UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

UNIVERSITÉ DE GENÈVE

Impact of mass loss in stellar evolution models

Understanding the massive-star origin of our elements:
A unified understanding of stellar yields
Heidelberg, September 2023

Joris Josiek*
Astronomisches Rechen-Institut, Universität Heidelberg
(Formerly: University of Geneva, Switzerland)

*Collaborators:
Sylvia Ekström, **Andreas Sander**

Context

- Massive stars (20–120 $M_\odot$) are subject to intense mass loss.

  45-65% of their initial mass is removed during their lifetimes

- Mass loss is a **major source of uncertainty** in stellar models, but has a large **impact on stellar evolution**.

  A wide range of mass loss scenarios must be considered.

Focus of this work:
Investigating the effect of main sequence mass loss on the evolution of massive stars. ***Josiek et al. (in prep.)***
→ *Stellar evolution models*

Convection

Mass loss

Hydrodynamics

Thermodynamics

Radiation

Stellar structure and evolution model

Gravity

Diffusion

Nuclear reactions

Need to describe the stellar structure and to describe all the relevant physics in an applicable way!

The Geneva stellar evolution code (GENEC)

1) Solving the stellar structure (in 1D)

A star is divided into around **1000 layers**.

Each layer has **local properties**, e.g. temperature, chemical composition, etc.

Physical equations determine how properties change from layer to layer.

The algorithm finds a **stable solution** to the equations.

The Geneva stellar evolution code (GENEC)

2) Making the structure evolve

The user specifies the initial **global properties**, e.g. mass, chemical composition, rotation rate.

The algorithm computes the **stable stellar structure**.

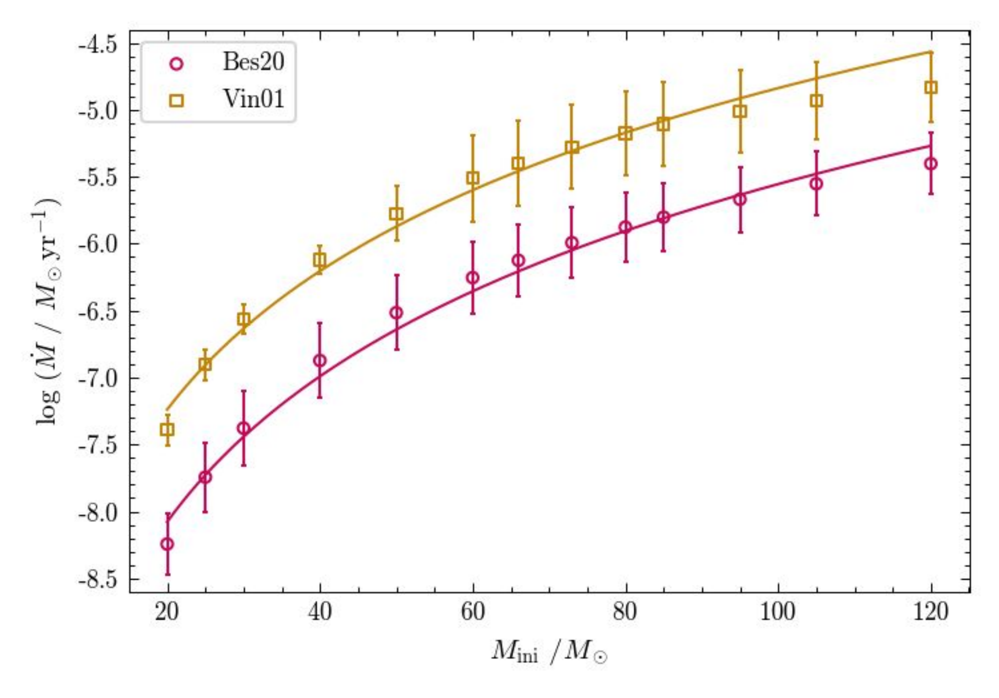
Changes are applied for a small timestep,

- Chemical structure changes (e.g. nuclear reactions).
- Mass decreases due to **stellar winds**.

