Uncertainties in 1D Massive Star Models

Jakub Klencki
Radboud University Nijmegen
Netherlands

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

DEPARTMENT OF ASTROPHYSICS • RADBOUD UNIVERSITY NIJMEGEN •

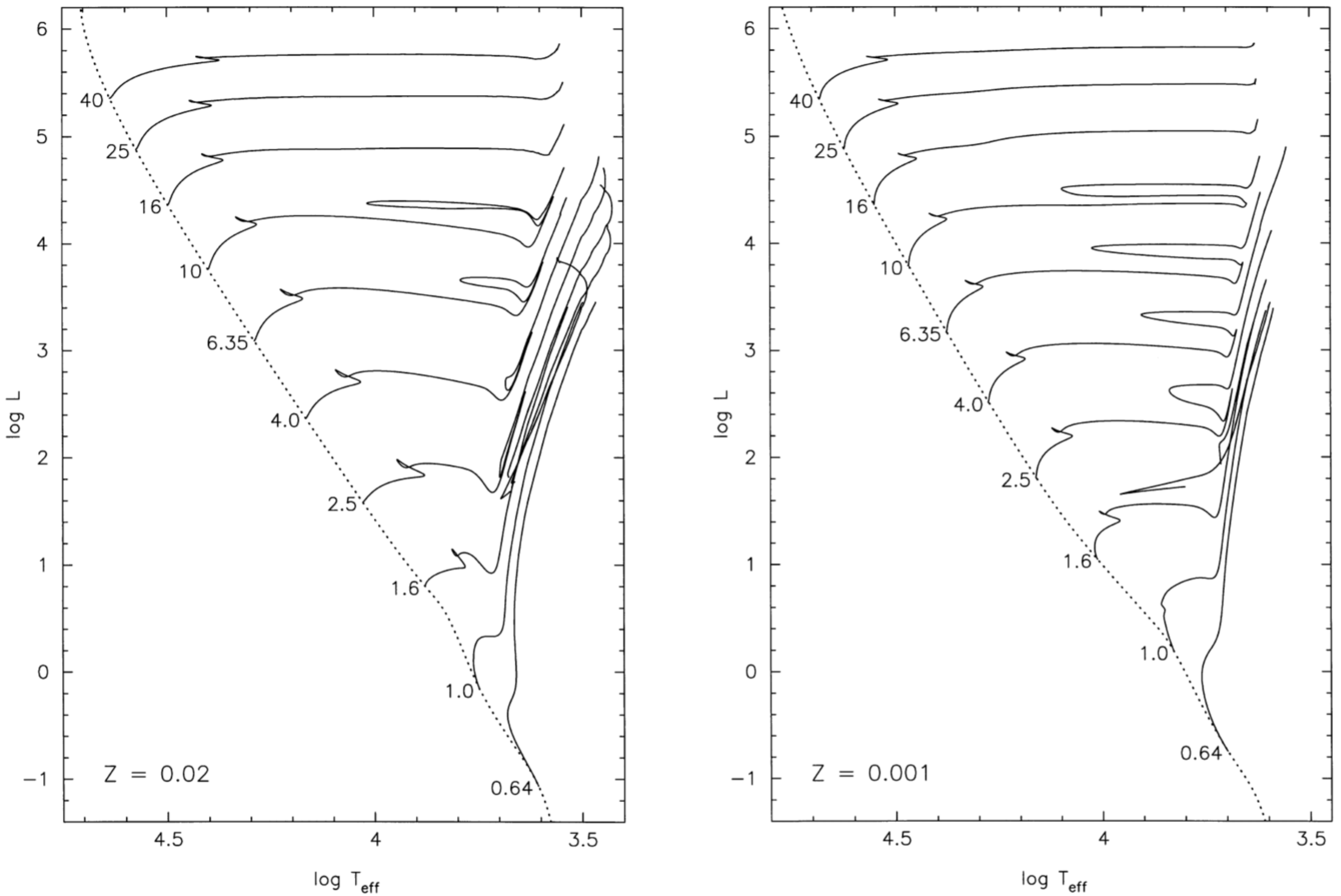
Uncertainties in Massive Star Models

Marco Limongi

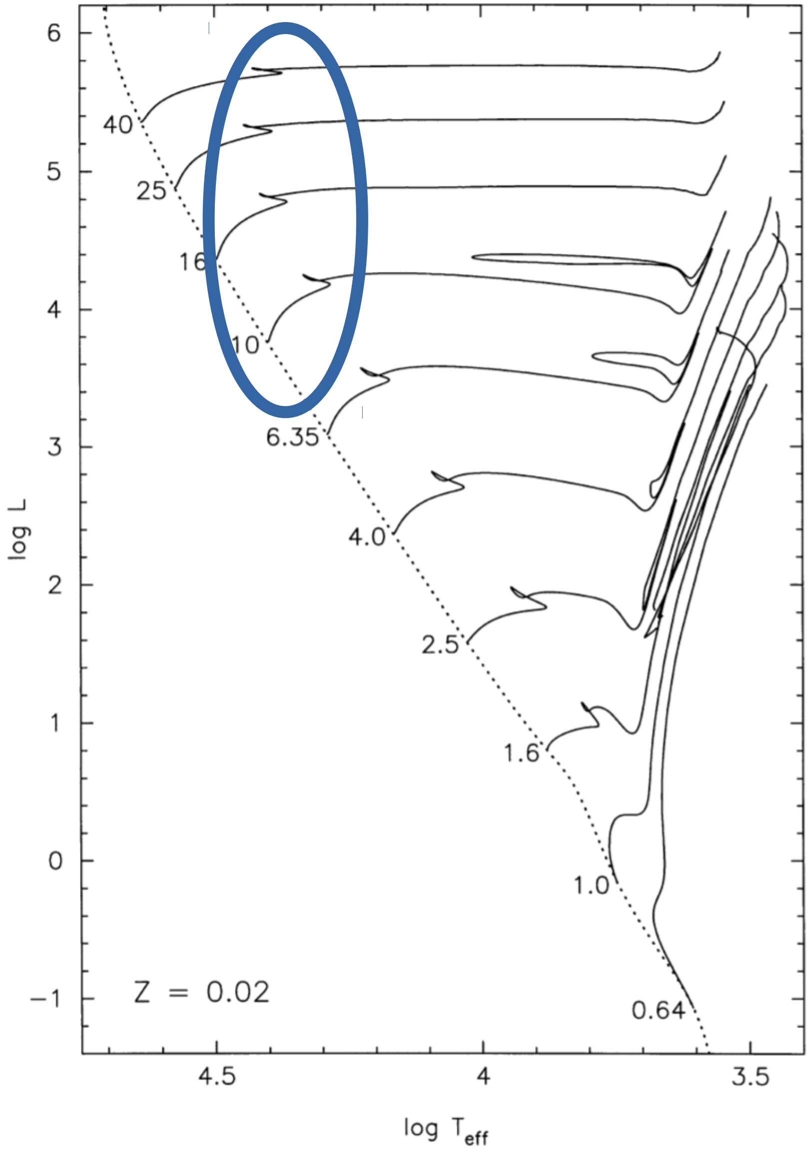
INAF – Osservatorio Astronomico di Roma, ITALY

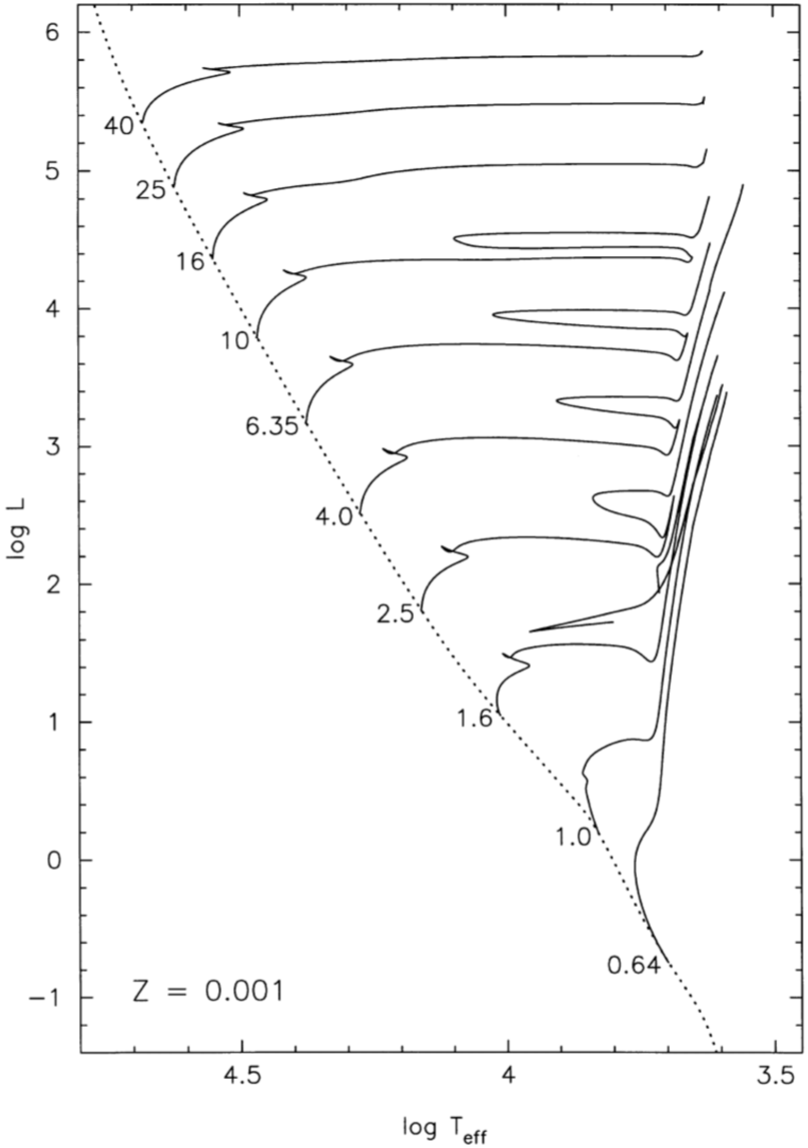
Kavli IPMU, University of Tokyo, JAPAN

marco.limongi@inaf.it

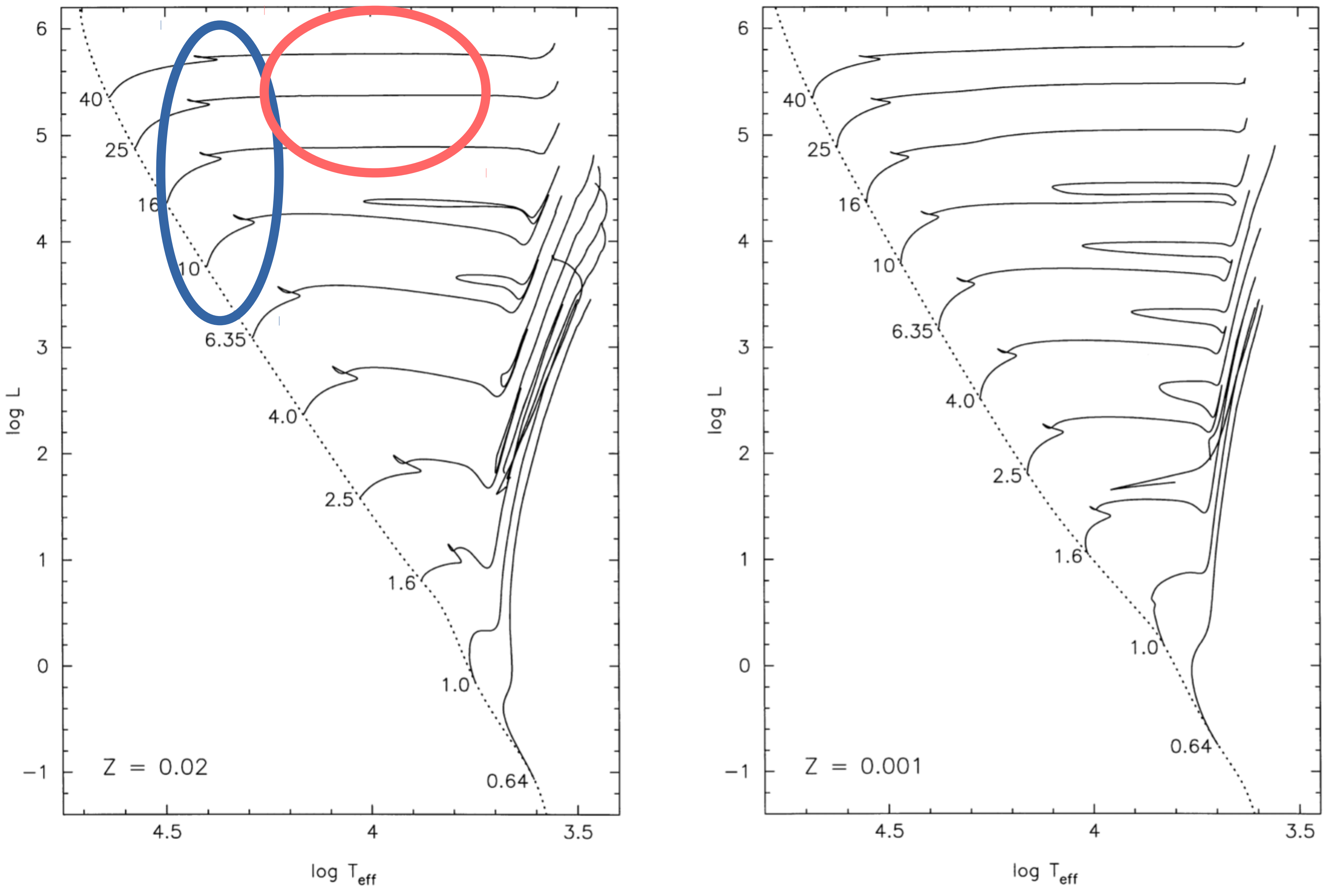


Pols et al. 1998

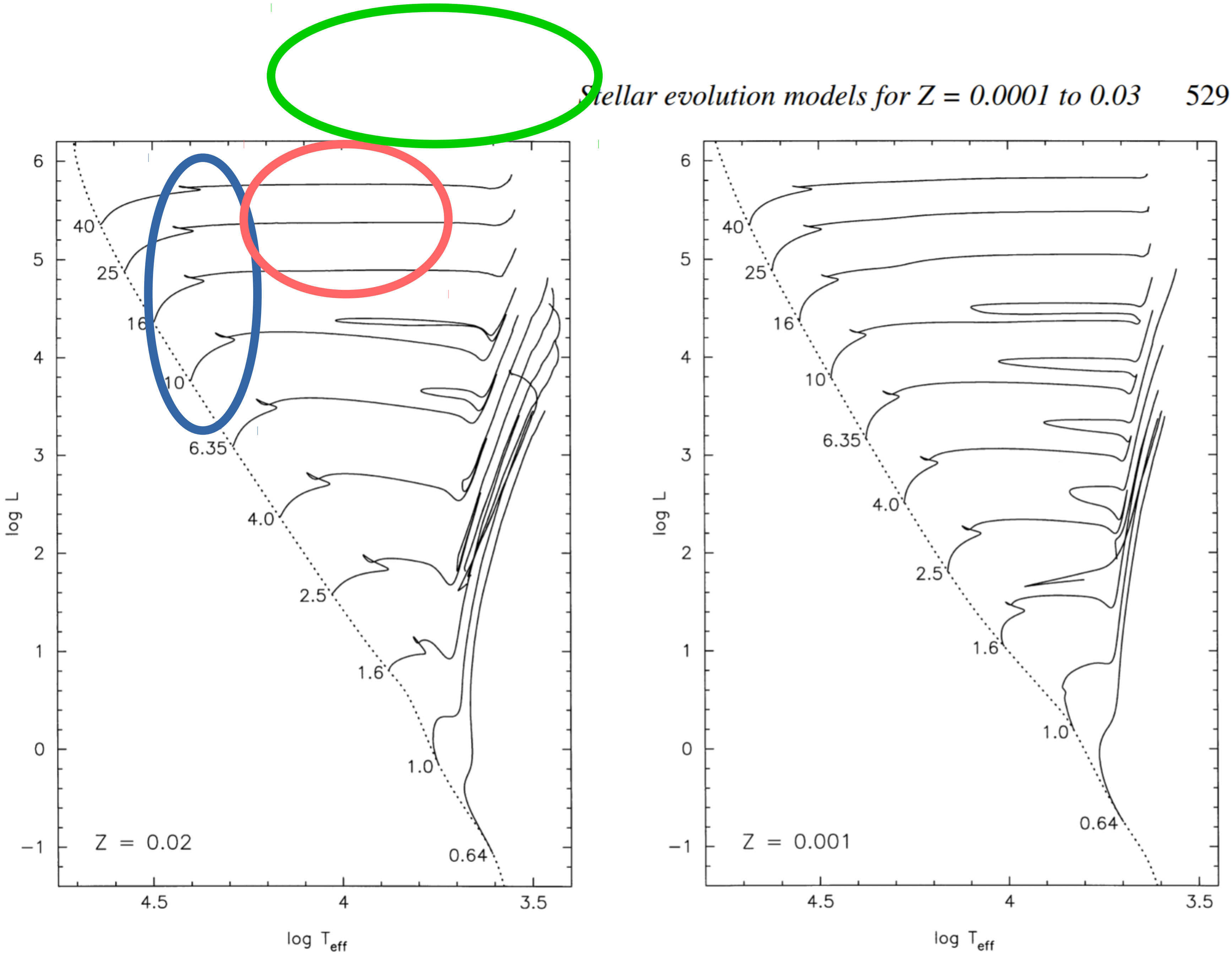




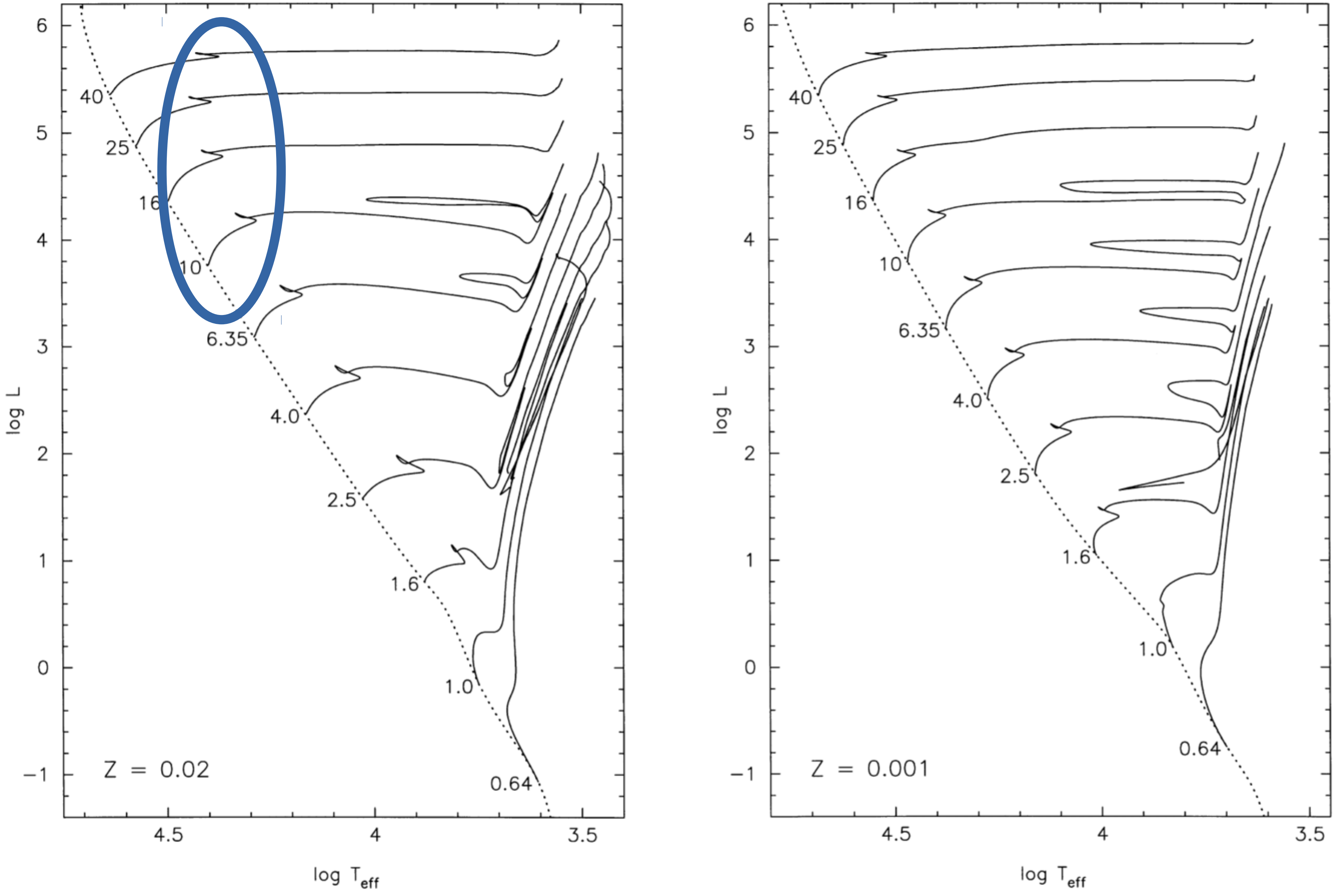
Pols et al. 1998



Pols et al. 1998



Pols et al. 1998

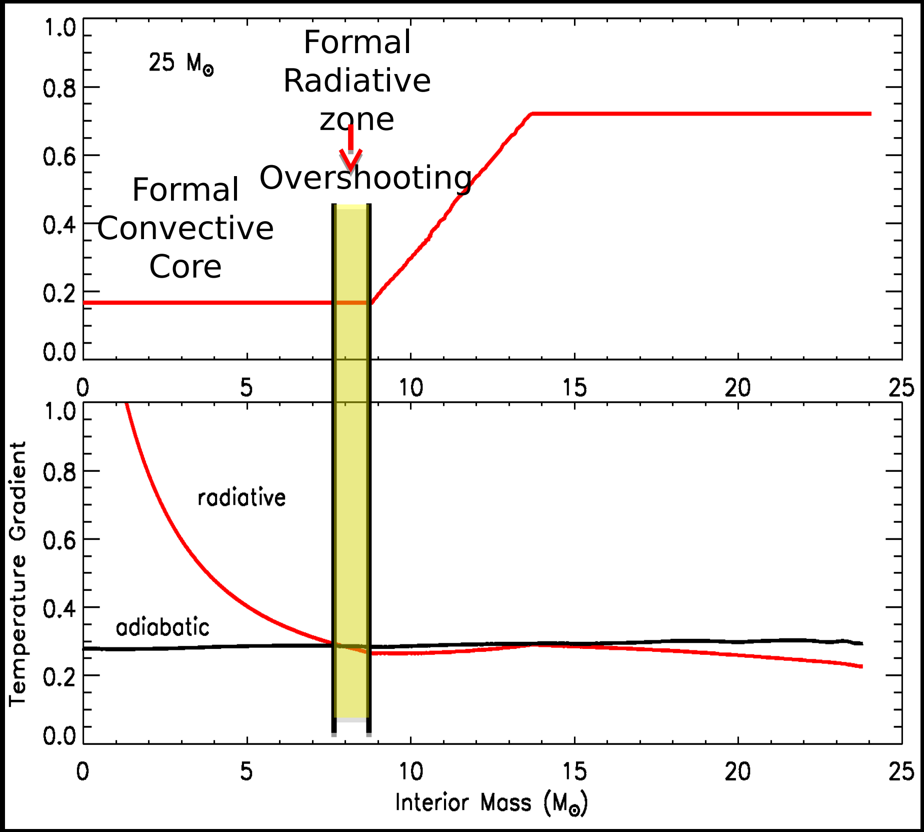


Pols et al. 1998

Overshooting during Core H burning

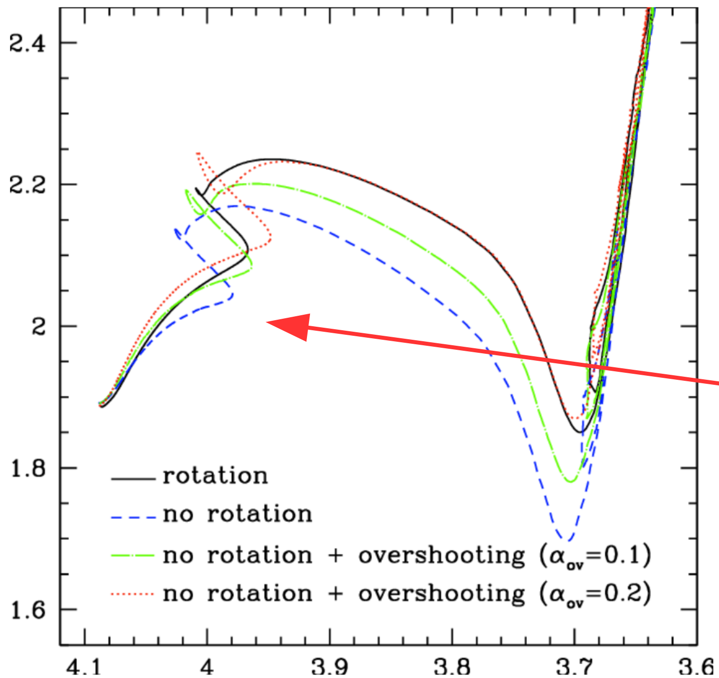
The acceleration imparted by the buoyancy force to convective elements vanishes at the boundary of the formal convective core, but the velocity is not zero there

The convective elements may penetrate (overshoot) into the formally stable radiative zone

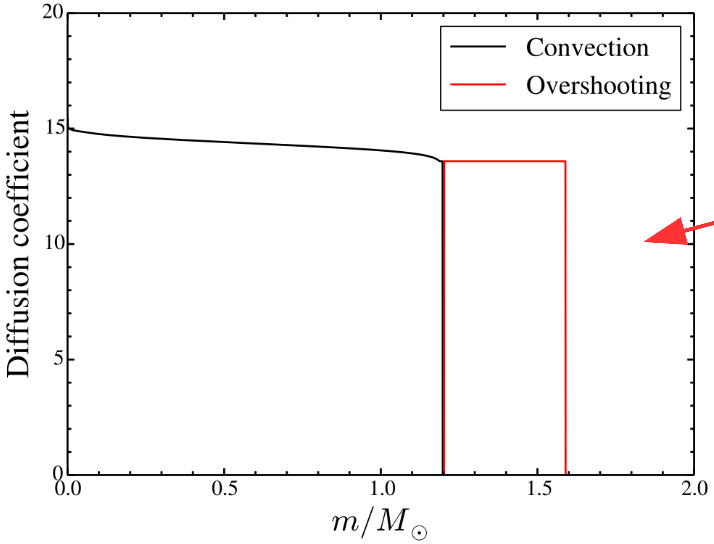


– No theory based on first principles
– Convective overshoot is formulated with the aid of the Mixing-Length theory
– parametrized in the models

