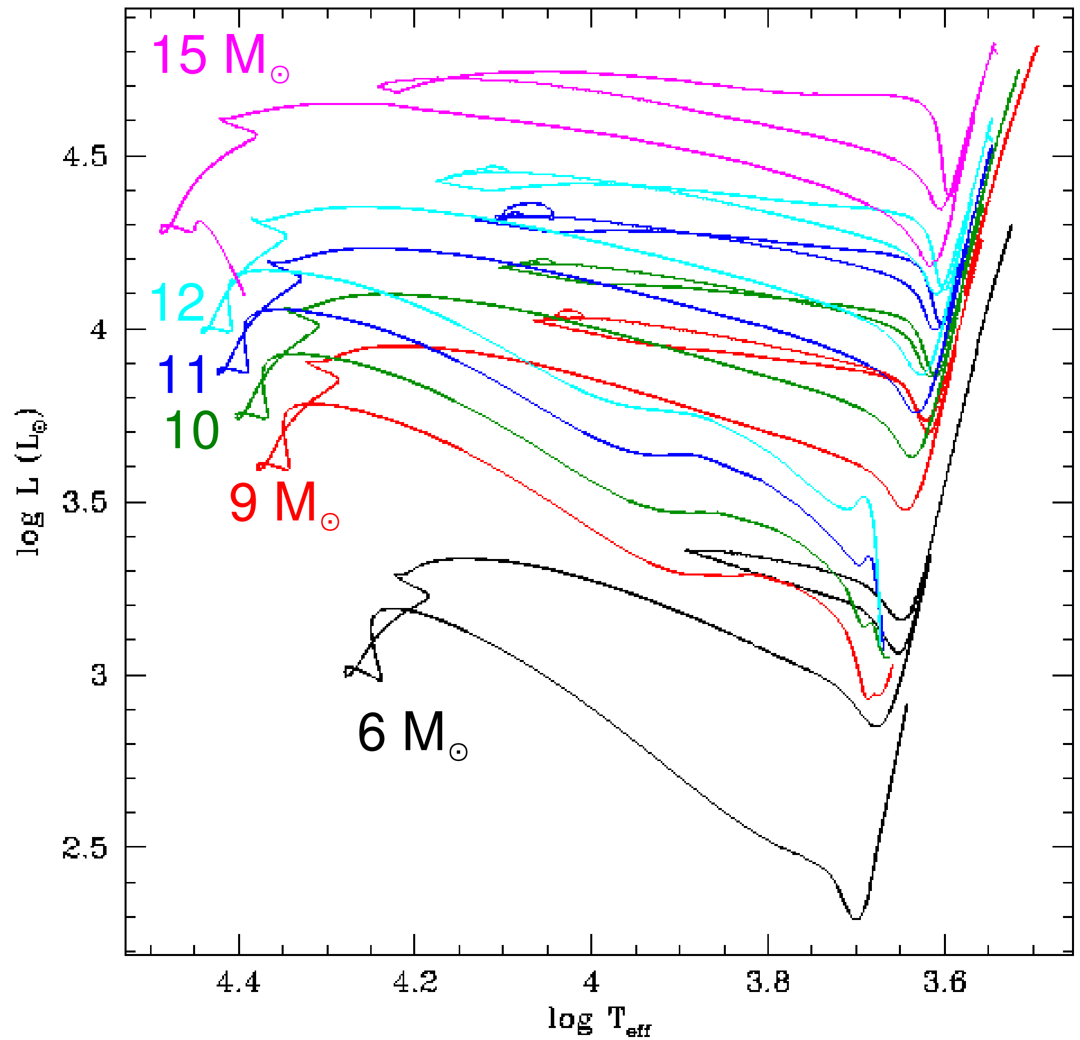
Evolution of massive AGB stars

Outline

- Introduction
- Carbon Burning Phase
- Mass transitions
- Super-AGB phase



Lionel Siess - IAA - Brussels

Introduction

SAGB stars : missing link between intermediate and massive stars
mass : $7\text{-}9\ M_\odot < M < 10\text{-}12\ M_\odot$

I. Entirely specific evolution

C ignition in condition of partial degeneracy
formation of a NeO core

→ Super-AGB (SAGB) phase : thermal pulses, 3DUP, HBB, mass loss

→ possibility to collapse by electron capture or to leave a WD

II. Involve complex and Interesting physics

- propagation of a carbon burning flame to the center
- electron captures on the products of C burning and URCA process can come into play in the most massive stars

III. Nucleosynthesis

s-process during the super AGB phase ?
r-process during the explosion ?

