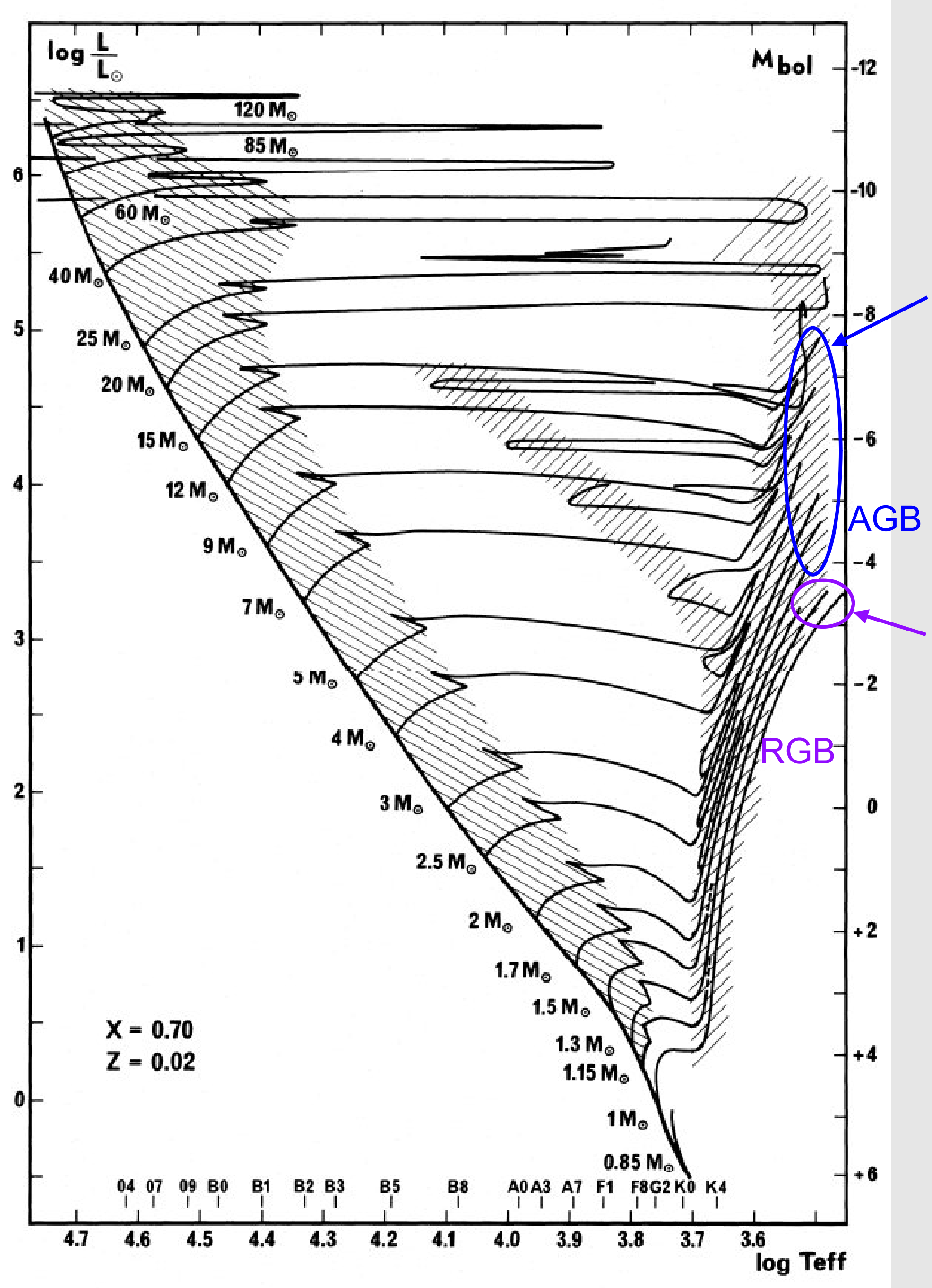
Evolution, Mass Loss and Variability of Low and Intermediate-Mass Stars

What are low and intermediate mass stars?



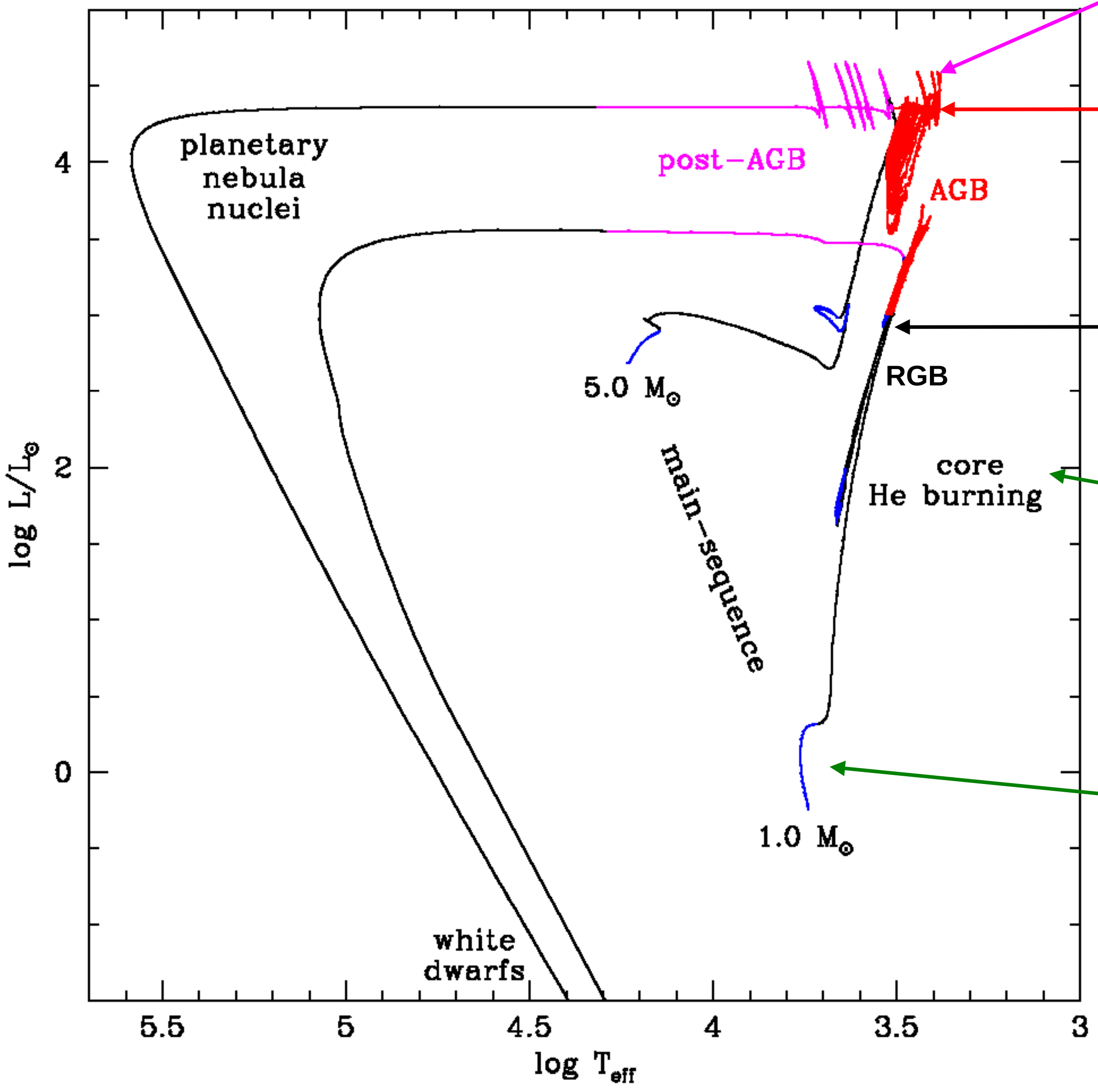
Maeder & Meynet 1989

Defined by properties of late stellar evolutionary stages

Intermediate mass stars: ~1.9 < M/Msun < ~7
Develop electron-degenerate cores after core helium burning and ascending the red giant branch for the second time i.e. on the Asymptotic Giant Branch (AGB).

Low mass stars: M/Msun < ~1.9
Develop electron-degenerate cores on leaving the main-sequence and ascending the red giant branch for the first time i.e. on the Red Giant Branch (RGB).

Stages in the evolution of low and intermediate-mass stars



Wood, P. R.,2007, ASP Conference Series, 374, 47

These spikes are real

The AGB
Surface enrichment
Pulsation
Mass loss

The RGB
Surface enrichment
Pulsation
Mass loss

About 10^8 years spent here

Most time spent on the main-sequence burning H in the core (~10^{10} years)

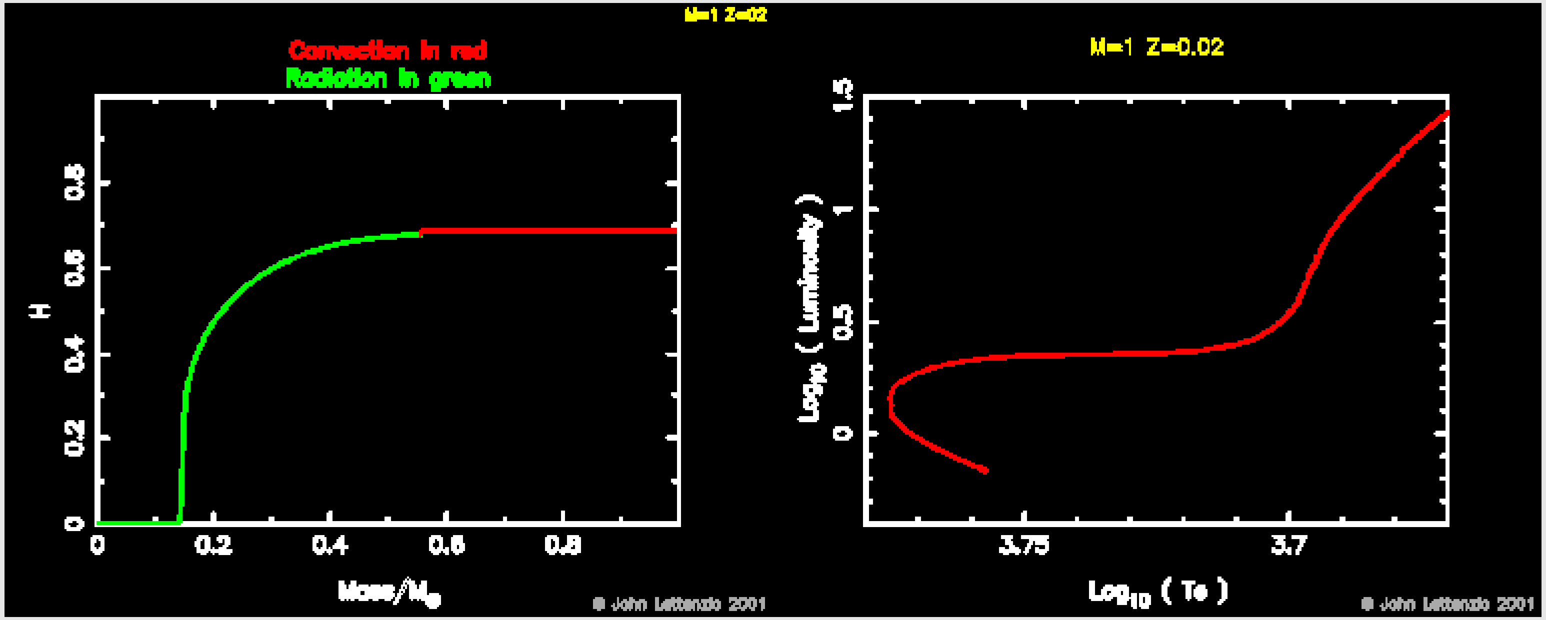
Low mass stars:
M < ~1.9 Msun

Intermediate mass stars:
~1.9 < M/Msun < ~7

Stellar evolution and surface enrichment

The Red giant Branch (RGB)

- Hydrogen burns in a shell around an electron-degenerate He core, star evolves to higher luminosity.
- First dredge-up occurs: The convection in the envelope moves in when the stars is near the bottom of the RGB and "dredges up" material that has been through partial hydrogen burning by the CNO cycle and pp chains.

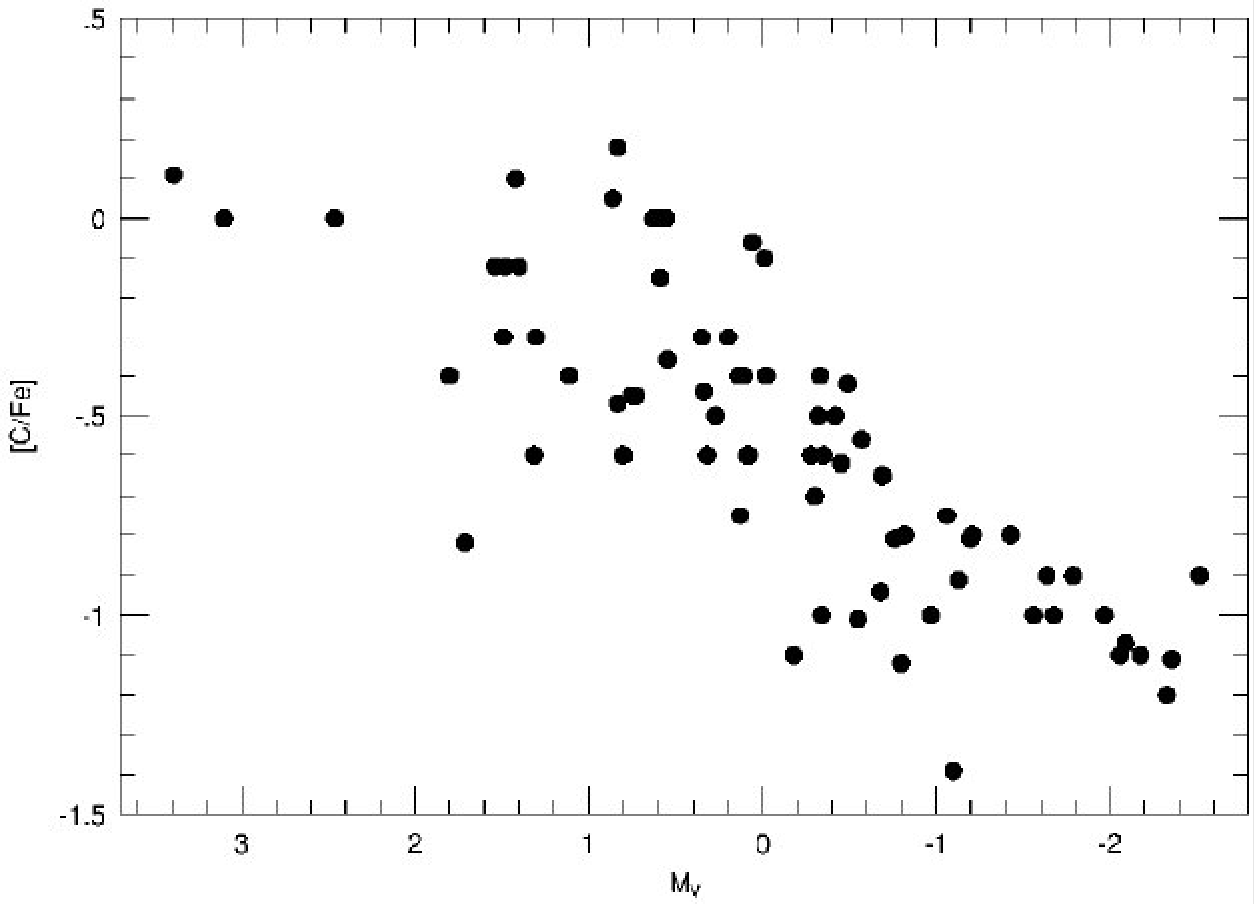


From John Lattanzio

But there's more: extra-mixing

What's the evidence?

