Very massive stars do not expand

The (un)eventful life at the massive end of the IMF

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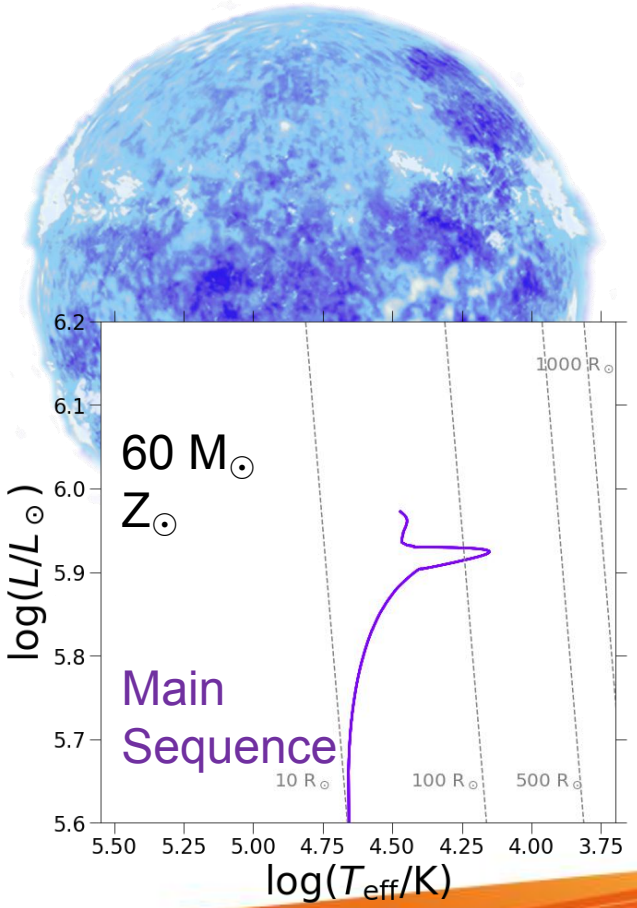
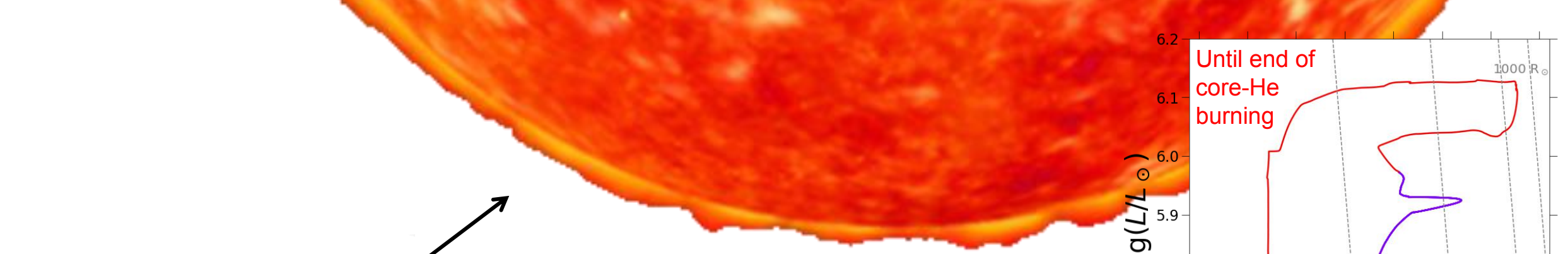
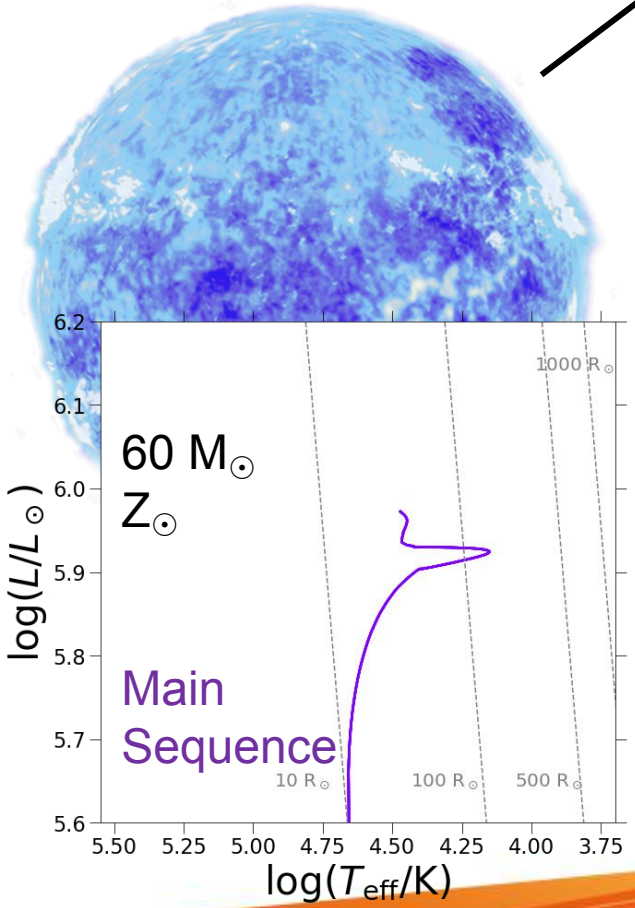
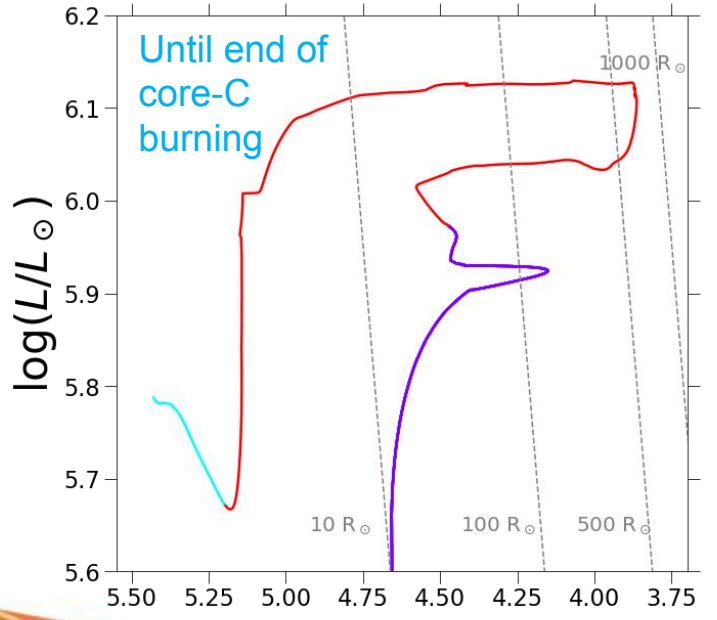
Massive stars - Evolutionary pathways

