Post-AGB evolution of low and intermediate mass stars

preliminary results

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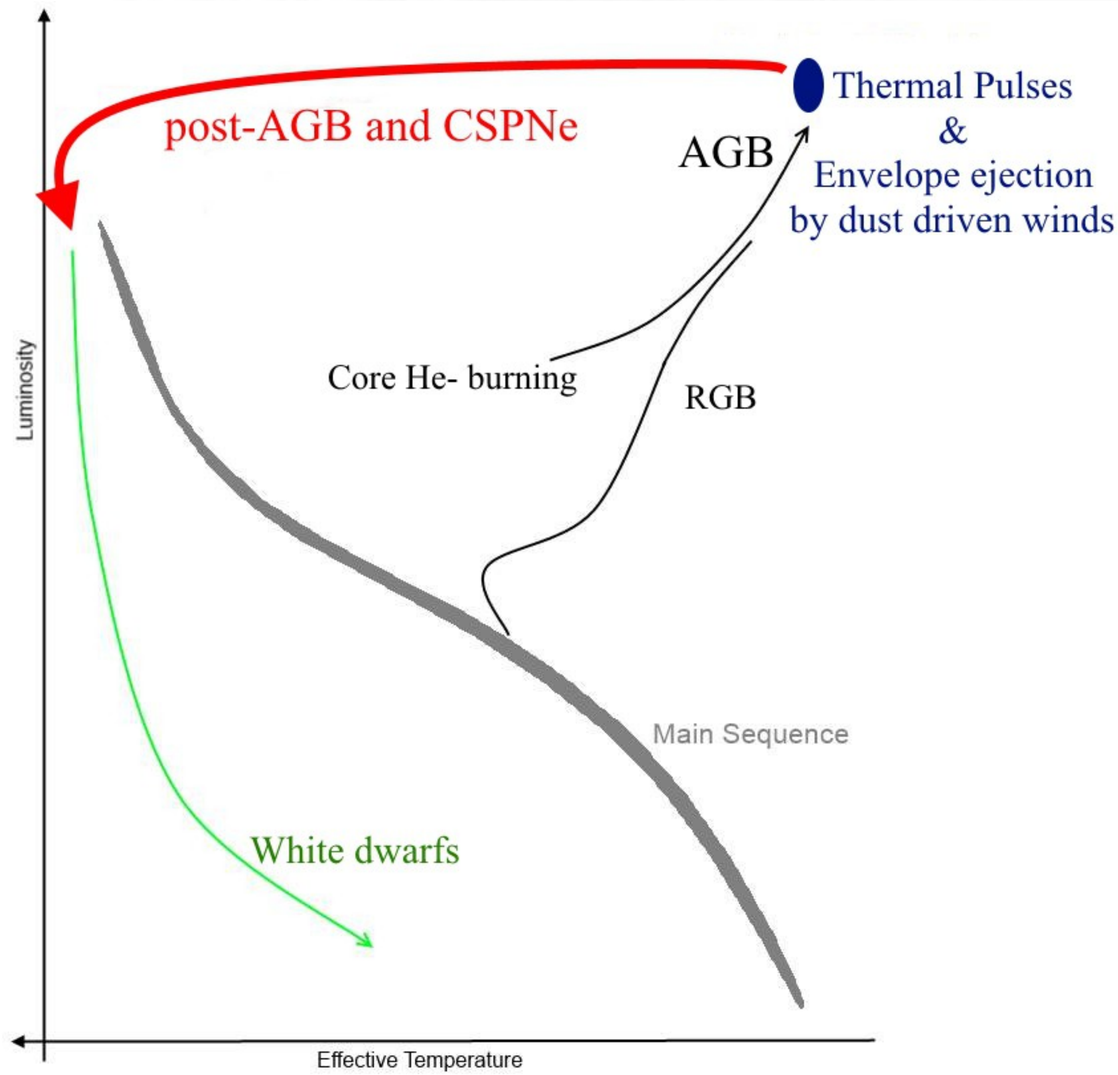
Introduction



Motivation

Post-AGB stellar evolution models and time scales are required for a variety of studies, e.g.:

- Study the formation of PNe.

- Mass & Age determinations of CSPNe.

- To link PNe and CSPNe to their progenitors stars and learn about nucleosynthesis on the AGB.

- Compute their contribution to the UV flux of old stellar populations.

- Help us understand the PNLF, in particular the invariance of the cut-off brightness.

Motivation (why new models?)

- Available post-AGB models (Vassiliadis & Wood 1994 and Bloecker 1995) are based on old microphysics. Particularly radiative opacities are **more than 40 years old**, and are expected to play a signifficant role in the timescales.
- Marigo (2002, also see Kitsikis 2008) showed that C-enriched molecular opacities strongly alter the effective temperatures of TP-AGB stars (*strong feedback on wind and mass loss*)
- There are indications that post-AGB timescales might be wrong:

  -Vassiliadis & Wood (1994) and Bloecker (1995) timescales do not agree with each other.

  - CSPNe mass-luminosity relation at variance with constraints from hydrodynamically consistent model atmospheres (Pauldrach et al. 2004)

  -Consistency between masses of WD and CSPNe requires *faster* evolutionary speeds (Gesicki et al. 2014)

This work:

- Compute post-AGB/CSPN models with updated physics and „realistic" previous evolution (i.e. in agreement with our current understanding)

  - Calibrate previous evolution to reproduce known observables.

  - Compute TP-AGB models that take into account the impact of C-rich composition on the molecular opacities.

  - Use consistent sets of mass loss prescriptions for O-rich and C-rich stars.

  - Test/calibrate models with two post-AGB observables: *Initial-Final Mass Relationship* and the *AGB intershell abundances* (assumed to be represented by those of PG1159 stars)

The *preliminary* experimental set up:

- Calibration of the solar model with diffusion: α_{MLT}=1.825
- Overshooting:

  - Calibration of the upper main sequence: *f=0.0174*, core convection

    (equivalent to R_{OV}=0.2 H_P, with the given cut-off)

  - Intershell abundances of PG1159 and M_iM_f relation: *f~0.005*, for the pulse driven convetion zone during TP-AGB.

  - *f*~0.1 at the base of the convective envelope (Lugaro et al. 2003, s-process)
- Updated mass loss prescriptions (including the transition to a C-rich AGB star):

  - Cold winds RGB/AGB: Schröder & Cuntz (2005)

  - Pulsation dust driven winds: C-rich stars Groenewegen et al. (1998)

    O-rich stars Groenewegen et al. (2009)

  - Hot wind from CSPN: based on Pauldrach et al (2004)

The *preliminary* results: Z=0.01, 0.001, 0.0001

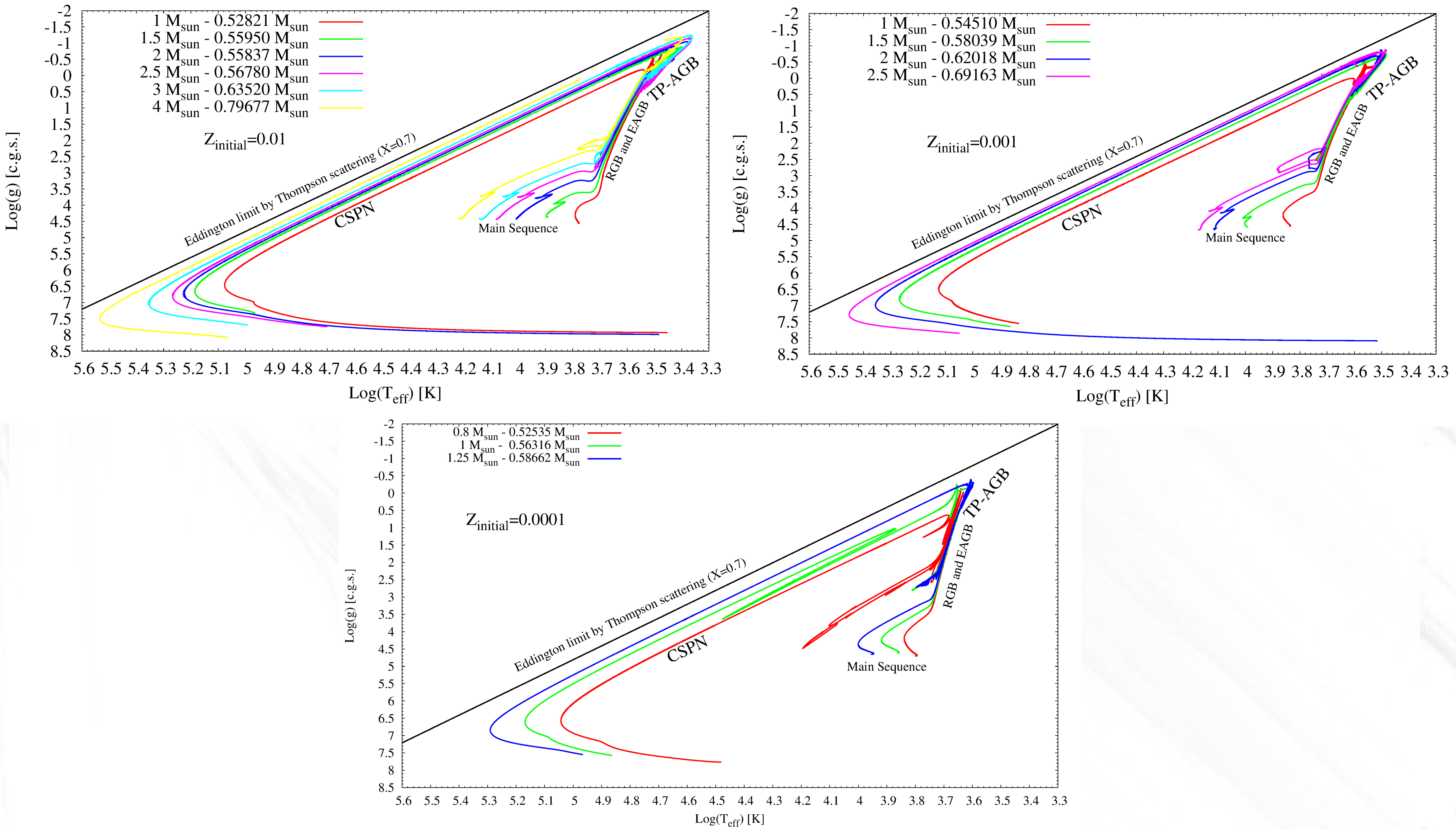


Table: Z_0=0.01 sequences.

