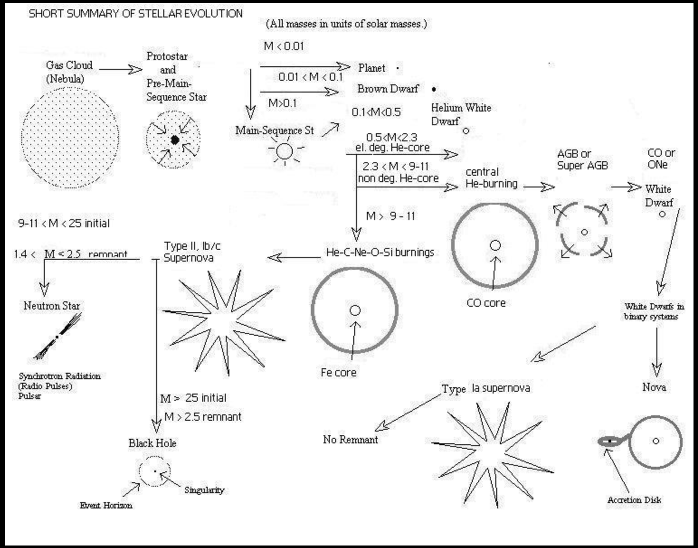
ADVANCED EVOLUTIONARY PHASES OF LOW- AND INTERMEDIATE-MASS STARS: CURRENT STATUS AND OPEN PROBLEMS

Pt. 1



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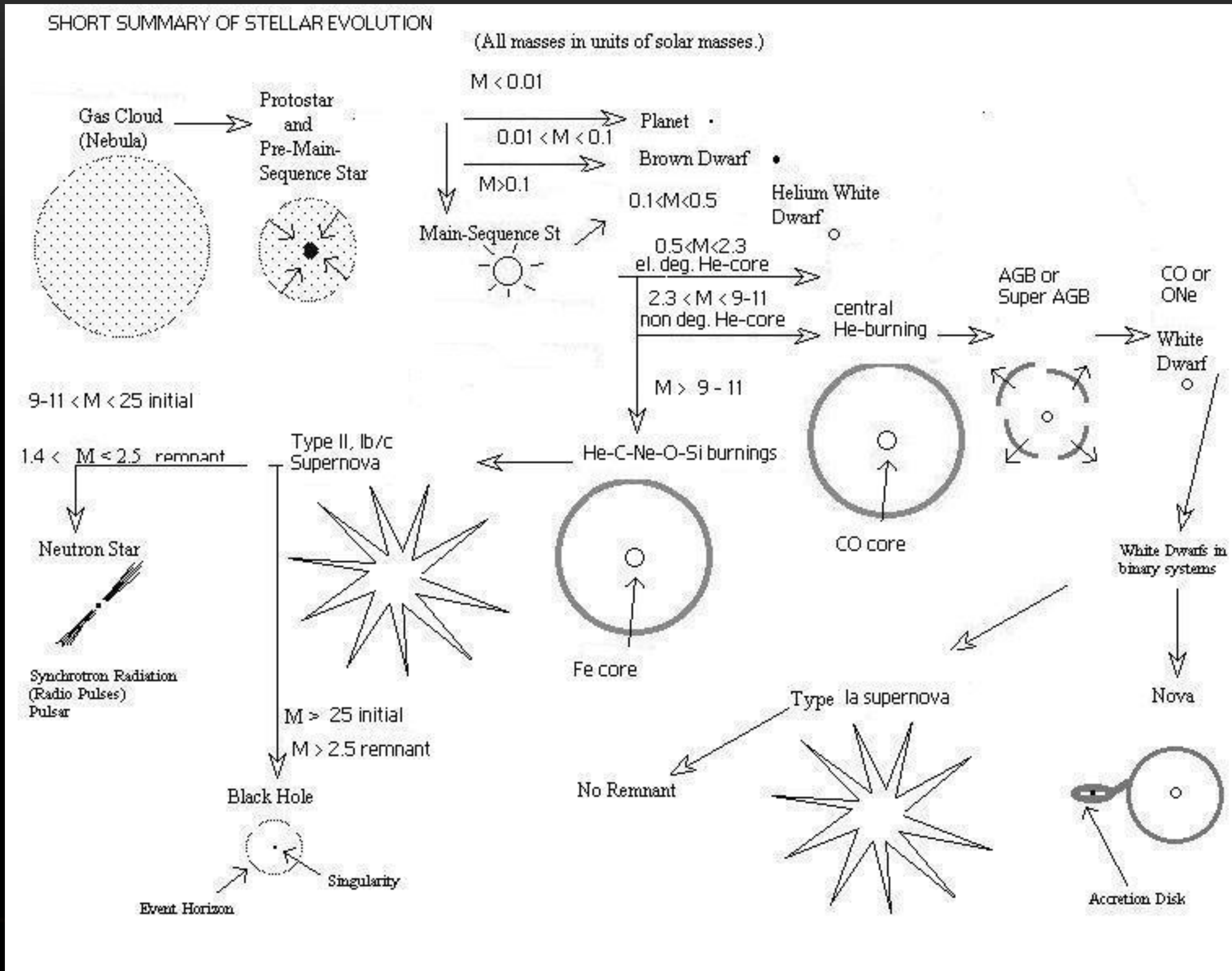
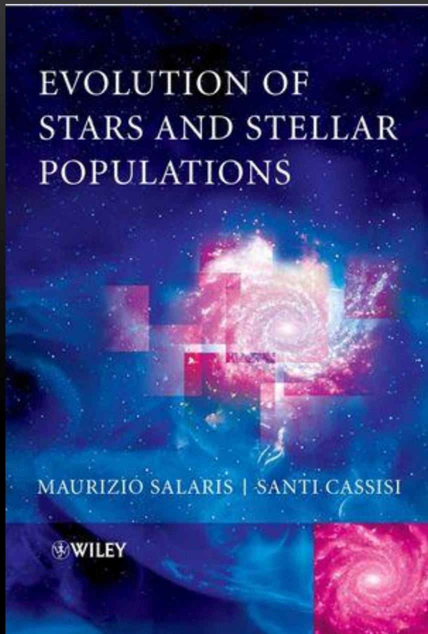
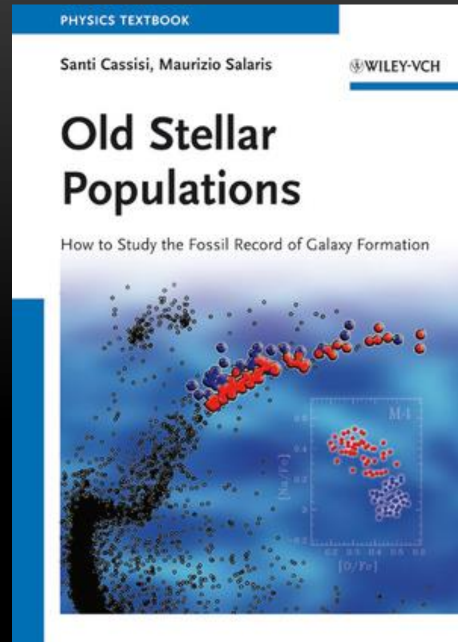
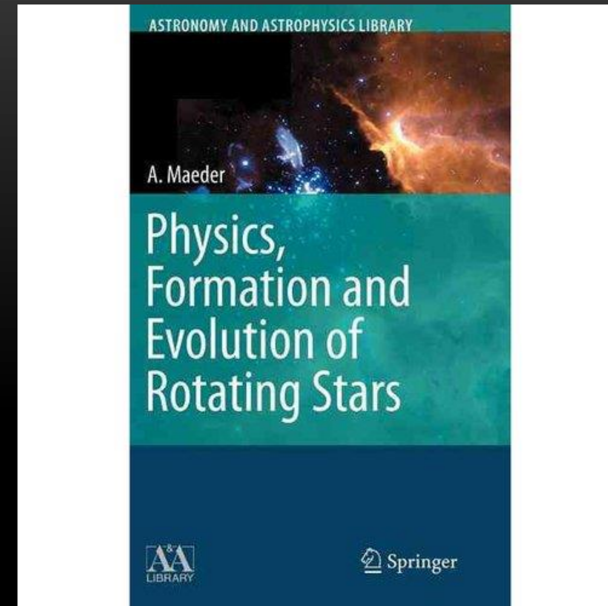


SHORT SUMMARY OF STELLAR EVOLUTION
(All masses in units of solar masses.)
M < 0.01
Gas Cloud (Nebula)
Protostar and Pre-Main-Sequence Star
Planet
0.01 < M < 0.1
Brown Dwarf
M>0.1
0.1<M<0.5
Helium White Dwarf
Main-Sequence St
0.5<M<2.3 el. deg. He-core
2.3 < M < 9-11 non deg. He-core
central He-burning
AGB or Super AGB
CO or ONe White Dwarf
M > 9 - 11
9-11 < M < 25 initial
1.4 < M < 2.5 remnant
Type II, Ib/c Supernova
He-C-Ne-O-Si burnings
CO core
Neutron Star
Fe core
White Dwarfs in binary systems
Synchrotron Radiation (Radio Pulses) Pulsar
M > 25 initial
M > 2.5 remnant
Type Ia supernova
Nova
No Remnant
Black Hole
Singularity
Event Horizon
Accretion Disk


EVOLUTION OF STARS AND STELLAR POPULATIONS
MAURIZIO SALARIS | SANTI CASSISI
WILEY


PHYSICS TEXTBOOK
Santi Cassisi, Maurizio Salaris
WILEY-VCH
Old Stellar Populations
How to Study the Fossil Record of Galaxy Formation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Physics, Formation and Evolution of Rotating Stars
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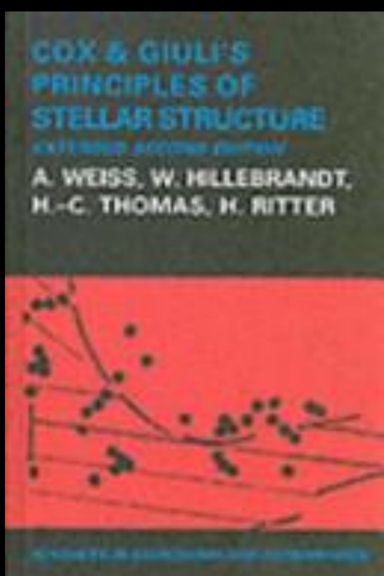
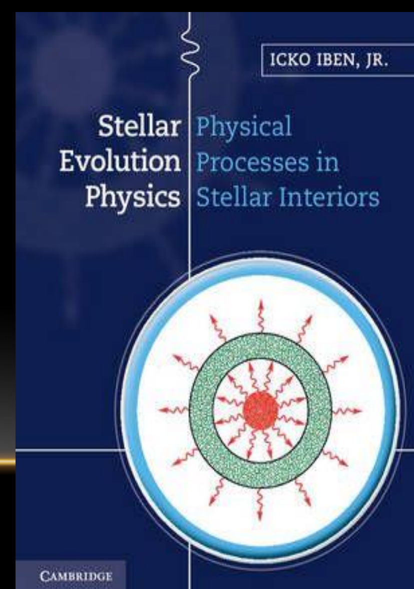

COX & GIULI'S PRINCIPLES OF STELLAR STRUCTURE
A. WEISS, W. HILLEBRANDT, H.-C. THOMAS, H. RITTER


Rudolf Kippenhahn
Alfred Weigert
Achim Weiss
Stellar Structure and Evolution
Second Edition
Springer


ICKO IBEN, JR.
Stellar Evolution Physics
Physical Processes in Stellar Interiors
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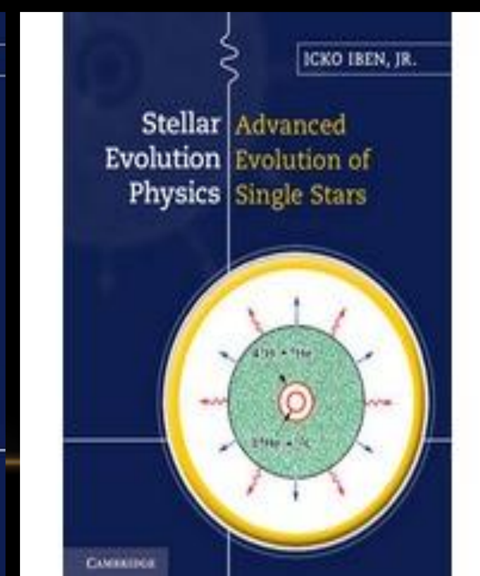
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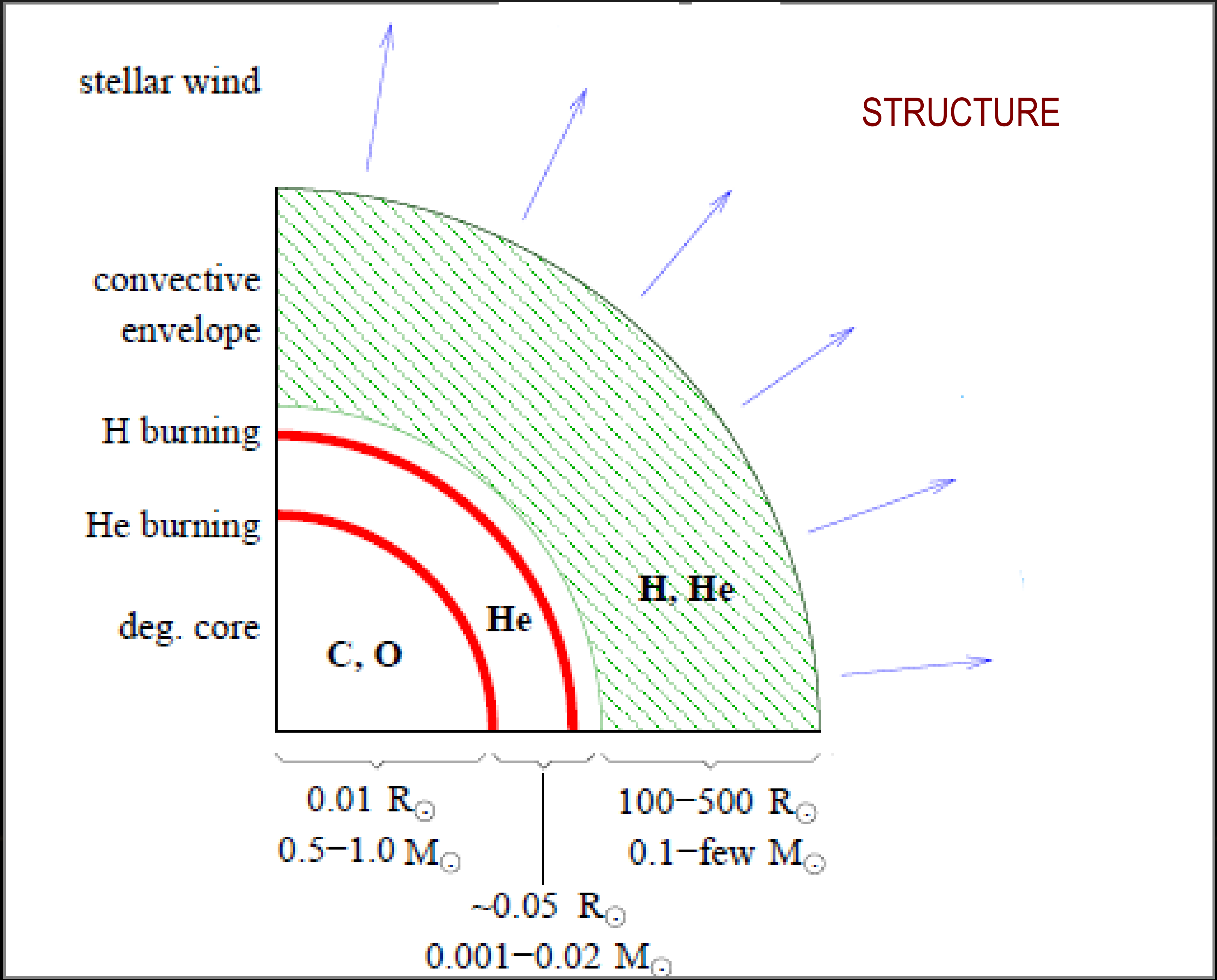
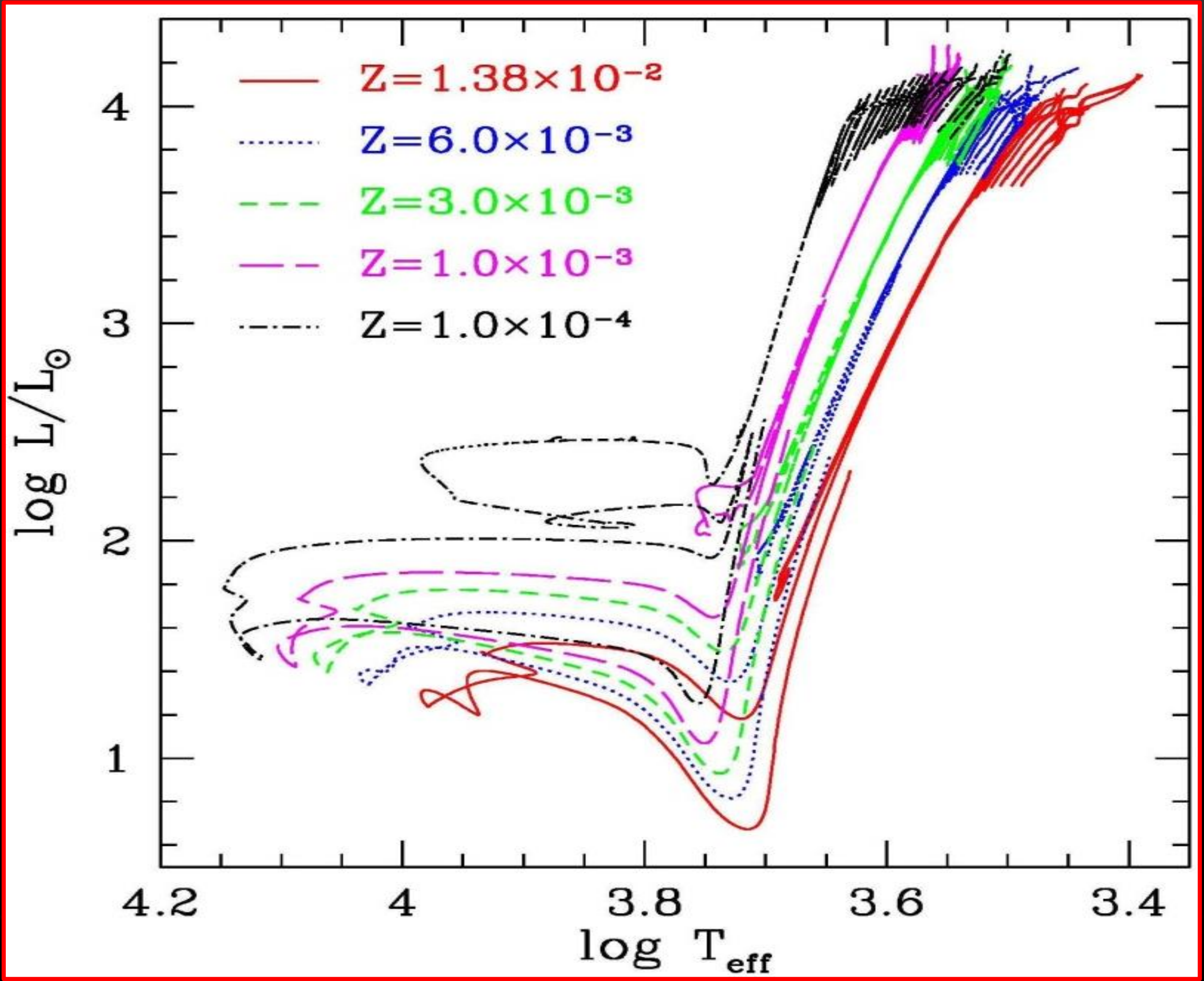
Stellar Evolution Physics
Advanced Evolution of Single Stars

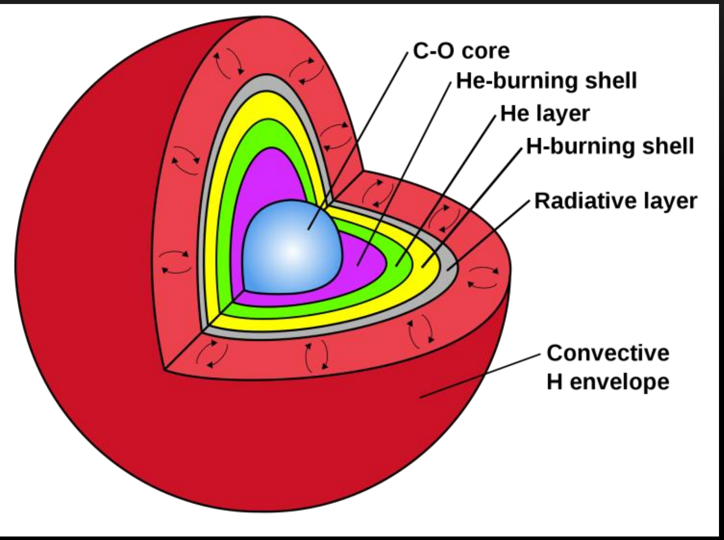
AGB STARS

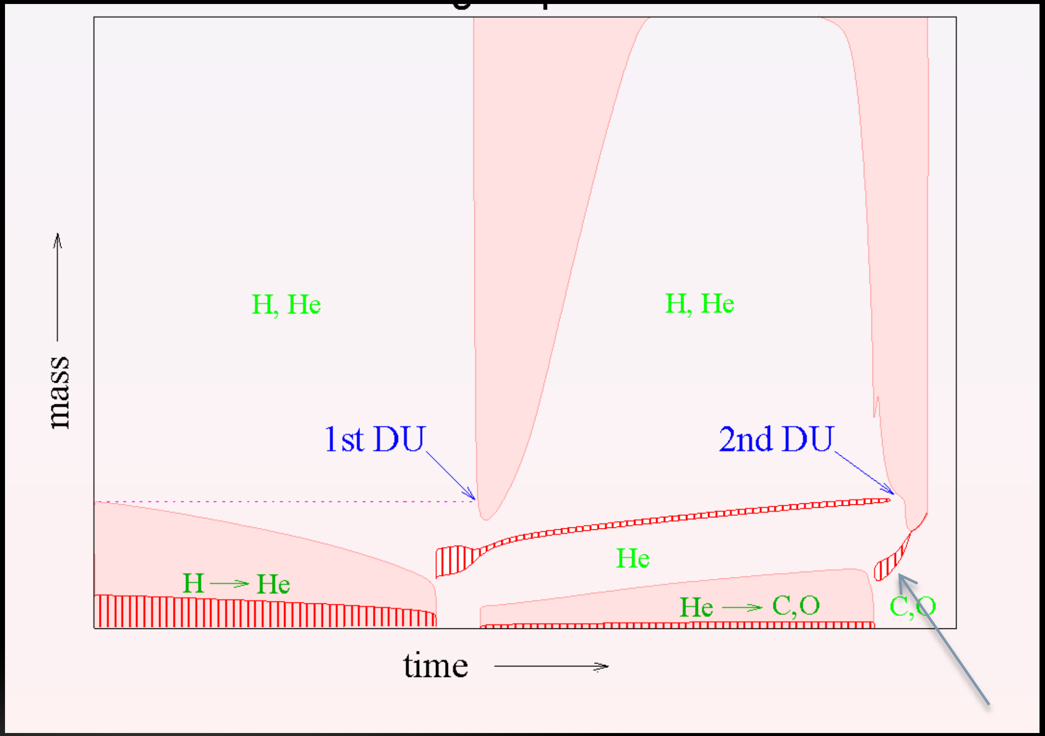

stellar wind
STRUCTURE
convective
envelope
H burning
He burning
deg. core
C, O
He
H, He
0.01 R☉
0.5–1.0 M☉
~0.05 R☉
0.001–0.02 M☉
100–500 R☉
0.1–few M☉



