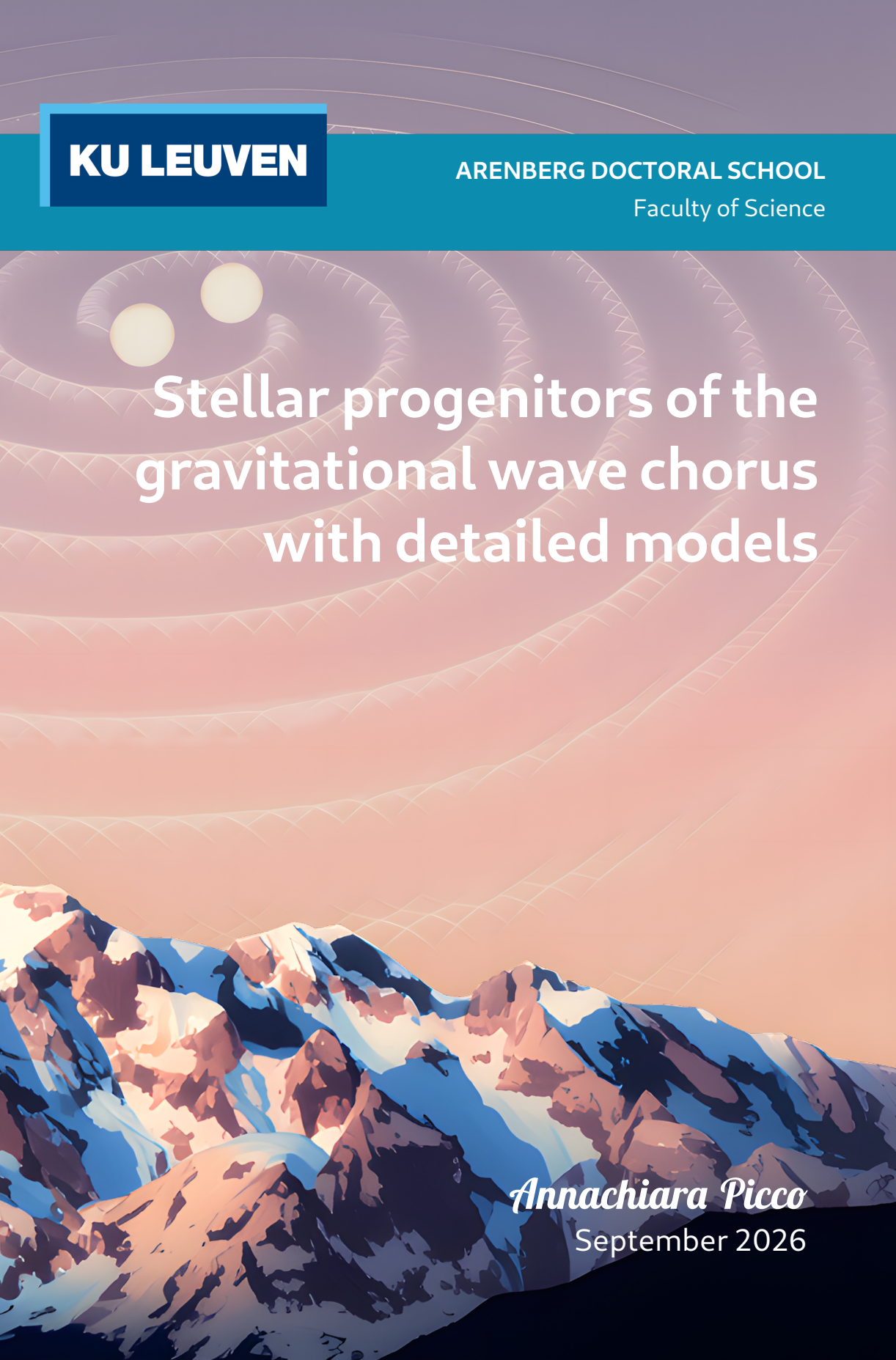


The background of the cover features a stylized illustration. The upper portion is a gradient of purple and blue, overlaid with concentric, wavy lines representing gravitational waves. Two bright yellow circles are positioned in the upper left. The lower portion of the cover shows a range of jagged, snow-capped mountains in shades of blue, white, and brown.

KU LEUVEN

ARENBERG DOCTORAL SCHOOL

Faculty of Science

Stellar progenitors of the gravitational wave chorus with detailed models

Annachiara Picco

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STELLAR PROGENITORS OF THE GRAVITATIONAL WAVE CHORUS WITH DETAILED MODELS

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Cover design by Annachiara Picco & Joey S. G. Mombarg: A cartoonized version of a real photograph of the [Carega Group](#), part of the Little Dolomites in the Venetian Prealps. The massif lies at the boundary of the provinces of Vicenza, Verona and Trento, and reaches its highest point at Cima Carega (2259 m). The mountain profile is shown as it appears from Recoaro Terme, at the head of the valley of Valdagno, where the author grew up and enjoyed this view every day. Stylized gravitational-wave ripples are superimposed on the mountain landscape. Artwork created using GIMP and Adobe Firefly.

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*Ai miei (pro)genitori stellari,
Bruna & Roberto*

*e alla mia compagna di orbita,
Valentina.*

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In September 2021, I took the first flight of my life to move to Belgium, a country I knew very little about, unsure whether my English was good enough to get by and with no idea of what life outside a mountain valley would look like. At the time of writing, I have now spent almost five years in beautiful Flanders, where life turned out to look like Gothic cathedrals and medieval castles, and colourful pastel houses woven among red-brick façades. And when the air smells like the best waffles, I feel that parts of me belong there, where so many people have crossed my path and participated in my PhD journey. It is a weighty task to acknowledge all of you, so, while reading this attempt to do so, please know that you have all done so much more than I could ever put into words.

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A warm thank you must then go to my research group, as I consider this thesis a many-body product of this chorus of massive binaries enthusiasts. The pizza nights, the bordspelavonden, the team buildings (at the castle), and the wonderful cakes at the weekly group meetings have been true highlights. While everyone is obviously doing incredible science, I have learned so much from each of you beyond science itself. Thank you for the uplifting atmosphere that made even the most difficult milestones feel surmountable, especially during this last year.

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Mighty thanks to everyone,
Annachiara
September 2026

In memory of Paola Marigo, my Master's thesis supervisor, who passed away on 20 October 2024. The first to inspire my path in stellar astrophysics, she told me that I would achieve great and bright things. This thesis, the first of those great and bright things, is dedicated to her.

Abstract

Massive stars, born with masses exceeding approximately eight times that of the Sun, are short-lived yet fundamental drivers of galactic evolution. Through their radiation, stellar winds, and eventual supernova explosions, they regulate star formation, enrich galaxies with heavy chemical elements, and leave behind compact remnants in the form of neutron stars and black holes. The majority of massive stars are born in close binary or higher-order multiple systems, and most of them will exchange mass with a companion during their lifetime. Mass transfer is the most defining interaction in binary evolution, as it alters the masses, rotation, chemical composition, and the further evolution of both stars in the binary. Its products shape a rich diversity of products that are required to explain numerous stellar populations and astrophysical phenomena, including hot subdwarfs, Wolf-Rayet stars, blue stragglers, supernovae, kilonovae, and gravitational waves.

The past decade has witnessed the emergence of two new and rapidly growing populations of products of binary interaction: stripped stars, that is, stars that lost their hydrogen-rich envelopes, and coalescing compact objects detected through gravitational waves. While stripped stars are being uncovered by dedicated ultraviolet surveys, gravitational-wave observatories are revealing an ever-growing population of merging binary black holes, enabling statistical studies of their properties for the very first time. These two populations together offer complementary observational anchors along the evolutionary sequence of interacting binaries, that start their lives as massive stellar pairs and may evolve into stripped stars after exchanging mass; subsequently, they may end their lives as compact binaries, that eventually merge through the emission of gravitational waves. This makes now a particularly timely moment to investigate *the stellar progenitors of the gravitational-wave chorus* with the best theoretical tools at hand, i.e. binary evolution models.

Central to this thesis is the question of how mass transfer shapes the evolution of the stellar progenitors of the stripped star and gravitational wave population.

To answer this question, we zoom in on three specific aspects of mass transfer that are currently poorly understood: (i) the orbital evolution during mass transfer, (ii) the formation of stripped stars through stellar mergers, and (iii) the conditions for mass transfer to (not) evolve in a common envelope enshrouding the system, i.e. the “mass transfer stability”.

During mass transfer, the binary orbit changes as mass and angular momentum are redistributed within the system or lost from it, causing the orbit to either shrink or widen. Understanding this process is essential to explain how compact objects can be brought into sufficiently tight orbits to merge within the age of the Universe due to gravitational-wave emission. In this thesis, we study the orbital evolution of interacting binaries and show that mass transfer can seal binaries with any compact object in orbits tight enough to be detected as gravitational-wave sources, and that this result is robust to different assumptions on how mass and angular momentum are lost. At the same time, binaries observed immediately after mass transfer, such as those composed of a stripped star and a rapidly rotating companion, provide unique empirical calibrators of binary interaction physics. By modelling the Galactic system HR6819, we show that mass transfer between two stellar components cannot produce arbitrarily extreme mass ratios at a given orbital period, such that systems with extreme properties like HR6819 remain challenging to explain.

Mass accretion also accelerates the evolution of the accreting star, allowing it sometimes to overtake the evolution of its companion and initiate a second mass-transfer episode. If this interaction evolves into a common-envelope phase, the two helium-rich cores may merge into a partially stripped product, i.e. a failed-common-envelope merger. Understanding this type of evolution is particularly timely because the number of stripped stars identified through ultraviolet photometry and spectroscopy is rapidly increasing, requiring robust formation models and observable predictions in preparation for future ultraviolet missions such as NASA’s UVEX. Motivated by the Galactic quasi-Wolf-Rayet star HD45166, the first system proposed to form through this channel, we investigate whether failed-common-envelope mergers contribute to the stripped-star population. We show that stripped stars may indeed form through this evolutionary pathway, producing objects across a wide range of masses that may appear as blue stragglers or as members of wide binaries, highlighting the importance of including them in future population studies.

Whether an interacting binary evolves through stable mass transfer or common-envelope evolution may leave distinct fingerprints in the observed population of gravitational-wave sources, making the understanding of mass-transfer stability essential to interpreting the gravitational-wave chorus. Since the treatment of mass-transfer stability remains the largest uncertainty in population studies of merging binary black holes, we investigate the physical origin of this process with

binary evolution models. We show that mass-transfer stability is determined by a complex interplay of stellar internal properties, with the mass of the stellar core and the metallicity playing a particularly important role: larger cores and higher metallicities independently favor mass transfer stability. These results have direct implications for the predicted population of coalescing binary black holes, indicating that current rapid population synthesis frameworks may be missing the origin of a significant fraction of gravitational-wave sources formed through isolated binary evolution.

With this thesis we aim at gaining a better understanding of the physics of mass transfer at multiple evolutionary stages, from stripped stars to coalescing compact objects. We demonstrate the diagnostic power of detailed binary evolution calculations for understanding uncertain binary interaction physics, identifying evolutionary channels, and improving the physical foundations of population synthesis models. These developments are particularly timely in view of the rapidly growing samples of stripped stars expected from upcoming ultraviolet surveys, such as NASA's UVEX, and the anticipated increase in gravitational-wave detections from current and next-generation observatories. Our results will help shape future observational strategies for stripped stars and enable astrophysical inference from gravitational-wave populations that is firmly grounded in detailed models of stellar evolution and mass-transfer physics.

Beknopte samenvatting

Massieve sterren, geboren met massa's groter dan acht keer die van de Zon, zijn kortlevend maar vormen fundamentele drijvende krachten achter de evolutie van sterrenstelsels. Door hun straling, sterrenwinden en uiteindelijke supernova-explosies reguleren zij stervorming, verrijken zij sterrenstelsels met zware chemische elementen en laten zij compacte restanten achter in de vorm van neutronensterren en zwarte gaten. De meerderheid van de massieve sterren wordt geboren in nauwe dubbelsterren of meervoudige systemen, en de meeste zullen tijdens hun leven massa uitwisselen met een begeleider. Massaoverdracht is de meest bepalende interactie in de evolutie van dubbelsterren, omdat zij de massa, rotatie, chemische samenstelling en verdere evolutie van beide sterren ingrijpend verandert. De producten van massaoverdracht vormen een grote verscheidenheid aan objecten die noodzakelijk zijn om talrijke sterrenpopulaties en astrofysische verschijnselen te verklaren, waaronder hete subdwergen, Wolf-Rayet-sterren, blue stragglers, supernovae, kilonovae en zwaartekrachtgolven.

Het afgelopen decennium heeft de opkomst gekend van twee nieuwe en snel groeiende populaties van producten van binaire interactie: gestripte sterren, die hun waterstofrijke omhulsel hebben verloren door interactie met een begeleider, en samensmeltende compacte objecten die worden waargenomen via zwaartekrachtgolven. Terwijl gestripte sterren worden ontdekt dankzij gerichte ultraviolette surveys, onthullen zwaartekrachtgolfobservatoria een steeds groter wordende populatie van samensmeltende binaire zwarte gaten, binaire neutronensterren en neutronenster-zwart gat-systemen, waardoor voor het eerst statistische studies van hun eigenschappen mogelijk worden. Deze twee populaties zijn met elkaar verbonden door één gemeenschappelijk fysisch proces: massaoverdracht. Samen vormen zij complementaire observationele ankerpunten langs de evolutionaire keten van interagerende dubbelsterren, van massieve sterrenparen die gestripte sterren vormen tot compacte dubbelsterren die uiteindelijk samensmelten onder uitzending van zwaartekrachtgolven. Dit maakt het een bijzonder geschikt moment om *the stellar progenitors of the gravitational wave chorus* te onderzoeken met de beste theoretische instrumenten

die momenteel beschikbaar zijn, namelijk modellen van binaire stellaire evolutie.

Centraal in dit proefschrift staat de vraag hoe massaoverdracht de evolutie van de voorlopers van gestripte sterren en zwaartekrachtgolfbronnen vormgeeft. Om deze vraag te beantwoorden richten wij ons op drie aspecten van massaoverdracht die momenteel nog onvoldoende begrepen zijn: (i) de evolutie van de baan tijdens massaoverdracht, (ii) de vorming van gestripte sterren via stellaire fusies, en (iii) de voorwaarden waaronder massaoverdracht al dan niet evolueert tot een gemeenschappelijke envelop die het systeem omhult, oftewel de “stabiliteit van massaoverdracht”.

Tijdens massaoverdracht verandert de baan van een dubbelster doordat massa en impulsmoment binnen het systeem worden herverdeeld of uit het systeem verloren gaan, waardoor de baan kan krimpen of juist wijder kan worden. Inzicht in dit proces is essentieel om te begrijpen hoe compacte objecten in voldoende nauwe banen terechtkomen om binnen de leeftijd van het heelal samen te smelten als gevolg van de emissie van zwaartekrachtgolven. In dit proefschrift bestuderen wij de baanevolutie van interagerende dubbelsterren en tonen wij aan dat massaoverdracht dubbelsterren met elk type compact object kan achterlaten in banen die voldoende compact zijn om waarneembare bronnen van zwaartekrachtgolven te vormen, en dat dit resultaat robuust is ten opzichte van verschillende aannames over het verlies van massa en impulsmoment. Tegelijkertijd vormen dubbelsterren die onmiddellijk na een massaoverdrachtsepisode worden waargenomen, zoals systemen bestaande uit een gestripte ster en een snel roterende begeleider, unieke empirische ijkpunten voor de fysica van binaire interacties. Door het Galactische systeem HR6819 te modelleren tonen wij aan dat massaoverdracht tussen twee sterren geen willekeurig extreme massaverhoudingen bij een gegeven omlooperperiode kan produceren, waardoor systemen met extreme eigenschappen zoals HR6819 moeilijk te verklaren blijven.

Massa-accretie versnelt bovendien de evolutie van de accreterende ster, waardoor deze haar begeleider kan inhalen en zelf een tweede episode van massaoverdracht kan initiëren. Indien deze interactie evolueert tot een gemeenschappelijke envelop, kunnen de twee heliumrijke kernen samensmelten tot een gedeeltelijk gestript product, een zogenoemde *failed-common-envelope merger*. Inzicht in dit evolutiekanaal is bijzonder actueel omdat het aantal gestripte sterren dat wordt geïdentificeerd via ultraviolette fotometrie en spectroscopie snel toeneemt, waardoor betrouwbare vormingsmodellen en voorspellingen van hun waarneembare eigenschappen nodig zijn ter voorbereiding op toekomstige ultraviolette missies zoals NASA’s UVEX. Gemotiveerd door de Galactische quasi-Wolf-Rayet-ster HD45166, het eerste object waarvan werd voorgesteld dat het via dit kanaal is ontstaan, onderzoeken wij of failed-common-envelope mergers bijdragen aan de populatie van gestripte sterren. Wij tonen aan

dat gestripte sterren inderdaad via dit evolutiepad kunnen ontstaan, waarbij objecten worden gevormd over een breed massabereik die kunnen verschijnen als blue stragglers of als leden van wijde dubbelsterren. Dit onderstreept het belang van het opnemen van dit kanaal in toekomstige populatiestudies.

Of een interagerende dubbelster evolueert via stabiele massaoverdracht of via een gemeenschappelijke envelop kan verschillende kenmerken achterlaten in de waargenomen populatie van zwaartekrachtgolfbronnen, waardoor inzicht in de stabiliteit van massaoverdracht essentieel is voor de interpretatie van het koor van zwaartekrachtgolven. Aangezien de behandeling van de stabiliteit van massaoverdracht nog steeds de grootste onzekerheid vormt in populatiestudies van samensmeltende binaire zwarte gaten, onderzoeken wij de fysische oorsprong van dit proces met behulp van gedetailleerde modellen van binaire evolutie. Wij tonen aan dat de stabiliteit van massaoverdracht wordt bepaald door een complexe wisselwerking tussen de interne eigenschappen van sterren, waarbij vooral de grootte van de sterrenkern en de metalliciteit een belangrijke rol spelen: grotere kernen en hogere metalliciteiten bevorderen onafhankelijk van elkaar stabiele massaoverdracht. Deze resultaten hebben directe gevolgen voor de voorspelde populatie van samensmeltende binaire zwarte gaten en wijzen erop dat huidige snelle populatiesynthesemodellen mogelijk de oorsprong missen van een aanzienlijk deel van de zwaartekrachtgolfbronnen die ontstaan via geïsoleerde binaire evolutie.

Met dit proefschrift streven wij naar een beter begrip van de fysica van massaoverdracht in verschillende evolutionaire stadia, van gestripte sterren tot samensmeltende compacte objecten. Wij tonen de diagnostische kracht aan van gedetailleerde modellen van binaire stellaire evolutie voor het begrijpen van onzekere fysica van binaire interacties, het identificeren van evolutionaire kanalen en het verbeteren van de fysische grondslagen van populatiesynthesemodellen. Deze ontwikkelingen zijn bijzonder actueel gezien de snel groeiende steekproeven van gestripte sterren die worden verwacht van toekomstige ultraviolette surveys, zoals NASA's UVEX, en de verwachte toename van zwaartekrachtgolfdetecties met huidige en volgende generatie observatoria. Onze resultaten zullen bijdragen aan de ontwikkeling van toekomstige observatiestrategieën voor gestripte sterren en aan astrofysische interpretaties van zwaartekrachtgolfpopulaties die stevig verankerd zijn in gedetailleerde modellen van stellaire evolutie en de fysica van massaoverdracht.

Sintesi divulgativa

Le stelle massicce, con una massa superiore a circa otto volte quella del nostro Sole, vivono relativamente poco, ma svolgono un ruolo fondamentale nell'evoluzione delle galassie. Attraverso la loro intensa radiazione, i venti stellari e le esplosioni finali come supernovae, regolano la formazione di nuove stelle, arricchiscono l'Universo degli elementi chimici più pesanti e, alla fine della loro vita, lasciano come eredità stelle di neutroni e buchi neri. La maggior parte delle stelle massicce nasce in sistemi binari, cioè in coppia con un'altra stella, e durante la propria vita le due compagne possono interagire trasferendo massa. Il *trasferimento di massa* è l'interazione più importante nell'evoluzione delle stelle binarie, perché ne modifica l'orbita, la rotazione, la composizione chimica e il destino evolutivo.

Negli ultimi anni sono emerse due nuove popolazioni di oggetti che testimoniano l'importanza del trasferimento di massa nei sistemi binari. Da un lato, le osservazioni nell'ultravioletto stanno rivelando un numero sempre maggiore di stelle ricche di elio superficiale, perché hanno donato tutto l'idrogeno, più leggero, ad una compagna. Dall'altro, gli osservatori di onde gravitazionali (tra cui quello italiano, [Virgo](#), attorno a Pisa!) hanno misurato nel 2015, per la prima volta, un segnale proveniente dalla fusione di due buchi neri, dando la prima conferma diretta della teoria della relatività generale di Einstein. Ad oggi, il numero di segnali di onde gravitazionali è arrivato già a centinaia, e cresce giorno per giorno, con segnali delle stesse frequenze del cinguettio degli uccelli del mattino. Sebbene differenti, le stelle di elio e i buchi neri raccontano la stessa storia: quella dell'evoluzione di sistemi binari massicci che interagiscono nel corso della loro vita. Comprendere il trasferimento di massa significa quindi ricostruire il percorso che porta da due giovani stelle massicce fino agli oggetti compatti che, milioni di anni dopo, producono il “coro” di onde gravitazionali oggi osservato (da cui, il titolo di questa tesi).

Questa tesi risponde ad una domanda fondamentale: in che modo il trasferimento di massa determina l'evoluzione delle stelle binarie progenitrici delle sorgenti di

onde gravitazionali?

Durante il trasferimento di massa, l'orbita delle due stelle cambia, perché massa e momento angolare vengono ridistribuiti o espulsi dal sistema. In questa tesi dimostro che il trasferimento di massa può portare sistemi di buchi neri o stelle di neutroni su orbite sufficientemente ravvicinate da fondersi da qualche parte nell'Universo osservabile. Diversi meccanismi di trasferimento di massa modificano la loro evoluzione, ma c'è sempre un modo per le stelle binarie di avvicinarsi abbastanza da produrre onde gravitazionali durante la loro fusione.

Anche alcune stelle di elio rivelano orbite molto ravvicinate, suggerendoci che il meccanismo di trasferimento di massa deve essere avvenuto anche nel loro caso. Il sistema stellare HR6819 (o, [QV Tel](#)) è uno dei migliori esempi osservati nella via Lattea: è costituito da una stella di elio più leggera del nostro Sole, e da una compagna sedici volte più massiccia, completando un'orbita in soli 40 giorni¹. I miei modelli indicano, però, che quest'orbita è fin troppo stretta perché il trasferimento di massa possa effettivamente produrlo. La cosa più interessante è che i dati sulle masse e l'orbita di HR6819 non possono essere sbagliati: sono infatti i più precisi mai ottenuti per un sistema binario di stelle massicce! Di conseguenza, abbiamo concluso che sono, invece, i modelli teorici delle stelle di elio ad essere incompleti, e mentre gli astrofisici teorici e la sottoscritta pensano a come risolvere il rompicapo, abbiamo intanto chiamato HR6819 "il sistema impossibile"...

Fortunatamente, ci sono molti tipi di trasferimento di massa, e in questa tesi ne abbiamo pensato uno nuovo per formare le stelle di elio. Quando una stella accresce materia dalla compagna, la sua evoluzione accelera e può diventare la prima delle due a espandersi nuovamente, dando origine a un secondo episodio di trasferimento di massa. Se questo trasferimento diventa instabile e violento, i nuclei delle due stelle, che sono ricchi di elio, possono fondersi e, durante la fusione, espellere l'involucro ricco di idrogeno. Ed ecco formata una nuova, più pesante e luminosa del normale, stella di elio. Abbiamo mostrato che questo meccanismo, finora inesplorato, può produrre stelle di elio di diverse masse e contribuire a spiegare delle popolazioni osservate, tra cui alcune stelle che appaiono misteriosamente [più' blu delle loro compagne](#) in un ammasso stellare. E, ancora più interessante, questi prodotti potrebbero essere molto magnetici e creare, alla fine della loro vita, [i magneti più' estremi dell'Universo](#), cioè stelle di neutroni con campi magnetici milioni di miliardi di volte più forti (sì, cifra giusta!) di quello terrestre.

Trasferire massa in grande quantità e troppo velocemente può destabilizzare

¹Come distanza, corrisponde a 58 milioni di chilometri, pari a circa il 40% della distanza tra la Terra e il Sole, cioè poco più dell'orbita di Mercurio. In astrofisica, questa distanza è molto piccola.

l'orbita stellare, e creare un involucro di gas che circonda tutto il sistema. Questo evento può essere spettacolare e produrre, per esempio, [nove rosse luminose](#), o [rapidi lampi ottici](#), o [dischi di gas](#). Tuttavia, molte volte questo significa che il sistema binario semplicemente si fonderà in una sola stella, senza finire la propria vita come una binaria di buchi neri che emette onde gravitazionali. Di conseguenza, è importante capire in quali condizioni il trasferimento di massa tra due stelle resta stabile. I nostri risultati mostrano che la stabilità del trasferimento di massa è determinato da una complessa combinazione di proprietà interne alle stelle, in particolare dalla dimensione del nucleo e dal contenuto di elementi pesanti (la cosiddetta metallicità): nuclei più grandi e una maggiore metallicità favoriscono un trasferimento di massa stabile. Questi risultati suggeriscono una prospettiva emozionante per le popolazioni di buchi neri che osserviamo con i telescopi di onde gravitazionali: forse, la chiave per capire come si sono formati sta nella struttura interna dei loro progenitori stellari.

Al tempo in cui sto scrivendo questa tesi, l'umanità si sta preparando a un'era rivoluzionaria per l'astrofisica. Se ora i segnali di onda gravitazionale sono solo centinaia, il telescopio sotterraneo Einstein Telescope (che forse verrà costruito in [Sardegna](#)) ne misurerà decine di migliaia ogni anno. E le nuove missioni spaziali LISA (Laser Interferometer Antenna, missione dell'Agenzia Spaziale Europea), Cosmic Explorer (Stati Uniti) e TianQin (Cina), saranno in grado di ascoltare un coro di onde proveniente dall'Universo più profondo, l'epoca del Big Bang, e della prima generazione di stelle.

Allo stesso tempo, fino a qualche anno fa non sapevamo che alcune stelle di elio sfuggivano ai nostri telescopi perché sono luminose nella lunghezza d'onda dell'ultravioletto, invece che nell'ottico. Dal 2023, abbiamo accumulato una decina di osservazioni di queste stelle, e ora stiamo costruendo telescopi sensibili all'ultravioletto, che voleranno con le missioni spaziali di UVEX (NASA) e CASTOR (Canadese). Studi teorici predicono che altre migliaia di stelle di elio risiedono nella via Lattea, e altrettante in galassie satellite, e sono ancora da scoprire.

Tutto questo significa che, nella prossima decade, si aprirà uno scrigno del tesoro di informazioni sul nostro Universo e sulla evoluzione stellare, e gli astrofisici teorici hanno ancora molto lavoro da fare per sfruttare a pieno i dati osservativi. Questa tesi non rappresenta soltanto un passo avanti nel migliorare i modelli teorici del trasferimento di massa nelle stelle binarie, ma pone anche le basi per affrontare la grande sfida dei prossimi anni: interpretare le enormi quantità di dati che arriveranno dai nuovi osservatori e trasformarle in una comprensione più solida di come nascono, evolvono e interagiscono le popolazioni stellari.

Buona lettura!

List of Acronyms

1D One-Dimensional.

3D Three-Dimensional.

AGB Asymptotic Giant Branch.

BH Black Hole.

CE Common Envelope.

CO Compact Object.

DDI Delayed Dynamical Instability.

ELT Extremely Large Telescope.

ERC European Research Council.

FWO Fonds Wetenschappelijk Onderzoek.

GW Gravitational Wave.

GWTC Gravitational Wave Transient Catalogue.

HD Humphrey-Davidson.

HG Hertzsprung Gap.

HM(XR)B High Mass (X-ray) Binary.

HR Hertzsprung-Russell (diagram).

LM(XR)B Low Mass (X-ray) Binary.

LMC Large Magellanic Cloud.

LVK LIGO, Virgo, and KAGRA.

MB Magnetic Braking.

MS Main Sequence.

MT Mass Transfer.

NS Neutron Star.

RGB Red Giant Branch.

sdOB Subdwarf of type O-B.

SMC Small Magellanic Cloud.

SNe Supernovae.

TAMS Terminal Age Main Sequence.

UV Ultraviolet.

UVEX Ultraviolet Explorer.

VLTI Very Large Telescope Interferometer.

WD White Dwarf.

WR Wolf-Rayet.

ZAMS Zero Age Main Sequence.

ZTF Zwicky Transient Facility.

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Chapter 1

Introduction

Massive stars, born with masses exceeding approximately eight times that of the Sun ($M_{\odot}$), are short-lived yet powerful drivers of galactic evolution. Through their intense radiation, stellar winds, and eventual supernova (SN) explosions, they inject both radiative and mechanical energy into the interstellar medium on million-year timescales (e.g. [Mac Low et al. 2005](#)). During their evolution, they synthesize and disperse chemical elements (e.g. [Burbidge et al. 1957](#); [Nomoto et al. 2013](#)), thereby contributing to the chemical enrichment of galaxies, regulating star formation (e.g. [Erb 2015](#); [Matteucci 2021](#)), and influencing the early evolution of the Universe (e.g. [Haiman & Loeb 1997](#); [Goswami et al. 2022](#)). Their life cycles ultimately produce compact remnants such as neutron stars (NSs) and stellar-mass black holes (BHs).

The majority of massive stars are found in close binary or higher-order multiple systems ([Mason et al. 2009](#); [Sana et al. 2014](#)), and observational and theoretical studies indicate that about 70% of O-type stars will interact via mass exchange during their lifetimes (e.g. [Sana et al. 2012](#); [de Mink et al. 2013, 2014](#)). Processes such as mass transfer (MT), tidal interaction, and stellar mergers profoundly alter stellar masses, rotation rates, surface chemical abundances, and evolutionary timescales, implying that only a minority of massive stars evolve as effectively isolated objects (see [Langer 2012](#); [Marchant & Bodensteiner 2024](#); [Chen et al. 2024](#) for recent reviews, and Section 1.1.5). As a consequence, many stars that presently appear single are in fact the products of previous binary interactions, such as mergers or mass gainers, complicating the efforts to test evolutionary models and to interpret stellar populations in galaxies (e.g. [de Mink et al. 2013](#); [Dorn-Wallenstein & Levesque 2018](#); [Renzo et al. 2019](#); [Eldridge & Stanway 2022](#)). Binary evolution also has important consequences on

cosmic scales, enhancing the production of ionizing radiation relevant for cosmic reionization (e.g. [Ma et al. 2016](#); [Götberg et al. 2019](#)) and producing stripped stars, rapidly rotating stars (e.g. [Packet 1981](#); [de Mink et al. 2013](#)), runaway systems (e.g. [Blaauw 1961](#); [Renzo et al. 2019](#)), and compact-object (CO) binaries that shape the observed populations of sources of powerful transients, such as SNe (e.g. [Podsiadlowski et al. 1992](#); [Zapartas et al. 2017](#)), gamma-ray bursts (e.g. [Cantiello et al. 2007](#)), and gravitational-waves (GWs) (e.g. [Smarr & Blandford 1976](#); [Mandel & Farmer 2022](#)).

Of special interest for this thesis are two recently detected, rapidly growing populations of binary interaction products: stars with hydrogen-poor envelopes (stripped stars) and double CO binaries coalescing through the emission of GWs. Stripped stars are helium-rich, hydrogen-poor stars whose envelopes have been removed either through binary interaction ([Paczyński 1967](#)) or via self-stripping through strong stellar wind (the “Conti scenario”, [Conti 1975](#)), or both effects combined. In this thesis we will mainly deal with stars stripped in binaries, where the stripping phenomenon may occur at all mass ranges and produce objects with diverse spectral appearances: Wolf-Rayet (WR) stars (e.g. [Crowther 2007](#); [Shenar et al. 2020a](#)), hot subdwarfs of type OB (sdOB; [Heber 2026](#)) and intermediate-mass stripped stars ([Götberg et al. 2018, 2023](#)). While WR stars and sdOBs are visible with optical telescopes and were known for several decades, intermediate-mass stripped stars are bright in the ultraviolet (UV), and it is only since the past few years that dedicated observational campaigns and follow-ups efforts are starting to reveal a **first sizeable sample of this hidden stripped-star population** ([Drout et al. 2023](#); [Götberg et al. 2023](#)) (see Section 1.2).

At the same time, ground-based GW observatories are uncovering a population of merging double COs, the vast majority of which are inferred to be binary BHs, followed by a few binary NSs and NS + BH systems. Since the first detection in 2015 ([Abbott et al. 2016](#)), the catalogue has been growing steadily and is **allowing, for the first time, statistical studies of COs populations and their properties** across cosmic distances (e.g. [Abbott et al. 2019a, 2021b, 2023b](#); [The LIGO Scientific Collaboration et al. 2025b](#)). This thesis will especially zoom in on massive stellar binaries, the stellar progenitors of these COs mergers, that experienced multiple binary interaction phases which shape the diversity of the GWs signals (see Section 1.3).

Crucially, binary interaction through MT is common to both stars stripped in binaries and coalescing COs that produce GW signals. Combined, they offer a unique window to investigate the physics of binary interaction from multiple evolutionary anchors. At the same time, both populations are entering a new observational era in which the number of detected systems is rapidly increasing and approaching population-level statistical significance. This means that now is

the right moment to investigate the *stellar progenitors of the gravitational wave chorus*, following their evolution from interacting massive binaries to chirping double COs.

The rest of this chapter introduces massive binary evolution, MT theory and products in Section 1.1. We briefly review the state of the art regarding the two populations of interest for the thesis: stripped stars in Section 1.2, and GWs in Section 1.3. Finally, Section 1.4 provides an outline of the thesis and a summary of the main science questions underlying the following chapters.

1.1 Massive binary evolution

This Section is mainly based on Onno Pols' lecture notes on binary evolution¹, the textbook "Physics of Binary Stars" by T. Tauris and E. P. J. van den Heuvel, and the review "The Evolution of Massive Binary Stars" by P. Marchant and J. Bodensteiner (2024).

Binary interaction through Roche-lobe overflow (RLOF) is one of the main processes driving the evolution of close binary systems. The classical description of RLOF is based on the Roche model, which assumes that the stars can be treated as point-mass gravitational potentials, that the orbit is circular², and that both stars rotate synchronously with the orbital motion. Under these assumptions, the effective potential is stationary in the co-rotating reference frame, giving rise to the classical Roche potential and its associated equipotential surfaces (Figure 1.1). As stars evolve and expand, one of the components may fill its Roche lobe, i.e. the critical equipotential surface surrounding the star in the Roche potential. Once this limit is reached, hydrostatic equilibrium can no longer be maintained near the inner Lagrangian point L_1 , and matter starts flowing from the donor star towards its companion through the L_1 nozzle.

The characteristic size of the Roche lobe is commonly described through the Roche-lobe radius $R_{\text{RL},1}$, defined as the radius of a sphere with the same volume, $V_{\text{RL},1} = 4\pi R_{\text{RL},1}^3/3$, as the Roche lobe. Let us define the binary mass ratio as

$$q = \frac{M_1}{M_2}, \quad (1.1)$$

with M_1 and M_2 being the masses of the primary (initially more massive) and secondary (initially less massive) star, respectively. For such a binary, the

¹To be found at www.astro.ru.nl/~onnop/education/binaries_utrecht_notes/

²In eccentric binaries, the Roche geometry becomes time dependent and must be treated using instantaneous or generalized Roche potentials (e.g., Rocha et al. 2025; Parkosidis et al. 2026a,b).

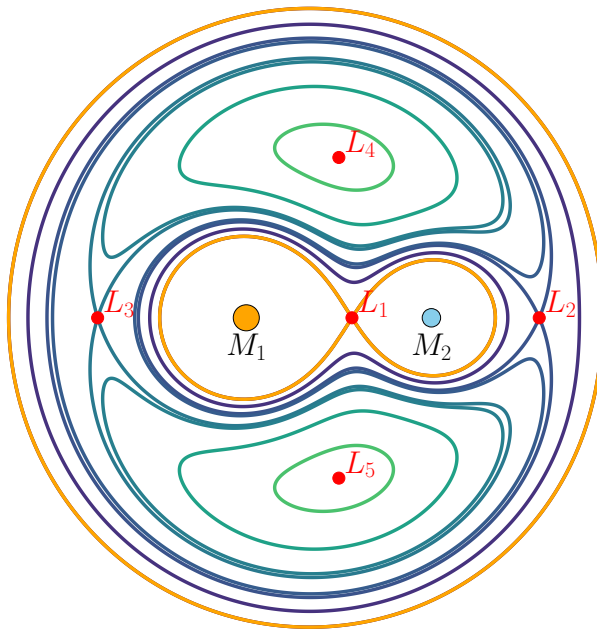


Figure 1.1: Roche equipotential iso-contours for a binary with mass ratio $q = M_1/M_2$ of primary M_1 over secondary M_2 equal to $q = 2$. The five Lagrangian points (L_1, L_2, L_3, L_4, L_5) are reported in red. The equipotential contour that passes through L_1 is highlighted in orange. Qualitatively, close to the center of each star, the equipotential surfaces are almost spherical. When one moves further away from the stellar center, the tidal effect of the companion and the centrifugal forces act such that the surfaces are distorted along the line connecting the centers. At sufficiently large distances, the gravitational contribution approaches that of a single point mass, while the centrifugal contribution dominates the effective potential in the co-rotating frame.

Roche-lobe radius of the primary can be approximated using the following analytical fit (Eggleton 1983):

$$\frac{R_{\text{RL},1}}{a} = \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})}, \quad (1.2)$$

where a is the orbital separation.

Hydrostatic equilibrium in the corotating frame requires that surfaces of constant pressure coincide with the equipotential surfaces. This allows three possible

configurations in which both stars are in hydrostatic equilibrium (Figure 1.2), all of which are observed to occur in nature. Detached binaries contain two stars well inside their Roche lobes. Semi-detached systems occur when one star fills its Roche lobe and transfers mass to its companion through RLOF. Finally, contact binaries are systems in which both stars fill a common equipotential surface. In practice, a contact configuration cannot generally satisfy both hydrostatic and thermal equilibrium simultaneously. According to the von Zeipel theorem (von Zeipel 1924), the radiative flux emerging from the stellar surface depends on the local effective gravity, implying non-uniform surface temperatures along a common equipotential. Consequently, maintaining thermal equilibrium requires large-scale energy transport between the two stars (Eddington 1925; Sweet 1950), making contact binaries intrinsically more complex than predicted by the simple Roche model (Fabry et al. 2022, 2023).

Binary systems are generally born in detached configurations, but stellar expansion during nuclear or thermal-timescale evolution and orbital evolution driven by tides or angular momentum losses can modify the ratio R/R_{RL} , eventually triggering MT.

Besides the inner Lagrangian point L_1 , through which Roche-lobe overflow occurs, the Roche potential also contains four additional equilibrium points (shown in Figure 1.1). The points L_2 and L_3 lie along the line connecting the two stars, beyond the secondary and primary star respectively, and correspond to unstable equilibrium points. A test particle placed exactly at either of these locations would remain stationary in the corotating frame, but any small perturbation would cause it to move away from equilibrium. Matter flowing through L_2 or L_3 can therefore escape the immediate vicinity of the binary and may lead to mass and angular momentum loss from the system (see e.g. Tauris & van den Heuvel 2023 for a review). The points L_4 and L_5 are located at the vertices of two equilateral triangles formed with the two stars. Unlike L_1 , L_2 , and L_3 , these points can be stable equilibrium points if the binary mass ratio is sufficiently small, i.e. if $M_1 \gg M_2$. In this case, a test particle slightly perturbed from L_4 or L_5 does not escape immediately, but instead performs oscillatory motions, governed by the Coriolis force (e.g. Binney & Tremaine 1987), around the equilibrium position in the corotating frame.

Although real binaries are not always perfectly circular or synchronized, tidal interaction becomes increasingly efficient as the donor approaches Roche-lobe overflow, driving synchronization and circularization on relatively short timescales (e.g., Zahn 1977). The classical Roche geometry therefore provides a good approximation for the onset of MT.

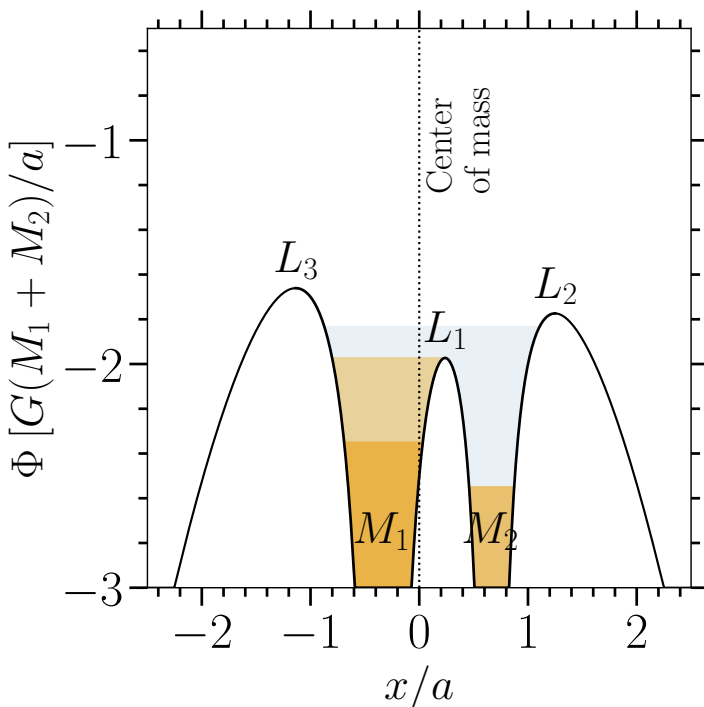


Figure 1.2: Shape of the Roche potential (solid) along the line connecting the two stars, for a binary with mass ratio $q = 2$. The locations of the centres of mass of the two stars are indicated by M_1 and M_2 , and the Lagrangian points by L_1 , L_2 and L_3 . Colors indicate the three possible stable binary configurations: detached (dark orange), semi-detached (light orange) and contact (light blue). Matter that reaches and escapes the L_1 , L_2 or L_3 point is not stationary anymore in the corotating frame, its motion will be influenced by the Coriolis force.

1.1.1 Mass transfer and orbital evolution

Following the classification introduced by [Kippenhahn & Weigert 1967](#) and [Lauterborn 1970](#), phases of MT are traditionally divided into different “Cases”. Case A MT refers to RLOF occurring while the donor star is still on the main sequence (MS), whereas Case B describes MT episodes taking place after the end of core-hydrogen burning but before core-helium depletion. Case C MT, instead, corresponds to interactions initiated after core-helium depletion. Multiple episodes of interaction are denoted by repeated letters; for example, Case AB

indicates a post-MS MT phase preceded by an earlier Case A interaction.

Because massive stars can increase their radii by more than two orders of magnitude during their evolution, RLOF may occur across a very broad range of orbital separations, from only a few tens to a $\sim$ thousand of solar radii. For instance, at solar metallicity, massive stars may already undergo RLOF close to the Zero Age Main Sequence (ZAMS) for orbital periods of roughly one day, while systems interacting near the maximum radial expansion of the donor may do so at periods approaching ~ 10 years (see [Marchant & Bodensteiner 2024](#), their figure 2). As a result, binaries born with different initial separations interact at different evolutionary stages, producing distinctive excursions across the Hertzsprung-Russell (HR) diagram, and different MT properties (see Section 1.1.2).

Let us consider the effects on the orbits of binaries produced by the exchange and / or the loss of mass and angular momentum of the stellar components (we mostly follow the derivations from [Soberman et al. 1997](#)). The total orbital angular momentum J of a binary with masses M_1 (primary) and M_2 (secondary), orbital separation a , and eccentricity e is

$$J^2 = G \frac{M_1^2 M_2^2}{M_1 + M_2} a(1 - e^2), \quad (1.3)$$

where $G = 6.67430 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2}$ is the gravitational constant. Differentiation yields

$$2 \frac{\dot{J}}{J} = \frac{\dot{a}}{a} + 2 \frac{\dot{M}_1}{M_1} + 2 \frac{\dot{M}_2}{M_2} - \frac{\dot{M}_1 + \dot{M}_2}{M_1 + M_2} - \frac{2e\dot{e}}{1 - e^2}. \quad (1.4)$$

It is common to assume near-RLOF systems to be efficiently circularized (e.g. [Verbunt & Phinney 1995](#); [Claret & Cunha 1997](#)), so that $\dot{e} = 0$. However, one must keep in mind the works from [Rocha et al. \(2025\)](#); [Parkosidis et al. \(2026a,b\)](#) with RLOF treated without this assumption, which have shown that consistent eccentricity pumping or quenching might be coupled with different MT regimes. Regardless, in the following we will stick with the common assumption of $\dot{e} = 0$ and neglect the last term of Equation 1.4.

Multiple processes can drive the orbital evolution of binaries, such as tidal spin-orbit interaction, magnetic braking (MB, e.g. [Verbunt & Zwaan 1981](#); [Rappaport et al. 1983](#)), and GWs emission (e.g., [Kraft et al. 1962](#)), such that we could factorize Equation 1.4 as

$$\frac{\dot{J}}{J} = \left(\frac{\dot{J}}{J} \right)_{\text{ml}} + \left(\frac{\dot{J}}{J} \right)_{\text{tides}} + \left(\frac{\dot{J}}{J} \right)_{\text{MB}} + \left(\frac{\dot{J}}{J} \right)_{\text{GW}}. \quad (1.5)$$

In this thesis we will focus on the orbital evolution driven by MT and mass loss, namely we will work under the assumption of $\dot{J} = \dot{J}_{\text{ml}}$. This is a good approximation for systems that are not too tight (e.g., with periods of the order of hours or $\lesssim 1$ day, depending also on the masses), such that GW and tides are negligible, and also not magnetically active, such that MB is negligible. This is the case for most of the systems we will be dealing with.

Solutions to Equation 1.4 can be derived for some simple, physically relevant *MT modes*, that is cases for which the specific angular momentum (i.e., the angular momentum per unit mass) of the moving material is known. We report here only the MT modes that are useful in this thesis, and we anchor each mode's physical relevance to observations of MT products (see also Section 1.1.5).

Conservative mass transfer MT is called conservative when no mass or angular momentum is lost from the binary system. Evidence for conservative MT is found in sdOBs binaries with classical Be stars (see below the Section 1.1.5), understood to be the products of stable RLOF undergoing significant accretion. A classical example is the prototypical system ϕ Persei (Poeckert 1981; Gies et al. 1998a; Mourard et al. 2015), which is thought to have accreted more than $\sim 70\%$ of its donor's mass (Vanbeveren et al. 1998b; Schootemeijer et al. 2018; Lechien et al. 2025). We can write the conservation laws for mass and angular momentum as

$$\dot{J} = 0, \quad \dot{M}_2 = -\dot{M}_1, \quad (1.6)$$

where M_1 and M_2 are the donor (primary) and accretor (secondary) masses, respectively. Under these assumptions, the orbital response of the binary is driven solely by the internal redistribution of mass between the two components. The evolution of the orbital separation a as derived from Equation 1.4 can then be written as

$$\frac{\dot{a}}{a} = 2 \left(\frac{M_1}{M_2} - 1 \right) \frac{\dot{M}_1}{M_1}. \quad (1.7)$$

To obtain the global change in orbital separation, we integrate over time under the assumption of conservative evolution (i.e., Equation 1.6 holds all the time). This yields

$$\frac{a_f}{a_i} = \left(\frac{M_{1,i}}{M_{1,f}} \frac{M_{2,i}}{M_{2,f}} \right)^2 = \left(\frac{q_i}{q_f} \right)^2 \left(\frac{q_f + 1}{q_i + 1} \right)^2 \quad (1.8)$$

where the subscripts i and f refer to the initial (at RLOF) and final (post-MT) values of the parameters, respectively. Using the third Kepler's law,

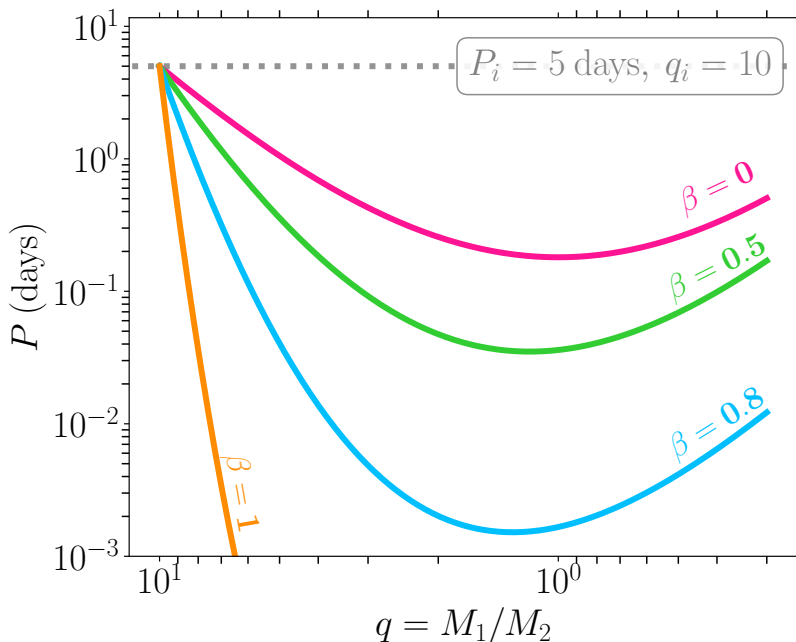


Figure 1.3: Evolution of the orbital period, P , as a function of the decreasing mass ratio, q , during a MT episode. The evolution is from left to right. The binary starts with an initial period $P_i = 5$ days, and a mass ratio $q_i = 10$. We consider isotropic re-emission with various degrees of mass loss from the accretor using $\beta = 0$ (conservative MT, see Equation (1.9)), and $\beta = 0.5, 0.8, 1$ (non-conservative MT, see Equation 1.12). We see that the orbit shrinks more and more as the degree of non-conservativeness increases, and for $\beta \neq 0$ the turnover point happens before mass-ratio reversal. This plot shows a purely analytical curve, therefore it does not take into account the stellar structure response to MT, which will determine the actual detachment mass ratio.

$a^3 \propto (M_1 + M_2)P^2$, we can derive the change in orbital period:

$$\frac{P_f}{P_i} = \left(\frac{M_{1,i}}{M_{1,f}} \frac{M_{2,i}}{M_{2,f}} \right)^3 = \left(\frac{q_i}{q_f} \right)^3 \left(\frac{q_f + 1}{q_i + 1} \right)^6 \quad (1.9)$$

In this MT mode, the orbit shrinks when $M_1 > M_2$, and expands after mass-ratio reversal, as shown in Figure 1.3.

Isotropic re-emission mode In the isotropic re-emission mode, MT is non-conservative: only a fraction of the transferred material is accreted by the secondary, while the remainder is ejected from the system carrying the specific orbital angular momentum of the accretor. This mode is motivated by observations of high-mass X-ray binaries (see Section 1.1.5) with highly super-Eddington MT rates (King & Ritter 1999; Podsiadlowski & Rappaport 2000; Podsiadlowski et al. 2002). During this phase, the system is expected to host an accretion disk and may appear as an ultraluminous X-ray source (Shakura & Sunyaev 1973; Poutanen et al. 2007; Lasota 2016). Observations of systems such as SS433, the prototype microquasar, reveal powerful jets, disk winds, and other outflows that can remove a large fraction of the transferred material before it is accreted (Fabrika 2004; Cherepashchuk et al. 2005; Blundell et al. 2008; Waisberg et al. 2019a; Middleton et al. 2021).

In the isotropic re-emission mode, the amount of accreted mass is commonly parametrised by the accretion efficiency β , defined as

$$\beta = -\frac{\dot{M}_2}{\dot{M}_1}, \quad 0 \leq \beta < 1, \quad (1.10)$$

such that $\beta = 1$ corresponds to fully conservative evolution and $\beta < 1$ implies mass loss from the system. The mass evolution then reads

$$\dot{M}_2 = -\beta\dot{M}_1, \quad \dot{M}_{\text{loss}} = (1 - \beta)(-\dot{M}_1) \equiv -\epsilon\dot{M}_1, \quad (1.11)$$

where we defined the conservativeness degree $\epsilon \equiv 1 - \beta$. One can proceed analogously to the conservative case to derive the global change in orbital period in the case of isotropic re-emission

$$\frac{P_f}{P_i} = \left(\frac{q_i(1 - \beta) + 1}{q_f(1 - \beta) + 1} \right)^{\frac{5\beta - 8}{1 - \beta}} \left(\frac{q_i + 1}{q_f + 1} \right)^2 \left(\frac{q_i}{q_f} \right)^3 \quad (1.12)$$

In the case in which all matter is expelled via isotropic re-emission, i.e. when $\beta = 1$, we find

$$\frac{P_f}{P_i} = e^{3(q_f - q_i)} \left(\frac{q_i + 1}{q_f + 1} \right)^2 \left(\frac{q_i}{q_f} \right)^3 \quad (1.13)$$

In this MT mode, the orbit shrinks when the mass ratio q is above a critical value that depends on β , and expands otherwise. For example, for $\beta = 0.8$ the orbit shrinks when $q \simeq 1.25$, and expands otherwise. In Figure 1.3, we show an example of the evolution of the orbital period for different values of β .

Outflow from the L_2 point During RLOF, the donor may also expand beyond its Roche lobe and approach the equipotential surface of L_2 (see Figure 1.1). Three-dimensional (3D) hydrodynamical simulations have shown that this can be achieved in cases of high MT rates through the inner Lagrangian point L_1 (e.g. [Lu et al. 2023](#); [Scherbak et al. 2025](#)). When this happens, matter may leave the L_2 point in a spiral stream, which is torqued and accelerated by the time-changing gravitational force of the central binary ([Kuiper 1941](#); [Shu et al. 1979](#); [Pejcha et al. 2016b,a](#); [MacLeod et al. 2018](#); [MacLeod & Loeb 2020](#)). Alternatively, the stream may remain bound and accumulate in a circumbinary ring, which continues to interact with the binary; in binary population synthesis this is often treated as a separate MT mode (e.g. [Soberman et al. 1997](#)).

Observationally, several systems exhibit features that are frequently interpreted as signatures of L_2 outflows. As an example, the already mentioned SS433 shows an equatorial circumbinary structure revealed by radio and infrared observations (e.g. [Paragi et al. 1999](#); [Waisberg et al. 2019b](#)). Recently, [Shepard et al. 2024](#) proposed that the interacting binary W Serpentis is undergoing L_2 outflows. Additionally, circumbinary outflows have been proposed to explain the infrared excess observed in ultra-luminous X-ray sources ([Lu et al. 2023](#)). Further support comes from red transients, which are often interpreted as binaries undergoing strong mass loss prior to a CE event (e.g. [Pejcha 2014](#); [Shen & Quataert 2022](#), and see the Section 1.1.3).

As compared to material transferred through L_1 or lost via isotropic re-emission, matter that escapes through L_2 carries away a much higher amount of orbital angular momentum, proportional to the second power of the distance of L_2 from the center of mass of the binary, or possibly higher if the material first settles into a circumbinary disk before ejection (e.g. [Valli et al. 2024](#)). The binary is, in this case, expected to experience a dramatic reduction in orbital separation. Deriving an analytical expression for the orbital evolution in this case is not trivial, as one needs to numerically calculate the location of L_2 . Such a solution for P_f/P_i in the presence of L_2 outflow is carried out in this thesis (see Chapter 2, Equation 2.21). Nevertheless, this regime is often associated with the onset of dynamical instability in the MT process (e.g. [Pavlovskii & Ivanova 2015](#), see also below), such that often, in binary population synthesis, the orbital evolution is described in terms of a common envelope (CE) phase (see Section 1.1.2).

1.1.2 Stability of mass transfer

Depending on the physical process that drives the overflow, MT may proceed on different timescales. If MT is driven either by nuclear evolution of the donor

(expansion, i.e. R_1 increases with time) or by orbital shrinkage due to angular momentum loss (where a , and therefore R_{RL} , decreases, see Equation 1.2), the donor can continuously readjust its structure and may remain in thermal equilibrium. Such MT would occur on the nuclear timescale of the donor, or on the timescale for angular momentum loss, whichever is shorter. On the other hand, MT may proceed on the thermal (or Kelvin–Helmholtz) timescale if it is driven by the donor’s thermal relaxation. Figure 1.4 provides a representation of the different MT cases and their timescales. In Case A systems, MT typically proceeds in two distinct stages: 1) the onset of Roche-lobe overflow during core-hydrogen burning causes the orbit to shrink, driving a rapid phase of MT on the donor’s thermal timescale; 2) once the mass ratio has reversed, the donor is able to re-establish thermal equilibrium within its Roche lobe and MT continues on the nuclear timescale. This long-lived semi-detached configuration is commonly referred to as the “Algol phase”. After core-hydrogen exhaustion, a further episode of Case AB MT removes most of the remaining hydrogen-rich envelope. In contrast, Case B systems initiate interaction after the end of the MS, when the donor expands due to hydrogen-shell burning. The resulting MT generally occurs in a single, thermal-timescale MT episode.

These situations correspond to *stable MT*, in which the donor is able to continuously adjust its structure while transferring mass. However, if the donor cannot restore hydrostatic equilibrium after losing mass, the MT rate increases in a runaway process and the interaction proceeds on the donor’s dynamical timescale. This regime is referred to as *unstable MT*.

The stability of MT in interacting binaries can be assessed by comparing the response of the donor-star radius to the response of its Roche-lobe radius during mass loss (see Webbink 1985; Ge et al. 2010). The variation of the donor radius R_1 may be expressed as

$$d \ln R_1 = \left(\frac{\partial \ln R_1}{\partial t} \right)_{M_1} dt + \left(\frac{\partial \ln R_1}{\partial \ln M_1} \right)_t d \ln M_1, \quad (1.14)$$

where M_1 and R_1 denote the mass and radius of the donor star, respectively.

The first term describes the intrinsic stellar expansion or contraction at constant mass, including both secular stellar evolution and thermal relaxation if the star is out of thermal equilibrium. The second term represents the hydrostatic response of the donor to mass loss with thermal and chemical diffusion, and nuclear evolution suppressed. This response is therefore commonly referred to as the adiabatic response to mass loss. One then defines the adiabatic mass–radius exponent as

$$\zeta_{\text{ad}} \equiv \left(\frac{\partial \ln R_1}{\partial \ln M_1} \right)_t. \quad (1.15)$$

For a binary in a circular orbit, the Roche-lobe radius R_{RL} depends on the donor mass M_1 , the total system mass M , and the orbital angular momentum J . This is easy to see if we rewrite it as follows:

$$R_{RL} = \frac{\overbrace{R_{RL}}^{f(M_1/M)}}{a} \times a = f\left(\frac{M_1}{M}\right) \frac{J^2 M}{GM_1^2(M - M_1)^2}, \quad (1.16)$$

where $f(M_1/M)$ is the dimensionless Roche-lobe radius that can be approximated by the Eggleton fit (Equation 1.2), and we used Equation 1.3 to express the orbital separation a in terms of the total mass M , the donor mass M_1 , and the orbital angular momentum J .

For a given mode of MT, one can relate the differential changes in total mass, $\partial \ln M$, and orbital angular momentum, $\partial \ln J$, to changes in the mass of the primary, $\partial \ln M_1$, such that the evolution of the Roche lobe radius can be written in an analogous form to that of the donor's radius in Equation 1.14:

$$d \ln R_{RL} = \left(\frac{\partial \ln R_{RL}}{\partial t} \right)_{M_1} dt + \left(\frac{\partial \ln R_{RL}}{\partial \ln M_1} \right)_t d \ln M_1. \quad (1.17)$$

In the above, the first term indicates the evolution of the orbit with time when the primary mass is constant, i.e. the binary is not yet at the RLOF stage and the orbital changes may still be driven by tidal evolution, MB or GW emission. By analogy with Equation 1.14, one defines the Roche-lobe mass-radius exponent as

$$\zeta_{RL} \equiv \left(\frac{\partial \ln R_{RL}}{\partial \ln M_1} \right)_t. \quad (1.18)$$

Combining the donor (Equation 1.14) and Roche-lobe (Equation 1.17) responses yields

$$d \ln \left(\frac{R_1}{R_{RL}} \right) = \left[\left(\frac{\partial \ln R_1}{\partial t} \right)_{M_1} - \left(\frac{\partial \ln R_{RL}}{\partial t} \right)_{M_1} \right] dt + (\zeta_{\text{ad}} - \zeta_{RL}) d \ln M_1. \quad (1.19)$$

Both terms proportional to $\partial \ln R_1 / \partial t$ and $\partial \ln R_{RL} / \partial t$ may be non vanishing: the donor may be expanding or contracting due to its nuclear evolution, and the Roche lobe may be expanding or contracting due to effects on a from tides, MB, or GW radiation. In general, however, in order for RLOF to even occur, this term must be positive: R_1 must increase faster (or decrease slower) than R_{RL} would, were it not for MT.

The second term of Equation 1.19 describes the response of the donor relative to its Roche lobe to mass loss. For MT to remain self-regulated, or *stable*, the stellar radius should parallel the Roche lobe radius, $d \ln(R_1/R_{RL}) \simeq 0$, otherwise it is expected to increase steeply with increasing overflow (e.g. Ritter 1988; Kolb & Ritter 1990). Since $d \ln M_1 < 0$, MT stability requires

$$\zeta_{\text{ad}} > \zeta_{RL}. \quad (1.20)$$

In this regime, the donor is able to adjust its structure to remain close to thermal or hydrostatic equilibrium while transferring mass. Conversely, if

$$\zeta_{\text{ad}} \leq \zeta_{RL}, \quad (1.21)$$

the donor rapidly overfills its Roche lobe on its dynamical timescale, therefore it cannot restore hydrostatic equilibrium and the MT rate increases in a runaway process (see Section 1.1.3). Therefore, in practice, the classical stability analysis is based on an understanding on how ζ_{ad} and ζ_{RL} depend on stellar structure and the mode of MT.

Roche-lobe response to mass transfer Given the dependences of R_{RL} on M_1 , M , and J (Equation 1.16), it is clear that the Roche-lobe response to mass loss must depend on the MT mode. This thesis derives and discusses such dependence for a number of modes, including conservative MT and isotropic re-emission, and we refer the reader to Chapter 2 for more details about the implications on MT stability (but see also Soberman et al. 1997). In general, it is found that ζ_{RL} mainly depends on the binary mass ratio, which implies that the stability criterion of Equation 1.20 can be rewritten as a critical mass ratio q_{crit} above which MT becomes unstable.

Stellar response to mass transfer The adiabatic response of a star to mass loss, ζ_{ad} , depends strongly on the structure of the stellar envelope, in particular on whether the envelope is radiative or convective. Studies with *simple polytropic models* (e.g. Paczyński 1965; Hjellming & Webbink 1987; Soberman et al. 1997) have established the following classical understanding: stars with radiative envelopes contract significantly in response to mass loss, whereas stars with deep convective envelopes tend to maintain approximately the same radius or expand slightly.

We can understand this behaviour by considering the density gradient with respect to pressure in the two types of envelopes. In radiative envelopes, such gradient is steeper than the adiabatic one, such that they are centrally

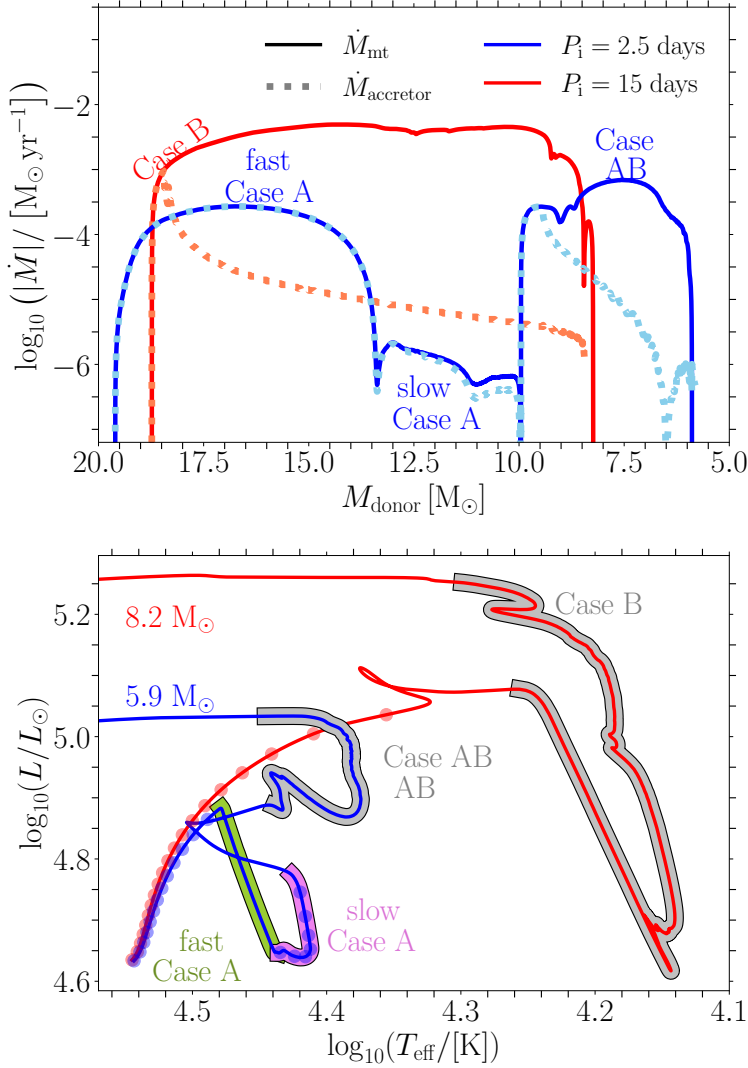


Figure 1.4: Top: MT rate $\dot{M}_{\text{mt}}$ and rate of change of mass of the accreting star $\dot{M}_2$ as a function of the donor mass for a Case A system ($20 M_{\odot} + 16 M_{\odot}$ with an initial period of 2.5 days) and an early Case B system (same masses but with an orbital period of 15 days). Simulations include rotation and mass accretion is limited after the accreting star reaches critical rotation. Bottom: Evolution of the donor star in the HR diagram for the same two binaries. Different MT phases are indicated with thick contours, and dots are placed in time intervals equal to 5% of the MS lifetime of the donor star. Figure from [Marchant & Bodensteiner 2024](#).

concentrated and have relatively low-density outer layers. When mass loss removes these outer layers, the deeper layers exposed by the mass stripping expand adiabatically but remain comparatively compact, leading to an overall contraction of the star. By contrast, convective envelopes are already nearly adiabatically stratified (i.e., $P \propto \rho^{\gamma_{\text{ad}}}$, where γ_{ad} is the adiabatic index). Following mass loss, we may therefore expect that the density distribution (measured at constant pressure) will remain the same, and the star will occupy about the same volume when hydrostatic equilibrium is restored.

