Impact of the stellar evolution adopting m-CAK self-consistent winds

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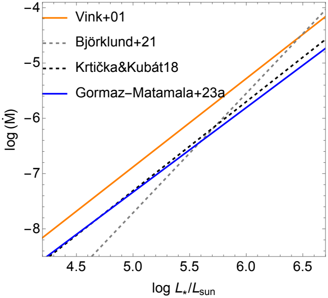
Part I

Self-consistent evolution models

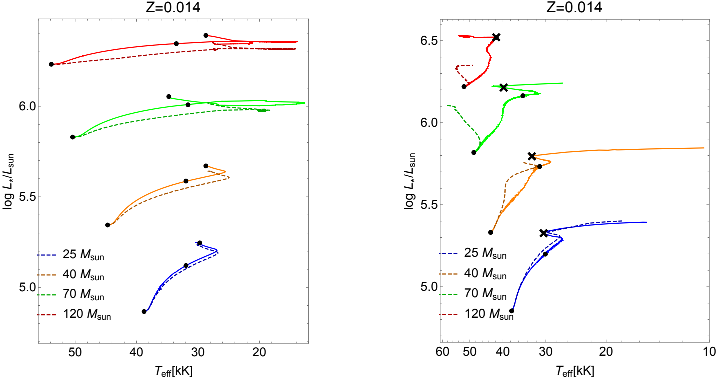
$\dot{M}$ from self-consistent line-driven winds (Gormaz-Matamala et al. 2019,2021,2022a)

- New self-consistent $\dot{M}$ based on the m-CAK theory (see talks from Curé, Araya and Figueroa-Tapia) are ~ 3 lower than standard V01 recipe.
- Beyond m-CAK theory, wind hydrodynamics can be analytically solved by using the Lambert W-function.
- Wind solutions are unique, and thus provide a self-consistent value for the mass-loss rate $\dot{M}$.



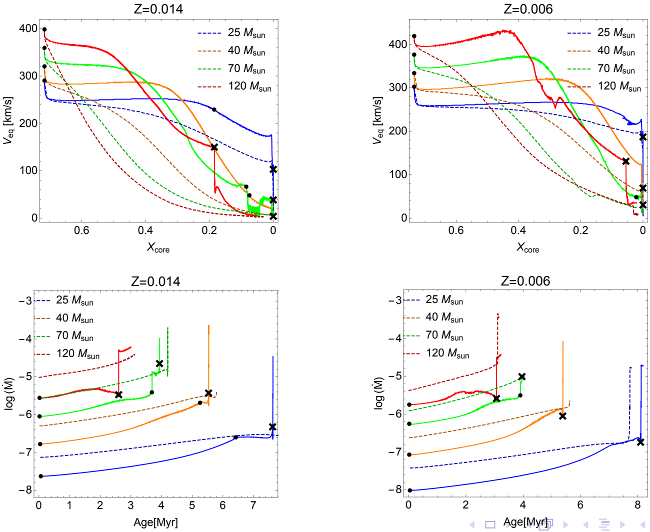
New vs old evolution models (Gormaz-Matamala et al. 2022b,2023)

- New stellar evolution models adopting lower $\dot{M}$ retain more mass and are brighter than old evolution models.
- Weaker winds for evolution also affect the rotation and the mixing of the stellar structures.



Old models from Ekström+2012 (dashed lines)

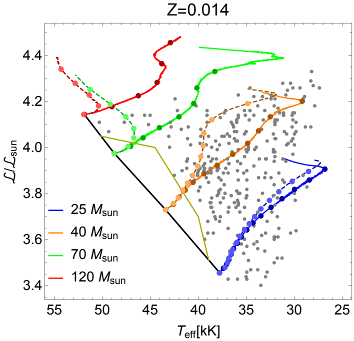
Evolution of equatorial rotation

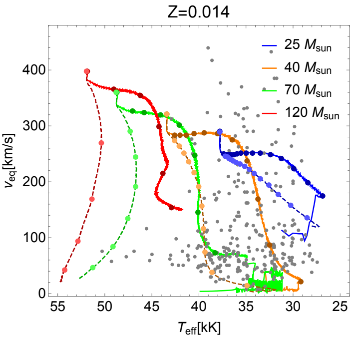


Properties of the stellar models at the end of the main sequence.

