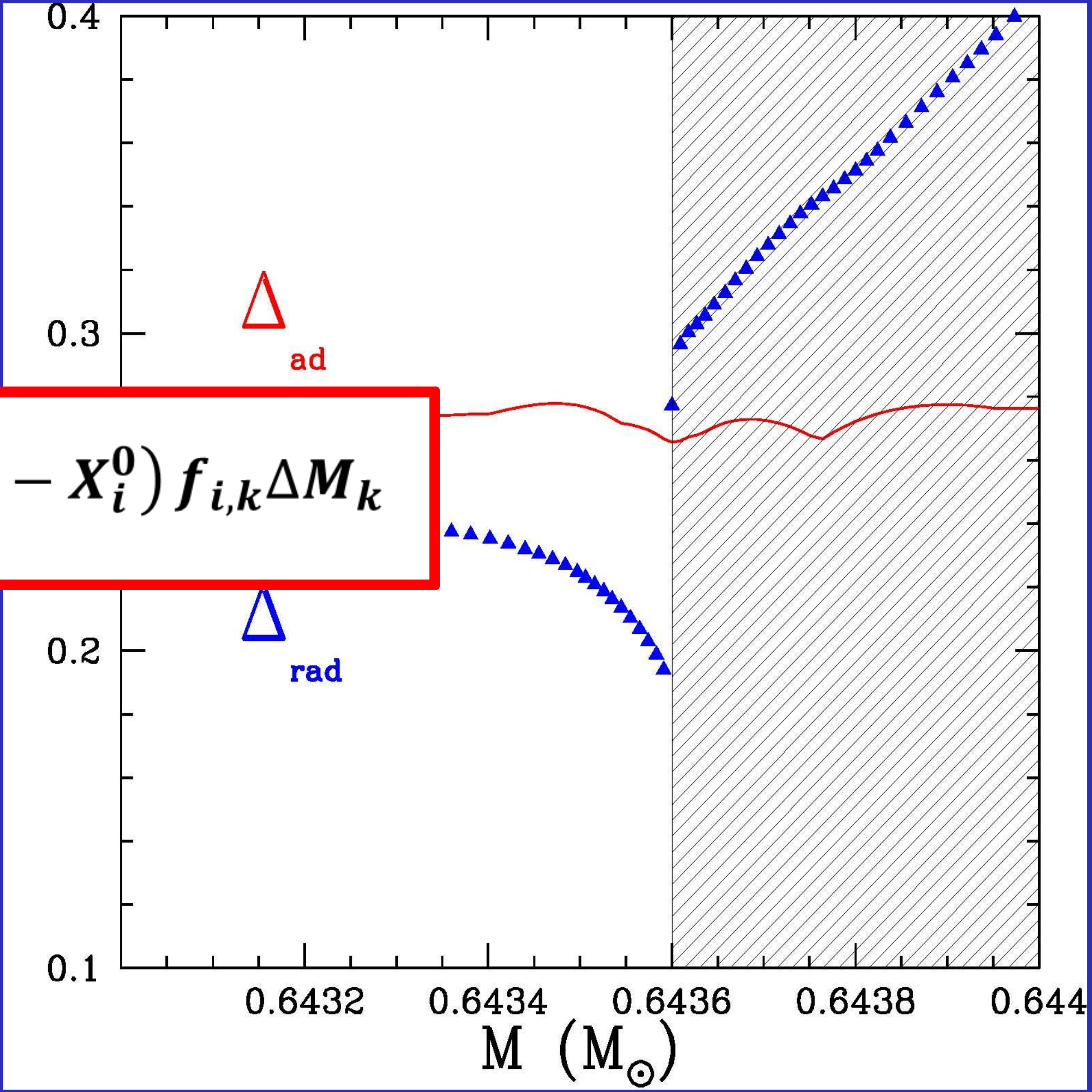
The inner border of CE is unstable!

Straniero et al. 2006

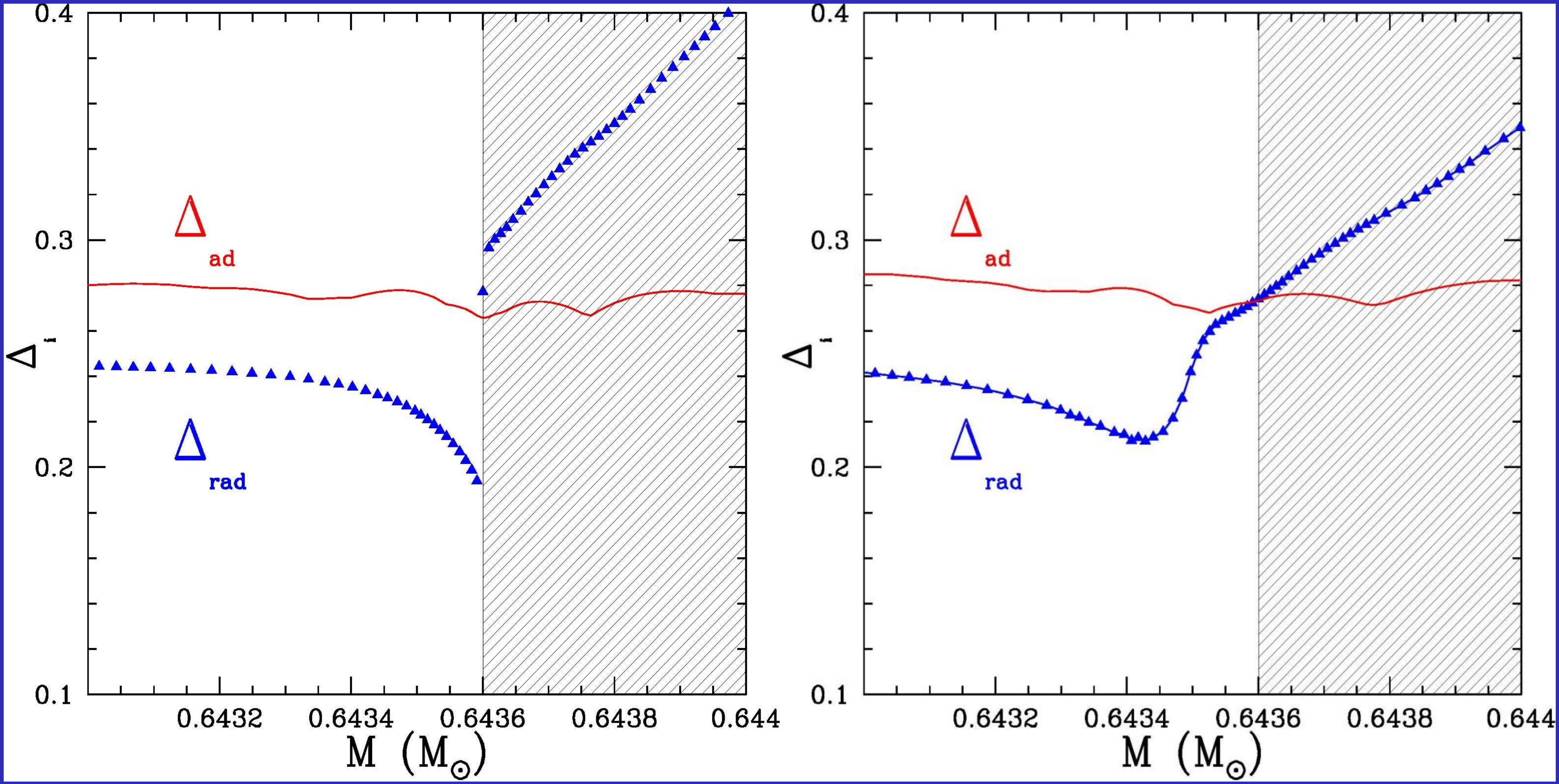
$$X_i = X_i^0 + \frac{1}{M_{conv}} \sum_k \left(X_k^0 - X_i^0\right) f_{i,k} \Delta M_k$$

