On the maximum black hole mass from updated stellar wind prescriptions

Alex C. Gormaz-Matamala

Astronomical Institute of the Czech Academy of Sciences (ASU-CAS)
Ondřejov Observatory
Ondřejov, Czech Republic

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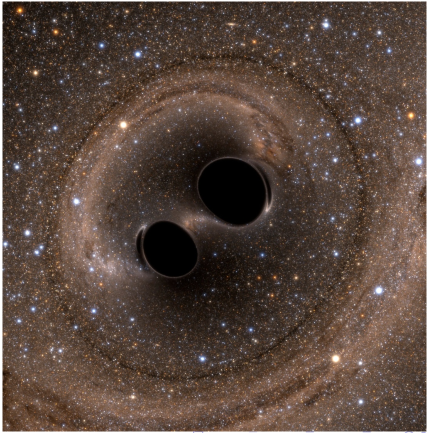
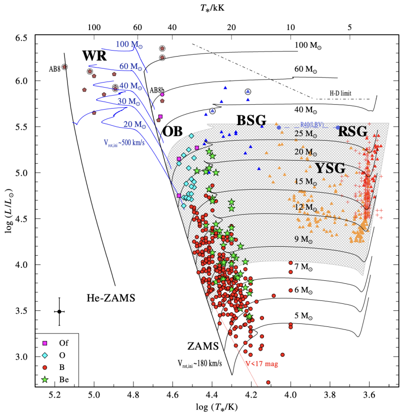
Black holes as sources of Gravitational Waves

- GW are generated due to the merge of double compact objects by gravitational interaction. Progenitors are binary systems of two massive stars, which form BH/NS at the end of their lives.
- But NOT ALL binary systems will evolve into the merge of compact objects! It depends on the mass of the stars and the distance between them.



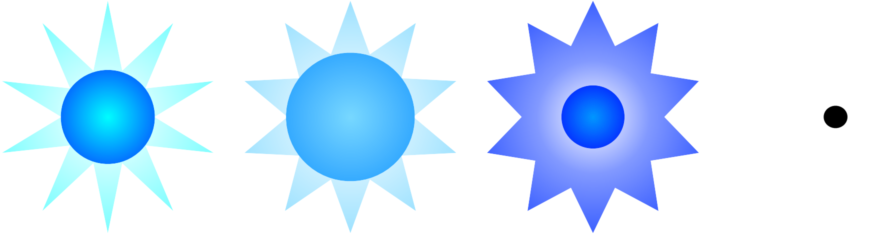
The origin of stellar black holes: massive stars

- Stars born with masses $M_{\text{zams}} \gtrsim 8\ M_\odot$.
- Strong mass loss ($\dot{M}$): they can lose $\sim 90\%$ of its mass during their lives!
- Massive stars pass through different evolutionary and spectroscopic phases, with different physical conditions for their winds and thus different mass-loss rates:
  - **OB:** OB-type stars ($\dot{M} \sim 10^{-9} - 10^{-5} M_\odot$ yr^{-1})
  - **WR:** Wolf-Rayet stars ($\dot{M} \sim 10^{-5.5} - 10^{-4} M_\odot$ yr^{-1})
  - **LBV:** luminous blue variables ($\dot{M} \sim 10^{-4} - 10^{-3} M_\odot$ yr^{-1})
  - **RSG:** red supergiants ($\dot{M} \sim 10^{-4} M_\odot$ yr^{-1})



Evolution of massive stars: very sensitive to $\dot{M}$!

O-type main sequence | O-supergiant | Wolf-Rayet star | Black hole



60 Msun | 53 Msun | 42 Msun | 17 Msun

(Gormaz-Matamala+25)

60 Msun | 39 Msun | 26 Msun | 12 Msun

(Groh+14)

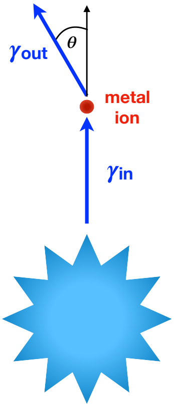
Line driven winds

- Radiation pressure accelerates the wind by electron scattering and line-driving: ions in the wind absorb and reemit photons coming from photosphere.
- Dependent on metallicity.
- $\dot{M}$ eigenvalue of wind hydrodynamics

$$v(r)\frac{dv(r)}{dr} = -\frac{1}{\rho(r)}\frac{dp}{dr} - \frac{GM_*(1-\Gamma_\mathrm{e})}{r^2} + g_\mathrm{line}\ ,$$