$M_{\rm zams}$	Z	$v_{\rm rot,ini}$	mass loss	End of Main Sequence						
				$t_{\rm MS}$	M_*	R_*	$v_{\rm rot,surf}$	$Y_{\rm surf}$	N/C	N/O
70.0	0.014	360.0	$\dot{M}_{\rm sc}$	3.9	60.4	26.9	3.9	0.63	18.2	5.6
			$\dot{M}_{\rm Vink}$	4.2	42.7	18.7	7.1	0.89	73.3	69.5
70.0	0.006	376.0	$\dot{M}_{\rm sc}$	4.0	64.6	21.7	26.2	0.51	8.0	2.4
			$\dot{M}_{\rm Vink}$	3.9	57.3	15.5	37.0	0.69	34.0	13.4
40.0	0.014	321.0	$\dot{M}_{\rm sc}$	5.5	36.4	23.6	37.4	0.46	5.5	1.5
			$\dot{M}_{\rm Vink}$	5.8	31.9	19.2	9.9	0.55	13.9	3.9
40.0	0.006	334.0	$\dot{M}_{\rm sc}$	5.4	38.2	18.5	71.7	0.37	3.7	1.0
			$\dot{M}_{\rm Vink}$	5.6	36.2	16.2	30.6	0.44	6.1	1.6
25.0	0.014	291.0	$\dot{M}_{\rm sc}$	7.6	24.3	16.0	113.0	0.32	2.6	0.6
			$\dot{M}_{\rm Vink}$	8.0	23.6	15.9	68.4	0.34	3.3	0.8
25.0	0.006	302.0	$\dot{M}_{\rm sc}$	8.1	24.6	16.7	185.0	s 0.33	4.3	0.8
			$\dot{M}_{\rm Vink}$	7.7	24.3	14.1	159.0	0.31	3.4	0.7

Comparison with rotational surveys from Holgado+22





Self-consistent evolution models (solid lines) explain better the lack of fast rotators ($v_{\rm rot} \gtrsim 150$ km s^{-1}) at $T_{\rm eff} \gtrsim 42.5$ kK and the abundance of stars with $v_{\rm rot} \lesssim 150$ km s^{-1} and $T_{\rm eff}$ between ~ 27 and 40 kK.

Highlights

- Self-consistent stellar winds gives lower $\dot{M}$ than the original values, thus generating important changes in the stellar evolution of massive stars.

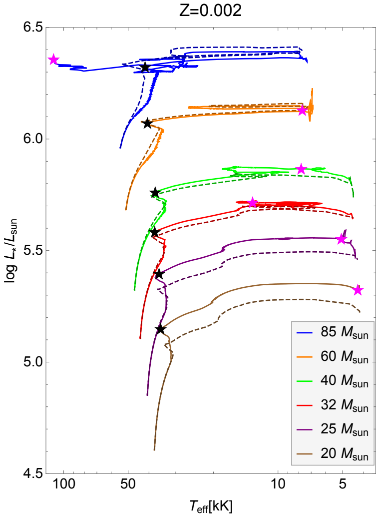
  $$\dot{M} \propto Z^{0.4+\frac{15.75}{M_*/M_\odot}}\ ,$$

  compare with Gräfener&Hamann08 for WNL and Krtička&Kubát24 for OB-stars.
- Rotational velocities predicted by the self-consistent evolution models are in agreement with the most recent observational surveys.
- Implications of new evolution models are wide, and can be extended for lower metallicities and more massive stars.

