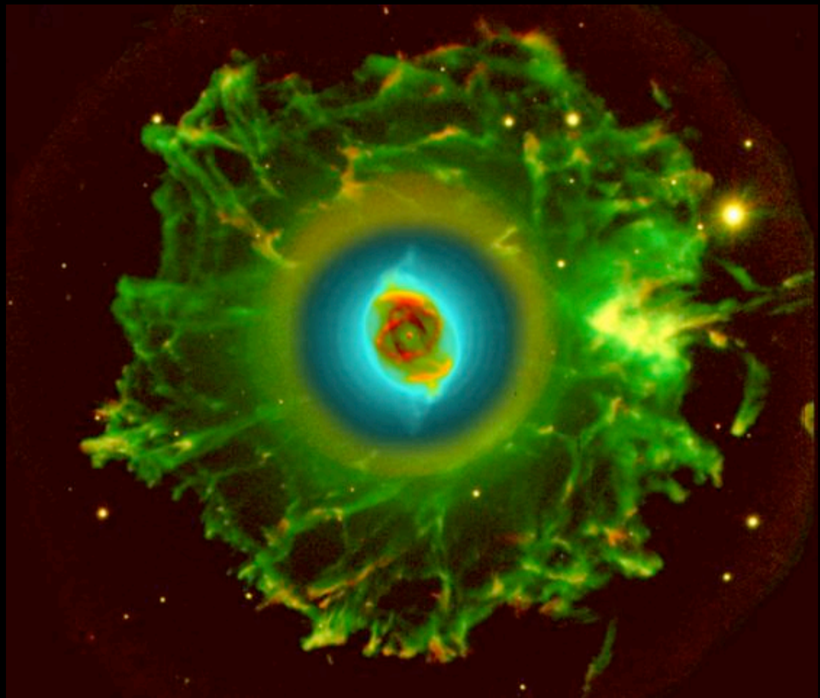
Stellar evolution and nucleosynthesis

- Low- and intermediate mass stars -



Corinne Charbonnel
CNRS & Geneva Observatory

Stellar evolution and nucleosynthesis

- Low and intermediate-mass stars -

- Evolution and nucleosynthesis in stars :
  A global overview of the hydrostatic phases

  Diagrams : HRD, log Tc vs log ρc, main evolution and nucleosynthetic phases, mass limits for the various nucleosynthetic paths

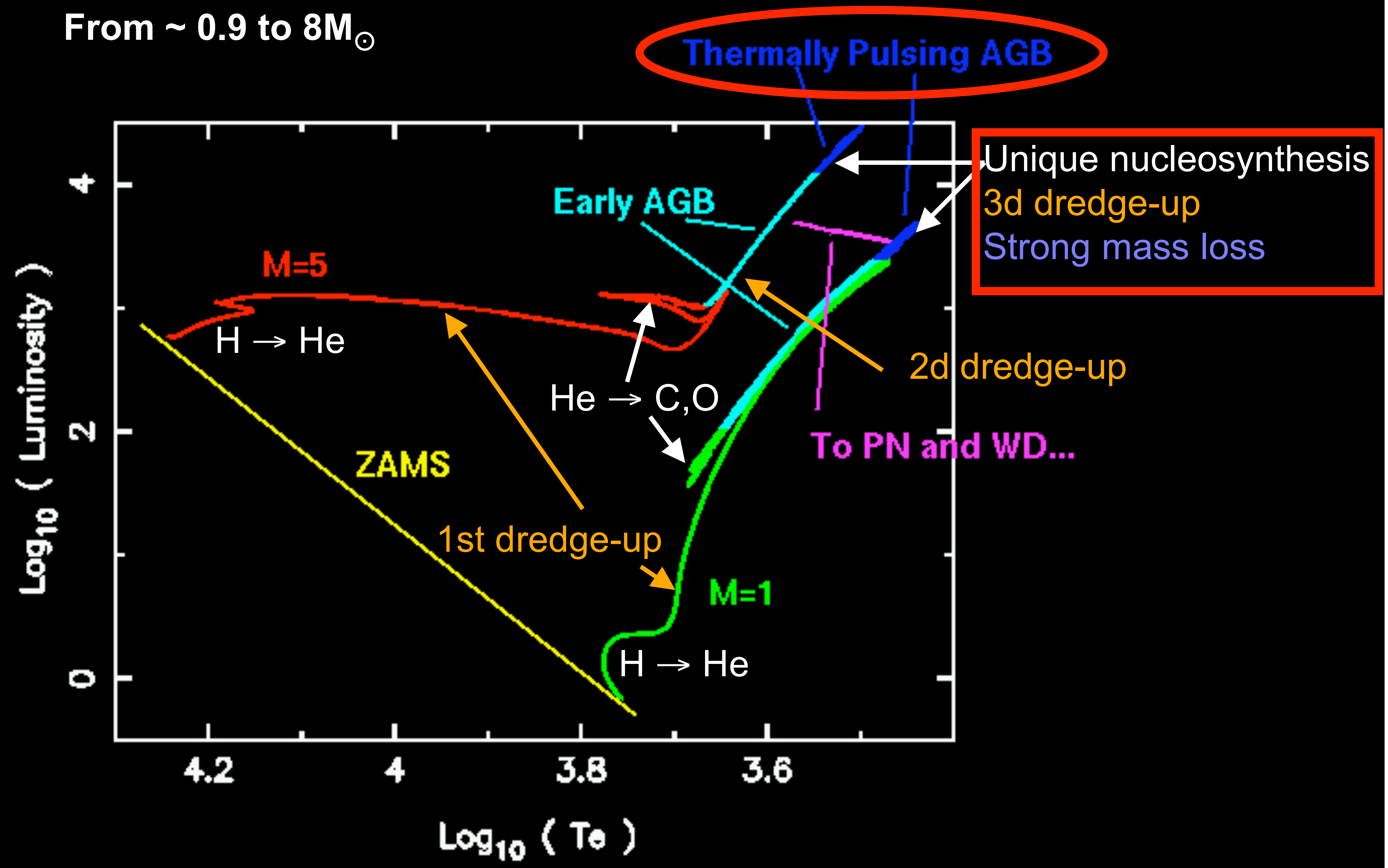
- Main sequence nucleosynthesis - Clues from ^{3}He

