

Optically thick winds of very massive stars suppress intermediate-mass black hole formation

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Received 24 October 2025 / Accepted 19 December 2025

ABSTRACT

Intermediate-mass black holes (IMBHs) are the link between stellar-mass and supermassive black holes. Gravitational waves have started to unveil a population of IMBHs in the $\sim 100\text{--}300 M_{\odot}$ range. Here, we investigate the formation of IMBHs from non-rotating very massive stars (VMSs, $> 100 M_{\odot}$). We calculate new VMS models that account for the transition from optically thin to optically thick winds, and study how this enhanced mass loss affects IMBH formation and the black hole mass function at intermediate and high metallicity ($Z = 10^{-4}\text{--}0.02$). We show that optically thick winds suppress the formation of IMBHs from direct VMS collapse at metallicities $Z > 0.001$, one order of magnitude lower than predicted by previous models. Our models indicate that the stellar progenitors of GW231123 must have had a metallicity $Z < 0.002$, if the primary black hole formed via direct VMS collapse.

Key words. stars: black holes – stars: massive – stars: mass-loss

1. Introduction

Intermediate-mass black holes (IMBHs), with masses $M_{\text{BH}} \sim 10^2\text{--}10^5 M_{\odot}$, are the link between stellar-mass and supermassive black holes at the center of galaxies (Greene et al. 2020). In the last few years, gravitational waves have provided the first compelling evidence of their existence. The merger remnant of GW190521 represents the first IMBH ever detected via gravitational waves, with a mass of $142^{+28}_{-16} M_{\odot}$ (Abbott et al. 2020b; Abbott et al. 2020a). More recently, parameter estimation for the event GW231123 (The LIGO Scientific Collaboration et al. 2025c) reveals a black hole (BH) remnant with $m \sim 240 M_{\odot}$. Both binary BH (BBH) components of GW231123 have masses within or above the pair-instability mass gap (Heger & Woosley 2002; Woosley et al. 2007), with peculiarly high spins ($\chi \gtrsim 0.7$) that hint at the dynamical origin of this merger (Gerosa & Berti 2017; Fishbach et al. 2017; Antonini et al. 2019; Gerosa & Fishbach 2021; Mapelli et al. 2021; Antonini et al. 2025; Kiroğlu et al. 2025a,b). The current fourth gravitational-wave transient catalog (The LIGO Scientific Collaboration et al. 2025a,b) already contains a number of other IMBH candidates, which number is expected to increase with the next observing runs.

At the same time, searches for IMBHs in the Milky Way globular clusters have mostly led to inconclusive results

(Mezcua 2017), with only a few debated candidate BHs (Miller-Jones et al. 2012; Tremou et al. 2018; Baumgardt et al. 2019). One notable exception is represented by ω Centauri, which hosts an IMBH with mass $\geq 8 \times 10^3 M_{\odot}$, as revealed by proper motions based on over 20 years of HST data (Häberle et al. 2024).

Possible IMBH formation pathways include the direct collapse of very massive stars (VMSs), with masses above $100 M_{\odot}$ (Belkus et al. 2007; Crowther et al. 2010; Bestenlehner et al. 2014; Vink et al. 2015; Costa et al. 2025; Shepherd et al. 2025), stellar collisions in dense young star clusters (Portegies Zwart & McMillan 2002; Freitag et al. 2006b,a; Vanbeveren et al. 2009; Mapelli 2016; Di Carlo et al. 2021; Torniamenti et al. 2022), and hierarchical BH mergers in dense and massive star clusters (Antonini et al. 2019, 2023; Mapelli et al. 2021; Rizzuto et al. 2021; Arca Sedda et al. 2023; Torniamenti et al. 2024). Very massive stars have been observed in star-forming regions and young massive clusters (Vink et al. 2015), such as the Arches cluster near the Galactic center (Martins et al. 2008), NGC 3603 (Crowther et al. 2010), and R136 in the Large Magellanic Cloud (LMC, Crowther et al. 2010; Bestenlehner et al. 2014, 2020). The estimated initial masses of these objects are up to $\sim 300 M_{\odot}$ (Crowther et al. 2010). Also, most of them are observed as single stars (Crowther et al. 2010), which may suggest that their formation is triggered or enhanced by stellar collisions during the earliest stellar phases (Portegies Zwart et al. 1999; Mapelli 2016). The possibility that VMSs form IMBHs,

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however, strongly depends on the amount of mass they lose during their life (Vink 2018).

At solar metallicity, VMSs can lose a large fraction of their initial mass during the main sequence, and leave relatively low-mass compact objects ($<30 M_{\odot}$, Belczynski et al. 2010; Mapelli et al. 2013; Romagnolo et al. 2024). At low metallicity, these stars could preserve enough mass to enter the pair-instability regime (Spera & Mapelli 2017; Renzo et al. 2020). Stars that develop He cores in the 64–135 M_{\odot} range at the end of carbon burning eventually explode as (pair-instability) supernovae and leave no compact remnant (Heger & Woosley 2002; Woosley et al. 2007; Yungelson et al. 2008), whereas stars that develop even more massive He cores efficiently undergo photodisintegration and possibly collapse into IMBHs (Spera & Mapelli 2017). Also, the retention of the envelope can trigger a dredge-up phase during the core helium-burning phase, remove mass from the stellar core, and, in turn, prevent pair-production episodes (Costa et al. 2021).

Most current models predict that VMSs can form IMBHs up to metallicities $Z \lesssim 0.014$ (see, e.g., Costa et al. 2025), where stellar winds become strong enough to prevent the formation of stellar cores with $>100 M_{\odot}$. Recently, Sabhahit et al. (2022, 2023, hereafter S22; S23) introduced a new model for stellar winds in VMSs based on the concept of transition mass loss (Vink et al. 2011; Vink & Gräfenor 2012) to account for the transition from optically thin winds of O-type stars to the optically thick wind regime. This predicts enhanced mass-loss rates ($\dot{M} \gtrsim 10^{-4} M_{\odot} \text{ yr}^{-1}$) during the main sequence, when the star is radiation-pressure dominated – i.e., when its luminosity is very close to or even above the Eddington value. In this case, the wind mass-loss rate is strong enough to reduce the core mass (S23). This improved wind implementation has proved to naturally account for the narrow range of observed VMS temperatures in the Galaxy and the LMC (S22). Also, it heavily suppresses the occurrence of pair instability due to lower core masses. In a recent work, we estimate that this new wind formalism can naturally yield rates of pair instability supernovae consistent with observations (Simonato et al. 2025). Another consequence we may naturally expect is the suppression of IMBH production from VMSs in the regime where optically thick winds become effective.

Here, we investigate the formation of IMBHs from VMSs. We account for optically thick winds to assess how different metallicities and mass-loss rates affect the formation of these objects. To this end, we ran an extensive set of VMS models with MESA (Paxton et al. 2011, 2018) to explore the impact of stellar winds on the mass of the VMS cores and the resulting BH masses. We find that IMBH formation is strongly suppressed by our optically thick wind model, even at the metallicity of the LMC.

This paper is organized as follows. In Sect. 2, we introduce our models for stars and stellar winds. In Sect. 3, we show the BH mass distributions from single and binary stars in the presence of optically thick winds. In Sect. 4, we discuss the possible impact of rotation and core overshooting. Finally, we summarize our results and conclusion in Sect. 5.

