

Super-AGB stars: fundamentals and recent progress

Pilar Gil-Pons, Leandro G. Althaus and Carolyn L. Doherty

AGB stars and stellar pulsations, Konkoly Observatory, Hungary

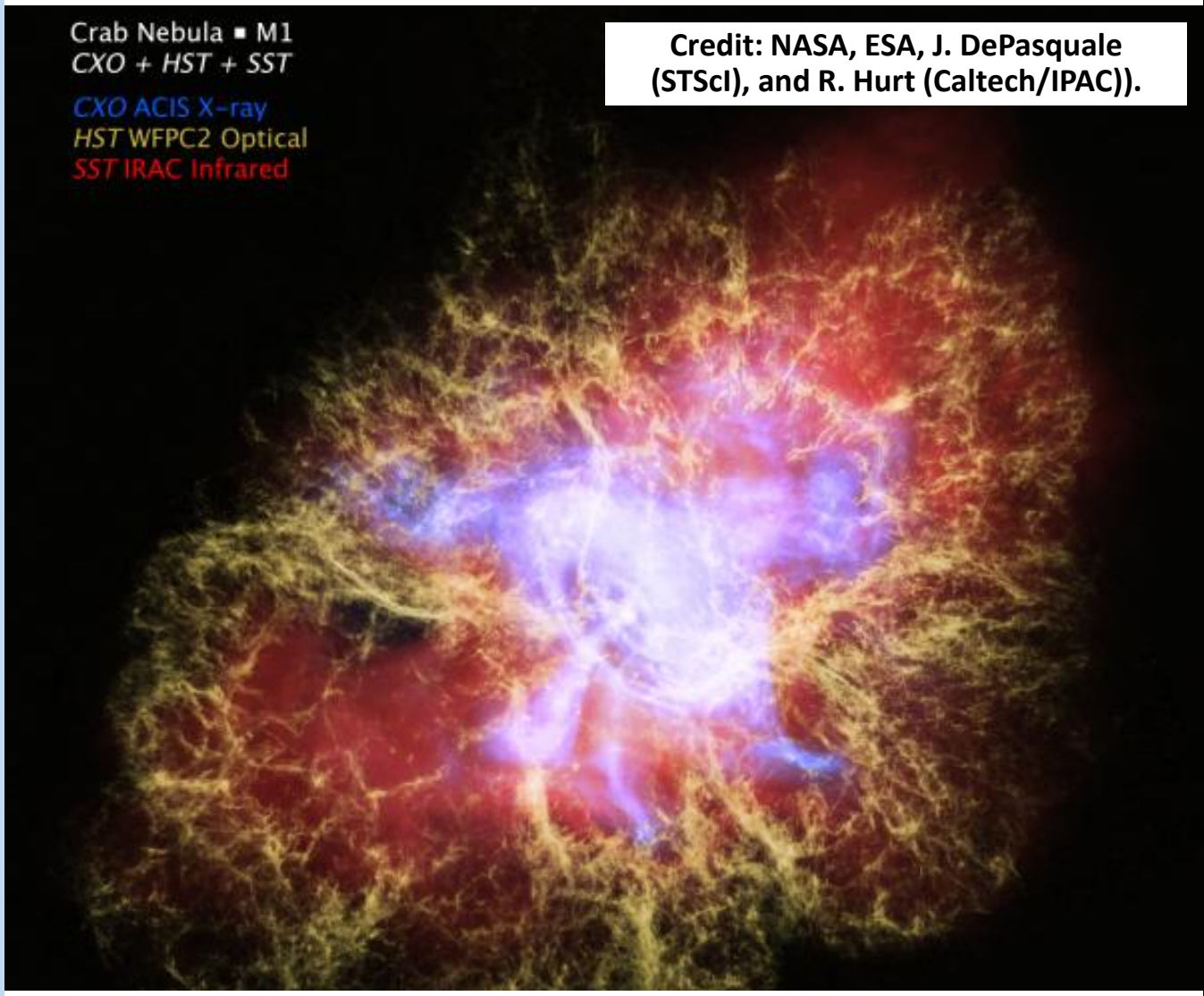
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IEEC

The relevance of SAGB stars

- They are at the boundary of intermediate-mass stars to massive stars.
- They form ONe (or hybrid CONe) cores, instead of CO-cores.
- The properties of some of the most massive white dwarfs are determined by the evolution of SAGBs.
- The most massive SAGBs might end their lives as electron-capture supernovae (ECSNe).
- As components of binary systems, some of them may contribute to the SN Iax population.

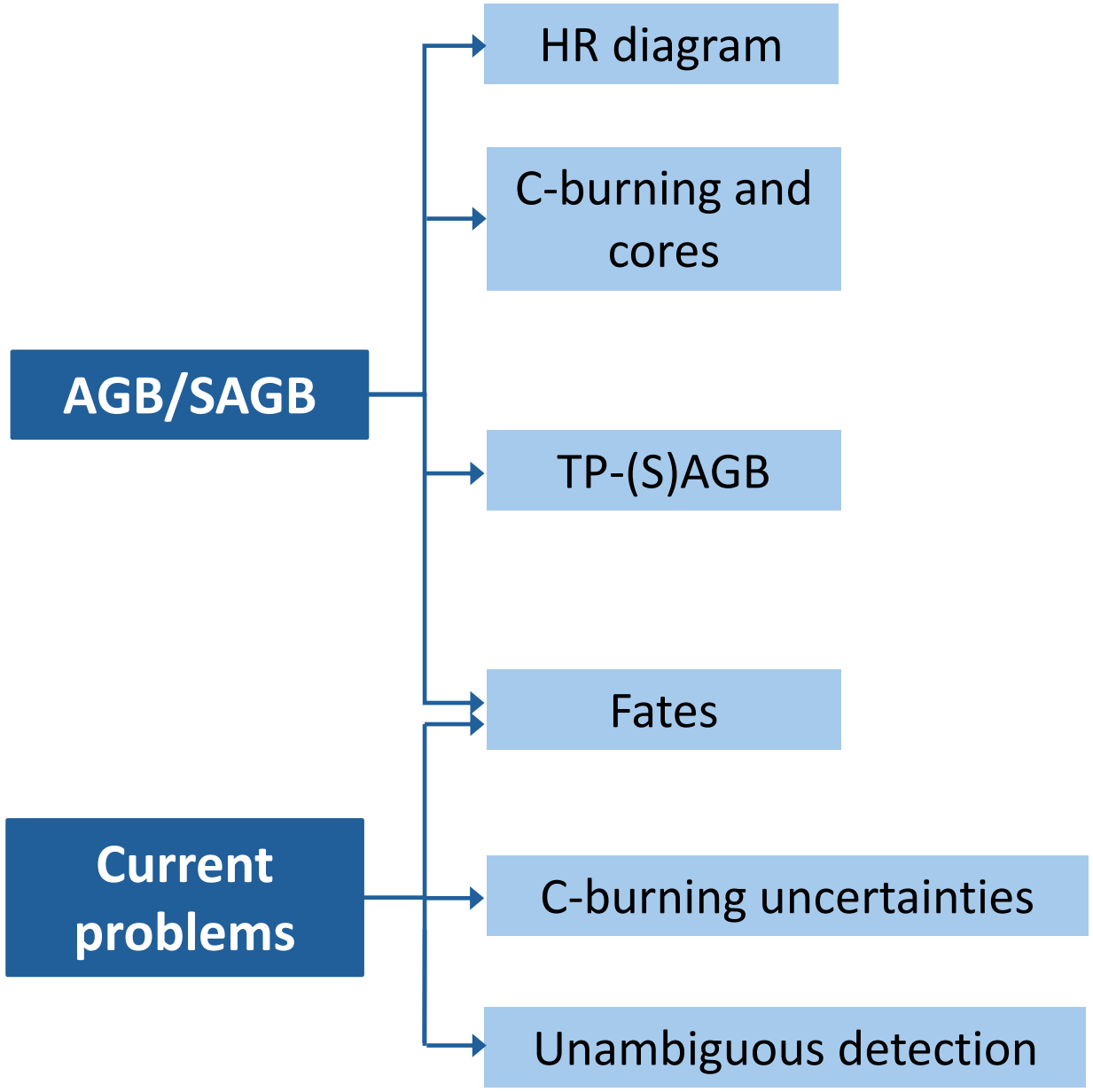
The elusive electron-capture supernovae



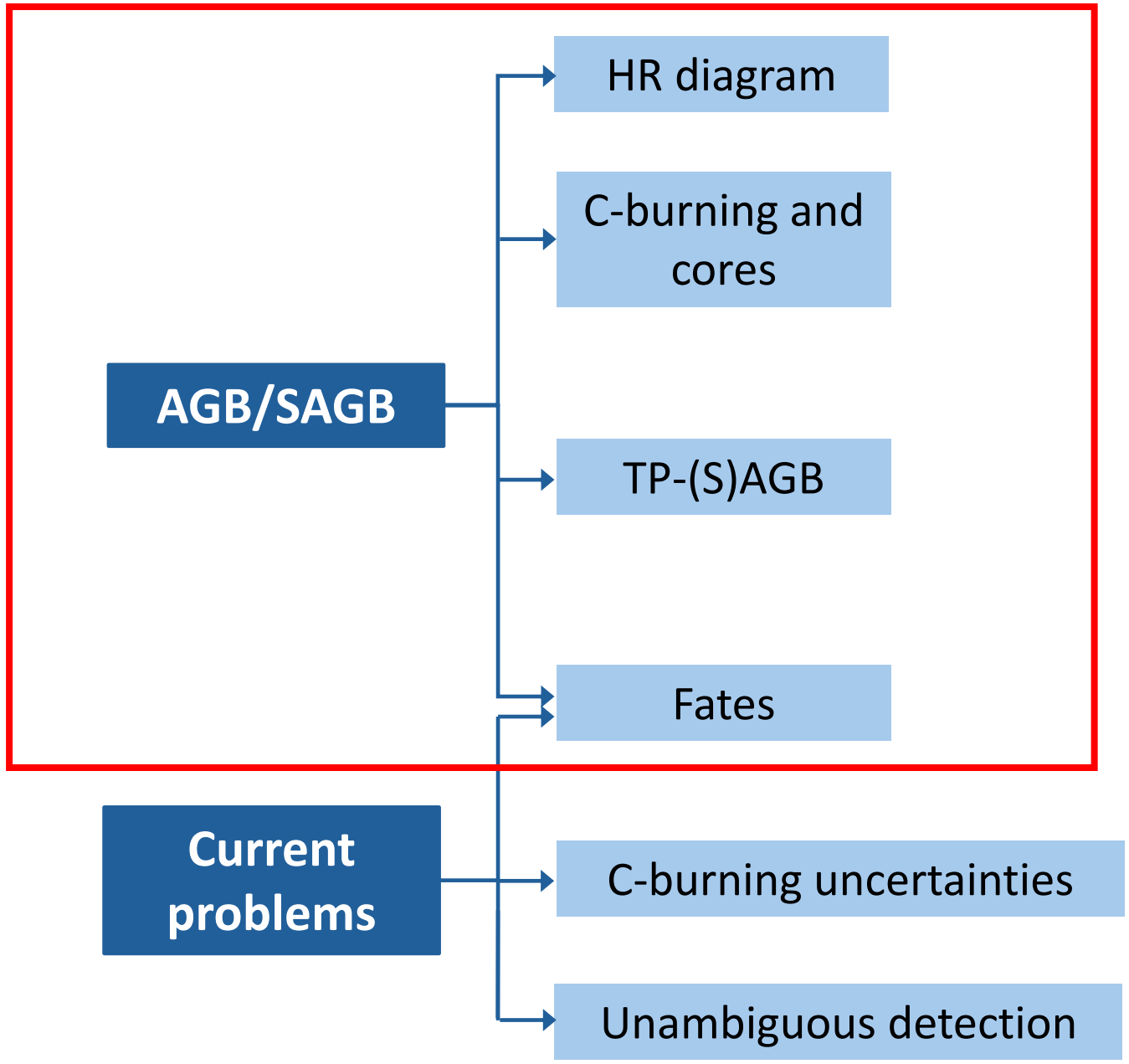
Nomoto et al. (1982) proposed that the Crab nebula was the remnant from an e-capture SN.

No concluding observational evidence yet.