- Nucleosynthesis in AGB stars

  AGB structure, TP, mass loss, HBB, 3d dredge-up, rotation, processus-s, yields

  Constraints from PNe and post-AGBs

From ~ 0.9 to 8$M_\odot$



Adapted from Lattanzio

C. Charbonnel. NIC IX summer school. CERN. June 21, 2006

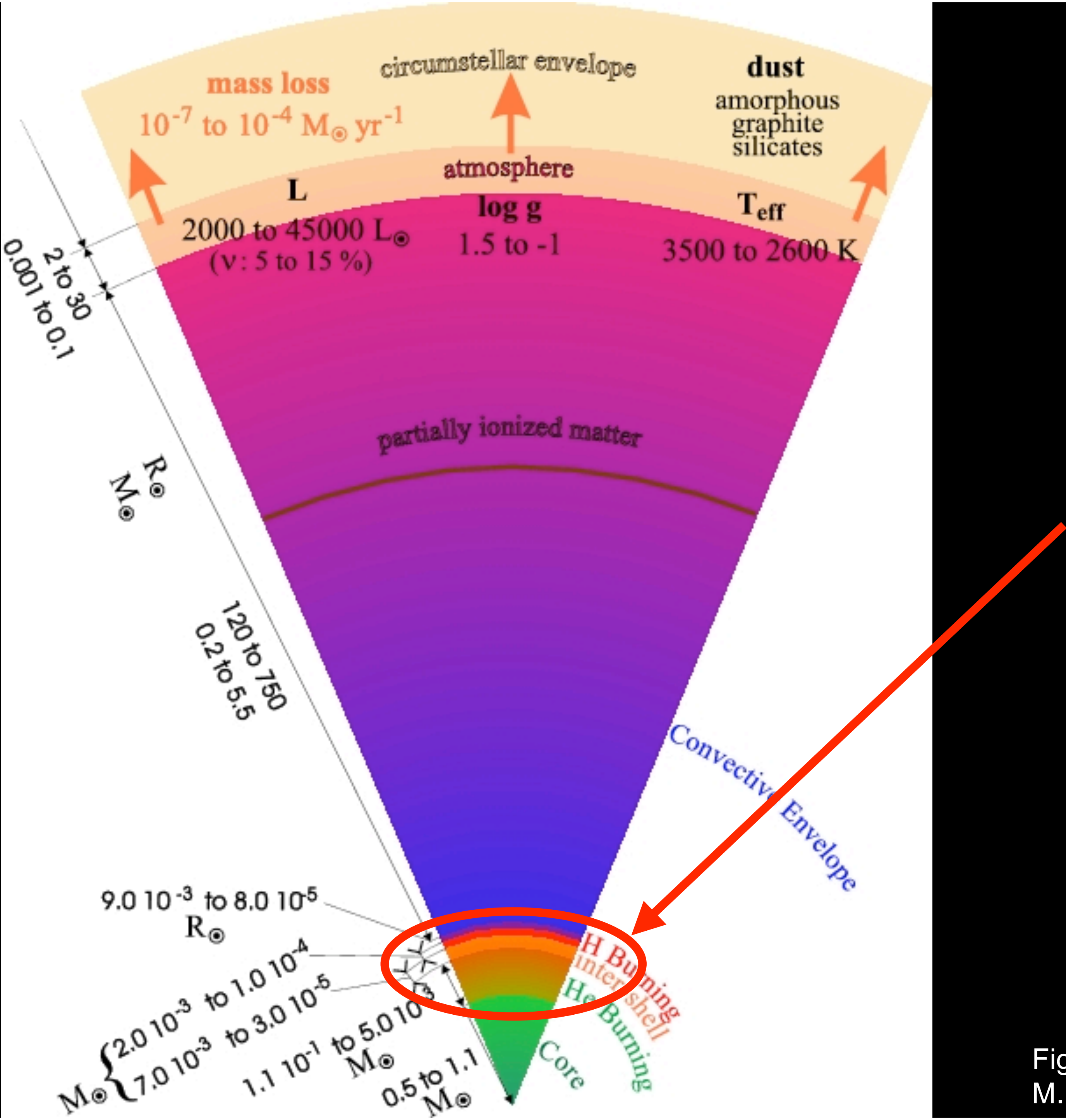


Figure by M.Forestini

Global Structure of an AGB star

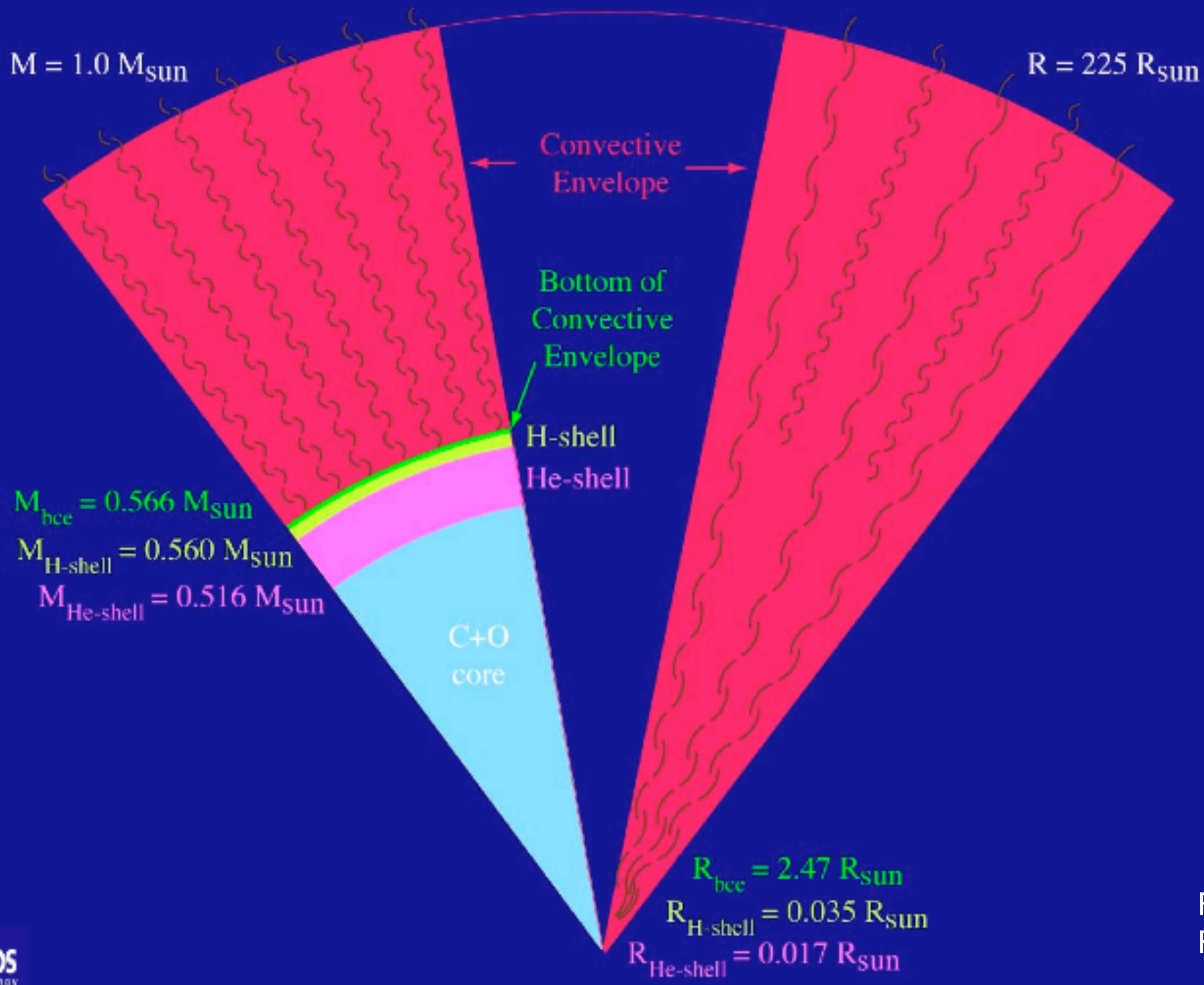
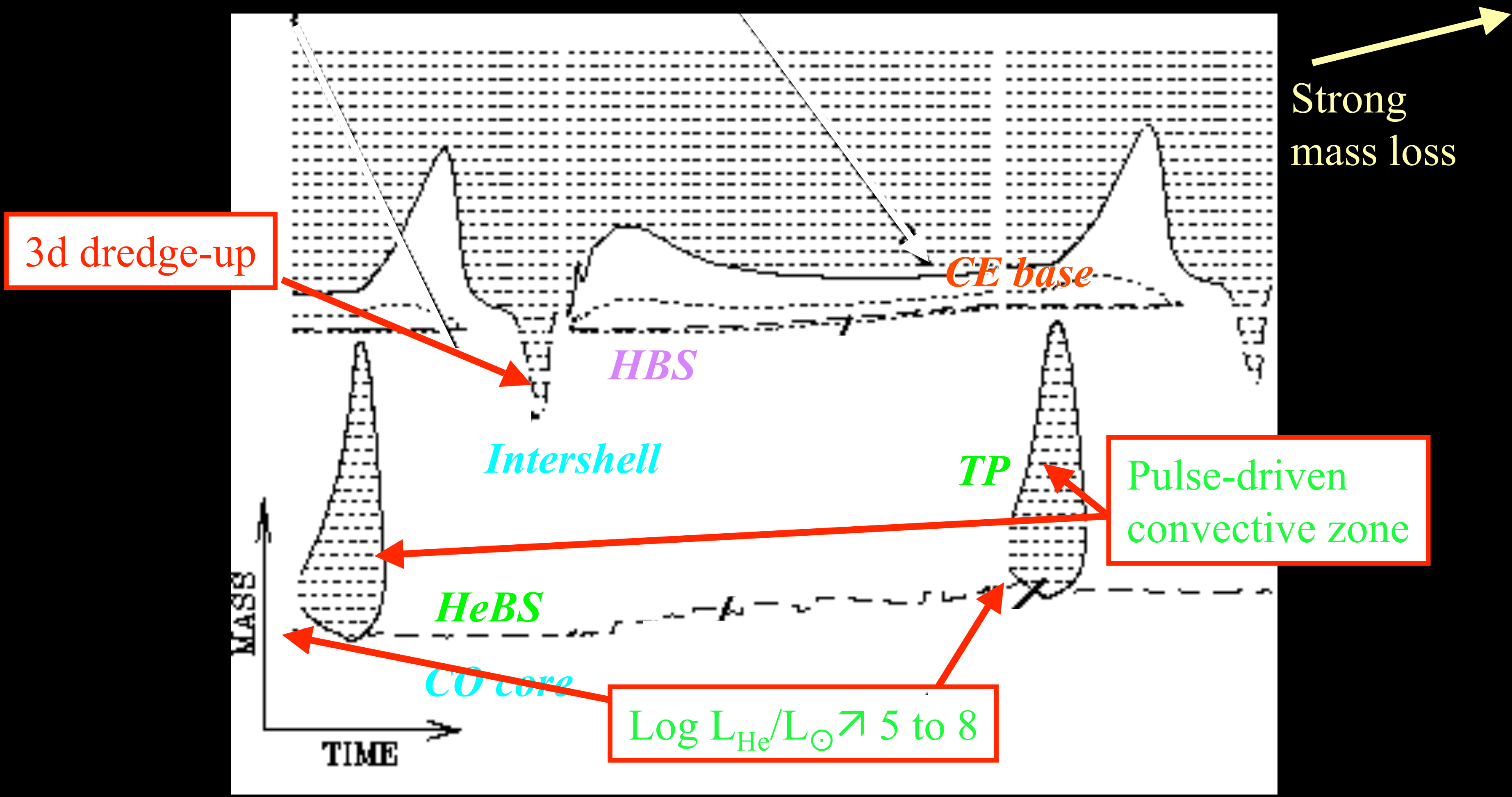


Figure by
F.Herwig

Kippenhahn diagram on TP-AGB phase



Adapted from N.Mowlavi

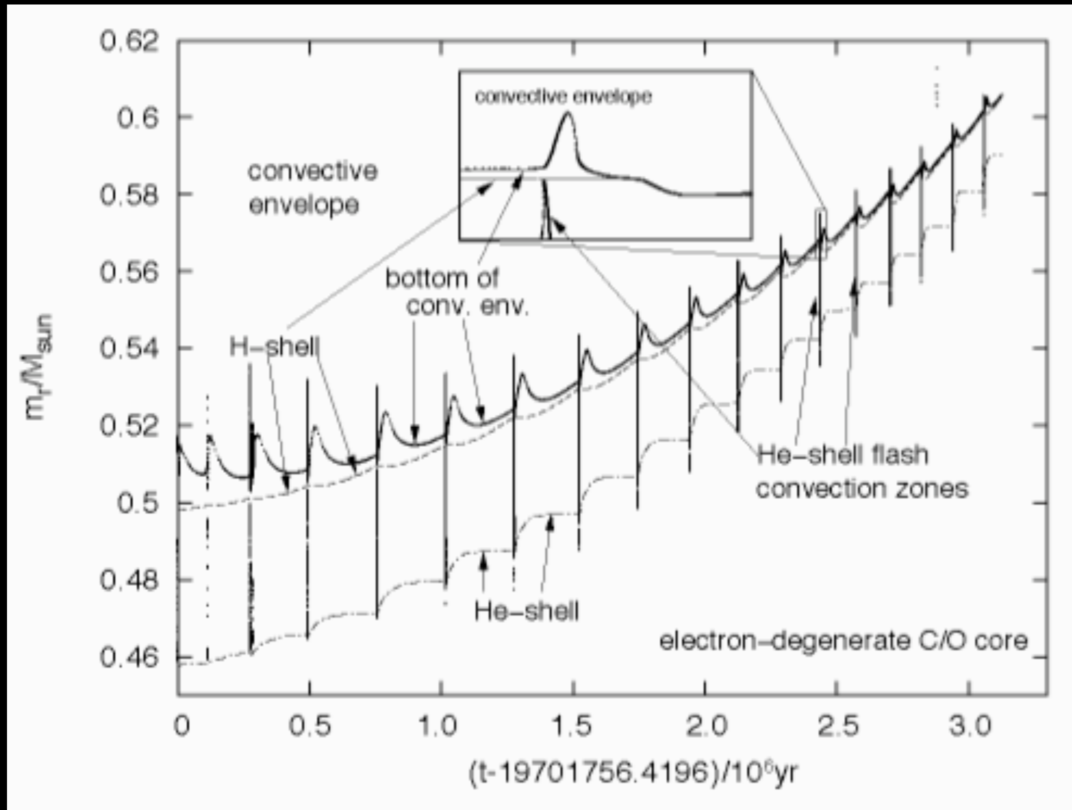


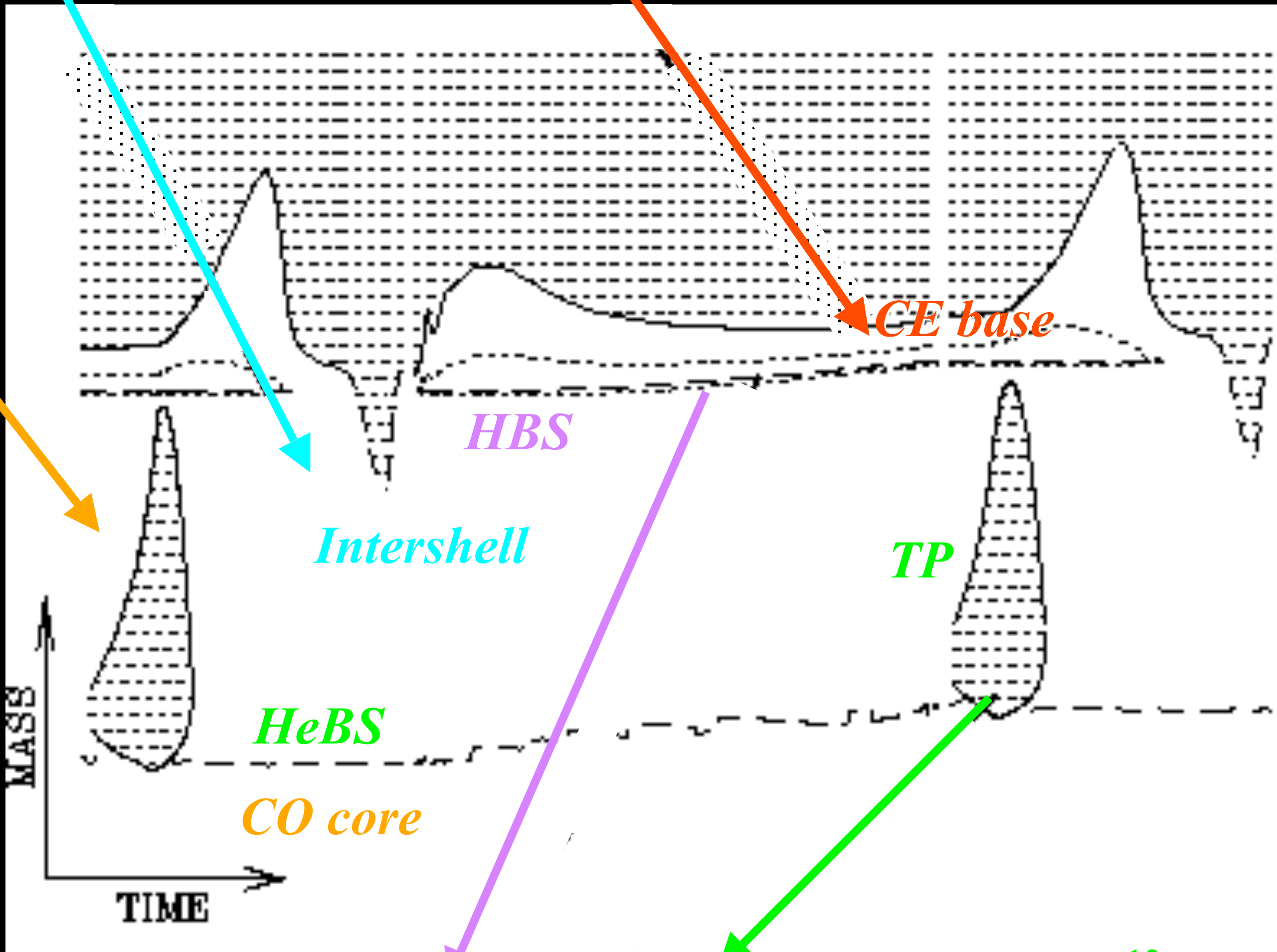
Figure by F.Herwig

Nucleosynthesis on the TP-AGB

Transport of H into C-rich layers
Radiative s-process via $^{13}C(\alpha,n)^{16}O$
during the interpulse