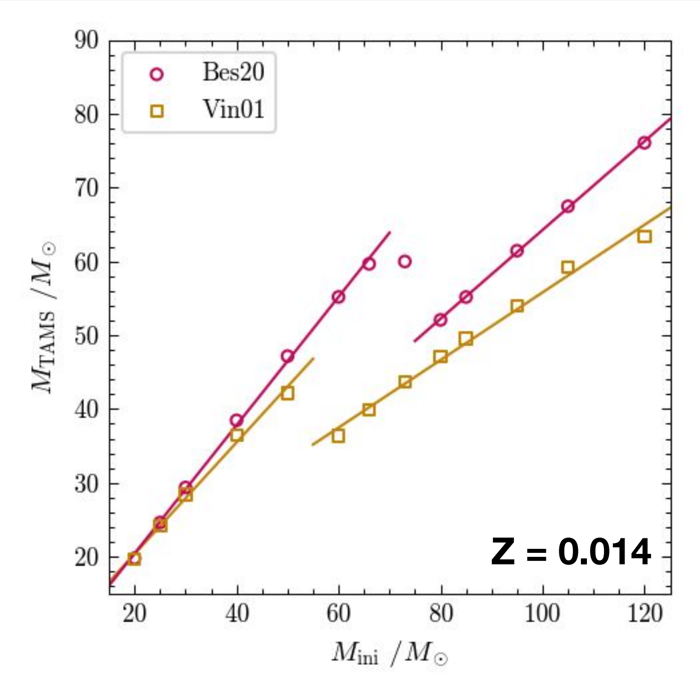
Models

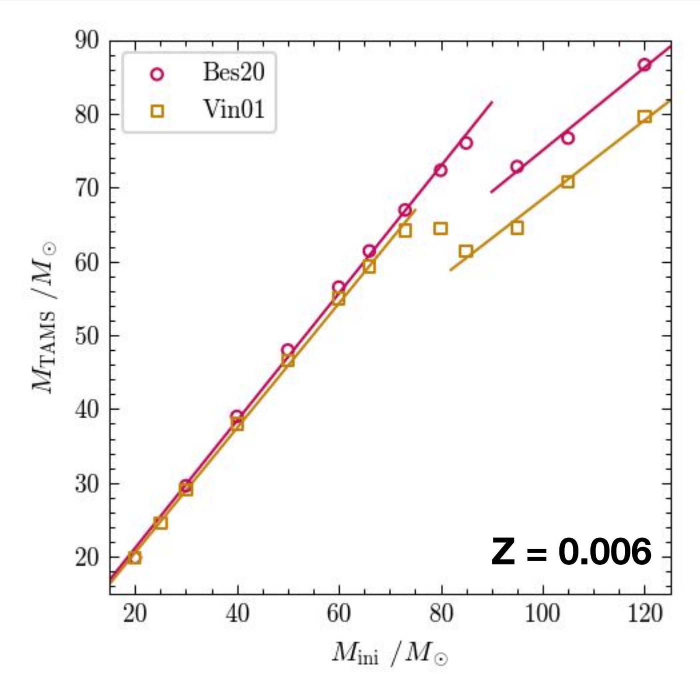
- Geneva Stellar Evolution Code (**GENEC**)
- Initial masses: **20–120 $M_\odot$**
- Metallicity: Solar (**0.014**), [LMC (**0.006**)]
- **Rotation-free**
- 2 **O/B mass loss** prescriptions:
  - Vink et al. (2001) [standard] **Vin01**
  - Bestenlehner (2020), calibrated on LMC by Brands et al. 2022 **Bes20**
- Run from **ZAMS** to the end of central **carbon burning**

Mass loss rates (Main sequence)