IV. Related to many astrophysical issues

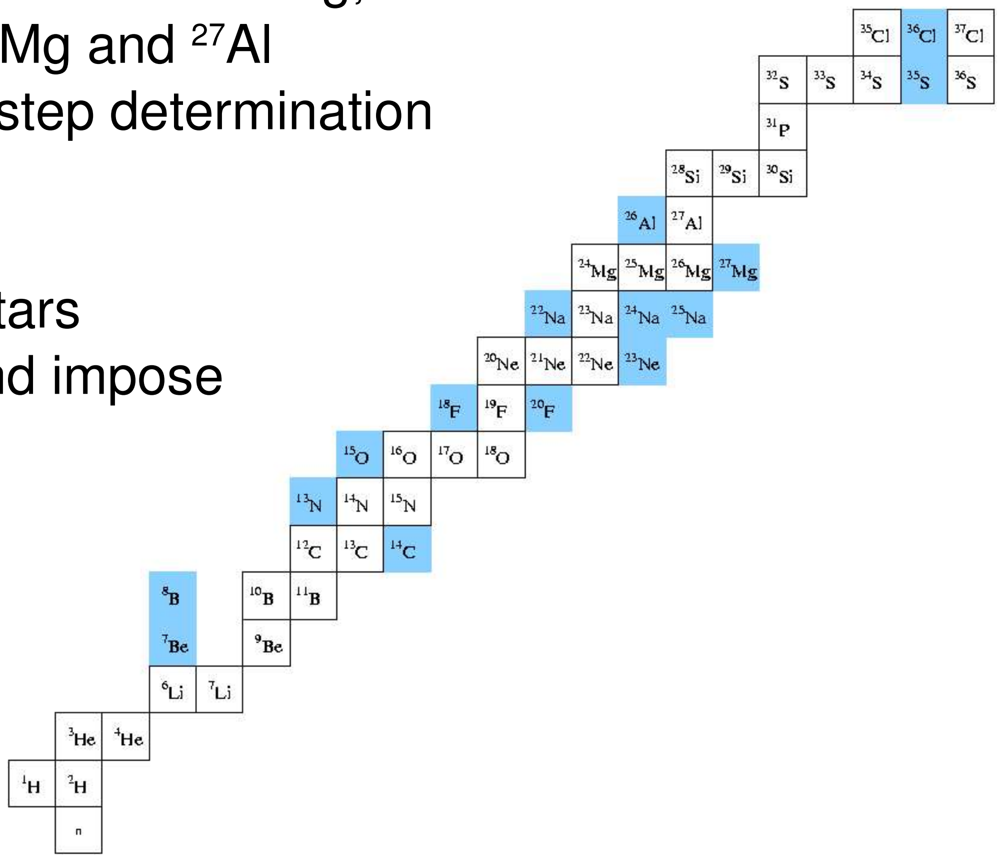
- Galactic chemical evolution :
  stars in the mass range 9 $M_{\odot}$ < M < 12 $M_{\odot}$ are numerous,
  → yields are unknown
  → depend on the final fate (WD or SN)
- Novae :
  ONe white dwarfs = progenitors of ONe novae
- Supernovae
  9 - 12 $M_{\odot}$ stars = progenitors of a special type of supernovae ?

Computations

STAREVOL evolutionary code improved :

- Update of nuclear network: C, Ne and O burning, e^- captures on ^{20}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg and ^{27}Al
- Update mesh algorithm and time step determination

- Mass loss rate: unknown ?
  between AGB and massive stars
  Vassiliadis & Wood (1993) and impose
  $M_{loss} < 10^{-4}\ M_\odot\ yr^{-1}$