This classical understanding remains useful as a rule of thumb to understand MT stability. Complementarily, *time-dependent one-dimensional (1D) binary evolution* calculations can follow the donor response along the MT episode, and solve realistic stellar structure equations at the same time. Some recent works have shown that the response of the donor to mass loss can be more complex than the classical picture, particularly when superadiabatic layers (e.g. Pavlovskii & Ivanova 2015; Pavlovskii et al. 2017; Temmink et al. 2023) appear in the envelopes of giants, or when a delayed dynamical instability (phase of thermal-timescale MT before unstable MT) develops for Hertzsprung Gap (HG) stars (e.g. Ivanova & Taam 2004; Temmink et al. 2025).

An additional approach to study the donor response to mass loss is through *adiabatic mass loss sequences*, based on realistic stellar models rather than polytropic models. Such an approach has been carried out for stars at multiple different evolutionary stages and metallicities in the series of papers by Ge et al. 2010, 2015, 2020, 2023, 2024. In these calculations, the donor star is assumed to fill its Roche lobe at a given evolutionary stage, after which mass is progressively removed from the stellar surface while keeping the specific entropy and chemical composition profiles fixed. Despite the limitation of assuming adiabatic response (which is generally valid in the deep stellar interior but will break down near the photosphere), these calculations are the first effort to survey values of ζ_{ad} for a wide range of stellar masses and evolutionary stages. Additionally, their results are in good agreement with time-dependent models: a) Evolved donors with surface convection zones generally develop dynamical instability shortly after the onset of MT. By contrast, MS stars with radiative envelopes often undergo delayed dynamical instability; b) For red giant branch (RGB) and asymptotic giant branch (AGB) stars, MT appears to be more stable than expected from polytropic models.

1.1.3 Unstable mass transfer and common envelope evolution

When MT evolves unstably (e.g., when the criterion in Equation 1.20 is not satisfied), the donor's envelope may engulf the companion star, leading to the

onset of a CE phase. As the companion “inspirals” through the envelope, energy and angular momentum are transferred to the envelope and may lead to its ejection. In case of successful ejection, the initial system may survive as a binary with a tighter orbital separation; if the ejection fails, then the stars merge.

CE evolution was originally proposed by Paczynski 1976 to explain the origin of cataclysmic variable stars. Their reasoning was based on the binary V471 Tau in the Hyades cluster: a $0.8 M_{\odot}$ white dwarf (WD) and a similar-mass MS star in a 12-hour orbit, presumed to be a direct predecessor of cataclysmic variables. The WD progenitor would have expanded several hundred solar radii (appropriate for an AGB star), requiring an orbital period of at least several years before CE. The present-day short period therefore indicated that the binary must have undergone a dramatic orbital contraction, motivating the need for a mechanism capable of shrinking the orbit by orders of magnitude on a short timescale. Since Paczynski’s original proposal, CE evolution has been invoked as a possible way to form a number of binaries with COs: Type Ia SNe (e.g. Webbink 1984), binary WDs (e.g. Iben & Tutukov 1984), X-ray binaries with NS and BH companions (e.g. Tauris & van den Heuvel 2006; see Section 1.1.5). Notably, CE evolution is thought to be a key channel for forming both coalescing double CO binaries (see Section 1.3.2), and stripped products (see Section 1.2).

Similar energetics argument used for V471 Tau are invoked to explain a number of systems that are thought to be post-CE binaries. Examples include progenitors of cataclysmic variables (e.g. Iaconi & De Marco 2019). Substellar companions such as brown dwarfs or giant planets may also be capable of surviving a CE interaction and ejecting the envelope of the giant donor (e.g. Geier et al. 2011; Schaffenroth et al. 2015; Vanderburg et al. 2020). Additional evidence comes from planetary nebulae, a significant fraction of which are thought to originate from CE envelope ejection (e.g. Jacoby et al. 2021). In recent years, time-domain surveys have also revealed a growing population of optical transients that may be linked to CE interaction. Some events, such as V1309 Sco, have been conclusively identified as merger products through pre-outburst observations (Tylenda et al. 2011), while others are strong CE candidates (e.g. V838 Mon, Bond et al. 2003). These transients are commonly classified as intermediate-luminosity optical transients, with a luminosity range between novae and SNe. Among them, luminous red novae (see the recent review Kaminski & Blagorodnova 2026) are widely interpreted as the observable signatures of CE inspirals and stellar mergers, particularly in systems containing evolved stars.

Theoretical studies of CE evolution have a long history, beginning with early 1D hydrodynamic calculations within the framework of classical stellar evolution (e.g. Taam et al. 1978; Meyer & Meyer-Hofmeister 1979; Podsiadlowski 2001).

These showed that the evolution can be divided into several distinct stages, including the loss of co-rotation between the binary and the giant envelope, a dynamical-timescale *plunge-in* phase, and a slower inspiral stage when the envelope expands. Today 3D (magneto)hydrodynamic simulations represent the most direct tool to study CE evolution (e.g. [Rasio & Livio 1996](#); [Ricker & Taam 2008](#); [Ohlmann et al. 2016](#); [Lau et al. 2022a](#), but see also [Bronner et al. 2024](#) and references therein for the importance of recombination and ionization processes). These calculations are computationally expensive, thus impractical for large-scale population studies. Consequently, phenomenological prescriptions remain widely used in binary population synthesis codes. The most common approach is the energy formalism ([Webbink 1984](#)), which compares the orbital energy released during the inspiral, ΔE_{orb} , to the binding energy of the envelope, E_{bind} :

$$E_{\text{bind}} = \alpha_{\text{CE}} \Delta E_{\text{orb}}, \quad (1.22)$$

In this framework, a parameter α_{CE} describes the efficiency with which orbital energy contributes to envelope ejection. While values $\alpha_{\text{CE}} \leq 1$ are often assumed, additional energy sources such as recombination energy, accretion onto the companion, jets, or dust formation may contribute to the ejection process, potentially leading to effective efficiencies exceeding unity ([Han et al. 1995](#); [Toonen & Nelemans 2013](#); [Lau et al. 2022b](#)). Besides this classical α -formalism, the γ -formalism represents an alternative prescription, introduced to explain several double helium WD binaries whose observed masses and orbital properties could not be reproduced using standard CE models ([Nelemans et al. 2000](#)). This γ -formalism is based on angular momentum conservation: the donor’s envelope is assumed to be completely expelled from the system, carrying away a specified fraction of the binary’s orbital angular momentum.

As this thesis mostly focuses on stable MT, we refer the reader to the reviews by [Ivanova et al. 2013](#); [Ivanova et al. 2020](#); [Röpke & De Marco 2023](#) for more details about the physics of CE. However, throughout the thesis we make some comparisons between the properties of binaries that undergo stable MT with those expected after undergoing CE, in the context of GW progenitors (Chapters 2, 5). This is relevant because CE and stable MT are expected to produce different types of coalescing double COs, according to binary population synthesis calculations (e.g. [van Son et al. 2022b](#); [Olejak et al. 2024](#), but see also Section 1.3.2), such that accurate models of their stellar progenitors may help to disentangle the relative contribution of double COs formation channels. Therefore, the treatment of CE in population synthesis tools (whether based the classical phenomenological prescriptions or on calibrations from 3D hydrodynamical simulations, e.g. [Trani et al. 2022](#)) influences the astrophysical

inference from GW observations as much as the adopted MT stability criterion (Li et al. 2025; Broekgaarden et al. 2026).

1.1.4 Accretor’s response to mass transfer

Rapid rotation MT redistributes not only mass but also angular momentum, such that it is expected to produce rapidly rotating stars (Struve 1963). A classical result by Packet 1981 demonstrated that a MS star accreting material from a companion can reach critical rotation after increasing its mass by only $\sim 5\text{--}10\%$. More modern population-synthesis studies predict that a significant fraction of fast rotators originate from previous MT episodes (de Mink et al. 2013), and this is supported by observational evidence. For example, surveys of star clusters reveal a velocity distribution of rotating OB stars that is difficult to explain through single-star evolution alone (e.g. Ramirez-Agudelo et al. 2013 for the 30 Dor region, Dufton et al. 2019 for NGC 346 in the Small Magellanic Cloud; SMC). Further observational evidence is provided by classical Be stars, both as single and in binaries (see Section 1.1.5).

Whether and how accretors can reach critical rotation remains an open question. On the one hand, accretion can efficiently spin up the stellar surface, potentially producing Be-star-like rotation (Packet 1981; Shao & Li 2014; Hastings et al. 2021, and see also Section 1.1.5). On the other hand, angular-momentum transport within the star, tidal interactions, post-accretion thermal relaxation, and possible mass and angular-momentum loss may all act to prevent or reduce critical rotation (Langer et al. 2003; Renzo & Götzberg 2021; Wang et al. 2026b). These uncertainties are closely connected to the poorly constrained accretion efficiency during MT: if further accretion becomes inhibited once the stellar surface reaches critical rotation, only a fraction of the transferred material can be retained by the companion (Langer et al. 2003). However, viscous angular-momentum transport within the star and through a surrounding accretion disk may allow accretion to continue even near critical rotation (Popham & Narayan 1991; Paczynski 1991). There is no consensus on how angular-momentum accretion should be treated in binary evolution models. Detailed calculations that simultaneously follow mass and angular-momentum transfer often predict that accretors reach critical rotation, conditions under which accretion is assumed to be rotation-limited leading to low overall accretion efficiencies (Wang et al. 2020; Xu et al. 2025). However, observations of post-interaction systems, including Be+sdO binaries and Be X-ray binaries (see also Section 1.1.5), seem to require substantially more efficient mass accretion than predicted (Shao & Li 2014; Schootemeijer et al. 2018; Lechien et al. 2025; Schürmann et al. 2025). In Figure 1.5 we show the evolution of the accretor in a Case A and a Case B system (the companions to the systems in Figure

1.4), including rotation and limiting accretion after the accretor reaches critical rotation.

By modifying the angular-momentum content of stellar cores, MT can also influence the spins of the compact remnants that subsequently form, thereby affecting the properties of BH and NS binaries observed through GWs. In most formation channels leading to merging COs (see Section 1.3.2), the initially less massive star accretes mass from its companion before the formation of the first CO and later becomes the donor that initiates a MT phase (Belczynski et al. 2016; Tauris et al. 2017). This prior accretion episode modifies its internal structure, (core) rotation rate, chemical composition, and rejuvenation history relative to an equivalent single star, thereby affecting the subsequent evolution (Klencki et al. 2021; Renzo et al. 2023; Xu et al. 2025; Briel et al. 2026). Moreover, the transfer of angular momentum during MT may directly influence the spins of the compact remnants that eventually form. Stable MT can increase the spins of BHs with super-Eddington accretion rates, potentially contributing to the population of high-spin GW mergers (Shao & Li 2022; Wang et al. 2024b). Additionally, population synthesis studies suggest that non-zero effective spins in detectable BBH populations mainly arise from tidal spin-up of the second-born BH after CE (Bavera et al. 2020), which has also been suggested as the origin of high black hole spins in high mass X-ray binaries (Valsecchi et al. 2010).

Enrichment and rejuvenation MT enriches accretors with CNO-processed material, particularly helium and nitrogen, originating from the donor’s inner layers (e.g. Wellstein et al. 2001; Langer et al. 2008). Thermohaline and rotational mixing subsequently redistribute the accreted material throughout the stellar envelope, modifying the surface abundances and internal structure of the star. At the same time, accretion increases the mass of the convective core and supplies fresh hydrogen fuel, effectively rejuvenating the star by resetting its evolutionary clock and extending its MS lifetime (Neo et al. 1977; Dray & Tout 2007; Renzo & Götzberg 2021; Renzo et al. 2023). As a consequence, mass gainers often appear younger, more massive, and more luminous than single stars of the same age. However, these signatures are not unique to binary interaction, since rapid rotation can also induce chemical mixing and surface abundance anomalies in single stars. Distinguishing between rotational mixing and binary-induced enrichment therefore remains challenging (Ekström et al. 2008; Brott et al. 2011; Langer 2012). Moreover, many post-interaction systems are difficult to recognize observationally: the accretor often outshines the stripped donor, orbital widening can leave the system as a long-period binary that is difficult to detect, and SN disruption may leave the rejuvenated mass gainer apparently single (de Mink et al. 2014).

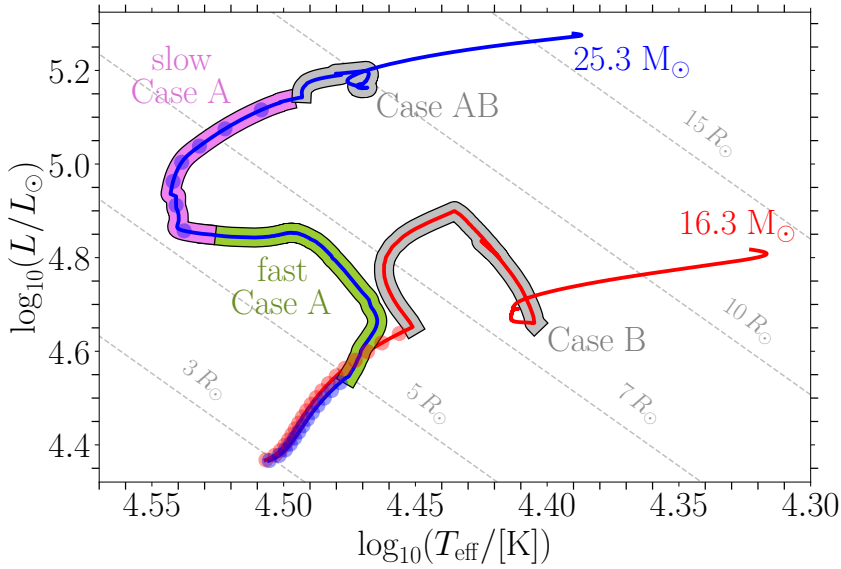


Figure 1.5: Hertzsprung–Russell diagram showing the evolution of the accreting star in the same Case A and B systems of Figure 1.4, and we use the same conventions as in that Figure. The simulations include rotation and mass accretion is limited after the accreting star reaches critical rotation. We see the effect of this in the Case A system, in which the accretor is able to gain more mass and reach higher luminosities than that of the Case B system. The accretor of the Case B system is undergoing accretion until critical rotation is reached, and then relaxation back to an equilibrium radius proper for its new mass. The data to produce this Figure is taken from [Marchant & Bodensteiner 2024](#).

Expansion and contact binaries The response of a mass-accreting star is primarily determined by the competition between the accretion timescale and the star’s thermal timescale. In general, accretion compresses the underlying stellar layers, releasing gravitational energy. If this energy can be radiated away efficiently, the star remains close to thermal equilibrium and adjusts quasi-statically to its increasing mass. However, during RLOF, the MT rate is often set by the thermal timescale of the donor star, while the accretor’s thermal timescale is generally longer. Consequently, mass is deposited onto the accretor faster than it can thermally adjust, driving it out of thermal equilibrium. The faster, radial response of the star then depends on its envelope structure. In

analogy to the response of mass-losing donors (see Section 1.1.2), a rule of thumb can be that accretion onto stars with convective envelopes tends to induce contraction, whereas stars with radiative envelopes generally expand. However, this classical picture is in fact more complicated, as such reaction would strongly depend on the actual accretion rate and the amount of energy deposited by the accreted matter (see e.g., the early detailed calculations from Webbink 1977; Prialnik & Livio 1985 for convective envelopes, and Ulrich & Burger 1976; Neo et al. 1977 for radiative accretors).

For massive MS stars with radiative envelopes, several modern stellar evolution calculations have confirmed that they are expected to inflate during rapid accretion, as the excess gravitational energy from compression cannot be radiated away efficiently and is instead invested in expanding the stellar envelope. As a result, the accretor becomes overluminous for its mass and inflates. In particular, models that neglect rotational constraints on accretion (and therefore permit high MT efficiencies) always predict strong inflation during rapid MT (e.g. de Mink et al. 2007; Lau et al. 2024, but see Schürmann & Langer 2024 for intermediate-mass stars). For accretion rates below the thermal rate, instead, the stellar radius remains relatively close to its thermal equilibrium configuration. Additionally, since mass accretion induces both rejuvenation and rotation, the thermal-equilibrium radius to which the accretor would adjust is expected to be impacted by the combined effects of enhanced core mixing and rotational support.

After the phase of rapid MT, the accretor gradually restores thermal equilibrium through a phase of thermal relaxation. This may occur once the donor detaches from its Roche lobe or once the accretor becomes sufficiently massive and luminous that its own thermal timescale becomes shorter than the accretion timescale. During this phase, the star radiates away the excess thermal energy stored in its inflated envelope and contracts toward a new equilibrium configuration (Renzo & Götzberg 2021; Lau et al. 2024). Recent models including rotation show that, once such thermal relaxation begins, the star contracts, causing the fraction of critical rotation (i.e., the ratio between the surface and the critical velocity) to decrease (Wang et al. 2026b).

The radial evolution of the accretor has important consequences for binary evolution. If its inflation becomes sufficiently large, the accretor may fill its own Roche lobe, leading to a contact configuration (Wellstein et al. 2001; see Figure 1.2). Continued expansion may subsequently trigger mass outflow from the L_2 point that may result in a CE phase (e.g. Nariai & Sugimoto 1976; Ivanova et al. 2013, and see also Section 1.1.1). Since the accretor’s thermal response, luminosity, and radius evolve during MT, reliably predicting the outcome of RLOF requires self-consistent modelling of both stellar components (e.g. de Mink et al. 2007; Deschamps et al. 2013; Fragos et al. 2023; Henneco et al.

2024b), as rapid population-synthesis prescriptions based on fixed accretion efficiencies or thermal-timescale limits cannot fully capture these structural adjustments (e.g., Hurley et al. 2002).

1.1.5 Binary interaction products

Here we briefly review those products of binary interaction through MT that are of special interest for this thesis: classical Be stars (interesting for Chapter 3), stellar mergers (modeled in Chapter 4), and binaries with COs (considered in Chapters 2 and 5). We reserve for the next Sections a special focus on (intermediate-mass) stripped stars (see Section 1.2) and double CO binaries (see Section 1.3).

Classical Be stars Classical Be stars are B-type stars that rotate rapidly and are surrounded by a gaseous decretion disk, which produces the characteristic emission lines observed in their spectra (Porter & Rivinius 2003; Rivinius et al. 2013). The origin of their rapid rotation remains debated, with proposed mechanisms including high natal rotation, angular-momentum transport during single-star evolution (e.g. Bodenheimer 1971; Hastings et al. 2020), and spin-up through binary MT. In recent years, with the support of theoretical studies (see Section 1.1.2), observational evidence has increasingly favored the idea that a large fraction of Be stars are the products of past MT episodes (Pols et al. 1991; de Mink et al. 2013; Bodensteiner et al. 2020b; Klement et al. 2024).

An example is provided by Be + sdOB binaries (see also Figure 1.6). In these systems, the sdOB companion is the stripped core of the original donor star, while the Be star is the spun-up mass gainer (Pols et al. 1991). Although such systems are difficult to find because the hot stripped companion is easily hidden by the bright Be star, recent UV surveys and interferometric observations have increased the number of confirmed Be + sdOB systems to approximately 20 (Wang et al. 2023a; Klement et al. 2024; Rivinius et al. 2025; Frost et al. 2024; Klement et al. 2025). Another important class is represented by Be X-ray binaries, which consist of a Be star orbited by a NS (Raguzova & Popov 2005; Reig 2011). These systems are understood as the descendants of binaries that experienced MT before the SN explosion of the NS progenitor (Tauris & van den Heuvel 2006, see also the discussion below regarding binaries with CO companions).

Stellar mergers Stellar mergers are expected to occur frequently among massive stars (e.g. de Mink et al. 2014) and may be the result of different

evolutionary routes (see the review [Schneider 2025](#) and [Henneco et al. 2024b](#)). As mentioned above, during RLOF, the accretor may expand and eventually fill its own Roche lobe, producing a contact configuration. Contact can also result from CE evolution, from tidal instabilities that drive orbital decay ([Hut 1980](#)), from non-conservative MT when matter lost from the system removes a substantial amount of angular momentum (e.g., in presence of L_2 outflows, [Nariai & Sugimoto 1976](#); [Pavlovskii & Ivanova 2015](#); [Pejcha et al. 2016b](#)). Population synthesis studies based on detailed binary evolution models ([Menon et al. 2021](#); [Henneco et al. 2024b](#); [Fabry et al. 2025](#)) predict that, when a binary reaches such contact configuration, more than half of the systems will eventually merge. Finally, stellar mergers can also result from direct collisions in dense stellar clusters (e.g. [Hills & Day 1976](#); [Portegies Zwart et al. 2004](#)).

The properties of merger remnants are predicted to depend strongly on the evolutionary state of the progenitors, which will determine whether or not the merger product readjusts its structure to that of an equivalent single star (see [Langer 2012](#); [Schneider 2025](#) for a discussion). Merger remnants are also expected to amplify magnetic fields through mechanisms like shear instabilities and dynamos ([Ferrario et al. 2009](#); [Wickramasinghe et al. 2014](#); [Schneider et al. 2019](#); [Ryu et al. 2025](#)). Another proposed signature is rejuvenation (e.g. [Schneider et al. 2016](#)), whereby the merger product appears younger and can be observed as a *blue straggler* in clusters (e.g. [Chen & Han 2009](#); [Wang et al. 2022](#)). Several merger candidates have been advanced on the basis of these properties. An example of a rejuvenated magnetic merger product is HD 148937 ([Frost et al. 2024](#)). It is also suggested that a large fraction of the blue supergiants are merger products (e.g. [Podsiadlowski et al. 1990](#); [Justham et al. 2014](#); [Menon et al. 2024](#)). Finally, in Section 1.2.4 we discuss the quasi-WR star HD 45166, recently proposed as a candidate merger product.

Single degenerate binaries Binaries composed of a star in orbit with a CO (or, *single degenerate binaries*) are predicted to be an intermediate evolutionary step in the life of (massive) stellar binaries (see Figure 1.8). In this thesis (Chapters 2 and 5) we study the stability of MT in such systems and argue about their final, post-MT fates as GW progenitors. We give here only a brief overview, and refer the reader to [Tauris & van den Heuvel 2023](#) for a more comprehensive summary.

Binaries with WDs. WD components are observed in a variety of binaries. In close systems, the WD may accompany a low-mass MS star, as in cataclysmic variables (Roche-lobe filling; e.g. [Warner 1995](#); [Ritter & Kolb 2003](#); [Chomiuk et al. 2021](#)) and pre-cataclysmic variables (not yet Roche-lobe filling; e.g. [Ritter & Kolb 2003](#); [Zorotovic et al. 2011](#); [Brown et al. 2023](#)); helium WD / stellar

companion (AM CVn systems, e.g. [Nelemans et al. 2001](#)); a NS accretor in ultracompact X-ray binaries (see [Wang et al. 2026a](#) for a review). Wider systems include Sirius-type binaries (e.g. [Holberg et al. 2013](#)), consisting of a WD and a MS companion as well as symbiotic binaries (e.g. reviews from [Mikołajewska 2003](#); [Munari 2019](#)), i.e. accreting WDs with a red-giant star.

Binaries with NSs. In this category fall the aforementioned Be X-ray binaries, consisting of a NS accreting from the decretion disk of a classical Be star. These are the dominant type of high-mass X-ray binaries (i.e., those that have a massive star as stellar companion; see the review from [Reig 2011](#), and the recent catalogue [Fortin et al. 2023](#)). Low-mass X-ray binaries (with low-mass stellar companions, $< 1.5 M_{\odot}$) may also contain a NS (e.g. [Fortin et al. 2024](#)).

Binaries with BHs. BHs in binaries may be bright in X-ray or electromagnetically dark, or *inert*. In high-mass X-ray binaries, a BH accretes from a massive companion through wind-fed MT ([Walter et al. 2015](#); [Fortin et al. 2023](#)). A well-studied galactic system is Cyg X-1 ([Miller-Jones et al. 2021](#); see also Table 2.1). As for inert BHs, population synthesis studies predict that that 3% of binaries with massive MS stars should contain inert BH companions ([Langer et al. 2020](#)). Yet, only a handful are currently known. Their detection relies on detecting the reflex motion of the companion star through astrometry and/or by measuring its radial velocity variations through spectroscopy. A notable example is VFTS 243 ([Shenar et al. 2022](#)), discovered with spectroscopic measurements. Additionally, low-mass BH candidates were discovered through Gaia astrometry ([El-Badry et al. 2023b,a](#)). With future Gaia data releases, hundreds to thousands more inert galactic BHs in binaries are expected to be unveiled (e.g. [Breivik et al. 2017](#); [Janssens et al. 2022](#)).

1.2 The population of stripped stars

When a star loses its hydrogen-rich envelope through RLOF (or CE), the hot helium core is exposed, producing a stripped star whose observational appearance depends primarily on its mass and wind properties. At the low-mass end, stripping gives rise to hot subdwarfs (with masses $M \lesssim 1 M_{\odot}$; see the recent review [Heber 2026](#)), while at the high-mass end it can produce WR stars characterized by strong stellar winds and emission-line spectra ($M \gtrsim 8 M_{\odot}$; [Crowther 2007](#)). The recent discovery of intermediate-mass stripped stars (with masses $1 \lesssim M/M_{\odot} \lesssim 8$) has filled the long-standing gap between these two populations, providing direct observational evidence that binary stripping operates continuously across a wide range of stellar masses ([Götberg et al. 2018, 2023](#); [Drout et al. 2023](#); [Ludwig et al. 2025](#)). Figure 1.6 shows an observational

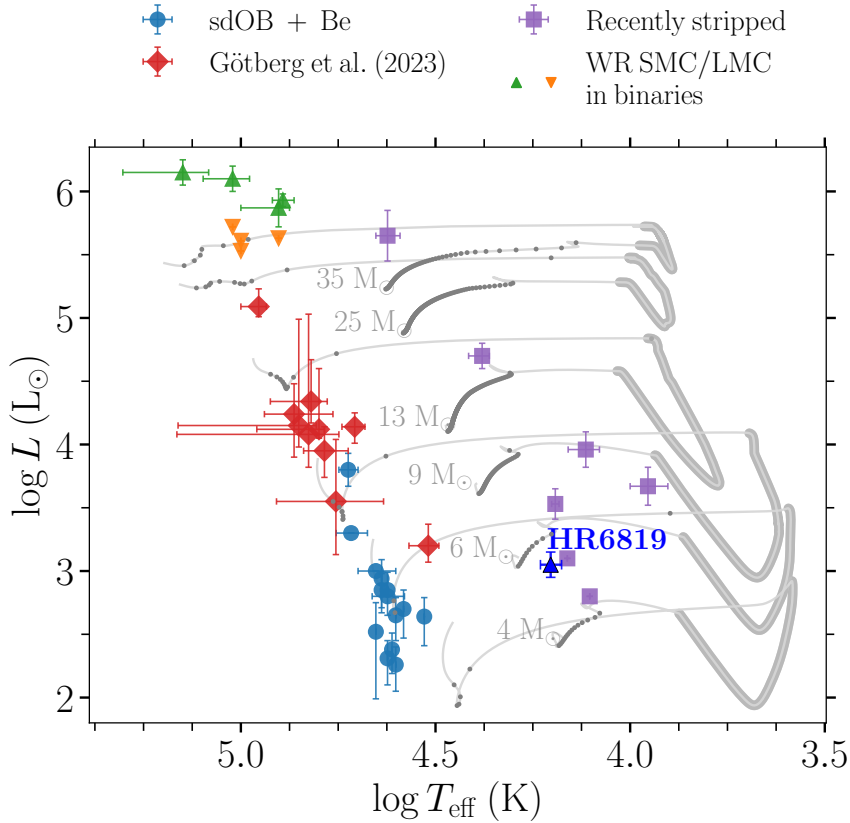


Figure 1.6: This figure is adapted from [Marchant & Bodensteiner 2024](#). It illustrates the observational zoo of binaries containing stripped-star products across the HR diagram: bloated, recently stripped stars (purple; see [Marchant & Bodensteiner 2024](#) for the corresponding references), among which HR6819 is highlighted with a blue marker (see Section 1.2.1 and Chapter 3); sdO stars with Be companions (steel blue; [Wang et al. 2021a](#) and references therein); WR stars in the Magellanic Clouds (green and orange; [Shenar et al. 2016, 2018, 2020b](#)); and intermediate-mass stripped stars (red; [Götberg et al. 2023](#)). Evolutionary tracks for donor stars of different masses undergoing Case B MT are also shown, with labels indicating both their ZAMS masses and their masses after stripping. Dots along the tracks are spaced at intervals corresponding to 1% of the donor's MS lifetime.

overview of the mass donors over the full mass regimes and various evolutionary stages post-MT.

1.2.1 Hot subdwarfs

Hot subdwarfs (we will refer to them as sdOBs, encompassing both O and B spectral types) are stripped stars that are commonly interpreted as helium-burning cores that lost their hydrogen-rich envelopes before or during helium ignition (see [Heber 2026](#) and references therein). Their masses are typically concentrated around $0.45\text{--}0.5\ M_{\odot}$, corresponding to the core mass required for helium ignition under degenerate conditions ([Iben 1967](#); [Salaris & Cassisi 2005](#)). They are thought to form via binary interaction, and population synthesis studies established three canonical formation channels: CE, stable RLOF, and the merger via GW emission of two helium WDs (e.g., [Han et al. 2002, 2003a](#); [Vos et al. 2020](#); [Arancibia-Rojas et al. 2024](#)). CE evolution is expected to produce compact sdOB binaries with orbital periods ranging from hours to a few days, typically hosting low-mass MS or WD companions. Stable RLOF instead leads to wider systems with periods of hundreds to thousands of days and more massive MS companions (such as F, G, K-type or Be stars). Finally, the merger of two helium WDs is often invoked to explain helium-rich, overmassive ($> 0.5\ M_{\odot}$) sdO(B) stars (e.g. [Saio & Jeffery 2000](#); [Justham et al. 2011](#)). Figure 1.7 shows examples of known helium sdOB stars ([Latour et al. 2026](#)) together with the growing population of the magnetic ones ([Pelisoli et al. 2022](#); [Dorsch et al. 2022, 2024](#)). Their higher masses inferred and distribution in the HR diagram are consistent with predictions from double-WD mergers ([Zhang & Jeffery 2012](#)). This is further supported by the very low fraction of short-period binaries among helium sdOs ([Geier et al. 2022](#); [Snowdon et al. 2025](#)).

Large catalogues (e.g., from the Sloan Digital Sky Survey, [Geier et al. 2015](#); Gaia, [Dawson et al. 2024](#)), compile to date more than 6,000 spectroscopically confirmed sdOBs and over 60,000 candidates ([Geier 2020](#); [Culpan et al. 2022](#)). Observationally, about one third of these known sdOBs are found to be short-period binaries hosting low-mass MS or WD companions (suggesting CE formation), and another third shows long-period composite-spectrum with F, G, or K-type companions (suggesting RLOF). And we can add to these also the small, but growing, sample of sdOBs with Be companions (see Section 1.1.5). These rapidly growing samples will be further expanded and characterized by future Gaia data releases ([Geier 2020](#)), large spectroscopic surveys such as 4MOST ([de Jong et al. 2019](#)), and high-precision photometry from the Transiting Exoplanet Survey Satellite ([Ricker et al. 2015](#)). In addition, future space-based GW observatories such as LISA ([Amaro-Seoane et al. 2017](#)) and TianQin ([Luo et al. 2016](#)) are expected to detect the most compact sdOB +

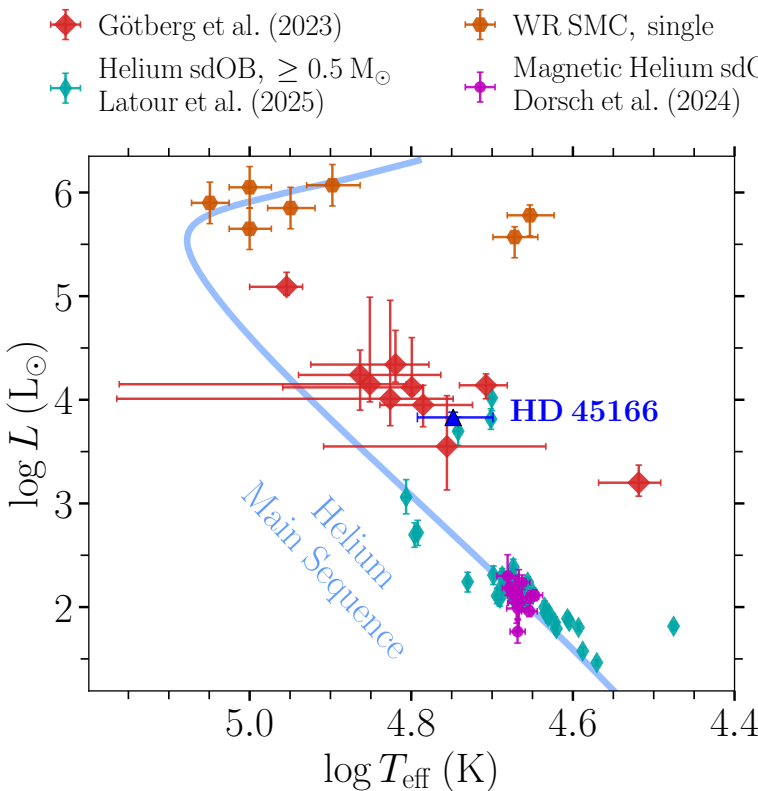


Figure 1.7: Observational sample of intermediate-mass stripped stars (same as in Figure 1.6; Götberg et al. 2023), together with the single WR stars in the SMC (from Table 2 of Schootemeijer et al. 2024), the helium sdO(B)s from the Arizona–Montréal spectroscopic program (Latour et al. 2026, their Table D.1), and an additional 12 magnetic helium sdOs from Pelisoli et al. 2022; Dorsch et al. 2022, 2024 (Tables 1 and A.2 of Dorsch et al. 2024). A theoretical helium-burning Main Sequence is also shown in light blue, and the quasi-WR HD45166 is also highlighted in blue (see Section 1.2.4). The single WR stars in the SMC have been conjectured to be products of stellar mergers (Schootemeijer & Langer 2018), while helium sdOBs with masses greater than $0.5 M_{\odot}$ are usually explained as products of double-WD mergers (see main text). The intermediate-mass stripped stars have been modelled with population-synthesis codes as products of stable RLOF and CE, without considering stellar mergers (Hovis-Afflerbach et al. 2025; but see also Wang et al. 2026c). This thesis discusses a possible formation channel for these objects involving stellar mergers (see Chapter 4).

WD binaries, providing a complementary probe of the shortest-period systems (e.g. [Lin et al. 2024](#)).

1.2.2 Bloated stripped stars

On the mass range of classical sdOBs (and, in few cases, also intermediate-mass stripped stars), *bloated* (or *puffed-up*) stripped stars are recently being observed shortly after MT, capturing the stage before the stripped remnant contracts to its compact helium-star configuration (one of the first examples being HR6819, [Bodensteiner et al. 2020a](#); [El-Badry & Quataert 2021](#), see also the below paragraph). They present inflated radii and cooler effective temperatures than the classical hot stripped stars (see Figure 1.6), resembling therefore ordinary B-type stars as they overlap with the MS. They can remain optically bright over a relatively long timescale due to their hydrogen-burning shell that can sustain thermal equilibrium ([El-Badry & Quataert 2021](#); [Dutta & Klencki 2024](#)).

The strange story of HR6819

Since HR6819 is modeled in Chapter 3, we dedicate a paragraph to this system (and we show it with a special blue marker in Figure 1.6).

HR6819 (QV Tel) belongs to the so-called *BH-impostors*, objects that were initially and erroneously proposed to host stellar-mass BHs ([Bodensteiner et al. 2022](#)). Specifically, HR6819 was spectroscopically interpreted as a hierarchical triple system consisting of a B-type giant in a ~ 40 -day orbit around an unseen CO, while a Be star appeared stationary (therefore, a distant tertiary) ([Rivinius et al. 2020](#)). Under the assumption that the visible B star was a normal $\sim 5 M_{\odot}$ giant, the inferred mass function implied a dark companion of at least $\sim 4 M_{\odot}$, making a BH interpretation plausible. This scenario was subsequently challenged when [El-Badry & Quataert 2021](#) and [Bodensteiner et al. 2020a](#), independently, applied spectral disentangling and revealed that the Be star is not a distant tertiary, but instead participates in the 40-day orbit, with a small reflex motion in anti-phase with the primary. This demonstrated that the system is a close binary with an extreme mass ratio, and that the optically bright B-type object could be interpreted as a low-mass, puffed-up stripped star, in a contraction phase shortly after MT. In this revised picture, no unseen CO is required. Using high-angular-resolution observations with the Very Large Telescope Interferometer (VLTI), [Frost et al. 2022](#) ruled out the bright wide companion required by the triple-system scenario and directly resolved two luminous sources whose motion was consistent with the known 40-day orbit,

thereby confirming the Be + stripped-star binary interpretation. Building on this result, [Klement et al. 2025](#) analysed twelve interferometric epochs and combined them with radial-velocity measurements to derive the astrometric orbit and model-independent dynamical masses.

In its current interpretation, HR6819 is a post-MT binary composed of a rapidly rotating Be star ($4.24 \pm 0.31 M_{\odot}$) and a *puffed-up* pre-subdwarf stripped star ($0.27 \pm 0.06 M_{\odot}$) in a (40.3266 ± 0.0016) -day circular orbit. Its properties are particularly extreme: HR6819 has the lowest-mass stripped component, the most extreme mass ratio, and one of the tightest orbital separations among the known sdOB + Be systems, being also one of the best constrained systems in terms of errors ([Klement et al. 2025](#)).

1.2.3 Classical Wolf-Rayet stars

Classical WR stars are the most massive stripped stars, typically characterized by hydrogen-poor surfaces and strong emission-line spectra produced by dense, radiatively driven winds (see [Crowther 2007](#); [Shenar 2026](#) and references therein). They are generally interpreted as the exposed helium cores of initially massive stars (with birth masses $M \gtrsim 25 M_{\odot}$), although the minimum mass required to display a WR spectrum depends on metallicity and wind strength ([Shenar et al. 2020b](#)). Two formation channels are thought to contribute to the WR population. In the single-star (or, “Conti”) scenario, sufficiently massive stars remove their own hydrogen-rich envelopes through powerful stellar winds and eruptive mass loss ([Abbott & Conti 1987](#); [Meynet & Maeder 2005](#); [Humphreys & Davidson 1994](#)). Alternatively, binary interaction can strip the envelope through stable RLOF or CE evolution ([Paczyński 1967](#); [Vanbeveren et al. 1998a](#)).

Current catalogues contain close to 700 known WR stars in the Milky Way ([Rosslowe & Crowther 2015](#)); in the Magellanic Clouds, around 150 WR stars are known in the Large Magellanic Cloud (LMC) and 12 in the SMC ([Neugent et al. 2018](#); see also [Figure 1.6](#) and [Figure 1.7](#)). Observational studies consistently find binary fractions of approximately 40–50% among Galactic WR stars ([van der Hucht 2001](#); [Dsilva et al. 2020, 2022, 2023](#); [Deshmukh et al. 2024](#)), with comparable values reported in the Magellanic Clouds ([Schnurr et al. 2008](#)). This is somewhat surprising, since weaker stellar winds at low metallicity are often expected to increase the importance of binary stripping. However, these expectations are complicated by the fact that lower metallicity increases both the minimum stripped-star mass required to appear as a WR star and the initial mass required for self-stripping, making the net dependence of the WR binary fraction on metallicity non-trivial ([Shenar et al. 2020b](#); [Gilkis et al. 2025](#)). Alternative explanations explored in literature include enhanced mass

loss (Owocki et al. 2004; Cheng et al. 2024; Pauli et al. 2026) and stellar mergers (Vanbeveren et al. 1998a; Schootemeijer et al. 2024; Li et al. 2024). Future surveys are expected to substantially improve the census and characterization of WR stars. In particular, 4MOST (de Jong et al. 2019) will monitor the WR population at subsolar metallicity, while next-generation facilities such as the Extremely Large Telescope (ELT; Gilmozzi & Spyromilio 2007; Padovani & Cirasuolo 2023) will enable studies of WR populations in more distant galaxies, helping to constrain the relative roles of stellar winds and binary interaction in their formation.

1.2.4 Intermediate-mass stripped stars

Intermediate-mass stripped stars ($\sim 1\text{--}8, M_{\odot}$) are thought to originate mainly through binary interaction, and population synthesis studies predict their formation through RLOF and CE evolution (e.g., Yungelson et al. 2024; Hovis-Afflerbach et al. 2025; Blomberg et al. 2025; Wang et al. 2026c). Despite being common outcomes of binary evolution, intermediate-mass stripped stars eluded direct detection until recently. After envelope stripping, these stars become hot helium-burning objects whose UV emission stands out against the optical (Götberg et al. 2017, 2018). In fact, in the optical bandwidths they are typically outshone by their rejuvenated MS companions, making them difficult to identify with ground-based telescopes. Additionally, unlike WR stars, they possess winds that are generally too weak to produce the strong emission-line spectra used to discover massive stripped stars. Interestingly, these intermediate-mass stripped stars can also expand again after core-helium depletion and cross the MS leading to bloated stars (e.g. Laplace et al. 2020a). The first substantial sample of intermediate-mass stripped stars was reported by Drout et al. 2023, who identified 25 candidates in the Magellanic Clouds with inferred masses of roughly 1 to 8 $M_{\odot}$ (Götberg et al. 2023; we show them in Figure 1.6 and Figure 1.7). Further, the recent SUMS survey uncovered over 800 photometric candidates, providing a rich target list for future spectroscopic follow-up (Ludwig et al. 2025).

Future progress is expected to come primarily from UV surveys, in particular the Ultraviolet Explorer (UVEX; Kulkarni et al. 2021, see their Science pillar 1), which will probe the far-UV regime and is designed to map the full mass distribution of stripped stars. Complementary UV imaging from the UV Imaging Telescope (Tandon et al. 2017) on Astrosat and ongoing UV spectroscopy with the Hubble Space Telescope continue to provide high-resolution constraints on their atmospheres and winds. In parallel, data from the Sloan Digital Sky Survey (see the ongoing SDSS-V, Kollmeier & The SDSS-V Collaboration 2025)

will enable spectroscopic confirmations, while upcoming Gaia releases will refine distances and improve the identification of genuine Magellanic Cloud members.

Another strange story: HD45166

Since HD45166 inspired the evolutionary channel explored in Chapter 4, we dedicate a paragraph to this system (and we show it with a special blue marker in Figure 1.7).

HD 45166 is a binary system containing a MS star (of spectral type B7 V) and a hot, stripped companion whose spectrum shows WR-like emission, but with unusually narrow lines, variability, and strong carbon, nitrogen, and oxygen features, which led to the label quasi-WR rather than classical WR (Steiner & Oliveira 2005; Shenar et al. 2023). Specifically, Shenar et al. 2023 utilized high-resolution spectropolarimetry and discovered that the quasi-WR star possesses an exceptionally strong 43-kilogauss magnetic field. Radial-velocity monitoring and TESS photometry further showed that the previously reported (Steiner & Oliveira 2005) 1.6-day period is instead produced by pulsations in the B7 V companion, while the true orbital solution corresponds to a much wider (~ 22.5 yr) orbit. This yielded a mass of $2.03 \pm 0.44 M_{\odot}$ for the helium star when combined with constraints from the B-star companion, further refined from interferometric data to a dynamical, model-independent mass of $1.96^{+0.74}_{-0.54} M_{\odot}$ (Deshmukh et al. 2025).

In terms of its evolutionary origin, HD 45166 is currently interpreted as the product of a CE merger of a helium star and a post-MS, hydrogen-rich star that is able to eject the hydrogen-rich layers during CE (see the diagram in Figure 4.1). The final fate of the stripped star remains uncertain. Depending on its final core mass, it may either form an oxygen-Neon-Magnesium WD or undergo core collapse, possibly through an electron-capture supernova (e.g. Chanlaridis et al. 2022). While stripped stars in sufficiently close binaries can expand again after core-helium exhaustion (e.g. Laplace et al. 2020a), the wide orbit of HD45166 makes it unlikely (Deshmukh et al. 2025). Its ultimate fate is therefore expected to be determined primarily by its own stellar evolution. If a NS is formed and the present-day magnetic field is preserved during collapse, magnetic-flux conservation would naturally amplify it to magnetar-strength fields (Shenar et al. 2023).

1.3 Gravitational wave astronomy

The first direct detection of GWs marked the beginning of a new observational window on the Universe. On 14 September 2015, during its first observing run, the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) registered the signal GW150914, originating from the coalescence of two stellar-mass BHs (Abbott et al. 2016). The event was observed coherently in the two LIGO detectors located in Louisiana and Washington (USA), where differential changes in the arm lengths corresponding to a fractional strain of $\sim 10^{-21}$ produced the characteristic chirp signal. This discovery provided the first direct detection of GWs, a fundamental prediction of general relativity (Einstein 1915). Prior to this breakthrough, GWs had only been inferred indirectly, most notably through the orbital decay of the Hulse–Taylor pulsar (Hulse & Taylor 1975).

The initial detection was rapidly followed by a growing sample of CO mergers. During the first two observing runs (O1 and O2), the LIGO and Virgo detectors identified several additional binary BH coalescences, bringing the sample to roughly ten confident detections (Abbott et al. 2019b, 2021c). The third observing run (O3) dramatically increased this number, with their data release yielding another ~ 70 BH mergers (Abbott et al. 2023a). At the time of writing, the second part of the fourth observing run (O4) is finished, and the full catalogue of GW events detected by the LIGO–Virgo–KAGRA (LVK) collaboration approaches approximately more than three hundred signals (The LIGO Scientific Collaboration et al. 2025a, 2026b). Shortly after the first binary BH detection came also the first binary NS merger GW170817 (Abbott et al. 2017b), observed across the electromagnetic spectrum, including a short gamma-ray burst (Abbott et al. 2017a) and a kilonova counterpart (Abbott et al. 2017c). Together with the first confirmed NS–BH mergers, GW200105 and GW200115 (Abbott et al. 2021a), a new probe for multimessenger astronomy of CO binaries became available.

It is clear that, beyond individual events, the broader astrophysical impact of GW astronomy is profound. BHs are electromagnetically dark and difficult to detect (see Section 1.1.5), but with the GWs catalogue the number of BH detections is growing exponentially, such that the number of stellar-mass BHs detected via GWs fairly outnumbers that from any other technique altogether. Additionally, it is not just a matter of numbers: waveforms studies provide a direct probe of BHs (chirp) masses, effective spins, mass ratios. Moreover, triangulation of arrival times across a global detector network enables sky localization of the sources, allowing alerts for multimessenger follow-ups and, when signals are sufficiently strong, host galaxy identification (this was the case for GW170817, see e.g. Hjorth et al. 2017), or at least galaxy catalogue cross-matching (e.g. Rinaldi & Del Pozzo 2022).

The future is certainly promising for GW science. At present, the global network of ground-based interferometers includes Advanced LIGO ([LIGO Scientific Collaboration et al. 2015](#)), Advanced Virgo ([Acernese et al. 2015](#)), and KAGRA ([Akutsu et al. 2021](#)), with the latter joining during the last part of O3. Continuous upgrades to detector sensitivity are expected to increase detection rates significantly, with projections suggesting hundreds of compact-binary mergers per year at design sensitivity ([Abbott et al. 2018](#)). Looking further ahead, next-generation observatories such as the Einstein Telescope (ET) ([Maggiore et al. 2020](#)) and the Cosmic Explorer ([Reitze et al. 2019](#)) are expected to expand the observable volume of the Universe down to the redshift of the formation of the first stars ([Hall & Evans 2019](#)), potentially increasing detection rates to tens of thousands of events per year ([Borhanian & Sathyaprakash 2024](#)). In parallel, space-based detectors such as LISA ([Amaro-Seoane et al. 2017](#)) and TianQin ([Luo et al. 2016](#)) will probe the milli-Hz GW regime, enabling observations of supermassive BH mergers (e.g. [Klein et al. 2016](#)), extreme mass-ratio inspirals (e.g. [Babak et al. 2017](#)), and compact Galactic binaries with WDs (e.g. [Nelemans 2009](#)).

1.3.1 The catalogue of gravitational wave events

As this thesis investigates the evolution of interacting massive binaries toward becoming CO mergers, we are particularly interested in how the properties of the observed GW population can constrain the evolutionary histories of their stellar progenitors, and conversely, how the physics of binary evolution shape the diversity of the CO binaries observed by the LVK network. To provide the necessary observational context, this Section briefly summarizes the main population properties inferred from the GWTC-5 catalogue (focusing on binary BHs), before discussing their proposed formation channels in Section 1.3.2. This Section is entirely based on the GWTC-5’s population paper, [The LIGO Scientific Collaboration et al. 2026a](#).

The broadest constraint provided by the observed population of GW sources is the local merger rate of binary BHs. For systems with component masses between $2.5 M_{\odot}$ and $200 M_{\odot}$, this is inferred to be $27.5\text{--}49.4 \text{ Gpc}^{-3} \text{ yr}^{-1}$ at a redshift of $z = 0.2$. The merger rate increases with redshift, approximately following the cosmic star-formation history ([Madau & Dickinson 2014](#)). This evolution is commonly parameterized as a power law of the cosmological scale factor, $R(z) \propto (1+z)^{\kappa}$, with $\kappa = 2.5^{+0.7}_{-0.7}$. The inference of the merger rate, however, relies on a model for the underlying mass distribution of the sources, which must be derived jointly from the observed population.

Features in the mass distribution The binary BH mass spectrum exhibits several distinct features rather than following a simple power-law distribution. The global peak in the primary-mass distribution lies around $10 M_{\odot}$. This peak is also discernible in the secondary-mass distribution, indicative of the fact that *very* uneven pairings are in general disfavored. While earlier studies suggested a preference for slightly unequal-mass systems ($q \approx 0.8$ from GWTC-4.0; [The LIGO Scientific Collaboration et al. 2025b](#)), GWTC-5.0 now finds inconclusive evidence for this trend, though mass ratios > 0.5 remains supported by all models. A second feature appears near $35 M_{\odot}$. Rather than representing a localized peak, it is now interpreted as a turnover in both the primary- and secondary-mass distributions, i.e. the onset of a decline in the merger rate density. Binary systems in this mass range show a preference for equal-mass pairing. Furthermore, current population models based on GWTC-5.0 rule out a completely empty lower mass gap between 3 and $5 M_{\odot}$, supporting a continuous transition between the NS and BH populations that was already suggested by a few electromagnetic ([Wang et al. 2024a](#); [Barr et al. 2024](#)) and microlensing ([Lam et al. 2022](#); [Kruszyńska et al. 2024](#)) observations. Finally, long-standing stellar evolution models predict that very massive stars may undergo pair-instability SNe, completely disrupting the star and preventing the formation of BHs within a characteristic mass range ([Barkat et al. 1967](#); [Fowler & Hoyle 1964](#); [Heger et al. 2003](#); [Woosley et al. 2007](#); [Woosley 2017](#); [Marchant et al. 2019](#); [Farmer et al. 2019](#)). This is expected to produce a “pair-instability mass gap” in the BH mass distribution. However, no clear evidence for such a gap is found in GWTC-5.0. The primary-mass distribution, while rapidly dropping with a power-law behavior, still extends smoothly beyond $100 M_{\odot}$ (but see also [Tong et al. 2026](#)). In particular, the most massive event, GW231123 ([Abac et al. 2025](#)), contains two BHs with inferred masses of $\sim 137 M_{\odot}$ and $\sim 103 M_{\odot}$.

Spin properties Spin measurements indicate that most merging BHs possess low to moderate spins, consistent with the findings of the previous catalogues. Approximately 69–84% of BHs have dimensionless spin magnitudes $\chi \leq 0.5$, and a distinct subpopulation with at least one rapidly rotating BH ($\chi \sim 0.7$) is confidently identified. The effective inspiral spin parameter, χ_{eff} , peaks near zero but exhibits a clear asymmetry toward positive values, corresponding to spins preferentially aligned with the orbital angular momentum vector. Conversely, approximately 30–46% of systems have $\chi_{\text{eff}} < 0$ (implying a tilt of more than 90° relative to the orbital angular momentum).

1.3.2 From stellar binaries to double black holes

This Section is mainly based on the review "Rates of compact object coalescences" by I. Mandel and F. Broekgaarden.

To explain the formation of binary BHs as GW sources, several scenarios have been proposed, including primordial BHs (that is, BHs formed and paired in the early Universe, e.g. [Bagui et al. 2025](#)), formation in the disks of active galactic nuclei (e.g. [Arca Sedda et al. 2023](#)), dynamical interactions in dense environments (e.g. [Kulkarni et al. 1993](#)), and the evolution of isolated binary stars (e.g. [van den Heuvel 1976a](#); [Marchant et al. 2016](#); [van den Heuvel et al. 2017](#)). Except for primordial formation, *ALL* these channels involve stars, making GWs a powerful new probe to understand stellar evolution. In this thesis we will focus on the formation in isolated binaries, i.e. the scenario in which the two COs are the final product of an evolutionary route of an isolated (massive) binary. In general, evolving to merging COs is a finely-tuned route of massive-star evolution, where the main challenge is to produce a orbital separations small enough for GWs to drive the coalescence within the age of the Universe, ~ 13.9 Gyr. As seen in Section 1.1.1, MT plays a crucial role in this context: it can provide the required orbital tightening in the parent stellar binaries. For a circular binary composed of two COs with masses m_1 and m_2 and orbital separation a , the delay time due to GW emission is given by

$$t_{\text{delay}} = \frac{5}{256} \frac{c^5 a^4}{G^3 m_1 m_2 (m_1 + m_2)}. \quad (1.23)$$

In the following, we present the four main isolated-binary formation channels that have been proposed to produce merging BHs binaries, two of which see MT as the main hardening mechanism and are the protagonists of this thesis (represented in Figure 1.8), and the other two do not involve MT and are briefly described for completeness. The relative contribution of the various proposed formation channels to the observed population of GW mergers remains an open question. It is generally expected that multiple channels operate simultaneously in nature (e.g. [Zevin et al. 2021](#)), but current theoretical uncertainties prevent a precise quantitative decomposition of their respective contributions (e.g. [Iorio et al. 2023](#); [Broekgaarden et al. 2026](#)).

Common-envelope evolution The classical formation channel for binary BHs involves a CE episode³ (e.g. [Tutukov & Yungelson 1993](#); [Tauris & van den](#)

³It is often found in literature that *CE channel* refers to either the presence of one or two CE episodes during the evolution from a binary with two stellar components to a double BH

Heuvel 2006). A pictorial representation is shown in Figure 1.8. After the first MT episode and the formation of the first BH, the secondary evolves and fills its Roche lobe. MT onto the CO becomes then dynamically unstable, leading to CE evolution. During this phase, the CO spirals into the envelope of the giant, losing orbital energy and angular momentum through drag forces (see the reviews by Ivanova et al. 2013; Ivanova et al. 2020, and also Section 1.1.2). To predict the final outcome of CE, binary population synthesis codes assume that part of the released orbital energy unbinds the envelope, which allows the binary separation to shrink by several orders of magnitude (e.g. Stevenson et al. 2017, Giacobbo & Mapelli 2018, van Son et al. 2022b), thereby comfortably entering the separation range required for GW mergers.

Astrophysical fingerprints. The resulting binary BH mergers are generally predicted to have relatively short delay times ($\lesssim 1$ Gyr) and component masses below $\sim 30 M_{\odot}$, reflecting the stringent conditions required for successful envelope ejection (e.g. Neijssel et al. 2019; Marchant et al. 2021; Klencki et al. 2021; van Son et al. 2022a; Hendriks et al. 2023; Briel et al. 2023). CE may also produce binary BHs with measurable positive effective spins through tidal spin-up of the progenitor of the second-born BH (Bavera et al. 2020, 2021; Olejak et al. 2024).

Stable mass transfer The alternative channel involves a stable MT RLOF episode in place of CE during the interaction of the original secondary with the already formed CO (see Figure 1.8). In particular, van den Heuvel et al. (2017) was the first to highlight that the isotropic re-emission mode (see Section 1.1.1) may be crucial in tightening the orbits of binaries with BHs. While SMT can produce a wide range of outcomes, from orbital expansion to only moderate hardening (Tauris & van den Heuvel 2023), population synthesis studies found that sufficiently compact merging systems can still form under favorable conditions (e.g. Kruckow et al. 2016; Neijssel et al. 2019; van Son et al. 2022b; Briel et al. 2026), including extreme orbital tightening due to mass outflows from L_2 (Willcox et al. 2023; Olejak et al. 2024; Gallegos-Garcia et al. 2024; Klencki et al. 2026, see also Chapter 2). Recent studies suggest that the contribution of the CE channel to the formation of merging binary BHs may have been overestimated due to uncertainties in envelope binding energies and MT stability criteria (Klencki et al. 2021; Olejak et al. 2021; Marchant et al. 2021; Gallegos-Garcia et al. 2021; Li et al. 2025; Broekgaarden et al. 2026, see also Chapter 5). At the same time, detailed binary evolution calculations have shown that MT stability generally increases with stellar mass (e.g. Ge et al. 2020, and this thesis, Chapters 2, 5). As a result, SMT is currently considered

binary, see Figure 1.8. In this thesis, we will label as CE (stable MT) channel the case in which the second MT episode is CE (stable MT), irrespective of the first MT episode.

one of the leading isolated-binary channels for the formation of merging binary BHs (e.g. [van Son et al. 2022b](#); [Briel et al. 2023, 2026](#); [Broekgaarden et al. 2026](#); [Willcox et al. 2025](#)).

Astrophysical fingerprints. The resulting binary BH mergers are predicted to have longer delay times ($\gtrsim 1$ Gyr) and can reach higher masses than their CE counterparts ([van Son et al. 2022a](#); [Briel et al. 2026](#); [Klencki et al. 2026](#)). Because stable MT typically leaves wider post-interaction binaries, tidal spin-up is less efficient, leading to predominantly low-spin BHs and distinctive mass-ratio distributions shaped by the preceding MT episode ([Olejak et al. 2024](#); [Banerjee & Olejak 2024](#); [Briel et al. 2026](#)). However, the effective spins remain sensitive to the adopted prescriptions for MT efficiency, stellar rotation, and angular-momentum transport, and may reach moderate spin values (e.g., [Belczynski et al. 2020](#); [Xu et al. 2025](#)).

Chemically homogeneous evolution In very close massive binaries (initial orbital periods of order ~ 1 day), tidal synchronisation can maintain extremely rapid stellar rotation. This is argued to induce strong rotational mixing leading to nearly homogeneous chemical composition throughout the star (e.g. [Mandel & De Mink 2016](#); [Marchant et al. 2016](#)). As a consequence, the stars avoid significant radial expansion, allowing them to remain compact enough to fit within short-period orbits until they evolve into double COs. Although this channel is expected to operate only under specific conditions, requiring very massive, rapidly rotating, and typically low-metallicity binaries, population synthesis studies suggest that it may contribute a significant fraction of the observable binary BH population, particularly at the highest BH masses ([Riley et al. 2021](#); [Stevenson & Clarke 2022](#); [van Son et al. 2025](#)). Observational examples of MS binaries evolving through chemically homogeneous evolution remain hard to obtain, especially as it requires high mass and low metallicity environments that are hardly accessible with current instrumentations.

Astrophysical fingerprints. According to binary population synthesis studies, binary BHs formed through chemically homogeneous evolution systems preferentially populate the high-mass end of the stellar-mass BH distribution, with nearly equal component masses ([Mandel & De Mink 2016](#); [Marchant et al. 2016](#); [Riley et al. 2021](#); [Broekgaarden et al. 2022b](#)). Owing to the tidally locked, rapidly rotating progenitors, the resulting BH spins are expected to be preferentially aligned with the orbital angular momentum, although their magnitudes remain sensitive to the progenitors' metallicity and core collapse physics ([Broekgaarden et al. 2022b](#); [Marchant & Bodensteiner 2024](#)). Finally, these binary BHs are predicted to merge predominantly after delay times of several Gyr ([Mandel & De Mink 2016](#); [du Buisson et al. 2020](#)).

Population III stars Population III stars represent the first generation of stars formed in the early Universe, expected to arise within the first billion years after the Big Bang (e.g. [Haiman et al. 1996](#); [Abel et al. 2002](#)). As they form from primordial gas, they are essentially metal-free, and therefore may avoid interaction while still fit in tight orbits, and may contribute non-negligibly to the population of merging BHs (e.g. [Kinugawa et al. 2014](#); [Mestichelli et al. 2025](#)).

Astrophysical fingerprints. Binary population synthesis calculations predict that Population III binary BHs are preferentially massive, with chirp masses typically peaking around $\sim 30 M_{\odot}$ (corresponding to total binary masses of $\sim 60 M_{\odot}$), and may also contribute to the lower part of the pair-instability mass gap ([Kinugawa et al. 2014, 2020, 2021](#); [Tanikawa et al. 2022](#); [Tanikawa 2024](#)). They are expected to have generally high mass ratios, low effective spins in the local Universe (with higher spins predicted at high redshift), and long delay times that allow stars formed in the early Universe to contribute to the present-day GW population ([Kinugawa et al. 2020](#); [Tanikawa 2024](#)).

1.4 Outline of the thesis

This thesis focuses on MT both in binaries containing a CO companion and in binaries composed of two stellar components. The overarching goal is to improve our understanding of the evolution of massive binary stars on their pathway toward becoming GW sources. The products of binary interaction are fundamentally shaped by the physics of MT, that is how mass is exchanged and lost from binary systems. This is evident both from the variety of stripped stars discussed in Section 1.2 and from the properties of the coalescing COs population presented in Section 1.3. Particular emphasis is placed on MT stability, as the distinction between stable and unstable MT introduces a major bifurcation in the evolutionary pathways of massive binaries at several stages of their evolution (see Figure 1.8). The central questions addressed in this thesis are summarized below.

Chapters 2, 3

How does the orbit of a binary evolve under different modes of mass loss, and what orbital configurations can(not) be produced by stable MT? This question is addressed from complementary perspectives in Chapters 2 and 3. Chapter 2 investigates the orbital evolution of binaries containing a CO companion undergoing non-conservative MT. This work is motivated by the need to understand how COs can be brought into sufficiently tight orbits to

merge within the age of the Universe and produce observable GW sources (see Section 1.3.2). Chapter 3 instead explores the evolution of binaries composed of two stellar components, focusing on evolutionary pathways capable of reproducing the peculiar post-interaction system HR6819 (see Section 1.2.1), for which accurate dynamical masses have recently been obtained through optical interferometry (Klement et al. 2025). This study is motivated by the goal of constraining MT physics using the growing sample of well-characterized post-interaction binaries as empirical calibrators of uncertain binary-interaction processes.

Chapter 4

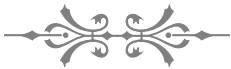
How do (intermediate-mass) stripped stars form, and can stellar mergers resulting from unstable MT contribute to their population? This question is explored in Chapter 4. In particular, we investigate a scenario in which a stripped star originates from a CE phase initiated by the secondary star after the primary has previously been stripped through stable MT. If the CE evolution leads to a merger of the two helium-rich cores while simultaneously ejecting part or all of the H-rich envelope, the resulting object may appear as a stripped star (see the evolution diagram in Figure 4.1; this is the scenario that was originally proposed to explain the formation of the quasi-WR HD45166, Shenar et al. 2023). This work is motivated by the rapidly increasing number of intermediate-mass stripped stars being identified and characterized through UV photometry and spectroscopy, and by the need to understand their formation and observable properties in preparation for future UV missions such as NASA’s UVEX.

Chapter 5

Which internal stellar properties determine the stability of MT in binaries? Chapter 5 addresses this question in binaries containing a CO companion. We investigate how stellar structure properties, including convective-core overshooting and metallicity, influence the stability of MT. This study is motivated by the need to better characterize the imprint of the stable MT channel on the merging binary-BH population. In particular, MT stability remains one of the dominant uncertainties in binary population synthesis, while many rapid population-synthesis tools do not explicitly keep track of the internal structure of stars. Understanding how stellar properties affect MT stability is therefore essential for improving astrophysical inference from current and future GW observations.

Chapter 6

Finally, Chapter 6 looks back at these questions and summarizes how the findings of this thesis contribute to advancing our knowledge in each of those. It then concludes the thesis with an outlook.



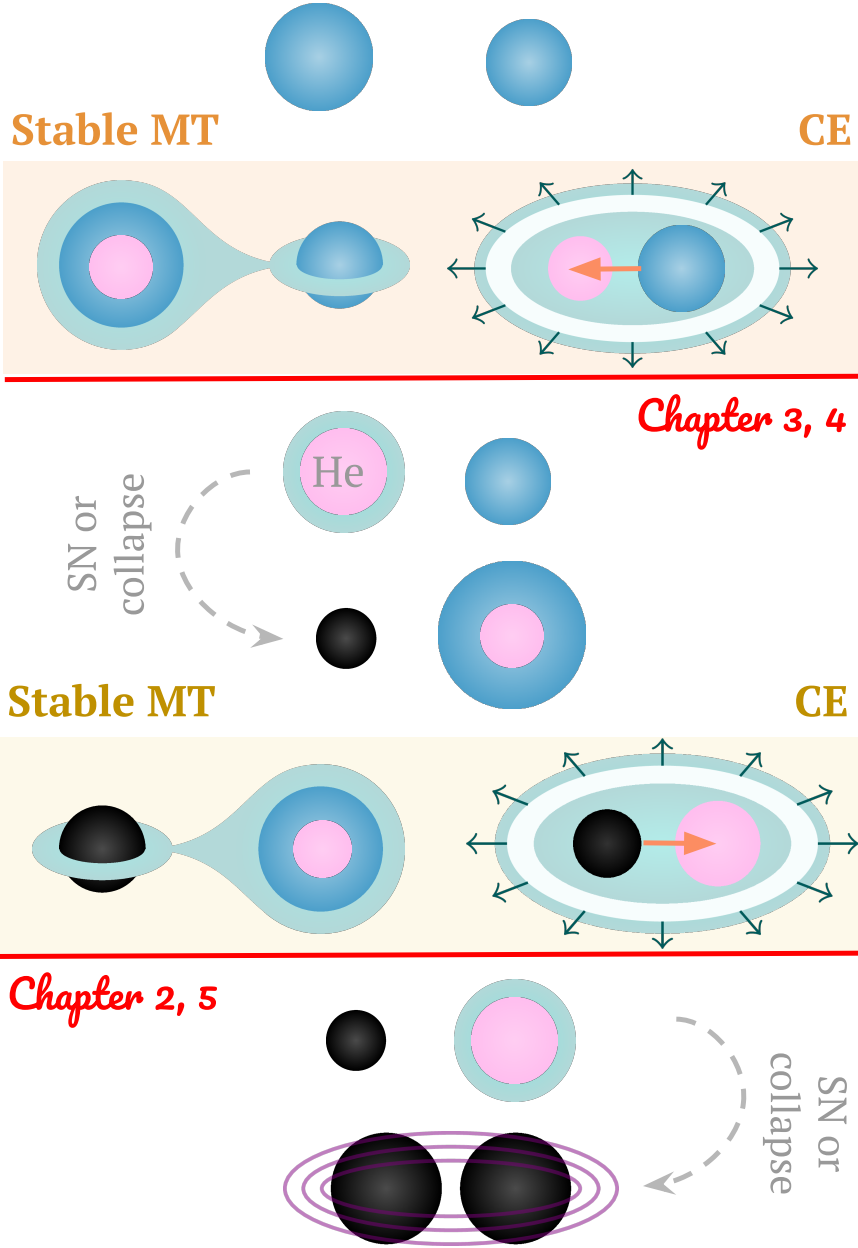


Figure 1.8: Schematic representation of the life of a massive stellar binary towards becoming a chirping BH binary. The diagram highlights that the outcome of MT stability introduces a key bifurcation in the evolutionary pathway in at least two anchors: the first MT episode decides whether a stripped star or a stellar merger is formed; the second MT episode determined whether the double CO will merge within the age of the universe. The Figure further illustrates the relevant Chapters of this thesis.