Various abundances and isotopic ratios vary **continuously** up the RGB.
This is not predicted by a single first dredge-up alone.



Bellman et al (2001)

M92 RGB stars

Possible sources of extra-mixing

- Rotation-induced mixing
- Magnetic fields
- Internal gravity waves
- Thermohaline mixing associated with the reaction $^3He(^3He,2p)^4He$

Thermohaline mixing is currently favoured (e.g. Angelou et al. 2010), perhaps with some modification by rotational-induced mixing (e.g. Charbonnel and Lagarde 2010).

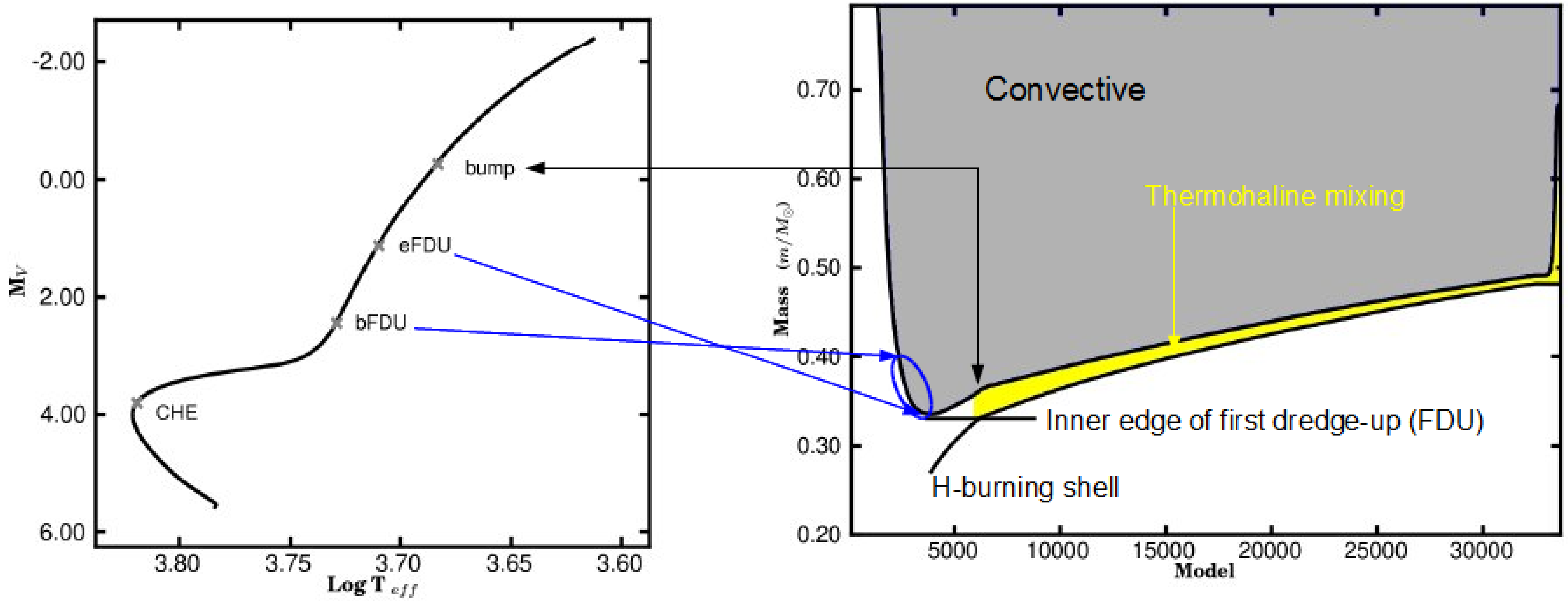
How does thermohaline mixing work?

The reaction ^{3}He(^{3}He,2p)^{4}He is unusual: it produces 3 particles from 2, thus reducing the molecular weight (and it provides extra particle energy as the reaction is exothermic).

The reacting gas expands, its density is lower than the surrounds, it rises and cools due to expansion until in density equilibrium with the surrounding (higher molecular weight) material. Thereafter, the rate of thermal diffusion into the blob governs its further rise. Named by analogy with salt (haline) fingers in the ocean.

Requirements: sufficient ^{3}He, temperatures hot enought to burn ^{3}He, and zero radial abundance gradient.

Where does it occur: outer edge of the H-burning shell when it burns into the envelope material homogenized and enriched in 3He by first dredge-up.



Angelou et al. (2010)

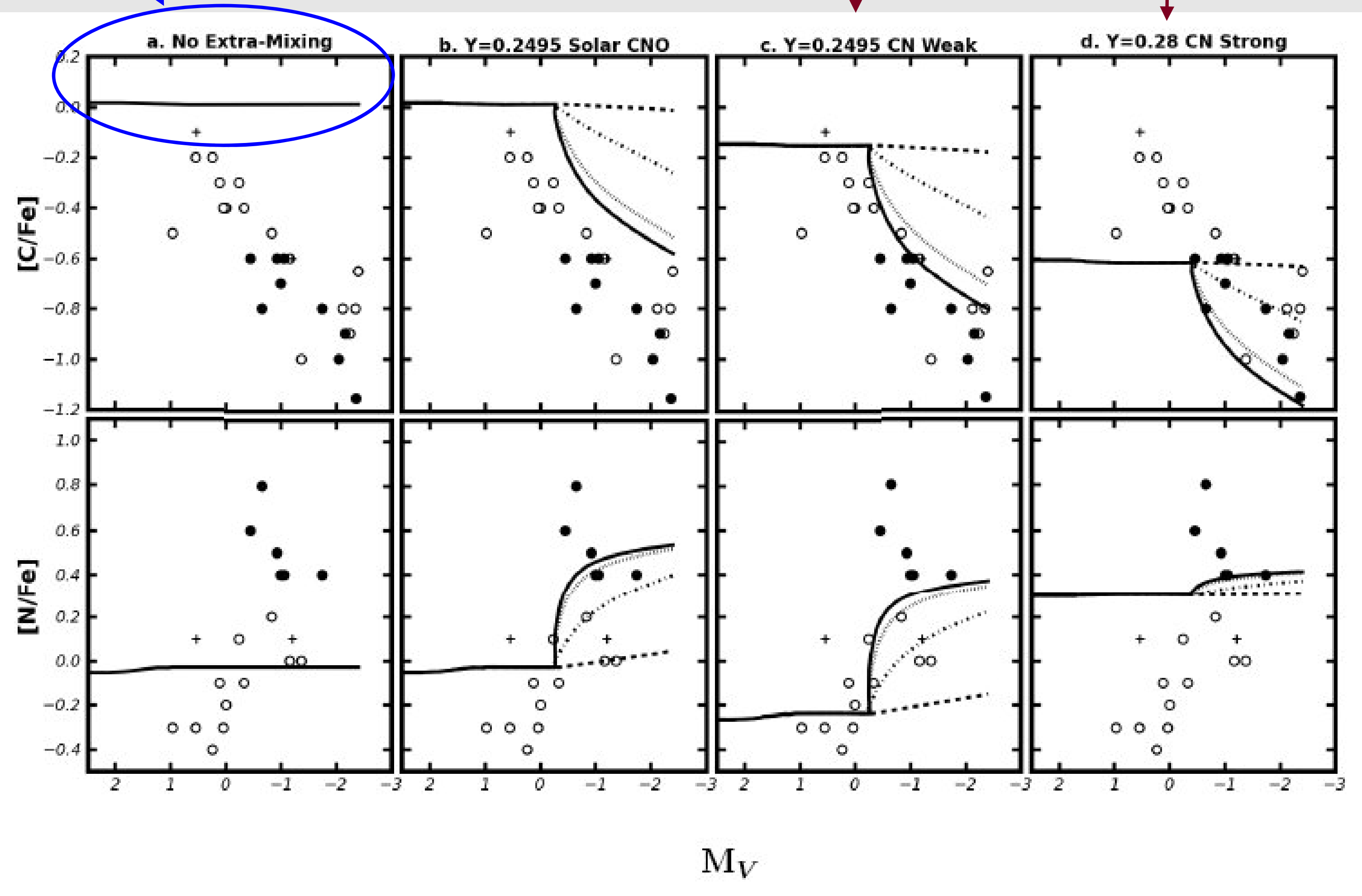
Comparison of thermohaline mixing models to observations of M3 RGB stars

Angelou et al. (2010)

No abundance change with M_v

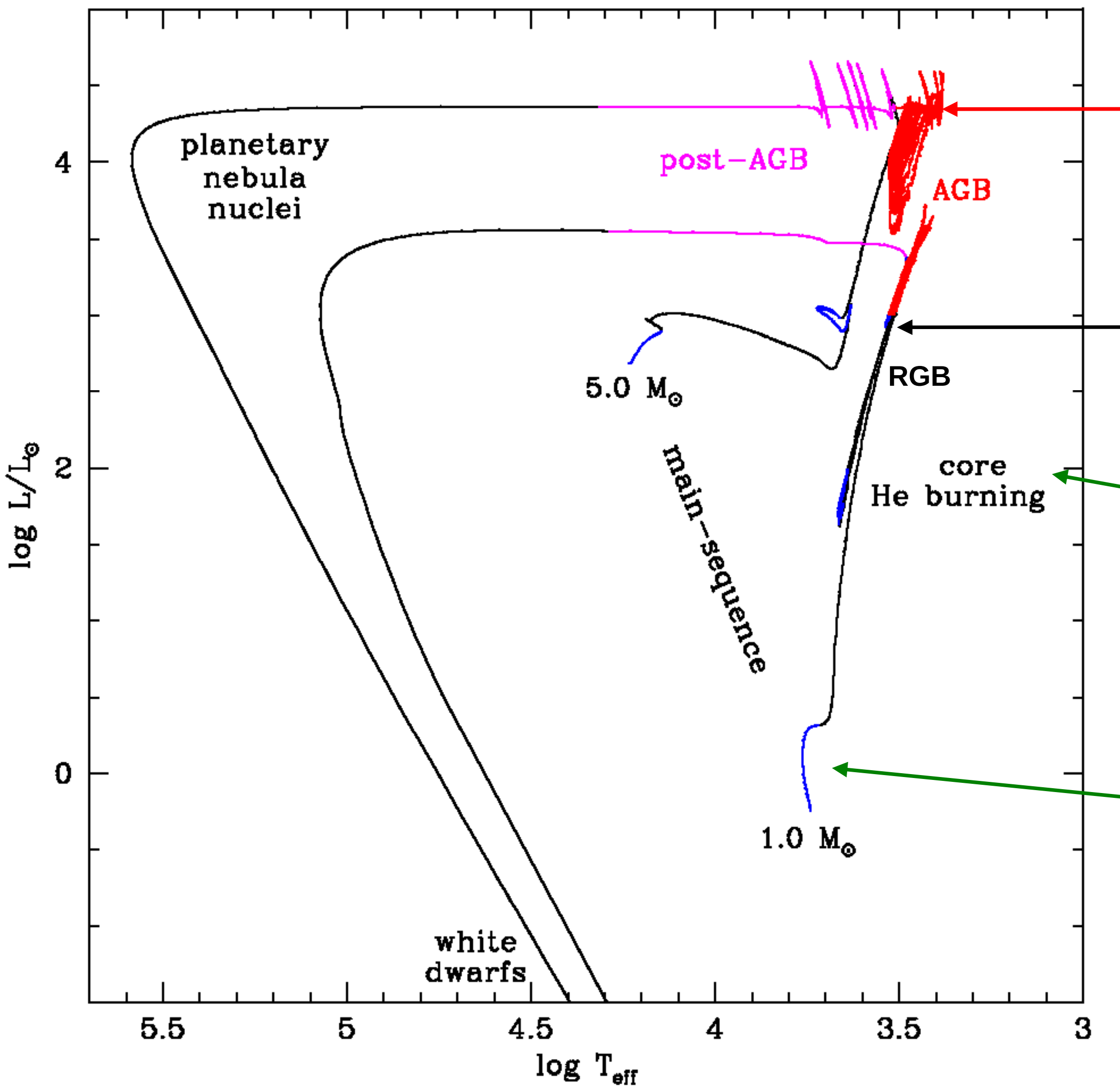
C and N changes reproduced

C/Fe reproduced
High N primordial



o - Open circles - CN weak stars
● - Filled circles - CN strong stars

The AGB - from the RGB via core-helium burning



The AGB
Surface enrichment
Pulsation
Mass loss

The RGB
Surface enrichment
Pulsation
Mass loss

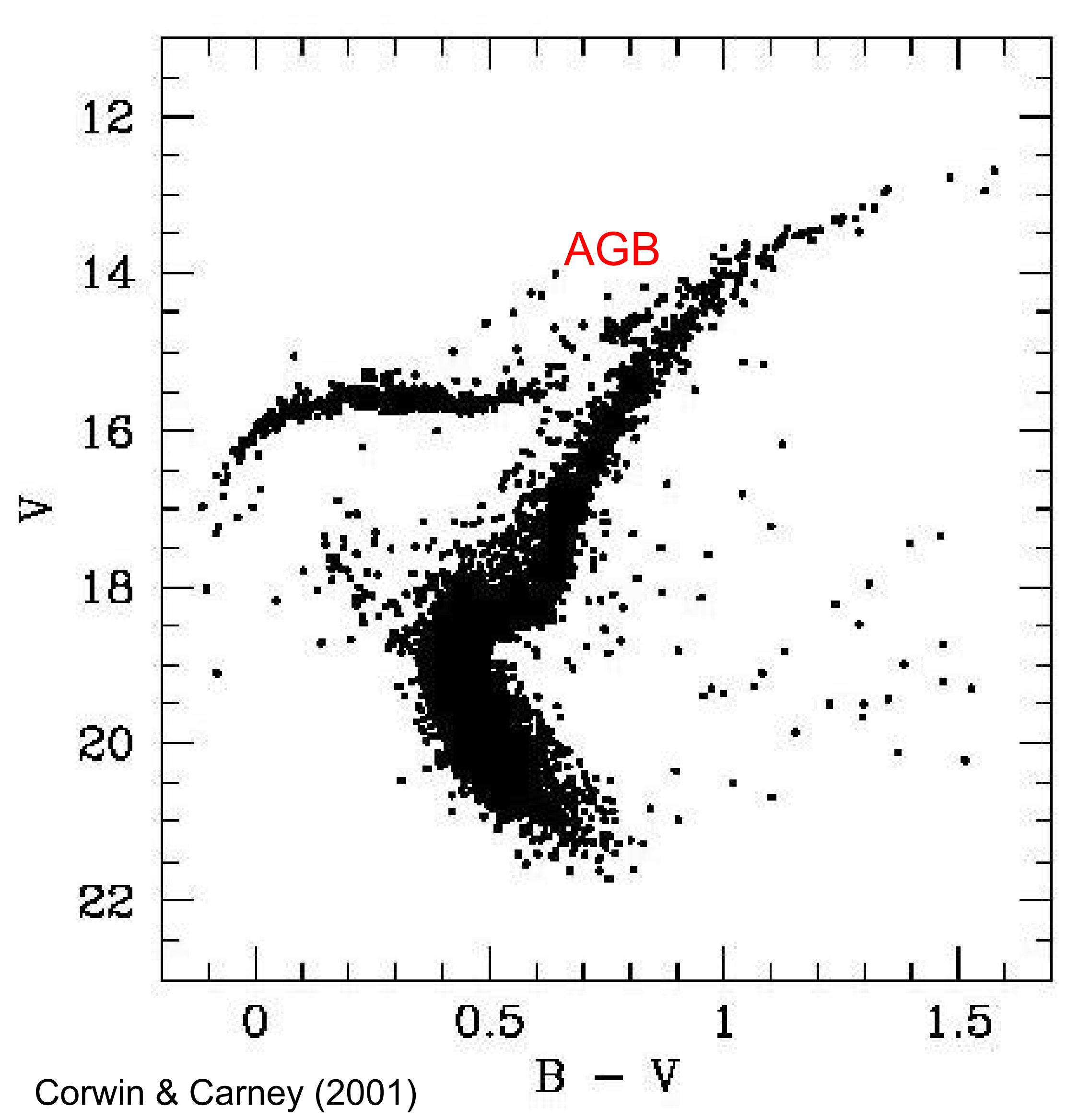
About 10^8 years spent here

Most time spent on the main-sequence burning H in the core (~10^{10} years)