HBB ($M \geq 4M_{sun}$)
CNO (primary ^{14}N), NeNa, MgAl
^{7}Li via Cameron-Fowler mechanism

Ashes of the interpulse HBS engulfed into the pulse convective tongue



Strong mass loss

3d dredge-up ashes of the thermal pulse brought to the surface
He, ^{12}C
^{16}O, ^{22}Ne, ^{25}Mg
s-process

H burning
CNO, NeNa, MgAl

He burning $3\alpha \rightarrow$ primary $^{12}C \rightarrow {}^{14}N$ (CNO)
$^{14}N(\alpha,\gamma)^{18}F(\beta+)^{18}O(\alpha,\gamma)^{22}Ne$
$^{22}Ne(\alpha,n)^{25}Mg$, $^{22}Ne(\alpha,\gamma)^{26}Mg$
s-elements and ^{15}N from intershell ^{13}C burning

- ✓ Third dredge-up ($M \geq 1.5M_\odot$ at $Z_\odot$)
  - products of He-burning in the TP
  - ^{4}He, ^{12}C, ^{16}O, ^{22}Ne, ^{25}Mg, s-process elements increase
- ✓ Hot-bottom burning ($M \geq 4 - 4.5M_\odot$)
  - CN-cycle : $^{12}C \rightarrow {}^{13}C \rightarrow {}^{14}N$
  - ON-cycle : $^{16}O \rightarrow {}^{14}N$

Predictions depend on

- ✓ Stellar parameters
  - M, Z
- ✓ Input physics prescriptions
  - Nuclear reaction rates, opacities, …
- ✓ Various incompletely understood physical parameters
  - Mass loss, convection, transport processes, rotation, …

which rests on *semiempirical calibrations*

(e.g. C star luminosity function, initial-final M relation)

that have to be *extrapolated*

to a range of M, Z for which *no empirical data* are available

Illustration of the uncertainties on the yields

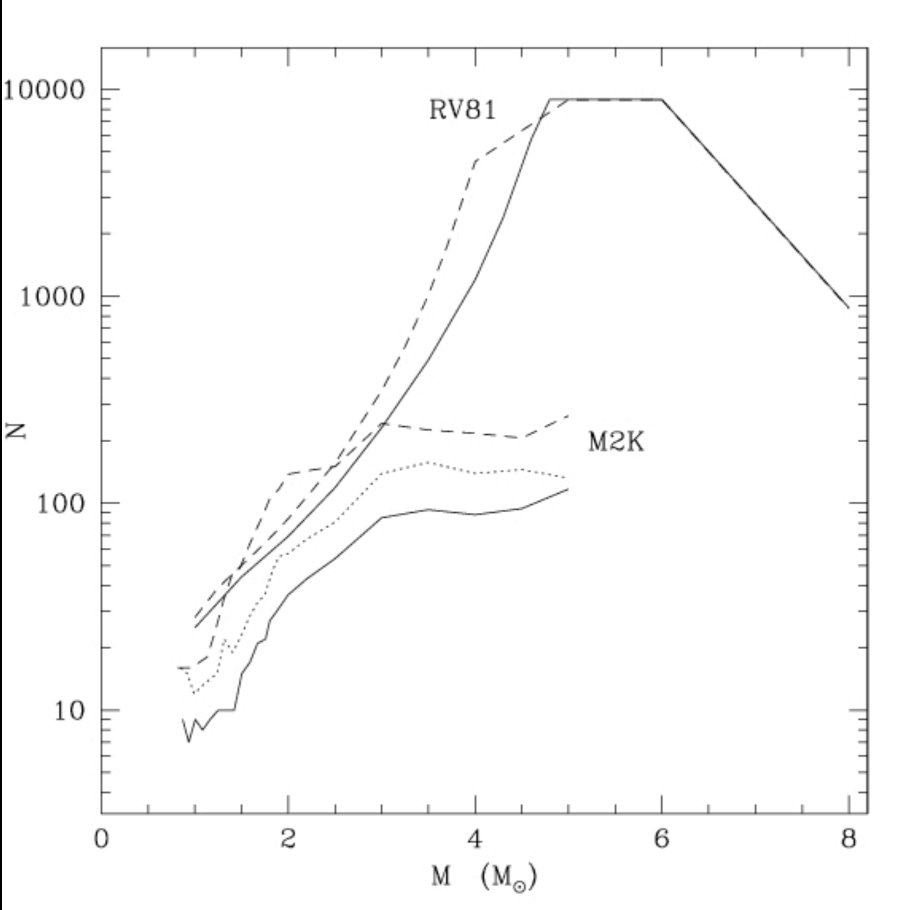
→ Mass loss

Mass loss affects the AGB duration, i.e.

the number and strength of TPs and subsequent 3d DUP events and the growth of Mcore

A minimum $M_{envelop}$ is required for HBB and 3d DUP to occur

HBB may be shut down long before 3d DUP ends



Expected number of TP vs initial M*

Renzini & Voli (81)
Reimers law (75), no superwind

Marigo (00)
Vassiliadis & Wood (93)

$Z = Z_\odot$ ———
0.008 ....
0.004 — — —

Marigo (00)

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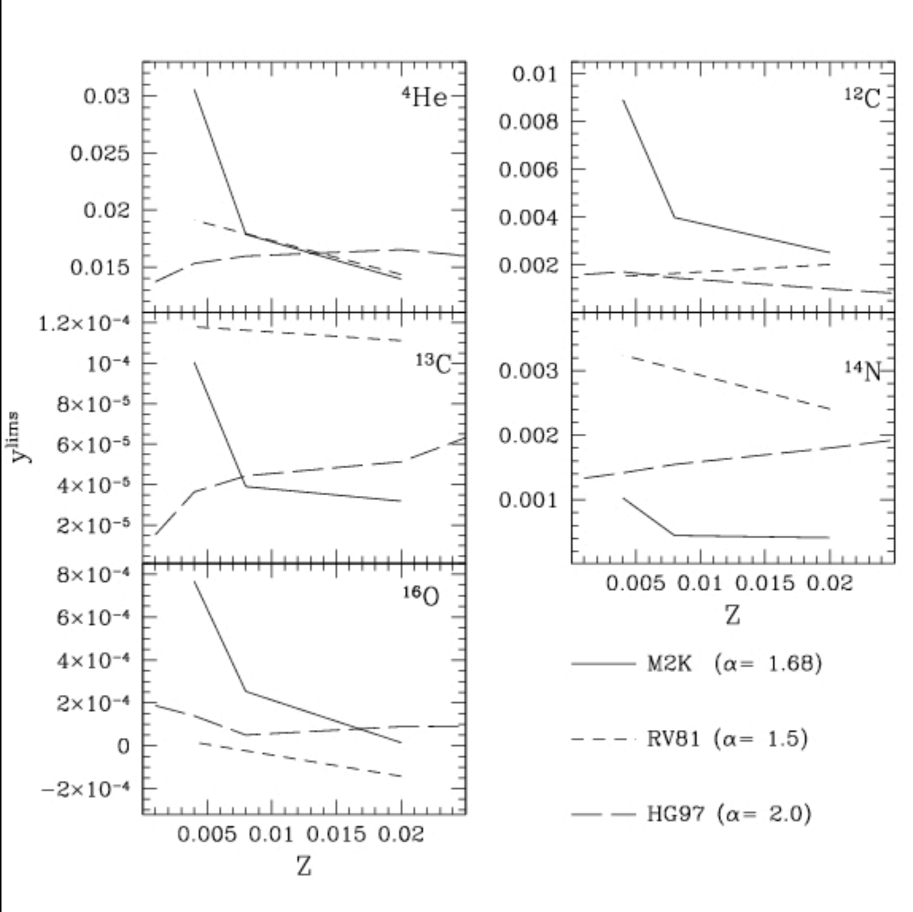


Integrated yields as a function of Z

Renzini & Voli (81) – – –

Reimers law (75), no superwind

Marigo (00) ———

Vassiliadis & Wood (93)

Marigo (00)

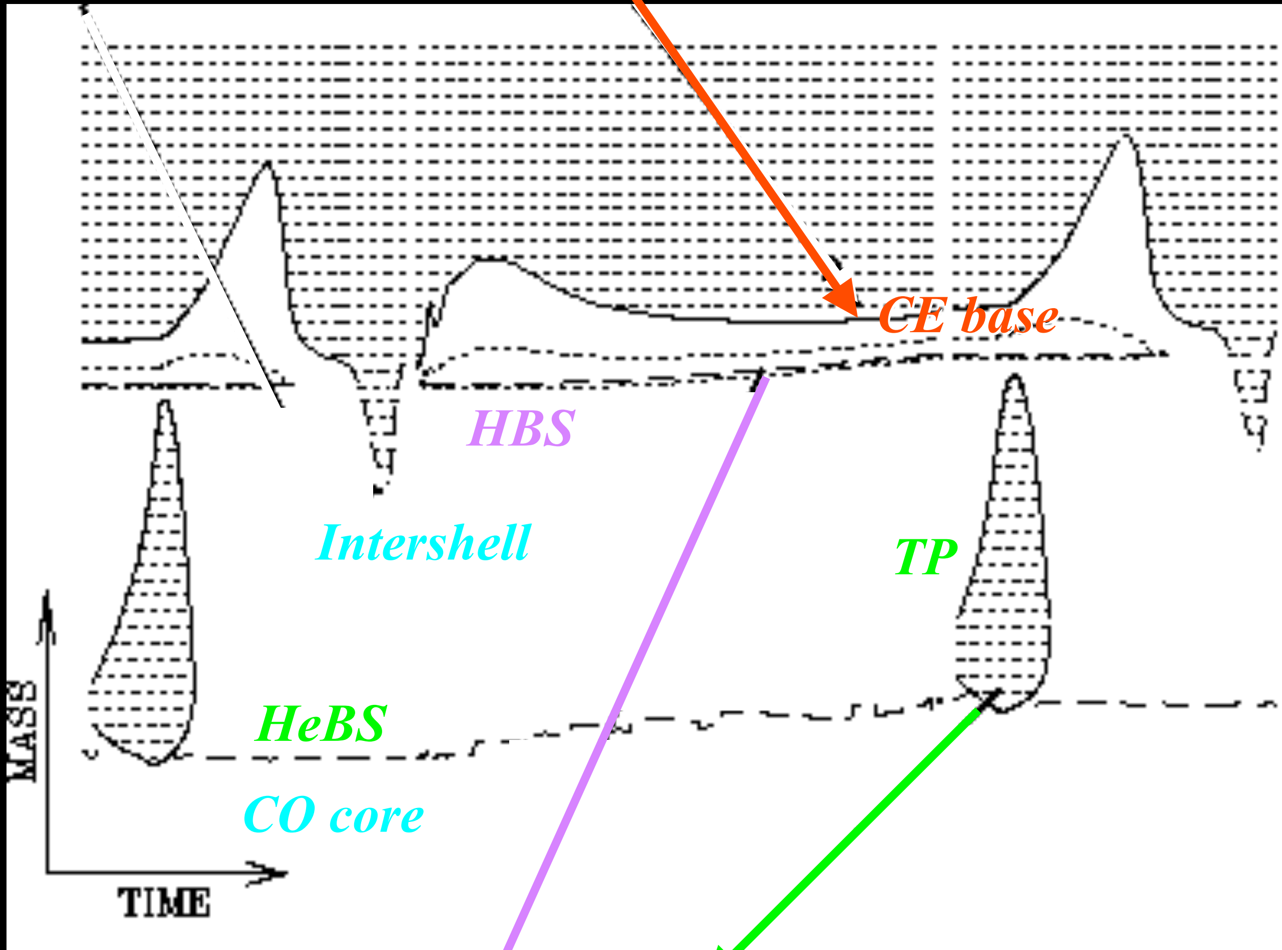
Illustration of the uncertainties on the yields

→ The case of O and Na

HBB (M > 4Msun)

CNO, NeNa

At higher T, ^{23}Na destroyed again via $^{23}Na(p,\gamma)^{24}Mg$



Strong mass loss

3d dredge-up ashes of the thermal pulse brought to the convective envelope (^{16}O, ^{22}Ne)

H burning

CNO, NeNa (negligible)