Chapter 2

Forming merging double compact objects with stable mass transfer

This chapter is based on

Forming merging double compact objects with stable mass transfer

A. Picco, P. Marchant, H. Sana, and G. Nelemans

[ASTRONOMY & ASTROPHYSICS, 681, A31 \(2024\)](#)

Author contributions A. Picco developed the code, performed the simulations, and wrote the manuscript of the paper. P. Marchant assisted in developing the methodology. During the whole process, A. Picco was guided by regular discussions with P. Marchant, H. Sana and G. Nelemans. The manuscript was improved by all co-authors. With respect to the original publication, some of the text was altered to fit the chapter format of this thesis.

Original abstract

Context. Merging double compact objects (COs) are one of the possible endpoints of the evolution of stellar binary systems. As they represent the inferred sources of every detected gravitational wave (GW) signal, modeling their progenitors is of paramount importance both to gain a better understanding of gravitational physics and to constrain stellar evolution theory.

Aims. Stable mass transfer (MT) between a donor star and a black hole (BH) is one of the proposed tightening mechanisms to form binary BHs that merge within the lifetime of the universe. We aim to assess the potential of stable non-conservative MT to produce different pairings of compact objects including BHs, neutron stars (NS) and white dwarfs (WD).

Methods. We investigated the conditions (orbital periods and mass ratios) required for MT between a star and a CO to be stable and to lead to binary COs that merge within a Hubble time. We use published results on the response of the stellar radii to rapid mass loss, covering different evolutionary stages and masses. Coupled with analytical models of orbital evolution, we determined the boundary for unstable MT as well as the post-interaction properties of binaries undergoing stable MT. In addition, we investigated the impact of the angular momentum loss prescription in the resulting hardening by accounting for both the isotropic re-emission from the accretor's vicinity and mass outflow from the second Lagrangian point.

Results. Stable MT in systems with a CO + Roche lobe-filling star, in the completely non-conservative limit of isotropic re-emission from the vicinity of the accretor, is shown to be able to form any pair of merging double COs, with the exception of WD + BH and with a limited parameter space for NS + NS. Considering the possibility of mass outflow from the Lagrangian point L_2 , the resulting parameter space for GW progenitors is shifted toward smaller initial mass ratios (defined as the ratio of the donor mass over the CO mass), consequently ruling out the formation of NS + NS pairs while allowing the production of merging WD + BH binaries. We compare our results with observations of single-degenerate binaries and find that the conditions for the stable MT channel to operate are present in nature. We then show that stable MT in the isotropic re-emission channel can produce merging binary BHs with mass ratios > 0.1 , consistent with the majority of inferred sources of the third gravitational wave transient catalogue. Enhanced angular momentum loss from L_2 increases the minimum final mass ratio achievable by stable MT.

2.1 Introduction

Ground-based gravitational wave (GW) observatories of the LIGO, Virgo, and KAGRA (LVK) network have successfully identified coalescing compact objects (COs) originating from binary black holes (BHs), binary neutron stars (NSs), and binaries containing both a BH and a NS. Signals from these sources are compiled in the third gravitational-wave transient catalogue (GWTC-3, [Abbott et al. 2023b](#)) and currently form a sample of over 90 detections, expected to grow significantly with future observing runs.

While the observed GW sample is increasing and progressively revealing new types of sources, our theoretical understanding of the evolutionary channels that form them is still limited. The main formation pathway leading to BH + BH and BH + NS mergers is still a matter of debate. On the one hand, dynamical interactions in globular clusters ([Kulkarni et al. 1993](#), [Sigurdsson & Hernquist 1993](#), [Portegies Zwart & McMillan 2000](#)), young stellar clusters (e.g., [Mapelli 2016](#)) or in isolated hierarchical systems (e.g., [Thompson 2011](#)) are predicted to contribute in forming close double BHs. On the other hand, isolated binary evolution scenarios rely either on a process that could prevent stars in very close binaries from expanding, like chemically homogeneous evolution ([Marchant et al. 2016](#), [Mandel & De Mink 2016](#)), or on a hardening mechanism that allows wide binaries to come close enough.

Two main hardening mechanisms have been proposed for isolated binaries: evolution of the binary through a common envelope (CE) phase ([Paczynski 1976](#)) or a stable mass transfer (MT) episode via Roche lobe overflow ([van den Heuvel et al. 2017](#)). The CE scenario was first contemplated in the context of the evolution of single-degenerate binaries with WD objects (e.g., [Sparks & Stecher 1974](#), [Chau et al. 1974](#)), then introduced to explain the origin of cataclysmic variable stars ([Webbink 1975](#)), and subsequently suggested as the origin of Type I supernovae (SNe, [Webbink 1984](#)). CE was also advanced as the standard, late-evolutionary channel toward double degenerate binaries, both in the context of the final evolution of massive X-ray binaries as well as in the formation of NS binaries ([van den Heuvel 1976b](#)) and double WDs (e.g., [Iben & Tutukov 1984](#)). During such CE phase, the components of the binary system are engulfed by a common gaseous envelope; the resulting drag dissipates energy (and momentum) and dramatically shrinks the orbit. This process is expected to happen on a dynamical timescale, and the survival of the shrunk binary is subject to the envelope structure and companion masses.

Conversely, stable MT via Roche lobe overflow implies a quiet, long-lived phase of tightening (or broadening) of the system's orbit. This happens on the thermal or nuclear timescale of the donor star and depends on the evolutionary stage of

the donor itself. During a stable MT episode, the donor keeps its radius close to that of its Roche lobe, while material from its envelope escapes the star's gravitational well and is transferred to the companion. The MT rate is governed by the response of the donor's own radius to mass loss, and by the Roche lobe radius response. The mechanism is self-regulating (i.e., a maximum MT rate is expected to be reached and, subsequently, quenched), and thus dubbed stable.

While stable MT is usually involved in interacting non-degenerate binary systems before the formation of the first CO (e.g., Dominik et al. 2012, Langer et al. 2020), CE evolution has been considered the classical hardening channel toward the merging double-degenerate configuration, after the first CO is already formed (e.g. Belczynski et al. 2016, Liu et al. 2022). However, van den Heuvel et al. (2017) recently argued that the role of stable MT might be crucial in tightening the orbit of systems composed by a donor and a CO. This evolutionary scenario hypothesizes the MT episode to be completely non-conservative, and the avoidance of a CE episode to be dependent on the mass ratio of the system.

More specifically, the assumption of complete non-conservativeness has been translated in the past into modeling mass leakage from the system in the vicinity of the first-born CO with its specific angular momentum, in the isotropic re-emission channel (see van den Heuvel et al. 2017), usually justified by super-Eddington accretion rates in proximity to a compact accretor. However, the isotropic re-emission channel is just one possibility. At very high MT rates, systems can potentially experience outflows of mass through the L_2 Lagrangian point (Lu et al. 2023), which would lead to further orbital shrinkage. The presence of a circumbinary outflow from systems such as the galactic microquasar SS433 could support this possibility (Fabrika 1993).

Population synthesis techniques are key to understanding the increasing sample of merging double COs via any kind of evolutionary channel, and recent studies have shown that the contribution from stable, non-conservative MT to the observed sample of merging binary BHs can be substantial and even larger than that from the CE channel (Neijssel et al. 2019, Bavera et al. 2021). There are however uncertainties in the critical mass ratios for CE. As the response of a star to mass loss depends on the structure of its envelope, several classical (e.g., Paczyński 1965) and more modern (e.g., Pavlovskii & Ivanova 2015) studies made use of stellar structure models to survey ranges of mass ratios and orbital periods for (un)stable MT; their results are subsequently implemented in binary population synthesis codes as physically motivated criteria for identifying CE. In particular, population synthesis studies usually assume a direct correlation between a specific stellar evolutionary stage with the (un-)successful CE survival (see, e.g., the mass ratio thresholds from Hjellming & Webbink (1987) and Hurley et al. (2002)). This approach gives an overestimate of the CE channel contribution to binary BHs (Marchant et al. 2021). Furthermore, the adopted

critical mass ratios for CE evolution may lead to an oversimplification of the progenitors' initial conditions to produce merging double COs (Gallegos-Garcia et al. 2021).

The aim of this work is to assess the potential of non-conservative stable MT as a candidate evolutionary channel toward the merging double CO configuration. We put the emphasis on the production of all the different pairings of compact objects other than just the double BH scenario. We did so by investigating the parameter space of progenitor systems composed by a CO orbiting a Roche lobe-filling donor, using existing results on the response to a star to rapid MT Ge et al. 2010, 2015, 2020 to resolve the boundary of critical mass ratios for CE evolution. We then computed the orbital shrinkage of the systems with angular momentum balance arguments and finally studied the possibility of the formation of the different GW source pairings. Crucially, our approach is semi-analytical, as it does not rely on the tools of population synthesis and/or detailed binary interaction simulations. Section 2.2 provides the methodology; we present our results for selected donor star's masses in Sect. 2.3, while Sect. 2.4 compares the results with observations. We conclude by summarizing the main findings and discussing remarks and prospective work in Sect. 2.5.

2.2 Methodology

We always refer to quantities concerning the donor (accretor) in the MT episode with the subscript d (a), and to quantities at the start (end) of the MT episode with i (f). If neither i nor f is specified, we refer to quantities as variables in the evolution of the systems. We define the binary mass ratio, q , between a donor of mass m_d and an accretor of mass m_a , at an arbitrary stage, as

$$q \equiv \frac{m_d}{m_a} . \quad (2.1)$$

We also define a stripping factor, α_{core} , as the fraction of initial donor's mass, $m_{d,i}$, that remains after the MT episode, leaving the donor with mass $m_{d,f}$:

$$\alpha_{\text{core}} \equiv \frac{m_{d,f}}{m_{d,i}} < 1 . \quad (2.2)$$

Therefore, the final mass ratio of the system is

$$q_f = \frac{m_{d,f}}{m_{a,f}} = \frac{\alpha_{\text{core}} m_{d,i}}{m_{a,f}} . \quad (2.3)$$

Section 2.2.1 and Sect. 2.2.2 set the hypothesis on the shrinking mechanism and the merging time calculation and also present a functional study for a simple

case of fixed donor mass $m_{\text{d},i} = 32 M_{\odot}$. Sect. 2.2.3 discusses the instability boundary calculation, with a description of the properties used from existing simulations in Sect. 2.2.4. Sect. 2.2.5 sets the constraint on the final donor star's radius. Sect. 2.2.6 shows how we model mass outflow from L_2 .

2.2.1 The parameter space for GW progenitors

We hypothesize a completely non-conservative MT episode: the first-born CO is assumed to be accreting material from the donor at a super-Eddington rate, thus expelling mass from its surroundings with the accretor's specific angular momentum. This scenario has been referred to as isotropic re-emission.

We defined the efficiency, ϵ , of the MT (i.e., the fraction of accreted mass, Δm_{a} , when the donor transfers Δm_{d}), as

$$\epsilon = \frac{\Delta m_{\text{a}}}{\Delta m_{\text{d}}} \equiv 1 - \beta. \quad (2.4)$$

Here, $\beta = 0$ is the limit of conservativeness (everything is accreted) and $\beta = 1$ describes the isotropic re-emission assumption. Assuming that β is a constant of evolution, an exact orbital solution for the period shrinkage, $P_{\text{i}}/P_{\text{f}}$, can be found by angular momentum balance arguments (Soberman et al. 1997):

$$\frac{P_{\text{i}}}{P_{\text{f}}} = e^{-3(q_{\text{f}} - q_{\text{i}})} \left(\frac{q_{\text{f}}}{q_{\text{i}}} \right)^3 \left(\frac{1 + q_{\text{f}}}{1 + q_{\text{i}}} \right)^2, \quad (2.5)$$

where, within our assumption of $\beta = 1$, the accretor mass will satisfy $m_{\text{a},i} = m_{\text{a},f}$, so that the final and initial mass ratio of the system are related by $q_{\text{f}} = \alpha_{\text{core}} q_{\text{i}}$.

To assess if the binary system at the end of the MT can evolve into a GW source, we adopted the analytical expression for the delay time t_{merge} of an inspiraling binary (Peters 1964),

$$t_{\text{merge}} = \frac{a_{\text{f}}^4}{4\mathcal{B}}, \quad \text{with} \quad (2.6)$$

$$\mathcal{B} \equiv \frac{64}{5} \frac{G^3}{c^5} (m_{\text{a},f} + m_{\text{d},f}) m_{\text{a},f} m_{\text{d},f}, \quad (2.7)$$

which holds for a circular orbit with final orbital separation a_{f} and neglects other sources of radiation apart from the gravitational quadrupole one. We therefore implicitly assume that the second born CO, at the start of the inspiral phase, has the post-MT mass $m_{\text{d},f}$ and starts the inspiraling at the post-MT separation a_{f} . We relax this assumption in Sect. 2.3.2.

2.2.2 Constant α_{core}

The initial conditions required for a GW progenitor system can be constrained by looking at the initial accretor mass vs initial orbital period ($m_{\text{a,i}} - \log P_{\text{i}}$) parameter space. To do so, we combined Eq. 2.5 with Eq. 5.3 and Kepler's third law for the final orbital separation, a_{f} . By imposing the merging time being less than a Hubble time t_{H} , in other words $t_{\text{merge}} < t_{\text{H}} \simeq 13.8$ Gyr, one finds

$$P_{\text{i}}(m_{\text{d,i}}, m_{\text{a,i}}, t_{\text{merge}}, \alpha_{\text{core}}) < \quad (2.8)$$

$$0.642 \left(\frac{t_{\text{merge}}}{t_{\text{H}}} \right)^{3/8} \left(\frac{m_{\text{a,i}} \alpha_{\text{core}} m_{\text{d,i}}}{M_{\odot}^2} \right)^{3/8} \left(\frac{m_{\text{a,i}} + \alpha_{\text{core}} m_{\text{d,i}}}{M_{\odot}} \right)^{-1/8}$$

$$\times \underbrace{e^{-3(q_{\text{f}} - q_{\text{i}})} \left(\frac{q_{\text{f}}}{q_{\text{i}}} \right)^3 \left(\frac{1 + q_{\text{f}}}{1 + q_{\text{i}}} \right)^2}_{=P_{\text{i}}/P_{\text{f}}} \text{ days},$$

This condition can be generalized to other hardening channels if the value of $P_{\text{i}}/P_{\text{f}}$ is a function of the initial and final mass ratios. We used this later when we considered outflows from the L_2 point.

A visualization of the locus for fixed values of the stripping factor, α_{core} , and a donor initial mass of $m_{\text{d,i}} = 30 M_{\odot}$ is shown in Fig. 2.1. The parameter space that stands below the solid curves is the promising portion for the initial properties of progenitor systems of GW sources. Systems with a larger initial orbital period, P_{i} , are more likely to originate sufficient shrinkage for a GW merger at large initial mass ratios, $q_{\text{i}} \gg 1$. These systems are also farther from reaching the mass ratio inversion (around $q = 1$, the colored diamonds along the curves) during the MT episode, and thus less likely to switch from orbital contraction to orbital expansion due to MT. The effect of different stripping factors, α_{core} , labeled along the correspondent curves, is also shown: we see that more stripping (moving from the $\alpha_{\text{core}} = 0.5$ to the $\alpha_{\text{core}} = 0.3$ curve) implies a less favorable parameter space for GW mergers after the mass inversion $q = 1$, as the broadening of the orbit during the MT is favored. On the other hand, less stripping of the donor (moving from the $\alpha_{\text{core}} = 0.5$ to the $\alpha_{\text{core}} = 0.8$ curve) allows for less extreme q_{i} to form GW mergers.

2.2.3 The common envelope boundary

The assumption of a constant stripping factor is useful for illustrative purposes, but we want to trace a more accurate boundary in the parameter space ($m_{\text{a,i}} - P_{\text{i}}$) of GW progenitors. To this purpose, we also want to take into account that,

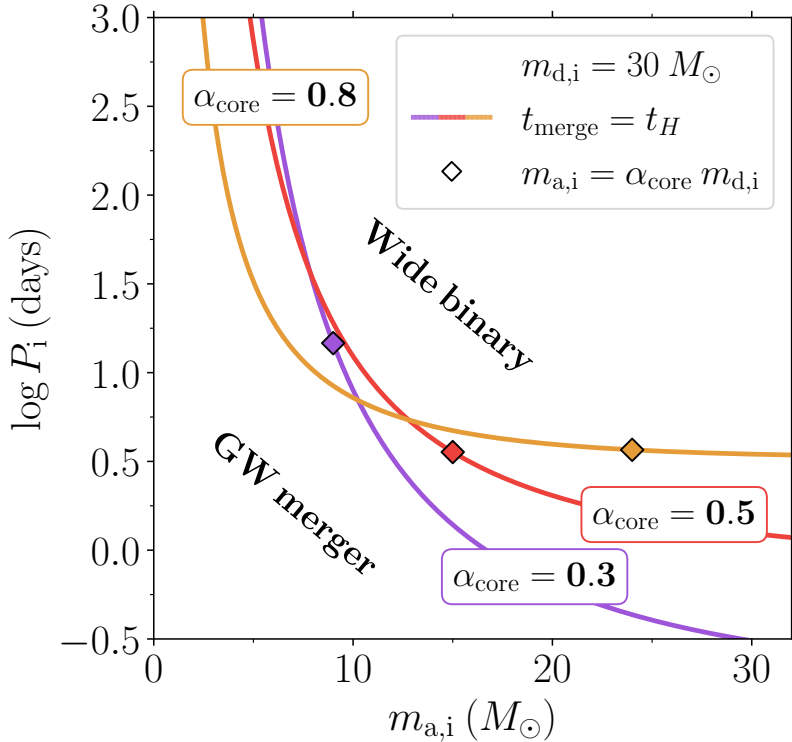


Figure 2.1: Locus (see Eq. 2.8) for the formation of a GW source through stable MT with a $30 M_{\odot}$ donor as a function of the CO accretor mass, $m_{a,i}$, and orbital period, P_i . The solid curves represent the upper bounds on initial periods $\log P_i$, to achieve a delay time of $t_{\text{merge}} = t_H$; different stripping factors, α_{core} , are labeled along the corresponding curves. Colored diamonds correspond to the point, along their respective curves, at which the MT episode is expected to invert the mass ratio.

keeping a fixed donor mass, $m_{d,i}$, for more extreme initial mass ratios we expect to encounter the boundary of critical mass ratios, q_{crit} , for CE evolution (Soberman et al. 1997).

The (in-)stability of a MT episode is usually characterized with mass-radius exponents. We followed Soberman et al. (1997) in writing the donor's mass-radius critical (or adiabatic) exponent ζ_{ad} :

$$\zeta_{\text{ad}} \equiv \left. \frac{\partial \log R_d}{\partial \log m_d} \right|_{\text{ad MT}}. \quad (2.9)$$

From the calculations of Ge et al. (2020) we took $\zeta_{\text{ad}}(R, M)$, that is the adiabatic mass radius exponent as a function of the stellar radius (encoding its evolutionary stage) and mass (see more in Sect. 2.2.4). The orbit response to the MT episode is quantified by the donor's Roche lobe mass-radius exponent, ζ_{RL} :

$$\zeta_{RL} \equiv \frac{\partial \log R_{RL}}{\partial \log m_d}. \quad (2.10)$$

Performing the stability analysis for the adiabatic MT episode amounts to comparing the two dimensionless exponents ζ_{RL} and ζ_{ad} . Stability requires that, after a mass loss-induced perturbation, $\delta m_d < 0$, the star's radius remains contained within its Roche lobe; in other words, $\zeta_{\text{ad}} > \zeta_{RL}$. If this is not satisfied, the MT is unstable and we expect CE evolution to happen.

The donor's Roche lobe mass-radius exponent, ζ_{RL} , must be computed according to the evolution of the binary system, so an assumption of the MT mode is needed; indeed, analytical expressions are provided in Soberman et al. (1997). In the case of conservative MT, one derives

$$\zeta_{RL}^{\text{cons}} = -2 + 2q + \frac{\partial \log(R_{RL}/a)}{\partial \log q}, \quad (2.11)$$

where we adopted the Eggleton (1983) prescription for R_{RL} :

$$\frac{R_{RL}}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \log(1 + q^{1/3})}, \quad 0 < q < \infty, \quad (2.12)$$

with a being the orbital separation.

If we include non-conservativeness, $\epsilon < 1$, by switching on an efficiency $\beta > 0$ for isotropic re-emission as in Eq. 2.4, the Roche lobe mass-radius exponent, $\zeta_{RL}^{\epsilon=1-\beta}$, assumes the following general form:

$$\zeta_{RL}^{\epsilon=1-\beta} = \quad (2.13)$$

$$-2 + \frac{2q(1 + \epsilon q)}{q + 1} - (1 - \epsilon) \frac{q}{1 + q} + \beta \frac{2q^2}{q + 1} + \frac{\partial \log(R_{RL}/a)}{\partial \log q}.$$

In the assumption of fully non-conservative MT, i.e. $\epsilon = 0$, and purely isotropic re-emission, i.e. $\beta = 1$, the above expression translates into

$$\zeta_{RL}^{\text{iso}} = \zeta_{RL}^{\text{cons}} - \frac{q}{q + 1}, \quad (2.14)$$

where the superscript "iso" stands for isotropic re-emission.

By comparing the adiabatic mass-radius exponent of donor stars, $\zeta_{\text{ad}}(R_{\text{d},i}, m_{\text{d},i})$, with a family of Roche lobe mass-radius exponents, $\zeta_{RL}^{\text{iso}} = \zeta_{RL}^{\text{iso}}(q)$, sharing the same initial mass, $m_{\text{d},i}$, and radius, $R_{\text{d},i}$, the threshold in mass ratio for which MT is unstable, $q_{\text{crit}}^{\text{iso}}$, is found by requesting

$$\zeta_{\text{ad}}(R_{\text{d},i}, m_{\text{d},i}) = \zeta_{RL}^{\text{iso}}(q_{\text{crit}}^{\text{iso}}), \quad (2.15)$$

where we called $q_{\text{crit}}^{\text{iso}}$ the critical mass ratio of an interacting binary system at the start of the unstable MT episode.

Once we derived critical mass ratios, we could build a common envelope boundary in the $(m_{\text{a},i} - P_i)$ parameter space, for fixed $m_{\text{d},i}$, with the following reasoning. Let us consider a donor star of radius $R_{\text{d},i}$, which we assume to be equal to the Roche lobe radius, $R_{RL,i}$, at the onset of MT. The value of ζ_{ad} of the star at the evolutionary stage in which it fills its Roche lobe then yields the critical mass ratio $q_{\text{crit}}^{\text{iso}}$ for unstable MT, by solving Eq. 2.15 (see also Fig. D.19). Combining the information of $q_{\text{crit}}^{\text{iso}}$ and $R_{\text{d},i} = R_{RL,i}$, we can then infer a critical period for the instability boundary using Kepler's third law:

$$P_{i,\text{crit}} = \frac{2\pi}{[G(m_{\text{d},i} + m_{\text{a},i})]^{1/2}} \left(\frac{R_{RL}}{a} \right) \bigg|_{q_{\text{crit}}^{\text{iso}}}^{-3/2} R_{\text{d},i}^{3/2}. \quad (2.16)$$

Here we isolated the factor R_{RL}/a , which is immediately known at the wanted mass ratio, $q = q_{\text{crit}}^{\text{iso}}$ (see Eq. 2.12). Notice that this factor was evaluated at $q_{\text{crit}}^{\text{iso}}$, in other words at the start of the MT episode. We determined ζ_{ad} as a function of the donor stars' initial mass, $m_{\text{d},i}$, and radius, $R_{\text{d},i}$, and we used the simulations of Ge et al. (2020), described in more detail in Sect. 2.2.4.

2.2.4 Ge et al. simulations

The set of simulations from Ge et al. (2020) covers a grid of Population I stars, $Z = 0.02$, spanning the zero age main sequence (ZAMS) mass range $0.10 \leq m_{\text{d},i}/M_{\odot} \leq 100$ and evolutionary stages from ZAMS through the

terminal age main sequence (TAMS), to the helium ignition, red giant branch (RGB and asymptotic giant branch (AGB), as the case may be. Following the methodology described in [Ge et al. \(2010\)](#), they build "adiabatic mass loss sequences": starting from an initial stellar model at an arbitrary state in its evolution, mass is removed from the surface while the stellar interior relaxes adiabatically to a new state of hydrostatic equilibrium. These adiabatic mass loss sequences yield ζ_{ad} , fixing the critical mass ratio for dynamical timescale MT. The Hertzsprung-Russell diagram of the mass loss sequences, for $1.6 \leq m_{\text{d},i}/M_{\odot} \leq 100$, is shown in Fig. 2.2.

We used the critical mass-radius exponents, ζ_{ad} , from [Ge et al. \(2020\)](#) to derive the threshold for unstable MT using Eq. 2.15. Their mass-radius relations' slopes are derived in the fully conservative approximation, namely by assuming a Roche lobe response, as in Eq. 2.11. They nevertheless claim that their exponents can also be used in the non-conservative cases to find critical mass-ratios for CE (see [Ge et al. 2010](#)).

From their simulations we also took the core mass, defined as the mass coordinate at which the helium abundance is halfway between the surface helium abundance and the maximum helium abundance in the stellar interior. We assumed this m_{c} to be the remaining mass after the MT episode, so that our stripping factor α_{core} became

$$\alpha_{\text{core}} \equiv \frac{m_{\text{d},f}}{m_{\text{d},i}} = \frac{m_{\text{c}}}{m_{\text{d},i}}. \quad (2.17)$$

Thus, if the binary system survives the MT episode, we assume it to be composed by an accretor with mass $m_{\text{a},f}$ and a donor with $m_{\text{d},f} = m_{\text{c}}$. There is a subtlety though: during the main sequence (MS), m_{c} as defined by [Ge et al. \(2020\)](#) recedes over a nuclear timescale. This receding resembles the monotonous one, predicted by single star evolution, of the convective core of massive stars. Adopting such m_{c} before TAMS can thus lead to a consistent overestimation of the core left after the MT episode, as a Case A MT is expected to quickly strip the donor and make the core retract deeper. In this respect, we modeled the remaining mass as follows:

$$\begin{aligned} \text{PRE-TAMS :} & \quad m_{\text{d},f} = m_{\text{c}}|_{\text{TAMS}}, \\ \text{POST-TAMS :} & \quad m_{\text{d},f} = m_{\text{c}}, \end{aligned}$$

namely, we used the core mass at TAMS, $m_{\text{c}}|_{\text{TAMS}}$, as the remaining mass, $m_{\text{d},f}$, after MT episodes initiated by pre-TAMS donors. This is still expected to be an overestimate of the final mass after MT.

For the largest initial donor star masses, namely $50 \leq m_{\text{d},i}/M_{\odot} \leq 100$, we limited our analysis to those initial models in the mass loss sequences that fall under the empirical Humphrey-Davidson limit (dashed red line in Fig. 2.2).

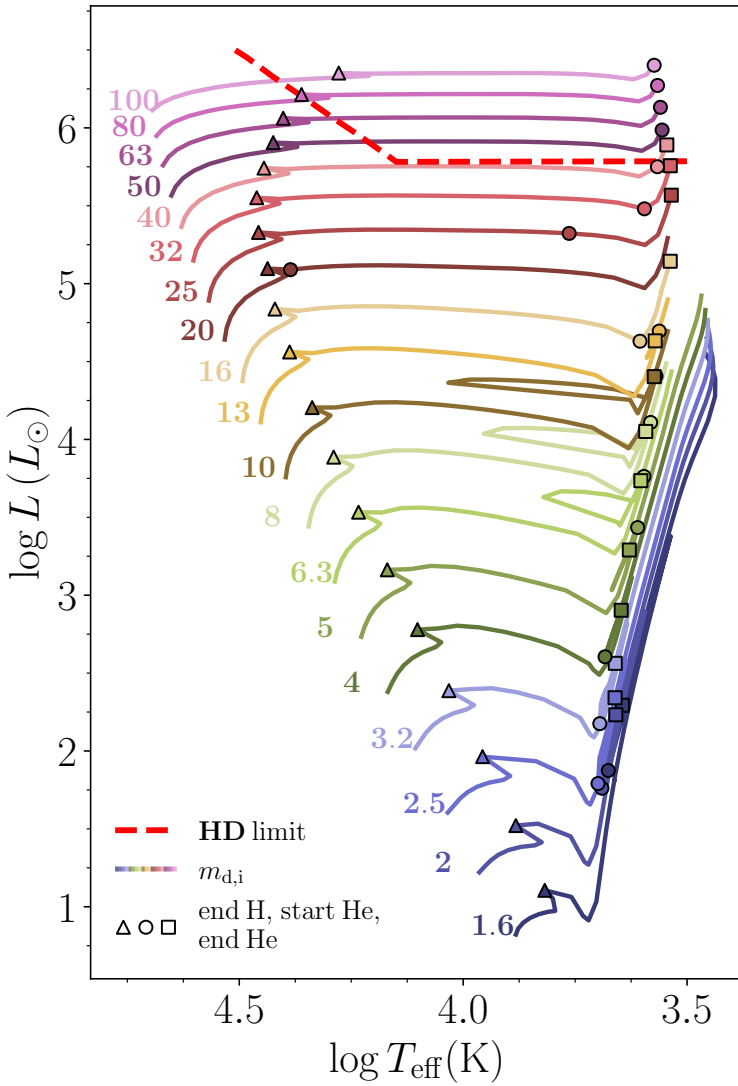


Figure 2.2: Hertzsprung-Russell diagram of the adiabatic mass loss sequences from [Ge et al. \(2020\)](#), labeled by their mass. Different evolutionary phases (TAMS, helium ignition and end of core He-burning) are highlighted with different icons (unfilled triangle, circle, and square). The empirical Humphrey-Davidson (HD) limit, in dashed red ([Humphreys & Davidson 1979](#)), is also reported.

Figure D.19 shows how the critical mass ratios for unstable MT are determined using two fixed donor masses from the Ge et al. (2020) grid. At any evolutionary stage, the critical mass ratios for isotropic re-emission, $q_{\text{crit}}^{\text{iso}}$, are shifted, with respect to the conservative case, toward smaller values (i.e., to larger accretor masses $m_{\text{a},i}$). Massive stars experience significant radial expansion in the Hertzsprung gap before developing a convective envelope, while lower mass stars develop a convective envelope and start rising on the Hayashi line without significant expansion after the MS. In terms of ζ_{ad} , this results in the more massive star experiencing a monotonic increase of ζ_{ad} over a large range of radii, while the opposite is the case for lower mass stars.

2.2.5 Final orbital separations

We computed the final orbital separations, a_{f} , by using the orbital shrinkage equation, Eq. 2.5, and Kepler’s third law. Even if the instability criterion is satisfied, we find cases where the predicted orbital separations a_{f} at the end of the MT episode are too small to contain a stripped helium star of the expected final mass. This is indicative of the occurrence of delayed dynamical instability (Hjellming & Webbink 1987) where, even if the start of the MT phase is stable, it can become unstable before the donor is fully stripped.

We thus set a hard boundary for the final Roche-lobe radius, $R_{\text{RL},\text{f}}$, of the donor at the end of the MT episode. We computed a set of MESA (Paxton et al. 2010, 2013, 2015, 2018, 2019) models of helium zero age main sequence (He-ZAMS) stars with initial masses $0.275 M_{\odot} \leq m_{\text{d},\text{f}} \leq 52.75 M_{\odot}$. We expanded the solar metallicity set of He-ZAMS in Poniatowski et al. (2021) with MESA v15140, and produced a set of values for the radius at the He-ZAMS stage, $R_{\text{He-ZAMS}}$, for each model. We then assumed that the limiting orbital separation for our model to hold is the one at which the final donor’s Roche-lobe radius, $R_{\text{RL},\text{f}}$, is equal to the He-ZAMS radius, $R_{\text{He-ZAMS}}$, of the He-ZAMS model with corresponding stripped star mass. Namely, we imposed:

$$R_{\text{d},\text{f}} \simeq R_{\text{He-ZAMS}} < R_{\text{RL},\text{f}}. \quad (2.18)$$

Physically, the condition in Eq. 2.18 also implies an equilibrium configuration of our final stage after the MT episode. However, it might be an oversimplification. Investigating the details of this hard boundary requires detailed MESA modeling of the binary interactions and is planned in a follow-up of this work.

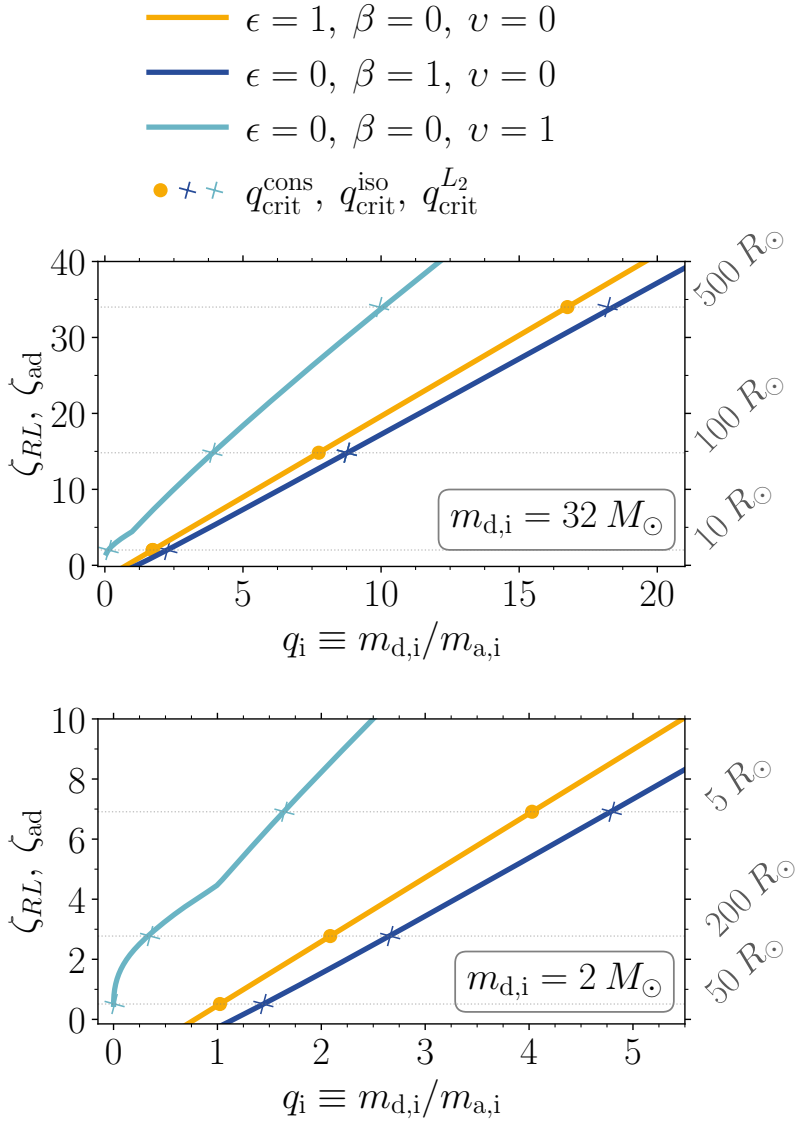


Figure 2.3: Functional dependence of ζ_{RL} on the binary mass ratio $q_i \equiv m_{d,i}/m_{a,i}$, compared to the adiabatic index, ζ_{ad} , for donor stars of $32 M_\odot$ (top panel) and $2 M_\odot$ (bottom panel) of different radii. The different colors of the solid lines show the conservative limit, $\epsilon = 1$ (golden), and the completely non-conservative cases of purely isotropic re-emission, $\beta = 1$ (dark blue), and mass outflow from L_2 (light blue), see the discussion in Sect. 2.2.6. Critical mass ratios, ζ_{ad} , for the MT to be unstable, as calculated by Ge et al. (2020), are shown as horizontal lines (labeled by the donor star radius). For each radius and mode of MT, the critical mass ratio corresponds to the crossing points between ζ_{ad} and ζ_{RL} .

2.2.6 Modeling L_2 outflow

Shrinkage of the orbit with L_2 outflow

Isotropic re-emission is a simplified model of the dynamics of ejected material in a binary, and real binary systems could exhibit more complex outflows. For WD accretors, high MT rates ($> 10^{-6} M_{\odot} \text{ yr}^{-1}$) are expected to result in rapid expansion and the formation of a red giant star (Nomoto 1982, Cassisi et al. 1998, Shen & Bildsten 2007, Wolf et al. 2013). In a binary system this expansion would lead to overflow of the outer Lagrangian points. It has also been argued that, at high MT rates onto NS or BH companions, the accretion disk would grow and start ejecting most of the mass transferred through L_2 (Lu et al. 2023), preventing in some cases the expansion of the orbit after the mass-ratio inversion. Such additional shrinkage sourced by L_2 angular momentum loss can therefore be key to favoring the formation of merging double COs, but also impact the stability of MT.

In this respect, we modeled the L_2 outflow in the form of a modified rule for the period shrinkage, P_i/P_f , using a generalized efficiency, ϵ , of the MT:

$$\epsilon = 1 - \beta - v. \quad (2.19)$$

Here, $\beta + v = 0$ is the limit of conservativeness and $v = 1$ corresponds to the assumption of all mass being lost through L_2 . The v efficiency is still modeled as a constant during the MT episode.

We first numerically computed the distance between the second Lagrangian point, x_{L_2} , and the center of mass, $x_{\text{cm}} \equiv 1/(1+q)$, of the system; we called such distance $x_{L_2} - x_{\text{cm}}$, expressed in units of orbital separation, a . We considered a Cartesian system with an origin ($x = 0, y = 0, z = 0$) located at the center of the donor star, with a $\hat{x}$ axis pointing toward the accretor and $\hat{z}$ toward the direction of the angular momentum vector. We then constructed the following fit to the numerical solution for $(x_{L_2} - x_{\text{cm}})^2$:

$$(x_{L_2} - x_{\text{cm}})^2(q) \simeq 1 + \sum_{n=1}^5 a_n \times \begin{cases} q^{-(n-n_0)} & q \geq 1 \\ q^{(n-n_0)} & q < 1 \end{cases} \quad (2.20)$$

with $n_0 = 0.658$,

$$a_1 = 1.544, a_2 = -3.118, a_3 = 4.387, a_4 = -3.567, a_5 = 1.190.$$

The fit has a fractional error $< 0.1\%$ over the range $1 \leq q < +\infty$. Thanks to the symmetry of the problem, the L_2 position $(x_{L_2} - x_{\text{cm}})(q)$ for $q < 1$ is obtained from $-(x_{L_2} - x_{\text{cm}})(1/q)$.

Material ejected through L_2 is assumed to carry away a specific angular momentum, j , corresponding to this Lagrangian point, $j = a^2 (x_{L_2} - x_{\text{cm}})^2 \Omega_{\text{orb}}$, with Ω_{orb} being the Keplerian angular frequency of the orbit. Following [Soberman et al. \(1997\)](#), the evolution of the orbital period, P_i/P_f , as a function of the mass ratio and including both isotropic re-emission and L_2 mass loss can then be computed analytically as

$$\frac{P_i}{P_f} = \exp[-3\beta(q_f - q_i)] \left(\frac{1+q_f}{1+q_i}\right)^{3\beta-1} \left(\frac{q_f}{q_i}\right)^3 \times \quad (2.21)$$

$$\exp\left[-3v \int_{q_i}^{q_f} f(q) dq\right], \quad \text{with}$$

$$f(q) \equiv \frac{(1+q)}{q} [x_{L_2} - x_{\text{cm}}]^2. \quad (2.22)$$

Using the fit for $(x_{L_2} - x_{\text{cm}})^2$ in Eq. 2.20, the integral $\int^q f(q) dq$ can be computed analytically, and we refer to App. A.1 for more details about its solution.

With such a modified period shrinkage rule, one can immediately define the parameter space $(m_{\text{a,i}}, \log P_i)$ for GW progenitor systems by using Eq. 2.8 with the adapted P_i/P_f of Eq. 2.21 and switching on an efficiency for L_2 mass loss with $v > 0$. Keeping the completely non-conservative limit $\epsilon = 0$, we then had $\beta = 1 - v$. The locus for fixed values of the stripping factor, α_{core} , and a donor initial mass of $m_{\text{d,i}} = 30 M_\odot$ is shown in Fig. 2.4, with analogous notation as Fig. 2.1. As expected, we see that the extra source of angular momentum loss implies that the locus for the formation of a gravitational wave source moves toward more massive accretors. However, the expected change in orbital evolution also impacts the stability of MT, as we discuss in Sect. 2.2.6.

Common envelope boundary with L_2 outflow

As an outflow from L_2 during the MT episode has consequences on the orbit evolution, the orbit response to MT is also affected and thus $\zeta_{RL}^{\epsilon=1-\beta}$ in Eq. 2.13 needs to be properly modified:

$$\zeta_{RL}^{\text{iso}+L_2} = \zeta_{RL}^{\epsilon=1-\beta} + 2v q f(q), \quad (2.23)$$

and $f(q)$ is defined by Eq. 2.22. Since $v > 0$ positively shifts the value of $\zeta_{RL}^{\text{iso}+L_2}$, the expected effect on the critical mass ratios, $q_{\text{crit}}^{\text{iso}+L_2}$, is a shift toward lower values (or accordingly, more massive CO accretors) with respect to $q_{\text{crit}}^{\text{iso}}$. This is clearly shown in Fig. D.19 for the limiting case of $v = 1$. Analogously to what we did in Sect. 2.2.3 for $q_{\text{crit}}^{\text{iso}}$, we determined $q_{\text{crit}}^{\text{iso}+L_2}$ for a donor with a

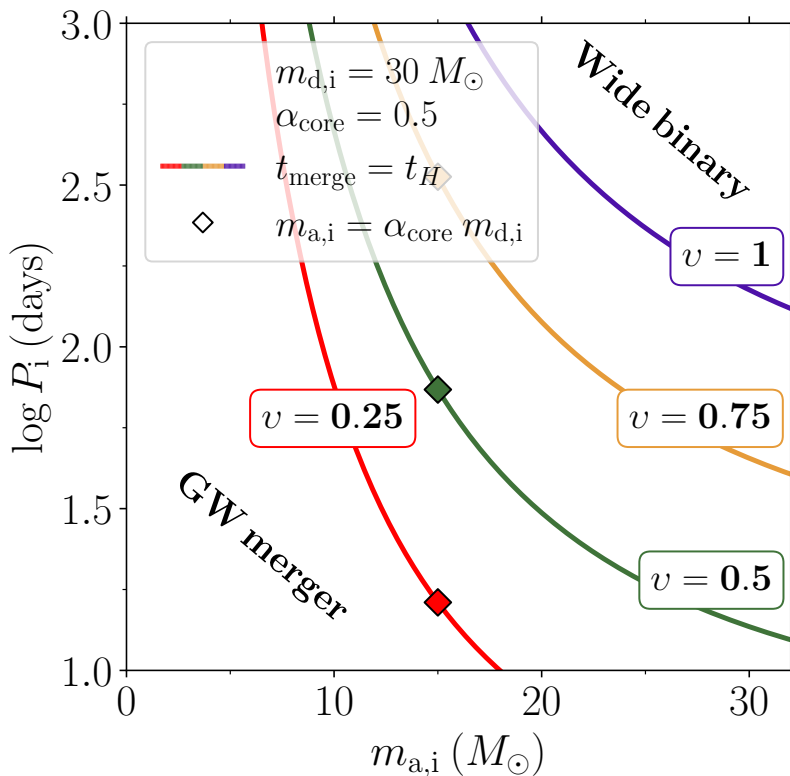


Figure 2.4: Same diagram as in Fig. 2.1 with the modified shrinkage relation P_i/P in Eq. 2.21, a fixed stripping factor, $\alpha_{\text{core}} = 0.5$, and a variable efficiency for L_2 mass outflow, v . Different efficiencies, v , are labeled along the correspondent curve.

given initial mass, $m_{d,i}$, and radius, $R_{d,i}$, in the presence of $v > 0$ and $\epsilon = 0$ by imposing the condition:

$$\zeta_{\text{ad}}(R_{d,i}, m_{d,i}) = \zeta_{RL}^{\text{iso}+L_2}(q_{\text{crit}}^{\text{iso}+L_2}). \quad (2.24)$$

2.3 Results

This section presents the results of the favorable parameter space for GW progenitor systems, in the form of $(m_{a,i}, \log P_i)$ diagrams with a fixed donor mass, $m_{d,i}$. We show the results for a BH direct collapse (Sect. 2.3.1), NS

remnant with kick velocity (Sect. 2.3.2), and WD accretors (Sect. 2.3.3); just one example for fixed $m_{d,i}$ is shown for each case. The full set of results for $2 < m_{d,i}/M_{\odot} < 100$ will be made publicly available at the time of publication on Zenodo¹.

2.3.1 BH progenitor as the donor

When the initial mass, $m_{d,i}$, of the donor is $m_{d,i} \geq 25 M_{\odot}$, we assume that, after a later evolution of the stripped star following the MT episode, the star undergoes direct collapse into a BH. As such, we modeled the evolutionary history from the end of the MT episode until merging as if the direct collapse happens immediately after the MT. Therefore, this model ignores possible mass loss between the end of the MT phase and BH formation, which is expected to widen the orbit (see discussion in Sect. 2.3.4). We briefly discuss the possibility of having BHs kick for $25 \lesssim m_{d,i} (M_{\odot}) \lesssim 40$ in Sec. 2.3.2. Afterward, the double CO system evolves only under the effect of gravitational interaction via quadrupole radiation emission (see Eq. 5.3).

Figure 2.5 shows the parameter space ($m_{a,i}, \log P_i$) for GW progenitor systems that results from the described approach. The Roche lobe-filling star is a $m_{d,i} = 32 M_{\odot}$ donor. Let us first consider the purely isotropic re-emission channel (solid lines). For any orbital period there is a range in mass ratio where MT is expected to be stable and to lead to sufficient hardening to produce a CO coalescence within a Hubble time. Such a strip extends between the common envelope boundary (solid red line) and the delay time boundary (solid blue line). Requiring that $R_{RL,f} > R_{d,f}$ at the end of the MT episode, as discussed in Sect. 2.2.5, significantly limits such a strip for more evolved donors. Nevertheless, the accretor masses, $m_{a,f}$, spanned by the strip at different stages are such that $5 \lesssim m_{a,i}/M_{\odot} \lesssim 37$. Therefore, we confirm that the production of merging double BH from stable MT via isotropic re-emission is possible. This, however, relies on the assumption that such initial conditions are realized in nature, which can be informed by observations of single-degenerate binaries (see Sect. 2.4.1). We also rely on the assumption that the response to MT of the donor star, which potentially accreted mass from the BH progenitor in a previous evolutionary phase, is well approximated with the single star models of Ge et al. (2020).

In Fig. 2.5 we also show the results after switching on an efficiency $\nu = 1$ for L_2 mass outflow. As illustrated in the simple model with fixed α_{core} of Fig. 2.4, the locus for the formation of a merging double CO is shifted toward higher accretor masses. However, the additional angular momentum loss also shifts

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the boundary for stability toward higher accretor masses. Nevertheless, a range in mass ratio and initial periods for merging double COs, from stable MT for $v > 0$, is still predicted. The masses of the CO accretor in this strip are such that $m_{a,i}(M_\odot) \gtrsim 11$, and thus the expected outcome is indeed merging binary BHs, though with different mass ratios with respect to the purely isotropic re-emission case.

The predicted strip for $m_{d,i} = 32 M_\odot$ can be compared to the one derived, with a set of MESA simulations, by [Marchant et al. \(2021\)](#) for a $30 M_\odot$ metal-poor ($Z = 0.00142$), Roche lobe-filling donor star orbiting a CO. The results from our semi-analytical model are qualitatively consistent with the ones from their set of detailed simulations, for both the instability boundary and the merging time constraint, although our predictions overestimate the set of initial conditions that lead to a GW source (see App. A.2 and Fig. A.1 for a discussion). As discussed in App. A.2, this holds for our results in the purely isotropic re-emission channel, as in their simulations the accretion rate for the stable MT episodes easily approaches the Eddington one, so that $\beta \simeq 1$ even though in the simulations the degree of non-conservativeness is not a free parameter.

Figure 2.6 summarizes our results for the GW merger strip in the form of a $(m_{a,i}, \log P_i)$ diagram similar to Fig. 2.5, with different donor masses in the range of BH progenitors, i.e. $m_{d,i} = 40 M_\odot, 32 M_\odot, 25 M_\odot$. In these diagrams we discretely vary the efficiencies for isotropic re-emission and mass outflow from L_2 , keeping the total $\epsilon = 1 - \beta - v = 0$. Firstly, we can see a shift toward larger accretor masses (i.e., smaller final mass ratios q_f) as we increase $m_{d,i}$. Secondly, we notice the possibility of the second-born CO to result in either the more massive object of the merging CO + CO pair (this happens at longer initial periods) or the less massive one (lower initial periods). Thirdly, we observe that the coupling of the second-born BH with a first-born NS accretor, within the stable MT channel, is excluded.

Although we place no constraints on the first-born CO mass in our analysis, stellar evolution can prevent the formation of arbitrarily large BH masses, $m_{a,i} \gtrsim 30 M_\odot$, as considered in Fig. 2.6. At the $Z = 0.02$ metallicity of the [Ge et al. 2020](#) simulation set, stellar winds potentially prevent the formation of such massive BHs (e.g., [Spera et al. 2015](#)). Nevertheless, we do not restrict the BH masses we study as we take the [Ge et al. 2020](#) results to be also representative of lower metallicity environments, which is supported by our comparison to the stability boundary at low metallicity of [Marchant et al. 2021](#) in Appendix A.2.

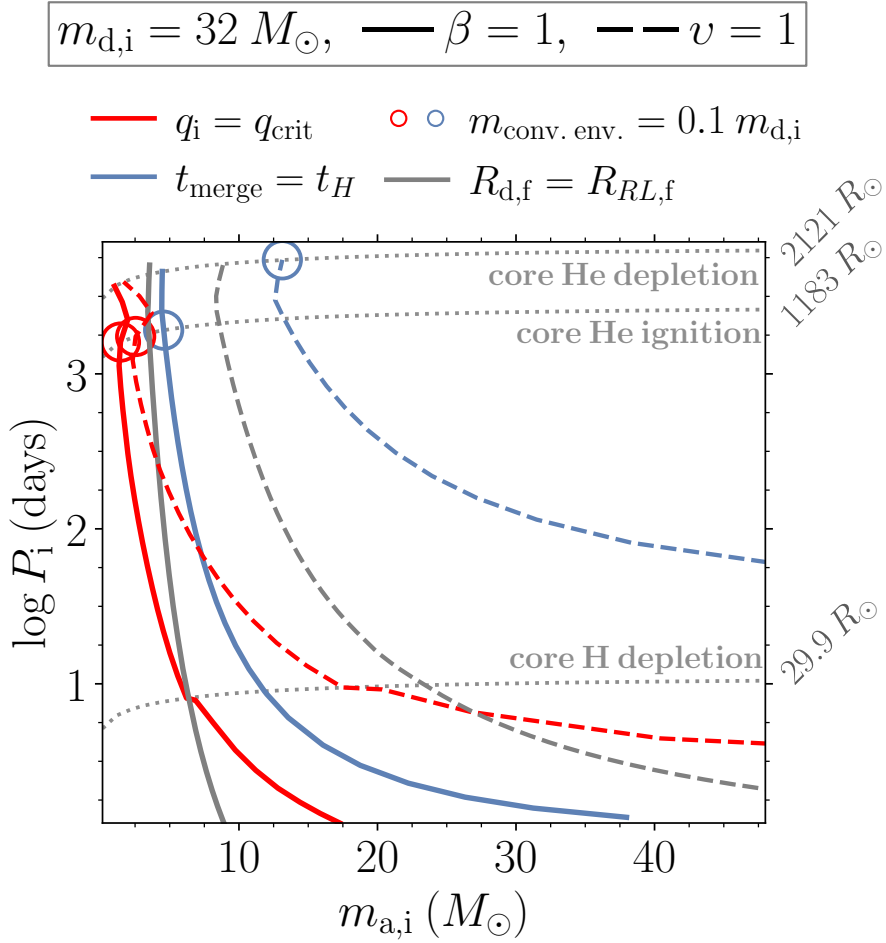


Figure 2.5: Boundaries for unstable MT (red) and the formation of GW sources (blue) for a $32 M_{\odot}$ donor orbiting a CO of mass $m_{a,i}$. The area below the gray line excludes systems for which the final orbital separation implies $R_{d,f} < R_{RL,f}$. Results are shown for full isotropic re-emission (solid) and assuming all matter is ejected from L_2 (dashed line). Different stages of evolution are illustrated by contours of constant Roche lobe radius (dotted gray line). Empty circles mark the formation of a convective envelope containing 10% of the donor’s mass.

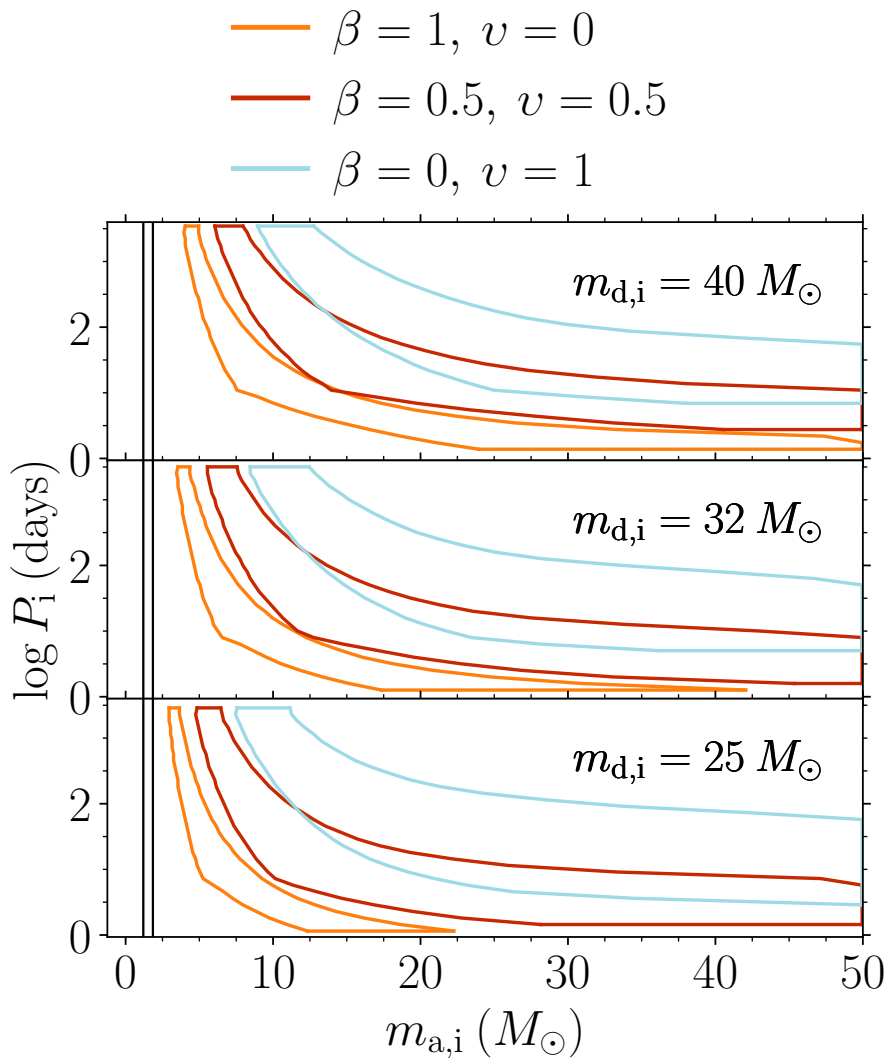


Figure 2.6: Locus for the formation of a GW source through stable MT with $40 M_\odot$, $32 M_\odot$, $25 M_\odot$ donors, i.e. BH progenitors, as a function of the CO accretor mass, $m_{a,i}$, and the orbital period, P_i . Different colors mark the favorable strips for merging double COs via purely isotropic re-emission ($\beta = 1$) and mass outflow from L_2 with variable efficiencies $v > 0$, keeping $\beta + v = 1$. Solid black lines mark the range of known NS masses from binary systems (Tauris et al. 2017).

2.3.2 NS progenitor as the donor

The range of ZAMS masses, m_{ZAMS} , for leaving behind a SN remnant is a matter of debate: the upper ZAMS mass limit, classically posited as $m_{\text{ZAMS}} \lesssim 25 M_{\odot}$ by, for example, [Fryer \(1999\)](#), has recently been argued to be formed by “islands of explodability” (e.g., [O’Connor & Ott 2011](#), [Ugiasco et al. 2012](#), [Müller et al. 2016](#), [Mabanta et al. 2019](#)). On the other hand, the lower ZAMS mass limit is canonically set at $m_{\text{ZAMS}} \gtrsim 8 M_{\odot}$ based evolution studies of single massive stars (e.g., [Poelarends et al. 2008](#)), but depends on metallicity (e.g., [Langer 2012](#)) and can be different for stars born in close binaries ([Wellstein et al. 2001](#)). In the following, we ignore the above complications and adopt the simplistic range $8 < m_{\text{ZAMS}}/M_{\odot} < 25$. In particular, when the initial mass, $m_{\text{d,i}}$, of the donor is such that $8 \leq m_{\text{d,i}}/M_{\odot} < 25$, we assume that, after the MT episode and the later evolution of the stripped star, it explodes as a SN, leaving a compact NS remnant.

Since the population of galactic NSs is known to have a velocity dispersion much larger than that of OB-type stars, indicative of kicks during a SN explosion (see [Lai et al. 2001](#) for a discussion), we also take this possibility into account in our calculations. As BHs have also been argued to have potential kick velocities at birth (see e.g., [Atri et al. 2019](#)), we also consider the case of a $m_{\text{d,i}} = 32 M_{\odot}$ BH progenitor at the end of this section.

In the case of NSs, the post-SN orbital parameters have been derived by several authors (e.g. [Sutantyo 1978](#), [Hills 1983](#), [Verbunt et al. 1990](#), [Brandt & Podsiadlowski 1995](#), [Kalogera 1996](#)); in particular, we follow the notation and expressions given in [Tauris et al. \(1999\)](#) (see equations 6 - 8 of that work). We point out that the calculation of the post-SN properties given by [Tauris et al. \(1999\)](#) assumes a circular pre-SN orbit followed by an instantaneous SN explosion and subsequent kick.

With these same assumptions, and adopting a canonical mass of $m_{\text{d, pSN}} = 1.4 M_{\odot}$ for the second-born CO, namely the NS remnant, we calculated the orbital separation, a_{pSN} , and the acquired eccentricity, e_{pSN} , of the system after the SN explosion; we used the subscript pSN to indicate the post-SN stage, to differentiate from the subscript f that we used above for the post-MT configuration. Also, as opposed to [Tauris et al. \(1999\)](#), we did not take into account the possible effects, on the orbit and on the first-born compact companion, of the passing shock wave from the SN (i.e., we set $v_{\text{im}} = 0$ in [Tauris et al. 1999](#)).

To assess if the binary system at the end of the MT can evolve into a GW source, we adopted the analytical expression for the delay time t_{merge} found by

Peters (1964):

$$t_{\text{merge}} = \frac{12}{19} \frac{c_{\text{pSN}}^4}{\mathcal{B}} \int_0^{e_{\text{pSN}}} de \frac{e^{29/19} [1 + (121/304) e^2]^{1181/2299}}{(1 - e^2)^{3/2}}, \quad (2.25)$$

$$\text{with } c_{\text{pSN}}^4 \equiv a_{\text{pSN}}^4 \left[\frac{1 - e_{\text{pSN}}^2}{e_{\text{pSN}}^{12/19}} \right]^4 \left\{ \left[1 + \frac{121}{304} e_{\text{pSN}}^2 \right]^{-870/2299} \right\}^4. \quad (2.26)$$

This expression is the generalized form of Eq. 5.3 in the case of non-zero post-SN eccentricity.

To account for the possibility of kicks, we adopted the kick velocity distribution in Hobbs et al. (2005) for the second-born CO, that is, a 1D Maxwellian with dispersion 260 km s^{-1} , and isotropic orientation in a frame of reference comoving with the SNe progenitor. For each initial orbital period, P_i , and compact object accretor mass, $m_{\text{a},i}$, we computed the post-MT orbital properties in the same way as we did for the BH progenitor in Sect. 2.3.1, obtaining a distribution of the post-SN properties, namely e_{pSN} , a_{pSN} due to the post-SN kick. Because of this, for each set of donor mass $8 \leq m_{\text{d},i}/M_{\odot} < 25$, accretor mass, and initial orbital period, we had a probability, $p_{t_{\text{merge}} < t_H}$, of forming a merging double CO binary.

To illustrate the impact of a SN kick, we considered one specific binary system with an $8 M_{\odot}$ donor star and a $2 M_{\odot}$ accretor with an orbital period of 10 days. The binary undergoes a stable MT episode with isotropic re-emission, after which the donor star is stripped to $m_{\text{d},f} = 2.06 M_{\odot}$ and the orbital period is $P_f = 0.48$ days, and these are considered to be the pre-SN properties. We considered the occurrence of a kick to the resulting CO according to the distribution of kick properties described in the previous paragraph. There is a 52.5% probability that the binary is disrupted from the kick. For the remaining 47.5%, Fig. 2.7 illustrates the resulting distribution of post-SN eccentricities and periods: a fraction of them (35.5%) has conditions that allow for a merger within 13.8 Gyr, and the remaining 12% end up being too wide for GW radiation to drive to a merger within the age of the Universe.

The resulting merger probabilities are shown in Fig. 2.8 for the case of a donor star of $m_{\text{d},i} = 8 M_{\odot}$ under the assumption of isotropic re-emission. The favorable strip for GW mergers comprises a small interval of accretor masses, and for later evolutionary stages the common envelope boundary (solid red line) takes over and overlays any possible system with $t_{\text{merge}} < t_H$. For this $8 M_{\odot}$ donor, we find that the CO accretors for which we form a GW source span, at different evolutionary stages, between $1.75 \lesssim m_{\text{a},i}(M_{\odot}) \lesssim 3.75$. As we can observe in Fig. 2.9 by looking at the $\beta = 1$ contours, for the case of a $m_{\text{d},i} = 16 M_{\odot}$ and a $m_{\text{d},i} = 20 M_{\odot}$ donor we find that the range of CO accretors

$$m_{\text{d,i}} = 8 M_{\odot}, P_{\text{i}} = 10 \text{ days}, m_{\text{a,i}} = 2 M_{\odot}$$

$$P_{\text{f}} = 0.48 \text{ days}$$

$$m_{\text{d,f}} = \alpha_{\text{core}} m_{\text{d,i}} = 2.06 M_{\odot} \rightarrow 1.4 M_{\odot}$$

$$t_{\text{merge}} = 13.8 \text{ Gyr}$$

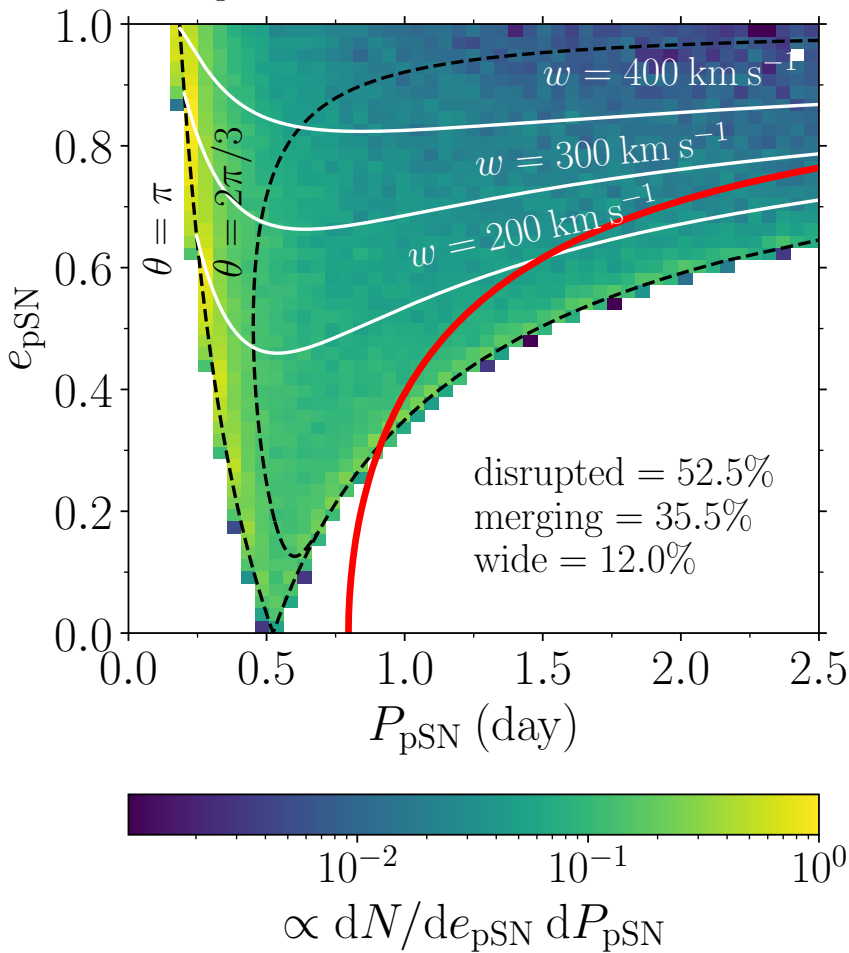


Figure 2.7: Distribution of post-SN eccentricity, e_{pSN} , and orbital period, P_{pSN} , for an example binary system (see Sect. 2.3.2 for details). Solid white lines indicate the final orbital parameters of the fixed kick velocity, w , and the variable angle, θ , formed between the kick velocity and the orbital velocity, assuming the kick to be on the orbital plane (i.e., $\phi = 0$). Dashed black lines indicate the same for a fixed θ and a variable w . A thick solid red line shows the boundary separating wide (right of the curve) from merging (left of the curve) systems.

spans $2 \lesssim m_{a,i}(M_\odot) \lesssim 10$ and $3 \lesssim m_{a,i}(M_\odot) \lesssim 15$, respectively. For a narrow range of donor masses, just above the limit at which we expect core-collapse SNe, stable MT can then produce merging binary NSs. However, for a wider range of donor masses that would result in a NS, we require a CO accretor with a mass consistent with a BH.

