The Impact of the Third-Dredge Up and Mass Loss in Shaping the Initial-Final Mass Relation of White Dwarfs

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1. Abstract

Despite their role in many astrophysical fields, the modeling of Asymptotic Giant Branch (AGB) stars is still plagued by uncertainties, due to the interplay of complex phenomena (mass-loss, convection..) which must be parametrized and lack a first-principles description. We aim to shed light on their evolution and the final endpoint by computing a large grid of models, using the Initial-Final Mass Relation (IFMR) of white dwarfs as a tool for understanding how the star grows its core, mixes the material and enriches its surface, responding with powerful stellar wind able to swiftly peel the envelope.

2. AGB stars in a nutshell

The AGB is the last phase of low and intermediate-mass stars' evolution, before becoming white dwarfs (WD). They have a deep convective envelope, a burning hydrogen shell and a thin He-shell, on top of a carbon-oxygen degenerate core. Their He-intershell is dormant most of the time, but it experiences recurrent nuclear runaways called thermal pulse (TP). After each TP, the AGB star' envelope may penetrate inside the He-intershell, polluting the surface with He-burning processed material, especially carbon. This mixing event is called Third Dredge-Up (TDU).

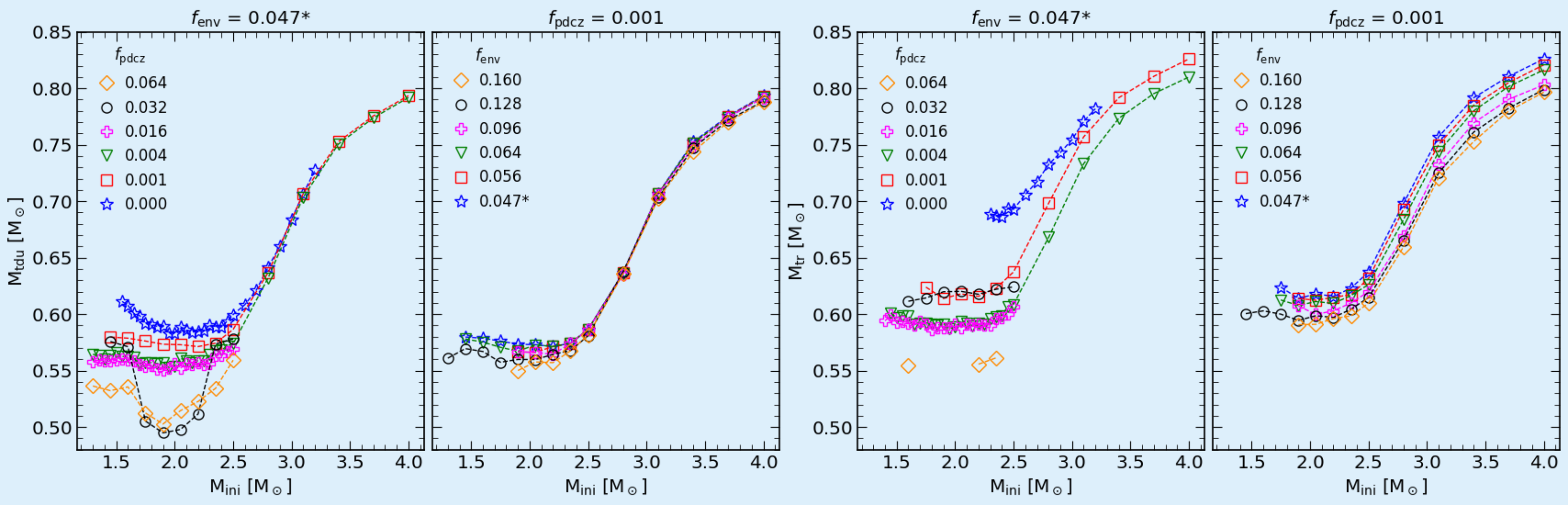

Figure 1. Core mass at the first TDU occurrence (left panels) and core mass at the transition from M-type to C-type (right panels). Title in each panel indicates which overshooting parameter is fixed and to which value. $f_{PDCZ} \geq 0.016$ sets are limited to $M_{ini} \leq 3.2\ M_\odot$. f_{ENV} = 0.056, 0.096, and 0.160 sets are limited to $M_{ini} \geq 1.9\ M_\odot$.