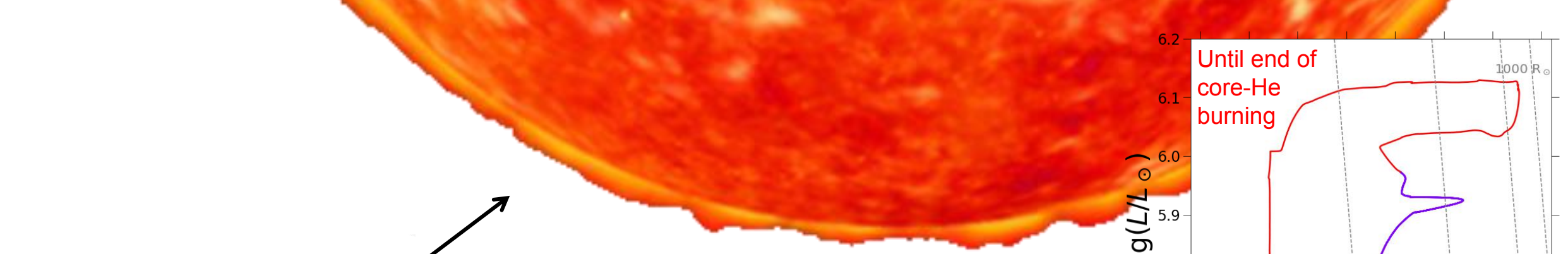


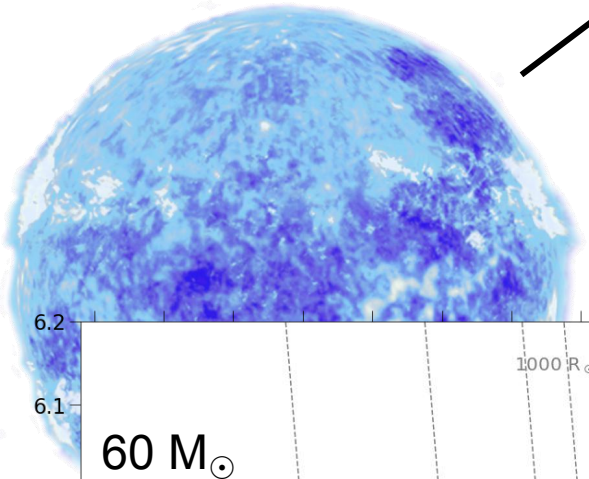


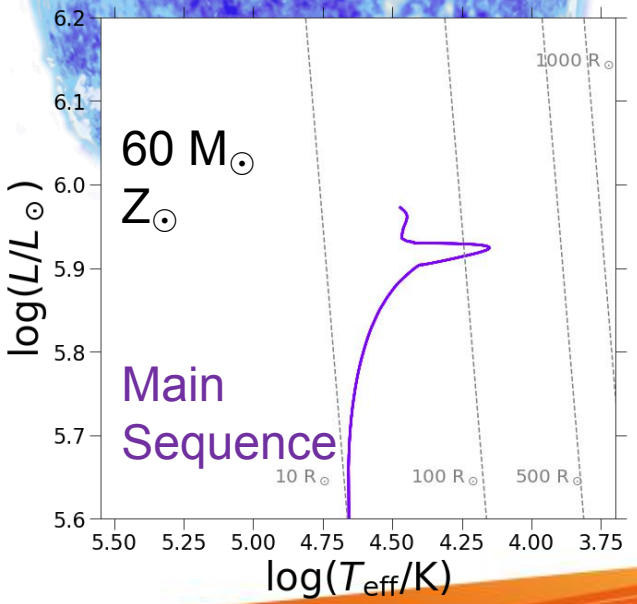
Yellow/Red supergiant





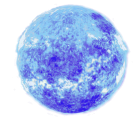




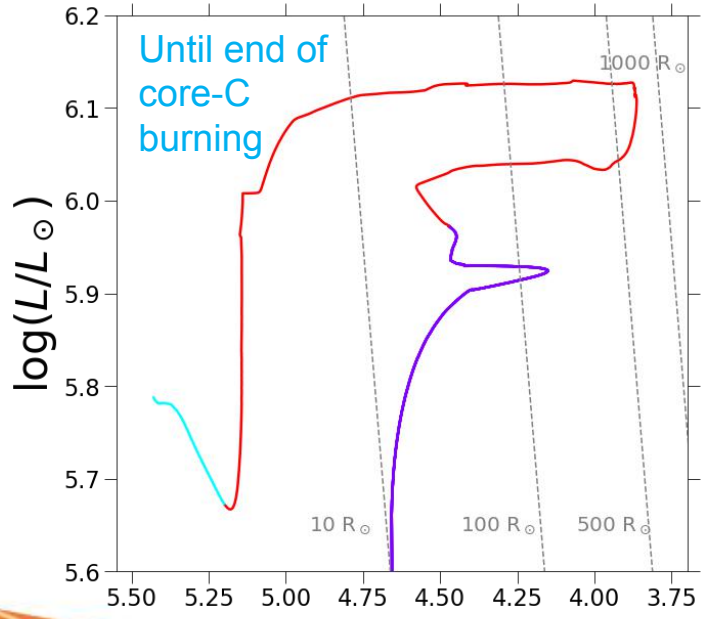


Yellow/Red supergiant

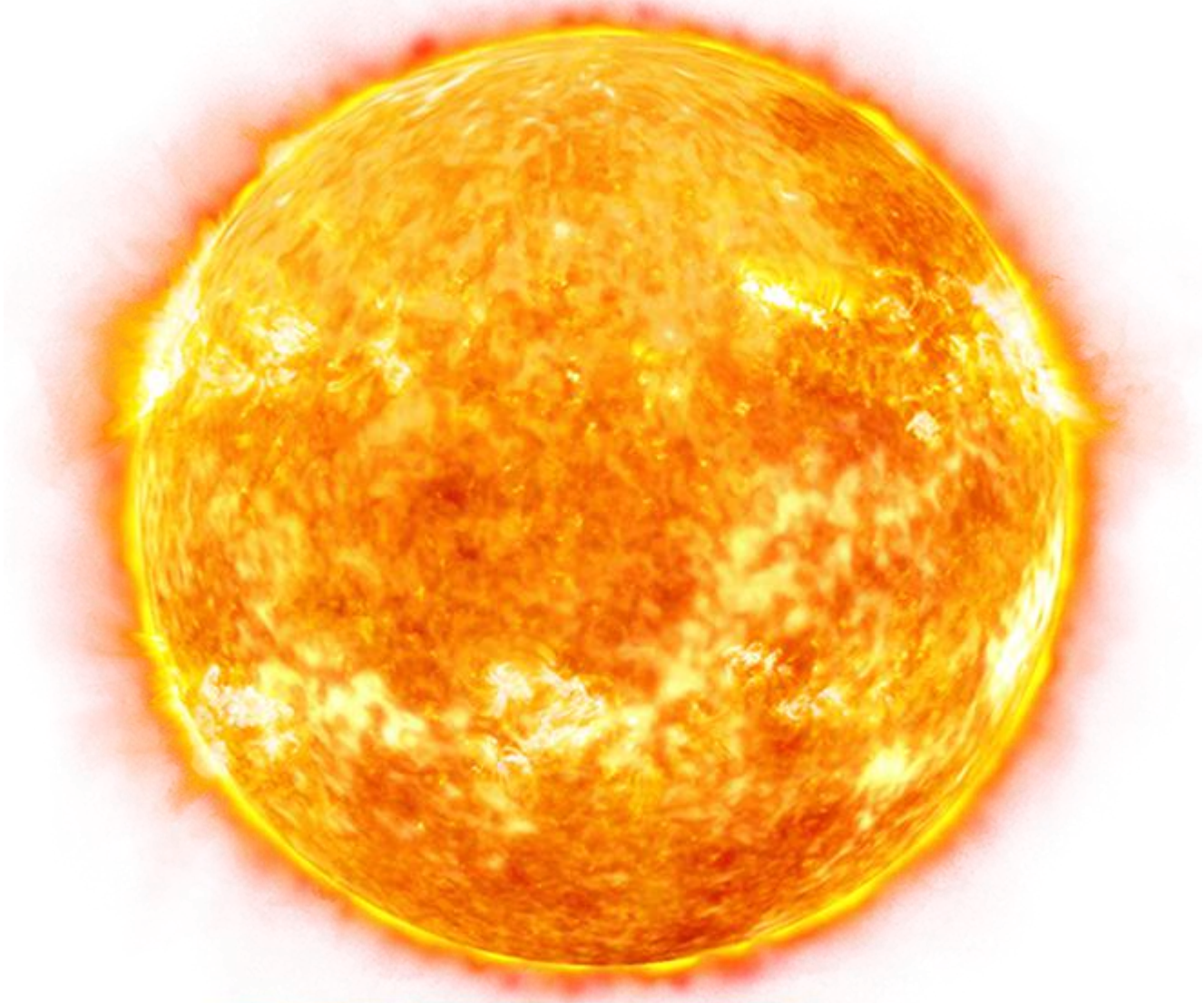
MAYBE



Wolf-Rayet star



How do we form a Wolf-Rayet?



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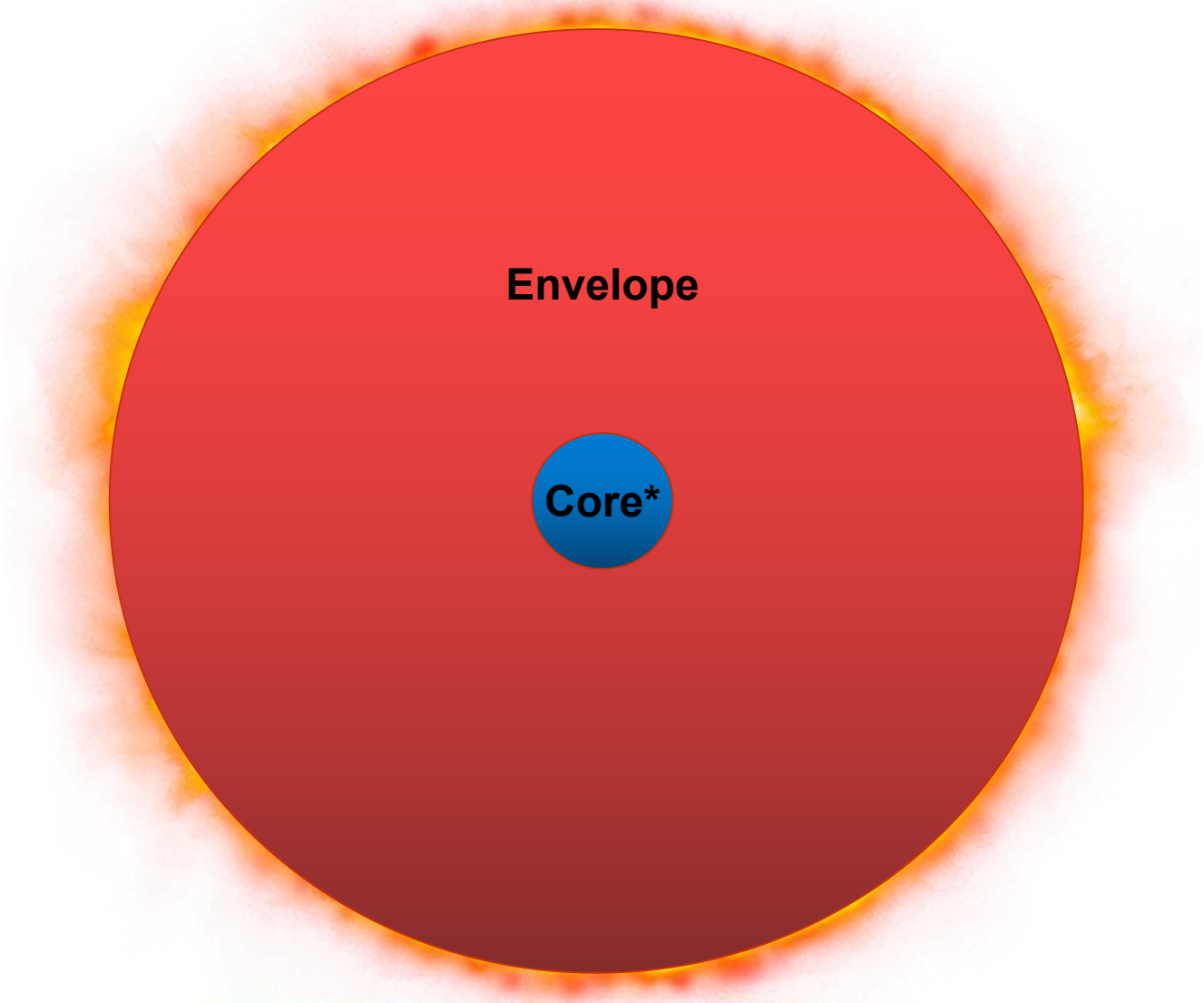
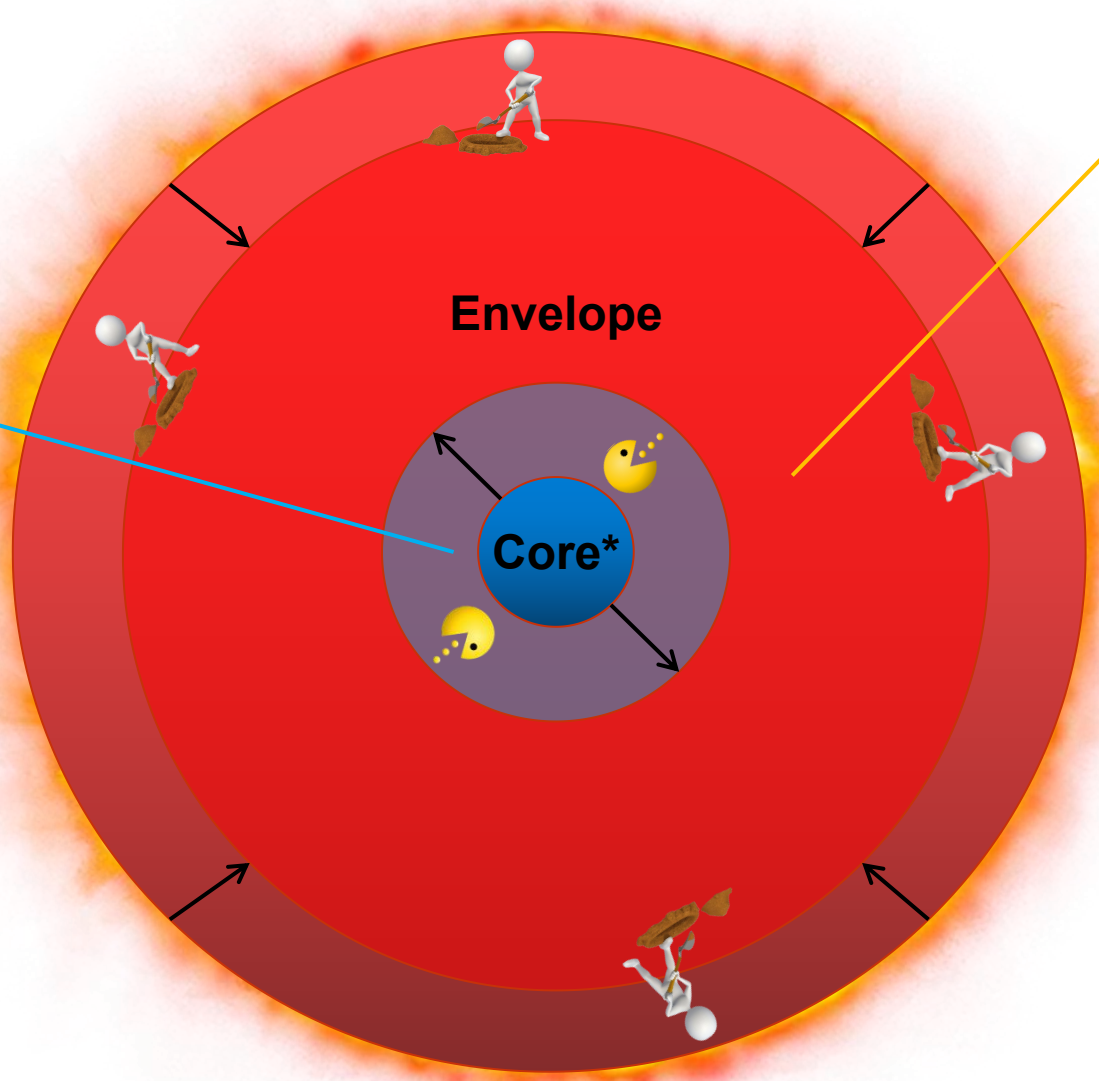


How do we form a Wolf-Rayet?