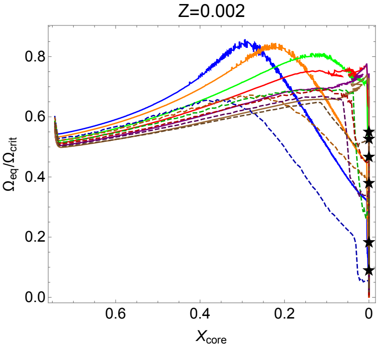
Part II

Implications: SMC massive stars

Massive stars at SMC metallicity (Gormaz-Matamala et al. 2024)



Lower $\dot{M}$, but larger $v_{\rm rot}$ (and thus more efficient rotational mixing).

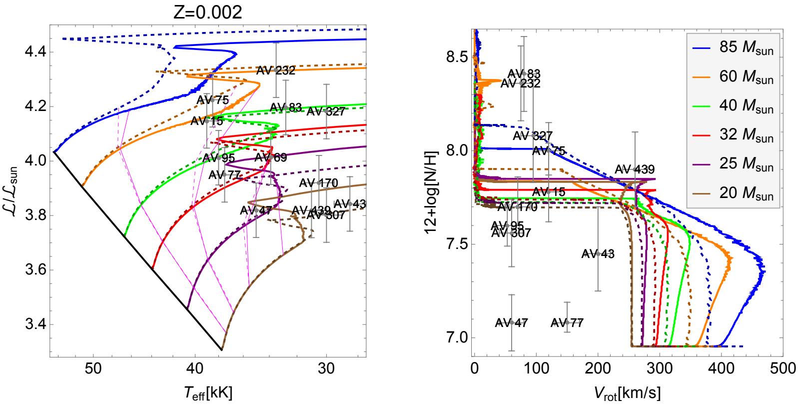


Rotation for massive stars at SMC metallicity

		H-core burning							He-core burning					
$M_{\rm zams}$	wind recipe	$\langle v_{\rm rot}\rangle$	$v_{\rm rot,final}$	$\tau_{\rm MS}$	$M_{\rm fin}$	$Y_{\rm surf}$	N/C	N/O	$\tau_{\rm He}$	$M_{\rm fin}$	$Y_{\rm surf,fin}$	N/C	N/O	$R_{\rm max}$
$[M_\odot]$		[km s^{-1}]		[Myr]	$[M_\odot]$	mass fraction			[Myr]	$[M_\odot]$	mass fraction			$[R_\odot]$
85	$\dot{M}_{\rm sc}$	323.	87.	3.6	80.1	0.47	5.7	2.3	0.33	47.4	0.60	0.3	0.1	831.0
85	$\dot{M}_{\rm Vink}$	319.	26.	3.6	77.2	0.54	9.8	3.8	0.31	51.36	0.83	132.2	89.0	882.4
60	$\dot{M}_{\rm sc}$	355.	111.	4.2	57.3	0.38	3.5	1.3	0.36	33.14	0.81	65.5	91.3	910.7
60	$\dot{M}_{\rm Vink}$	317.	85.	4.2	56.3	0.41	4.7	1.6	0.35	39.45	0.74	64.0	33.8	744.8
40	$\dot{M}_{\rm sc}$	323.	210.	5.4	39.1	0.33	3.2	1.0	0.46	30.24	0.63	27.0	8.4	1280.7
40	$\dot{M}_{\rm Vink}$	300.	125.	5.3	38.7	0.31	3.2	0.9	0.45	29.16	0.57	20.0	5.0	1288.3
32	$\dot{M}_{\rm sc}$	299.	258.	6.6	31.5	0.34	4.5	1.1	0.55	24.53	0.61	31.6	7.7	1106.1
32	$\dot{M}_{\rm Vink}$	282.	177.	6.4	31.2	0.31	4.1	0.9	0.54	24.68	0.58	28.2	5.5	1103.6
25	$\dot{M}_{\rm sc}$	273.	285.	8.6	24.8	0.36	7.4	1.2	0.66	20.04	0.44	12.0	1.7	984.2
25	$\dot{M}_{\rm Vink}$	262.	132.	7.7	24.7	0.29	4.7	0.9	0.69	22.77	0.32	6.4	1.0	987.3
20	$\dot{M}_{\rm sc}$	252.	277.	10.5	19.9	0.34	8.8	1.1	0.87	18.88	0.36	10.6	1.3	899.4
20	$\dot{M}_{\rm Vink}$	248.	194.	9.3	19.9	0.28	4.7	0.8	0.95	19.25	0.23	5.7	0.9	793.0

Applications for studies analysing rotation and chemical enrichment in SMC (Gómez-González et al. in prep.)