Overshooting during core H burning



Eggenberger +2010



– convective **cores are larger** than predicted classically

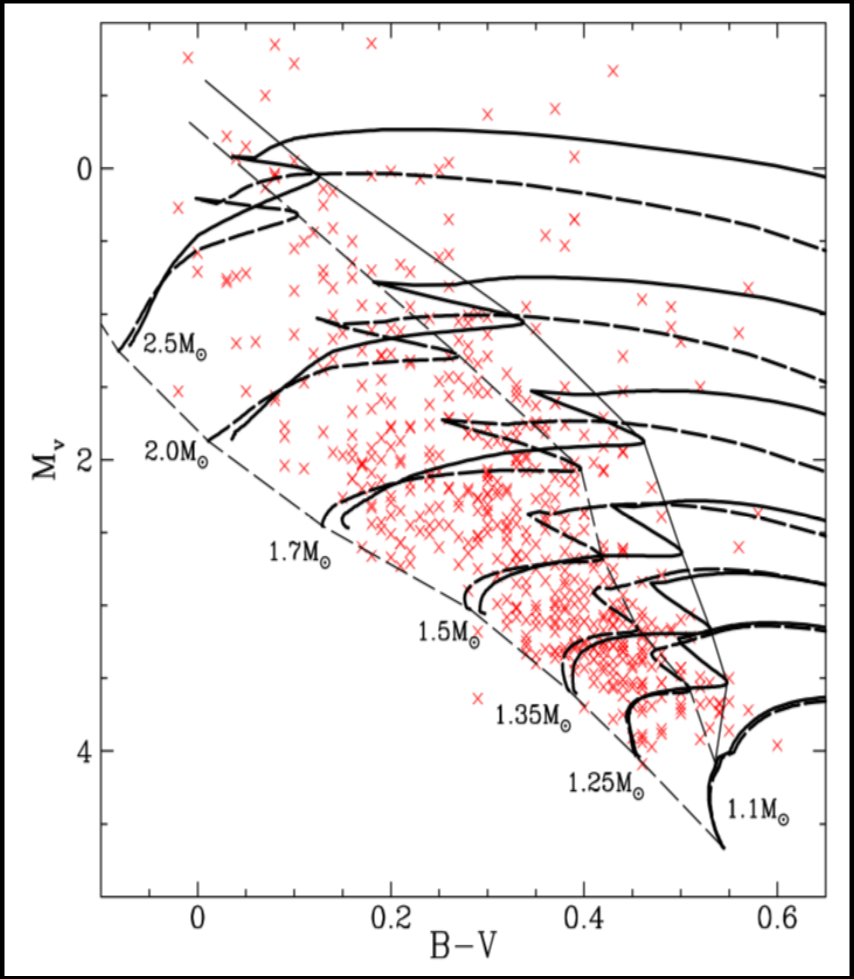
– basic effects (on MS): stars are **bigger, more luminous, live longer**

– theoretically (practically) unconstrained → **calibration**

– eg. step overshooting parametrization ***(α_{OV} x H_P)***

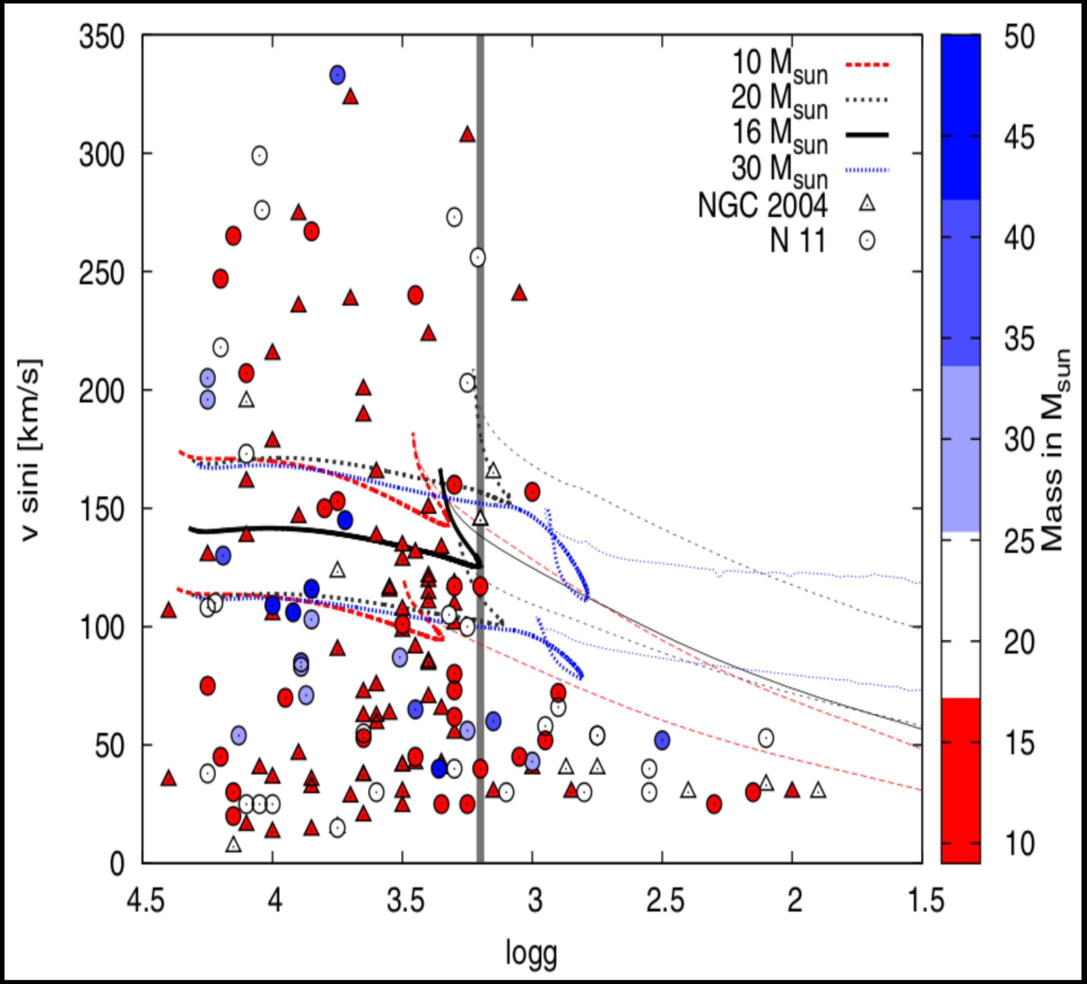
Calibration of Overshooting during Core H burning

Main Sequence Width



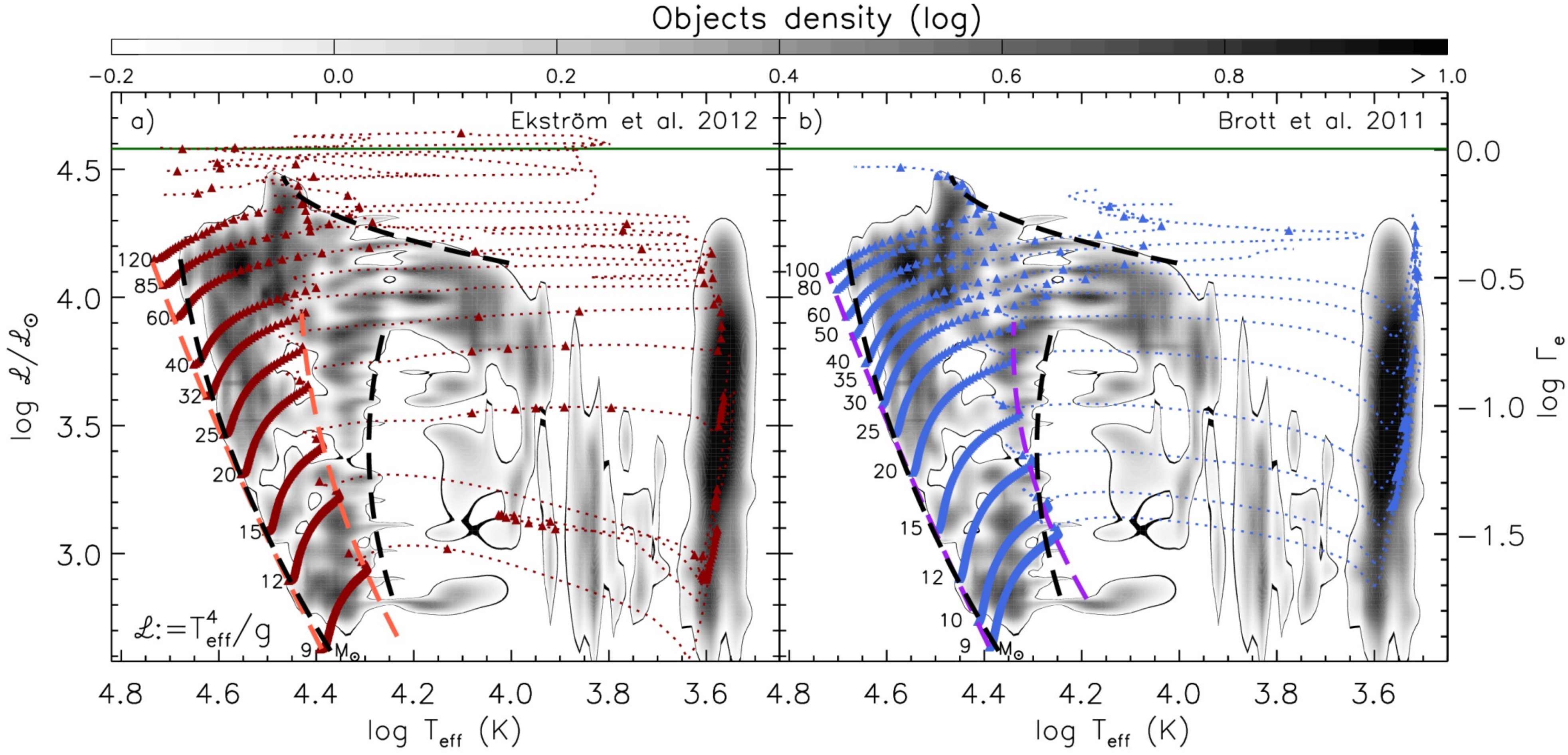
Models from Ekström+ 2012,
data points from Wolff+ 1997

Drop in the v_{surf} vs g_{surf}



Models from Brott+ 2011,
data points from Hunter+ 2008

Overshooting vs Galactic stars

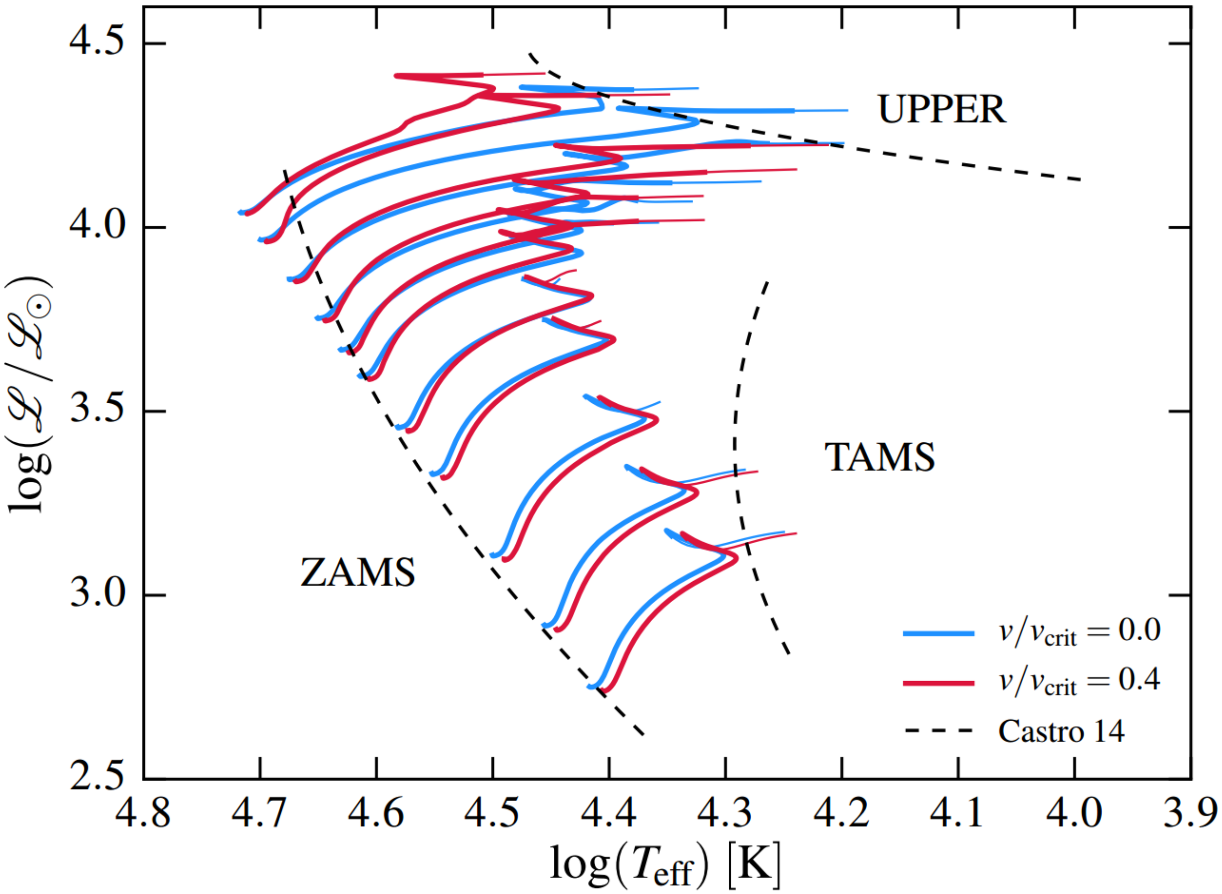


Models by Ekström et al. 2012
α_{OV} **= 0.1** (similar to Pols+1998)

Models by Brott et al. 2011
α_{OV} **= 0.335**

Castro+2014

Overshooting vs Galactic stars (II)



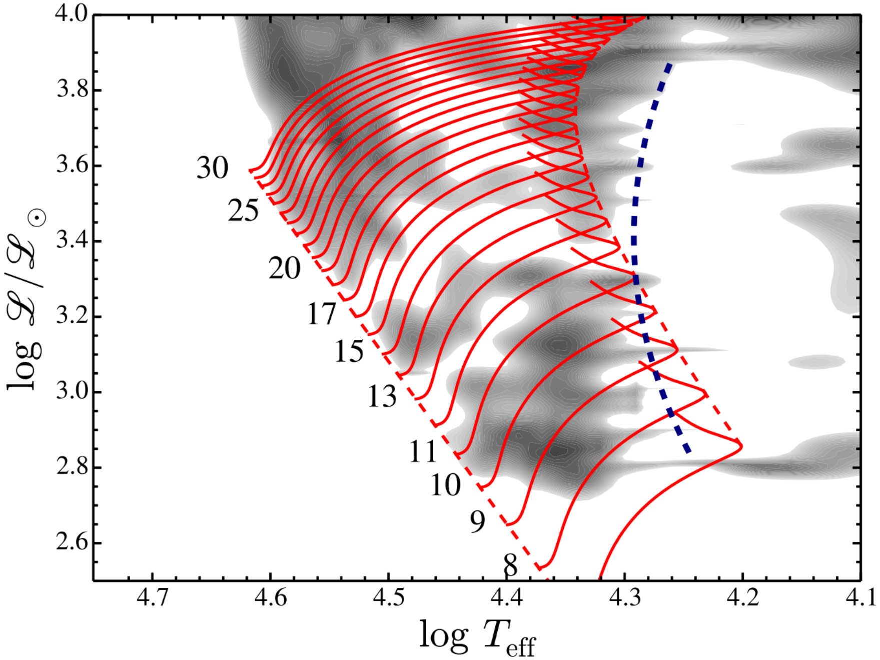
Models by Choi et al. 2016

α_{OV} ~ 0.16 (exponential formalism with f_{OV} = 0.016)

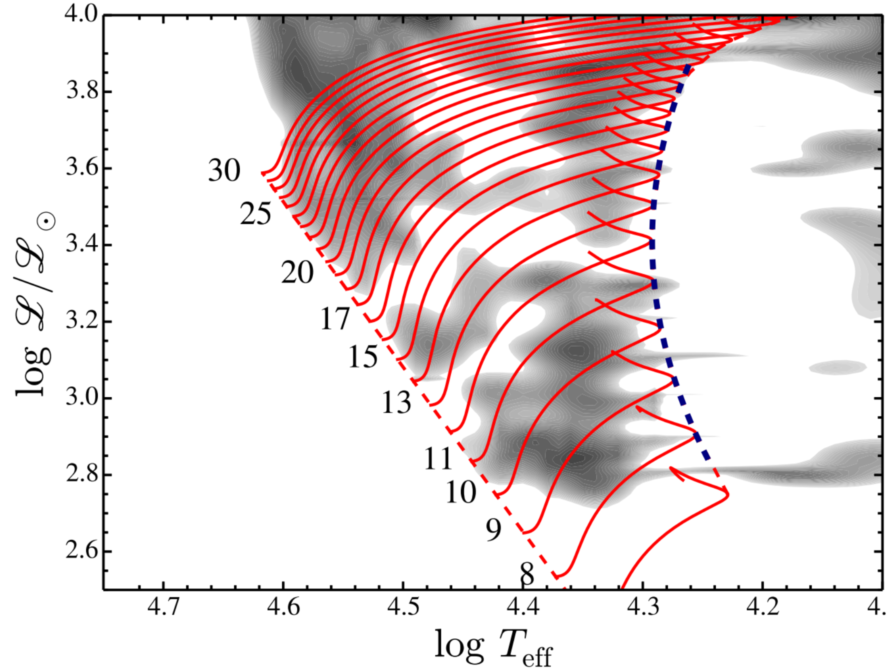
Overshooting vs Galactic stars (III)

Grin et al. (in prep)

Fixed overshooting

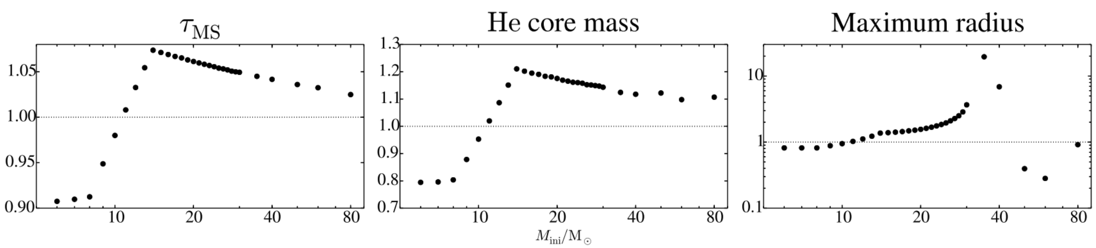


Mass-dependent overshooting

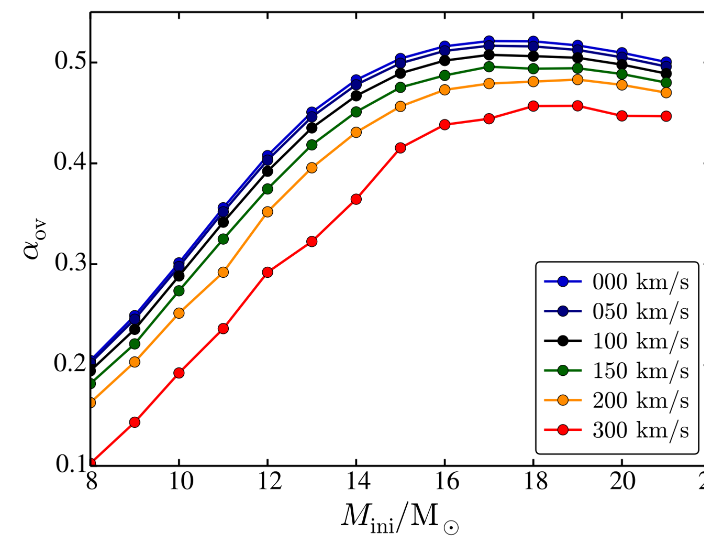


Compare grids $\alpha_{\rm ov} = f(M)$ vs. $\alpha_{\rm ov} \equiv 0.335$

Plotted: Quantity Q(Mass dependent)/Q(0.335)



Values at TAMS

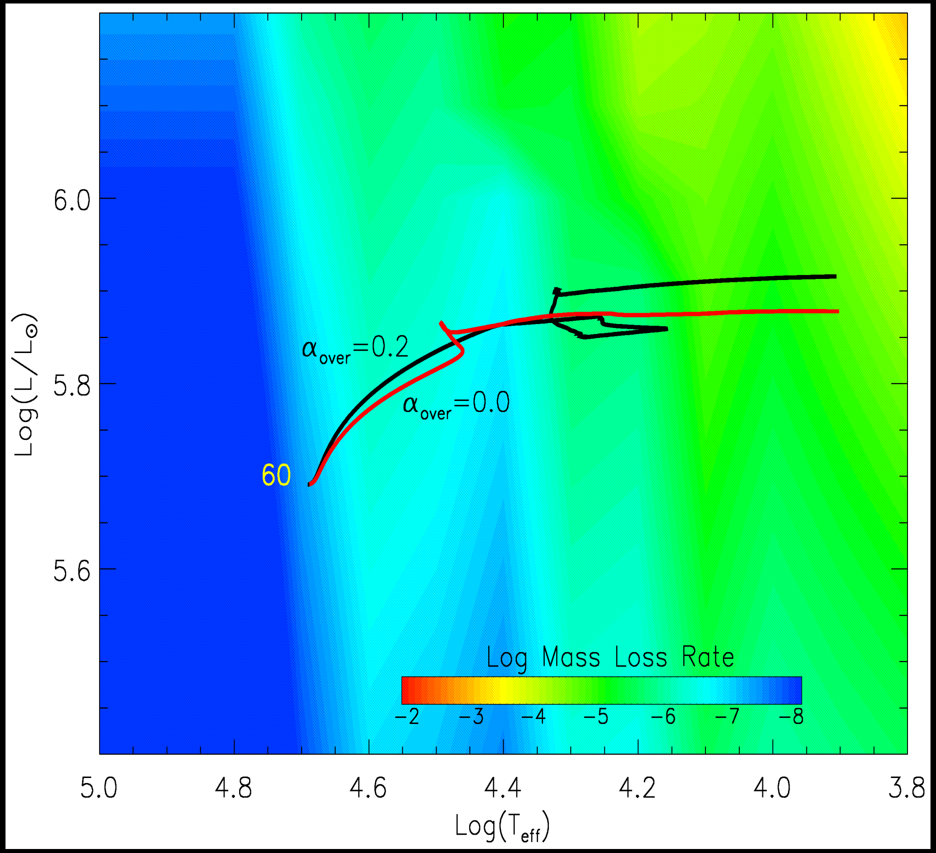


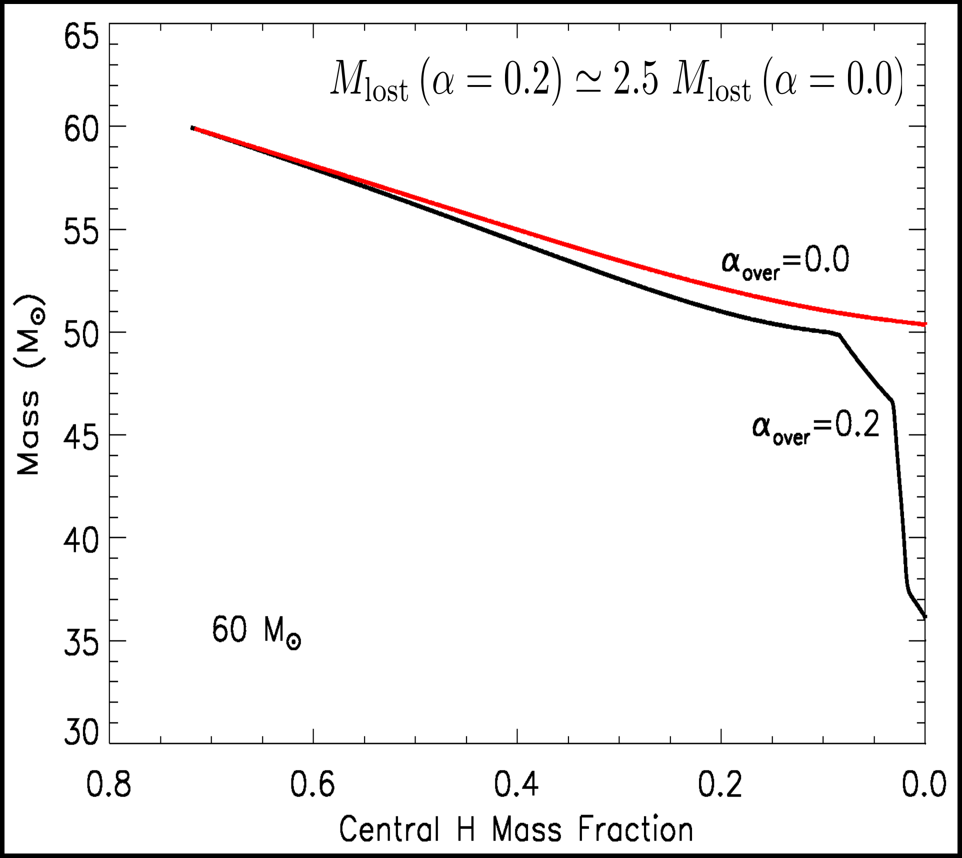
Overshooting during Core H burning

The effect of the overshooting is that

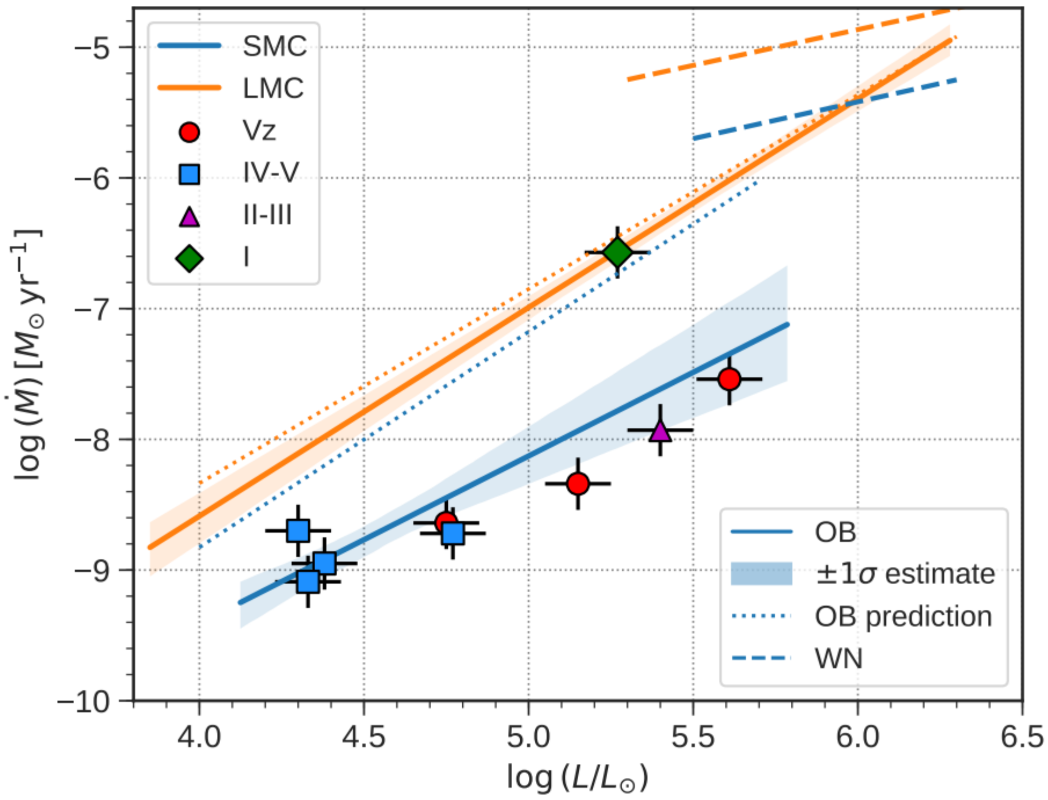
- the evolutionary track is more luminous and more extended to lower effective temperatures
- the core H burning lifetime is significantly higher