He burning $3\alpha \rightarrow$ primary ^{12}C

Primary production of ^{16}O by $^{12}C(\alpha,\gamma)$

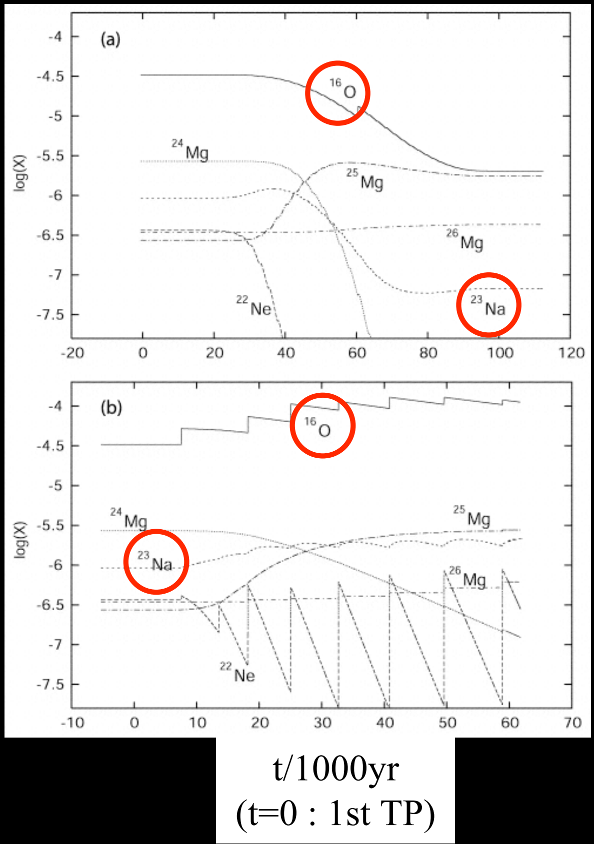
^{14}N (CNO) $\rightarrow$ $^{14}N(\alpha,\gamma)^{18}F(\beta+)^{18}O(\alpha,\gamma)^{22}Ne$

Illustration of the uncertainties on the yields

→ HBB and 3d DUP

O, Na evolution at the surface of a low-Z massive TP-AGB star

Delicate interplay of 3d dredge-up and hot bottom burning



(a) <u>No 3DUP, only HBB</u>

→ Large ^{16}O depletion

→ ^{23}Na depletion

(due to the lack of ^{22}Ne dredged-up)

(b) <u>Strong 3DUP, HBB, no mass loss</u>

→ 3DUP of the ^{16}O-rich layers below the TP

→ ^{23}Na increase (from dredged-up ^{22}Ne)

Full evolution models

Denissenkov & Herwig (03)

Illustration of the uncertainties on the yields

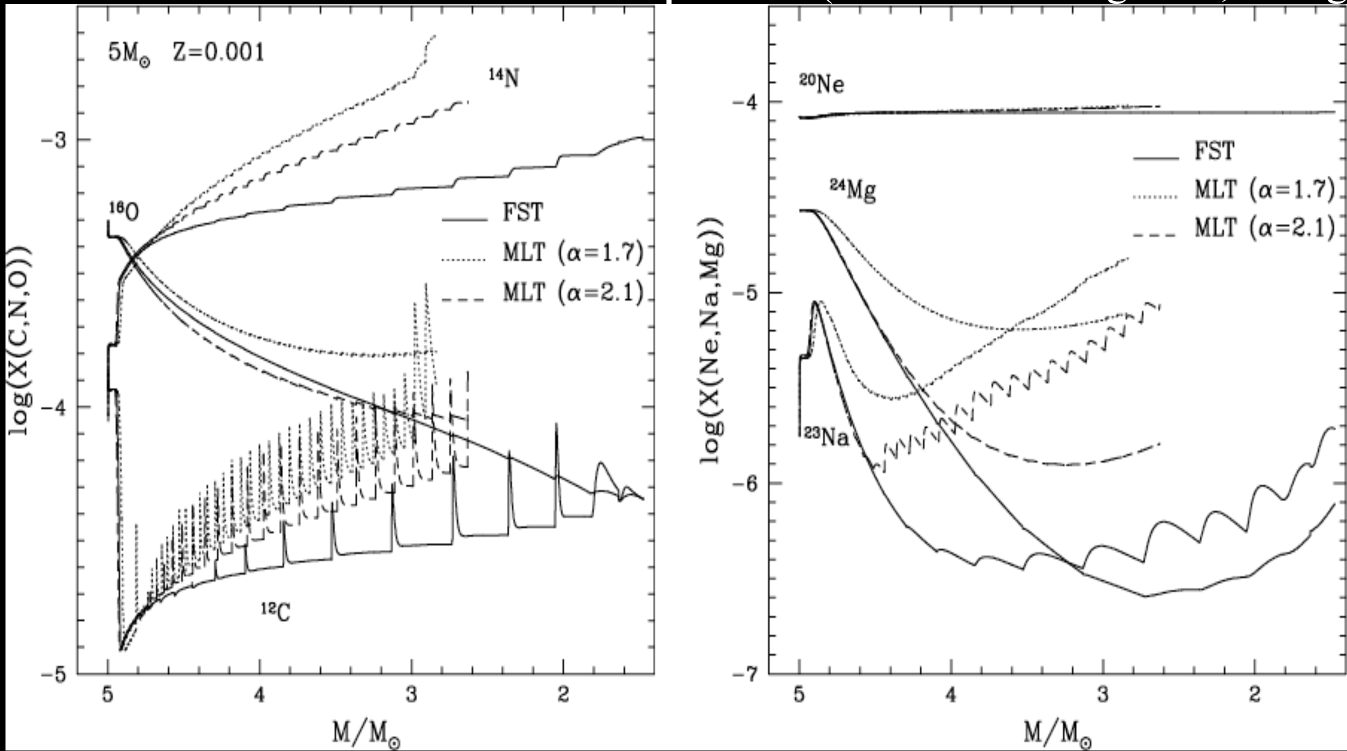
→ Convection

Impact of convection

Ventura & D'Antona (05 I)

See also Renzini & Voli (81), Sackmann & Boothroyd (91), Blöcker & Schönberner (91), D'Antona & Mazzitelli (96)

Full Spectrum of Turbulence (Canuto & Mazzitelli 91)
→ **much more efficient HBB** than with MLT
(on the AGB : higher L, stronger mass loss)



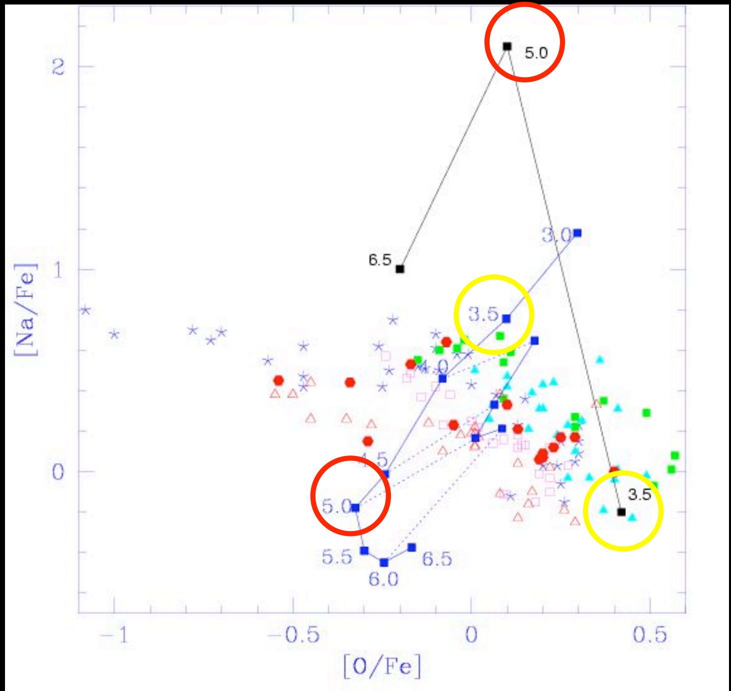
C. Charbonnel

MLT17 :
Little O depletion (factor of ~2)
Extremely large increase of Na and N
C+N+O increase by ~ 0.8dex

FST :
Largest O depletion
Slight decrease of Na
C+N+0 conserved

Impact of convection on nucleosynthesis

Ventura & D'Antona (05 II)



<u>Fenner et al.(04)</u>

Overproduction of (primary) ^{23}Na
due to the burning of dredged-up ^{20}Ne

<u>Ventura & D'Antona (05II)</u>

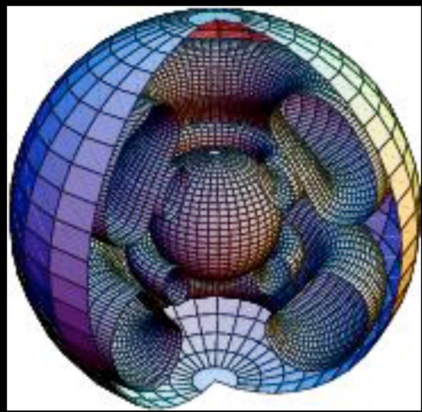
Underproduction of ^{23}Na
due to smaller number of 3DUP episodes
and larger T

Both sets are unable to reproduce the data

« The predictive power of AGB models
is still undermined by many uncertainties » (VD'A05)

Illustration of the uncertainties on the yields

→ Rotation



Rotating AGB models

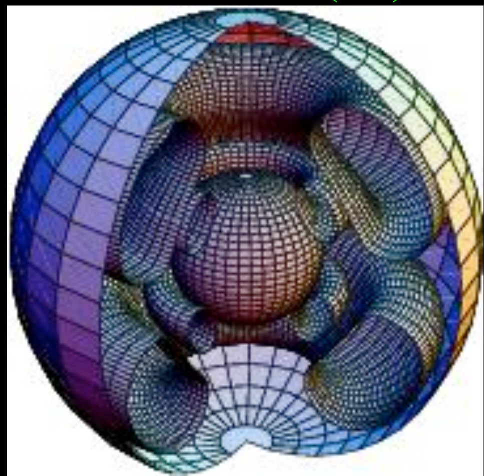
Decressin, Charbonnel, Siess, Palacios, Meynet (06)

STAREVOL

Meridional circulation and shear turbulence

Zahn (92), Chaboyer & Zahn (95)

Talon & Zahn (97), Maeder & Zahn (98)



Courtesy of Georges Meynet

Same physics successfully applied to

Massive stars : HeBCN anomalies (see references in Maeder & Meynet 00)

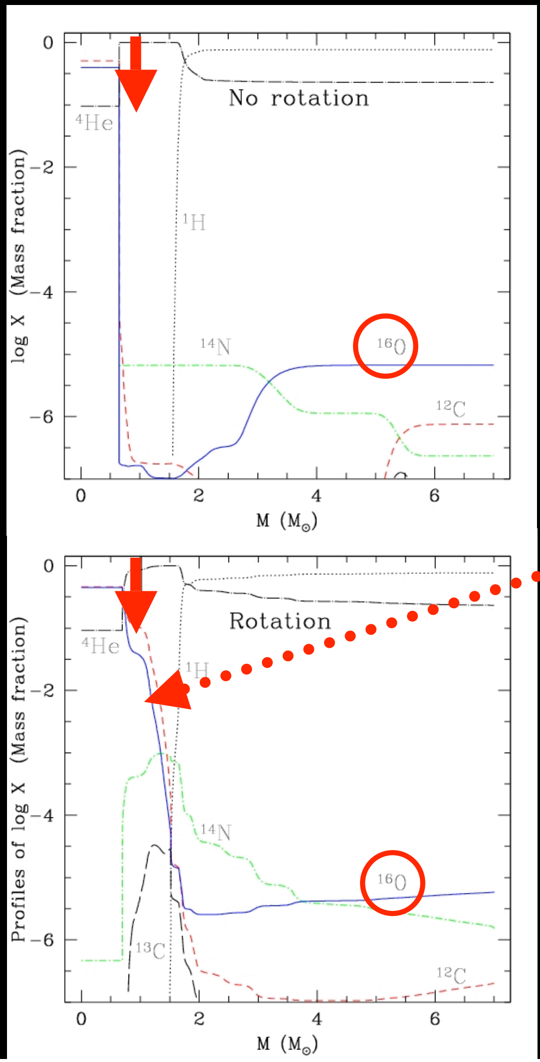
Low-mass stars : Hot side of the Li dip, Li in subgiants (Charbonnel & Talon 99, Palacios et al.03, Pasquini et al.04)