Mass lost during the main sequence



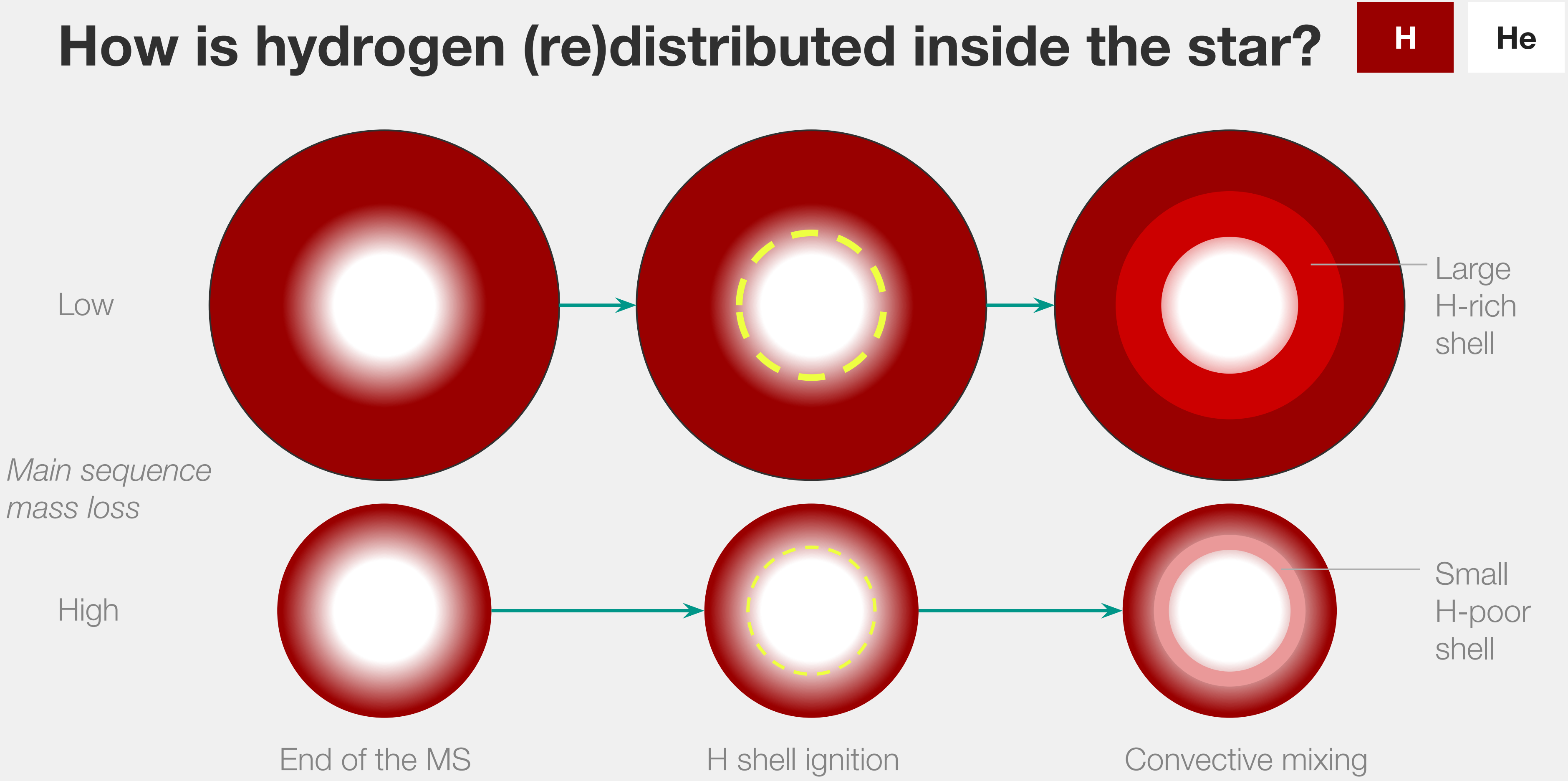


Regime Transition

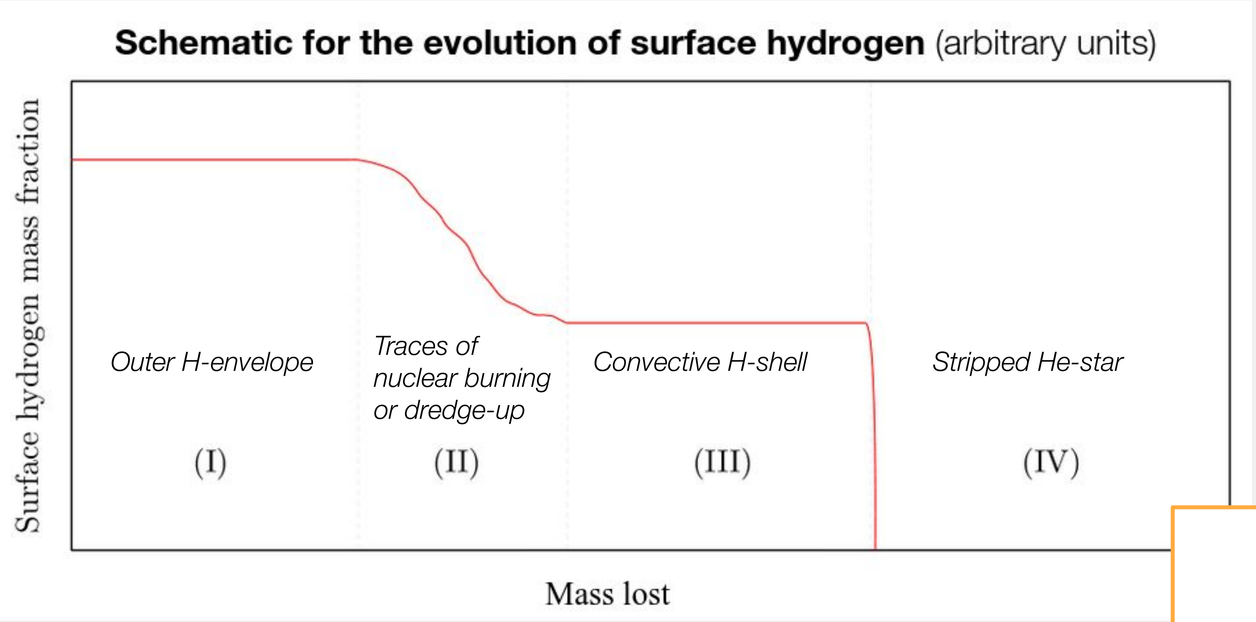
Vin01:
Bistability jump

Bes20:
Optically thin/thick winds ($\Gamma_{\rm Edd}$)

How is hydrogen (re)distributed inside the star?



Evolution of surface hydrogen



Typical "hydrogen depletion curve"

Yield:

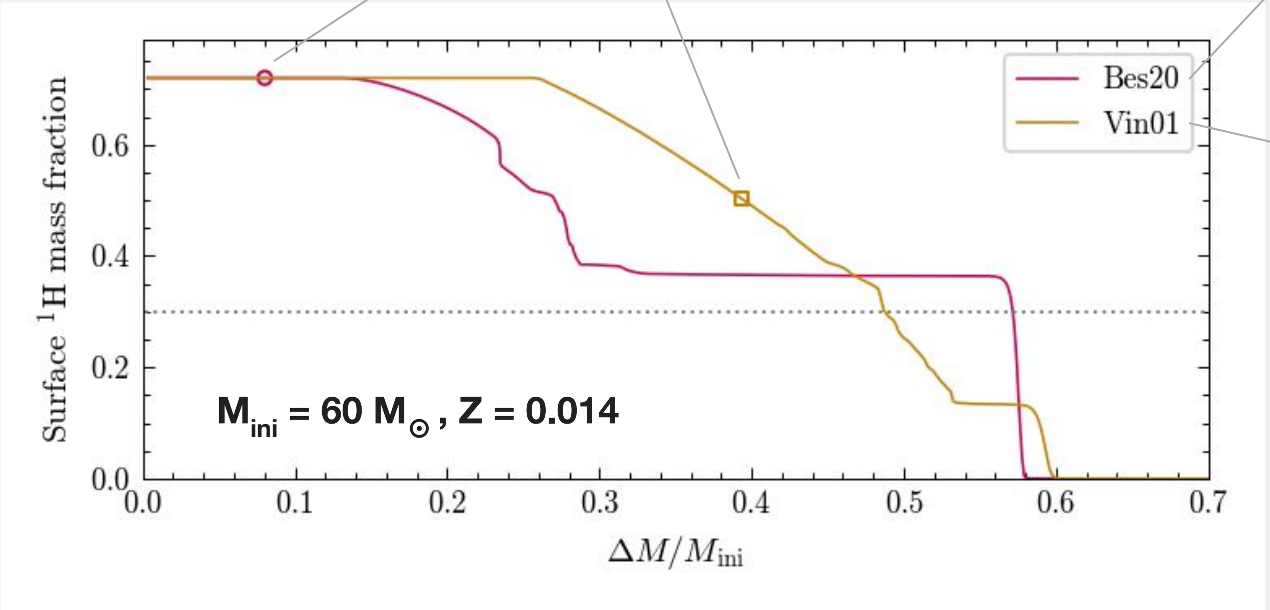
$$M_X = \int X_s(M)\, dM$$

Evolution of surface hydrogen

End of the MS

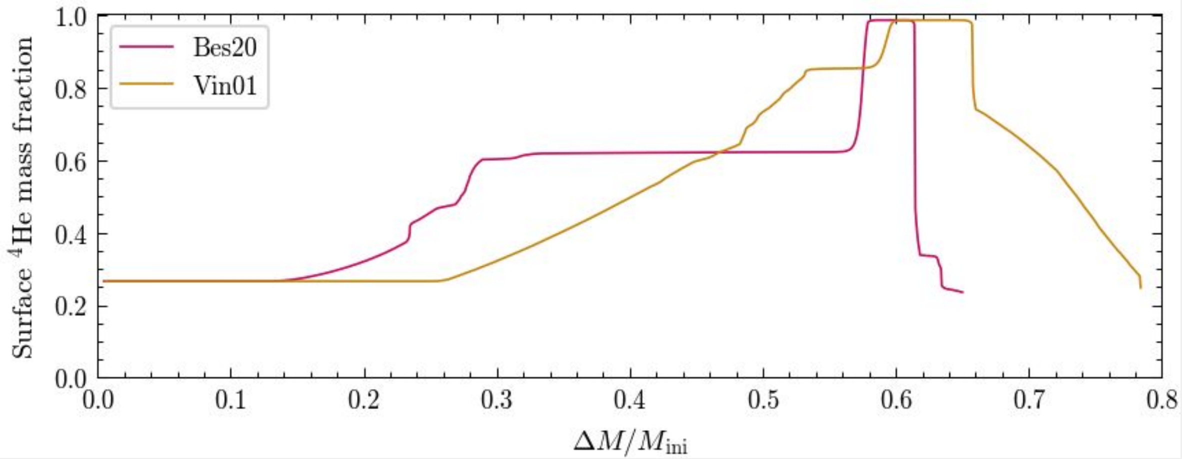
Low MS mass loss regime

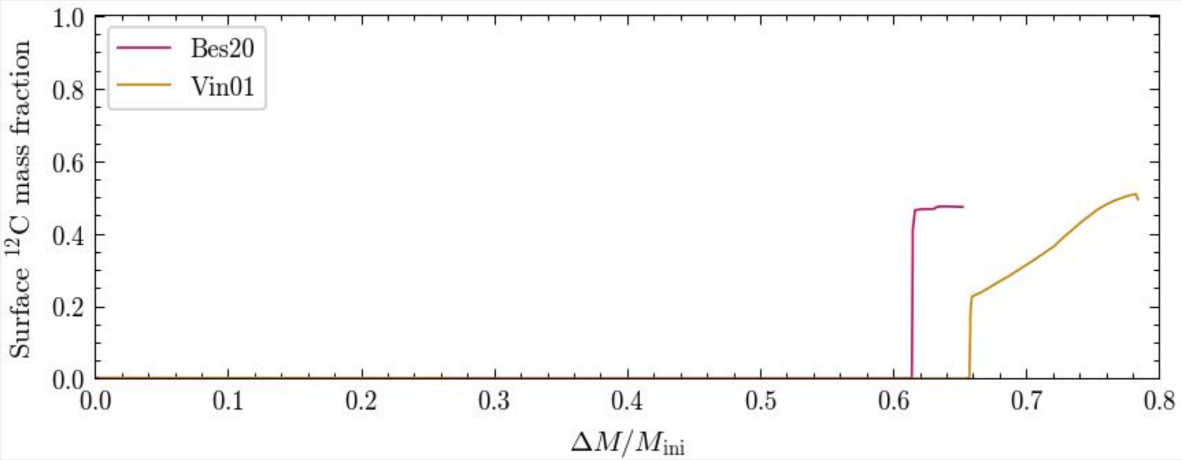
High MS mass loss regime



"Hydrogen depletion curve" with model data

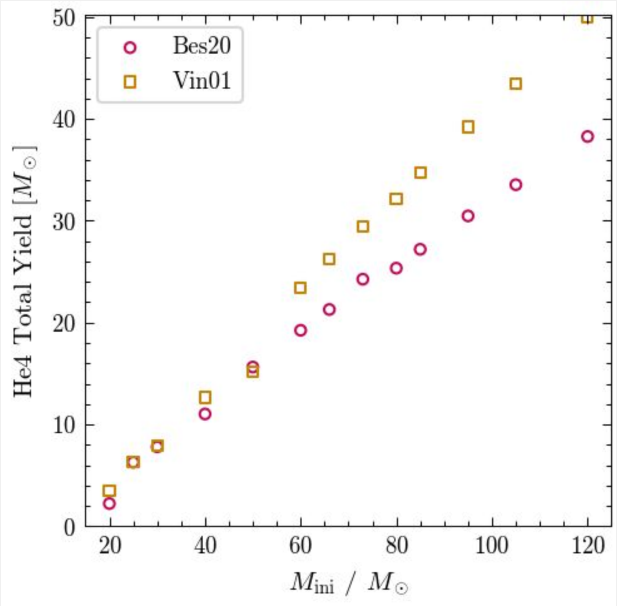
Other Elements



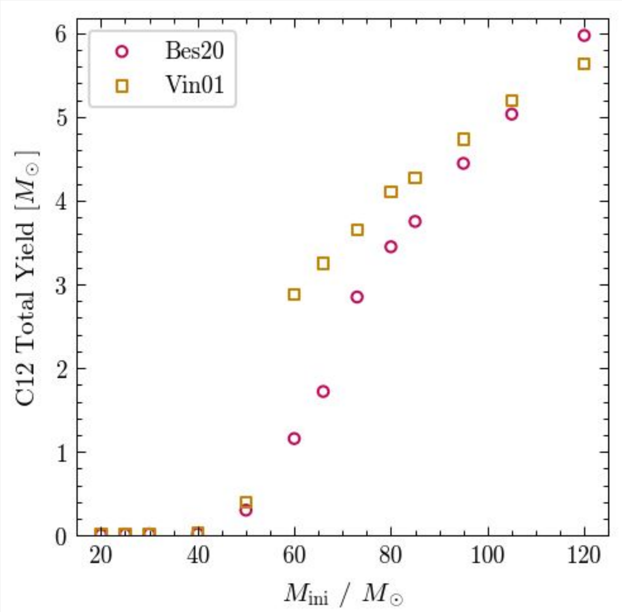


	Net Yields (Msol)	
	Bes20	Vin01
H	-10.5	-14.3
He	8.8	10.9
C	1.1	2.8
N	0.2	0.2
O	0.4	0.3
Total Mass Loss	39.3	47.1