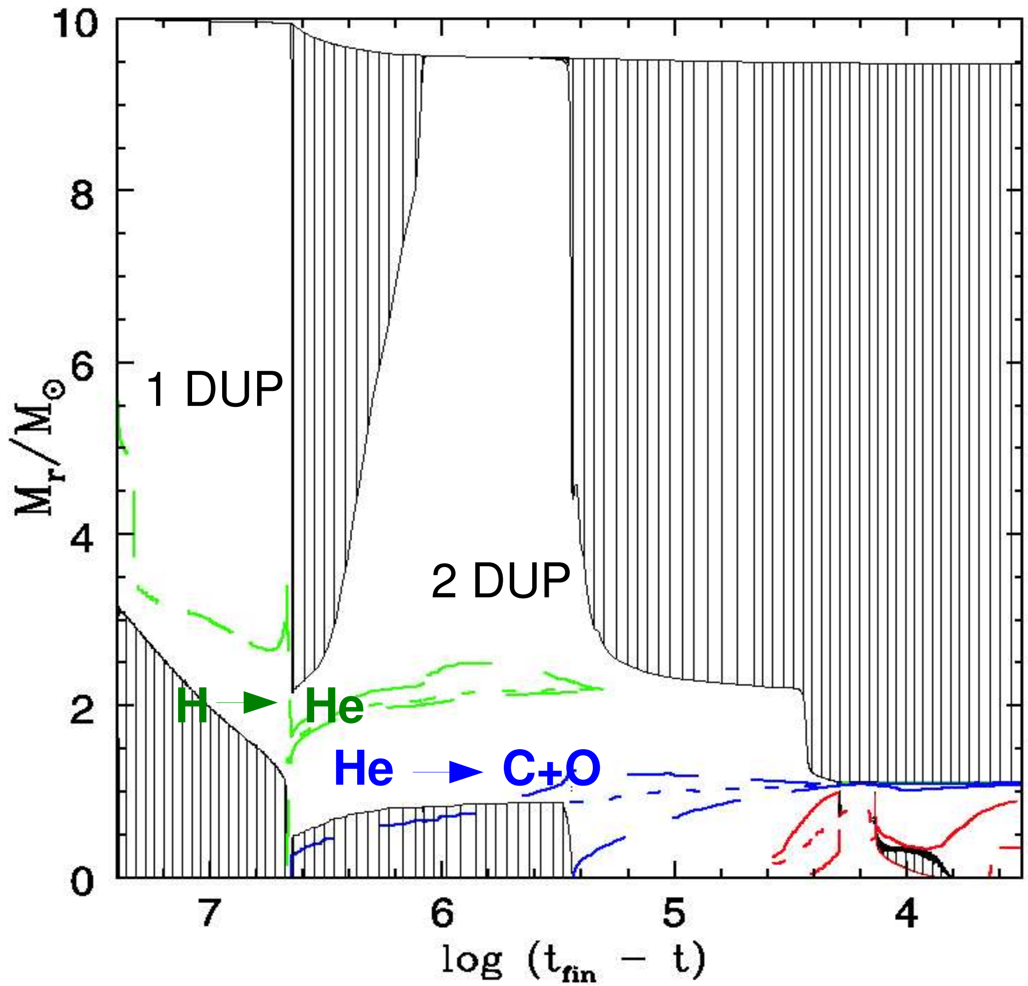
MODELS

$7\ M_\odot < M < 12\ M_\odot$

$10^{-5} \leq Z \leq 0.04$

Pre - Carbon evolution

- Standard evolution until C ignition
  - convective core H burning
  - 1DUP
  - convective core He burning
  - 2DUP



- **1DUP**
  - effects similar to lower mass stars

↗ $^{3,4}He$, ^{13}C, ^{14}N

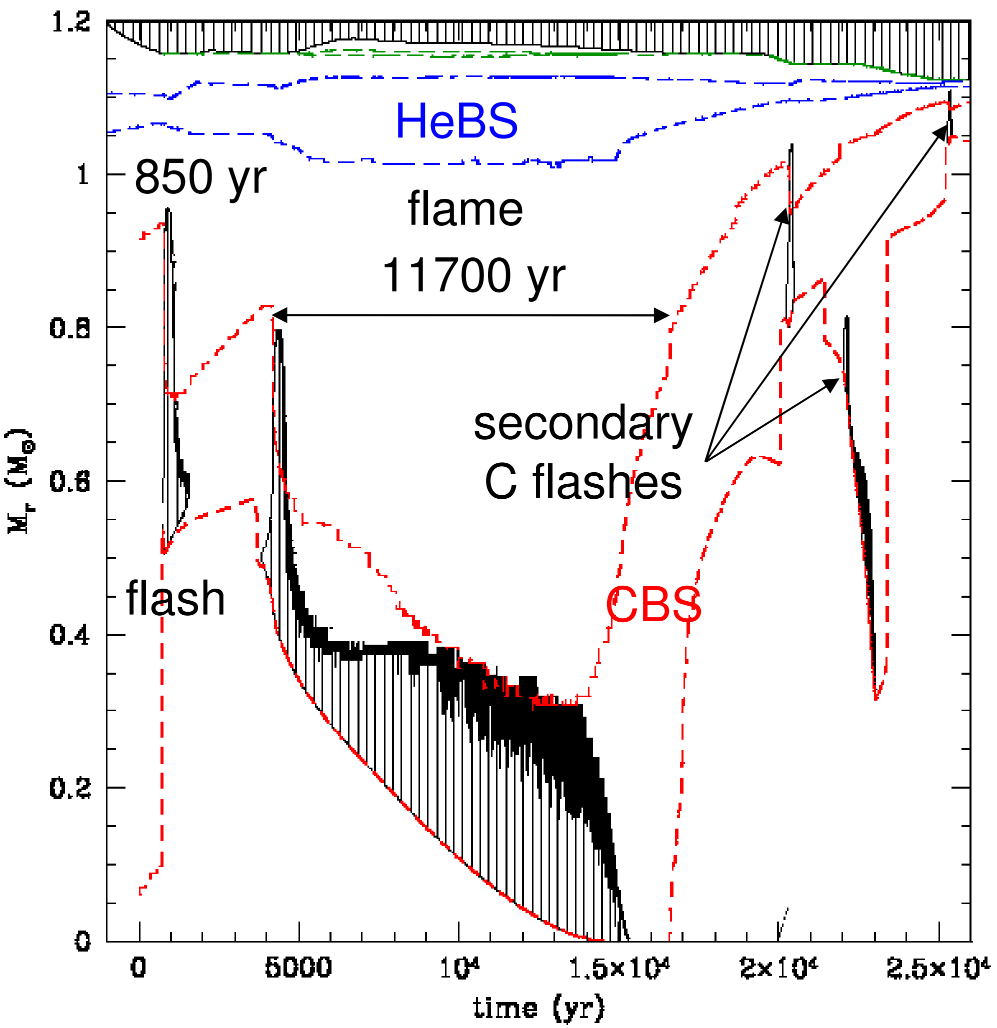
↘ H, ^{12}C, O

Carbon ignition I

- off center ignition : $T_{max} \sim 6\text{x}10^8$ K
- partial degeneracy : η = 2-3
- **proceeds in 2 steps**