Low mass stars:
M < ~1.9 Msun

Intermediate mass stars:
~1.9 < M/Msun < ~7

Origin of the term AGB



Corwin & Carney (2001)

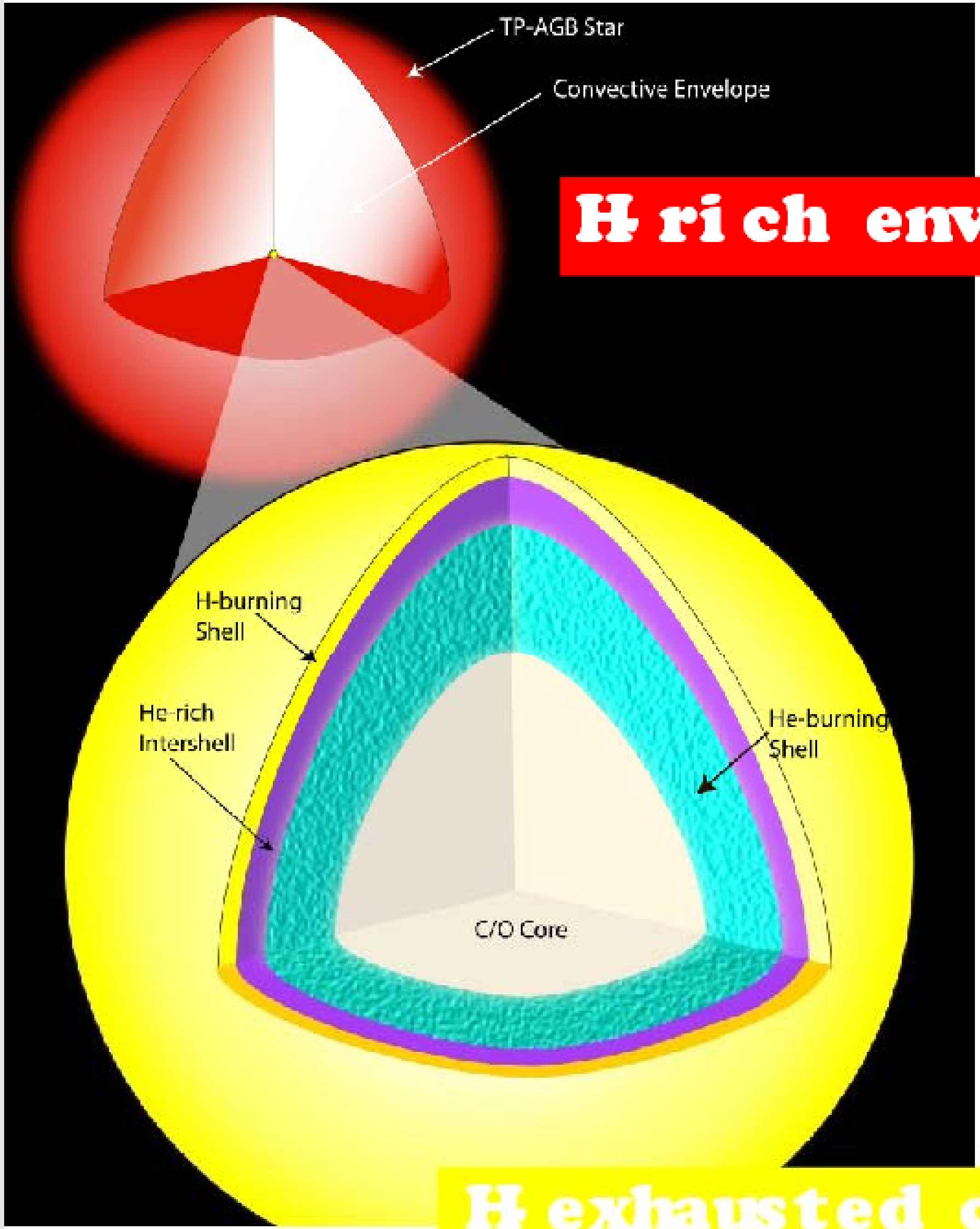
The Asymptotic Giant Branch (AGB) approaches the Red Giant Branch (RGB) asymptotically in old stellar systems.

The Red Giant Branch (RGB) is much more populous than the AGB.

Generally, AGB is used to refer to red giant stars beyond core He burning, and with electron degenerate cores burning H and He in shells.
This requires $M_{initial} < \sim 7$ Msun.

Globular cluster M3 (very old, Population II)

Structure of an AGB star



H rich envelope

R ~ 200-400 Rsun
M ~ 0.1-6 Msun
Convective
Pulsation
Mass loss

H-burning shell
4H → He (CNO cycle)

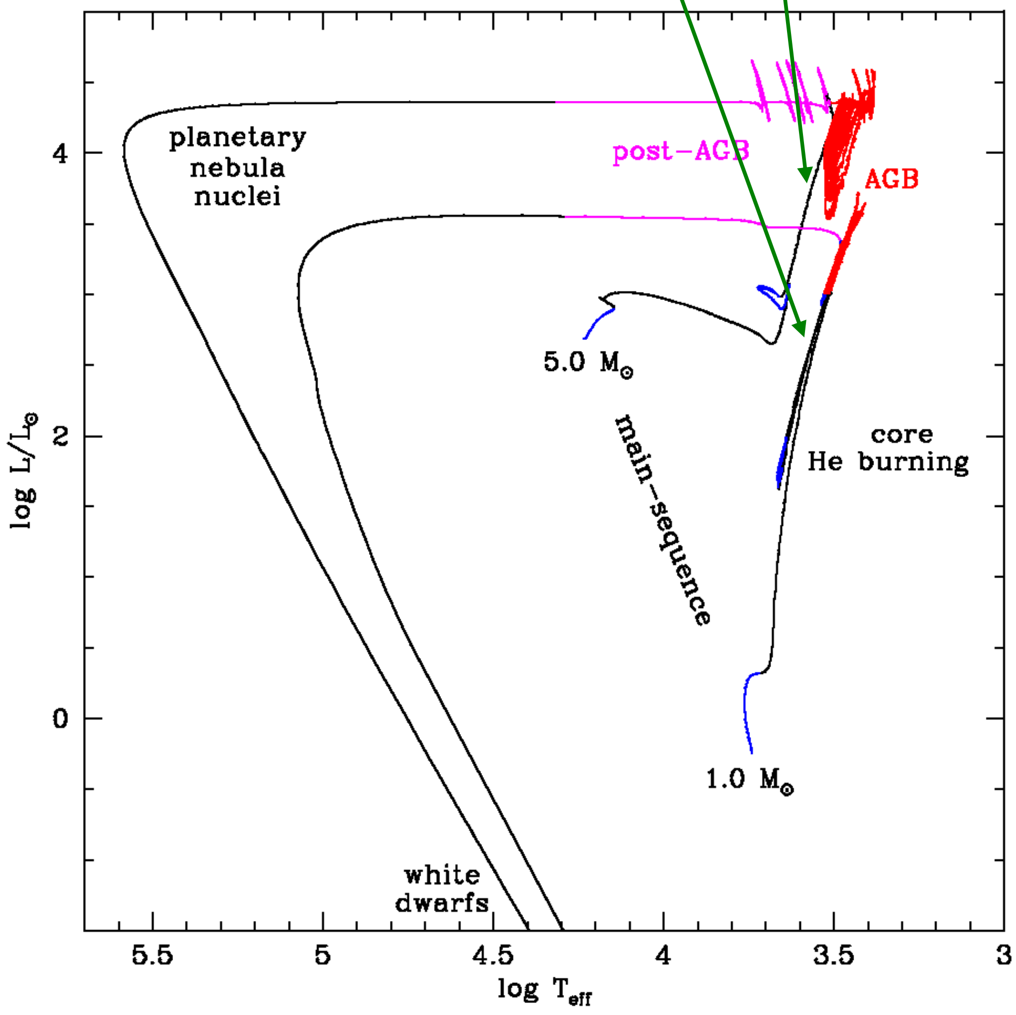
He-burning shell
3He → C (triple-alpha reaction)
C → O ($^{12}C(\alpha,\gamma)^{16}O$)

H exhausted core

R ~ 0.1 Rsun
M ~ 0.5-1.2 Msun
Radiative (most of the time)

From Amanda Karakas

The early-AGB (or EAGB): before the onset of Thermal Pulses



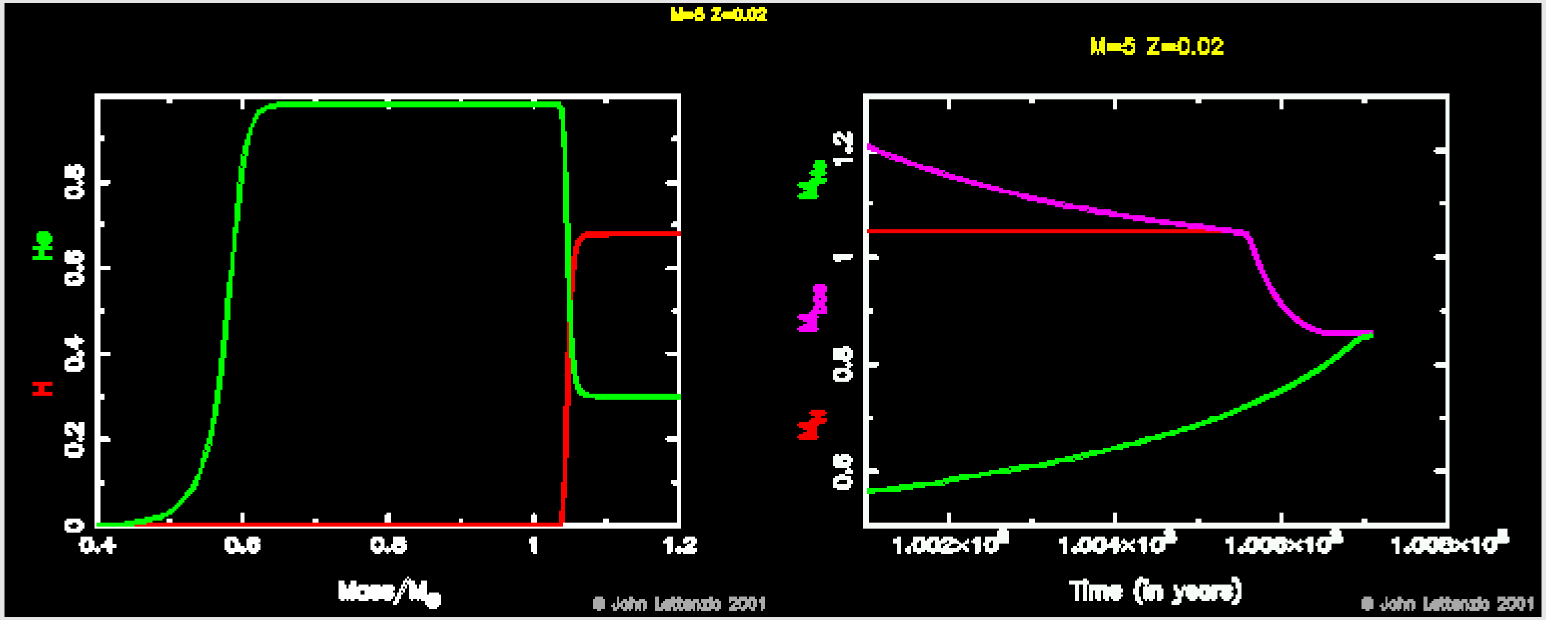
Getting nuclear-processed material to the stellar surface

The early-AGB (or EAGB)

He-shell is burning continuously
H-shell is dormant

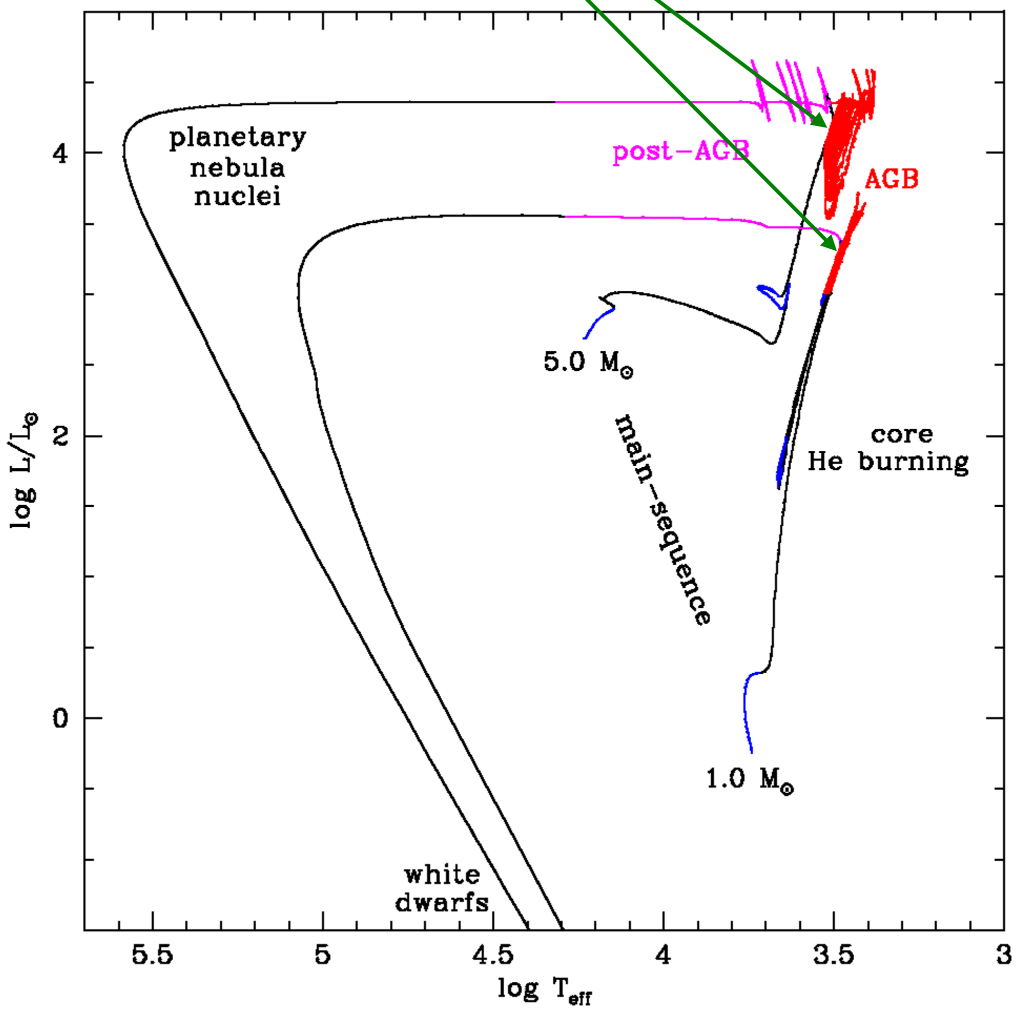
2^{nd} dredge-up

Dredged-up material (He, N) is transported to the stellar surface by convection.
It can then be ejected via the stellar wind.
2^{nd} dredge-up is only important for M > ~4 Msun.
He, N are enriched at the surface (CNO cycle converts most CNO to N).