Z=1.38×10⁻²
Z=6.0×10⁻³
Z=3.0×10⁻³
Z=1.0×10⁻³
Z=1.0×10⁻⁴
log L/L⊙
log Teff
4.2
4
3.8
3.6
3.4
1
2
3
4

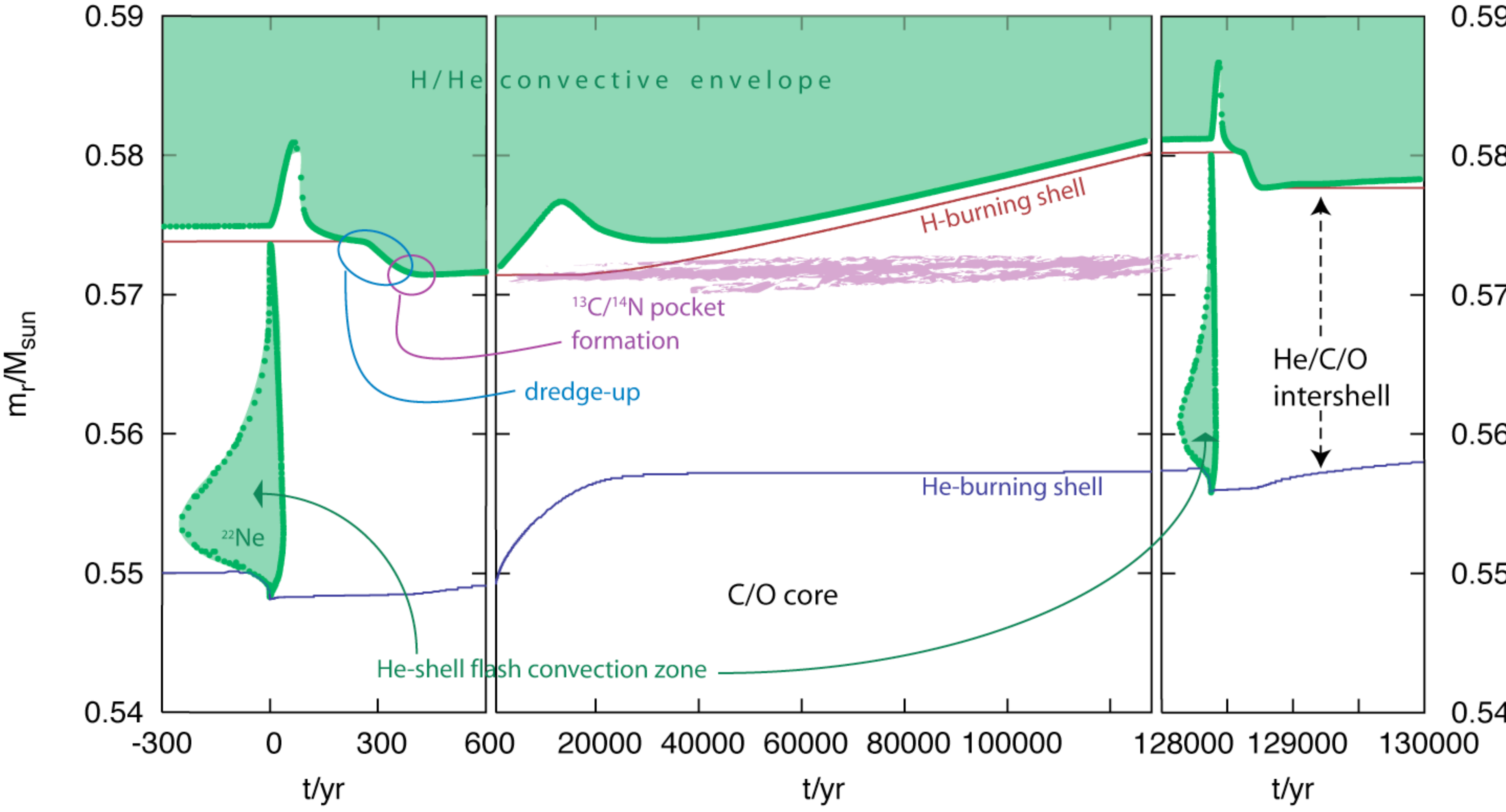
2^{nd} dredge up only for masses above ~4 $M_\odot$

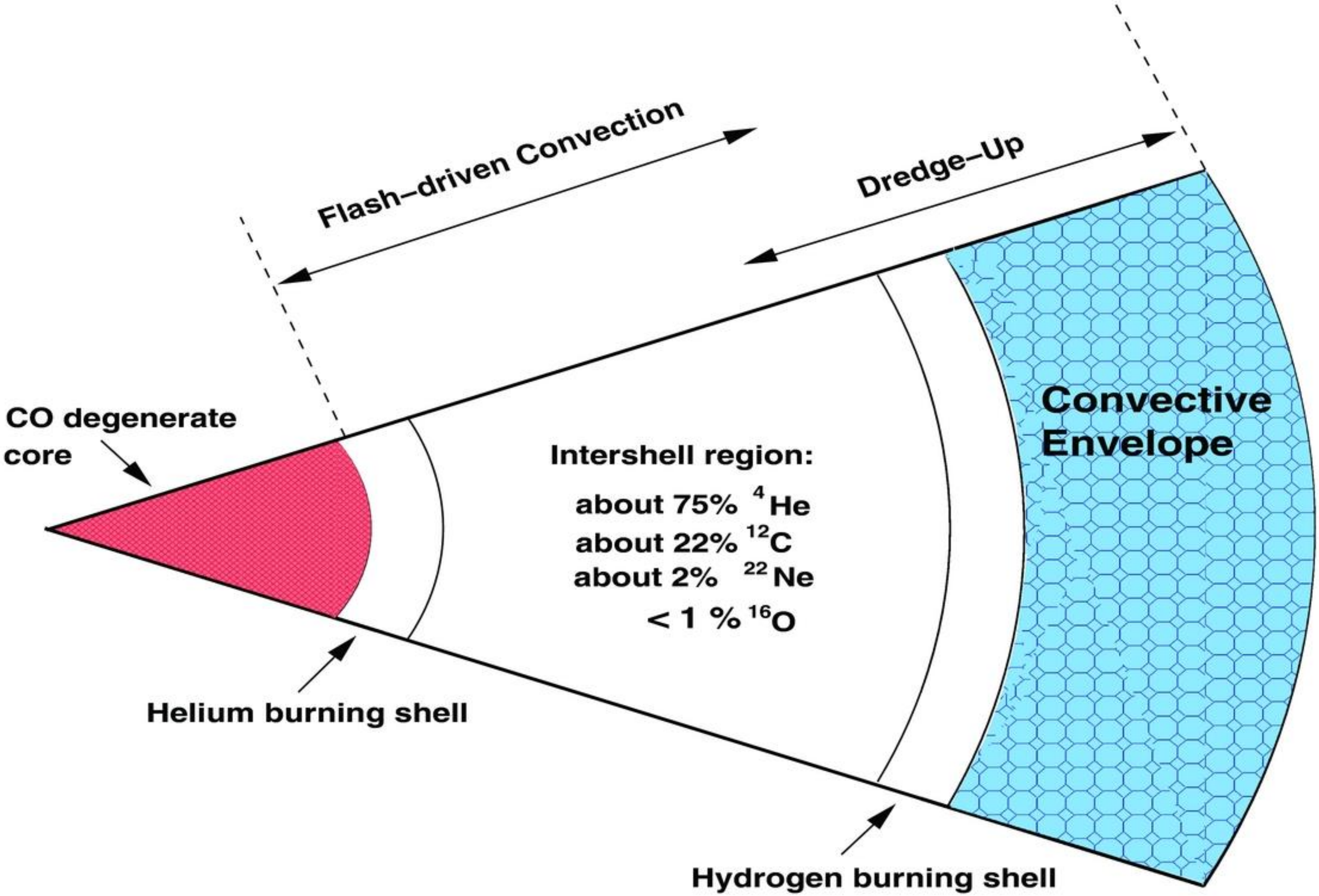




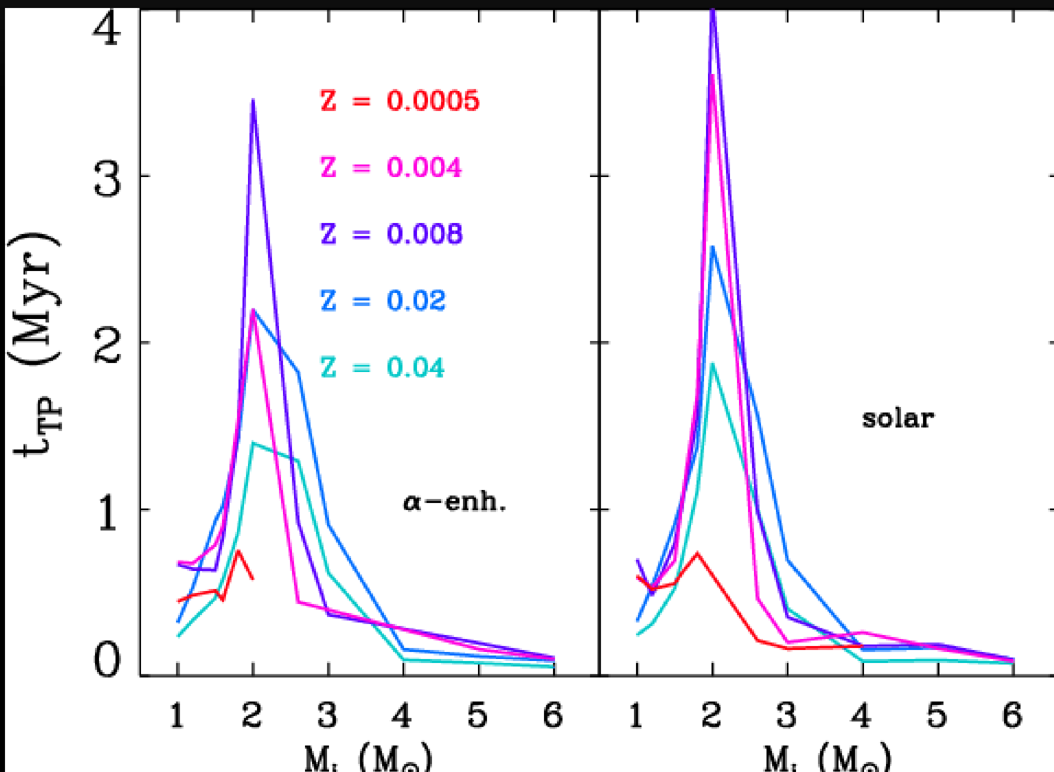
Early AGB

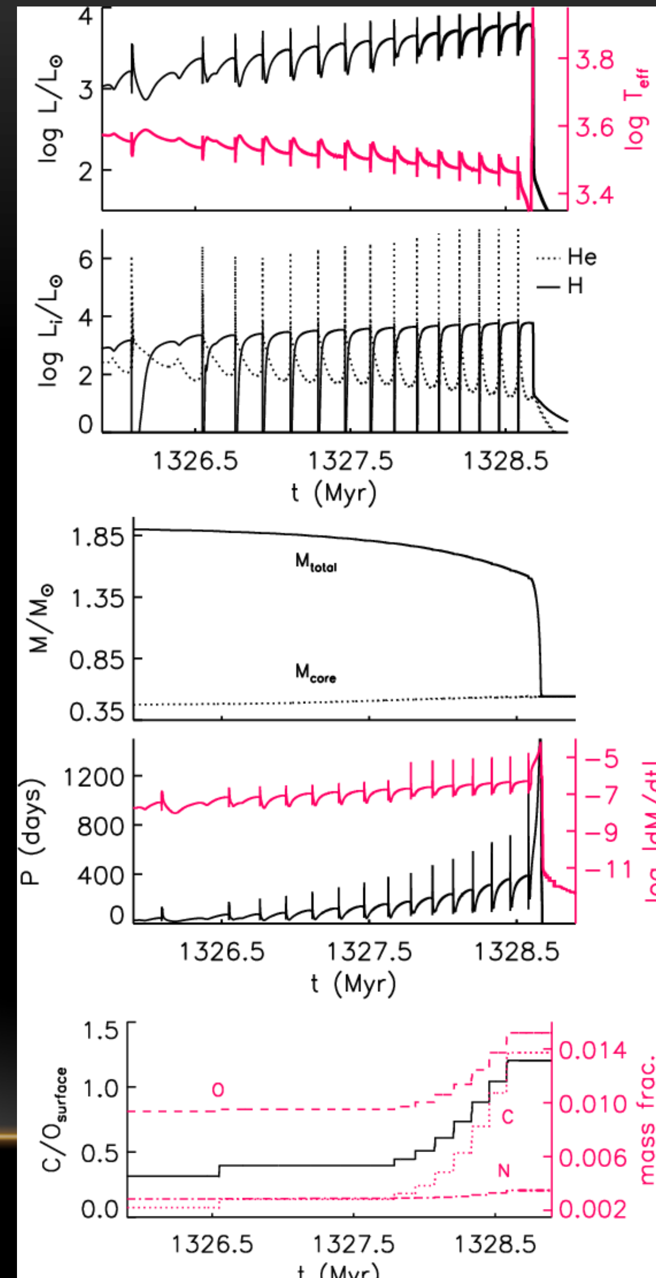
Thermal pulses



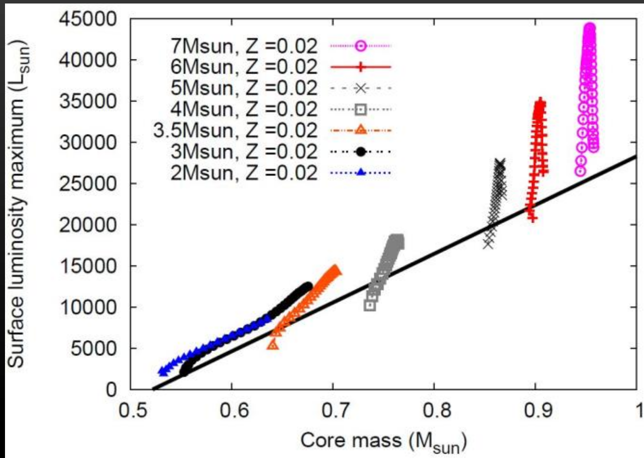

Flash–driven Convection
Dredge–Up
CO degenerate core
Convective Envelope
Intershell region:
about 75% ^{4}He
about 22% ^{12}C
about 2% ^{22}Ne
< 1 % ^{16}O
Helium burning shell
Hydrogen burning shell

M=2.0M$_\odot$
Z=0.02 Weiss & Ferguson (2009)





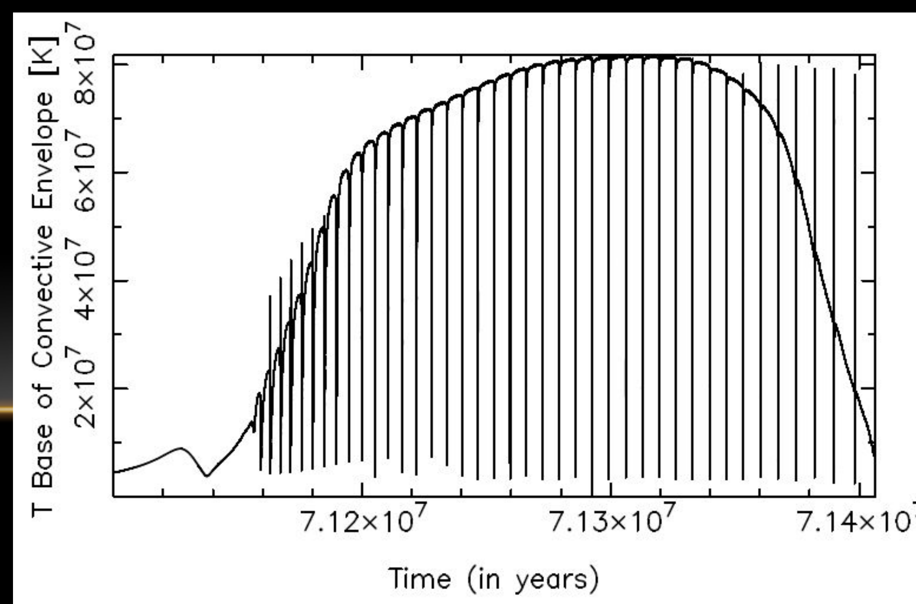
HOT BOTTOM BURNING

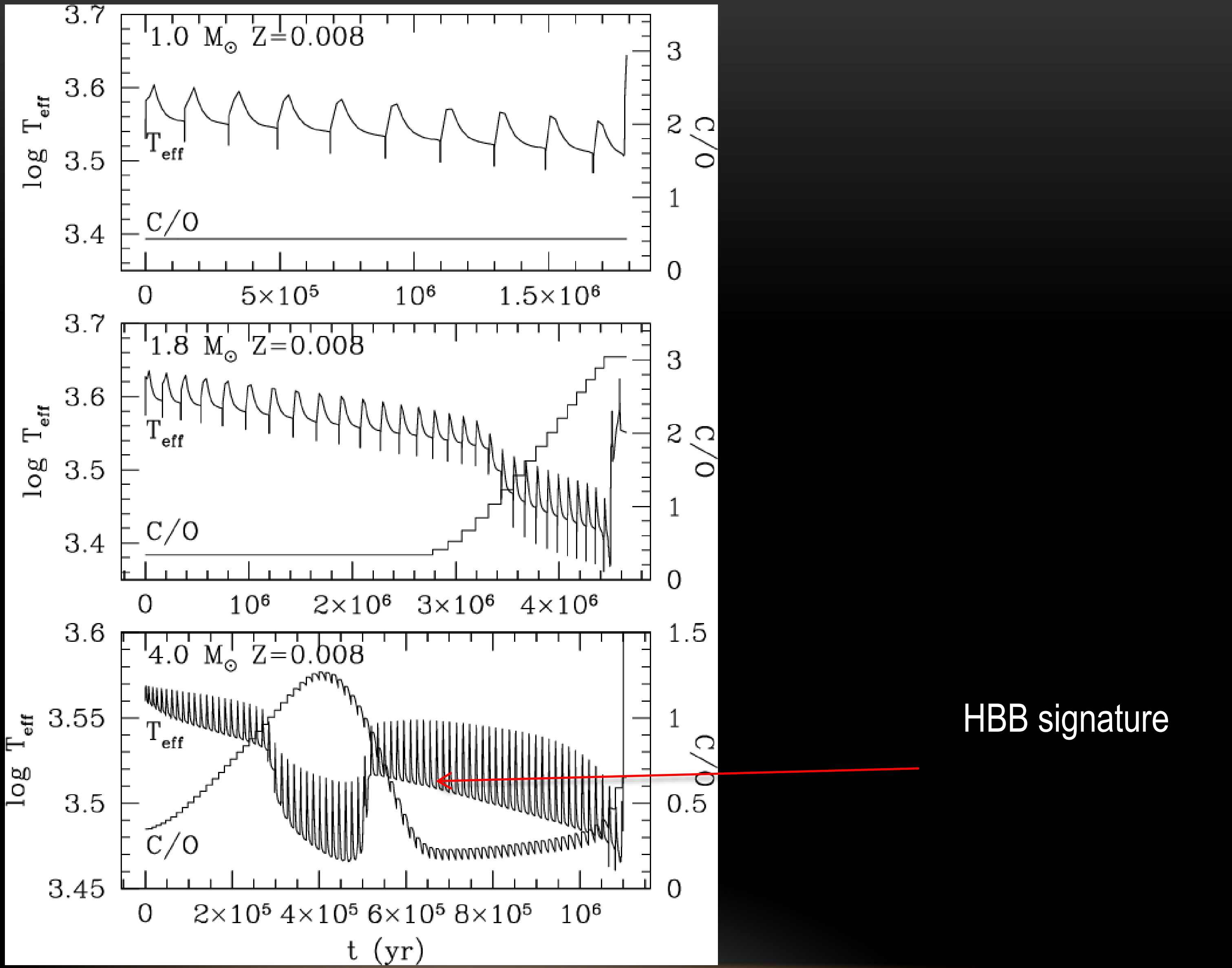


In stars with $M \gtrsim 4$–$5\ M_{\odot}$, the temperature at the base of the convective envelope during the interpulse period becomes so high ($T_{\rm BCE} \gtrsim 3 \times 10^7$ K) that H-burning reactions take place. The CNO cycle then operates on material in the convective envelope, a process known as *hot bottom burning*. Its main effects are: (1) an increase in the surface luminosity, which breaks the core mass-luminosity relation; (2) the conversion of dredged-up ^{12}C into ^{14}N, besides many other changes in the surface composition. Hot bottom burning thus prevents massive AGB stars from becoming carbon stars, and turns such stars into efficient producers of *nitrogen*.