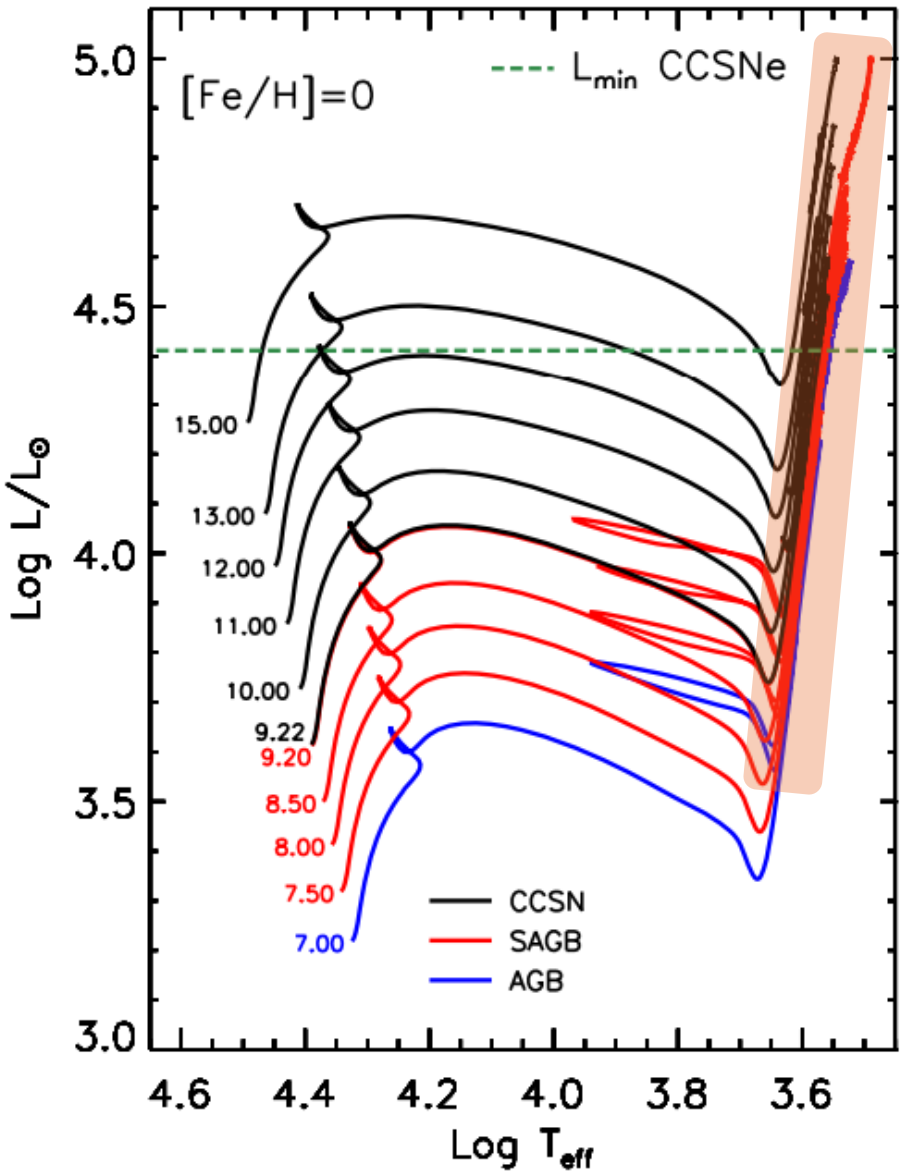
Outline


HR diagram
C-burning and cores
AGB/SAGB
TP-(S)AGB
Fates
Current problems
C-burning uncertainties
Unambiguous detection

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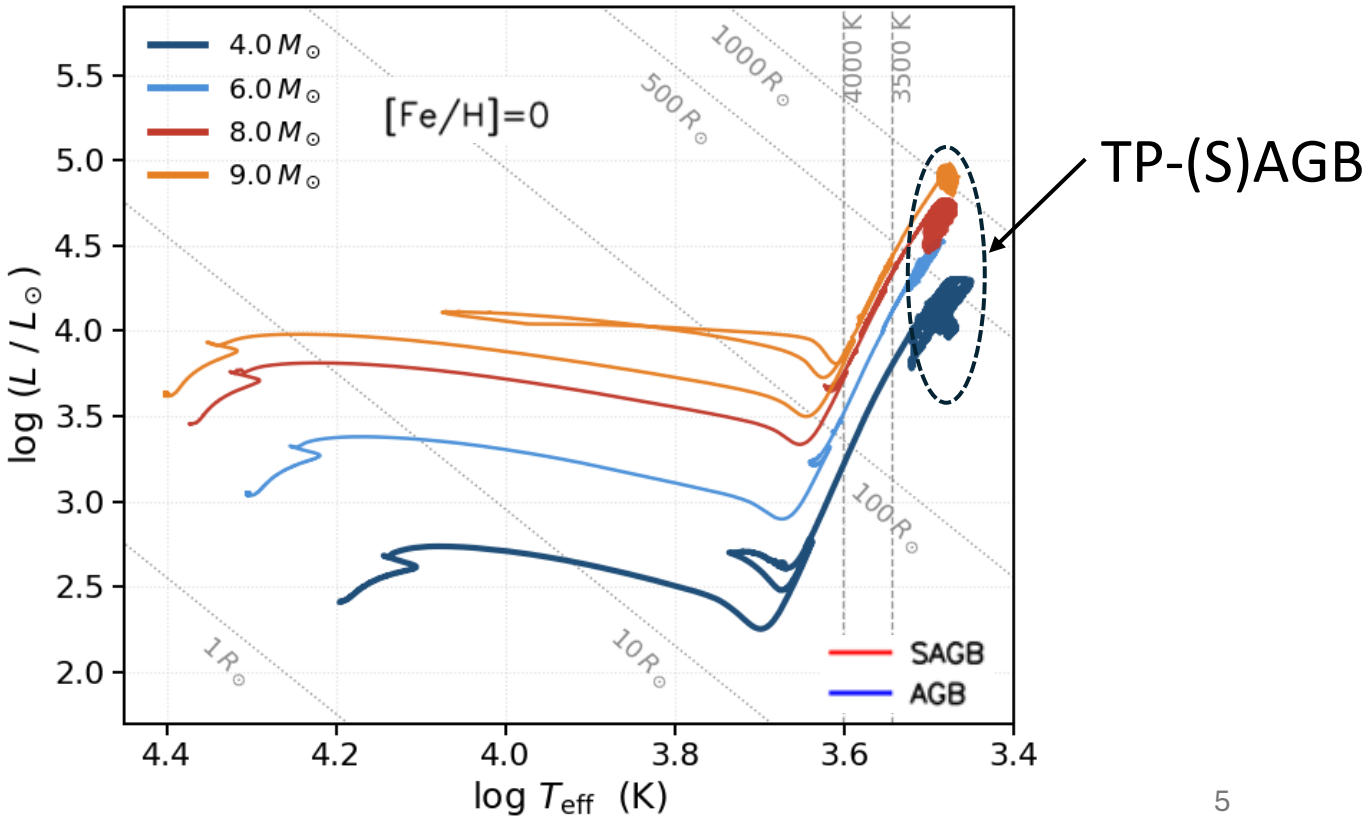
1. AGBs and SAGBs in the HR diagram



Limongi and Chieffi, 2024

AGBs and SAGBs are LPVs/Miras, but SAGB stars display:

- Higher L (Log $L/L_{\odot} \gtrsim 4.5$) than AGBs.
- Larger radii ($\gtrsim$ 900-1000 $R_{\odot}$).
- Larger pulsation periods (≈100-1000 days).



TP-(S)AGB

2. Cores and CO-burning

SAGBs are the most massive intermediate-mass stars (around 8-10 $M_\odot$).

Unlike AGBs, **SAGB stars burn C.**

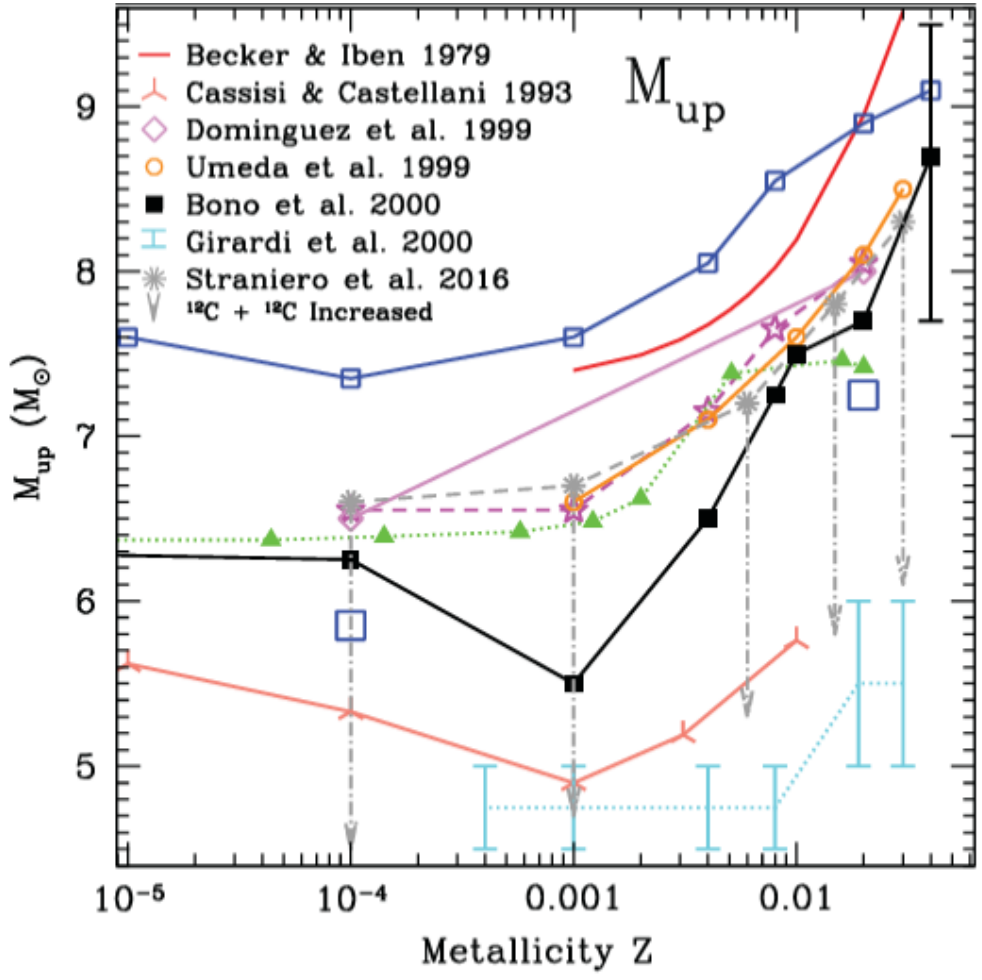
What is necessary for carbon-burning to occur?

A (degenerate) **CO core of mass ≥ 1.05 $M_\odot$**.

M_{up} is the minimum M_{ZAMS} that allows C-burning. It is affected by:

- The **initial composition** ,
- the treatment of convection and **convective boundaries,**
- **C-burning rates** (e.g. Straniero et al., 2008; Gesue et al. 2026).

M_{up} = Minimum M_{ZAMS} for C-burning



Doherty et al., 2017

2. Cores and CO-burning

Carbon-burning in degeneracy

- Efficient neutrino cooling

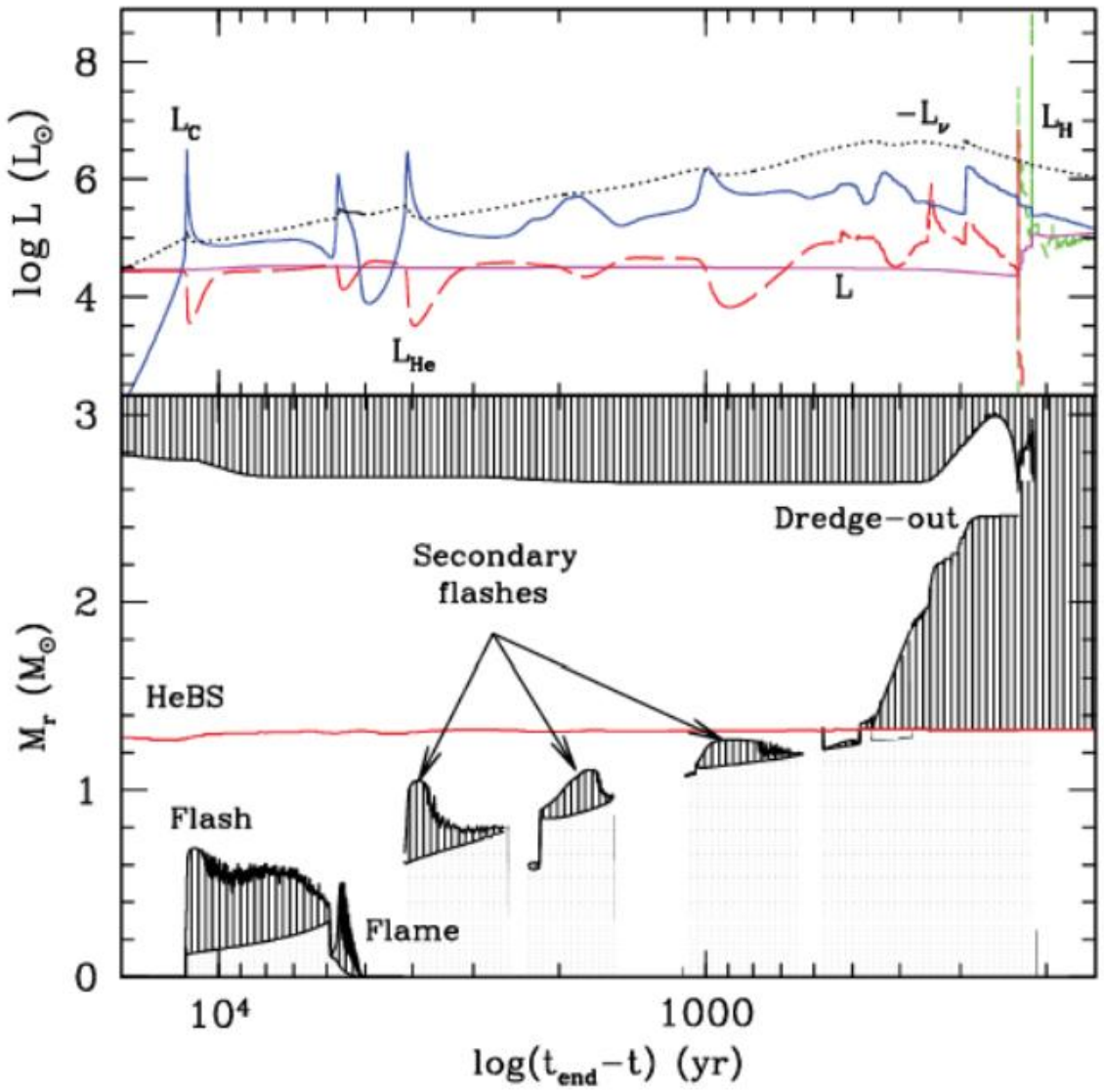
  ⇨ C-burning starts **off-centre**.