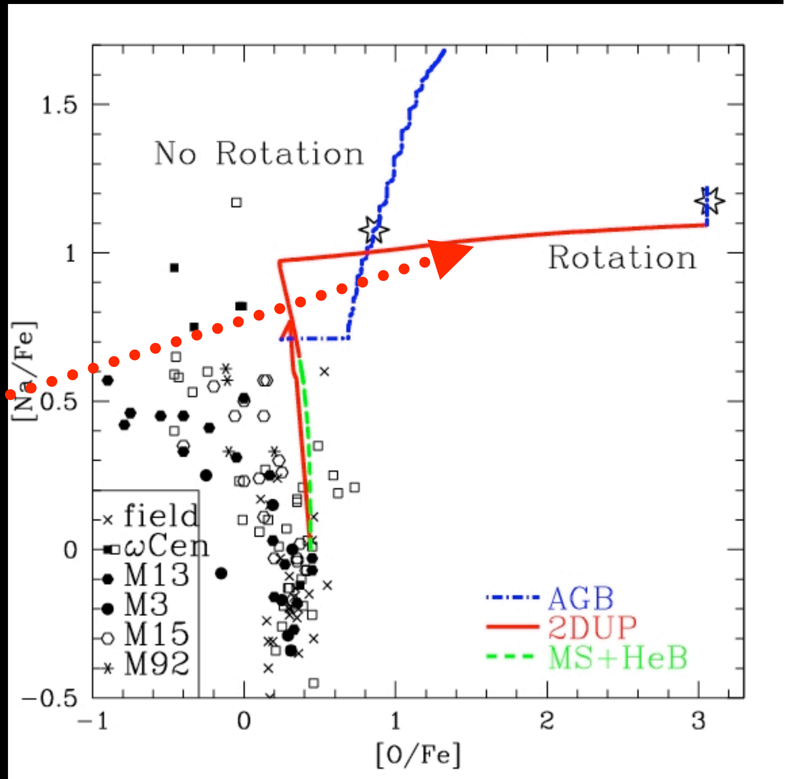
Rotating AGB models

Decressin, Charbonnel, Siess, Palacios, Meynet (06)

$7M_\odot$ star,
$Z = 10^{-5}$

Profiles
at the end of
central He-burning



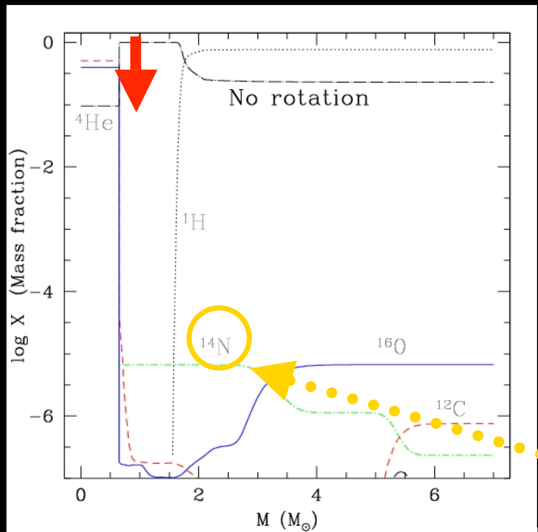


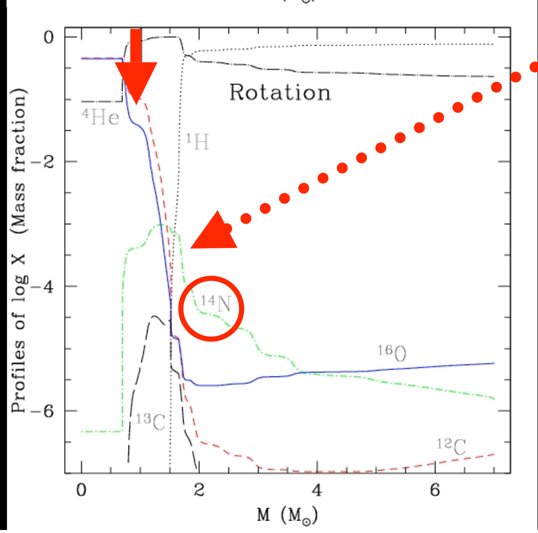
Primary ^{14}N
in rotating intermediate-mass stars

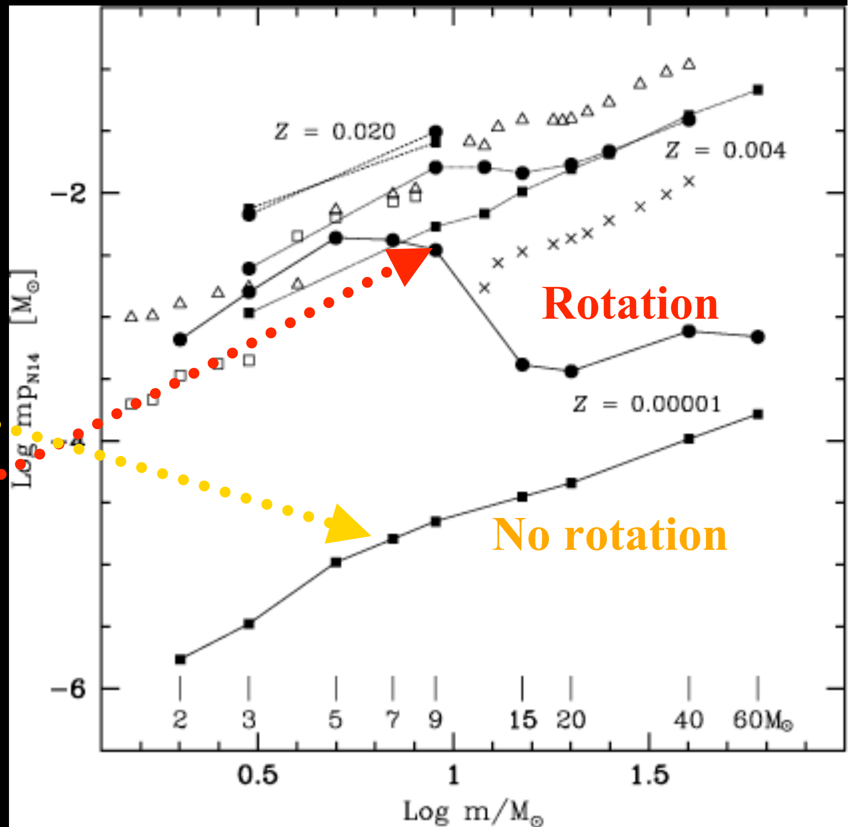
Meynet & Maeder (02)

$7M_M$ star,
$Z = 10^{-5}$

Profiles
at the end of
central He-burning



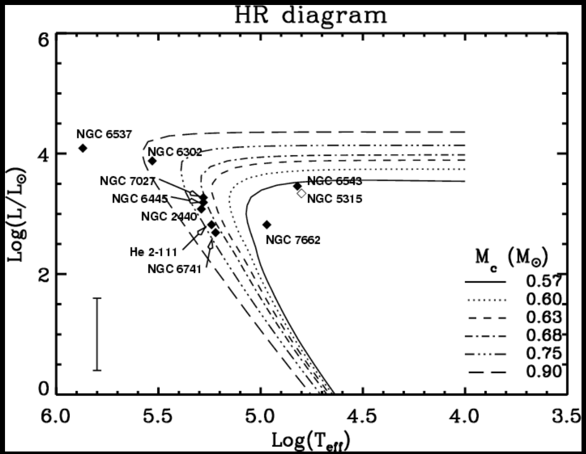




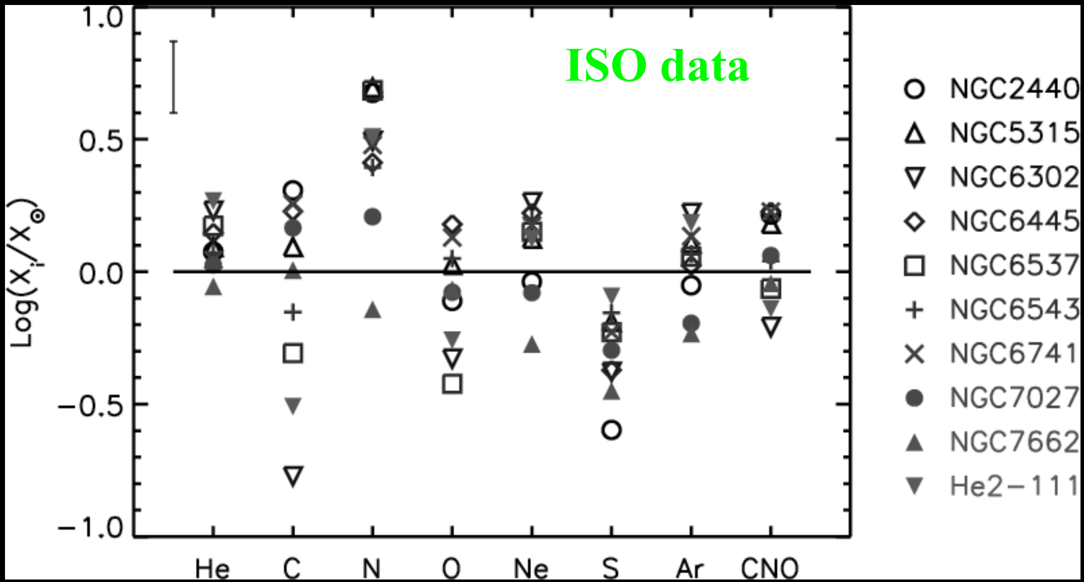
The importance of PNe as constraints on nucleosynthesis

Insight on the nucleosynthetic properties of the PNe progenitors

- ✓ C, N : Efficiency of 3d DUP vs HBB
- ✓ He : Cumulative effect of the 1st, 2d, 3d dredge-up, and HBB
- ✓ O : Composition of the TP, efficiency of HBB
- ✓ Ne : Synthesis during the TP, efficiency of HBB, s-process $^{22}Ne(\alpha,n)^{25}Mg$



Marigo et al. (03)
vs Grevesse & Sauval (98)
+ O from Allende-Prieto et al. (01)



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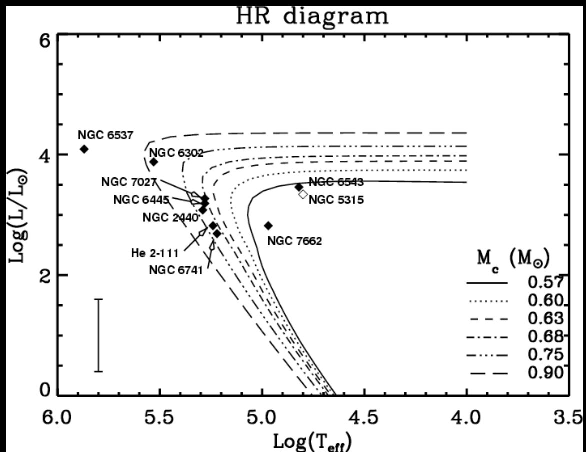
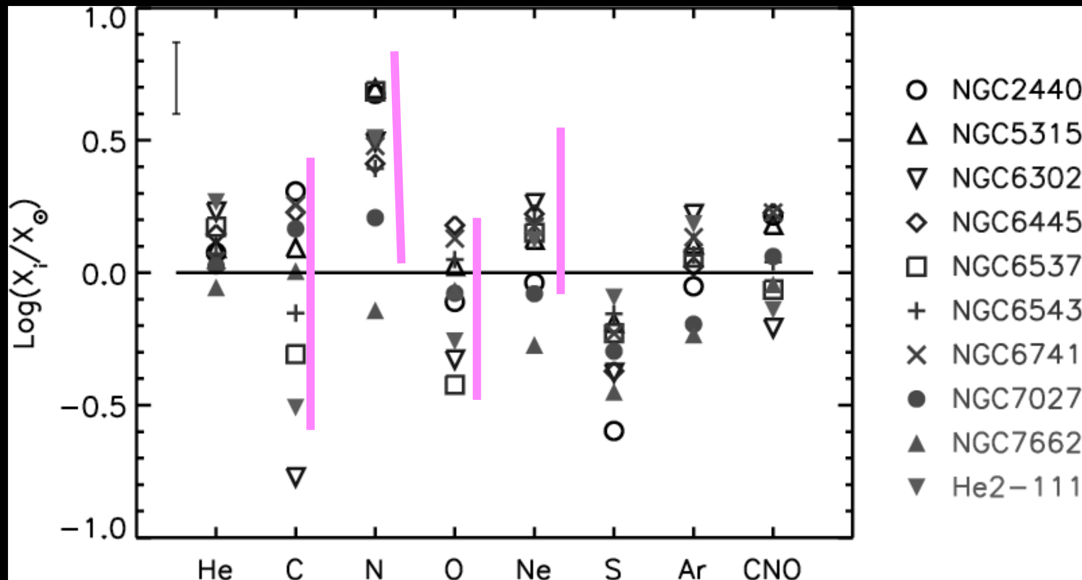