$$f_{i,k} = \Delta t \left[\int_{r_i}^{r_k} \frac{dr}{v(r)} \right]^{-1}$$

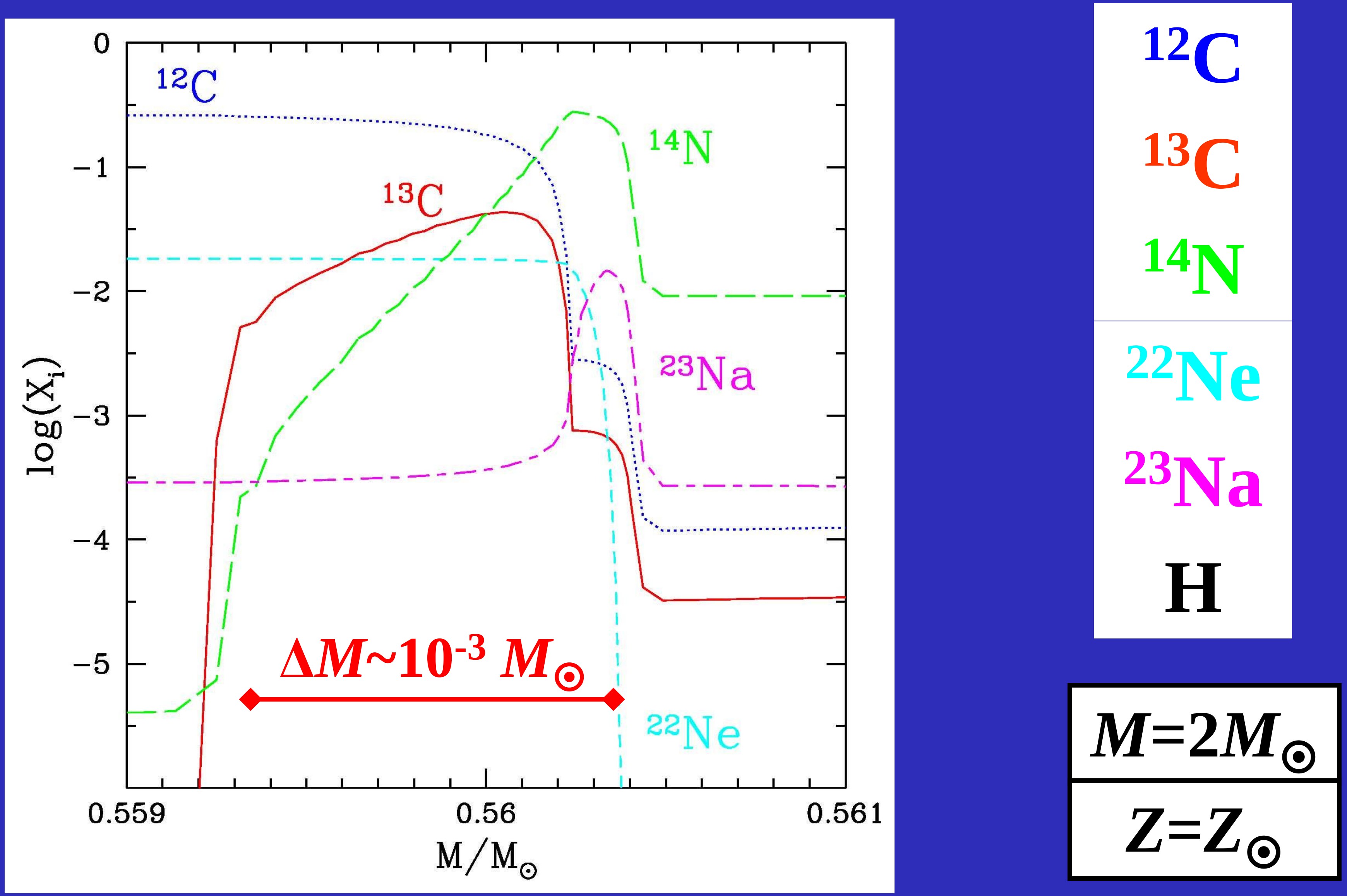
$$v = v_{BCE}\, e^{-\frac{d}{\beta H_P}}$$