- **Degeneracy** conditions

  ⇨ **flashes and convective zones**.

- The C-burning flame eventually reaches the centre (or not, leading to hybrid CONe cores, Denissenkov et al., 2013).
- C-burning ends in outer/secondary core flashes.
- Most massive cases experience the **dredge-out**, a proton-ingestion episode that might be a site for i-process nucleosynthesis.

See e.g. García-Berro, Iben and Ritossa, 1994,1996,1999; Domínguez et al., 1999; Siess, 2006,2008,2010; Gil-Pons et al., 2001,2002, 2007; Doherty et al., 2010, 2014, 2015ab, 2017; Lau et al., 2012; Ventura et al., 2011, 2012; Farmer et al., 2015, Jones et al., 2013 ; Limongi and Chieffi, 2024.

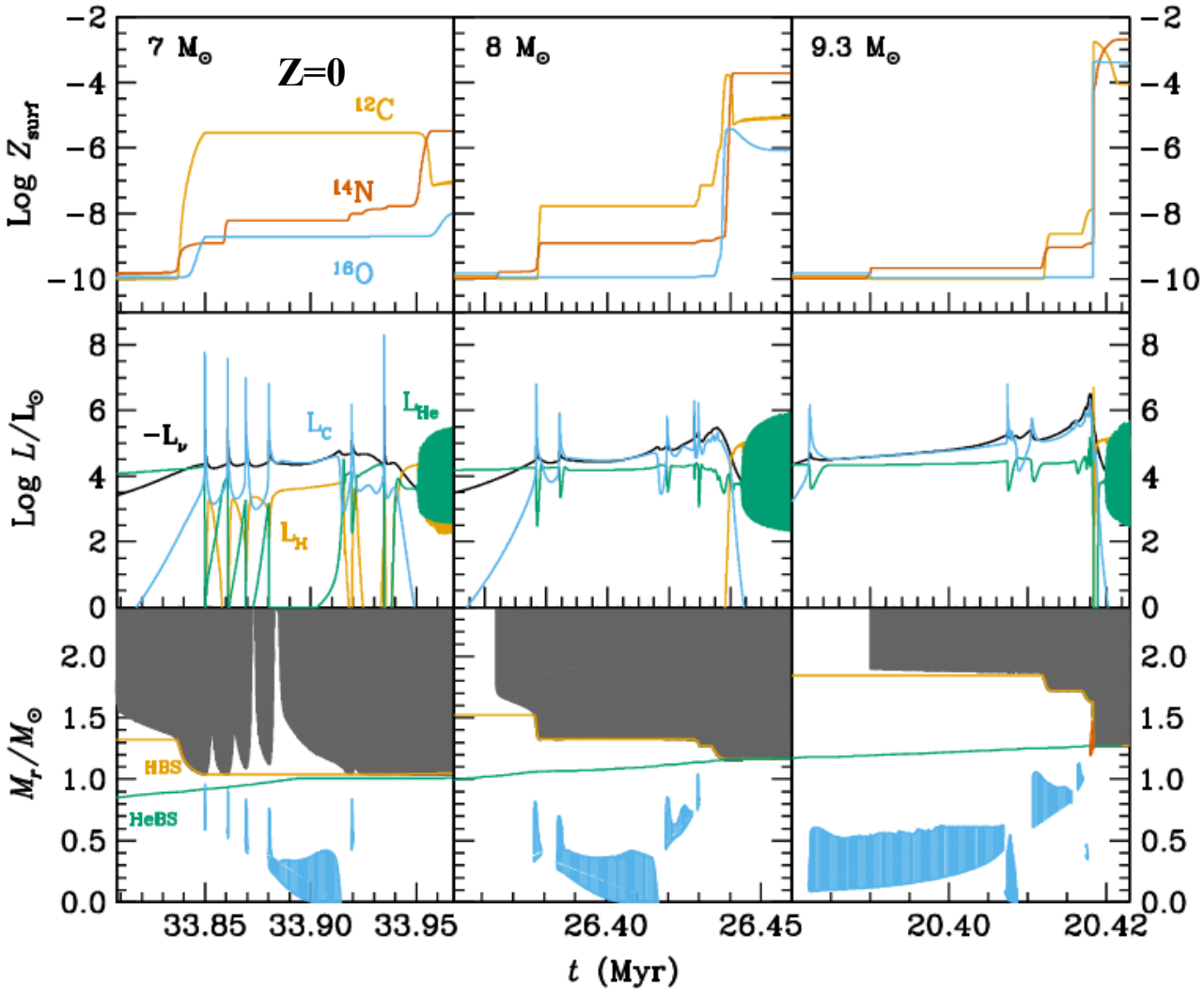


Doherty et al., 2017

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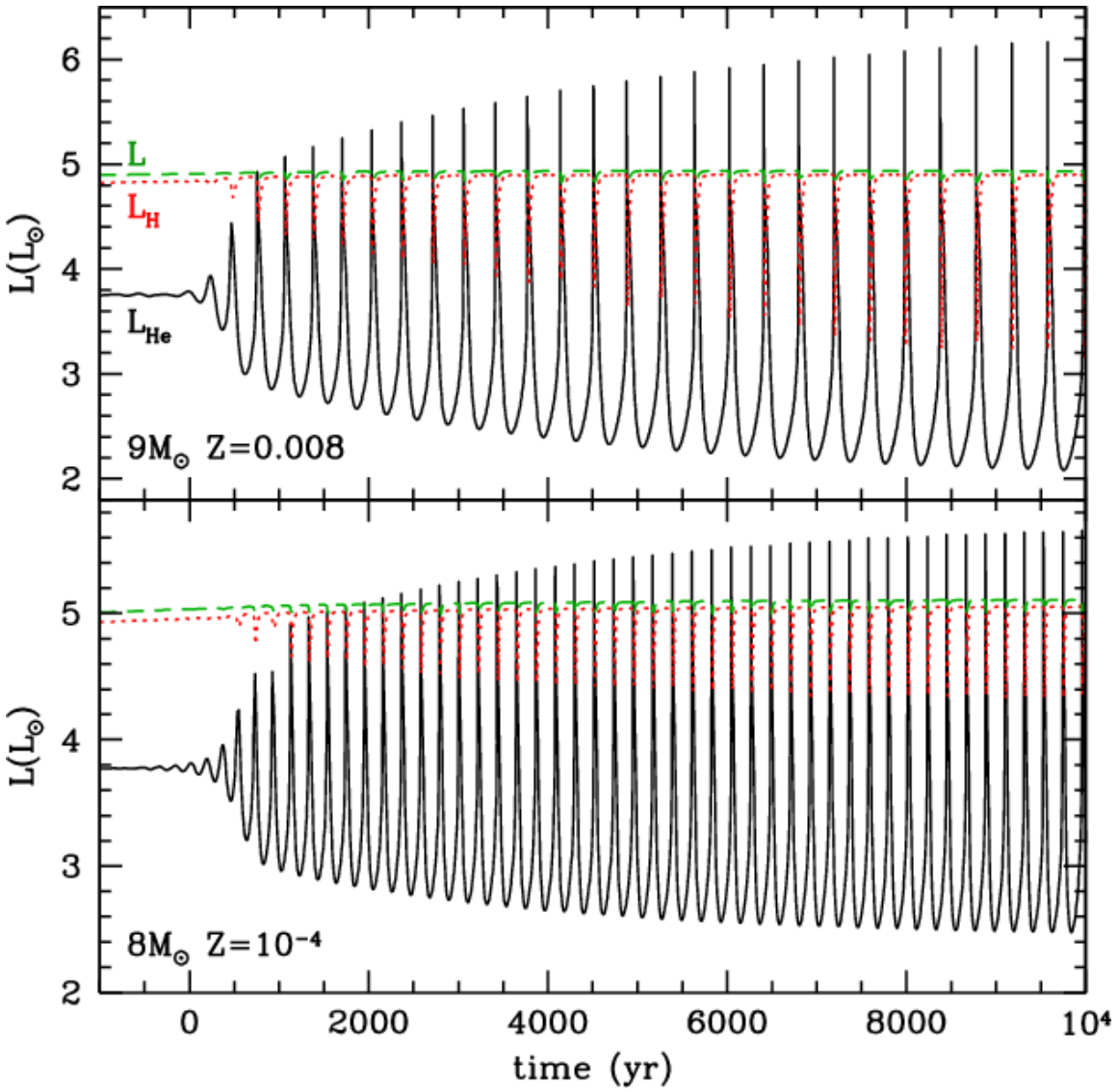
Carbon-burning in degeneracy

- **Similar general behaviour, regardless the initial Z** (but M_{ZAMS} thresholds vary).
- The **second dredge-up episode** happens before C-burning for the less massive SAGB and during C-burning for more massive ones.



Gil-Pons et al., 2018

3. The thermally-pulsing (S)AGB



Siess 2010

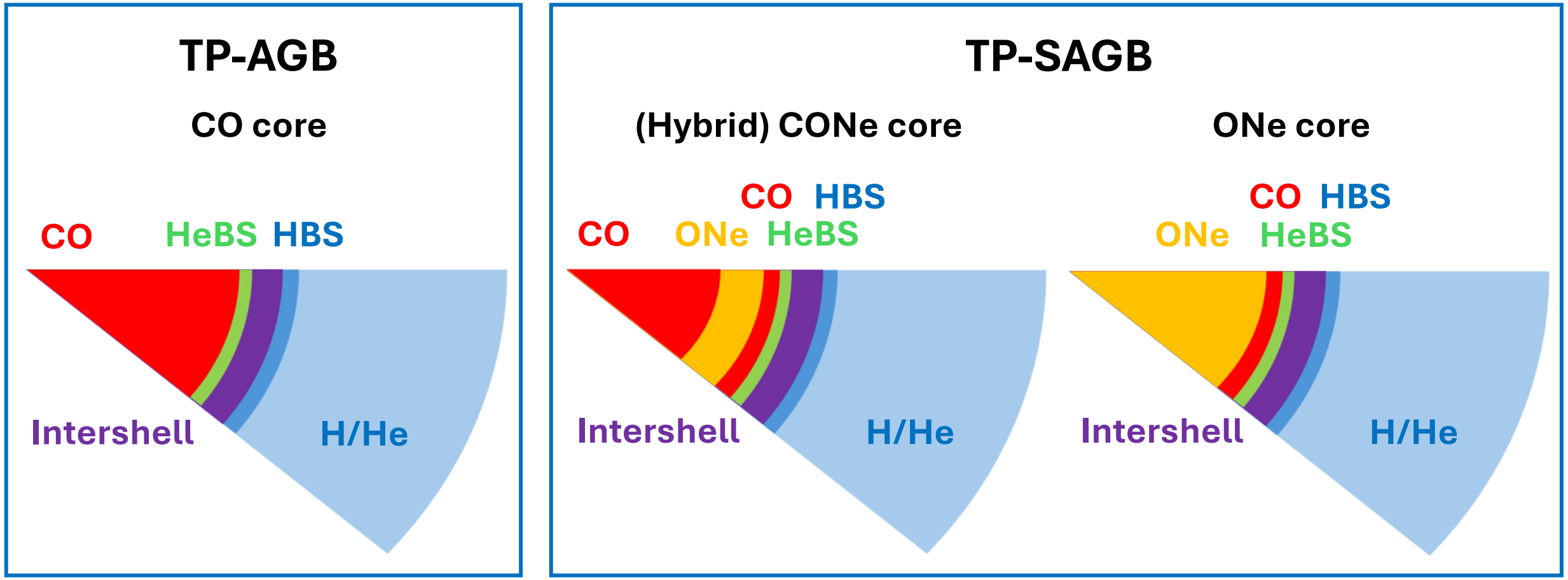
Thermal pulses

- The **same mechanism as in standard AGB stars**: shell H- and He-burning alternate as main energy producers.
- The degenerate core grows due to nuclear reactions, and the envelope is lost due to winds.
- The TP-SAGB is typically shorter than the TP-AGB.
- The **number of pulses** can be very high in the case of SAGB stars (10s, 100s or **even 1000s**) and **the interpulse period is very short** (a few tens to a few hundred yr).
- **As metallicity decreases**, winds tend to become less efficient, and **the number of thermal pulses increases**.