CORE GROWS

- Convection
- Overshooting
- Rotation

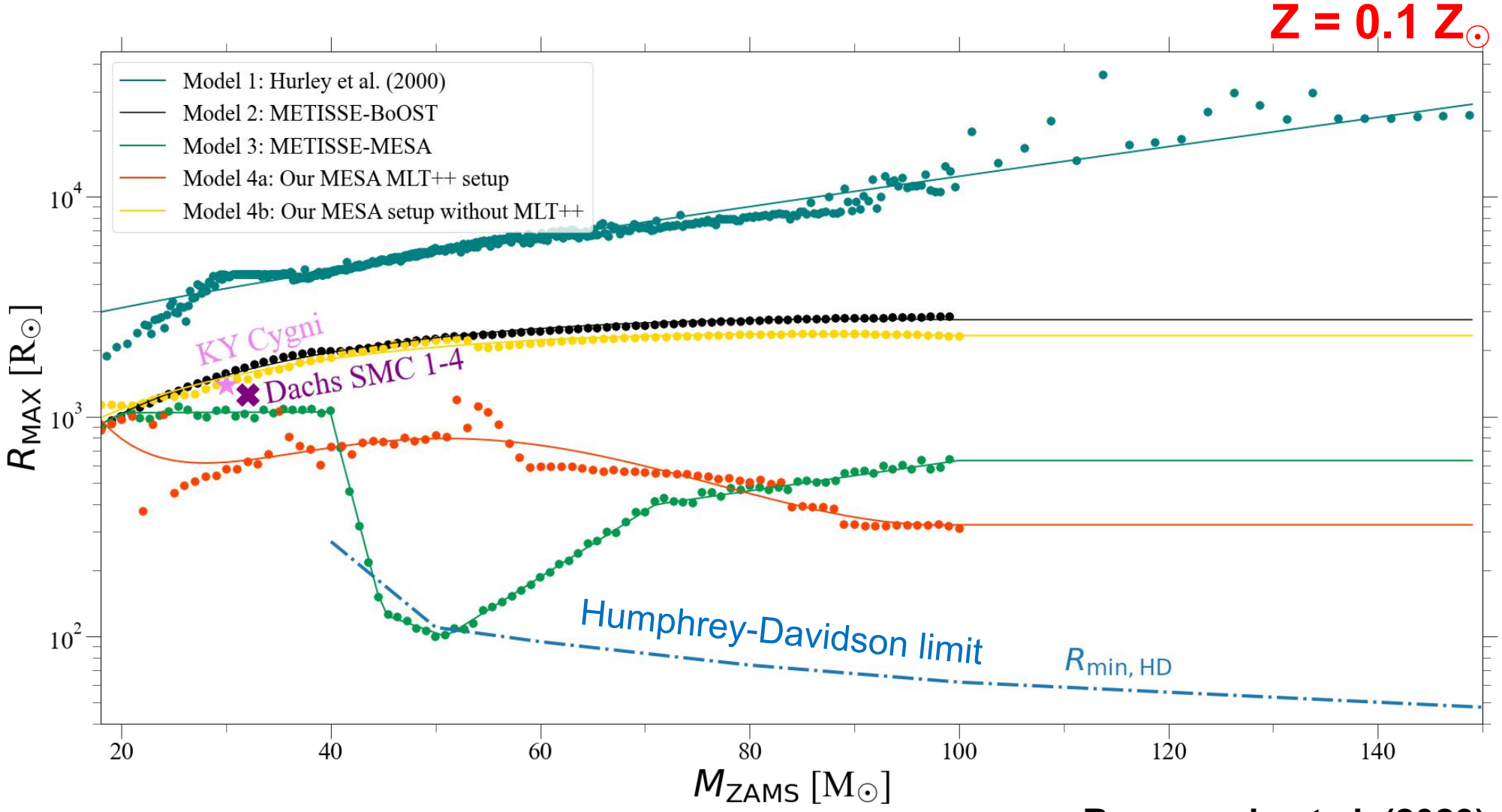


ENVELOPE GETS EJECTED

- Stellar winds
- LBV ejections
- Mass transfer events

*Core/envelope size not in scale

How do massive stars expand?



Rapid analytical model (similar to **SSE/BSE**)

MESA

Observational limit

Romagnolo et al. (2023)

Stellar wind models

ORIGINALLY

	$T_{eff} < 10^4$ K	$T_{eff} \geq 10^4$ K
	Dust-driven winds	
$X_{surf} \geq 0.4$		Optically thin line-driven winds
$X_{surf} < 0.4$		**Optically thick/Wolf-Rayet winds**

BUT

We observe H-rich Wolf-Rayet stars!!
(e.g. Bestenlhener+2020)

Wolf-Rayet stars have high L/M ratios and their winds are very strong

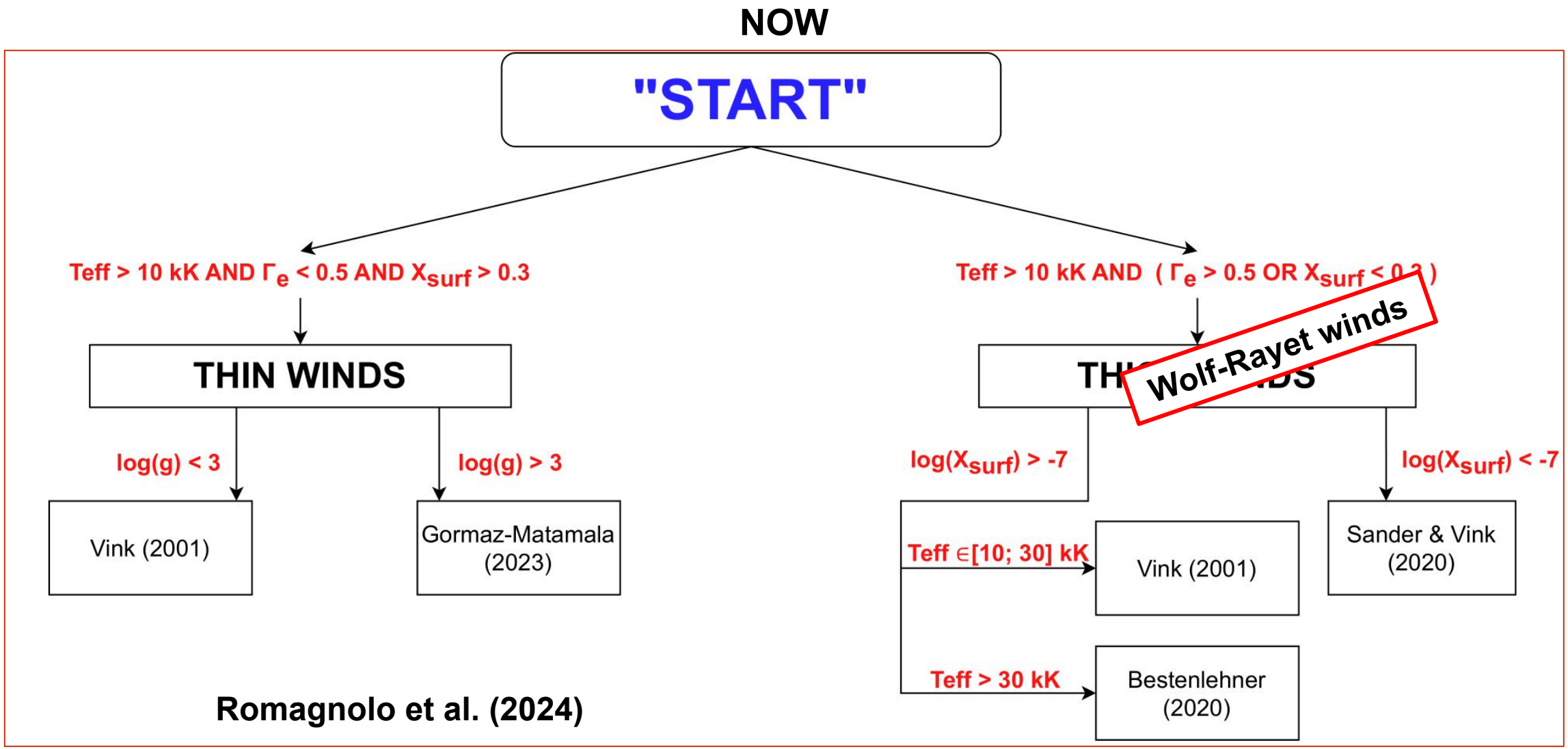
L/M ratio the actual reason why Wolf-Rayet winds are strong!

Stellar wind models

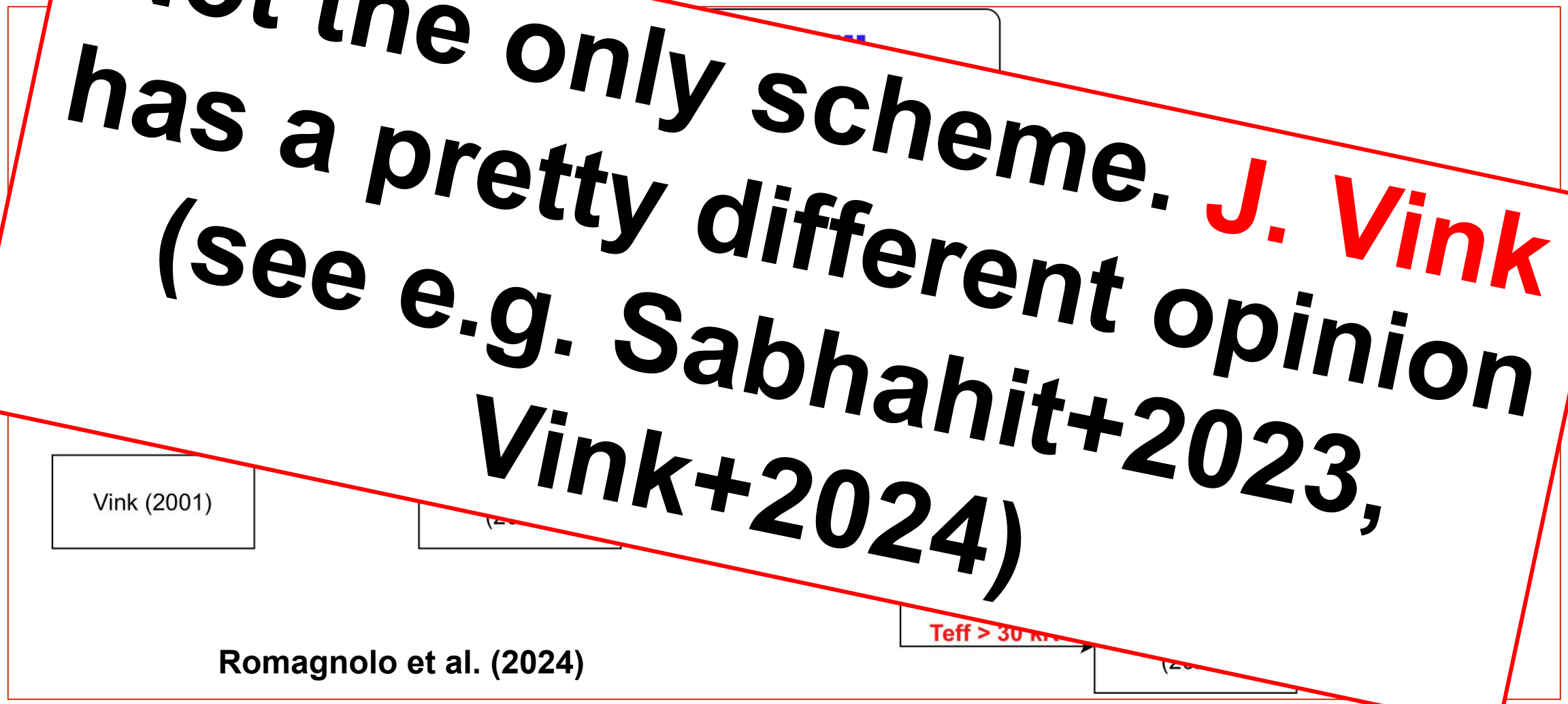
ORIGINALLY

	$T_{eff} < 10^4$ K	$T_{eff} \geq 10^4$ K
	Dust-driven winds	
$X_{surf} \geq 0.4$		Optically thin line-driven winds
$X_{surf} < 0.4$		**Optically thick/Wolf-Rayet winds**

Stellar wind models

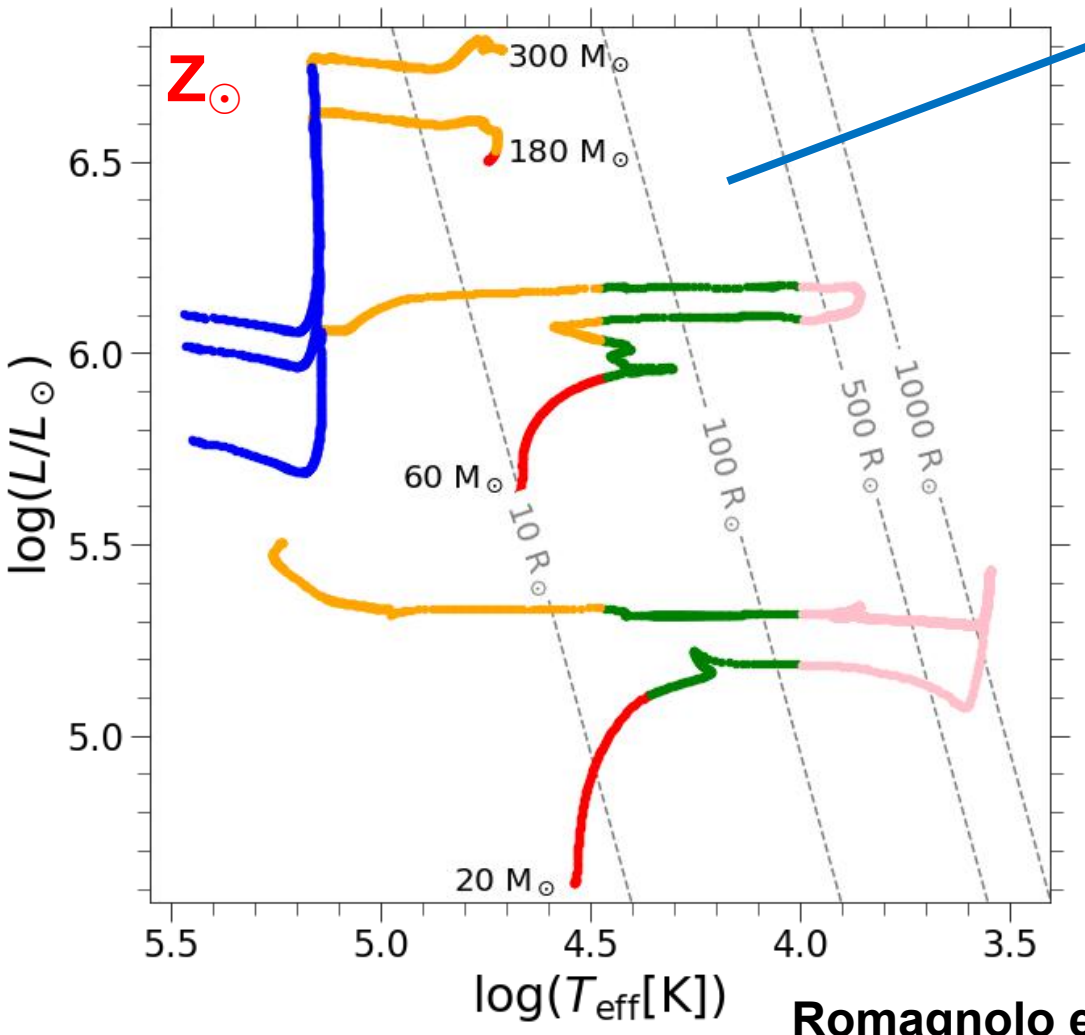


St ind models



Not the only scheme. J. Vink has a pretty different opinion (see e.g. Sabhahit+2023, Vink+2024)

Near-Eddington winds also during main sequence for high M_{ZAMS}!