Marigo et al. (03)
vs Asplund et al. (05)

The s-process

s-process

$(Z,A) + n \rightarrow (Z,A+1) + \gamma$

If (Z,A+1) is stable, it will capture another neutron latter on

If (Z,A+1) is unstable :

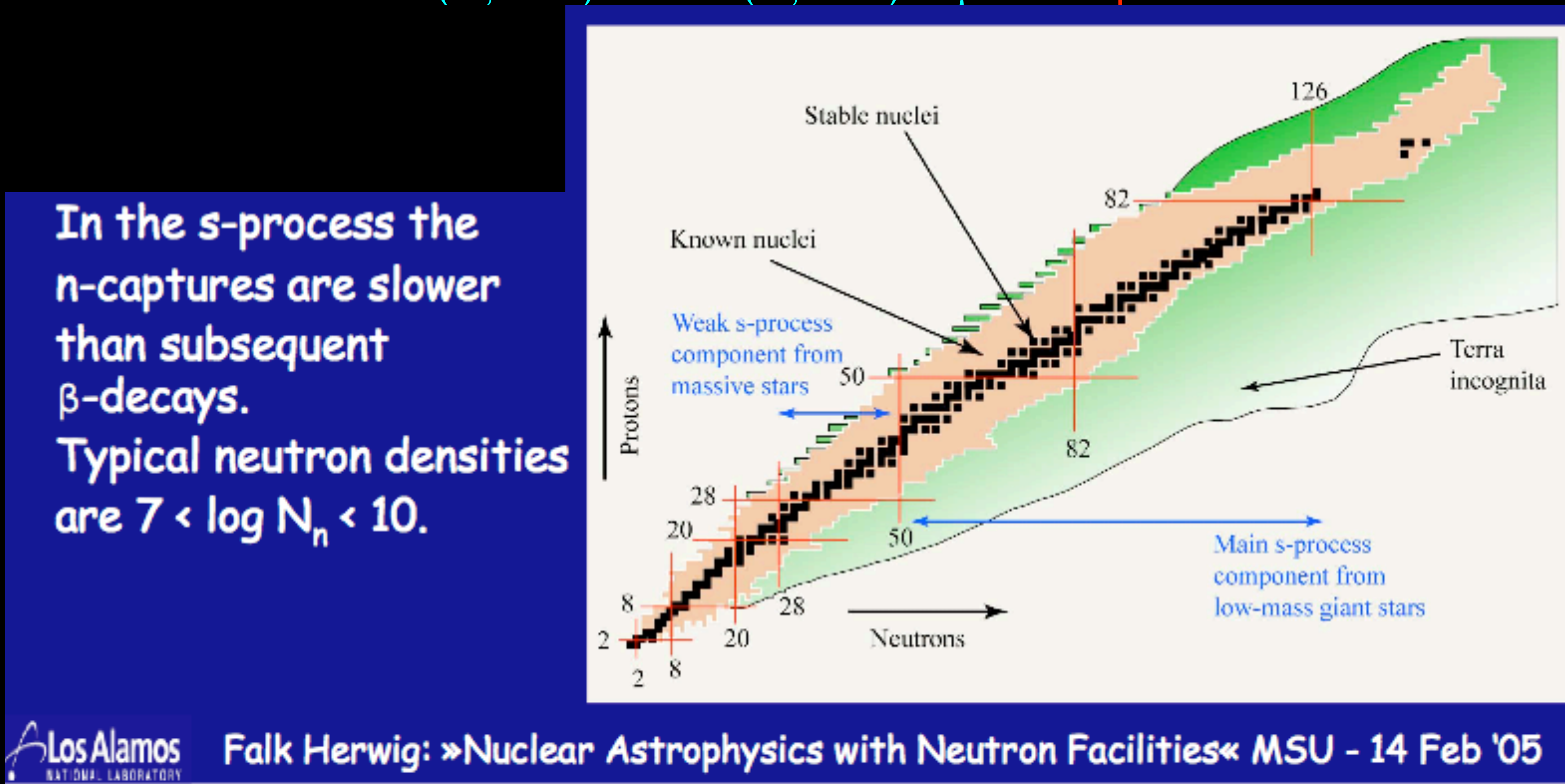
With a low neutron flux, (Z,A+1) may decay before next n-capture

$(Z,A+1) \rightarrow \beta^- + \nu + (Z+1,A+1)$: s-process

Nuclei symetric in proton and neutron numbers

With a strong neutron flux,

$(Z,A+1) + n \rightarrow (Z,A+2) + \gamma$: r-process



s-process : two neutron sources

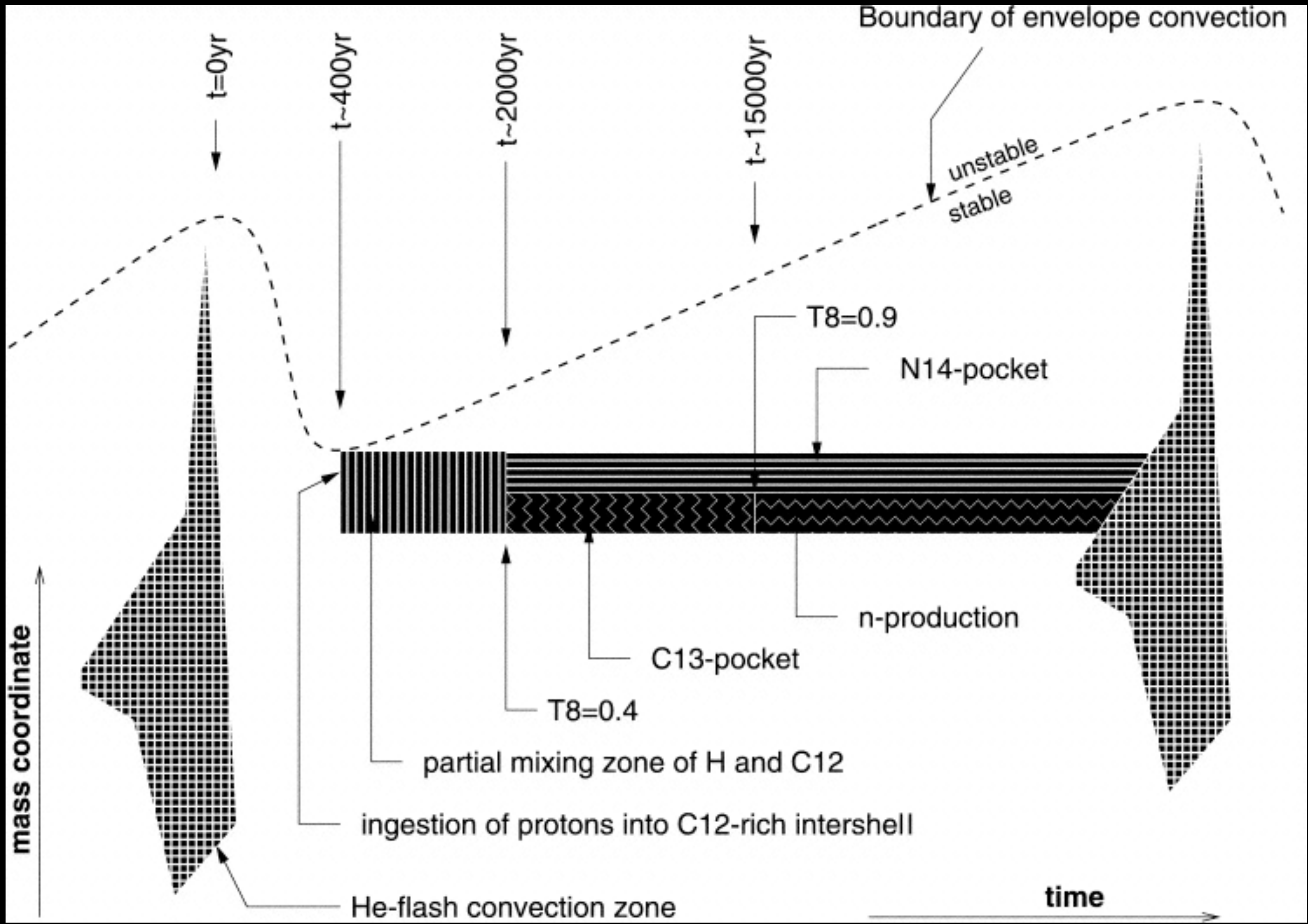
$^{12}C + \alpha \rightarrow n + ^{16}O$

- n-release during the interpulse phase
- radiative conditions, T8 > 0.9
- low-n densities : Nn < 10^{7} cm^{-3}
- no activation of branchings

$^{22}Ne + \alpha \rightarrow n + ^{25}Mg$

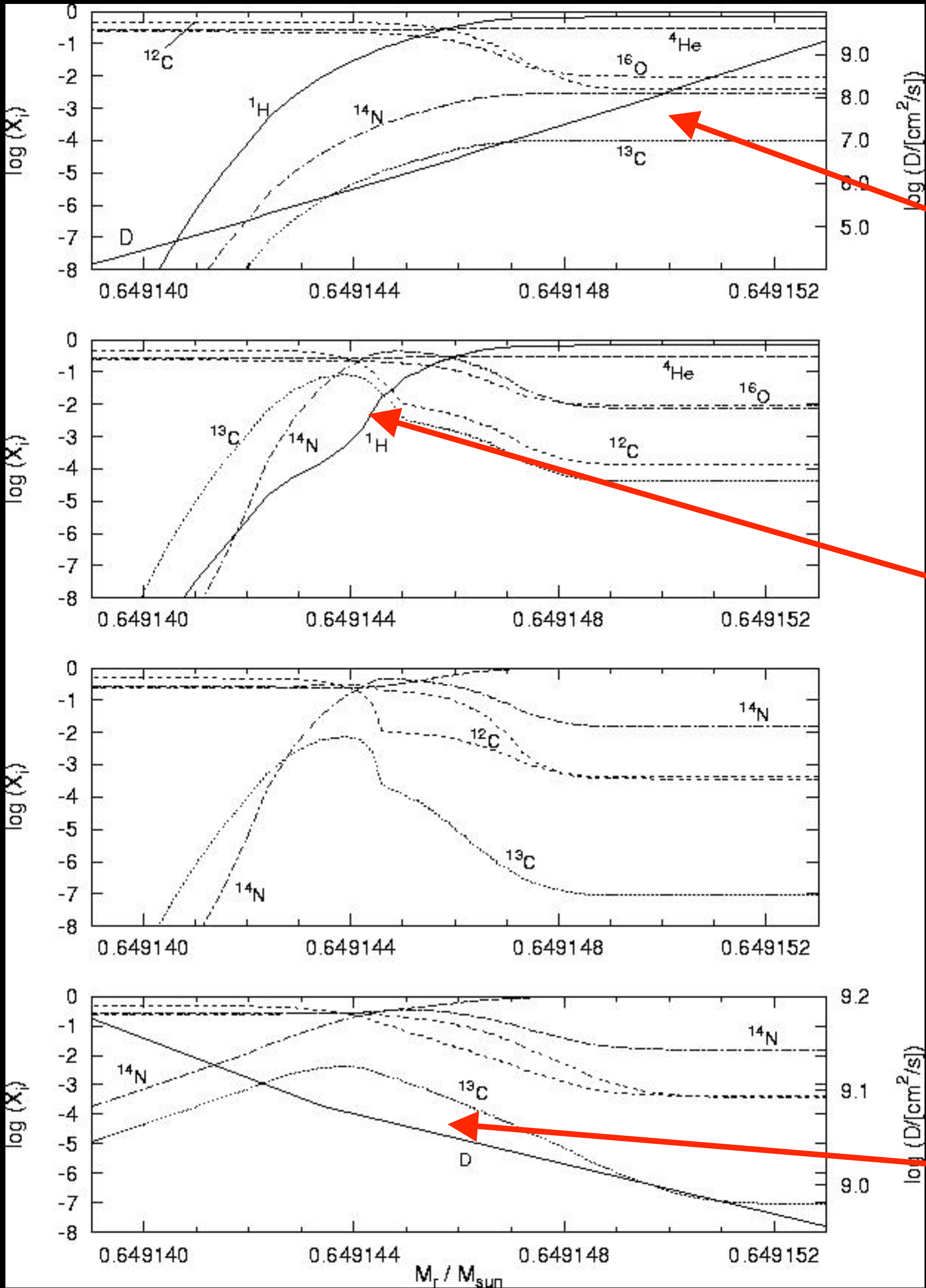
- n-release in intershell during TP
- convective conditions, T8 > 2.5
- high-n densities : Nn < 10^{10} cm^{-3}
- activation of branchings