Initial **Mass**	Final **Mass**	#Thermal Pulses	**Age** at the end of AGB*	Post-AGB **Crossing time**
1.00 M_{sun}	0.52821 M_{sun}	4	10511 Myr	22660 yr
1.50 M_{sun}	0.55950 M_{sun}	7	2585 Myr	5319 yr
2.00 M_{sun}	0.55837 M_{sun}	12	1208 Myr	2936 yr
2.50 M_{sun}	0.56780M_{sun}	11	721.4 Myr	1722 yr
3.00 M_{sun}	0.63520 M_{sun}	8	431.5 Myr	708 yr
4.00 M_{sun}	0.79677 M_{sun}	11	195 Myr	*67 yr*
5.00 M_{sun}	~0.861 M_{sun}	39	~110 Myr	-

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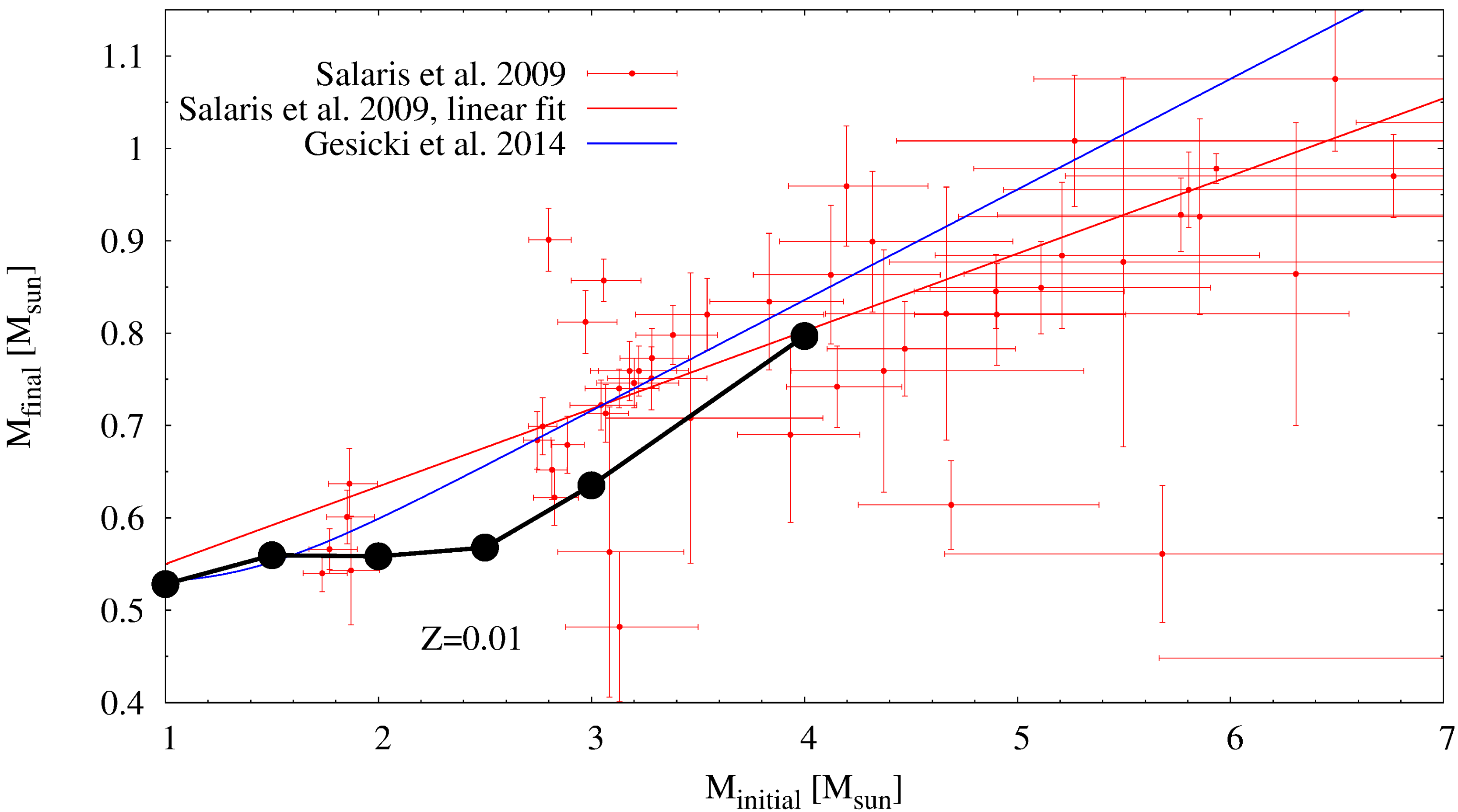
Test: Initial-Final Mass Relationship



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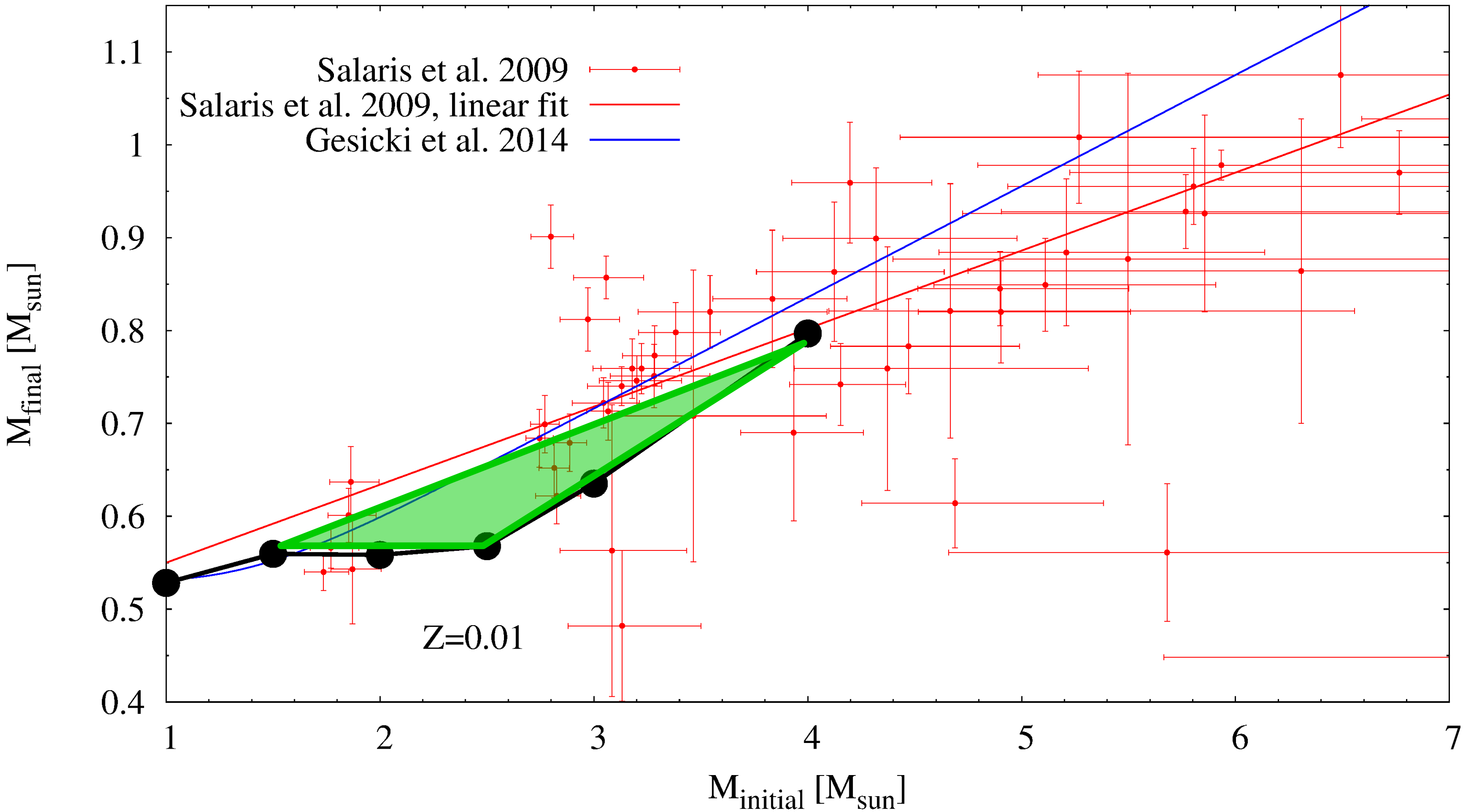
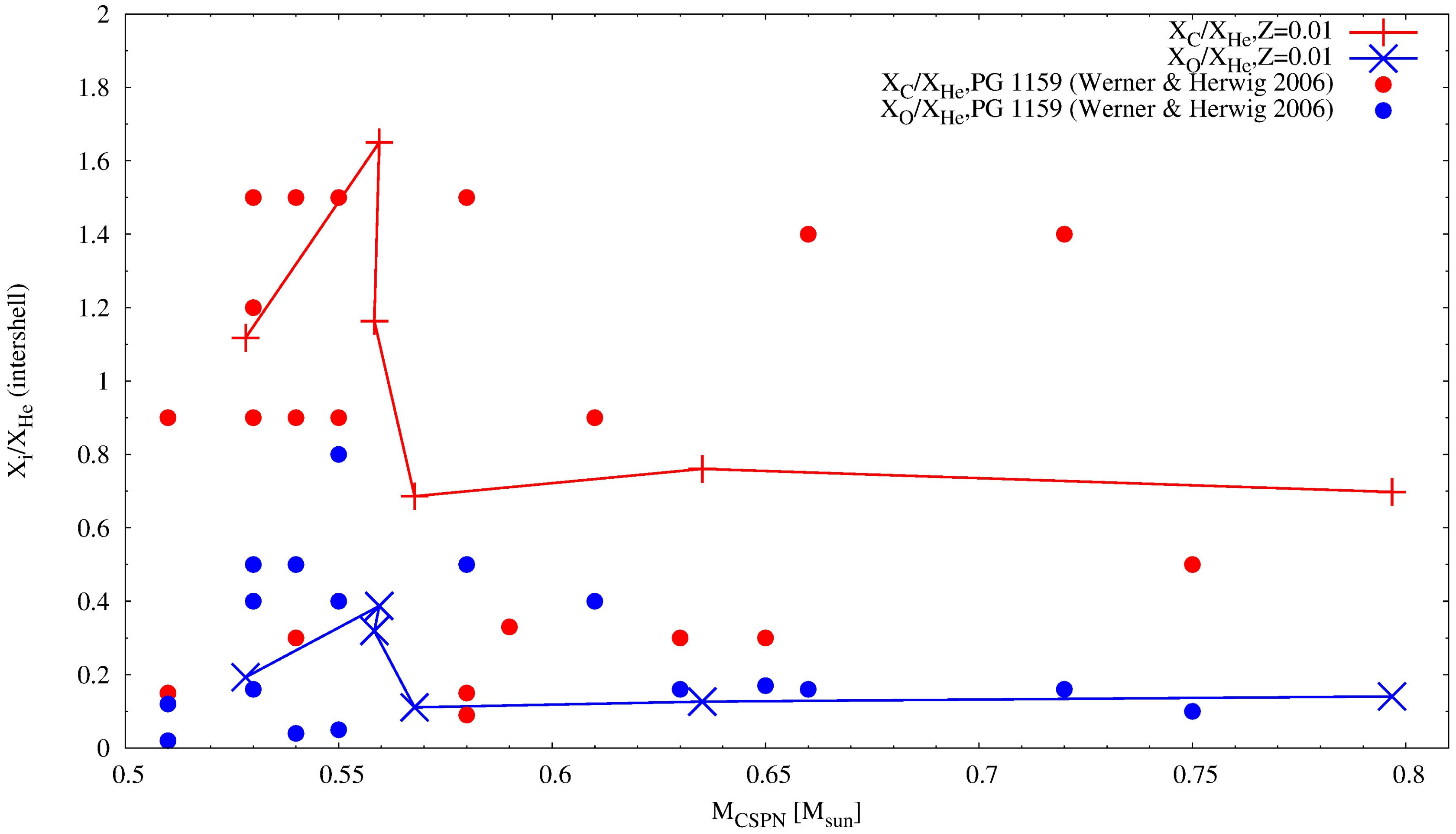
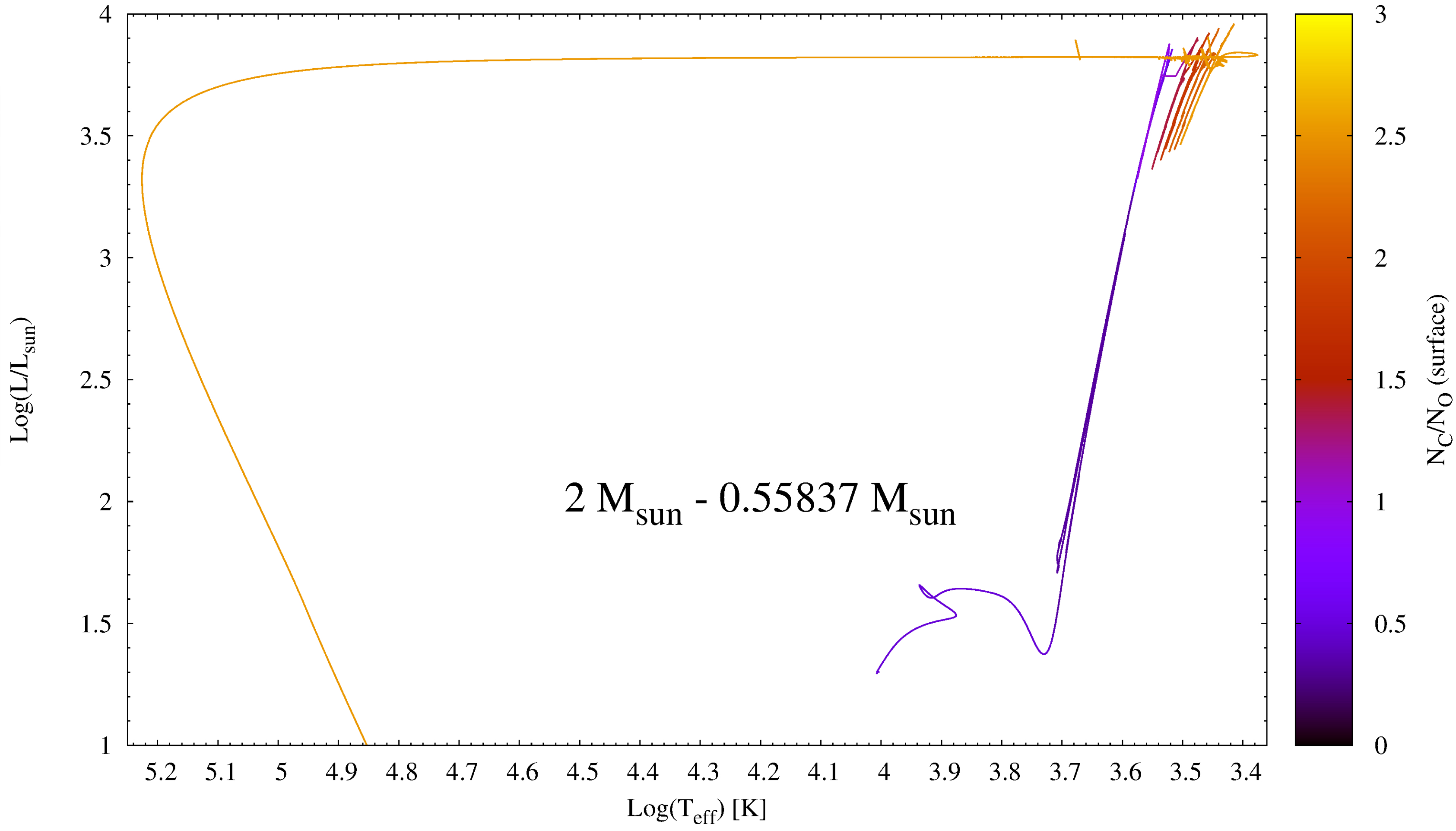