3. The thermally-pulsing (S)AGB

Composition profile during the TP-(S)AGB phase

HBS= H-burning shell
HeBS= He-burning shell



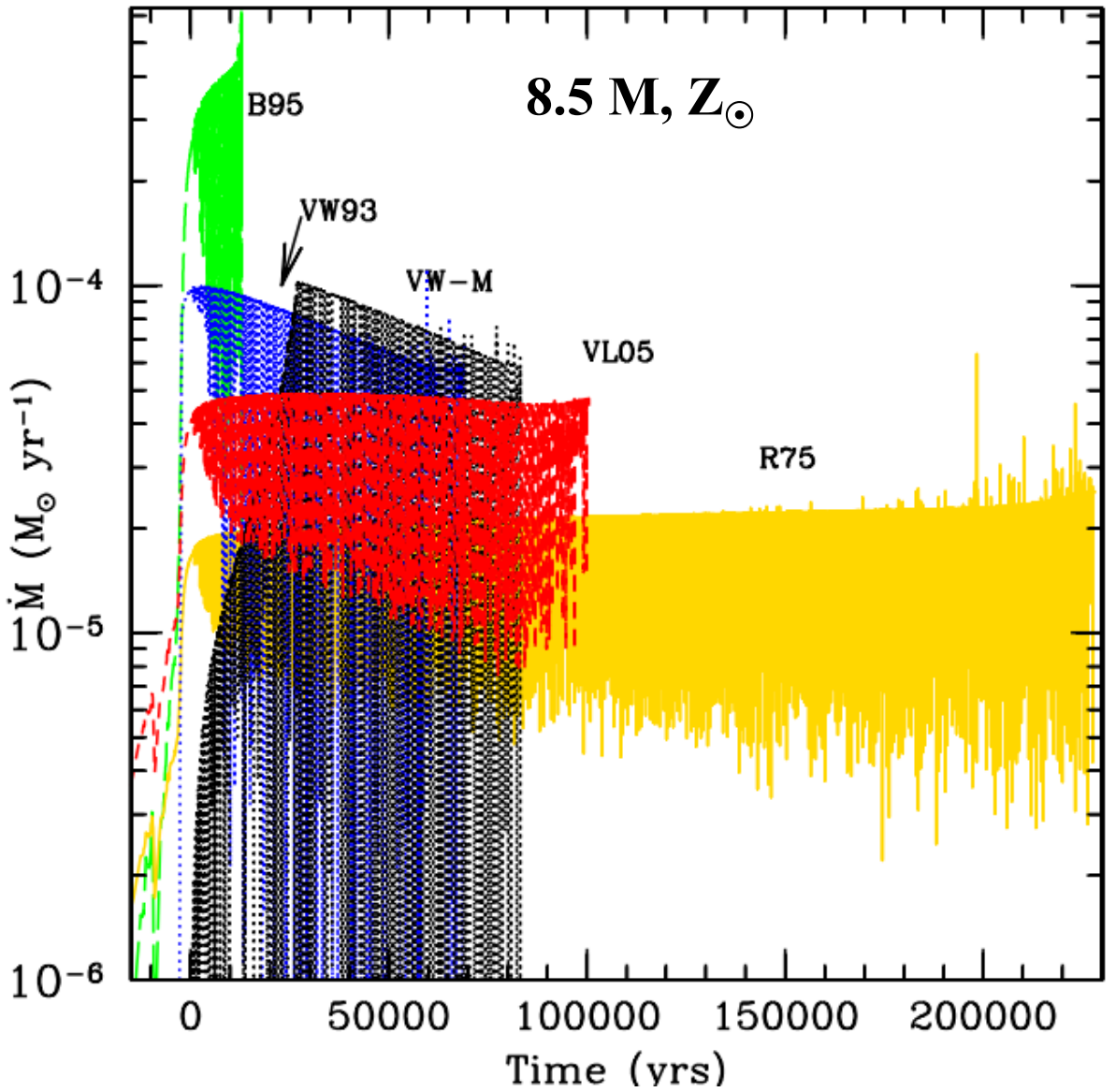
3. The thermally-pulsing (S)AGB

Stellar winds

- The evolution is very sensitive to the treatment of convection, convective boundaries and wind efficiency.
- Different prescriptions may affect the M_{ZAMS} range to form e-capture SNe.

	T_{BCE}^{Max} (MK)	M_{Dredge}^{Tot} ($M_\odot$)	M_{2DU} ($M_\odot$)	M_C^F ($M_\odot$)	M_{env}^F ($M_\odot$)	N_{TP}	$\tau_{(S)AGB}$ (yr)
			$Z = 0.02$ 8.5 $M_\odot$				
VW93	106	3.64(−2)	1.14	1.15	1.78	110[35]	6.60(4)
VW-M	106	4.75(−2)	1.14	1.16	1.87	149[40]	8.63(5)
VL05	107	5.66(−2)	1.14	1.16	1.93	165[54]	9.87(4)
B95	98	4.34(−3)	1.14	1.15	1.56	29[2]	1.16(4)
R75	107	1.35(−1)	1.14	1.17	2.01	381[174]	2.26(5)
$\alpha_{mlt} \times 1.5$	109	2.40(−2)	1.14	1.15	1.36	84[28]	4.38(4)
$\alpha_{mlt} \times 2$	112	1.62(−2)	1.14	1.15	1.17	65[18]	3.06(4)

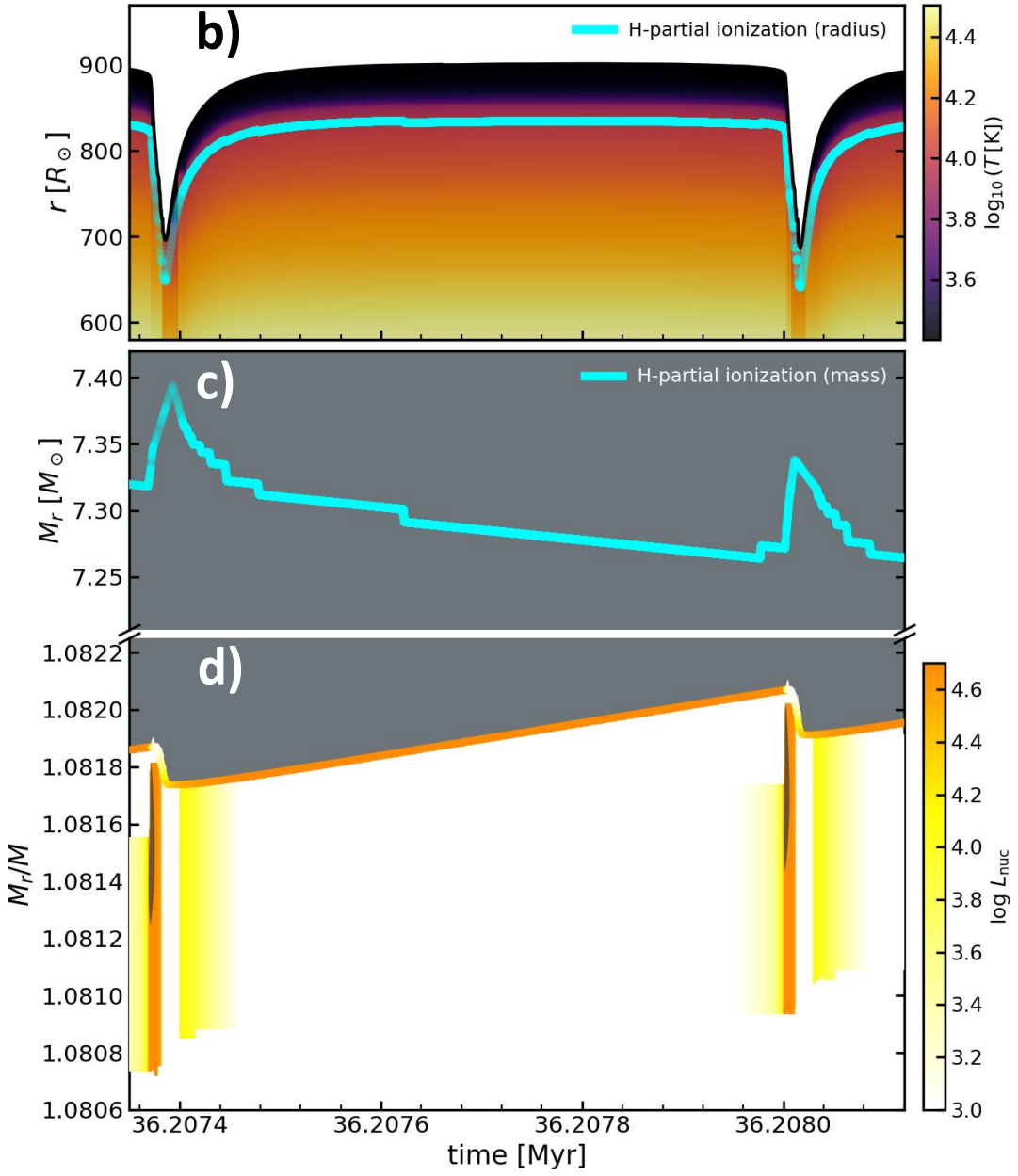
Doherty et al., 2014a



3. The thermally-pulsing (S)AGB

TP-SAGB structure

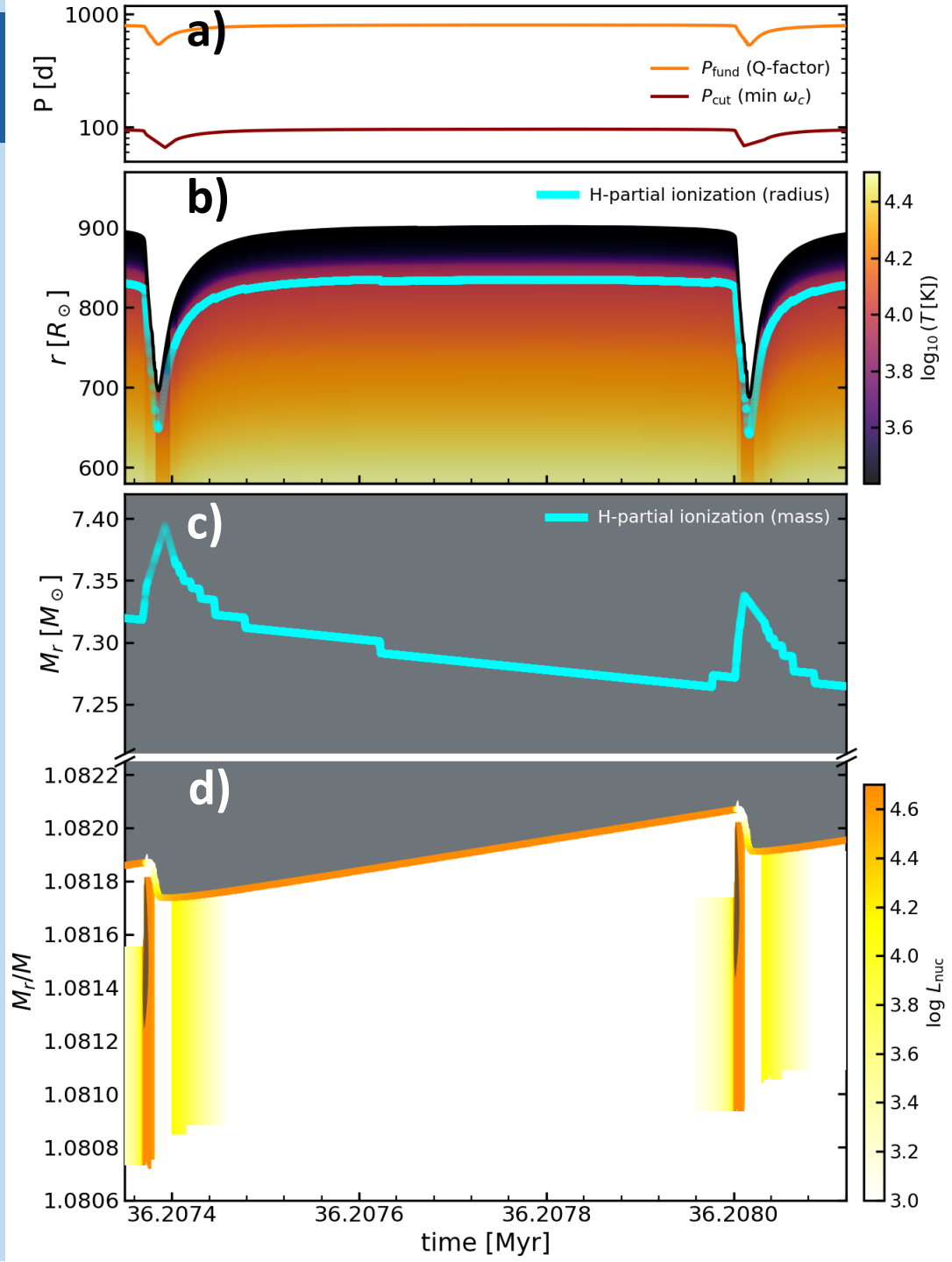
- **Panel d**: Base of the convective envelope (BCE) and inner convective shells associated to the flashes.
- As a He-flash develops, the HBS switches off, and the convective envelope contracts and heats (**panel b**).
- Thus, the thermodynamical conditions for the formation of the partial ionization region of H (PIH), potentially relevant for pulsation driving, shift outwards in mass (**panel c**).