The formation of ^{13}C pocket



The formation of ^{13}C pocket



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

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

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

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

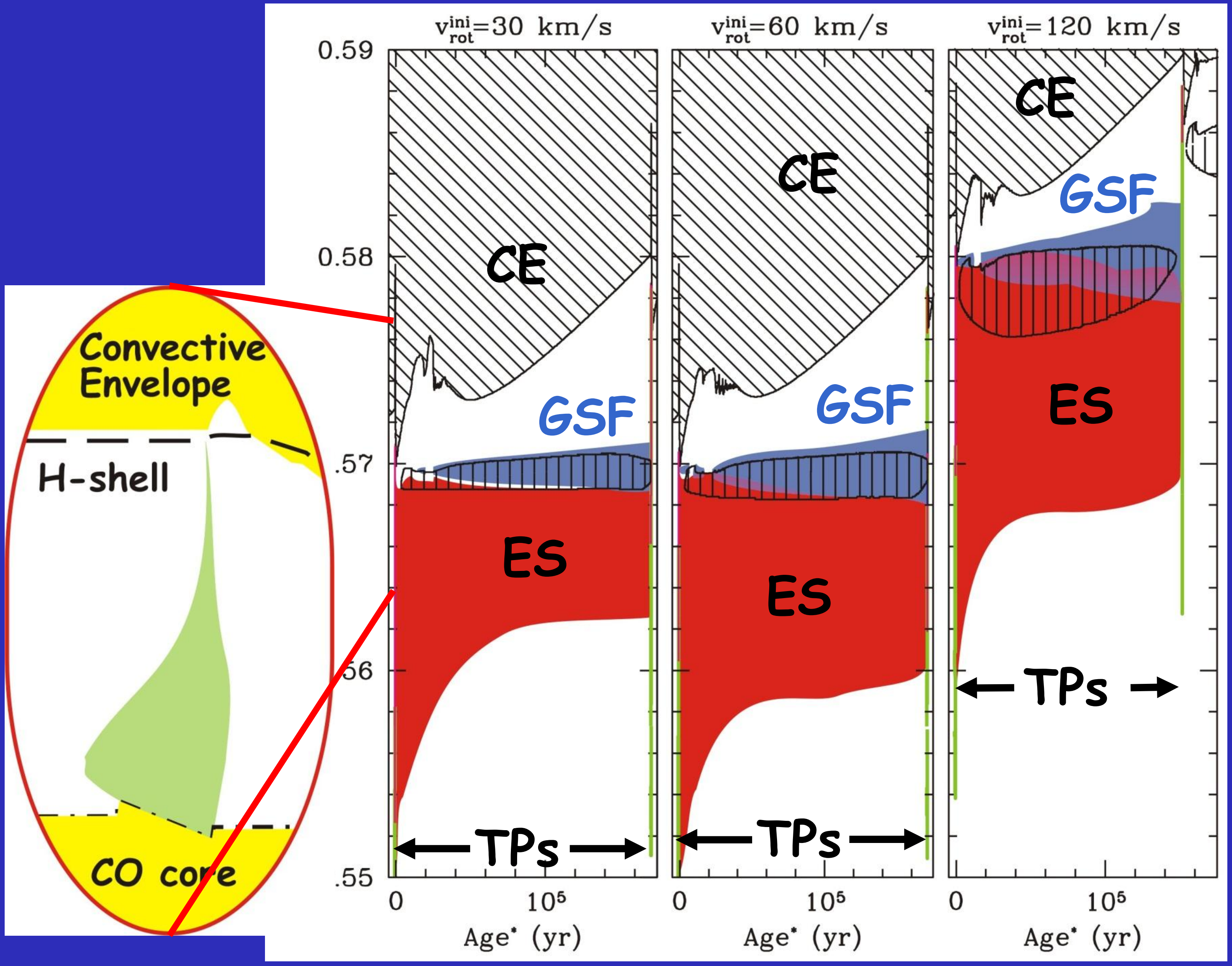
$$D_J = D_{conv} + f_{\omega} f_c (D_{ES} + D_{GSF} + D_{SS} + D_{DS} + D_{SH})$$

The models

M=2 M_{sun} – [Fe/H]=0						
V_{ini} [km/s]	τ_{MS} [10^8 yr]	M_H^{Tip} [M_{sun}]	τ_{He} [10^8 yr]	C/O	$M^{CO}{}_{AGB}$ [M_{sun}]	$M^H{}_{AGB}$ [M_{sun}]
0	9.693	0.4628	1.212	0.253	0.512	0.545
10	9.702	0.4651	1.196	0.255	0.513	0.545
30	9.706	0.4653	1.194	0.257	0.517	0.550
60	9.714	0.4659	1.190	0.257	0.519	0.550
120	9.783	0.4686	1.147	0.267	0.532	0.561

M=1.5 M_{sun} – [Fe/H]=-1.7 – [α/Fe]=0.5						
0	16.470	0.4794	0.913	0.394	0.548	0.579
10	16.468	0.4795	0.913	0.395	0.545	0.574
30	16.493	0.4797	0.908	0.399	0.548	0.577
60	16.542	0.4799	0.900	0.404	0.552	0.581
120	16.905	0.4811	0.885	0.406	0.561	0.587