5. What's the deal?

The IFMR is an extremely valuable tool to understand and calibrate the mixing parameters, especially convective overshooting in the TP-AGB phase.

The value of f_{ENV} ,and f_{PDCZ} itself is not the main point. Instead, we showed that extra mixing over the canonical boundary have to be included, and it must be adapted to the initial mass, to give the right core mass evolution and surface enrichment. This work stands as further evidence for the need of convective overshooting (Tang+16) to be included and carefully calibrated on observations.

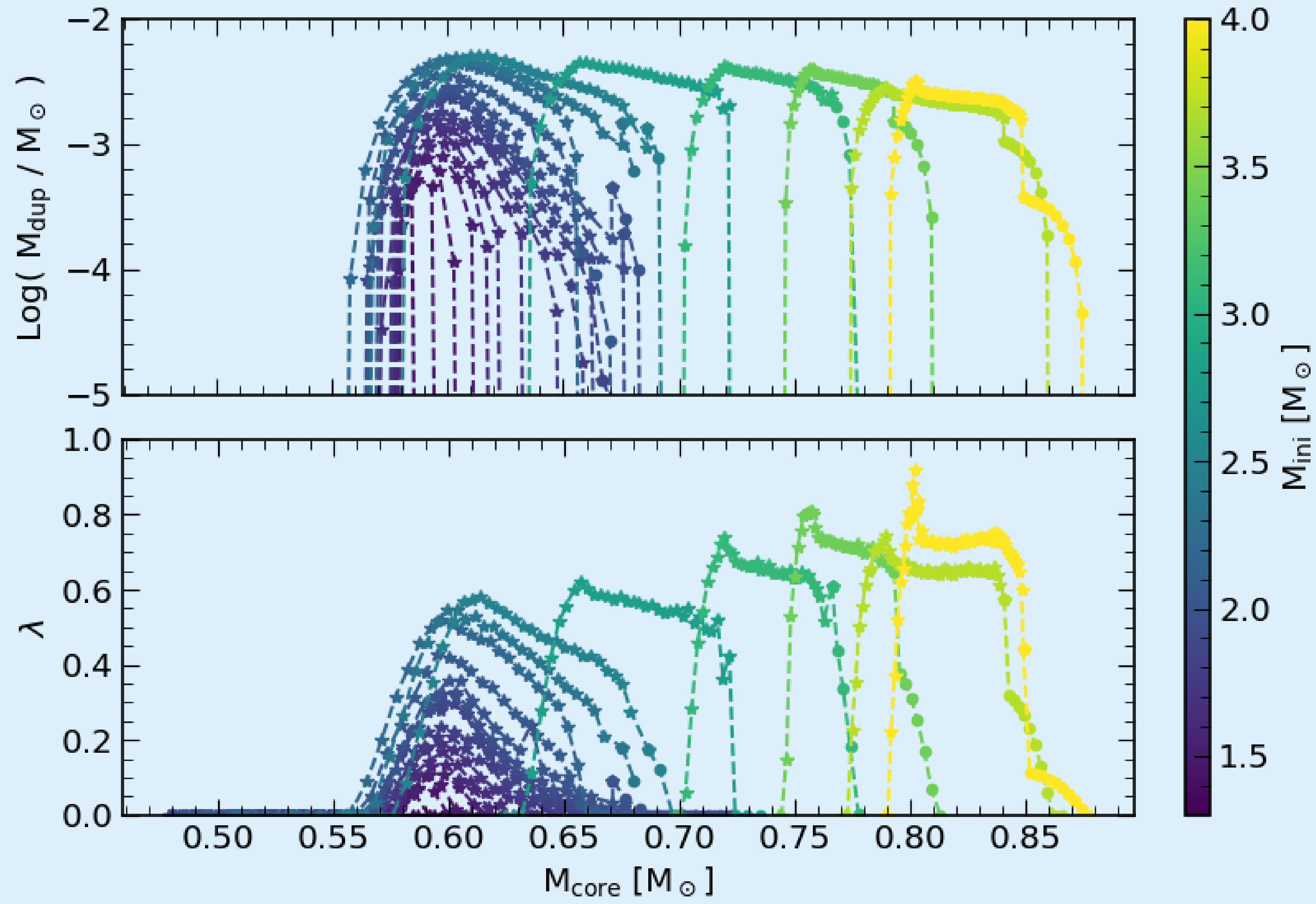

Figure 2. Dredge-up mass per pulse cycle (top panel) and dredge-up efficiency (bottom panel) at constant f_{PDCZ} = 0.001 and varying envelope overshooting.

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COLIBRI
PARSEC

3. Input Physics

We use PARSEC (Bressan+12, Costa+19, Nguyen+22) from the pre-main sequence to the coolest point in TP-AGB it can reach.

After we follow the evolution of the very last few pulses with COLIBRI (Marigo+13, Pastorelli+19). Rotation or magnetic fields are not included.

- Solar metallcity Z = 0.014 with Caffau+11 solar chemical composition.
- Convection described with Mixing Length Theory (Bohm-Vitense+58) with solar calibrated parameter α_{MLT} = 1.74.
- Exponential overshooting (Herwig+00). $D(r) = D_0 \exp\left(-2\frac{|r - r_0|}{f_{ov}H_P}\right)$
- Reimers' law (η_R=0.2) after main sequence to the AGB.