3. The thermally-pulsing (S)AGB

TP-SAGB structure

- **Panel a**: Fundamental period (P_{fund}), and period associated to the cutoff-frequency (P_{cut}).
- $P_{fund} \sim (R)^{\frac{3}{2}}(M)^{\frac{1}{2}} \rightarrow \frac{\dot{P}_{fund}}{P_{fund}} \sim \frac{3}{2}\frac{\dot{R}}{R}$ Thus, the dip in P_{fund} is a consequence of the drop in the radius (associated to each He-flash).
- Hydrodynamic calculations (**Fadeyev et al., 2017**) show that such secular period changes can actually be very large during thermal pulses.



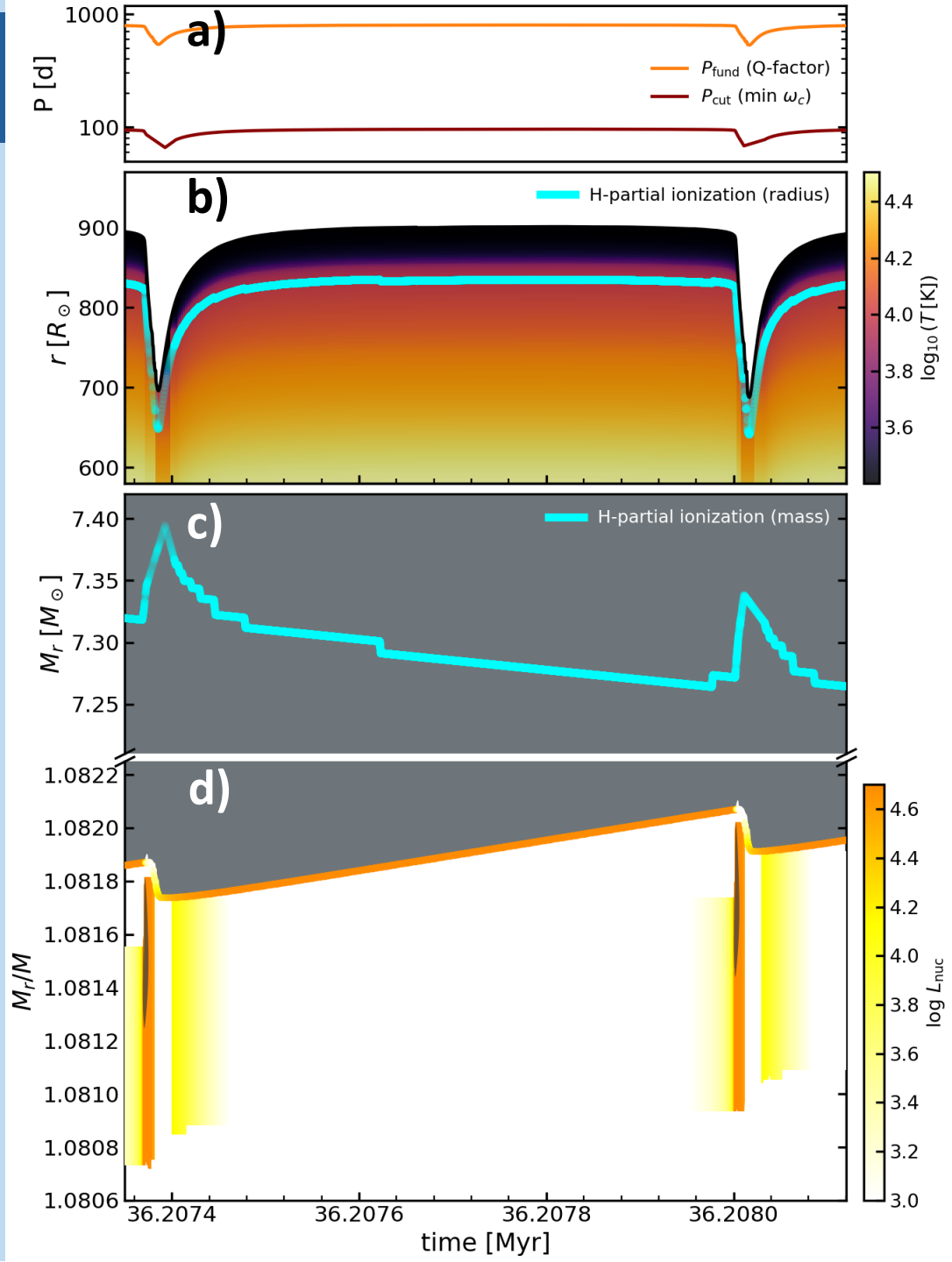
3. The thermally-pulsing (S)AGB

TP-SAGB structure

The structural response to a thermal pulse may affect pulsations:

- Locally, the restructuring of the envelope changes the location and properties of PIH, which is relevant for pulsation driving.
- Globally, the large change in stellar radius directly changes the pulsation timescale, producing a strong secular variation of the fundamental period.

Could period evolution provide an additional observational diagnostic for massive AGB and SAGB stars?

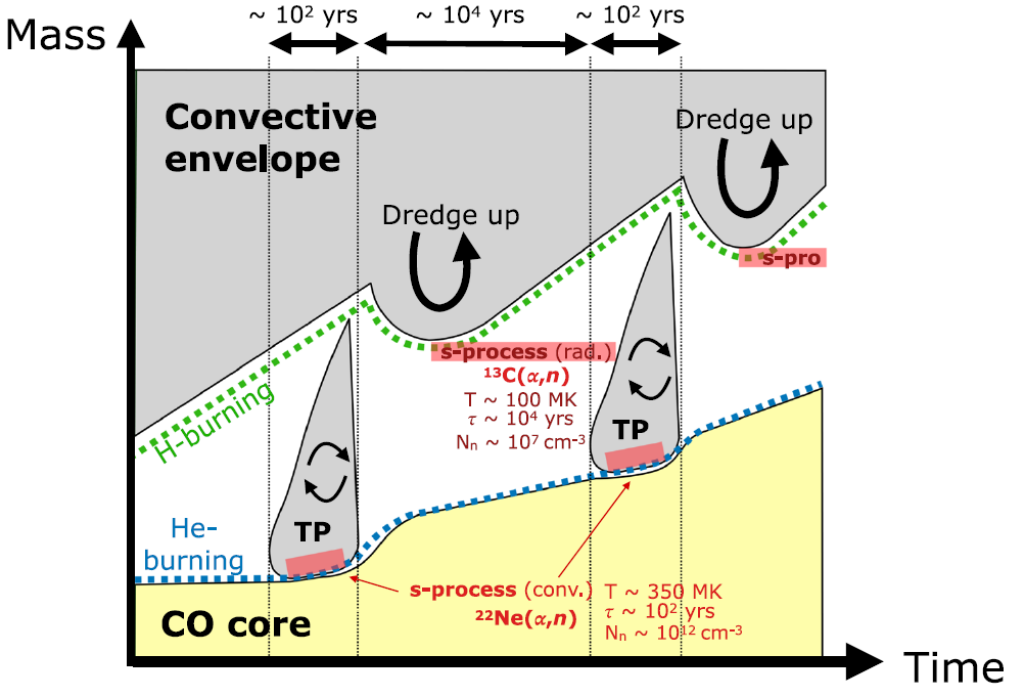


3. The thermally-pulsing (S)AGB

Hot-bottom burning (HBB), third dredge-up (TDU) efficiency and s-process sites

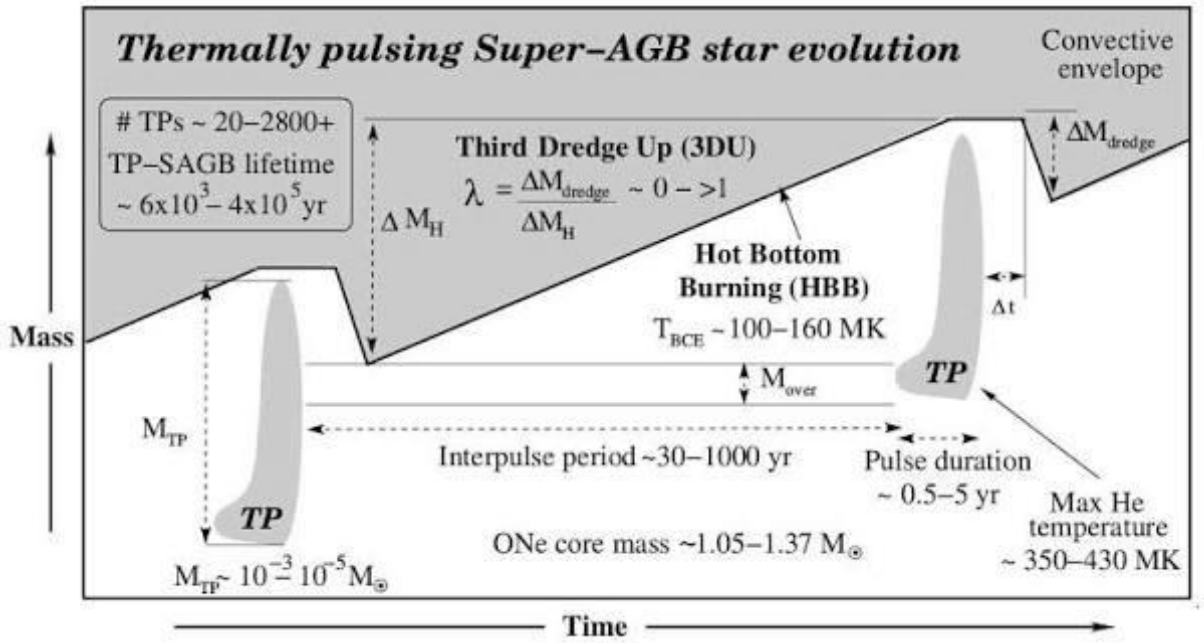
- **HBB**: As in massive AGBs ($\gtrsim$ 4-5 $M_\odot$), T at the base of the convective envelope is so high ($T_{BCE} \geq 100$ MK) that H-burning develops => ^{4}He, ^{14}N, ^{13}C ↑, ^{12}C ↓. Thus, they all become **O-rich stars (M-type)**.
- **TDU**: its **efficiency varies** in a wide range. The size of the dredged-up layers is very small: 10^{-4} – 10^{-5} $M_\odot$ => **overall dredged-up matter is relatively modest**. HBB quickly converts dredged-up ^{12}C into ^{14}N.
- **s-process** nucleosynthesis: only in inner convective shells (although TDU). **Neutrons produced via ^{22}Ne(α,n)^{25}Mg**.

TP-AGB



Choplin et al., 2025

TP-SAGB

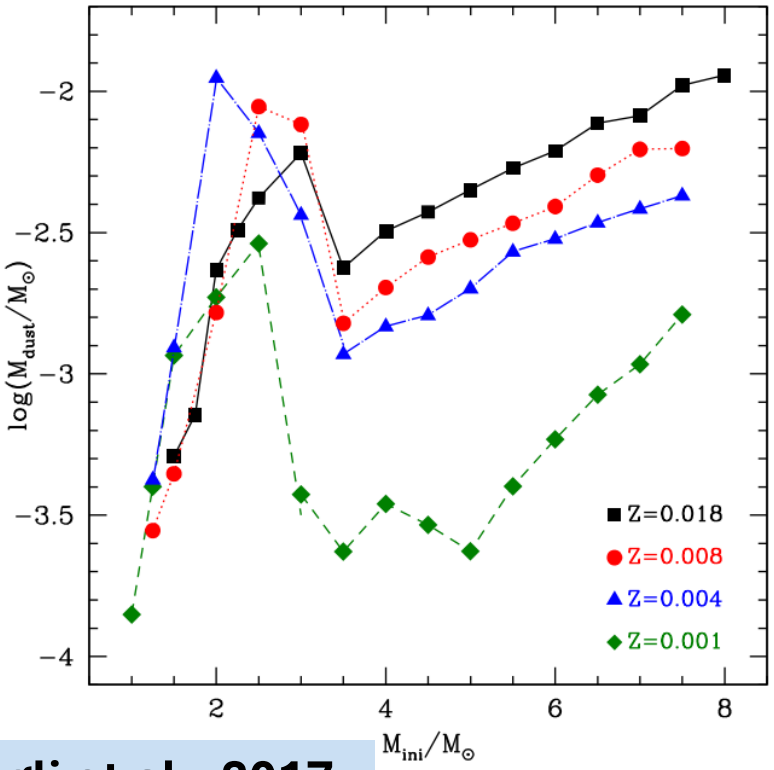


Doherty et al., 2017

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Dell'Agli et al., 2017

SAGBs produce silicate and alumina dust. They are the most efficient silicate dust producers.