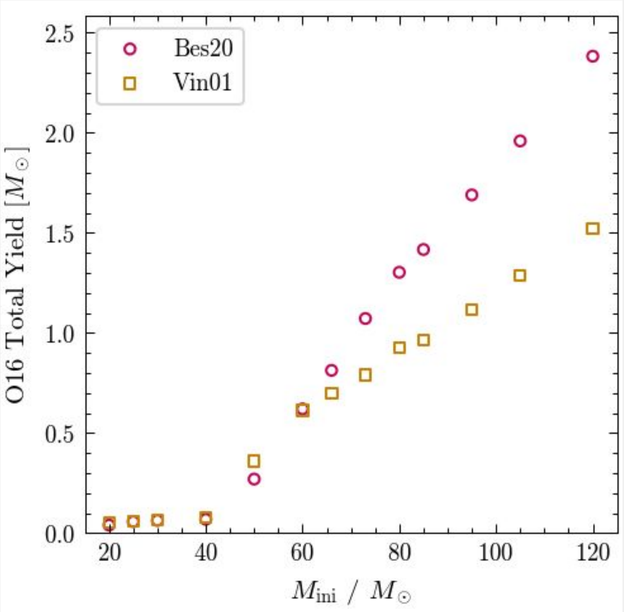
Total Yields



Helium

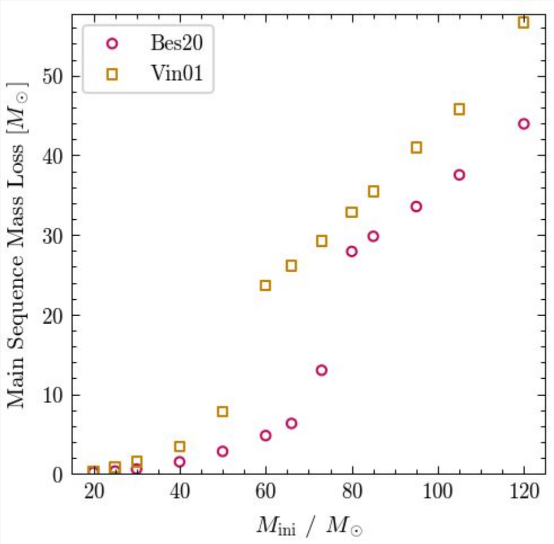


Carbon

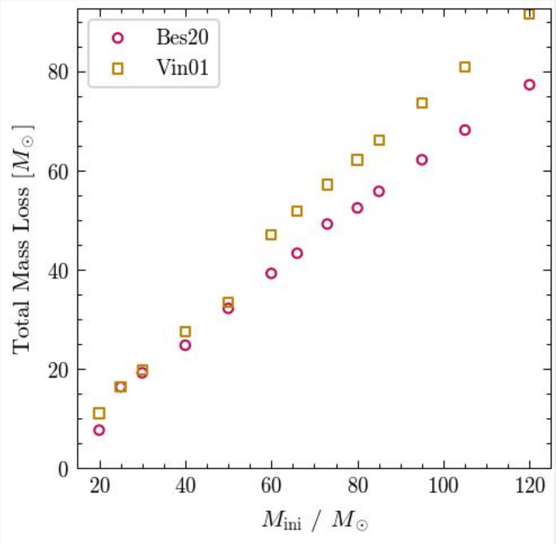


Oxygen

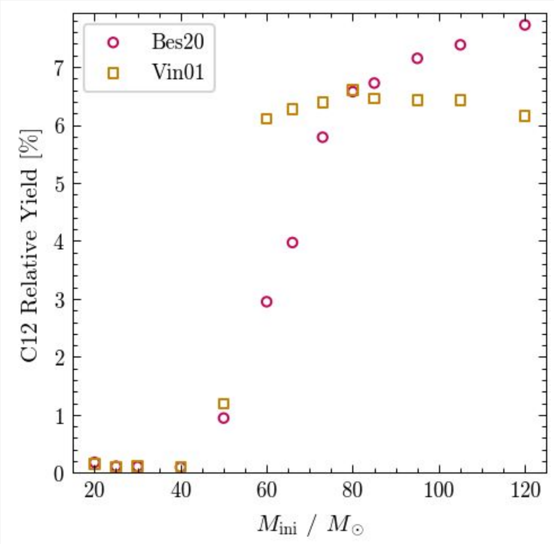
Relative Yields (e.g. Carbon)



Trend doesn't reverse!

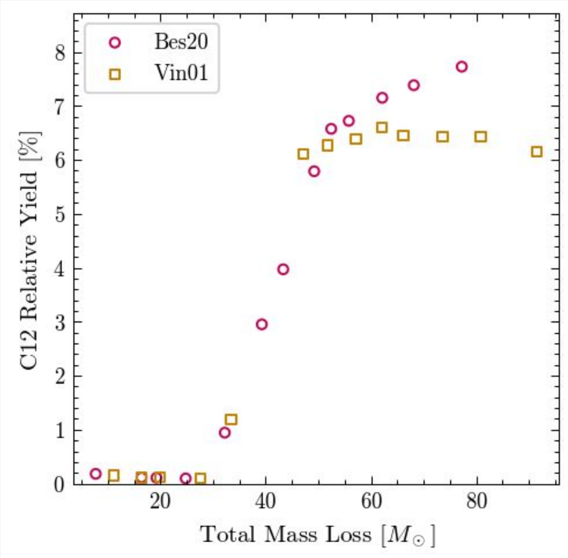


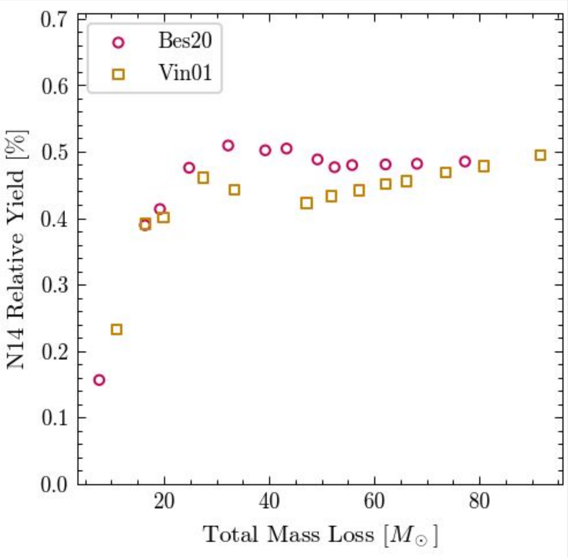
Trend doesn't reverse!

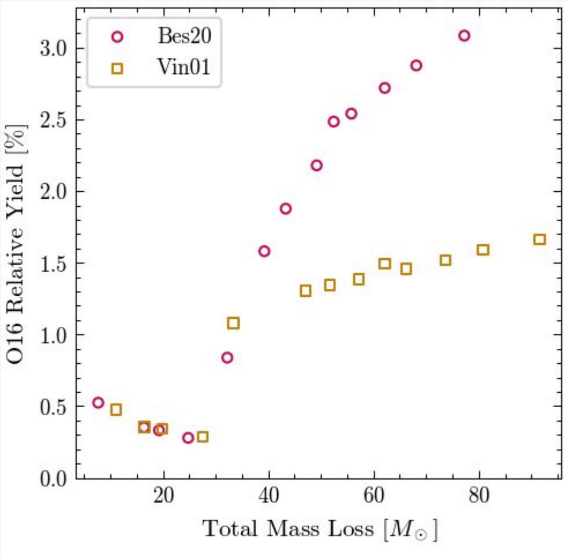


Trend ***reverses***!