2. Methods

We modeled the evolution of VMSs with the hydro-static stellar evolution code MESA (version r12115; Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023) and adopted the radiation-driven wind models from S23. First, we evolved VMSs until the

last phases before core collapse. Then, we used the population-synthesis code SEVN (Spera et al. 2019; Mapelli et al. 2020; Iorio et al. 2023) to explore the BH mass distribution of single and binary VMSs with different wind models and to study a population of massive binary stars. In the following, we introduce our initial conditions and model parameters.

2.1. VMS models with MESA

We adopted the same initial setup as Simonato et al. (2025), based on the wind mass-loss scheme by S22 and S23¹. This wind model is based on the concept of transition mass loss introduced by Vink & Gräfenor (2012): the transition from optically thin to optically thick winds takes place when the Eddington ratio of the star (Γ_{Edd}) exceeds the ratio at the transition point $\Gamma_{\text{Edd, tr}}$. At each iteration, we calculated the mass-loss rate, \dot{M}_{Vink} , the escape velocity, v_{esc} , and the terminal speed, v_{∞} , from the stellar luminosity as described in S23. We used these quantities to calculate the wind efficiency parameter, which determines when the switch occurs:

$$\eta_{\text{Vink}}(L) \equiv \frac{\dot{M}_{\text{Vink}} v_{\infty}}{L/c} = \frac{\eta}{\tau_{F,s}} \left(\frac{v_{\infty}}{v_{\text{esc}}} \right) = 0.75 \left(1 + \frac{v_{\text{esc}}^2}{v_{\infty}^2} \right)^{-1}, \quad (1)$$

where $\tau_{F,s}$ is the flux-weighted mean optical depth at the sonic point. In the optically thick regime, the wind mass loss follows Vink et al. (2011):

$$\dot{M} = \dot{M}_{\text{tr}} \left(\frac{L}{L_{\text{tr}}} \right)^{4.77} \left(\frac{M}{M_{\text{tr}}} \right)^{-3.99}, \quad (2)$$

where \dot{M}_{tr} , L_{tr} , and M_{tr} are the mass-loss rate, the luminosity, and the mass at the transition point, respectively. During the main sequence, we used Eq. (2) to describe the wind mass loss in the optically thick regime. Otherwise, we referred to Vink et al. (2001). In the core He-burning phase, we used Eq. (2) for temperatures between 4×10^3 K and 10^5 K, while for $T < 4 \times 10^3$ K, we used the formalism by de Jager et al. (1988). For $T > 10^5$ K and the central hydrogen mass fraction $X_{\text{C}} < 0.01$, we adopted the Wolf–Rayet mass loss by Sander & Vink (2020).

We modeled convective mixing with the mixing-length theory (Cox & Giuli 1968), adopting a constant mixing-length ratio $\alpha_{\text{MLT}} = 1.5$. We determined the convective boundaries by applying the Ledoux criterion (Ledoux 1947). We used the semi-convective diffusion parameter $\alpha_{\text{SC}} = 1$. We chose the exponential overshooting formalism by Herwig (2000), with the efficiency parameter $f_{\text{OV}} = 0.03$, to describe this process above the convective regions.

Finally, we activated the `co_burn_net` (parameter `auto_extend_net = true`) after the main sequence to have a complete and extended network for C- and O-burning and α -chains. Following Simonato et al. (2025), we defined the core radius of each element as the radius inside which the fraction of the lighter element below $f_{\text{X}} = 10^{-4}$. For example, the helium (carbon) core radius is the radius inside which the mass fraction of H (^4He) drops below $f_{\text{X}} = 10^{-4}$ ($f_{\text{Y}} = 10^{-4}$). Our definition is the same as the MIST libraries, and yields an accurate description of the core boundary (Paxton et al. 2011, 2013, 2015; Dotter 2016; Choi et al. 2016).

¹ The MESA inlists and `run_star_extras` files by Sabhahit et al. (2023) are publicly available at [this link](#).

2.2. Initial conditions and stopping criteria

We considered a grid of VMS models with masses from 50 to 500 M_{\odot} , in intervals of 25 M_{\odot} . We considered 14 metallicities from $Z = 10^{-4}$ to $Z = 0.02$. The initial He mass fraction is $Y = Y_{\text{prim}} + Z \Delta Y / \Delta Z$, with $Y_{\text{prim}} = 0.24$ as the primordial He abundance, and $\Delta Y / \Delta Z$ is parameterized so that we range from a primordial ($Y = 0.24$, $Z = 0$) to nearly a solar abundance ($Y = 0.28$, $Z = 0.02$, Pols et al. 1998)². Finally, we calculated the H mass fraction as $X = 1 - Y - Z$. We only considered non-rotating stellar models.

We evolved the MESA models until the star exceeded a central temperature $\log T_c / \text{K} = 9.55$, which corresponds to the very last stages before core collapse, or it undergoes (pulsational) pair-instability. In the latter case, the creation of electron–positron pairs removes thermal pressure from the gas, possibly triggering a state of global dynamical instability. Because we use the hydrostatic integrator of MESA, we cannot integrate the models until (pulsational) pair instability kicks in, but we verify a posteriori the global stability of the star. Specifically, we calculated the first adiabatic exponent Γ_1 (e.g., see also Marchant et al. 2019; Farmer et al. 2019, 2020; Costa et al. 2021), properly weighted and integrated over the mass domain (Stothers 1999):

$$\langle \Gamma_1 \rangle = \frac{\int_0^M \frac{P}{\rho} \Gamma_1 dm}{\int_0^M \frac{P}{\rho} dm}. \quad (3)$$

Here, P is the pressure, ρ is the density, and the integral is calculated up to the surface of the star. If a star enters a regime $\langle \Gamma_1 \rangle < 4/3 + 0.01$, we label it as pair-instability and no longer integrate its evolution.

2.3. BH masses

If a star enters the (pulsational) pair-instability regime, we calculate the final BH mass with the fitting formulas from Mapelli et al. (2020), based on the models by Woosley (2017). In this model, a star undergoes a pulsational pair-instability supernova if the He core has a final mass in the range $32 M_{\odot} \leq M_{\text{He,f}} < 64 M_{\odot}$. The mass of the BH is therefore estimated as

$$M_{\text{BH}} = \alpha_P M_{\text{CCSN}}, \quad (4)$$

where M_{CCSN} is the expected BH mass after a core-collapse supernova, based on the fitting formulas by Fryer et al. (2012), and α_P depends on the mass of the He-core and on the ratio between the He-core mass and the total mass in the pre-supernova stage.

If $64 M_{\odot} \leq M_{\text{He,f}} \leq 135 M_{\odot}$, instead, the star undergoes a pair-instability supernova, leaving no compact remnant. If the core mass exceeds $135 M_{\odot}$, pair instability triggers photodisintegration and the star directly collapses into a BH, leaving a compact remnant with a M_{BH} equal to the total mass of the star.

Mass ejection can also occur in stars that undergo a failed supernova because of the shock triggered by instantaneous neutrino loss (Lovegrove & Woosley 2013; Fernández et al. 2018). The ejected mass depends on the ejected energy and the compactness of the star (Fernández et al. 2018). In particular, the ejected energy depends on the core compactness, $\xi_{2.5}$ (O’Connor & Ott 2011; Burrows & Vartanyan 2021; Burrows et al. 2024).

² Here, we refer to the traditionally considered value for solar metallicity $Z = 0.02$ (Grevesse & Sauval 1998; but see, e.g., Magg et al. 2022 for more recent estimates).