SMC O-type giants and supergiants from Bouret+21



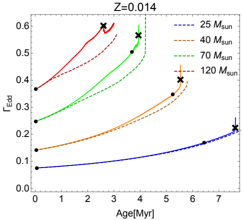
Analyses of theoretical chemical enrichment must be extended for BSG and RSG (see talks from Venero, Sánchez-Arias, and poster from González-Torà).

Part III

Implications for stellar evolution close to the Eddington limit

Stellar winds in the proximity to the Eddington limit

- Very massive stars: born with $M_\text{zams} \gtrsim 100$ $M_\odot$, with large convective cores.
- Strong stellar winds make VMS become WR (WNh) stars during their main sequence phase (Crowther+10).
- The $\dot{M} \sim \Gamma_\text{e}$ relationship changes its slope over a certain $\Gamma_\text{e,trans}$ (Vink+11; Vink&Gräfener12).
- "Proximity" to Eddington limit? $\Gamma_\text{e} \gtrsim 0.3$? $\Gamma_\text{e} \gtrsim 0.7$?



Sabhahit+23

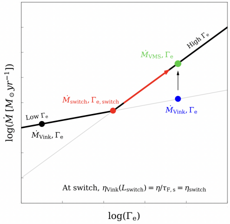
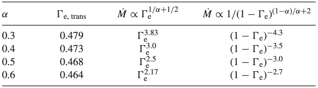


Figure 4. Schematic representation of the new VMS mass-loss framework where the condition to switch to a high-Γ_e, optically-thick wind is based on wind efficiency parameters. A step-by-step method is described in the text.

Table 1. For given CAK force multiplier α we list expected transition Eddington parameters and mass-loss rate dependence for $\Gamma_\text{e} \ll 1$ and $\Gamma_\text{e} \to 1$.



α	$\Gamma_\text{e, trans}$	$\dot{M} \propto \Gamma_\text{e}^{1/\alpha+1/2}$	$\dot{M} \propto 1/(1-\Gamma_\text{e})^{(1-\alpha)/\alpha+2}$
0.3	0.479	$\Gamma_\text{e}^{3.83}$	$(1-\Gamma_\text{e})^{-4.3}$
0.4	0.473	$\Gamma_\text{e}^{3.0}$	$(1-\Gamma_\text{e})^{-3.5}$
0.5	0.468	$\Gamma_\text{e}^{2.5}$	$(1-\Gamma_\text{e})^{-3.0}$
0.6	0.464	$\Gamma_\text{e}^{2.17}$	$(1-\Gamma_\text{e})^{-2.7}$

Bestenlehner20

New mass loss prescription for thin and thick winds

- Optically thin winds ($X_\mathrm{surf} \geqslant 0.3$ & $\Gamma_\mathrm{e} \leqslant 0.5$)

  $\Rightarrow$ Gormaz-Matamala et al. (2023)

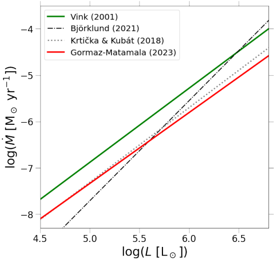
- H-rich optically thick winds ($\Gamma_\mathrm{e} > 0.5$ & $X_\mathrm{surf} \geqslant 10^{-7}$)

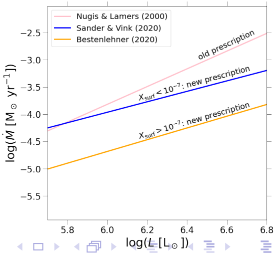
  $\Rightarrow$ Bestenlehner (2020)