  ➔ carbon flash :
  short lived (few 100 yr)
  energy : $10^6 < L_C/L_\odot < 2\text{x}10^8$
  used to lift the degeneracy and expand the structure
  ➔ quenches the instability

  ➔ deflagration : laminar flame that propagates to the center



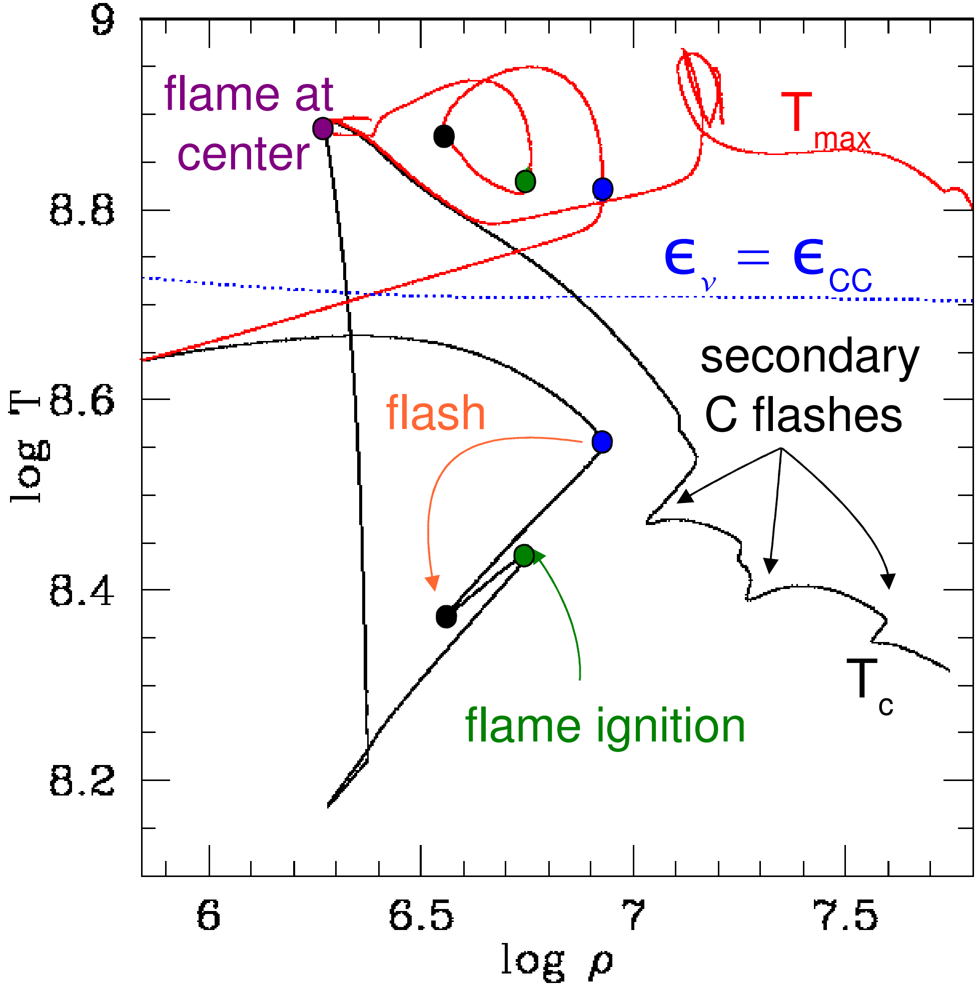
Energetics powered by $^{12}C+^{12}C$ reactions ➔ production of ^{16}O, ^{20}Ne and ^{23}Na