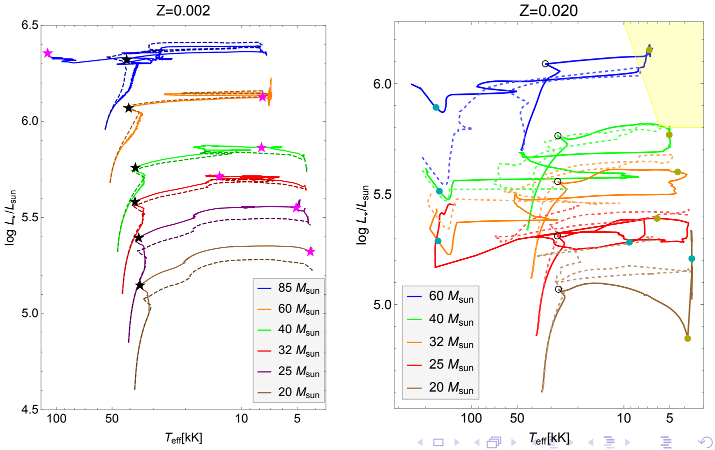
$$\dot{M} = 4\pi\rho(r)r^2v(r)\ ,$$

$$g_\mathrm{line} = \frac{\Gamma_\mathrm{e}GM_*k}{r^2}\left(\frac{4\pi}{\sigma_\mathrm{e}v_\mathrm{th}\dot{M}}\right)^\alpha \mathcal{C}_{R_*}\left(r,v,\frac{dv}{dr}\right)\left(r^2v\frac{dv}{dr}\right)^\alpha\left(\frac{N_\mathrm{e}}{W(r)}\right)^\delta\ .$$



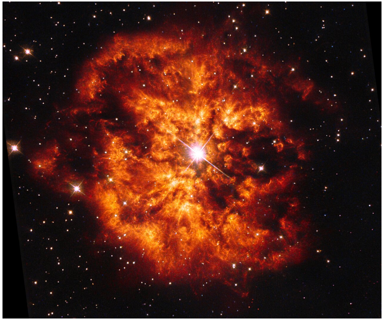
New vs old evolution models (Gormaz-Matamala et al. 2024,2026)

- Mass loss is stronger in high metallicity environments, leading to more massive mass remnants.
- Stripped WR stars (with denser winds and higher $\dot{M}$) to be formed from lower initial masses.



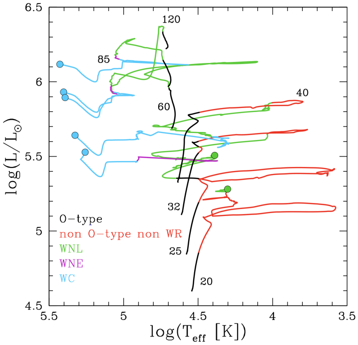
On the evolutionary status of Wolf-Rayet stars

- Very hot stars ($T_* \simeq 30 - 300$ kK!!!), with broad emission lines and optically thick winds.
- Formed by the removal of the outer envelope due to stellar winds ('classical' Wolf-Rayet stars).
- WR classification and their subtypes based in spectroscopic criteria, still needed to establish a criteria to determine WR phases in evolution models based on surface properties.



On the evolutionary status of Wolf-Rayet stars

- In evolution models, transition between optically thin winds (OB-type stars) and thick winds (WR stars) is done at H-core burning stage once some threshold on $X_{\rm surf}(\geqslant 0.3)$ is reached.
- However, there is spectroscopical evidence of hydrogen-rich WN stars (WNh) with $X_{\rm surf} \gg 0.3$ (Martins+08, Crowther+10, Hamann+19, Martins 2023).
- Can we establish an additional criteria to set the O/WNh transition in evolution models for massive stars?