Romagnolo et al. (2024)

HD limit respected for M_{ZAMS} > 80 $M_{\odot}$

Clumped line-driven winds
Gormaz-Matamala+ 2023

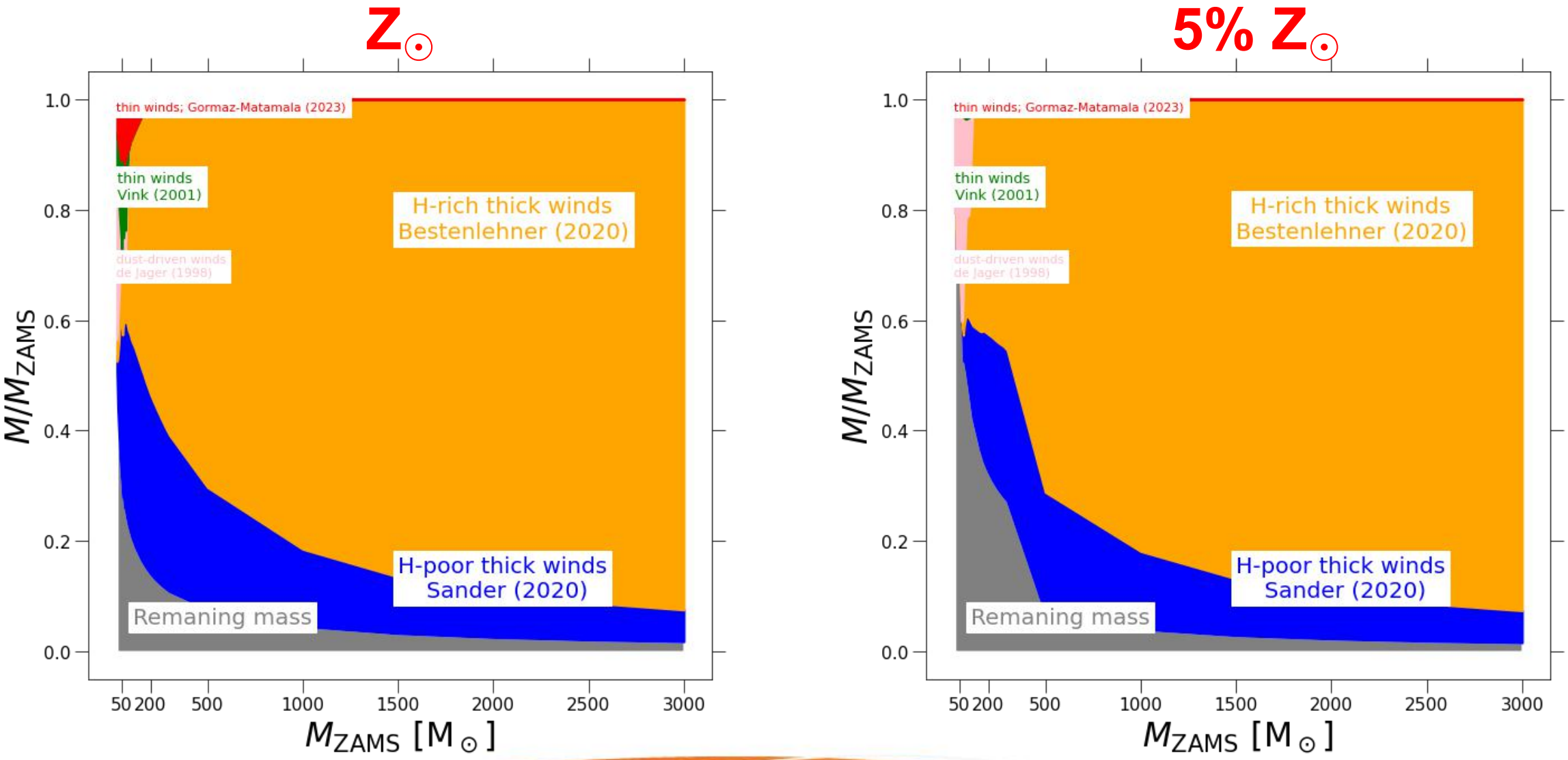
Homogeneous line-driven winds
Vink+ 2001

Dust-driven winds
de Jager+ 1998

Continuum-driven winds [T_{eff} > 30 kK, Γ_e > 0.5]
Bestenlehner+ 2020

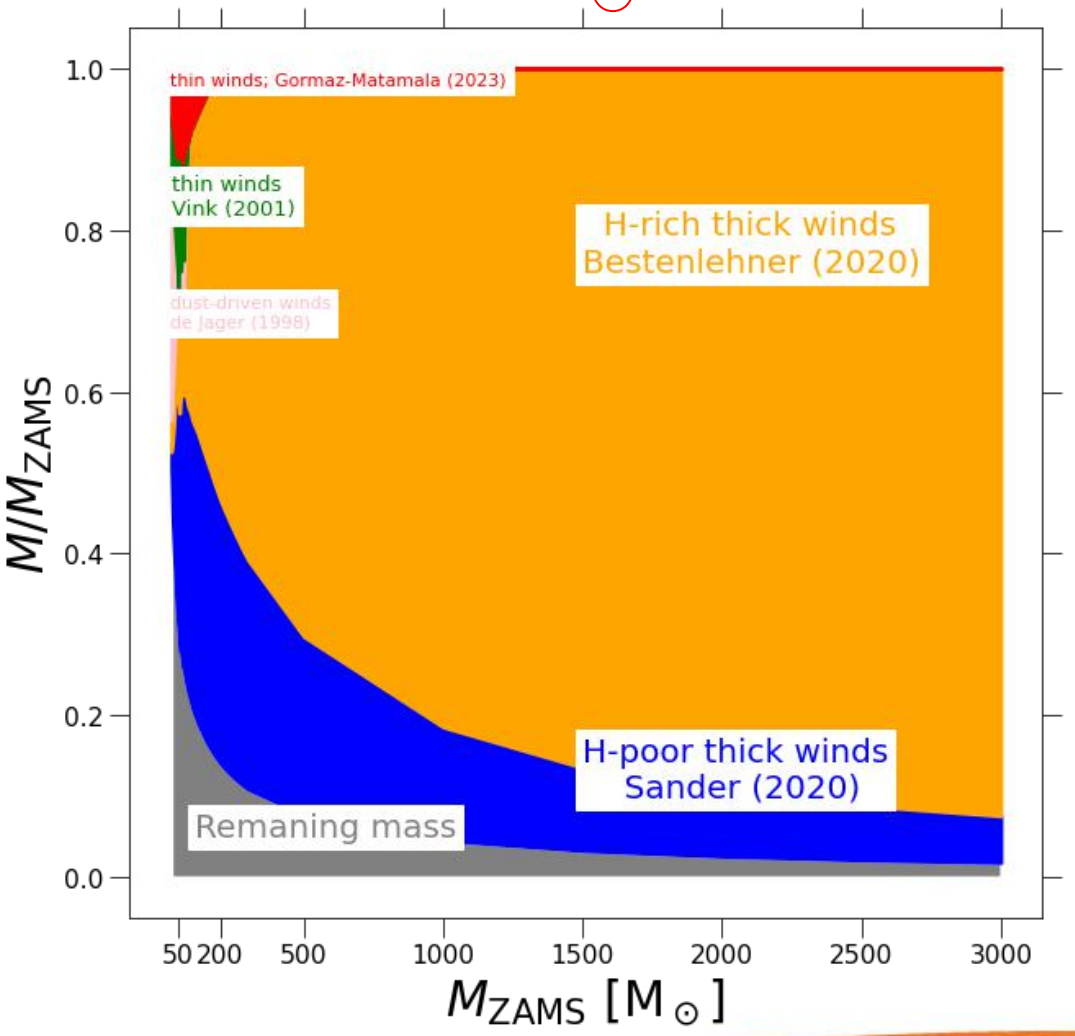
H-poor continuum-driven winds [$X_{surf} < 10^{-7}$]
Sander & Vink 2020

How much mass is loss via winds?



How much mass is loss via winds?