Also, the ejected mass decreases with the stellar envelope compactness, $\xi_{\text{env}} = M_*/R_*$, where R_* is the total radius of the star. The ejected mass depends on ξ_{env} (Fernández et al. 2018), and ranges from $M_{\text{ej}} \sim 10 M_{\odot}$ for red supergiant stars ($\xi_{\text{env}} \sim 10^{-2}$) to $M_{\text{ej}} \lesssim 10^{-3} M_{\odot}$ if the star dies as a Wolf–Rayet object ($\xi_{\text{env}} \sim 10$).

Following Costa et al. (2022), we estimate the BH mass for the stars that do not undergo a (pulsational) pair instability supernova as

$$M_{\text{BH}} = M_* - \delta M_G - M_{\text{ej}}, \quad (5)$$

where M_* is the final stellar mass, δM_G is the instantaneous gravitational mass loss, and M_{ej} is the mass induced by neutrino-driven shocks in a failed supernova. Here, we assume $\delta M_G = 0.3 M_{\odot}$ (Fernández et al. 2018; Costa et al. 2025), which typically yields a corresponding ejected energy between 10^{47} and 5×10^{47} erg. We thus calculate M_{ej} as the mass of the star with a binding energy less than 3×10^{47} erg.

2.4. Population synthesis with SEVN

We explore the effect of optically thick winds on the mass spectrum of BHs, BBHs, and BBH mergers using the population-synthesis code SEVN (Spera & Mapelli 2017; Spera et al. 2019; Mapelli et al. 2020; Iorio et al. 2023)³. SEVN interpolates pre-computed stellar tracks to evolve single and binary stars. It also incorporates semi-analytic formulas for processes such as binary mass transfer, tides, supernova explosions, and gravitational-wave decay. We refer to Iorio et al. (2023) for a complete description of the code.

We generated new evolutionary tables for stars with mass $M_* \geq 50 M_{\odot}$ from the aforementioned VMS models with MESA. We then evolved single and binary stars with a primary mass in this mass range. For binary stars, we used the stellar tables from PARSEC (Bressan et al. 2012; Chen et al. 2015; Costa et al. 2019a,b; Nguyen et al. 2022; Costa et al. 2025) to account for the evolution of secondary stars with mass $M_* < 50 M_{\odot}$.

When two stars collided, we used the standard formalism of SEVN as described by Iorio et al. (2023). Specifically, we assumed that the collision product retains the total mass of the two stars. The CO and He core masses of the collision product are the sum of the CO and He core masses of the two colliding stars. Finally, the collision product inherits the phase and percentage of life of the most evolved progenitor star. Therefore, our models probably overestimate the total mass of the collision product and underestimate mixing. For a more self-consistent treatment of massive star collisions, see for example Costa et al. (2022) and Ballone et al. (2023).

We randomly drew the zero-age main-sequence (ZAMS) primary star masses from a Kroupa (2001) initial mass function, with $M_{\text{ZAMS}} \in [50, 500]$. For binaries, we drew the secondary masses from the observation-based mass ratio distribution $\mathcal{F}(q) \propto q^{-0.1}$, with $q \in [0.1, 1]$ from Sana et al. (2012). We generated the initial orbital periods (P) and eccentricities (e) from the distributions by Sana et al. (2012): $\mathcal{F}(P) \propto P^{-0.55}$, with $P = \log_{10}(P/\text{days}) \in [0.15, 5.5]$ and $\mathcal{F}(e) \propto e^{-0.45}$, with $e \in [10^{-5}, e_{\text{max}}(P)]$, respectively. For a given orbital period, we set the upper limit of the eccentricity distribution $e_{\text{max}}(P)$ as $e_{\text{max}}(P) = 1 - [P/(2 \text{ days})]^{-2/3}$ (Moe & Di Stefano 2017).

³ We used version 2.10.1 of SEVN, updated to commit c9dc8e457. SEVN is publicly available here.

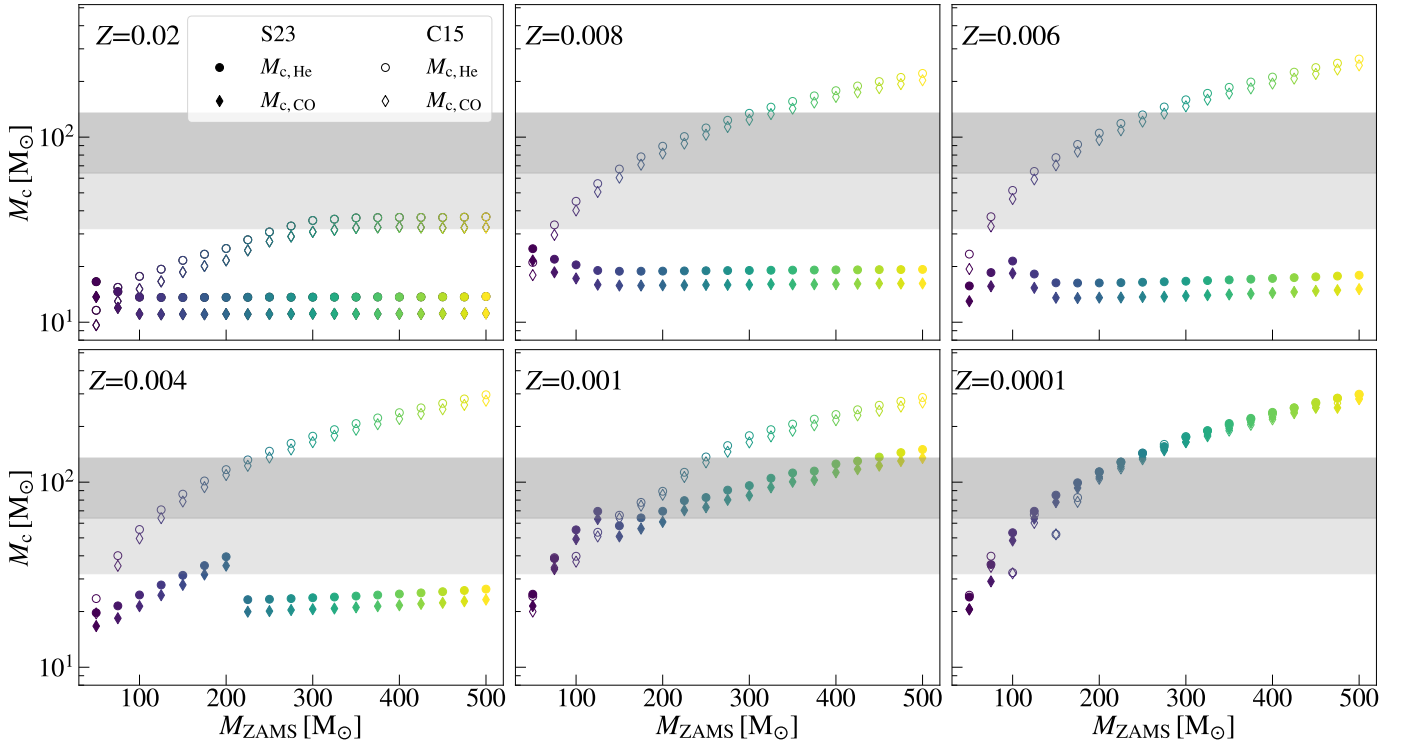


Fig. 1. Masses of the He (circles) and CO (diamonds) cores for the wind model from **S23** (full markers) and **C15** (void markers). The (light) gray shaded areas represent the regime for (pulsational) pair-instability supernovae.