(Georgy+12)

Stellar winds in the proximity to the Eddington limit

- The $\dot{M} \sim \Gamma_e$ relationship changes its slope over a certain $\Gamma_{e,\mathrm{trans}}$ (Vink+11; Vink&Gräfener12; Sabhahit+23).
- Transition from thin to thick winds, thought to be when the wind efficiency number η reaches certain value (Vink&Gräfener12), with the sonic point of the wind structure to be sub-surface (Gräfener21)

$$\eta = \frac{\dot{M} v_\infty}{L_*/c}\;, \qquad \tau_s \simeq \frac{\dot{M} v_\infty}{L_*/c}\left(1 + \frac{v_{\mathrm{esc}}^2}{v_\infty^2}\right)\;.$$

- This approach however, still depends on the initial mass-loss rate for the thin regime.

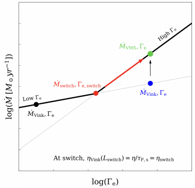
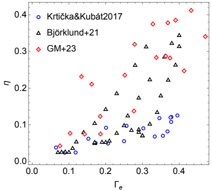


Figure 4. Schematic representation of the new VMS mass-loss framework where the condition to switch to a high-Γ_e, optically-thick wind is based on wind efficiency parameters. A step-by-step method is described in the text.



Why thick winds are formed in WNh stars?

- Wind efficiency? multi-scattering more dominant for line-driven.
- Larger Eddington factor? larger dominance of electron scattering for the radiation force.
- Transition between thin and thick winds based on $\dot{M} - \Gamma_e$ according to CAK theory (Bestenlehner 2020)

$$\log \dot{M} = \log M_0 + \left(\frac{1}{\alpha} + 0.5\right) \log(\Gamma_e) - \left(\frac{1-\alpha}{\alpha} + 2\right) \log(1 - \Gamma_e) \,,$$

- We set switch from thin to thick winds at $\Gamma_e = 0.5$.

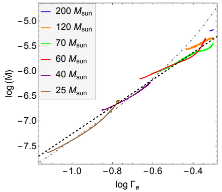


Table 1. For given CAK force multiplier α we list expected transition Eddington parameters and mass-loss rate dependence for $\Gamma_e \ll 1$ and $\Gamma_e \rightarrow 1$.

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

New BH masses for the $Z_\odot$ (Romagnolo et al. 2024)

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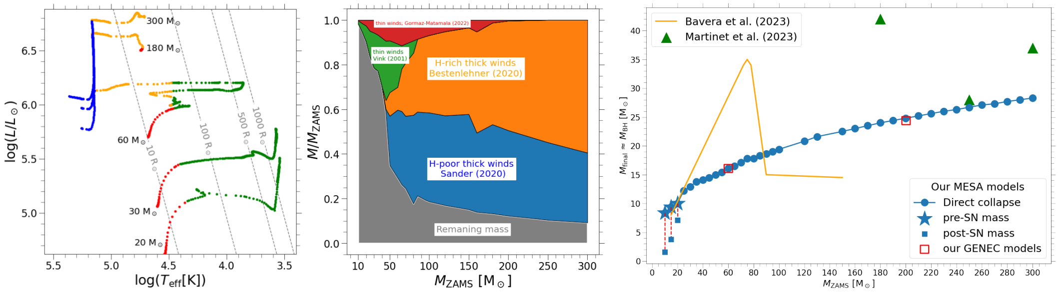
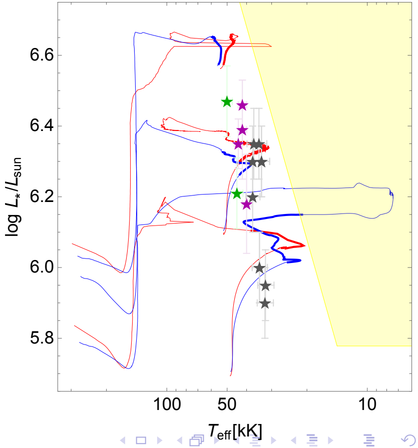


We predict a new initial-final mass relationship, by upgrading the mass-loss recipe for optically thin winds of O-type stars and thick winds of WNh stars.