Dust-driven wind:

Pulsations

⇒ envelope expands and cools

⇒ dust forms

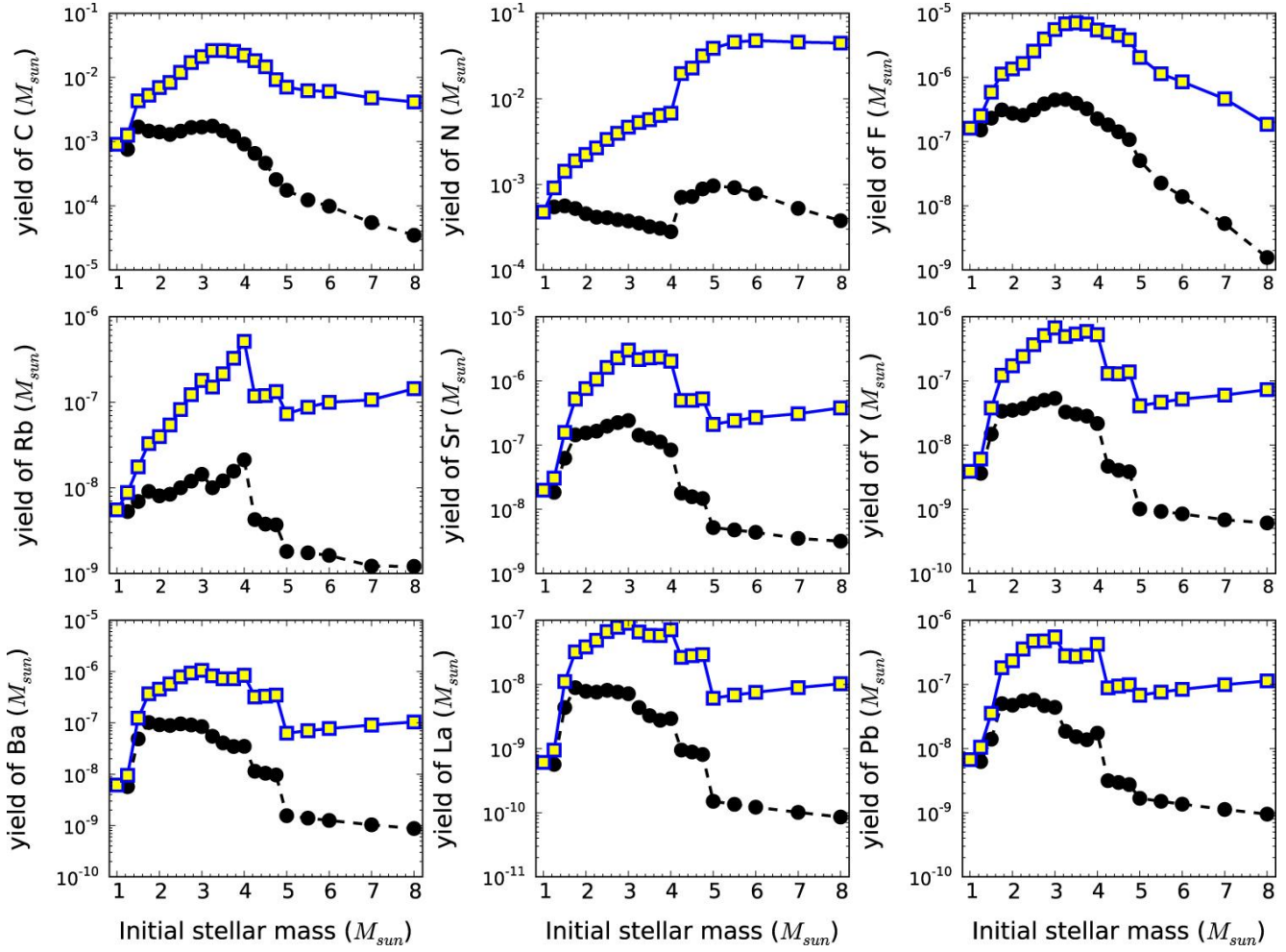
⇒ dust is accelerated by P_{rad} and drags gas with it.

3. The thermally-pulsing (S)AGB

Nucleosynthesis

- From the nucleosynthesis point of view, they are **not easy to distinguish from massive AGB stars**.
- From the point of view of Galactic Chemical evolution (**Kobayashi, Karakas and Lugaro, 2020**), **the contribution from SAGB stars is almost negligible**, unless:
  - SAGB binary components hosting a hybrid CONe core explode as SNe Iax.
  - Massive SAGBs explode as e-capture SNe.

Z = 0.014 models

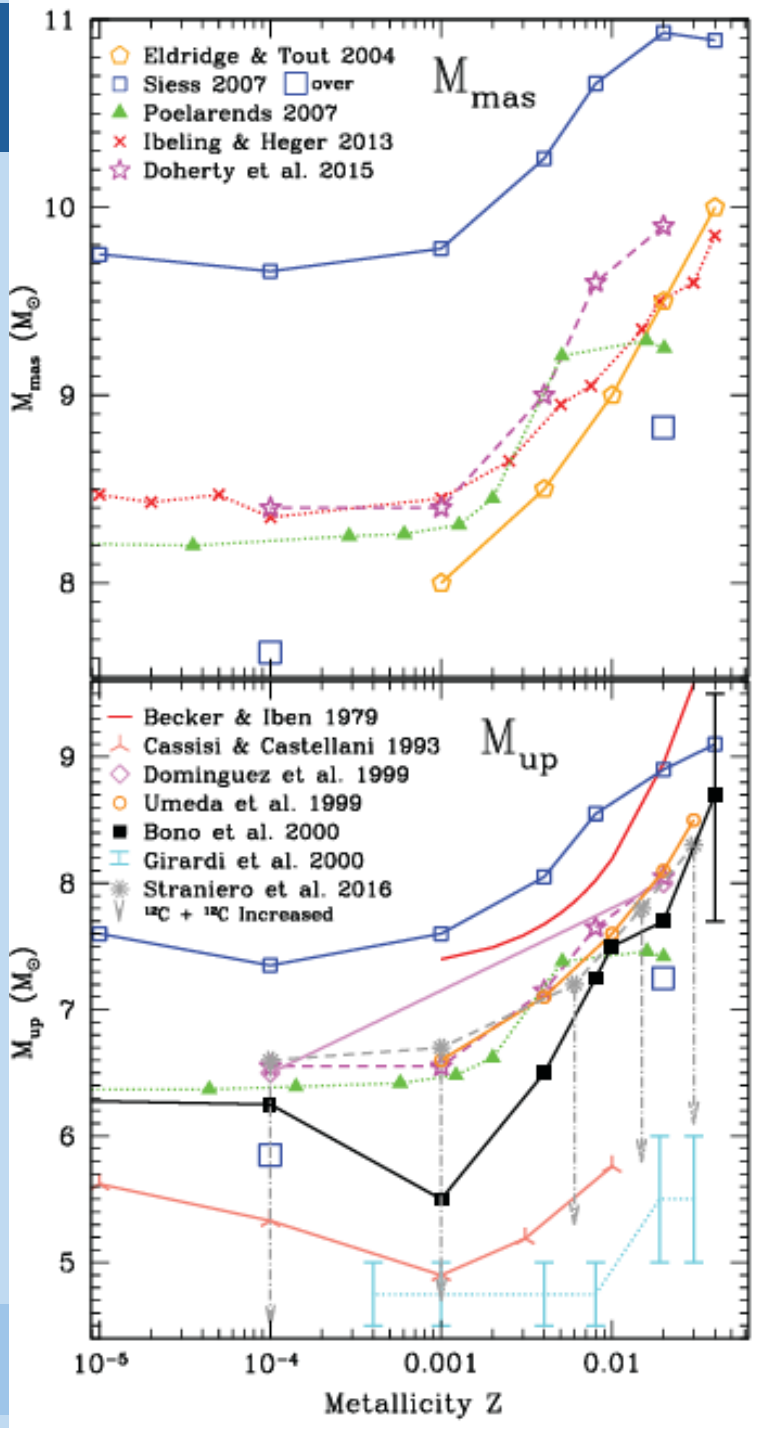


Karakas & Lugaro, 2016

4. Fates and remnants

Can the second dredge-up (or dredge-out) decrease the core mass below the Chandrasekhar mass?

- **M_{mass}**: minimum M_{ZAMS} to form a core-collapse SN.
- **M_n**: minimum M_{ZAMS} to form an e-capture SN.
- **M_{up} and M_{mass} vary** in a relatively wide range, depending on the metallicity and input physics.
- That **affects (via IFM) expected populations of massive WD, SNe Iax and e-capture SNe**.



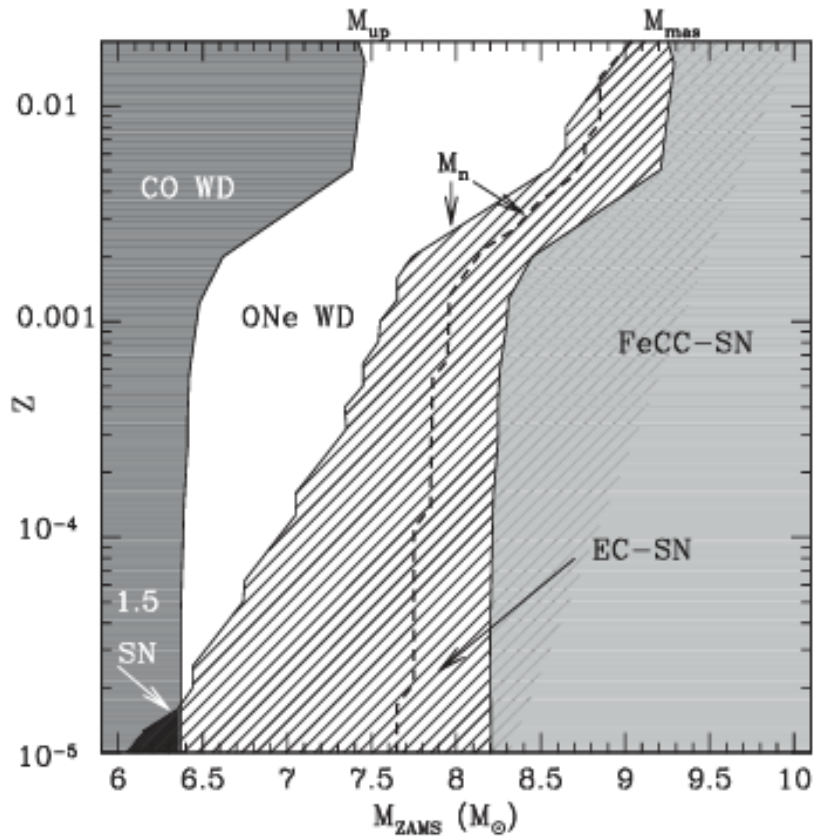
Doherty et al., 2015,2017

4. Fates and remnants

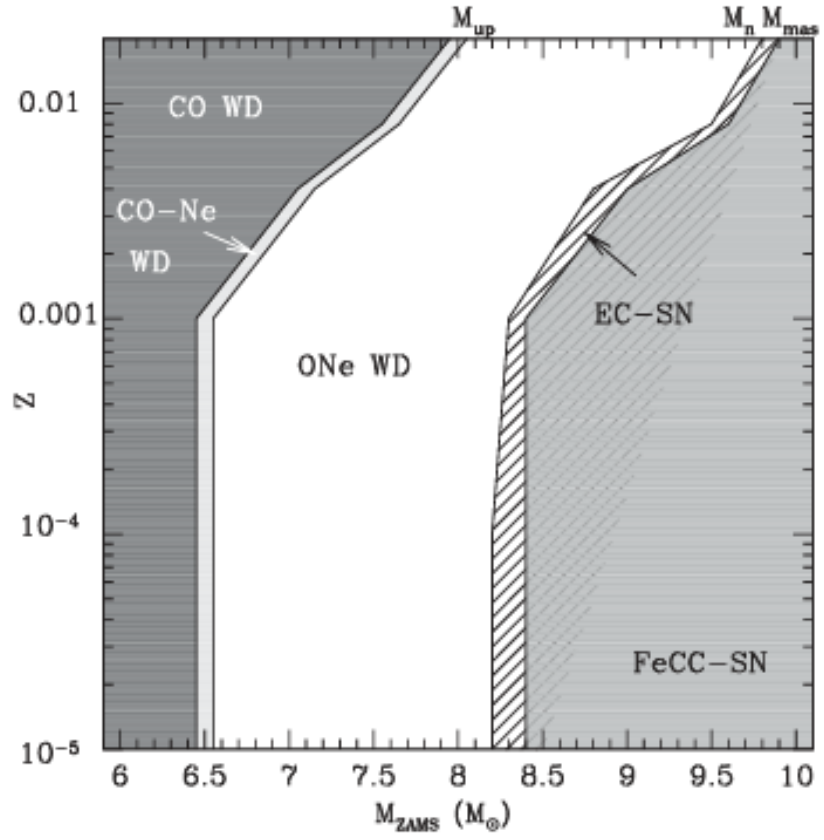
Different inputs physics lead to different final fates.

The M_{ZAMS} range to for e-capture SN varies drastically as Z decreases.