The bottom panel of Fig. 2.9 shows the results for $m_{d,i} = 8 M_\odot$ after switching on an efficiency $v = 1$ for L_2 mass outflow (light blue area). The pairing between NS and BH is here predicted all along the favorable GW strip. However, the additional angular momentum loss during the MT episode removes the possibility of forming a merging binary NSs, allowing solely for the formation of merging NS + BH systems where the NS is the second-born CO. The other panels in Fig. 2.9 show the results for $m_{d,i} = 20 M_\odot$, $16 M_\odot$ and different efficiencies, β and v . For these cases, we confirm the aforesaid prediction for merging NS + BH pairs with a second-born NS; this is true for any value of L_2 outflow efficiency $v > 0$.

Lastly, to investigate the effect of a possible kick imparted to a BH progenitor, we calculated the probability, $p_{t_{\text{merge}} < t_H}$, in the same fashion as for NS progenitors, for the case $m_{d,i} = 32 M_\odot$. We assumed a) a mass loss of 10%, that is, the mass of the second-born BH was assumed to be $m_{d, \text{pSN}} = 0.1 \times m_{d,f}$, and b) an imparted kick magnitude of 100 km s^{-1} . The resulting parameter space for GW mergers is superimposable with the direct collapse results shown in Fig. 2.5. Assuming a small, fixed fraction of mass loss makes the system stay massive, and thus $p_{t_{\text{merge}} < t_H} \simeq 1$ are found below the time delay boundary at any $\log P_i$.

2.3.3 WD progenitor as the donor

When the initial mass of the donor is $m_{d,i} < 8 M_\odot$ we assume that, after the MT episode, the stripped star evolves into a WD, orbiting its compact companion with no further interaction.

Figure 2.10 shows the resulting diagram ($m_{a,i}, \log P_i$) of GW progenitors for the case of $m_{d,i} = 3.2 M_\odot$. In the purely isotropic re-emission channel (solid lines), the favorable parameter space for merging WD + CO from stable MT is visibly limited to a thin strip of mostly systems with pre-TAMS interaction. A small post-TAMS region is also situated between the common envelope (solid red line) and the merging time (solid blue line) boundaries. The possible accretor masses, $m_{a,i}$, at different initial orbital period are such that $0.75 \lesssim m_{a,i}/M_\odot \lesssim 1.25$: this predicts merging WD + WD pairs. As shown in Fig. 2.11 for the $\beta = 1$ contours, when we scale the donor mass, $m_{d,i}$, to larger values the strip shifts to larger values for $m_{a,i}$. For $m_{d,i} = 4 M_\odot$ in Fig. 2.11 (top panel), we find that the $m_{a,i}$ accretor masses spanned are such that $0.8 \lesssim m_{a,i}/M_\odot \lesssim 1.5$. We thus find space for a merging system with a first-born NS orbiting the second-born

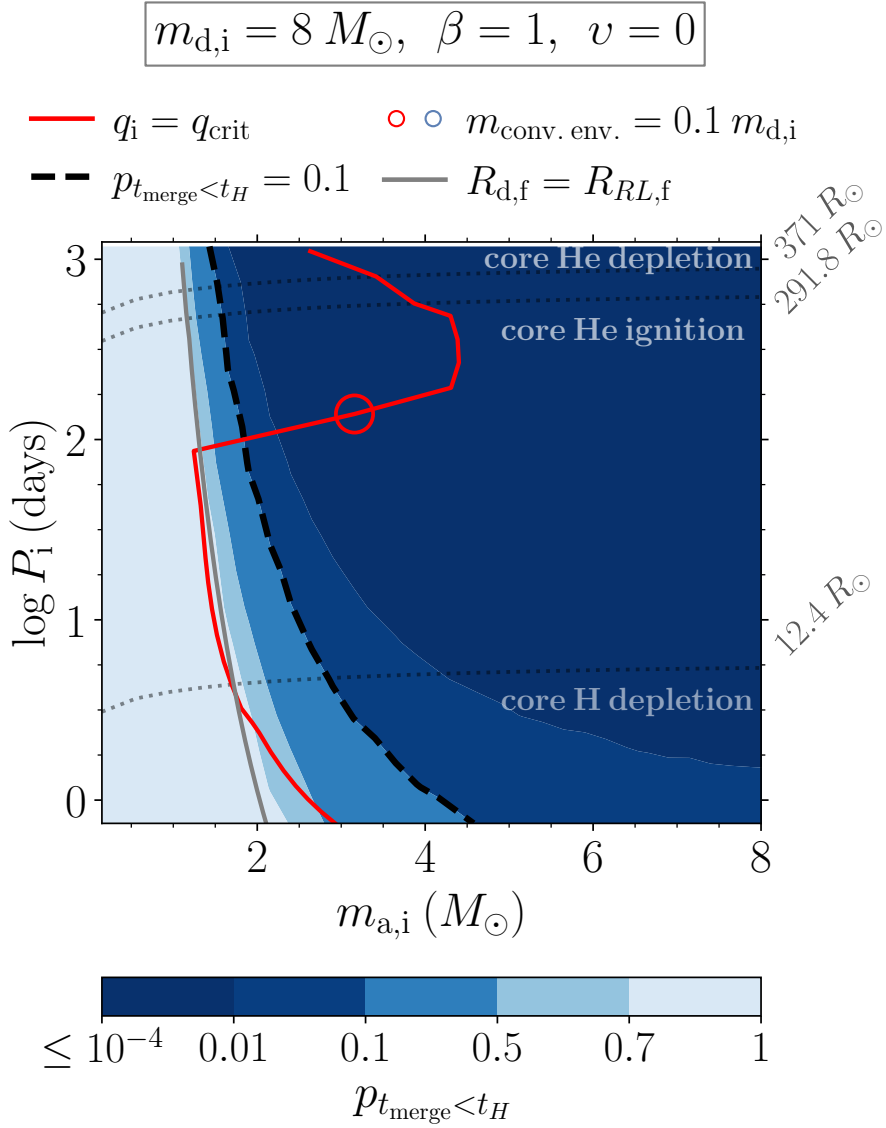


Figure 2.8: Probability of forming a GW source through stable MT with an $8 M_{\odot}$ donor as a function of the CO accretor mass $m_{a,i}$ and orbital period P_i . The donor star is assumed to form a NS with an isotropic kick (see Sect. 2.3.2). Analogous symbols and notation, as in Fig. 2.5, are employed for the purely isotropic re-emission channel ($\beta = 1$). The contour color code maps the probabilities, $p_{t_{\text{merge}} < t_H}$, of obtaining merging times $t_{\text{merge}} < t_H$, given the distribution of kick velocities from Hobbs et al. (2005) and isotropic kick directions, as explained in Sect. 2.3.2.

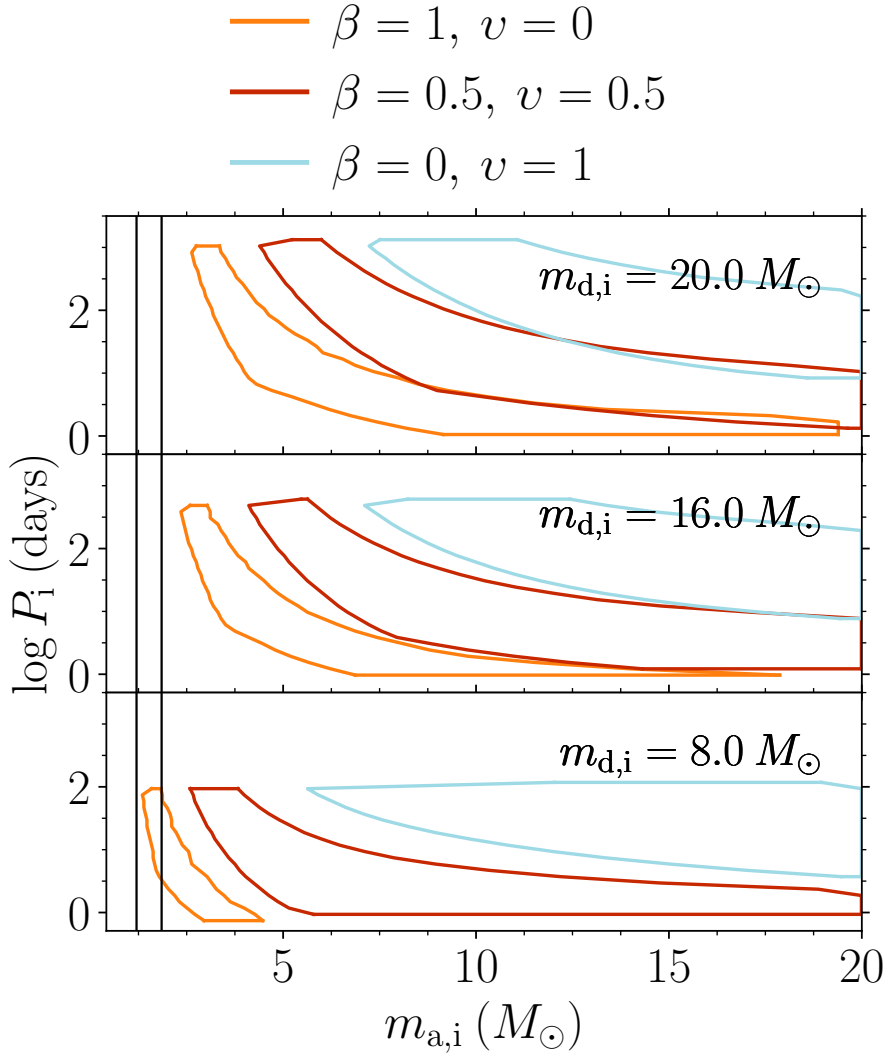


Figure 2.9: Locus for the formation of a GW source through stable MT with $20 M_{\odot}$, $16 M_{\odot}$, $8 M_{\odot}$ donor, i.e., NS object progenitors, as a function of the CO accretor mass, $m_{a,i}$, and orbital period, P_i . Contours indicate the region where the merger probability after the SN kick is $p_{t_{\text{merge}} < t_H} > 0.1$. Analogous notation to Fig. 2.6 is employed.

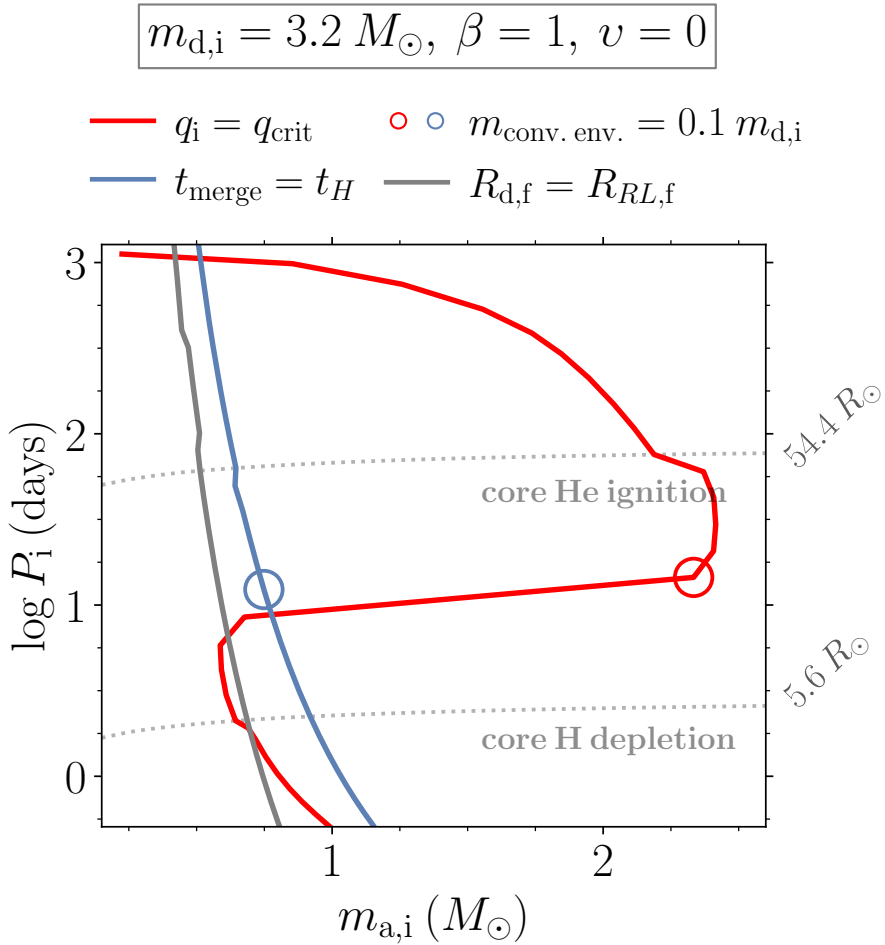


Figure 2.10: Boundaries of unstable MT (red line) and the formation of GW sources (blue line) for a $3.2 M_{\odot}$ donor orbiting a CO of mass $m_{a,i}$. Analogous symbols and notation to Fig. 2.5 are employed for the purely isotropic re-emission channel, $\beta = 1$.

WD. On the other hand, for $m_{d,i} = 2 M_{\odot}$ in Fig. 2.11 (bottom panel), we see that the favorable region is almost entirely suppressed.

The middle panel of Fig. 2.11 shows the results for $m_{d,i} = 3.2 M_{\odot}$, with an efficiency $v = 1$ for L_2 mass outflow (light blue area). Similar to the BH and the NS progenitor cases, the favorable strip to form a GW source via

stable MT is shifted toward larger accretor masses with respect to the purely isotropic re-emission case. In this case, it could also be consistent with the formation of a WD + BH compact binary, where the WD is the second-born CO. This is also shown in the other panels of Fig. 2.11 with the results for $m_{d,i} = 4 M_{\odot}, 1.6 M_{\odot}$: the additional angular momentum loss ($v > 0.5$ contours) allows for the formation of the WD + BH coupling for each of these systems. Like in the earlier cases, our results depend on whether systems with these properties form in nature, as the realization of such initial conditions is sensitive to the evolution of the binary system prior to the formation of the first-born CO.

2.3.4 The effect of wind mass loss

The set of simulations from Ge et al. series (Ge et al. 2020, 2015, 2010) has been produced without modeling wind mass loss. We may expect, however, that mass lost via winds from the donor stars could impact their radii, $R_{d,i}$, and thus the evolutionary stage at which the MT episode is initiated, as well as the core mass, m_c , hence the post-MT stage of the systems. This is especially true for the larger masses of the grid, $m_{d,i} \gtrsim 10 M_{\odot}$, for which large fractions of the initial mass might be expelled via radiation-driven winds in a $Z = 0.02$ environment.

Wind mass loss from the more massive donor stars can also impact the orbital evolution between the end of the MT episode and the formation of the second-born CO. Mass loss after MT translates into larger merging times, as the final CO + CO system is less massive when gravitational radiation takes over in determining the orbital evolution during the inspiral phase. Additionally, mass lost from the vicinity of the donor star with its specific angular momentum is expected to widen the orbit. Angular momentum balance arguments yield that the orbital period P_f at the end of the MT episode can be widened to $P_{f,\text{wind}}$ by a correcting factor

$$\frac{P_{f,\text{wind}}}{P_f} = \left(\frac{q_f + 1}{q_{f,\text{wind}} + 1} \right)^2 > 1, \quad (2.27)$$

which solely depends on the mass ratios $q_f = m_{d,f}/m_{a,f}$ and $q_{f,\text{wind}} \equiv m_{d,f}|_{\text{wind}}/m_{a,f}$. We are here referring to a $P_{f,\text{wind}}$ period in which the donor star has reached the mass $m_{d,f}|_{\text{wind}}$ due to the wind mass loss effect.

As this correction can have an impact on resolving the GW merger boundaries, we want to be more quantitative and study the impact of wind mass loss in systems composed by a CO orbiting a donor star of mass $m_{d,i} = 32 M_{\odot}$. To do so, we computed a set of simulations with MESA. We modeled the evolution of helium

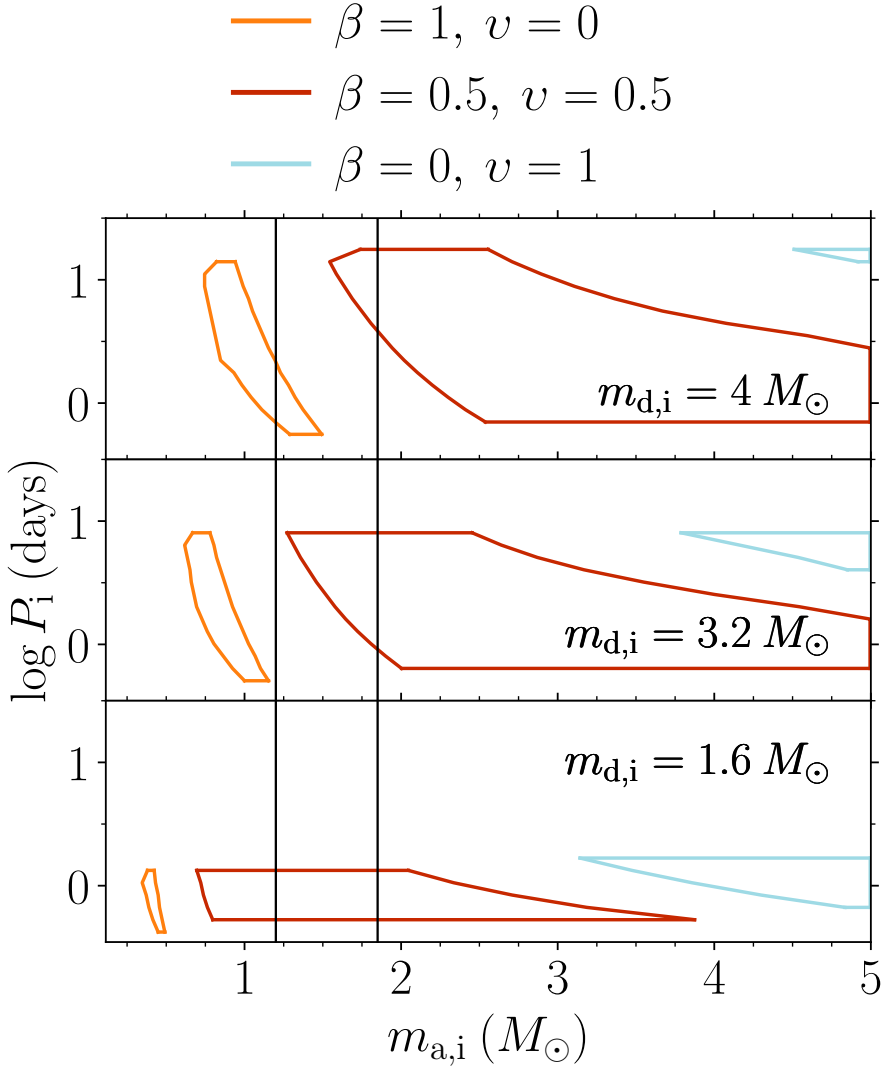


Figure 2.11: Locus for the formation of a GW source through stable MT with $4 M_{\odot}$, $3.2 M_{\odot}$, $1.6 M_{\odot}$ donors, i.e., WD object progenitors, as a function of the CO accretor mass, $m_{a,i}$, and orbital period, P_i . Analogous notation to Fig. 2.6 is employed.

stars with initial masses $m_{d,f}$ from Ge et al. (2020) (see Sect. 2.2.4) resulting after the stripping MT episode from the donor star with $m_{d,i} = 32 M_{\odot}$. The evolution of the models' set was stopped at the end of the stars' core C-burning phase. During this evolution, wind mass loss following the prescription from Sander & Vink (2020) was computed and accounted for. We used the final masses, $m_{d,f}|_{\text{wind}}$, from the simulations to re-compute the merging times, $t_{\text{merge}}|_{\text{wind}}$, with the described corrections on the masses and the orbital separation at the start of the inspiral phase.

We computed the correction in Eq. 2.27 first with a metallicity $Z = 0.02$, suitable for a Milky Way-like environment; subsequently, we explored the possibility of a Large Magellanic Cloud-like environment ($Z = 0.008$). Figure 2.12 shows the resulting modified boundaries of the isotropic re-emission channel, both for the Milky Way and for the Large Magellanic Cloud. The favorable strip for merging double COs is significantly reduced, as the time delay boundary is shifted toward larger initial mass ratios and eventually reaches the Roche-lobe boundary at advanced evolutionary stages. This is especially true for $Z = 0.02$.

This test case shows that the effect of wind mass loss physics on our results can be impactful, at least in the cases of massive donors ($m_{d,i} \gtrsim 10 M_{\odot}$) in Milky Way-like environments. We thus reserve a more extensive investigation of winds for future work.

2.3.5 Including conservativeness $\epsilon > 0$

So far we have carried out our calculations assuming completely non-conservative MT, either in the isotropic re-emission channel with $\beta = 1$ and $\epsilon = 1 - \beta = 0$ (Sect. 2.2.2), or with a L_2 mass outflow with $\beta + \nu = 1$ and $\epsilon = 1 - \beta - \nu = 0$ (Sect. 2.2.6). We want to quantify the impact of including an efficiency $\epsilon > 0$ in our calculations of the GW merger boundaries. To this purpose, we are not considering here the additional source of loss from L_2 , and therefore the efficiency for conservative MT is such that $\epsilon = 1 - \beta$.

Both the common envelope and the time delay boundaries are expected to change when conservative MT plays a role. The Roche lobe mass-radius exponent is expected to vary smoothly between the limiting cases of $\beta = 1$ (Eq. 2.14) and $\epsilon = 1$ (Eq. 2.11), and is described in Eq. 2.13. In Fig. D.19, this translates into a smooth variation between the solid blue line (isotropic re-emission) and the solid golden line (fully conservative). As a consequence, a shift in critical mass ratios is also expected. In practice, we derived the modified critical mass ratios, $q_{\text{crit}}^{\epsilon=1-\beta}$, by solving

$$\zeta_{\text{ad}}(R_{d,i}, m_{d,i}) = \zeta_{RL}^{\epsilon=1-\beta}(q_{\text{crit}}^{\epsilon=1-\beta}). \quad (2.28)$$

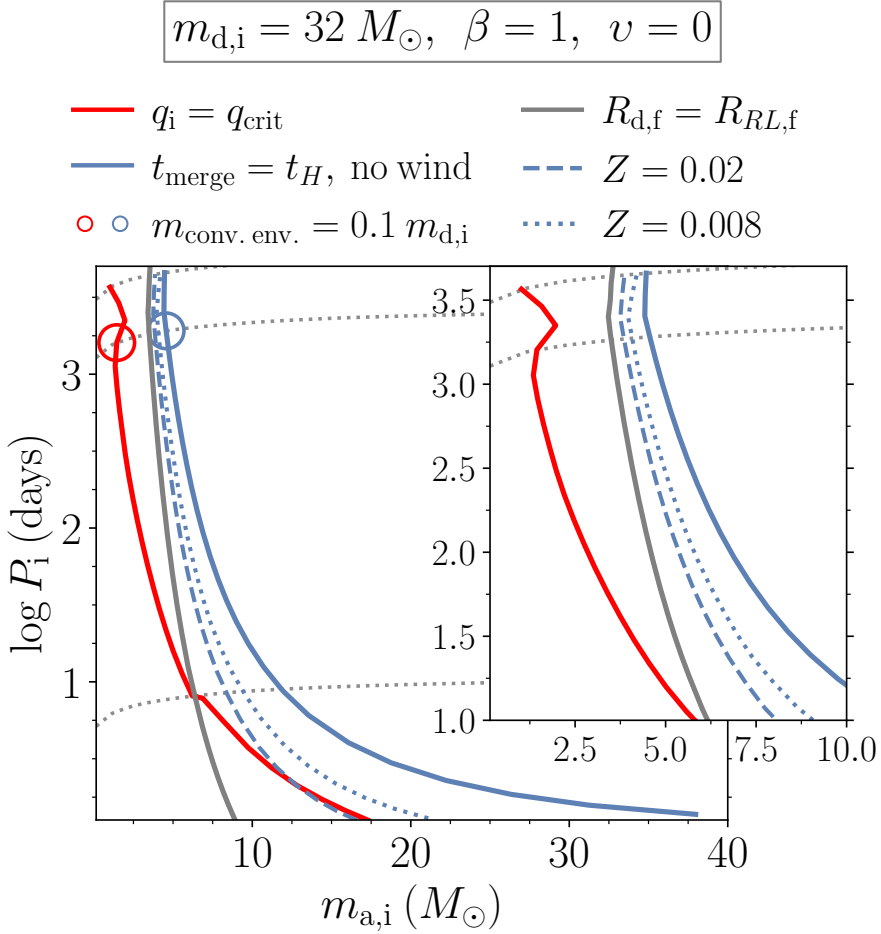


Figure 2.12: Same as Fig. 2.5, but illustrating the impact of wind mass loss after the phase of stable MT. The dashed (dotted) blue line shows the modified delay time boundary (solid blue) due to wind mass loss effects, in an environment with $Z = 0.02$ ($Z = 0.008$), on the post-MT mass of the stripped star and on the orbital separation at the start of the inspiral phase (see text in Sect. 2.3.4 for more details). It is important to note that we are considering the effect under the isotropic re-emission $\beta = 1$ assumption on the MT episode. For the rest, analogous symbols and notation to Fig. 2.5 are employed.

On the other hand, the period shrinkage (or widening) P_f/P_i is also modified, varying smoothly between Eq. 2.5 and the conservative limit (see, e.g., Eq. 33 in [Soberman et al. 1997](#)). By solving the equation of angular momentum balance, one can find

$$\frac{P_i}{P_f} = \left(\frac{q_f + 1}{q_i + 1} \right)^{-\frac{3\beta\epsilon}{\epsilon(\epsilon-1)}-1} \left(\frac{\epsilon q_f + 1}{\epsilon q_i + 1} \right)^{\frac{3\beta}{\epsilon(\epsilon-1)}-5} \left(\frac{q_f}{q_i} \right)^3, \quad (2.29)$$

where the final mass ratio $q = m_{d,f}/m_{a,f}$ takes into account that the final accretor mass is

$$m_{a,f} = m_{a,i} + \epsilon (1 - \alpha_{\text{core}}) m_{d,i}. \quad (2.30)$$

Lastly, the boundary for $R_{d,f} \leq R_{RL,f}$ depends on the amount of shrinkage (widening) of the orbit, and thus is also affected. In Fig. 2.13 we show the results of our calculations for a donor star of $m_{d,i} = 32 M_\odot$. We discretely varied the efficiencies for isotropic re-emission $\beta = 0, 0.5, 1$ and conservative MT $\epsilon = 1 - \beta$. Including conservativeness leads to less shrinkage (and / or widening, if the mass-ratio inversion is reached) of the orbit at the end of the MT episode; on the other hand, the accretor retains some transferred mass, so that the final binary is more massive. This explains the cut in parameter space at the longer initial periods, $\log P_i > 1.5$, and the turnover of the delay time boundary (blue lines) at $\sim 15 M_\odot$. Additionally, the Roche lobe boundary $R_{d,f} < R_{RL,f}$ becomes less stringent as the shrinkage is less extreme, and the instability boundary is mainly affected at the larger accretor masses, where the shift in $q_{\text{crit}}^{\epsilon=1-\beta}$ is larger (see Fig. D.19, top panel).

Although we find that conservative MT can still produce merging binary BHs, the situation is different for donor stars that produce NSs and WDs. The same analysis done for those lower mass donors indicate that the favorable strip for GW formation vanishes for all possible orbital periods. This implies that understanding the conservativeness of MT with CO accretors is critical.

2.4 Comparison with observations

2.4.1 Single-degenerate binaries

Even if we expect a set of conditions for a single-degenerate system to lead to coalescing COs, it is not a given that those conditions are realized in nature. Whether the CO + star systems studied in Sect. 2.3 are formed depends on the evolution of the initially more massive star and its potential interaction with its companion before the formation of the first CO of the system. To

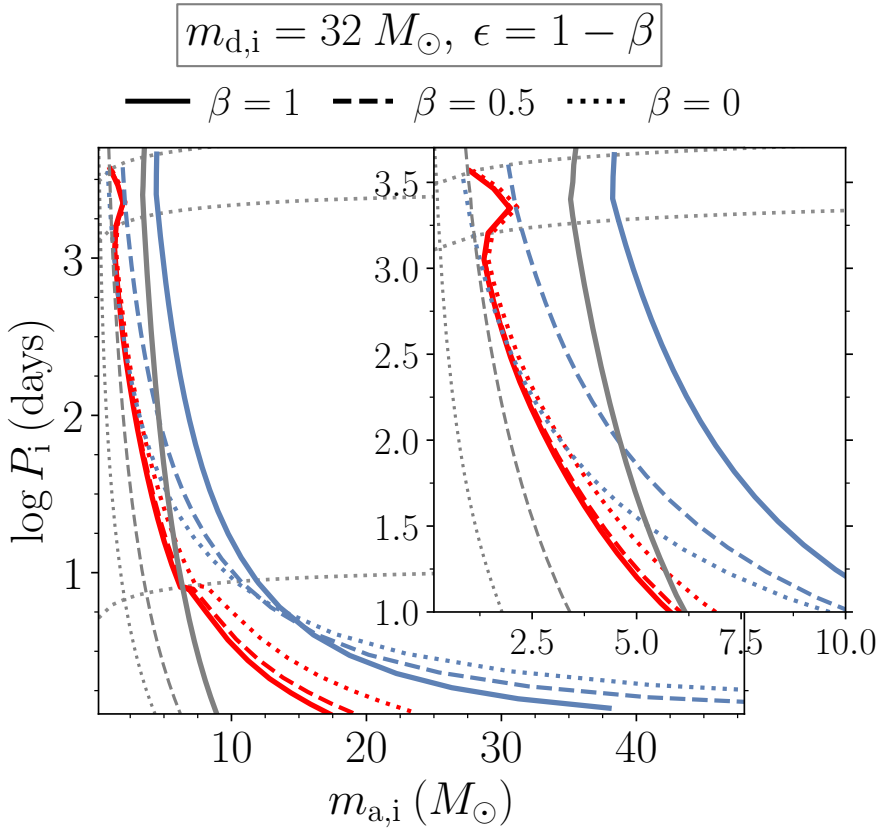


Figure 2.13: Same as Fig. 2.5, but illustrating the impact of conservative MT. Boundaries are shown for the case of full isotropic re-emission, with $\epsilon = 0$ (solid line), $\epsilon = 0.5$ (dashed line) and $\epsilon = 1$ (dotted line). The efficiency of isotropic re-emission and conservativeness are varied such that $\epsilon = 1 - \beta$.

check for the existence of the necessary conditions in the single-degenerate stage, we compared the properties of known systems at the CO + star stage to our theoretical predictions of GW progenitors' initial properties.

To this purpose, we compiled data of known CO + star systems from the literature. For the high mass (X-ray) binaries (HM(XR)Bs) with BHs we collect the data for the six known systems with characterized orbital properties and masses: HD 96670 (Gomez & Grindlay 2021), M33 X-7 (Pietsch et al. 2006, Orosz et al. 2007), LMC X-1 (Mark et al. 1969, Hutchings et al. 1983, Hutchings et al. 1987), Cyg X-1 (Miller-Jones et al. 2021), VFTS 243 (Shenar et al. 2022) and HD 130298 (Mahy et al. 2022) (see Table 2.1 for a summary of these systems' properties). In this context, we call m_{star} the mass of the optical companion to the CO, m_{CO} .

For HM(XR)Bs with NSs, we considered the galactic systems of Be/X-ray binaries where the CO is a NS, of which a sample of 60-80 is known in the Milky Way (Reig 2011). We collected the data listed in Table 1 of Tomsick & Muterspaugh (2010), which summarizes the sample with estimates of the Be star masses, m_{star} . To compute the ratio, $m_{\text{CO}}/m_{\text{star}}$, of the NS mass versus the mass of the optical companion, we adopted the reference values for the masses shown in Tomsick & Muterspaugh (2010), without accounting for their uncertainties.

For low mass X-ray Binaries (LM(XR)Bs), multiple examples exist, in the literature, with WD objects as accretors. However, these are Roche lobe-filling / strongly interacting systems (e.g., cataclysmic variables, Ritter & Kolb 2003 or classical novae, Darnley et al. 2004) where the current mass of the donor star does not represent its pre-interaction properties required in our analysis. Determinations of masses and periods for detached single-degenerate binaries with WDs are not commonly found in the literature. We first considered systems composed by a WD + MS star with determined orbital properties: the Zwicky Transient Facility (ZTF) catalogue by Brown et al. (2023) of ZTF systems (MS companions of spectral type M or later), and the compilation by Holberg et al. (2013) of Sirius-like systems (MS companions of spectral type K or earlier). We then considered systems composed of hot subdwarf stars of spectral type B or O (sdB/O) + MS companions (named ELCVNs after the prototype system, Maxted et al. 2011) and binaries with sdO + Be stars companions. These systems are assumed to be representative of a non-interacting stage preceding the single-degenerate configuration, as the subdwarf star is expected to evolve into a Helium WD. ELCVNs with determined mass ratios and orbital periods were taken from the catalogues in van Roestel et al. (2018a) (their table A4.2) and Maxted et al. (2014) (their table 2). To these, we added ten systems found in the Kepler survey, with references in van Roestel et al. (2018a). For sdO + Be/X-ray stars, we used the compilation in Wang et al. (2023a) (table 9).

In each of these cases, we took the reference values for q and P_{orb} without uncertainties.

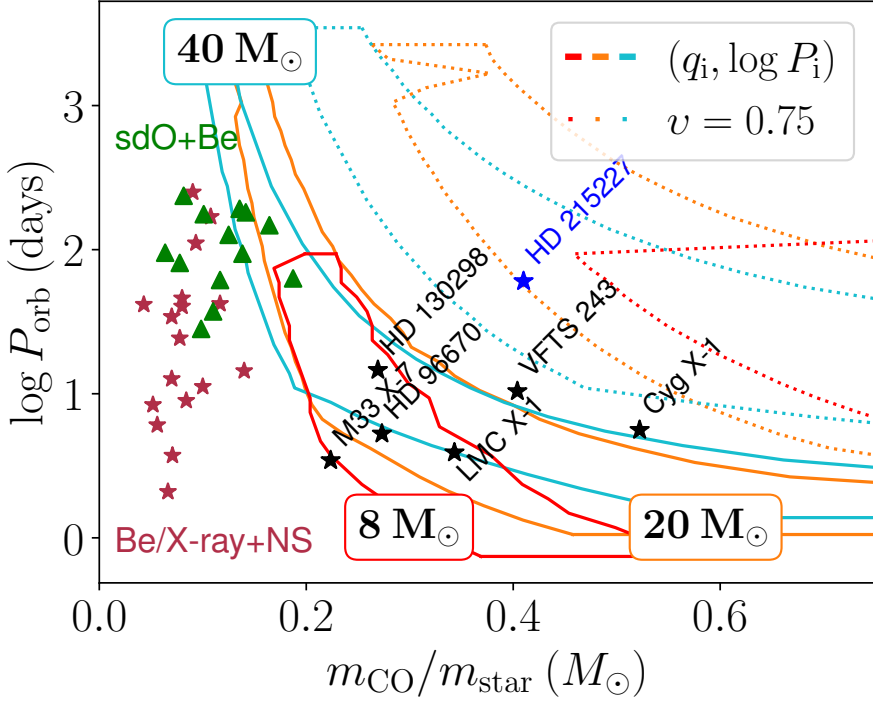


Figure 2.14: Observed orbital periods, $\log P_{\text{orb}}$, and mass ratios, i.e. $m_{\text{CO}}/m_{\text{star}}$, for high (and intermediate) mass X-ray binaries and quiescent OB + BH systems. The markers report data points (uncertainties are neglected) listed in a) table 2.1 for HM(XR)Bs with BHs (black stars), with the corresponding labeled names, and b) table 1 from Tomsick & Muterspaugh (2010) for HM(XR)Bs with NS (red stars). We also report the Casares et al. (2014) system (blue star). The triangles show the sample of confirmed sdO + Be stars in table 9 of Wang et al. (2023a). The solid, colored contours are the correspondent loci predicted by our calculations to be promising for GW progenitor systems via stable MT, within the assumption of purely isotropic re-emission, $\beta = 1$. Every contour is labeled with the associated fixed donor’s initial mass, $m_{\text{d},i}$. The dotted, colored contours show the same loci ($m_{\text{d},i}/m_{\text{a},i}, \log P_i$) within the assumption of an efficiency for mass outflow via L_2 such that $v = 0.5$.

Figure 2.14 shows the comparison between our theoretical predictions of the conditions needed to form a GW source (solid lines) and the six known

HM(XR)Bs with BHs together with the considered sample of Be stars orbiting NSs and sdO + Be binaries (single markers). The population of HM(XR)Bs with BHs extends within $0 \lesssim \log P_{\text{orb}}(\text{day}) \lesssim 1$. The population of Be-Xray binaries with NSs lies within $0.05 \leq m_{\text{CO}}/m_{\text{star}} \leq 0.18$, with mass ratios for which we predict MT to be unstable. Similarly, the sample of sdO + Be stars lies in the unstable MT region (see also Fig. 2.15), spanning larger periods, $1.5 \lesssim \log P_{\text{orb}}(\text{day}) \lesssim 2.5$. The lack of lower-mass Be stars in X-ray binaries (barring uncertainties in mass determinations from spectral types) has been used to argue for efficient MT in binary systems before the formation of the first CO (Vinciguerra et al. 2020). In this context, efficient MT is able to preclude the formation of Be/X-ray binaries with higher mass ratios than the ones that would evolve stably and form merging binary NSs. Conservative MT prior to the first CO formation has also been advanced as an explanation for the evolutionary stage of some sdO + Be star systems (e.g. HR6819, Bodensteiner et al. 2020a). As for Be/X-ray systems with BHs, only one candidate is known, HD 215227 (MWC 656, Casares et al. 2014), also reported in Fig. 2.14. However, this system might contain a hot subdwarf object orbiting the Be-star (Rivinius et al. 2024).

Figure 2.14 shows also the results of switching on an efficiency for mass outflow from L_2 of $v = 0.75$ (dashed lines). The predicted regions for GW progenitors' parameter space are consistently shifted toward more extreme mass ratios in an area that is not yet populated by known observations of CO + star binaries prior to the remaining star filling its Roche lobe. HD 215227 is the only system within the region with a massive donor predicted to directly collapse into a BH (the representative contour being the one for $m_{\text{d},i} = 40 M_{\odot}$) and at the same time close to the predicted region for a NS remnant (the representative contour being the one for $m_{\text{d},i} = 20 M_{\odot}$).

Assuming that the post-MT state and the final fate of the optical companions for HM(XR)Bs are described by those of our theoretical results for the closest initial donor's mass found in the Ge et al. (2020) table, we can assess if the conditions for the stable MT channel to produce a GW source are realized in nature. Some of these systems, however, present a non-negligible eccentricity (see Table 2.1). Our predictions, on the other hand, assume that, at the stage of the Roche lobe-filling donor, the CO + star system is already circular (we use Kepler's third law in the form of Eq. 2.16). To compare with our results for circular orbits we assume that, near the onset of Roche lobe overflow, the orbit circularizes to a period, $P_{\text{orb}}^{e=0}$, such that

$$P_{\text{orb}}^{e=0} = P_{\text{orb}} \times (1 - e^2)^{2/3}, \quad (2.31)$$

resulting from the preservation of orbital angular momentum. For e we used the values of the observed eccentricities in Table 2.1. We then associated each

m_{star} with the closest initial donor’s mass in our simulation set, $m_{\text{d,i}}^{\text{Ge}}$. We finally made a comparison, in Fig. 2.14, of the systems with the theoretical contours for different $m_{\text{d,i}}^{\text{Ge}}$.

Table 2.2 summarizes the predicted evolution (or outcome) of the known systems with BHs, based on our purely isotropic re-emission, $\beta = 1$, and mass outflow from L_2 , $v = 0.75$, evolutionary channels. We report the associated initial donor’s mass in the Ge et al. (2020) data and the modeled fate of the second-born CO. Lastly, we tabulate whether the systems have a set of initial properties that can lead to the evolution into merging double COs via stable MT (GW merger), or whether they are expected to evolve into a wide binary or undergo unstable MT.

Barring the limitations of this comparison, for the isotropic re-emission case, $\beta = 1$, we find systems covering all outcomes, including unstable MT, the formation of wide CO + CO systems and merging CO + CO expected to undergo stable MT (i.e., they appear within their associated theoretical contours in Fig. 2.14). This provides support for the idea that the conditions for the stable MT channel are realized in nature, provided that we neglect stellar winds widening the orbit after interaction (see Sect. 2.3.4). Interestingly, HD 96670 presents conditions that can be compatible with the formation of a NS-BH merger. Considering cases with L_2 mass outflow, $v > 0$, the conditions for forming a GW source shift to larger CO masses, m_{CO} . In particular, for $v = 0.75$ we find that only MWC 656 (for which the presence of a BH is contested, Rivinius et al. 2024) is compatible with the formation of a GW source. We also notice that two systems, VFTS 243 and M33 X-7, do not show in Fig. 2.14 suitable properties for being GW progenitor systems via stable MT with either $\beta = 1$ or with $v = 0.75$. For VFTS 243, however, we can find a GW merger outcome via stable MT by switching on an efficiency for L_2 such that $0.25 \lesssim v \lesssim 0.5$ (see Fig. 2.6).

We show in Fig. 2.15 the same comparison as in Fig. 2.14 between our theoretical predictions and the compilation of LM(XR)Bs and single-degenerate representative systems collected from literature (colored markers). The systems with sdO + Be stars are separated into candidate systems (candidate sdO/B + Be) from optical spectroscopy and confirmed sdO + Be and γ Cas-like systems (from the prototype Secchi 1866); see table 9 in Wang et al. (2023a) for the distinction. For the single-degenerate binaries WD + MS, consistent biases toward small orbital period ($\log P_{\text{orb}} < 0$) binaries (as well as low mass for the MS companion) are present in photometric surveys such as ZTF. On the other hand, Sirius-like systems are usually best resolved with proper motion surveys, causing biases toward the wide orbits (mostly with $\log P_{\text{orb}} > 3$). The sample of ELCVNs and sdB/O + Be/Xray stars extends within $-0.1 \lesssim \log P_{\text{orb}}(\text{day}) \lesssim 2.5$ and mostly encompasses mass ratios for which we predict MT to be unstable.

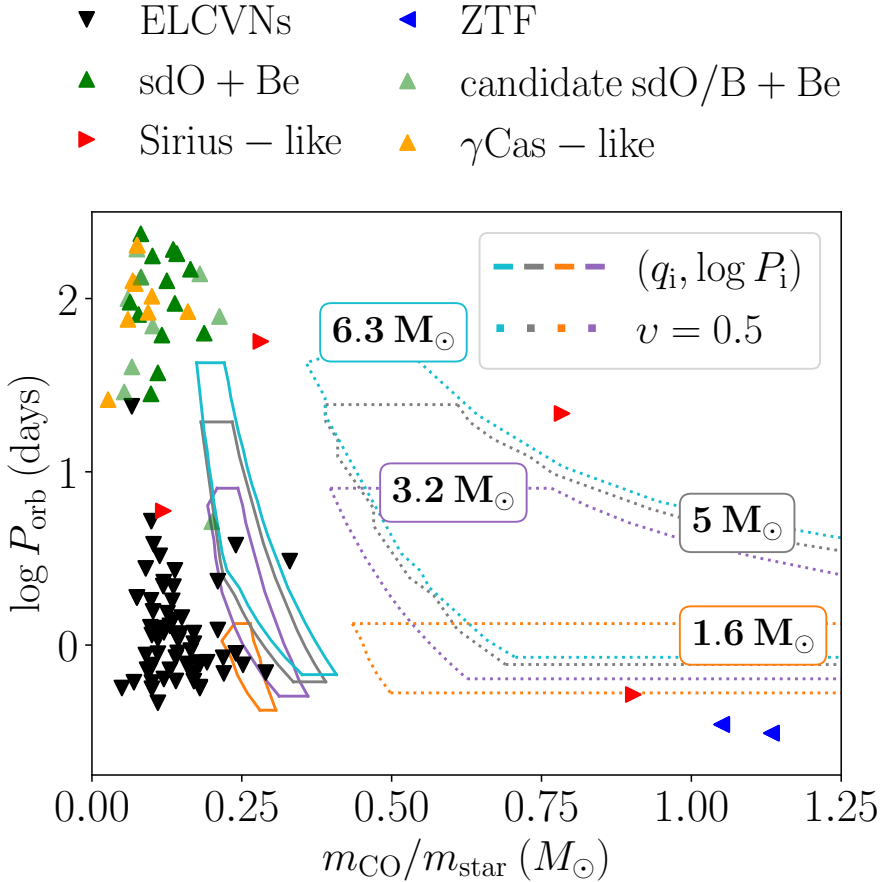


Figure 2.15: Observed orbital periods, $\log P_{\text{orb}}$, and mass ratios, $m_{\text{CO}}/m_{\text{star}}$, for low (and intermediate) mass single-degenerate binaries. More specifically: WD + MS stars from the ZTF catalogue of [Brown et al. \(2023\)](#) (ZTF) and [Holberg et al. \(2013\)](#) (Sirius-like); sdO/B + MS stars from [van Roestel et al. \(2018a\)](#), [Maxted et al. \(2014\)](#) and ten Kepler systems (see main text); sdO/B + Be stars, which are separated into candidate systems (candidate sdO/B + Be), confirmed sdO + Be, and γ Cas-like systems, as in [Wang et al. \(2023a\)](#). Markers report the reference data points without uncertainties. Solid, colored contours are the correspondent loci predicted by our calculations to be promising for GW progenitor systems via stable MT and follow the same notation as in Fig. 2.14.

This holds true whether or not additional L_2 momentum loss is accounted for (dotted lines). The degenerate companions in ELCVNs systems are generally very low mass ($\sim 0.2 M_\odot$) pre-Helium WDs, but more massive companions could shift the populated region to that predicted by us for GW mergers via stable MT.

Table 2.1: Summary of the six known HM(XR)Bs with BHs.

Source	P_{orb} (days)	m_{BH} ($M_{\odot}$)	m_{star} ($M_{\odot}$)	e	q
HD 96670 ⁽¹⁾	5.28388±0.00046	6.2 ^{+0.9} _{-0.7}	22.7 ^{+5.2} _{-3.6}	0.12 ± 0.01	0.273
M33 X-7 ⁽²⁾	3.45301±0.00002	15.65 ± 1.45	70.0 ± 6.9	0.0185 ± 0.0077	0.224
LMC X-1 ⁽³⁾	3.90917 ± 0.00005	10.91 ± 1.41	31.79 ± 3.48	0.0256 ± 0.0066	0.343
Cyg X-1 ⁽⁴⁾	5.599836 ± 0.000024	21.2 ^{+2.2} _{-2.3}	40.6 ^{+7.7} _{-7.1}	0.0189 ^{+0.0163} _{-0.0217}	0.522
VFTS 243 ⁽⁵⁾	10.4031 ± 0.0004	10.1 ± 2.0	25.0 ± 2.3	0.017 ± 0.012	0.404
HD 130298 ⁽⁶⁾	14.62959 ± 0.000854	> 7.7 ± 1.5	28.0 ^{+5.2} _{-4.1}	0.468	0.275
HD 215227 ⁽⁷⁾	60.37	3.8 – 6.9	10 – 16	0.10 ± 0.04	0.410

Notes. Columns 2 to 5 give the orbital periods P_{orb} in days, masses of the BH m_{BH} , masses of the optical companion m_{star} , and eccentricities e . The given mass ratio $q = m_{\text{BH}}/m_{\text{star}}$ is indicative and provided with no uncertainties (see main text). ⁽¹⁾Gomez & Grindlay (2021). ⁽²⁾Orosz et al. (2007). ⁽³⁾Orosz et al. (2009). ⁽⁴⁾Miller-Jones et al. (2021). ⁽⁵⁾Shenar et al. (2022). For this system we do not have a measurement of the inclination, so there is a large range of possible masses for the BH; we report here the weighted mean, between their spectroscopic and evolutionary mass, i.e. M_1 of their Table 1. ⁽⁶⁾Mahy et al. (2022). Similar to VFTS 243, we have a large range of possible m_{BH} for HD 130298; we thus use their lower limit on m_{BH} based on the binary mass function. We also use their evolutionary mass for the optical companion, see their appendix E.1.10. Their eccentricity value is also reported without uncertainty. ⁽⁷⁾Casares et al. (2014). The orbital parameters (provided in their table 1) have been derived by Casares et al. (2014) by fixing the orbital period to the shown value here, which is thus reported without uncertainty.

Table 2.2: Predicted outcome of the second-born (2nd) CO for the known HM(XR)Bs with BHs.

Source	$P_{\text{orb}}^{e=0}$ (days)	$m_{\text{d,i}}^{\text{Ge}} (M_{\odot})$	2nd born CO	OUTCOME	
				$\beta = 1$	$v = 0.75$
HD 96670	5.23	20	NS	GW merger	unstable MT
		25	BH	GW merger	unstable MT
M33 X-7	3.4522	63	BH	unstable MT	unstable MT
LMC X-1	3.9075	32	BH	GW merger	unstable MT
Cyg X-1	5.5985	40	BH	wide binary	unstable MT
VFTS 243	10.401	25	BH	wide binary	unstable MT
HD 130298	12.407	25	BH	GW merger	unstable MT
		32	BH	GW merger	unstable MT
HD 215227	59.97	10	NS	wide binary	GW merger
		16	NS	wide binary	GW merger

Notes. The mass of the systems is assumed to be $m_{\text{star}} = m_{\text{d,i}}^{\text{Ge}}$, where $m_{\text{d,i}}^{\text{Ge}}$ represents the initial donor's mass closest to the actual m_{star} in Ge et al. (2020) tables. Comparison to our results is made using the circularised orbital period $P_{\text{orb}}^{e=0}$ as in Eq. 2.31, for eccentric systems with $e > 0$. The estimate of $P_{\text{orb}}^{e=0}$ is reported with the same significant digits as the eccentricities in Table 2.1. The hypothesized channels of purely isotropic re-emission, $\beta = 1$, and mass outflow from L_2 with efficiency $v = 0.75$ are both considered. The outcomes are also labeled to argue whether the systems have a set of initial properties ($m_{\text{CO}}/m_{\text{star}}, P_{\text{orb}}^{e=0}$) that can lead to the evolution into merging double COs via stable MT (GW merger), or are expected to evolve into a wide binary (wide binary) or undergo unstable MT (unstable MT).

2.4.2 Compact object mergers

We want to compare the GWTC-3 information with the results from our simulation set for the mass ratios, q_f , and the total mass, $m_f = m_{a,f} + \alpha_{\text{core}} m_{d,i}$, achievable after the stable MT episode. To this purpose, Fig. 2.16 compares the total mass and mass ratios of detected CO mergers against our predictions for stable MT. Together with the results from our study, we show the 90% density interval as the credible region for some representative systems to illustrate the uncertainties in the total mass and mass ratios of the GW observations.

We notice a difference in the $(m_{\text{tot}}, q_{\text{fin}})$ shapes between the donor masses in the range of BH progenitors, namely $m_{d,i} \gtrsim 20 M_\odot$, and the ones in the range of NS progenitors, i.e. $8 \lesssim m_{d,i}/M_\odot \lesssim 20$. As for the BH progenitors, for each given donor mass the shape extends till $q_{\text{fin}} = 1$, showing again that for all such donors the second-born CO could be either the more massive one (which happens at longer initial periods, P_i , see e.g., Fig. 2.6), or the less massive one (happening, conversely, at smaller initial periods, P_i in Fig. 2.6). For the NS progenitors, the shape does not reach the unitary final mass ratio (aside from a small portion of points in the case of $m_{d,i} = 8 M_\odot$) because we assumed that the post-SN object would have a canonical mass of $1.4 M_\odot$ (see Sect. 2.3.2), resulting in a final mass ratio $q_f = 1.4/m_{a,f}$ mostly such that $q_f < 1$. Therefore, if the second-born CO is a NS (i.e., coming from a SN explosion of a donor star such that $8 \lesssim m_{d,i}/M_\odot \lesssim 20$) of canonical mass, it will most likely be the less massive object in the CO + CO pair.

We also observe that the stable MT channel, in the purely isotropic re-emission limit, has the potential to reproduce the final properties of the majority of GWTC-3 signals, in terms of final mass ratios and the total mass of the mergers. Covered mass ratios are such that $q_{\text{fin}} \gtrsim 0.1$. On the other hand, our predictions cover the full range of final total masses m_{tot} (although we do not include the effect of pair instability SNe in our treatment of BH progenitors, which could limit the possible ranges). Notable exceptions are GW191219-163120, which stands at $q_{\text{fin}} = 0.04^{+0.01}_{-0.01}$ and $m_{\text{tot}} = 32.3^{+2.2}_{-2.7} M_\odot$; GW200210-092254 at $q_{\text{fin}} = 0.12^{+0.05}_{-0.04}$ and $m_{\text{tot}} = 27.0^{+7.1}_{-4.3} M_\odot$; GW190814 at $q_{\text{fin}} = 0.11^{+0.03}_{-0.02}$ and $m_{\text{tot}} = 25.9^{+1.3}_{-1.3} M_\odot$.

Including higher angular momentum loss by switching on an efficiency $\nu > 0$ for L_2 outflow (Fig. 2.16 - bottom) results in less extreme final mass ratios ($q_{\text{fin}} \gtrsim 0.25$ for $\nu = 0.75$, as opposed to $q_{\text{fin}} \gtrsim 0.1$ for $\beta = 1$) coming from merging binary BHs, and no possible path to the formation of a merging binary NSs from stable mass transfer (see Sect. 2.3.2). This is due to the common envelope boundary being shifted to smaller final mass ratios, q_f , at the end of the MT episode, making any MT event from a hydrogen rich NS progenitor

onto a NS unstable (see e.g. Fig. 2.8).

An important limitation of this comparison with the population of observed GWTC-3 CO + CO mergers comes from the fact that we are not considering the information on spins. The high inferred BH spins in HM(XR)Bs have been used to argue that they are subdominant progenitors of the observed population of binary BH mergers (e.g. Fishbach & Kalogera 2022, Gallegos-Garcia et al. 2022), while others think that spin measurements in HM(XB)s should be taken with care (Belczynski et al. 2024). Among the models that attempt to explain the near critical spins inferred for HM(XR)Bs, one idea is that the spin is inherited from their progenitor star being tidally locked in a short period orbit during its main sequence (Valsecchi et al. 2010, Qin et al. 2019). If this were the case, longer period OB + BH systems would be expected to have lower BH spins potentially consistent with the observed binary BH population. The detections of VFTS 243 (Shenar et al. 2022) and HD 130298 (Mahy et al. 2022) have started to probe these longer orbital periods and the Gaia mission is expected to provide hundreds of additional detections in this regime (e.g., Breivik et al. 2017, Mashian & Loeb 2017, Wiktorowicz et al. 2019, Janssens et al. 2022, Janssens et al. 2023). However, such wide systems are expected to lack accretion disks (Sen et al. 2021, Hirai & Mandel 2021), making it impossible to apply current methods to measuring BH spins.

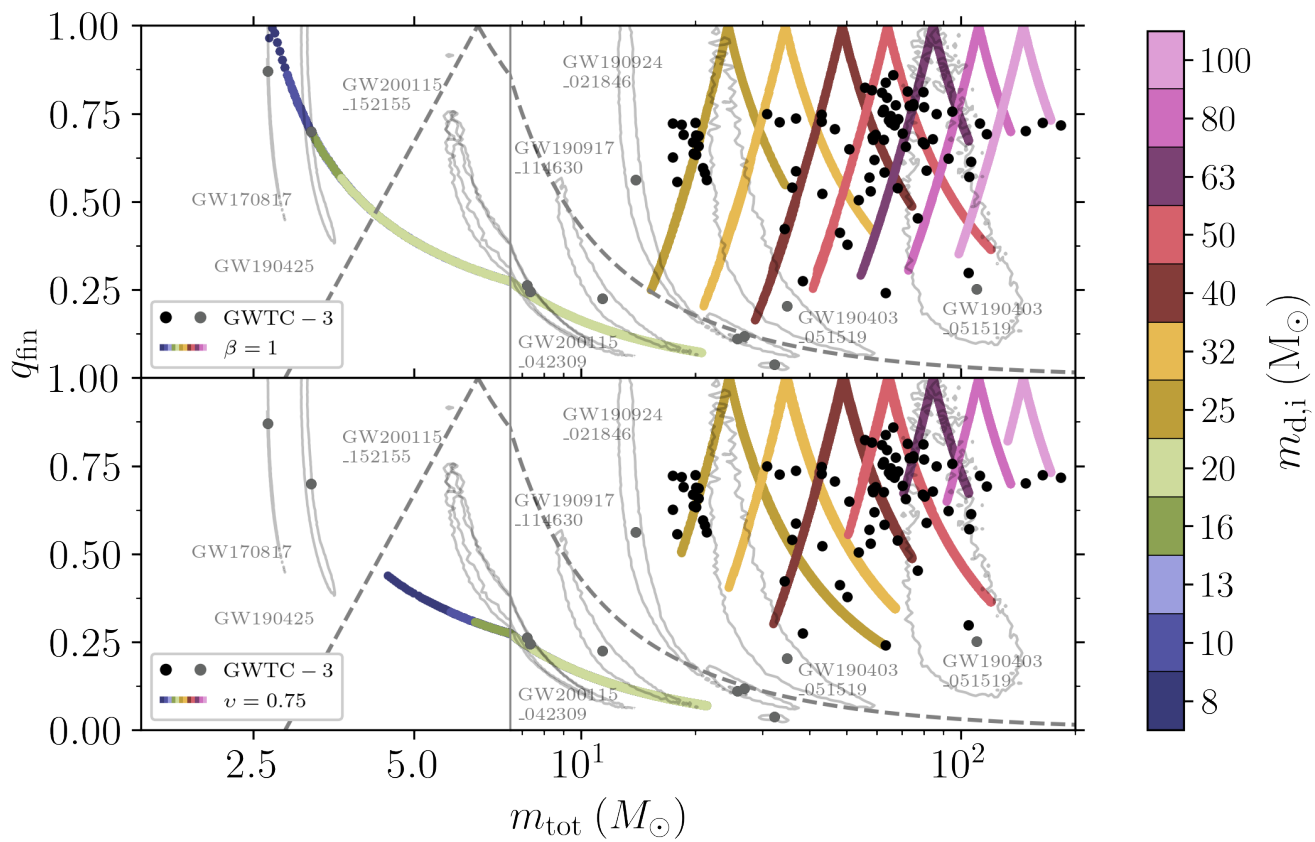


Figure 2.16: Plane of final mass ratio $q_{\text{fin}} < 1$ and total final mass, m_{tot} . We report the estimation values with corresponding 90% credible intervals for the GWTC-3 signal (gray/black dots) and the posterior 90% iso-contour for a selection of those (gray dots and light gray curves). Resulting final mass ratios and total mass from our treatment are reported with color coding referring to different donor masses $m_{\text{d},i}$ in the simulation grid from Ge et al. series (Ge et al. 2020, 2015, 2010). The assumption of completely non-conservative, purely isotropic re-emission, $\beta = 1$, channel is adopted in the top panel, while the bottom panel shows the results when switching on an efficiency for L_2 mass outflow of $v = 0.75$. Solid gray, dashed lines delineate regions where the primary and secondary can have a mass below $3 M_{\odot}$, and where both objects in the binary have masses above $3 M_{\odot}$.

2.5 Conclusions

We studied the parameter space of the initial properties of systems composed of a first-born CO orbiting a Roche lobe-filling donor. At an arbitrary evolutionary stage, the system is expected to undergo a stable MT episode and, after the formation of the second-born CO, to evolve into a double CO configuration able to merge within a Hubble time. We summarize our main findings in the following:

1. Under the assumption of fully non-conservative MT and isotropic re-emission from the accreting CO, we find that stable MT can produce all possible pairings of merging double COs except for WD + BH binaries. This holds, barring limitations on the properties (masses and orbital periods) of single-degenerate binaries that arise from the evolution until the formation of the first CO.
2. The possible formation of NS + NS mergers from stable MT is limited to a narrow range in the initial properties. For a typical NS mass of $1.4 M_{\odot}$, any companion massive enough to form a second-born NS ($m_{\text{d},i} \gtrsim 8 M_{\odot}$) will have an extreme mass ratio, such that binary NSs can only be produced in a narrow range of donor masses and orbital periods.
3. Including additional angular momentum loss (by considering a fraction of the mass removing the angular momentum corresponding to L_2), the initial orbital periods suitable for GW mergers via stable MT are shifted toward larger initial mass ratios $q = m_{\text{d},i}/m_{\text{a},i}$. Such additional angular momentum loss can prevent stable MT from forming merging binary NSs.

On the other hand, the inclusion of L_2 mass outflow with efficiency $\geq 50\%$ can allow a WD + BH pair to merge within the age of the universe.

4. We compared our results with observations of single-degenerate binaries, that is, HM(XR)Bs with black holes and Be-Xray binaries with NSs. For the isotropic re-emission calculations, the conditions required for the stable MT channel to operate seem to be present in nature. In particular, the candidate BH system HD 96670 (Gomez & Grindlay 2021) has properties consistent with the formation of a merging NS + BH. As future (and current) surveys are expected to unveil more high-mass BHs, in particular the wider-orbit counterparts to BH companions and the lower-mass optical companions to NS, we can expect to observe more systems showing such favorable conditions.
5. Considering isotropic re-emission, stable MT can produce merging binary BHs with mass ratios $q \geq 0.1$. This covers the majority of the sources observed in the GWTC-3 catalogue, except for extreme cases such as GW190814. Considering enhanced angular momentum loss limits the minimum mass ratios that can be achieved. In particular, under the assumption that 75% of the material is removed with the angular momentum of the L_2 point, we do not find BH mergers with $q < 0.25$.

We have made our results available to the community in tabular, machine-readable form on Zenodo (doi.org/10.5281/zenodo.8334056): tables at fixed donor mass, $m_{d,i}$, listing the boundaries ($m_{a,i}, \log P_i$) of GW progenitor systems at different efficiencies of angular momentum loss, i.e. varying discretely $\beta \in [0, 1]$ and $v \in [0, 1]$ and keeping the total efficiency $\epsilon = \beta + v = 1$. Modified boundaries with some degree of conservativeness are also provided in the case $\epsilon = 1 - \beta$, for $\beta = 0, 0.5, 1.$.

Our work provides a simple, semi-analytical approach to studying the physics and limitations of the stable MT channel. We therefore implicitly assume the existence of specific configurations of CO + star systems. Although we have shown that a comparison to known systems in that intermediate stage is promising, it is important to validate our results using detailed binary evolution calculations, which we aim to do in future work. Simulations starting from two stars at the ZAMS, rather than after the formation of the first CO, are also necessary to determine the formation rates of these systems (e.g. Bavera et al. 2021, Gallegos-Garcia et al. 2021) and compare them to observed rates of CO coalescences. Detailed simulations can also show the impact of a previous MT phase on the donor star in a CO + star system, which will modify its response to MT and thus the MT stability itself.

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Chapter 3

HR6819: a puffed-up stripped star system challenging stable mass transfer theory

This chapter is based on

HR6819: a puffed-up stripped star system challenging stable mass transfer theory

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Author contributions A. Picco developed the code, performed the simulations, and wrote the manuscript of the paper. P. Marchant assisted in developing the methodology. During the whole process, A. Picco was guided by regular discussions with P. Marchant and H. Sana. K. Deshmukh, J. S. G. Mombarg, D. Pauli provided critical insights and engaged in discussions throughout the process. The manuscript was improved by all co-authors. With respect to the original publication, some of the text was altered to fit the chapter format of this thesis.

Original abstract

Context. HR6819 is the first system with a puffed-up low-mass stripped star + a classical Be star whose nature has been confirmed by optical interferometry. The system exhibits the most extreme mass ratio (15.7 ± 1.1), the lowest stripped star mass ($0.270 \pm 0.056 M_{\odot}$), and one of the shortest orbital periods (40.3266 ± 0.0016 days) compared to similar observed binaries. As a post mass transfer candidate, HR6819 offers a unique opportunity to test the physics of binary interaction, especially the fraction of mass accreted by the Be progenitor (the efficiency of the mass transfer) required to produce the system's extreme mass ratio.

Aims. This work aims to reconstruct the possible evolutionary history of HR6819 in the context of stable mass transfer via Roche lobe overflow. We want to explore how the tight constraints on the system's total mass, mass ratio and orbital period are limiting the range of possible progenitors of the system.

Methods. Based on analytical expectations for the orbital evolution, we build grids of MESA simulations designed to match the present-day orbital period and mass ratio of the system, with different mass transfer efficiencies from fully conservative to 50% efficient.

Results. We show that evolution via stable mass transfer cannot explain the combined extreme current mass ratio and tight orbital period of the system. There is a limit on how extreme the post-mass transfer mass ratio of the progenitor binary can be at a fixed detachment period, and this limit is dependent on the efficiency of the mass transfer episode: the less efficient the mass transfer episode, the less extreme the mass ratio at detachment. Even in the case of fully conservative mass transfer, the most extreme mass ratio we can produce with binary evolution simulations is $q \sim 11.5$ at $P \sim 40$ days, which is significantly below the observed value. We also show that the reported luminosities for each component significantly exceed the value expected from their mass. In particular, based on simple stripped star models, we find that the luminosity of the bloated stripped star requires a star with a mass of $\sim 0.7 M_{\odot}$, which is over twice the measured value.

Conclusions. Our work shows that the post-interaction properties of HR6819, especially its extreme mass ratio and orbital period, cannot be produced by stable mass transfer under standard assumptions.