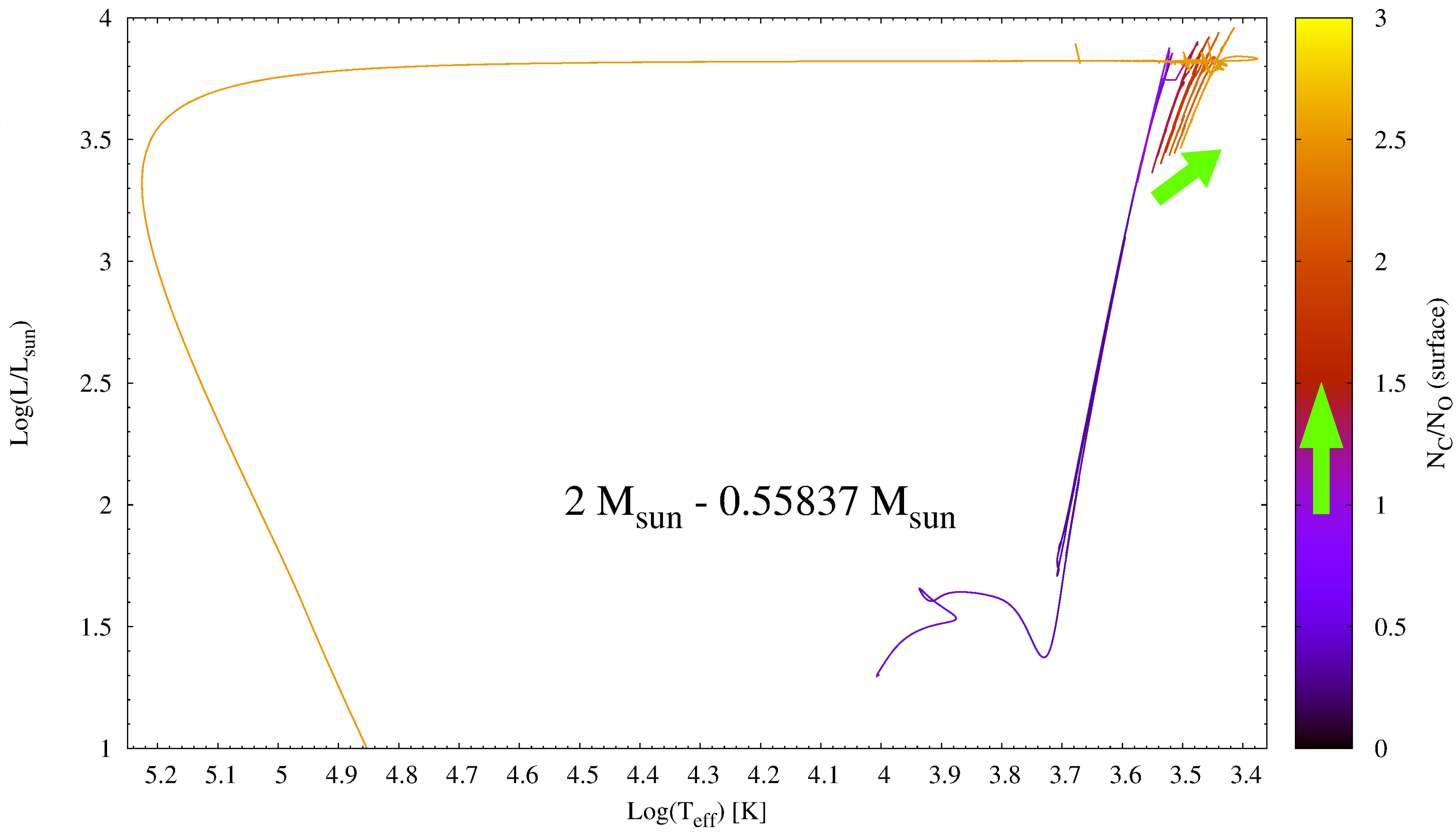
Test: Intershell abundances of the post-AGB models