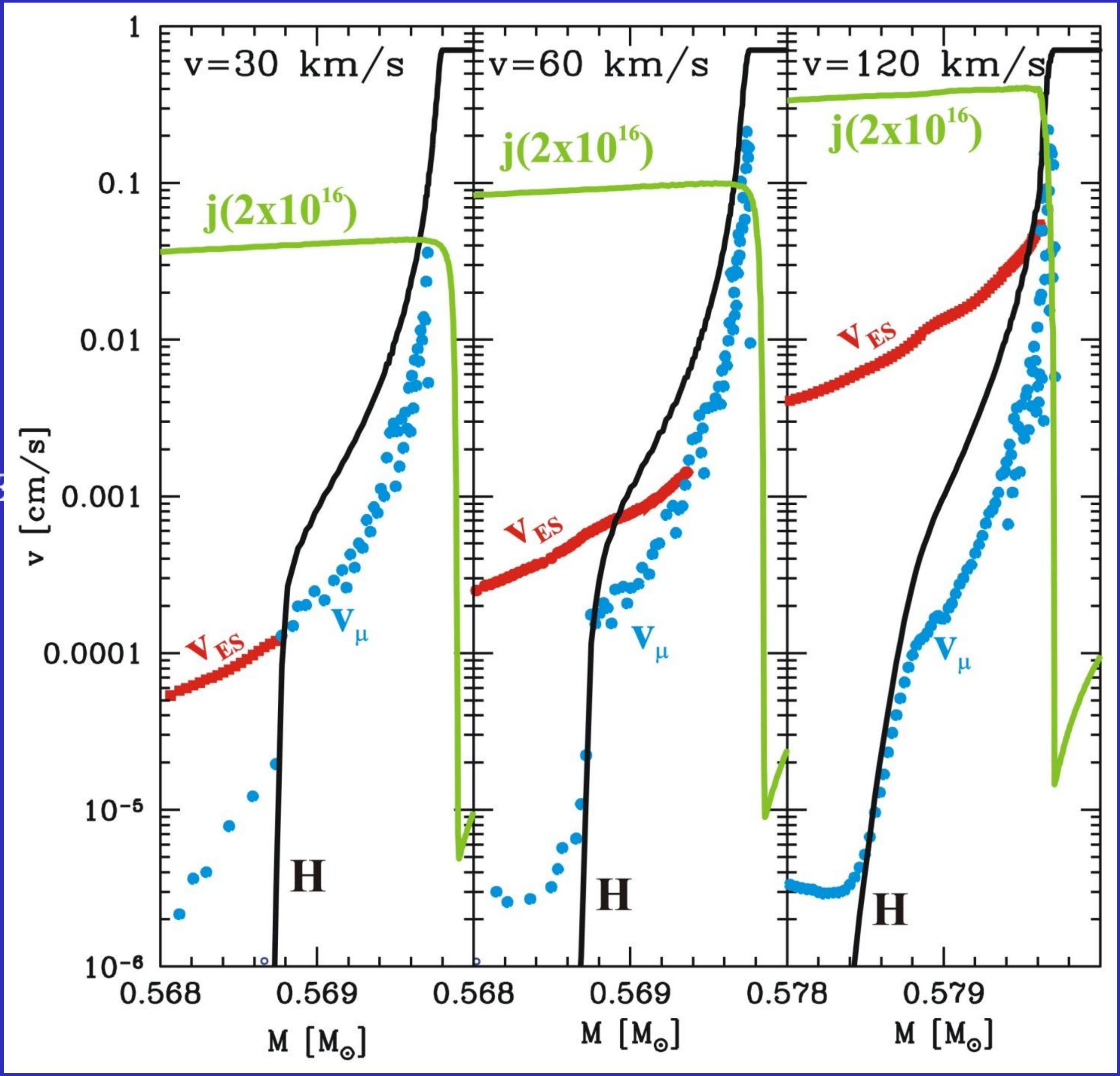
The AGB phase: the [Fe/H]=0 case



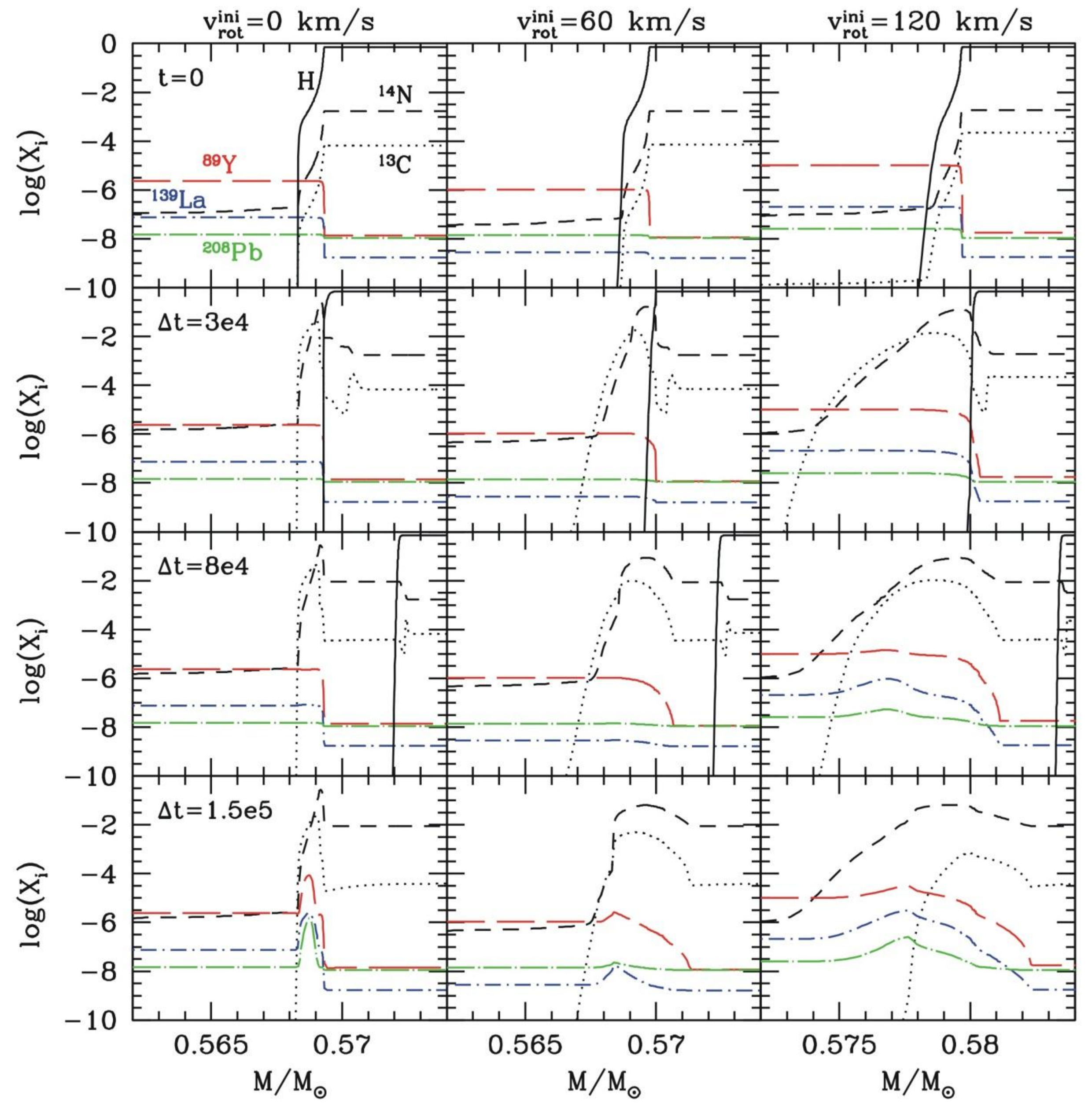
The ES circulation velocity