The minimum mass for HBB decreases with decreasing metallicity

T_{BC} eventually decreases when the envelope mass becomes too small

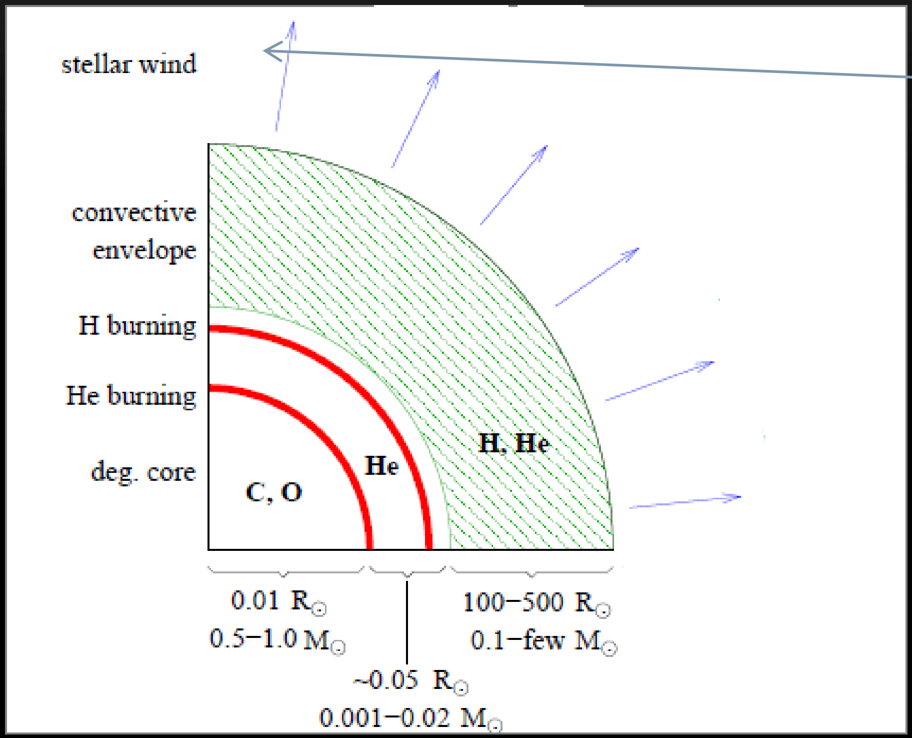




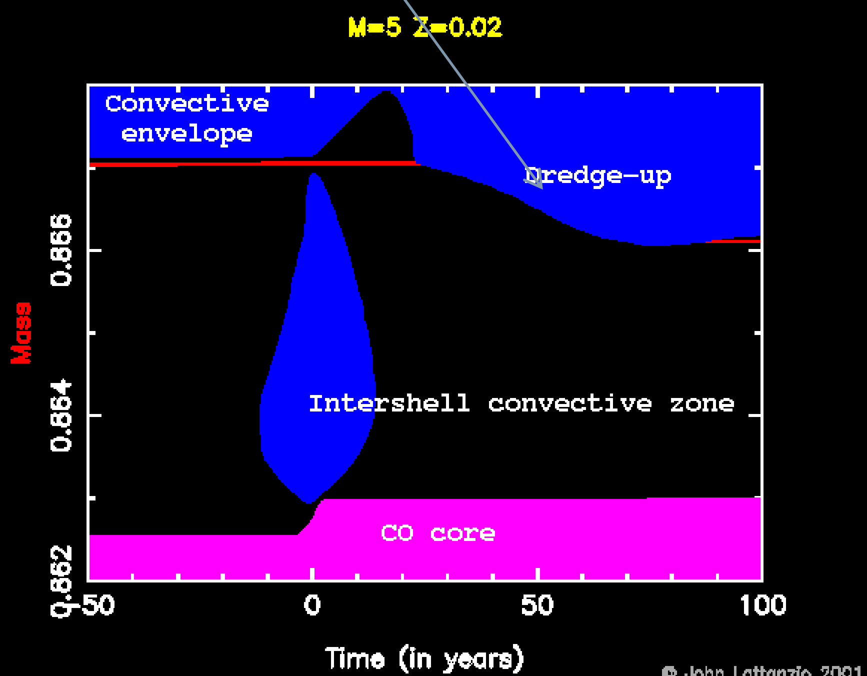
Marigo & Girardi (2007)

MAIN UNCERTAINTIES

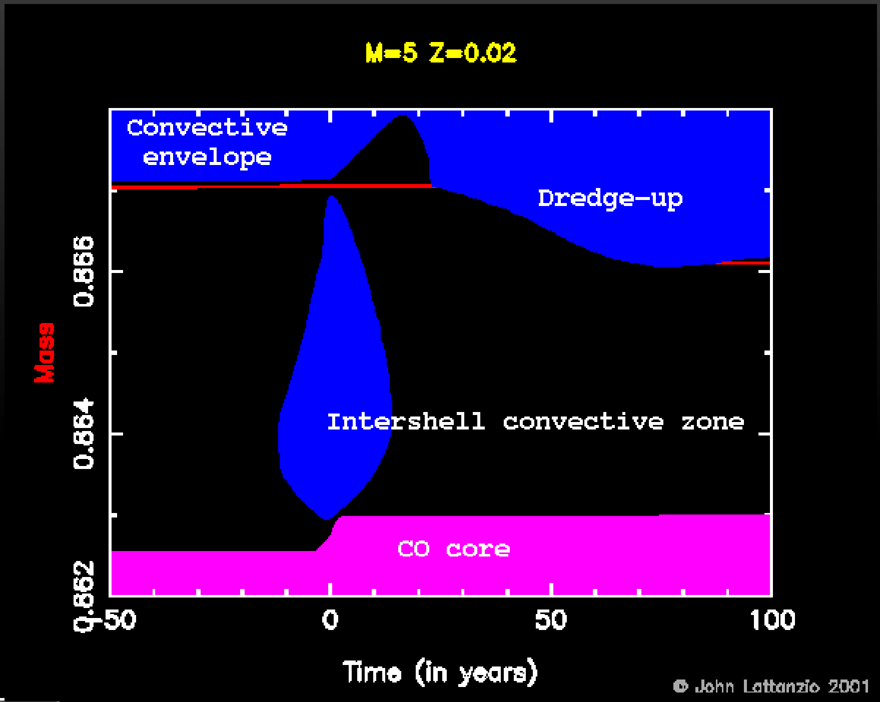
Mass loss, boundaries of convection

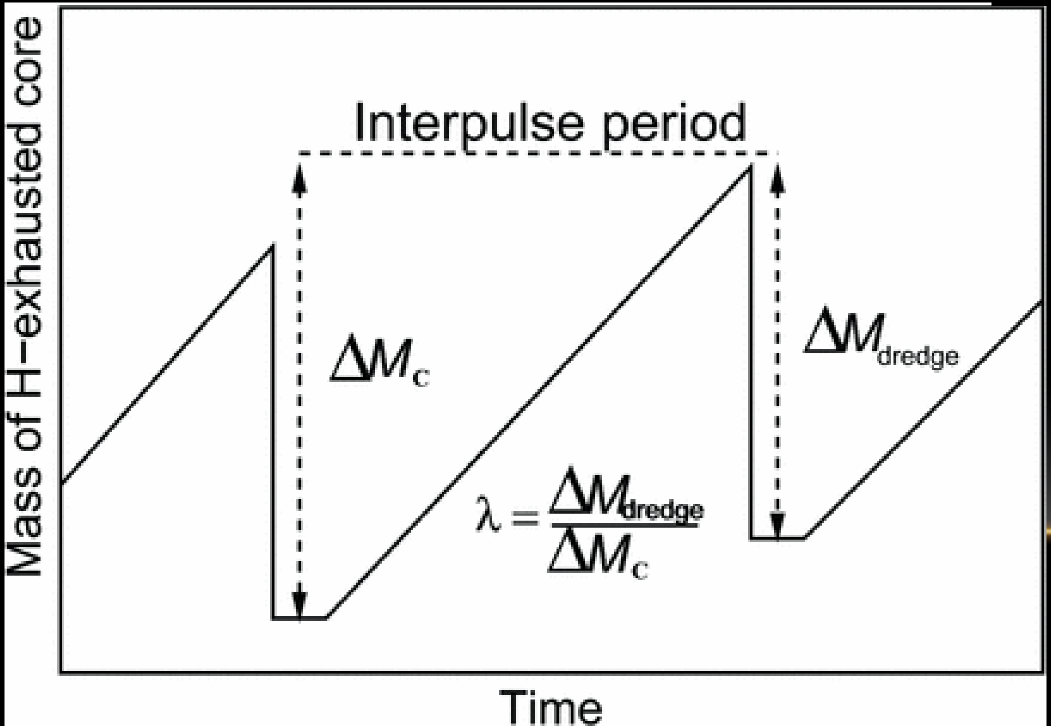


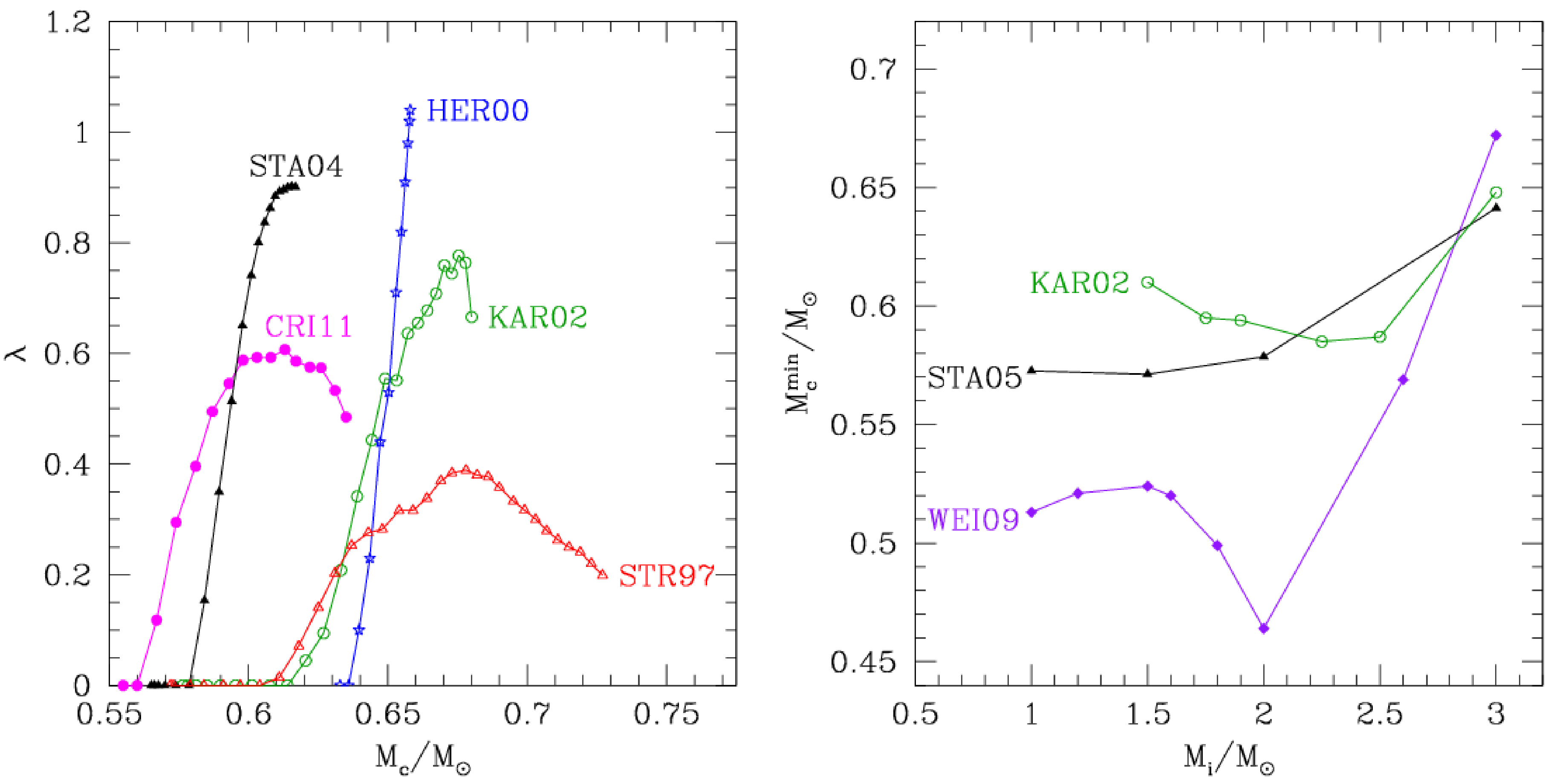
UNCERTAIN !!!!!



Dredge-up efficiency

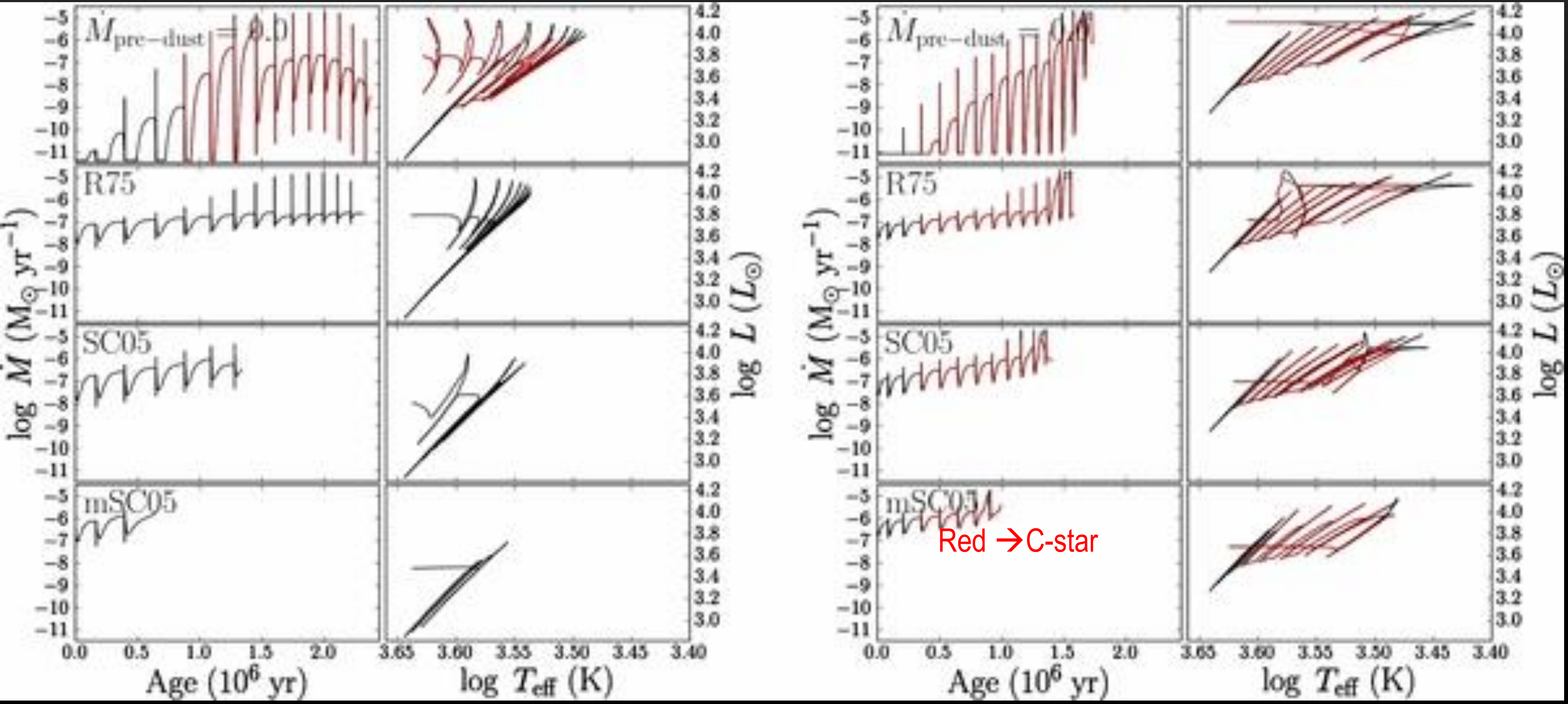






HER00
STA04
CRI11
KAR02
STR97
λ
$M_c/M_\odot$
KAR02
STA05
WEI09
$M_c^{min}/M_\odot$
$M_i/M_\odot$

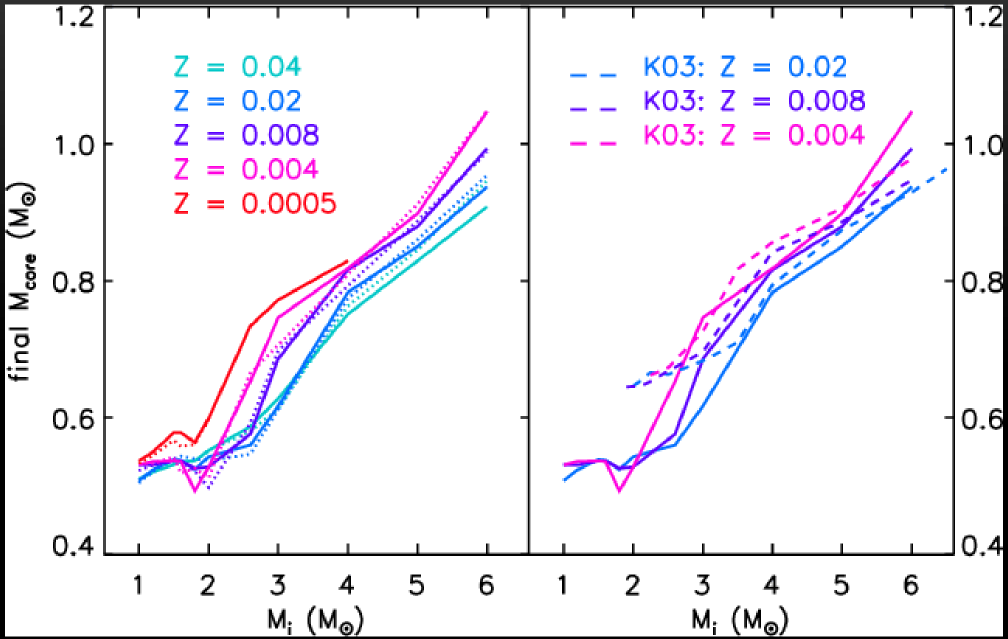
Mass loss

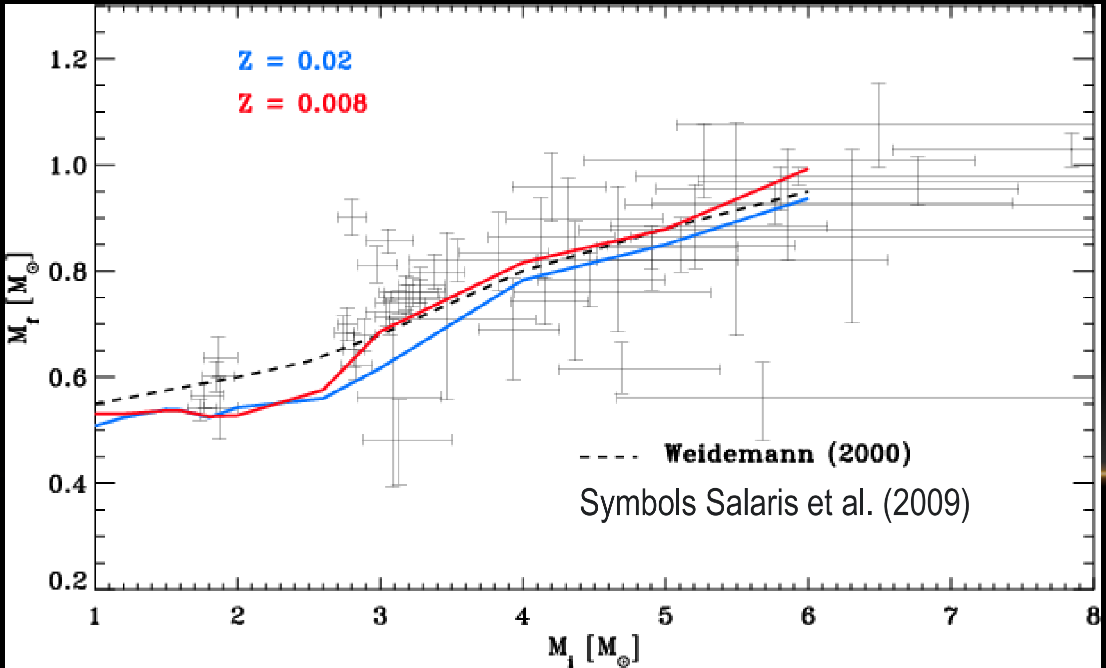


Four different prescriptions for mass loss before the TPs (1 and 2 $M_\odot$ models) (Z=0.001)

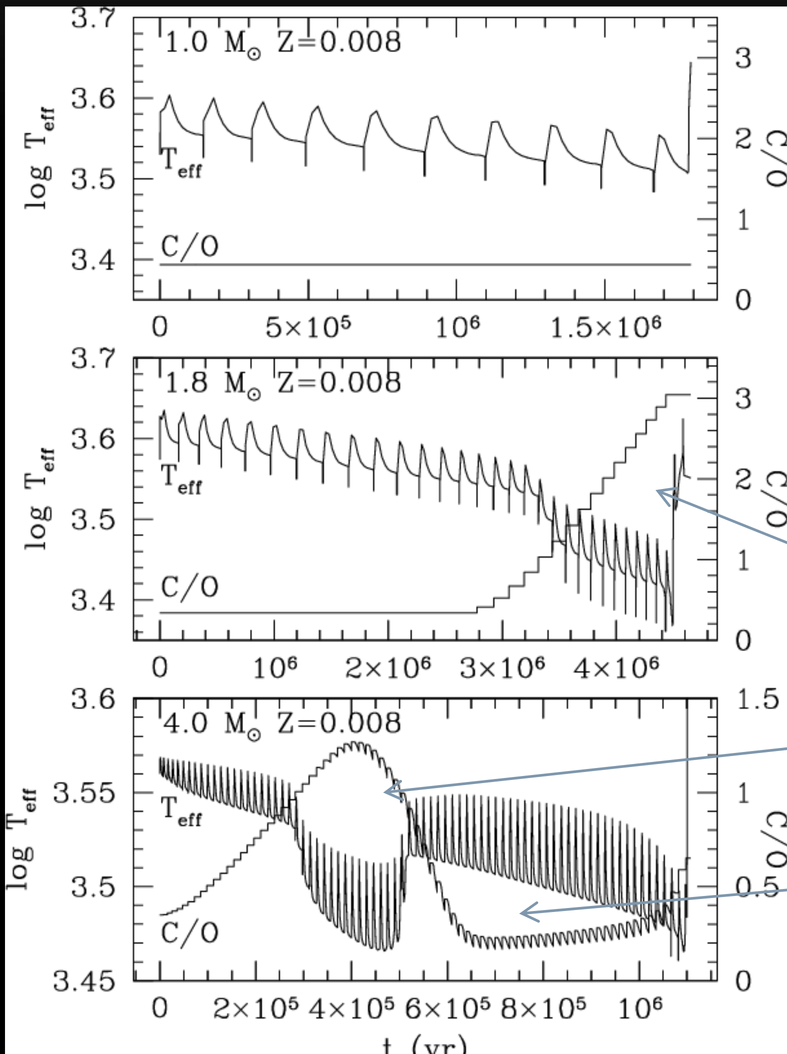
Rosenfield et al (2014)

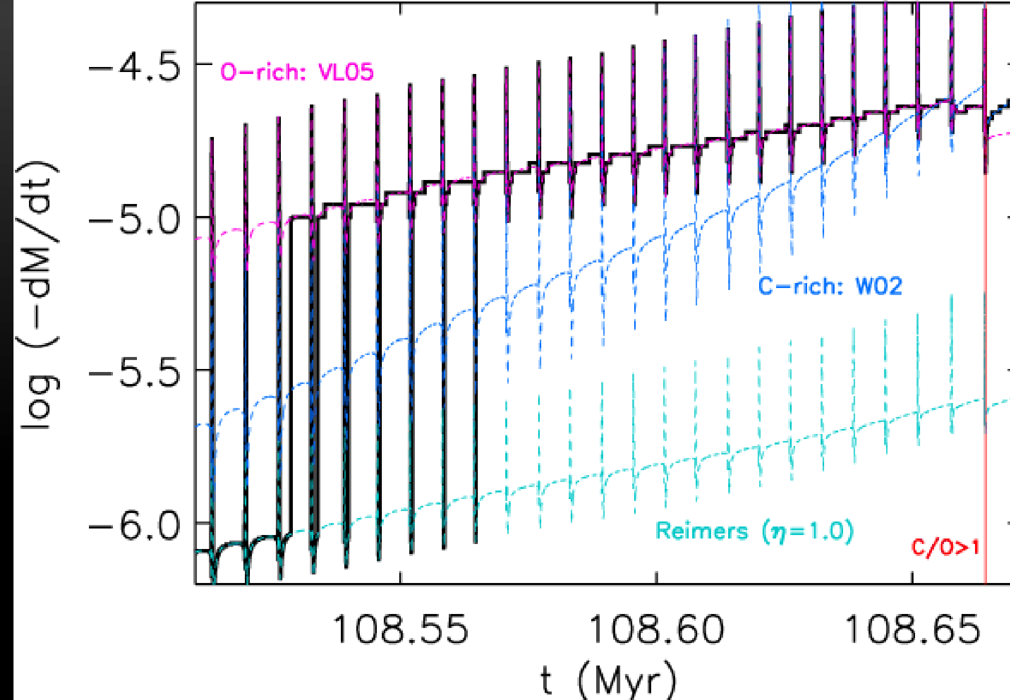
Predicted initial-final mass relationships