From John Lattanzio

The Thermally Pulsing AGB



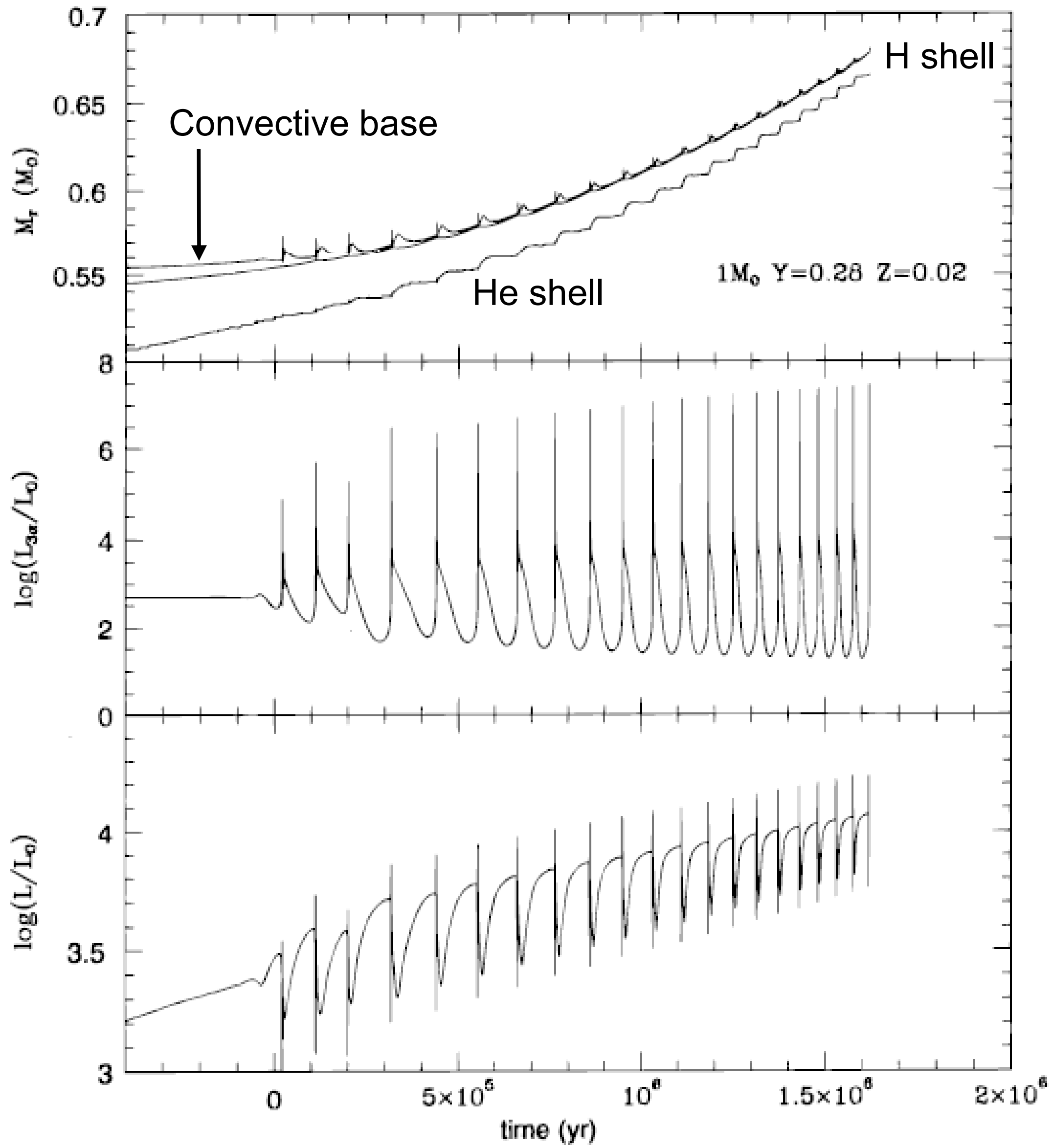


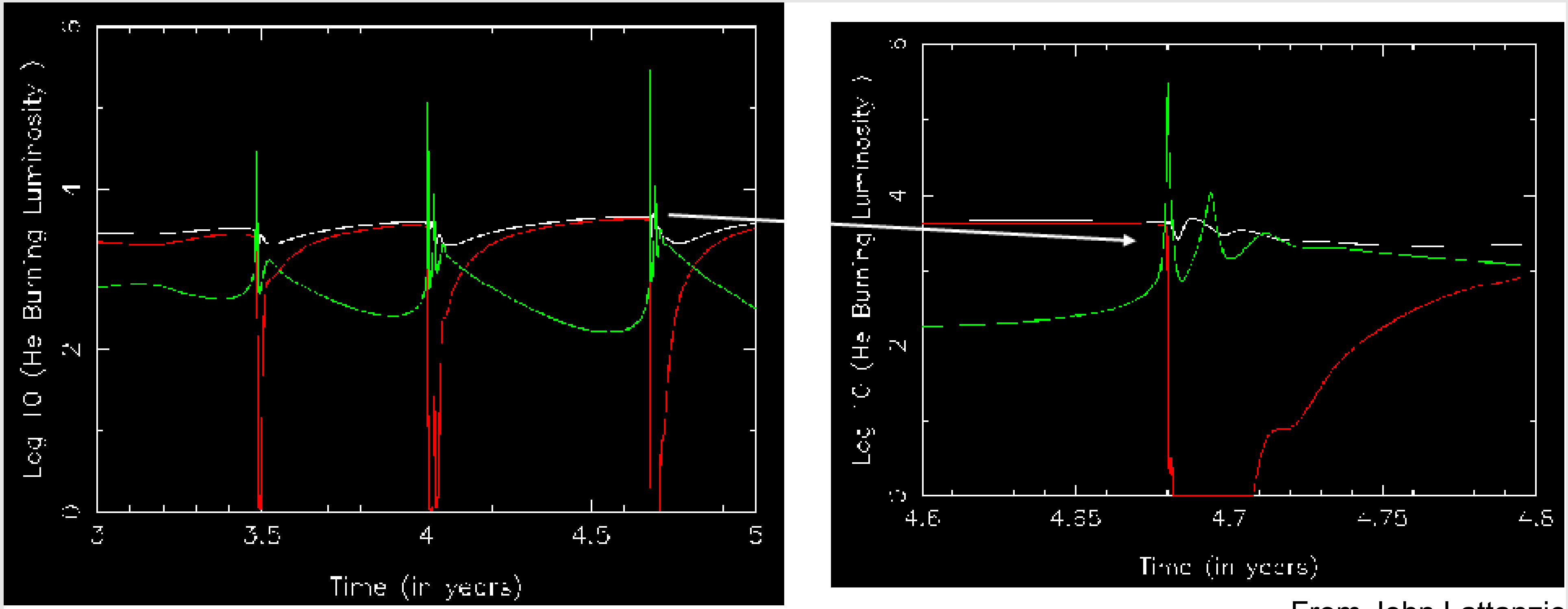
FIG. 2.—Run of relevant parameters as a function of time for the 1 $M_\odot$ sequence: (*a*) the mass coordinates of the H-exhausted core $M_{\rm H}$, the He-exhausted core $M_{\rm He}$, and the lower limit of the convective envelope ($M_{\rm CE}$); (*b*) the pulse luminosity $L_{\rm He}$; and (*c*) the total luminosity at stellar surface.

Thermal Pulses
(also known as Helium Shell Flashes)

This behaviour is due to the He-burning shell igniting in an episodic fashion.

It is extinct most of the time and H-burning supplies the stellar luminosity between flashes.

Straniero et al (1997)



From John Lattanzio

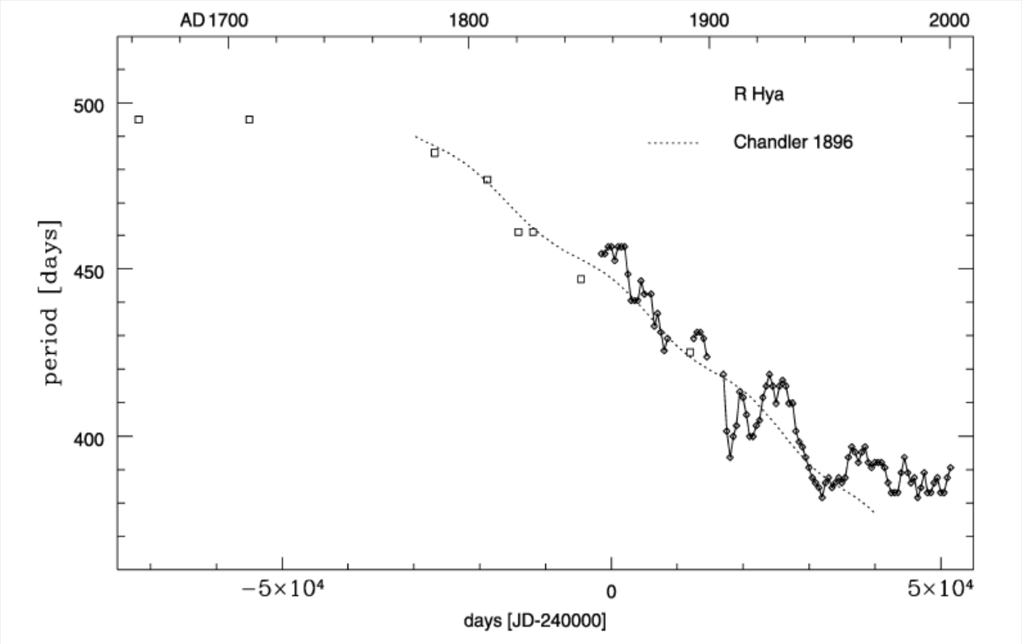
Green: He-burning luminosity
Red: H-burning luminosity
White: Total surface luminosity

H-burning is the main luminosity source over a whole cycle

Multiple flashes occur in the He-burning shell in early thermal pulse cycles

Direct evidence for the existence of Thermal Pulses (He Shell Flashes)

Period changes in Mira variables



Zijlstra et al (2002)

Period changes are so rapid that they are only explained by the rapid L change at a He Shell Flash

Tc is observed in the atmospheres of some AGB stars: longest half-life is 4.2×10^6 yr, and the common isotope ^{99}Tc has a half-life of 2.1×10^5 yr.

Wood and Zarro (1981)

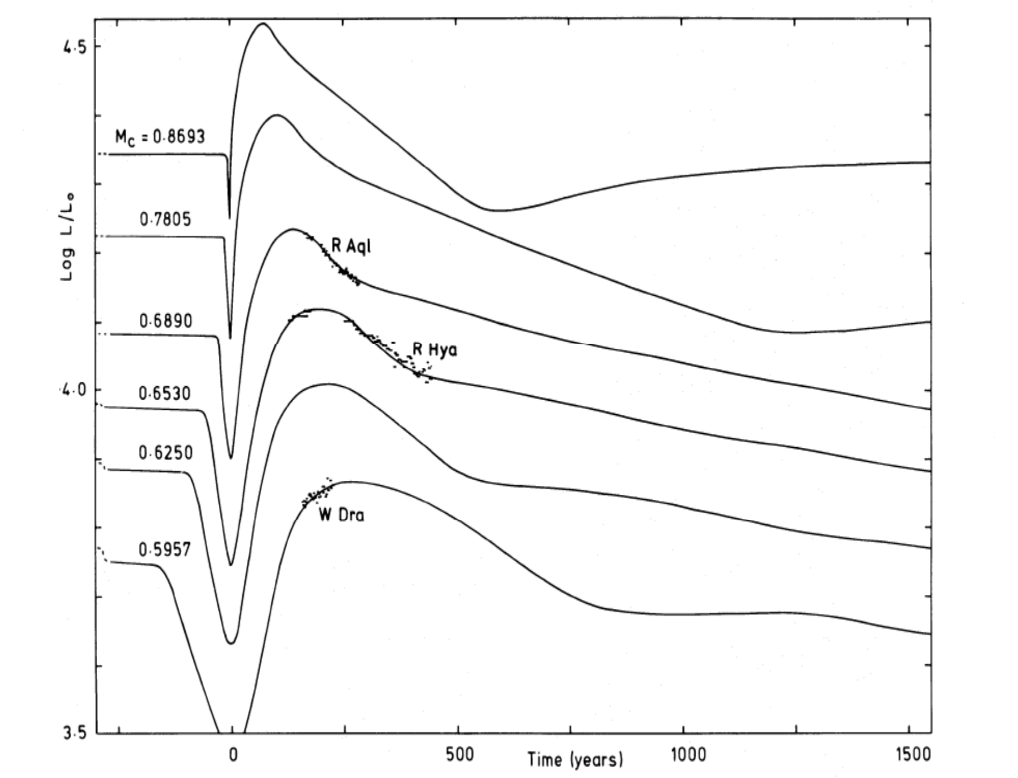
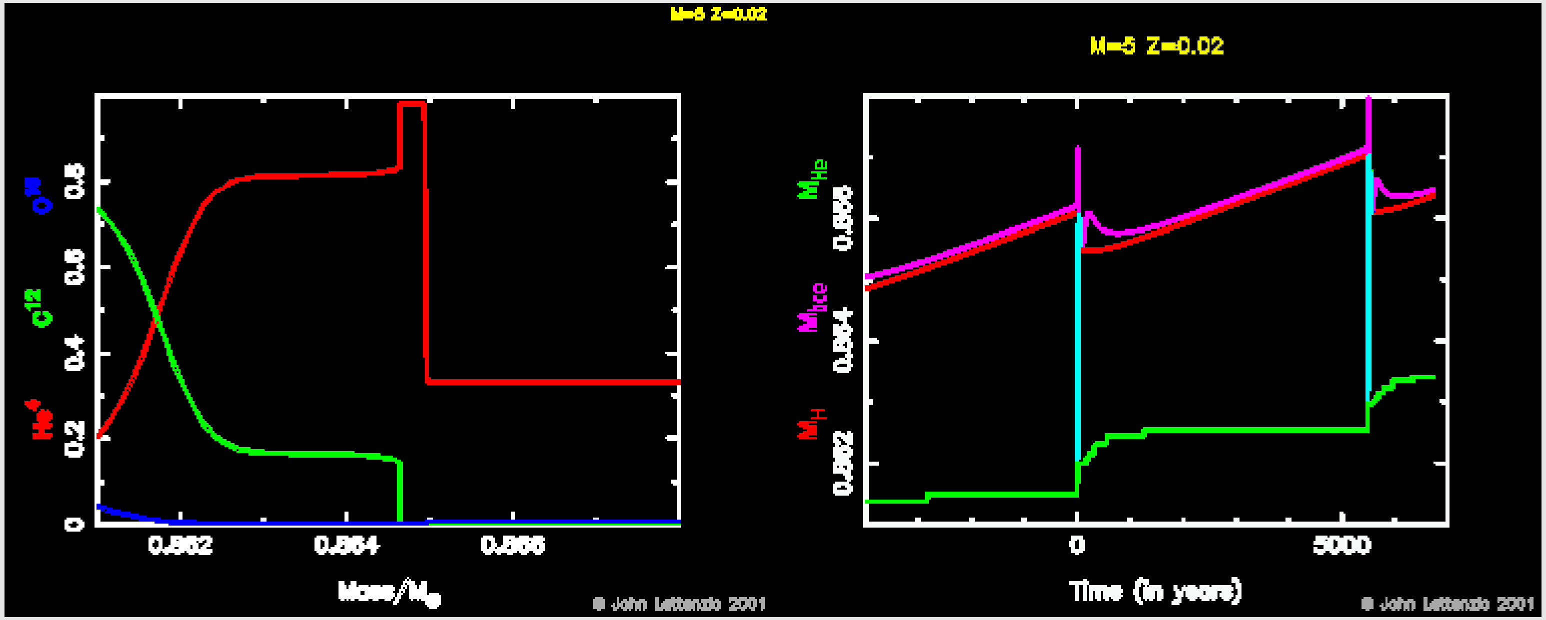


FIG. 3.—Behavior of surface luminosity L as a function of time for a number of different values of core mass M_c. The variation of the surface luminosity of the Mira variables R Hya, R Aql, and W Dra as deduced from changes in period is also shown (see text for details).