We investigated eight different metallicities: $Z = 0.0001, 0.001, 0.002, 0.004, 0.006, 0.008, 0.01,$ and 0.02 . For each metallicity, we generated 2×10^6 single and 1×10^7 binary systems. Our initial setup corresponds to the same as the fiducial model by [Iorio et al. \(2023\)](#).

To highlight the impact of stellar winds on the resulting BH mass distribution, we also performed a run with tables from the nonrotating PARSEC tracks presented by [Costa et al. \(2025\)](#)⁴. In this case, the adopted wind model is the same as described by [Chen et al. \(2015, hereafter C15\)](#). Specifically, the winds of massive O-type stars are modeled adopting the fitting formulas by [Vink et al. \(2000\)](#) and [Vink et al. \(2001\)](#), with the correction by [Gräfenner & Hamann \(2008\)](#) to account for the effects of electron scattering. The mass-loss rate of an O-type star scales with the metallicity as $\dot{M} \propto Z^\beta$, where β depends on the Eddington ratio Γ_{Edd} : $\beta = 0.85$ for $\Gamma_{\text{Edd}} < 2/3$, $\beta = 2.45 - 2.4 \times \Gamma_{\text{Edd}}$ for $2/3 \leq \Gamma_{\text{Edd}} < 1$, and $\beta = 0.05$ for $\Gamma_{\text{Edd}} \geq 1$ ([Chen et al. 2015](#)). In this way, this formalism incorporates the dependence of mass loss on the Eddington ratio ([Gräfenner & Hamann 2008; Vink et al. 2011](#)). As for Wolf–Rayet stars, PARSEC adopts the prescriptions by [Sander et al. \(2019\)](#), which match the properties of Galactic WR stars of type C and type O. We refer to [Costa et al. \(2025\)](#) for other details on these stellar tracks.

3. Results

3.1. Stellar cores

Figure 1 shows the final He and CO core masses for the **S23** and **C15** wind models. At low metallicity ($Z \leq 0.0001$), the two wind models predict the same monotonic increase of the He and CO core mass with M_{ZAMS} , because VMSs do not enter the optically

⁴ The PARSEC stellar tracks are publicly available at <http://stev.oapd.inaf.it/PARSEC/> ([Costa et al. 2025](#)).

thick wind regime. At these metallicities, the **C15** models generally yield slightly smaller cores, due to the different envelope undershooting and convection models ([Simonato et al. 2025](#)).

At higher metallicity, the two considered models **C15** and **S23** behave in a dramatically different way. According to **S23**, VMSs can enter the optically thick wind regime at $Z \geq 0.001$: such strong winds reduce the final total mass and core mass of VMSs, resulting in a flat or even decreasing trend of M_c with M_{ZAMS} . Hence, the **S23** model predicts smaller He and CO cores compared to **C15**, with a significant impact on the occurrence of (pulsational) pair instability.

The effect of optically thick winds in the **S23** model is twofold. On the one hand, the **S23** model results in a lower metallicity threshold below which VMSs can enter the (pulsational) pair instability regime: the threshold is $Z_{\text{th}} = 0.004$ and 0.01 for **S23** and **C15**, respectively. On the other hand, the formation of IMBHs via direct collapse is suppressed in the **S23** model for metallicity $Z \geq 0.001$, whereas the **C15** model allows the formation of IMBHs at $Z \leq 0.008$ because of the lower wind mass loss.

For example, at $Z = 0.001$ optically thick winds become effective for $M_{\text{ZAMS}} > 200 M_\odot$, when the stellar core is already well within the pair-instability regime. Mass loss prevents the He core mass from increasing above $135 M_\odot$. As a consequence, only VMSs with $M_{\text{ZAMS}} \geq 450 M_\odot$ undergo direct collapse into a IMBH in the **S23** model, whereas in **C15** IMBHs can form via direct collapse at $M_{\text{ZAMS}} \sim 300 M_\odot$.

For $Z = 0.004$, VMSs with $M_{\text{ZAMS}} \geq 200 M_\odot$ develop stellar winds that are strong enough to reduce the stellar core to $M_c < 30 M_\odot$, where even pulsational pair instability is inhibited. For $Z \geq 0.006$, VMSs in the **S23** models undergo optically thick stellar winds throughout the mass range considered. This dramatically reduces the final core masses, which display a weak dependence on M_{ZAMS} . For example, at $Z \sim 0.006$ the core mass

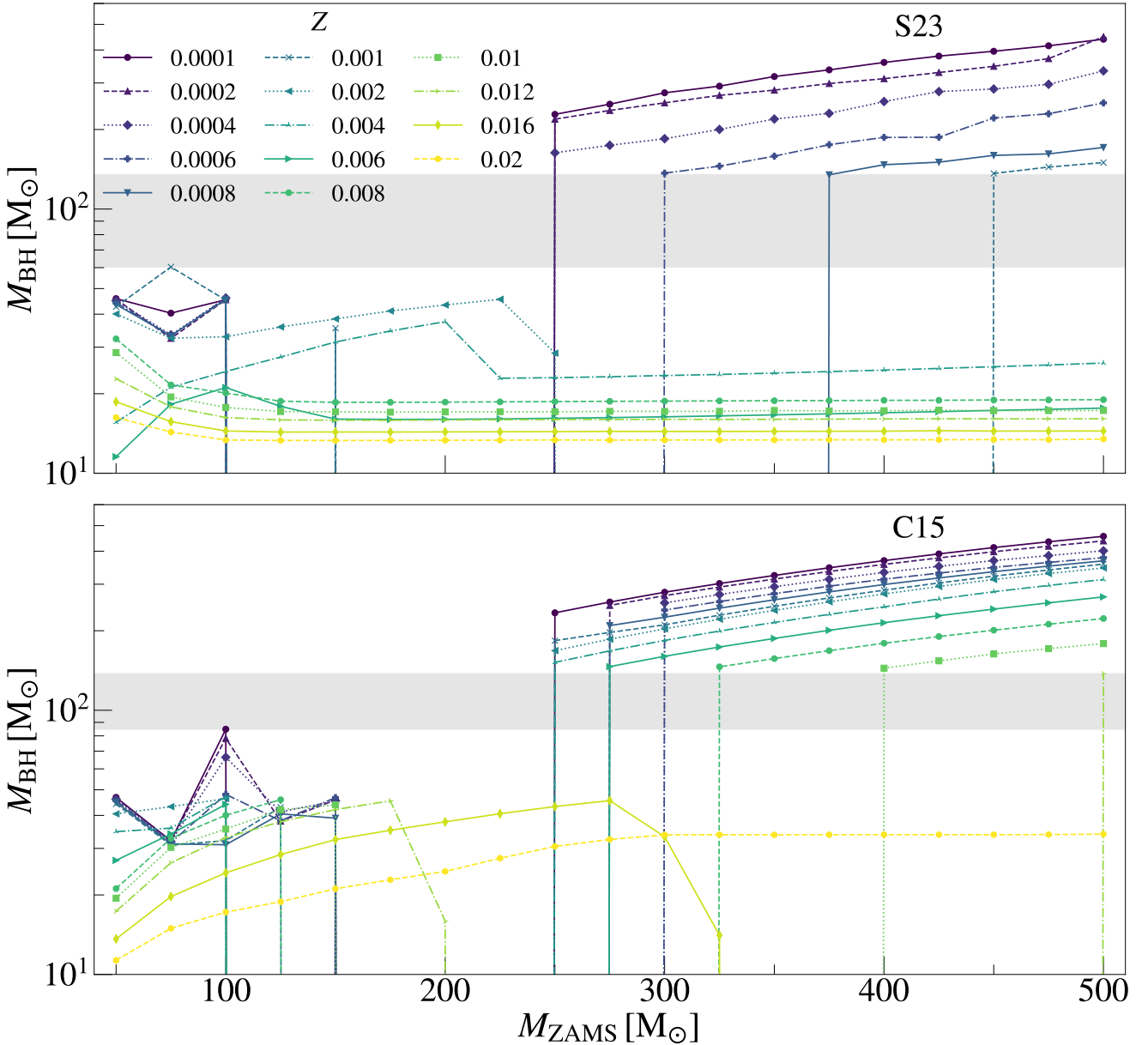


Fig. 2. Final BH mass as a function of M_{ZAMS} for different metallicities, Z , for the **S23** (upper) and **C15** (lower) wind mass-loss prescription. The gray shaded area shows the resulting pair-instability mass gap for the two wind models.