Weiss & Ferguson (2009)



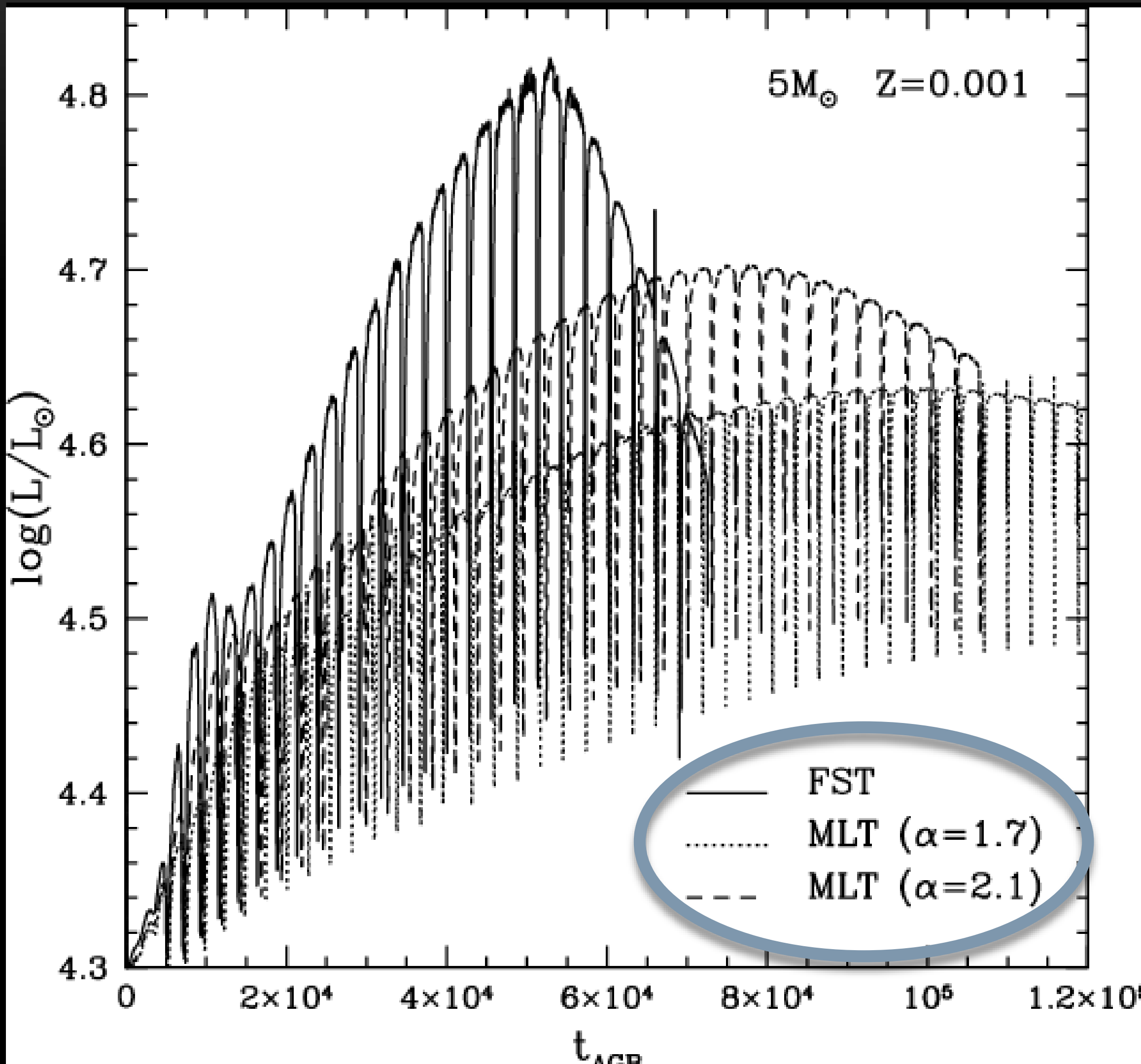


Importance of mass loss choice

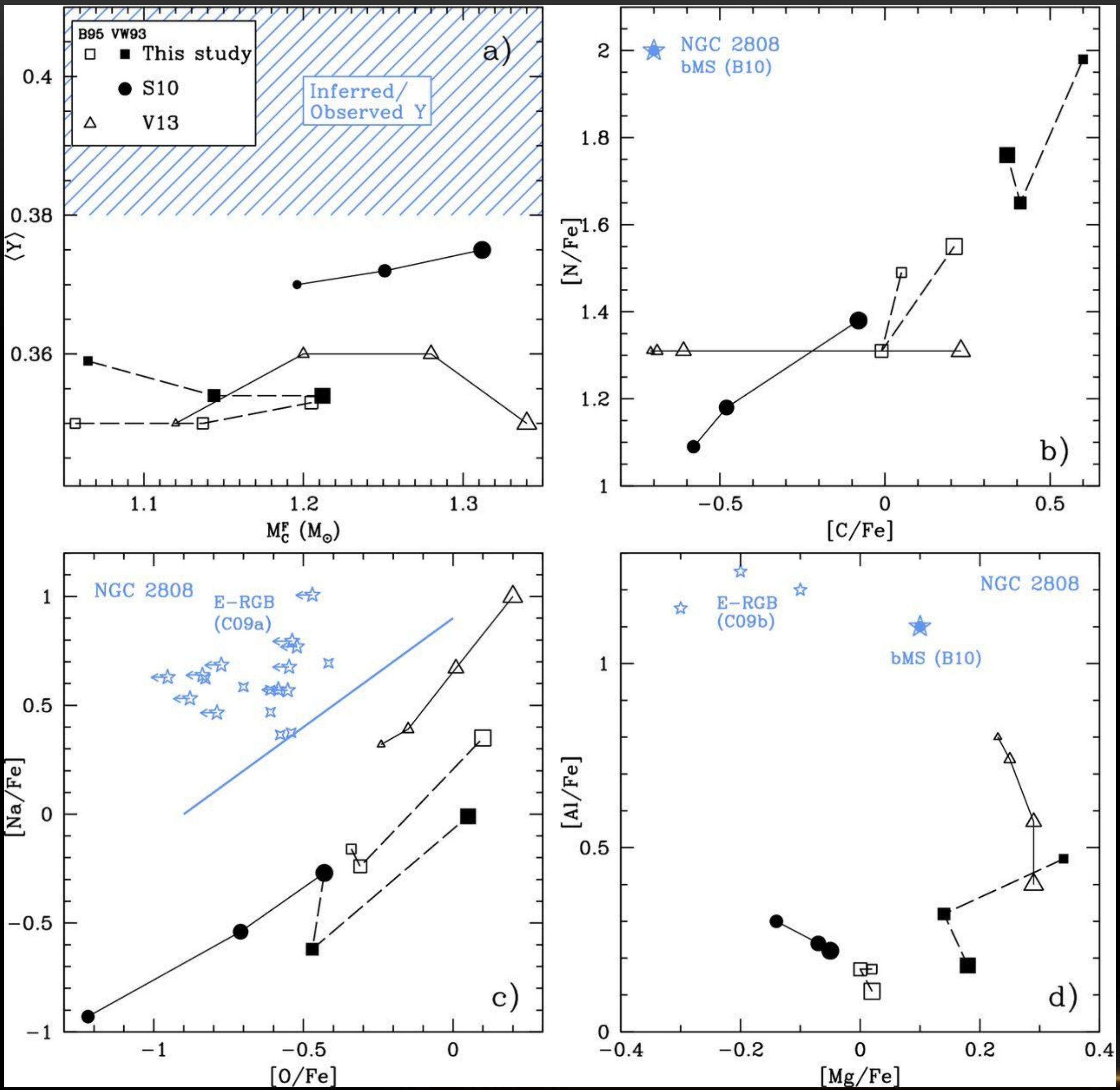
Importance of 3rd dredge up efficiency

Importance of hot bottom burning efficiency

Marigo & Girardi (2007)

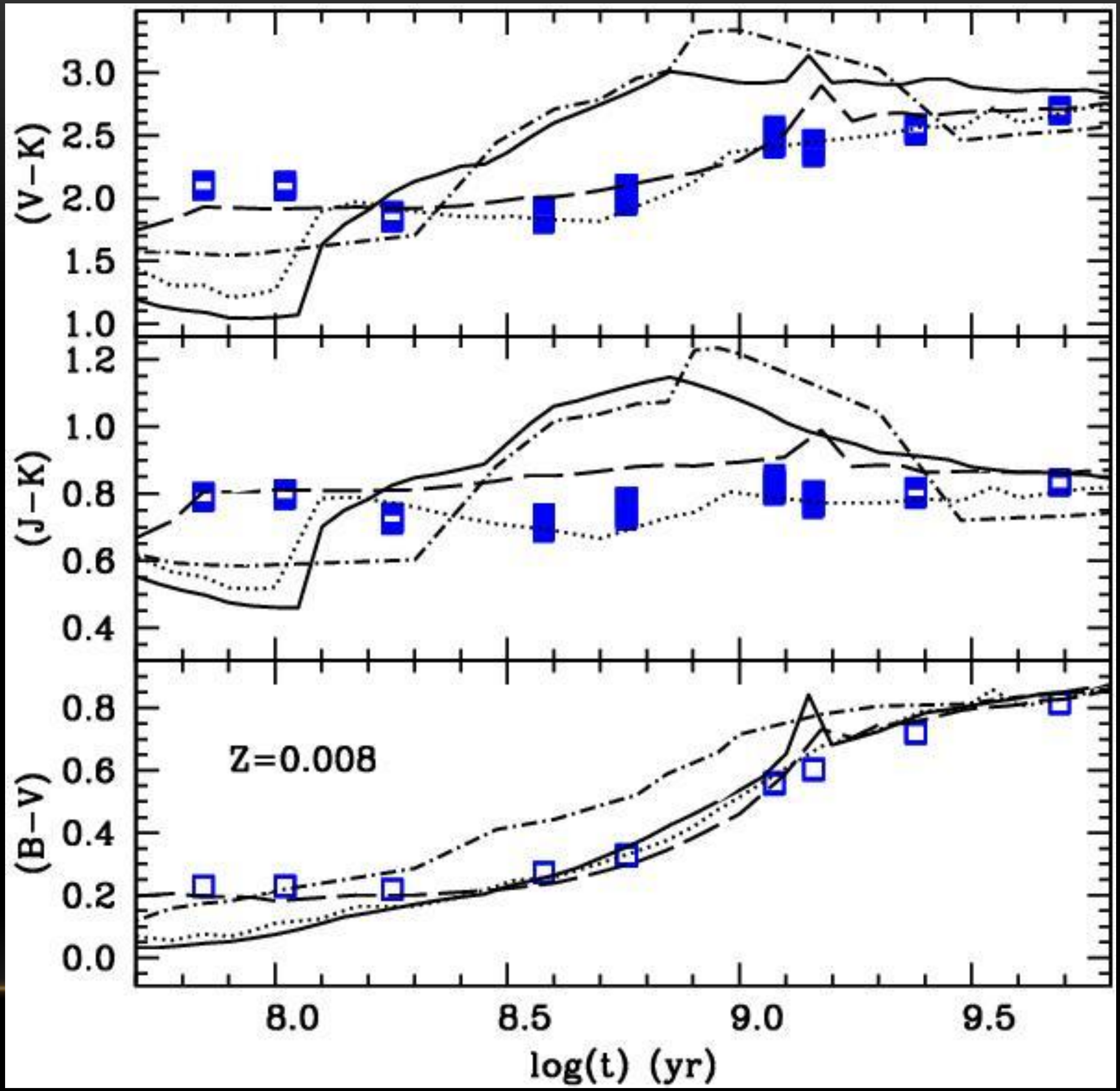


Different HBB efficiencies



Doherty et al. (2014)

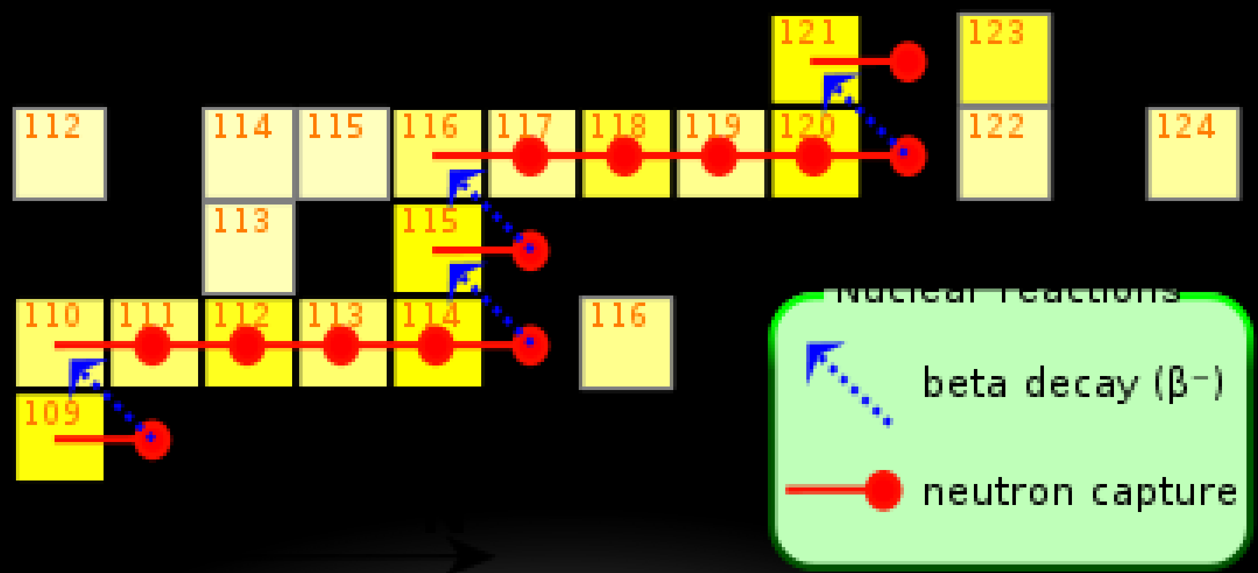
Salaris et al. (2014)



s-process nucleosynthesis

Nuclei with atomic mass, A > 56 (e.g. Zr, Sr, Ba, Eu, Pb, La)
formed by neutron addition onto Fe peak elements

Neutrons are added slowly, so that unstable nuclei generally have time to β-decay before capturing another neutron



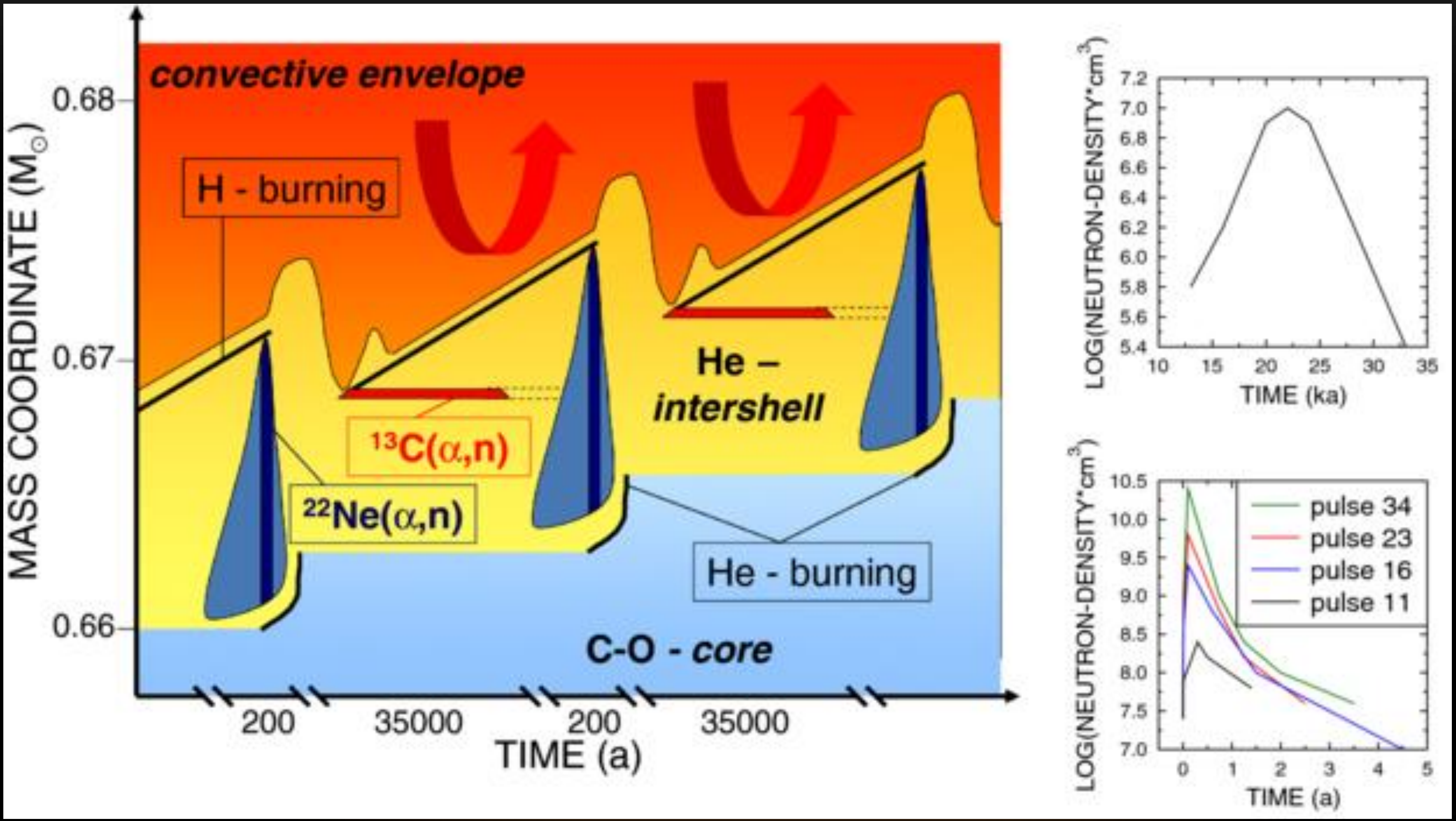
$^{12}C(p, \gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)^{16}O$

– Requires the presence of both H and He in a He-burning region when normally there is no hydrogen
– Occurs at $T \sim 10^8$ K, in between thermal pulses, and in radiative layers. But needs protons to be injected in some way in the intershell region
Timescales ~ 10000 yr, maximum neutron densities 10^8 n/cm^3
– Dominant neutron source in low-mass AGB stars (1 to 3$M_\odot$ stars)

$^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$

– Plenty of ^{14}N left over at the top of the intershell region from CNO cycling to produce the ^{22}Ne
– Occurs during thermal pulses when the temperature exceeds ~3 x 10^8 K, in convective layers
– These temperatures are not reached in the He-shells of low-mass AGB stars, except perhaps in the last few TPs, but are reached in massive AGB stars (~3 to 8$M_\odot$) during He-shell flashes
Timescales ~ 10 yr, maximum neutron densities 10^{13} n/cm^3

How do you create the ^{13}C pocket ?



Reifarth et al. (2014)

EVOLUTION OF HIGH MASS STARS WITH $7 < M/M_{\odot} < 9 - 11$

These stars ignite the fusion of carbon in a non degenerate core, when $T \sim 5 - 6 \times 10^{8}$ K.

$$
\begin{aligned}
{}^{12}C + {}^{12}C \longrightarrow {}^{24}Mg &\longrightarrow {}^{20}Ne + {}^{4}He \\
&\longrightarrow {}^{23}Na + p \\
&\longrightarrow {}^{23}Mg + n
\end{aligned}
$$

During carbon burning and more advanced nuclear burnings, a lot of energy is lost in form of neutrinos. This means that from now on nuclear burning is not able to provide all the energy required by the star. As a consequence, the star rapidly contracts to produce the missing energy through the work of gravitation (virial theorem).

At the end of central C burning the core (made mainly of oxygen from the previous He burning, and Ne produced by the C burning) becomes electron degenerate, and the stars evolve as an ONe WD.