Getting nuclear-processed material to the stellar surface

3rd dredge-up on the Thermally-Pulsing AGB (TP-AGB)



From John Lattanzio

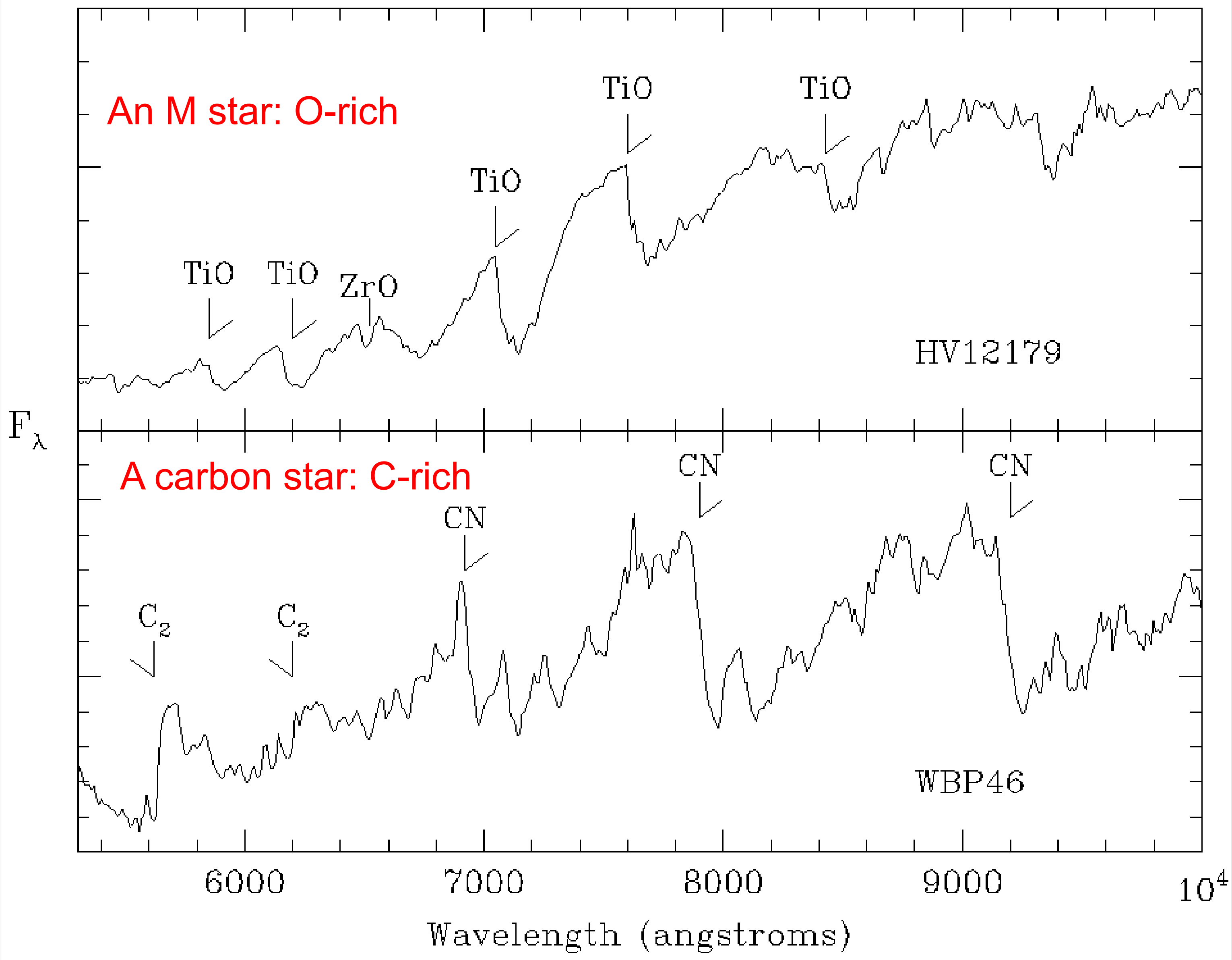
H-shell burns outward most of the time
He shell burns in flashes

Envelope convection dredges up C-enriched matter to the surface

This can lead to the formation of Carbon Stars

More evidence for the existence of Thermal Pulses (He Shell Flashes)

The existence of Carbon Stars



Spectra of M and C stars are very easily distinguished by characteristic molecules.

Testing models for 3rd dredge-up: the C star luminosity function.

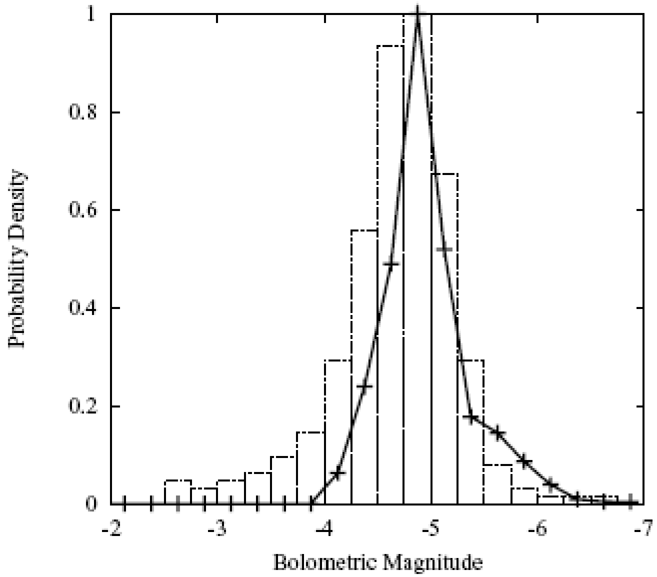


Figure 4. The theoretical fit (solid line) to the LMC CSLF. The histogram is observational data taken from Groenewegen (2004). The CSLF is reasonably well reproduced by the theoretical models.

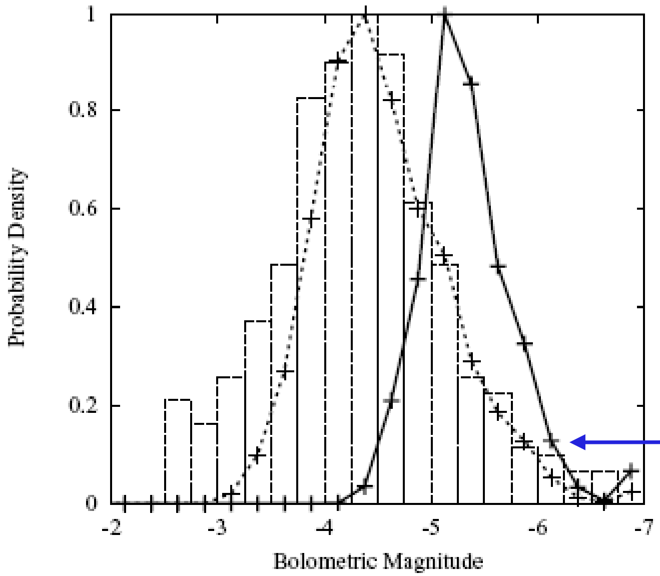


Figure 5. Theoretical fits to the SMC CSLF. The histogram is observational data taken from Groenewegen (2004). The unadjusted theoretical model (solid line) reproduces the shape of the luminosity function well, but it is too bright by almost 1 mag. If the minimum core mass required for TDUP is reduced by 0.06 $M_\odot$ (dashed line) then the CSLF is well reproduced.

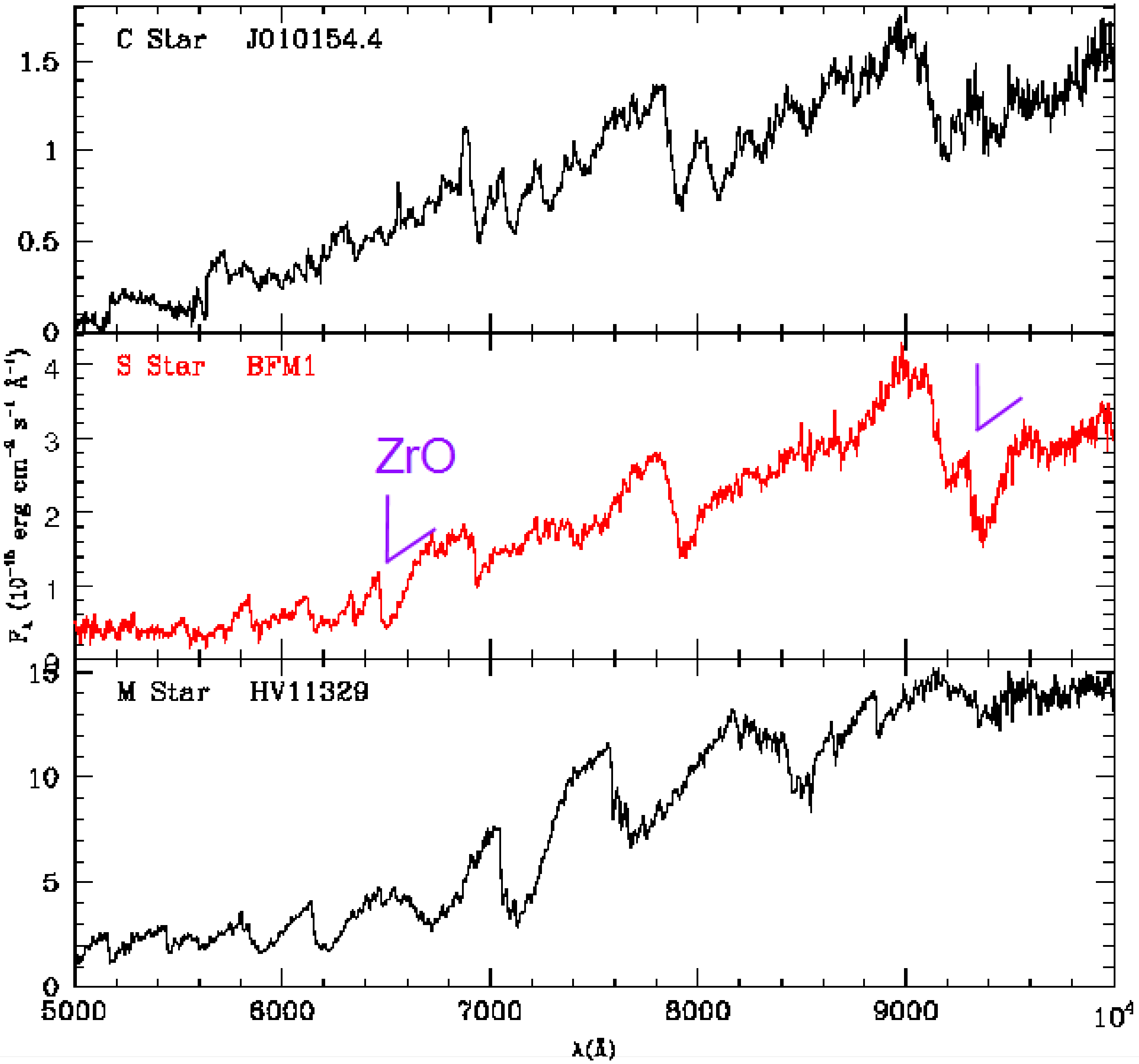
Full calculations have usually failed to reproduce the observed C-star luminosity function – the depth of 3rd dredge-up is never deep enough. This requires an artificial “overshoot” at convective boundaries (which would occur naturally in a full 3-D convection calculation). Failure of simple convection theories is a recurring theme in AGB star studies.

There are many “synthetic AGB calculations” e.g. Marigo et al (2008).

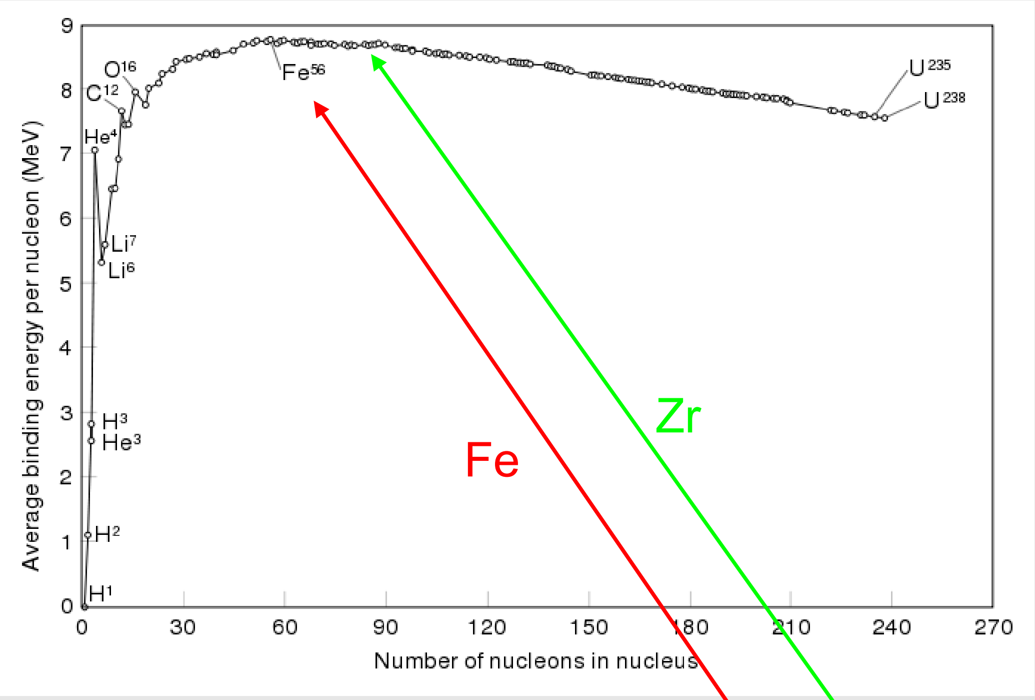
Model C stars are too bright.

Stancliffe, Izzard & Tout (2005)

S Stars – AGB stars with very enhanced s-process abundances (and C/O ~ 1)



The s-process elements have been produced in the AGB star and convected to the stellar surface.