3.1 Introduction

HR6819 (HD 167128) is the first system that has been unambiguously confirmed by optical interferometry to contain a low-mass stripped star caught in a puffed-up stage and a rapidly rotating Be companion. Initially thought to be a hierarchical triple hosting an outer Be tertiary and an inner binary with a black hole + a B-type star (Rivinius et al. 2020), it was later proposed (Bodensteiner et al. (2020a), El-Badry & Quataert (2021), Gies & Wang (2020)) as one of the so-called black-hole impostor systems (Bodensteiner et al. 2022). Given the reflex motion of the Be star’s emission lines with respect to the B-type star and the large mass ratio inferred from spectroscopy, they proposed that HR6819 was instead a post-mass-transfer binary with a low-mass stripped star and a Be companion. This configuration was then confirmed (Frost et al. 2022) by optical interferometry with long-baseline data taken by the Very Large Telescope Interferometer (VLTI, Haubois et al. 2022) with the GRAVITY instrument (GRAVITY Collaboration et al. 2017) at high spectral resolution. These data clearly resolved a stripped object and the decretion disk surrounding the Be star and gave a first estimate of a mass for the system ($3 - 7 M_{\odot}$). More recently, further interferometric monitoring together with existing spectroscopy has made it possible to constrain the full three-dimensional orbit (Klement et al. 2025), revealing an extreme mass ratio of $m_{\text{Be}}/m_{\text{stripped}} = 15.7 \pm 1.1$.

Stripped stars are stars that have lost most of their hydrogen-rich envelope to a companion and they are a common outcome of the evolution of close binary systems (Sana et al. 2012). At low initial masses the removal of the envelope is mainly achieved through stable mass transfer (MT) via Roche lobe overflow (RLOF) (Kippenhahn & Weigert 1967) or through common envelope evolution (Paczynski 1971). Evolutionary models predict that, after the stripping, the star is a puffed-up naked helium core undergoing a contraction phase (e.g., Claeys et al. 2011). Subsequently, a long-lived phase of helium burning (10% of the stellar lifetime) is expected, during which the stripped star will appear hot and bright in the UV (Götberg et al. 2018) and challenging to observe with optical telescopes due to its much lower luminosity with respect to the companion. Due to the accretion of mass and angular momentum, the companion star is predicted to rapidly rotate, possibly producing a decretion disk aligned with the orbital plane (Rivinius et al. 2013), therefore producing a Be companion.

The stripping phenomenon in binaries can occur at any mass, but their spectral appearance will strongly depend on the stripped star’s mass and its mass-loss properties. It can produce Wolf Rayet stars (with masses of $M \gtrsim 8M_{\odot}$, Crowther 2007, Shenar et al. 2020b), intermediate-mass stripped stars ($2M_{\odot} \lesssim M \lesssim 8M_{\odot}$, Drouot et al. 2023, Götberg et al. 2023, Ludwig et al. 2025) and OB-type subdwarfs (sdOBs, $M \lesssim 2 M_{\odot}$, Heber 2026), depending on the metallicity of

the environment. In particular, sdOBs are thought to be sustained by core- or shell-helium burning as they transition to the white dwarfs' (WDs) sequence, though the lowest mass subdwarfs may evolve through this stage without any support by nuclear fusion (e.g. Heber et al. 2003). They are found in orbit with WDs (Kupfer et al. 2015), main sequence (MS) stars (van Roestel et al. 2018b, Vos et al. 2018, Schaffenroth et al. 2022) and Be stars. The sdOB companions to bright Be stars can be directly detected with UV spectroscopy (e.g. Wang et al. 2021b) and infrared interferometry (e.g. Klement et al. 2024), a prototypical example being ϕ Per (Gies et al. 1998b, Mourard et al. 2015). To date, targeted explorations have confirmed roughly two dozen Be + sdOB binaries with orbital periods of the order of months (e.g. Klement et al. 2024, Wang et al. 2023b), which seems to support the stable MT formation scenario according to population synthesis studies (Han et al. 2003b).

In HR6819, the stripped star is observed with a larger radius (hence, puffed-up) and a cooler effective temperature than normal helium-burning sdOBs, a stage that has been referred to as "bloated stripped star" and is possibly representative of the contraction stage prior to sdOBs. The bloated stage was traditionally expected to be short-lived (with a duration on the order of the thermal timescale of the stripped star; see, e.g. Kippenhahn & Weigert 1967, van den Heuvel 1975) and out of thermal equilibrium. However, evolutionary models have recently shown this stage to be near thermal equilibrium, and to last longer than expected (El-Badry & Quataert 2021, Dutta & Klencki 2024), possibly solving the tension with the growing number of puffed-up stripped stars observed so far. In contrast to standard sdOBs, bloated stripped stars are detectable in the optical and their surface properties closely resemble those of B-type MS stars of much higher mass, making their identification challenging. A first example was the case of LB-1, thought to host an $\sim 70 M_{\odot}$ black hole (Liu et al. 2019) and later proposed to hide a puffed-up stripped star with a mass of $\sim 1.5 M_{\odot}$ and a $\sim 7 M_{\odot}$ Be companion (Irrgang et al. 2020, Shenar et al. 2020a). Along with HR6819 and LB-1, there are currently a handful of such low-mass bloated stripped stars + Be star candidates (NGC 1850; Saracino et al. (2022), El-Badry & Burdge 2022 and Rivinius et al. 2025), and there are a few more in the intermediate-mass range (e.g., γ Columbae, Irrgang et al. 2022, VFTS-291, Villaseñor et al. 2023). Notably, the very low-mass of the stripped star in HR6819 sits right at the lower boundary of possible sdOB masses (Zhang et al. 2009, Bauer & Kupfer 2021, Arancibia-Rojas et al. 2024).

The rapidly rotating Be companion in HR6819 is thought to be a representative of a post-MT spun-up accretor, supporting the idea that Be stars are formed more commonly in binaries (e.g. de Mink et al. 2013, Shao & Li 2014) than in single-star scenarios (Ekström et al. 2008, Granada et al. 2013, Hastings et al. 2020). However, the amount of mass that such an accretor can retain

during the MT (the efficiency) is still unconstrained. The traditional view is that after mass growth of just a few percent the mass gainer would spin up to critical rotation (Packet 1981), therefore stopping the accretion. Additionally, rotationally enhanced winds can make the MT very inefficient, unless strong tides are preventing the spin up to critical (Langer et al. 2003). State-of-the-art evolutionary models usually account for tides and rotationally limited accretion, but the low MT efficiencies are challenged by the observations of sdOB + Be binaries, for which there is evidence for substantial accretion (Pols 2007, Bao et al. 2025, Lechien et al. 2025, Xu et al. 2025). An alternative explanation may be that the specific angular momentum of the accreted material is only a fraction of the respective Keplerian momentum (Paczynski 1971), but this effect has so far not been explored.

Systems such as HR6819 are of special interest, as they can be representative of the immediate post-MT stage, providing a window into a previously unprobed stage of binary evolution and the opportunity to test MT theory. Compared to the other well-characterised puffed-up stripped star + Be star systems, HR6819 exhibits the most extreme mass ratio ($m_{\text{Be}}/m_{\text{stripped}} = 15.7 \pm 1.1$), the lowest stripped star mass ($m_{\text{stripped}} = 0.270 \pm 0.056 M_{\odot}$) and one of the shortest orbital periods (40.3266 ± 0.0016 days), being also one of the best constrained systems in terms of errors. In this work, we used the refined constraints on the dynamical masses from combined interferometry and spectroscopy (Klement et al. 2025) to model the evolution of a progenitor of HR6819; we discuss this in Sect. 3.2. In Sect. 5.3, we show that evolution via stable MT cannot explain the combined extreme current mass ratio and tight orbital period of the system. We further discuss the generality of the problem and provide our conclusions in Sect. 3.4.

3.2 Methodology

We used version 24.03.1 of Modules for Experiments in Stellar Astrophysics (MESA, Paxton et al. 2011, 2013, 2015, 2018, 2019; ?) to model the evolution of a progenitor binary to HR6819. A detailed description of our simulation setup is provided in Appendix B.1 and the input files are uploaded in Zenodo¹ for reproducibility.

We started our simulations from two ZAMS stars in orbit with an initial period P_1 and with initial masses $m_{\text{stripped},i}$ and $m_{\text{Be},i}$ for HR6819's stripped and Be star progenitors, respectively. We investigated the stable MT formation scenario, in which the initially more massive (primary) star is stripped of its envelope by

¹doi.org/10.5281/zenodo.15662480

a MT episode onto the initially less massive companion (secondary). We define the binary mass ratio, q , as

$$q \equiv \frac{m_{\text{Be}}}{m_{\text{stripped}}} . \quad (3.1)$$

We computed the MT rates with the contact scheme from [Marchant et al. \(2016\)](#). During the MT, the secondary accretes mass and becomes more massive than the primary, thus proceeding faster in its evolution and expanding within its own Roche lobe. When MT from the secondary onto the primary (inverse MT) is initiated, we stopped the simulation. We also singled out the simulation where the accreting star expands beyond the volume-equivalent radius at the L2 Lagrangian point (L2 limit) following Eq. 2 in [Marchant et al. \(2016\)](#), and excluded them from the analysis as they are assumed to become unstable.

To determine the initial conditions for our simulations, P_i , $m_{\text{stripped},i}$, and $m_{\text{Be},i}$, we considered mass and angular momentum conservation during stable MT ([Soberman et al. 1997](#), but see also [Tauris & van den Heuvel 2023](#)). We define the efficiency, ϵ , of the MT as

$$\epsilon = \frac{\Delta m_{\text{accretor}}}{\Delta m_{\text{donor}}} \equiv 1 - \beta , \quad (3.2)$$

where $\Delta m_{\text{accretor}}$ is the fraction of accreted mass when the donor transfers Δm_{donor} . Here, we allowed for a fraction, β , of the transferred mass to leave the system with the specific angular momentum of the accreting star (commonly referred to as isotropic re-emission). Note that $\beta = 0$ is the limit of conservative MT and $\beta = 1$ describes fully inefficient accretion. Given a certain efficiency, ϵ , mass conservation imposes the following relation between the initial total mass, $m_{\text{tot},i} = m_{\text{Be},i} + m_{\text{stripped},i}$, and the total mass at a reference point, $m_{\text{tot},r}$:

$$\frac{m_{\text{tot},i}}{m_{\text{tot},r}} = \left(\frac{1 + q_i}{1 + q_r} \right) \left(\frac{1 + \epsilon q_i}{1 + \epsilon q_r} \right)^{-1} . \quad (3.3)$$

Finally, we assumed circular orbits and constant fractions ϵ and β along the MT, and we ignored other mechanisms for angular momentum loss from the system. Our models do not include rotation, since including a rotationally limited accretion would reduce the MT efficiency and possibly mimic a very inefficient MT episode, in contrast with the observed sample of sdOBs + Be systems. For this reason, we rather wanted to explore different fixed efficiencies in order to make a statement about how conservative the MT needs to be to reproduce the orbital properties of the system. Under these assumptions, one can derive the following map between the initial orbital period, P_i , and the period at any reference point, P_r , along the MT:

$$\frac{P_i}{P_r} = \left(\frac{q_r + 1}{q_i + 1} \right)^{-\frac{3\beta\epsilon}{\epsilon(\epsilon-1)}-1} \left(\frac{\epsilon q_r + 1}{\epsilon q_i + 1} \right)^{\frac{3\beta}{\epsilon(\epsilon-1)}-5} \left(\frac{q_r}{q_i} \right)^3 . \quad (3.4)$$

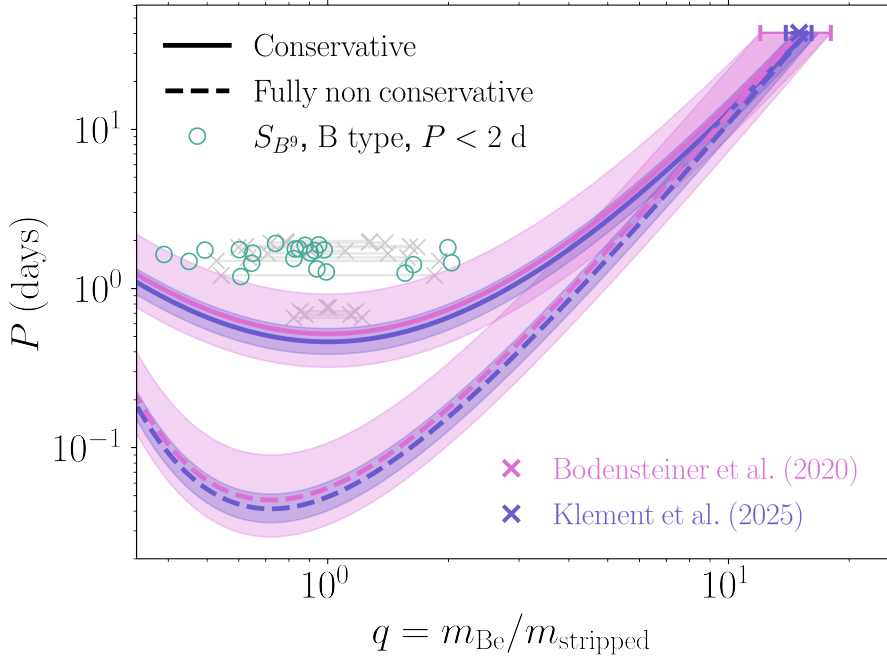


Figure 3.1: Orbital period, P , of the binary system as a function of mass ratio q , assuming a present-day period of $P_r \sim 40$ days and the two estimates of the current mass ratio from spectroscopy alone (purple; Bodensteiner et al. 2020a, 15 ± 3) and combined spectroscopy and optical interferometry (pink; Klement et al. 2025, 15.7 ± 1.1), with their respective uncertainties (lighter colored bands around the respective line). HR6819 properties from these two works are also reported as scatter points, with their error bars on the mass ratio (the error bars on the period are too small to be visible). MT is assumed to be either fully conservative (solid) with $\epsilon = 1$ or fully non conservative (dashed) with $\beta = 1$. Circles represent a selection of detached and semidetached systems from the S_{B^9} catalogue, as in Figure 15 from Bodensteiner et al. (2020a); see also their Appendix D.

For the references q_r , P_r , and $m_{\text{tot},r}$, we consider today's values q_{today} , P_{today} and $m_{\text{tot,today}}$ constrained by combined spectroscopy and optical interferometry (Klement et al. 2025); this is summarized in Table 3.1. In Fig. 3.1, we show the result of evaluating Eq. 3.4 for $q_r = q_{\text{today}}$, compared with the mass ratio as given by spectroscopy alone (Bodensteiner et al. 2020a). The binary system starts the MT with a mass ratio $q < 1$ and, as the MT proceeds, the Be star becomes the more massive object and $q > 1$; i.e., the diagram follows the time

Table 3.1: Properties of HR6819

q_{today}	15.7 ± 1.1
P_{today} (days)	40.3266 ± 0.0016
$m_{\text{tot,today}} (M_{\odot})$	4.28 ± 0.36
$m_{\text{stripped,today}} (M_{\odot})$	0.270 ± 0.056
$m_{\text{Be,today}} (M_{\odot})$	4.03 ± 0.34

Notes. Reference values for HR6819 used in this work to set up the MESA simulations. This table is a subset of Table 3 of Klement et al. (2025), where we use their circular solution derived from astrometry and radial-velocity fitting. The individual masses $m_{\text{stripped,today}}$ and $m_{\text{Be,today}}$ are not directly used in the setup, but are reported for completeness. Note that their table uses the inverse definition of the mass ratio $q = m_{\text{stripped}}/m_{\text{Be}} = 0.0638 \pm 0.0045$.

from left to right. The current constraints on the mass ratio of HR6819 from the updated orbital solution limit the possible initial orbital periods to $P_i \lesssim 1.25$ days, when the MT is assumed to be conservative. Fully non conservative MT requires even tighter initial configurations: $P_i \lesssim 4$ h. When also considering the double-line spectroscopic binaries with a period of less than 2 d in the S_B^9 catalog (Pourbaix et al. 2004), we see that none of these systems could serve as the progenitor of HR6819, given the tight constraints on the present-day mass ratio from Klement et al. (2025). The possible initial configurations can be wider if one allows for a less extreme value of q_r to be reached at the present-day period, P_{today} . In particular, Bodensteiner et al. (2020a) modeled a progenitor system with masses of $6 M_{\odot}$ and $2 M_{\odot}$ and a period of 2 days. Their model undergoes conservative case A MT and reaches a mass ratio at detachment as high as $m_{\text{Be}}/m_{\text{stripped}} \sim 12.5$, which falls within the uncertainty range of the mass ratio estimate from spectroscopy alone, but it is inconsistent with the tighter constraints from Klement et al. (2025).

At fixed efficiencies, ϵ and β , Eq. 3.4 and Eq. 3.3 combined give us the possible initial values for our simulations. However, fixing $q_r = q_{\text{today}}$ and $P_r = P_{\text{today}}$ does not guarantee that the binary simulation will reach the target mass ratio, as the system can detach before or after reaching q_{today} , or the MT might become unstable. As we show in Sect. 5.3, if we fix both $P_r = P_{\text{today}}$ and $q_r = q_{\text{today}}$, we find no solution due to these factors.

Given these considerations, we produced simulations of progenitor systems

exploring different MT efficiencies, ϵ , and different target mass ratios, q_r , always keeping the reference period at $P_r = P_{\text{today}}$. Figure 3.2 showcases our determination of P_i , $m_{\text{stripped},i}$, and $m_{\text{Be},i}$ for one of our grids. In this example, we show the results of fixing q_r to 10.5 as an illustration. We computed P_i from Eq. 3.4 at 45 values of initial mass ratios ($0.25 \leq q_i \leq 0.95$), such that Eq. 3.3 is also fulfilled if the model reaches q_{today} . We did this for the median value of today's total mass ($4.28 M_{\odot}$) and repeated it for the $\pm 2\sigma$ values, so the pixels in Fig. 3.2 are lining the three diagonals of constant $m_{\text{tot},r}$.

3.3 Results

The example grid in Fig. 3.2 shows several possible outcomes. We find that the smaller the initial mass ratio, the easier it is for the primary to overflow beyond L2 and break the stable MT scenario; furthermore, the tighter the initial orbital period and the closer the mass ratio to unity, the easier it is for the binary to initiate inverse MT from the secondary onto the primary. If inverse MT happens before detachment, the secondary overfills its own Roche lobe before the primary can be stripped of its envelope. Therefore, the system is expected to undergo a contact phase, and we do not consider it in the analysis, as such systems typically evolve into a merger (see e.g., Fabry et al. 2025). In case where inverse MT happens after successful detachment, the primary is a stripped star when the secondary overfills its own Roche lobe. By construction, these systems will evolve during the MT along a similar curve to that in Fig. 3.1. If the mass ratio at detachment, q_{detach} , is such that $q_{\text{detach}} \geq q_r$, the stable MT episode has succeeded in producing a stripped star in a system with a mass ratio as high as q_r at P_{today} . Depending on their mass ratio at the onset of the inverse MT, such systems may undergo a merger leading to a more massive stripped star, similarly to the scenario proposed for the quasi-Wolf Rayet star HD 45166 (Shenar et al. 2023).

We first produced a grid similar to that in Fig. 3.2, with initial conditions determined by $q_r = q_{\text{today}}$ from Table 3.1 and MT efficiencies of $0.50 \leq \epsilon \leq 1.00$, spaced by $\Delta\epsilon = 0.05$ (we did not consider ϵ values lower than 0.5 for computational reasons). We found no solution for the median of the present-day mass ratio $q_r = 15.7$, as anticipated from Fig. 3.1; to produce HR6819's extreme mass ratio with stable MT, very tight initial orbital configurations are required, and all simulations experienced either L2 overflow or inverse MT before forming a stripped star. Similarly, no solutions were found for the -2σ or -3σ values of $q_r = 13.5$ or 12.4, respectively.

Since we found no progenitor system that can reach HR6819's extreme mass

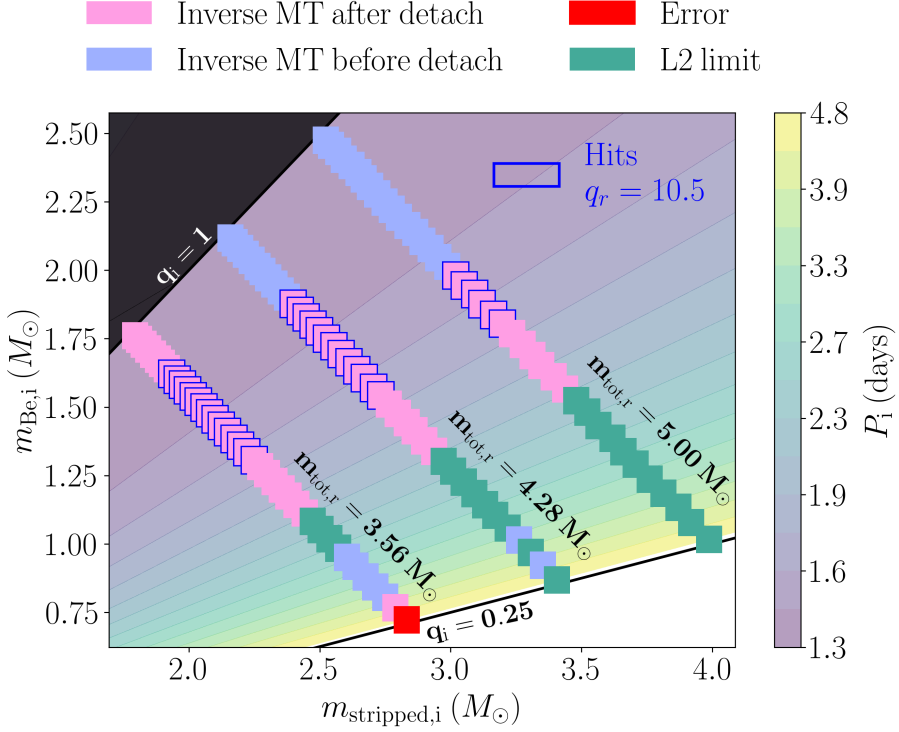


Figure 3.2: Contour levels of initial orbital periods, P_i , allowed by stable MT with $\epsilon = 1$ efficiency, if the period at detachment is imposed to be $P_r = P_{\text{today}}$ from Table 3.1 and the reference mass ratio is $q_r = 10.5$. We populate the lines of constant total mass at the present-day with MESA simulations, represented by their outcome with color-coded pixels. If these simulations reach a mass ratio at detachment q_{detach} such that $q_{\text{detach}} \geq q_r$, we mark them as hits (blue edges). This is shown as a function of stripped and Be star initial masses, $m_{\text{stripped},i}$ and $m_{\text{Be},i}$. The black region indicates initial mass ratios of $q_i > 1$, and the solid black line delimiting the base of the contour plot corresponds to $q_i = 0.25$; i.e., the lowest mass ratio we evolved.

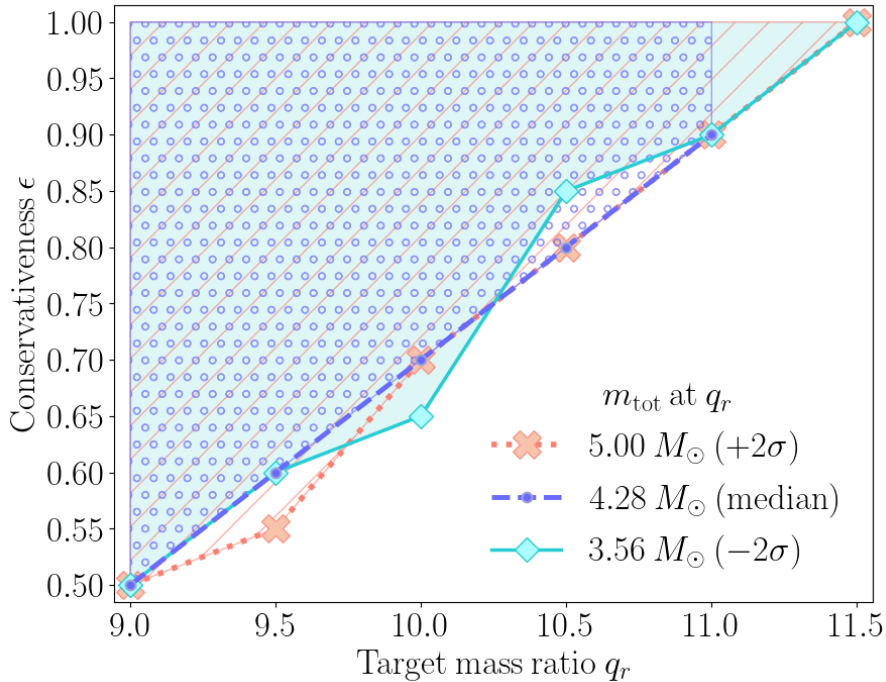


Figure 3.3: Summary plot of our grid exploration for different degrees of conservativeness, ϵ , and different target mass ratios, q_r . The area is filled where at least a solution with $q_{\text{detach}} \geq q_r$ is found, for three different values of the present-day total mass, m_{tot} : median (violet, with circular hatching); -2σ value (cyan, with shading); $+2\sigma$ (salmon, with diagonal hatching). The scatter points along the respective lines indicate where the minimum value of ϵ that gives a solution is found.

ratio at the present-day period, we investigated how extreme the mass ratio q_{detach} can become via stable MT, and the dependence of this limit on the conservativeness of the MT episode. For this purpose, we explored lower values for the target mass ratio q_r . We produced several grids similar to those of Fig. 3.2, with $9.0 \leq q_r \leq 12.0$ and spaced by $\Delta q_r = 0.5$. The results of the exploration are summarized in Fig. 3.3. We show that to form a system with a more extreme mass ratio at period, P_{today} , one needs a more conservative stable MT episode. In particular, we find that the most extreme mass ratio that can be produced consistently with the present-day period P_{today} is $q_r \sim 11.5$ (with a small dependence on the total mass of the system). This mass ratio is well below the 3σ lower limit for HR6819 given in Table 3.1.

Figure 3.4 presents a selection of our results for the detachment mass ratio at $m_{\text{tot},r} = 4.28 M_{\odot}$. For each initial mass ratio, we show the value of q_{detach} for systems that undergo inverse MT after successful detachment and stripping of the primary. The three panels show that increasing the target q_r makes it harder for the stable MT episode to fully strip the primary before inverse MT, due to tighter initial orbital configurations. Given the dependence of the initial period on the target mass ratio, the type of MT we expect (case AB or case B) is also influenced. Lastly, the systems that undergo detachment with $q_{\text{detach}} > q_r$, have, by construction, a longer detachment orbital period than P_{today} , as dictated by Eq. 3.4. These systems show that stable MT can produce detachment mass ratios as high as $m_{\text{Be}}/m_{\text{stripped}} \sim 13$. These systems would have a period of $P \sim 90$ days, which is comparable with the observed sample of Be + sdOB binaries, but not compatible with HR6819’s present-day period.

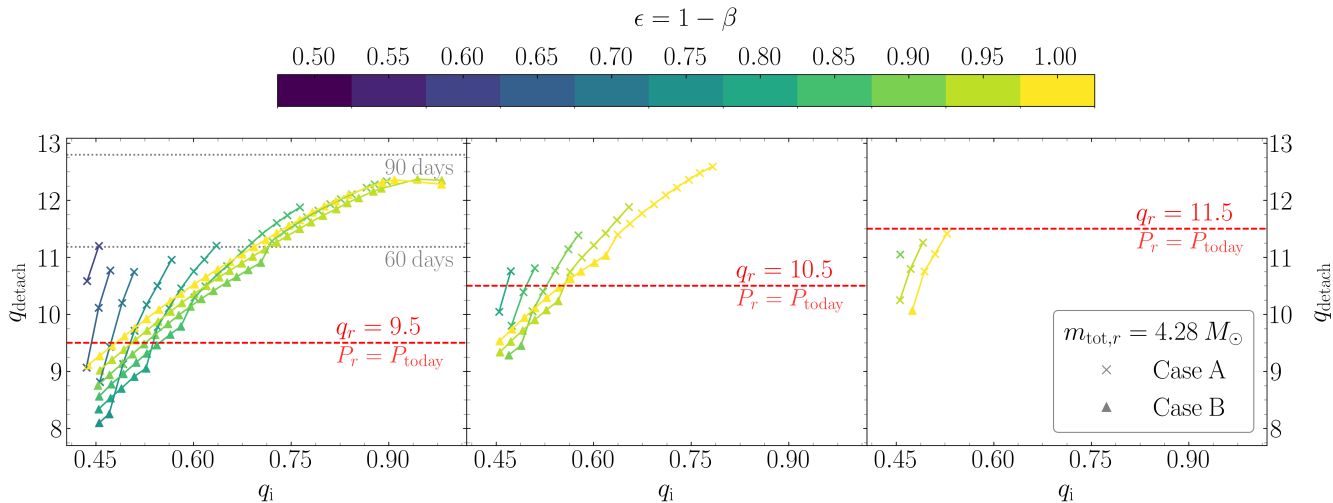


Figure 3.4: Detachment mass ratio as function of initial mass ratio for a selection of our results. The three panels refer to three different grids for target mass ratio q_r as indicated by the dashed red line, which also corresponds to a detachment period of $P_r = P_{\text{today}}$, by construction. Different MT efficiencies are color-coded according to the color bar, and the scatter points mark case A (x marker) and case B (triangle marker) MT. The systems have total mass $m_{\text{tot},r} = 4.28 M_{\odot}$ (median for HR6819) at q_r . In the first panel, we also show the detachment ratios corresponding to periods of 60 and 90 days in gray, as a reference.

3.4 Discussion and conclusions

We calculated the evolution via stable MT of progenitors of stripped star systems and showed that it is not possible to produce mass ratios as extreme as the one measured for HR6819 from combined spectroscopy and interferometry. The initial orbital configurations of possible progenitors of HR6819 are too tight and would engage in a) MT from the secondary onto the primary before the complete stripping of the primary; b) L2 Lagrangian point overflow, depending on their initial mass ratio. High MT efficiency allows for larger initial periods and can help to overcome such difficulties; however, there is a limit to how extreme the mass ratio can become at a fixed post-interaction orbital period. A system that has evolved through stable MT can host a stripped star and its companion in an orbit of $P \sim 40$ days with a mass ratio at most as high as $m_{\text{Be}}/m_{\text{stripped}} \sim 11.5$. Conversely, the channel can produce mass ratios as high as ~ 13 ; i.e., possibly right at the 3σ limit of the observed value, but such a system would have a much wider orbital period ($P \sim 90$ days) than that of HR6819.

Figure 3.5 shows an example of a binary that, after the stripping of the primary via conservative MT, detaches with a mass ratio of $q \simeq 11.65$ at $P \simeq 41.79$ days. By construction, this system has a total mass at detachment of $\simeq 5 M_{\odot}$ (the $+2\sigma$ value for HR6819's total mass), and crosses the target mass ratio $q_{\text{r}} = 11.5$ at $P_{\text{r}} = P_{\text{today}}$. The stripped star mass at detachment is $\simeq 0.4 M_{\odot}$, and the secondary has become a $\simeq 4.6 M_{\odot}$ star still on its MS. These masses are much too low to cross HR6819's observed values on the HRD, despite our specific choice to match the higher 2σ limit for the total mass of the system. To alleviate this problem, one could consider non conservative MT, which would allow for even higher initial masses of the components; however, our work shows that non conservative MT requires tighter initial orbital configurations and cannot reproduce the mass ratio at the observed period.

Furthermore, the present-day luminosity and effective temperature of HR6819 cannot be matched with a post-stable MT system, as both binary components would need to have a much higher ZAMS mass given the current total mass constraint. To visualize this, we produced evolutionary tracks for donor stars of different masses undergoing case B fully conservative MT and found an appropriate ZAMS mass that would explain HR6819's stripped star (see Fig. 3.5). We found that our model with a ZAMS mass of $\sim 4.6 M_{\odot}$ would have the luminosity and effective temperature of HR6819 at the contraction stage, but with a stripped star mass as high as $\sim 0.7 M_{\odot}$. Such a stripped star mass is too high given the observed $m_{\text{stripped}} = 0.270 \pm 0.056 M_{\odot}$ (see Table 3.1). We

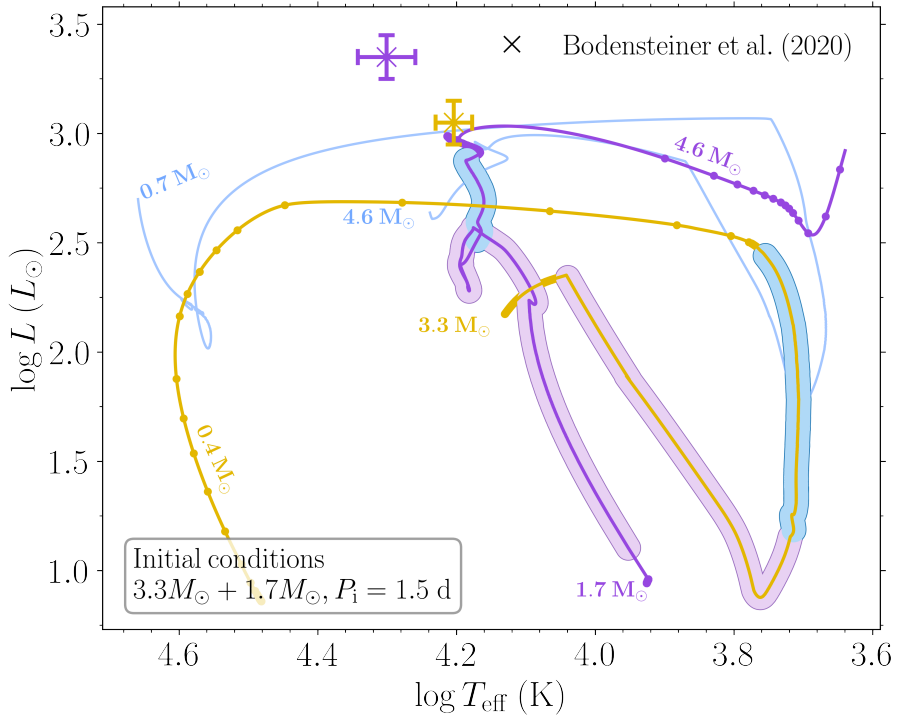


Figure 3.5: HR diagram showing the evolution of a system composed of a primary (the stripped star progenitor) with $m_{\text{stripped},i} = 3.3 M_{\odot}$ and a secondary (the Be star progenitor) with $m_{\text{Be},i} = 1.7 M_{\odot}$, in orbit with an initial period of $P_i = 1.5$ days. The system evolves via fully conservative MT. Dots along the tracks are separated by 0.1 Myr of evolution. Purple and blue highlighted regions correspond to mass transfer on the MS (case A) and after the MS (case AB), respectively. The scatter points mark the observed locations of HR6819 according to Bodensteiner et al. (2020a), with 1σ error bars. An evolutionary track for a donor star (ZAMS mass $4.6 M_{\odot}$) undergoing case B mass transfer is shown in blue as it crosses HR6819’s observable at its median. The ZAMS and stripped stars’ masses for every track are also reported along the track with corresponding colors.

used the BONNSAI² tool (Schneider et al. 2014) to infer the appropriate mass of the secondary given its HRD properties, after its accretion from the primary: this would need to be a $7_{-0.62}^{+0.52} M_{\odot}$ star on its MS. This is expected as the mass gainer is enriched with helium and has a higher luminosity than a single star model of similar mass.

As our results from conservative stable MT are inconsistent with HR6819’s observational constraints, one should think of possible ways to alleviate the tension. We expect convective overshooting to have an impact: a smaller core would lead to a more extreme mass ratio at detachment, as the donor star will then form a smaller helium core and, thus, a lower stripped star mass. Since we used a step-overshooting scheme of the hydrogen-burning convective core, extending its size by 0.1 pressure scale heights (see also Appendix B.1), we also explored a much lower value of 0.01 as a parameter variation, and present the results in Appendix B.2. In the case of a lowered overshooting parameter, we found that systems with mass ratios at most as high as $q \sim 12$ at P_{today} can be formed via stable MT. We therefore conclude that the tension cannot be solved with a lower overshooting parameter.

Our assumption of fixed accretion efficiency throughout the MT episode might also have a significant impact on our outcomes. In HR6819, the Be star component is rotating near critically, and analytical considerations predict that during the MT episode such a critical rotation rate is reached soon after the onset of RLOF, after accreting a few percent of its mass with the specific angular momentum of its surface (Packet 1981). In this case, part of the momentum exchanged during RLOF feeds a nonzero-spin angular momentum of the accretor instead of being transferred to the orbit. At this point, the spun-up star could keep accreting mass while maintaining its rotation thanks to a braking mechanism (Deschamps et al. 2013 and references therein). Alternatively, mass may be lost from the system by feeding circumbinary outflows (e.g. Lu et al. 2023) or via localized radiation-driven winds from spots of direct-impact accretion (van Rensbergen et al. 2008). The occurrence of either of the two cases, and the subsequent degree of non conservativeness they might introduce, are major uncertainties that we did not account for in our work. As a simple estimate, we can assess the quota of spin angular momentum necessary to spin the Be star progenitor up to its critical rate and evaluate the impact of such spin-up on the final period of our models. For our models that reach a mass ratio at detachment as high as $m_{\text{Be}}/m_{\text{stripped}} \sim 13$ with a period of $P \sim 90$ days, we find that such a final period would only be reduced by $\sim 7\%$, if the Be star progenitor spun up to critical at detachment.

Other angular momentum loss mechanisms than the isotropic re-emission mode

²The BONNSAI web-service is available at www.astro.uni-bonn.de/stars/bonnsai.

could also have an influence on our results. Fully non conservative MT via isotropic re-emission requires much tighter initial orbital configurations than the conservative case (see Fig. 3.1), and this makes our models experience L2 overflow or inverse MT before forming a stripped + Be star system. However, larger initial periods are allowed if material is removed from the system carrying a specific angular momentum lower than that of the accretor. We decided to explore the case in which material is expelled from the system with a fixed fraction of the specific total orbital momentum, and we recomputed our grids as described in Appendix B.2. Our results show that, for the same amount of mass lost from the system, stable MT with this mode of angular momentum loss can achieve a target mass ratio at P_{today} more extreme than with the isotropic re-emission mode. However, the most extreme mass ratio achievable at P_{today} with this mode is $q_r \sim 11.5$; therefore, it cannot explain HR6819's properties (see Appendix B.2).

The total mass determination of $m_{\text{tot, today}} = 4.28 M_{\odot}$ from Klement et al. (2025) is dependent on the distance measurement. They found $d = 296.0 \pm 8.0$ pc from dynamical parallax, which to 2σ uncertainty allows for a total mass between $3.56 \leq m_{\text{tot, today}} (M_{\odot}) \leq 5.00$, the range explored in this work. Following the calibration of Maíz Apellániz (2022) with an OB-type prior for the Gaia DR3 parallax, the distance can be much higher: $d_{\text{GAIA}} = 375_{-58}^{+85}$ pc. Considering that the total mass scales with the distance to the third power and $(d_{\text{GAIA}}/d)^3 \simeq 2.03$, the total mass determination could potentially shift to $\simeq 8.70 M_{\odot}$. This much higher total mass could help explain the high luminosity of the system, as we could have an $\sim 8 M_{\odot}$ Be star in orbit with an $\sim 0.5 M_{\odot}$ stripped star (consistent with the typical masses of sdOBs; e.g., Arancibia-Rojas et al. 2024), provided that we accept a possible inconsistency on the individual masses determinations from Klement et al. (2025). However, a higher present-day total mass implies higher mass progenitors, which would in turn undergo L2 overflow, given how tight the allowed initial orbital periods are. We confirmed this prediction by producing grids similar to that of Fig. 3.2 but relaxing the total mass constraint to match a present-day value of $\sim 8 M_{\odot}$, and we found no solutions.

Lastly, one could think of a possible formation scenario that includes a common envelope episode in place of stable MT. This can be motivated by the relatively short period of HR6819 with respect to the other known (bloated) sdOB + Be binaries, which have orbits on the order of months. However, this relatively moderate separation still appears too wide to be the result of CE ejection, according to binary population synthesis studies (e.g. Han et al. 2003b). Nevertheless, the uncertainties in common envelope theory would make the outcomes largely unpredictable, and we did not attempt any modeling. We can stress that highly non conservative MT would imply a much larger initial total mass than the present-day value. For case A systems, which is what is

needed to achieve the lowest possible stripped star mass, unstable MT can be triggered at moderate-to-high initial mass ratios, but the absence of a defined core-envelope structure would make it harder for the binary to survive (e.g., [Ivanova et al. 2013](#)). A Case B or later MT phase offers a greater chance of survival and envelope ejection due to the presence of a compact core, but only stars with masses as low as $\sim 2.5 M_{\odot}$ can produce a $\sim 0.27 M_{\odot}$ helium core at the terminal age MS. Such a star could initiate the common envelope in a binary with a relatively moderate mass ratio, but the constraint on the present-day total mass would be hard to meet if the stripped star progenitor successfully ejects its $\sim 2.2 M_{\odot}$ envelope.

HR6819 is the best constrained system with a puffed-up stripped star + Be star and, compared to the other similar known systems, it exhibits the most extreme mass ratio. Such a mass ratio of $m_{\text{Be}}/m_{\text{stripped}} = 15.7 \pm 1.1$ is also very extreme when compared with those of the sdOB + Be star system with constrained dynamical solutions (ϕ Persei [Mourard et al. 2015](#); κ Dra [Klement et al. 2022a](#); and another 6 in [Klement et al. 2024](#)). Among these, HR2142 is the only one showing a more extreme median value for its mass ratio, with $m_{\text{Be}}/m_{\text{stripped}} = 17.12 \pm 2.11$, $m_{\text{Be}} = 17.6 \pm 5.7 M_{\odot}$, and $m_{\text{stripped}} = 1.03 \pm 0.22 M_{\odot}$ (see [Klement et al. 2024](#), their Table 5). Within these large uncertainties, this system may still fall within the range of mass ratios achievable with stable MT, given its wider orbital period of $P = 80.8733 \pm 0.0044$ days. Nevertheless, systems like HR6819 and HR2142 might both be pushing the stable MT channel to its limit, substantiating our finding that something is missing from our understanding of how stripped stars + Be star systems can form. Interestingly, [Lechien et al. 2025](#) also point out that both HR6819 and HR2142 are difficult to explain in their study, which assumes that systems evolve through case B stable MT, and state that they might have been formed by case A MT given their short initial periods and high accretion efficiency constraints. In this respect, our study of HR6819 complements theirs and further confirms the problematic nature of the system, since we have investigated both case A and B interactions and found no consistent solution.

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Chapter 4

Mergers via failed common envelope as a route towards intermediate-mass stripped stars

This chapter is based on

Mergers via failed common envelope as a route towards intermediate-mass stripped stars

A. Picco, P. Marchant, D. Pauli, H. Sana

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Author contributions A. Picco developed the code, performed the simulations, and wrote the manuscript of the paper. P. Marchant assisted in developing the methodology. During the whole process, A. Picco was guided by regular discussions with P. Marchant and H. Sana. D. Pauli provided critical insights and engaged in discussions throughout the process. The manuscript was improved by all co-authors. With respect to the original publication, some of the text was altered to fit the chapter format of this thesis.

Original abstract

Stripped stars are a common product of binary stellar systems, spanning a wide mass range from Wolf-Rayet stars to hot subdwarfs and helium white dwarfs. The recent discovery of intermediate-mass stripped stars, with masses between those of WRs and subdwarfs, provides a continuous evolutionary sequence and valuable test beds for binary interaction models. Population synthesis studies explain the formation of stripped products through stable mass transfer or common envelope evolution. Recently, however, a merger scenario (or, a "failed common envelope") between a stripped star and a post-main sequence companion was suggested to explain the formation of the magnetic intermediate-mass stripped star HD 45166. In this Letter, we investigate this channel using detailed interacting binary simulations at Galactic metallicity and model their stripped merger products. We find that these merger products can contribute to the population of stripped stars across the Hertzsprung-Russell diagram and produce a blue-straggler effect, with merger masses spanning from $0.6 M_{\odot}$ to $14 M_{\odot}$. These objects would be consistent with long-lived core He-burning stars retaining thin hydrogen envelopes after a partial CE ejection, and would appear as single or members of wide binaries that were originally hierarchical triples.

4.1 Introduction

Stripped stars are stars that have lost their hydrogen-rich envelopes to a companion, and they are a common outcome of the evolution of binary systems (Sana et al. 2012; Sana et al. 2025). The stripping phenomenon in binaries occurs at any stellar mass, but the spectral appearance of the resulting stripped star strongly depends on its mass and mass-loss properties. At the high-mass end, stripping can produce Wolf-Rayet (WR) stars of mass $M \gtrsim 8 M_{\odot}$ (Crowther 2007; Shenar et al. 2020a); at the low-mass end, it produces OB-type subdwarfs (sdOBs; Heber 2026) and helium (He) white dwarfs (Brown et al. 2020) of mass $M \lesssim 2 M_{\odot}$. The recent discovery of intermediate-mass ($2 \lesssim M/M_{\odot} \lesssim 8$) stripped stars (Drout et al. 2023) has completed the observational bridge between the low- and high-mass stripped products.

The formation of stripped stars has been widely studied in the low-mass regime, where population synthesis models (Han et al. 2002) are able to reproduce the observed properties of sdOBs through two evolutionary channels that remove the envelope: stable mass transfer (MT) via Roche-lobe overflow (RLOF; Kippenhahn & Weigert 1967) and common envelope (CE) evolution (Paczynski

1971). At higher masses, the same MT channels may produce both intermediate-mass stripped stars (Shao & Li 2021, Yungelson et al. 2024, Hovis-Afflerbach et al. 2025) and WR stars (Vanbeveren et al. 1998a), which can also form in isolation via stellar winds in the Conti scenario (Conti 1975). For intermediate-mass stripped stars, the sample is still limited to a few spectroscopically confirmed objects (see Götberg et al. 2023 for the Magellanic Clouds; HD 45166 Shenar et al. 2023 in the Galaxy) and recent UV surveys identified 820 more candidates (Ludwig et al. 2025).

The idea that two stripped stars may merge to form a more massive stripped product has been invoked for sdBs. In particular, the merger of two He white dwarfs driven by gravitational-wave emission represents a third formation channel (Webbink 1984), in addition to stable RLOF and CE evolution. Observationally, this scenario may explain a third of the known single sdBs (Heber 2026) and the growing sample of massive ($\sim 0.6 M_{\odot}$) He sdOs (Latour et al. 2026). Similarly, mergers have been suggested as an origin for WR stars, in cases where hydrogen-rich massive merger products undergo self-stripping via wind-driven mass loss. These may account for up to $\sim 60\%$ of the WR population in the Milky Way (Li et al. 2024), consistent with the sample of Deshmukh et al. (2024). Such a channel may also aid in explaining single WR stars in low metallicity environments (Schootemeijer et al. 2024, Gilkis et al. 2025).

An especially interesting case is HD 45166, a so-called quasi-WR star due to its spectral appearance (Steiner & Oliveira 2005). Interpreted originally as the first example of an intermediate-mass stripped star in the Galaxy, it was then also proposed to have formed through the merger (or via a "failed CE") of a stripped He star (the core of the initially more massive component) with a hydrogen-rich post-MS star (the accretor during the first stable RLOF) (Shenar et al. 2023). The energy released through this merger would eject almost the entire hydrogen envelope, leaving an isolated stripped star. So far, no population synthesis study has considered such mergers as a possible way of forming stripped stars. This Letter builds upon the evolutionary interpretation of HD 45166 and explores the failed-CE mergers scenario (sketched in Fig. 4.1) in the context of the formation of galactic intermediate-mass stripped stars.

4.2 Methodology

We used version 24.03.1 of Modules for Experiments in Stellar Astrophysics (MESA Paxton et al. 2011, 2015; ?). Details about our setup are provided in

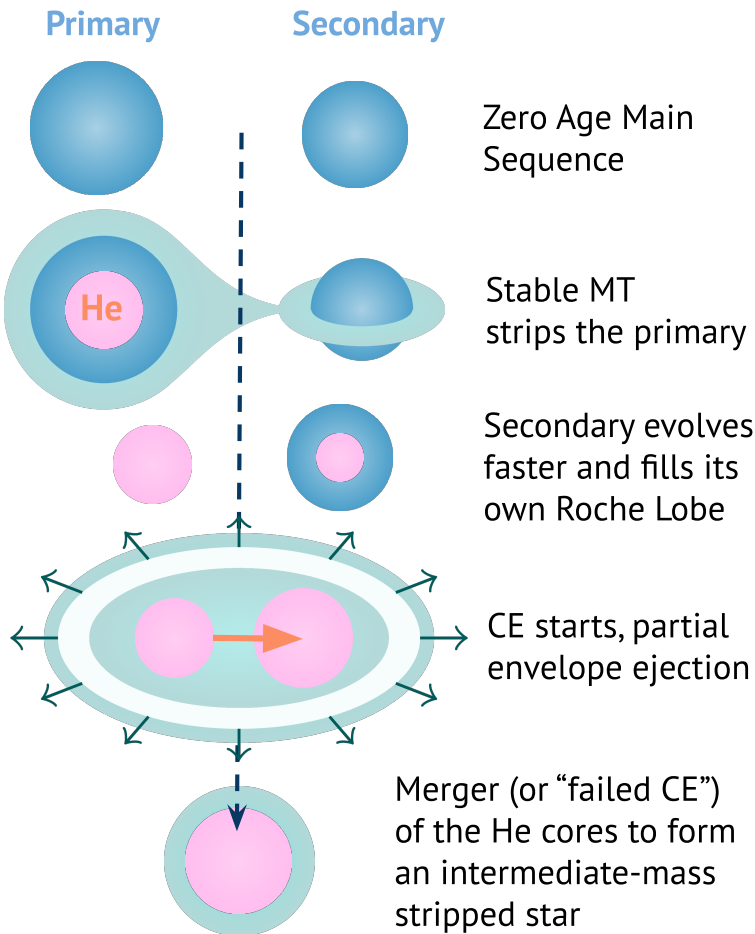


Figure 4.1: Sketch of the merger via failed CE channel

Appendix C.1 and the input files are uploaded to Zenodo¹.

First, we produced single-star tracks at solar metallicity, $Z_{\odot}$, at initial masses $2 < M_{1,i}/M_{\odot} < 20$ in steps of $\Delta M_{1,i} = 1 M_{\odot}$, until core He depletion. We refer to the primary (secondary) star with a mass of $M_{1,i}$ ($M_{2,i}$) as the initially more (less) massive component. From the single-star tracks, we extract the minimum and maximum orbital periods, $\log P_{\min}$ and $\log P_{\max}$ (days), corresponding to binaries in which the primary undergoes RLOF at the zero-age main sequence

¹doi.org/10.5281/zenodo.17424084

(ZAMS) and in which no interaction occurs up to He depletion, respectively, for a given initial mass ratio $q_i \equiv M_{2,i}/M_{1,i}$. For each $M_{1,i}$ we computed a grid of binary models spanning $0.275 \leq q_i \leq 1$ with spacing $\Delta q_i = 0.05$, and a variable resolution in orbital period across $\log P_{\min} \leq \log P \text{ (days)} \leq \log P_{\max}$ such that each grid spans 28 period values. We additionally refine the sampling around the terminal-age main sequence (TAMS) and around $q_i = 1$ to resolve the parameter space relevant for the failed CE mergers (see below). An example grid for $M_{1,i} = 6 M_{\odot}$ is shown in Fig. 4.2.

We flagged a system as stripped star produced by a failed CE when both of the following conditions were met: 1) the binary merges in a CE episode and 2) at the onset of such CE episode, both stars have evolved past their TAMS, while one star has already been stripped by a (stable) MT episode before (as in Fig. 4.1). We modeled the CE evolution using a double-core energy formalism where both stellar components contribute to the envelope ejection and orbital shrinkage. The CE mass-loss rate is regulated by the degree of Roche-lobe overfilling of both the donor and accretor, allowing mass loss to persist until both stars either detach or merge. Full details about our definition of CE onset and the CE treatment are provided in Appendix C.2.

4.3 Results

The parameter space in initial orbital period, P_i , and mass ratio, q_i , leading to failed-CE stripped stars depends on the initial primary mass $M_{1,i}$, as shown in Fig. 4.3 (see also Appendix C.3). The channel is present for all primary masses, but the allowed parameter space is increasingly suppressed for $M_{1,i} > 10 M_{\odot}$ and disappears entirely (at our resolution) for $M_{1,i} > 18 M_{\odot}$ (see Appendix C.3); additionally, we see a suppression for $M_{1,i} < 3 M_{\odot}$.

At any $M_{1,i}$, systems undergoing a first case A stable MT episode from the primary may result in failed-CE mergers even for extreme initial mass ratios. These are mainly binaries in which the primary undergoes stable case AB MT and, while it burns He in its core as a detached stripped star, the secondary evolves past-TAMS and initiates the failed CE (scenario of Fig. 4.1). In a few systems, the secondary completes core-hydrogen burning and triggers the merger during the case AB MT. Instead, binaries that form failed-CE stripped stars after a first case B stable MT episode, always follow the evolutionary scenario depicted in Fig. 4.1 and form stripped stars through failed CE at initial mass ratios closer and closer to unity, as $M_{1,i}$ increases.

In general, we expect a region below the TAMS to always favor the failed-CE stripped star outcome, due to the tight initial orbits and the possibility to

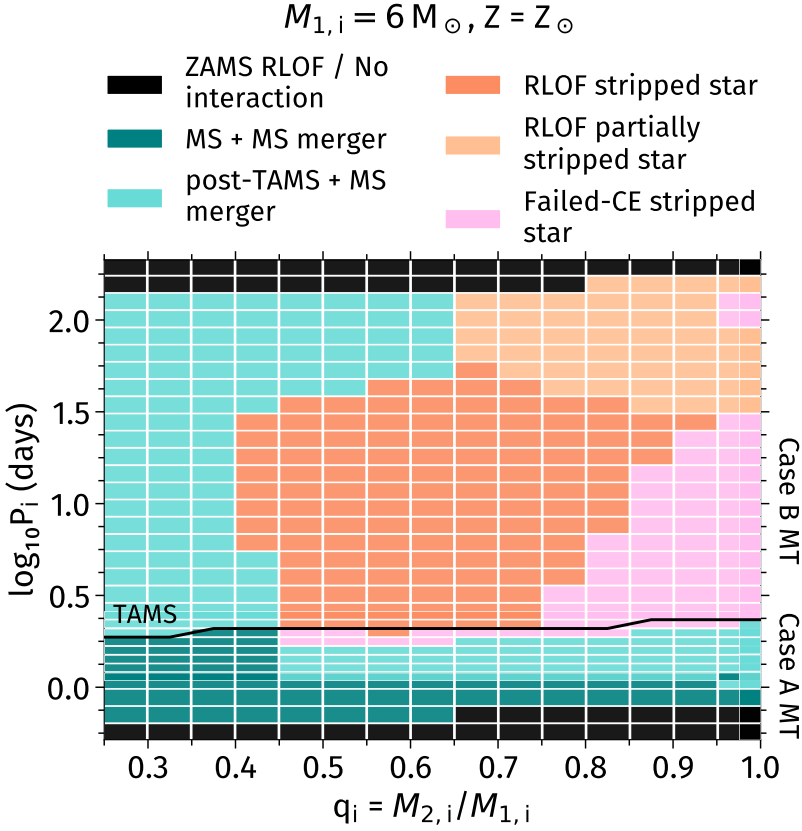


Figure 4.2: Example of one of our MESA grids for a primary star with mass $M_{1,i} = 6 M_{\odot}$ at solar metallicity, spanning initial mass ratios, $q_i \equiv M_{2,i}/M_{1,i}$ and orbital periods, P_i . The resolution is finer around the TAMS (black line) and around $q_i = 1$. Different outcomes are color-coded as in the legend: post-TAMS (MS) + MS merger refer to mergers between a post-TAMS (MS) star with a MS companion. RLOF stripped stars are formed after stable MT from the primary and detachment, and we refer to RLOF partial stripping when the He core is $< 90\%$ of the total mass.

strip the primary down to its not fully formed He core, leading to an extreme post-MT mass ratio. Additionally, we expect mass ratios $q_i \simeq 1$ to favor the merger outcome, as the stars evolve at nearly the same pace and a small amount of MT is needed to invert the mass ratio. Our resolution, however, does not resolve the narrow region around $q_i \simeq 1$ for $M_{1,i} \geq 10 M_{\odot}$. Similarly, despite

our increased resolution around TAMS, we do not see the failed-CE stripped star region for $M_{1,i} \geq 18 M_{\odot}$. Even if it were possible to resolve the region with a better sampling of the initial conditions, this is indicative of a fine-tuning of the channel at higher masses.

For case B systems, the failed-CE stripped star outcome is inhibited at longer initial orbital periods, with a dependence on how close the mass ratio is to unity (see, e.g., the triangular shape above TAMS in Fig. 4.2, and Appendix C.4). This dependence is present at all primary masses, but with decreasing importance at lower $M_{1,i}$ (see, e.g., the semi-rectangular shape of $M_{1,i} = 4 M_{\odot}$ in Fig. 4.3), due to the combination of two effects: lower mass stars 1) have less massive He cores relative to their total mass, so they can transfer more mass during MT and produce more extreme post-MT mass ratios; 2) have a steeper mass-luminosity relation, such that the secondary’s evolutionary acceleration due to accretion is favored. We can see these effects in action for primary masses $M_{1,i} < 6 M_{\odot}$, where case B systems can form stripped stars via failed-CE for initial mass ratios farther from unity than for more massive primaries (see also Appendix C.4).

4.4 Discussion

The failed-CE merger channel is robust across all the considered masses. At our resolution, the minimum and maximum merger-product masses are $0.6 M_{\odot}$ and $14 M_{\odot}$, respectively. We expect that higher mass stripped products may be produced for $M_{1,i} \geq 18 M_{\odot}$, at fine-tuned mass ratios (around unity or close to TAMS) that we do not resolve. This shows that the channel may contribute to the population of stripped products across the HR diagram, from high-mass He subdwarfs (Latour et al. 2026) to stripped stars showing the WR phenomenon at solar metallicity (Sander & Vink 2020). We expect the population of failed-CE stripped stars to produce a blue-straggler effect, due to the creation of higher-mass (and therefore higher-luminosity) interaction products than those expected to accumulate at a cluster’s turn-off from standard RLOF stripping. This is illustrated in Fig. 4.4 for an example case of a $2.5 M_{\odot}$ failed-CE stripped star, which populates the HR diagram at a much higher luminosity than its $6 M_{\odot}$ star progenitor; such a massive stripped product may be produced by simple RLOF stripping only from a much more massive progenitor, with initial mass $11 M_{\odot}$ (see also Appendix C.5). Observationally, the failed-CE stripped stars are expected to appear in isolation or as members of wide binaries that were originally hierarchical triples and may show signatures of magnetism, as in the case of HD 45166 (Shenar et al. 2023). As shown by Shenar et al. (2023), the effective temperature reached by such products (and, therefore, their proximity

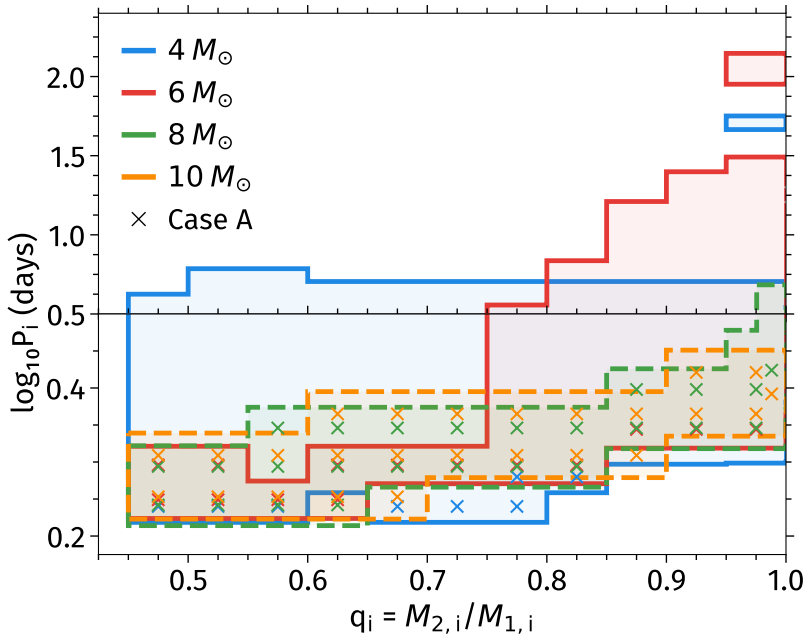


Figure 4.3: Parameter space in initial period, P_i and mass ratio, q_i , for failed-CE stripped stars for a selection of values of initial primary masses $M_{1,i}$ (color-coded). The part of the parameter space that undergoes case A MT in the first interaction is also indicated with x scatter points. Full grids similar to Fig. 4.2 but for the considered $M_{1,i}$ are shown in Appendix C.3.

to the sample of Götberg et al. (2023), see Fig. 4.4) depends on the assumed CE ejection efficiency, which we do not explore in this study.

A full population synthesis study is needed to assess the effective contribution of this channel to the overall population of stripped stars. Nevertheless, we can already provide an estimate of the likelihood of a binary with a given initial primary mass to produce a failed-CE stripped star relative to that of producing other binary interaction outcomes (Fig. 4.5), assuming uniform distribution in $\log P_i$ and q_i . We find that the failed-CE merger products can constitute between 6 and 20% of the outcomes of interacting binaries for primary masses $3 < M_{1,i} (M_\odot) < 7$. Restricting to systems that form stripped stars, we find that the failed-CE outcome is less likely than regular RLOF stripping at all primary masses, but their formation rate can still be comparable; at $4 M_\odot$, in particular, the ratio of systems producing stripped stars through failed CE versus those with stable RLOF peaks at 75% (see inset of Fig. 4.5). A population

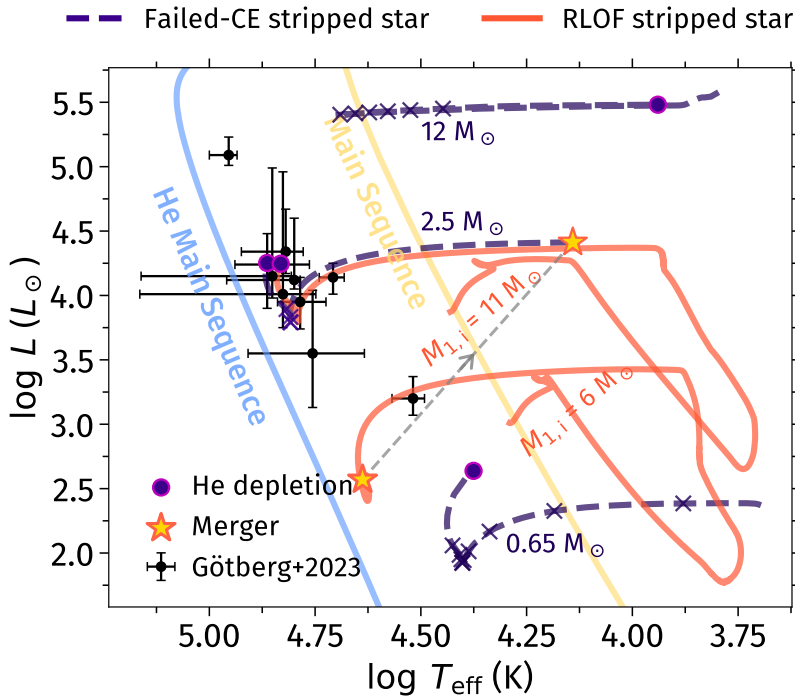


Figure 4.4: Location of the stripped star sample of Göteborg et al. 2023 in the HR diagram compared to a selection of our failed-CE stripped star models. For the $2.5 M_{\odot}$ we show the evolution of its $6 M_{\odot}$ primary prior to the failed CE (pre- and post-merger stages connected through an arrow). We also show the evolution of a $11 M_{\odot}$ donor star which produces a $2.5 M_{\odot}$ stripped star through RLOF. Cross markers for the merger models are equally spaced by 5, 0.5 and 0.05 Myr for the 0.65 , 2.5 and $12 M_{\odot}$ stripped star models, respectively. In Appendix C.5 we show the complete evolution of the represented tracks. We also show a theoretical main sequence and He main sequence in blue and yellow.

synthesis analysis should, however, account for evolutionary timescales and the birth distributions of binary parameters. On the one hand, failed-CE stripped stars undergo a RLOF stripped-star phase before merging; on the other hand, this channel is favored at shorter initial orbital periods, at which high-mass binaries are more likely to exist (Sana et al. 2025). In addition, our models are terminated at core He depletion, but post-He-depletion expansion (Laplace et al. 2020b) might trigger a late MT episode, or the rejuvenated secondary may initiate a late CE phase and a possible merger. These systems would host

inert carbon-oxygen cores and are expected to be short-lived and, therefore, unlikely to make a significant contribution to the population. Additionally, there is a number of unknowns in our results that we do not explore, the most important ones being the effect of metallicity, the assumption on the overshooting parameter, and the MT efficiency. Initial experiments, which we discuss in Appendix C.6, indicate that the failed-CE channel may be suppressed for lower metallicities and higher overshooting, as well as at lower MT efficiency. We defer the treatment of these effects to future work.

The hydrogen envelope left behind by a successful CE ejection determines the excursion in the HR diagram and the observational properties of the merger products (Shenar et al. 2023); mass loss during a failed CE can also shape the resulting supernova type (Zapartas et al. 2019). Our models compute self-consistently the remaining post-merger hydrogen layer from the binding energy of the expelled envelopes of both stars (see also Appendix C.2). This represents an improvement over standard binary population synthesis frameworks, which typically assume either complete envelope removal or rely on crude approximations based only on the donor’s envelope. Although our model is self-consistent, it still relies on a free parameter describing the CE efficiency. Nevertheless, we expect our results to provide a lower limit on the amount of envelope removed, as we consider fully efficient CE and ignore any additional energy resulting from the coalescence of the cores (see Appendix C.2). Tailored multidimensional hydrodynamical simulations are critical to assess the aptness of our assumptions.

4.5 Conclusions

We find that failed-CE stripped stars might populate regions of the HR diagram where intermediate-mass stripped stars are expected. These products would appear as single or members of wide binaries that were originally hierarchical triples, and produce a blue-straggler effect. Their post-merger evolution strongly depends on the remaining hydrogen envelope mass, for which we can compute a self-consistent lower bound within one-dimensional CE simulations, but this scenario ultimately calls out for dedicated multidimensional hydrodynamical studies.