(Probably)

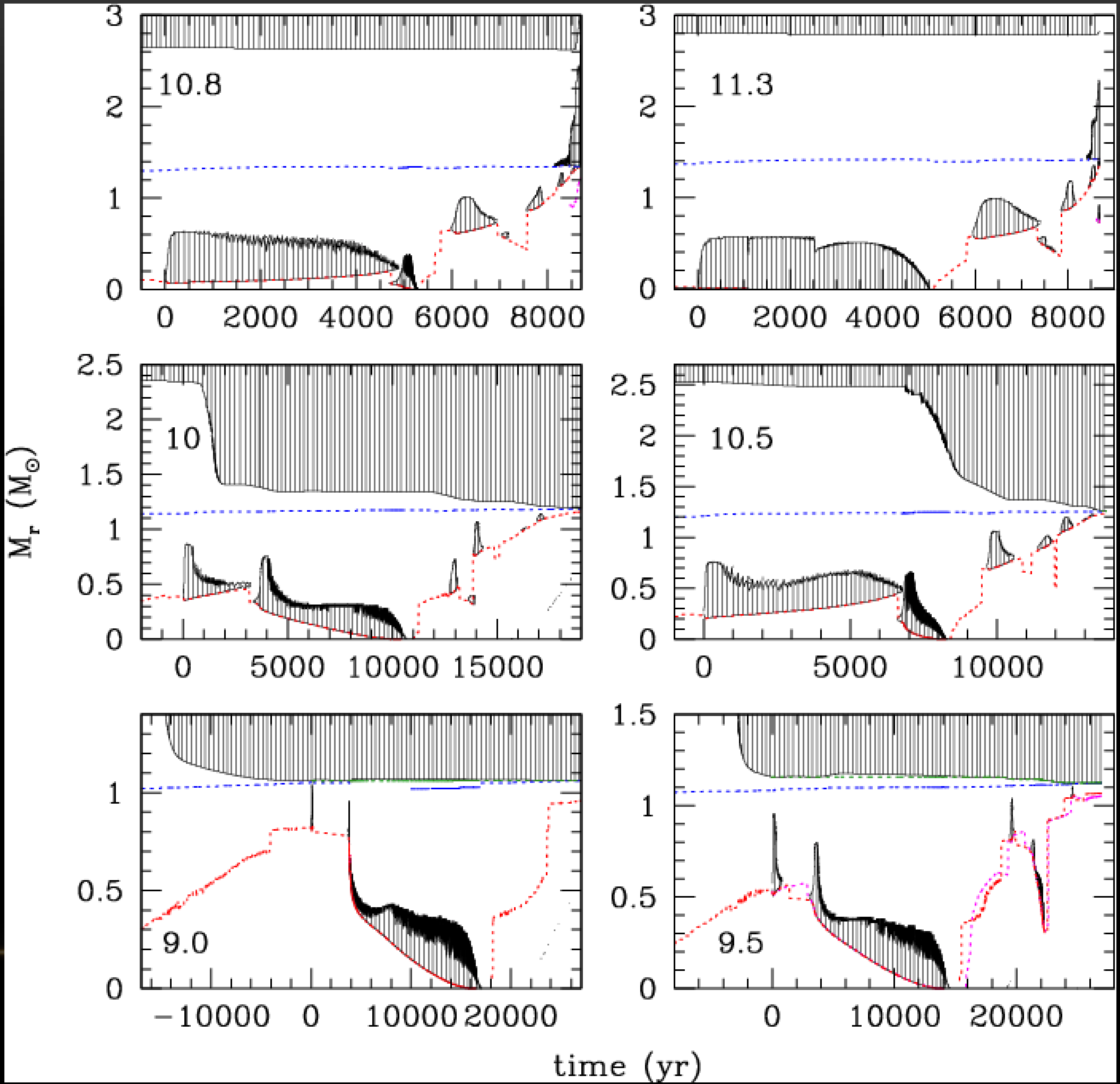
Green→maximum H-burning

Blue→maximum He-burning

Red→maximum C-burning

After the 2nd dredge-up thermal pulses starts (with associated 3rd dredge-up and

The so-called super-AGB (SAGB) phase starts

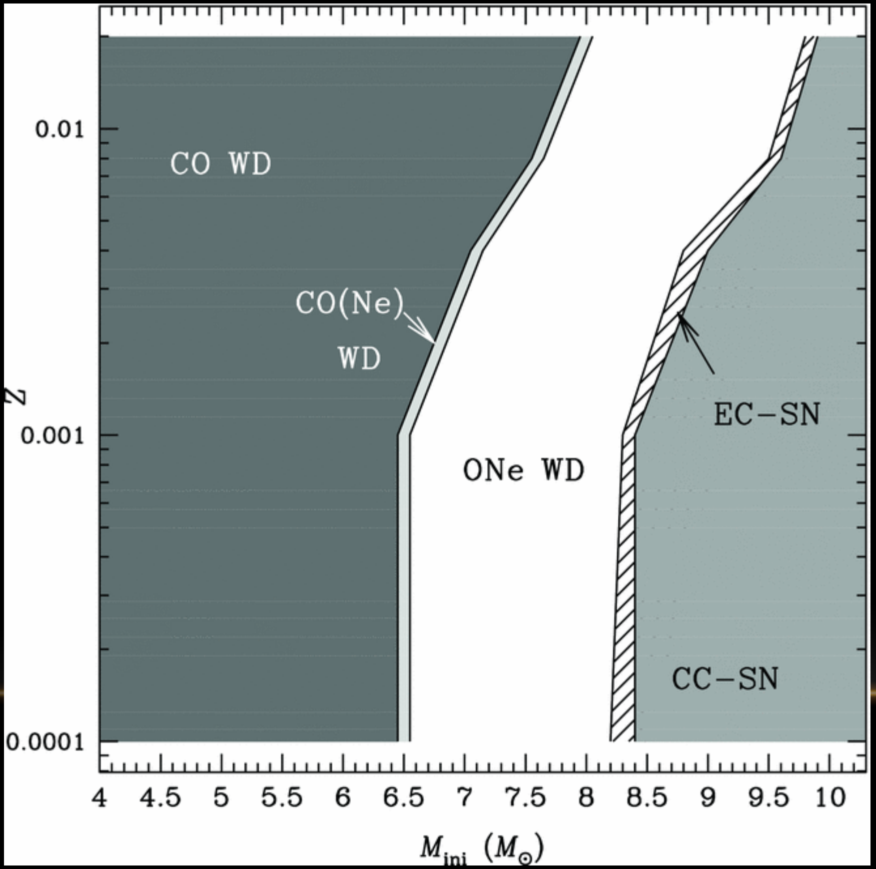


If after the carbon burning phase the degenerate core mass grows to the Chandrasekhar mass electron-capture reactions are activated at the centre and induce core collapse, leading to the formation of a neutron star.

Whether or not the SAGB core mass reaches this critical value depends on the interplay between mass loss and core growth.

If during the post-C burning evolution the mass loss rate is high enough, the envelope is lost before the core mass reaches the Chandrasekhar mass and the remnant is a ONe white dwarf (WD).

On the contrary, if the mass loss rate is not large enough, the endpoint of SAGB evolution is probably the explosion as electron-capture supernova and the formation of a neutron star remnant.

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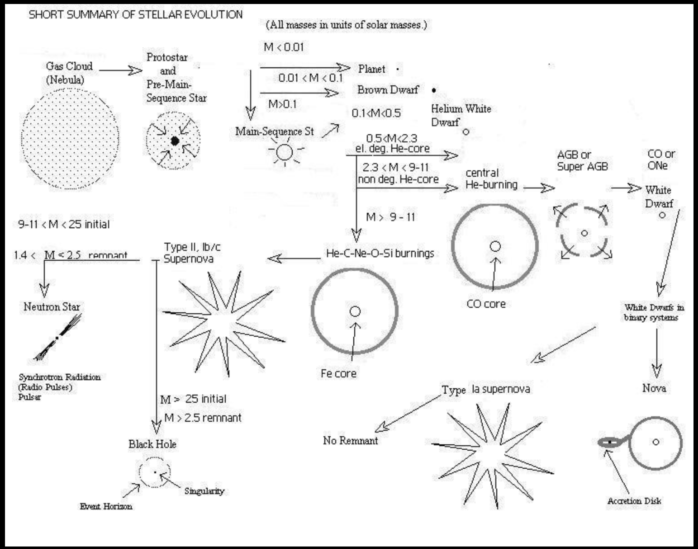
ADVANCED EVOLUTIONARY PHASES OF LOW- AND INTERMEDIATE-MASS STARS: CURRENT STATUS AND OPEN PROBLEMS

Pt. 2



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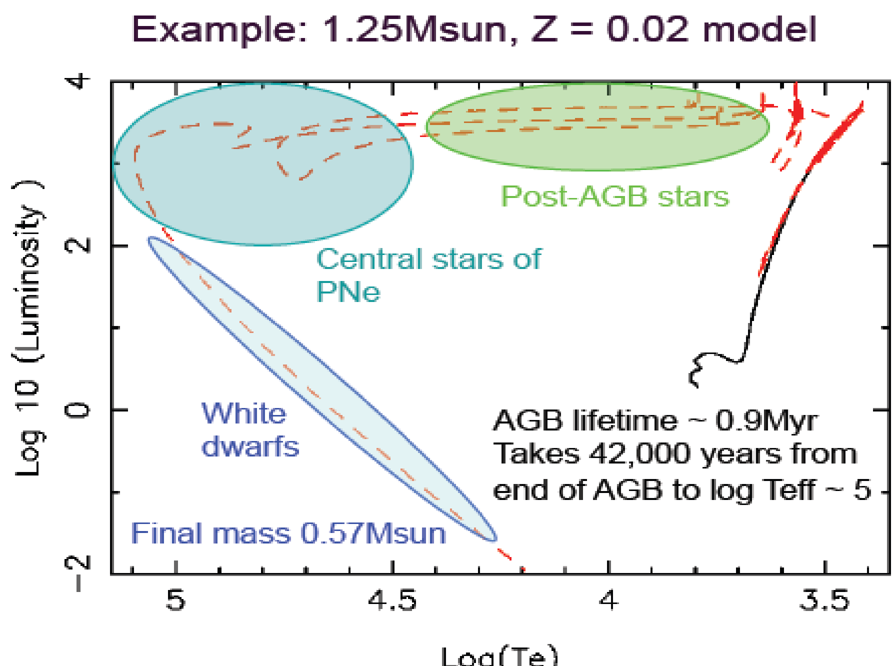
Post-AGB stars

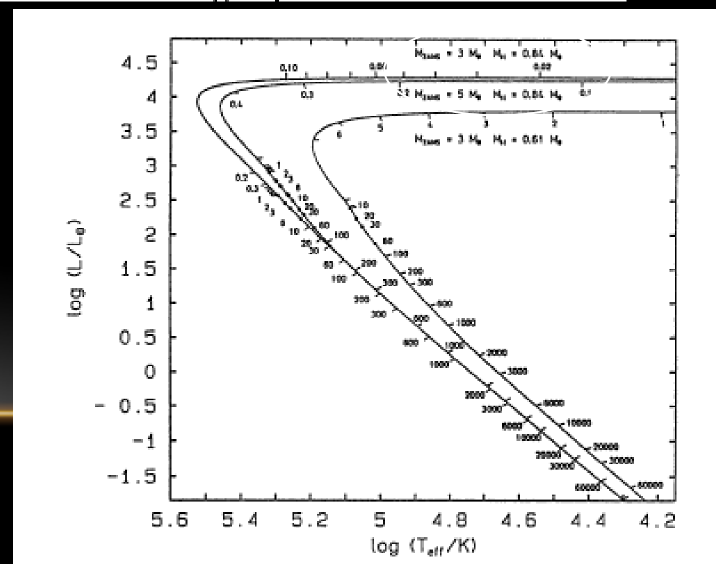
- Once the envelope mass drops below ~0.01Msun, the star leaves the AGB
- Evolves at almost constant luminosity toward hotter Teff
- Transition times very rapid (~100 years) for most massive objects → No PN
- Transition times ~10^4 years for low-mass objects
- Mass loss rates are low (~10^{-8} Msun yr^{-1})



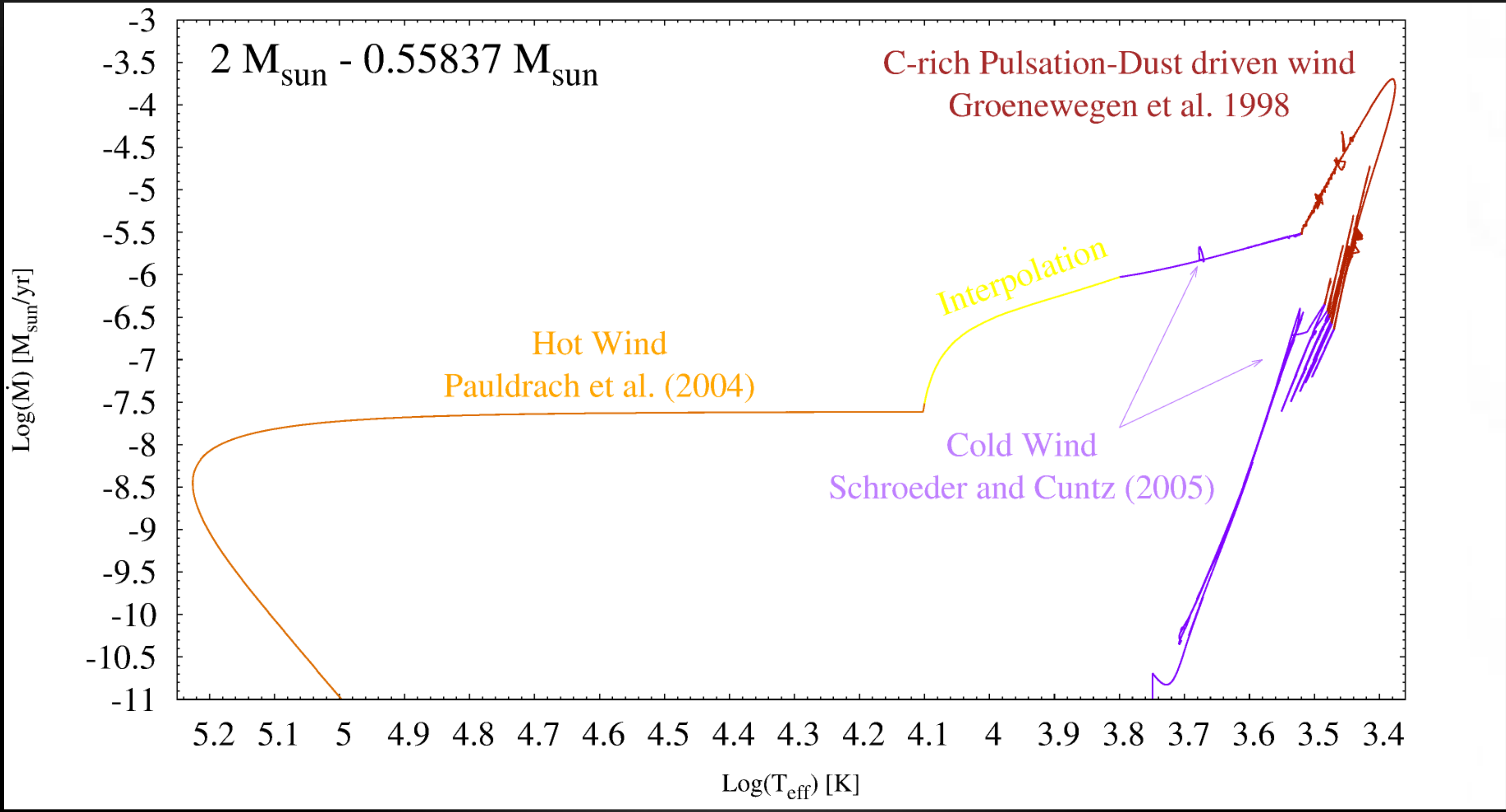
Larger envelope mass → slower evolution

H- or He-burners, depending on the moment they leave the AGB during the TP cycle. He-burners evolve more slowly for a given core mass

Transition times at fixed post-AGB mass depend on progenitor history (Bloecker 1995), because of the different T-P stratification.
Lower mass progenitor, faster transition

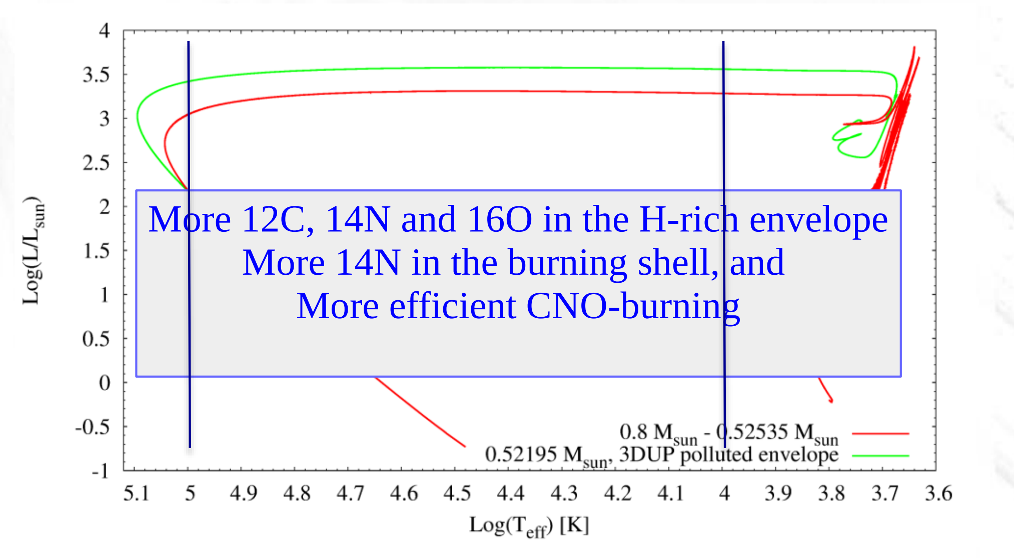


Mass loss treatment



From a talk by Miller Bertolami (2014)

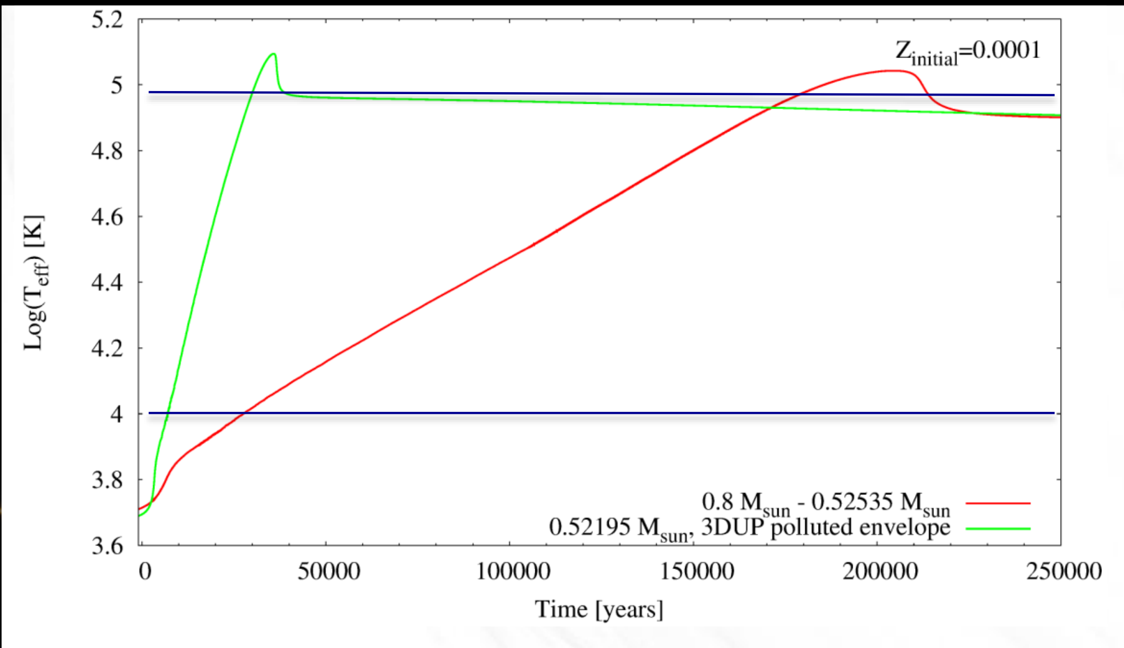
Post-AGB timescale and third dredge up on the AGB



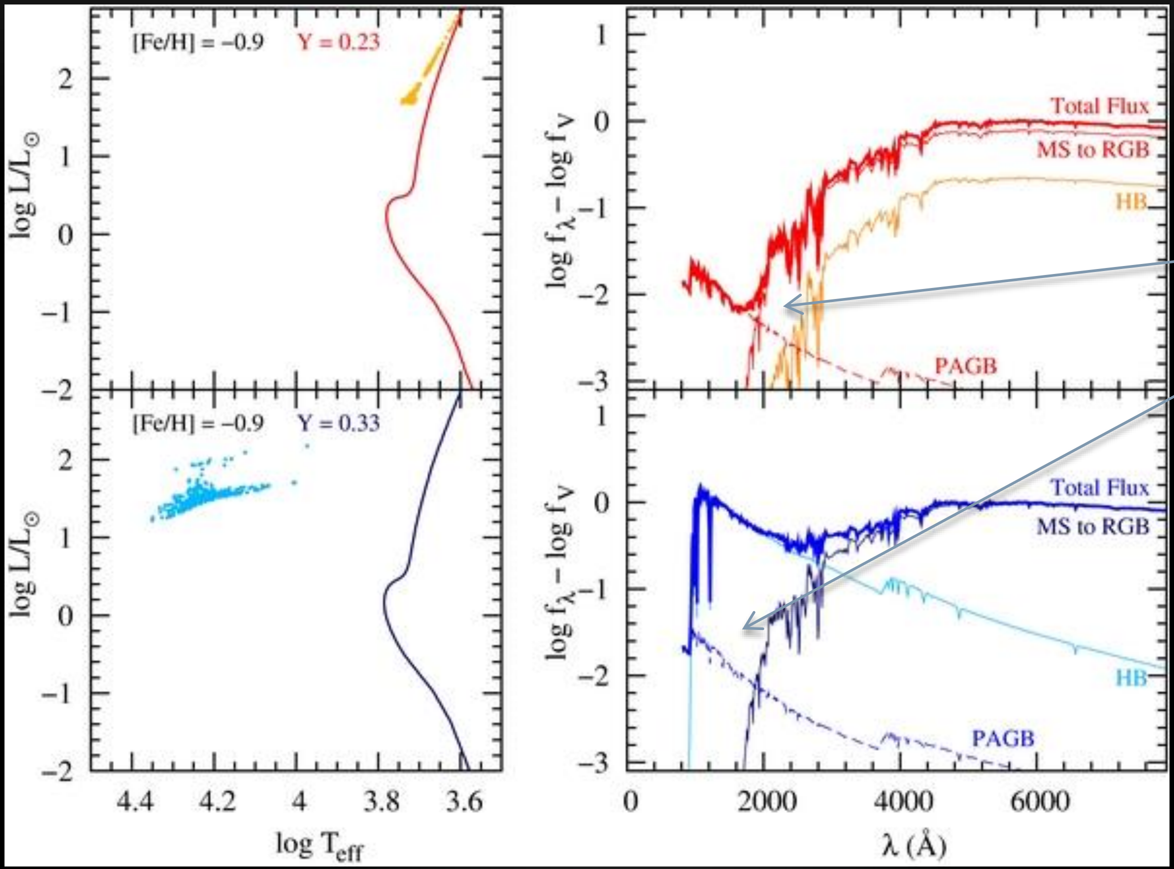
From a talk by Miller Bertolami (2014)

Post-AGB crossing time (T_{eff} from 10^4 to 10^5 K)

More dredge-up, shorter transition times



Contribution of post-AGB stars to integrated spectra of unresolved stellar populations



Cassisi & Salaris (2013)

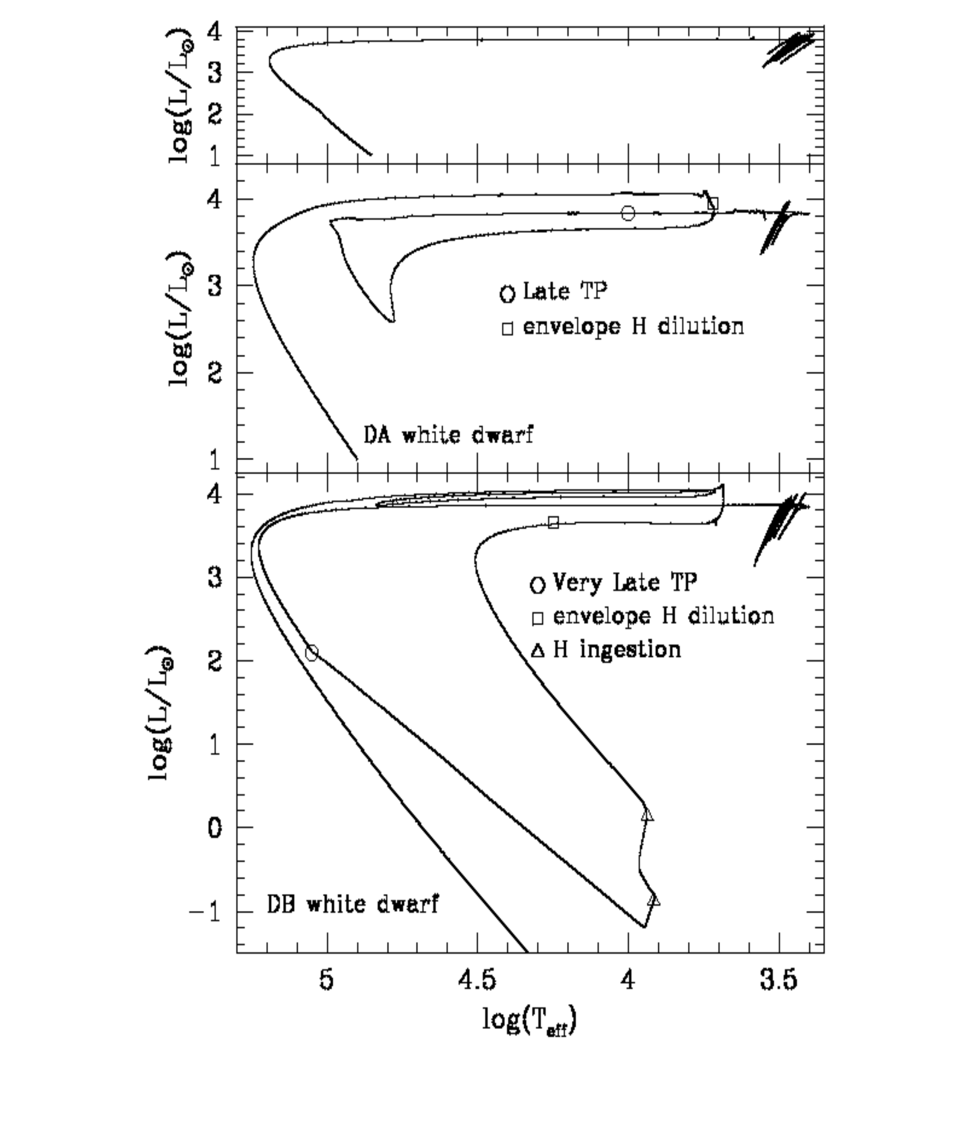
Late Thermal Pulse

Late-TP

No dredge-up expected unless high mass loss and/or some overshooting. At most some dilution of H