for VMSs with $M_{\text{ZAMS}} > 400 M_{\odot}$ decreases from $\sim 200 M_{\odot}$ in the **C15** model to $\sim 20 M_{\odot}$ in **S23**.

3.2. BH masses

Figure 2 shows the final BH mass as a function of M_{ZAMS} for models **C15** and **S23**. The key difference between the two models is the metallicity threshold to form IMBHs; this is $Z_{\text{IMBH}} = 0.001$ and 0.012 for models **S23** and **C15**, respectively. In model **S23**, IMBH formation is suppressed at metallicity $Z > 0.001$ by the onset of optically thick winds. These strong winds erode the mass of the He core and prevent it from reaching the threshold $M_{\text{He}} \sim 135 M_{\odot}$, above which the star avoids exploding as a pair-instability supernova. Thus, even the most massive stars do not produce IMBHs in the **S23** model unless they have metallicity $Z \leq 0.001$. In contrast, the lower mass loss in model **C15** allows larger cores to grow and enables the formation of IMBHs up to $Z \sim 0.012$.

In the absence of optically thick winds, the BH mass increases with M_{ZAMS} , up to the onset of (pulsational) pair instability, at $M_{\text{ZAMS}} \gtrsim 75 M_{\odot}$. For larger initial masses, the onset of direct collapse depends on metallicity. In the **C15** model, VMSs undergo (pulsational) pair instability up to $Z = 0.01$. At lower metallicities, all the models with $M_{\text{ZAMS}} > 400 M_{\odot}$ produce IMBHs, with masses ranging from $135 M_{\odot}$ to $450 M_{\odot}$. At $Z = 0.02$, instead, wind mass loss is strong enough to prevent the onset of pair instability, leading to a maximum BH mass $M_{\text{BH}} \sim 30 M_{\odot}$.

In the **S23** model, the maximum metallicity at which IMBHs form is an order of magnitude lower ($Z = 0.001$) compared to **C15**. Below this threshold, the **S23** model produces IMBHs with masses in the same range as **C15**. At higher metallicities, the most massive BHs originate from stars with $M_{\text{ZAMS}} \sim 50 M_{\odot}$, while more massive stars deliver $M_{\text{BH}} \lesssim 15 M_{\odot}$. This happens because VMSs develop optically thick winds at an early stage, and spend all their lifetime with $\dot{M} > 10^{-5} M_{\odot} \text{ yr}^{-1}$. This results

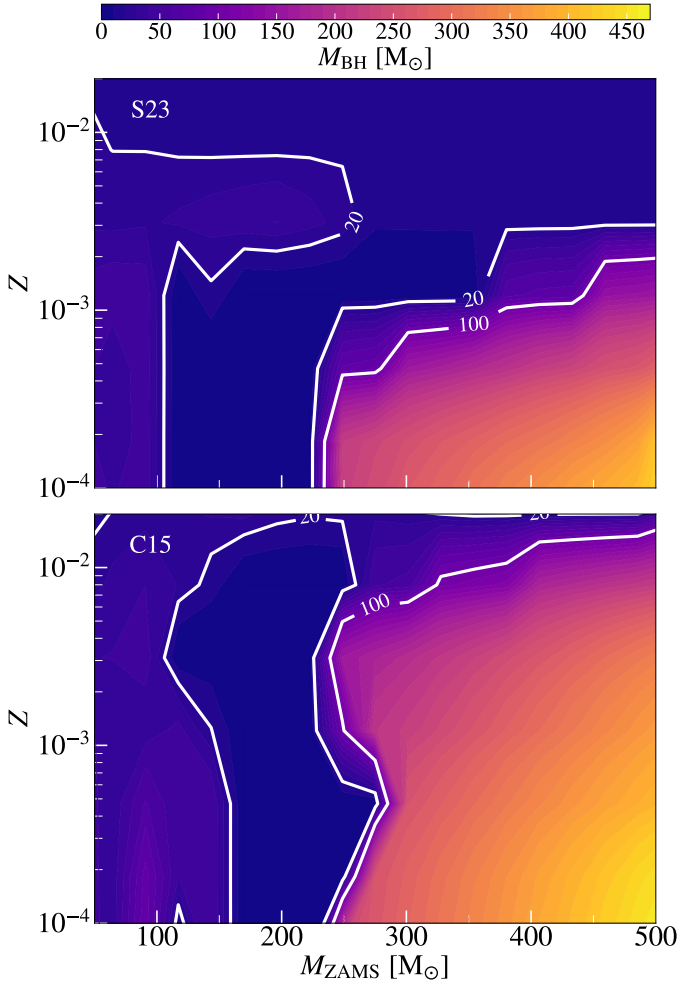


Fig. 3. Contour plot showing the final BH mass as a function of M_{ZAMS} and Z , for the **S23** (upper panel) and the **C15** (lower panel) models. The white contours highlight the levels at $20 M_{\odot}$ and $100 M_{\odot}$.

in a severe erosion of the core (Simonato et al. 2025; Boco et al. 2025). Overall, the **S23** models predict a pair-instability BH mass gap from $65 M_{\odot}$ to $135 M_{\odot}$.

Figure 3 shows the final BH mass as a function of the ZAMS mass and the metallicity for the **S23** model. The formation of IMBHs only takes place for VMSs with $M_{\text{ZAMS}} \gtrsim 250 M_{\odot}$ at $Z \leq 0.001$. Also, the formation of BHs with $M_{\text{BH}} > 20 M_{\odot}$ is suppressed for $Z > 0.01$ throughout the mass range.

3.3. BH mass function

3.3.1. BHs from single VMSs

Figure 4 shows the BH mass function from single VMSs assuming a Kroupa (Kroupa 2001) initial mass function. For $Z > 0.001$ optically thick winds strongly suppress the production of IMBHs from single stars. At $Z = 0.001$, the **S23** model still allows IMBH formation, but the efficient mass loss limits the maximum BH mass to $150 M_{\odot}$, compared to $350 M_{\odot}$ in the **C15** model. For higher metallicities, stellar winds progressively reduce the maximum BH mass in the **S23** model, down to $20 M_{\odot}$ at $Z = 0.02$.