$Z_\odot$

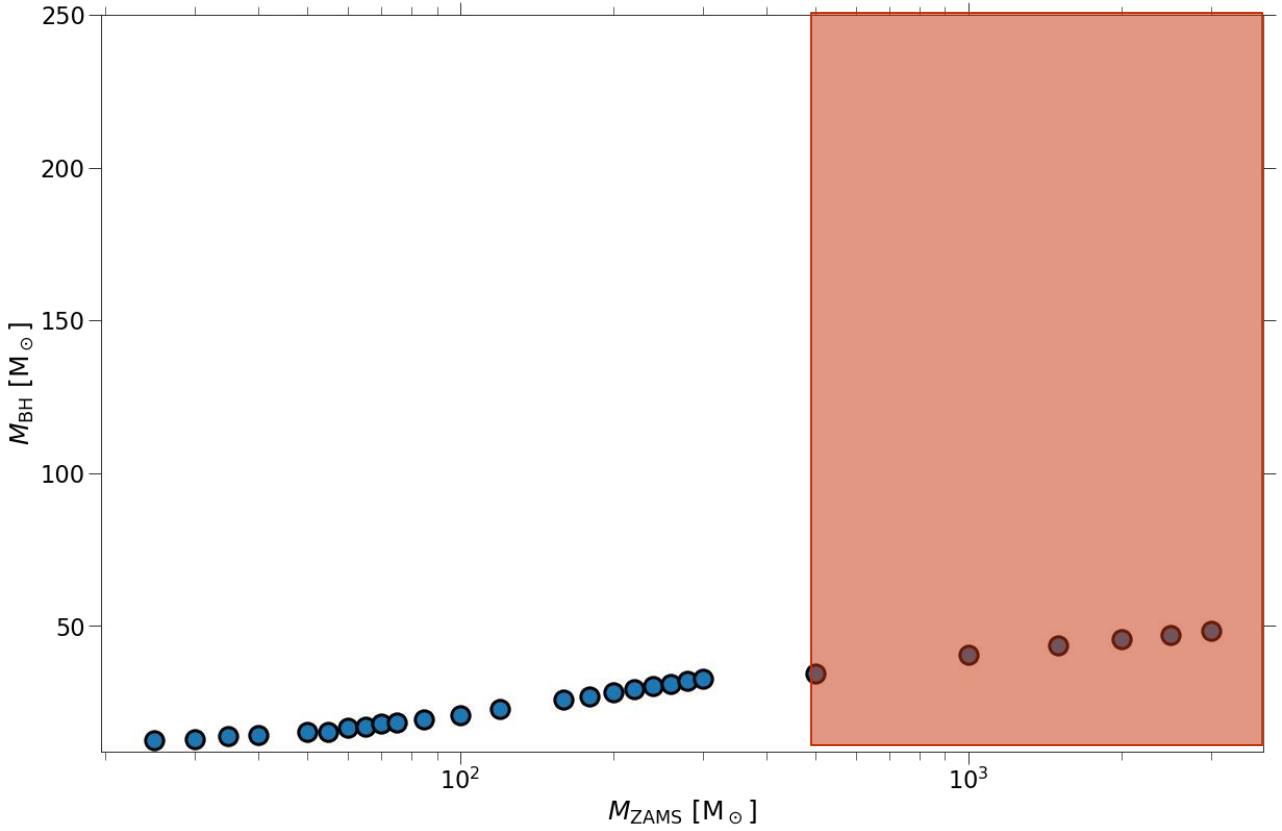


5% $Z_\odot$

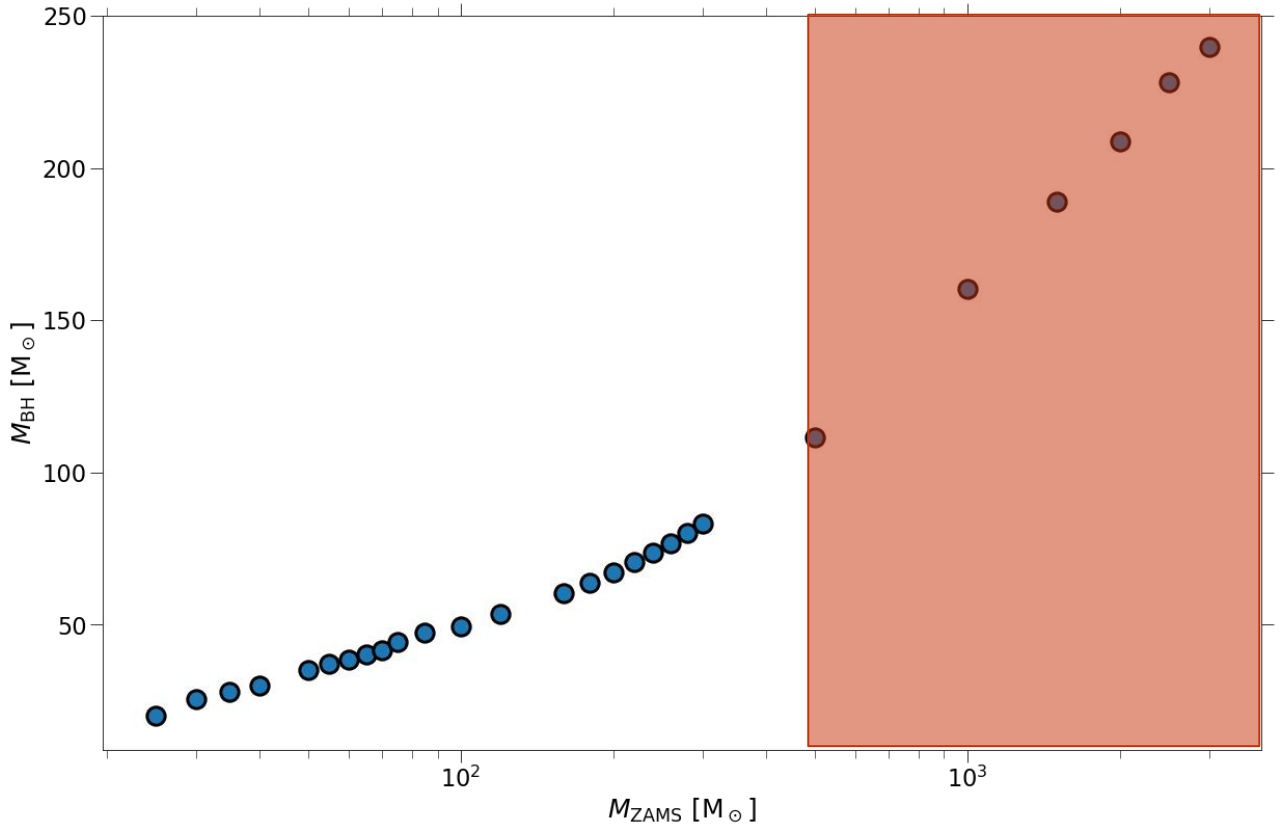
- At high M_{ZAMS} most of the mass is ejected via strong Wolf-Rayet winds
- Not only envelopes, but also cores
- A lot of mass with low-H content ejected very soon (metallicity changes in clusters?)

New BH masses from stellar evolution seem pretty low

$Z_\odot$



5% $Z_\odot$



New BH masses from stellar evolution seem pretty low

In our models even stars at very high M_{ZAMS} cannot form BHs at $M > 250\ M_{\odot}$

↓

Intermediate mass black holes do not come from these stars?

Not a wide range of M_{BH} from stellar evolution

↓

When BHs merge, $q=M_{BH1}/M_{BH2}$ should be high!