The interplay of these effects and the variation of the Mass Loss rate in the HR diagram may have dramatic consequences on the final mass



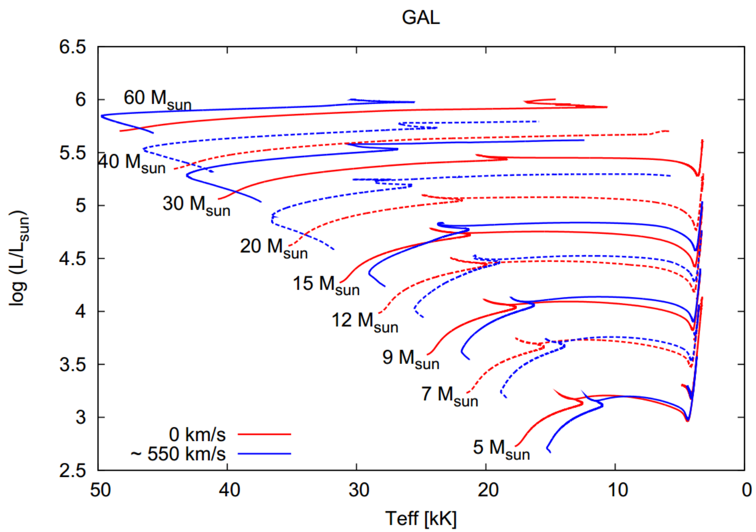


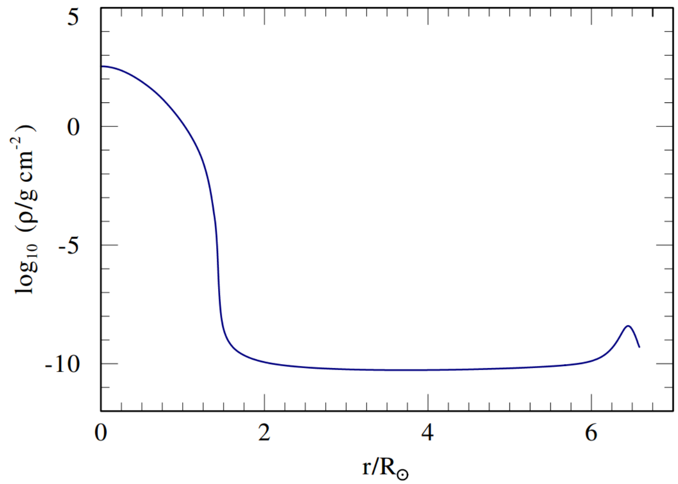
OB winds? (massive MS stars)



Ramachandran et al. 2019

Inflated envelopes of massive MS stars?

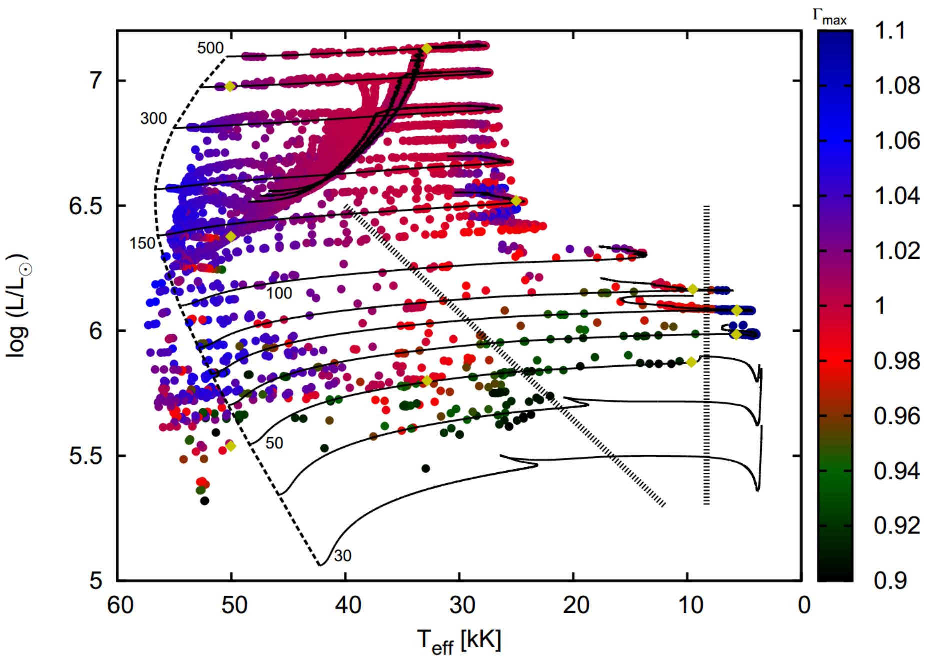


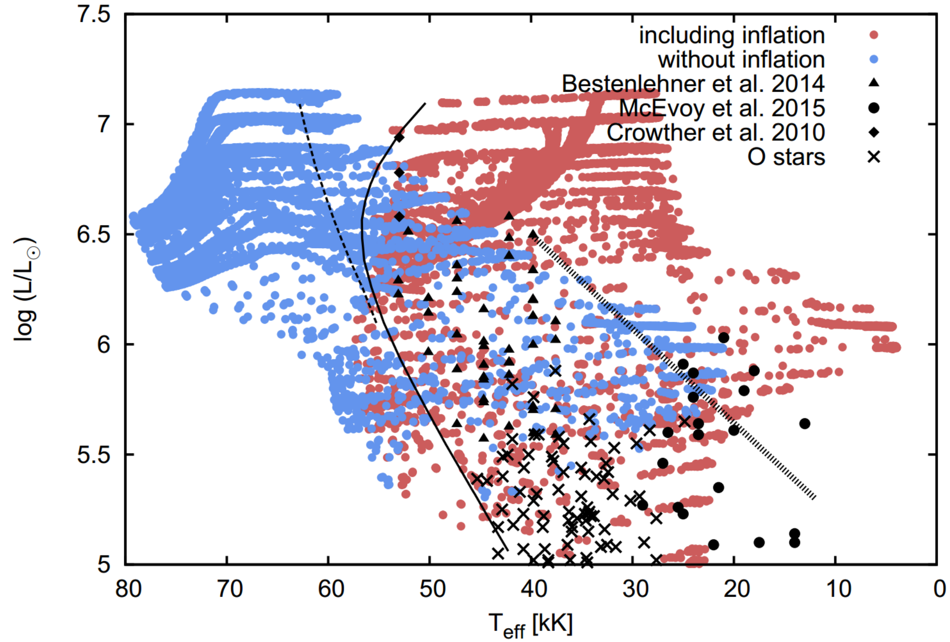


Grafener+2011

Brott+2011, Sanyal+2015 → M models

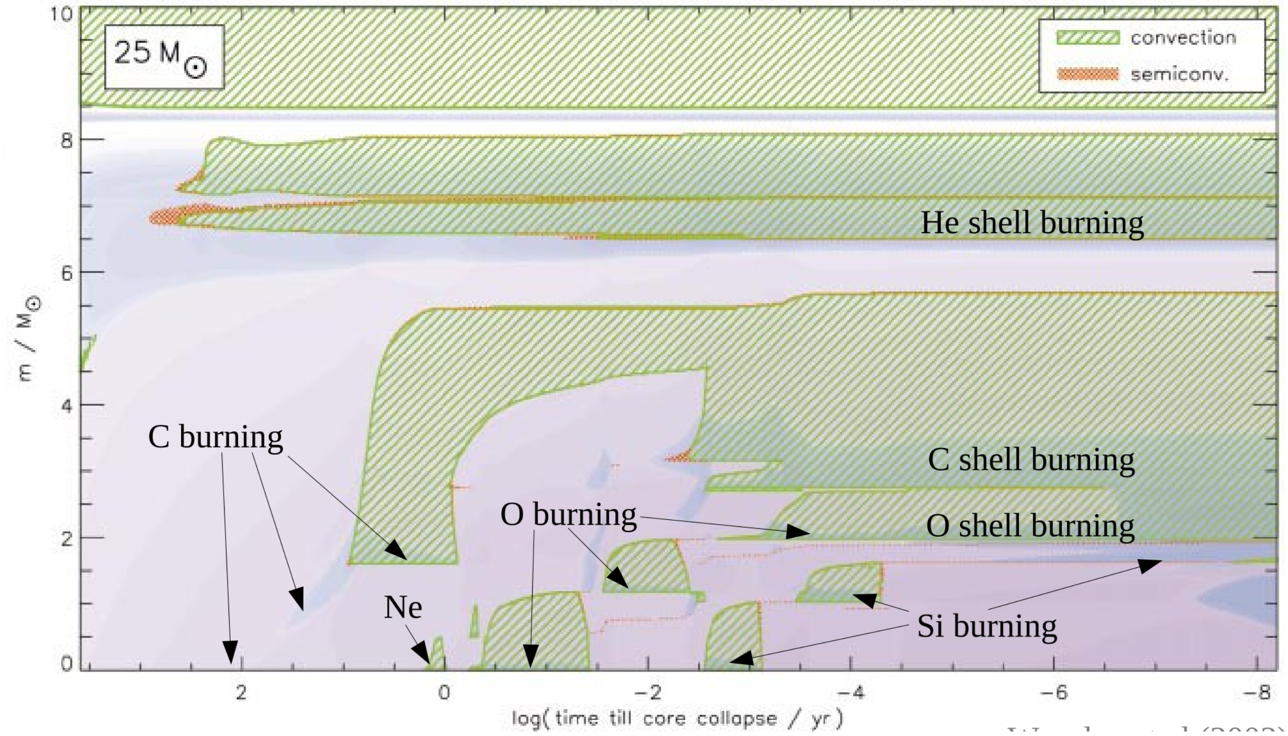
M > 40 M$_\odot$ getting big (inflated)





Short-lived phase.
Link with the LBV phenomenon?
Mass transfer?

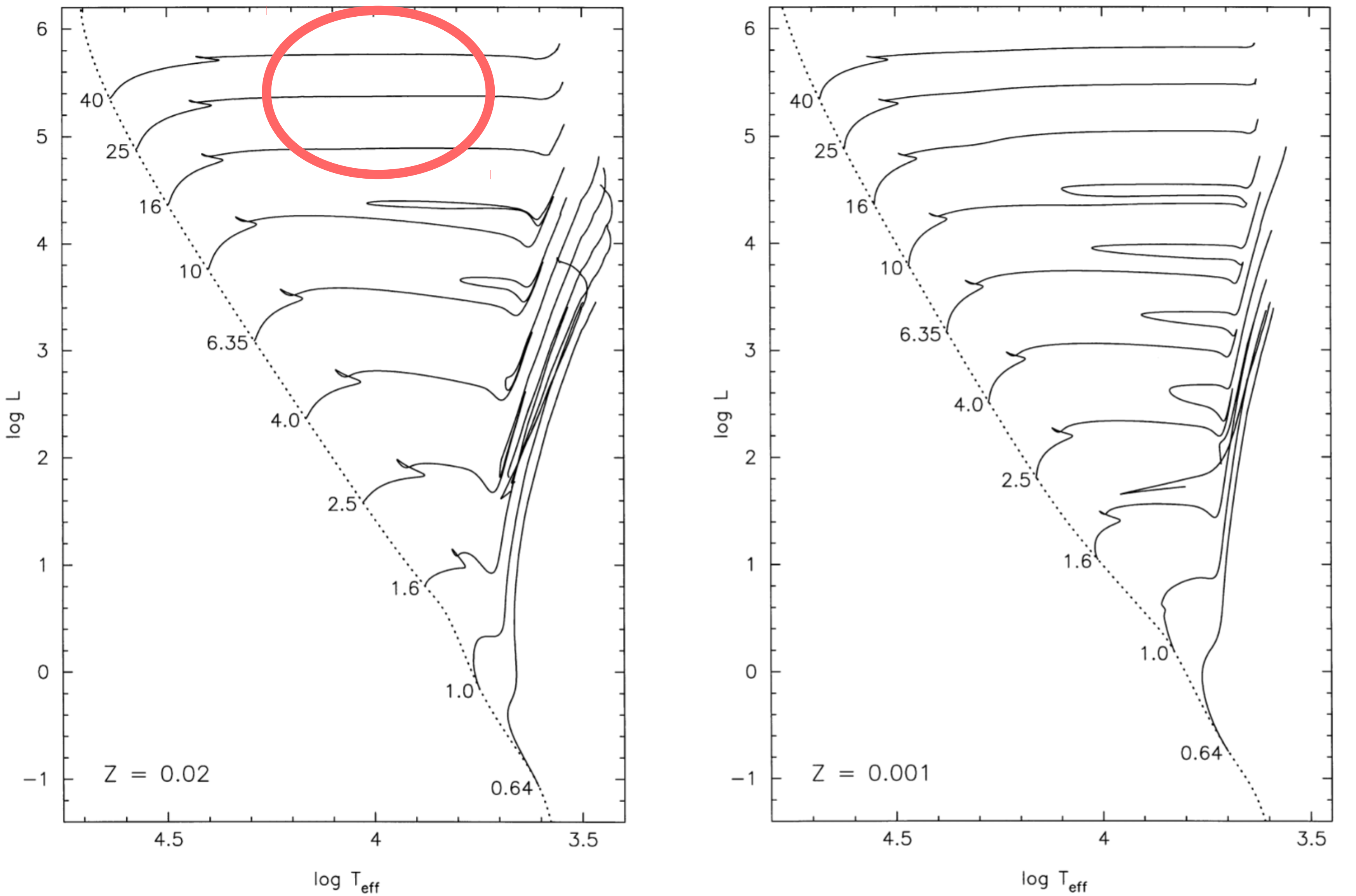
Post-MS overshooting?



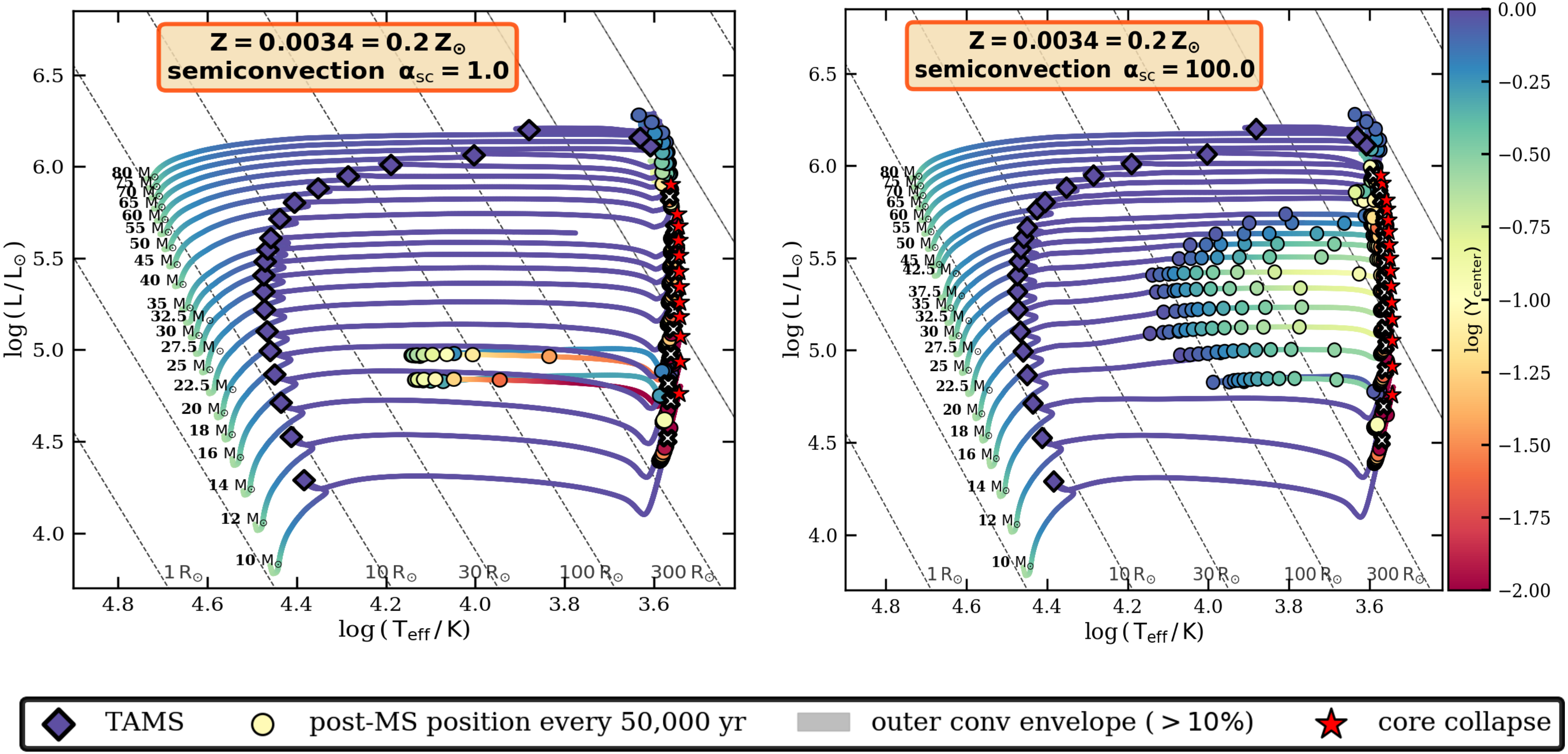
Woosley et al. 2002

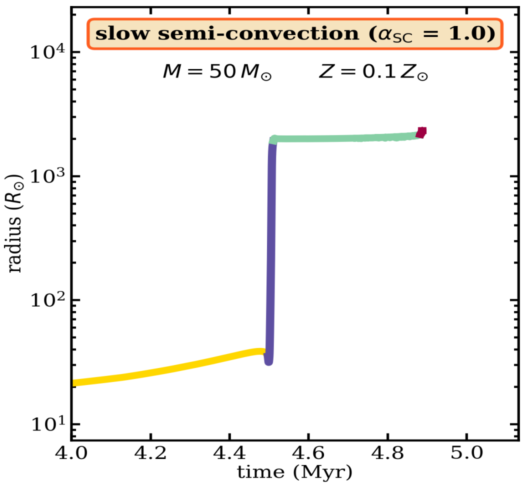
Overshooting around convective regions during advanced burning?

Stellar evolution models for Z = 0.0001 to 0.03 529

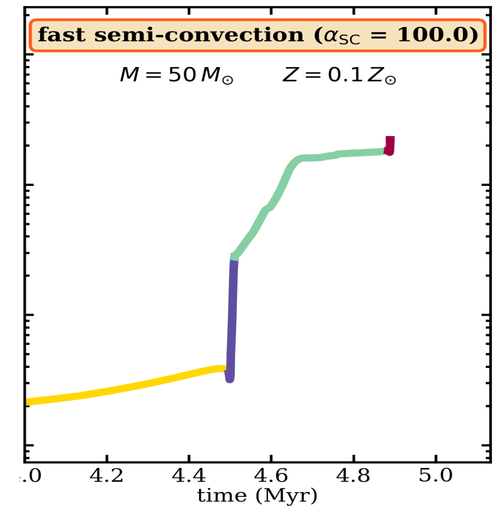


Pols et al. 1998

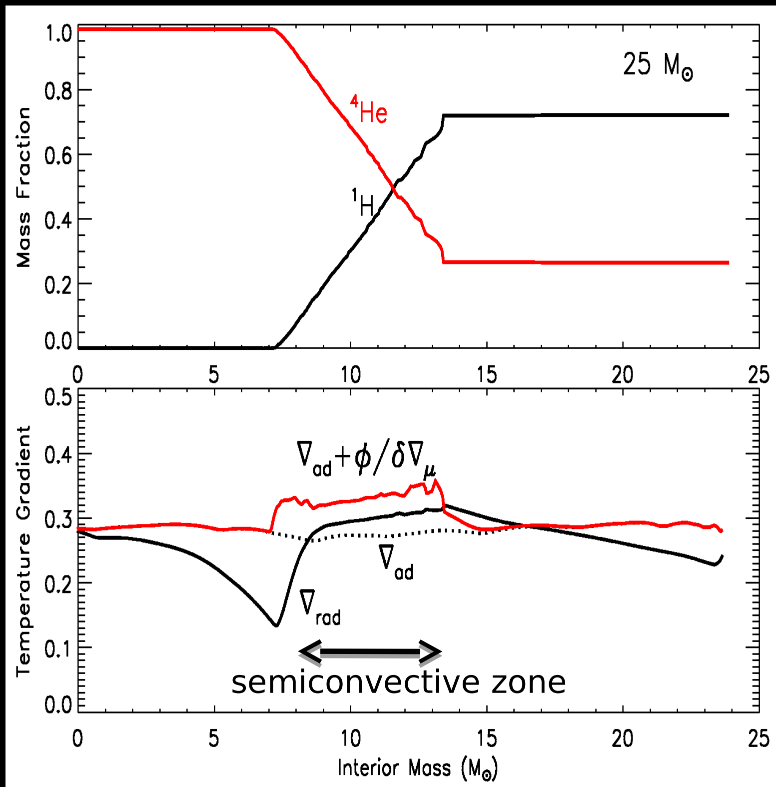




Klencki et al.
(to be submitted)



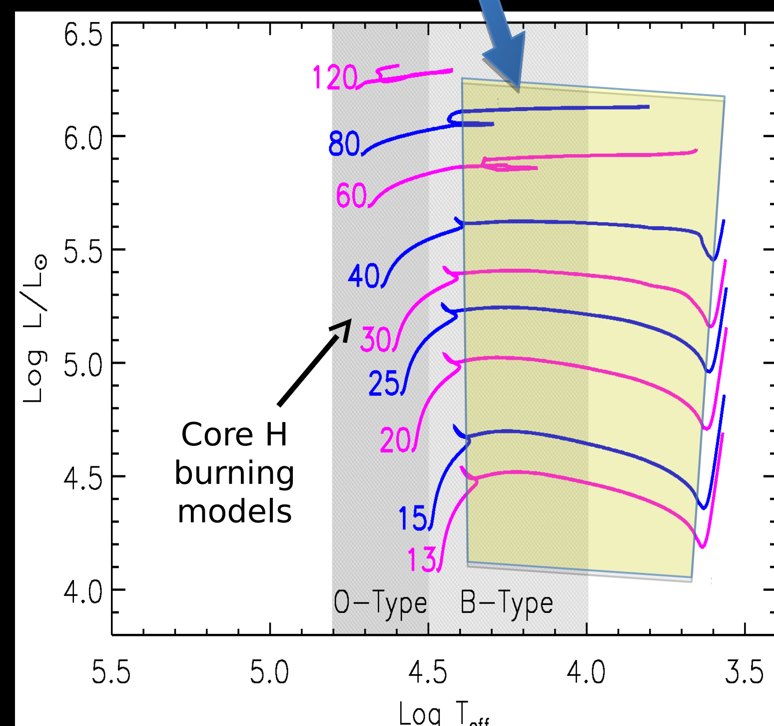
Semiconvection



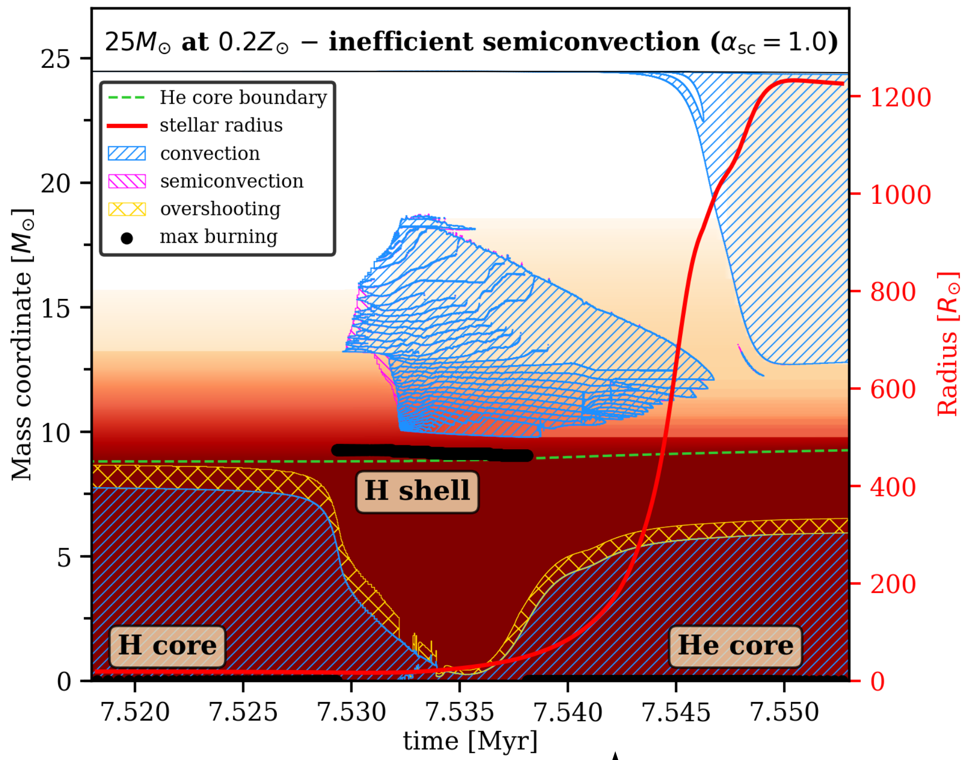
Unstable (Schwarzschild) $\nabla_{\rm ad} < \nabla_{\rm rad}$