In the **C15** model, the formation of IMBHs takes place up to $Z = 0.01$, where the maximum BH mass is $\sim 180 M_{\odot}$

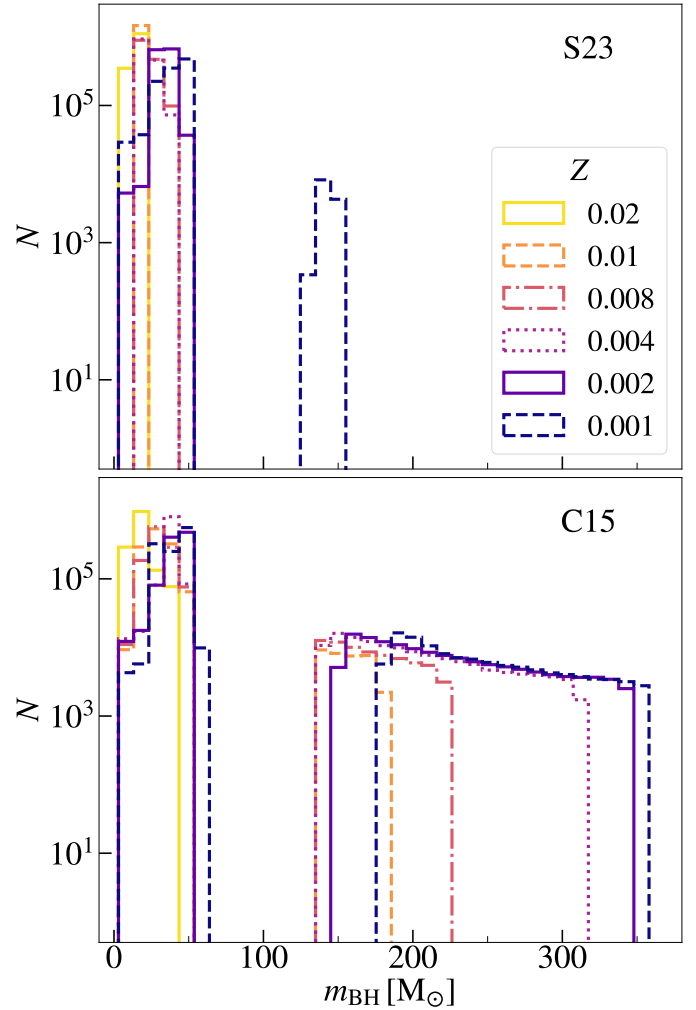


Fig. 4. Black hole mass distribution from single stars with $M_{\text{ZAMS}} > 50 M_{\odot}$, for the models adopting the **S23** (upper panel) and **C15** (lower panel) wind prescriptions and for different metallicities.

(also see Costa et al. 2025). At lower metallicities, the maximum IMBH mass reaches $\sim 400 M_{\odot}$, for ZAMS masses up to $M_{\text{ZAMS}} = 500 M_{\odot}$. In this model, IMBH formation from single VMSs is only suppressed at $Z = 0.02$, where BHs can form with a mass up to $33 M_{\odot}$.

3.3.2. BBHs from VMS binaries

Figure 5 shows the primary BH masses from binaries with primary mass $M_{\text{ZAMS},1} > 50 M_{\odot}$, distributed according to a Kroupa (Kroupa 2001) mass function. We refer to Section 2.4 for more details on the initial conditions. We display the mass distribution of both primary BHs in BBHs and single BHs from disrupted binaries. Star-star collisions dramatically extend the BH mass function to larger values compared to the single stellar-evolution case in Fig. 4.

The **C15** model predicts the formation of BHs as massive as $\gtrsim 700 M_{\odot}$ for $Z \leq 0.002$. Also, IMBHs up to $\sim 400 M_{\odot}$ can still form at $Z = 0.01$. In the **S23** model, instead, the formation of IMBHs is already suppressed at $Z = 0.004$, where they represent less than 0.2% of the total BH number, despite the occurrence of star-star collisions. In contrast, the percentage of IMBHs is 21% in the **C15** model at $Z = 0.004$. We find that, in the metallicity range $Z = 0.004$ – 0.008 , our distributions are consistent with

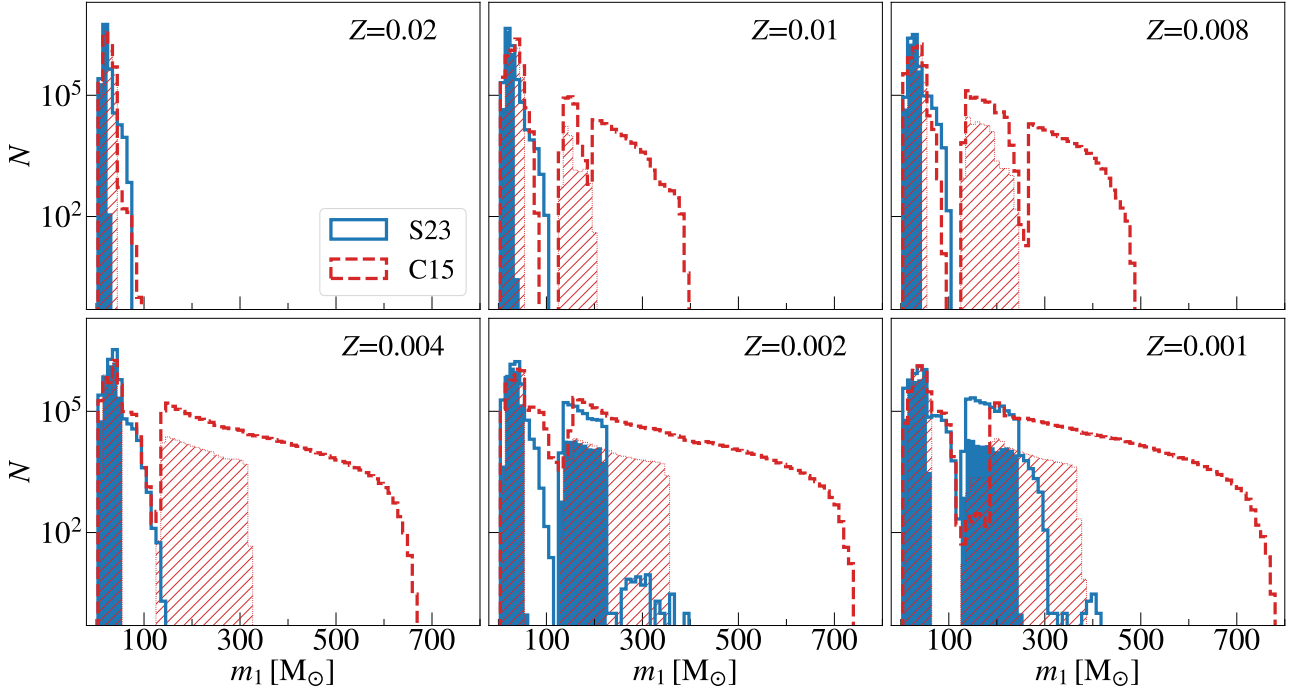


Fig. 5. Black hole mass distribution from binaries with $M_{\text{ZAMS},1} > 50 M_{\odot}$, for models adopting the **S23** (solid blue line, solid fill) and **C15** (dashed red line, hatched area) wind prescriptions. The shaded (hatched) areas indicate the BHs in BBHs, while the empty histograms display the single BHs from disrupted binaries, including BHs that form from stellar collisions.

those from [Shepherd et al. \(2025\)](#) when they consider the same wind prescription.