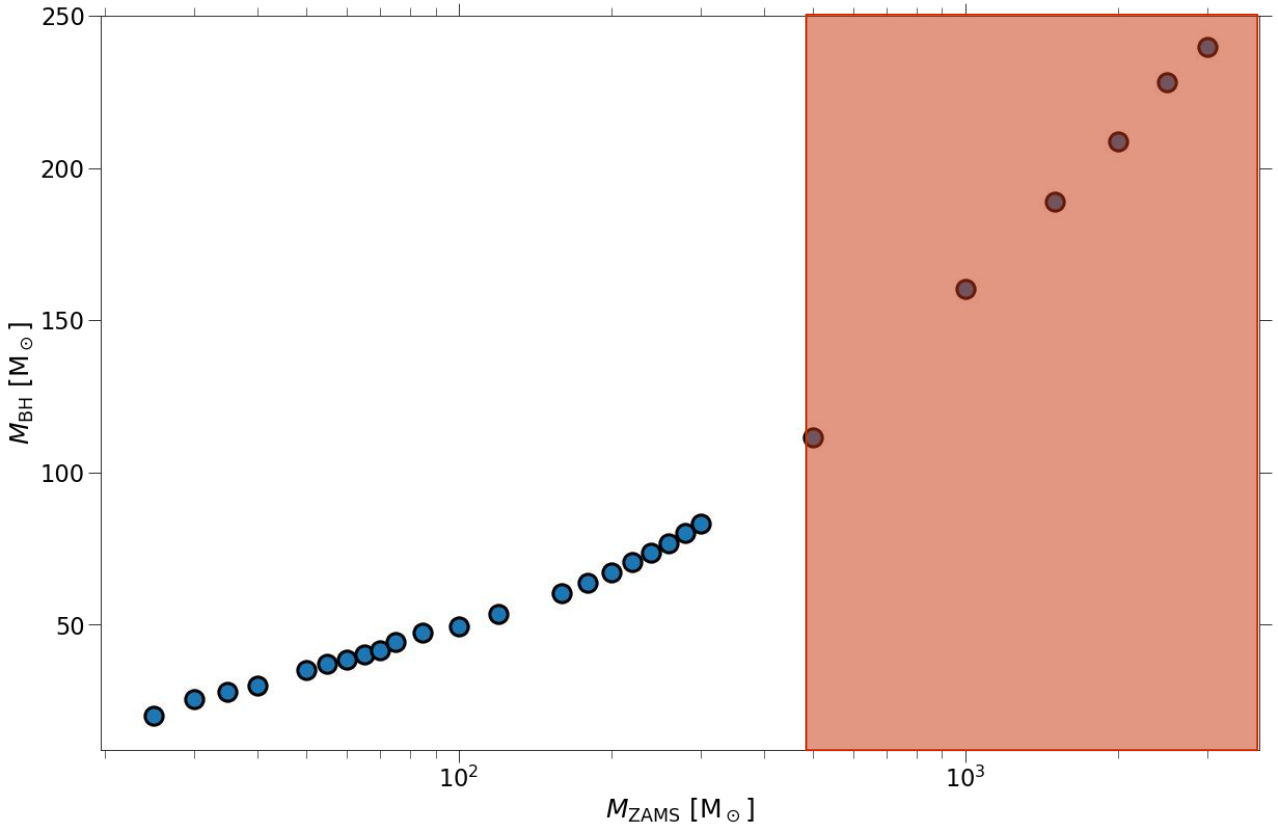
↓

e.g. Morawski+(2018): high q → strong GW kicks

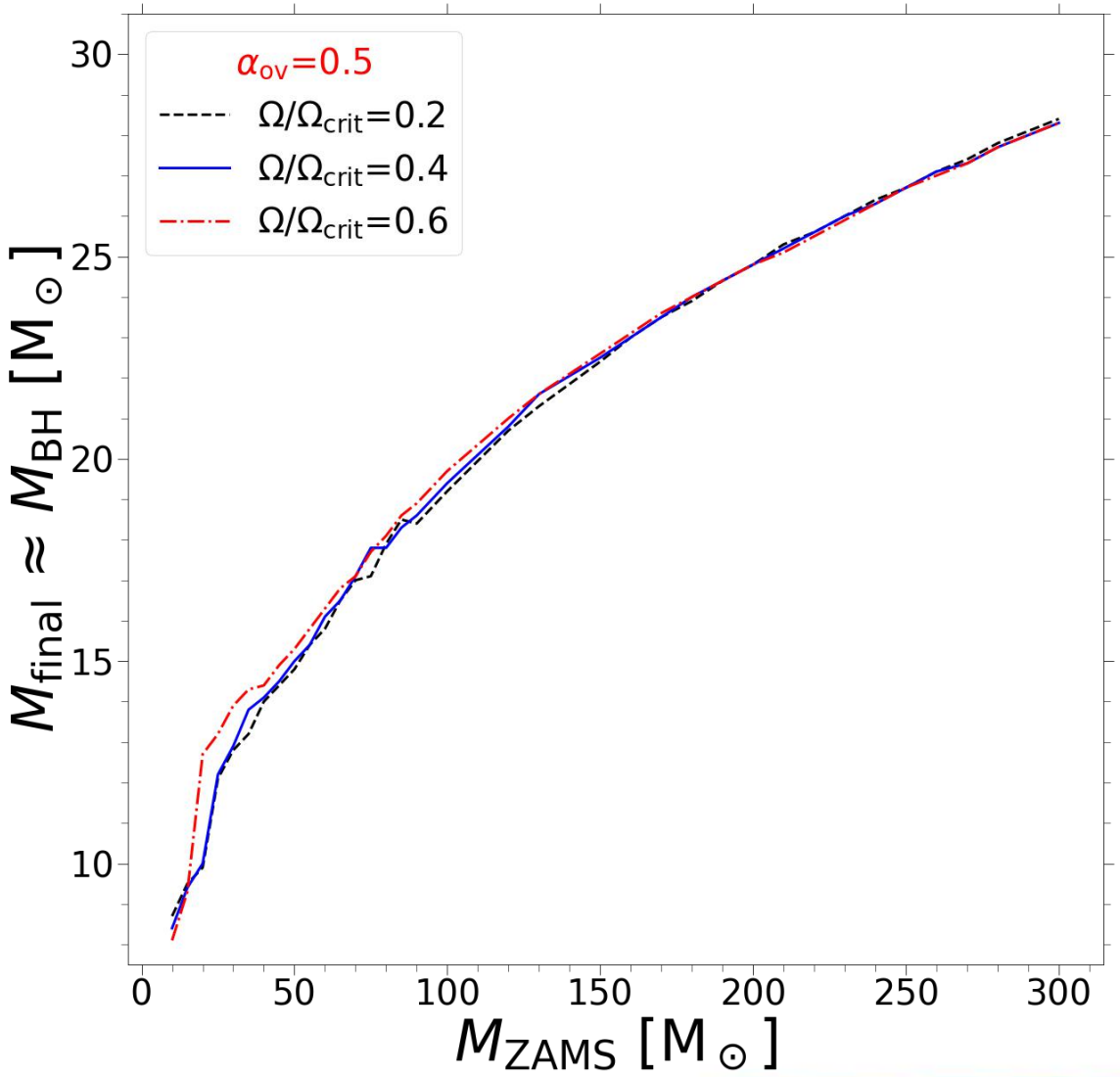
↓

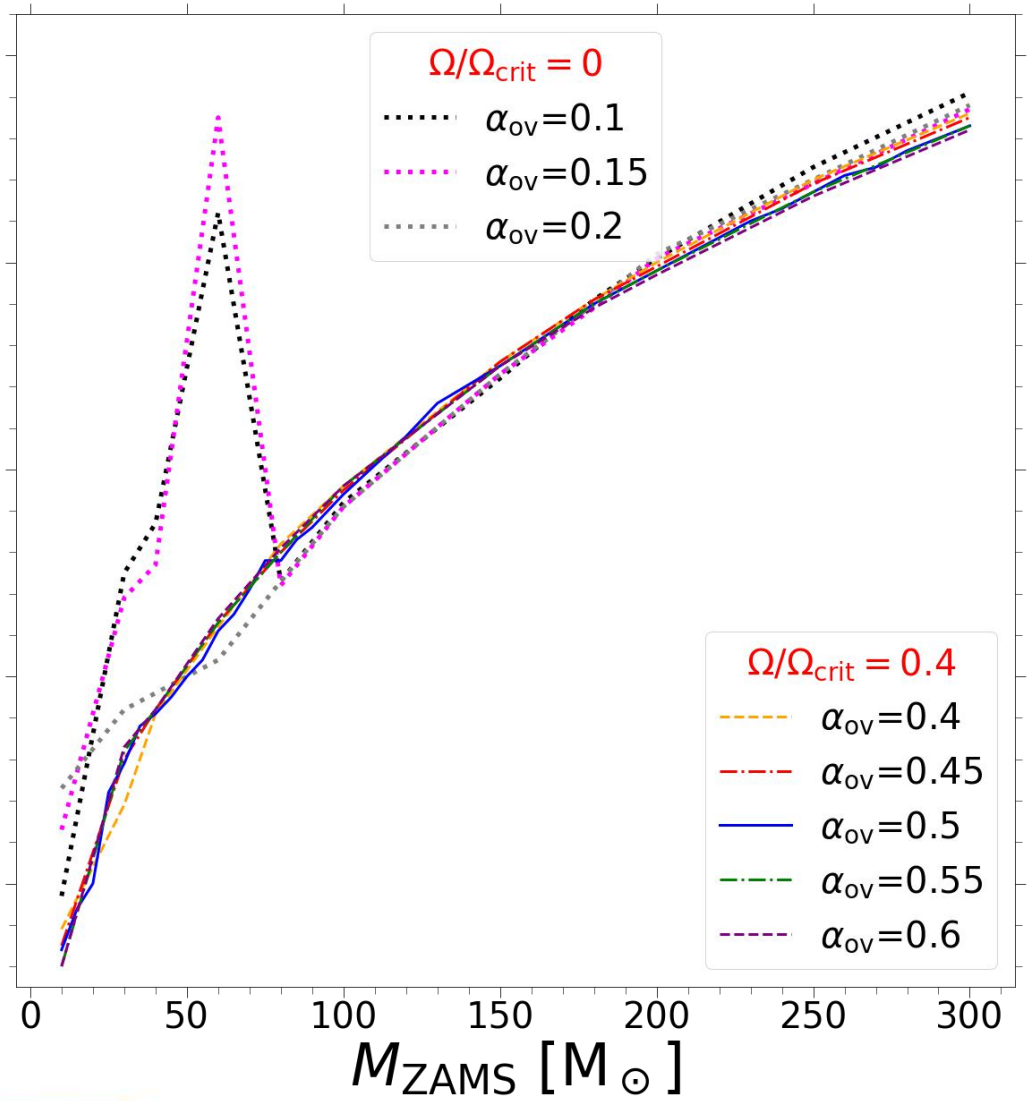
post-merger BHs ejected out clusters?

5% $Z_{\odot}$

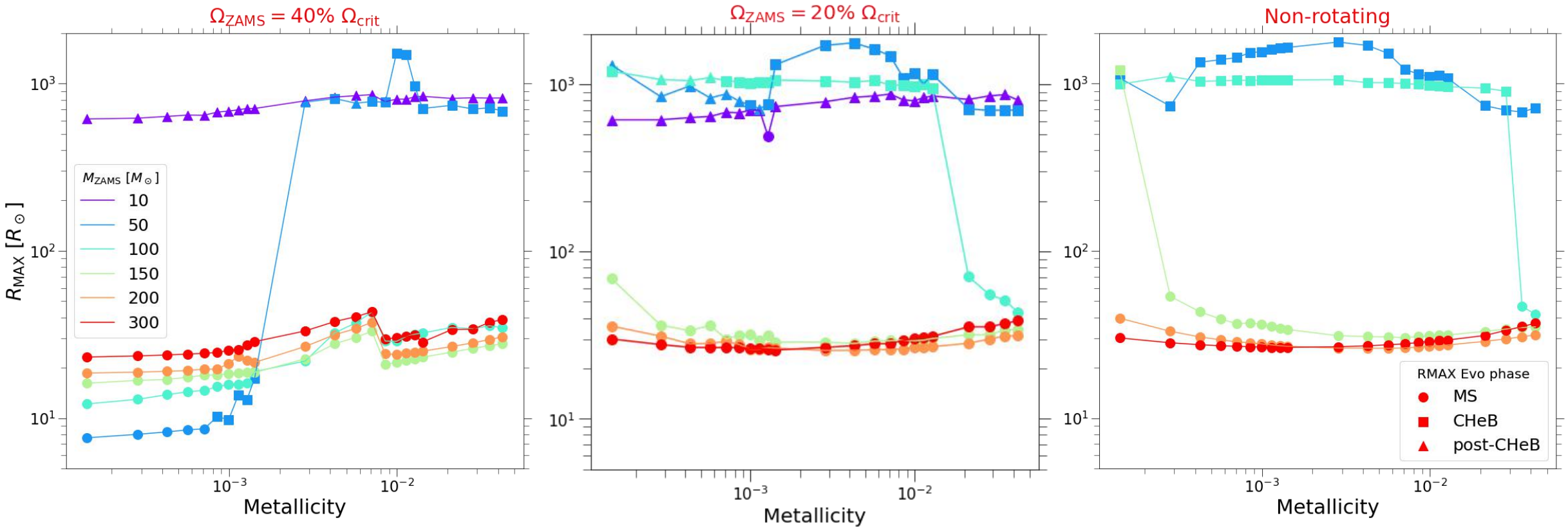


“But Amedeo, what about different overshooting or initial rotations?”





How does this affect stellar expansion?



At M_{ZAMS} > 150 $M_\odot$ the evolution of stars is **wind-dominated**

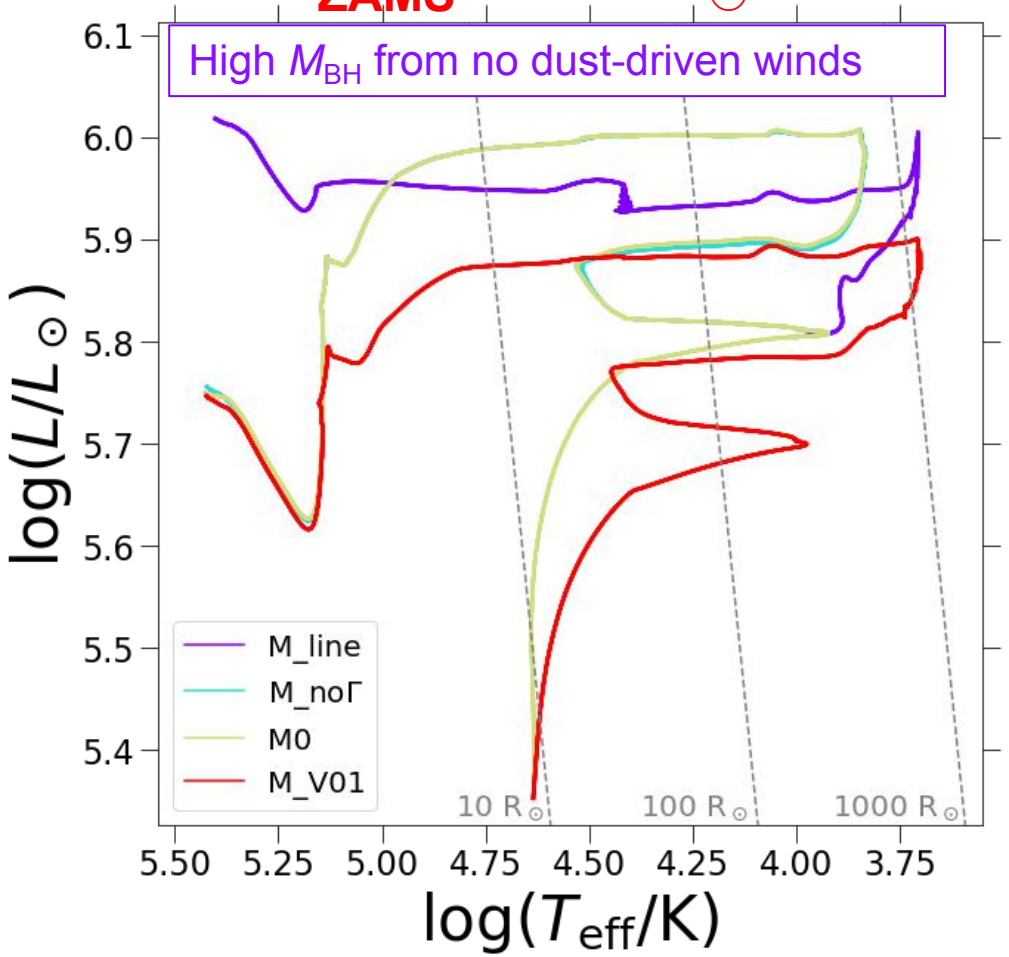
At M_{ZAMS} > 150 $M_\odot$ stars cannot expand enough to start mass transfer events in binaries

Conclusions

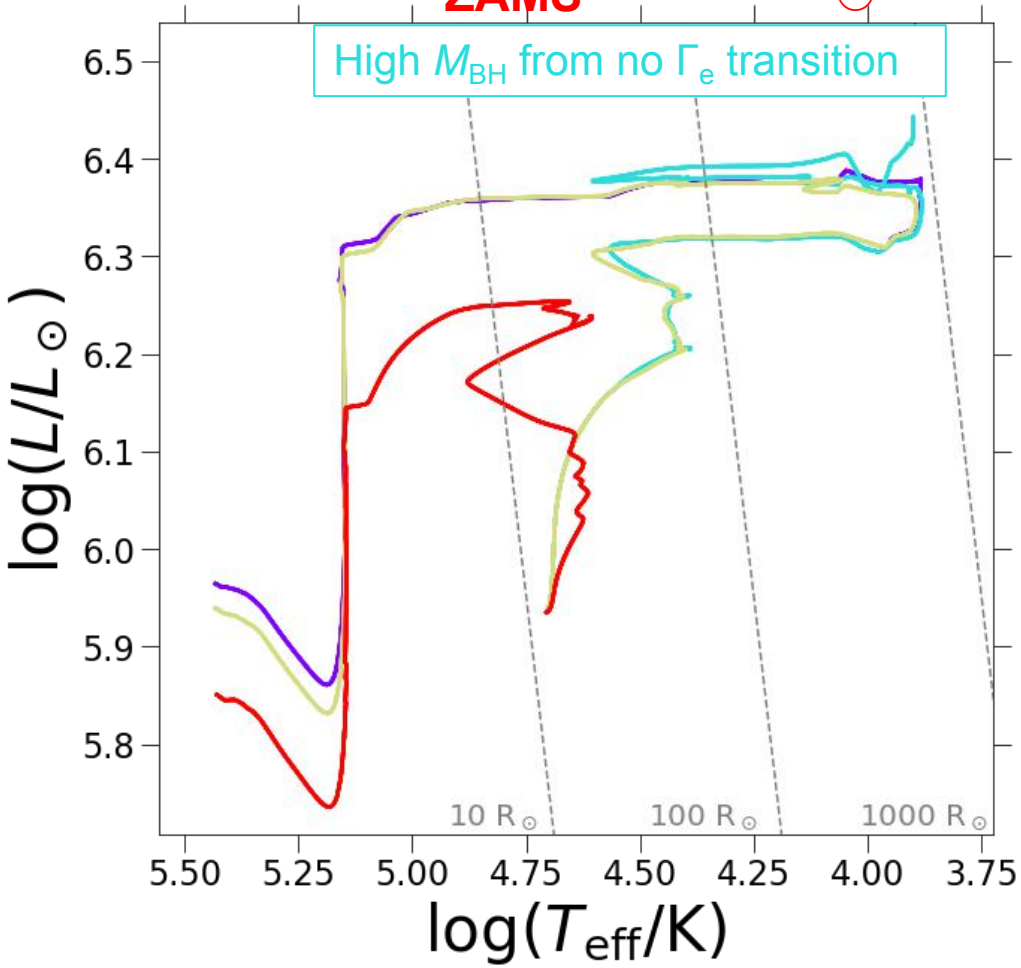
- Super-eddington winds dominate the evolution of very massive stars (M_{ZAMS}>150 $M_{\odot}$)
  - No expansion
  - Small BH masses
- A lot of low-H/He pollution from very massive stars
- Intermediate-mass black holes are hard to form from very massive stars
- Post-GW merger BHs have higher GW kick velocities and are ejected

Black hole masses: to peak or not to peak?