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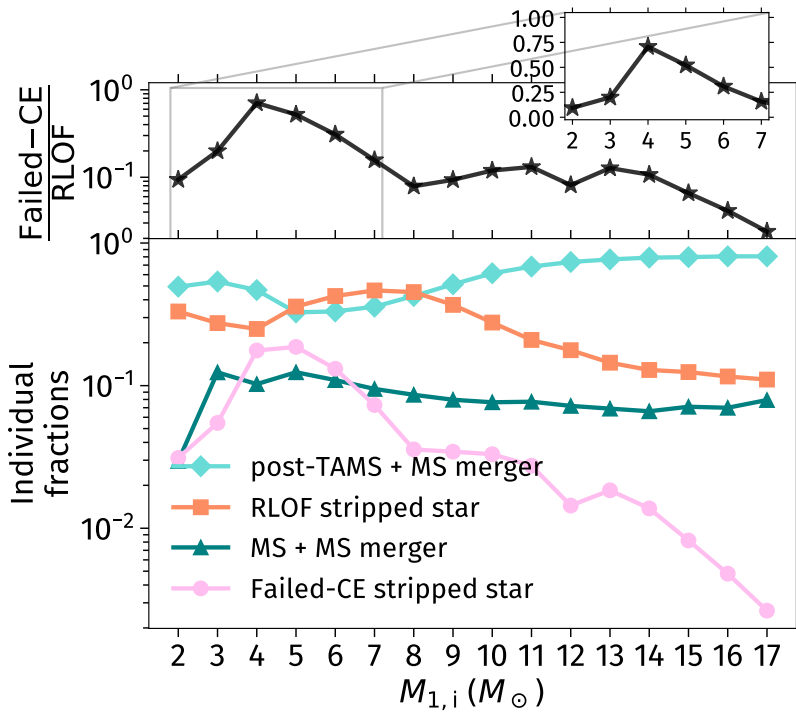


Figure 4.5: Bottom panel: Fractions of systems with different outcomes (color coded) with respect to the total area of interacting binaries for each of our grids at different primary mass $M_{1,i}$, as a function of $M_{1,i}$. Top panel: Relative fraction of systems with outcome failed-CE versus those with RLOF stripped star.

stage of the project; Max Briel and Anastasios Fragkos for the interesting discussions. AP acknowledges support from the Research Foundation - Flanders (FWO), grant agreement No. 11M8325N (PhD Fellowship), and the European Union's Horizon (ERC) Europe programme under grant agreement No. 101131928, project ACME. PM acknowledges support from the ERC (European Union's Horizon 2020 research and innovation programme) under grant No. 101165213/Star-Grasp, and FWO postdoctoral fellowship number 12ZY523N. DP acknowledges financial support from the FWO postdoctoral fellowship No. 1256225N. The resources used in this work were provided by the Flemish Supercomputer Center, funded by the FWO and the Flemish Government.

Chapter 5

No hard boundaries: the mass transfer stability depends on overshooting and metallicity

This chapter is based on work in preparation for submission:

No hard boundaries: the mass transfer stability depends on overshooting and metallicity

A. Picco, P. Marchant, H. Sana

ASTRONOMY & ASTROPHYSICS, in prep. (2026)

Author contributions A. Picco developed the code, performed the simulations, and wrote the manuscript of the paper. P. Marchant assisted in developing the methodology. During the whole process, A. Picco was guided by regular discussions with P. Marchant and H. Sana.

Abstract

Context. As the number of gravitational-wave (GW) detections from binary compact-object (CO) coalescences continues to grow, our theoretical understanding of how stellar interactions place such binaries into tight enough orbits to induce their inspiral still remains uncertain. Mass transfer (MT) stability remains one of the main uncertainties in binary population synthesis predictions, leading to large variations in predicted merger rates and CO properties, and limiting robust astrophysical inference on their stellar progenitors.

Aims. We aim to predict the properties of GW sources formed through stable MT and their sensitivity to input physics, in particular core size and metallicity. We also want to assess the impact of using fixed critical mass ratios in population synthesis codes to determine whether the parent massive binaries evolve through the common-envelope (CE) or stable MT formation channel.

Methods. We compute detailed, 1D evolution simulations of interacting binaries composed of a CO accretor and a Roche lobe-filling donor star (star+CO binaries). Using a bisection search, we resolve the regions of the initial mass-ratio and orbital-period parameter space that lead to the stable MT channel and the formation of GW sources, focusing on binary black hole (BH) and neutron star (NS) progenitors. We vary both the extent of convective core-overshooting and the metallicity.

Results. We find that the stable MT channel to produce GW sources is robust and operates over a broad range of core sizes and metallicities. The combined effect of stronger core overshooting and lower metallicity allows wider and more unequal-mass progenitor star+CO binaries to form GW sources, enhancing the contribution of the stable MT channel by up to two orders of magnitude compared to when using fiducial values. Crucially, we predict different properties for the resulting coalescing CO binaries depending on the input physics: at fixed metallicity, stronger overshooting favors more unequal-mass CO binaries with shorter delay times; at fixed overshooting, higher metallicity produces a similar effect. In addition, progenitor binaries close to the MT stability threshold initiate a CE phase with a delay, leading to moderate to large shifts in the binary properties between the onset of MT and the onset of CE. This effect is strongest for donors with radiative envelopes.

Conclusions. The properties of coalescing double CO binaries formed through stable MT depend sensitively on the internal physics of their progenitor stellar binaries, and arise from a complex interplay between core size and metallicity.

This reflects the fact that MT stability is intrinsically determined by stellar internal structure, such that there are *no hard boundaries*, e.g. universal critical mass ratios, separating stable MT from CE evolution. Furthermore, the properties of double CO binaries formed through the CE channel may be systematically shifted relative to the predictions of modern population synthesis codes due to the effect of delayed MT instability.

5.1 Introduction

The number of gravitational wave (GW) signals from binary black hole (BH) and neutron star (NS) mergers is expected to grow from over 300 to date, in the fifth Gravitational Wave Transient Catalogue (GWTC-5.0, [The LIGO Scientific Collaboration et al. 2026b](#)) by the LIGO, Virgo, and KAGRA (LVK) network, to order thousands by the end of the next observing run. This growing sample of GW signals is beginning to reveal the population properties of coalescing double compact objects (CO) ([The LIGO Scientific Collaboration et al. 2026a](#)), and modeling their stellar progenitors opens a window into understanding and constraining (binary) stellar physics and interaction. In fact, while the observed GW sample is increasing, our theoretical understanding of the evolutionary channels that form these systems, and place them into orbits tight enough to induce a GW inspiral, still features many open questions.

Various scenarios (see, e.g., [Mandel & Broekgaarden 2022](#)) have been advanced, and several of them likely contribute to the population of double COs. Dynamical formation channels in star clusters (e.g., [Mapelli et al. 2022](#)) or in isolated hierarchical systems (e.g., [Vigna-Gómez et al. 2021](#)) rely on gravitational dynamics to produce double COs in tight orbits. Conversely, binary stellar progenitors evolving in isolation rely either on a process that could prevent stars in very close binaries from expanding, like chemically homogeneous evolution ([Marchant et al. 2016](#), [Mandel & De Mink 2016](#)), or on a hardening mechanism that allows wide binaries to come close enough. These hardening mechanisms usually involve mass transfer (MT) between the stellar companions. Such transfer can be stable via Roche Lobe overflow (RLOF; [Kippenhahn & Weigert 1967](#)) or evolve through a common envelope phase (CE, or unstable MT; [Paczynski 1971](#)). In the case of CE, the binary components are engulfed by a common gaseous envelope, and the shrinkage of the orbit results from the drag forces dissipating the energy (and momentum) of the system. This is expected to happen when the MT rate reaches a dynamical timescale ([Ivanova et al. 2013](#)), and the survival of the binary is subject to the envelope structure and

companion masses. Stable MT, on the other hand, is self-regulated and evolves on the thermal or nuclear timescale of the donor star. The system’s orbit can result tightened or widened, depending on the specific angular momentum and energy redistribution during MT.

In the classical isolated binary formation scenario for BH-BH mergers, both a stable MT phase and a CE phase are expected: the first MT episode between two non-degenerate stars may be stable (e.g., [Dominik et al. 2012](#), [Langer et al. 2020](#)); after the formation of the first CO, CE evolution is then invoked (e.g. [Belczynski et al. 2016](#), [Bavera et al. 2020](#), [Liu et al. 2022](#)) to explain the shrinkage of the orbit required for a GW merger. In the past few years, this picture has been challenged, as several studies have shown that MT in massive binaries with COs could be more stable than previously thought (e.g., [van den Heuvel et al. 2017](#), [Pavlovskii et al. 2017](#), [Marchant et al. 2021](#)), while a successful envelope ejection requires restrictive conditions and, even if the system survives, the post-CE orbit may be too wide for a GW merger ([Klencki et al. 2021](#)). As a result, the contribution of the classical CE scenario to the binary BH merger population could be overestimated ([Gallegos-Garcia et al. 2021](#)). Consequently, the alternative scenario in which a second stable MT episode occurs after the formation of the first CO has gained popularity. In this case, the orbit may be efficiently tightened with non-conservative MT, that is with a net loss of energy and angular momentum from the system (e.g., the isotropic re-emission mode of [van den Heuvel et al. 2017](#), that assumes that the transferred mass is lost from the system with the specific angular momentum of the compact accretor). Following, several population synthesis studies have shown that the contribution from stable, non-conservative MT to the observed sample of merging binary BHs is substantial and may be even larger than that from the CE channel (e.g. [Neijssel et al. 2019](#), [Bavera et al. 2021](#), [Briel et al. 2026](#)).

Stable MT and CE are qualitatively different processes, expected to proceed on different timescales and to track a different orbital evolution. Such qualitative differences determine distinct final fates for the binary system, and impact the final masses, orbital parameters, spins, and merger rates of binary COs (see e.g. [Olejak et al. 2021](#), [van Son et al. 2022b](#), [Broekgaarden et al. 2022b](#)). Therefore, understanding under which conditions MT evolves (un)stable is crucial to produce accurate predictions on the relative significance of each formation channel and on GW merger population properties ([Broekgaarden et al. 2026](#)). Yet, binary population synthesis codes have traditionally adopted crude simplifications, such that MT stability, in practice, remains one of the biggest sources of uncertainty when it comes to large-scale population predictions of GW progenitors (see e.g. [Li et al. 2023](#), [Willcox et al. 2023](#), [Iorio et al. 2023](#)). Specifically, classical population studies have been assuming a direct correlation

between a specific stellar evolutionary stage and the (un-)stable MT outcome (see, e.g., the fixed thresholds in [Hurley et al. 2002](#), [Belczynski et al. 2008](#)). These compilations of *critical mass ratios* are based on (semi-)analytical polytropic models (e.g. [Paczynski 1965](#), [Hjellming & Webbink 1987](#), [Soberman et al. 1997](#)) and / or early libraries of few binary evolution models limited to specific types of objects (e.g., [Han et al. 2000](#) for Hertzsprung-gap stars, [Ivanova et al. 2003](#) for helium stars with NS accretors) and initial properties. Ultimately, this approach has been shown to oversimplify the progenitors' initial conditions to produce merging double COs ([Gallegos-Garcia et al. 2021](#)).

Fundamentally, the stability of the MT episode is determined by the interplay between a) the response of the donor star's radius to mass loss, which in turn depends on the envelope's structure; b) the Roche lobe radius response, that is how the orbit reacts to the redistribution (or systemic loss) of mass and angular momentum (for foundations, see [Webbink 1985](#)). Whether driven by nuclear timescale expansion or thermal relaxation, the MT can stay stable if the donor star keeps its radius close to that of its Roche lobe and the mechanism is self-regulating (i.e., a maximum MT rate is expected to be reached and, subsequently, quenched). Given the complexity of such interplay, and the importance of the stability criterion in binary population synthesis, modern studies have started to survey larger ranges of mass ratios and orbital periods for (un)stable MT, using two methods: time-dependent (binary) stellar models and adiabatic mass loss models. Time-dependent models are especially advantageous because they can track the evolution of the star and Roche lobe's radii along the MT episode and can reveal the behavior of super-adiabatic convective zones (e.g., [Pavlovskii & Ivanova 2015](#); [Woods & Ivanova 2011](#); [Temmink et al. 2023](#)), but are computationally expensive. On the other hand, adiabatic models ([Ge et al. 2010, 2015, 2020, 2023, 2024](#)) can study the dynamical-timescale envelope's response by treating single stars with artificially imposed high mass loss. This mimics a donor's expansion during a CE without following a companion and the orbital response. Adiabatic mass loss models have been carried out on a large parameter space and provide tabulated MT stability thresholds, which can then be implemented in binary population synthesis codes as physically motivated stability criteria, in the form of look-up tables (e.g. as is done in COMPAS [Riley et al. 2022](#) and `binary_c`). To date, the series from [Ge et al. 2010](#) is the largest effort to map critical thresholds for stable MT based on stellar structure models.

Crucially, such stellar structure models are computed with fixed input physics. Consequently, the derived critical mass ratios are not universal but rather model-dependent, yet used in population synthesis studies to make general predictions on the GW mergers populations. Additionally, the Roche lobe radius response depends on the (non-)conservativeness degree of the MT episode. Grids of

single-star models do not capture the orbital evolution and its coupling with MT stability, but rather fix the MT efficiency (e.g., fully conservative in Ge et al. 2010, 2015, 2020), and compute the critical mass ratios under this assumption. Nonetheless, sub-grid physics and orbital evolution are expected to govern the conditions under which MT produces merging double COs (Picco et al. 2024), might exacerbate or diminish the stable MT merger parameter space as predicted by standard population synthesis codes (e.g. Broekgaarden et al. 2026), and will have a non-trivial time-dependent coupling with the stellar response (e.g., Temmink et al. 2026). In contrast, grids of detailed models of interacting binaries can provide more accurate mass ratio thresholds, but are available in the literature under fixed assumptions and in limited extent (Fragos et al. 2023; Briel et al. 2026), due to their computational cost. Notable recent efforts to assess the impact of physical ingredients that are typically held fixed include Klencki et al. 2026, who investigated the effect of different modes of non-conservative MT (isotropic re-emission and mass loss through the second Lagrangian point) and Xu et al. 2025, who account for rotation and chemical enrichment induced by prior MT episodes. However, such studies remain scarce, despite the urgent need for more robust MT stability criteria to reliably disentangle the formation channels of GW sources.

The aim of this work is to use time-dependent models to probe the sensitivity of the stable MT mergers parameter space with respect to input physics, focusing in particular on convective overshooting and metallicity. We are especially interested in assessing the impact of using fixed critical mass ratios, i.e. *hard boundaries*, as stability thresholds in population studies. We do so by investigating the parameter space of progenitor systems composed by a CO orbiting a Roche lobe-filling donor, with the MESA (Paxton et al. 2010, 2013, 2015, 2018, 2019, 2023) binary stellar evolution code.

5.2 Methodology

We will refer to quantities concerning the donor (accretor) in the MT episode with the subscript d (a), and to quantities at the start (end) of the simulation with i (f). As discussed below, the starting point of our simulations is the formation of a first CO in the binary. If neither i nor f is specified, we refer to these quantities as variables in the evolution of the systems. We define the binary mass ratio, q , between a donor of mass m_d and an accretor of mass m_a , at an arbitrary stage, as

$$q \equiv \frac{m_a}{m_d} . \quad (5.1)$$

5.2.1 MESA setup and grids

We perform our simulations using version 24.03.1 of the MESA (Paxton et al. 2010, 2013, 2015, 2018, 2019, 2023) stellar evolution code. Our models consist of binary systems with a donor star (of mass m_d) and a point mass accretor (of mass m_a), such that at the start of the simulation $m_{d,i} > m_{a,i}$. The objective is to study the stability of a MT event happening after the formation of the first CO in the binary, which is argued to be the key MT phase where the orbital separation tightens to enable the formation of double COs merging within the age of the Universe. Since we do not model the previous evolutionary history of the system, which possibly includes a first MT episode, we initialize the donor star in its zero-age main sequence (ZAMS) with initial mass $m_{d,i}$. We consider 10 different values of $m_{d,i}$, approximately logarithmically spaced between $8 M_\odot$ and $80 M_\odot$.

The setup builds upon that of Marchant et al. (2021), to which we refer for more details. MT rates are computed taking into account MT through the first Lagrangian point L_1 from an extended atmosphere and optically thick regions (Ritter 1988; Kolb & Ritter 1990), with the possibility of outflows from the outer Lagrangian point of the donor star. The actual accretion rate into the point mass accretor is limited to its Eddington rate as described in Marchant et al. (2017). Matter removed from the system via stellar winds from the donor, or from the vicinity of the compact accretor due to super-Eddington MT rates, is assumed to carry away the specific orbital angular momentum of the donor or the accretor, respectively. Mass and angular momentum loss from the outer Lagrangian point of the donor is calculated following Marchant et al. 2021. No stellar rotation or spin-orbit coupling is included in our setup. Stellar winds are computed according to Brott et al. 2011.

The stellar models are computed at three different metallicities Z :

$$Z = Z_\odot, Z_\odot/10, Z_\odot/100,$$

where we refer to Asplund et al. (2009) for the solar abundance $Z_\odot$ to be equal to $Z_\odot = 0.0142$ and their relative metal mass fractions.

We model convection within the mixing length theory framework of Böhm-Vitense (1958) as described by Cox & Giuli (1968), with the mixing length parameter $\alpha_{\text{MLT}} = 2$. We use the Ledoux criterion (Ledoux 1947) for instability to convection. For the hydrogen-burning convective core we use the step-overshooting scheme, at three different overshooting parameter α_{ov} :

$$\alpha_{\text{ov}} = 0.1, 0.3, 0.5.$$

The adopted range spans the current uncertainty in the efficiency of convective boundary mixing. The lower value, $\alpha_{\text{ov}} = 0.1$, is consistent with empirical calibrations for intermediate-mass stars (Claret & Torres 2016), whereas $\alpha_{\text{ov}} = 0.3$ closely matches the calibration of massive stars by Brott et al. (2011) and is widely used in contemporary stellar evolution calculations. The larger value, $\alpha_{\text{ov}} = 0.5$, explores a regime of more efficient mixing than typically assumed, motivated by recent evidence that standard stellar evolution models may systematically underestimate the extent of internal mixing (Marchant & Shenar 2026; Rosu et al. 2026).

For convective cores after the main-sequence we include exponential overshooting (Herwig 2000) with decay length of $f = 0.01$. In the following, we will refer to the following combination of parameters as our fiducial setup:

$$\text{FIDUCIAL SETUP :} \quad \alpha_{\text{ov}} = 0.30, \quad Z_{\odot}/10,$$

and we choose this set because it is at the center of our model variations, so it serves as a comparison point for all the explored shifts.

5.2.2 Single stars tracks and grids resolution

For each donor star with ZAMS mass $m_{\text{d},i}$ we use the same setup as described above to compute a single star evolutionary track with mass $m = m_{\text{d},i}$, from ZAMS to carbon depletion in the core (with depletion threshold on the carbon mass fraction $X_{\text{C}} < 0.01$). From the single stars tracks we extract the following information:

- a) Maximum Kelvin-Helmholtz mass-loss rate achieved during the evolution, $\dot{M}_{\text{KH}}^{\text{max}}$, i.e. the highest value of the ratio $\dot{M}/t_{\text{KH}}$, where t_{KH} is the Kelvin-Helmholtz timescale, computed as

$$t_{\text{KH}} = \frac{E_{\text{bind}}}{L} \quad \text{with} \quad E_{\text{bind}} = \int_{m_{\text{core}}}^M \left(-\frac{Gm}{r} + u \right) dm, \quad (5.2)$$

following Marchant et al. (2021), where m_{core} is the mass coordinate of the star's core (defined as the location where the hydrogen mass fraction first drops below 0.1), E_{bind} is the binding energy, r is the radial coordinate, L is the luminosity, G is the gravitational constant, and the specific internal energy of the gas u takes into account the recombination energy from hydrogen and helium.

- b) Radius of the star at the ZAMS stage, maximum radius achieved during the evolution and radius at which a 5% fraction of the total mass of the star is contained in a convective envelope.

We use information a), $\dot{M}_{\text{KH}}^{\text{max}}$, to calculate an upper limit $\dot{M}_{\text{MT}}^{\text{max}}$ to the MT rate in the binary runs: $\dot{M}_{\text{MT}}^{\text{max}} = 10 \times \dot{M}_{\text{KH}}^{\text{max}}$. Above this rate, the MT episode is considered unstable (see also Section 5.2.3 and Section 5.4.3 for a discussion on the limitations of this assumption).

We initialize our binary systems with initial mass ratios such that $0.005 < q_i < 1$ per each $m_{\text{d},i}$. We choose the extent and the resolution in initial orbital period P_i using information b) from the single stars tracks. From the maximum radius, we compute the correspondent maximum orbital period, P_i , for a binary system with initial mass ratio q_i above which no interaction is expected; from the ZAMS radius, we derive the minimum P_i below which the systems would initiate RLOF at ZAMS. These are the upper and lower limit in P_i of our grids. Additionally, we sample with a finer resolution at P_i values corresponding to when the stars have developed a convective envelope. We show in Figure 5.1 an example for the case $m_{\text{d},i} = 29 M_{\odot}$, $Z = Z_{\odot}/10$ and $\alpha_{\text{ov}} = 0.3$, and show all of them in Appendix D.1. In every grid, we make sure to have a total of ~ 60 values of $\log P_i(\text{days})$, ~ 30 before the occurrence of convective envelope and ~ 30 after.

All input files necessary to reproduce our simulations will be made publicly available at the time of publication on Zenodo ¹.

5.2.3 Resolving the stability and GW mergers boundaries

Our aim is to determine the boundary between CE evolution and stable MT, as well as the region in which the stable MT leads to a GW merger within the age of the Universe. To do this, we perform bisection searches for the critical mass ratio q_{crit} at fixed initial orbital period P_i , starting the search by assuming CE happens at $q_i = 0.005$ and stable MT happens at $q_i = 1$. The bisection algorithm performs iterations based on the outcomes of the binary runs to resolve the stability boundary, to a precision $\delta q = 0.001$. The binary runs can have the following outcomes:

1. *stable MT*: The binary interacts and transfers mass with rates $\dot{M}_{\text{MT}}$ always lower than $\dot{M}_{\text{MT}}^{\text{max}}$. The MT episode is self-regulating and the binary detaches. The run is ended when either the central carbon is depleted in the donor (most of the cases), or the surface luminosity L drops below $0.1 L_{\odot}$ (when the stripped star becomes a WD and evolves in its cooling sequence), or when central helium is depleted and the binary is detached (this terminating condition is switched on for $m_{\text{d},i} > 40 M_{\odot}$ to facilitate convergence).

¹doi.org/10.5281/zenodo.14411662

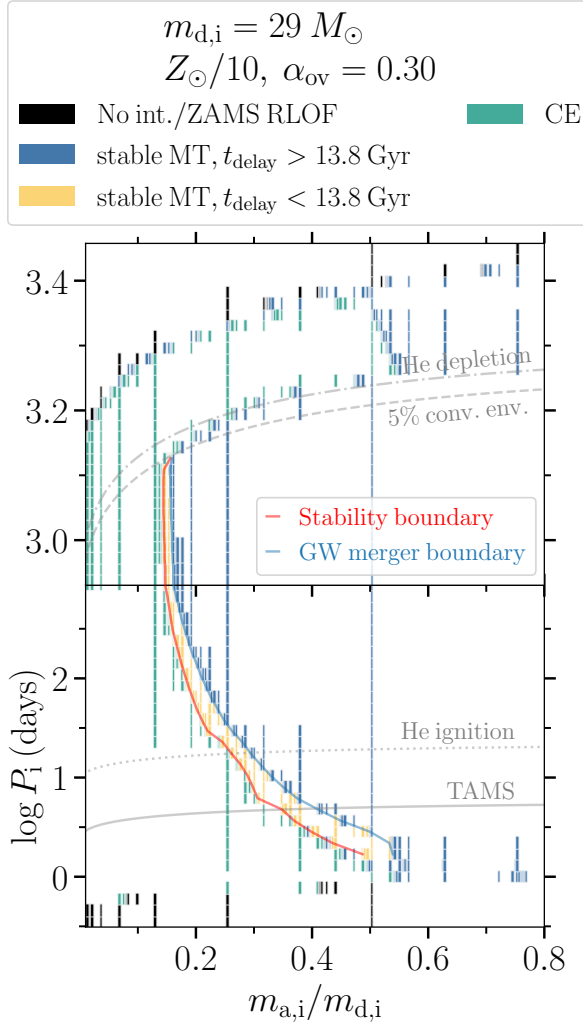


Figure 5.1: Example grid of MESA simulations of interacting binaries, with a donor star of initial mass $m_{d,i} = 29 M_{\odot}$ in orbit with a point mass $m_{a,i}$. The systems are initialized at different initial mass ratios $m_{a,i}/m_{d,i}$ and orbital period P_1 , and the outcomes are color coded following the legend. The specific example is for $Z = Z_{\odot}/10$ and $\alpha_{ov} = 0.3$. Different evolutionary stages are also highlighted (solid curves): terminal age main sequence (TAMS), central helium ignition, central helium depletion, and when 5% of initial mass is contained in a convective envelope. We also show the stability boundary (red) and the GW merger boundary (blue curve) as derived from the bisection search (see Section 5.2.3). In this case, the grid extends as $-0.450 \leq \log P_1(\text{days}) < 3.449$. We resolve the interval $-0.450 \leq \log P_1(\text{days}) < 2.940$ with a spacing $\delta \log P_1(\text{days}) = 0.10$, and the interval $2.940 \leq \log P_1(\text{days}) < 3.449$ with increased resolution $\delta \log P_1(\text{days}) = 0.01$.

2. *CE evolution*: The binary undergoes unstable MT, reaching the MT rate of $\dot{M}_{\text{MT}}^{\text{max}}$. At this point, we assume to have CE evolution, and stop the simulation.
3. *ZAMS RLOF*: If the binary is initiating RLOF right at ZAMS, we stop the simulation. We specifically designed our grids to include this outcome at the lowest initial orbital periods, to ensure that we are not missing any interacting binaries.
4. *no interaction*: If the binary never interacts, we use the same set of stopping conditions we described for the case of stable MT.

A first run of the bisection algorithm finds the boundary between the outcomes *stable MT* and *CE evolution* (the “stability boundary” in Figure 5.1). We additionally run a second bisection algorithm, instructed to resolve the boundary between the systems that end up with delay times $t_{\text{delay}} < 13.8 \text{ Gyr}$ (*stable MT mergers*) and $t_{\text{delay}} > 13.8 \text{ Gyr}$ (*stable MT wide*) (the “GW merger boundary” in Figure 5.1). We compute the delay times following Peters (1964):

$$t_{\text{delay}} = \frac{a_f^4}{4\mathcal{B}}, \quad \text{with} \quad (5.3)$$

$$\mathcal{B} \equiv \frac{64 \text{ G}^3}{5 \text{ c}^5} (m_{\text{a,f}} + m_{\text{d,f}}) m_{\text{a,f}} m_{\text{d,f}}, \quad (5.4)$$

which holds for a circular orbit with final orbital separation a and neglects other sources of radiation apart from the gravitational quadrupole one. We therefore implicitly assume that the second born CO, at the start of the inspiral phase, has the same mass $m_{\text{d,f}}$ of the stripped donor at the end of the simulation, and starts the inspiraling at the same final orbital separation a_f . A third and final run of the bisection algorithm resolves the regions in which a second transition between *CE evolution* and *stable MT* is expected (e.g., in the high $\log P_i$ part of Figure 5.1, below the *no interaction* systems). We refer again to Figure 5.1 as an example of such a multi-stage run.

5.3 Results

Our detailed binary evolution calculations show that stable MT can form GW mergers at different stellar masses, $m_{\text{d,i}}$, metallicities, Z , and overshooting parameters, α_{ov} . Our main results are summarized below:

- i **Higher mass donors are more stable**, and the stable MT mergers outcome (or, “parameter window” in initial period P_i and mass ratio q_i)

is always closely confined around the boundary for MT stability (see the yellow pixels in Figure 5.1). This is in agreement with several works (e.g. Marchant et al. 2021; Gallegos-Garcia et al. 2021; Klencki et al. 2026).

- ii **Convective overshooting and metallicity affect which systems evolve into GW mergers**, and we discuss their impact in Section 5.3.1 and Section 5.3.2. The combined effect of higher α_{ov} and lower Z may enhance the stable MT channel outcome by up to two orders of magnitude (see Figure 5.5). Notably, a low α_{ov} combined with a high Z can completely suppress the stable MT outcome even at high donor star masses.
- iii **Pairings of COs**: For $m_{\text{d},i} \geq 17 M_{\odot}$ and the fiducial values of $\alpha_{\text{ov}} = 0.30$ and $Z = Z_{\odot}/10$, we find that stable MT can form GW mergers consisting of a first born BH plus a) a second born BH formed by direct collapse of the stripped donor; b) a second born NS, in the assumption of no kicks. However, option b) requires finely tuned initial conditions, but might be enhanced with a favorable α_{ov} and Z combination. For $m_{\text{d},i} < 17 M_{\odot}$, we do not find any stable MT merger with the fiducial values of α_{ov} and Z .
- iv **BH formation order**: We find support for double BH mergers when massive donors ($m_{\text{d},i} > 48 M_{\odot}$) evolve via stable case-A MT and are in orbit with a compact companion with higher mass. This implies that, in binary BH mergers, the more massive BH may have formed first *OR* second.

In Figure 5.2 we show a selection of our results for the stable MT mergers parameter window that showcases the aforementioned points, except for the effects of convective overshooting and metallicity, discussed separately below.

5.3.1 Convective overshooting

Convective overshooting is known to influence the radius evolution of stars (e.g. Schootemeijer et al. 2019): increased overshooting leads to larger convective cores, extending the main sequence lifetime and resulting in larger stellar radii during later evolutionary phases. The radial extension of the envelope determines at which evolutionary stage and orbital period RLOF from the primary is initiated. This is in turn expected to influence the response of the envelope itself to mass loss, determining the stability of a MT episode. Additionally, larger convective cores lead to bigger post-MT products, directly impacting the outcome masses of double COs (e.g. Temaj et al. 2024) and their delay times (see Eq. 5.3).

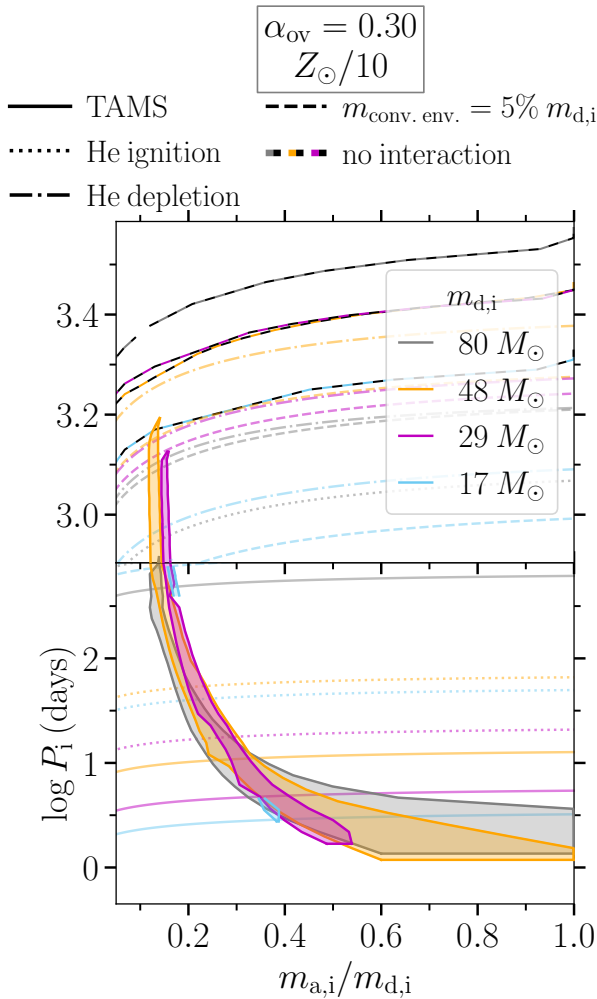


Figure 5.2: Boundaries for stable MT mergers for donor initial masses $m_{d,i}$ (in different colors), in orbit with a compact accretor of mass $m_{a,i}$. The results are shown at fixed overshooting $\alpha_{ov} = 0.3$, and metallicity $Z = Z_\odot/10$, see text for a more general overview of the results. Different evolutionary stages (TAMS, central He ignition, central He depletion and occurrence of convective envelope) are color coded based on the respective donor mass.

Brott et al. (2011) calibrated an overshooting parameter of $\alpha_{\text{ov}} = 0.335$ using observations of $\sim 10\text{--}20 M_{\odot}$ stars, and adopted this value throughout their $5\text{--}60 M_{\odot}$ model grid. However, several studies have suggested that higher values, up to ~ 0.5 , may be more appropriate for high-mass stars (e.g. Marchant & Shenar 2026; Rosu et al. 2026) and better match asteroseismological constraints from observations (e.g. Pedersen et al. 2021). In contrast, lower overshooting values $\sim 0.1\text{--}0.2$ have been proposed for lower-mass stars based on double-lined eclipsing binaries (e.g. Claret & Torres 2016).

Our study explores α_{ov} values of $\alpha_{\text{ov}} = 0.1, 0.3, 0.5$, and shows that the stable MT mergers parameter window is impacted by the choice of α_{ov} . We show an example in Figure 5.3 and summarize the results here below.

Impact of α_{ov} on the GW merger boundary The GW merger boundary is affected by the different α_{ov} due to the direct dependence of Eq. (5.3) on both the masses and the orbital separation at the moment of formation of the second CO, which we take to be equal to those at the end of the simulation. Both these quantities are determined by the MT episode, in particular by how much mass and angular momentum is transferred or lost (the MT efficiency). We showed analytically the interplay between the mass and orbital separation in setting the stability boundary in Picco et al. 2024 (or, Chapter 2, see Figure 2.1, where a bigger “stripping factor” α_{core} is mappable to a bigger core’s size, hence to a bigger overshooting parameter) in the simplified case of fixed MT efficiency. Our results are in agreement with such theoretical expectations: if the binary initiates RLOF at small separation (with low $\log P_i$), a higher α_{ov} will favor $t_{\text{delay}} < 13.8\text{Gyr}$ at less extreme mass ratios, enhancing the stable MT parameter space. In Figure 5.3, this creates the wide gray pocket for $\alpha_{\text{ov}} = 0.5$ of stable MT mergers from case-A interaction, which extends to a wider space than the blue pocket for $\alpha_{\text{ov}} = 0.3$. On the other hand, at higher $\log P_i$ the opposite happens due to the following effects: 1) a higher α_{ov} leads to a less massive envelope, hence less hardening of the binary; 2) at a given fixed $\log P_i$, a star with higher α_{ov} is less evolved than one with lower overshooting, sometimes even still on the MS (its core is decreasing) while the other is growing its core via shell burning. These effects add up to create smaller delay times for higher α_{ov} . Therefore, a *bigger (smaller) α_{ov} favors (suppresses) stable MT GW mergers from case A (B) MT.*

Impact of α_{ov} on the stability boundary The stability boundary is also affected by the different α_{ov} . The dependence of the adiabatic stellar response on the core-to-envelope mass ratio has been shown first by Hjellming & Webbink 1987 in the context of simple polytropic models. For radiative envelopes, our

time-dependent models find *higher* α_{ov} to be consistently more stable than lower overshooting values at any $\log P_i$ (see Figure D.11, where we isolate the stability boundary). As a rule of thumb to understand this, one can think that a star with higher overshooting must have a steeper outward entropy profile at the onset of RLOF than one with lower overshooting (at fixed total mass). This leads to a stronger contracting response to adiabatic mass loss and therefore promotes stability (Webbink 1985). As we will explain in Section 5.3.3, these donors undergo delayed instability, i.e. they first lose a consistent amount of mass before the MT rate grows from thermal to dynamical timescales. Additionally, these are the stars that we predict to create merging binary BHs (see, in Figure 5.3, the location of $m_{\text{conv. env.}} = 5\% m_{\text{d,i}}$). For donors with convective envelopes, the stability boundary dependence on α_{ov} appears to be more complex and we do not focus on it in this work. In Appendix D.2, we show an overview of stability boundaries and their dependence on α_{ov} , Figure D.11, and Z , Figure D.12 (see also below).

Combining the two ingredients, the net effect of increasing α_{ov} is to stretch the stable MT mergers parameter space to more extreme q_i at high $\log P_i$, and to less extreme q_i at lower $\log P_i$ (see Figure 5.3 and also Figure D.17). This implies that our model grids at $m_{\text{d,i}} = 10, 13 M_{\odot}$ do not produce any stable MT mergers for $\alpha_{\text{ov}} = 0.3$, but they do for $\alpha_{\text{ov}} = 0.5$ at subsolar metallicity (see the grids in Appendix D.1). Consequently, our conclusions on the possible binary CO pairings are sensitive to the choice of α_{ov} (for example, we encounter the outcome of a first born BH paired with a NS under less restrictive conditions in $\log P_i$ and q_i). Additionally, the stable MT mergers parameter window is either consistently magnified (in the case of case A MT) or at least shifted by an amount comparable to its width (for case B MT), underscoring the significance of the choice of α_{ov} . In Appendix D.3, we show a larger set of GW mergers parameter windows that highlights the effect of α_{ov} , Figure D.13, and Z , Figure D.14 (see also below).

5.3.2 Metallicity

To investigate the formation of the binary BHs detected by the LVK collaboration, it is essential to study binary interaction in low-metallicity environments (e.g., the most distant GW merger event reported in GWTC-5.0 is inferred to lie at a median luminosity distance of $\simeq 7$ Gpc, corresponding to a median redshift of $\simeq 1.0$; The LIGO Scientific Collaboration et al. 2026c). Both rapid population synthesis studies and detailed binary evolution calculations predict that low metallicity strongly favors the formation of merging binary BHs in the context of isolated binary evolution channels (e.g. Belczynski et al. 2016; van Son et al. 2022a; Broekgaarden et al. 2022a; Briel et al. 2023, 2026). This

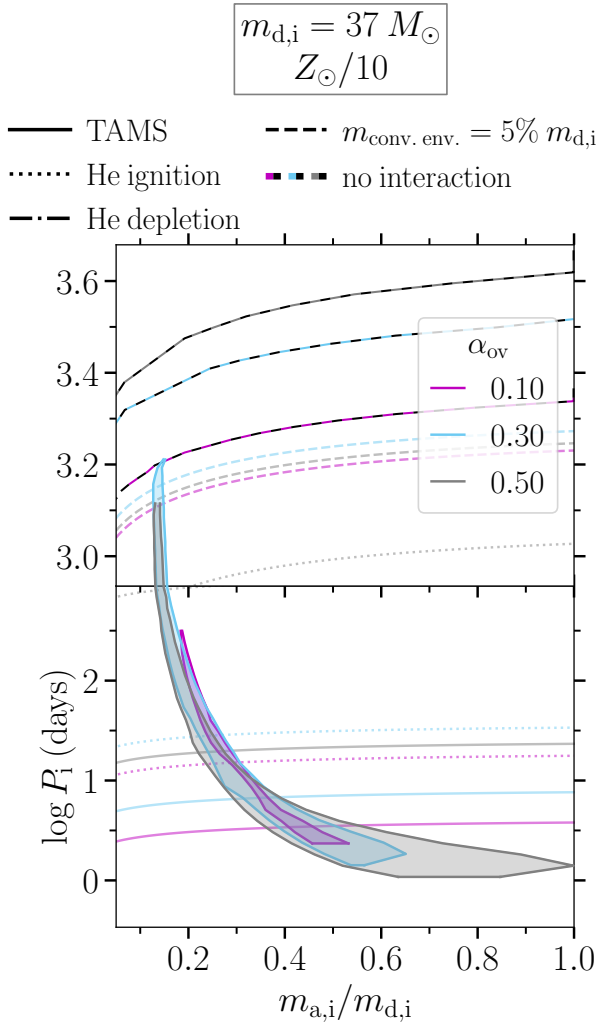


Figure 5.3: Boundaries for stable MT mergers for donor initial masses $m_{d,i} = 37 M_{\odot}$, metallicity $Z = Z_{\odot}/10$ and different α_{ov} (different colors). Same conventions as Figure 5.2 are adopted.

is mainly due to weaker radiation-driven stellar winds at low metallicity, that allow massive stars to retain more of their mass and avoid consistent orbital widening after the first BH formation (e.g., [Briel et al. 2026](#)). Rapid population synthesis models also find that low-metallicity progenitors tend to initiate MT while maintaining radiative envelopes, which generally promotes stability (e.g., [van Son et al. 2022a, 2025](#)). In the absence of natal kicks, the stable MT channel is found to be quenched above metallicities of $0.2 - 0.4 Z_{\odot}$ ([Briel et al. 2026](#); [Klencki et al. 2026](#)).

Detailed binary evolution studies that investigate the metallicity dependence of the stability of MT between a stellar donor and a first born CO are limited ([Marchant et al. 2021](#); [Gallegos-Garcia et al. 2021](#); [Klencki et al. 2026](#)). Our work explores three different metallicities, $Z_{\odot}$, $Z_{\odot}/10$, $Z_{\odot}/100$, and focuses on how the stable MT mergers parameter window is impacted by the choice of Z . We show an example in Figure 5.4 and summarize the results here below.

Impact of Z on the GW merger boundary The GW merger boundary is affected by the different Z due to two effects: a) stellar winds, causing orbital widening before and after interaction and mass loss from the donor, and b) different stellar radius of the stars at a certain evolutionary stage, which determines how compact the binary orbits can be in the first place. Effect a) suppresses the number of stable MT mergers at higher Z , acting more strongly on systems that interact later (case B MT); effect b) enhances the parameter window for case A systems at low Z donors, as low metallicity make stars more compact at ZAMS, allowing for tighter orbits and shorter delay times. One can see the result of the interplay of the two effects in Figure 5.4 (and also Figure D.17), where the stable MT mergers parameter space is consistently larger at lower Z for case A MT, while it is suppressed at higher Z for case B MT (and almost disappears at $Z_{\odot}$ metallicity).

Impact of Z on the stability boundary The effect of metallicity on the stability boundary has been studied in the context of adiabatic mass loss sequences by [Ge et al. \(2023, 2024\)](#). They find that, for radiative envelopes, metal-poor donors are less stable than their metal-rich counterparts. Viceversa, when stars develop a convective envelope, they find the opposite behavior. Our time-dependent models confirm the picture for radiative donors: *systems at solar metallicity, $Z_{\odot}$, are (equally or) more stable than those at $Z_{\odot}/10$ and $Z_{\odot}/100$* (see Figure D.12, where we isolate the stability boundary). The physical reason why this happens may stem from the specific entropy profiles of these types of stars ([Ge et al. 2023](#) suggests this, and [Klencki et al. 2026](#) expands on it), see also the discussion in Section 5.3.3. We point out that this result remains true

when we compare the critical mass ratios at the onset of RLOF (instead of initial mass ratios), confirming that previous mass loss from stellar winds does not introduce an "artifact" to our findings. On the other hand, we do not see a consistent trend for convective donors that may confirm the results from adiabatic models. Nevertheless, we do not focus on these types of donors in this work (see Appendix D.2 to inspect what we find for convective donors).

Combining the two ingredients, the net effect is to favor (disfavor) the stable MT mergers outcome at low (high) Z (very evident in Figure 5.4). Similarly to Section 5.3.1, we find that a favorable pairing of α_{ov} and Z (e.g., $\alpha_{\text{ov}} = 0.50$ at $Z_{\odot}/100$ metallicity) can produce stable MT mergers for lower mass donors ($m_{\text{d},i} = 8, 10, 13 M_{\odot}$), while the fiducial values of $\alpha_{\text{ov}} = 0.3$ and $Z = Z_{\odot}/10$ do not. This implies that the possible pairings of COs are sensitive to the choice of Z , such that low metallicity environments may favor the formation of first born BHs paired with second born NSs.

In Figure 5.5 we summarize the net effect of both α_{ov} and Z on the number of stable MT mergers, by showing their enhancement (or suppression) with respect to the fiducial values of $\alpha_{\text{ov}} = 0.30$ and $Z = Z_{\odot}/10$. Summarizing: the stable MT channel is enhanced at low metallicity and high overshooting, while it is suppressed at high metallicity and low overshooting. The combined effect of higher α_{ov} and lower Z may enhance the stable MT channel outcome by up to two orders of magnitude. The suppression of the channel at low α_{ov} is robust at all masses, while high Z acts more strongly on higher mass donors.

5.3.3 Delayed instability

As explained in Section 5.2.2, as soon as the MT rate reaches the value $\dot{M}_{\text{MT}}^{\text{max}}$, we flag the outcome as CE evolution and stop our simulations. The onset of CE some time after the start of RLOF has been referred in literature as delayed dynamical instability (DDI), and was discussed in early studies (e.g., Hjellming & Webbink 1987; Han & Podsiadlowski 2006) as well as in recent more systematic explorations with time-dependent models (e.g. Temmink et al. 2025 for intermediate-mass donors, and Klencki et al. 2026 for massive stars) and in the context of adiabatic mass-loss sequences (see especially Ge et al. 2010, 2015, 2020).

The delayed onset of CE has been associated with a flattening of the entropy profiles in the stellar interiors. Where or how deep this flattening occurs depends on the star's structure, therefore on its evolutionary stage. For example, stars with radiative envelopes (like main sequence, Hertzsprung-gap, helium-burning donors) will have steeply increasing entropy profiles in the outer layers, with a plateau appearing deep in mass coordinate in their interiors. Therefore,

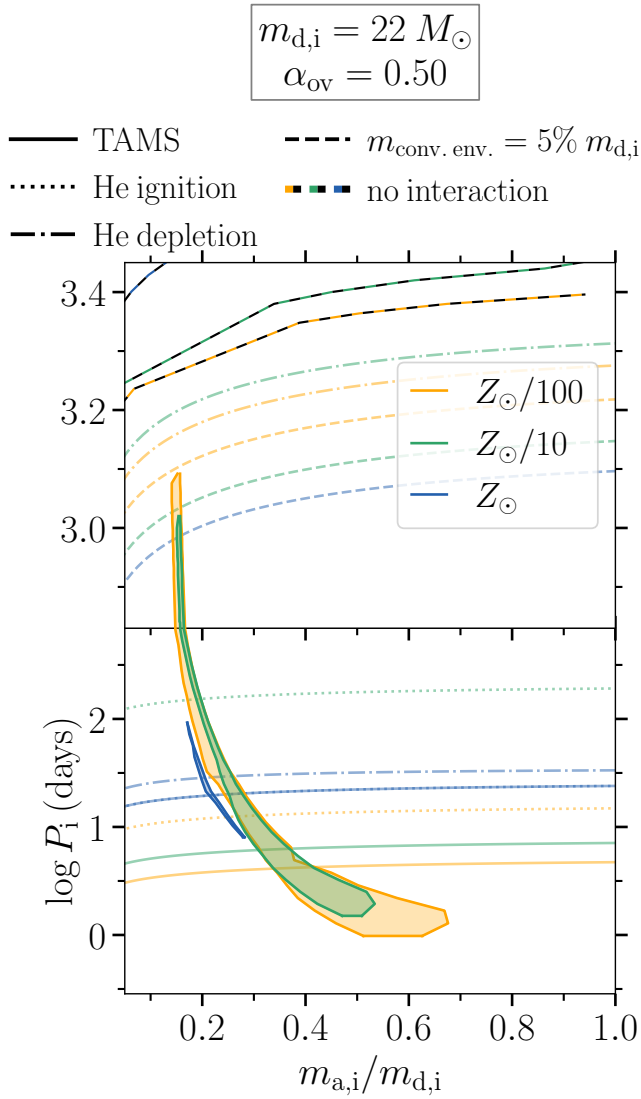


Figure 5.4: Boundaries for stable MT mergers for donor initial masses $m_{d,i} = 22 M_{\odot}$, convective overshooting $\alpha_{ov} = 0.50$ and different metallicity Z (different colors). Same conventions as Figure 5.2 are adopted.

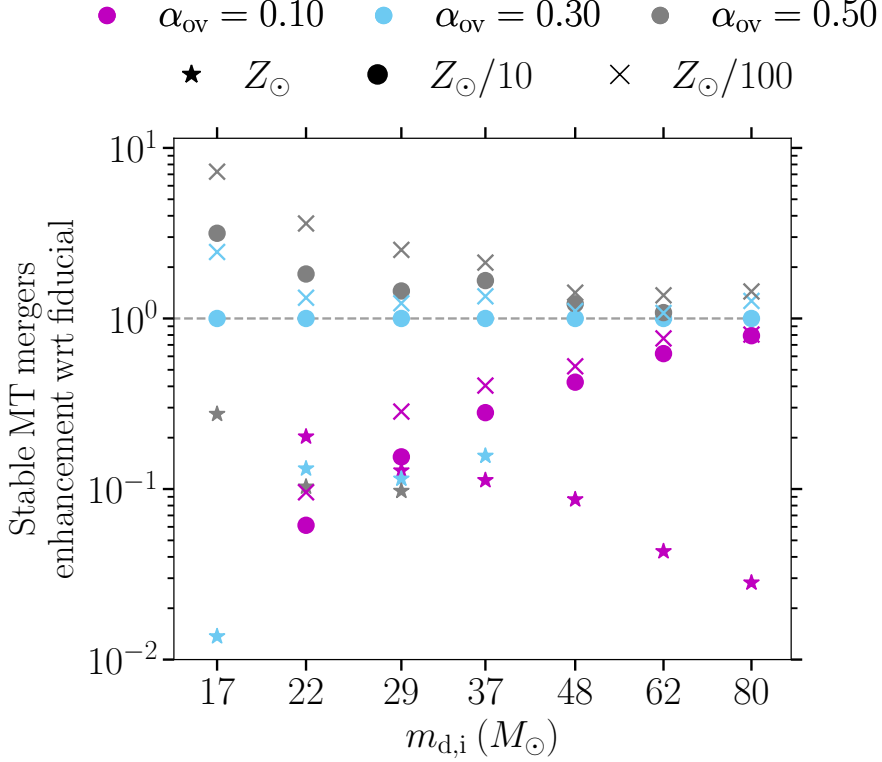


Figure 5.5: Summary plot: enhancement (suppression) of the number of stable MT mergers with respect to the fiducial values of $\alpha_{ov} = 0.30$ and $Z = Z_{\odot}/10$ (blue dots), for different donor star masses, $m_{d,i}$. This enhancement factor is computed assuming uniform distribution in $\log P_i$ and q_i , and normalized to the fiducial case. The results for solar metallicity (colored stars) are so low that some are cut from the plot. We do not find stable MT mergers for $m_{d,i} = 8, 10, 13 M_{\odot}$ at the fiducial values of α_{ov} and Z , therefore we do not show them in the plot; however, we do find that favorable combinations of α_{ov} and Z can produce stable MT mergers for these lower mass donors (see main text).

when MT removes the outer layers, it will first reveal lower entropy sub-surface layers that react with a contraction of the star. However, as MT proceeds, layers with flatter entropy profiles are revealed, and the donor's reaction on the dynamical timescale will be to expand and cause a peak in the MT rate, ultimately triggering CE. This simple picture is presented in the adiabatic mass-loss sequences of [Ge et al. 2010](#) for radiative donors, and broadly confirmed with time-dependent models that can capture the thermal relaxation during MT ([Ge et al. 2015](#), and see also the discussion in [Klencki et al. 2026](#)). This is because the flattening of the entropy profile happens in the deep interiors of the star, where the adiabatic approximation has been shown to hold ([Webbink 1977](#); [Hjellming & Webbink 1987](#); [Ge et al. 2015](#)). However, this picture becomes much more complex for stars with convective envelopes, where large super-adiabatic convective zones can react thermally on very short timescales (see the discussion in [Woods & Ivanova 2011](#); [Pavlovskii & Ivanova 2015](#); [Timmink et al. 2023](#) for giant donors) and introduce a stabilizing effect that adiabatic models cannot predict. Nevertheless, at sufficiently high MT rates for which CE onset is expected, donors with convective envelopes are expected to undergo prompt instability ([Ge et al. 2015](#); [Timmink et al. 2023](#)).

In this work, we are not aiming at specifically studying the thermal response during the DDI, nor to resolve its onset at the region of entropy flattening (but see Chapter 6, about our plans for future work). We are rather interested in: a) confirming the above picture (i.e., radiative donors are prone to DDI, while convective donors enter CE promptly) for massive binaries that are progenitors of GWs; b) survey the extent of this delayed instability over different donor masses, metallicities and overshooting parameters; c) understand its impact on stability criteria and post-CE properties as implemented in rapid population synthesis codes.

For these purposes, we compute an additional set of grids that explore the region below the stability boundary, i.e. the region in which we predict CE evolution. We show an example of one of these grids in Figure 5.6, where we see that DDI is indeed prominent for radiative donors: before the formation of a convective envelope, systems at the instability boundary may lose up to 45% of their initial mass before CE onset. However, DDI appears to be a complex function of the initial orbital period P_i and mass ratio q_i . DDI is conversely suppressed for convective donors, which enter CE promptly (with the exception of systems with mass ratios closer to unity). This behavior remains consistent across the considered donor masses, although small variations are present. This is shown in the top panel of Figure 5.7, where we present the cumulative distribution functions (CDFs; computed assuming uniform distribution in $\log P_i$ and q_i) of the amount of mass lost before CE onset for different donor masses (see also Figure D.15 in Appendix D.4 for all the correspondent grids). The CDFs show

small variations with donor mass, with 60% of the binaries losing less than 10% of their initial mass due to DDI, while a few system (less than 5%, see insert) show extreme DDI, losing up to 45% of their initial mass. These are always located along the boundary for stability and mainly correspond to case A systems (see Figure D.15), where a clear separation between helium-rich core and envelope is still building up, and the MT is able to dig deep into the star before CE onset. Additionally, after core-helium burning ignition, DDI also increases, and we refer to the discussion in Klencki et al. 2026 for a dedicated explanation of this behavior, which we confirm with our models.

DDI is also robust to variations in metallicity and overshooting, as shown in the top panel of Figure 5.9. In particular, we find that higher metallicity enhances DDI at any value of α_{ov} . Conversely, we do not find a clear trend with α_{ov} . We reserve a more detailed investigation of the physics that drive these behaviors to future work.

Finally, we note that CDFs are sensitive to the stopping condition we adopt for the CE onset (see Section 5.2.2). A different choice of CE threshold would impact the amount of mass lost before CE onset, and therefore the extent of DDI. We discuss this effect in Section 5.4.2.

5.3.4 The GW mergers properties: mass ratios and delay times

Section 5.3.1 and Section 5.3.2 have shown that the stable MT mergers parameter window is sensitive to the choice of α_{ov} and Z . This has a direct impact on the properties of the post-MT binaries, in particular on their mass ratios q_f and delay times t_{delay} as binary COs observable as GW sources. In this section we discuss these properties based on the CDFs shown in Figure 5.7 and Figure 5.9. We remind the reader that we are assuming the systems' properties at the end of our simulations to correspond to those at the stage of inspiral, i.e. we do not include any natal kick in our models. We briefly discuss the impact of this assumption in Section 5.4.3. Additionally, we will discuss the final mass ratios q_f computed as the ratio between the least over the most massive CO mass, and therefore $q_f \leq 1$ by definition (analogously to the GWTC-5.0 convention).

Binary BHs mass ratios In agreement with both rapid and detailed population studies (e.g., van Son et al. 2022a; Briel et al. 2026; Klencki et al. 2026), we find that (at the reference mass of $m_{\text{d},i} = 29 M_{\odot}$) more than 60% of stable MT mergers have final mass ratios $q_f < 0.5$, and more than 80% of the systems have $q_f < 0.8$. Higher-mass systems (with higher $m_{\text{d},i}$) tend to produce more extreme

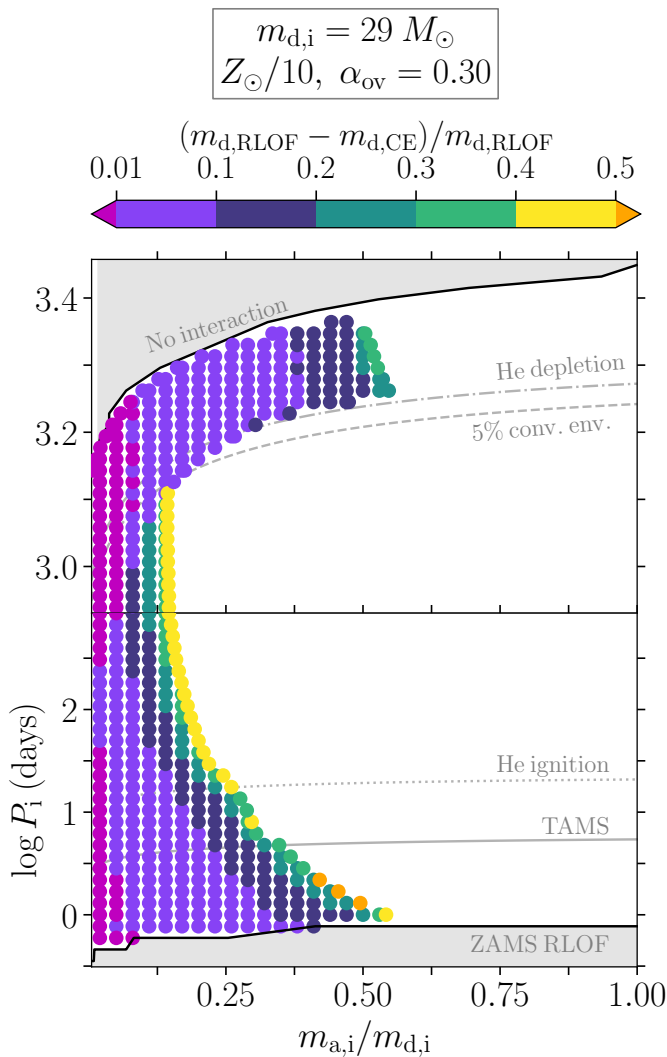


Figure 5.6: Example grid of MESA simulations of interacting binaries, with a donor star of initial mass $m_{d,i} = 29 M_{\odot}$, convective overshooting $\alpha_{ov} = 0.30$ and metallicity $Z = Z_{\odot}/10$. The amount of mass that is lost from the onset of RLOF to the onset of CE is color coded, and we refer to this as the delayed dynamical instability in the main text. These types of grid are produced after having resolved the stability boundary as explained in Section 5.2.3, i.e. after having computed the correspondent grid like that of Figure 5.1 (and we adopt the same convention for the evolutionary stages as in there).

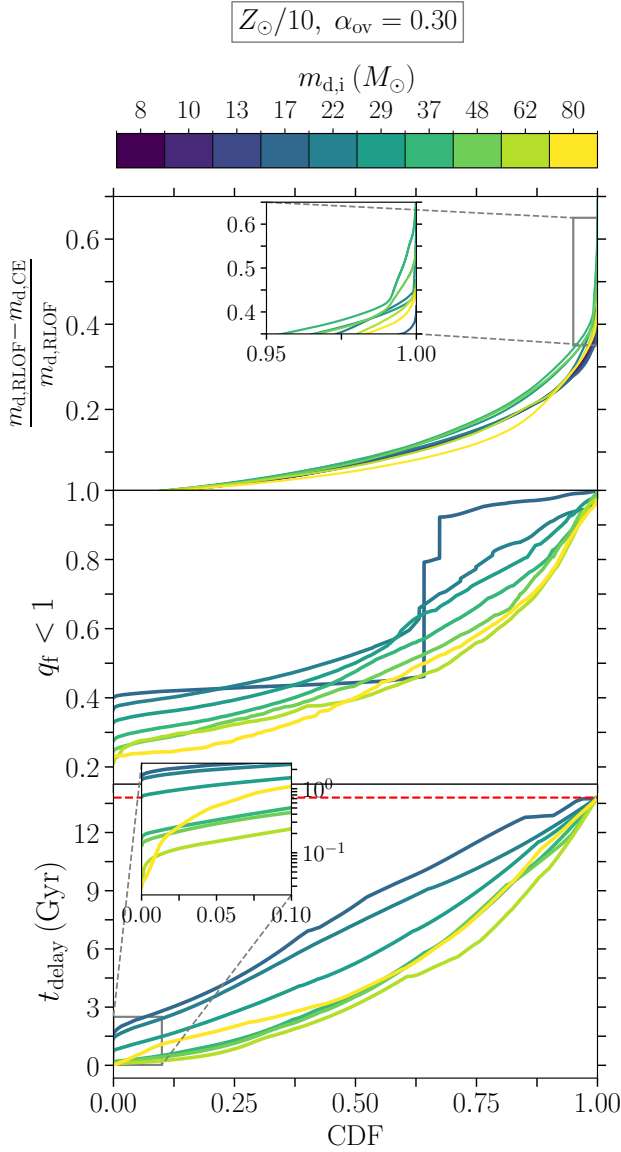


Figure 5.7: CDFs (computed assuming uniform distribution in $\log P_i$ and q_i). **Top panel.** The amount of mass lost before CE onset from our DDI grids (e.g., Figure 5.6); **Middle panel.** The final mass ratios of stable MT mergers, from our grids that resolve the GW mergers boundary (e.g., Figure 5.1); **Bottom panel.** The delay times of stable MT mergers. The different colors correspond to different donor initial masses $m_{\text{d},i}$, and the overshooting and metallicity are fixed to $\alpha_{\text{ov}} = 0.30$ and $Z = Z_{\odot}/10$. The two insets zoom in on a) extreme values of DDI, shown by only a 5% of the systems, i.e. those undergoing case A at the instability boundary; b) extreme values of delay times, reached by 10% of the systems, mainly undergoing case B MT (see also Figure 5.8).

(departing from unity) values. Accross all masses, we find a 25% fraction of systems that show extreme values as $q_f \lesssim 0.4$ (see Figure 5.7, middle panel). These extreme values of q_f are usually reached by case B systems, as those systems start MT with an already extreme initial mass ratio and do not invert it during MT (as shown in Figure 5.8). However, case A systems can also reach extreme values of q_f , especially with high α_{ov} (see Figure (D.17) and Figure 5.9, middle panel). In general, the final mass ratios are sensitive to the choice of α_{ov} and Z , as shown in Figure 5.9. We find that *a higher α_{ov} favors more extreme binary BHs mass ratios, while a lower Z favors mass ratios closer to unity*².

Binary BHs time delays At the reference mass of $m_{d,i} = 29 M_\odot$, delay times < 6 Gyrs are created by more than 60% of our stable MT mergers, and < 10 Gyrs by more than 80% of them (see Figure 5.7, bottom panel), but this result shows a dependence on masses: higher mass systems (with higher $m_{d,i}$) tend to produce shorter time delays (although stellar winds may affect this trend at the highest masses, see the curve for $m_{d,i} = 80 M_\odot$ in Figure 5.7). The shortest delay times may reach values as extreme as ~ 30 Myrs for a small fraction ($\lesssim 10\%$) of systems. These correspond to case B systems, which are able to strongly shrink the orbit as they start MT with already extreme mass ratios, and never initiate orbital widening (see Figure 5.8). The delay times are also sensitive to the choice of α_{ov} and Z , as shown in Figure 5.9. We find that *a higher α_{ov} and a lower Z independently favor shorter delay times*, such that their effect combined produce the tightest pairs of chirping BHs. This is because a higher α_{ov} increases stability (as seen in Section 5.3.1), and the systems close to the stability boundary are those with the shortest time delays; a lower Z allows more massive systems to exist in tighter initial orbits and reduces the widening due to stellar winds (as seen in Section 5.3.2).

²In Figure 5.9, we see that, at $\alpha_{ov} = 0.50$, there is little difference in the mass ratios created at $Z_\odot/10$ and $Z_\odot/100$. Why so? In general, lower Z enhances case A systems towards less extreme initial mass ratios (effect b) discussed in Section 5.3.2, while also suppressing case B systems that start MT with already extreme mass ratios (effect a)). In practice, the two regions would both feed the final mass ratios outcomes that depart the most from unity (see Figure 5.8). Nevertheless, in the vast majority of our models and across all masses, we find that the simple picture of the main text holds: the lower the Z , the less extreme the final mass ratios.

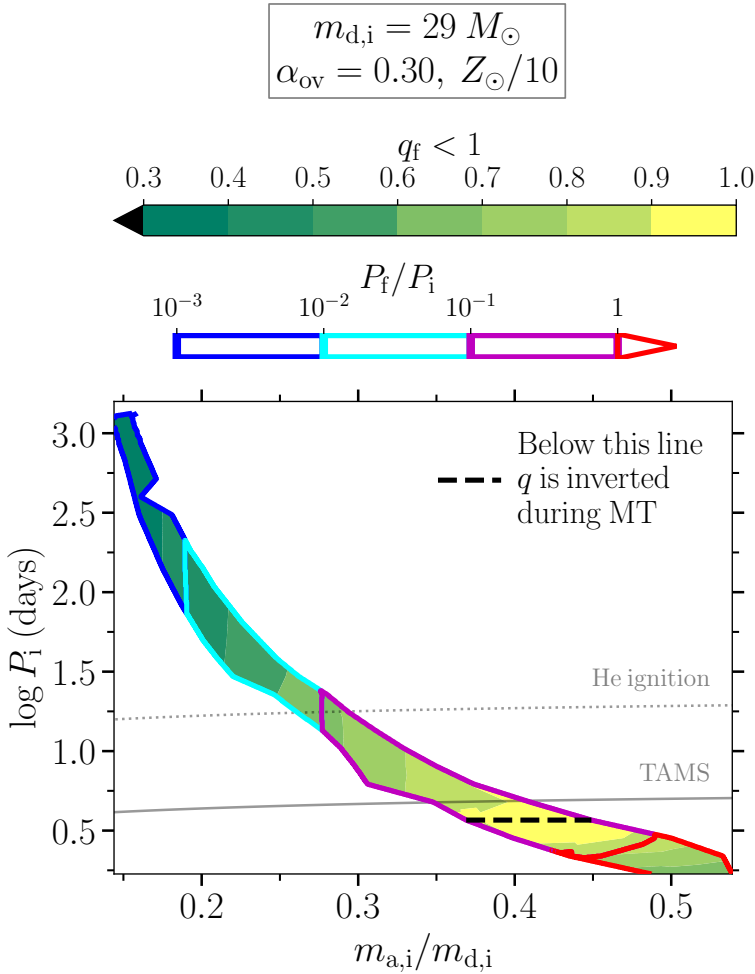


Figure 5.8: Parameter window for stable MT GW mergers for a donor star of initial mass $m_{d,i} = 29 M_\odot$, convective overshooting $\alpha_{ov} = 0.30$ and metallicity $Z = Z_\odot/10$. We use this as a case study to understand the post-MT mass ratios q_f and orbital periods P_f , but refer to Appendix D.5 for more examples. The color coding shows q_f of the post-MT binary (always defined as smaller than unity for consistency with the LVK network’s convention), and the black dashed line indicates the boundary for $q_f = 1$. Additionally, regions that undergo different levels of tightening, P_f/P_i , during MT are contoured with different colors. The different evolutionary stages (TAMS and center-helium ignition) follow the convention of Figure 5.1.