- H-poor optically thick winds ($X_\mathrm{surf} < 10^{-7}$)

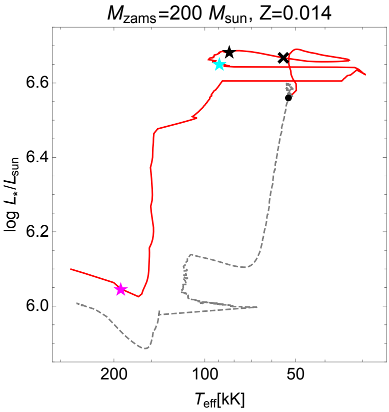
  $\Rightarrow$ Sander & Vink (2020)

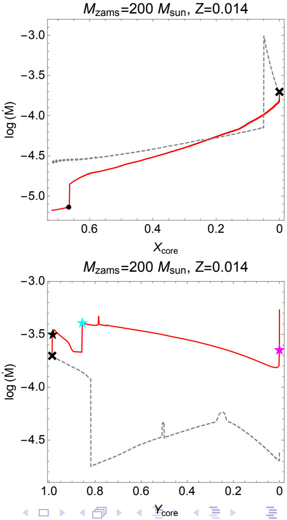
Full scheme in Romagnolo et al. (2024).





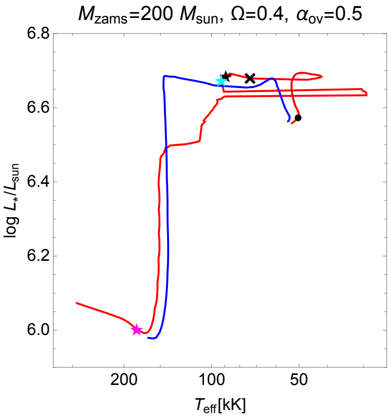
Evolution for $M_{\rm zams} = 200\ M_\odot$, $\Omega = 0.4$, $\alpha_{\rm ov} = 0.1$.

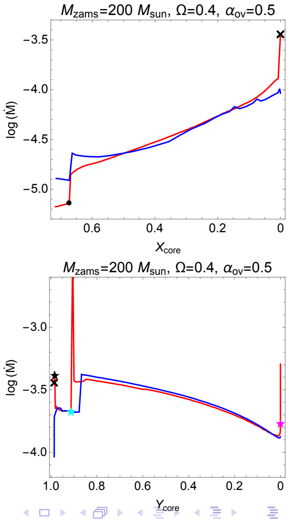




Grey dashed model from Yusof+13.

$\alpha_{\rm ov} = 0.5$, Ledoux criterion, and Tayler-Spruit dynamo.

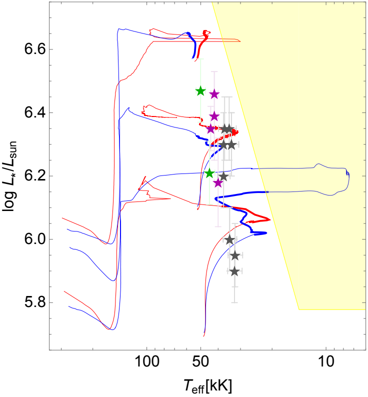




GENEC (red) vs Mesa (blue) models

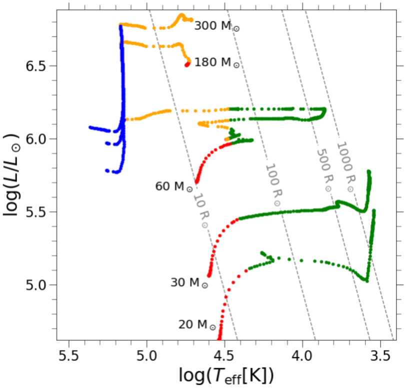
Existence of WNh evolved from $M_{\rm zams} = 60\,M_\odot$