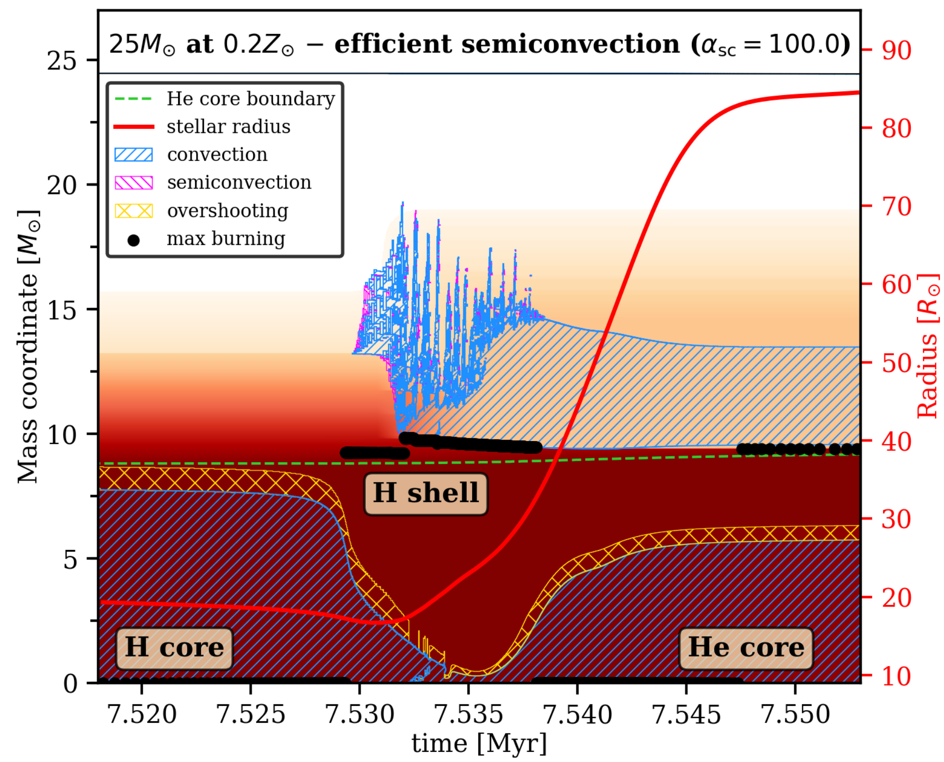
Stable (Ledoux) $\nabla_{\rm ad} < \nabla_{\rm rad} < \nabla_{\rm ad} + \frac{\varphi}{\delta}\nabla_\mu$

The mixing efficiency in the semiconvective zone determines the timescales of the redward evolution after the MS phase



No theory based on first principles can provide the mixing velocity in this zone

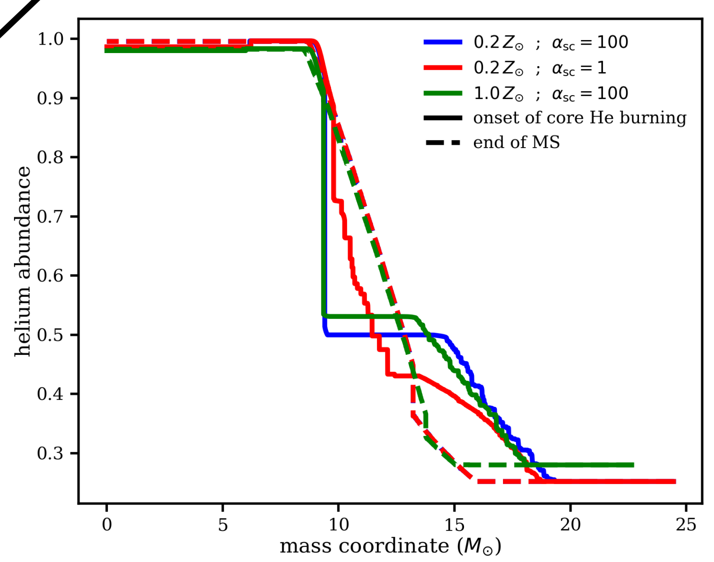




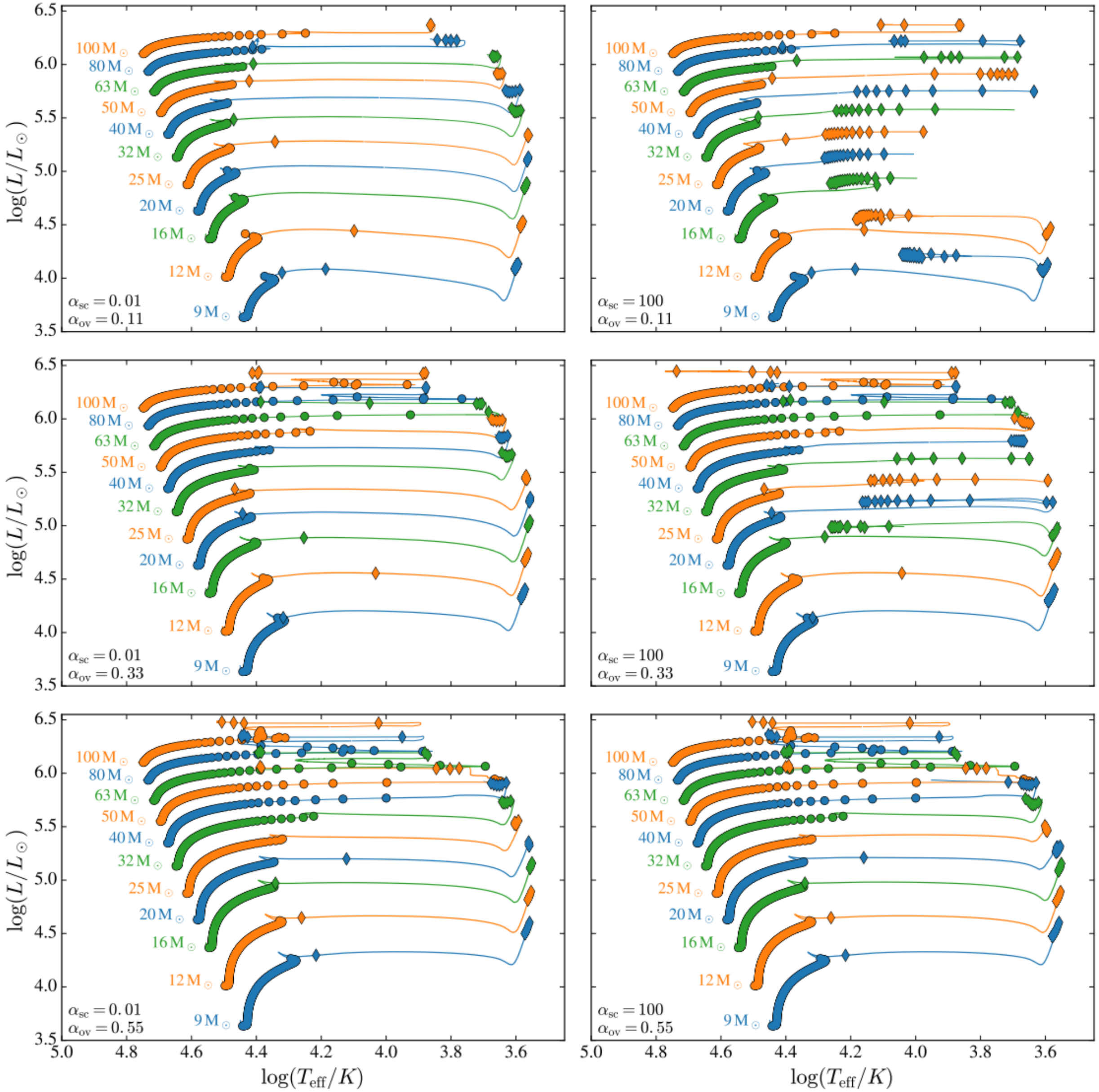
Inefficient mixing → rapid expansion (thermal timescale), **RSG soon after the and of MS**

Efficient mixing → slow expansion (nuclear timescale of CHeB), **RSG at the end of He burning**

Well known since 80' (at least)

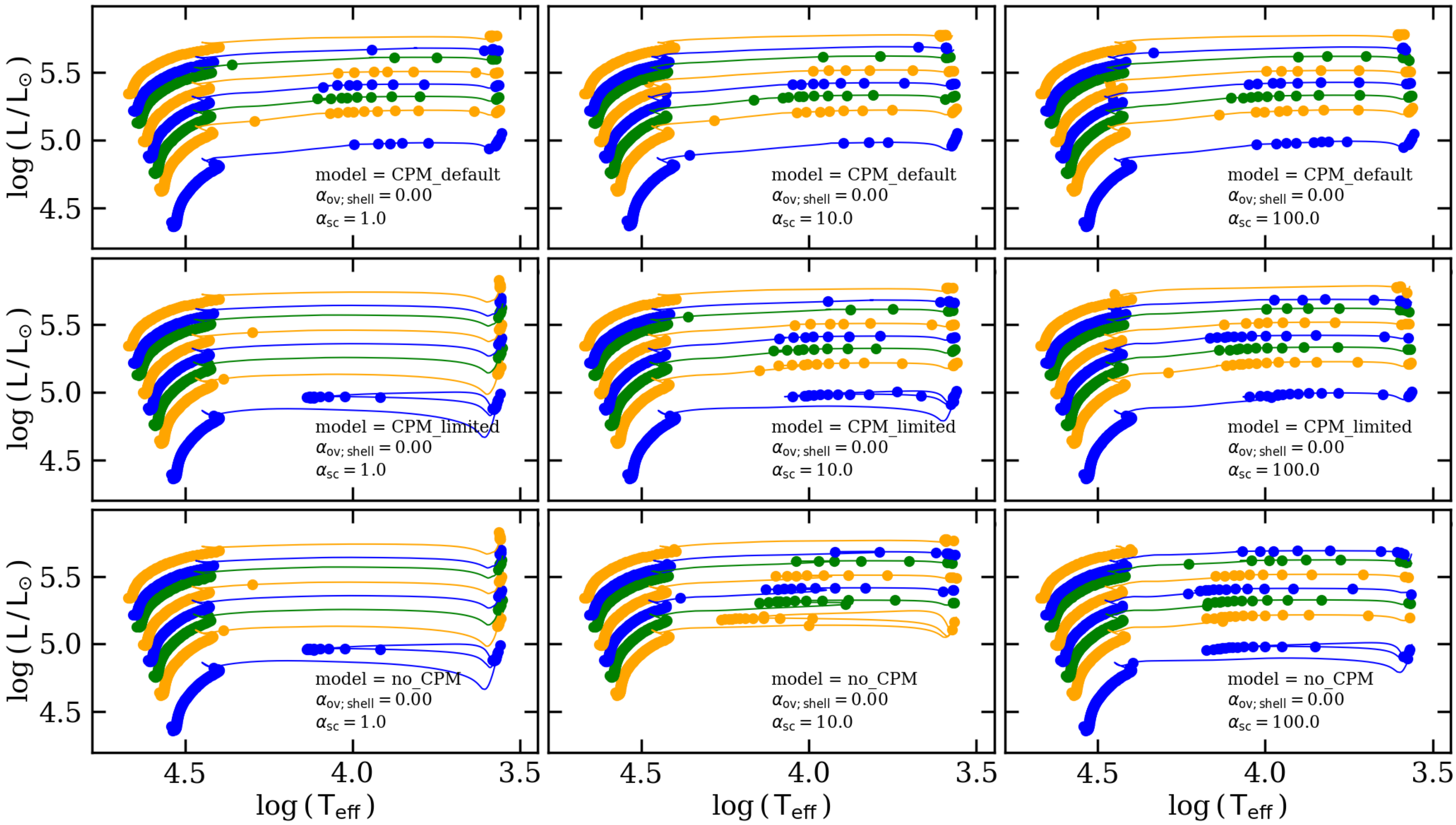


Sensitive to overshooting, semi-convection,...



Schootemeijer et al. 2019

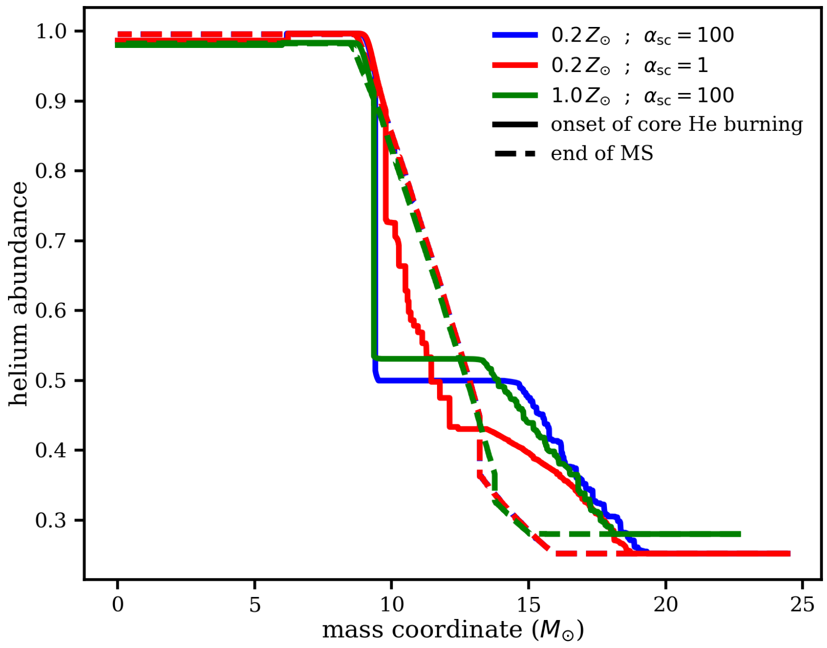
… convective boundary treatment, shell overshooting …



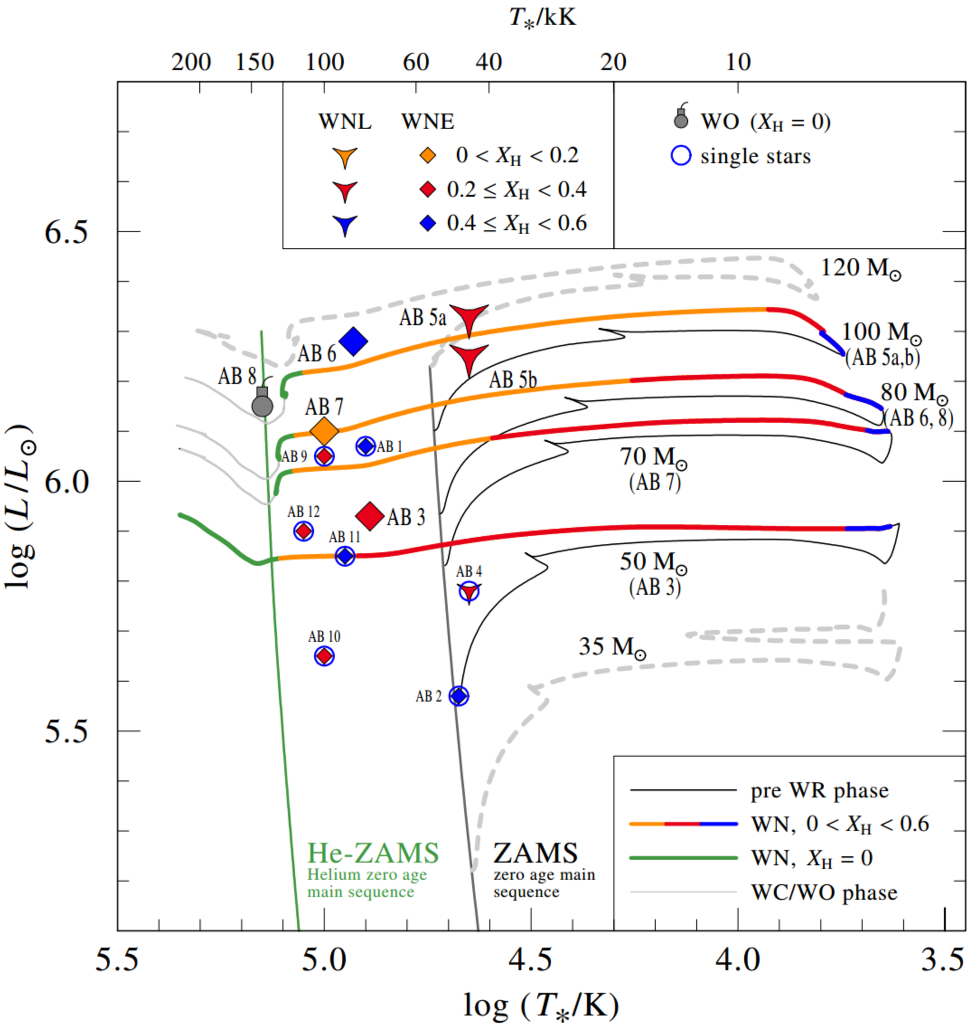
… and other factors

- Rotational mixing (eg. shear diffusion Georgy et al. 2013)
- Mesh resolution, time-step controls (eg. Farmer et al. 2017)

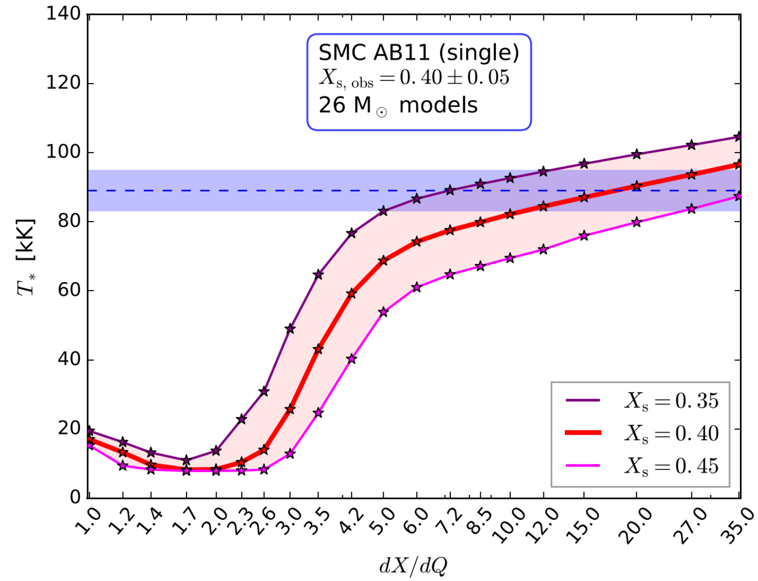
Result notoriously model-sensitive. **Need observational constraints.**

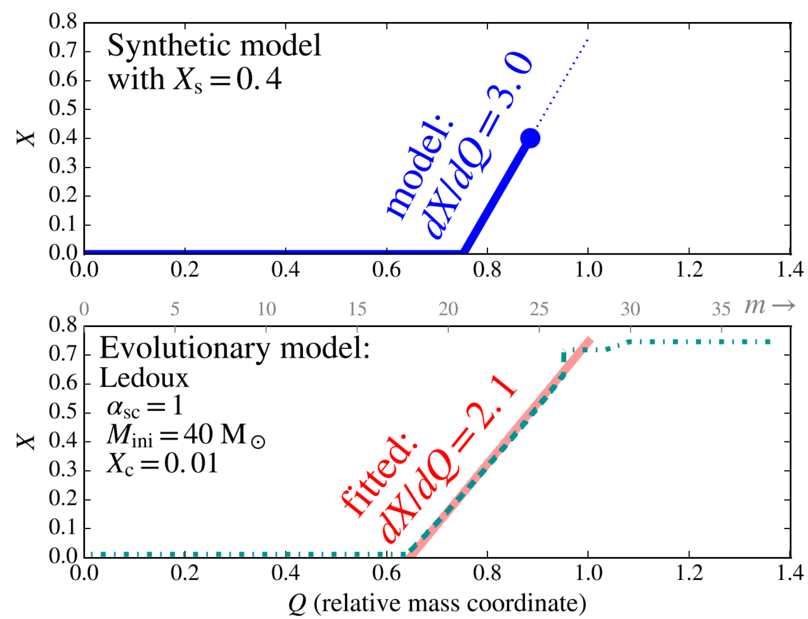


surface H in WR stars of the SMC



Shenar et al. 2016

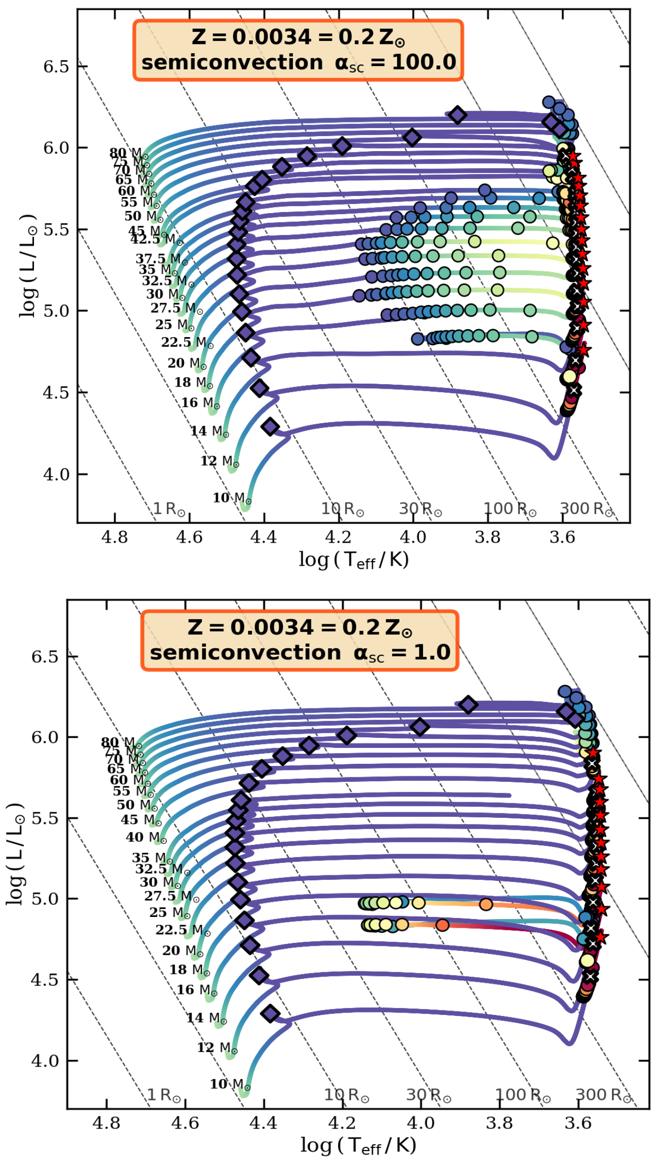




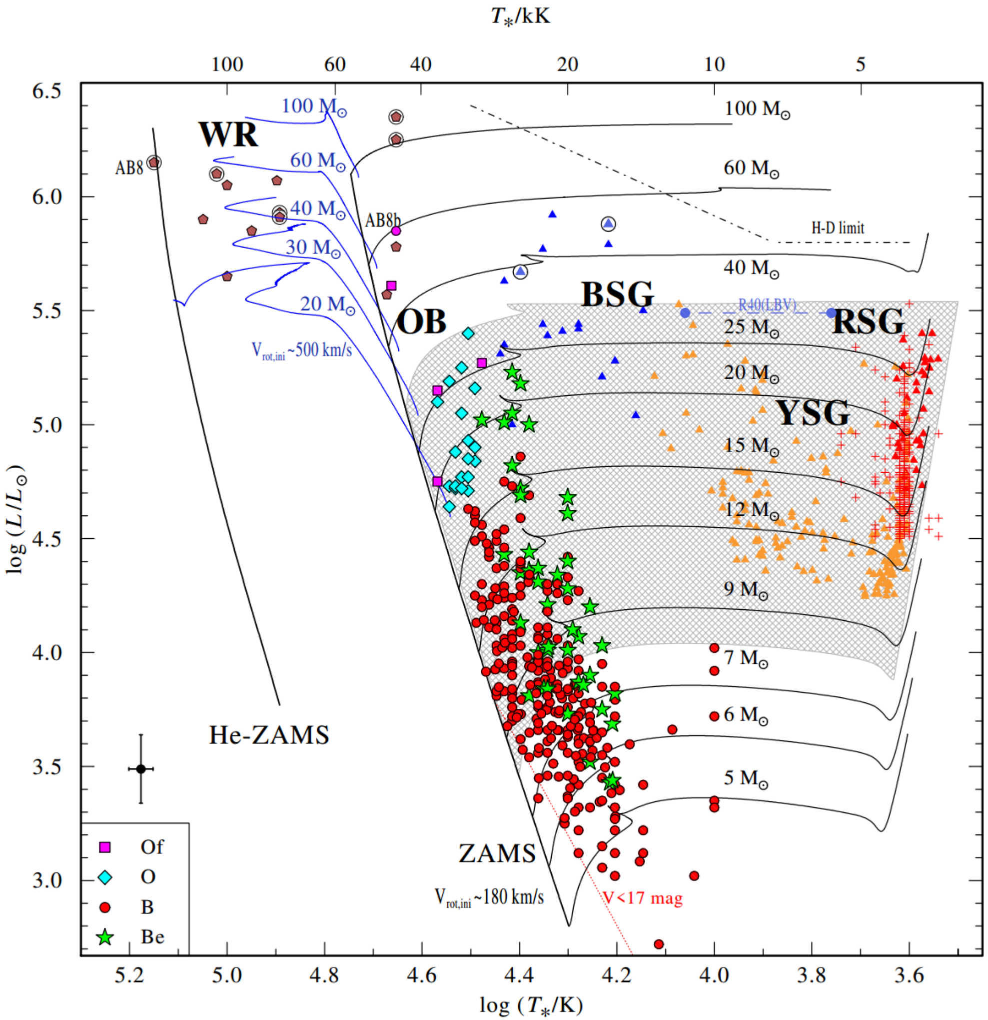
Schootemeijer et al. 2018

Blue & Red supergiants in the HR diagram (SMC)