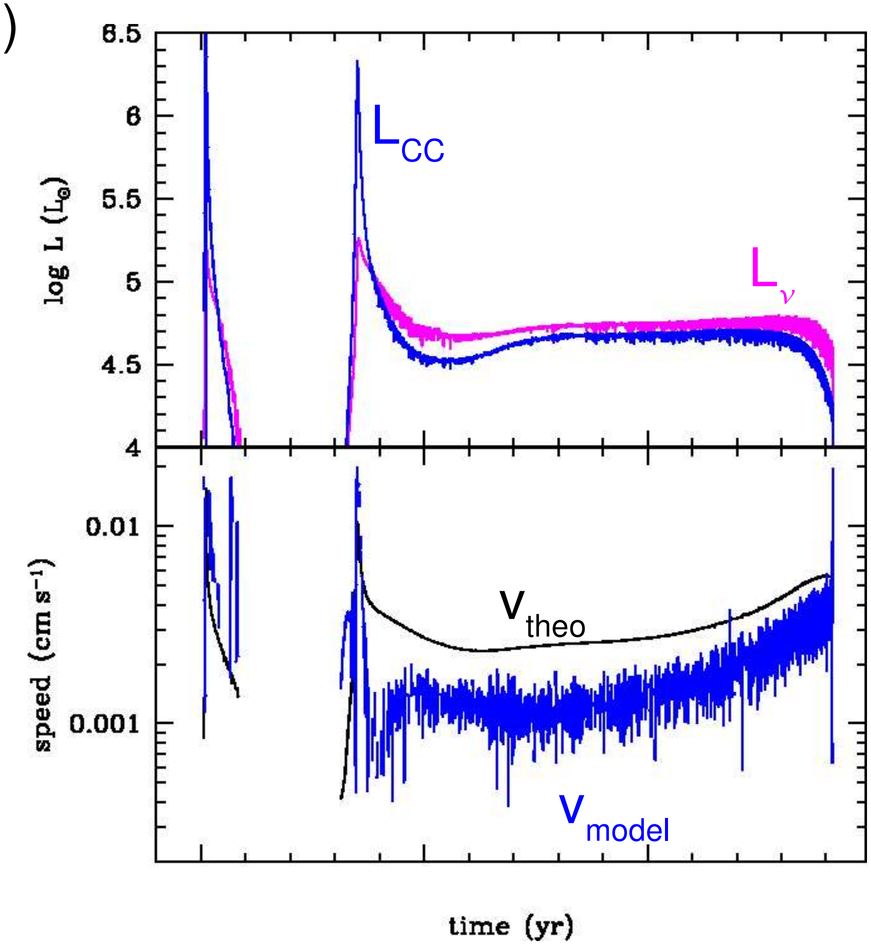
Carbon ignition II

Flame speed in good agreement (~ factor of 2) with Timmes et al (1994)