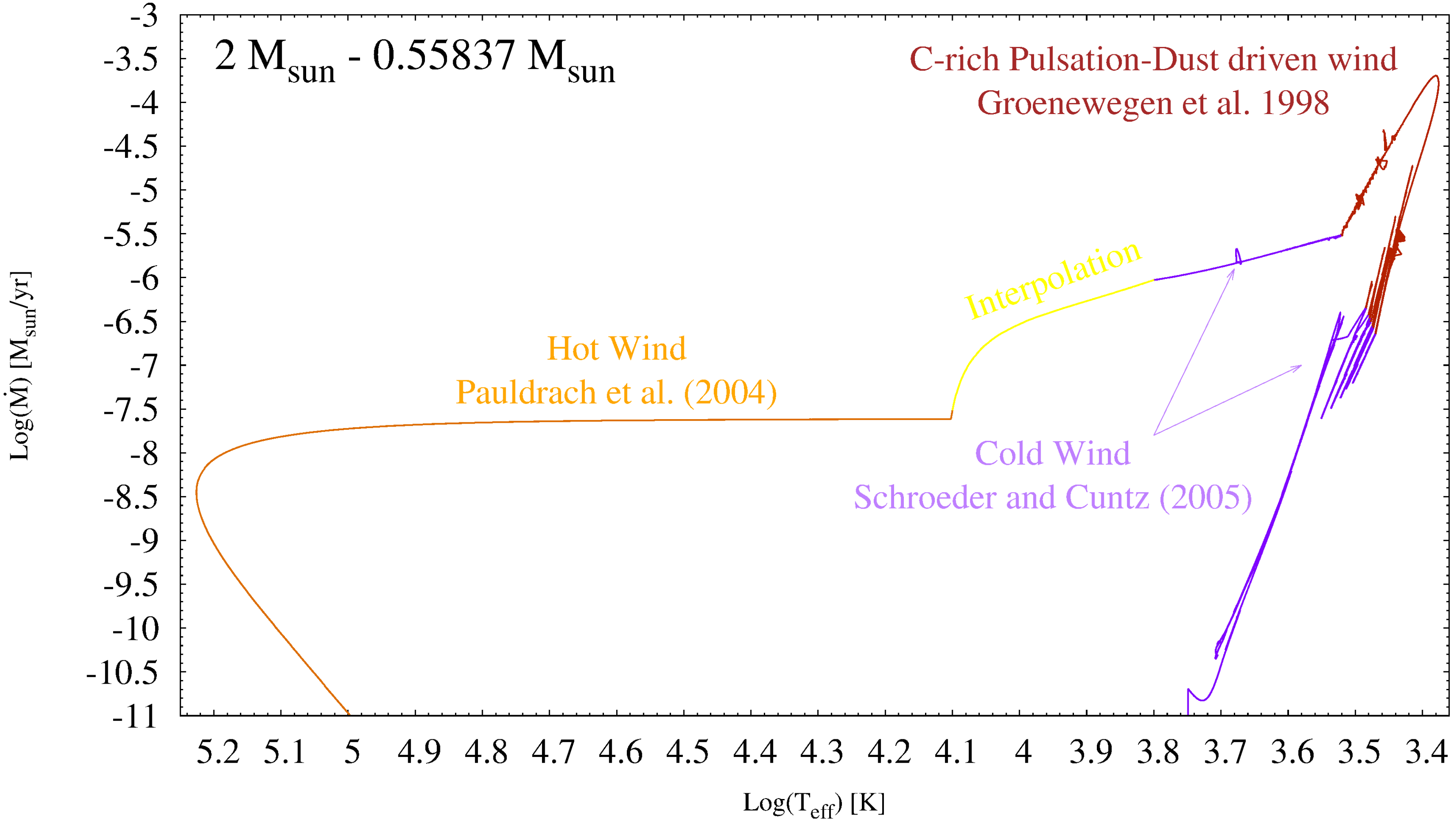
Example: 2M_{sun}, Z=0.01, HR-diagram & C/O ratio



Example: $2M_{sun}$, Z=0.01, HR-diagram & C/O ratio



Example: 2Msun, Z=0.01. **Winds.**



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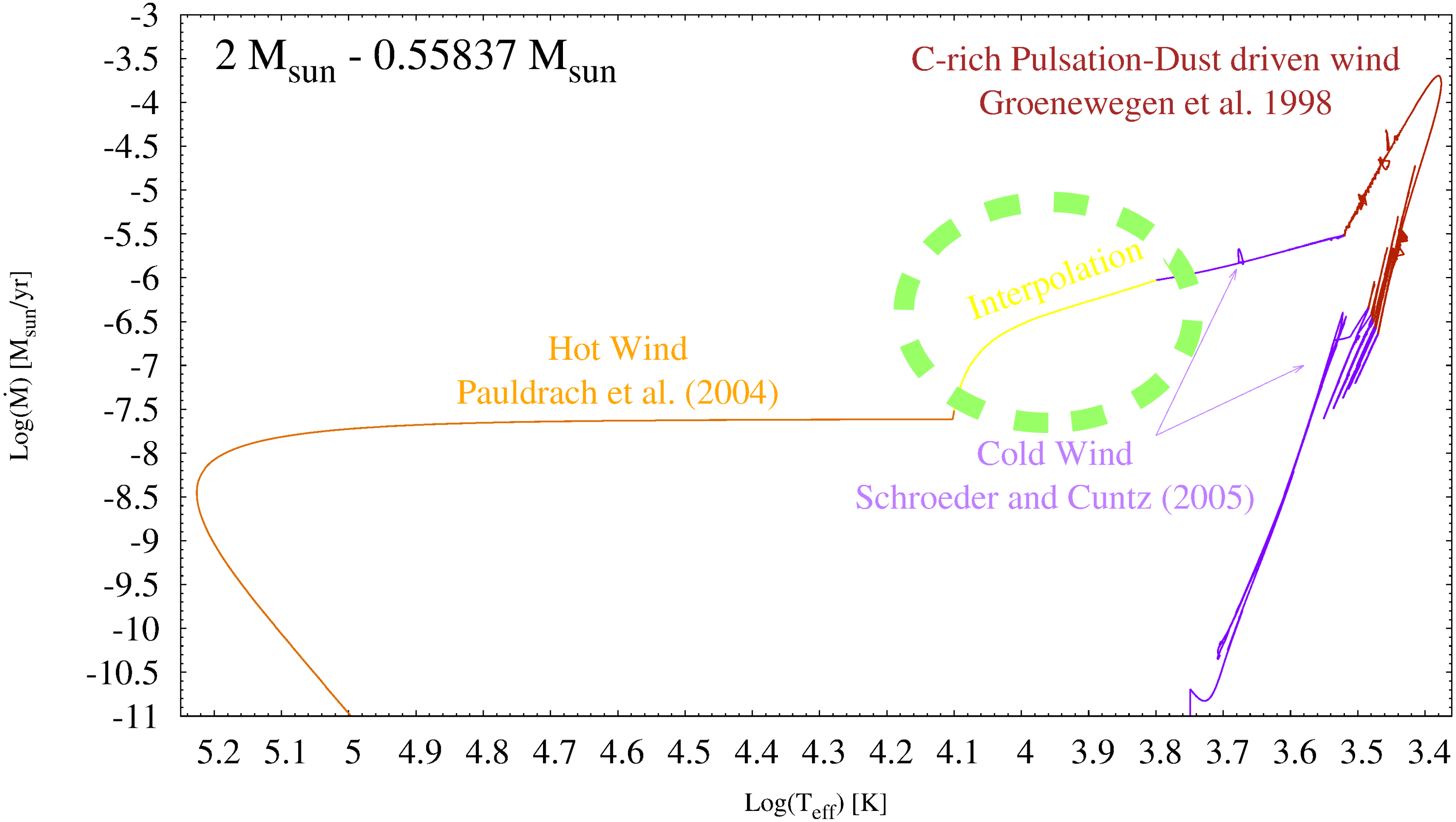
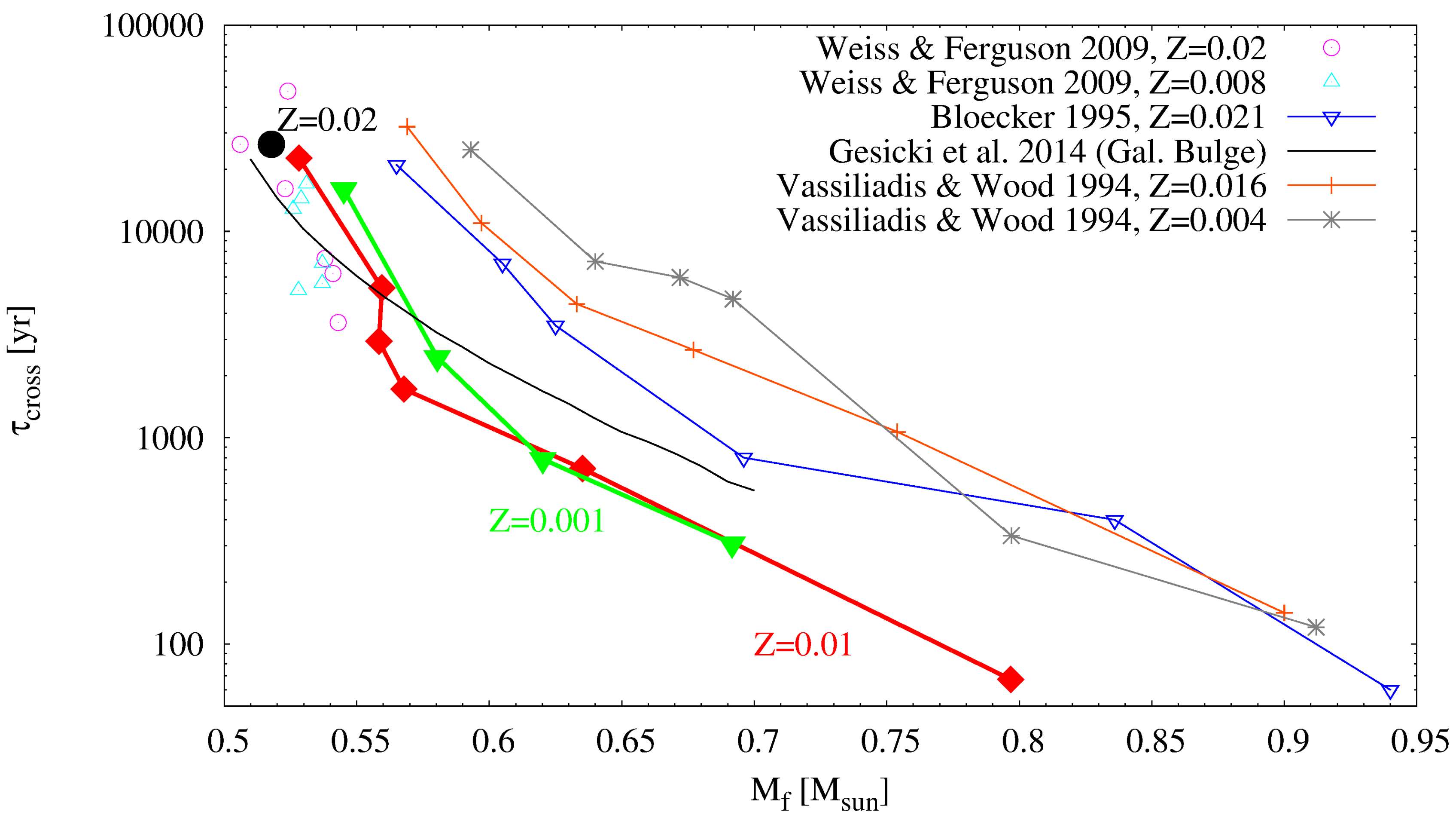