MAKING s-PROCESS ELEMENTS

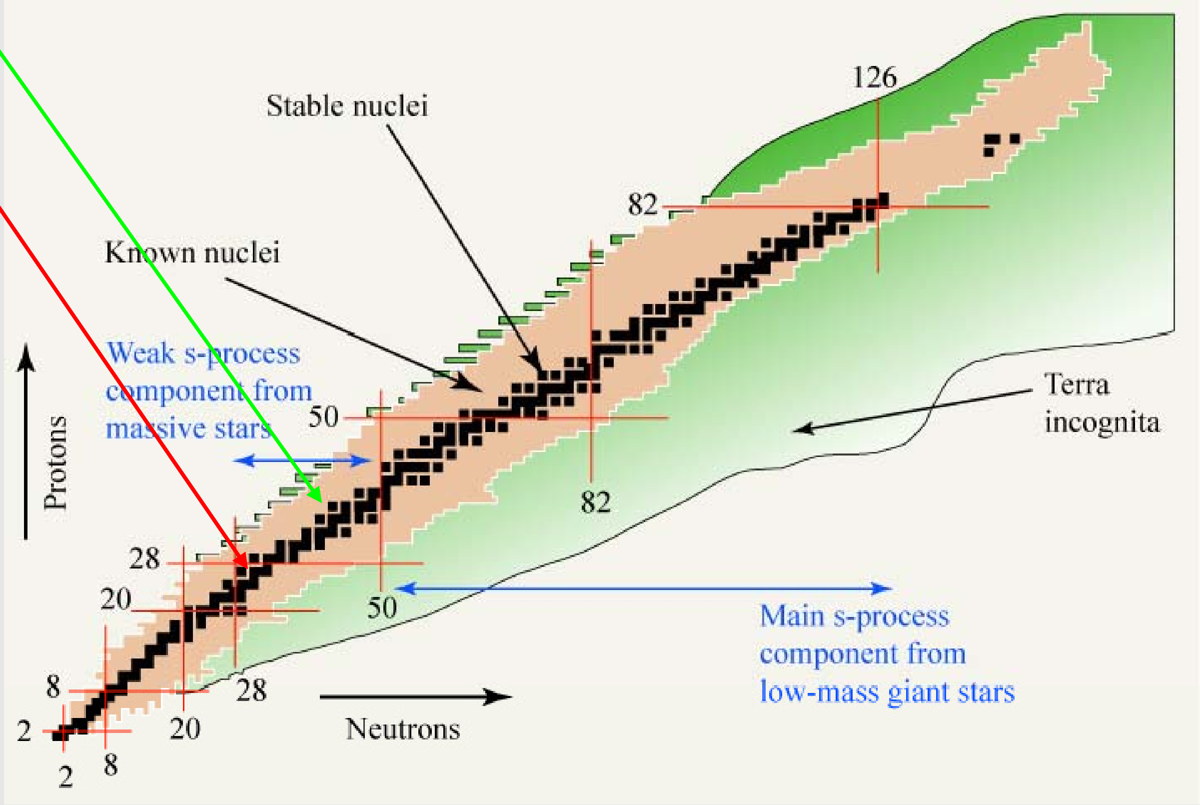
^{56} Fe is the most stably bound nucleus. Heavier elements can not be produced by thermal nuclear reactions.

They are created by neutron addition to elements similar to Fe (no electrostatic repulsion):

s-process: slow neutron addition

r-process: rapid neutron addition (in SN)

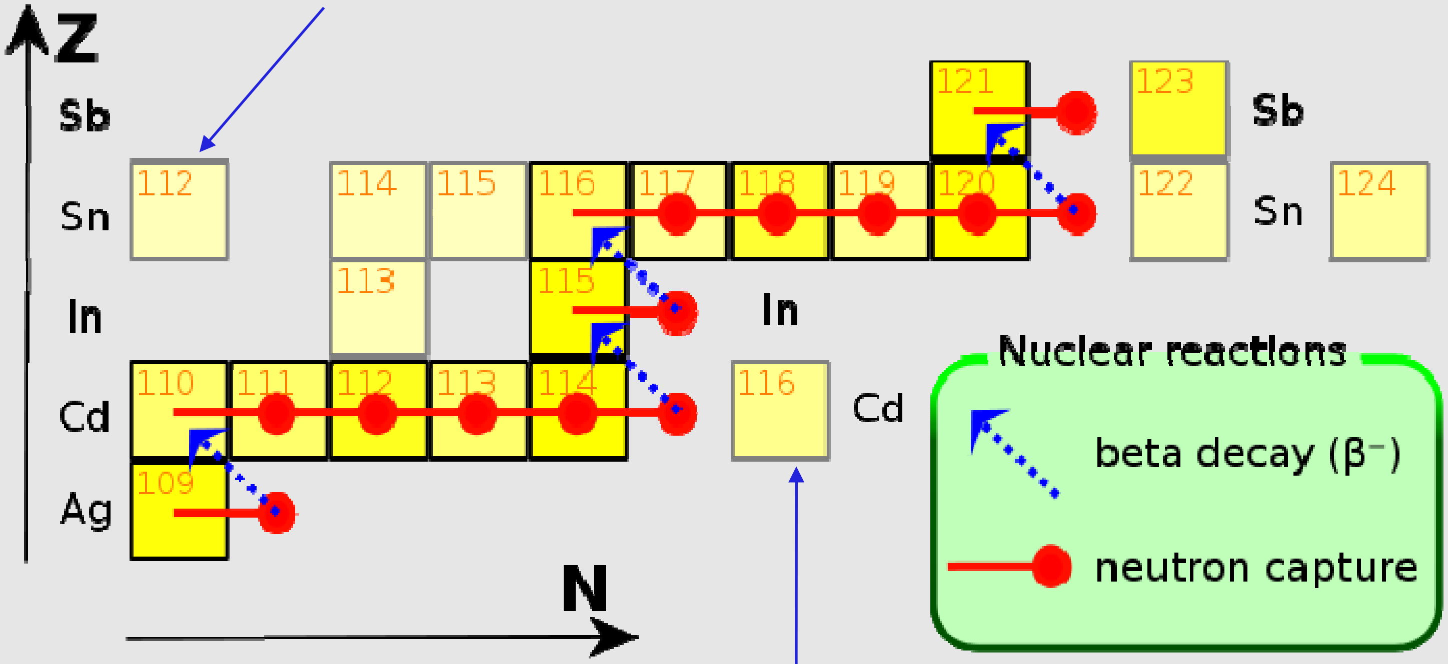
The Valley of Nuclear Stability



From Frank Timmes website

How to build stable nuclei by neutron addition

p-process element



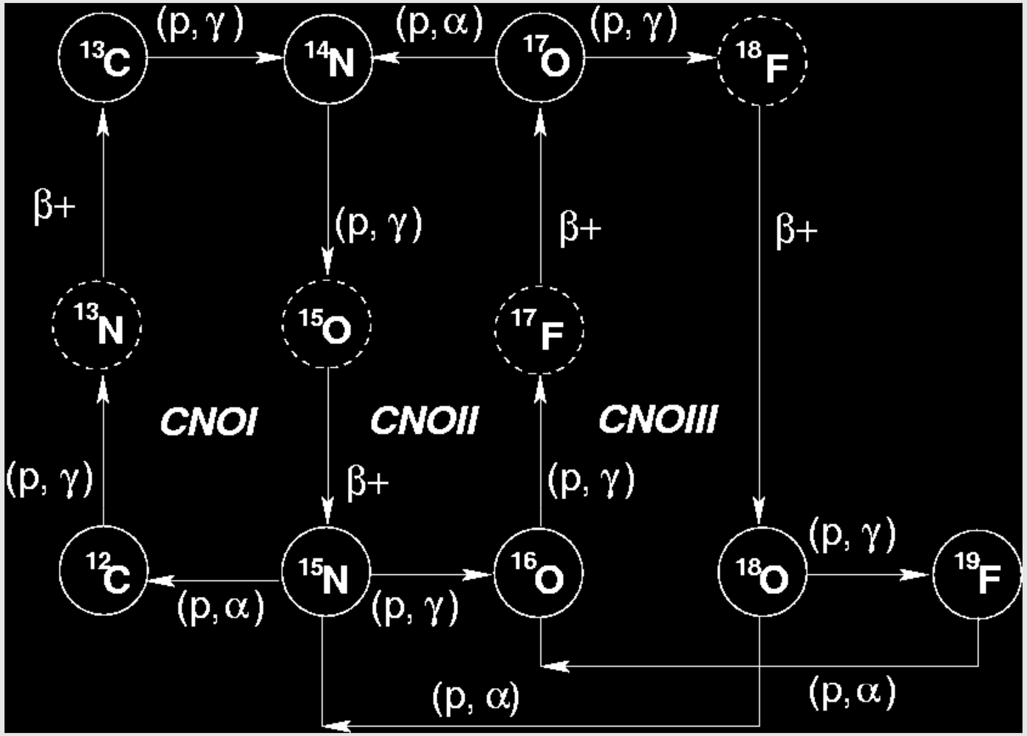
Wikimedia commons

r-process element

Neutron sources - at He burning temperatures

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

But how is a significant ^{13}C abundance obtained?
It is normally mostly burnt to ^{14}N in the CN cycle.



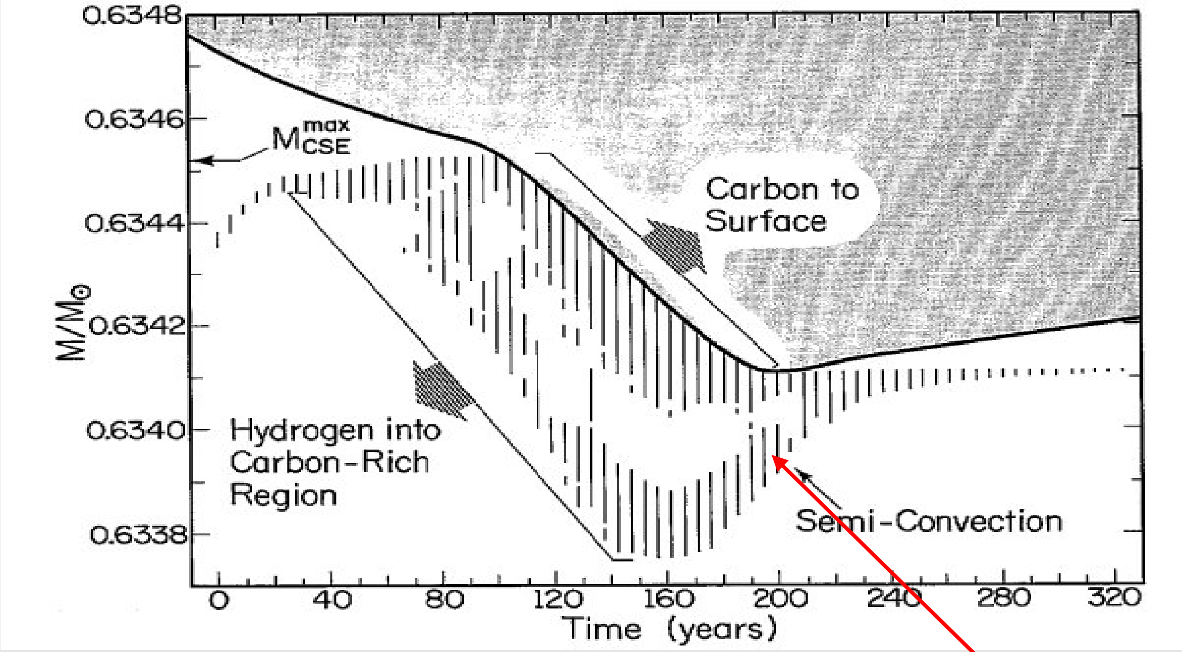
From Amanda Karakas

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

^{22}Ne comes from burning ^{14}N (left over from the CNO cycle)
$^{14}N(\alpha,\gamma)^{18}F(,\beta+v)^{18}O(\alpha,\gamma)^{22}Ne$

$^{22}Ne(\alpha,n)^{25}Mg$ requires higher temperatures than those found during He burning in lower mass stars < ~4 Msun.

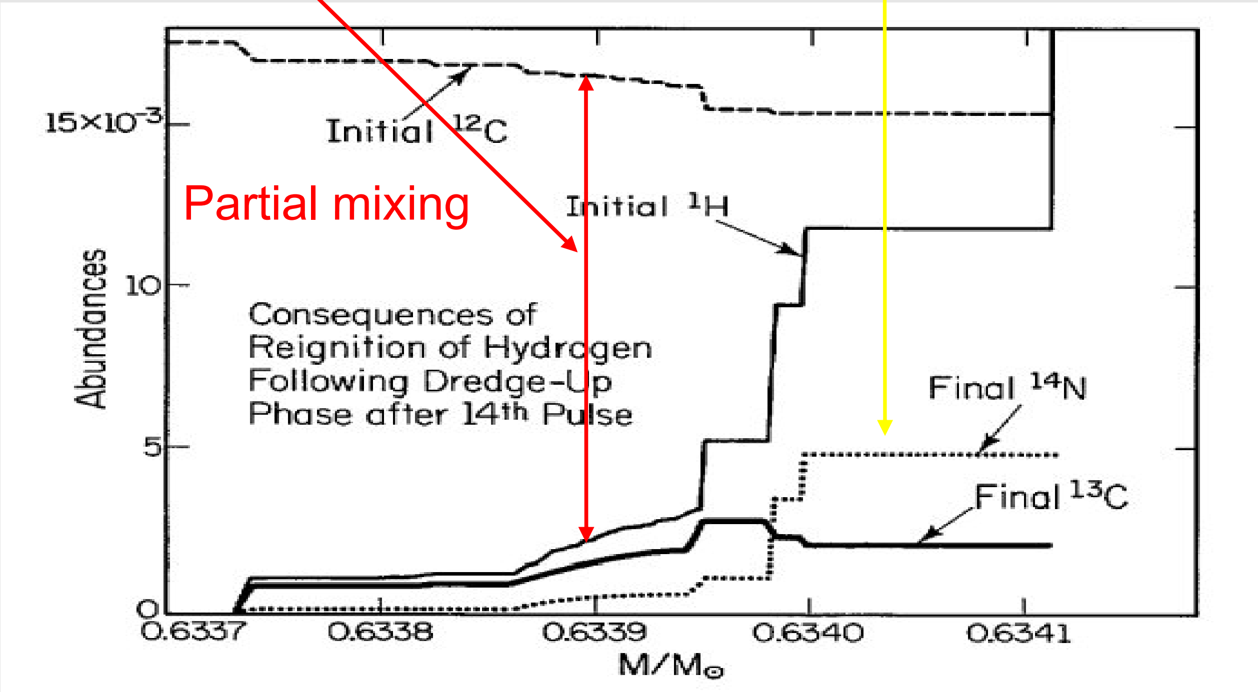
Iben & Renzini (1982) (see Herwig 2005 for more recent calculations)



Burn to produce ^{13}C

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

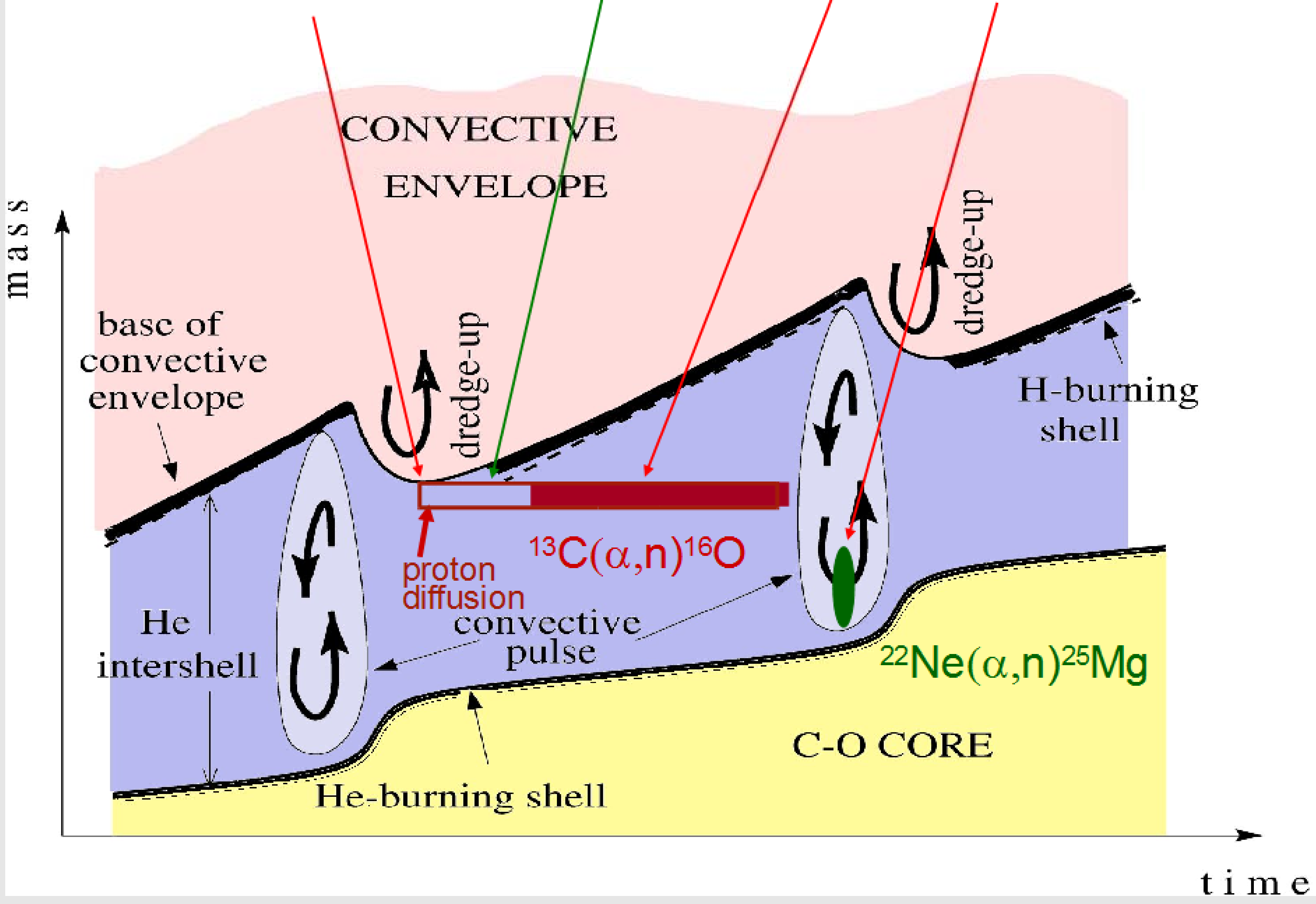
Then, if still protons left
$^{13}C(p,\gamma)^{14}N$