Radiative s-process in AGB stars



Herwig et al. (2003)

Convective ov



500yr after the He-flash
After the end of the DUP episode
D : overshoot of the envelope convection

1800yr after the He-flash
HBS has set in again

M(^{13}Cpocket) ~ 2 to 4 x 10^{-7} M$_\odot$
s-process element distribution requires M(^{13}Cpocket) ~ 1 to 2 x 10^{-5} M$_\odot$

Very end of the interpulse
^{13}C has already been destroyed

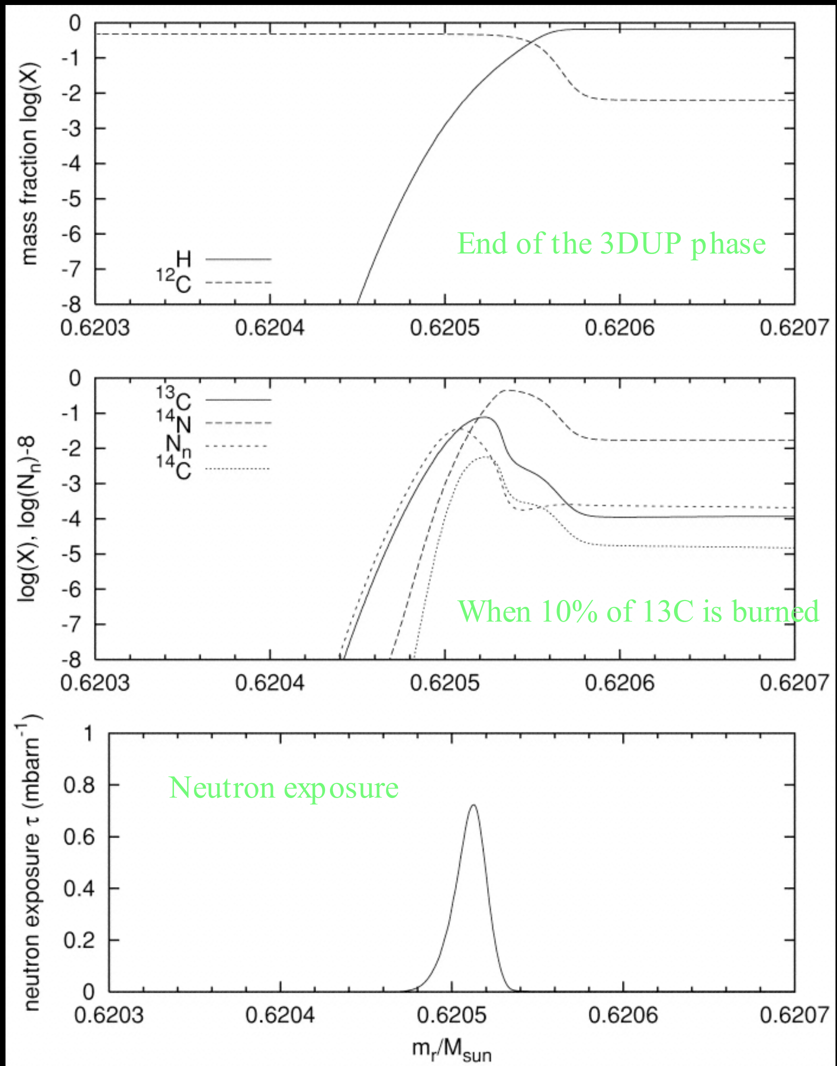
Onset of the next thermal pulse
D : upper overshoot zone of the TP

Herwig (2000)

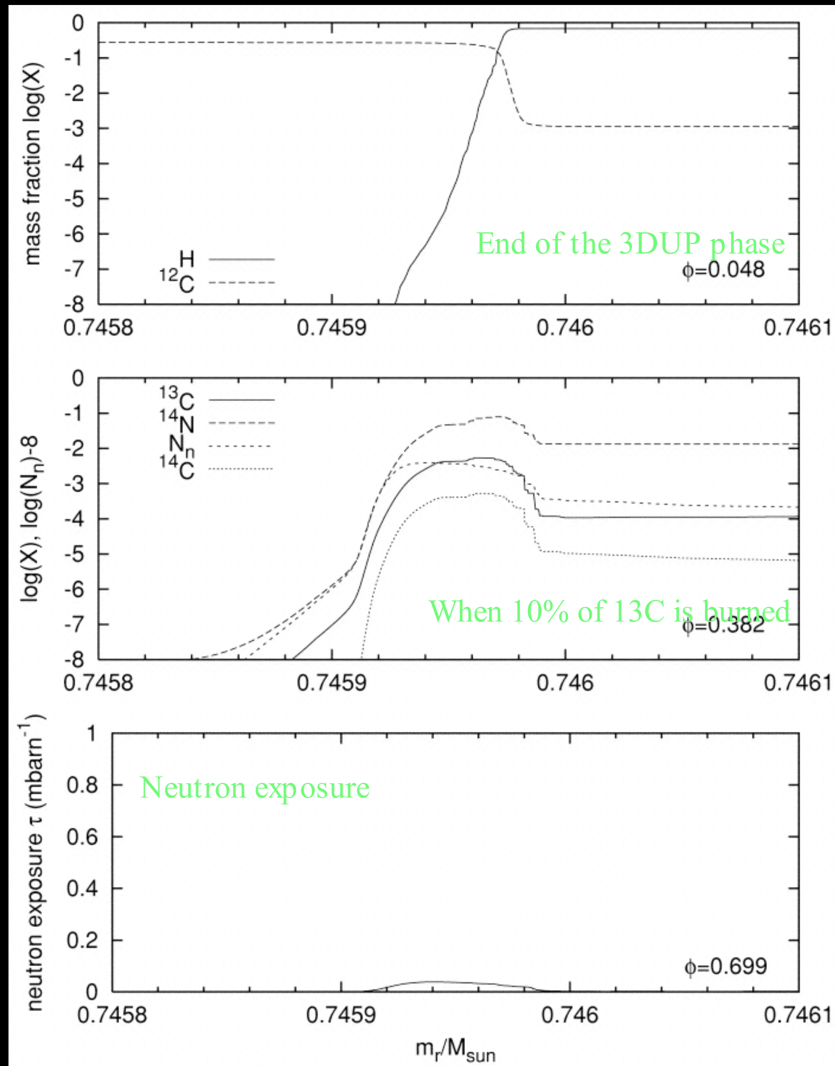
Herwig et al. (2003)

$3M_\odot$, $Z_\odot$

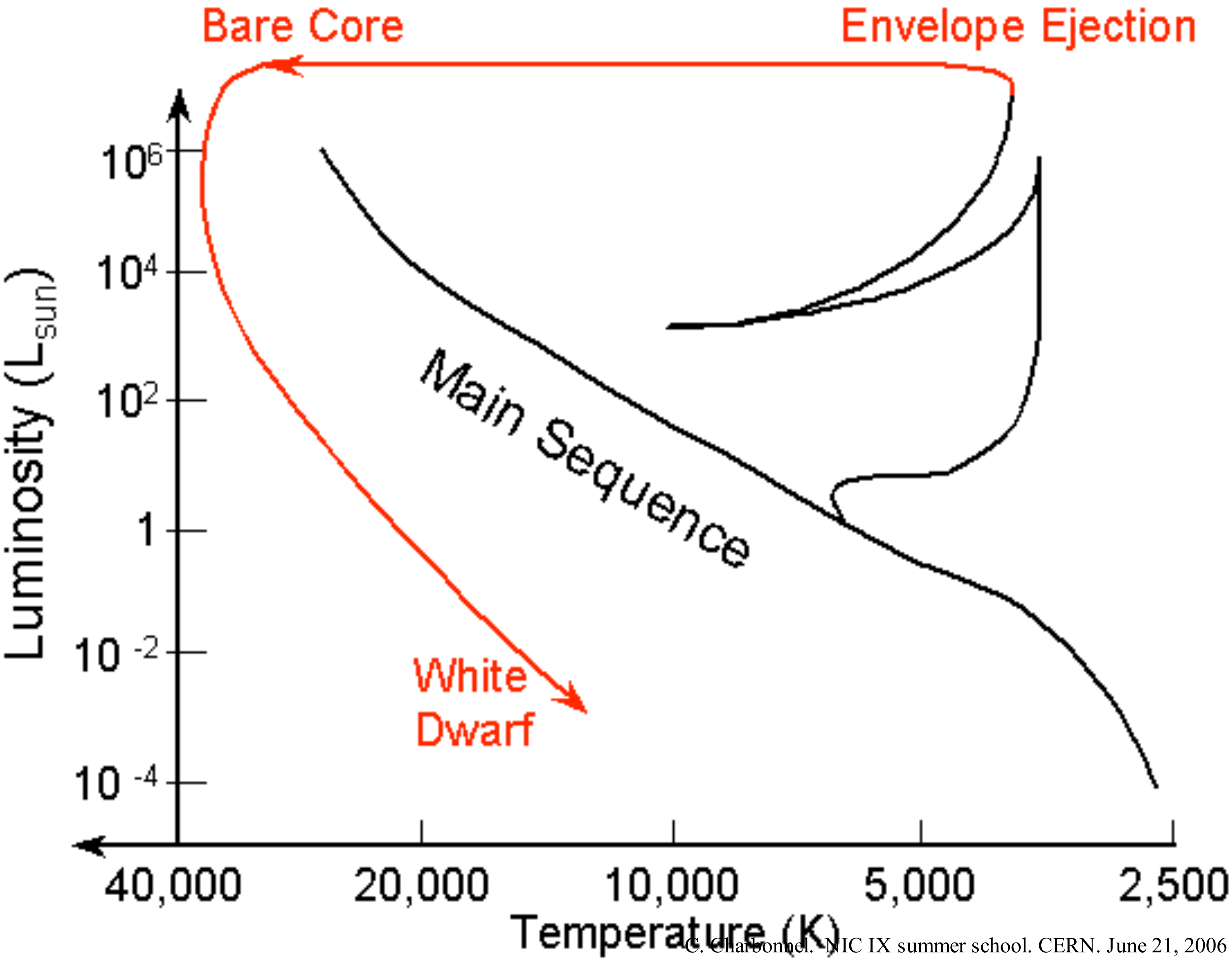
Abundance profiles in the partial mixing zone at 3 times during the interpulse