$v_{flame} \simeq 10^{-3}$ cm/s

In the flame, during propagation $L_\nu \simeq L_{CC}$





Technically tedious to compute

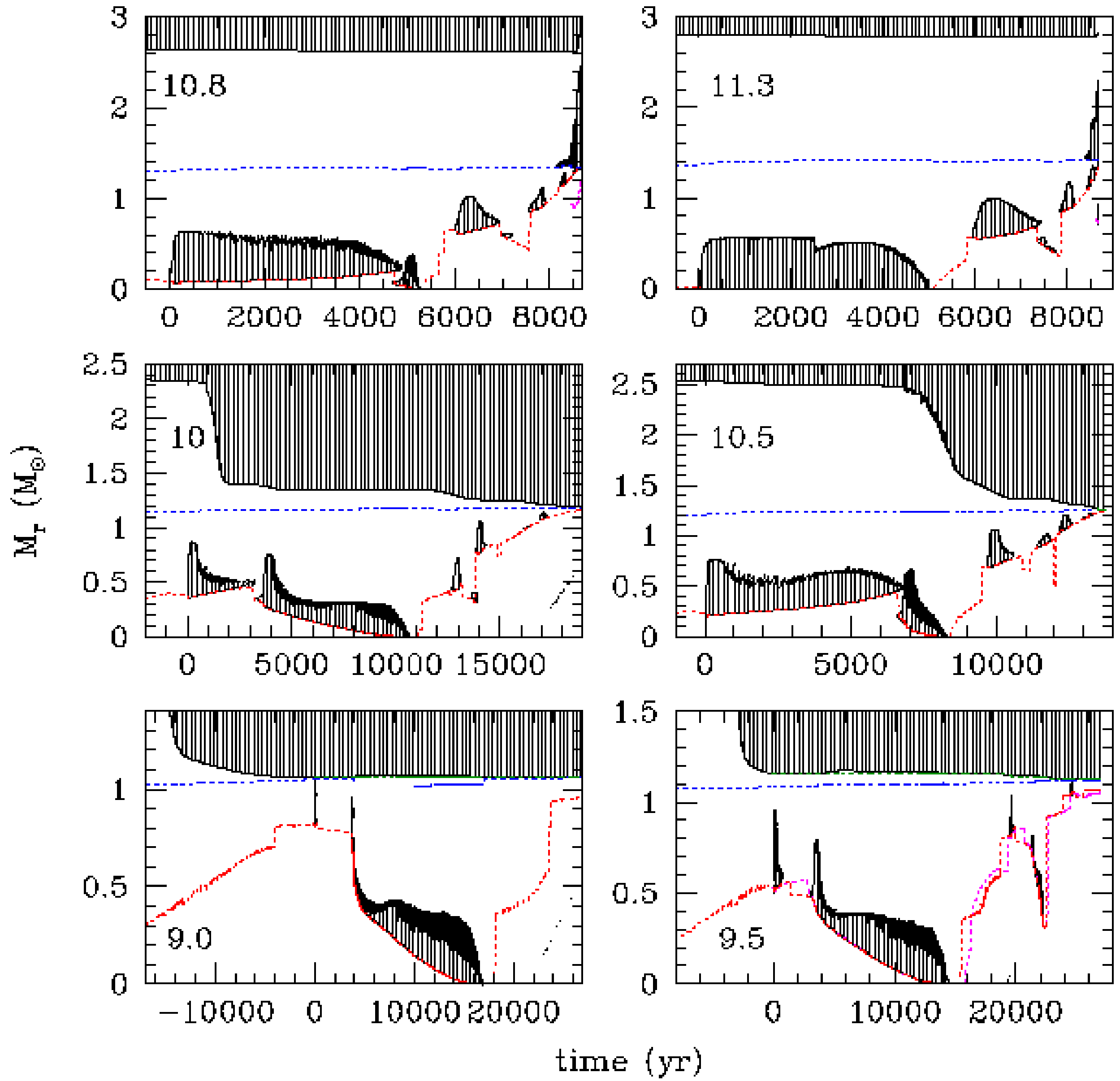
<dt> = 1.5 yr

Δr ~ 1 km

Evolution as a function of mass

Characteristics

- when initial mass ↗ the degeneracy ↘
  - → M_{igni} ↘
  - → L_{flash} ↘
  - → dt_{flame} ↘



2DUP

- deep into the HeBS
- Dredge-out in massive stars

The Dredge-out phenomenon

In massive SAGB stars, near the end of C-burning

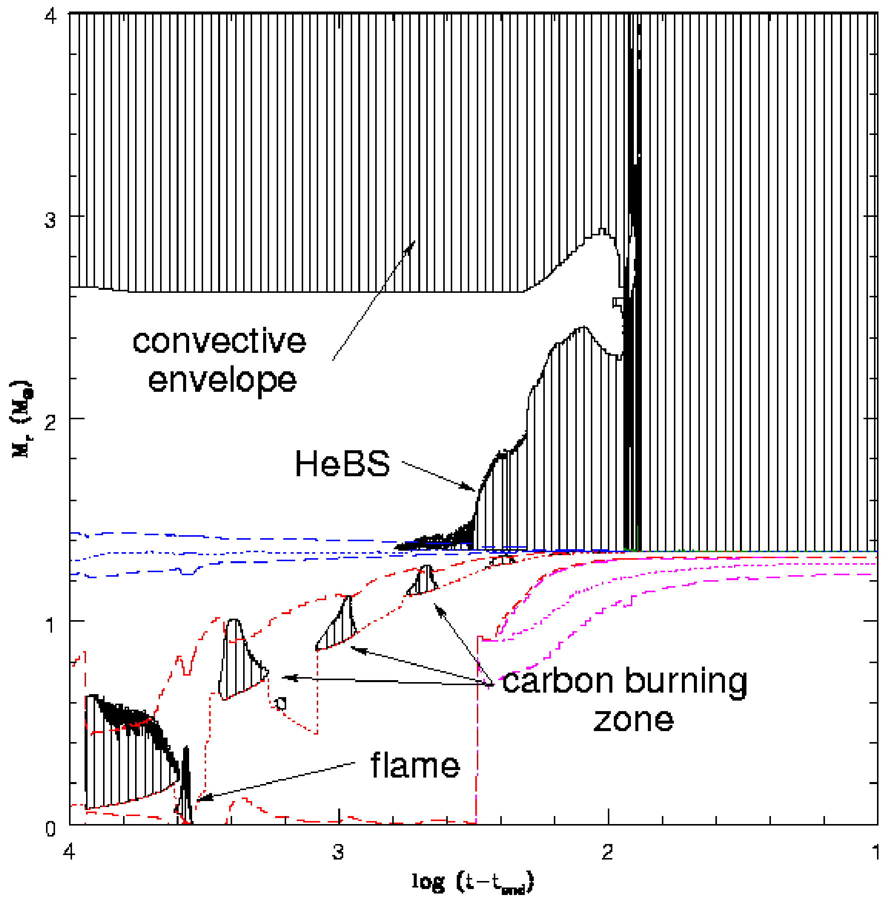
• convective zone develops in the HeBS

• the convective HeBS moves outward

→ merges with the envelope

Consequences

- envelope pollution
- decrease in the core mass



10.8 $M_\odot$

Mass transitions I

Between AGB and massive stars : different mass transitions

- **M_{up}** : transition between CO and NeO WD
- **M_{n}** : transition between NeO WD and electron capture SN
  if the mass of the WD : $M_{NeO} > 1.37\ M_{\odot}$ then electron capture will come into play and core collapse will ensue