$v_{ES} =$

v_E



The AGB phase: the [Fe/H]=0 case



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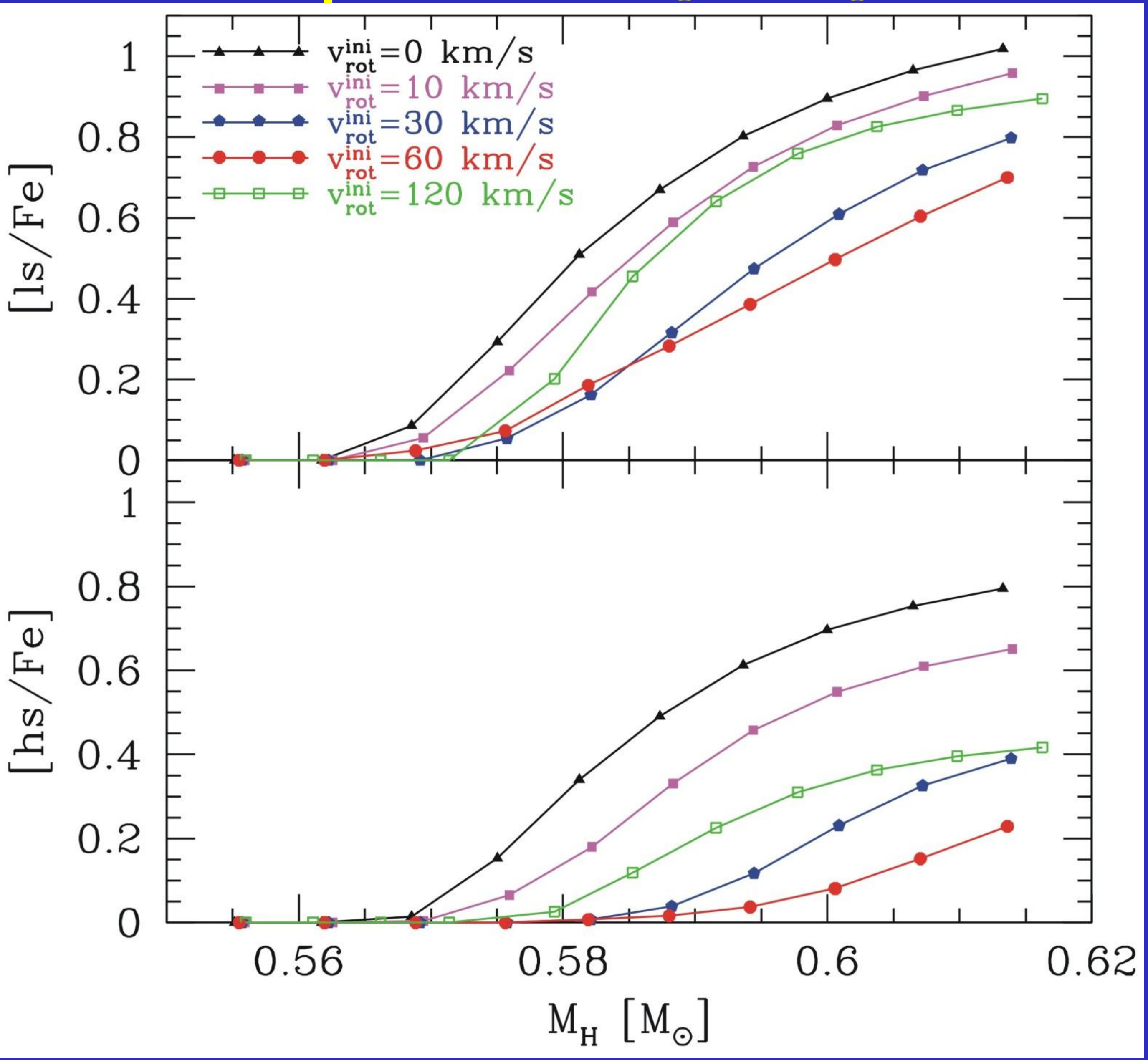