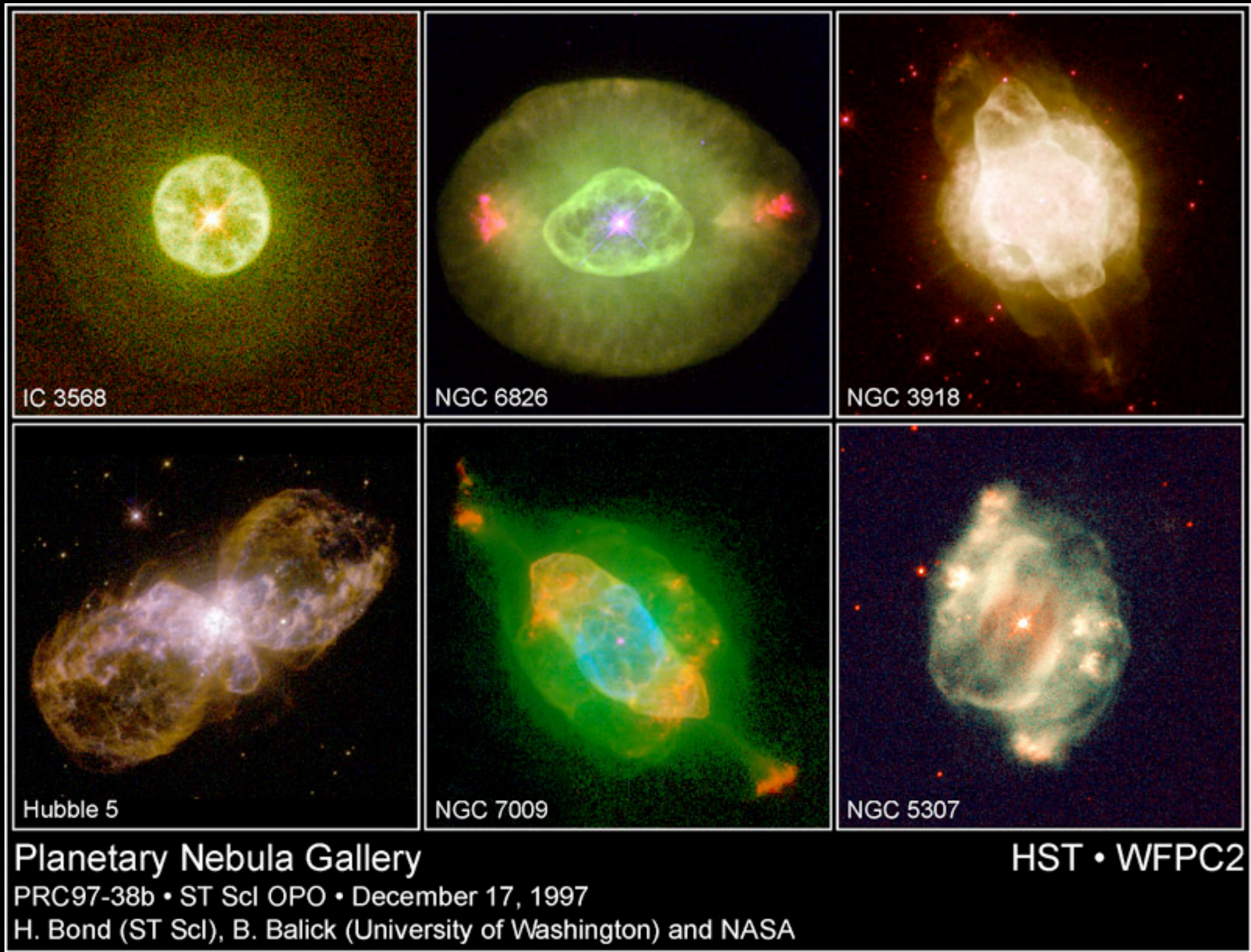
Overshoot and no rotation
Seventh TP



Rotation and no overshoot
25th TP


Bare Core
Envelope Ejection
Luminosity (L_{sun})
10^6
10^4
10^2
1
10^{-2}
10^{-4}
Main Sequence
White Dwarf
40,000
20,000
10,000
5,000
2,500
Temperature (K)

Helix nebula **(The closest PN from Earth)**


IC 3568
NGC 6826
NGC 3918
Hubble 5
NGC 7009
NGC 5307
Planetary Nebula Gallery
HST • WFPC2
PRC97-38b • ST Scl OPO • December 17, 1997
H. Bond (ST Scl), B. Balick (University of Washington) and NASA

White dwarf

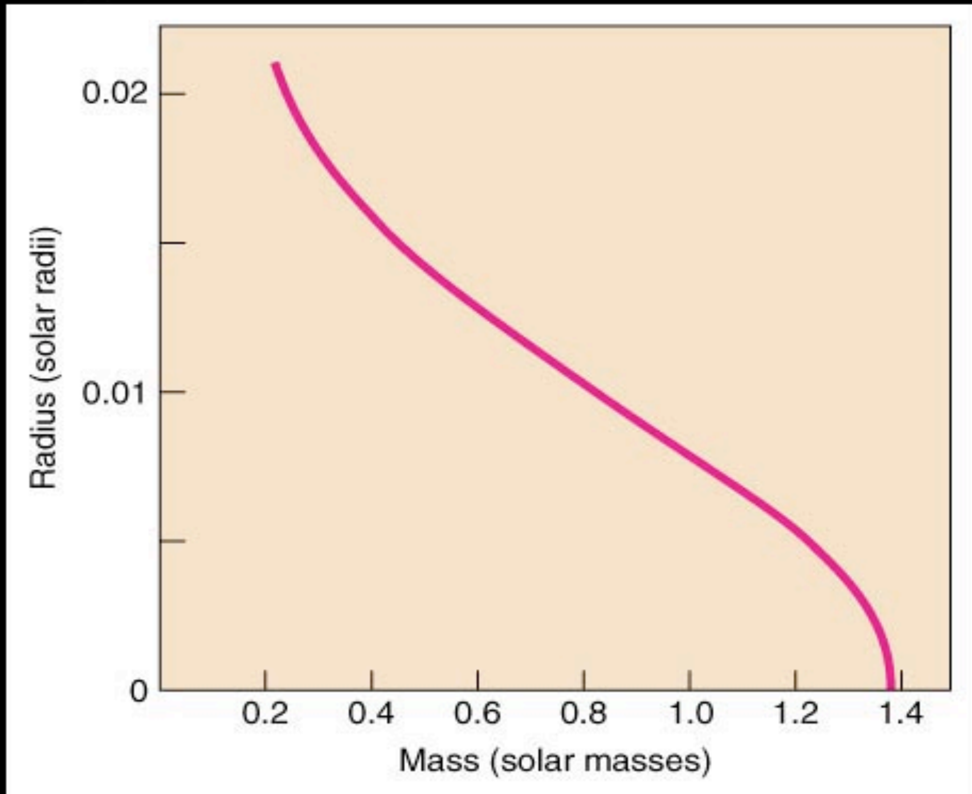
- Form as the outer layers of a low-mass red giant star puff out to make a planetary nebula.
- Since the lower mass stars make the white dwarfs, this type of remnant is the most common endpoint for stellar evolution.
- If the remaining mass of the core is less than 1.4 solar masses, the pressure from the degenerate electrons (called **electron degeneracy pressure**) is enough to prevent further collapse.

White dwarf density

- Because the core has about the mass of the Sun compressed to something the size of the Earth, the density is tremendous: around 10^6 times denser than water (one sugarcube volume's worth of white dwarf gas has a mass > 1 car)!
- A higher mass core is compressed to a smaller radius so the densities are even higher.
- Despite the huge densities and the "stiff"" electrons, the neutrons and protons have room to move around freely : they are not degenerate.

Radius of a white dwarf

Fraknoi/Morrison/Wolff, Voyages Through the Universe, 2/e
Figure 22.1 Relating Masses and Radii of White Dwarfs

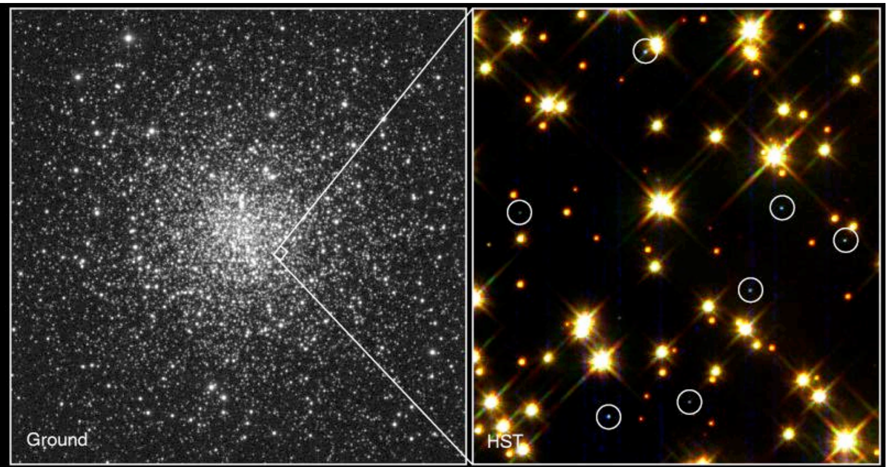


White dwarf cooling

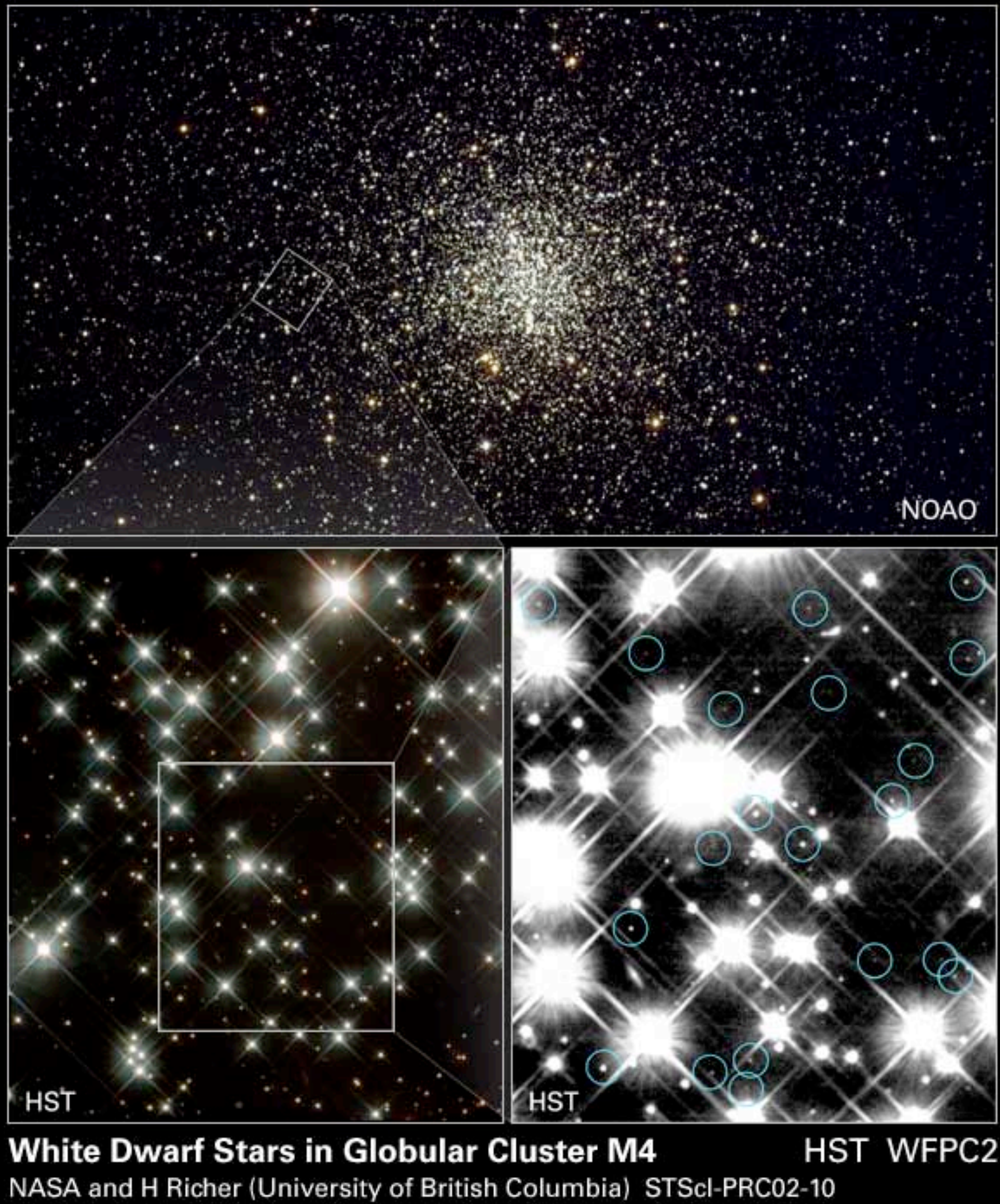
- White dwarfs shine simply from the release of the heat left over from when the star was still producing energy from nuclear reactions
- There are no more nuclear reactions occurring so the white dwarf cools off from an initial temperature of about 100,000 K
- The white dwarf loses heat quickly at first cooling off to 20,000 K in only about 100 million years, but then the cooling rate slows down:

it takes about another 800 million years to cool down to 10,000 K and another 4 to 5 billion years to cool down to the Sun's temperature of 5,800 K

White dwarf cooling



- Their rate of cooling and the distribution of their current temperatures can be used to determine the age of our galaxy or old star clusters that have white dwarfs in them
  - However, their small size makes them extremely difficult to detect
- Because it is above the atmosphere, the HST can detect these small dead stars in nearby old star clusters called *globular clusters*
- Analysis of the white dwarfs may provide an independent way of measuring the ages of the globular clusters and provide a verification of their very old ages derived from main sequence fitting


NOAO
HST
HST
White Dwarf Stars in Globular Cluster M4
HST WFPC2
NASA and H Richer (University of British Columbia) STScI-PRC02-10

White dwarfs in globular clusters
An independent measure of the age of the Univers