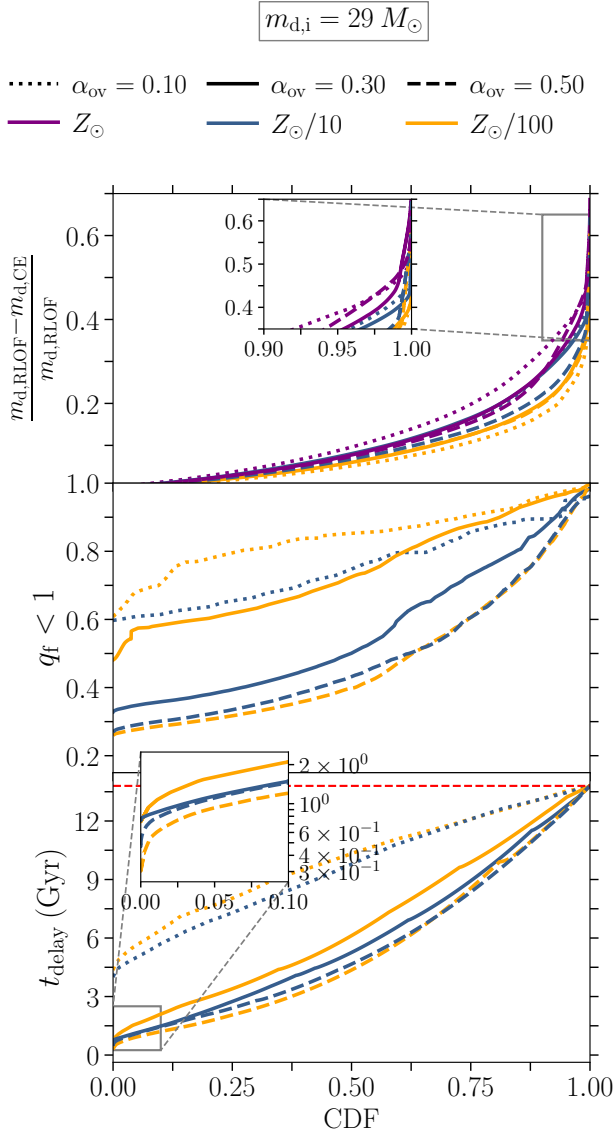


Figure 5.9: CDFs (computed assuming uniform distribution in $\log P_i$ and q_i) of the same quantities as in Figure 5.7, but for a donor star of initial mass $m_{d,i} = 29 M_{\odot}$, and different convective overshooting α_{ov} and metallicity Z . The two insets zoom in to show that a) higher metallicity enhances the most extreme values of DDI, i.e. case A systems at the instability boundary; b) the tightest time delays from stable MT are achieved for the highest α_{ov} during case B MT (see also Figure 5.8). The results for solar metallicity are not shown for the stable MT mergers mass ratios and time delays, as in this case the stable MT channel is largely suppressed (see Figure D.17).

5.4 Discussion

5.4.1 Instability boundaries from mass-radius exponents

In the context of rapid population synthesis codes, the stability of MT is usually determined with the " ζ -method", i.e. by comparing the adiabatic mass-radius exponent of the donor star, ζ_{ad} , with that of its Roche lobe, ζ_{RL} (e.g. Tauris & van den Heuvel 2023). The former are tabulated from adiabatic mass loss sequences (the series from Ge et al. 2010); the latter can be computed analytically, as a function of the binary mass ratio q , from angular momentum and mass conservation arguments, assuming a specific MT mode (e.g. Soberman et al. 1997). In practice, ζ_{ad} is usually kept fixed to a single value (van Son et al. 2022b) or a few indicative values based on the calculations from Ge et al. 2020 (e.g. Vigna-Gómez et al. 2018; Riley et al. 2021). In particular, these sets of fixed ζ_{ad} are then used to compute the critical mass ratios for MT stability, q_{crit} , under different types of MT modes, by solving the equality $\zeta_{\text{ad}} = \zeta_{\text{RL}}(q_{\text{crit}})$. Crucially: 1) the adiabatic response of a donor star is a complex function of its evolutionary stage, and fixing ζ_{ad} to a specific (set of) values is an oversimplification (Ge et al. 2020; Zhang et al. 2024); 2) adiabatic mass loss models compute ζ_{ad} under specific the assumptions for the MT mode, and they hold only under those assumptions (Ge et al. 2020, 2023, 2024), i.e. they are not to be treated as universal intrinsic properties of donors (but see also the discussion in Ge et al. 2015); 3) the ζ -method does not capture the time-dependent response to MT and its coupling to the MT mode (e.g., Temmink et al. 2026).

To make an assessment of the goodness of the ζ -method to translate critical mass ratios between different MT modes, we specifically compute two additional MESA grids at $m_{\text{d},i} = 29 M_{\odot}$ (and fiducial α_{ov} and Z): one that is undergoing conservative MT, and one undergoing fully non-conservative MT with the isotropic re-emission mode³. We show the resulting stability boundaries in Figure 5.10: conservative MT is more stable than fully non-conservative MT. This is opposite to what the ζ -method determines: the mass-radius exponent of the Roche lobe in presence of conservative MT, $\zeta_{\text{RL}}^{\text{CONS}}$, is always larger than that of isotropic re-emission MT, $\zeta_{\text{RL}}^{\text{ISO}}$, such that stability would be disfavored for conservative MT (see Soberman et al. 1997; Picco et al. 2024; Temmink et al. 2026, and also Appendix D.6, where we show the analytical ζ_{RL} in Figure D.19). An example of this inconsistency is shown in Figure 5.10: if one assumes that the adiabatic response under conservative MT, $\zeta_{\text{ad}}^{\text{CONS}}$, is the same as in the fully non-conservative case, and then solves the equality $\zeta_{\text{ad}}^{\text{CONS}} = \zeta_{\text{RL}}^{\text{ISO}}(q_{\text{crit}})$

³The results of the grid with artificially imposed isotropic re-emission are fully consistent with those of our fiducial setup, i.e. with Eddington-limited MT, at least for $m_{\text{d},i} = 29 M_{\odot}$.

following the ζ -method, they would predict many more systems to undergo stable MT, and more stability than in the conservative case at every initial period.

This picture has important consequences for GW progenitors: as shown in Figure 5.10, our grid for conservative MT shows a largely suppressed parameter window for GW mergers, limited to systems that begin RLOF in very tight initial orbits (case A MT) and with massive accretors. On the other hand, the isotropic re-emission mode shows the familiar window (similar to that of Figure 5.1) that is able to produce GW mergers for case A and B MT. Consequently, the critical mass ratios for isotropic re-emission as derived from the ζ -method may consistently exaggerate the stable MT systems, thereby predicting the wrong relative importance of the stable MT and CE channels. Summarizing: our results imply that *a simple translation of ζ_{ad} into a critical mass ratio q_{crit} leads to incorrect conclusions about MT stability and GW progenitors.*

5.4.2 Delayed instability and relevance for rapid population synthesis codes

As mentioned in Section 5.3.3, we expect the extent of DDI as we calculate it to be sensitive to the choice of CE threshold. As explained in Section 5.2.2, we are adopting, for the different $m_{\text{d,i}}$, thresholds of $\dot{M}_{\text{MT}}^{\text{max}}$ equal to ten times the global thermal MT rate that a single star of equal mass would ever achieve during its evolution till central carbon depletion. This choice is designed to be conservative, as such values of $\dot{M}_{\text{MT}}^{\text{max}}$ are as high as $1 - 6 M_{\odot} \text{ yr}^{-1}$ (higher than the typical maximum rates used in literature, e.g. Marchant et al. 2021; Henneco et al. 2024b; Briel et al. 2026). Nevertheless, a lower (higher) value of $\dot{M}_{\text{MT}}^{\text{max}}$ would result in a larger (smaller) amount of mass lost before CE onset, and therefore a more (less) prominent DDI. To test the impact of this choice, we compute additional MESA grids varying $\dot{M}_{\text{MT}}^{\text{max}}$ by factors of 10 and 100. The results are shown in Figure 5.11, where we present the CDFs of the amount of mass lost before CE onset, and Figure 5.12, where we also show the impact of the CE threshold on the stability boundaries. We find that stopping the simulation at a rate 10 times smaller than the thermal rate (i.e., 100 times smaller than our fiducial threshold $\dot{M}_{\text{MT}}^{\text{max}}$) yields more than 80% of the systems to lose at least 15% of their initial mass before CE onset, while the systems that would lose the same (or smaller) amount of mass before reaching a MT rate 100 times larger than the thermal would be less than 60%.

Given the sensitivity of DDI to the CE threshold, one may ask the question of when it is safe to say that the system is entering CE, in the context of 1D time-dependent models. This is a long standing question, as it marks the limit

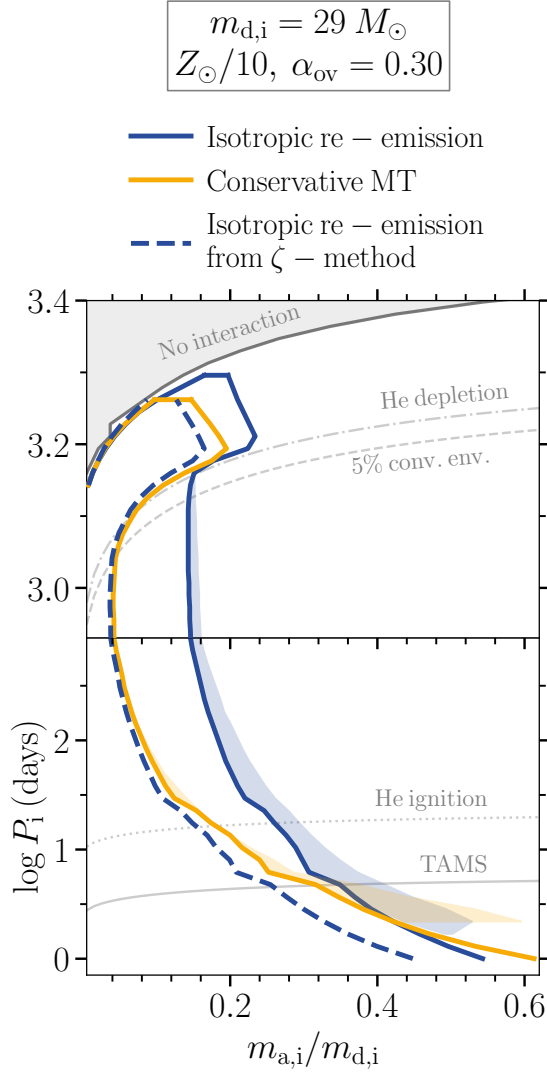


Figure 5.10: Stability boundaries for a donor star of initial mass $m_{d,i} = 29 M_{\odot}$, convective overshooting $\alpha_{ov} = 0.30$ and metallicity $Z = Z_{\odot}/10$, computed with our time-dependent models under conservative MT (golden) and isotropic re-emission MT (blue). The dashed line show the critical mass ratios for stability derived from the ζ -method, fixing the adiabatic response to be equal to the one computed for the conservative case, $\zeta_{\text{ad}}^{\text{CONS}}$, and solving the equality $\zeta_{\text{ad}}^{\text{CONS}} = \zeta_{\text{RL}}^{\text{ISO}}(q_{\text{crit}})$. The ζ -method predicts more stability for isotropic re-emission MT, while our time-dependent models show the opposite behavior. The parameter window for GW mergers (shaded regions) is largely suppressed in the conservative case, while it is similar to that of our fiducial setup (see Figure 5.1) in the isotropic re-emission case.

of validity of 1D models (Ivanova et al. 2013; Pavlovskii & Ivanova 2015) and is relevant for the problem of mapping of evolved donors' structures into 3D hydrodynamical simulations of CE (e.g. Sand et al. 2020). We did not attempt at answering this question with this work, as our main objective is to confirm the robustness of DDI for those donors that are predicted to evolve as GW sources, and quantify its impact on common assumptions in rapid population synthesis codes. For example, the stability boundaries in Figure 5.12 are rather similar in presence of radiative envelopes, and the stable MT mergers parameter window is only affected when we stop our simulation at a rate 100 times smaller than the fiducial one. Under this restrictive stopping condition, many systems with convective envelopes that would remain stable otherwise are flagged as unstable. This is reassuring for rapid population synthesis frameworks: critical mass ratios from time-dependent models are robust to the choice of CE threshold within an order of magnitude, in the case of radiative envelopes (i.e., precisely when we need to discern between the stable MT and CE channel for GW progenitors!).

In progress work at the time of writing Despite the small change in the location of the stability boundary, the mass transferred prior to instability modifies both the orbital separation and the internal structure of the donor (and thus its binding energy), which makes the applicability of an energy criterion at the onset of RLOF uncertain. At the time of writing, we are working on addressing one further question to complete our message to the rapid population synthesis community: what is the impact of DDI on the post-CE properties that are computed according to the energy formalism? Is there a significant shift in the final mass ratios and delay times of binary BHs, as computed from the properties at onset of RLOF, versus those at the *true* onset of CE? This issue will be partially addressed in this publication in the context of the fiducial model, and we will explore it in more detail in future work (see Chapter 6).

5.4.3 Caveats to our models

In this work, we made a number of simplifying assumptions that allow us to isolate the complex interplay of convective overshooting and metallicity in determining MT stability, and their possible imprints on the population of binary BHs observed by the LVK network. While the physical picture remains our most important message, these simplifications may affect our specific number predictions and distributions in several ways.

First, we do not model the binary evolution prior to the onset of the MT episode in a binary with an already formed CO. In particular, the first MT episode between two stars strongly affects the structural properties of the donor that later initiates MT onto the CO companion (Braun & Langer 1995; Renzo &

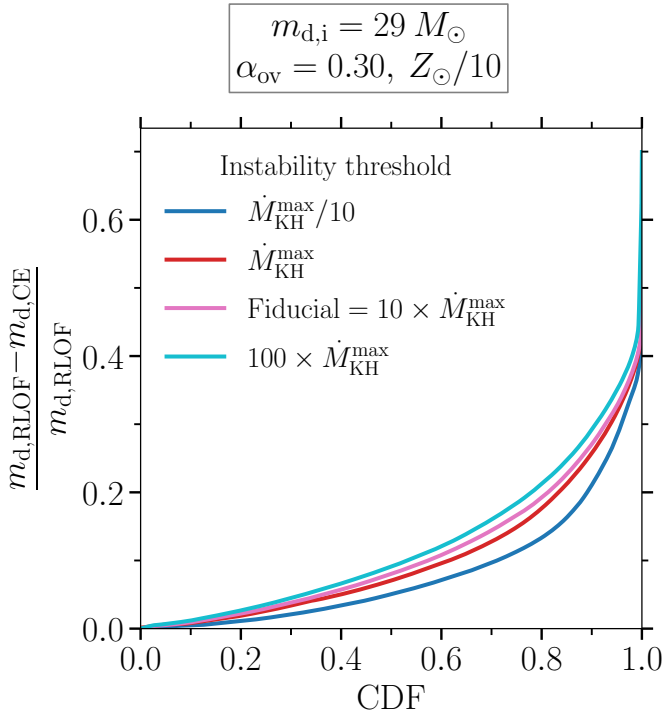


Figure 5.11: CDFs of the amount of mass lost before CE onset, for different choices of the CE threshold $\dot{M}_{\text{MT}}^{\text{max}}$, but fixed donor mass $m_{d,i} = 29 M_{\odot}$, overshooting $\alpha_{\text{ov}} = 0.30$ and metallicity $Z = Z_{\odot}/10$. The fiducial choice is 10 times the maximum thermal MT rate, $\dot{M}_{\text{KH}}^{\text{max}}$, that a single star of equal mass would achieve during its evolution. We also show the results for thresholds 10 and 100 times smaller and 10 times larger than the fiducial one (color coded).

Götberg 2021), thereby influencing the stability of the subsequent MT phase (Xu et al. 2025). The first MT episode also determines which star–CO binaries are formed in the first place (Langer et al. 2020; van Son et al. 2022b; Olejak et al. 2022, 2024; Schürmann et al. 2025; Briel et al. 2026). Furthermore, the formation of the first CO may impart a natal kick capable of disrupting the binary (e.g. Renzo et al. 2019; Igoshev et al. 2021). Wind mass loss following the formation of the first CO also widens the orbit and modifies the post-MT binary properties (van Son et al. 2025; Briel et al. 2026). In addition, stellar winds and pair instability supernova physics can prevent the formation of the massive first-born COs (Spera et al. 2015; Winch et al. 2025) that are present in our initial binary models.

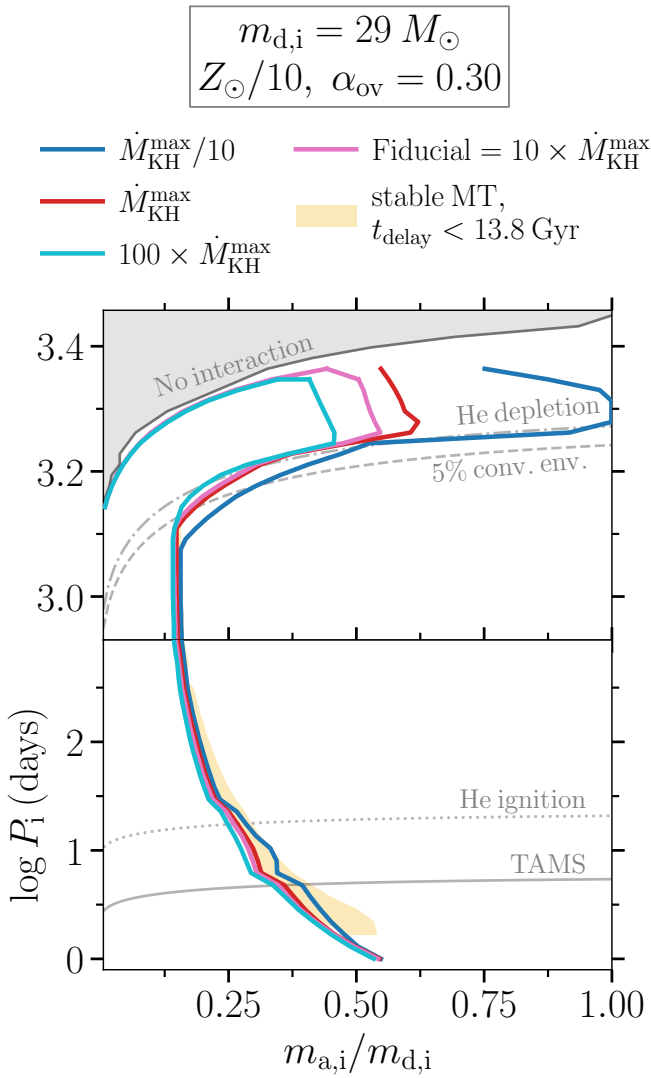


Figure 5.12: Stability boundaries for a donor star of initial mass $m_{d,i} = 29 M_{\odot}$, convective overshooting $\alpha_{ov} = 0.30$ and metallicity $Z_{\odot}/10$, computed for the same different choices of the CE threshold $\dot{M}_{MT}^{max}$ as in Figure 5.11. The GW mergers parameter space is highlighted in yellow, and is the same for all the different choices of CE threshold.

We also adopt several simplifying assumptions for the evolution following the second MT episode. For donor masses in the NS progenitor regime ($m_{d,i} \lesssim 20 M_{\odot}$; e.g. Poelarends et al. 2008; Fryer 1999), we do not model the SN explosion to determine the final remnant masses, including the effects of the islands of explodability (O’Connor & Ott 2011; Müller et al. 2016; Sukhbold et al. 2018; Laplace et al. 2025), nor do we account for natal kicks. For donor masses in the BH progenitor regime ($m_{d,i} \gtrsim 20 M_{\odot}$; e.g. Fryer 1999; Heger et al. 2003), we assume that the stripped He star always collapses to form a second BH. To relate the final orbital separations to binary BH delay times, we further assume that this collapse occurs through direct collapse, without natal kicks or mass loss (Janka 2013; Atri et al. 2019; Vigna-Gómez 2025). Non-zero BH natal kicks or mass loss at BH formation would modify the predicted merger times, potentially allowing a small population of rapidly merging binary BHs to form from relatively wide but eccentric binaries (Stevenson 2022; Klencki et al. 2026).

These assumptions may affect the properties of the resulting binary BH population (Olejak et al. 2022; van Son et al. 2022b,a; Zevin & Bavera 2022; Banerjee & Olejak 2024; Dorozsmai & Toonen 2024). We also neglect stellar rotation, which can influence both the evolution and the outcome of the two MT episodes (Xu et al. 2025). Consequently, we do not make predictions for the spins of BH binaries (Qin et al. 2018; Belczynski et al. 2020; Bavera et al. 2022; Shao & Li 2022), which may provide an observational signature distinguishing the stable MT and CE formation channels (Olejak et al. 2024).

5.5 Conclusions

The main message that we want to bring forward is that there are no hard boundaries for MT stability. Structural properties of stars, such as the extent of convective core overshooting, α_{ov} , and metallicity, Z , couple in a non-trivial way to determine the stellar response to MT, such that no universal “critical mass ratios” or “adiabatic mass-radius exponents” can separate stable MT from CE evolution. This has profound implications for the formation of binary COs that are observable as GW sources, and for the relative importance of the stable MT and CE channels: when varying the convective overshooting and metallicity, the stable MT outcome can be either suppressed (e.g., at low α_{ov} and / or high Z) or enhanced (at high α_{ov} and / or low Z) by up to two orders of magnitude, and it can produce different types of binary COs.

1. *Impact of overshooting and metallicity on coalescing binary COs.*

Which systems evolve into GW mergers via stable MT is sensitive

to the interplay between metallicity and convective core overshooting. Consequently, the properties of the resulting binary COs will depend on these parameters: stronger overshooting at fixed metallicity favors more unequal-mass binary COs with shorter delay times; increasing metallicity at fixed overshooting produces a similar trend. Furthermore, stable MT robustly forms GW mergers accross a wide range of progenitors masses (with the more massive component $m_{\text{d},i} \geq 17 M_{\odot}$), and the possible pairs of COs will also depend on α_{ov} and Z . Notably, binaries with a first-born BH with a second-born NS are more likely to form at high α_{ov} and / or low Z , while double BH binaries may be completely suppressed with a sufficiently low α_{ov} and / or high Z .

2. *Delayed dynamical instability of radiative donors.*

Donors with radiative envelopes do not enter a CE phase promptly, but instead undergo a phase of DDI, losing a substantial fraction of their mass before MT becomes unstable. The biggest effect is seen in systems that initiate MT with mass ratios very close to the stability boundary, where DDI may amount to up to $\sim 45\%$ of mass loss, in the case of RLOF during core-hydrogen burning (“case A” MT). Consequently, the binary properties at the onset of CE can differ significantly from those at the onset of MT. Notably, this is highly sensitive to the binary mass ratio, implying that current population synthesis models may systematically mispredict the binary post-CE properties as computed from the energy formalism at fixed “critical mass ratio” thresholds. This puts in question the use of the energy principle at the onset of RLOF to determine post-CE properties in population synthesis.

3. *Limitations of the ζ -method to determine MT stability.*

The commonly adopted ζ -method, which uses look-up tables of fixed adiabatic mass-radius exponents, ζ_{ad} , and compares it to the analytical Roche-lobe response, ζ_{RL} , *cannot* be used to compute MT stability under different MT modes. Such a method leads to a) the wrong implications on which MT modes are more stable, as it neglects the time-dependent response of the donor; b) biased estimates of the relative importance of the stable MT and CE channels for GW progenitors. Notably, the ζ -method predicts that fully non-conservative MT is always more stable than conservative MT, while our time-dependent models show the opposite (see also [Temmmink et al. 2026](#)).

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Chapter 6

Conclusions and outlook

In this thesis we have investigated the evolution of binary stellar systems that exchange mass through mass transfer (MT). MT is the most defining interaction in stellar binaries and its products build a rich diversity of stellar populations that are necessary to explain numerous astronomical phenomena, including blue stragglers (Leigh et al. 2013), hot subdwarfs (sdOBs; Heber 2026), Type Ia supernovae (Toonen et al. 2012), kilonovae (Metzger 2019), and gravitational waves (GW) (Abbott et al. 2016). Despite MT being the key to understanding these populations, theoretical models of MT and the physics that drives its (in)stability remain highly uncertain.

This thesis represents an effort to advance our understanding of MT throughout the evolutionary pathway of stellar binaries, from their birth as gravitationally bound pairs of young stars, to their final fate as coalescing compact objects detectable through GWs by the LIGO, Virgo, and KAGRA (LVK) network. In particular, we have focused on stripped stars, which have lost their hydrogen-rich envelopes through binary interaction, and on the population of binary BHs that source most of the observed GW sources. These recently detected, rapidly growing populations (see Section 6.1.1 and Section 6.1.2), revealed through UV surveys (Drout et al. 2023) and ground-based GW interferometers (The LIGO Scientific Collaboration et al. 2026b), offer us a timely motivation to understand MT physics with detailed binary evolution models. With this work, we have placed theoretical anchors at multiple stages of binary evolution (see Figure 1.8) and addressed the overarching question:

HOW DOES MASS TRANSFER SHAPE THE EVOLUTION OF THE STELLAR
PROGENITORS OF THE GRAVITATIONAL WAVE CHORUS?

We approached this question by investigating the following key problems.

Chapters 2, 3

How does the orbit of a binary evolve under different modes of mass loss, and what orbital configurations can(not) be produced by stable MT? In Chapter 2, we addressed the question in the context of MT between a Roche lobe-filling donor star in orbit with a first born compact object. We computed analytically the amount of orbital shrinkage or expansion that can be produced by stable MT, in the cases in which the transferred matter is expelled from the system with the specific angular momentum of the accretor (isotropic re-emission) and / or through the second Lagrangian point L_2 . The orbit of a binary undergoes shrinkage or expansion, depending on the mass ratio of the two stars, and the amount of orbital shrinkage is determined by the mode of mass loss. In particular, we found that, may the companion be a BH, neutron star (NS) or a white dwarf (WD), the orbit can shrink enough to produce double compact objects that will merge within the age of the Universe. We also adopted a semi-analytical framework to assess the MT stability in the different MT modes, and found that, with L_2 mass outflow, systems with more equal masses may form GW sources than in the case of isotropic re-emission. However, the stable MT channel remains robust to changes in the mode of mass loss. Additionally, the final mass ratios of the double compact objects produced by stable MT are consistent with the majority of the observed LVK population. Therefore:

Stable MT can seal binaries with compact objects in orbits tight enough to source GWs within the age of the Universe, and this result is robust to changes in the mass loss mode.

In Chapter 3, we addressed the question from a different angle, i.e. by studying MT between two stellar components. In particular, we analysed the case of HR6819 (see Section 1.2.1), a binary composed of a bloated stripped star and a rapidly rotating Be star, that is a prime candidate to represent an evolutionary stage right after a MT episode. HR6819 is especially interesting because of its precise characterization from combined spectroscopy and interferometry, that pose the lowest stripped star mass, the tightest orbital period, and the most extreme mass ratio compared to similar binaries. Therefore, we studied the formation of the system with evolutionary models, with the aim to understand whether stable MT could explain the extreme properties of HR6819 and constrain MT efficiency. As opposed to the case of compact object companions, for which it is physically reasonable to assume low MT efficiency, we modeled (partially)

conservative MT and considered the orbital evolution without stellar rotation. Our evolutionary models show that MT produces tighter orbital configurations with lower MT efficiency, such that the binary would enter a contact phase before the stripped star is formed; viceversa, conservative MT may evolve with a less extreme orbital shrinkage and allow stable evolution, but it will detach at a much wider orbital period and lower mass ratio than those observed. This leaves us with the compelling result that the orbital properties of HR6819 cannot be explained by stable MT, opening the discussion on which physical ingredients are missing from our current MT models with two stellar components (see Section 1.1.4). We already know that our current theoretical description of this problem is incomplete, and systems such as HR6819 therefore represent both a red flag and an opportunity to identify and constrain the missing physical ingredients. Summarizing:

Stable MT between stellar components cannot produce arbitrarily extreme mass ratios at a given orbital period, and the possible post-MT configurations depend on the mass loss mode. Conservative MT is the best solution to produce post-MT binaries with extreme mass ratios, yet HR6819 remains challenging to explain.

Chapter 4

How do (intermediate-mass) stripped stars form, and can stellar mergers resulting from unstable MT contribute to their population? In Chapter 4 we addressed this question by analysing a formation channel for intermediate-mass stripped stars that has not been considered before in population studies: the failed-common envelope (CE) channel, previously proposed in the context of HD45166 (see Section 1.2.4). In this scenario, a first MT episode produces a stripped star, while the companion evolves and initiates an inverse MT episode that leads to a CE event. The two helium-rich cores merge into a more massive stripped star, which may be observed as an intermediate-mass stripped star. To assess the importance of this channel as compared to the classic stable MT and CE ones, we produced grids of MT models between stellar binaries across the mass range of intermediate-mass stripped stars progenitors. We find that the failed-CE outcome is always favored in binaries that initiate MT at mass ratios close to unity; at lower total mass, systems with more unequal mass ratios may also evolve into failed-CE mergers, due to the fact that accretion accelerates the evolution of low mass stars more efficiently than for high mass ones. Additionally, our results show that the failed-CE merger products have masses spanning a defined range ($0.6 M_{\odot}$ to $14 M_{\odot}$) and therefore

may contribute to the population of both low- and high-mass stripped products (subdwarfs and Wolf-Rayet stars), but their exact fractions would require a complete population weighting. Observationally, the failed-CE stripped objects can populate the whole helium-burning sequence of the Hertzsprung-Russell diagram and produce a blue-straggler effect, while appearing as single stars or members of wide binaries that were originally hierarchical triples. Our study demonstrates the importance of detailed MT models for identifying and characterizing binary evolution channels that are overlooked in rapid population synthesis frameworks, and highlights the need to include failed-CE mergers in future predictions of stripped-star populations. In summary:

Beside the classic stable MT and CE channels, (intermediate-mass) stripped stars may also form through failed-CE mergers. The products of these mergers may contribute to the population of stripped products across a wide range of masses, and may be observed as blue stragglers or as members of wide binaries.

Chapter 5

Which internal stellar properties determine the stability of MT in binaries?

In Chapter 5 we tackled this question by studying the MT between a Roche lobe-filling star and a first born compact object. We focused on stellar progenitors of NSs and BHs, and we investigated the role of core size (in terms of the overshooting parameter α_{ov}) and metal content in driving MT stability. To do so, we produced grids of detailed binary evolution models designed to resolve the (in)stability boundary in initial period and mass ratio, enabling the study of how such boundary shifts under different physical assumptions that are usually held fixed in rapid population synthesis codes. We find that a larger core size and a higher metallicity independently favor MT stability in the presence of radiative envelopes. Stellar donors with radiative envelopes will also initiate CE with a degree of delay, which is more pronounced for systems close to the instability boundary and with high metallicity. This has important implications for population synthesis tools that often impose oversimplified *hard boundaries* for MT stability, while there is instead a complex interplay of internal properties of stars that play a role in determining whether a binary will evolve through stable MT or CE. Additionally, the post-CE properties calculated with the standard energy formalism for CE might be inaccurate due to the delayed dynamical instability.

We applied this analysis to the case of GW progenitors, to investigate the physical effects of core size and metallicity on the produced coalescing binary

BHs. We found that the combined effect of stronger core overshooting and lower metallicity allows wider and more unequal-mass progenitor binaries to form GW sources, which may enhance the stable MT channel outcome by up to two orders of magnitude. Crucially, we predict different properties for the resulting coalescing binaries depending on the input physics: at fixed metallicity, stronger overshooting favors more unequal-mass compact-object binaries with shorter delay times; at fixed overshooting, higher metallicity produces a similar effect. Our results lay the foundation for a broader understanding of how stellar internal properties govern MT stability throughout the evolution of a binary, and shape the diversity of post-interaction systems. In summary:

The size of the core and the metallicity of the stellar progenitor play a key role in determining the stability of MT in binaries with compact objects. This has direct implications in the produced GW sources, such that current population synthesis frameworks might be missing the origin of many coalescing binary BHs formed within the isolated binary evolution scenario.

6.1 Future prospects

6.1.1 The future is UV-bright...

The outlook for the study of intermediate-mass stripped stars is UV-bright, driven by the development of a new generation of observational facilities. Dedicated UV missions such as [UVEX](#) ([Kulkarni et al. 2021](#)), [ULTRASAT](#) ([Shvartzvald et al. 2024](#)), [CASTOR](#) ([Cote et al. 2019](#)), will improve the detection of these hot, compact stars through wide-field UV imaging, while the [UV Imaging Telescope](#) ([Tandon et al. 2017](#)) aboard [AstroSat](#) already provides high-angular-resolution UV observations (e.g. [Devaraj et al. 2023](#)). In parallel, large spectroscopic facilities such as [SDSS-V](#) ([Kollmeier & The SDSS-V Collaboration 2025](#)) and [ESO's 4MOST](#) ([de Jong et al. 2019](#)) will enable systematic spectroscopic searches and confirmations of stripped-star candidates. These surveys will naturally complement the capabilities of the [ELT](#) ([Gilmozzi & Spyromilio 2007](#); [Padovani & Cirasuolo 2023](#)), which will make the spectroscopic characterization of stripped stars routinely possible. Beyond electromagnetic observations, future GW observations with [LISA](#) ([Amaro-Seoane et al. 2017](#)) will probe binaries containing stripped stars and compact

objects (Nelemans et al. 2004; Göteborg et al. 2020b; Wu et al. 2020), while continued UV spectroscopy with the Hubble Space Telescope will further constrain the winds and atmospheres of these stars (e.g. Hillier 2020; Roman-Duval et al. 2025).

Already at the time of writing, the number of observed intermediate-mass stripped stars is steadily growing. Searches based on UV-excess selection with *Swift*-UVOT (Drout et al. 2023; Ludwig et al. 2025), often followed by spectroscopic confirmation, have uncovered an increasing number of intermediate-mass stripped stars in the Magellanic Clouds (Pauli et al. 2022; Villaseñor et al. 2023; Ramachandran et al. 2023, 2024; Müller-Horn et al. 2025) and in the Galaxy (like HD45166, Shenar et al. 2023). These discoveries are supported by population synthesis studies, which predict that thousands more should reside in the Milky Way (Yungelson et al. 2024; Hovis-Afflerbach et al. 2025) and in the Magellanic Clouds (Blomberg et al. 2025, in agreement with the ~ 800 candidates from the catalogue by Ludwig et al. 2025).

As the observed population of stripped products continues to grow, substantial work remains to be done to understand the role of MT physics in shaping their formation channels and diversity, across the full range of masses and evolutionary stages. In the following, I highlight several promising research directions through which this work will be extended in the future.

Constraining mass transfer efficiency The fraction of transferred mass that is actually accreted by a stellar companion, i.e., the efficiency of MT, is a key ingredient in binary evolution models, but it remains poorly constrained. The population of stripped stars in binaries, representing an evolutionary stage immediately after MT, offers a unique opportunity to place constraints on this process.

In HR6819 (see Chapter 3 and Section 1.2.1; Bodensteiner et al. 2020a, El-Badry & Quataert 2021), the case is especially suitable, since the system hosts a bloated stripped star. As explained in the introduction, these objects are inflated in radius and optically bright, making them easier to detect than their compact, UV-bright counterparts, although they can also be easily confused with normal Main Sequence stars (Bodensteiner et al. 2022). In the case of HR6819, model-independent dynamical masses were measured thanks to long-baseline optical interferometry (Klement et al. 2025), which can detect stripped star companions with low flux contributions (as small as $\sim 1\%$) and spatially resolve binary orbits. This technique has also been successfully applied to several other systems composed of a (bloated) stripped star and a rapidly rotating Be star (Mourard et al. 2015, Klement et al. 2022a, Klement et al. 2022b, Klement et al. 2024), bringing the current sample to nine well-characterized systems with

precise dynamical masses. These dynamical mass estimates are particularly valuable for testing binary evolution models and the efficiency of MT, as we did for HR6819. Building a sample of such systems to anchor binary evolution models provides a promising route to constrain MT physics beyond individual “peculiar” systems (Lechien et al. 2025).

Inspired by the technique applied for HR6819, in Deshmukh et al. (2026) we carried out the first long-baseline interferometry campaign to observe wide sdOB with Main Sequence stars binaries. These systems have traditionally been characterized through spectroscopy with long-term monitoring of their radial velocity (RV) amplitudes (e.g. Vos et al. 2017; Molina et al. 2026). However, while the RVs of the Main Sequence companions can usually be measured accurately, the sdO/B RVs remain much more uncertain because of their broader and fewer spectral lines, leading to poorly constrained mass ratios and, consequently, uncertain sdOB masses. The astrometric orbital solutions expected from the fourth Gaia Data Release (Nagarajan et al. 2026) will provide a major step forward, but the photocenter motion alone does not fully determine the orbit. By combining Gaia astrometry with relative astrometry from long-baseline interferometry, it will be possible to derive complete orbital solutions and precise dynamical masses for both components.

This interferometric campaign represents a first step toward establishing this approach for the population of wide sdOB + Main Sequence star binaries. As the number of systems with well-constrained orbital solutions and dynamical masses increases (Molina et al. 2026), it will become possible to identify statistically robust correlations between orbital and stellar properties, such as orbital period, eccentricity, rotational velocity, and mass ratio (Parkosidis et al. 2026a). Building on the methodology developed for HR6819, we will model these systems with detailed binary evolution calculations to constrain the efficiency of MT under different assumptions for the orbital evolution. In particular, the combination of precise dynamical masses and orbital parameters will allow us to investigate whether the observed eccentricities provide additional constraints on the physics of stable MT (Parkosidis et al. 2026a,b) (and help solving the mystery of HR6819).

Predicting the population of failed-common envelope stripped stars Population synthesis studies have shown that the different binary interaction channels leading to stripped stars produce distinct distributions of orbital periods and masses, in good agreement with observations (Han et al. 2002). While the standard stable MT and CE channels are expected to produce sdOBs (Han et al. 2002, 2003a; Vos et al. 2020; Arancibia-Rojas et al. 2024), intermediate-mass stripped stars (Yungelson et al. 2024; Hovis-Afflerbach et al. 2025; Blomberg

et al. 2025; Wang et al. 2026c), and Wolf-Rayet stars (Vanbeveren et al. 1998a), stellar mergers have also been proposed as an important formation pathway for several objects across the Hertzsprung-Russell diagram (see Figure 1.7). In the low-mass regime, the merger of two helium white dwarfs may explain the growing population of massive helium sdOBs (Latour et al. 2026), while at higher masses mergers have been suggested as a possible explanation for apparently single Wolf-Rayet stars in both the Small Magellanic Cloud and the Milky Way (Schootemeijer et al. 2024; Deshmukh et al. 2024; Li et al. 2024). An especially interesting case is HD45166 (Steiner & Oliveira 2005; Shenar et al. 2023), whose formation was investigated in Chapter 4. In this scenario, an initial phase of stable MT produces the first stripped star, while the rejuvenated companion subsequently evolves, initiates an inverse MT episode leading to a CE event, and, after envelope ejection (the “failed CE”), the two helium-rich cores merge into a more massive stripped star. Despite its potential to contribute to the stripped-star population over a wide mass range, the failed-CE channel has not yet been explored with population synthesis calculations.

Building on the results of this thesis (Chapter 4), I will perform the first population synthesis study including failed-CE stellar mergers based on detailed binary evolution models. The resulting models will be used to predict the formation rates and observable properties of merger products, assess their contribution to the overall stripped-star population, and compare the predictions with the growing sample of intermediate-mass stripped stars. The population synthesis framework will also allow us to assess whether helium-star mergers populate the predicted “helium-star desert” (Hovis-Afflerbach et al. 2025) at low metallicity, and to quantify their importance relative to the standard stable MT and CE channels across cosmic time. The resulting models will provide a more complete characterization of the stripped-star population, thereby supporting the interpretation of systems discovered by ongoing and future surveys such as BLOeM (Shenar et al. 2024) and UVEX (Kulkarni et al. 2021).

Additionally, such models will be essential to quantify the stripped-star population contribution to the ionizing radiation in galaxies, including the contribution from failed-CE mergers. Owing to their high effective temperatures, stripped stars can continue to ionize their surroundings after the most massive stars have already exploded, making their contribution to the integrated ionizing flux potentially significant (Götberg et al. 2017, 2020a; Hovis-Afflerbach et al. 2025). The importance of this contribution depends on the fraction of stripped stars as a function of metallicity, which can only be predicted through population synthesis. These models can also provide predictions for the rates of hydrogen-poor core-collapse supernovae, whose progenitors are stripped stars (Smartt 2009), thereby constraining their role in the chemical and dynamical evolution of galaxies.

Finally, these models will also lay the groundwork for establishing observational diagnostics of failed-CE mergers based on surface abundance patterns, and signatures of magnetism, when coupled with spectral modeling (as demonstrated for HD45166; [Shenar et al. 2023](#)), as well as through asteroseismology ([Henneco et al. 2024a](#)).

6.1.2 ...and loud!

We are now only beginning to listen to the Universe’s chorus, as the future looks particularly exciting for GW astronomy. The coming decades will witness a rapid expansion of GW observatories on the ground and in space, enabling the detection of increasingly larger and more diverse populations of compact-object binaries and opening new avenues to study their progenitor stellar systems.

For the current generation of ground-based detectors, continuous improvements to the Advanced LIGO–Advanced Virgo–KAGRA network are expected to substantially increase the detection rate. Projections for the upcoming LVK observing runs indicate an increase from a few tens of compact-binary mergers per year, during O3, to hundreds of detections per year during O4 and at design sensitivity, with binary BH mergers dominating the sample and NS mergers remaining comparatively rare ([Abbott et al. 2018](#), [Kunnumkai et al. 2025](#)). At the same time, improved detector sensitivity and a larger network will significantly enhance sky localization, increasing the prospects for multimessenger observations.

Looking further ahead, third-generation observatories such as the [Einstein Telescope](#) ([Maggiore et al. 2020](#)) and the [Cosmic Explorer](#) ([Reitze et al. 2019](#)) are expected to revolutionize the field. Their improved sensitivity will extend the observable volume of the Universe to the epoch of the first stars ([Hall & Evans 2019](#)), allowing detections of binary NSs out to redshift $\gtrsim 1$ and binary BHs out to ~ 20 ([Borhanian & Sathyaprakash 2024](#)) (for reference, at the time of writing the binary BH redshift distribution in GWTC-5.0 has almost no support beyond ~ 1 !). Detection rates are expected to increase to tens of thousands of mergers per year, with some estimates reaching up to millions annually depending on the underlying source population ([Broekgaarden et al. 2024](#)). The resulting catalogs, together with the large number of high signal-to-noise detections, will enable precision population studies and dramatically increase the number of multimessenger observations ([Kaur et al. 2026](#)).

In parallel, future space-based GW observatories such as [LISA](#) ([Amaro-Seoane et al. 2017](#)), [TianQin](#) ([Luo et al. 2016](#)), and [Taiji](#) ([Gong et al. 2021](#)) will open the milli-Hz GW window. These missions will observe source classes inaccessible to ground-based detectors, including supermassive BH mergers ([Klein et al. 2016](#)),

extreme mass-ratio inspirals (Babak et al. 2017), and compact Galactic WDs binaries (Nelemans 2009). They will also detect stellar-mass BH binaries years before they merge in the LVK band, enabling multiband GW astronomy (Gerosa et al. 2019; Du et al. 2026). Together, ground- and space-based observatories will transform GW astronomy into a precision probe of compact-object populations and their progenitor stellar binaries across cosmic time.

While this is a vibrant time for GW astronomy, our understanding of how their stellar progenitor binaries actually form is still riddled with theoretical uncertainties. This thesis marks only the beginning of a broader effort to understand the isolated binary formation channel, and many routes remain to be explored before we can fully interpret the treasure trove of observations that the next decade will bring.

Understanding the drivers of mass transfer instability Whether a binary evolves through stable MT or CE remains one of the largest uncertainties in population models of compact-object binaries (e.g. Li et al. 2025; Broekgaarden et al. 2026; Shi et al. 2026). Crucially, which of the two channels is followed by the progenitor binary may leave distinct fingerprints in the observed population of GW sources (van Son et al. 2022a). However, current rapid population synthesis predictions are still strongly affected by uncertainties in the treatment of MT stability. As a consequence, we may presently be missing the origin of a large fraction of GW sources (Marchant et al. 2021; Gallegos-Garcia et al. 2021).

In Chapter 5, I have built the foundations to investigate the physical origin of MT instability using tailored simulations of MT in binaries with a BH companion. However, the study is just the beginning, as internal properties of stars that may influence MT stability are multiple and highly coupled. I intend to extend this study to improve our understanding of the role of core size, semi-convective mixing efficiency, metallicity, and rotation, and their interplay in driving the (in)stability of MT and its delay in radiative donors. By making use of these simulations, I will be able to identify the most relevant structural parameters at each evolutionary stage, while quantifying the offsets in donor mass and orbital separation caused by delayed instability. The ultimate goal is to develop parametrizations that can be directly implemented in rapid population synthesis codes (see the paragraph below).

Finally, the impact of a prior MT episode on the internal structure and subsequent MT response of the donor is the last piece of the puzzle to understand MT stability. These models will allow me to calibrate corrections to the stability boundary caused by chemical enrichment and altered stellar structure, ultimately improving population synthesis predictions for the formation of double BHs

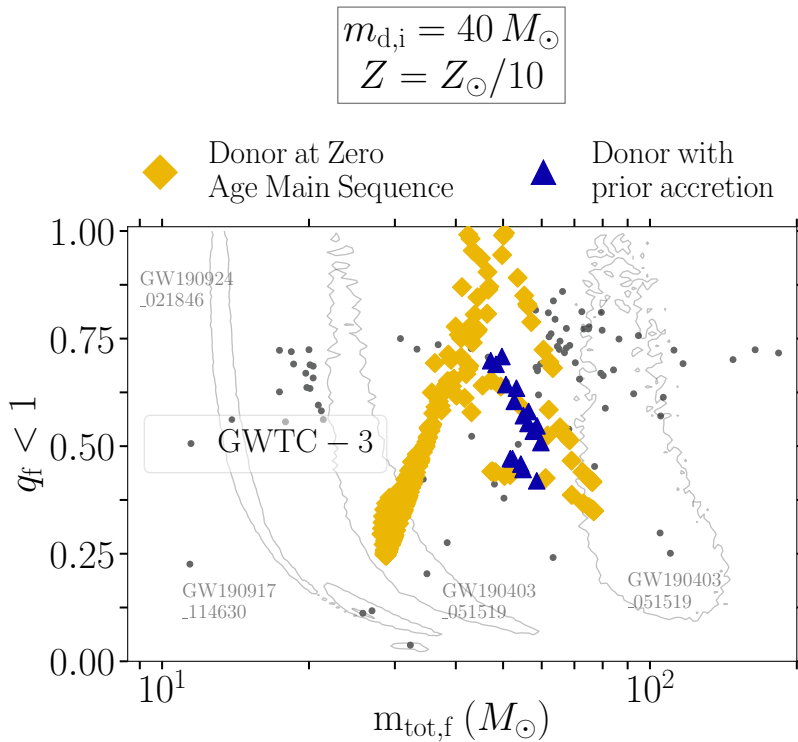


Figure 6.1: Mass ratio, $q_f < 1$ (following the notation of Chapter 5), and total mass, $m_{\text{tot},f}$, of the double BHs from the GWTC-3 catalogue (Abbott et al. 2023a) (gray points for the 90% confidence estimate and posterior 90% iso-contours, for a selection of signals). The colored scatter points represent our results from detailed MESA models: final (i.e., at inspiral) mass ratios and total mass of double BHs evolving via stable MT from a zero age Main Sequence $40 M_{\odot}$ donor star (golden diamonds) in orbit with a first-born BH (calculations carried out with the setup described in Chapter 5); these are compared with the case in which the stellar donor has undergone enrichment from prior MT (blue triangles).

through stable MT. Preliminary results from Sasha Graulus (2025)¹, our student at KU Leuven, indicate that prior chemical enrichment may produce a preferred range of mass ratios for GW sources formed through stable MT, as shown in Figure 6.1 (see also Xu et al. 2025).

¹The Master thesis can be found following [this link](#).

Building a stability recipe for population synthesis codes The interpretation of the growing population of binary BH mergers detected by the LVK network often relies on rapid population synthesis codes, which combine detailed single-star evolution models with semi-analytical prescriptions for binary interactions (Hurley et al. 2002) (see also Chapter 5). While this approach enables efficient exploration of the binary parameter space, the treatment of MT stability remains one of its largest sources of uncertainty. Current prescriptions typically rely either on constant mass-ratio thresholds (Belczynski et al. 2008) or on criteria derived from single-star models with adiabatic mass loss (Ge et al. 2020, see also Section 1.1.2), neglecting the response of the companion and the orbit, despite their strong influence on MT stability and the post-MT binary properties (e.g. de Mink et al. 2007, and this thesis, Chapters 2 and 5). Furthermore, rapid codes cannot account for structural properties that are expected to affect the stability boundary, as listed above. As a consequence, the astrophysical implications inferred from observed GW mergers may be significantly misinformed.

A physically motivated understanding of the ingredients that govern MT stability will make it possible to develop improved stability prescriptions that can be implemented in rapid population synthesis frameworks. This synergy between detailed and rapid modeling will enable more reliable predictions for the rates and observable properties of compact-object binaries, as well as other post-MT products such as stripped stars. Ultimately, it will ensure that the astrophysical interpretation of the observed GW population is grounded in detailed MT physics, allowing robust tests of the relative importance of the stable MT and CE channels and identifying their observational fingerprints in the population of merging binary BHs.



Appendix A

Appendix to Chapter 2

A.1 L_2 calculations

To determine the change in orbital period due to an outflow from the L_2 point one needs to compute the integral (see Section 2.2.6)

$$\int_{q_i}^{q_f} \frac{1+q}{q} [x_{L_2}(q) - x_{\text{cm}}]^2 dq = \int_{q_i}^{q_f} f(q) dq, \quad (\text{A.1})$$

where $f(q)$ is defined as

$$f(q) = \frac{1+q}{q} \left[1 + \sum_{n=1}^5 a_n \times \begin{cases} q^{-(n-n_0)} & q \geq 1 \\ q^{(n-n_0)} & q < 1 \end{cases} \right] \quad (\text{A.2})$$

$$\equiv \begin{cases} f_{>}(q) & q \geq 1 \\ f_{<}(q) & q < 1 \end{cases} \quad (\text{A.3})$$

with $n_0 = 0.658$,

$$a_1 = 1.544, a_2 = -3.118, a_3 = 4.387, a_4 = -3.567, a_5 = 1.190.$$

In the above we made use of the fit to $x_{L_2} - x_{\text{cm}}$ in Eq. 2.20. We also introduced the functions $f_{\gtrless}(q)$ to describe the piece-wise function $f(q)$ in the mass ratio regimes $q \gtrless 1$, respectively. As the integrand $f(q)$ is a piecewise function, we

need to consider different possible outcomes depending on whether or not the binary crosses a mass ratio of unity during the MT event. Let us first consider the indefinite integral, $I(q)$:

$$I(q) = \begin{cases} I_{>}(q) \equiv \int f_{>}(q) dq & q \geq 1 \\ I_{<}(q) \equiv \int f_{<}(q) dq & q < 1 \end{cases}. \quad (\text{A.4})$$

By direct integration we have that

$$I(q) = \begin{cases} I_{>}(q) = q + \log q + \sum_{n=0}^{n_{\max}} a_n^{>} q^{-(n-n_0)} & q \geq 1 \\ I_{<}(q) = q + \log q + \sum_{n=0}^{n_{\max}} a_n^{<} q^{(n-n_0+1)} & q < 1 \end{cases} \quad (\text{A.5})$$

with

$$a_n^{>} = -\frac{a_n + a_{n+1}}{n - n_0}, \quad a_n^{<} = \frac{a_n + a_{n+1}}{n - n_0 + 1},$$

and the coefficients a_n and n_0 are given in Eq. 2.20. In this expression $n_{\max} = 5$ and $a_0 = 0 = a_{n>5}$. The result of the definite integral can then be computed as

$$\int_{q_i}^{q_f} f(q) dq = \begin{cases} I_{>}(q_f) - I_{>}(q_i) & q_f > 1, q_i \geq 1 \\ I_{<}(q_f) - I_{<}(1) + I_{>}(1) - I_{>}(q_i) & q_f < 1, q_i \geq 1 \\ I_{<}(q_f) - I_{<}(q_i) & q_f < 1, q_i < 1 \end{cases}. \quad (\text{A.6})$$

A.2 Comparison to Marchant et al. (2021) results

As this work serves as a benchmark and is meant to be followed by a detailed set of MESA simulations, we also want to compare our results for a donor of $m_{\text{d},i} = 32 M_{\odot}$ with the ones presently available. To this purpose, we consider the work from Marchant et al. (2021), in which the evolution of a metal-poor ($Z = 0.00142$) $30 M_{\odot}$ donor star orbiting a CO is modeled with MESA. For the comparison, we show in Fig. A.1 the $(m_{\text{a},i}/m_{\text{d},i} - \log P_i)$ parameter space. Their grid of simulations spans initial orbital periods, P_i , ranging from $-0.3 < \log P_i(\text{days}) < 3.5$, and initial mass ratios, $m_{\text{a},i}/m_{\text{d},i}$, between 0.01 and 0.59 (see Sect. 3.1 of their paper for more details on the grid), translating into CO masses $0.3 < m_{\text{a},i}/M_{\odot} < 17.7$.

The delay time boundary computed by us in the isotropic re-emission channel is close to the one found by Marchant et al., in which the degree of non-conservativeness is not a free parameter (i.e., they are not fixing an efficiency,

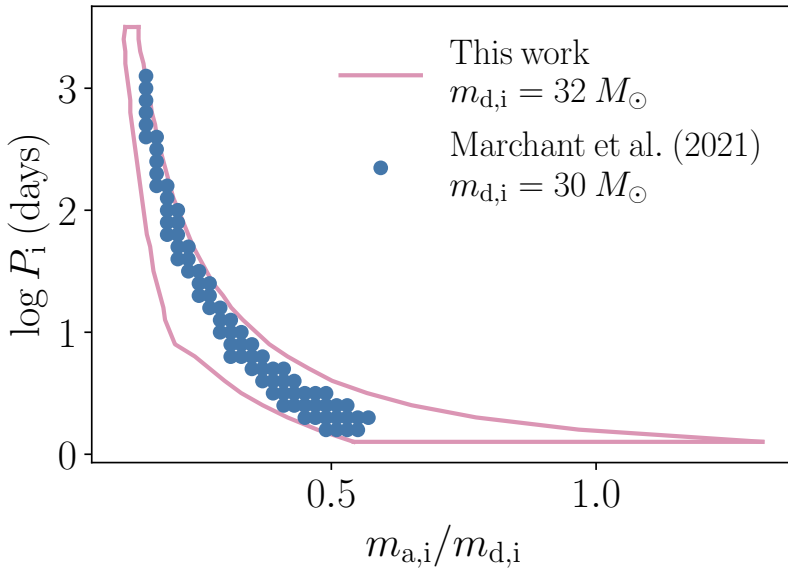


Figure A.1: Parameter space ($q_0 = m_{a,i}/m_{d,i} - \log P_i$) of GW progenitors initial properties, comparing results from the simulations from [Marchant et al. \(2021\)](#) (blue dots), for a donor of $m_{d,i} = 30 M_\odot$ and results from this work (pink contour), for a donor of $m_{d,i} = 32 M_\odot$.

β). The efficiency of MT is instead determined by limiting the accretion rate into the CO by its Eddington limit, with all the surplus material being removed under the assumption of isotropic re-emission. For the $30 M_\odot$ donor considered by [Marchant et al. \(2021\)](#), MT rates exceed the Eddington limit of the CO by orders of magnitude, resulting in a near-zero efficiency. The simulations of [Marchant et al. \(2021\)](#) also include a treatment for outflows from the outer Lagrangian points (in situations in which the donor grows significantly beyond its Roche lobe); these outflows account for only a small fraction of the total ejected mass (see their figure 13). Considering this, their simulations can be compared to our results with $\beta = 1$.

The instability boundary in our study is pushed to lower mass ratios compared to the results of detailed simulations in [Marchant et al. \(2021\)](#). Our instability boundary for $m_{d,i} = 32 M_\odot$ is much influenced by the hard limit on $R_{\text{He-ZAMS}} < R_{\text{RL},f}$ (see Sect. 2.2.5), and a realistic condition can be even more conservative. This apparent discrepancy might therefore attenuate or disappear, once one resolves the boundaries with detailed simulations.

Appendix B

Appendix to Chapter 3

B.1 Details of MESA simulations

Our simulations are computed using version 24.03.1 of MESA. Our setup is similar to that of [Marchant et al. \(2016\)](#), to which we refer for more details. We set the initial composition to correspond to the Galactic one from [Brott et al. \(2011\)](#), for both stars. We used custom opacity tables computed from the OPAL project ([Iglesias & Rogers 1996](#)) with solar-scaled metal abundances from [Grevesse et al. \(1996\)](#).

Convection was modelled using the Ledoux criterion ([Ledoux 1947](#)) within the standard mixing-length theory ([Böhm-Vitense 1958](#)), with a mixing-length parameter $\alpha_{\text{MLT}} = 1.5$. Semiconvection was modelled according to [Langer et al. \(1983\)](#) with an efficiency parameter $\alpha_{\text{sc}} = 1$. For hydrogen burning cores, we include step-overshooting extending the convective region by 0.10 pressure scale height at the convective boundary (but see main text where we discussed the impact of varying this number). For convective cores after the main-sequence we include exponential overshooting ([Herwig 2000](#)) with decay length of $f = 0.01$. Thermohaline mixing is modeled as in [Kippenhahn et al. \(1980\)](#) with an efficiency parameter of $\alpha_{\text{th}} = 1$.

Stellar winds follow [Yoon & Langer \(2005\)](#), with mass-loss rates for hydrogen-rich stars (with a surface helium abundance $Y < 0.4$) computed as in [Vink et al. \(2001\)](#), while for hydrogen-poor stars ($Y > 0.7$) we use those from [Hamann et al. \(1995\)](#) multiplied by a factor of one tenth. In the range $0.4 < Y < 0.7$, the rate is interpolated between the two.

Nuclear reaction rates in MESA are from JINA REACLIB (Cyburt et al. 2010), NACRE (Angulo et al. 1999) and additional tabulated weak reaction rates Fuller et al. (1985); Oda et al. (1994); Langanke & Martínez-Pinedo (2000). We use the simple networks provided with MESA `basic.net` for H and He burning, `co_burn.net` for C and O burning, and `approx21.net` for later phases, with the inclusion of iron and calcium.

Roche lobe radii in binary systems are computed using the fit of Eggleton (1983). Mass transfer rates in Roche lobe overflowing binary systems are computed with the contact scheme from Marchant et al. (2016). This is an implicit scheme in which the mass transfer rate is iteratively adjusted to ensure that the donor star remains within its Roche lobe. The method can also accommodate contact phases where both stars overfill their Roche lobes, provided that mass loss through the second Lagrangian point L2 does not occur.

B.2 Parameter variations

B.2.1 Reduced overshooting

All our simulations have been carried out with a step-overshooting scheme of the hydrogen burning convective core, extending its size by 0.1 pressure scale heights. This was picked because lower overshooting values ~ 0.1 -0.2 have been proposed for lower-mass stars based on double-lined eclipsing binaries (Claret & Torres 2016). To evaluate the impact of this choice, we re-computed our grids with a much lower value $\alpha_{ov} = 0.01$, to see if the limit on the maximum mass ratio at P_{today} achievable with stable MT would significantly shift. We show the result of the comparison in Fig. B.1. Notice that we have also computed grids of simulations with $q_r = 12.5$ and $0.50 \leq \epsilon \leq 1.00$, spaced by $\Delta\epsilon = 0.50$, but found no solution.

B.2.2 Average orbital angular momentum

We introduce a fixed fraction α_{avg} of material leaving the system with the average specific orbital momentum of the system (the total angular momentum of the orbit, divided by its total mass). Under these assumptions, one can derive another map between the initial orbital period P_i and the reference period P_r :

$$\frac{P_i}{P_r} = \left(\frac{q_r + 1}{q_i + 1} \right)^{-\frac{3\alpha_{\text{avg}}}{1-\epsilon} + 1} \left(\frac{\epsilon q_r + 1}{\epsilon q_i + 1} \right)^{\frac{3\alpha_{\text{avg}}}{1-\epsilon} - 5} \left(\frac{q_r}{q_i} \right)^3, \quad (\text{B.1})$$

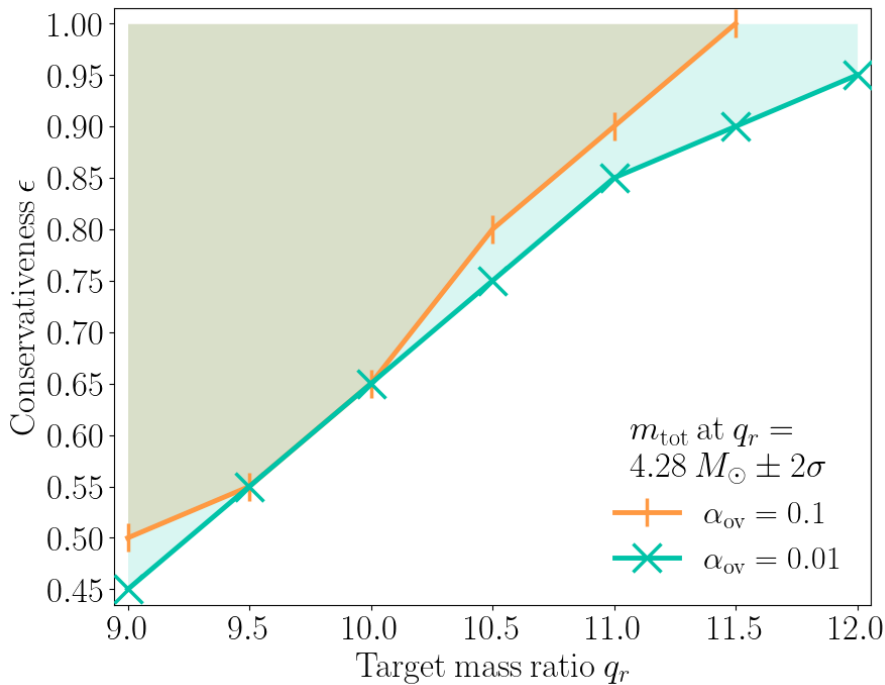


Figure B.1: Comparison of our grid exploration for different conservativeness degree ϵ and different target mass ratios q_r , for two different values of the overshooting parameter. The area is filled where a solution with $q_{detach} \geq q_r$ is found for a value of the present-day total mass $m_{tot,r}$ within 2σ uncertainty. The scatter points along the respective lines indicate where the minimum value of ϵ that gives a solution is found.

where the efficiency ϵ is defined as

$$\epsilon = 1 - \alpha_{avg} . \quad (\text{B.2})$$

Notice that the exponents show a factor $\alpha_{avg}/(1 - \epsilon)$: when MT is fully conservative (non conservative), this factor is zero (unity). We use this map combined with the total mass constraint in Eq. 3.3 to determine initial conditions for a new set of grids, analogously to Sect. 3.2. The results are shown in Fig. B.2, compared with the isotropic re-emission mode. Grids of simulations with $q_r = 12$ and $0.50 \leq \epsilon \leq 1.00$, spaced by $\Delta\epsilon = 0.50$, gave no solution.

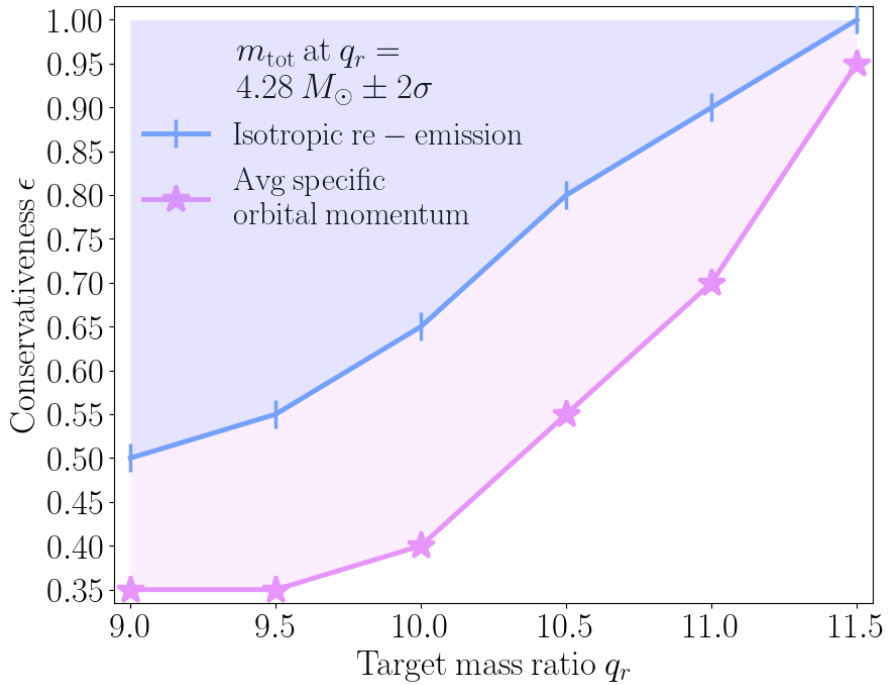


Figure B.2: Similar to Fig. B.1, but comparing two different angular momentum loss mechanisms: isotropic re-emission with efficiency $\beta = 1 - \epsilon$, and loss of a fixed fraction $\alpha_{\text{avg}} = 1 - \epsilon$ of the specific total orbital momentum.

Appendix C

Appendix to Chapter 4

C.1 Details of MESA simulations

Our simulations are computed using version 24.03.1 of MESA. Our setup is builds upon that of [Marchant et al. \(2021\)](#), to which we refer for more details. MT rates are computed taking into account MT through the first Lagrangian point L_1 from an extended atmosphere and optically thick regions. Notably, mass and angular momentum loss from the outer Lagrangian point (L2) of the donor is not calculated in our setup (see also Appendix C.2). We use such a modified ‘Kolb’ scheme ([Kolb & Ritter 1990](#)) because we model a mass loss rate from both stars during CE (see below).

The stellar models are computed at solar metallicity following [Asplund et al. 2009](#) for the solar abundance $Z_{\odot} = 0.0142$ and their relative metal mass fractions.