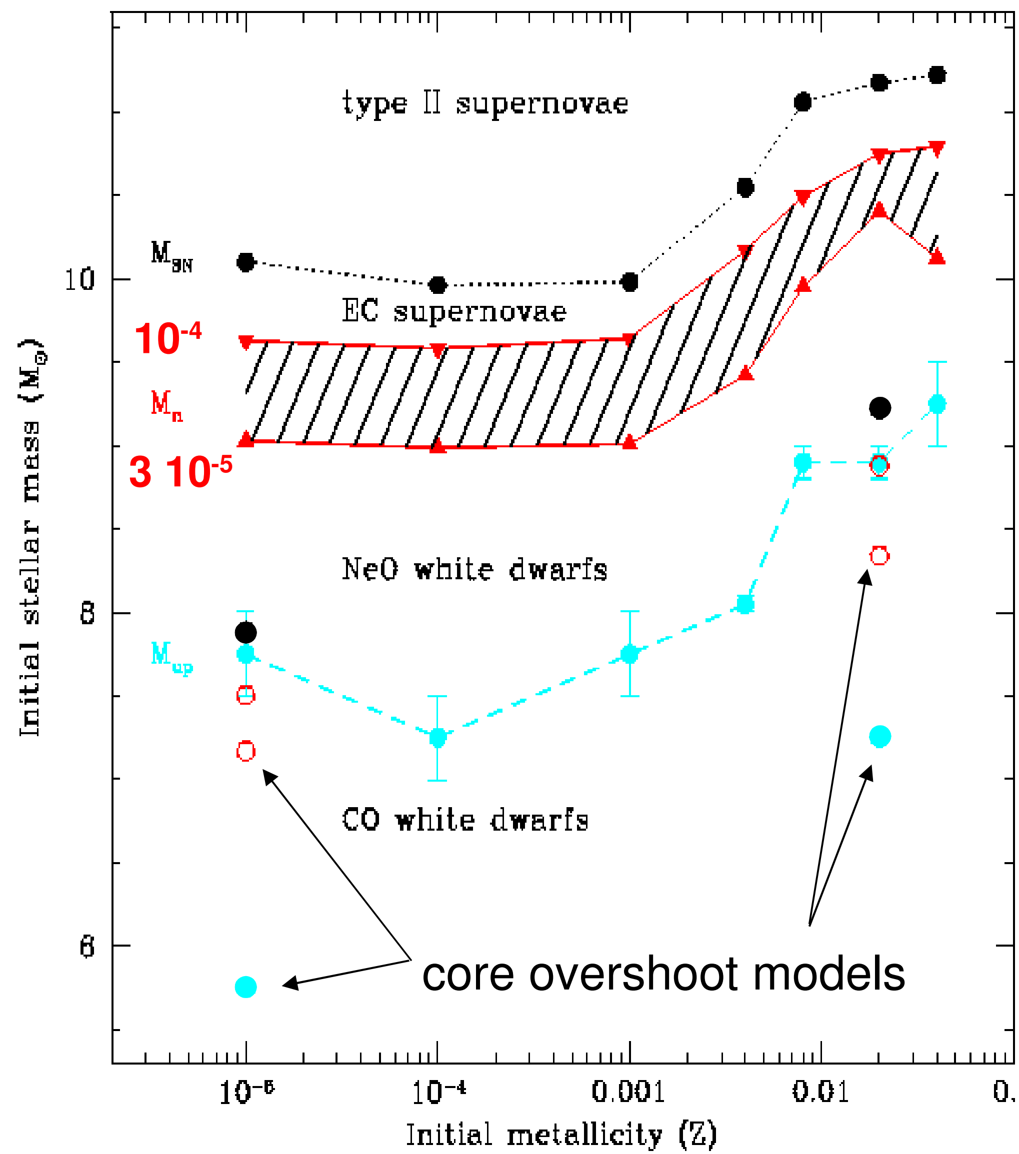
  This minimum for the formation of a neutron star critically depends on mass loss ! ➔ Arend Jan's talk !
- **M_{SN}** : minimum mass for a core-collapse SN
  if the mass of the He core $M_{He} > 1.4\ M_{\odot}$, the star will evolve through all nuclear burning stages

Mass transitions II

- M_{up} ↘ with Z : opacity effects
  - at lower Z, L larger, M_{He} core larger
  - at very low Z, opacity effects weaker

- M_n : large range depending on M_{loss}
  → EC-SN : small window ~ 1$M_\odot$

- Mass range for the formation of NeO WD is small : width ~ 1-1.5 $M_\odot$



WARNING

M_{up} , M_n, M_{SN} : strongly depend on mixing at the edge of He core (overshooting, semi-convection, ...)