MODELS



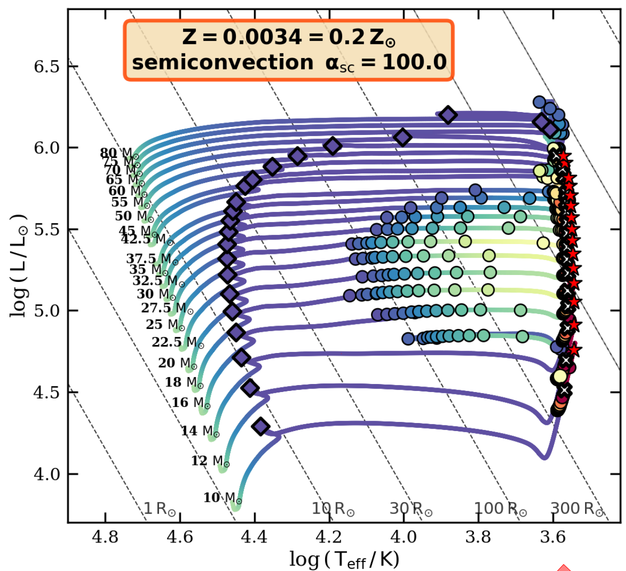
OBSERVATIONS

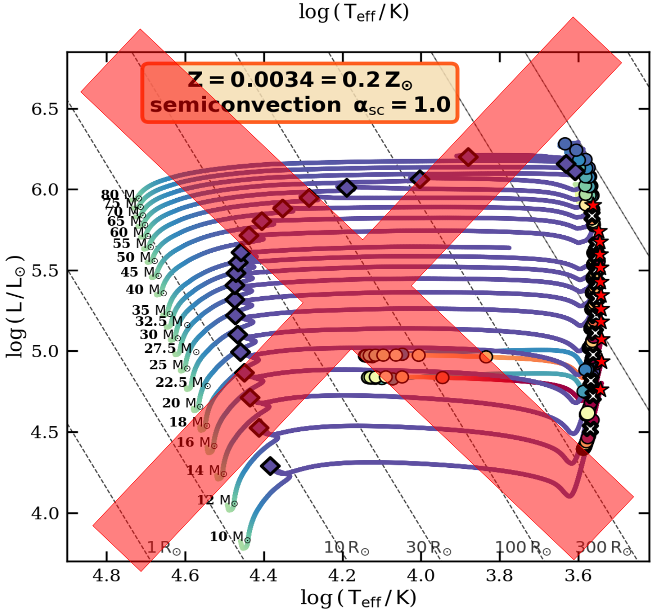


Ramachandran et al. 2019

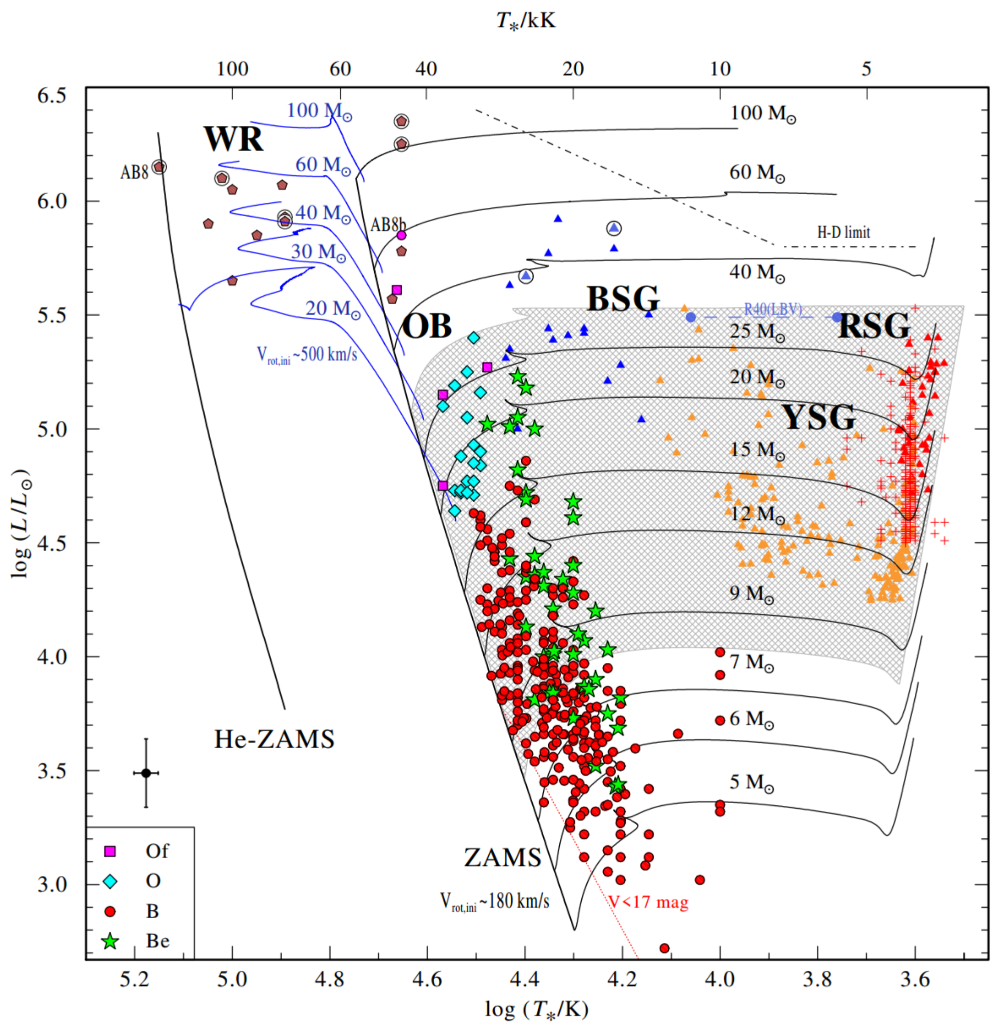
Blue & Red supergiants in the HR diagram (SMC)

MODELS



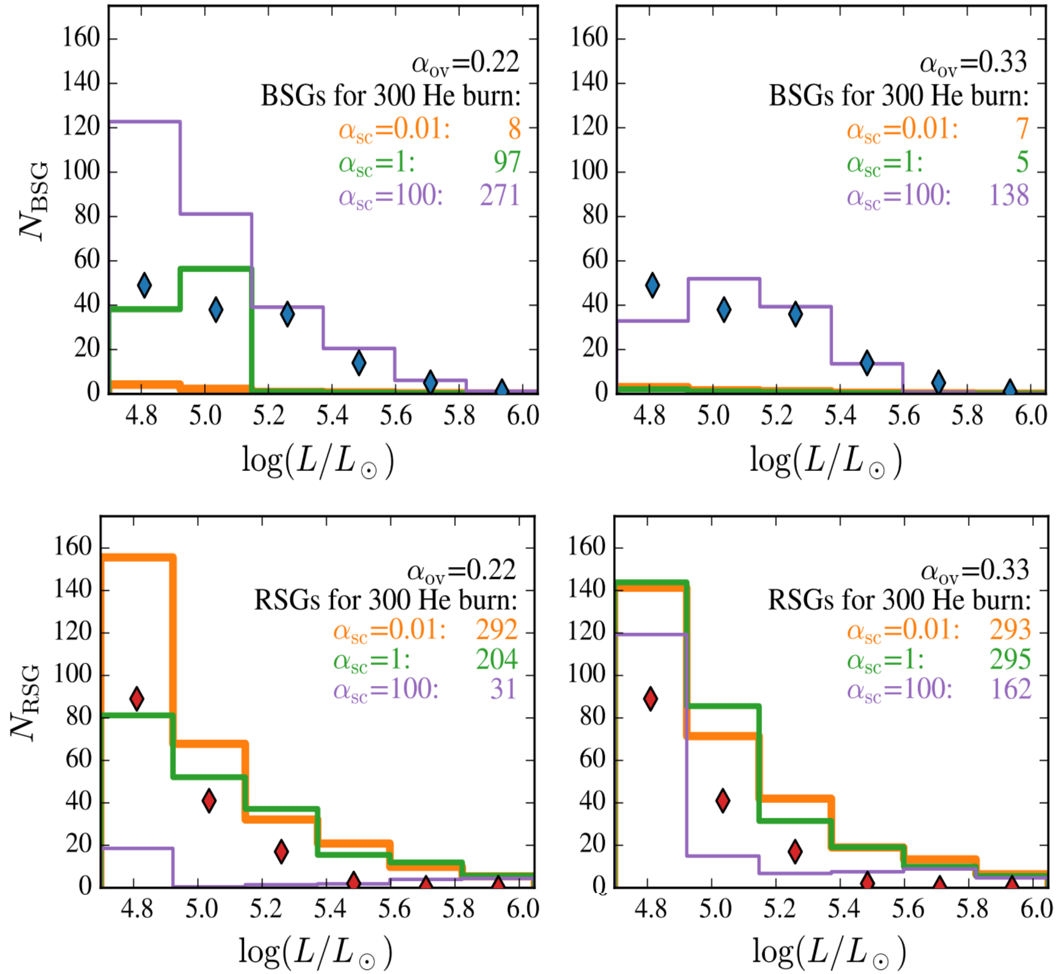


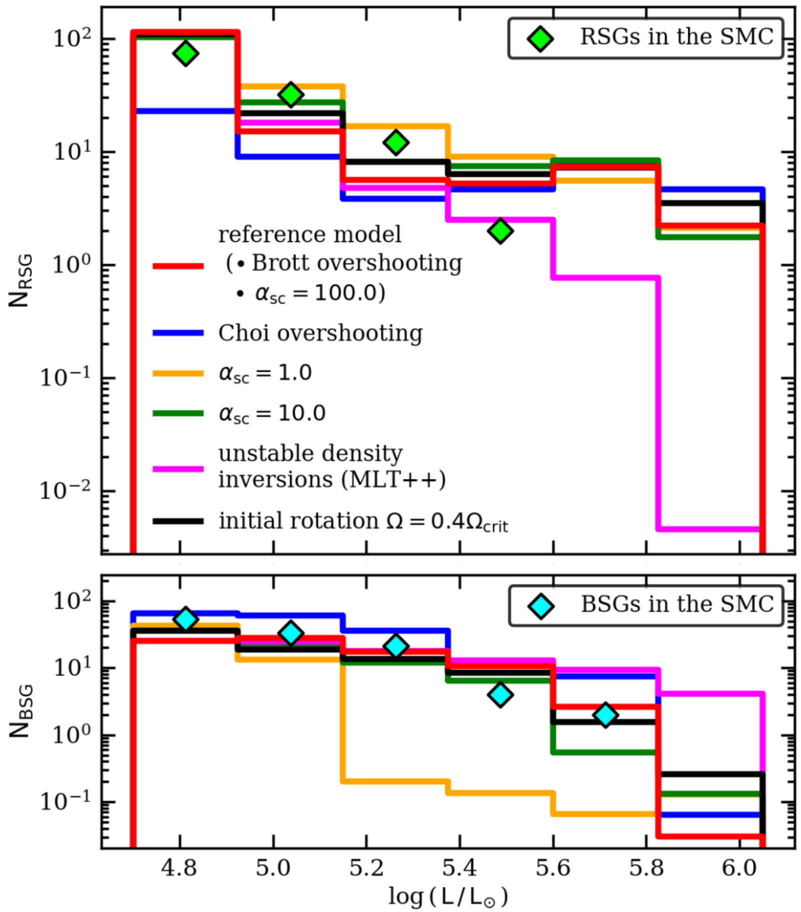
OBSERVATIONS



Ramachandran et al. 2019

post-MS models vs SMC supergiants

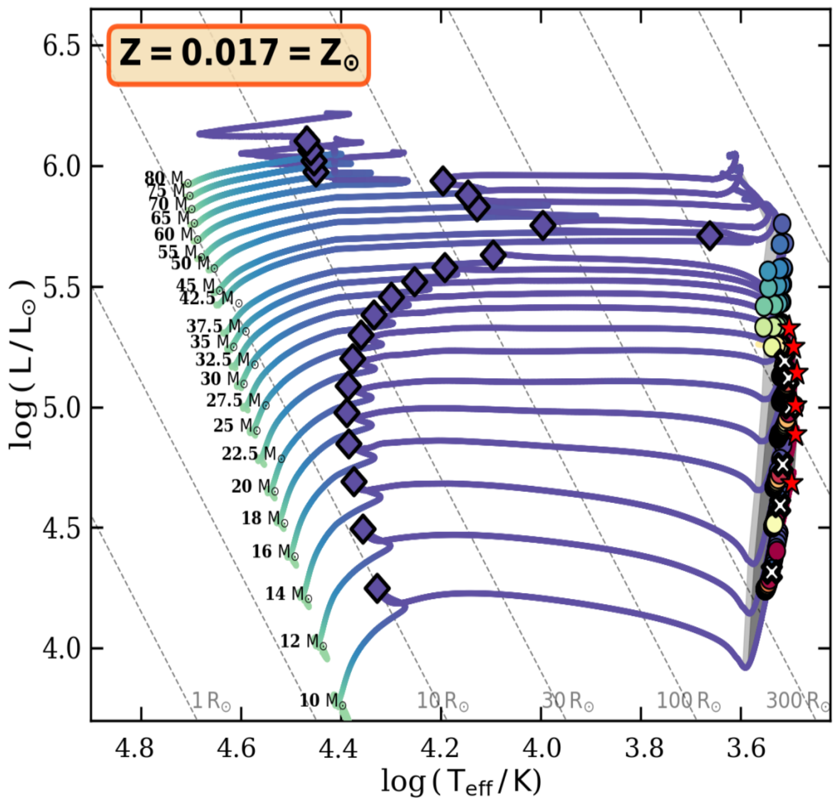


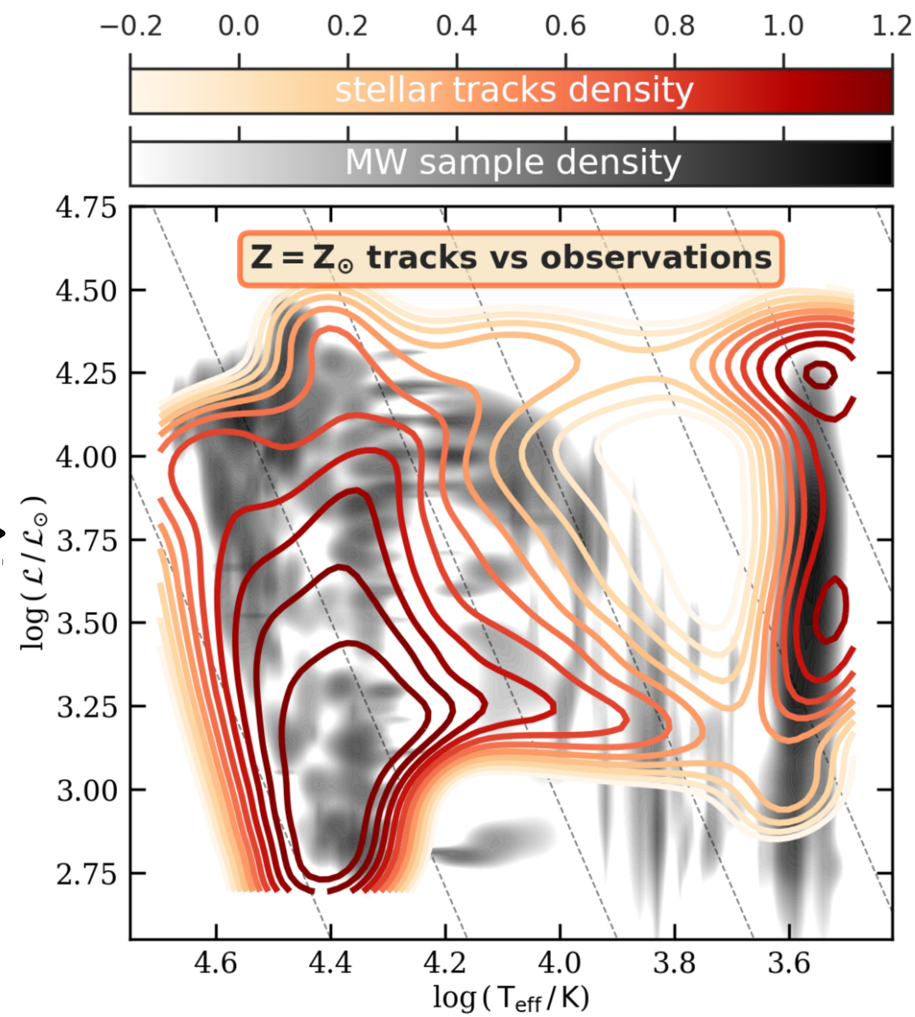


Schootemeijer et al. 2019

Klencki et al. (to be submitted)

models vs Galactic supergiants (?)





data from Castro et al. 2014

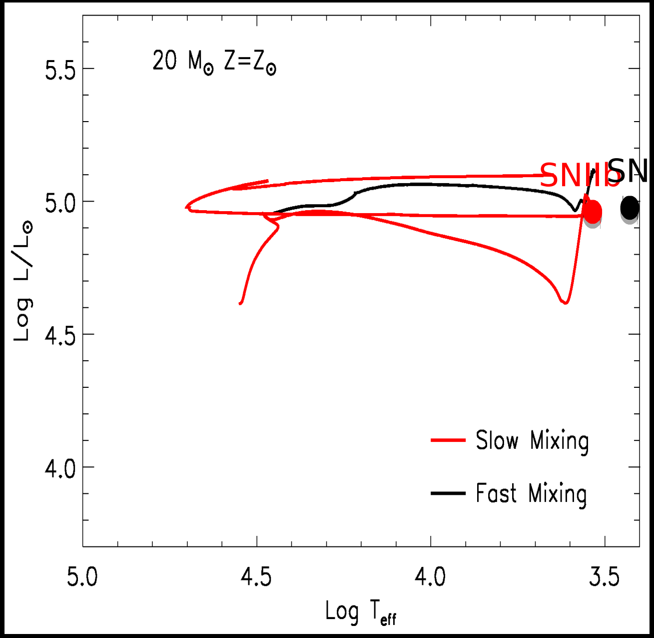
Semiconvection

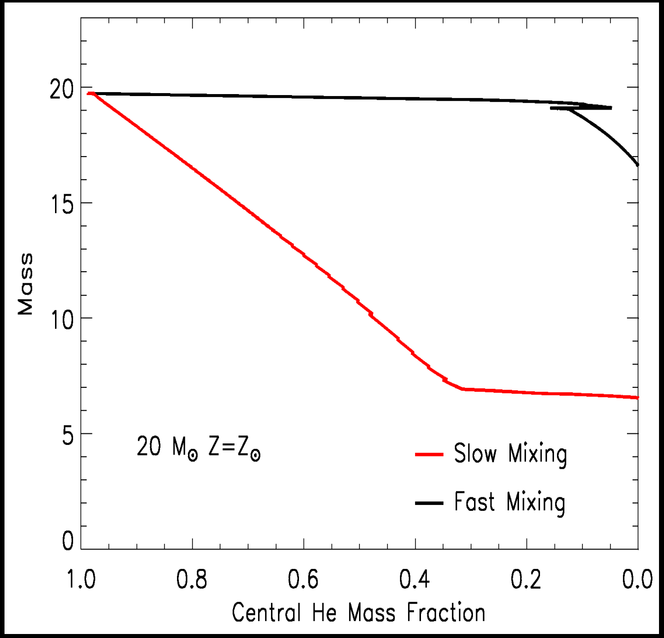
Fast Mixing

- the redward evolution occurs on nuclear timescales
- the star becomes RSG in an advanced stage of core He burnin
- small RSG lifetime
- small amount of mass lost
- RSG configuration and SNIIP explosion favored

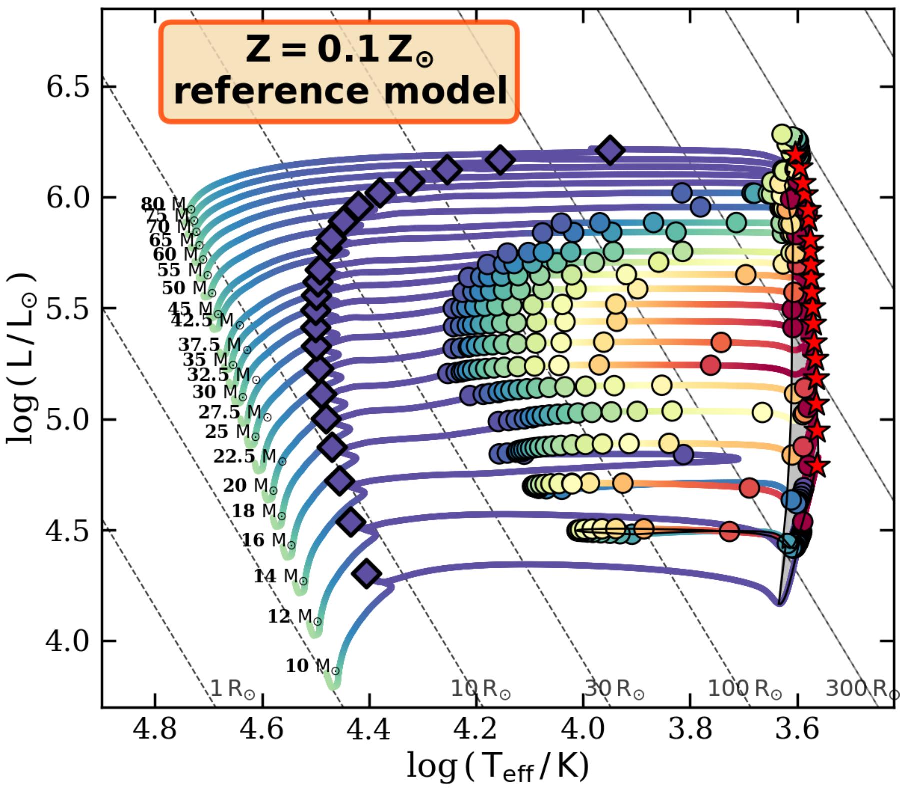
Slow Mixing

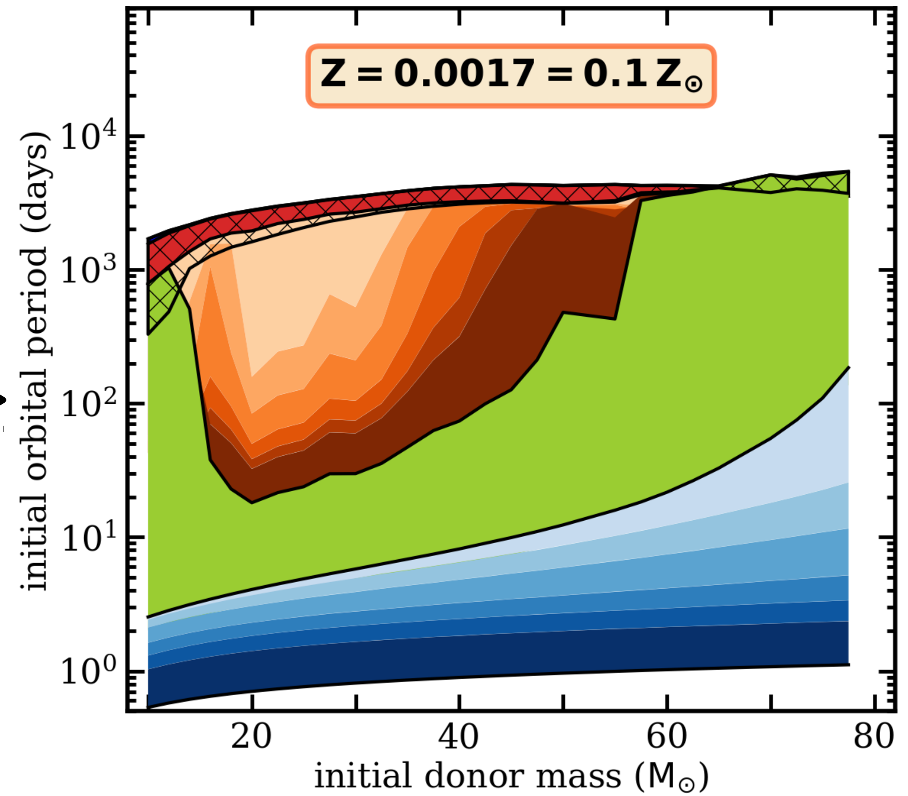
- the redward evolution occurs on thermodynamic timescales
- the star becomes RSG at the very beginning of core He burnin
- large RSG lifetime
- large amount of mass lost
- blueward evolution WR formation and SNIIb/SNIb favored





Binary perspective:

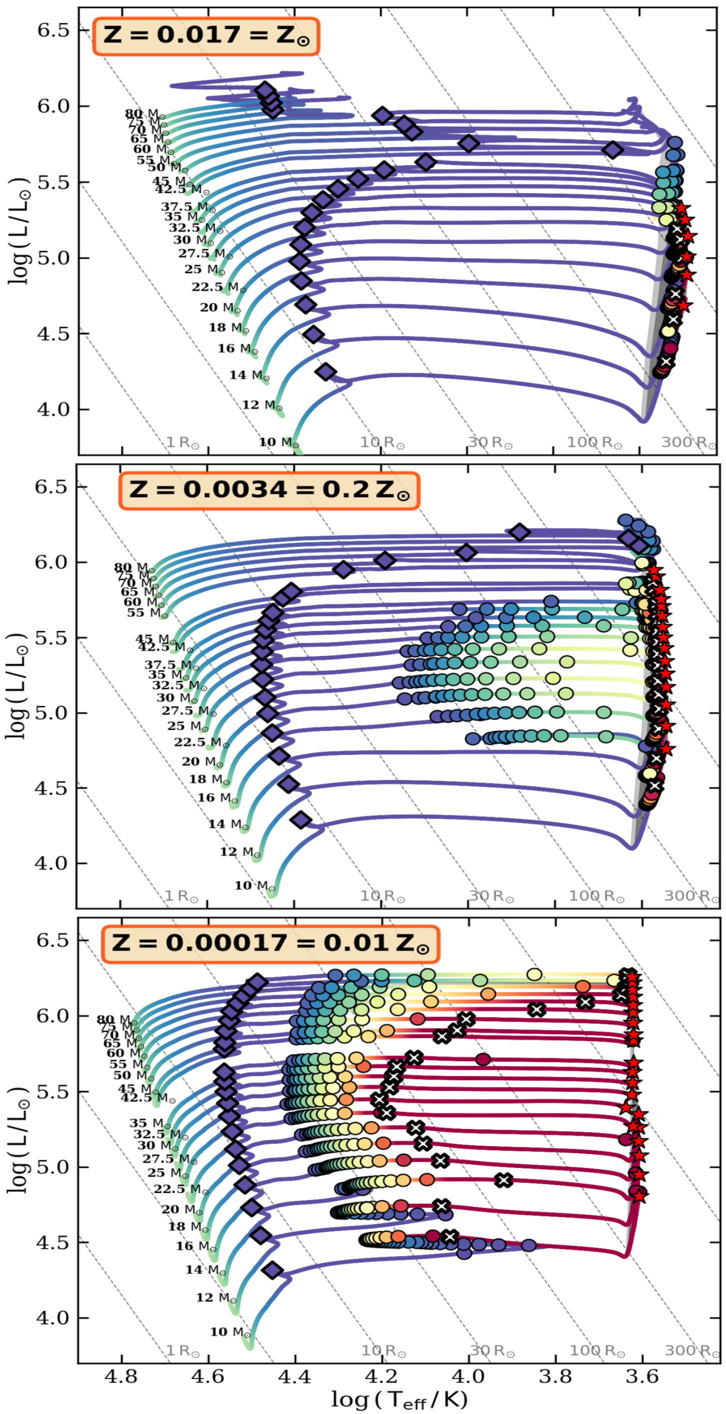


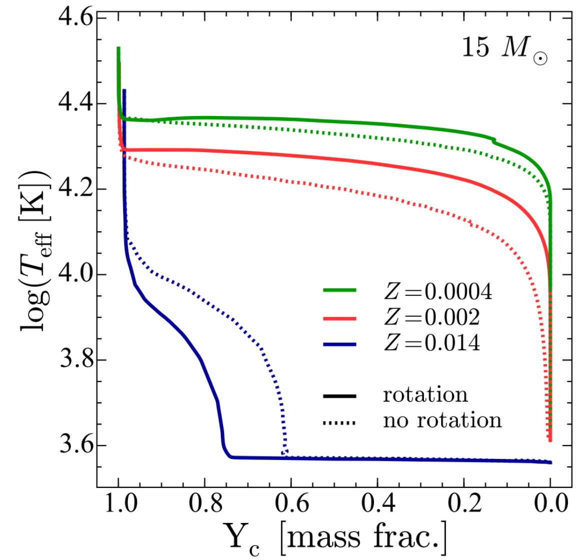


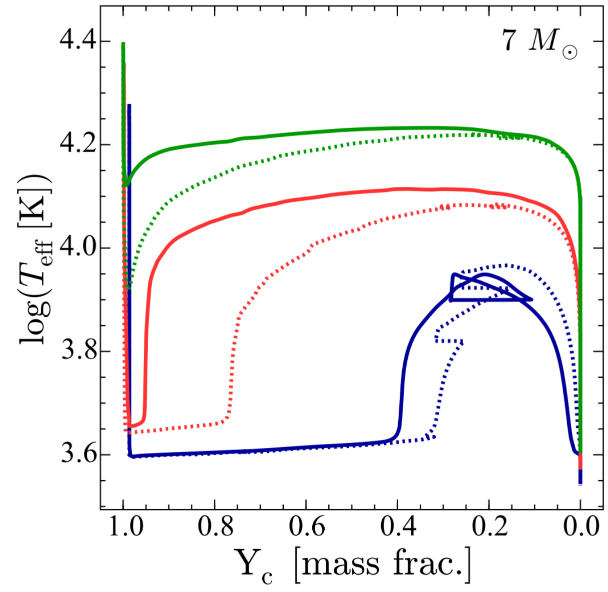
Evolutionary state at RLOF:

- MS
- HG
- CHeB
- HeHG
- conv env

Impact of metallicity

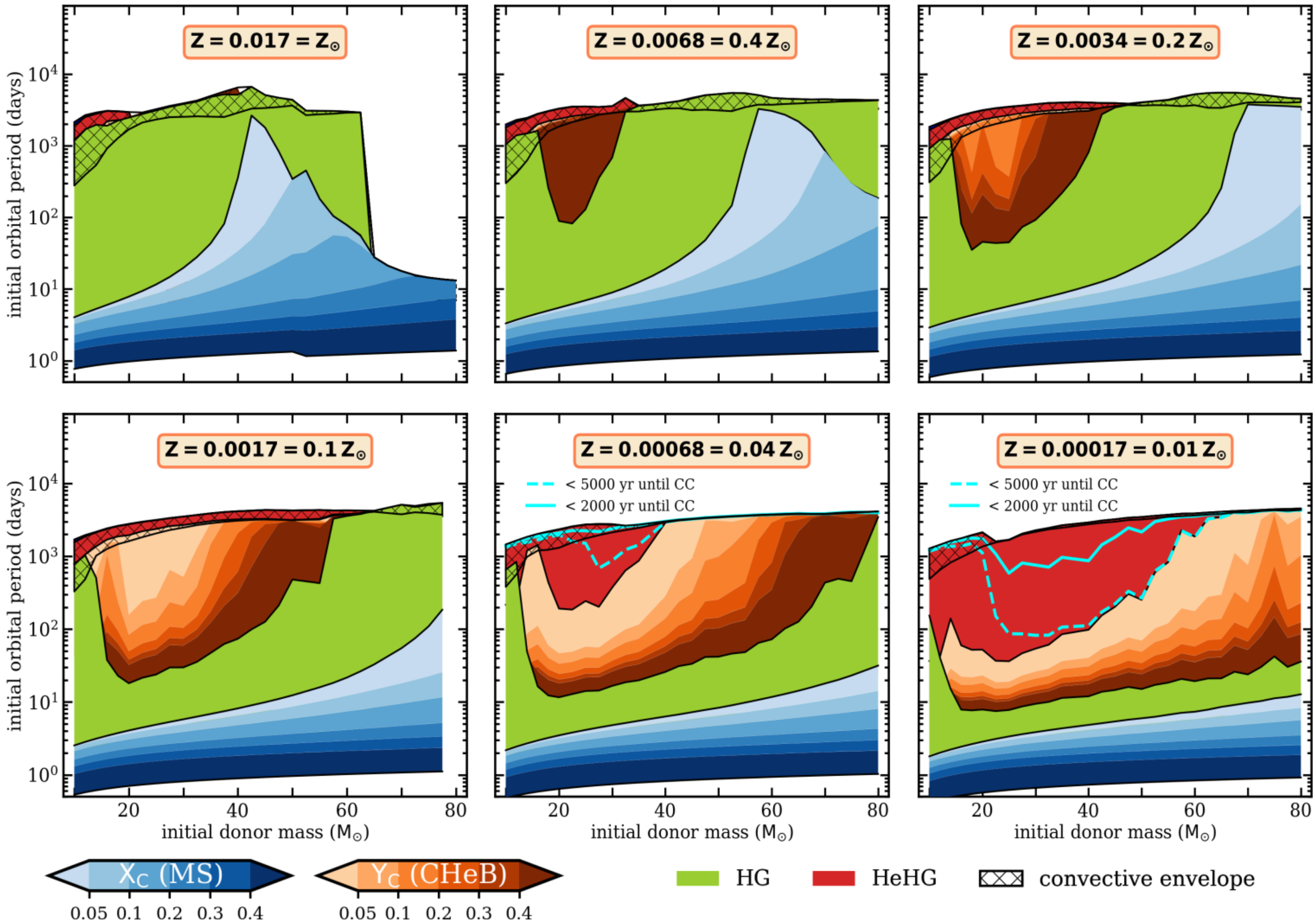






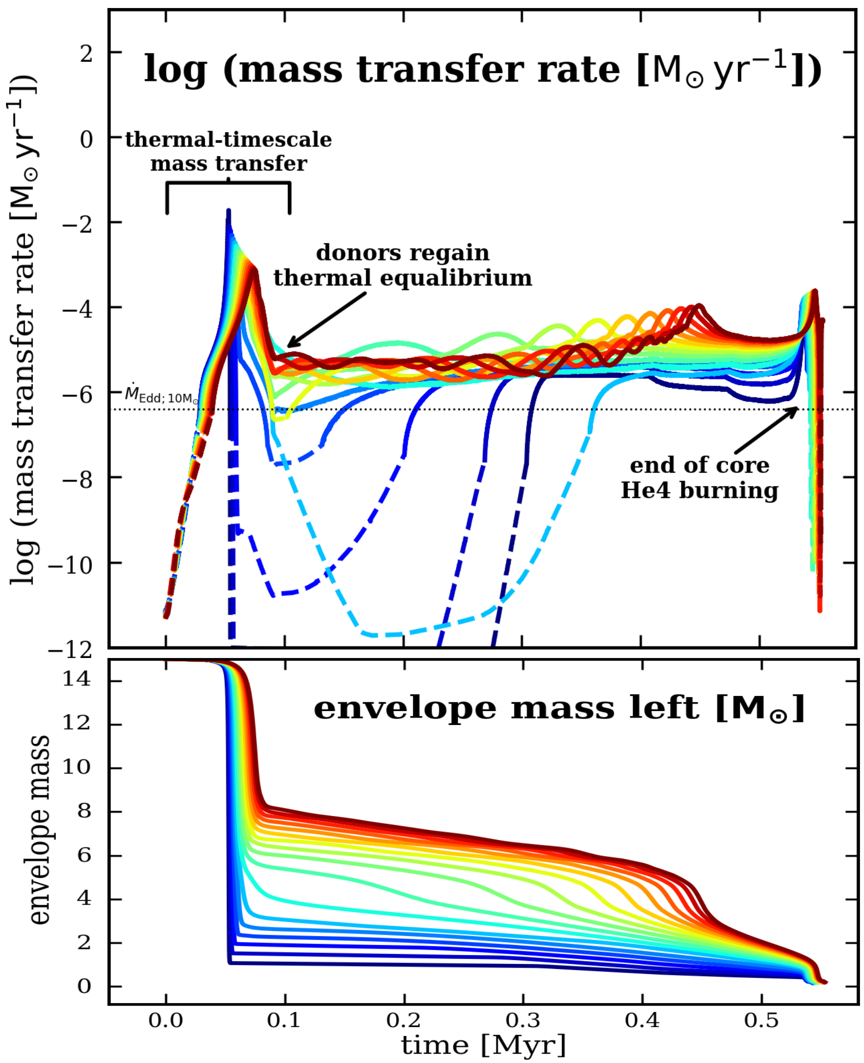
Groh et al. 2019, …

Impact of metallicity

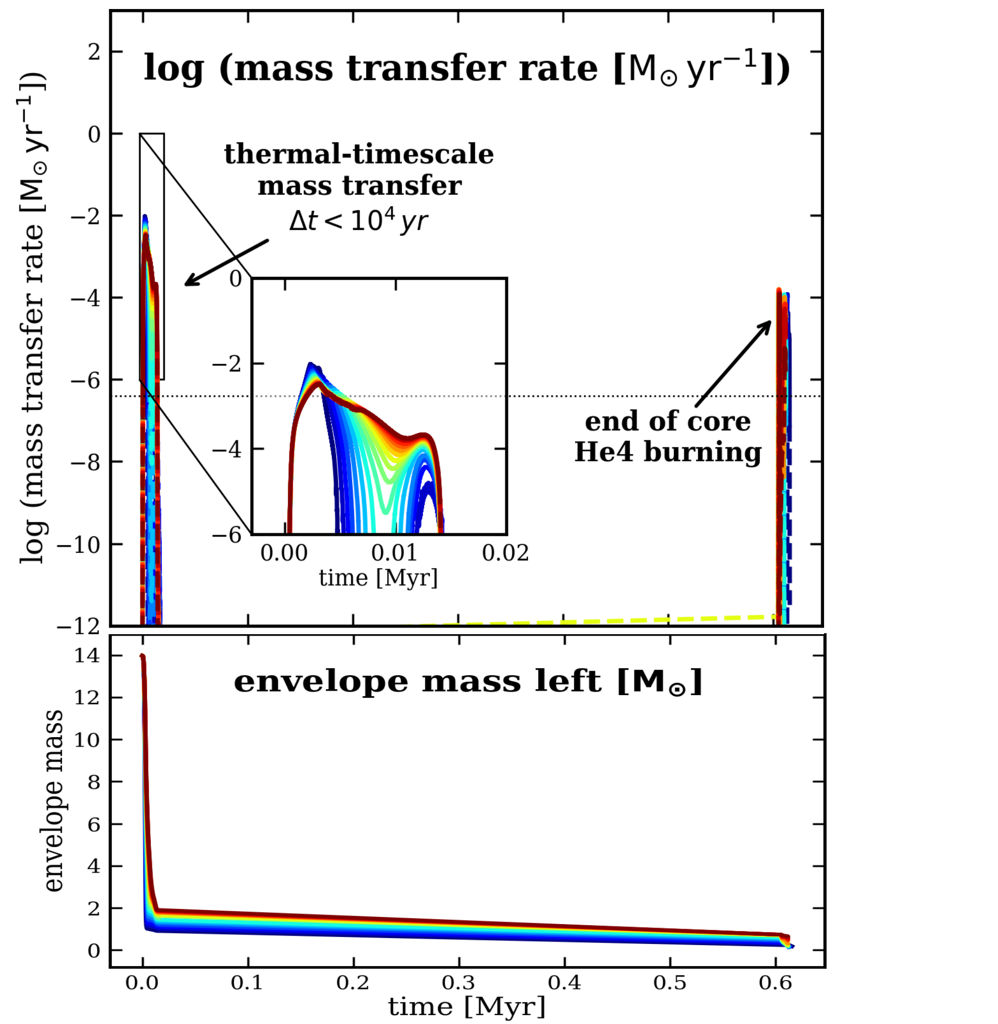


Klencki et al. (to be submitted)

subsolar metallicity (0.2 $Z_\odot$)
CheB, slowly expanding 25 $M_\odot$ donor

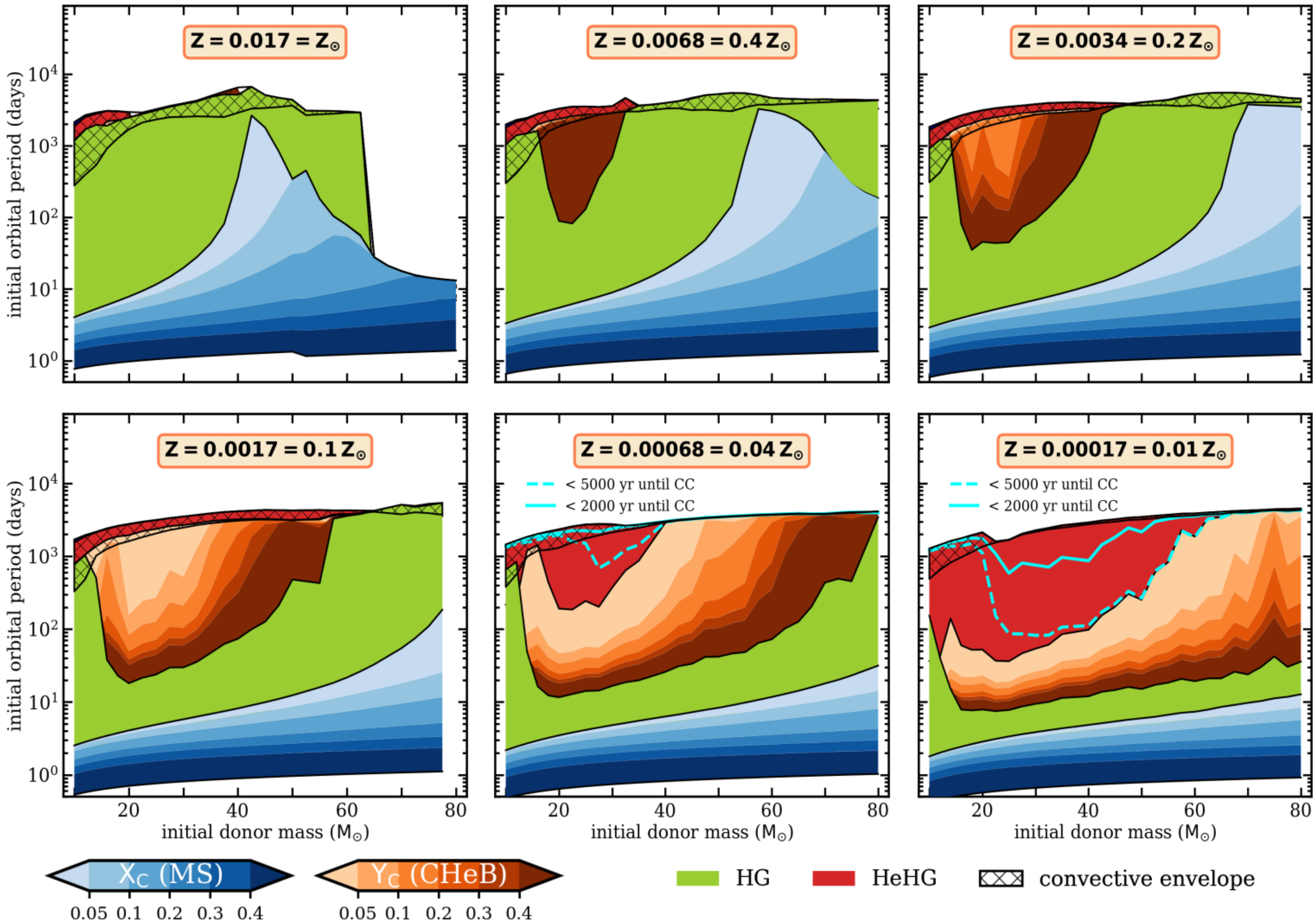


Solar metallicity (1.0 $Z_\odot$)
HG, thermally-expanding 25 $M_\odot$ donor



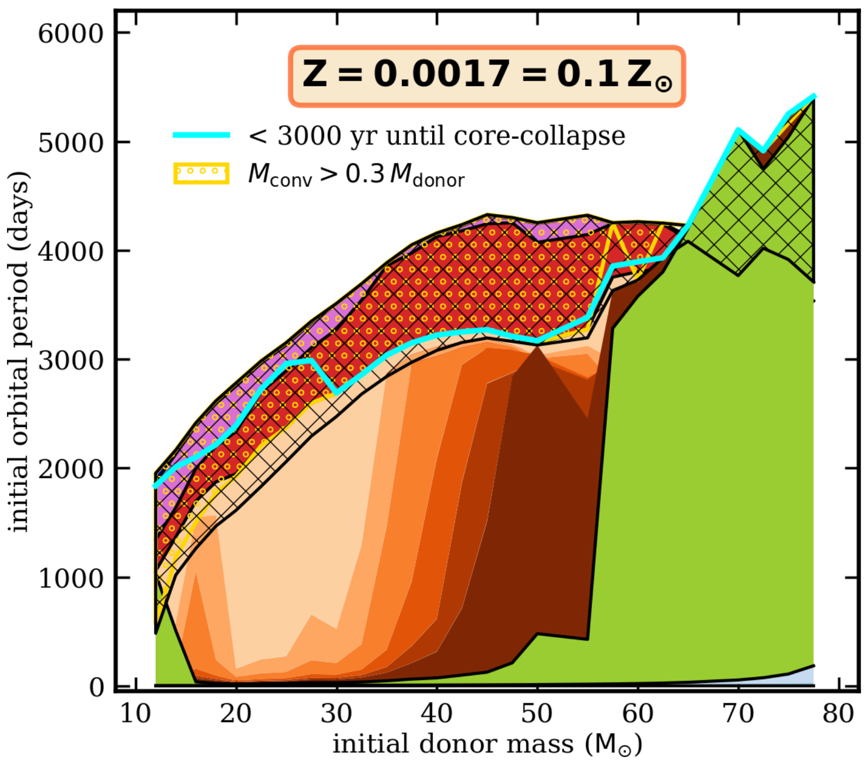
BH accretor masses, eg:

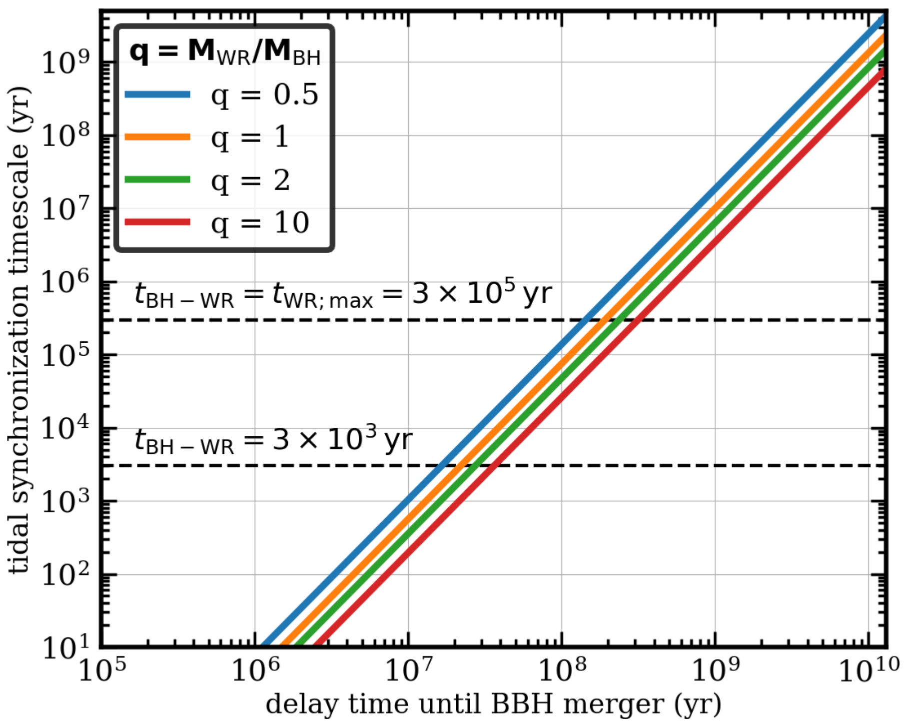
Impact of metallicity



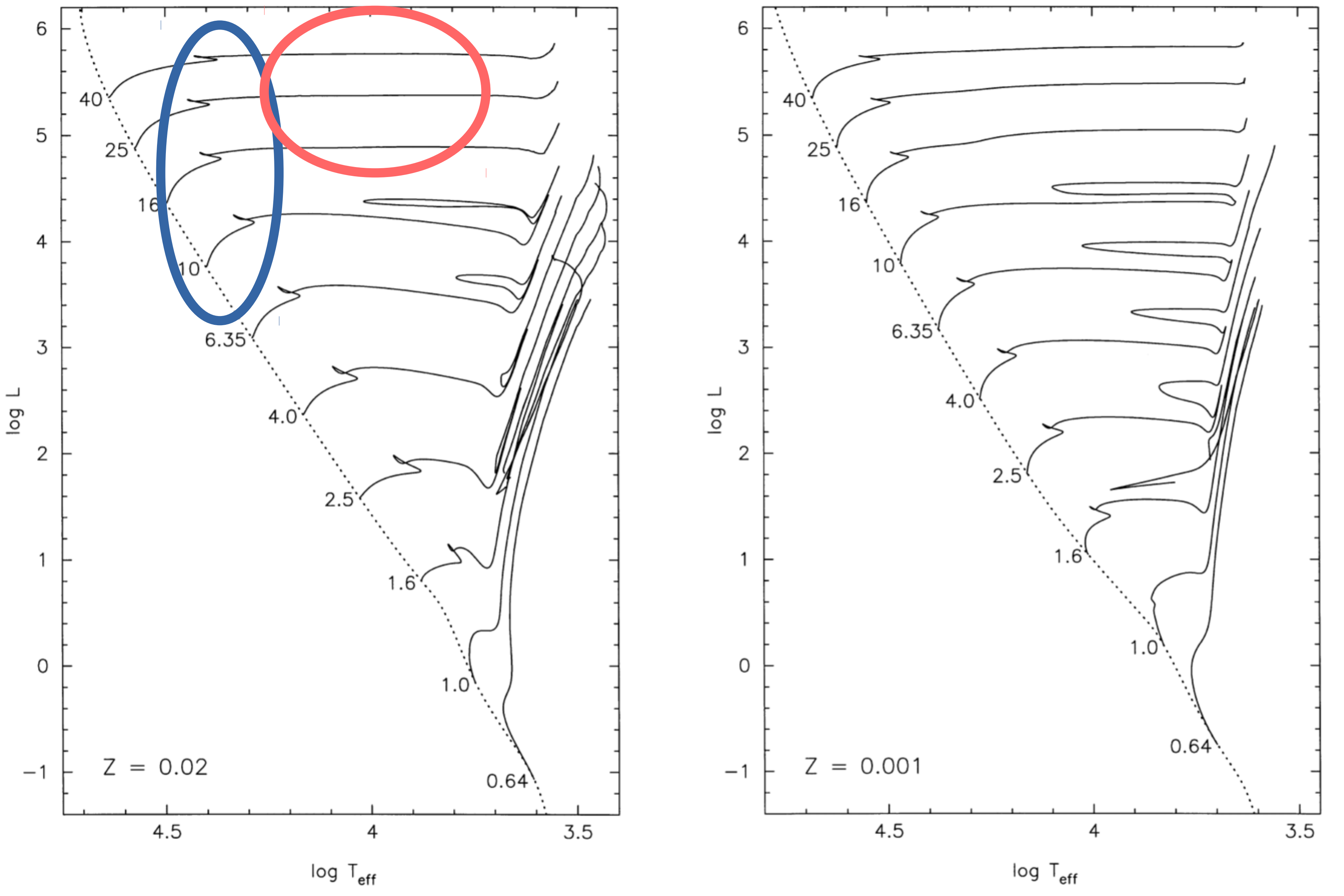
Klencki et al. (to be submitted)

BH-WR stage duration → tidal spin-up?