M_{ZAMS} = 40 $M_\odot$

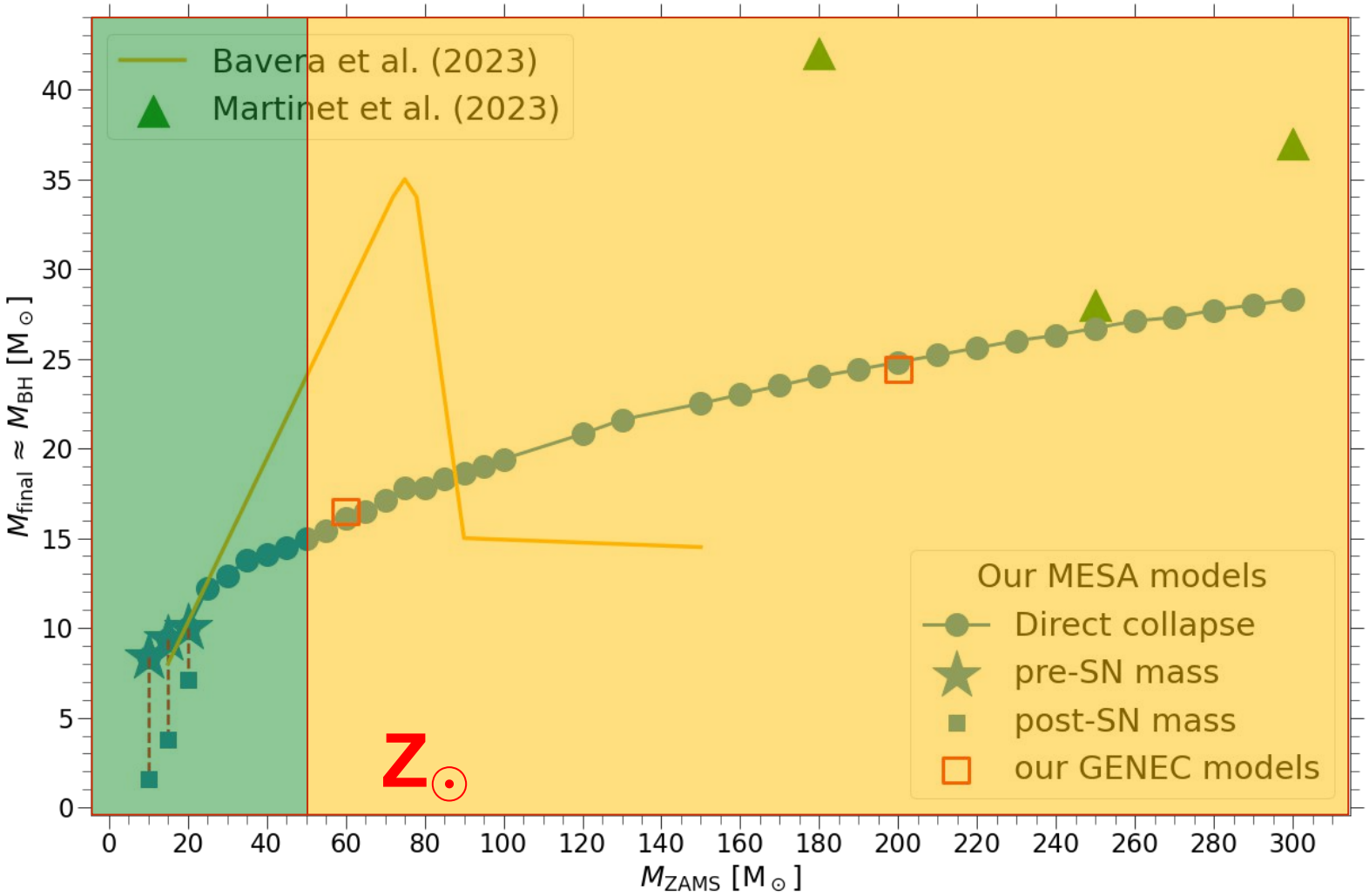


M_{ZAMS} = 80 $M_\odot$



Black hole masses: to peak or not to peak?

Dust-driven winds have a stronger effect

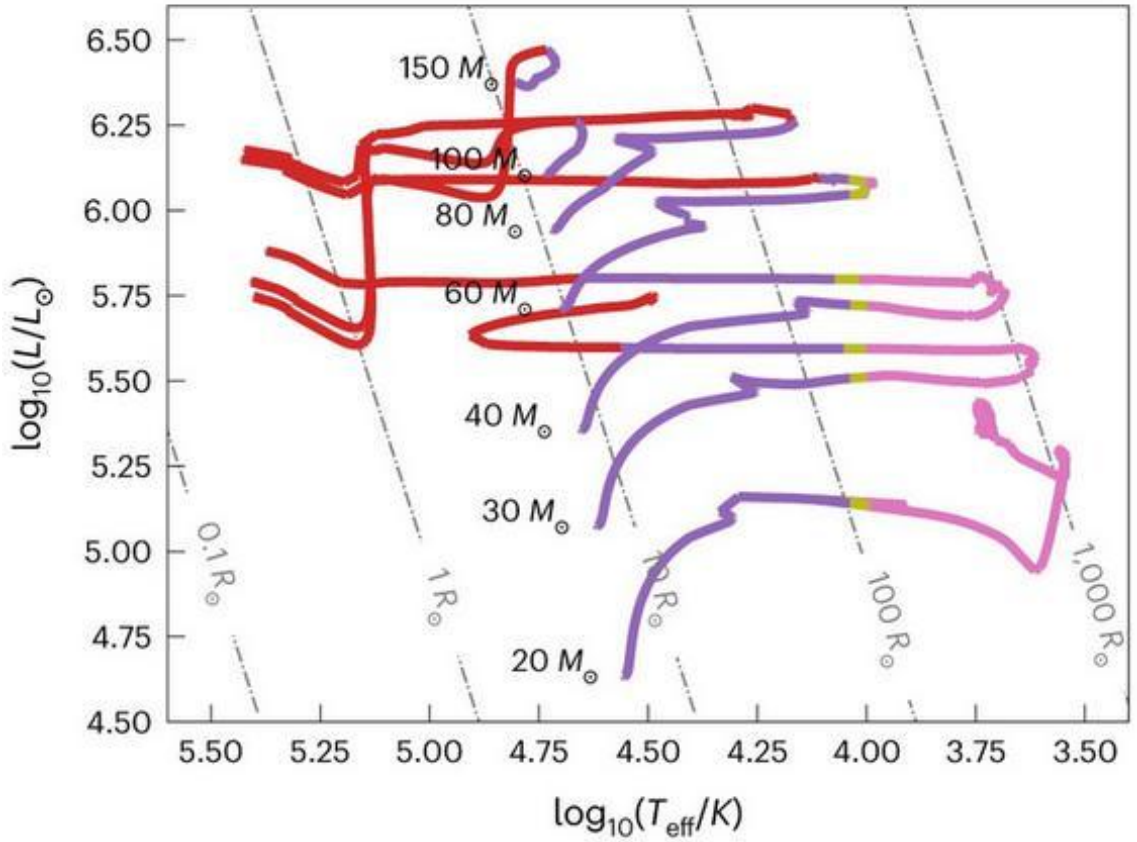


Wolf-Rayet winds have a stronger effect

Romagnolo et al. (2024)

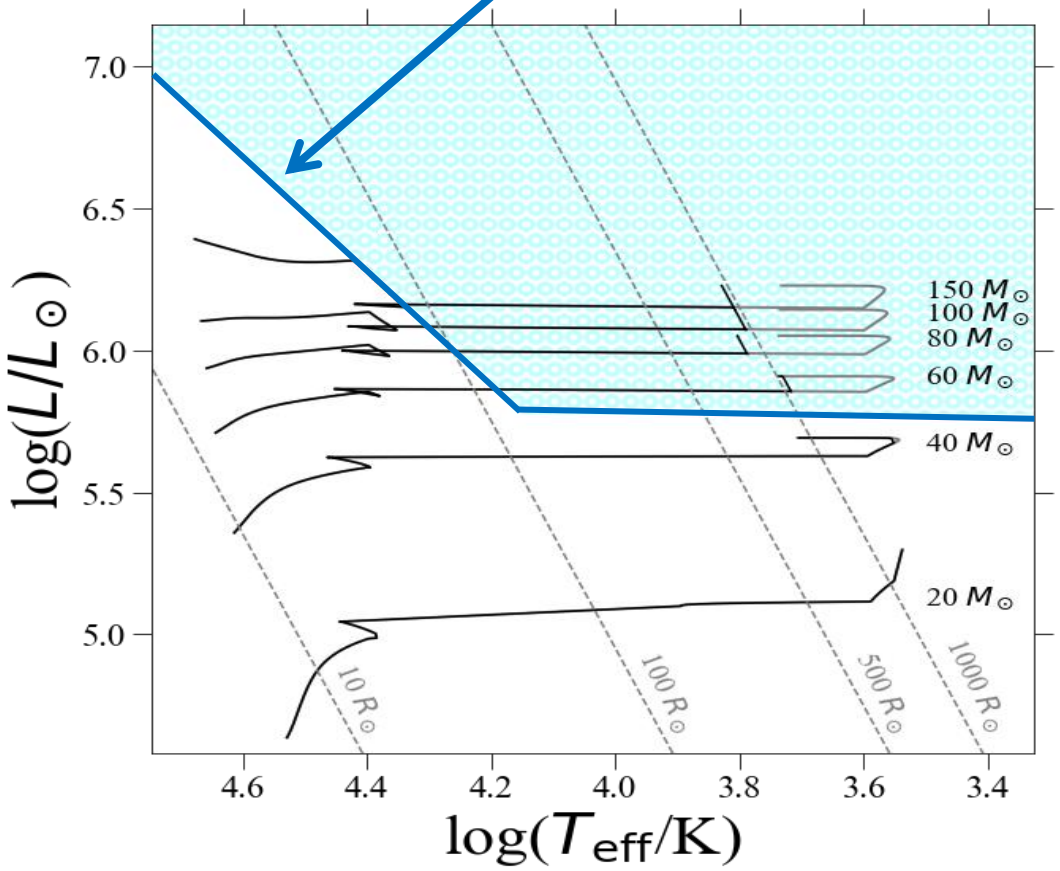
Do models prescribe stellar structure evolution right?

$Z = Z_{\odot}$



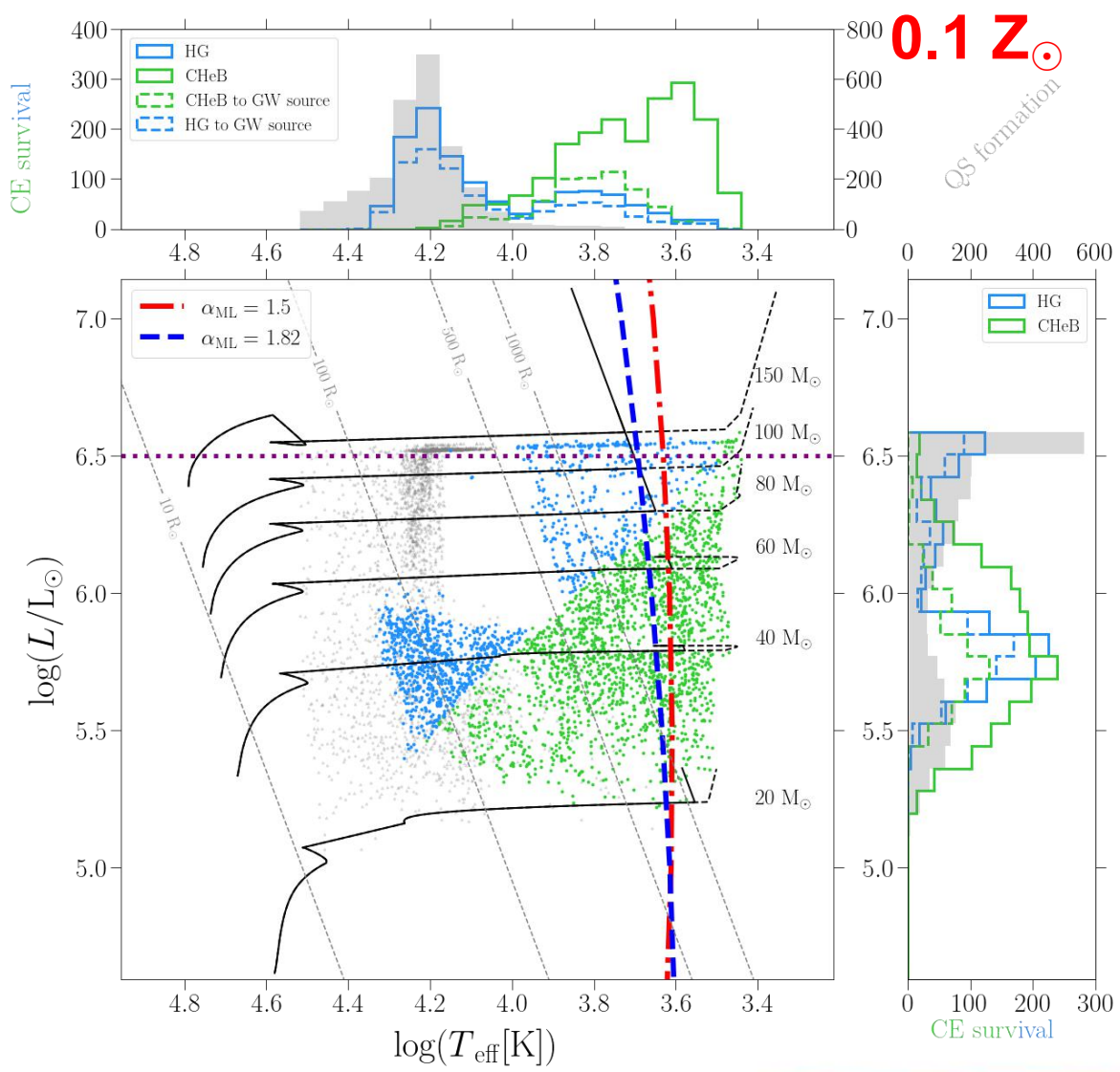
MESA [Bavera et al. (2023)]