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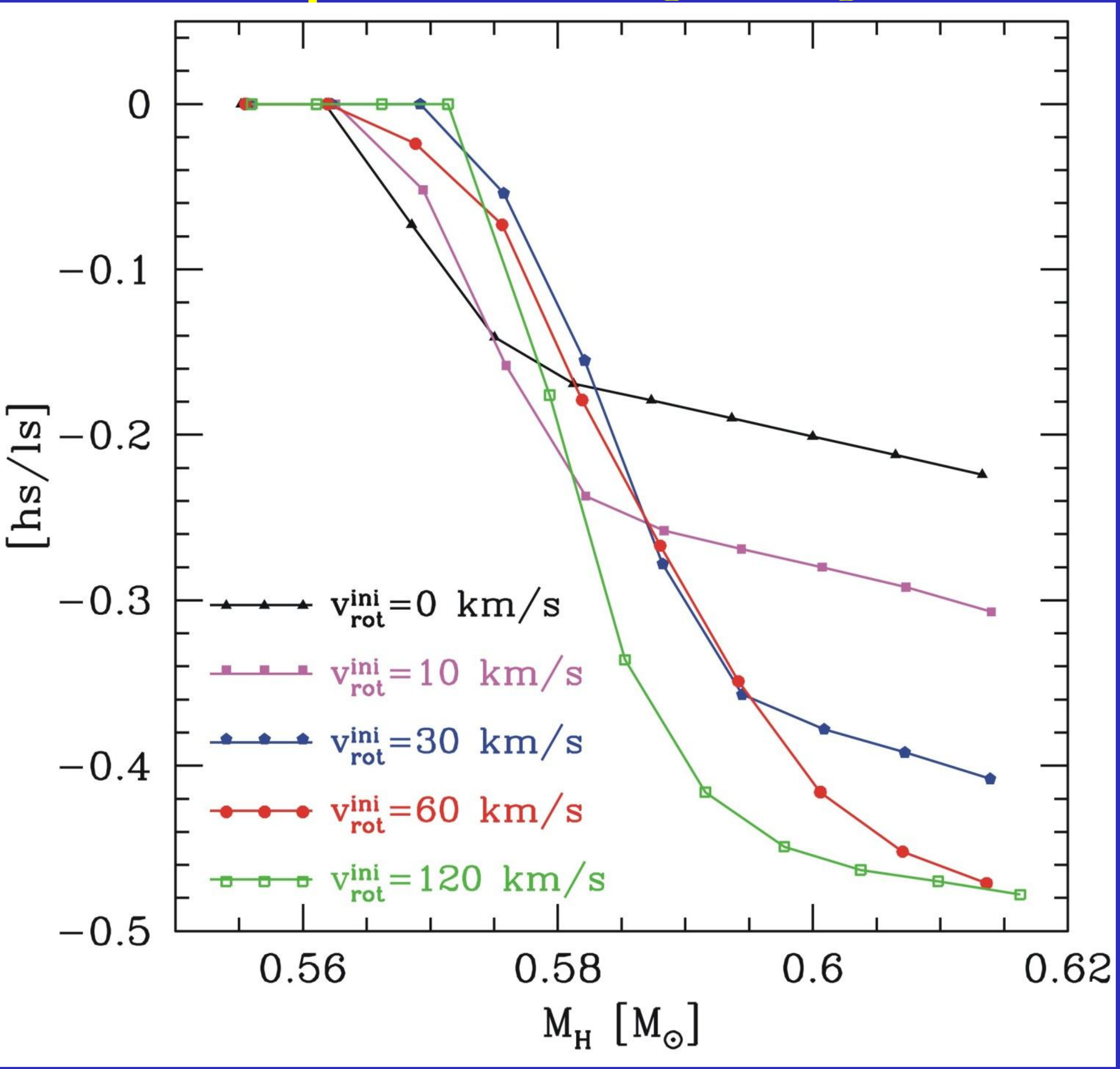
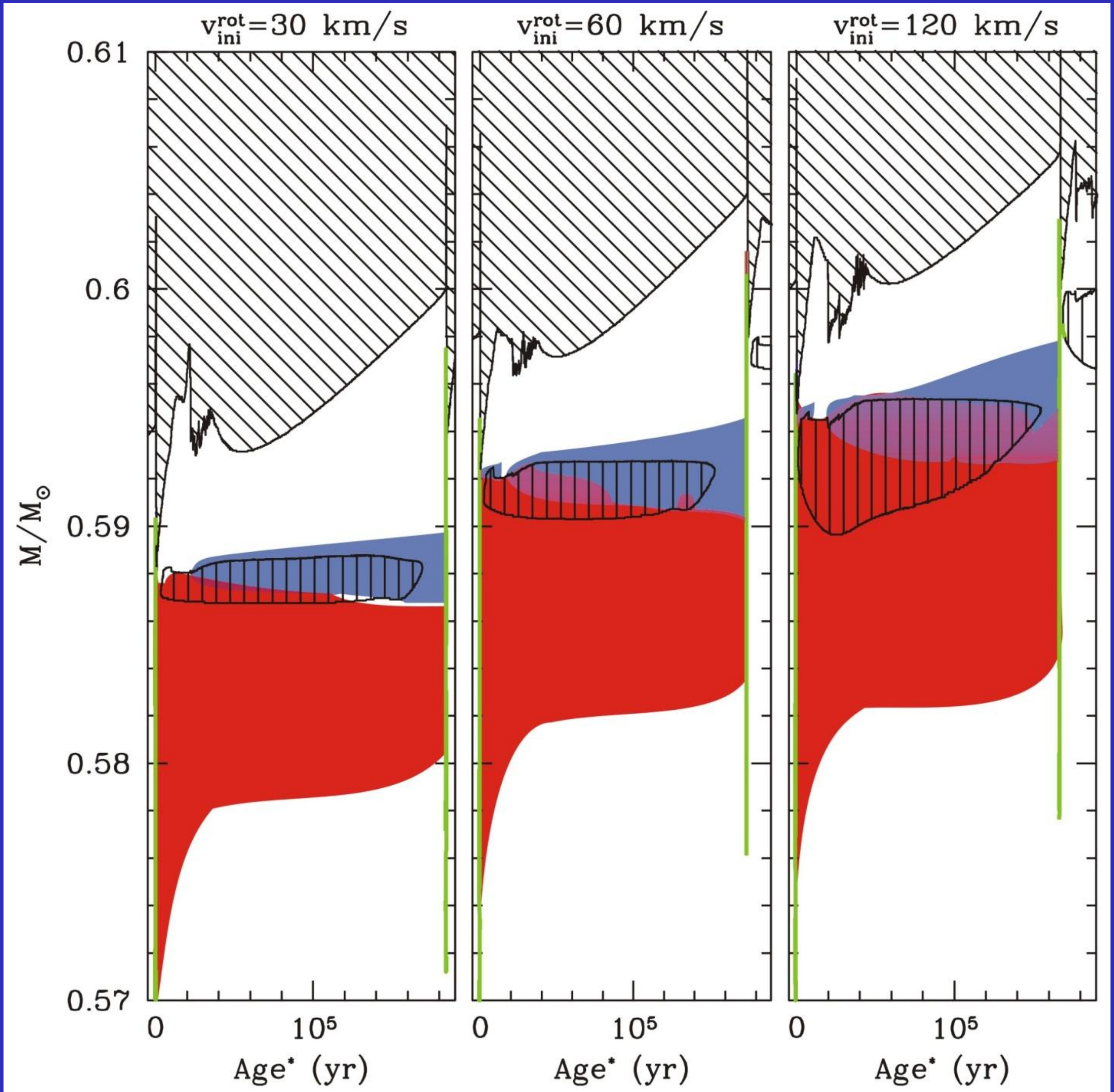