Relative Yields vs Total Mass Loss

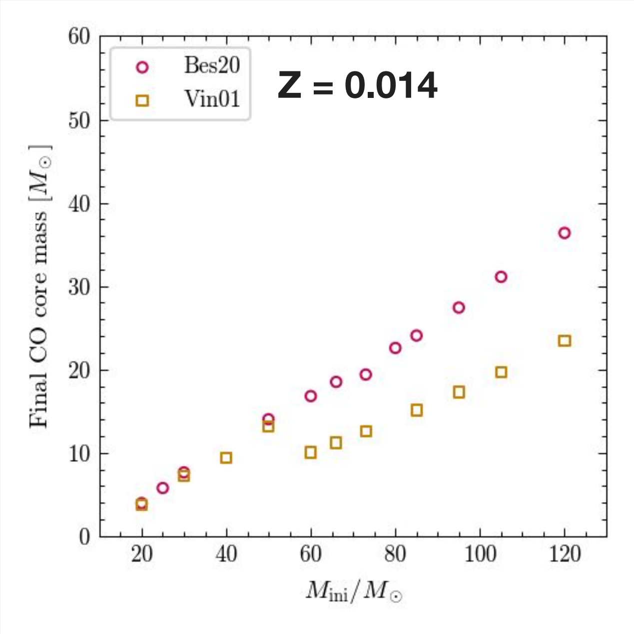


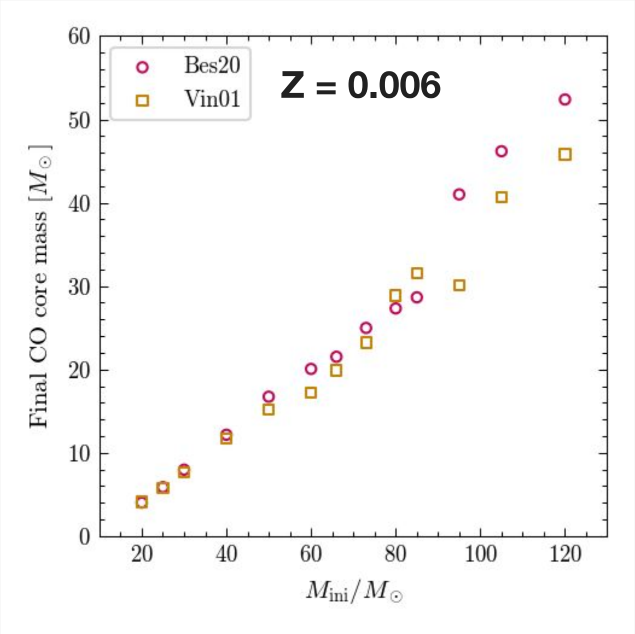




Total mass loss does not predict yields ⇒ **Must account for mass loss history!**

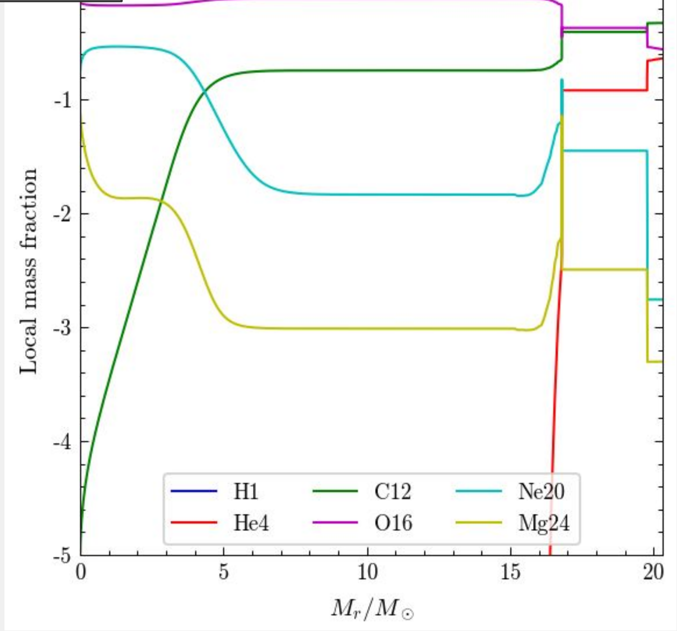
“Final” core mass



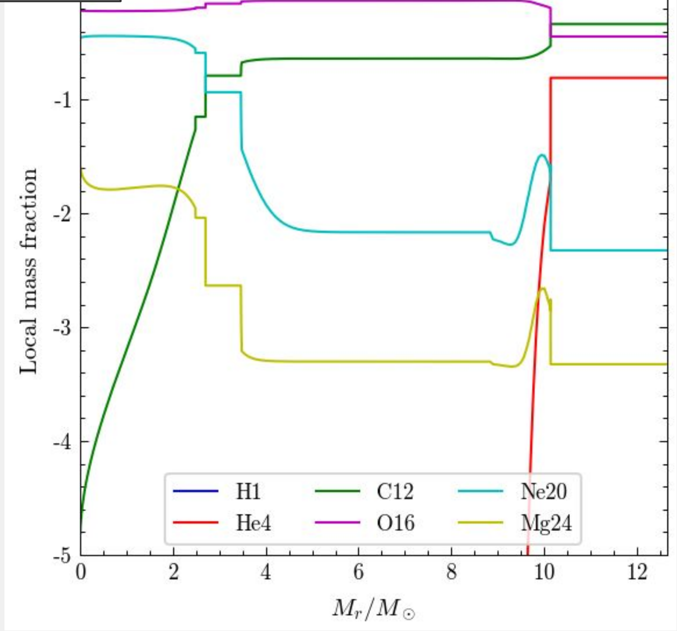


“Final” abundance profile

Bes20



Vin01



60 solar mass, solar metallicity models at the end of central carbon burning

What influences mass loss history?

In evolution codes + in reality : **Evolutionary phases**

Main sequence

Red supergiant

LBV / Yellow supergiant

Wolf-Rayet stars

Wolf-Rayet stars

In evolution models:

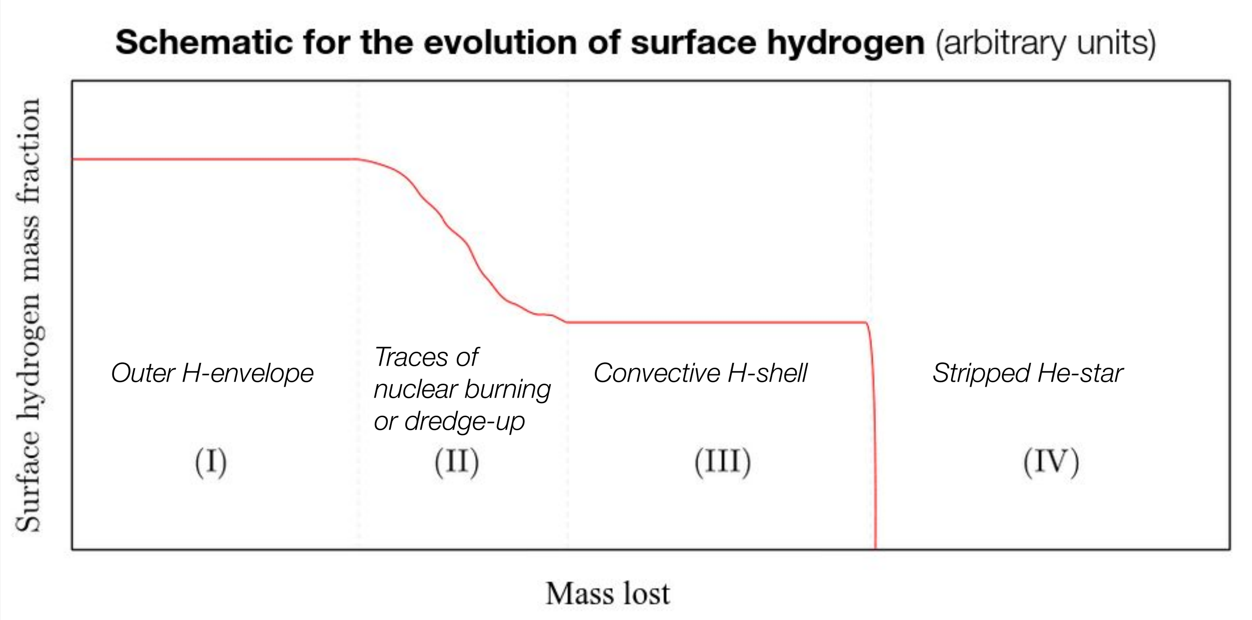
T_{eff} > 10 000 K
X_{surf} < 0.3

Subtypes:

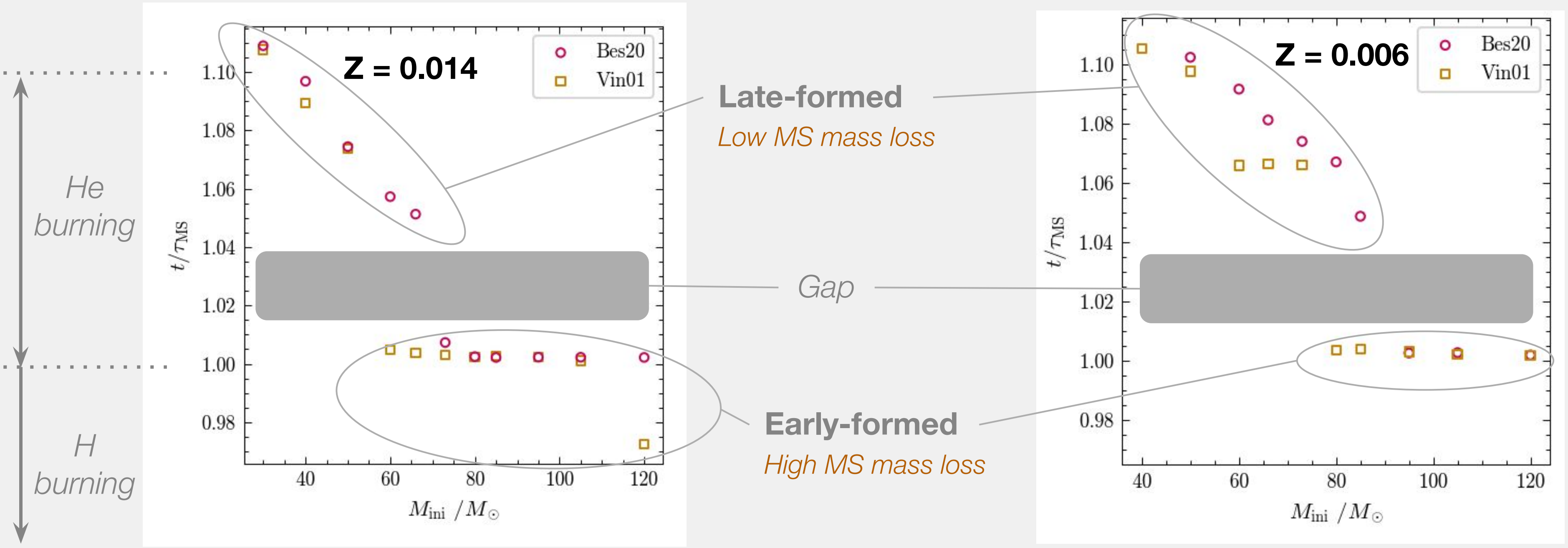
WNL	N/C > 1, $X_{surf}>10^{-5}$,
WNE	N/C > 1, $X_{surf}<10^{-5}$,
WC	N/C < 1, $T_{eff} < 10^{5.25}$ K,
WO	N/C < 1, $T_{eff} > 10^{5.25}$ K

- Mass loss is closely linked to these criteria ($T_{eff}\uparrow$ & $X_{surf}\downarrow$ by removing surface material)
- Not applicable to non-WR stripped stars (e.g. through binary mass transfer) (e.g. Shenar et al. 2020)
- **Spectroscopic classification ≠ Theoretical classification**

H-depletion curve (Repeat)



Time of WR formation



Post-Main-Sequence evolutionary paths

Low Mass Loss Regime

RSG/**YSG** → Remove mass, incr. Teff →

BSG → Remove H-rich shell →

H-depleted **WR** (WNE/WC)

High Mass Loss regime

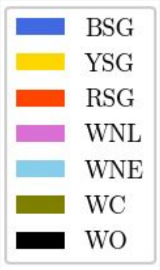
YSG (very short, a few 1000 years)

→ Remove mass, incr. Teff →

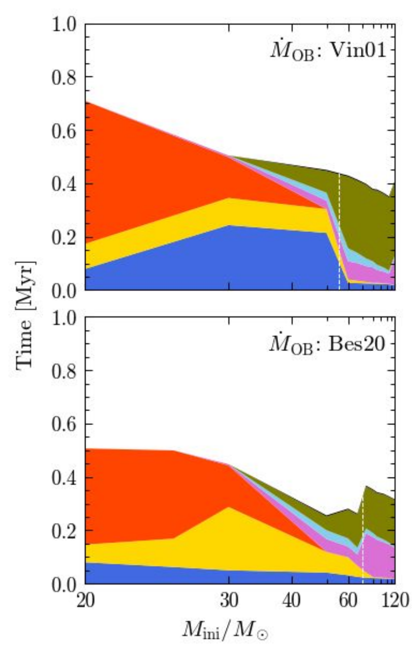
H-poor **WR** (WNL) → Remove H-poor shell →

H-depleted **WR** (WNE/WC)