Primary BHs in BBHs also reach higher masses than BHs from single stellar evolution, due to mass accretion from the stellar companion. In the **S23** model, IMBH formation in BBHs is possible for $Z \leq 0.002$, while for $Z = 0.004$, the maximum primary BH mass in BBHs decreases to $45 M_{\odot}$. At $Z = 0.02$, the BH mass function in the **S23** model extends from $5 M_{\odot}$ to $20 M_{\odot}$.

Black holes in BBHs display a pair-instability mass gap between $65 M_{\odot}$ and $135 M_{\odot}$ for both the **C15** and the **S23** models. In contrast, star-star collisions can produce BHs in this mass range, and fill the pair-instability mass gap with single BHs.

3.3.3. BBH mergers

Figures 6 and 7 show the primary and remnant mass distributions for BBHs that merge within a Hubble time. In the **S23** model, no BBH merger has a primary mass $m_1 > 50 M_{\odot}$ for $Z > 0.002$. In the **C15** case, IMBH mergers can occur up to a metallicity of $Z = 0.004$. In general, the BBH merger mass distribution displays a mild dependence on metallicity, with a peak at $\sim 10 M_{\odot}$.

The maximum merger remnant produced by these BBHs is usually two times as massive as the maximum primary BH mass. In the presence of optically thick winds (model **S23**), the formation of IMBHs from BBH mergers is thus possible up to $Z = 0.002$, where $m_{\text{BH,max}} \sim 240 M_{\odot}$. At higher metallicities, the maximum BH remnant mass progressively decreases down to $35 M_{\odot}$ at $Z = 0.02$. In the **C15** models, the masses delivered by BBH mergers are larger, with the possibility of having IMBH remnants up to a metallicity of $Z = 0.006$.

3.3.4. Progenitors of GW231123 and GW190521

We qualitatively compare our models with the most massive BBH mergers detected by the LIGO-Virgo-KAGRA

interferometers, namely GW231123 ([The LIGO Scientific Collaboration et al. 2025c](#)) and GW190521 ([Abbott et al. 2020b; Abbott et al. 2020a](#)). According to our **S23** model, the progenitors of GW231123 should have had a metallicity $Z \leq 0.002$. The primary mass of GW190521 ([Abbott et al. 2020b; Abbott et al. 2020a](#)), instead, lies well within the mass gap predicted by both our **C15** and **S23** models. In a follow-up work, we will explore the dynamical formation of such mergers with our new **S23** models (Torniamenti et al., in prep.).

4. Discussion

4.1. Impact of rotation and overshooting

In this work, we investigate the impact of a recent model that accounts for optically thick winds (**S23**) in the formation of IMBHs from VMSs. We considered nonrotating stellar models with a fixed overshooting parameter. However, both stellar rotation and core overshooting may have a relevant impact on the final BH mass. In a follow-up paper, we will include these additional parameters in detail. In the following, we briefly discuss their expected impact on our results.

Stellar rotation affects both the envelope and the core mass, leading to enhanced stellar-mass loss during the main sequence ([Langer 1998](#), but also see [Müller & Vink 2014](#)), and triggering chemical mixing in the core ([Sabahit et al. 2023](#)). In the optically thin regime, rotation generally results in enhanced mass loss when the critical rotation is approached ($\Omega/\Omega_c > 0.4$). As a consequence, it can further quench the BH production at low metallicity $Z < 0.01 Z_{\odot}$, where optically thick winds are not activated ([Winch et al. 2024, 2025](#)). Also, rotation can drive the transition to the optically thick regime at lower initial masses ([Sabahit et al. 2023; Boco et al. 2025](#)). For VMSs, this mainly affects the evolution at low Z , where the star can retain a large fraction of its angular momentum due to weaker mass loss.

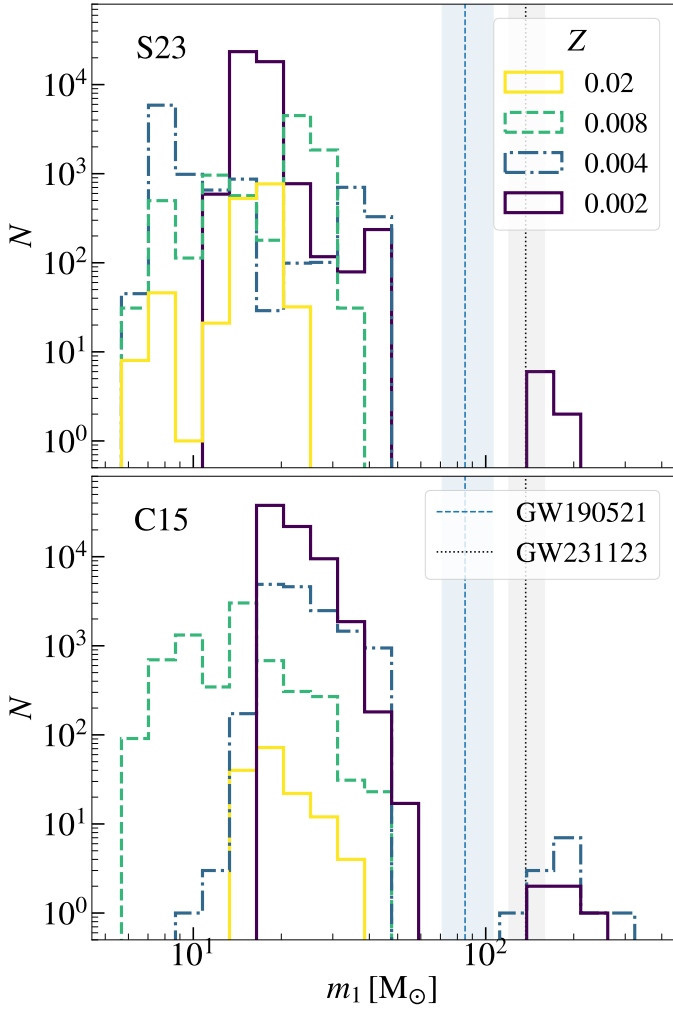


Fig. 6. Primary BH mass distribution in BBH mergers with $M_{ZAMS,1} > 50M_{\odot}$, for the **S23** (upper) and **C15** (lower) wind prescriptions, and for different metallicities. The dashed blue (dotted black) line displays the inferred value for GW190521 (GW231123), with the estimated uncertainty (shaded area).

At high Z , wind mass loss can efficiently remove the angular momentum, leading to a minor impact from stellar rotation on the final BH mass.

Core overshooting also triggers chemical mixing, affecting the final core mass in a similar way to rotation (Sabahit et al. 2022). In the optically thin regime, increasing the overshooting parameter leads to more massive cores, with larger values of M_{BH} for the same M_{ZAMS} (Winch et al. 2024). For VMSs, optically thick winds already lead to the formation of a fully mixed star if the initial stellar mass is large enough ($M_{ZAMS} > 200M_{\odot}$, Sabahit et al. 2022), while removing the stellar envelope. As a consequence, overshooting is not expected to play an important role in the final BH mass.

In summary, we expect overshooting and rotation to affect the relation between M_{ZAMS} and M_{BH} in the low-metallicity and low-mass end of the parameter space considered, where mass loss is driven by optically thin winds. In such regimes, a larger overshooting parameter and a fast rotation may further reduce the maximum value of Z at which IMBHs are produced. When more vigorous stellar winds are present, VMS evolution is expected to be mainly driven by stellar mass loss, with a less relevant impact from these parameters.