Doherty et al., 2017

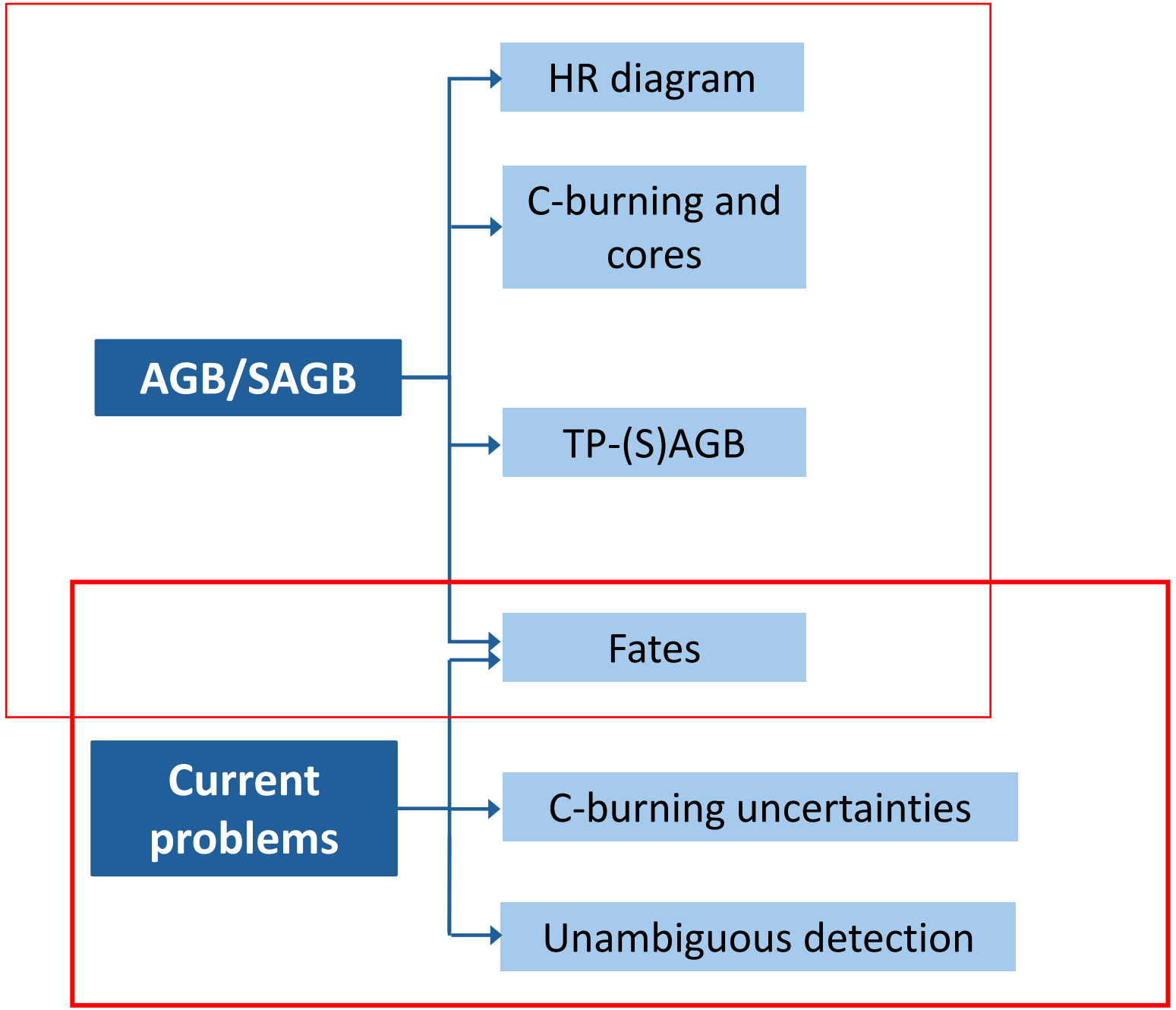


Poelarends et al. 2007 (overshooting, synthetic evolution)

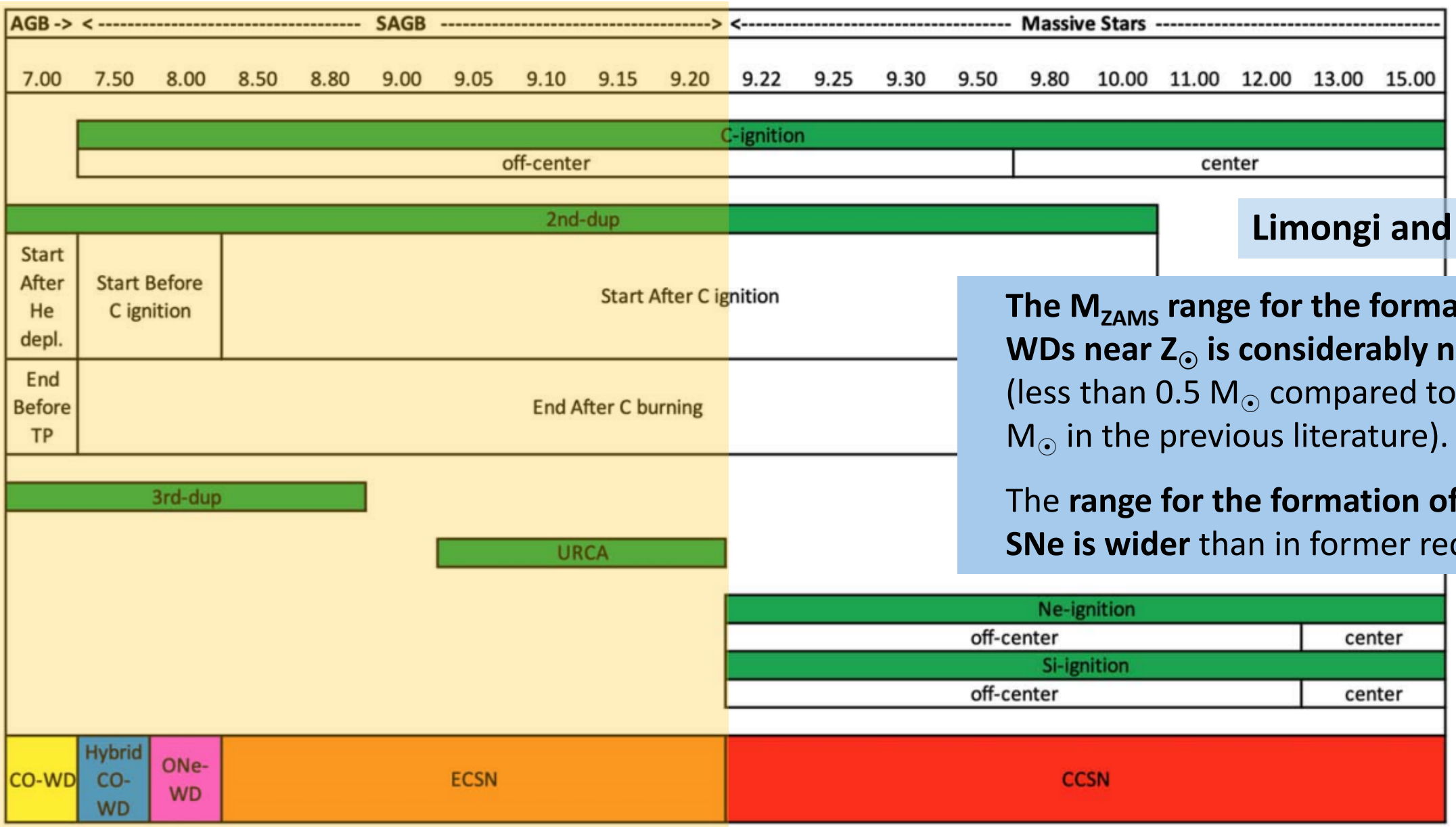


Doherty et al. 2015

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HR diagram
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Unambiguous detection

4. Fates and remnants / 5. Current problems: fates

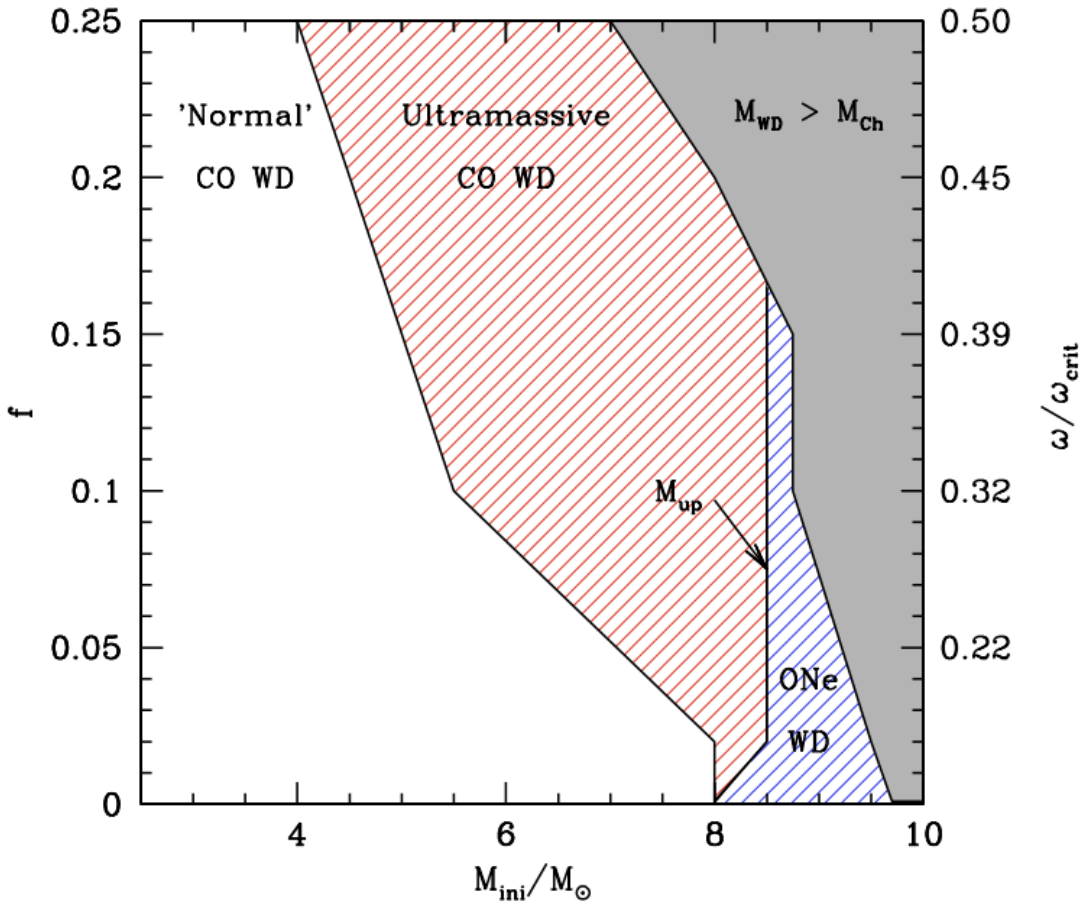


Limongi and Chieffi, 2024

The M_{ZAMS} range for the formation of ONe WDs near $Z_{\odot}$ is considerably narrower (less than 0.5 $M_{\odot}$ compared to typical 2 $M_{\odot}$ in the previous literature).

The **range for the formation of e-capture SNe is wider** than in former recent works.

4. Fates and remnants / 5. Current problems: fates



Althaus et al., 2021

Rotation may also affect the M_{ZAMS} mass range for the occurrence of C-burning and favour the formation of ultra-massive CO (UMCO) white dwarfs ($M_{WD} \geq 1.05\ M_{\odot}$).

These ultra-massive CO WDs may help explain the Q-branch (Cheng et al., 2020).

Their occurrence would also affect the rate of Type-Ia SNe, of high-field magnetic white dwarfs, and double-white-dwarf mergers.

5. Current problems: C-burning

Carbon-burning rates

C-burning rates are being revisited. Might be considerably lower or higher than currently assumed (Straniero et al., 2016, Chieffi et al., 2024, Gesue et al., 2026).

Models computed with standard CF88/5, and the hindrance case (HIND) yield UMCO WDs, and a wider range for the formation of hybrid CONe WDs.