Small amount of H mixed
down to C-rich region
(Iben & Renzini 1982)

^{13}C created

S-process nucleosynthesis
between pulses (Straniero 1995),
as well as in pulses (Busso et al 2001)

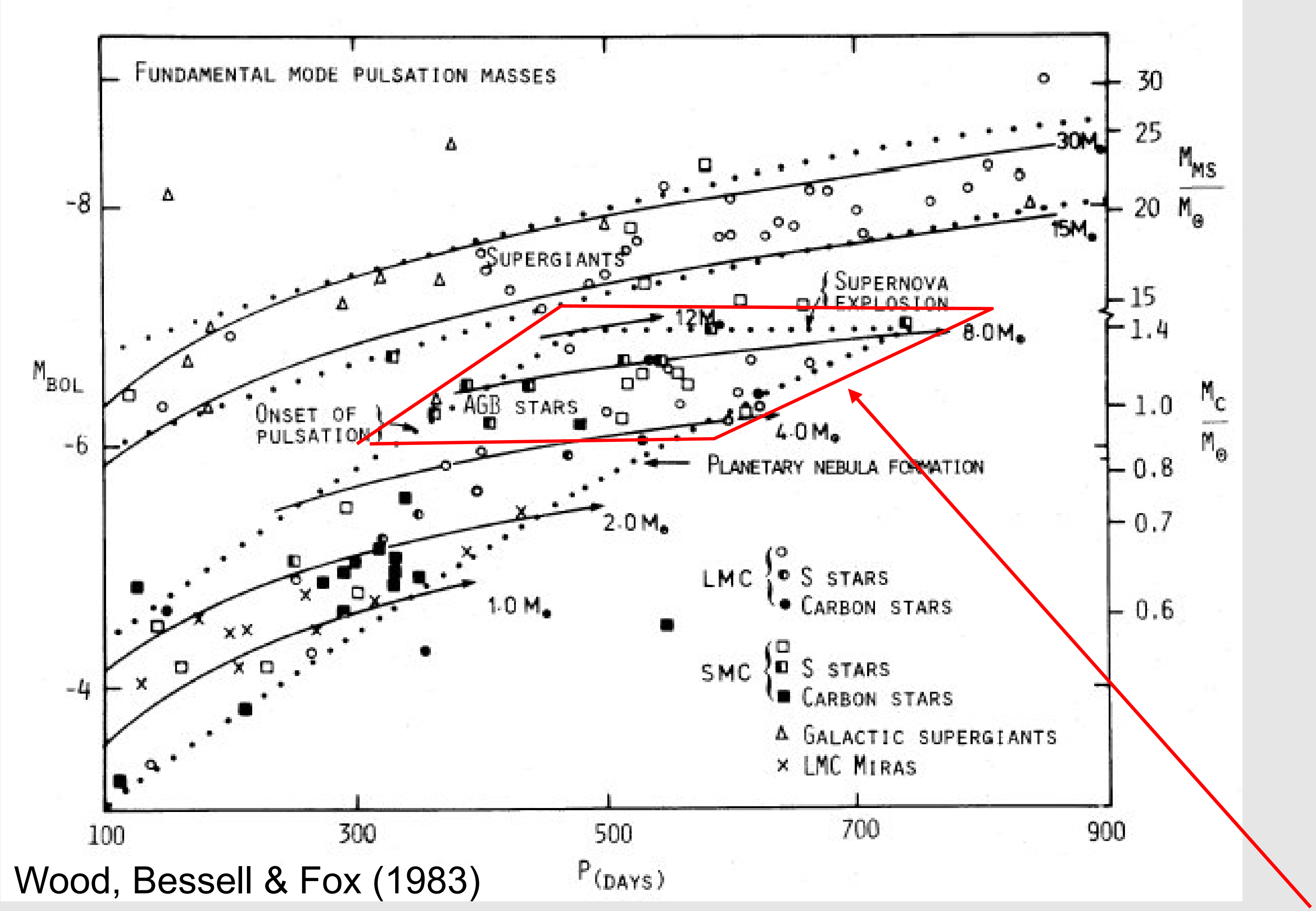


AGB stars can produce heavy s-process elements.

This is because of the repeated application of neutron fluxes
to elements that are becoming heavier with each application.

In the cores of massive stars, s-processing also occurs, but
with only a single application of a neutron flux, only light s-process
elements are made.

Hot Bottom Burning - a source of primary ^{14}N.

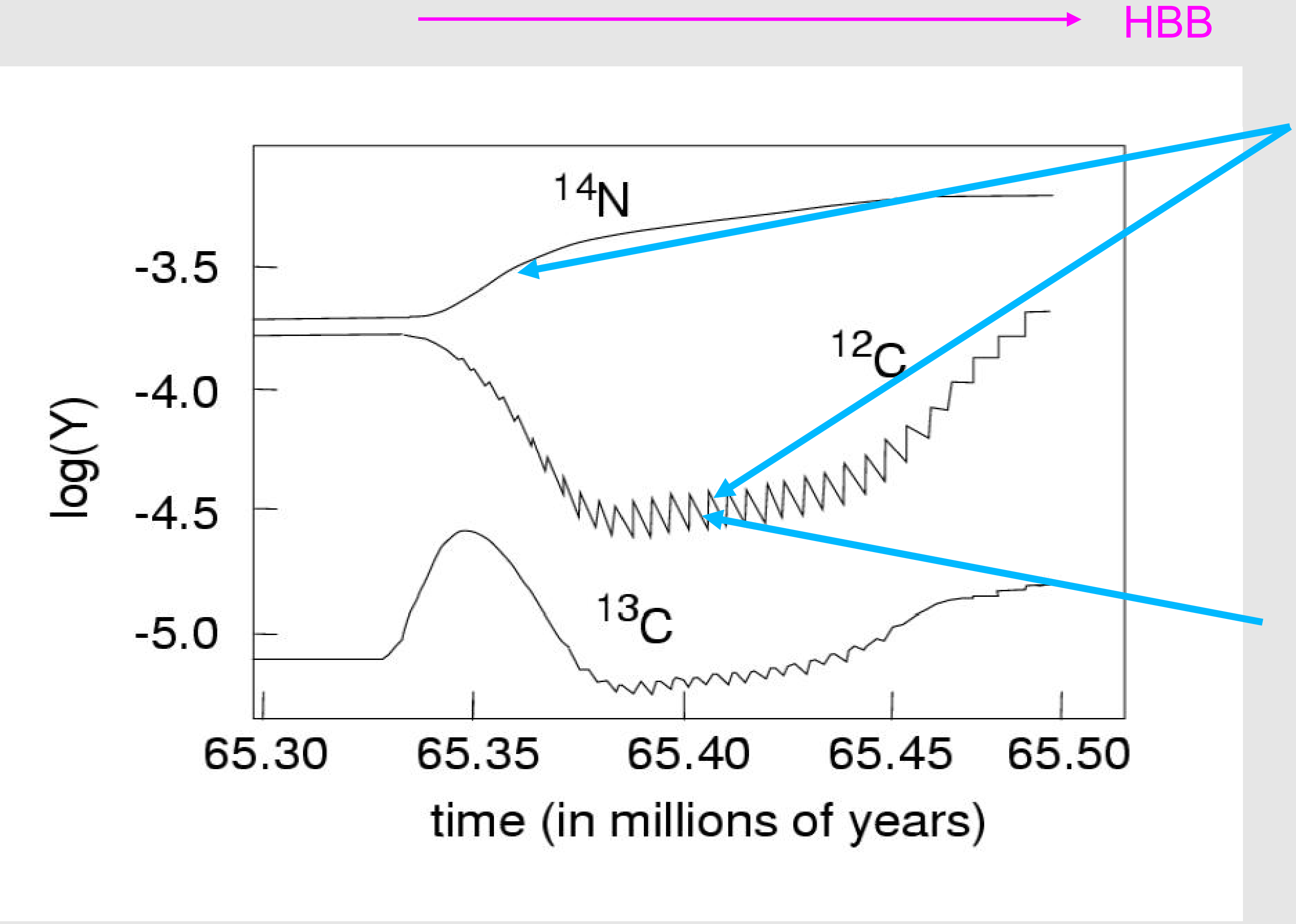


Wood, Bessell & Fox (1983)

- Wood, Bessell & Fox (1983) noted that massive (M > 4 Msun), luminous AGB stars were not C stars, even though they had s-process enrichments (and hence were undergoing 3rd dredge-up).
- Smith & Lambert (1989) showed these stars were Li-rich.
- Garcia-Hernandez et al (2006) confirmed the s-process enrichment.
- McSaveney et al (2007) found N enrichments by a factor of ~10.

Hot Bottom Burning

In AGB stars with M > ~3-4 Msun, the envelope convection extends down to the H-burning shell. Thus the whole envelope is subject to H-burning by the pp-chains and the CN cycle (Scalo, Despain & Ulrich 1975).

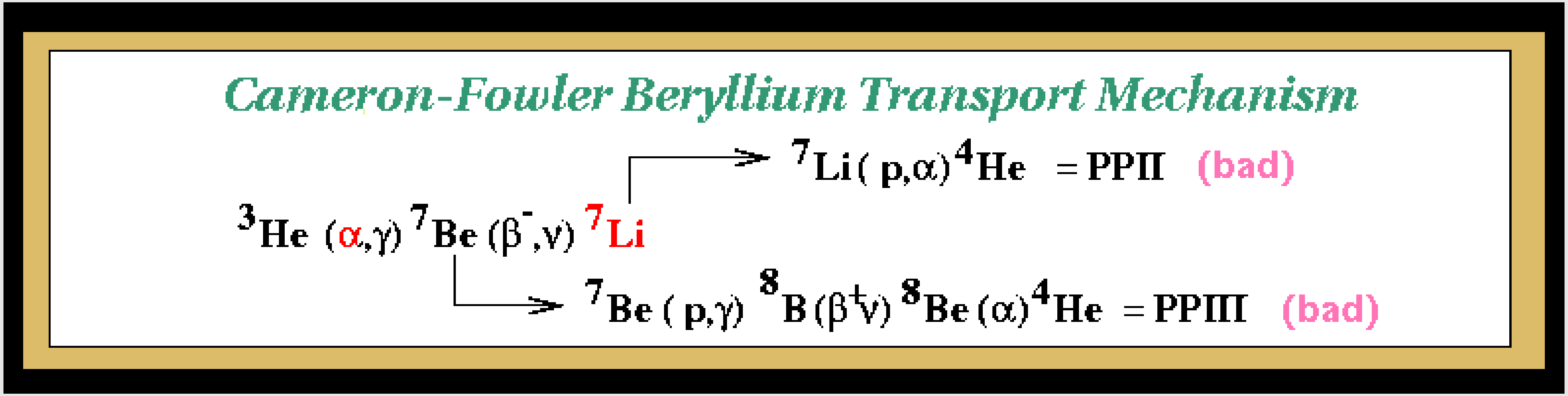


CN cycle

N up
C down

Third dredge-up
of primary ^{12}C
$4{*}H \rightarrow {}^{4}He$
$3{*}{}^{4}He \rightarrow {}^{12}C$

Li production during Hot Bottom Burning



Cameron-Fowler Beryllium Transport Mechanism

$^{7}\mathrm{Li}(p,\alpha)^{4}\mathrm{He}$ = PPII (bad)

$^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}(\beta^{-},\nu)^{7}\mathrm{Li}$

$^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}(\beta^{+}\nu)^{8}\mathrm{Be}(\alpha)^{4}\mathrm{He}$ = PPIII (bad)

Convection must carry the ^{7}Be away from the H-shell to cooler regions before PPI or PPIII can destroy ^{7}Li or ^{7}Be.

Carbon down by a factor ~5

Nitrogen up by a factor ~10

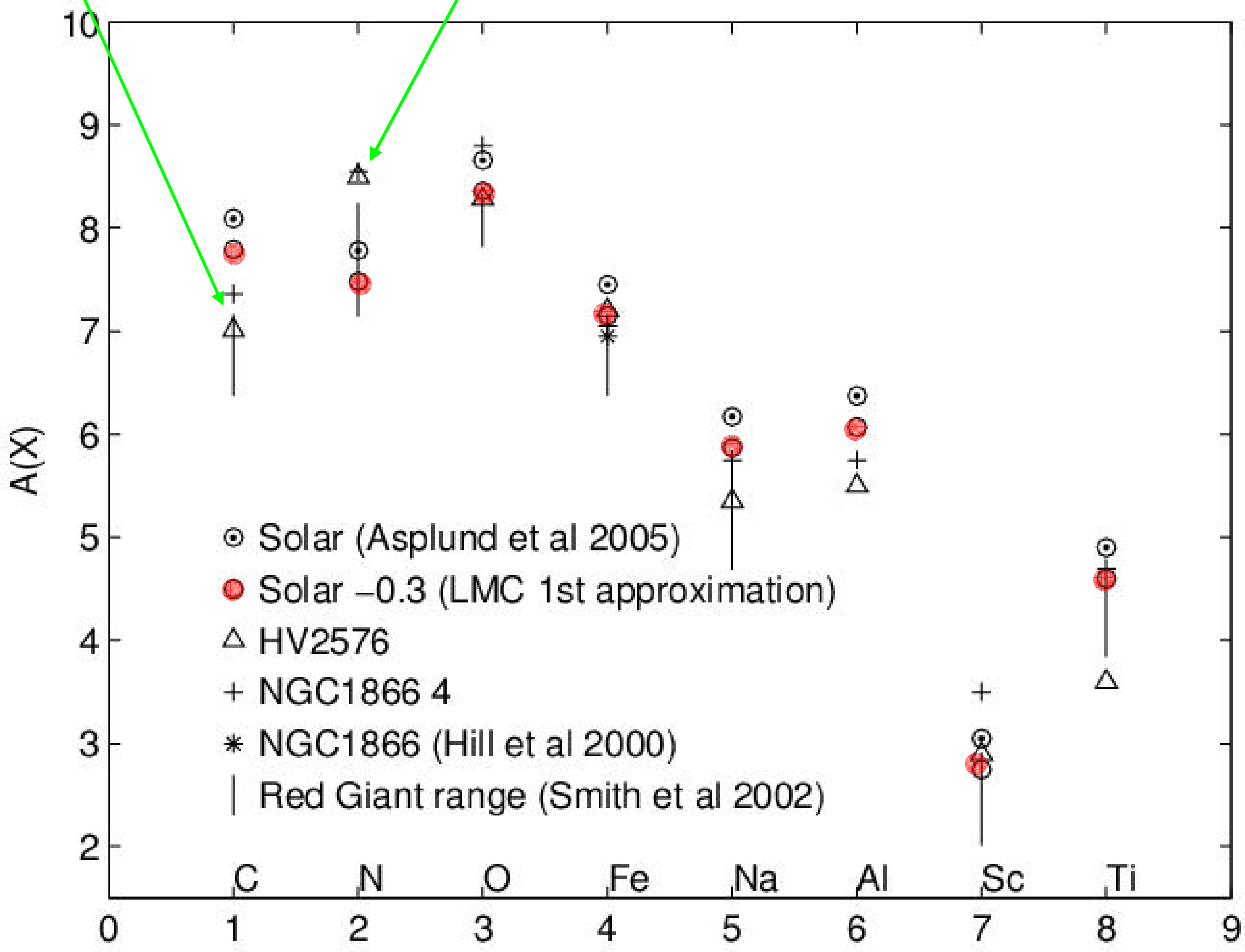


Figure 27. Final abundances.