- Mass loss in AGB as in Marigo+20, in particular carbon excess dependent stellar wind during C-type phase (Mattsson+10, Eriksson+11, Bladh+19).
- Opacity from AESOPUS (log T < 4.20) (Marigo+09, Marigo+22) and OPAL (log T ≥ 4.20) (Iglesias and Rogers 96). Low temperature opacities depend upon C, N and O abundances.

4. Results' outline

We calculated 429 tracks in 24 sets with different (f_{ENV} , f_{PDCZ}) overshooting couples.

- IFMR is sensitive on how surface is being enriched over time, the response being with the mass-loss. The interplay between carbon enrichment, growth of the core and surface response is not straightforward, a large grid of models is needed. (Fig.1)
- Tracks with no extra mixing in the PDCZ experience too shallow dredge-ups, thus little amounts of carbon accumulate in the surface. (Fig. 1, right panels).
- Extreme PDCZ overshooting results in low carbon surface abundances too. That is due to the oxygen rich intershell composition (Fig. 1, right panels).
- f_{ENV} and f_{PDCZ} are mildly degenerate: while f_{ENV} enhances the TDU efficiency, f_{PDCZ} alters the inter-shell composition, and both concur to alter the surface composition and the mass loss rate. For any choice of the parameters, keeping them constant with M_{ini} produces a monotonic IFMR.
- The observed kink can be reproduced assuming a constant f_{PDCZ} (~0.001) and an envelope overshooting efficiency, f_{ENV}, that increases with the initial mass, reaching a maximum value significantly higher than usually adopted in model calculations (Fig. 2 and Fig. 3).