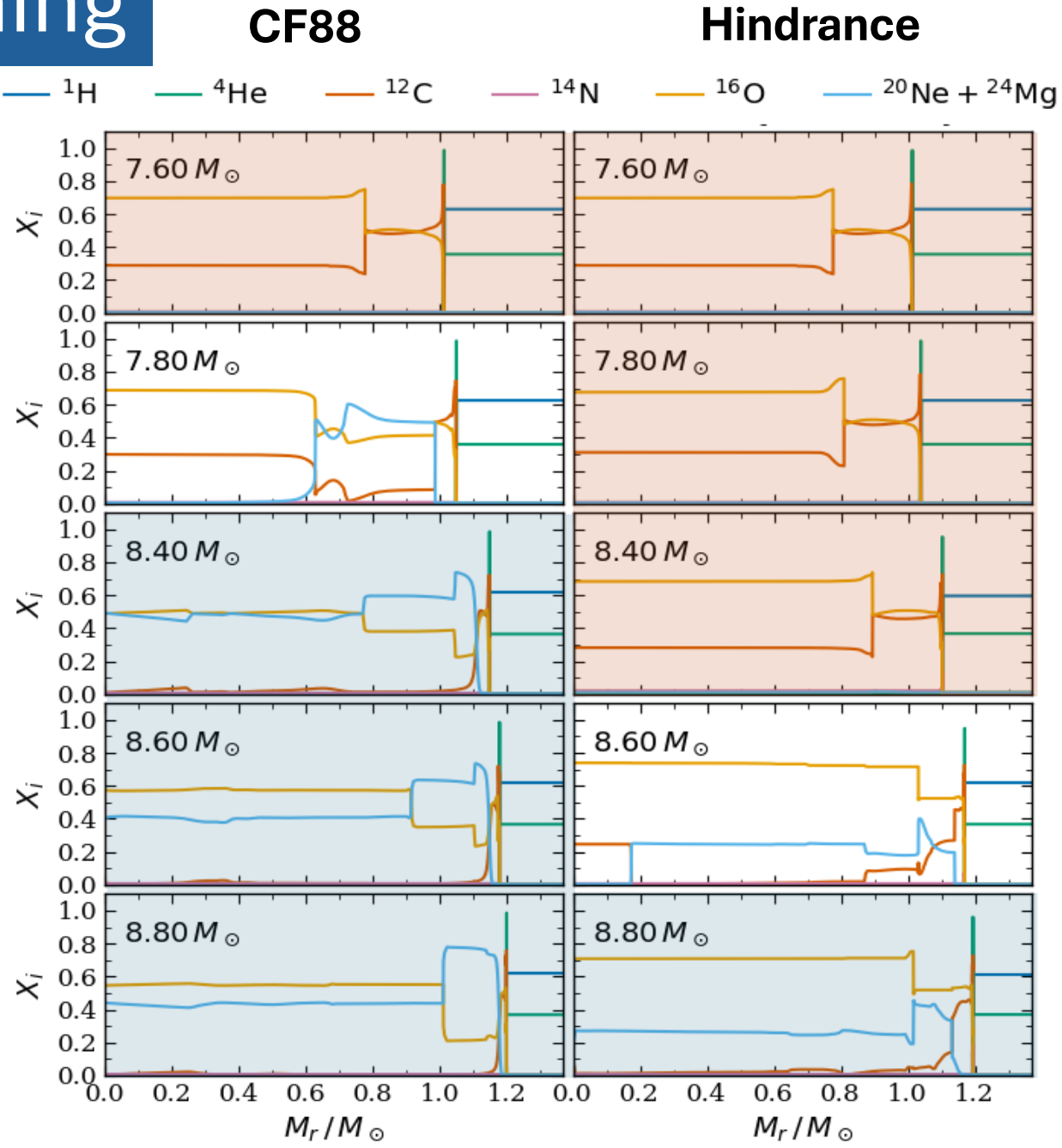
Maximum CO WD mass ≈ 1.15 $M_\odot$ instead of 1.05 $M_\odot$.

C-burning	M_{up}	M_{CONe}	M_n	M_{mass}
CF1988 (unsuppressed)	7.8	8.0	9.6	9.8
Suppressed (CF1988/5)	8.0	8.4	9.6	9.8
Suppressed (HIND)	8.5	8.7	9.6	9.8

Red → CO/UMCO WDs

White→ hybrid / CONe WDs

Blue → ONe WDs

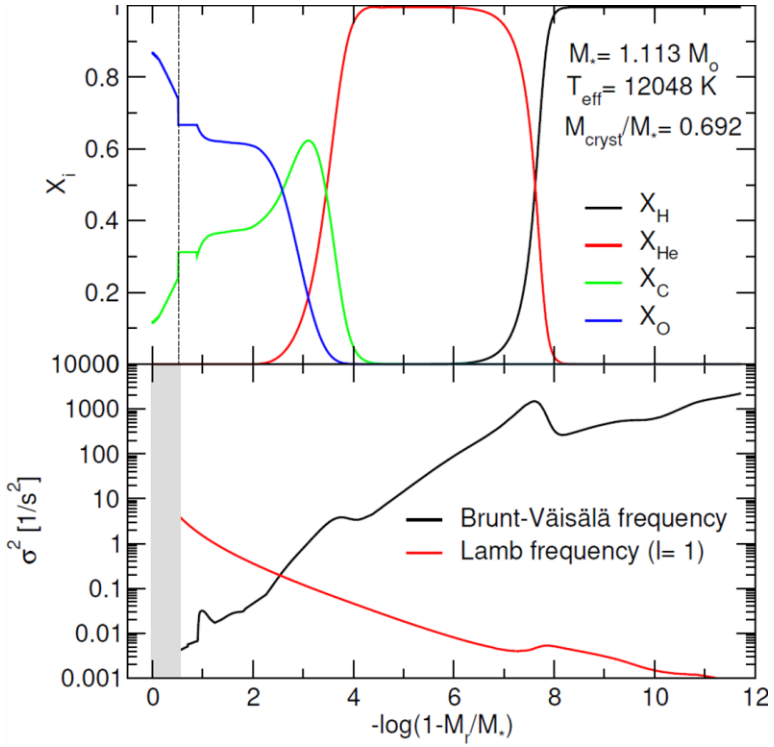


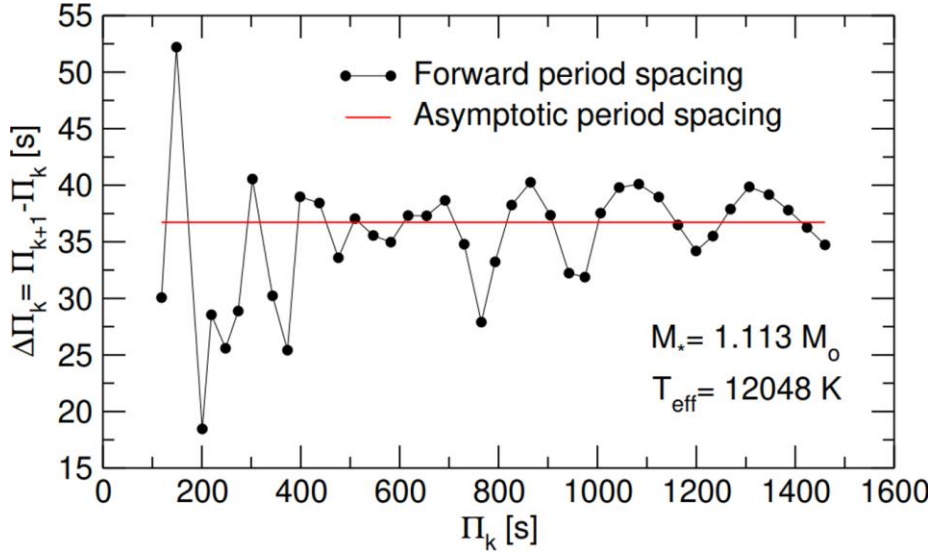
5. Current problems: C-burning and remnants

Stellar pulsations and the composition of massive AGB/SAGB remnants

The **internal chemical structure shapes both the pulsation properties and the crystallization process of white dwarfs. As the crystallized core modifies the g-mode propagation cavity, both effects leave an imprint on the period-spacing pattern**.

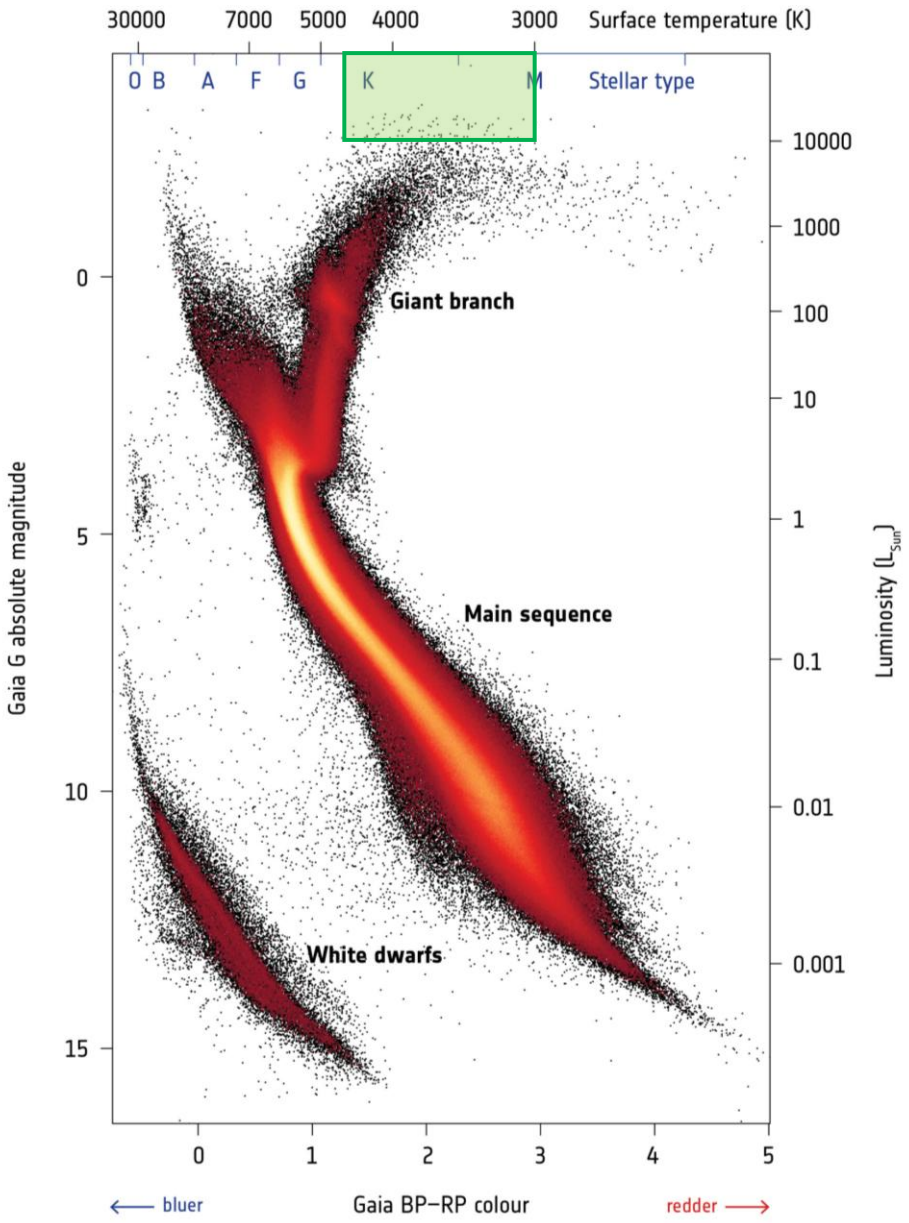
These preliminary results provide the basis for future comparisons with different CO and ONe-core models.





Gil-Pons, Althaus, Córsico et al., Euro-WD 2026

5. Current problems: can we tell when we see a SAGB?



Red Super Giants (RSG), Thorne-Żytkov Objects (TŻO), massive AGBs and SAGBs

- All these objects ocupy the cool (T_{eff} ≈ 3500 – 4500 K), high L (>10000 $L_{\odot}$) region of the HR diagram.
- Have extended convective envelopes: 100s-1000s $R_{\odot}$ and strong winds.
- Exhibit large-amplitude pulsations.
- Although they have very different origin (RSG are massive stars prior to core-collapse, TZO are descendants of massive binary systems/HMXBs, hosting neutron-star core).

5. Current problems: can we tell when we see a SAGB?

Red Super Giants (RSG), Thorne-Żytkov Objects (TZO), massive AGBs and SAGBs

	RSG	TZO	Massive AGB	Super-AGB
HBB	x	? (Li)	✓ (Li)	✓ (Li)
TDU	x	x	✓	✓ (?)
s-process	x	No, but irp (Rb, Mo)	✓	✓ (?)
Pulsations	LPVs: SR (SRb, SRc)	LPVs	LPVs: Miras, Δm>2.5 mag	LPVs: Miras, Δm>2.5 mag
Obs	✓	HV2112?	✓	**Ambiguous**
Diagnosis	Recent star formation/SN environment	Li, Rb, Mo	HBB, s-process	HBB, s-process?, higher L than AGB (?)

- **No SAGB has been unambiguously detected**.
- In HR-diagram, very similar to RSG, TZO and massive AGB.
- Chemically very similar to massive AGB stars.
- **Pulsations?** Probably also too similar to massive AGBs. Most massive ones might be distinguishable, although they are more scarce.

Levesque et al., 2014; O'Grady et al., 2020, 2023; Farmer et al. 2023

Summary

AGB/SAGB

- HR diagram → SAGB stars become cooler and more luminous than AGBs.
- C-burning and cores → SAGB stars burn C in degenerate cores ⇨ flashes and convective zones. Mup depends on Z, input physics.
- TP-(S)AGB → Narrower interpulse-periods, more TPs, narrower burning shells and intershells. TPs affect the H-partial ionization region ⇨ effect on pulsations. Very efficient HBB, TDU (and s-process) model-dependant.
- Fates → Still a considerable disagreement between authors. Strong Z + input physics dependance.

Current problems

- C-burning uncertainties → Remnants? Can WD pulsations help?
- Unambiguous detection → RSG? TZO? Massive AGB? SAGB?

Thanks