The „crossing times”: from T_{eff}=10000 K to T_{eff}^{Max}



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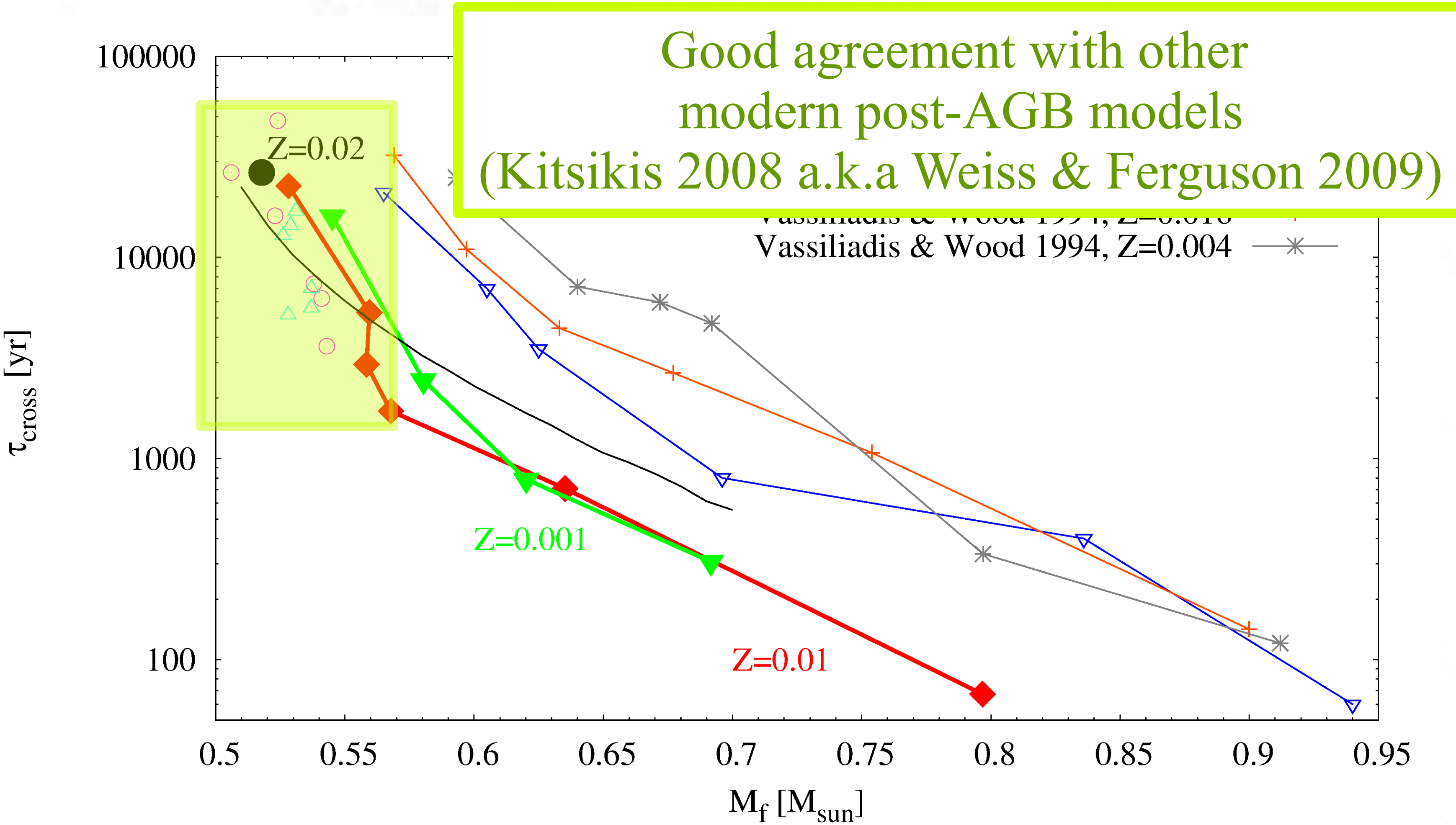

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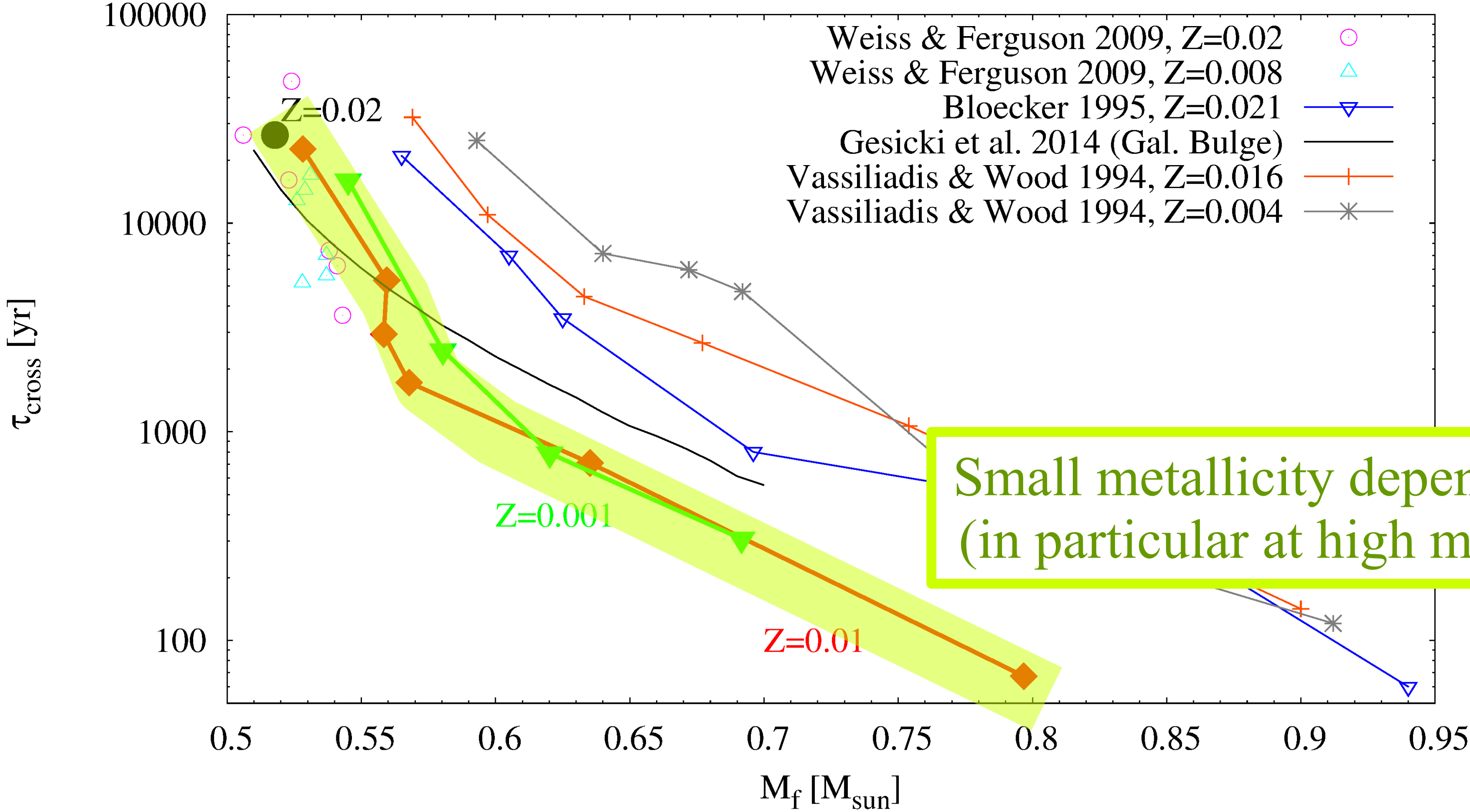

Small metallicity dependence
(in particular at high masses)

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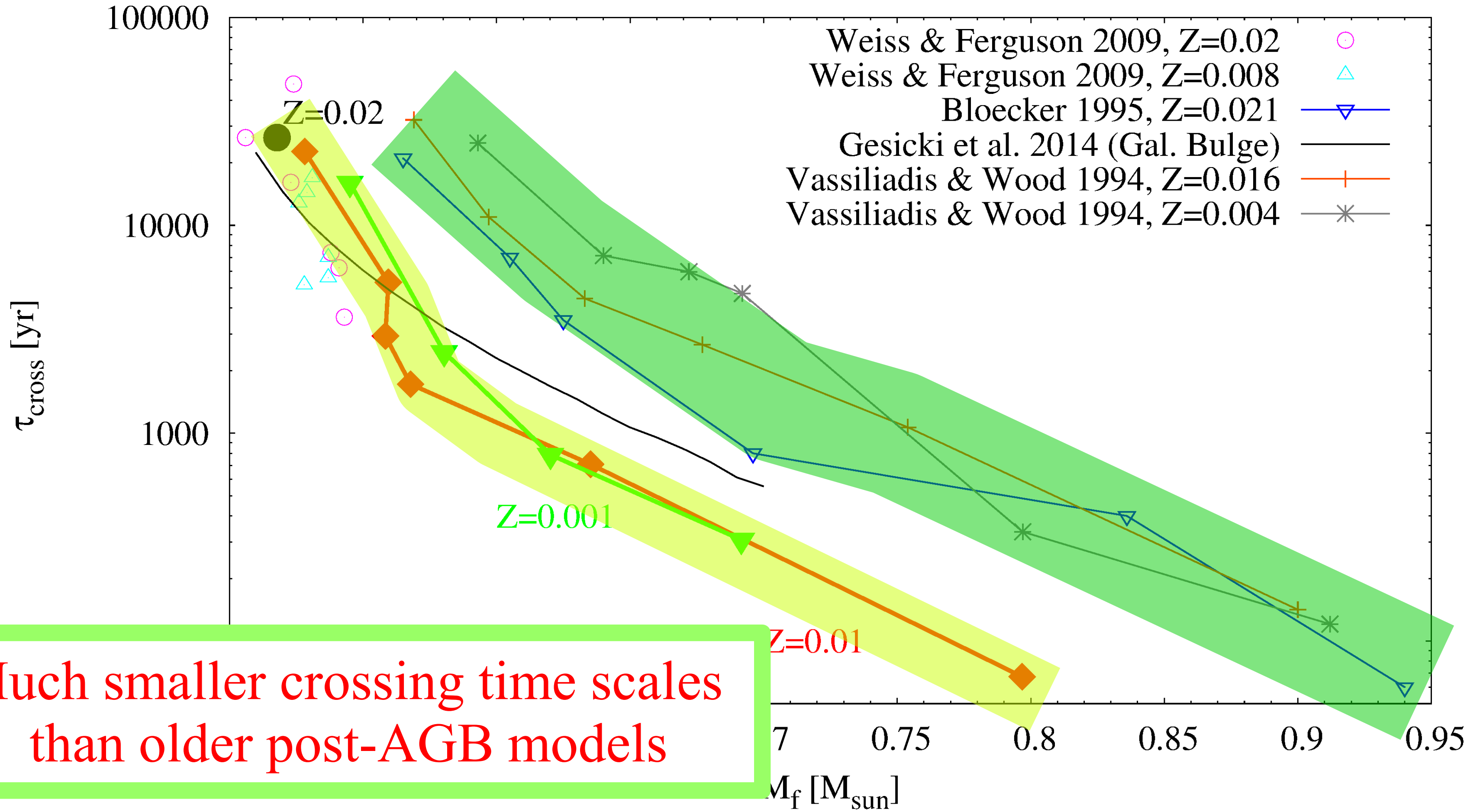