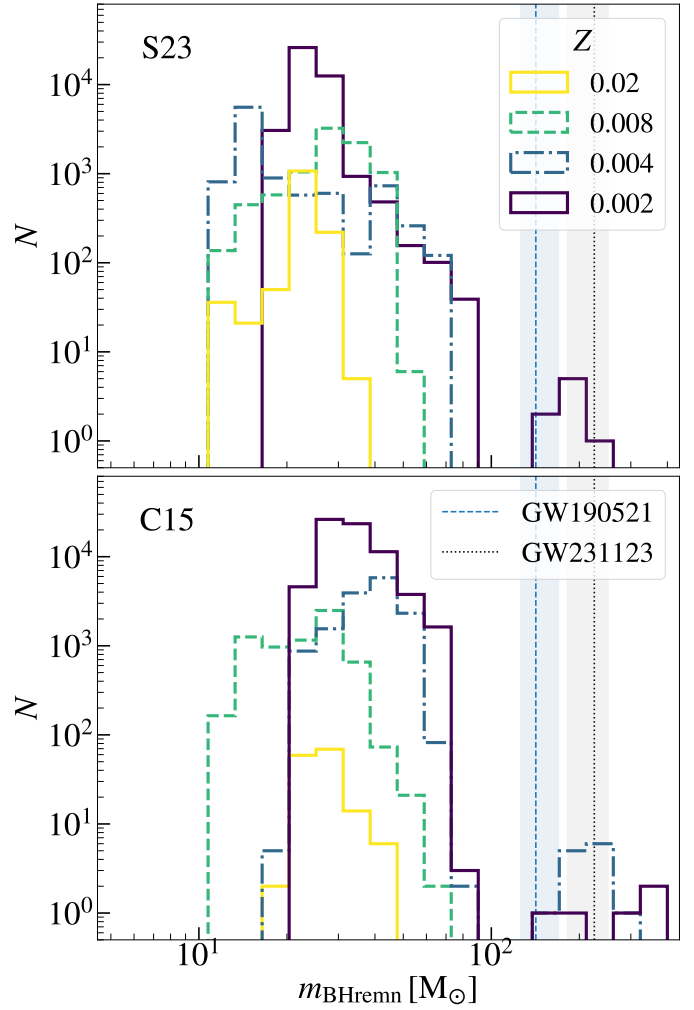


Fig. 7. Same as Fig. 6, but for the resulting BH remnant mass.

4.2. Caveats of VMS population models

In our population-synthesis models, we drew primary stellar masses from a Kroupa IMF between 50 and 500 M_{\odot} , corresponding to the extreme high-mass end of the mass function. In most star-forming regions, the presence of stars in this mass range is dominated by stochastic effects or possibly by additional quenching effects (e.g., Weidner & Kroupa 2006). Thus, the conclusions of our population-synthesis simulations only apply to extreme star-forming regions, such as the R136 cluster in the LMC (Crowther et al. 2010; Bestenlehner et al. 2020), the super-star clusters in starburst galaxies (e.g., the Antennae galaxies, Whitmore & Schweizer 1995), and the high-redshift massive clusters recently discovered by the James Webb Space Telescope (Vanzella et al. 2023; Adamo et al. 2024; Mowla et al. 2024). Moreover, it is also possible that VMSs are the result of multiple stellar collisions in very dense star clusters (Portegies Zwart & McMillan 2002). In such case, population studies require dedicated N -body simulations (e.g., Di Carlo et al. 2021; Rantala et al. 2024).

5. Conclusions

We investigated the impact of a new optically thick wind model (S23) on the formation of IMBHs in nonrotating isolated single and binary very massive stars (VMSs). The new model

is supported by several observational constraints, such as the pair-instability supernova rate (Simonato et al. 2025) and the existence of single Wolf–Rayet stars at low metallicity (Boco et al. 2025). We integrated the evolution of VMSs with MESA (Paxton et al. 2019) and folded our new MESA tracks inside our binary population-synthesis code SEVN (Iorio et al. 2023).

We find that IMBH production is suppressed at intermediate metallicity ($Z \in [10^{-3}, 0.01]$), compared to less effective wind models. According to our models, IMBHs cannot form from VMS collapse at the metallicity of the LMC ($Z \sim 0.008$) and possibly even the Small Magellanic Cloud ($Z \sim 0.0025$).

Intermediate mass black holes might be able to form via stellar collisions at a metallicity as high as $Z = 0.004$, but only under the very optimistic assumption that each collision triggers no mass loss. However, even with this assumption for stellar collisions, the occurrence fraction of IMBHs over the total number of BHs ($\lesssim 0.2\%$) is two orders of magnitude lower compared to models with less effective wind mass loss.

Binary BH mergers can produce IMBH remnants at metallicity $Z \leq 0.002$. At higher metallicities, the enhanced mass loss produces BBH mergers with primary mass $m_1 < 50 M_\odot$, making it impossible to form IMBHs from first-generation BH mergers.

The BH mass spectrum from single VMSs shows a pair-instability mass gap from $65 M_\odot$ to $135 M_\odot$. Such a mass gap is still present in the mass distribution of BHs in BBHs and BBH mergers.

According to our S23 models, the progenitors of the most massive BBH observed by the LIGO–Virgo–KAGRA collaboration, GW231123 (The LIGO Scientific Collaboration et al. 2025c), must have had a metallicity $Z \leq 0.002$. In a follow-up study, we will explore the impact of star cluster dynamics on this result.

Acknowledgements. We thank the anonymous referee for their insightful comments and suggestions. We thank Gautham Sabhahit and collaborators for sharing their MESA inlists (https://github.com/Apophis-1/VMS_Paper1, https://github.com/Apophis-1/VMS_Paper2). We thank Guglielmo Costa and Kendall Shepherd for useful comments and discussions. ST acknowledges financial support from the Alexander von Humboldt Foundation for the Humboldt Research Fellowship. ST, MM and GI acknowledge financial support from the European Research Council for the ERC Consolidator grant DEMOBLACK, under contract no. 770017. ST, MM and LB also acknowledge financial support from the German Excellence Strategy via the Heidelberg Cluster of Excellence (EXC 2181 – 390900948) STRUCTURES. GI acknowledges financial support from the La Caixa Foundation for the La Caixa Junior Leader fellowship 2024. GI also acknowledges financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.4, – Call for tender No. 3138 of 18/12/2021 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU. EK and MM acknowledge support from the PRIN grant METE under contract No. 2020KB33TP. EK acknowledges financial support from the Fondazioni Gini for the Gini grant. The authors acknowledge support by the state of Baden-Württemberg through bwHPC and the German Research Foundation (DFG) through grants INST 35/1597-1 FUGG and INST 35/1503-1 FUGG. We use the MESA software (<https://docs.mesastar.org/en/latest/>) version r12115; (Paxton et al. 2011, 2013, 2015, 2018, 2019). We use SEVN (<https://gitlab.com/sevncodes/sevn>) to generate our BBHs catalogs (Spera et al. 2019; Mapelli et al. 2020; Iorio et al. 2023), TRACKCRUNCHER (<https://gitlab.com/sevncodes/trackcruncher>) (Iorio et al. 2023) to produce the tables for the interpolation. The PARSEC stellar tracks that we used for this work are publicly available at <http://stev.oapd.inaf.it/PARSEC/> (Costa et al. 2025). This research made use of NUMPY (Harris et al. 2020), PANDAS (The pandas development Team 2024), SCIPY (Virtanen et al. 2020) and MATPLOTLIB (Hunter 2007).

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