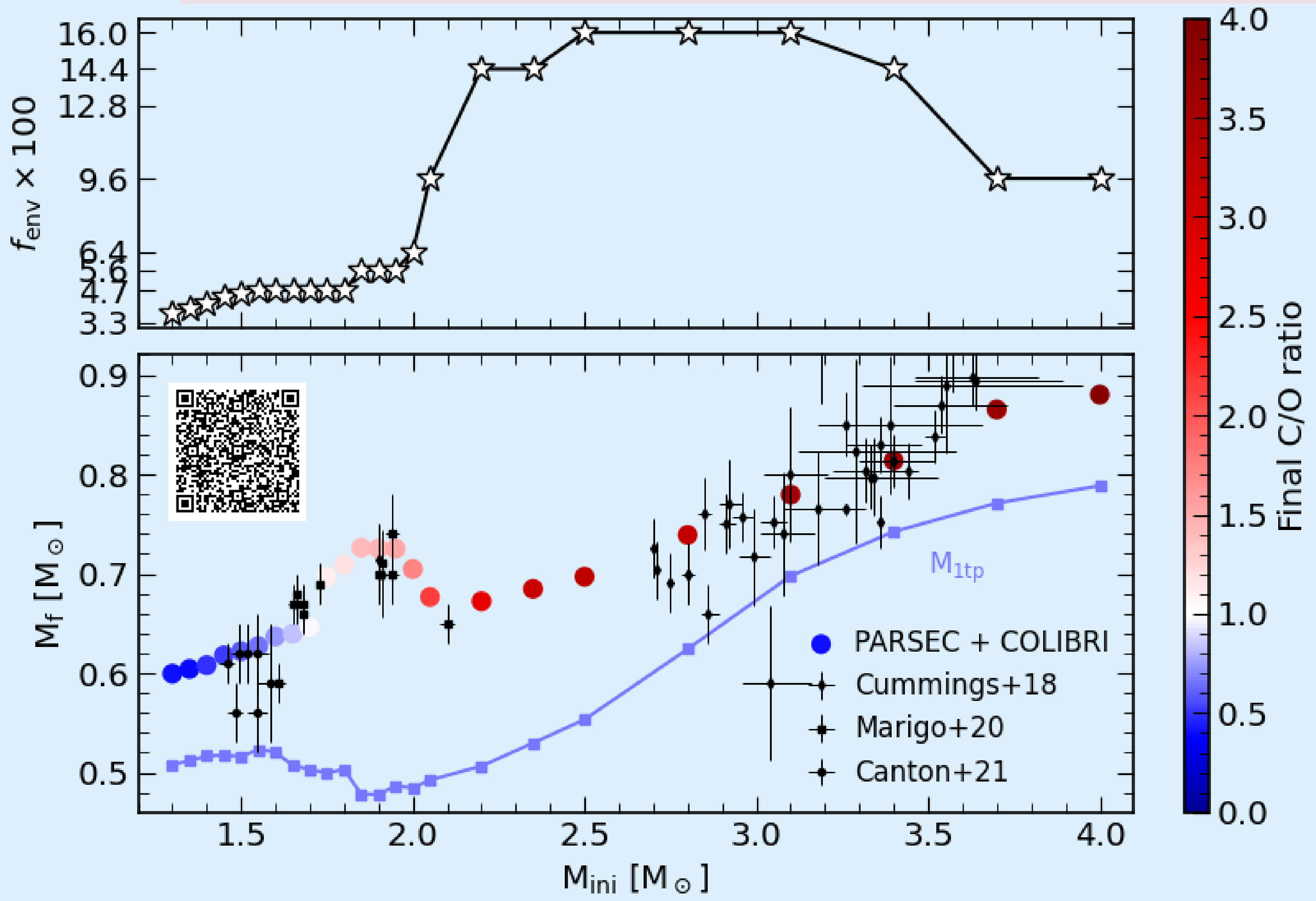

Figure 3. IFMR for the final set (bottom panel), at constant f_{PDCZ} = 0.001 and varying envelope overshooting (top panel). M_{1tp} is the core mass at the first thermal pulse.

Stay tuned!

In future works we aim to investigate and disentangle the mild degeneracy, by including the information from the intershell composition of [WC]-type stars of planetary nebulae (Wagstaff+20).

Scan the QR code to reach out to a table containing the data (and more) in Fig. 3!