Much smaller crossing time scales than older post-AGB models

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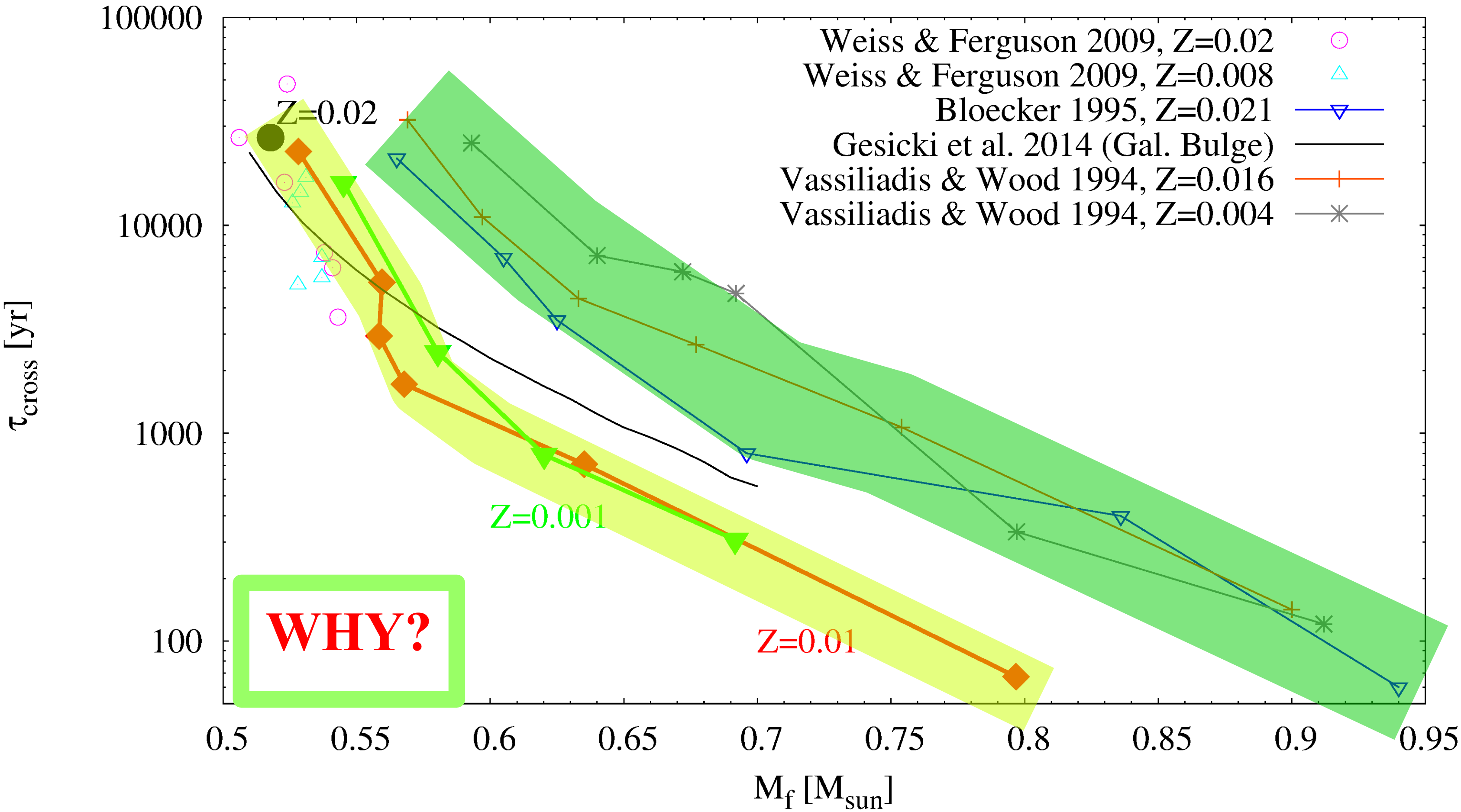
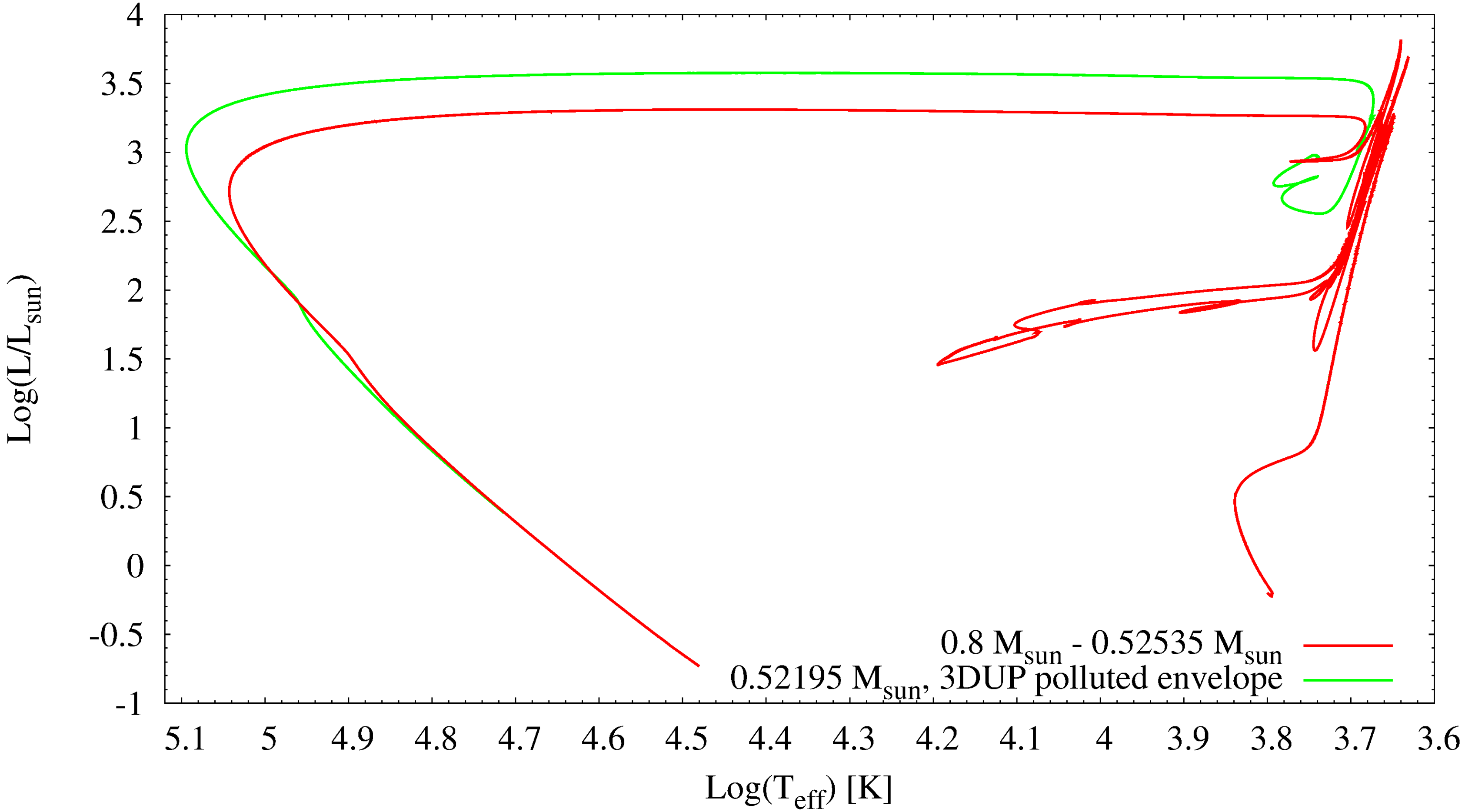