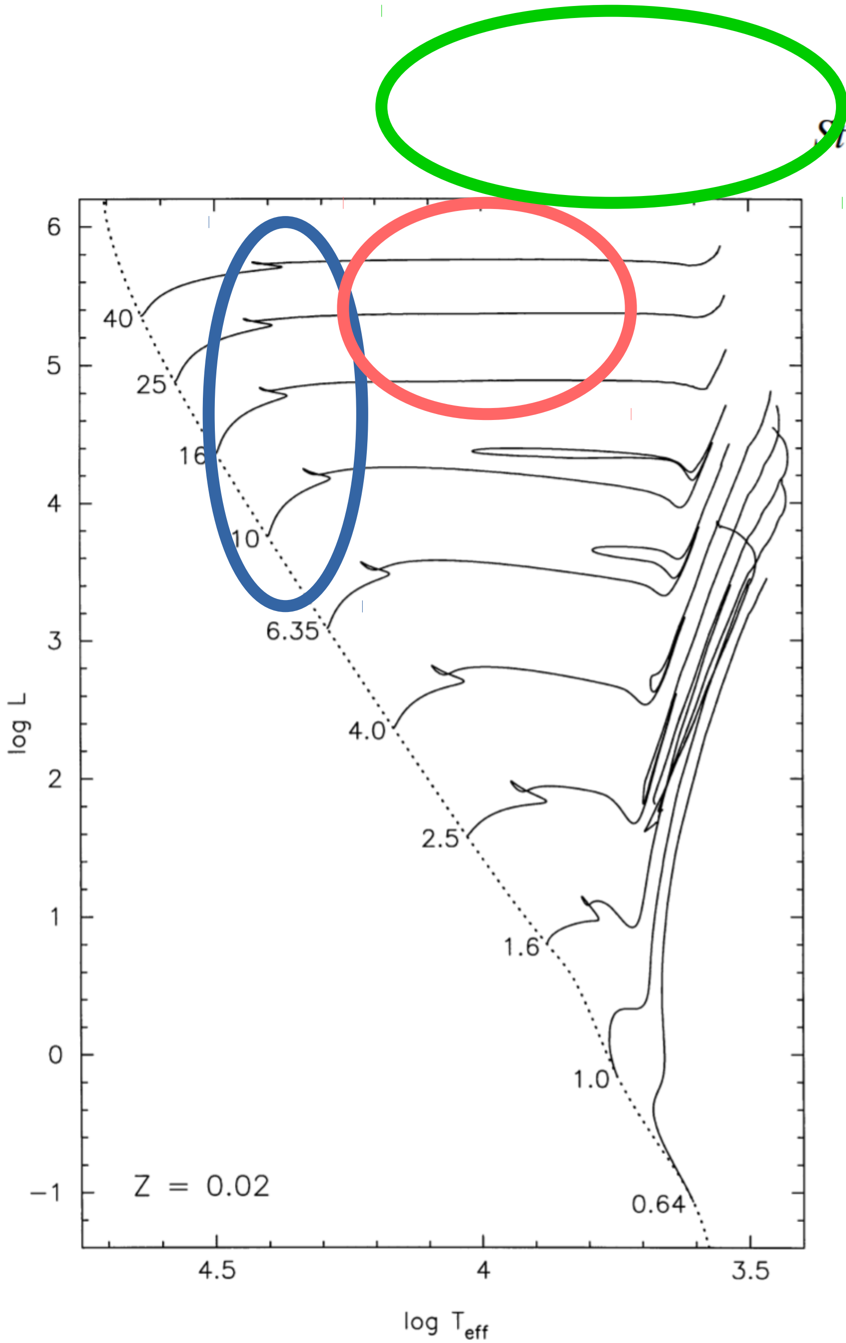


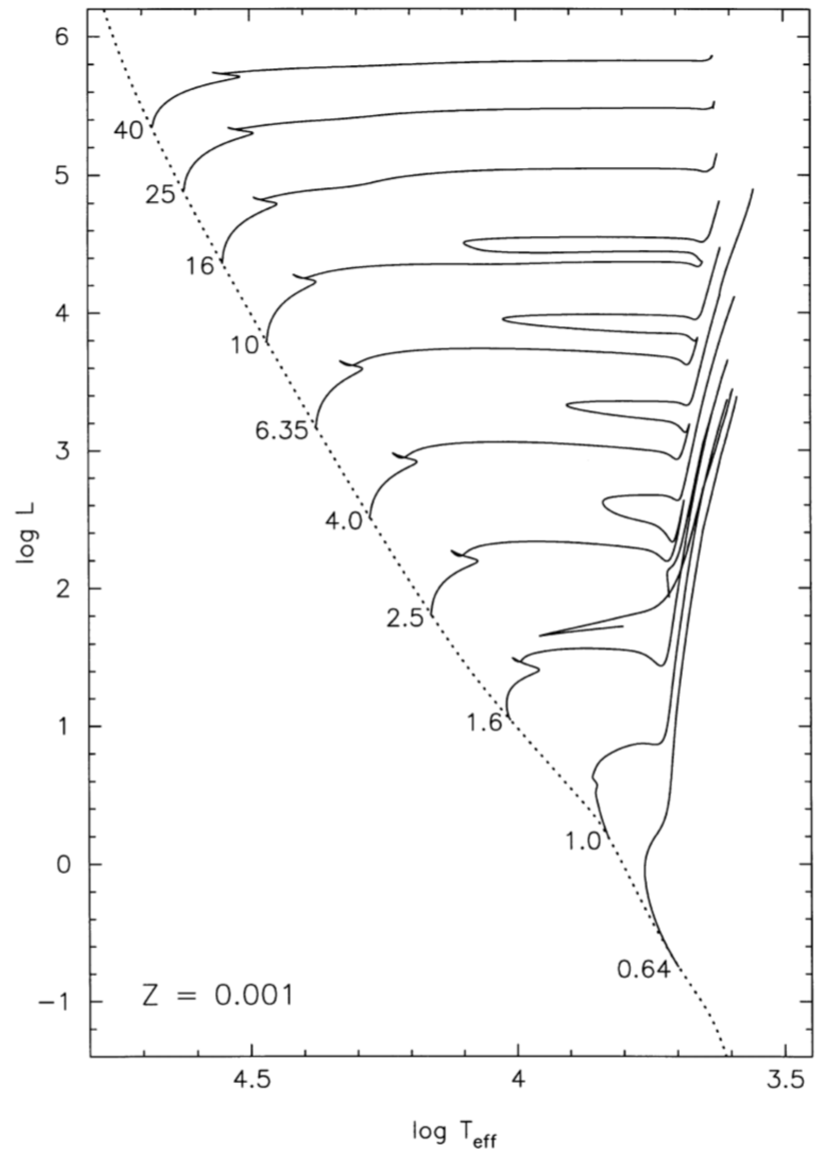


Kushnir+2016, Zaldarriga+2017, Hotokezaka & Piran 2017, Piran & Hotokezaka 2018



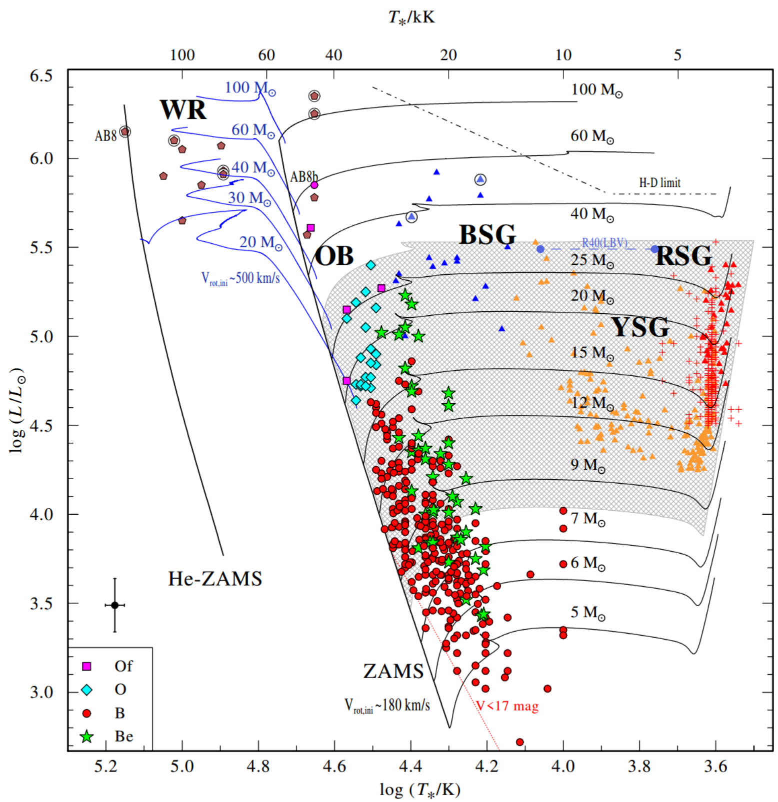
Pols et al. 1998



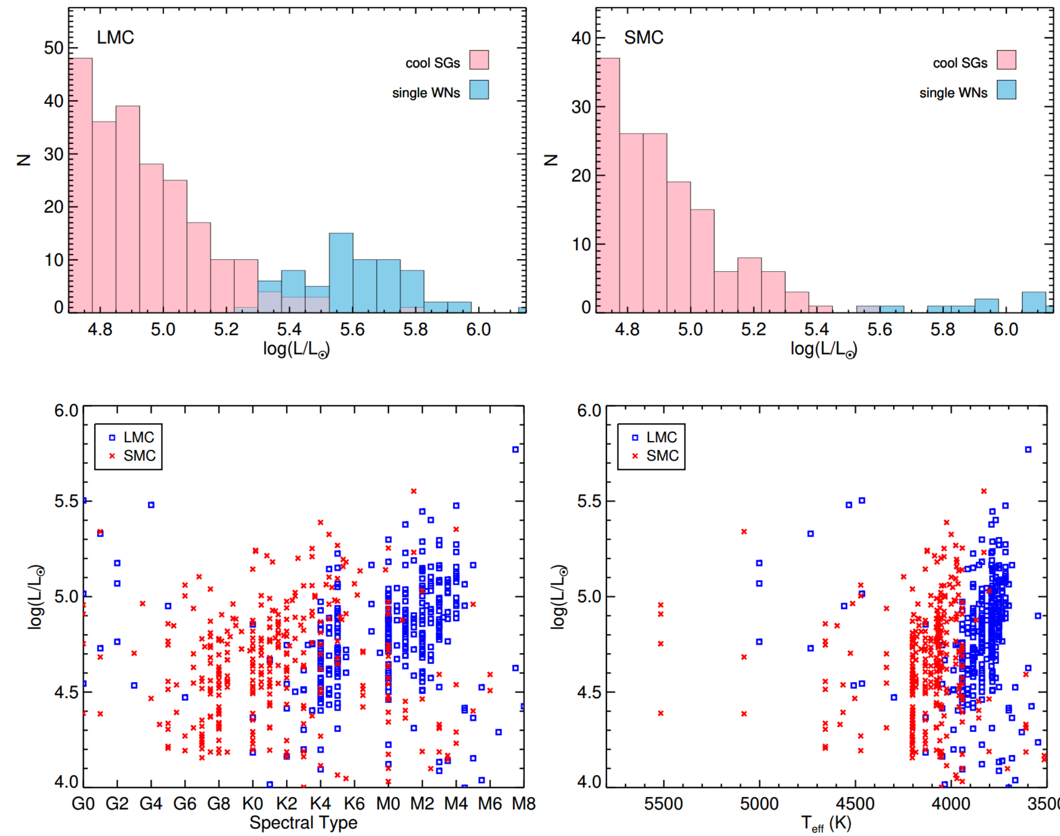


Pols et al. 1998

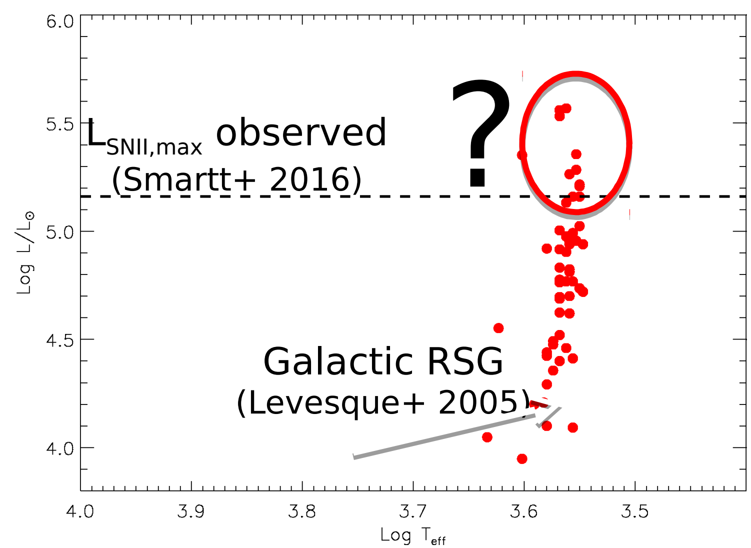
No luminous red supergiants



SMC, Ramachandran et al. 2019



SMC & LMC, Davies et al. 2018



There are **no observed red supergiants above the luminosity $\log(L/L_\odot)$ = 5.6**.

1D models can easily produce them.

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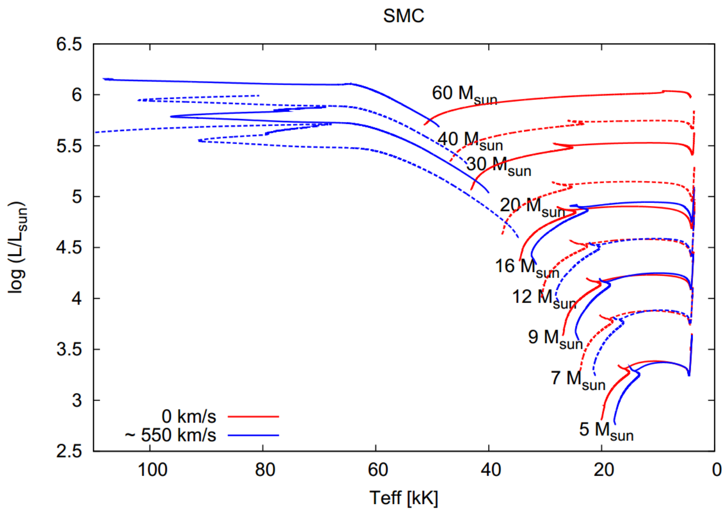

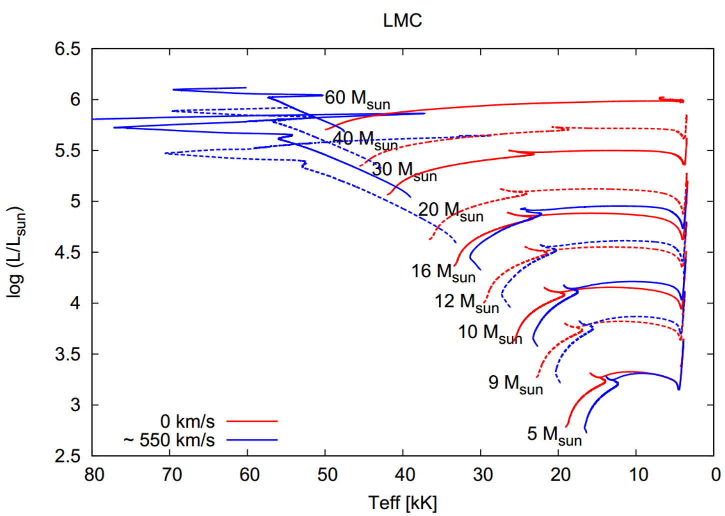

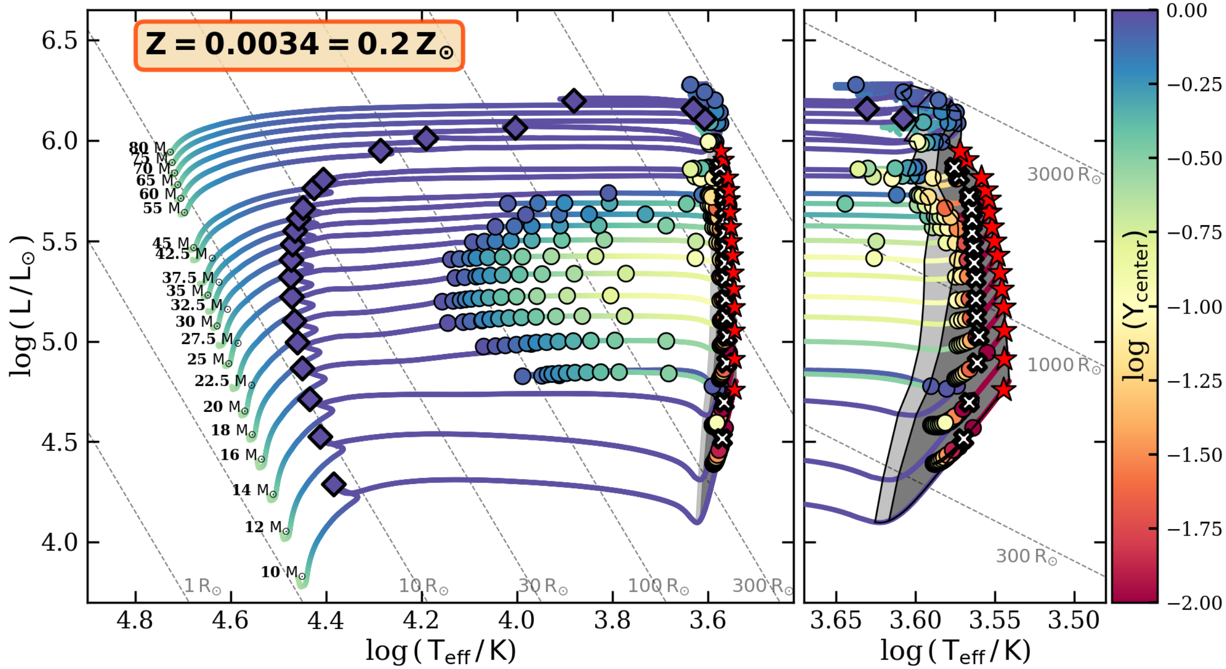

Brott et al. 2011

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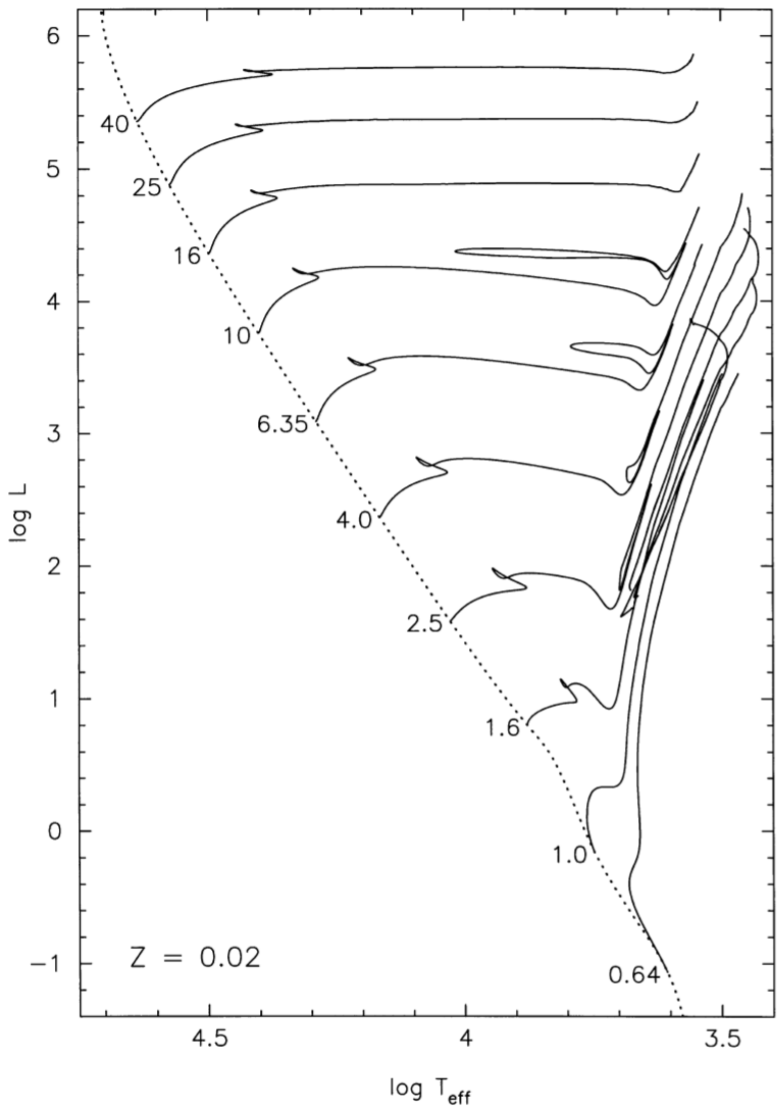
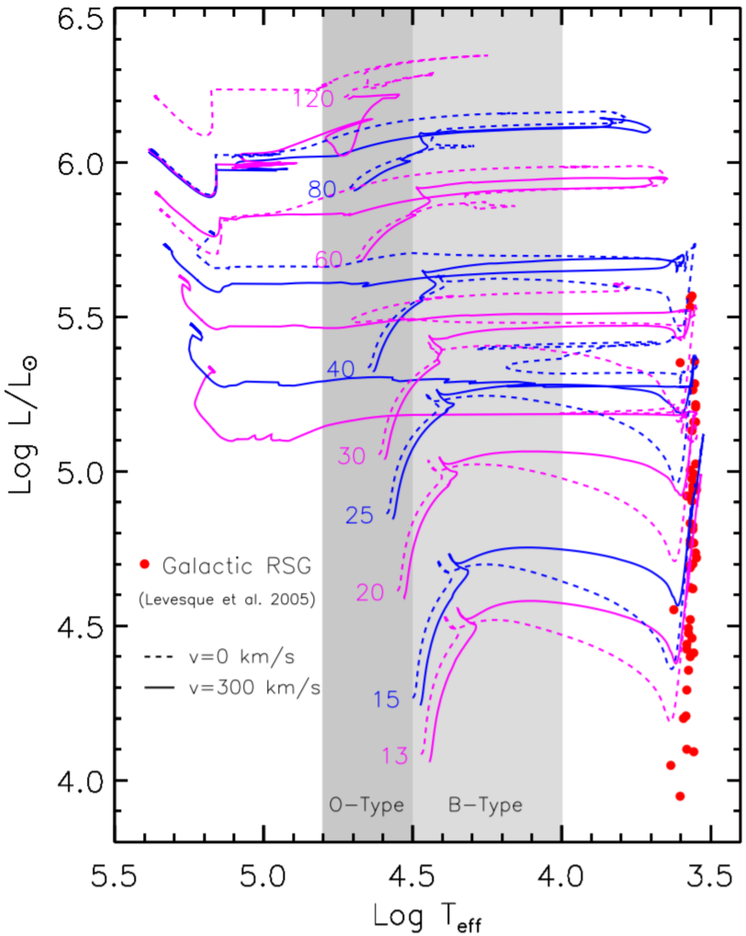
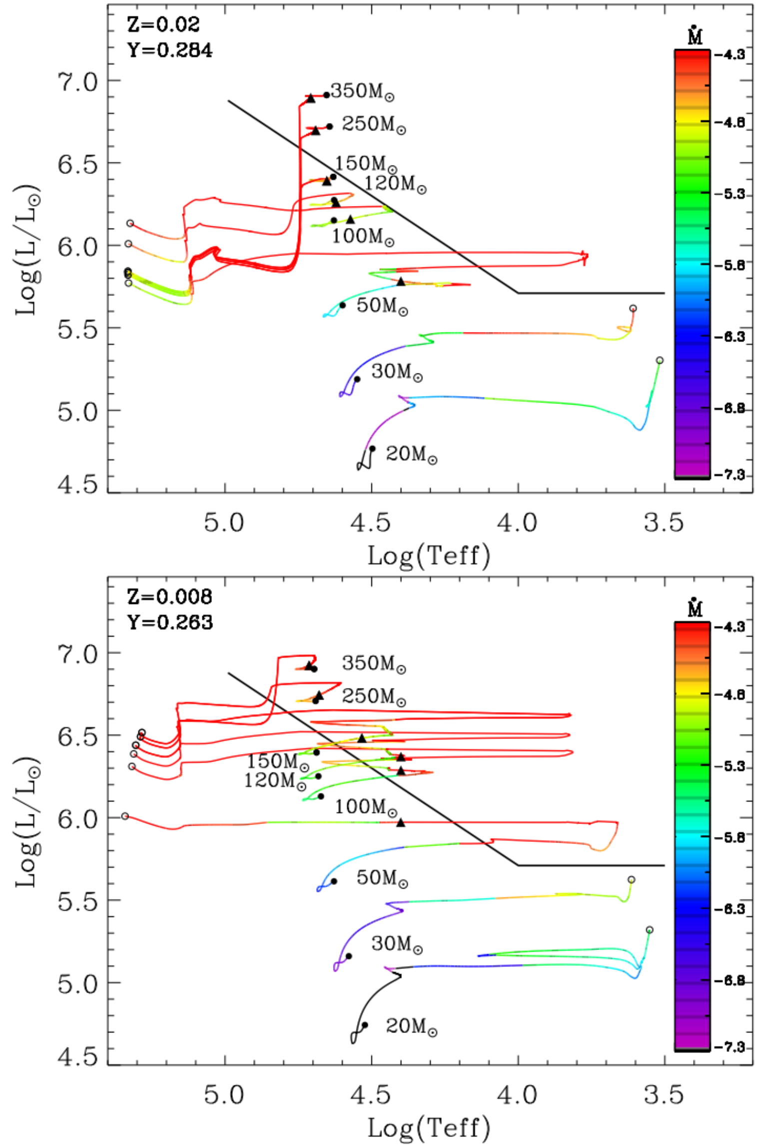