Very late TP

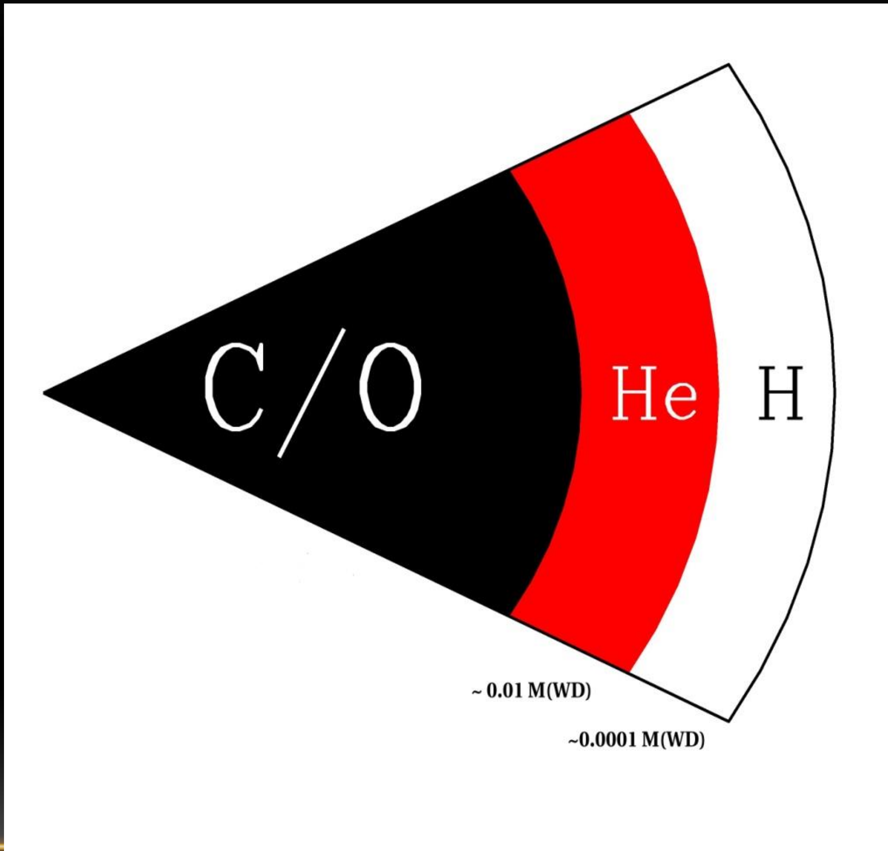
Surface H depletion, enrichment of C and O



WHITE DWARFS

- Isothermal core (because of very high conductivity of degenerate electrons) that contains about 99% of the WD mass, surrounded by a largely non degenerate thin envelope

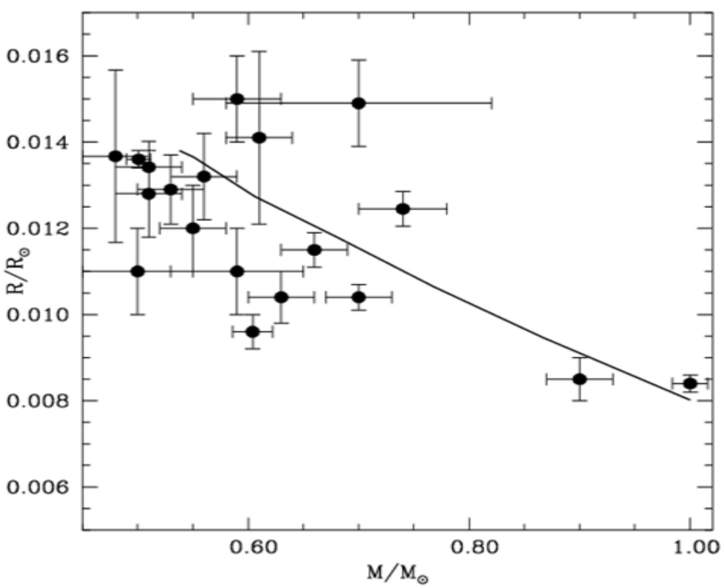
- The degenerate layers act as a reservoir of energy (internal energy of the ions), while the outer layers control the energy outflow



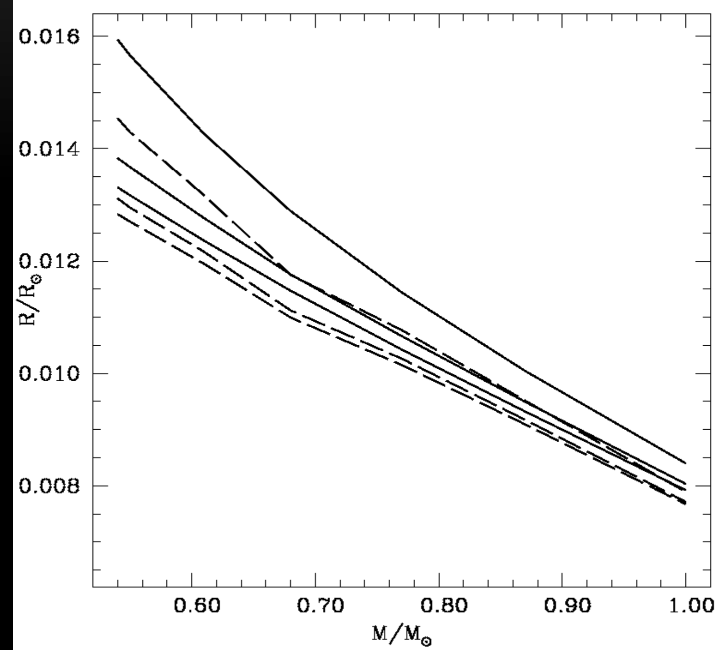
To a first approximation the cooling time t down to luminosity L of a WD with mass M, core atomic weight A and envelope molecular weight μ is given by the Mestel law:

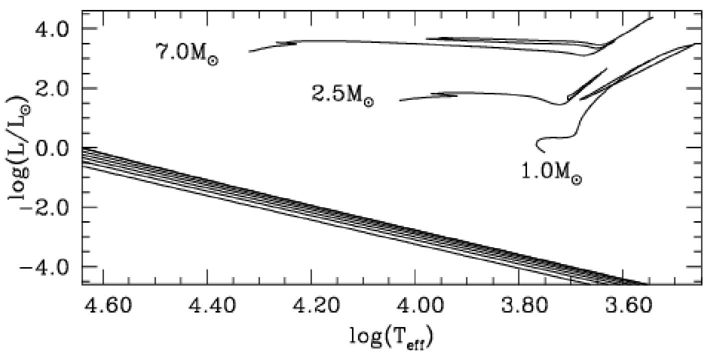
$$t \approx A^{-1}\, \mu^{-2/7}\, M^{5/7}\, L^{-5/7}$$

Mass-radius relationship



Comparison of the theoretical mass-radius relationship predicted by theoretical models with observations.





Actually radius depends also on T_{eff} and envelope composition

MESTEL LAW

Core (isothermal) made of a perfect gas of ions and zero-temperature degenerate electrons.
Thin envelope made of a perfect gas of electrons and ions in radiative equilibrium

The energy radiated by the WD is the internal energy of the ions in the core

C_v=3/2 K per ion
E=3/2KT per ion

Cooling times (yr) are given by

$$\Delta t(yr) \propto \left(\frac{L}{M}\right)^{-5/7} \approx \frac{4.5\ 10^7}{\mu_i}\left(\frac{LM_\odot}{ML_\odot}\right)^{-5/7}$$

μ_i is the mean molecular weight of the core

$$L + L_\nu = -\int_0^{M_{WD}} C_v \frac{dT}{dt}\, dm - \int_0^{M_{WD}} T\left(\frac{\partial P}{\partial T}\right)_{V,X_0} \frac{dV}{dt}\, dm + l_s \frac{dM_s}{dt} - \int_0^{M_{WD}} \left(\frac{\partial E}{\partial X_0}\right)_{T,V} \frac{dX_0}{dt}\, dm$$

i) $\log(L/L_o) > -1.5$ Neutrino cooling

Different thermal structures due to different initial conditions tend to converge to a unique one.

ii) $-1.5 < \log(L/L_o) < -3$ Fluid cooling

($1 < \Gamma < 180$)

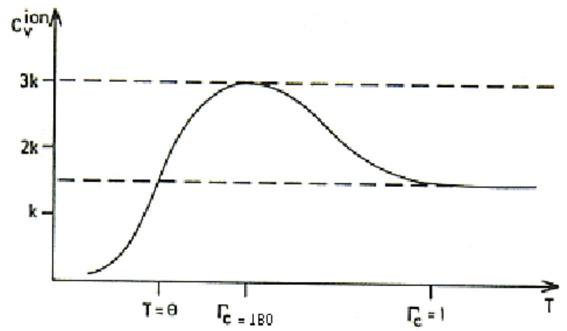
iii) $\log(L/L_o) < -3$ Crystallization

($\Gamma > 180$)

-Latent heat release

-Chemical separation

$$\Gamma = \frac{E_C}{kT_e}$$



Run of the specific heat per ion with temperature

iv) Debye cooling (c_V drops as T^3)

The complete energy budget for a two-component mixture like C/O

$$\frac{dL_r}{dm} = -\epsilon_\nu - P\frac{dV}{dt} - \frac{dE}{dt},$$

V = 1/ρ
E=internal energy per unit mass

$$\frac{dE}{dt} = \left(\frac{\partial E}{\partial T}\right)_{V,X_O}\frac{dT}{dt} + \left(\frac{\partial E}{\partial V}\right)_{T,X_O}\frac{dV}{dt} + \left(\frac{\partial E}{\partial X_O}\right)_{T,V}\frac{dX_O}{dt}$$

$$\left(\frac{\partial E}{\partial V}\right)_{T,X_O} = -P + T\left(\frac{\partial P}{\partial T}\right)_{V,X_O},$$

from thermodynamics

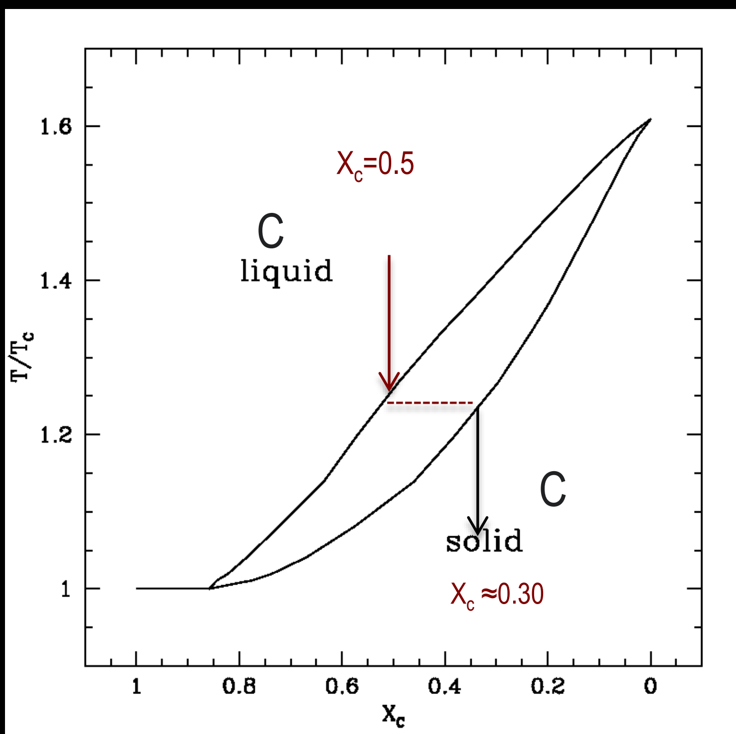
$$-\left(\frac{dL_r}{dm} + \epsilon_\nu\right) = C_v\frac{dT}{dt} + T\left(\frac{\partial P}{\partial T}\right)_{V,X_O}\frac{dV}{dt} - l_s \times \frac{dM_s}{dt}\delta(m - M_s) + \left(\frac{\partial E}{\partial X_O}\right)_{T,V}\frac{dX_O}{dt}$$

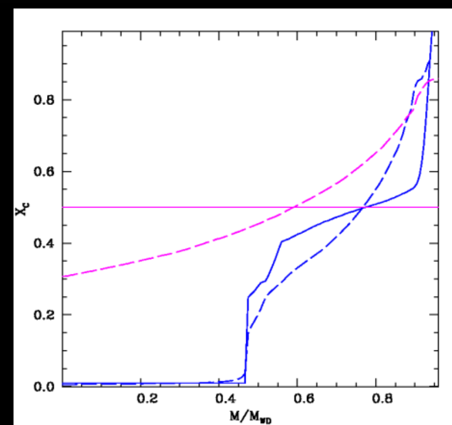
Phase separation upon crystallization

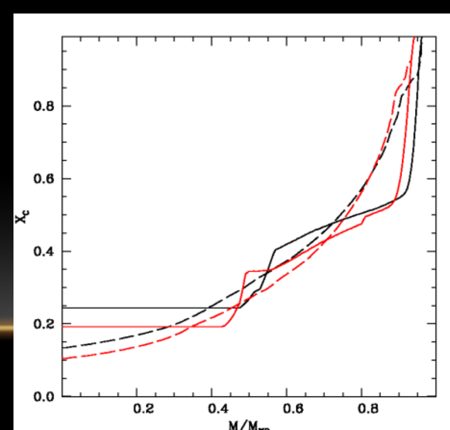
Garcia-Berro et al. (1988)

Crystallization → μ decreases locally in the liquid phase → instability → mixing → as a result the overall profile changes

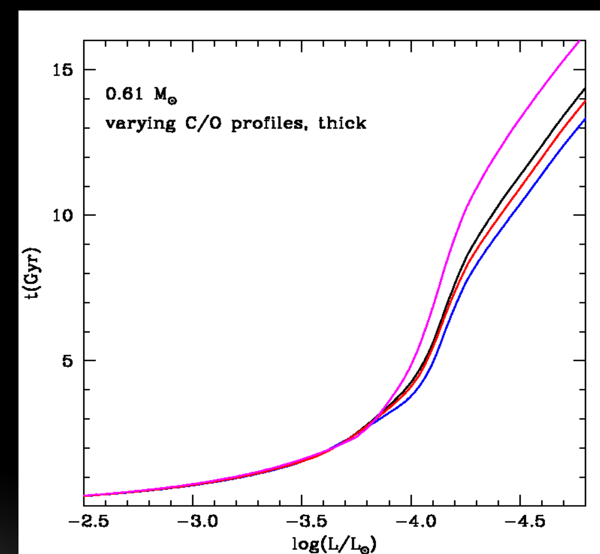
Phase diagram CO binary mixture







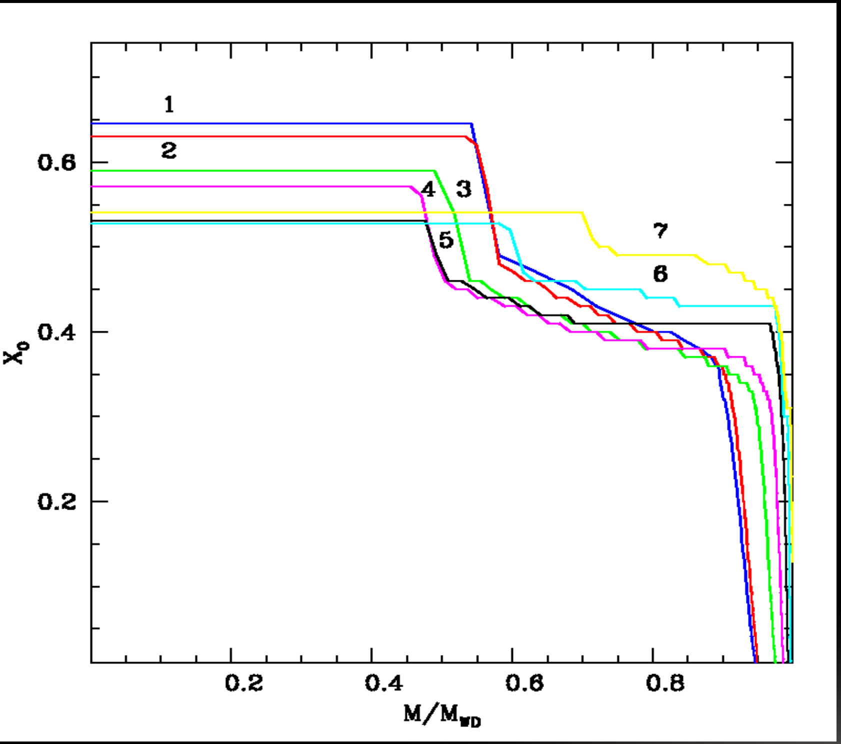
Initial and final oxygen profiles inside a $0.6 M_{\odot}$ WD

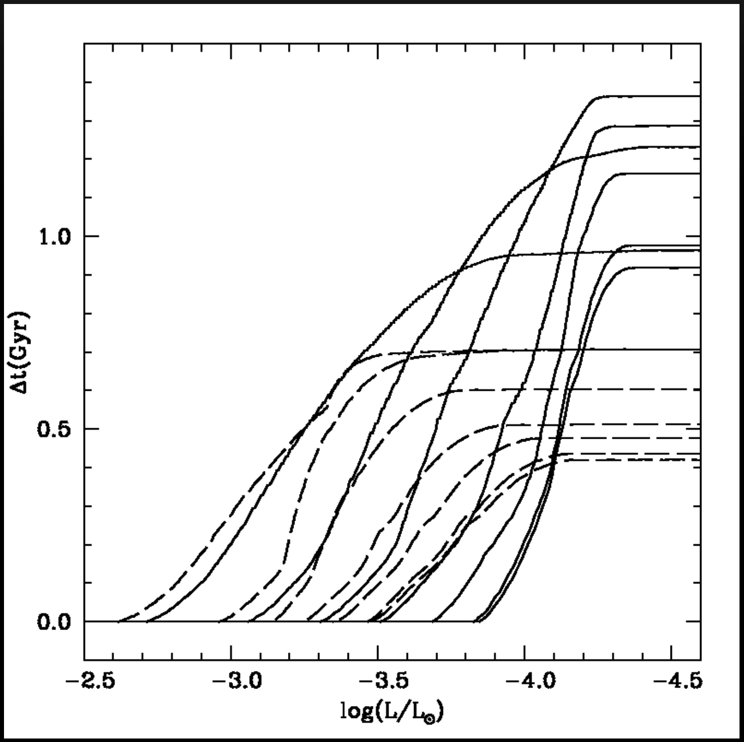


Salaris (2009)

Time-delay caused by phase separation depends on the envelope composition

Age delay due to separation

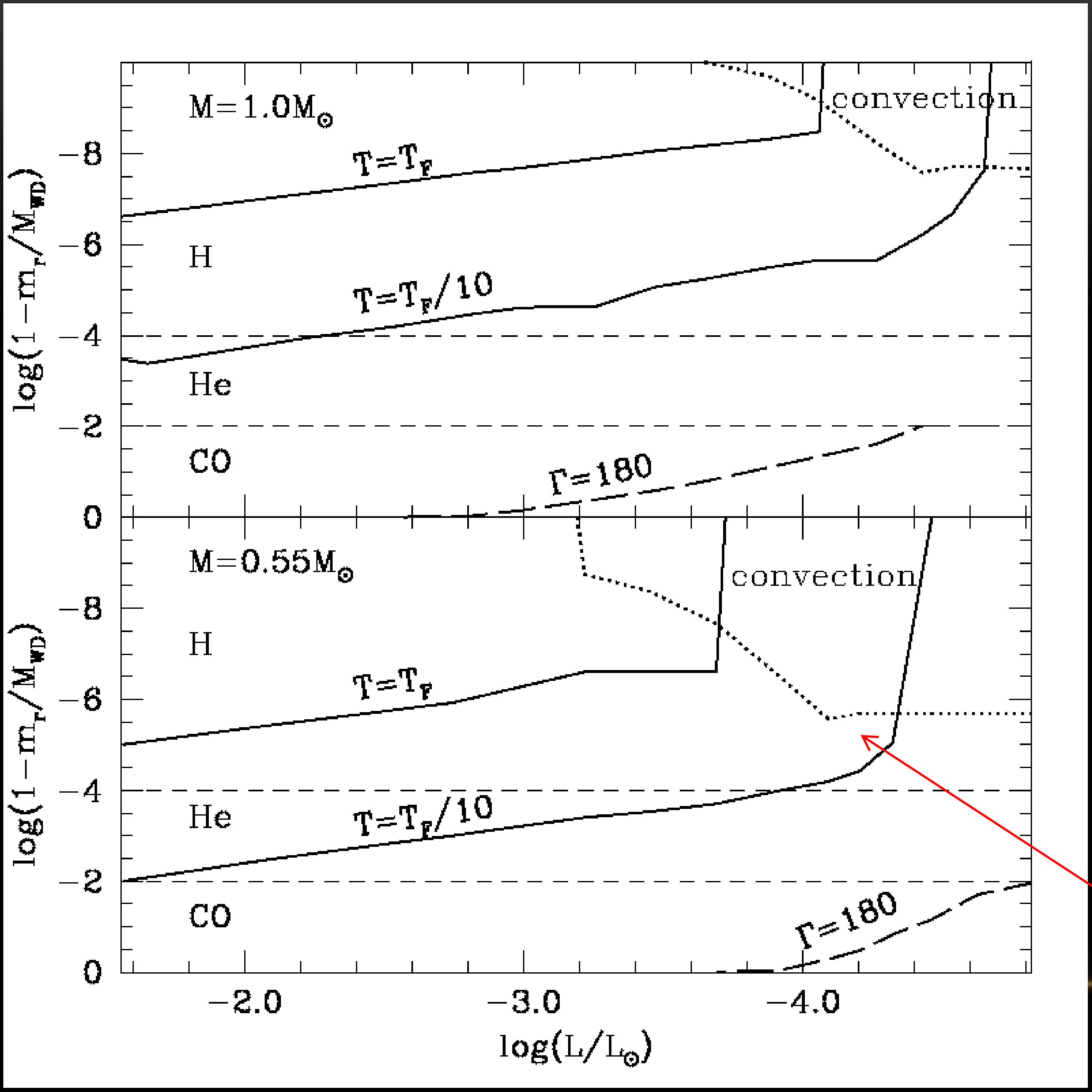




H-envelopes (solid)