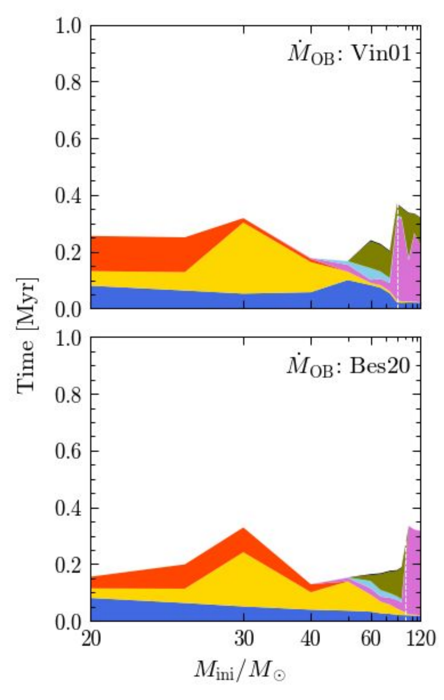
Timescales/Populations



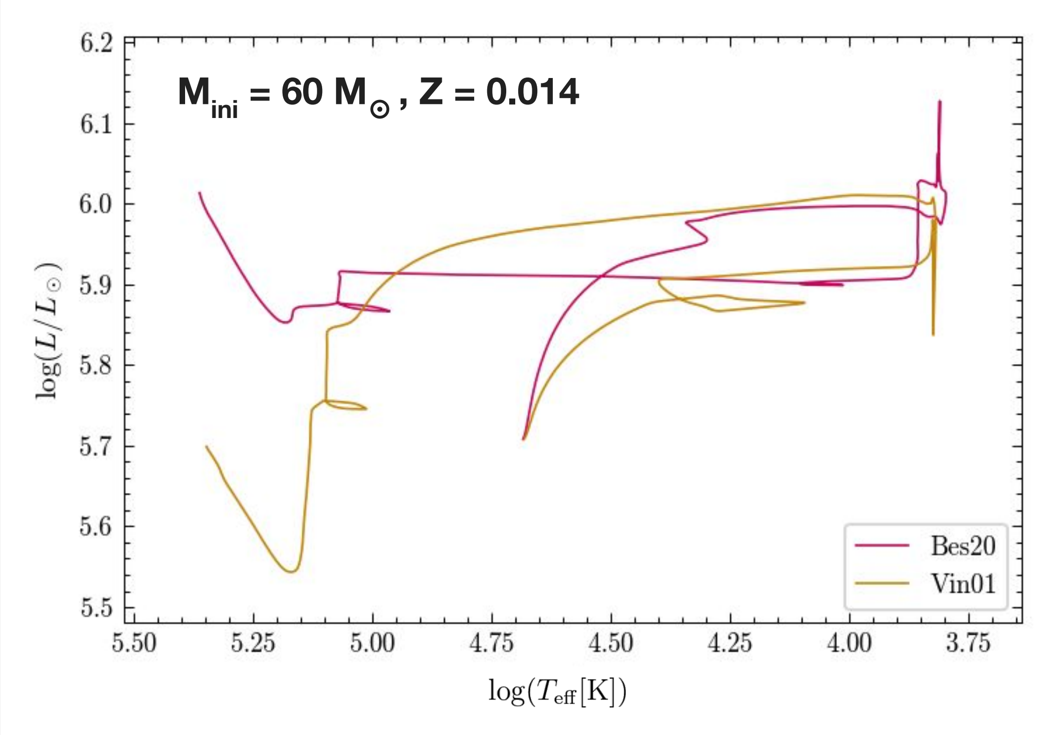
Z = 0.014



Z = 0.006

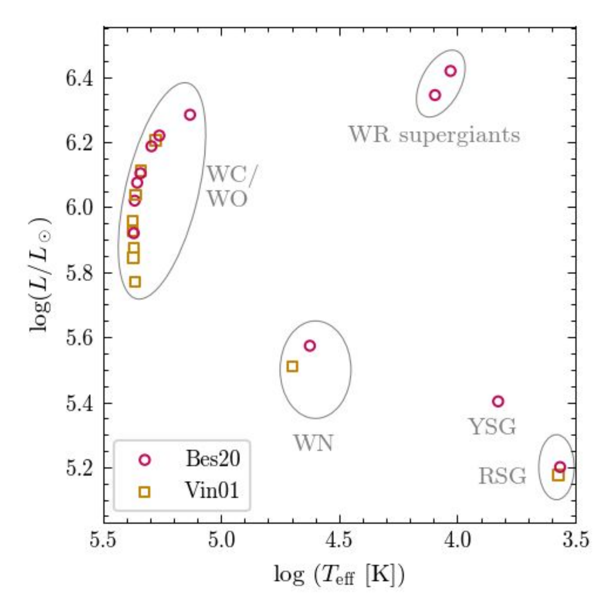


Evolution in the HRD

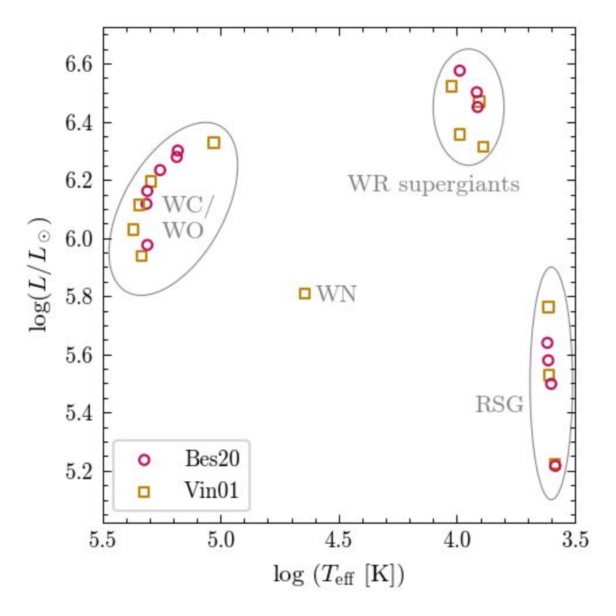


Evolution endpoint

Z = 0.014



Z = 0.006



Conclusions / Summary

- Mass loss (especially in MS) influences the **interior structure of stars**.
- Mass loss history determines the **exposure of elements** on the surface and therefore **yields**.
- Mass loss during the main sequence determines the sequence and duration of subsequent **evolutionary phases**.
- **Mass loss effects on the evolution are complex!**

Problems

- Mass loss domain definition in evolution codes is arbitrary.
- Other effects: convection, rotation, binarity, nuclear reaction networks …
- **Which mass loss rate is the best??**