Post-AGB timescale and third dredge up on the AGB



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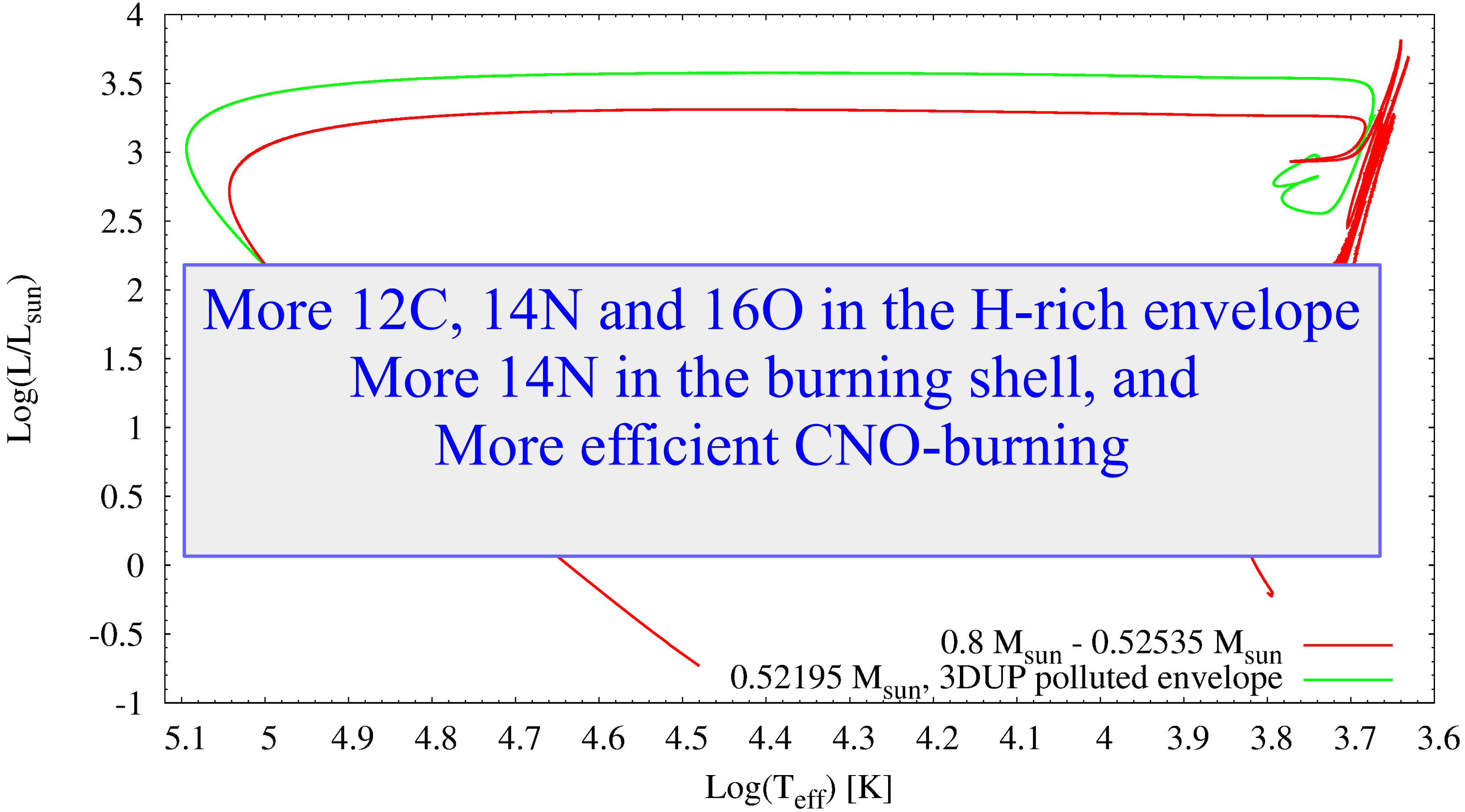
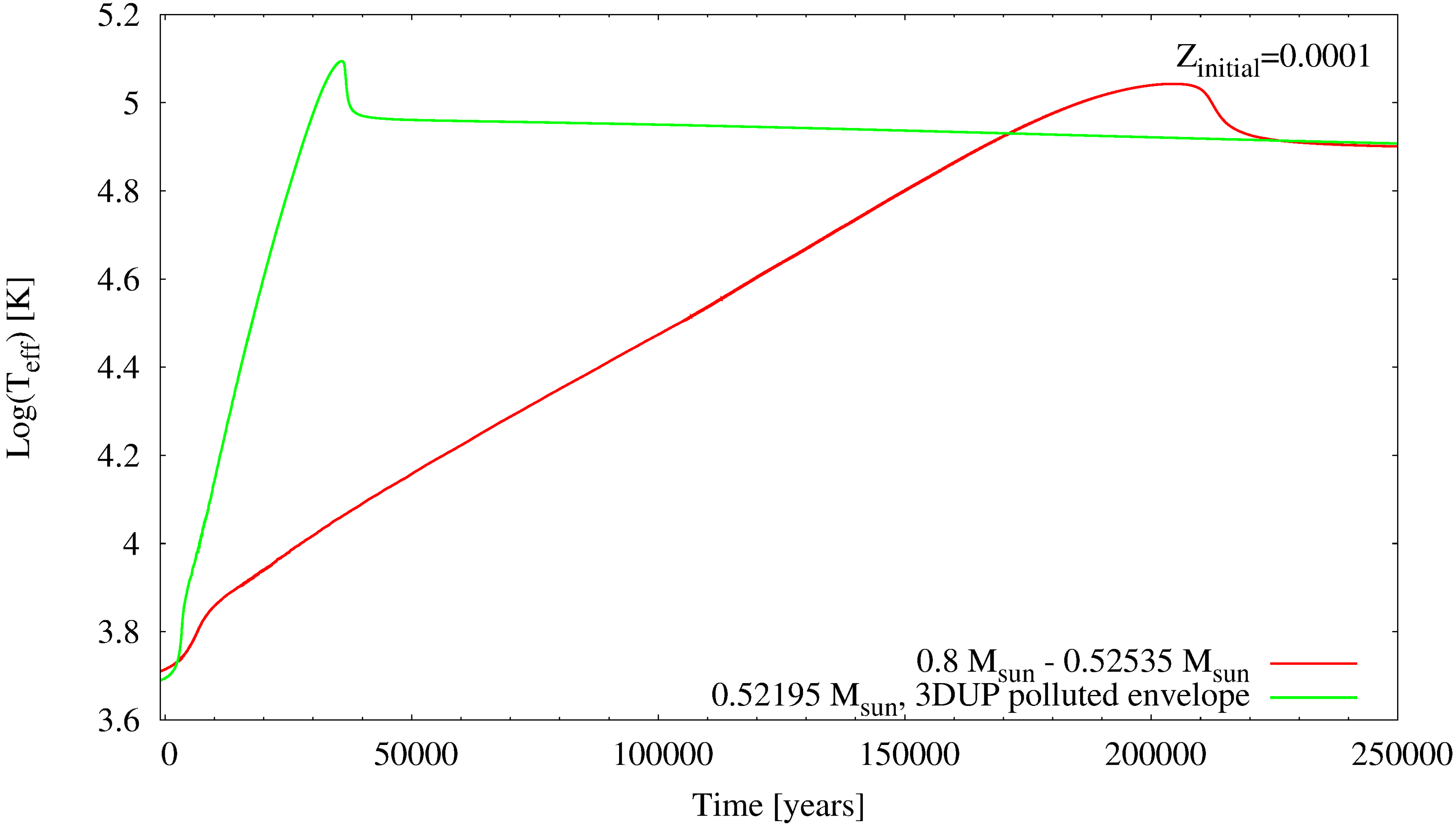
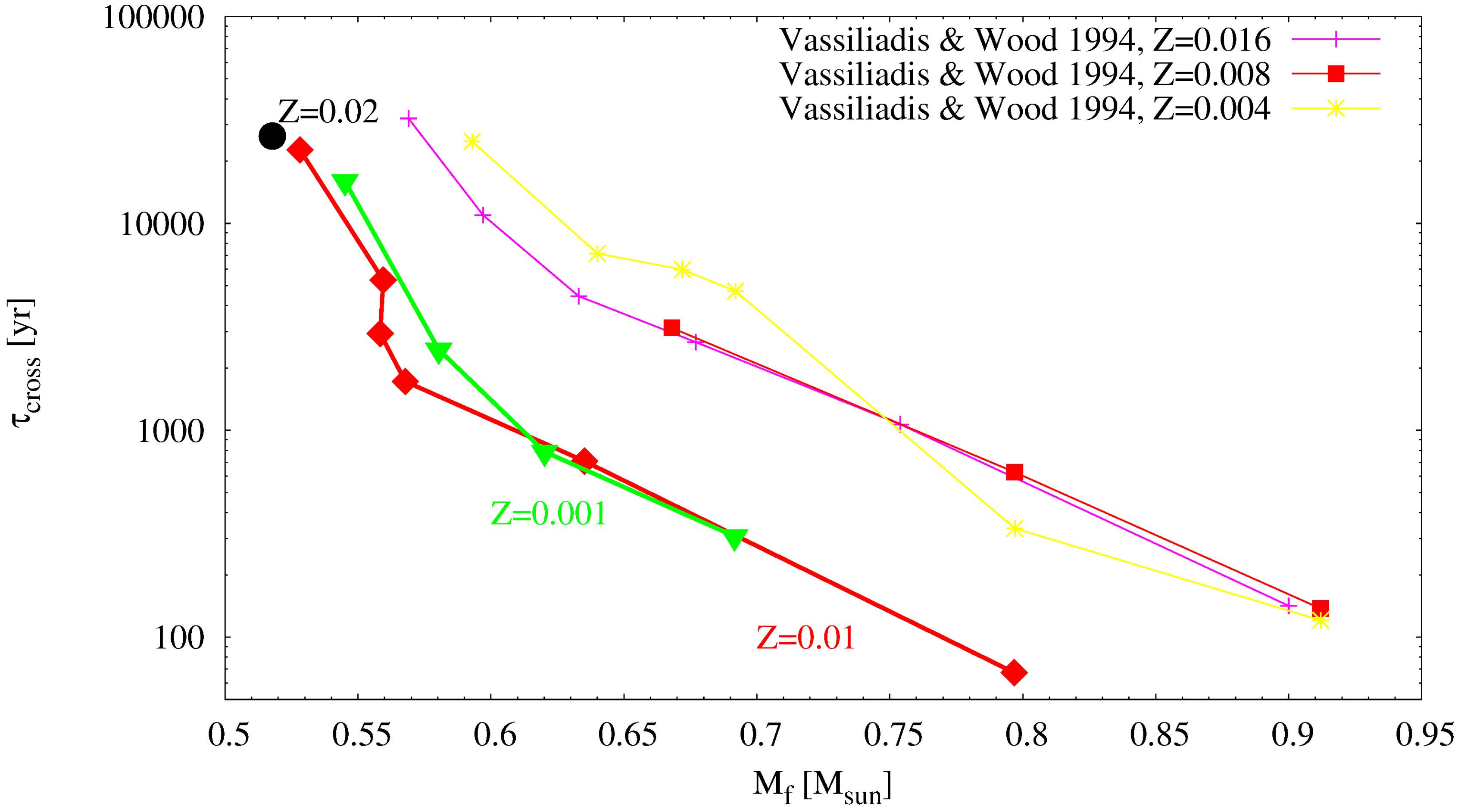


3rd Dredge Up on the AGB shortens post-AGB times



Looking back to the PNe Luminosity Function...