He-envelopes (dashed)

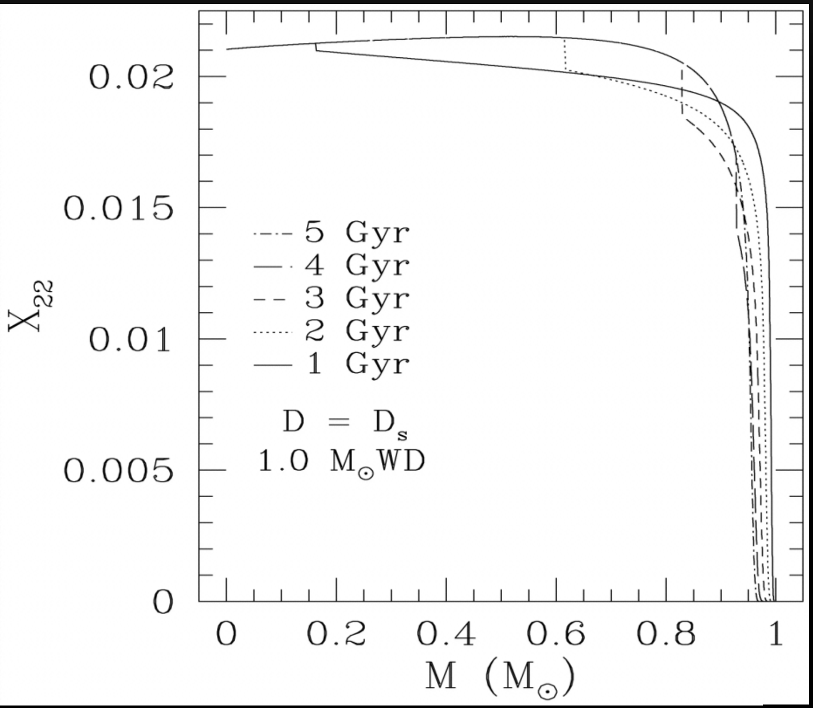
Salaris et al. (2010)



Convective coupling

^{22}Ne diffusion in the liquid phase of WD cores

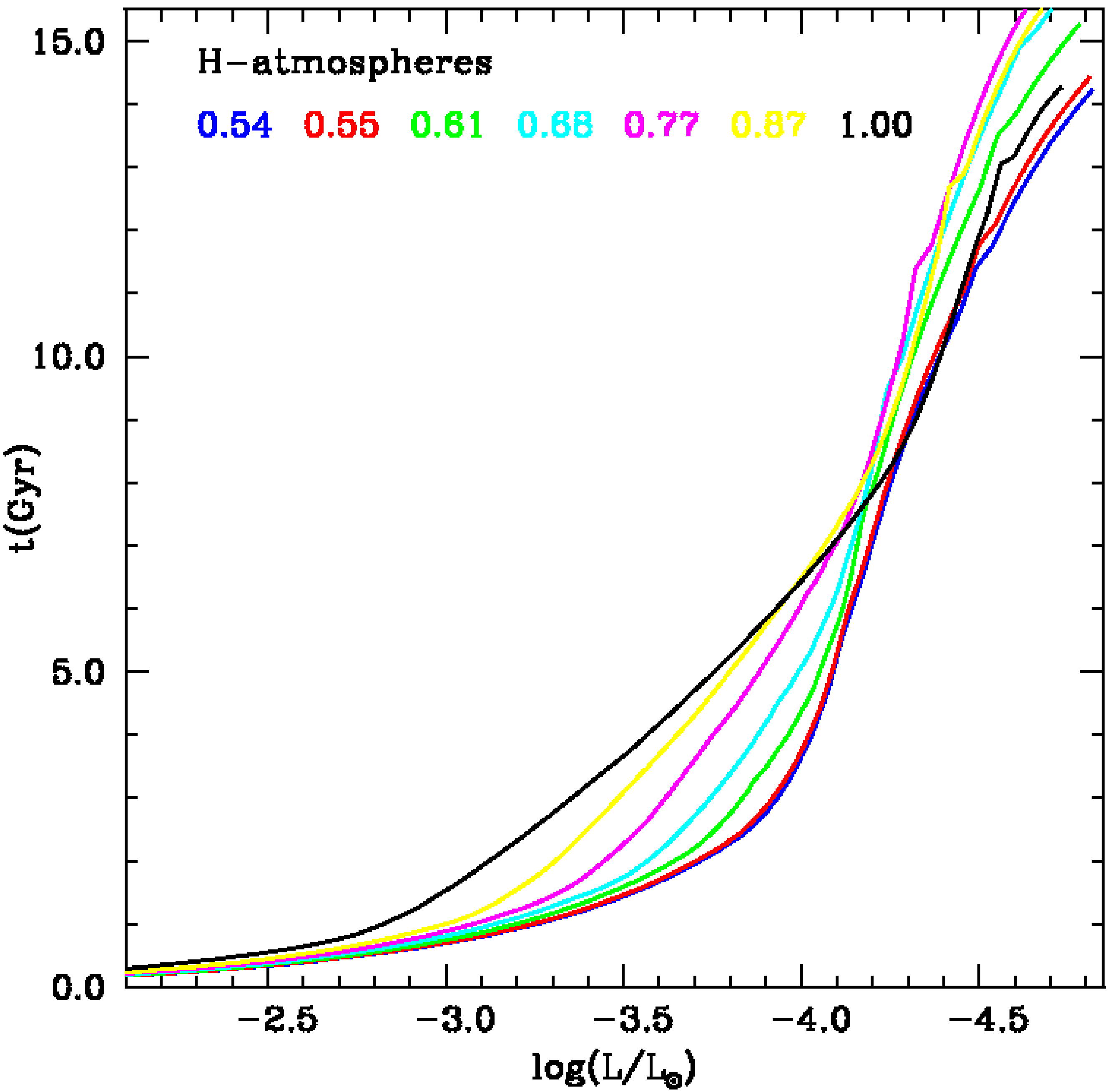
(Bravo et al. 1992, Deloye & Bildsten 2002, Garcia Berro et al.2010)



The ^{22}Ne is produced by helium captures on ^{14}N left from hydrogen burning via the CNO cycle. By virtue of its two excess neutrons (relative to the predominant A = 2Z nuclei), a downward force of $\approx 2m_p g$ is exerted on ^{22}Ne in the WD interior. This biases its diffusive equilibrium, forcing ^{22}Ne to settle toward the centre of the WD.

Ne sinks towards the centre of the core during the liquid phase. Sinking is stopped at the crystallization boundary

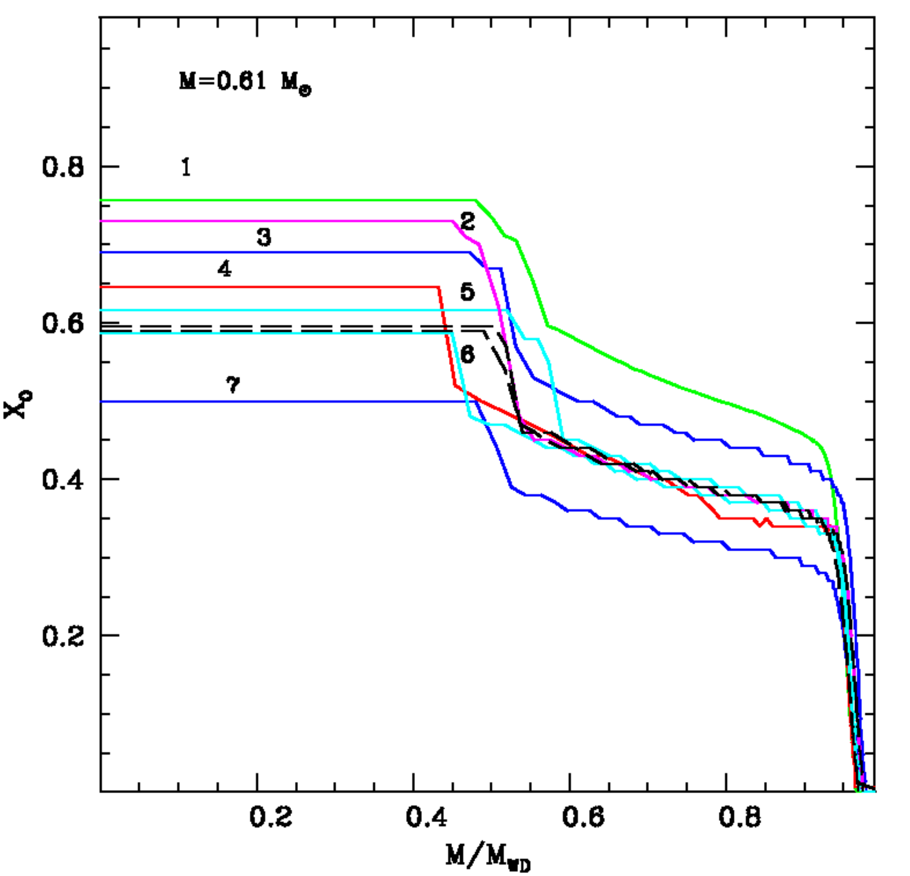
$$L + L_\nu = -\int_0^{M_{WD}} C_v \frac{dT}{dt}\, dm - \int_0^{M_{WD}} T\left(\frac{\partial P}{\partial T}\right)_{V,X_0} \frac{dV}{dt}\, dm + l_s \frac{dM_s}{dt} - \int_0^{M_{WD}} \left(\frac{\partial E}{\partial X_0}\right)_{T,V} \frac{dX_0}{dt}\, dm$$

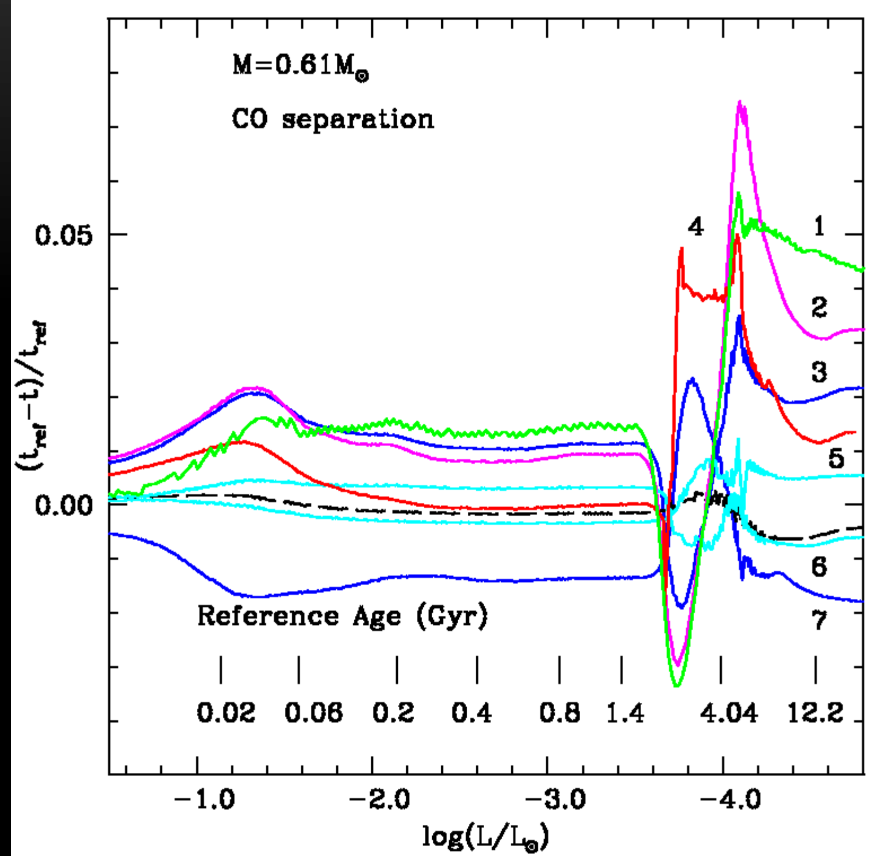


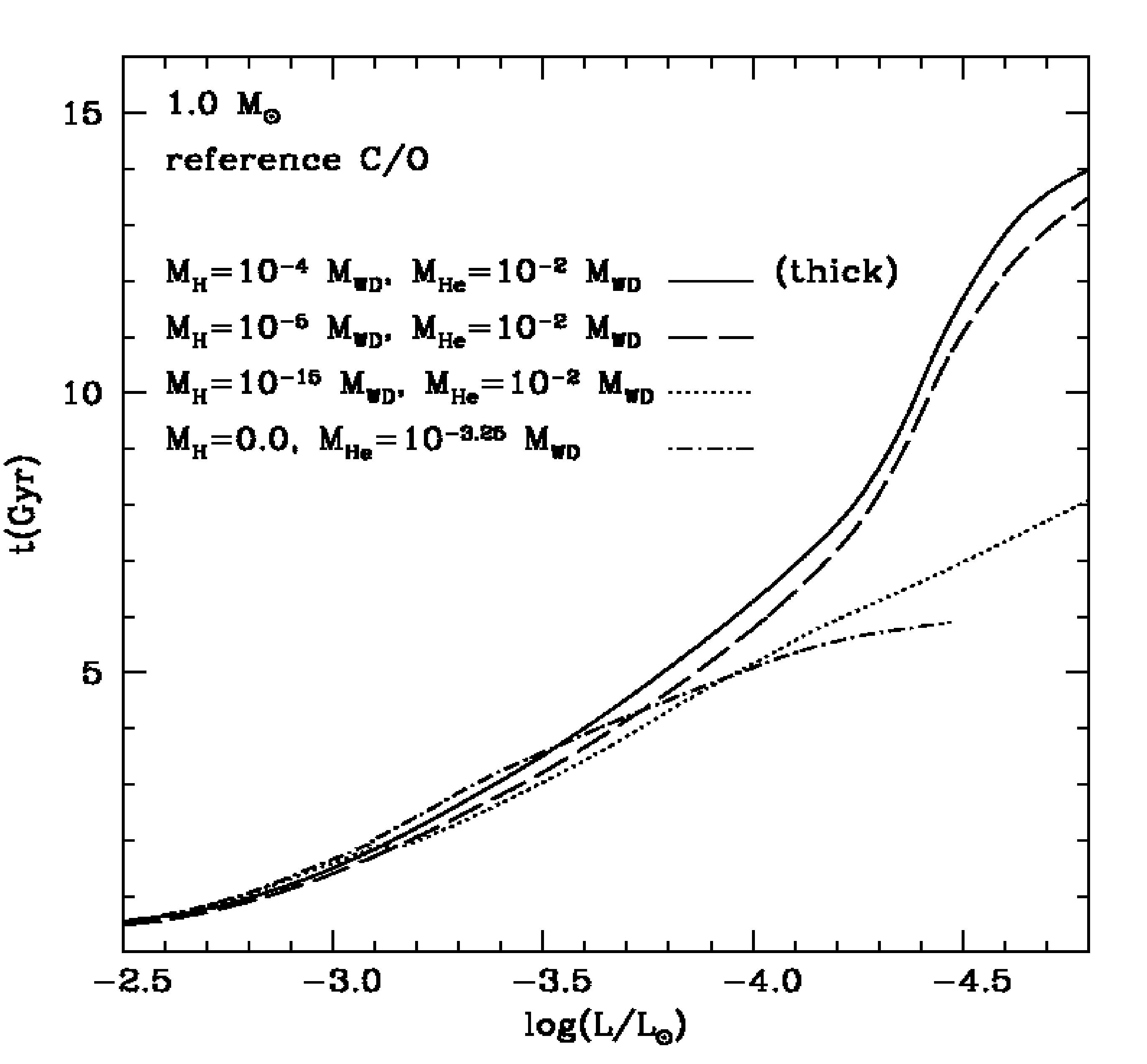
H−atmospheres
0.54
0.55
0.61
0.68
0.77
0.87
1.00
t(Gyr)
15.0
10.0
5.0
0.0
−2.5
−3.0
−3.5
−4.0
−4.5
log(L/L⊙)

Uncertainties in core stratification

1 old $^{12}C+\alpha$ estimate
2 breathing pulses suppression
4 Initial mass lower by $1M_o$
5-6 variation Z (x2 /10)
3-7 current uncertainties $^{12}C+\alpha$
Dashed no core overshooting







1.0 $M_\odot$
reference C/O
$M_H=10^{-4}\ M_{WD}$, $M_{He}=10^{-2}\ M_{WD}$ (thick)
$M_H=10^{-6}\ M_{WD}$, $M_{He}=10^{-2}\ M_{WD}$
$M_H=10^{-15}\ M_{WD}$, $M_{He}=10^{-2}\ M_{WD}$
$M_H=0.0$, $M_{He}=10^{-3.25}\ M_{WD}$
t(Gyr)
15
10
5
−2.5
−3.0
−3.5
−4.0
−4.5
$\log(L/L_\odot)$

Thickness and chemical composition of the envelope

There are two major classes of WDs according to their spectra:

DA → H spectra

Non-DA → no H in the spectra

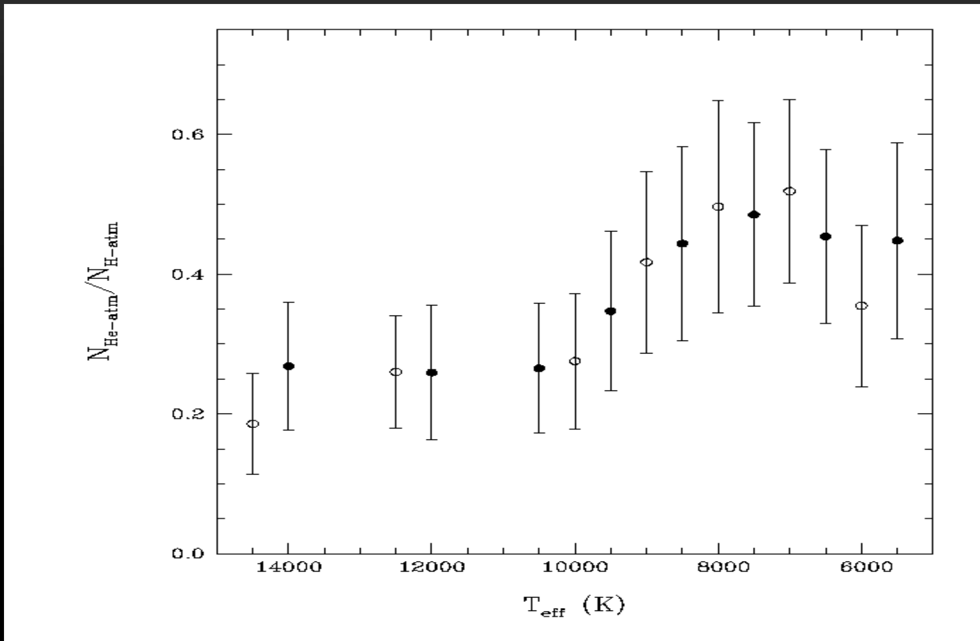
Among non-DA objects there are various subclasses.

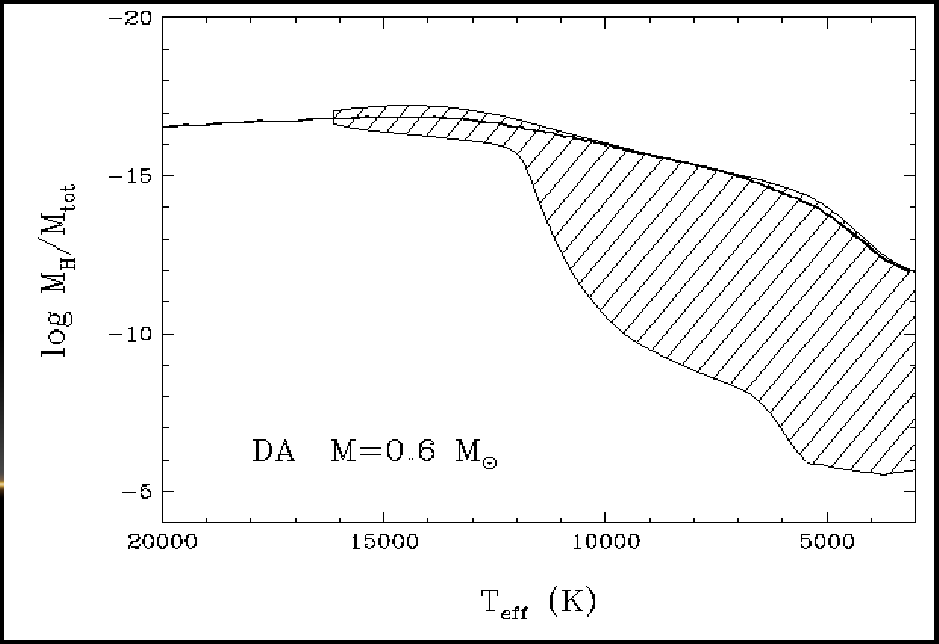
DB is the subclass of pure He spectra

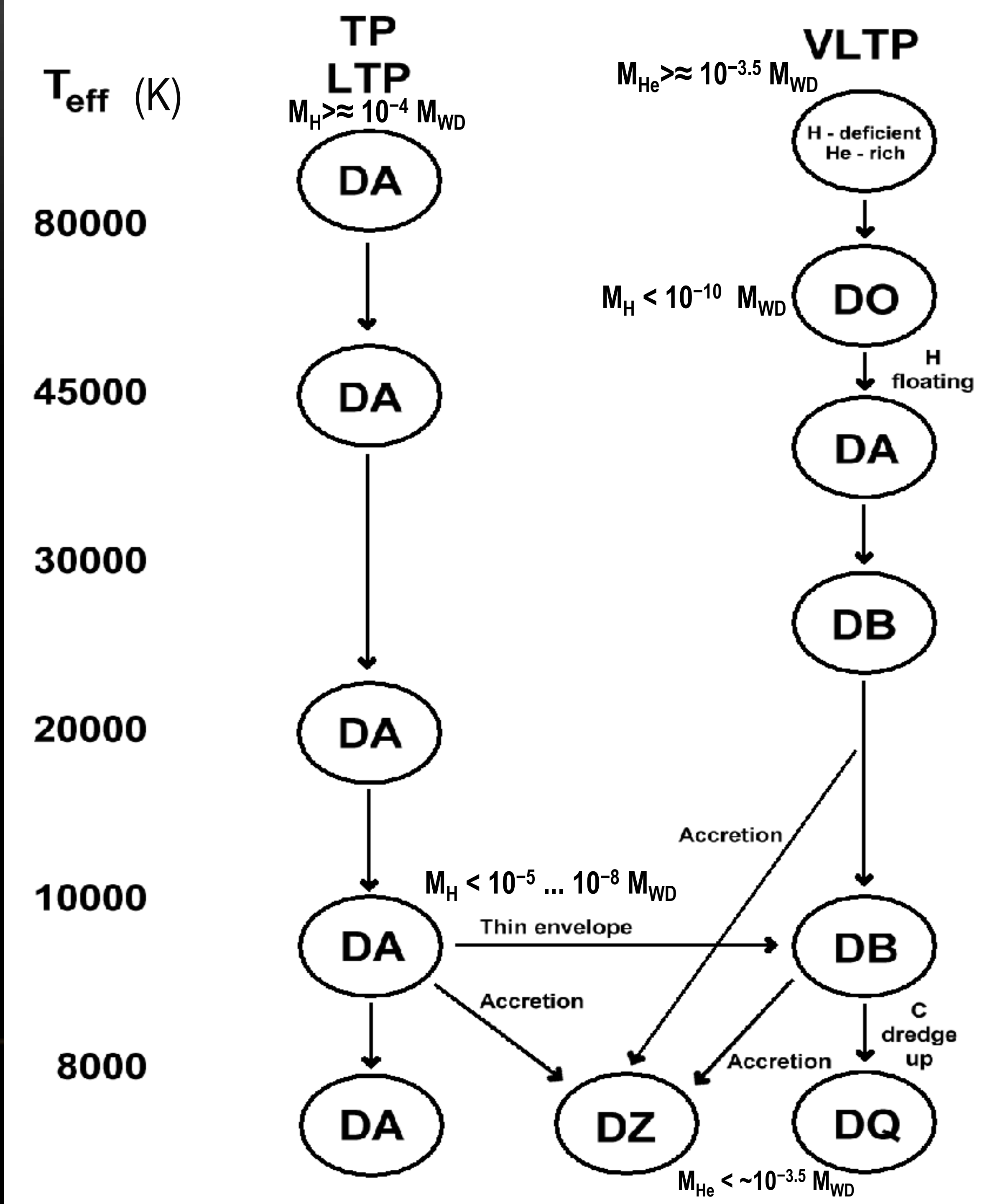
Do DA objects transform into non-DA ? This occurrence would put constraints on the H-envelope thickness

If so, what about their cooling timescales?