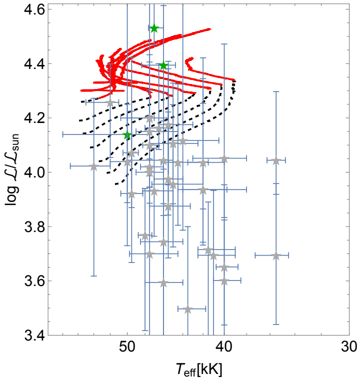
Existence of WNh evolved from $M_{\rm zams} = 60\,M_\odot$

- We took a list of Galactic WNh stars with $X_{\rm H} \geqslant 0.3$ (samples from Martins+08, Crowther+10, Hamann+19).
- New evolution models with GENEC and MESA accurately predicts WNh stars from $M_{\rm zams} \gtrsim 60\,M_\odot$ (Gormaz-Matamala, Romagnolo & Belczynski 2025).
- WNh stars with $X_{\rm H} \gg 0.3$ constrain to $\log T_* \simeq 4.5 - 4.62$.



Open questions for O/WNh transition

- Is our fixed value $\Gamma_{\text{e,trans}} = 0.5$ operational for all metallicities?
- Can we match the observational constrains in LMC R136 cluster (Brands+22)?
- How accurate are new wind prescriptions for thin winds (GM23,K24) for $\Gamma_{\text{e}} \gtrsim 0.4$?
- Can we appropriately **reproduce** the O/WNh transition? (i.e., see the changes in the stellar spectra)

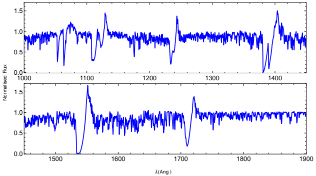


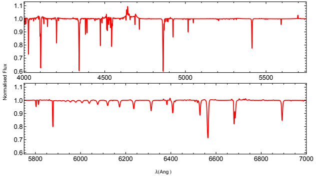
Self-consistent spectra at high Γ_e

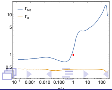
- $v(r)$ by Lambert W-procedure (Gormaz-Matamala+21).

$$-\hat{v}^2 e^{-\hat{v}^2} = -\left(\frac{\hat{r}_c}{\hat{r}}\right)^4 e^{-1-2\,\hat{v}_{\text{crit}}^2\left(\frac{1}{\hat{r}}-\frac{1}{\hat{r}_c}\right)-2\int_{\hat{r}_c}^{\hat{r}} \hat{g}_{\text{line}}\,d\hat{r}}$$

- Model for $T_{\text{eff}} = 34.7$ kK, $\log g = 3.27$, $\log L_*/L_\odot = 6.04$, $\Gamma_e = 0.45$.
  - $\dot{M}_{\text{Vink+01}}$: $9.2 \times 10^{-6}\, M_\odot$ yr^{-1}
  - $\dot{M}_{\text{Gormaz-Matamala+23}}$: $3.9 \times 10^{-6}\, M_\odot$ yr^{-1}
  - $\dot{M}_{\text{Krtička+Kubát21}}$: $1.8 \times 10^{-6}\, M_\odot$ yr^{-1}
- Up-to-date mass-loss rate: $2.5 \times 10^{-6}\, M_\odot$ yr^{-1} $\Rightarrow \eta = 0.316$.
- More RT codes? (FASTWIND, METUJE, PoWR?)







Conclusions

New evolution models adopting new self-consistent winds:

- calculate different mass history and chemical evolution, leading into
- predict $M_{\rm bh,max} \simeq 28\,M_\odot$ for the Milky Way ($Z = 0.014$), far larger than $M_{\rm Cyg\ X\text{-}1} = 21.2 \pm 2.2\,M_\odot$ (Miller-Jones+21) and lower than $M_{\rm Gaia\ BH3} = 32.7 \pm 0.7\,M_\odot$ (formed from a metal poor MW massive star).
- predict WNh stars (WR winds, $X_{\rm surf} \geqslant 0.3$) to be descendant of stars with $M_{\rm zams} \gtrsim 60\,M_\odot$.

Summary and future work

- New evolution models to calculate final BH/NS masses beyond the MW.
- Incorporate new evolution results into predictions of GW progenitors.
- New hydrodynamics $v(r)$ and $\rho(r)$, to revisit properties of HMXBs ($N_{\rm H}(\phi)$, $R_{\rm acc}$, $\dot{M}_{\rm cap}$...).

¡Muchísimas gracias!

Thanks a lot!

Dziękuję bardzo!

Mockrát děkuju!