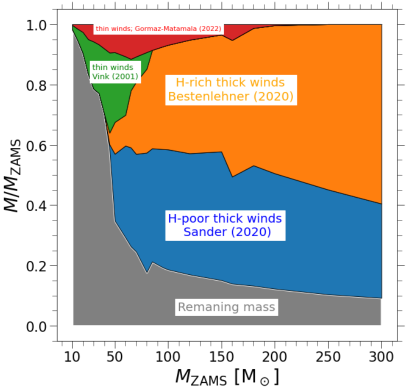
- In evolution models, transition between optically thin winds (OB-type stars) and thick winds (WNh stars) is done at H-core burning stage once some threshold on $X_{\rm surf}$ is reached: 0.3 for GENEC, 0.4 for Mesa.
- However, there is spectroscopical evidence of WNh with $X_{\rm surf} \gg 0.3$ (Martins+08, Crowther+10, Hamann+19, Martins 2023).
- New evolution models with GENEC and MESA accurately predicts WNh stars from $M_{\rm zams} \gtrsim 60\,M_\odot$.



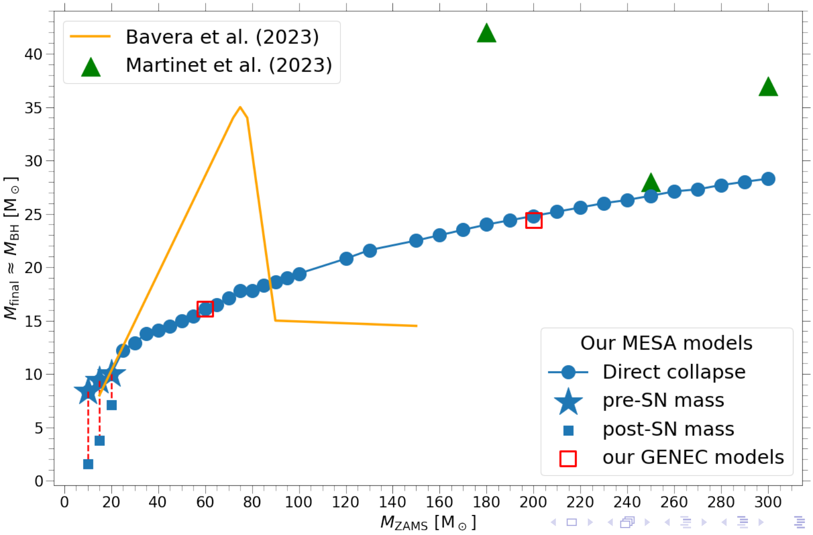
Gormaz-Matamala, Romagnolo & Belczynski (2024, in prep.)

New BH masses for the MW (Romagnolo et al. 2024)





Final masses from new winds



Conclusions

Evolution adopting new self-consistent winds:

- predict stronger chemical enrichment for $\sim 20 - 40\,M_\odot$ stars at SMC metallicity, because of a lower loss of angular momentum.
- predict $M_\text{bh,max} \simeq 28\,M_\odot$ for the Milky Way ($Z = 0.014$), far larger than $M_\text{Cyg X-1} = 21.2 \pm 2.2\,M_\odot$ and lower than $M_\text{Gaia BH3} = 32.7 \pm 0.7\,M_\odot$ (formed from a metal poor MW massive star).
- predict WNh stars (WR winds, $X_\text{surf} \gtrsim 0.3$) to be descendant of stars with $M_\text{zams} \gtrsim 60\,M_\odot$.

Summary and future work

Based in our new evolution models:

- New evolution tracks for lower ($Z \ll 0.002$) metallicities, plus diagnostics over XShootU sources.
- Evaluate the expected luminosities, abundances and mass losses for Ofpe/WR stars in the GC.
- Extend the transition between thin (O-type) to thick (WNh) winds for VMS based on $\Gamma_e = 0.5$ to lower metallicities (Tehrani+19, Martins&Palacios22).
- BH/NS masses beyond the MW.

¡Muchísimas gracias!

Thanks a lot!

Dziękuję bardzo!

Muito obrigado!