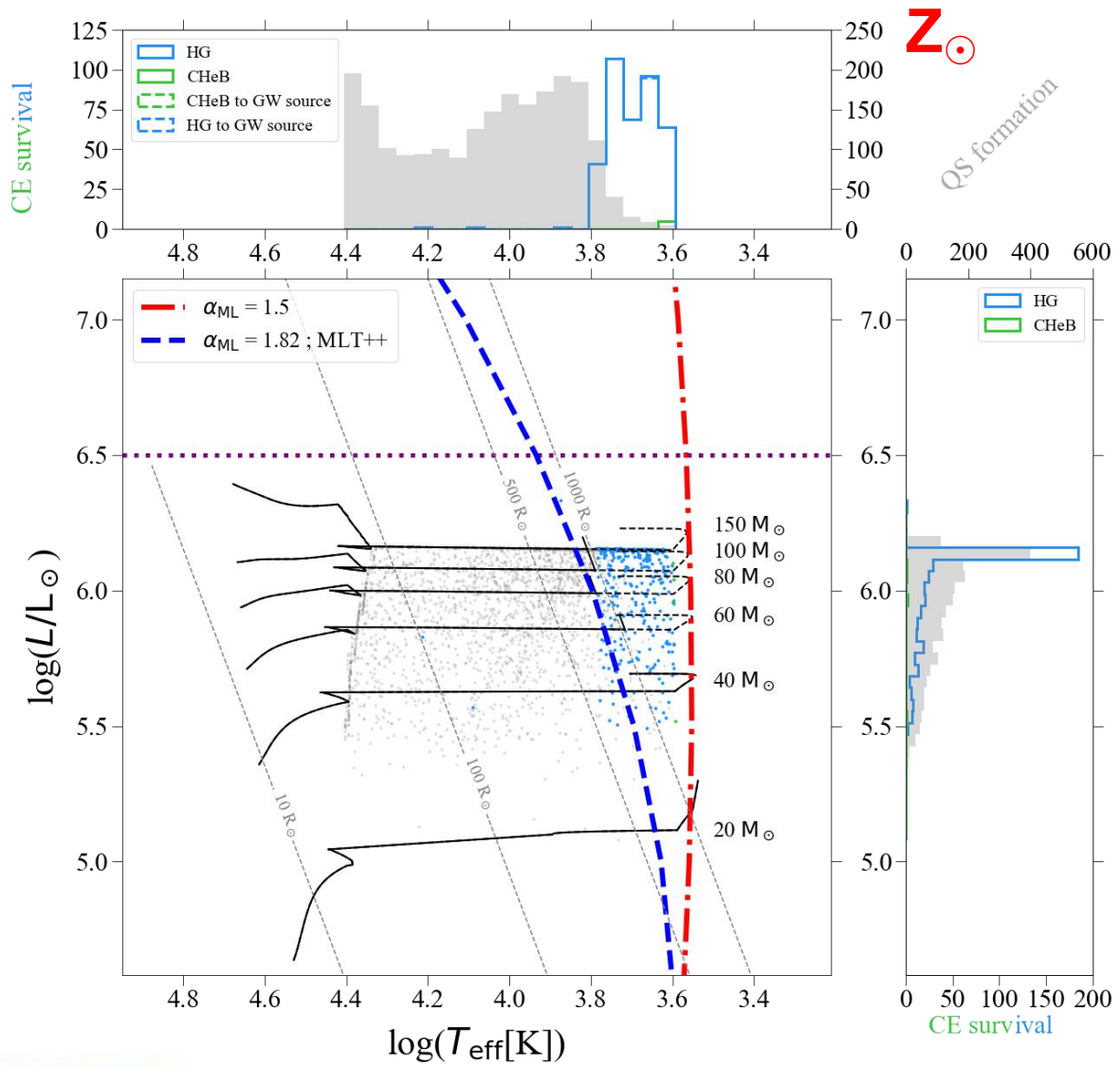
Humphrey-Davidson limit



Hurley et al. (2000) evolutionary formuale **[SSE/BSE]**

CE donors for close binary BHs

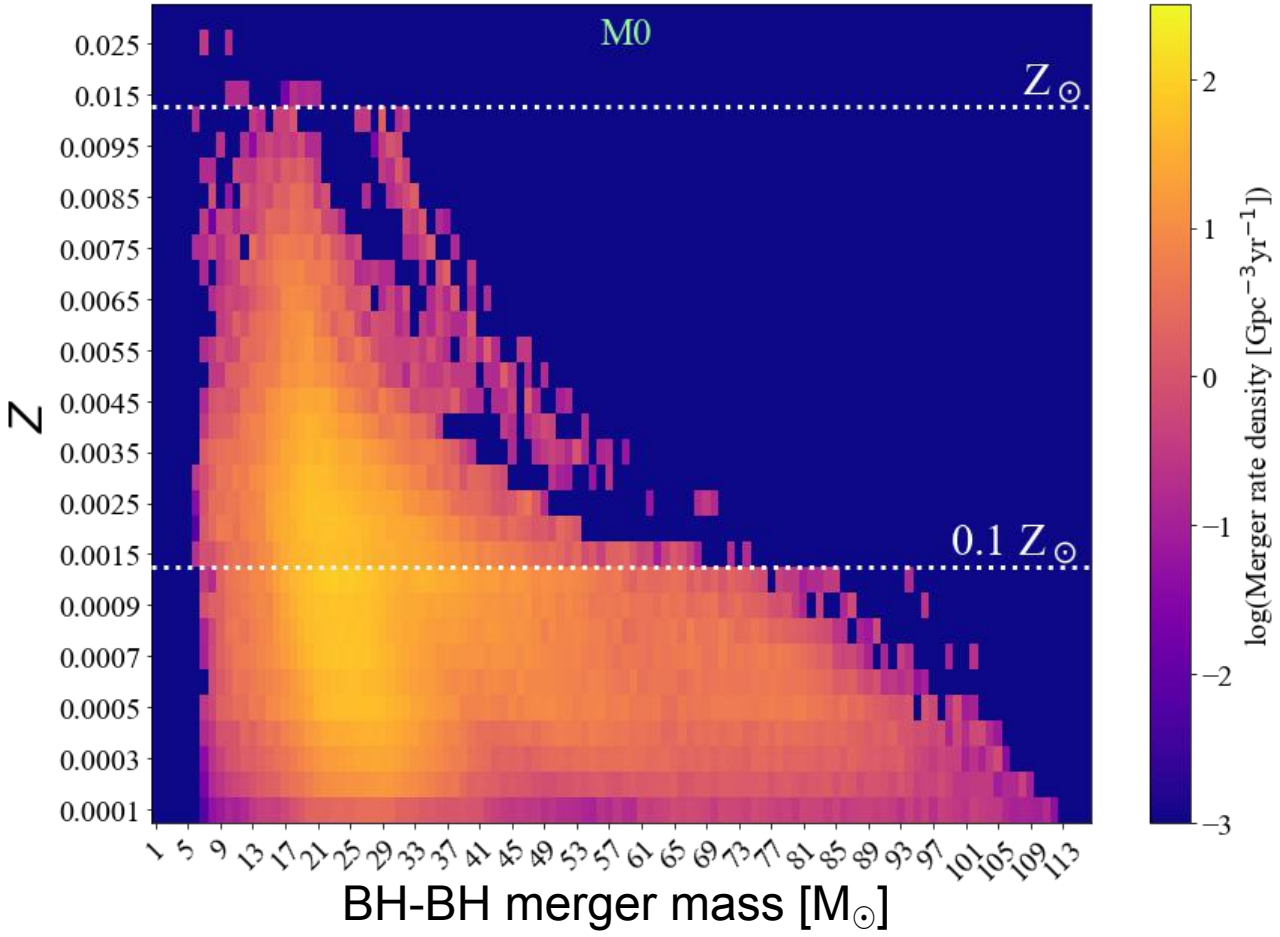




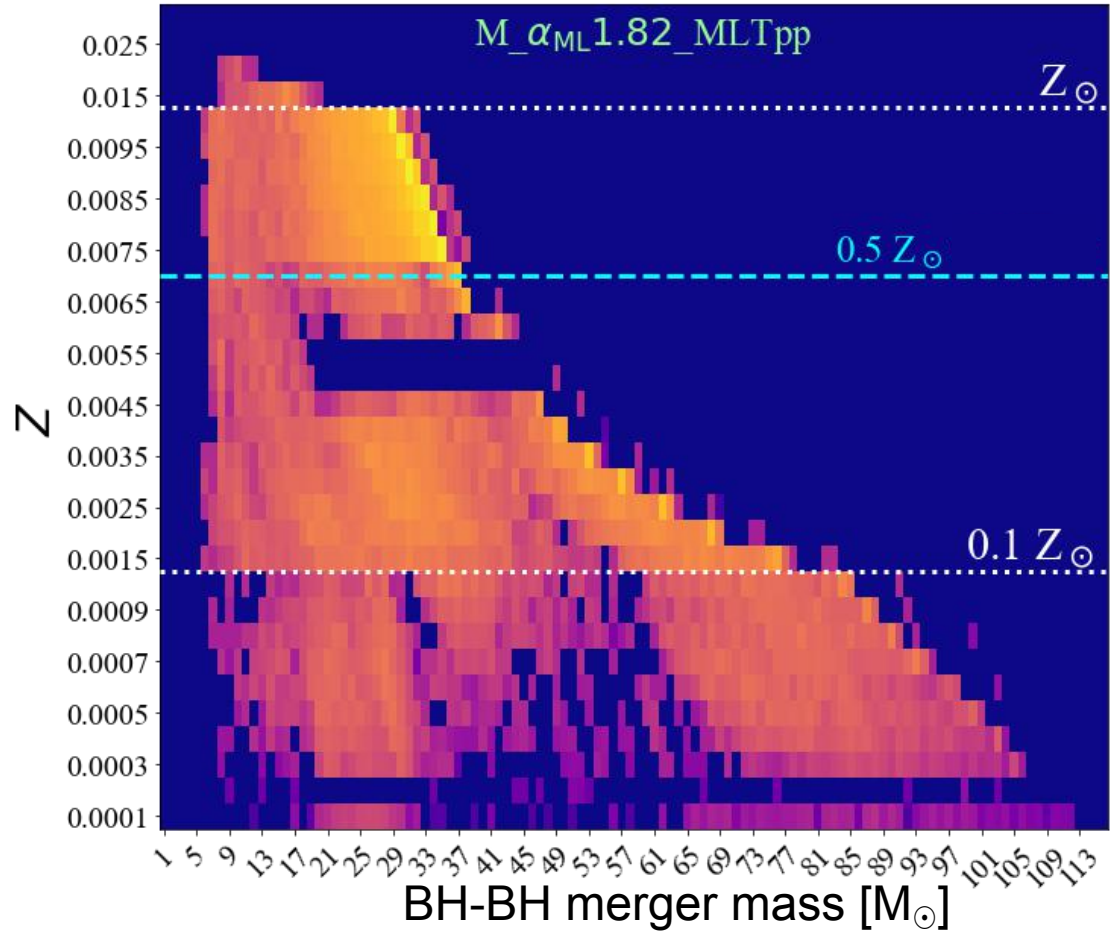
Romagnolo et al. (in prep.)

CE donors for close binary BHs

(**Default**) CE survival from evolutionary type



CE survival from envelope type



Romagnolo et al. (in prep.)