McSaveney et al. (2007)

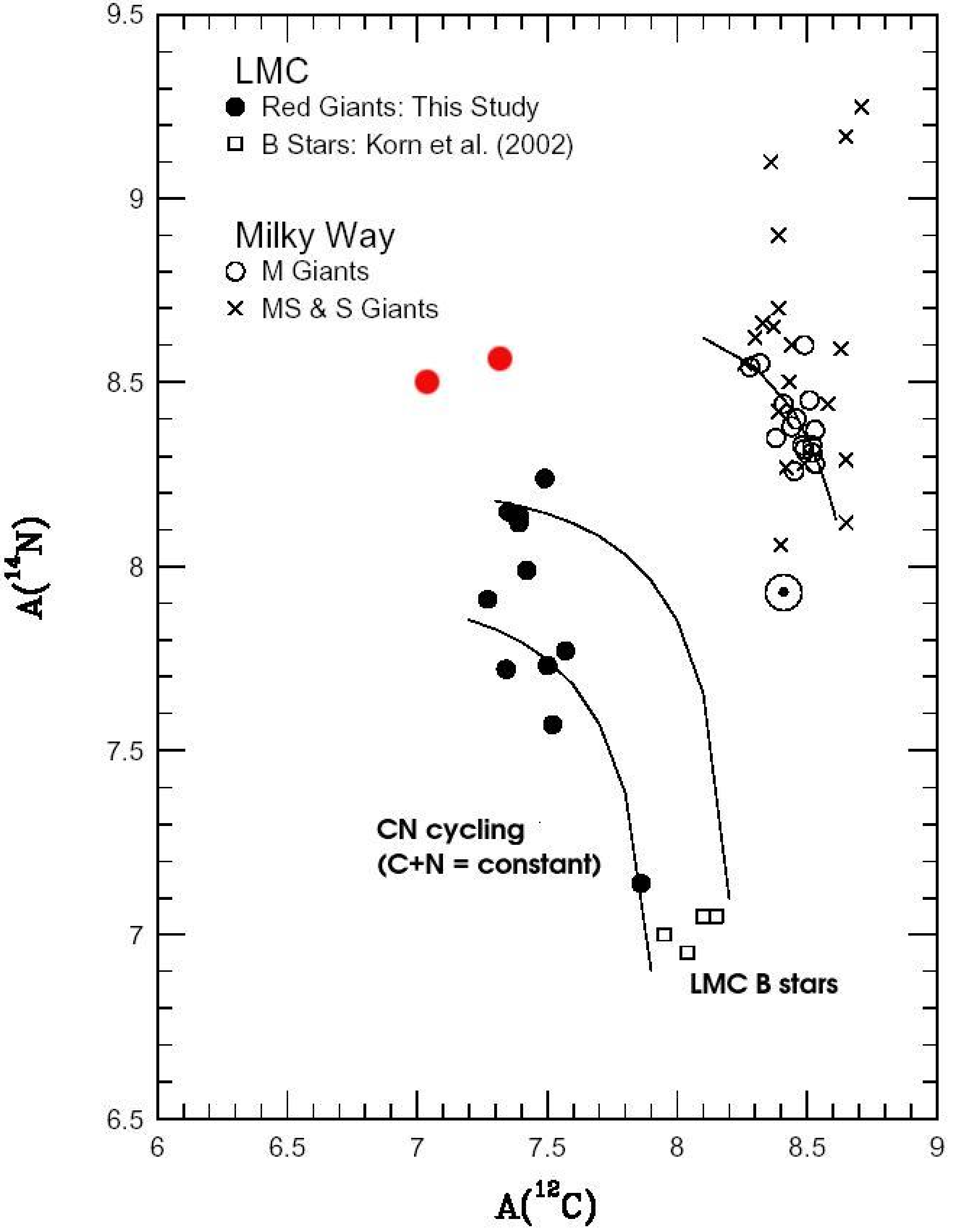


FIG. 8.—Abundances of ^{14}N vs. ^{12}C (on a scale with $A(\mathrm{X}) = \log [n(\mathrm{X})/n(\mathrm{H})] + 12$) for the LMC red giants along with other LMC samples, as well as Galactic red giants (from Smith & Lambert 1985, 1986, 1990).

Smith et al. (2002)

The N abundances are larger than can be produced by CN cycling of pre-existing C + N nuclei – require Third Dredge-Up + HBB.

Summary of surface enrichments in AGB stars

1. Early AGB => 2nd dredge-up, He and N enrichment (M_i > 4 Msun)
2. Thermally-pulsing AGB:3rd dredge-up => C enrichment (C stars)
3. “ “ “ : heavy s-process elements
4. Hot-bottom burning => N + Li enrichments

Evolution of Extremely Metal Poor (EMP) stars of low and intermediate mass

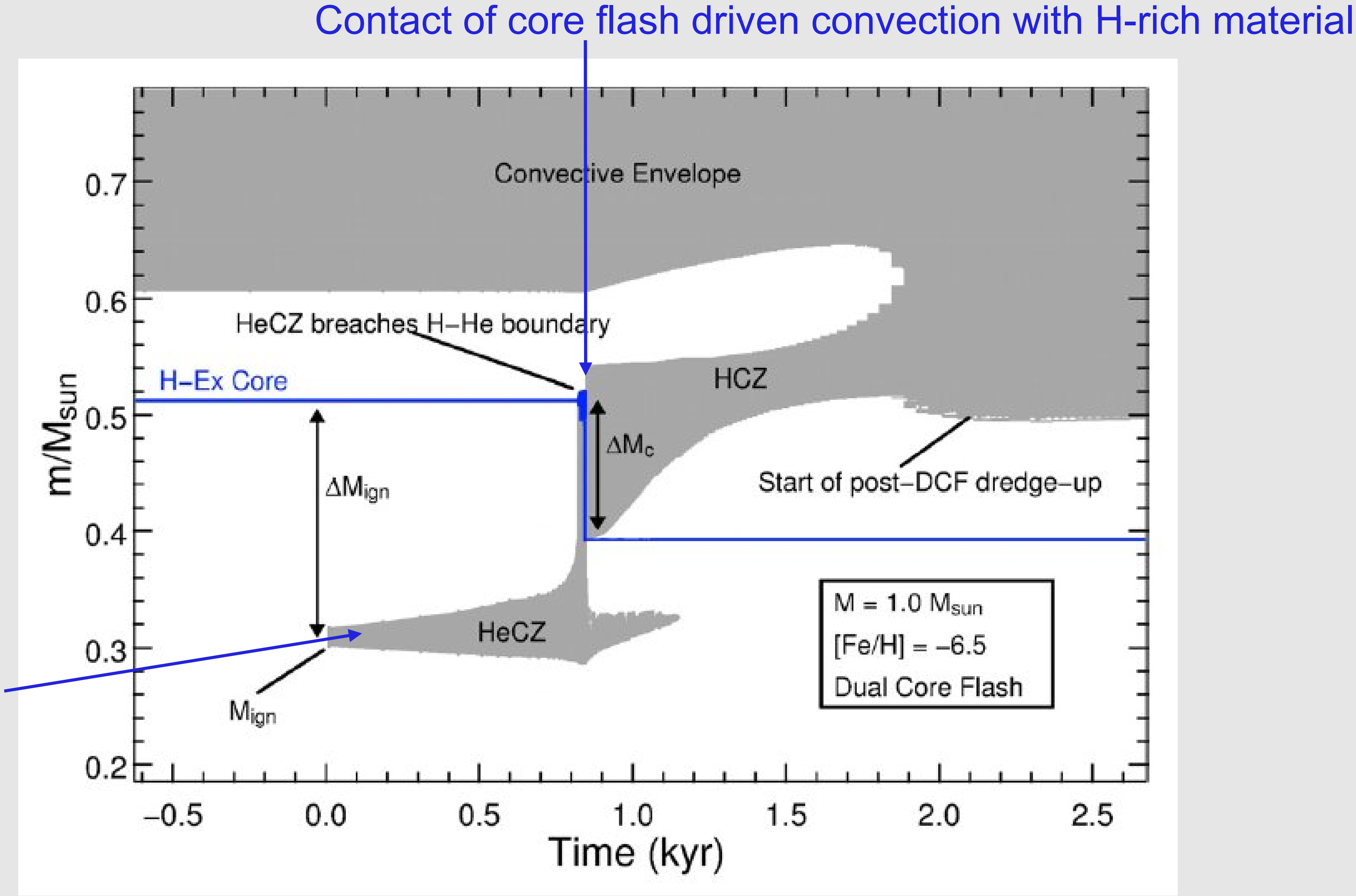
Currently of interest due to discovery of EMP stars with variable enhancements in C, N and s-process elements.

In these stars:

- The convective zone above the He burning layer during either the He core flash or He shell flashes can extend upward to H-rich layers bringing H into the hot He burning region and liberating large amounts of energy (dual flash) and potentially bringing C, N and s-process elements to the surface (Fujimoto et al. 1990; Hollowell et al. 1990).
- He shell flashes may be too weak for third dredge-up to occur.

Behaviour varies with mass and metallicity in a complicated way (modelling is difficult). Recent studies are given in Lau et al. (2009) and Suda & Fujimoto (2010).

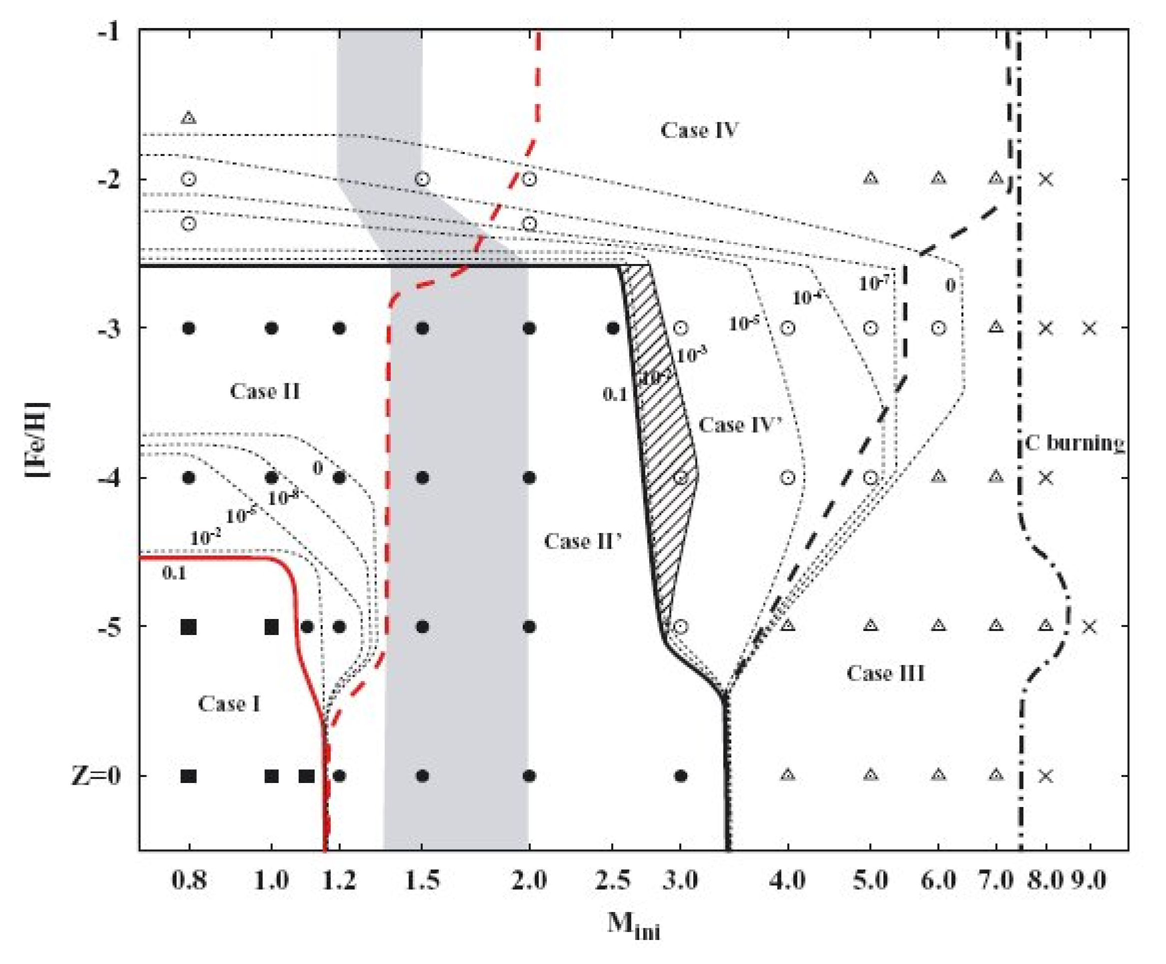
The Dual Core Flash
(also called Helium Flash Induced Mixing
or Helium Flash-Driven Deep Mixing)

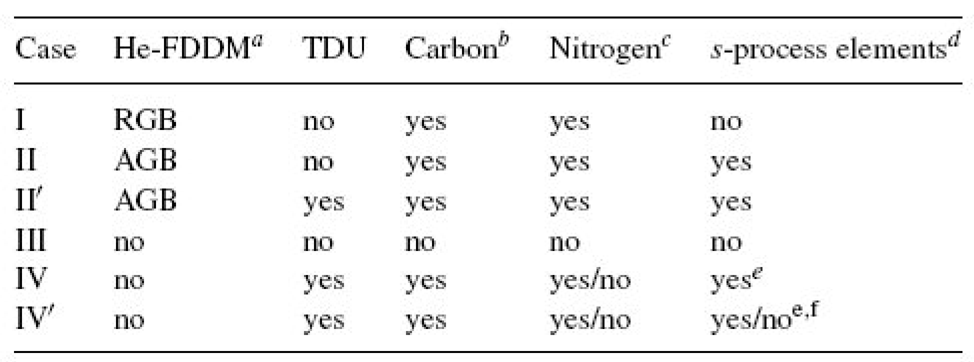


He core flash driven convection

Campbell & Lattanzio (2008)

The complicated M and [Fe/H] dependence of AGB star evolution





Case	He-FDDM[a]	TDU	Carbon[b]	Nitrogen[c]	*s*-process elements[d]
I	RGB	no	yes	yes	no
II	AGB	no	yes	yes	yes
II′	AGB	yes	yes	yes	yes
III	no	no	no	no	no
IV	no	yes	yes	yes/no	yes[e]
IV′	no	yes	yes	yes/no	yes/no[e,f]

He-FDDM = He flash driven deep mixing
TDU = Third dredge-up
C, N, s-process surface enrichment

Suda and Fujimoto (2010)

THE END (stellar evolution and surface enrichment)

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