The AGB phase: the [Fe/H]=-1.7 case



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

Without rotation ...

The Fe abundance is low

The neutrons-to-seeds ratio is very high

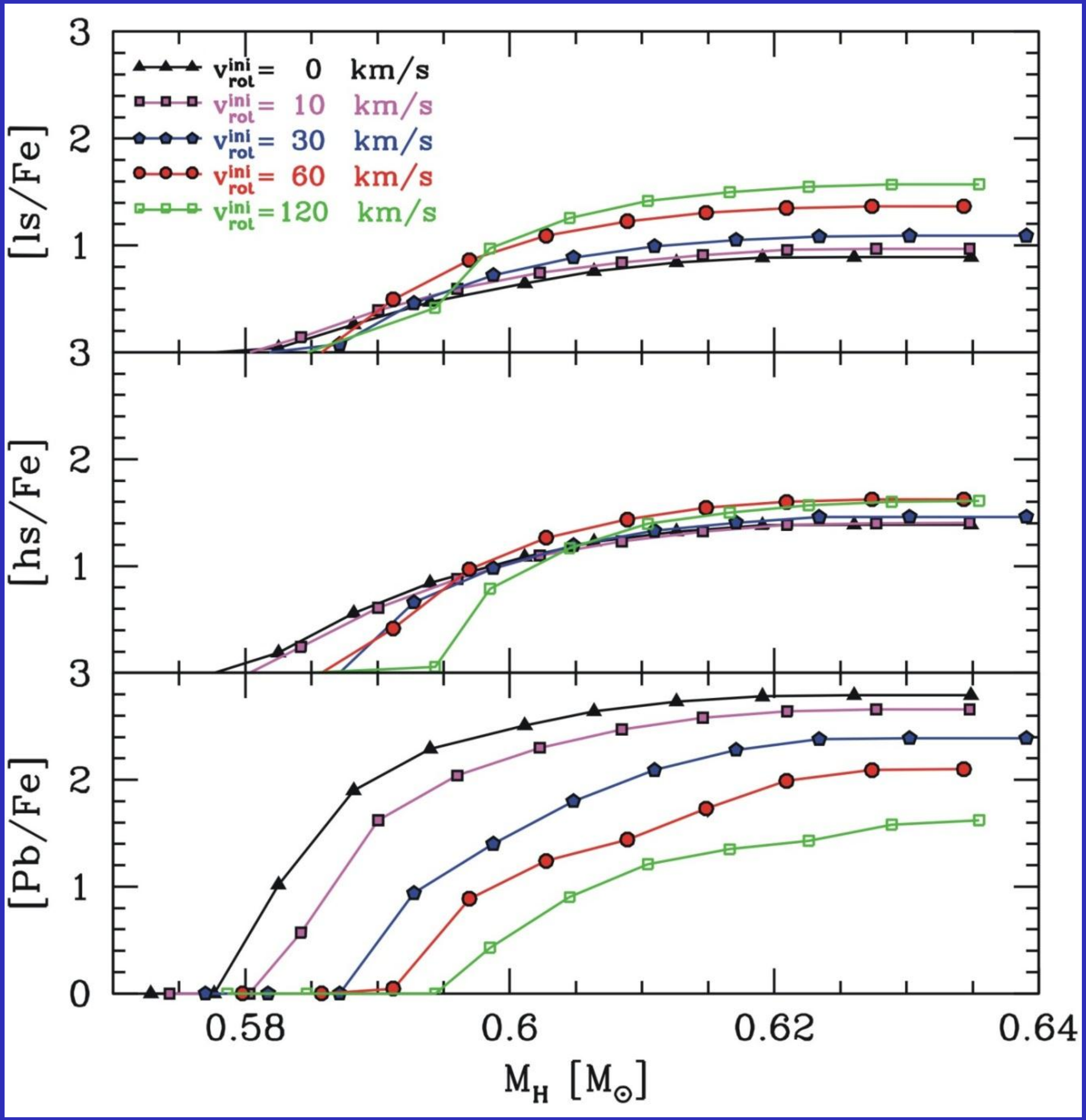
The s-process produces large amount a Pb