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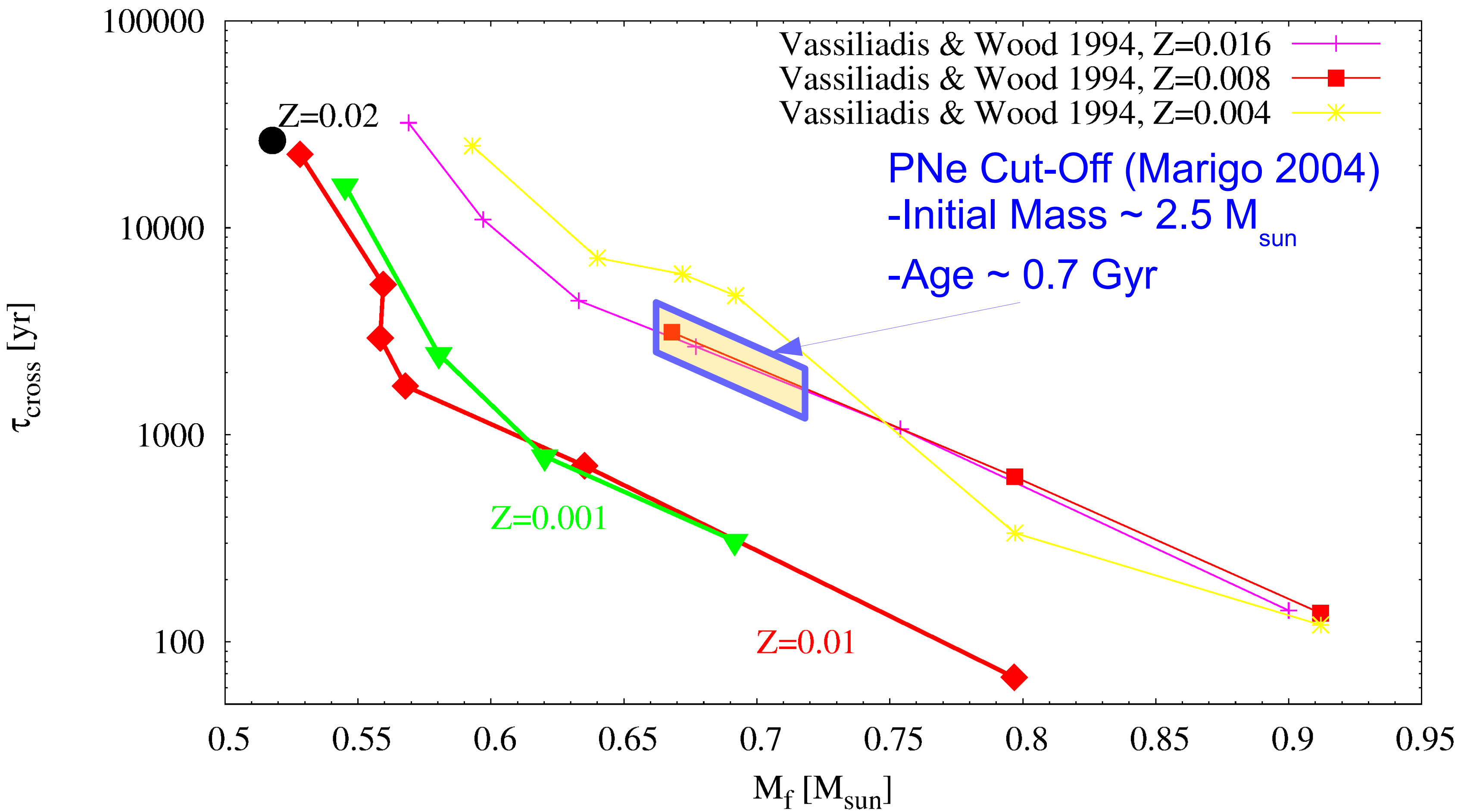

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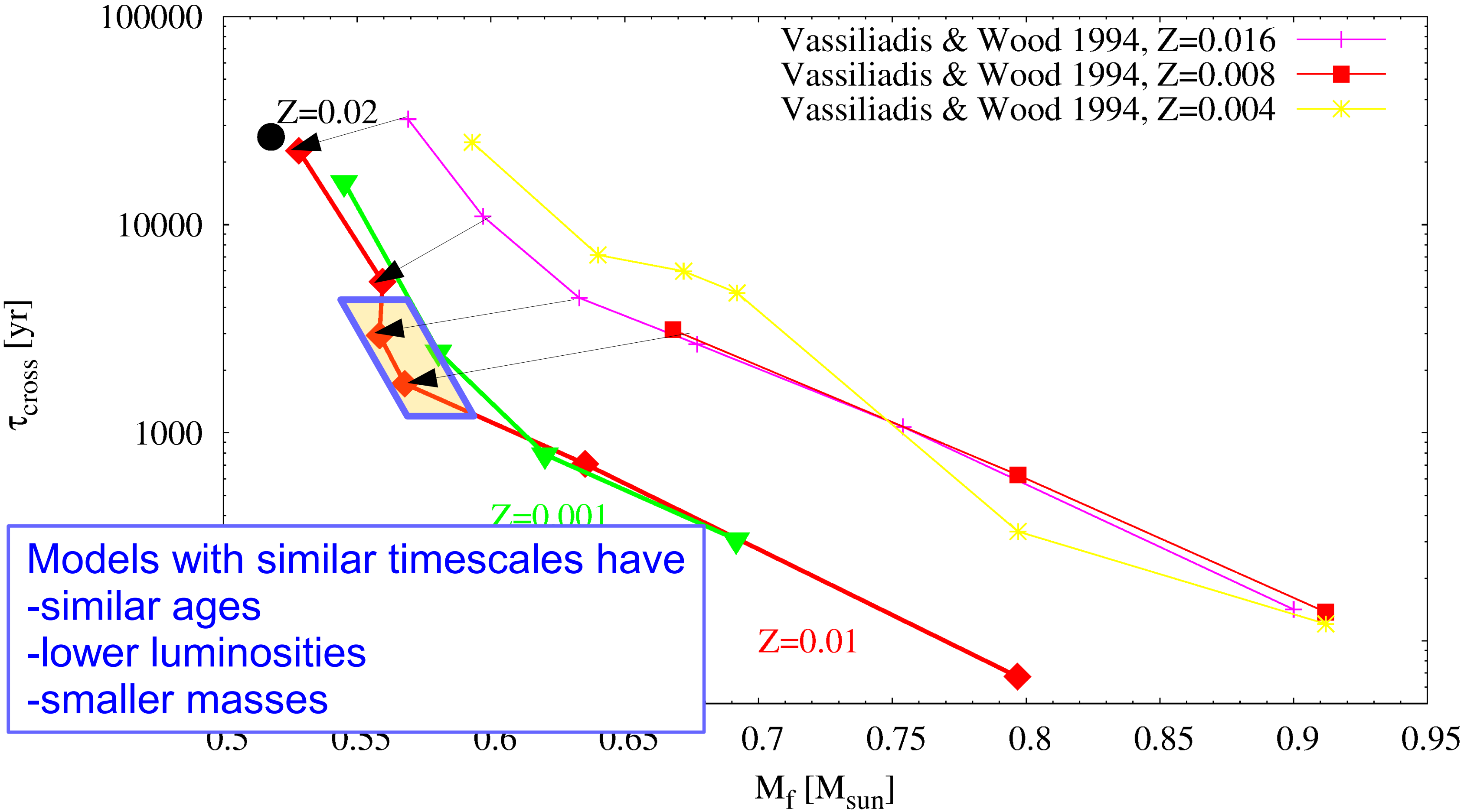

Models with similar timescales have
- similar ages
- lower luminosities
- smaller masses

"Preliminary conclusions":

- Post-AGB tests/calibration:

  - Comparison with semiempirical IFMRs indicates these models might have too much third dredge up for ~$2M_{sun}$ & Z=0.01 models.

  - PG1159 abundances are fairly well reproduced with *f*~0.005

- Modern stellar evolution **simulations suggest that old models** (Vassiliadis & Wood 1994 and Bloecker 1995) **significcantly overestimated the post-AGB crossing times.** This is in agreement with the semiempirical determination by Gesicki et al. (2014, Galactic Bulge).

- ***There is not* a very strong metallicity dependence** in the predicted post-AGB times.

- ...But ***there is a dependence* with the amount of CNO elements dredged up to the envelope during the AGB** (particularly important at low metallicities)

Thanks

Table 1. Properties of the AGB and post-AGB (H-burning) stellar evolution models: metallicity (Z), initial mass (M_i), final mass (M_f), number of thermal pulses on the AGB (N_{TP}), age of the model at the first thermal pulse (τ_{1TP}), length of the O-rich TP-AGB (τ_O), length of the C-rich TP-AGB (τ_C), the luminosity of the post-AGB remnant in the plateau phase ($L^{\rm post-AGB}_{\log T_{\rm eff}=4}$, taken at $\log T_{\rm eff} = 4$), and the crossing time ($\tau_{\rm cross}$) of the post-AGB remnant form $\log T_{\rm eff} = 4$ to the point of maximum effective temperature ("knee", see Fig. 1).

Z	M_i [$M_\odot$]	M_f [$M_\odot$]	N_{TP}	τ_{1TP} [Myr]	τ_O [Kyr]	τ_C [Kyr]	$L^{\rm post-AGB}_{\log T_{\rm eff}=4}$ [$L_\odot$]	$\tau_{\rm cross}$ [yr]
0.02	1.0	0.51781	3	11923	626$\lesssim$	0	2966	26407
0.01	1.0	0.52821	4	10510	728$\lesssim$	0	3396	22660
0.01	1.5	0.55950	7	2584	814	260$\lesssim$	5674	5319
0.01	2.0	0.55837	12	1206	1513	654$\lesssim$	6624	2936
0.01	2.5	0.56780	11	720	611	1105$\lesssim$	7700	1722
0.01	3.0	0.63520	8	431	177	345$\lesssim$	10524	708
0.01	4.0	0.79677	11	195	28	109$\lesssim$	18270	$\sim$ 67
0.001	1.0	0.54510	4	6594	625	249$\lesssim$	4477	15983
0.001	1.5	0.58039	7	1754	0	1017$\lesssim$	8100	2454
0.001	2.0	0.62018	10	797	82	774$\lesssim$	11434	787
0.001	2.5	0.69163	12	492	0	570$\lesssim$	14920	307

This work:

- Computations done with **LPCODE** (La Plata's Stellar Evolution Code, Althaus et al. 2012 and references therein). *Upgraded for more numerical stability and checked for consistency with other stellar evolution codes on the WD and RGB phases.*

  - LPCODE uses updated OPAL2005 EOS for H or He rich regions, and a simplified EOS for other regimes in the pre-WD phase.

  - Updated radiative opacities for high and low temperatures (Iglesias & Rogers 1996, Ferguson et al. 2005). Updated conductive opacities (Cassisi et al. 2007).

  - C-rich molecular opacities (from Kitsikis 2008, *a.k.a. Weiss & Ferguson 2009*)

  - Diffusive convective mixing with overshooting

$$D_{OV}=D_{CB} \times \exp[\,-2\times|r-r_{CB}|/(H_P\times \boldsymbol{f})\,]$$