overshoot : shift mass transitions by ~ 2 $M_\odot$

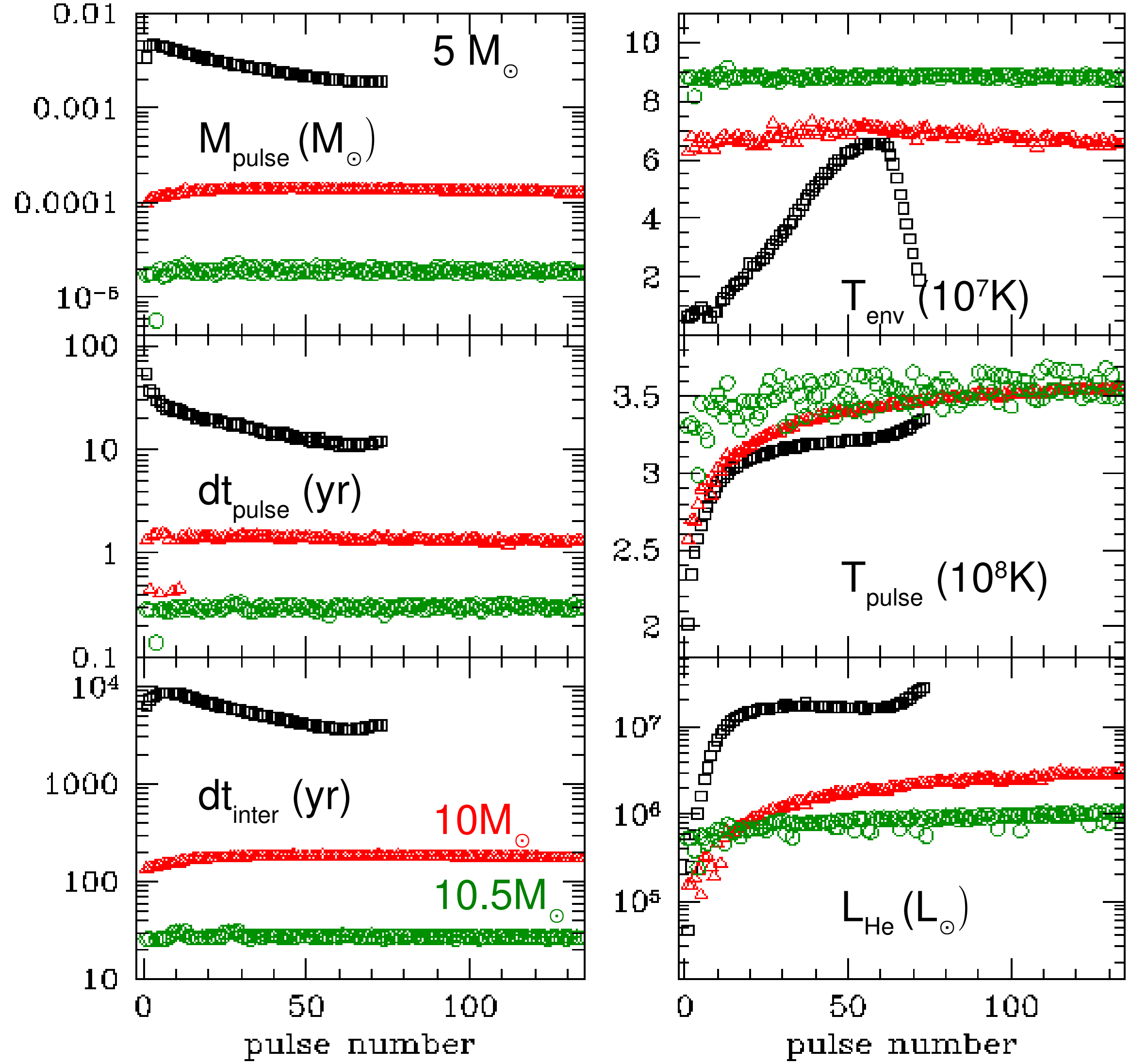
Super AGB phase I : pulse characteristics

- weak pulse : $L_{He} \sim 10^6 L_\odot$
- small pulse $M_{pulse} < 2\ 10^{-4} M_\odot$

- interpulse periods : < few 100 yr
- short pulse duration ~ 1 yr

- high temperatures
  - at the base of the pulse
  - at the base of the envelope

- (too) many pulses ~ 300-1000 !



$Z = Z_\odot$

Super AGB phase II : nucleosynthesis

High temperature

- at the base of the convective envelope ($T_{env} > 6\ 10^7$ K)

  HBB (CNO, NeNa and MgAl cycles)

  ➔ Production of ^{26}Al, ^{14}N, ^{23}Na, $^{25,26}Mg$, radiative s-process weak

- in the pulse ($T_{pulse} > 3.4\ 10^8$ K) ➔ convective s-process ?

3DUP

➔ hard do develop because L_{He} weak : radiation pressure large

Yields

Production of nuclei moderated by

- short lifetime (not enough time to burn unless T_{env} very high (> 10^8 K))
- large envelope mass and small pulse mass (large dilution factors)

--> much more in Carolyn's talk !

END. Thanks