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



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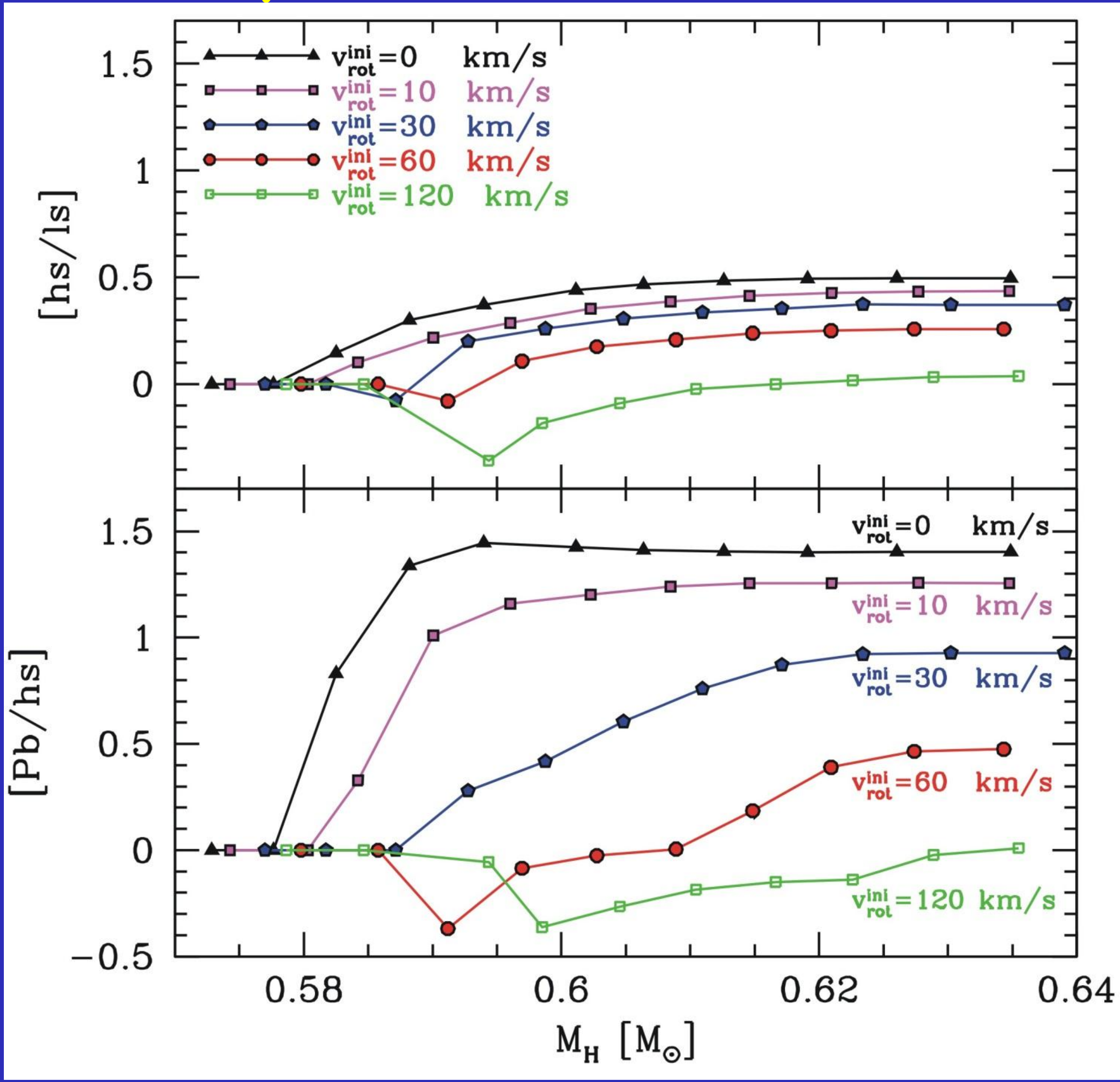
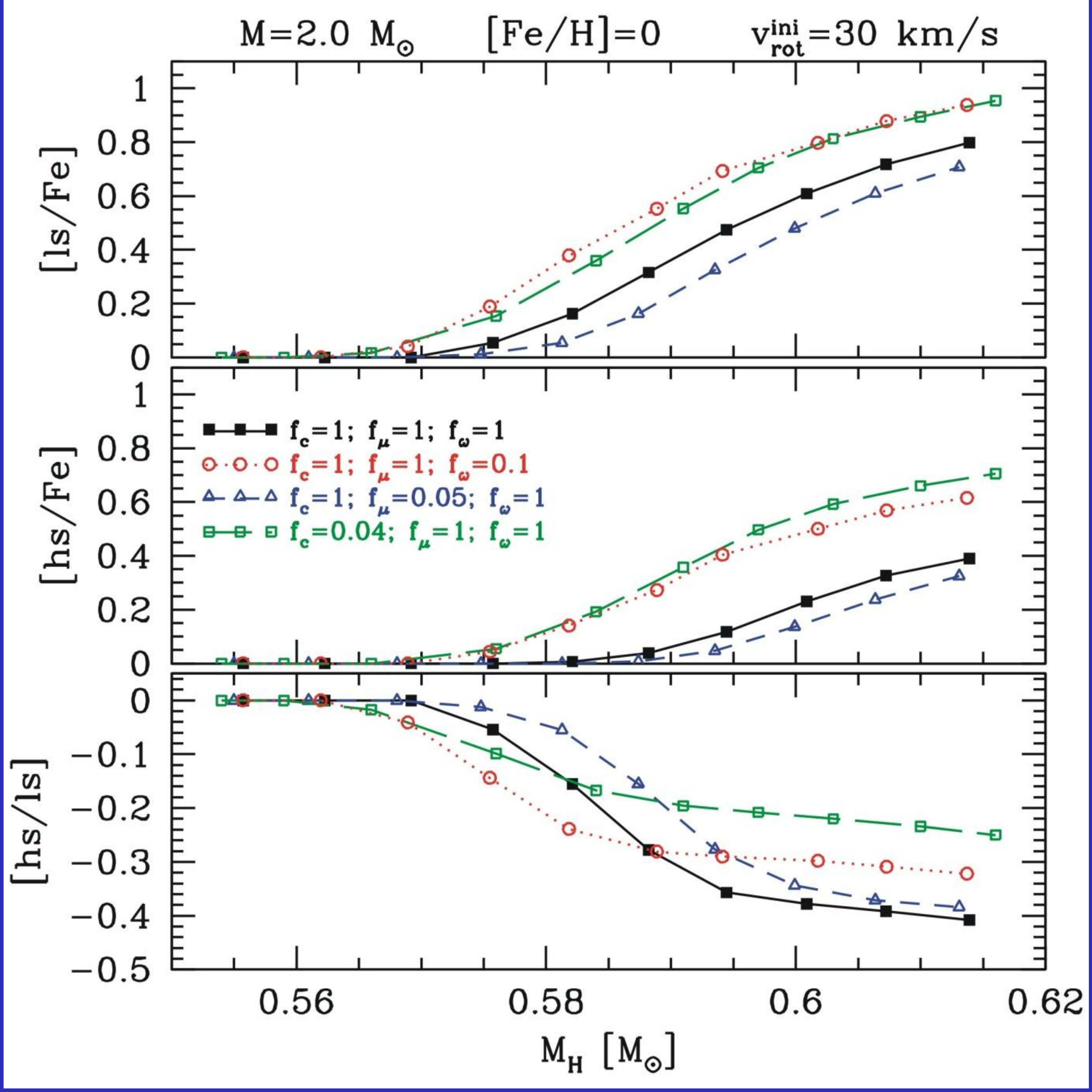
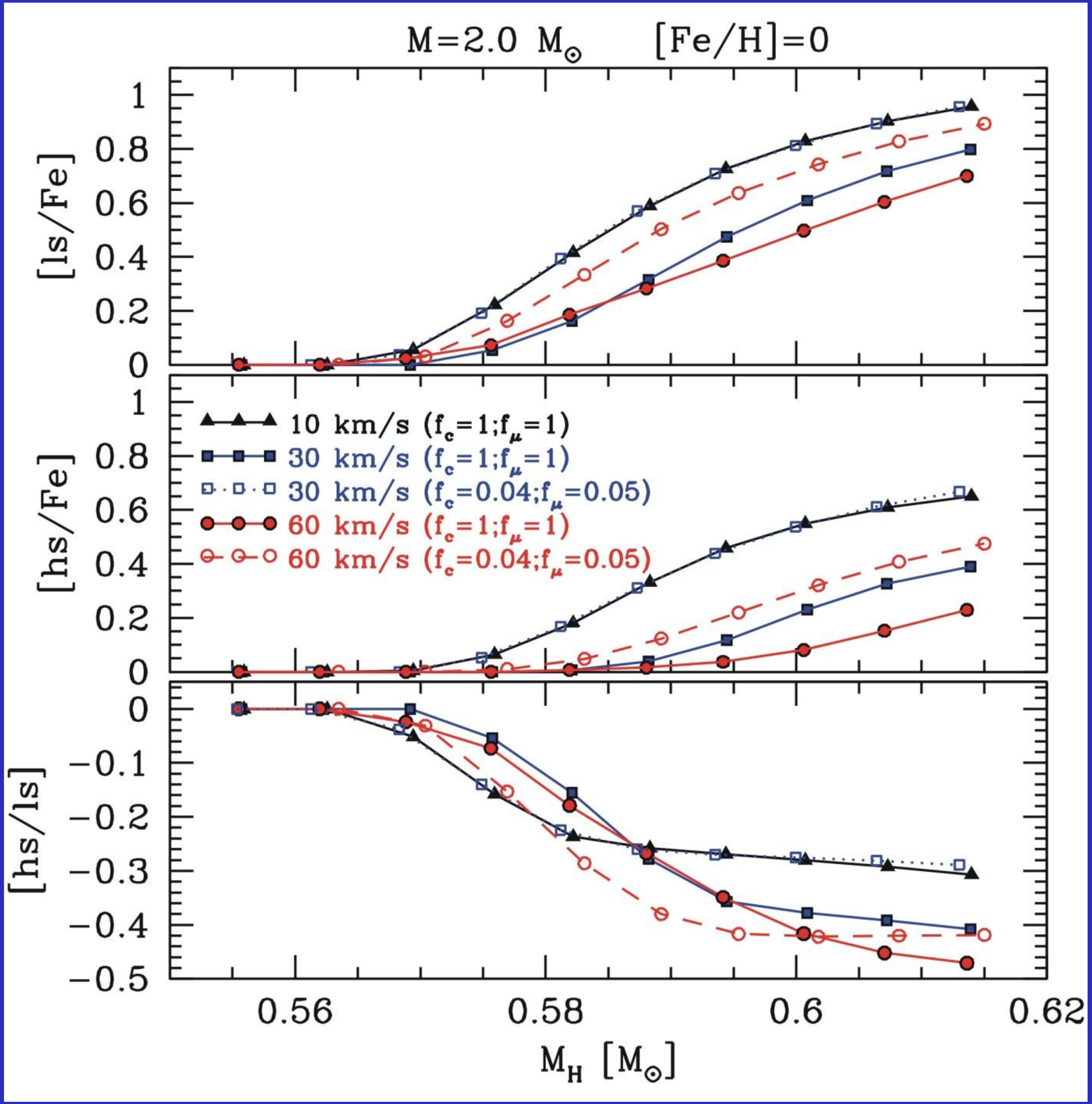


What are the uncertainties? (I)



What are the uncertainties? (II)



Summary

Rotation-induced mixing…

Modify the mass extension of ^{13}C and ^{14}N pocket and their relative overlap.

Reduce the average neutrons-to-seeds ratio

the total amount of heavy elements is lower

ls production is favoured with respect to hs

Increasing v_{rot}^{ini} both [hs/ls] and [Pb/hs] decrease

Some CEMP have low [Pb/hs]… (Bisterzo et al 2011)

Rotating Models vs Observations