Tremblay & Bergeron (2008)







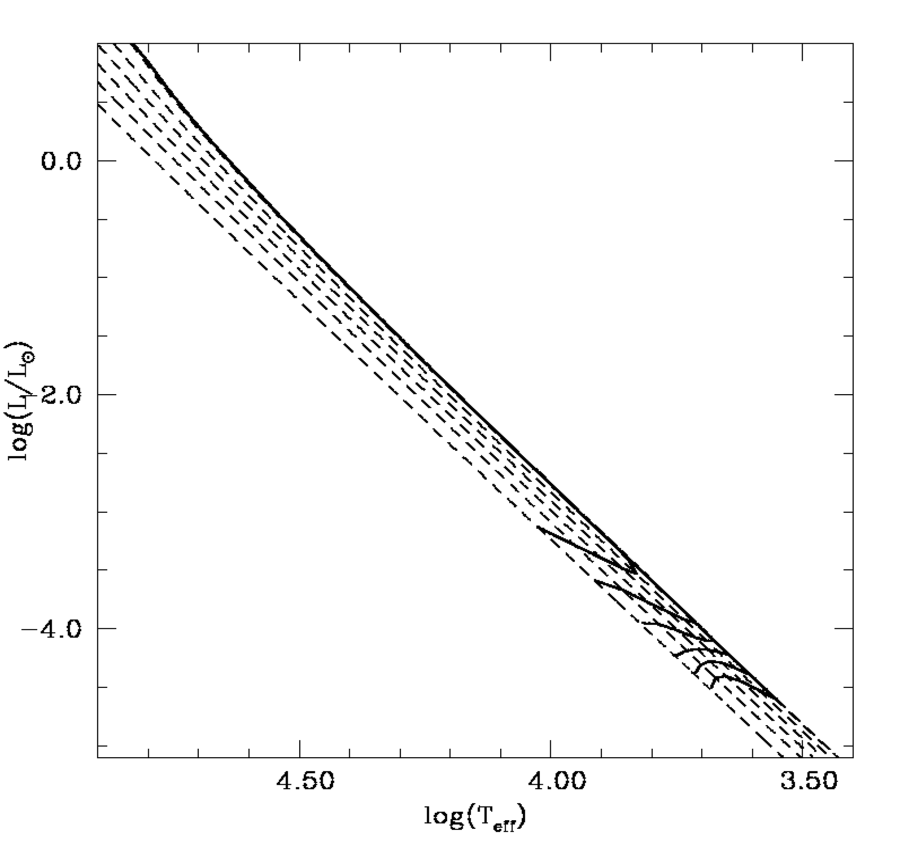
Range of envelope thickness for Field Disk WDs

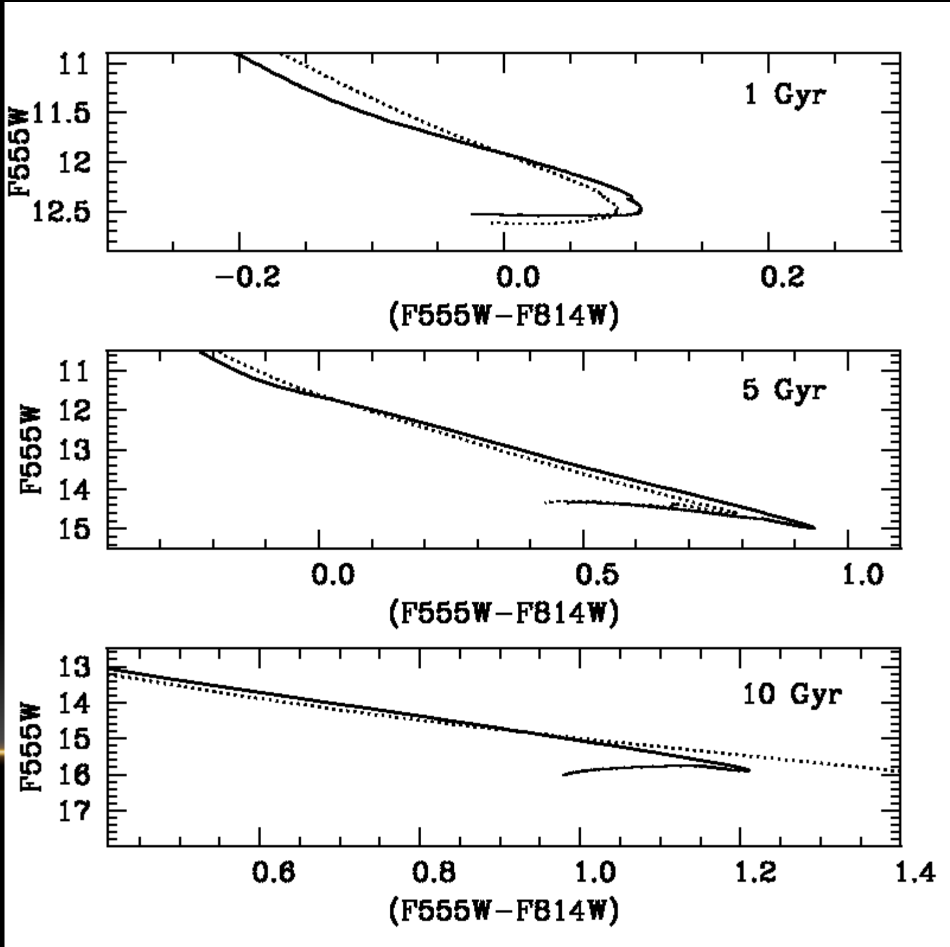
Towards a WD cosmochronology

Ingredients: WD cooling models – Initial-final mass relationship – progenitor ages – bolometric corrections

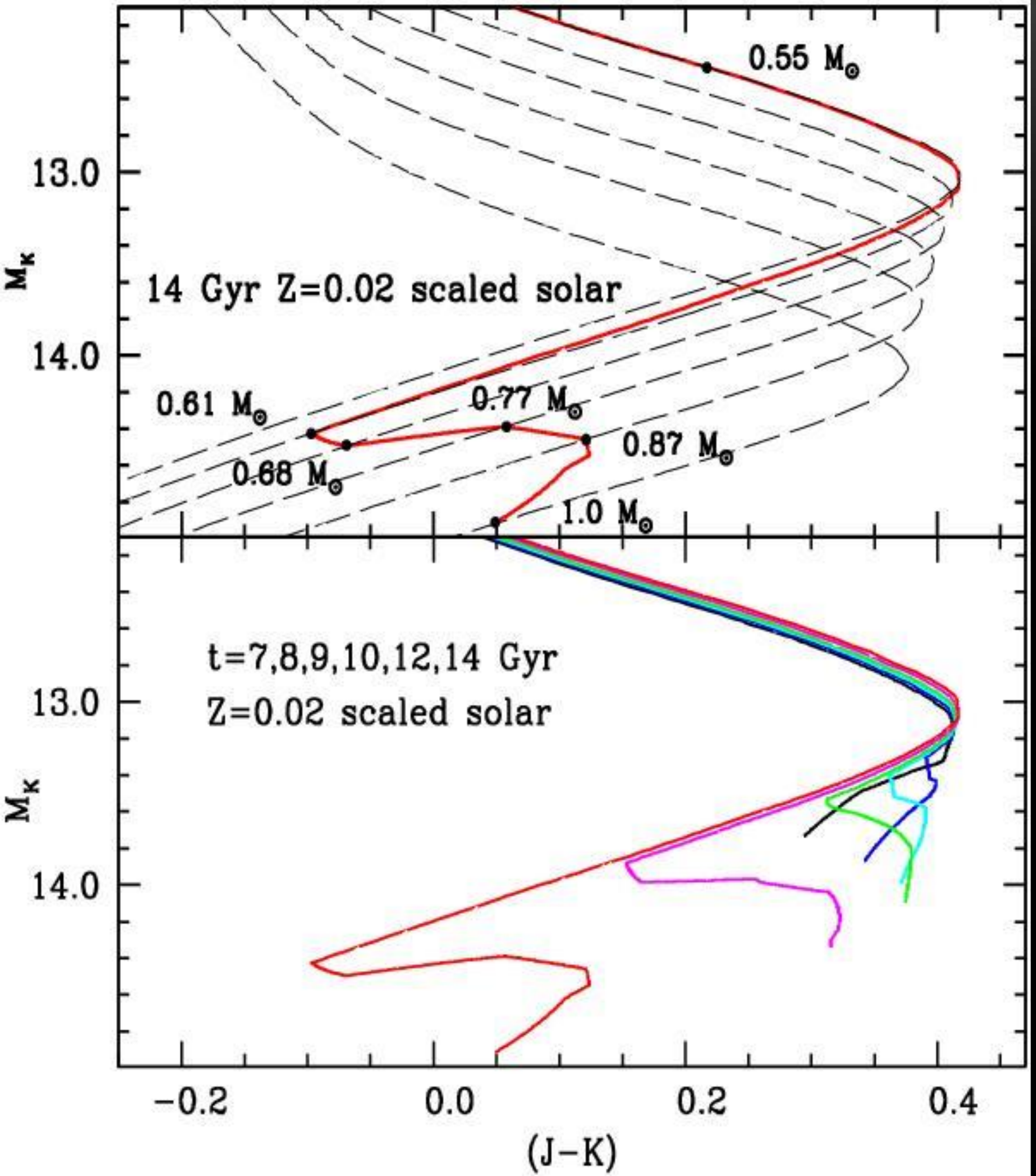
Salaris et al. (2010)

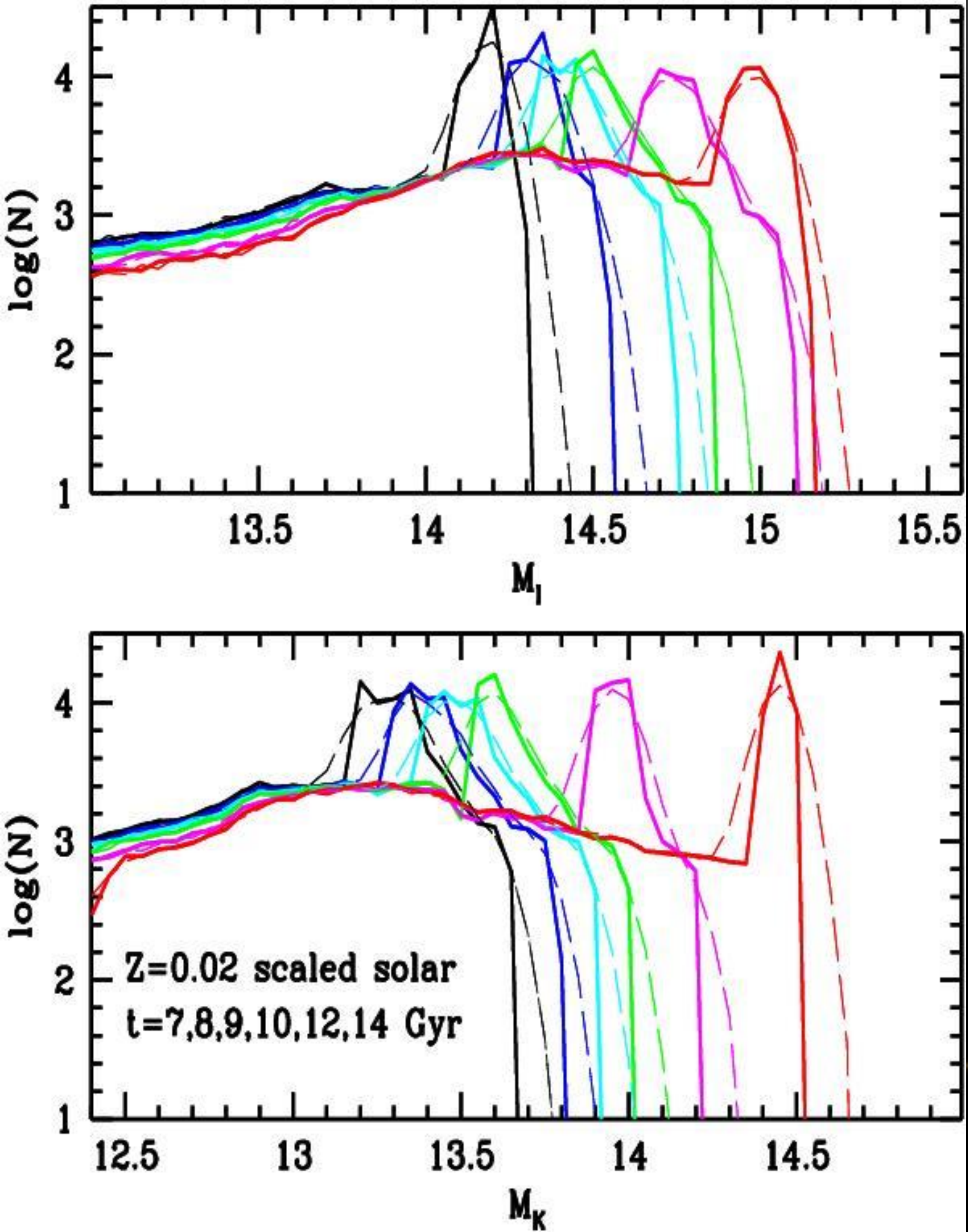
t(iso)=t(WD)+t(prog)



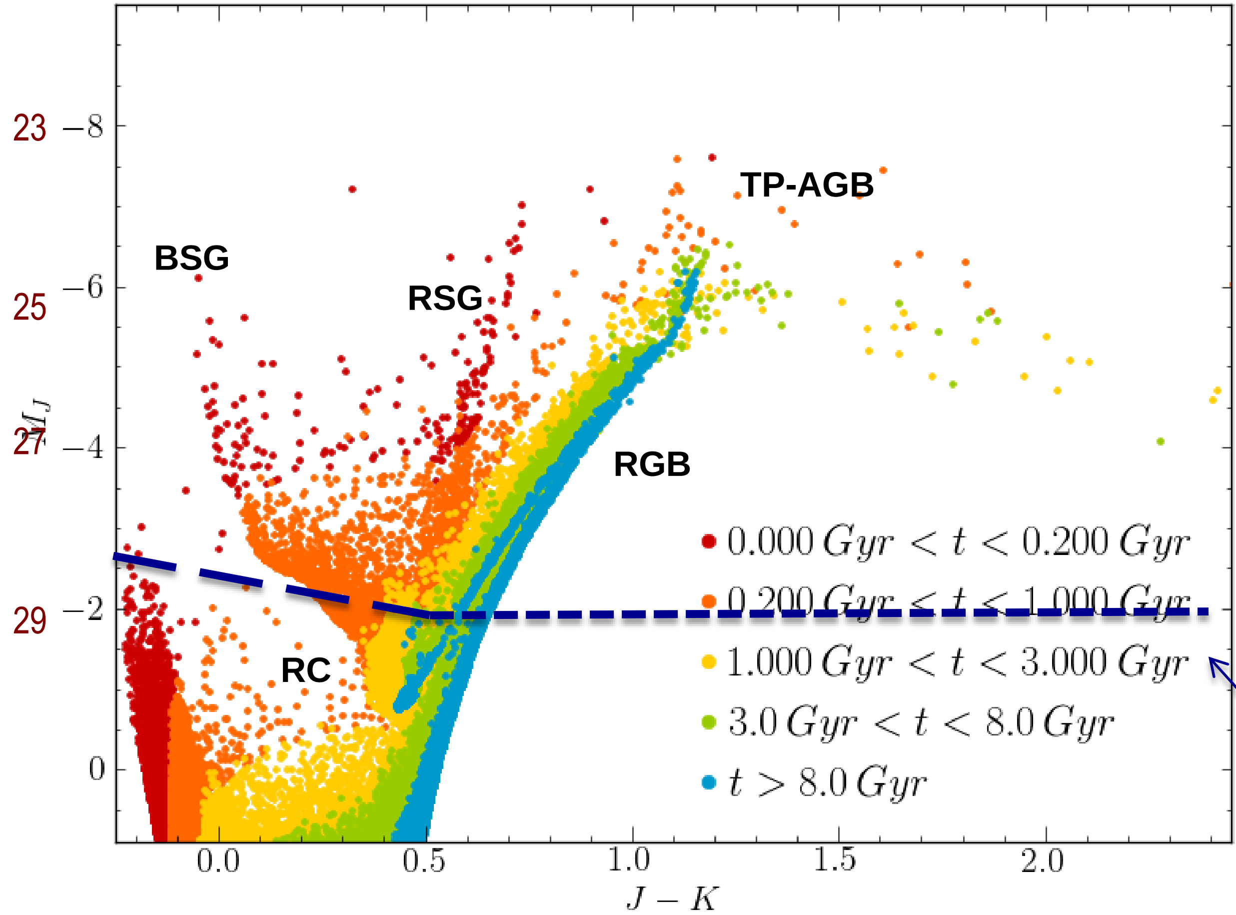


Bono, Salaris & Gilmozzi (2013)




log(N)
M_I
log(N)
M_K
Z=0.02 scaled solar
t=7,8,9,10,12,14 Gyr

Resolved distant galaxies with ELT
Virgo cluster distance $(m-M)_0=31$



MSTO > ALL stars

RGB > low mass stars (t > ~2Gyr)

RC > intermediate-age (few Gyrs)

BSG > young (few Myr)

RSG > young (few Myr)

AGB > intermediate age (few Gyr) #modeldependent

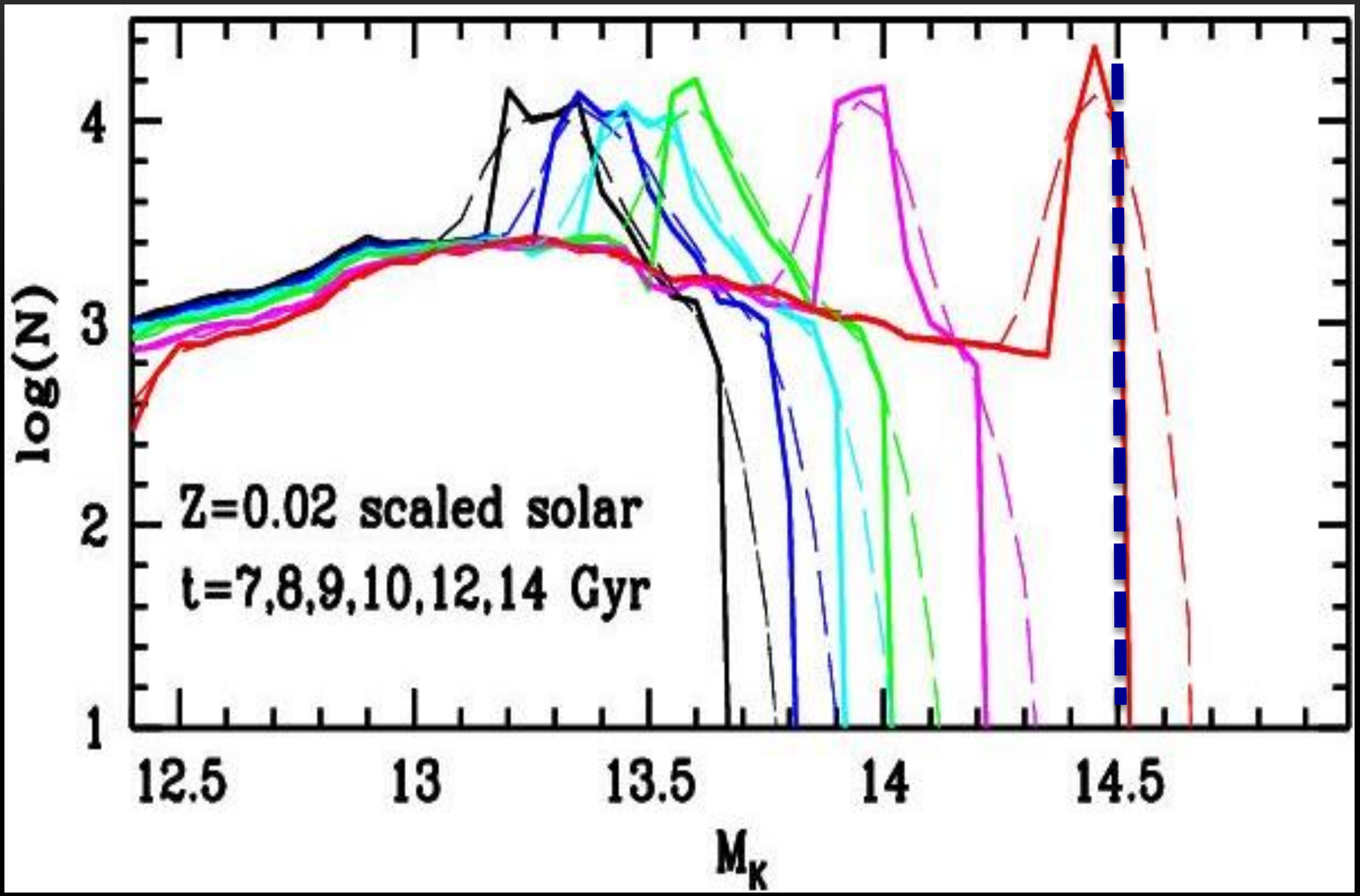
S/N=5
5h exposures

Evolved stellar populations provide clues on SFR for young and intermediate-age stellar populations

Synthetic CMD from Gullieuszik (2014)

Constant SFR typical of disks

WDs in globular clusters



Maximum distance modulus $(m\text{-}M)_0 \approx 14.0$