Pols et al. 1998

Models without the RSG problem – mass loss

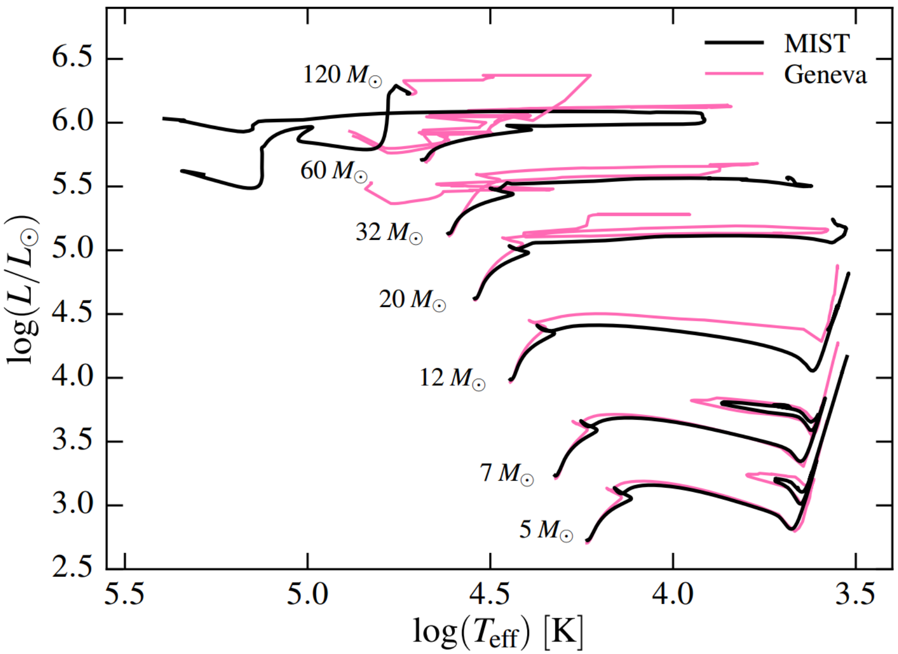


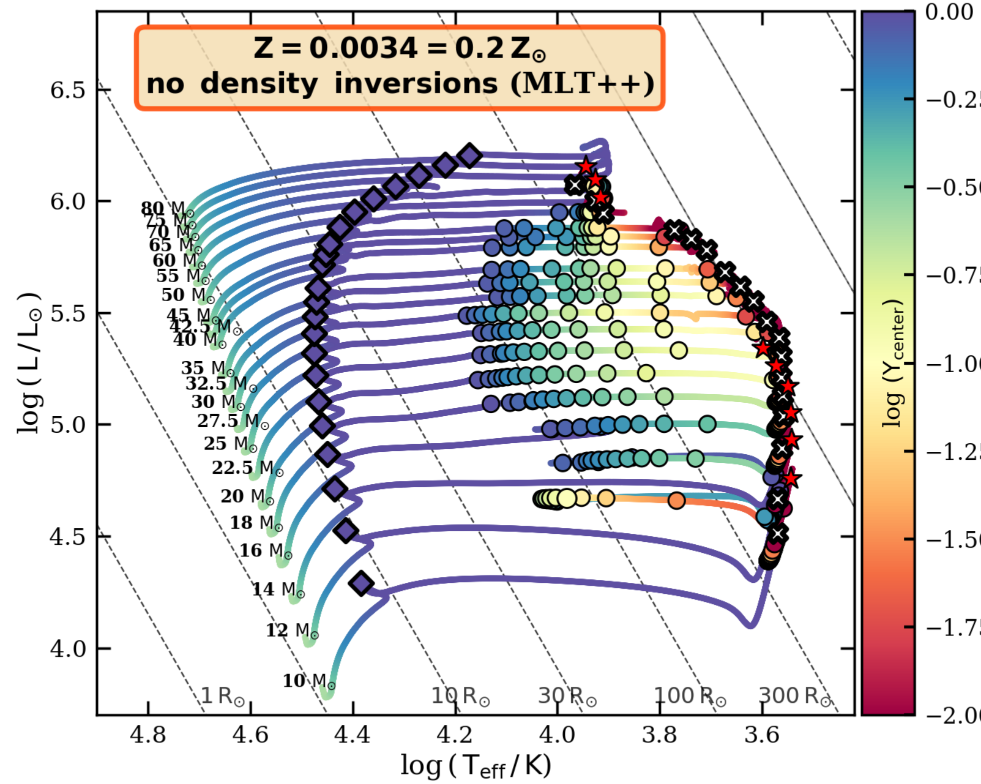
Chieffi & Limongi (2013)
(dust driven winds from van Loon 2005)



Chen, Bressan, et al. 2015
(winds enhanced by the Eddington factor, guided by Grafener & Hamann 2008)

Models without the RSG problem – reduced superadiabaticy, eliminated density inversions (~ more efficient convection in the outer envelope)

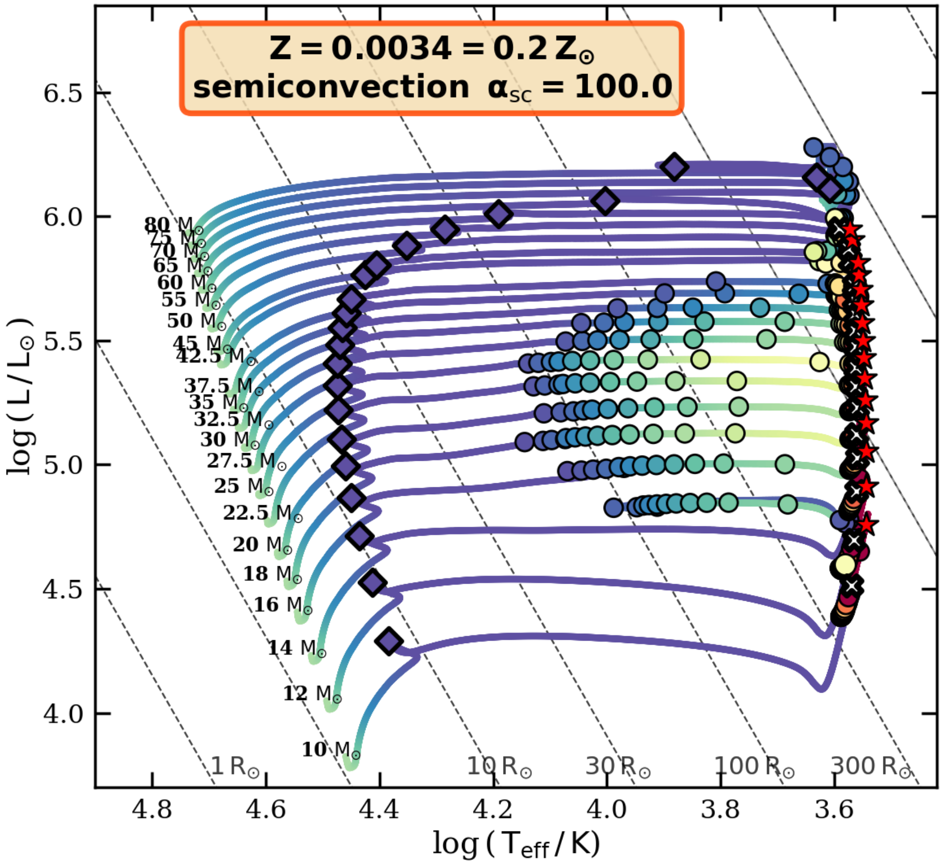


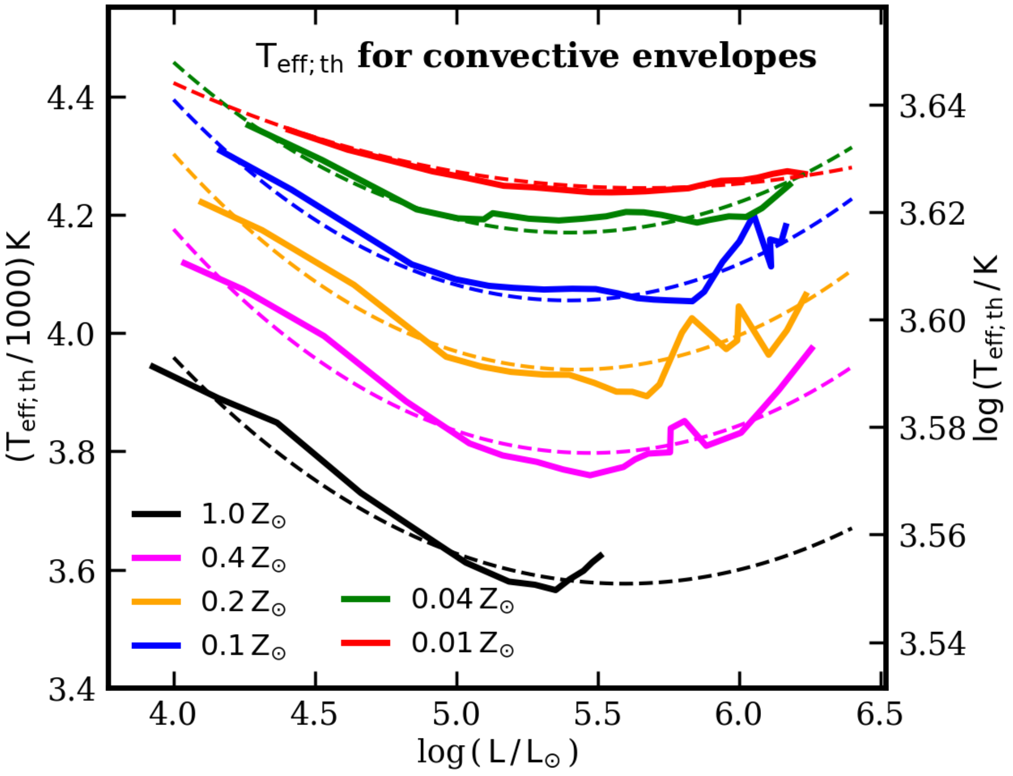


Choi et al. (2016) – MLT++

Ekstrom et al. (2013) – $H_p \rightarrow H_d$

No high-mass RSGs → stars M > 40 $M_\odot$ never develop outer convective envelopes?





Common envelope donors

Critical mass ratio:

q > **$q_{critical}$** → **unstable MT, common envelope**

<u>Radiative envelopes:</u>

~~$q_{critical}$ = 3.5 (Ge et al. 2010)~~ mis-used…

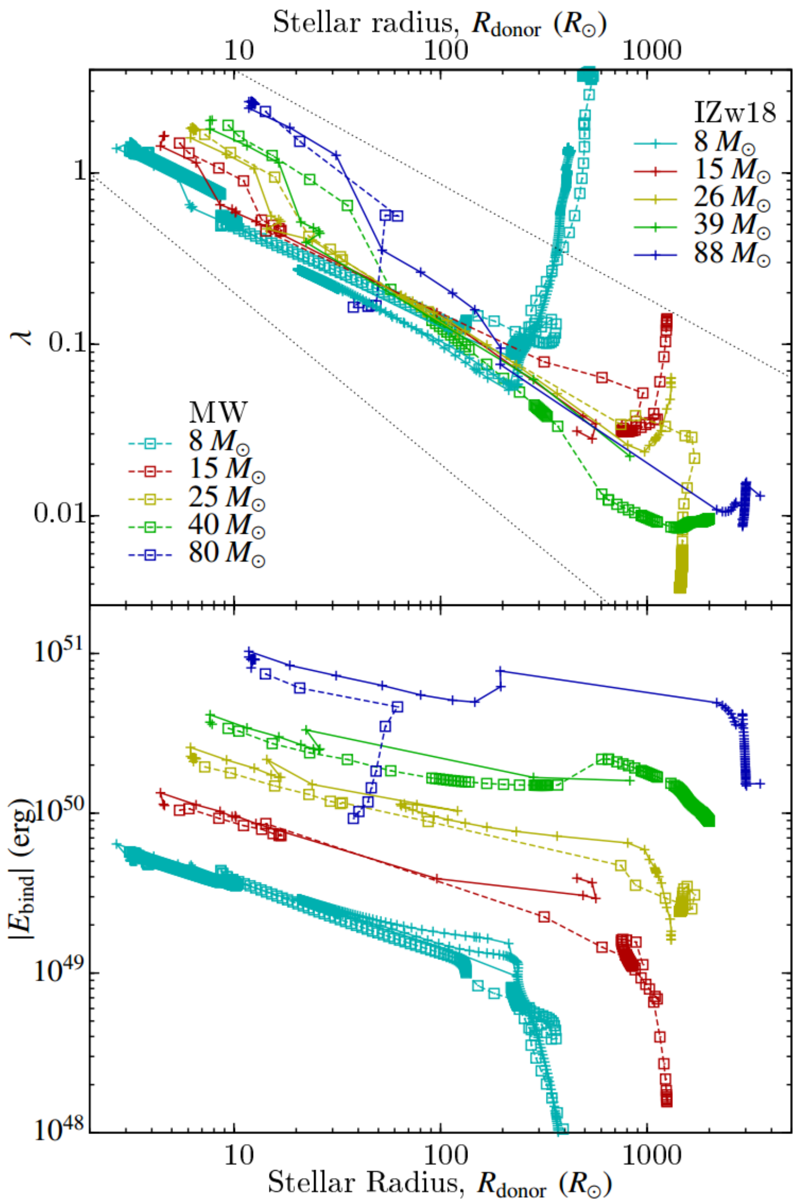
$q_{critical}$ > 5 (Ge et al. 2015) for M > 20 $M_{\odot}$

$q_{critical}$ ~ 8 (Pavlovskii et al. 2017)

$q_{critical}$ ~ 4-6 (Klencki et al, prelim; also Garcia in prep.)

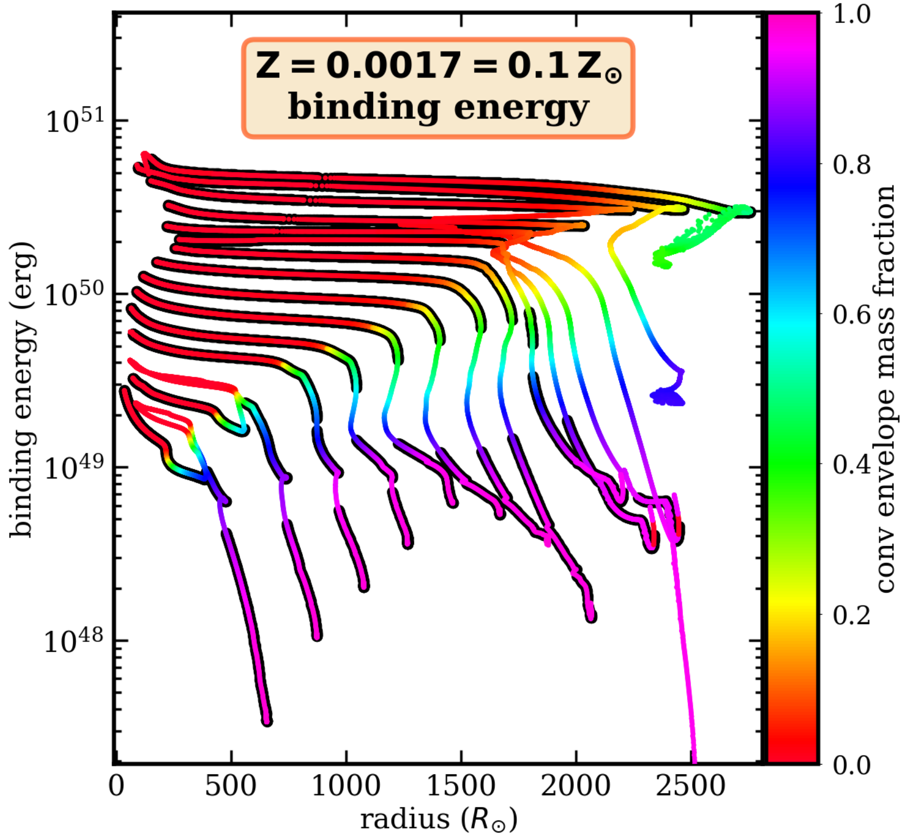
<u>Convective envelopes (30% in mass):</u>

$q_{critical}$ ~ 1.5 – 2.2 (Pavlovskii et al. 2015)

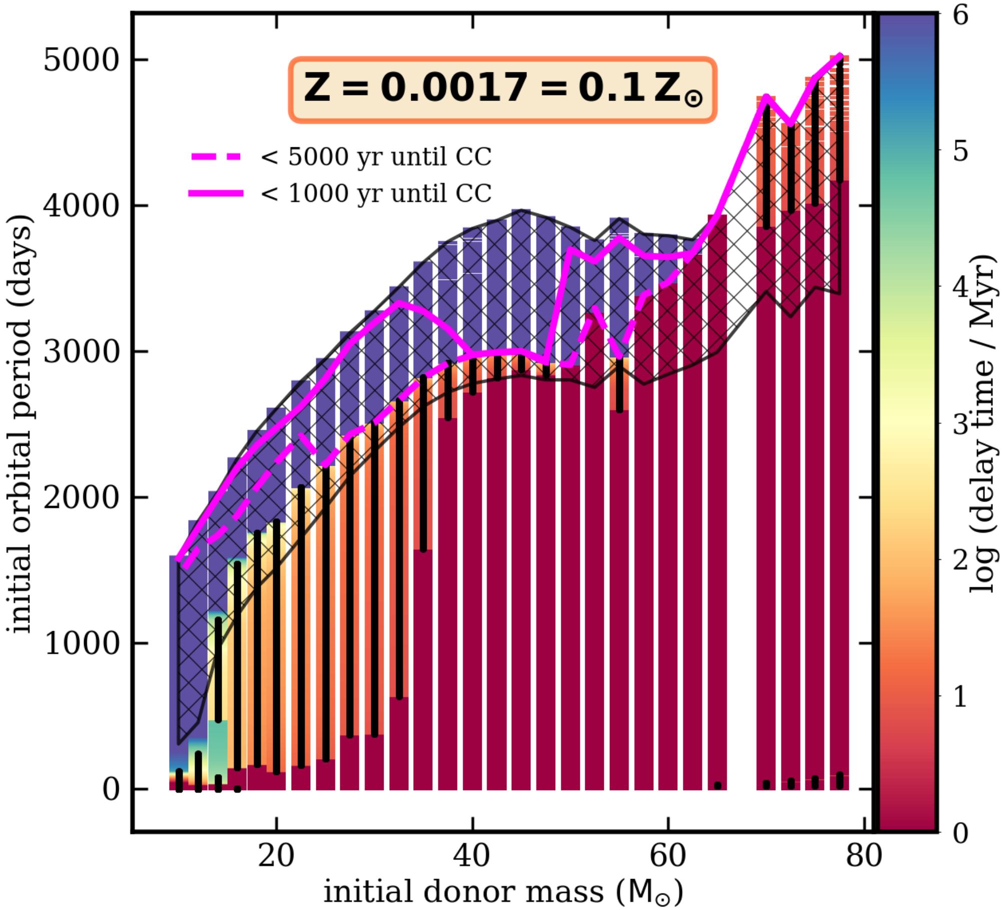


Kruckow et al. 2015

Outer convective-envelope → much lower binding energy of the envelope (1-2 orders of magnitude)



Klencki et al. (in prep)



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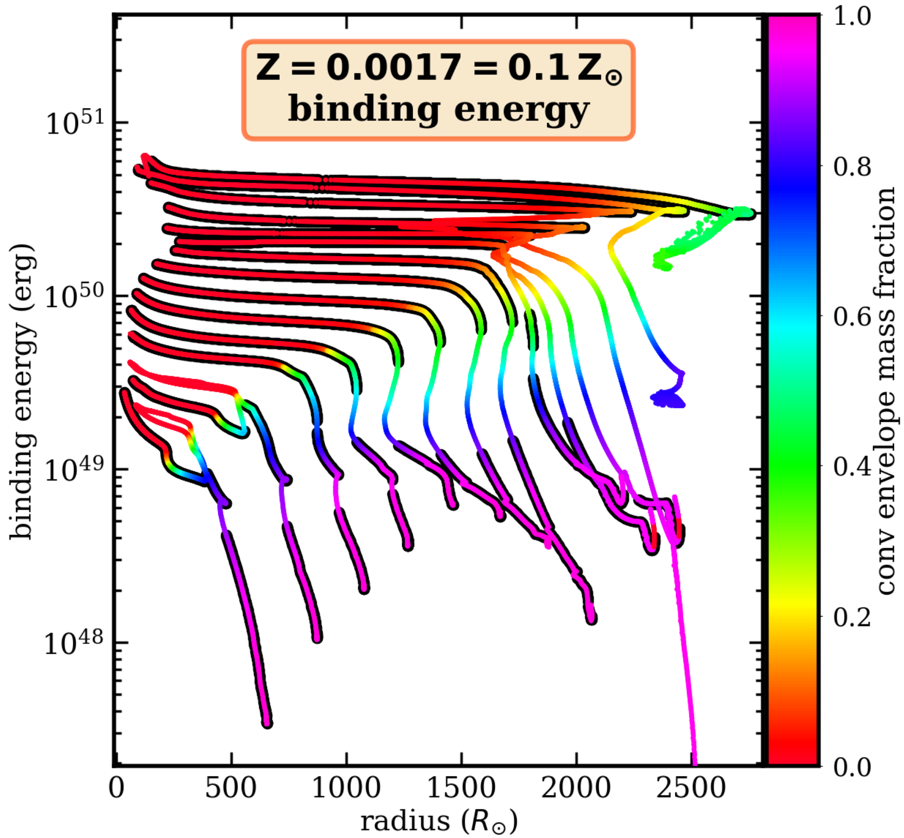
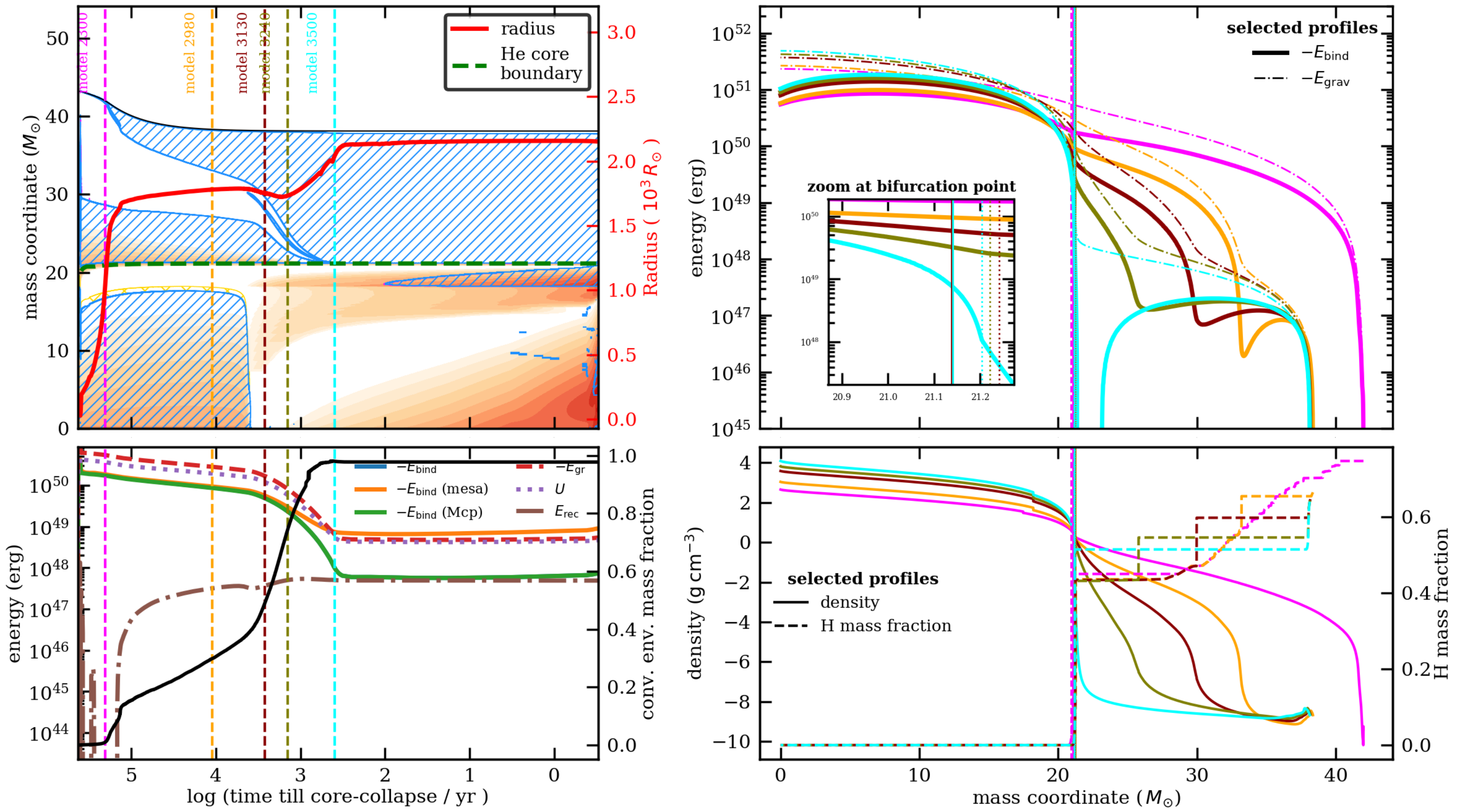


Without convective envelope E_{bind} drop not enough energy to eject CE?

Klencki et al. (in prep)


model 2500
model 2980
model 3130
model 3240
model 3500
radius
He core boundary
mass coordinate ($M_\odot$)
Radius ($10^3 R_\odot$)
energy (erg)
conv. env. mass fraction
$-E_{\rm bind}$
$-E_{\rm bind}$ (mesa)
$-E_{\rm bind}$ (Mcp)
$-E_{\rm gr}$
U
$E_{\rm rec}$
log (time till core-collapse / yr)
selected profiles
$-E_{\rm bind}$
$-E_{\rm grav}$
zoom at bifurcation point
density
H mass fraction
density (g cm^{-3})
H mass fraction
mass coordinate ($M_\odot$)