Convection was modelled using the Ledoux criterion ([Ledoux 1947](#)) within the standard mixing-length theory ([Böhm-Vitense 1958](#)), with a mixing-length parameter $\alpha_{\text{MLT}} = 2$. Semiconvection was modelled according to [Langer et al. \(1983\)](#) with an efficiency parameter $\alpha_{\text{sc}} = 1$. For hydrogen-burning cores, we include step-overshooting extending the convective region by 0.10 pressure scale height at the convective boundary (but see Appendix C.6 where we discuss the impact of varying this number). For convective cores after the main-sequence, we include exponential overshooting ([Herwig 2000](#)) with decay length of $f = 0.01$. Thermohaline mixing is modeled as in [Kippenhahn et al. \(1980\)](#) with an efficiency parameter of $\alpha_{\text{thermohaline}} = 1$.

Nuclear reaction rates in MESA are from JINA REACLIB ([Cyburt et al. 2010](#)),

NACRE (Angulo et al. 1999) and additional tabulated weak reaction rates Fuller et al. (1985); Oda et al. (1994); Langanke & Martínez-Pinedo (2000). We use the simple networks provided with MESA `basic.net` for H and He burning, which includes H^1 , He^3 , He^4 , C^{12} , N^{14} , O^{16} , Ne^{20} and Mg^{24} . As mentioned in the main text, our models run until core He-depletion, as failed-CE stripped stars produced from the merger of stars with inert carbon-oxygen cores are expected to be short-lived and therefore unlikely to contribute significantly to the overall population.

Our models have no stellar winds. Firstly, for the considered mass range we expect radiation-driven winds to be weak on the Main Sequence (e.g. Björklund et al. 2023). Additionally, we adopt this approximation due to the low ($10^{-7} - 10^{-9} M_{\odot} \text{ yr}^{-1}$) wind mass-loss rates measured for intermediate-mass stripped stars from the sample of Göteborg et al. 2023. We defer an exploration with a mass loss rate recipe for the different stripped products to future work. Additionally, we do not take into account stellar rotation or spin-orbit coupling.

C.2 CE formalism and merger products

C.2.1 Onset of CE

We define the CE onset as the first step in the simulation in which either of these conditions occurs:

- a) L2-overflow: both stars overflow past the distance of their own outer Lagrangian point L2. We calculate the volume equivalent radii associated with the L2 point for the two components following Eq. (5.4) and Eq. (5.5) in Marchant (2017). We do not stop our MESA runs but rather let our simulations go further than this point. However, after the L2-overflow condition is hit, we do not implement any L2 overflow mass and angular momentum loss (see also below). In the vast majority of our systems, after this condition a) is hit, we find that condition b) (see below) is also hit shortly after. In our analysis, we simply flag the systems that would trigger the L2-overflow condition and assume that the merger happens shortly after that point.
- b) MT rate limit: the MT rate $\dot{M}$ becomes larger than 10 times the Kelvin-Helmholtz rate of the donor star, $\dot{M}_{\text{KH,d}}$:

$$\dot{M}_{\text{KH,d}} \equiv \frac{M}{t_{\text{KH,d}}} \quad \text{with} \quad t_{\text{KH,d}} \equiv \frac{GM^2}{RL}, \quad (\text{C.1})$$

where we calculate this quantity at each timestep, with R being the radius, L the luminosity, M the mass of the star and $G = 6.67 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-2}$. This is also the starting condition of our double core CE scheme (see below), regardless of whether or not condition a) is also holding.

Based on the properties of the systems when one of these conditions is hit, we classify them as failed-CE stripped stars if they are additionally post-TAMS and there has been a previous stable MT episode; MS mergers otherwise (see the different types of MS mergers in Fig. 4.2). We further model the evolution of these binaries following the double core CE scheme described below.

C.2.2 CE evolution

Once the MT rate limit (condition b) above) is hit, we start with our double core CE scheme. This is an extension of the method by Marchant et al. (2021) to the case of two stellar cores.

CE MT rate We compute the MT rate during CE, $\dot{M}_{\text{CE}}$, depending on the degree of RLOF of both components: at each timestep, we consider their overfilling factor, Δ_j for $j \in \{d, a\}$, and the maximum value, Δ_{max} , as:

$$\Delta_j \equiv \frac{R_j - R_{L,j}}{R_{L,j}}, \quad \Delta_{\text{max}} = \max(\Delta_a, \Delta_d), \quad (\text{C.2})$$

where R_j and $R_{L,j}$ are the radius and Roche-lobe radius of the accretor for $j = a$ (donor for $j = d$). If either star overfills its Roche lobe, the MT rate is set to $\dot{M}_{\text{high}} = 10 \times \dot{M}_{\text{KH},d}$. Once both stars are detached, $\dot{M}_{\text{CE}}$ is smoothly reduced to $\dot{M}_{\text{low}} = 10^{-8} M_{\odot} \text{ yr}^{-1}$. Specifically:

$$\dot{M}_{\text{CE}} = \begin{cases} \dot{M}_{\text{high}}, & \Delta_{\text{max}} > 0, \\ \dot{M}_{\text{low}}, & \Delta_{\text{max}} < -0.02 \\ \dot{M}_{\text{high}} \exp \left[\frac{\ln(\dot{M}_{\text{high}}/\dot{M}_{\text{low}})}{0.02} \Delta_{\text{max}} \right], & -0.02 \leq \Delta_{\text{max}} \leq 0. \end{cases} \quad (\text{C.3})$$

This prescription ensures a smooth transition between contact and detachment, and allows CE mass loss to persist until both stars are detached. Notice that the exponential form ensures that for $\Delta_{\text{max}} \rightarrow 0$ (i.e., when at least one star is about to fill its own Roche lobe), the CE mass loss rate $\dot{M}_{\text{CE}} \rightarrow \dot{M}_{\text{high}}$; vice versa, for $\Delta_{\text{max}} \rightarrow -0.02$ (i.e., both stars are detached), then $\dot{M}_{\text{CE}} \rightarrow \dot{M}_{\text{low}}$.

Additionally, we allow both binary components to lose mass. The total CE mass-loss rate $\dot{M}_{\text{CE}}$ is distributed between the donor and accretor according to their degree of Roche-lobe overfilling. For each component $j \in \{\text{d}, \text{a}\}$, we define

$$\delta_j = \frac{R_j - R_{L,j}}{\min(R_j, R_{L,j})}, \quad (\text{C.4})$$

and assign a weighting factor $f_j = \exp(\delta_j)$. The resulting mass-loss rates of the donor and accretor are then given by

$$\dot{M}_{\text{d}} = \dot{M}_{\text{CE}} \frac{f_{\text{d}}}{f_{\text{d}} + f_{\text{a}}}, \quad \dot{M}_{\text{a}} = \dot{M}_{\text{CE}} \frac{f_{\text{a}}}{f_{\text{d}} + f_{\text{a}}}, \quad (\text{C.5})$$

such that the component that more strongly overfills its Roche lobe contributes a larger fraction of the envelope mass loss. This prescription allows both stars to participate in the envelope ejection during CE evolution.

Energy formalism for the double-core CE Our double-core CE scheme includes both the donor and accretor envelopes. At the onset of CE, we compute and store the mass-coordinate-dependent internal and gravitational energies of both stars, $U(m)$ and $\Omega(m)$, corrected for recombination energies. These are later used to compute the amount of envelope binding energy E_{bind} that has been removed at each timestep t as the stars are stripped to a mass coordinate m_t .

During CE evolution, the binary orbital separation is updated using the energy formalism: for each star stripped to m_t , the envelope binding energy is given by

$$E_{\text{bind}} = \alpha_{\text{th}} U(m_t) + \Omega(m_t), \quad (\text{C.6})$$

where α_{th} is the CE thermal efficiency factor, for which we assume $\alpha_{\text{th}} = 1$, $U(m_t)$ and $\Omega(m_t)$ are the internal and gravitational energies, respectively, interpolated from the stored profiles $U(m)$ and $\Omega(m)$ at CE onset. The orbital separation at each timestep, a_t , is updated by solving the energy equation including both stellar envelopes,

$$\alpha_{\text{CE}} (E_{\text{orb},t} - E_{\text{orb},i}) = - (E_{\text{bind},\text{a}} + E_{\text{bind},\text{d}}), \quad (\text{C.7})$$

where $\alpha_{\text{CE}} = 1$ is the CE efficiency factor, $E_{\text{orb},i} = -GM_{\text{d},i}M_{\text{a},i}/(2a_i)$ is the initial orbital energy, and $E_{\text{bind},\text{a}}$ ($E_{\text{bind},\text{d}}$) is the binding energy of the accretor (donor).

C.2.3 End of CE and the merger product

The system survives the CE as a binary if both the donor and the accretor a) detach from their Roche lobes, i.e. $\Delta_{\text{a}}, \Delta_{\text{d}} < -0.02$; b) maintain their radius

such that $R < R_L$ for longer than 1% of the Kelvin-Helmholtz timescale of the donor, $t_{\text{KH,d}}$. If either condition is met, the CE phase is terminated and binary evolution resumes.

Otherwise, the CE is terminated as a merger if one of the following conditions is met:

- a) The donor is stripped to a chemically homogeneous core, defined by

$$|X_{\text{H,center}} - X_{\text{H,surface}}| < 0.01 \quad \text{and} \quad (\text{C.8})$$

$$|X_{\text{He,center}} - X_{\text{He,surface}}| < 0.01 ,$$

where X represents mass fractions of the considered element.

- b) After CE stripping, the core, at mass coordinate m_{core} , of either the donor or the accretor, would have a radius R_{core} such that it would overflow the Roche lobe:

$$R_{\text{core}} > R_L(m_{\text{core}}) . \quad (\text{C.9})$$

- c) The final orbital period, after CE, falls below 5 hours.

We build the merger product by combining the mass shells of both stars into a total mass $m_{\text{merger}} = m_1 + m_2$, with more evolved (hydrogen-poor) material placed at smaller mass coordinates. The merged star is then relaxed in composition before further evolution till He depletion.

C.3 A selection of our grids

As discussed in the main text, after $M_{1,i} \geq 10 M_{\odot}$ we stop resolving the failed-CE stripped stars produced by a first stage of case B MT, due to the region becoming closer and closer to $q_i \simeq 1$. On the other hand, case AB MT systems are still present at our resolution for $M_{1,i} = 10 M_{\odot}$, but we stop resolving them at $M_{1,i} > 18 M_{\odot}$, as shown below in Fig. C.1. We note that, in this case, the region below TAMS becomes instead populated by RLOF stripped stars.

Additionally, to support Fig. 4.3, we show in Fig. C.2 the full model grids of primary masses $M_{1,i} = 4, 8, 10 M_{\odot}$. This is only a selection of the full set of computed grids; the remaining figures will be available at the time of publication on the dedicated [Zenodo](#) entry for this work.

Interestingly, we note that we predict only a small subset of our models to survive the CE episode as a binary, at least until core-He depletion (at which we terminate our simulations). We do not study these further in this work.

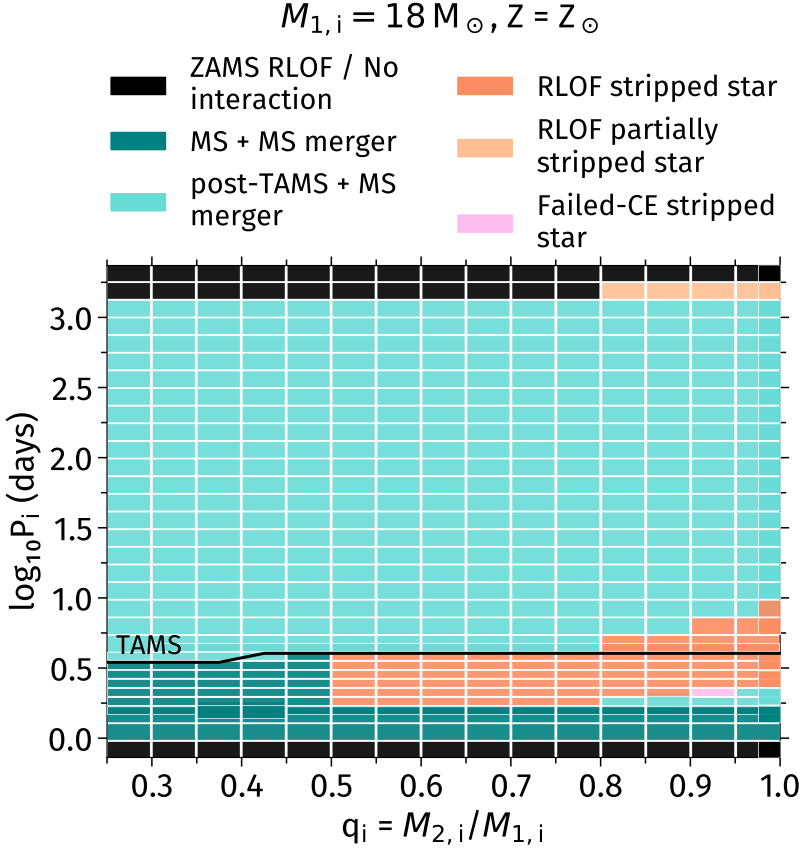


Figure C.1: Grid of the primary mass $M_{1,i} = 18 M_{\odot}$, with the same color coding and conventions of Fig. 4.2. At our resolution, we stop resolving the failed-CE parameter space for $M_{1,i} > 18 M_{\odot}$.

Notably, none of the systems that initiate a post-TAMS inverse MT survives the CE episode; they all evolve into failed-CE stripped stars.

C.4 Who is the fastest? The shape of the failed-CE parameter space

As discussed in the main text, the failed-CE stripped star outcome from an initial case B MT episode is limited from above at initial orbital periods that depend on the initial mass ratio. This gives rise to the "triangular" shape above TAMS that we see in Fig. 4.2, and shapes the parameter space of failed-CE mergers at different masses as shown in Fig. 4.3.

In Fig. C.3, we illustrate such a behavior in terms of the masses of the binary components after the first stable MT episode. At a fixed initial mass ratio, longer initial periods result in partial envelope stripping of the primary after the first MT episode, thereby producing more massive RLOF stripped stars that will evolve on a faster timescale. This effect is acting against the failed-CE stripped star outcome, as the secondary has less time to initiate the CE before the stripped primary depletes He in its core. However, for initial mass ratios sufficiently close to unity, the secondary star at detachment can be heavy enough to *be the fastest*, but this will depend on how much mass is actually transferred from the primary (we refer to this as effect 1) in the main text), and on its mass-luminosity relationship, which dictates how much faster a star effectively evolves after accreting mass (effect 2) in the main text).

C.5 Full evolutionary tracks of Figure 4

To support Fig. 4.4, we show in Fig. C.4 the evolutionary tracks of the failed-CE stripped stars with their progenitor binaries.

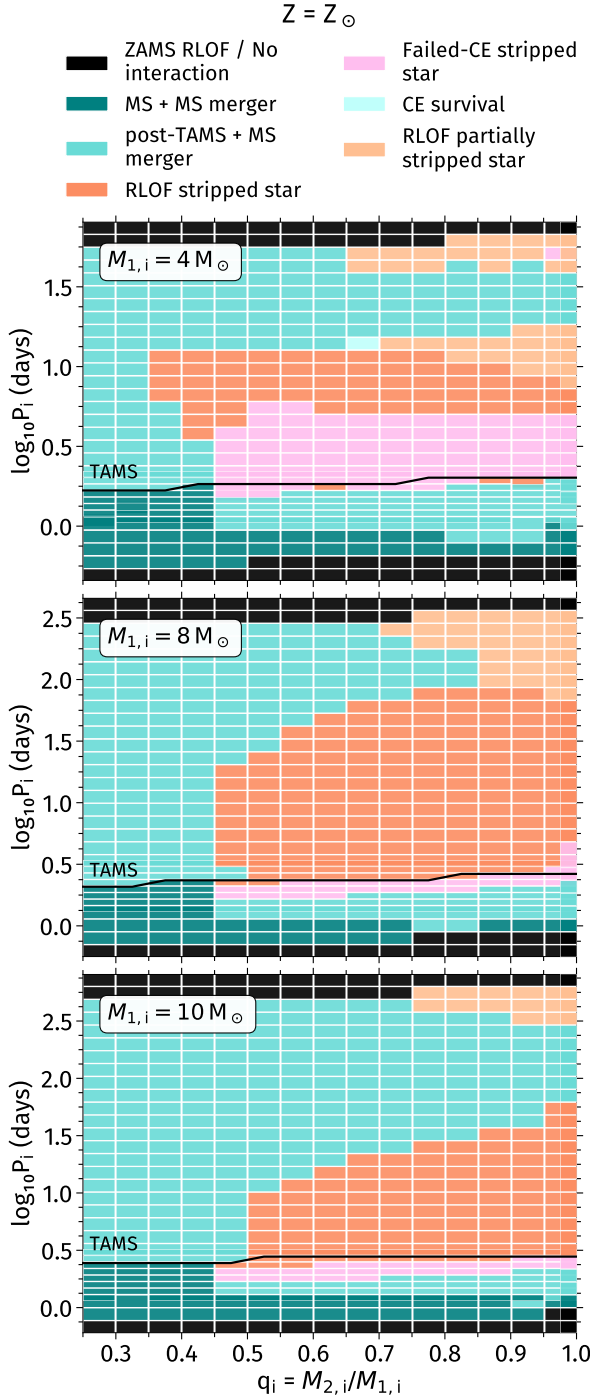


Figure C.2: Grids for primary masses $M_{1,i} = 4, 8, 10 M_{\odot}$ considered in Fig. 4.3, with the same conventions of Fig. 4.2. With respect to Fig. 4.2, one additional possible outcome is shown here: CE survival, i.e. systems surviving as binaries after CE. This happens for a small subset of our models and we do not study it further.

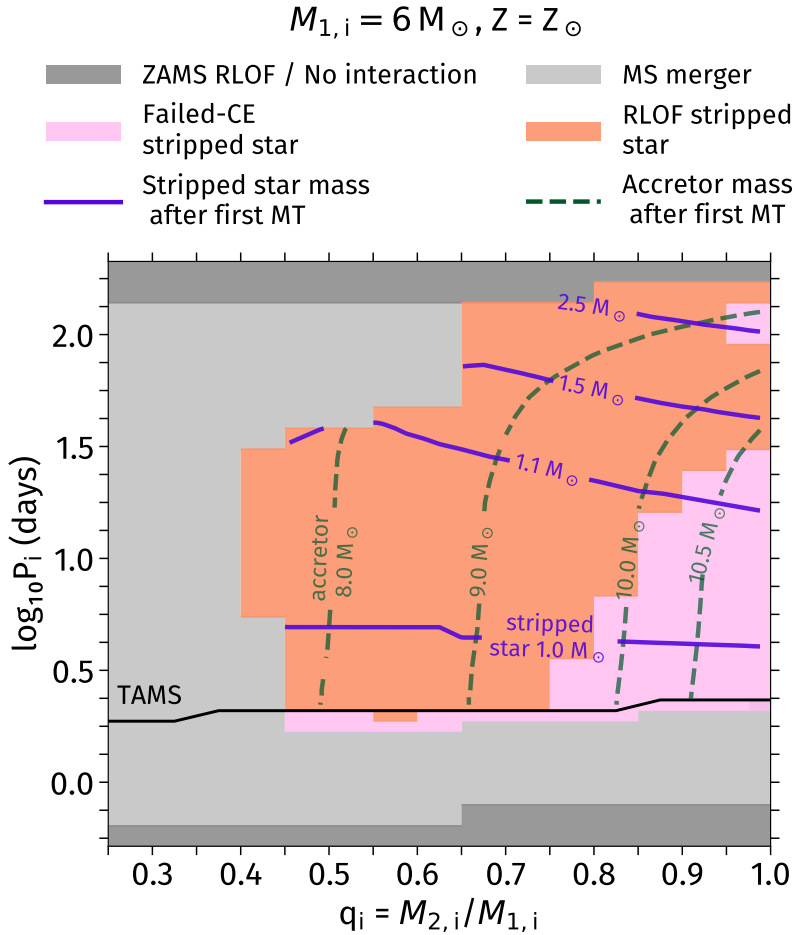


Figure C.3: Same model grid as Fig. 4.2, but with a different color coding to better highlight the RLOF and Failed-CE stripped stars outcomes. We refer to any merger happening with at least one MS star as MS merger (collectively describing both the post-TAMS + MS and MS + MS merger outcomes). Iso-contours of fixed accretor (stripped star) mass after the first stable MT episode are shown in dashed green (solid violet) lines.

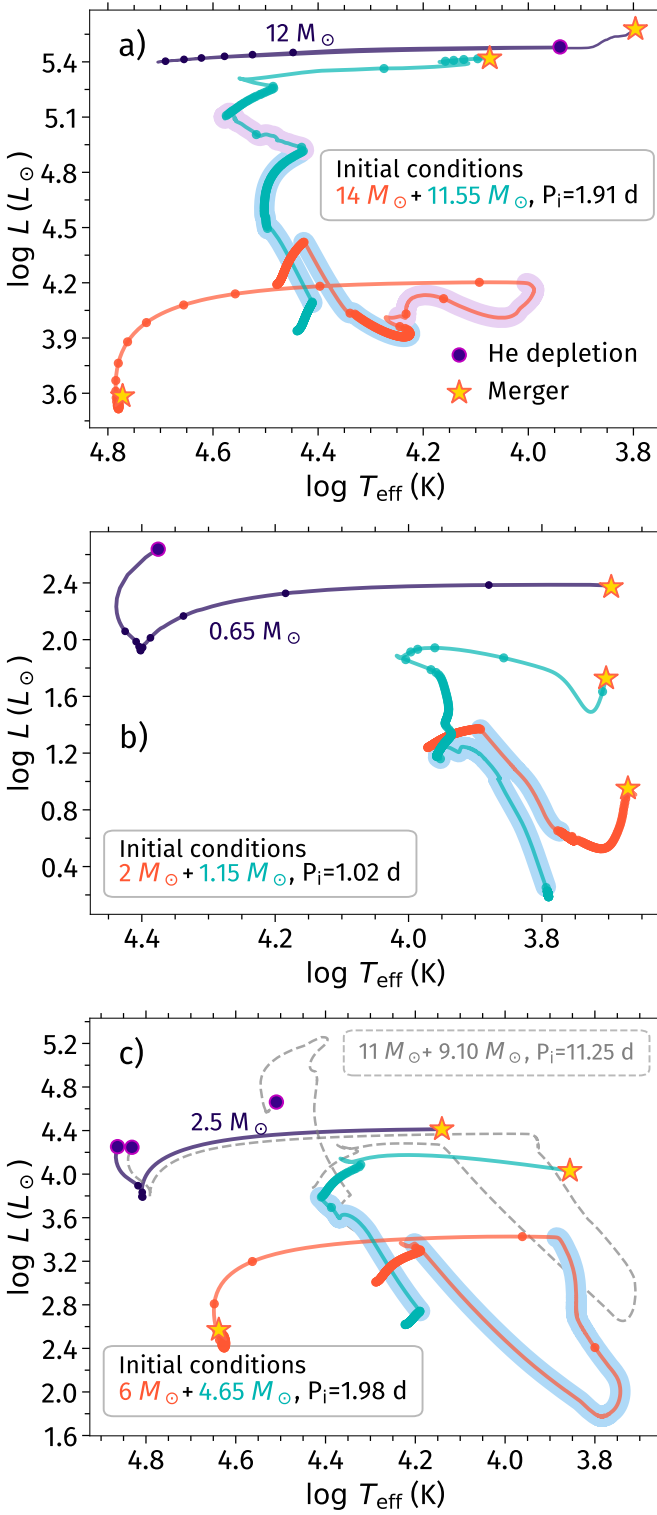


Figure C.4: a) HR diagram of a $12 M_{\odot}$ failed-CE stripped star model (purple line), up to He depletion (purple marker). This is the product of a binary with $14 M_{\odot}$ and $11.55 M_{\odot}$ and initial orbital period $P_i = 1.91$ days. We show the evolution of the progenitor primary (secondary) in orange (cyan), up to the failed-CE merger onset (star marker). Scatter points along the tracks are spaced by 0.05 Myrs, and MT episodes (case A and AB) are highlighted as colored areas;

b) Failed-CE stripped star of mass $0.65 M_{\odot}$, produced by a binary of $2 M_{\odot}$ and $1.15 M_{\odot}$ and initial orbital period $P_i = 1.02$ days. Scatter points along the tracks are every 5 Myrs;

c) Failed-CE stripped star of mass $2.5 M_{\odot}$, formed by a binary of $6 M_{\odot}$ and $4.65 M_{\odot}$ and initial orbital period $P_i = 1.98$ days. Scatter points along the tracks are every 0.5 Myrs. We add the evolution (dashed gray) of a binary with an $11 M_{\odot}$ primary that evolves into a $2.5 M_{\odot}$ RLOF stripped star, when in orbit with a $9.10 M_{\odot}$ secondary at $P_i = 11.25$ days.

C.6 Parameter variations

Our results assume a fixed fiducial threshold for CE at $\dot{M}_{\text{high}} = 10 \times \dot{M}_{\text{KH,d}}$, and then adapts the MT rate based on the recipe described in Eq. C.3. We performed a test (see Fig. C.5), relaxing the CE threshold within one order of magnitude and found that the remaining hydrogen envelope may vary by 10%, which is not negligible. While this does not affect our conclusions, we note that it will pose a significant effect in population predictions.

Our results are computed at solar metallicity. However, the observed sample of Götberg et al. (2023) is drawn from the Magellanic Clouds, and metallicity is expected to affect both the predicted fraction of stripped stars (Hovis-Afflerbach et al. 2025) and the parameter space for (un)stable reverse MT (e.g. Pauli 2024; Briel et al. 2025). Lower metallicity modifies the expansion history of the binary components, shifting the failed-CE stripped star parameter space toward shorter initial periods. We verify this expectation using one grid at $Z = Z_{\odot}/5$, which posed 24% reduction of the failed-CE mergers parameter space with respect to $Z = Z_{\odot}$. The results of this experiment are presented in Fig. C.6, where the failed-CE parameter space at $Z_{\odot}/5$ is compared to the fiducial case at galactic metallicity; for completeness, we also show in Fig. C.7 (top panel) the full models grid. We defer a systematic exploration of metallicity to future work. Convective overshooting is also expected to affect stellar expansion. In Fig. C.6 and Fig. C.7 (middle panel) we show the results from a test with enhanced overshooting, extending the α_{ov} parameter to 0.3 pressure scale heights compared to the fiducial value 0.1. We find that stronger overshooting accelerates the

primary evolution and suppresses the failed-CE stripped star parameter space by 64%, especially at longer periods. Although we performed only one test, we can see that a higher overshooting parameter acts to produce a parameter space that mimicks that of a higher initial primary mass, in which the preference for $q_i \simeq 1$ becomes stronger due to the effects described in the main text.

Finally, the efficiency of MT will have an impact on our results, as lower accretion efficiency would limit the rejuvenation of the secondary and the growth of its Roche lobe. Our fiducial models assume fully conservative MT, motivated by recent evidence that conservative MT is the most likely formation channel for sdO + Be binaries (Lechien et al. 2025). We have carried on an experiment with an example grid computed with 50% MT efficiency, which shows that longer-period systems are suppressed due to less mass being accreted from the secondary, with an overall suppression of the failed-CE stripped star parameter space of 50%. These results are showcased in Fig. C.6 and Fig. C.7 (bottom panel). Additionally, our models do not include rotation, which may further affect MT efficiency and the stability of inverse MT onto the stripped primary (Briel et al. 2025).

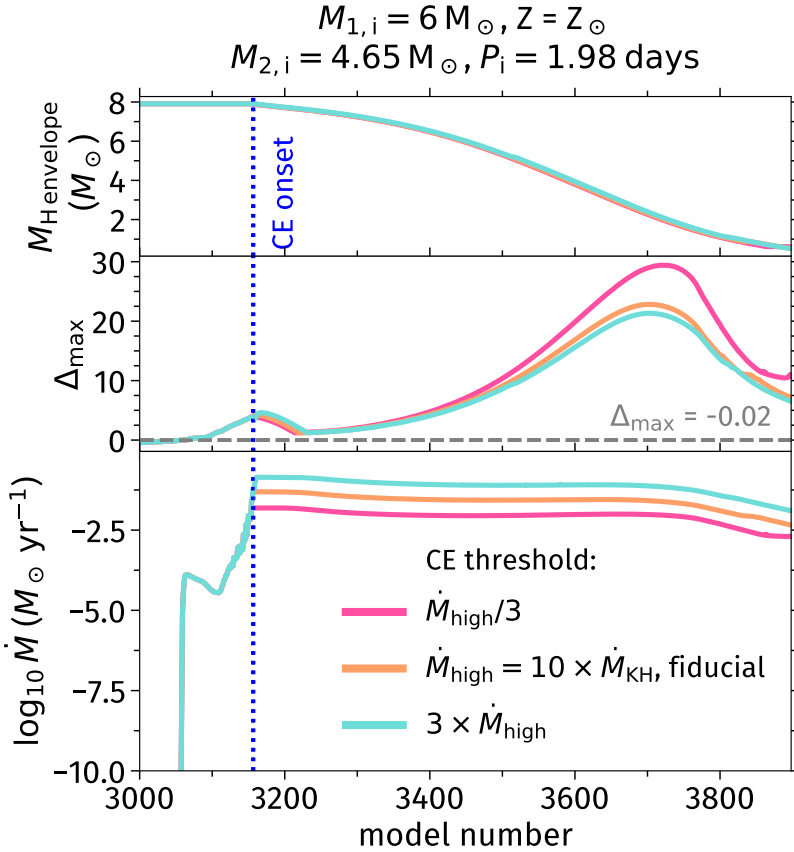


Figure C.5: Example of MT history during the failed CE episode for our system with initial masses $6 M_{\odot}$ and $4.65 M_{\odot}$ at initial orbital period $P_i = 1.98$ days (the same represented in panel c) of Fig. C.4, and in Fig. 4.4 as progenitor of the $2.5 M_{\odot}$ merger). As described in Appendix C.2, we switch on our double-core CE scheme when different CE thresholds are reached for the first time; after this, we adopt the recipe of Eq. C.3 based on $\Delta_{\max}$.

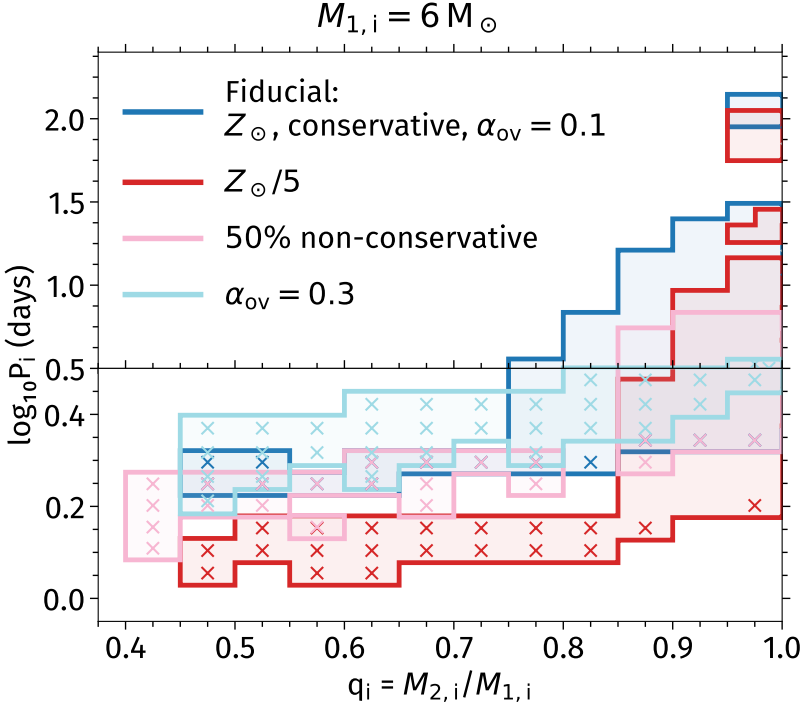


Figure C.6: Parameter space in initial period P_i and mass ratio q_i for failed-CE stripped stars for an initial primary mass $M_{1,i} = 6 M_{\odot}$. Different colors show the variations with respect to our fiducial model with solar metallicity, fully conservative MT, and convective overshooting parameter $\alpha_{ov} = 0.1$. As in Fig. 4.3, systems undergoing case A MT in the first interaction are indicated with x scatter points.

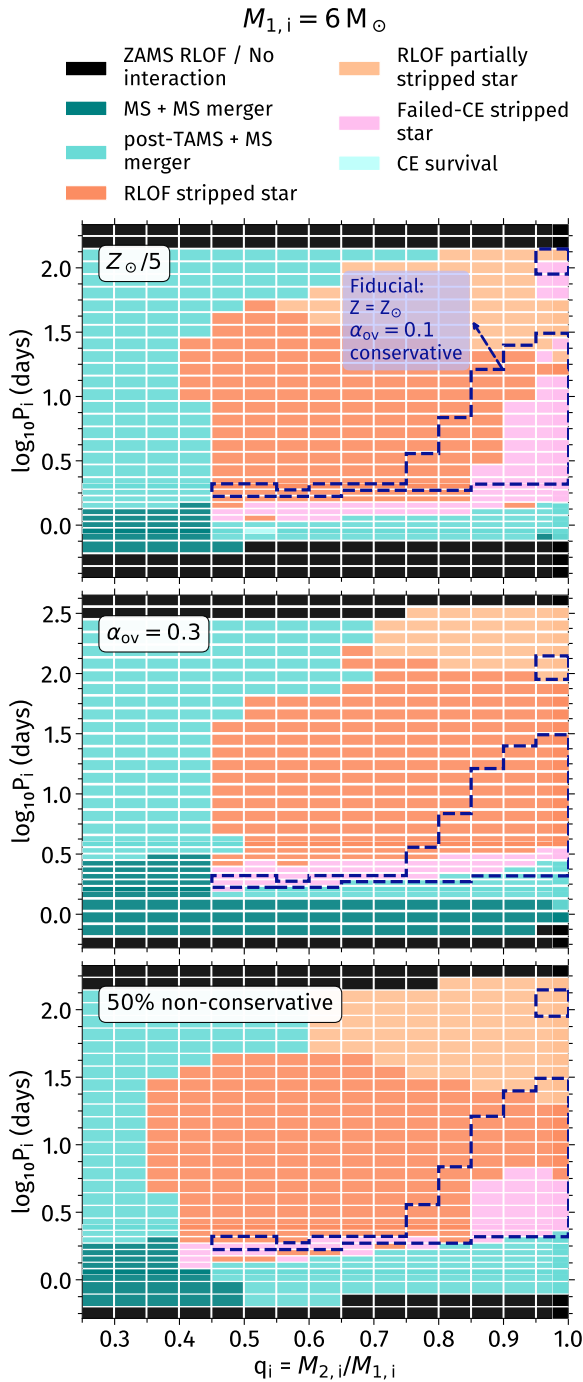


Figure C.7: Model grids of initial primary mass $M_{1,i} = 6 M_{\odot}$ considered in Fig. C.6, with the same color coding and conventions of Fig. 4.2 and Fig. C.2. The three panels show the three parameter variations we have explored, and we overplot the failed-CE stripped star parameter space of the fiducial model grid (that of Fig. 4.2) as an indigo-dashed region.

Appendix D

Appendix to Chapter 5

D.1 Additional grids: bisection search for the stability boundary

In this section we show additional figures related to the bisection search for the stability and GW merger boundaries discussed in Sect. (5.2). This is the complete set of grids for different initial masses of the donor $m_{d,i}$, at fixed metallicity Z and overshooting parameter α_{ov} , in Fig. (D.1) and following. As discussed in Sect. (5.2), each grid is designed to increase the resolution when the donors start to develop a convective envelope, which corresponds to a period above which our grids become finer. This point is different for every grid, but for the sake of clarity we keep the same axis limits at each row of the figures, to allow for a direct comparison. Therefore, the Figures might show some artificial distortion or empty spaces. Additionally, the grid at $m_{d,i} = 80M_{\odot}$, $\alpha_{ov} = 0.30$ and $Z = Z_{\odot}/10$ was not computed due to convergence issues.

D.2 The stability boundary dependence on $m_{d,i}$, α_{ov} and Z

In this section we show additional figures related to the stability boundary as discussed in Sect. (5.3). These represent a subset of the full set of figures, which will be made available in the supplementary material ([Zenodo](#)). In particular, we show the dependence of the stability boundary on:

- a) the initial masses of the donor in Fig. (D.10): in presence of radiative envelopes (of interest for the stable MT GW mergers on which we focus

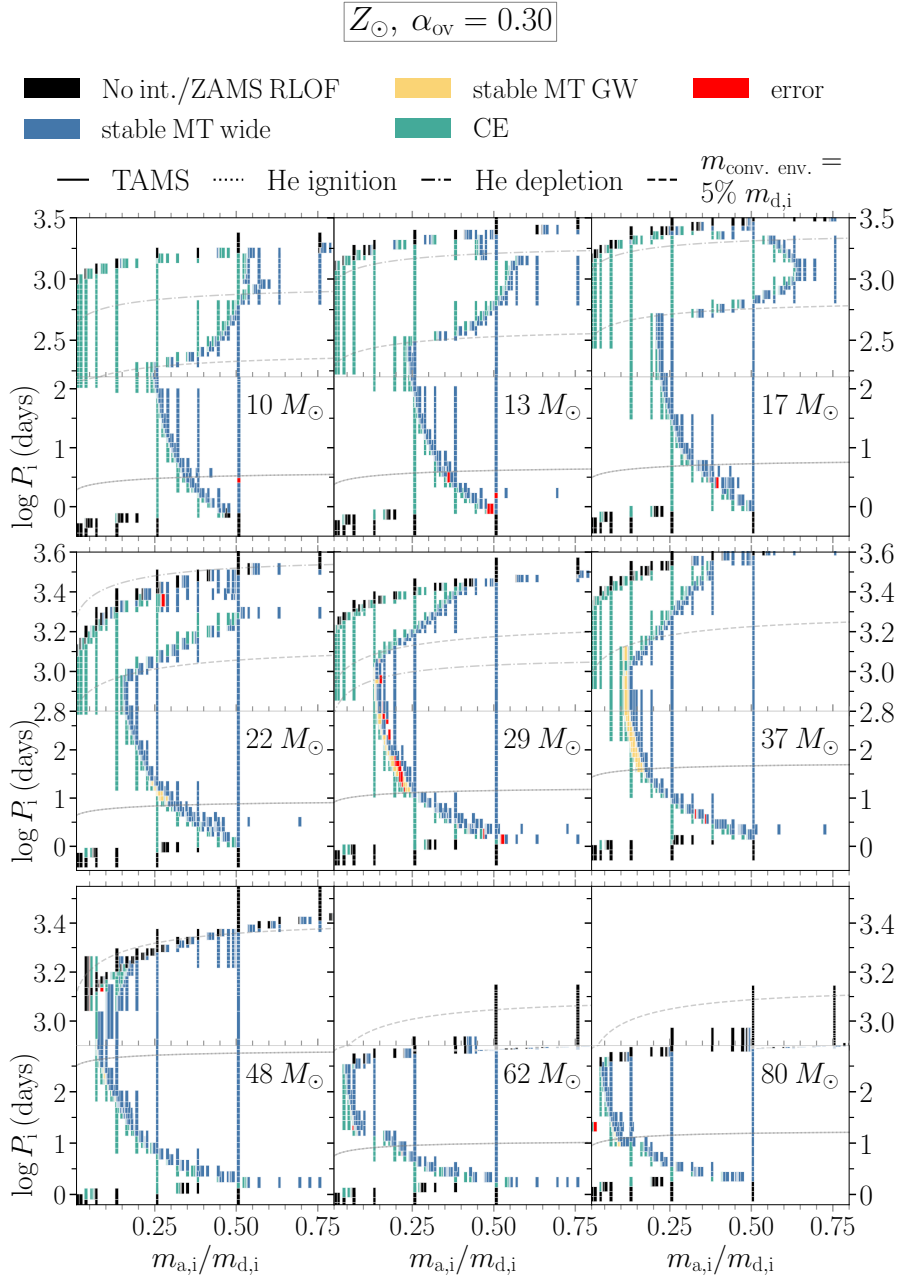
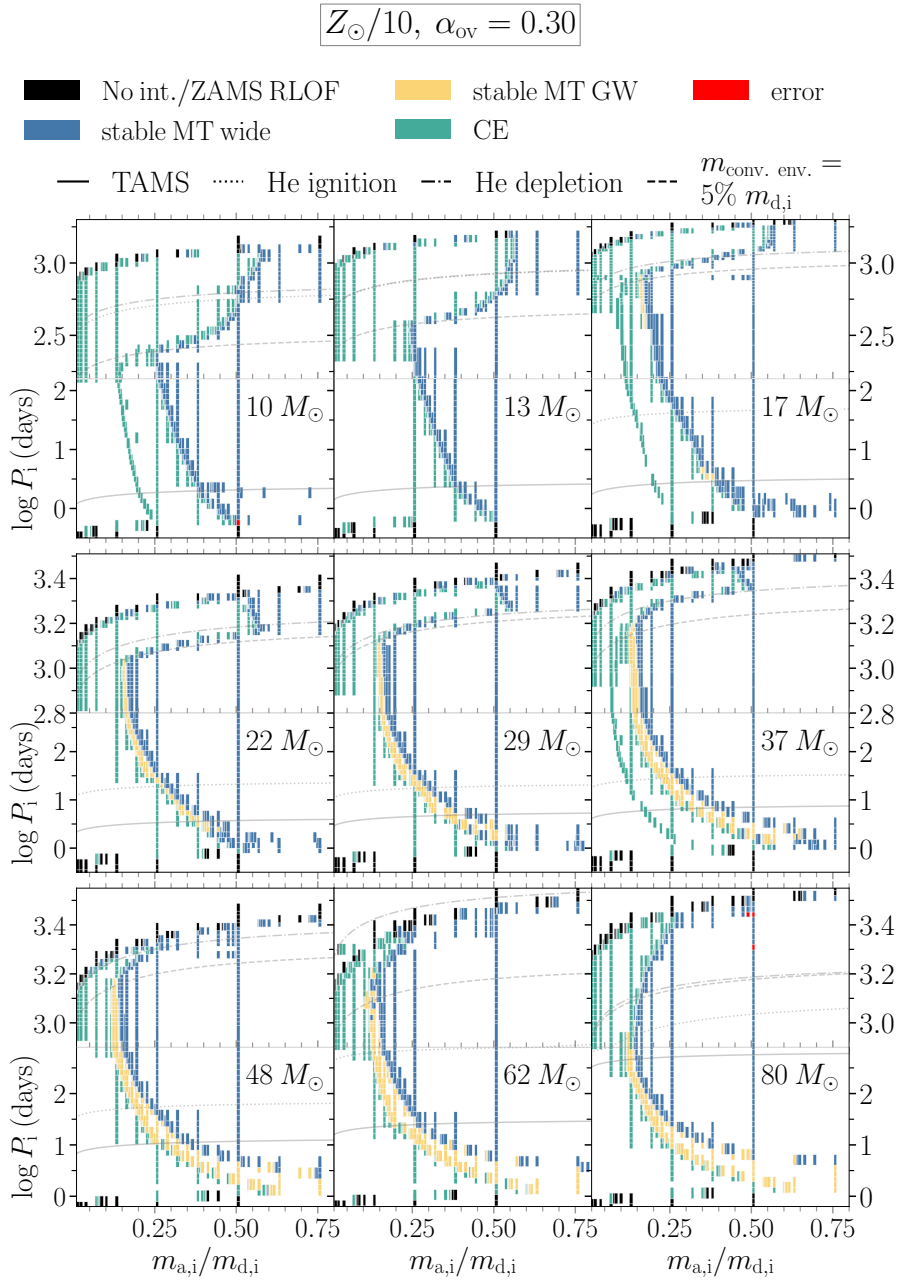


Figure D.1: Simulation grids showcasing the bisection search for the stability and GW merger boundaries, for different initial masses of the donor $m_{\text{d,i}}$, at fixed metallicity $Z = Z_{\odot}$ and overshooting parameter $\alpha_{\text{ov}} = 0.31$. The same convention on evolutionary stages as in Fig. (5.1) is used.

Figure D.2: Same as Fig. (D.1), for $Z = Z_{\odot}/10$ and $\alpha_{OV} = 0.30$.

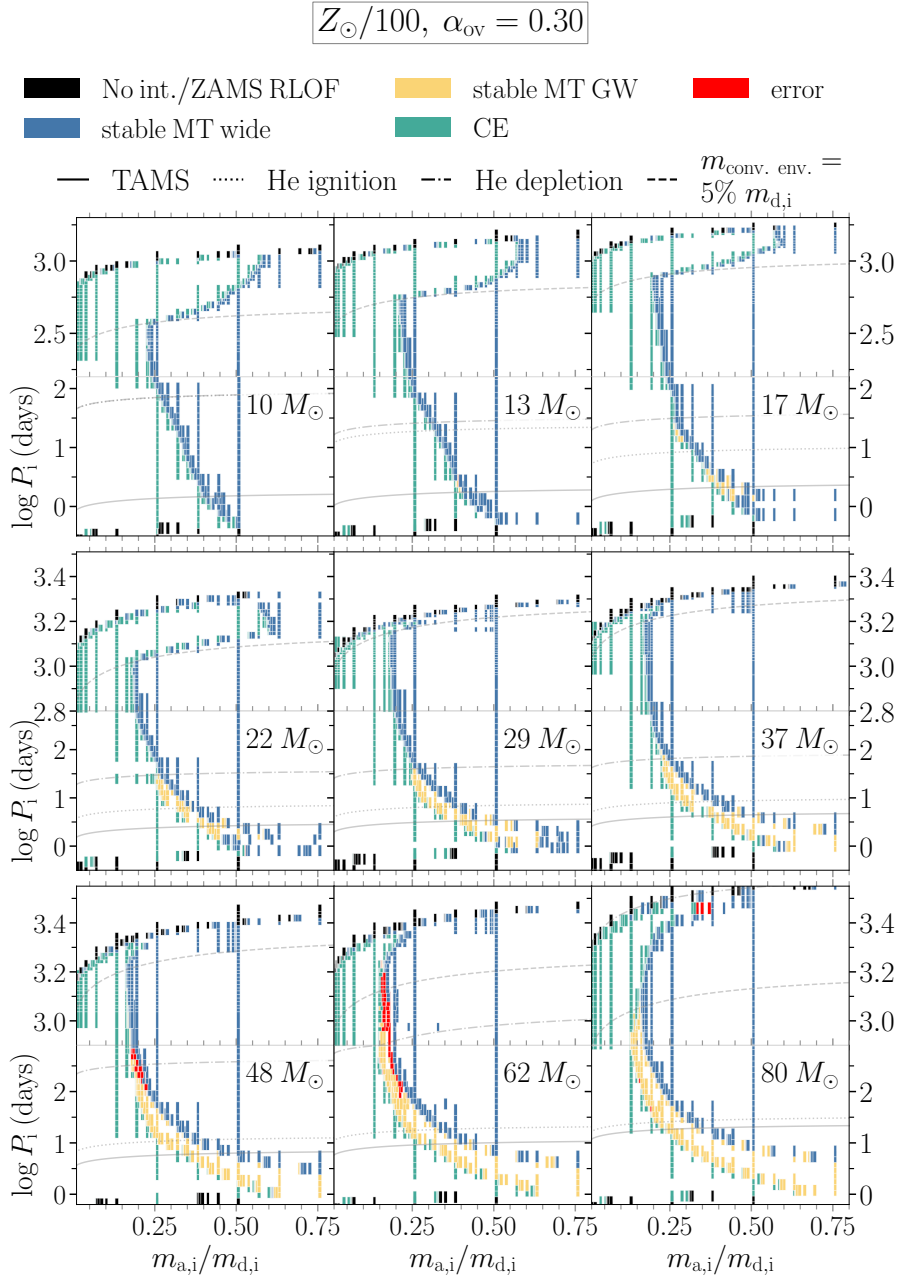
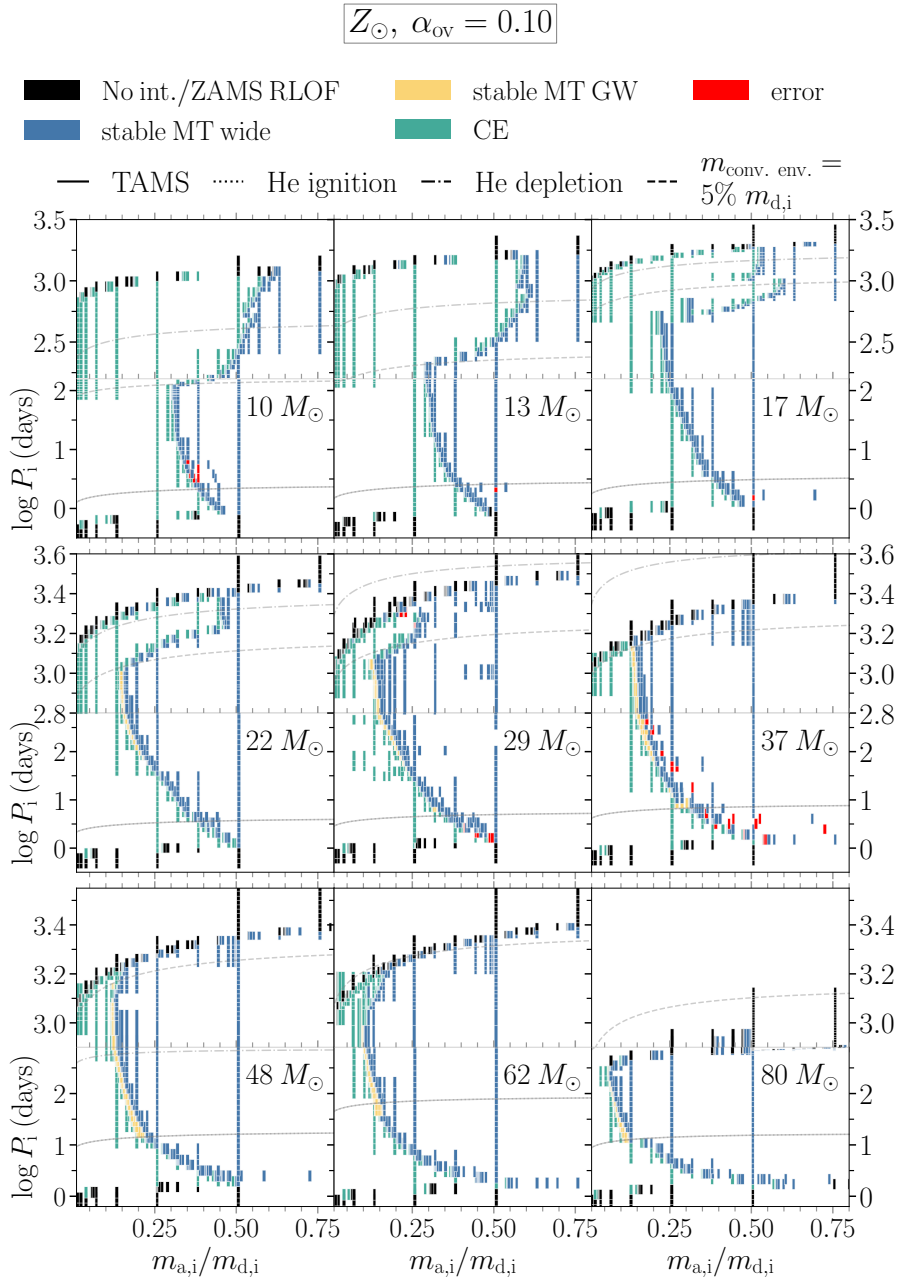


Figure D.3: Same as Fig. (D.1), for $Z = Z_{\odot}/100$ and $\alpha_{\text{ov}} = 0.30$.

Figure D.4: Same as Fig. (D.1), for $Z = Z_{\odot}$ and $\alpha_{ov} = 0.10$.

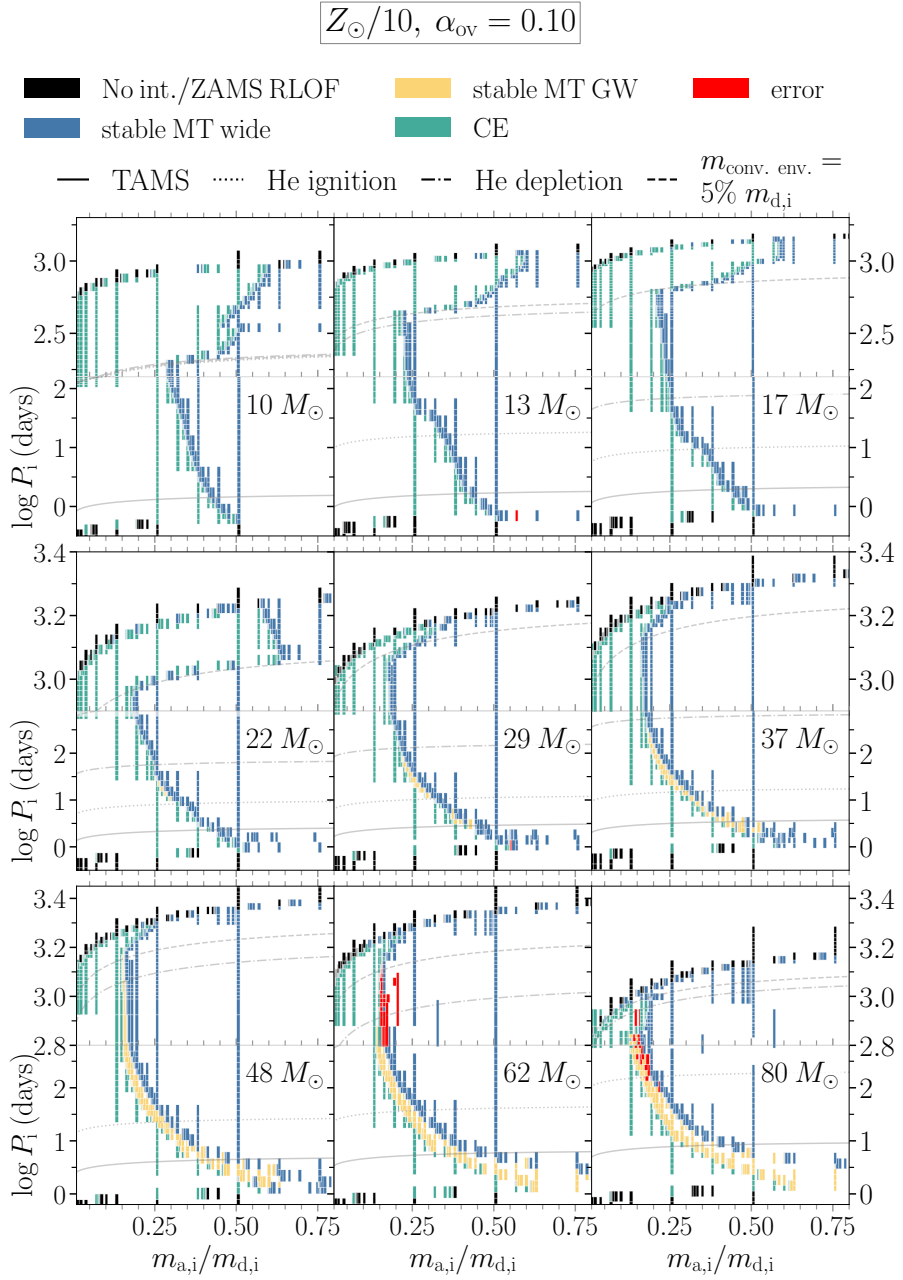
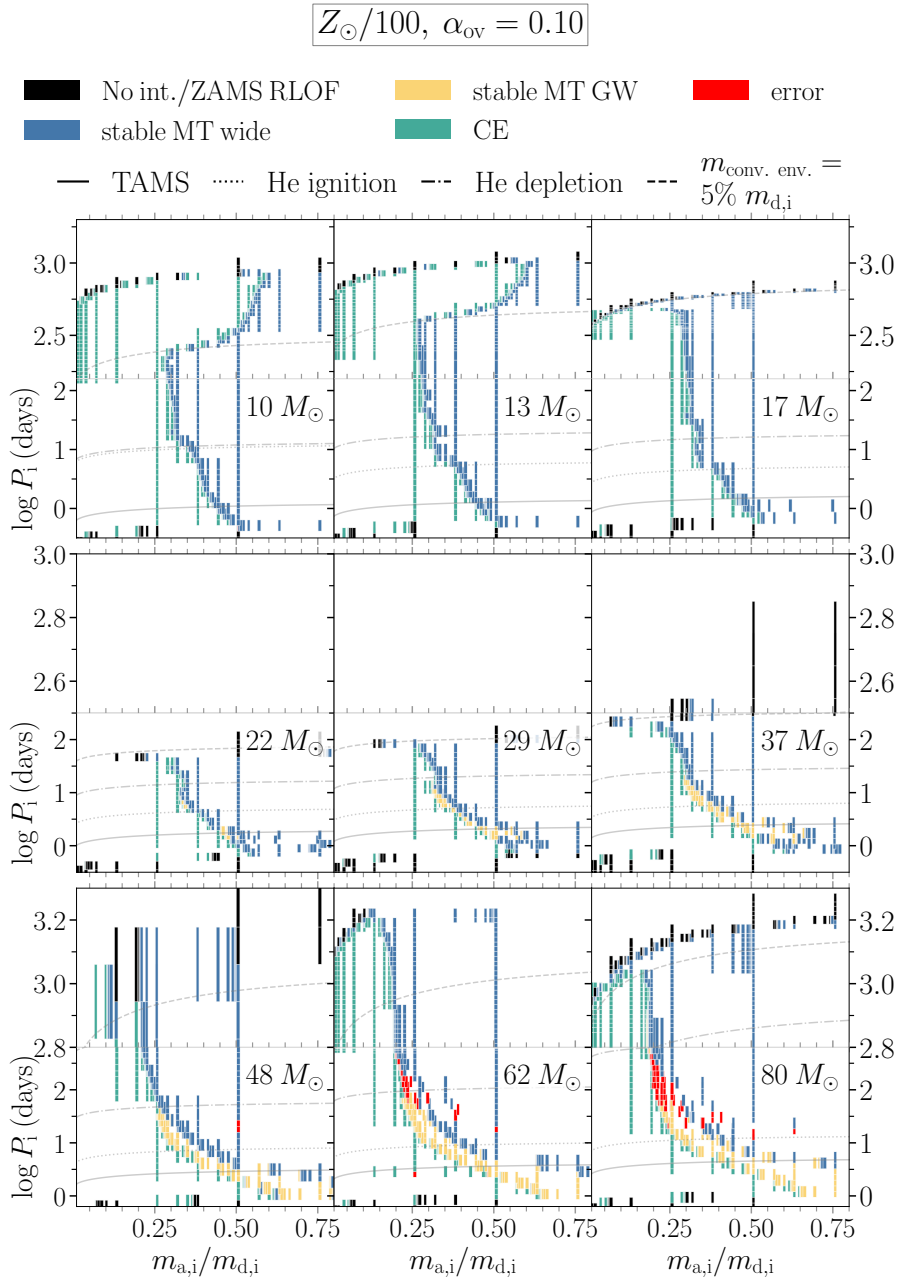


Figure D.5: Same as Fig. (D.1), for $Z = Z_{\odot}/10$ and $\alpha_{\text{ov}} = 0.10$.

Figure D.6: Same as Fig. (D.1), for $Z = Z_{\odot}/100$ and $\alpha_{ov} = 0.10$.

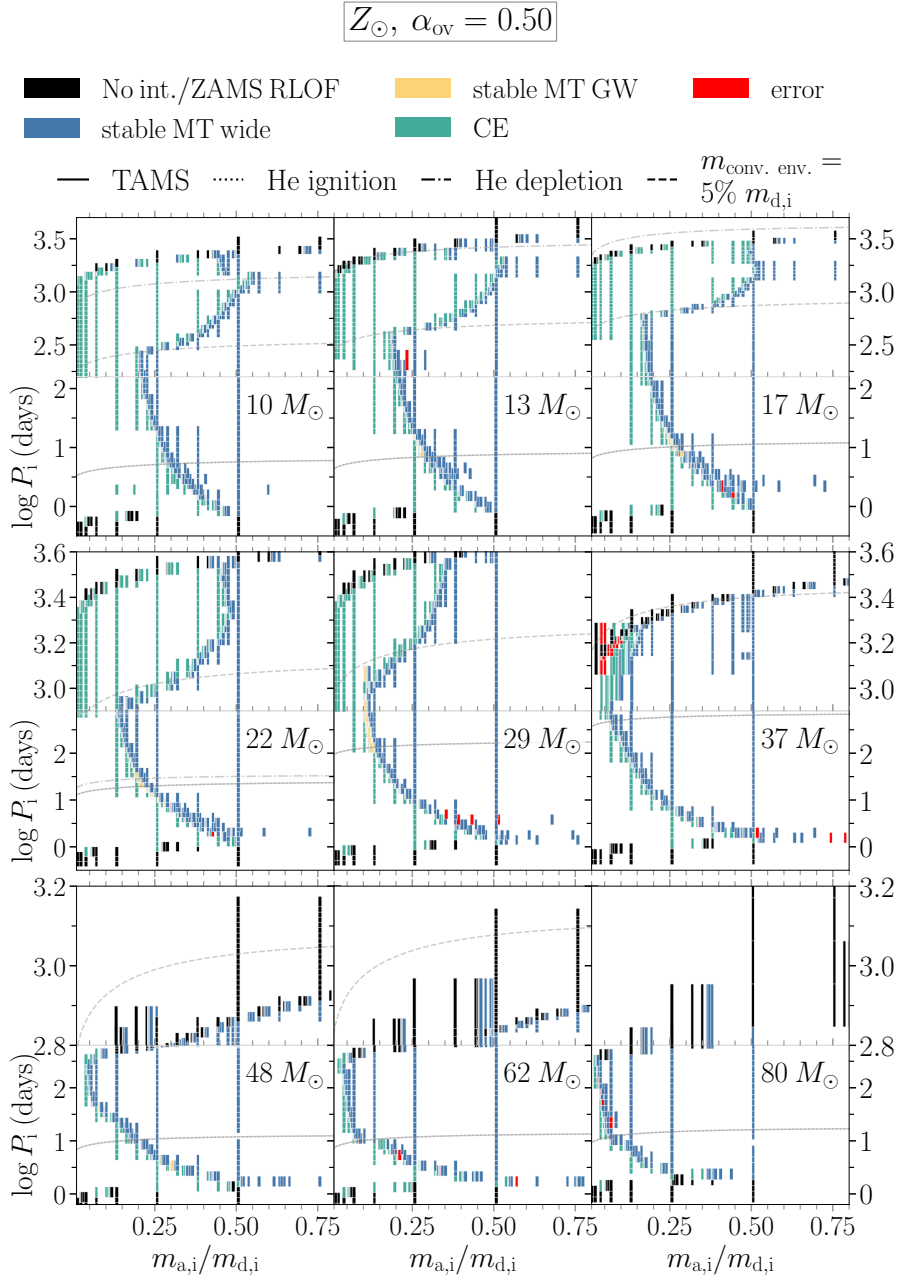
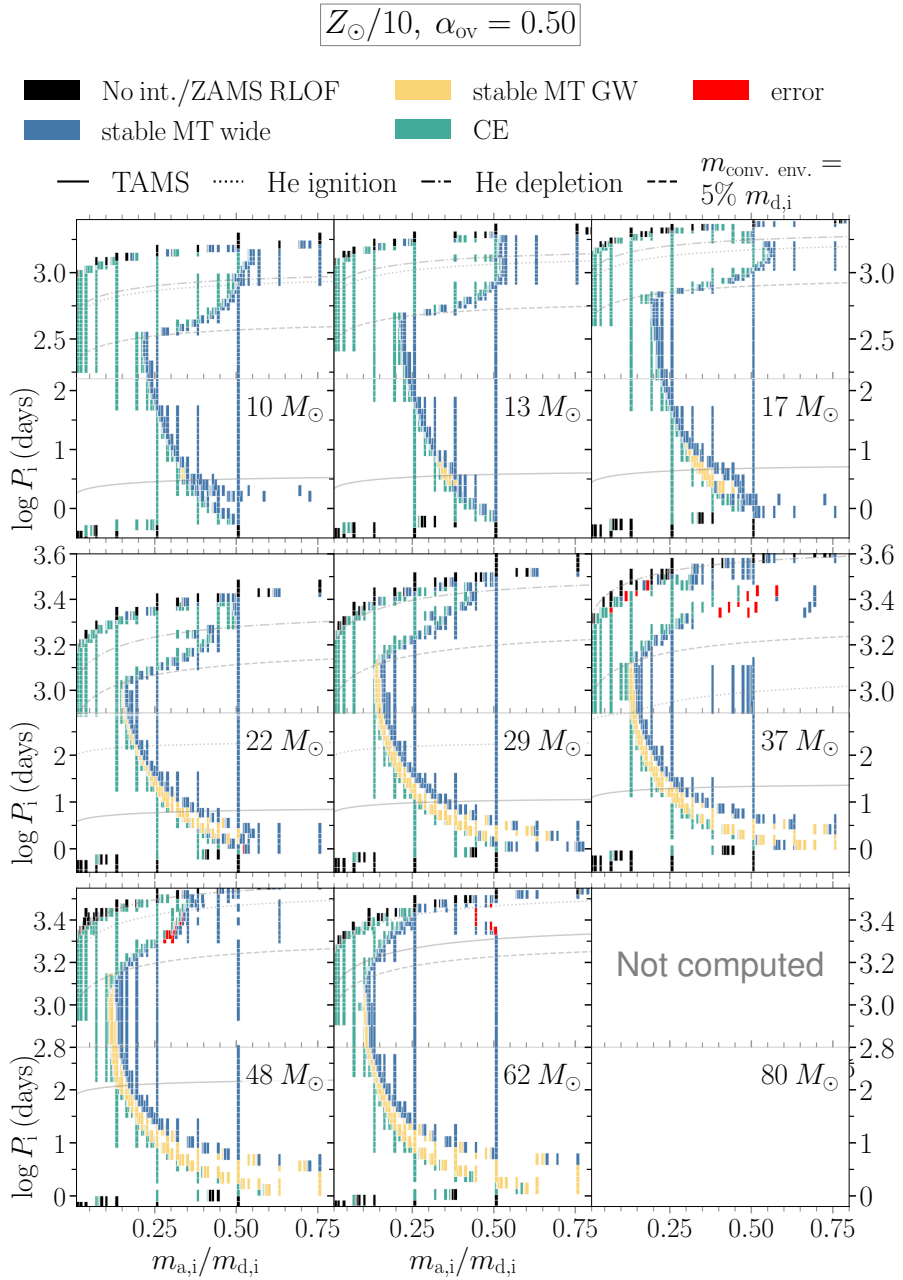


Figure D.7: Same as Fig. (D.1), for $Z = Z_{\odot}$ and $\alpha_{\text{ov}} = 0.50$.

Figure D.8: Same as Fig. (D.1), for $Z = Z_{\odot}/10$ and $\alpha_{OV} = 0.50$.

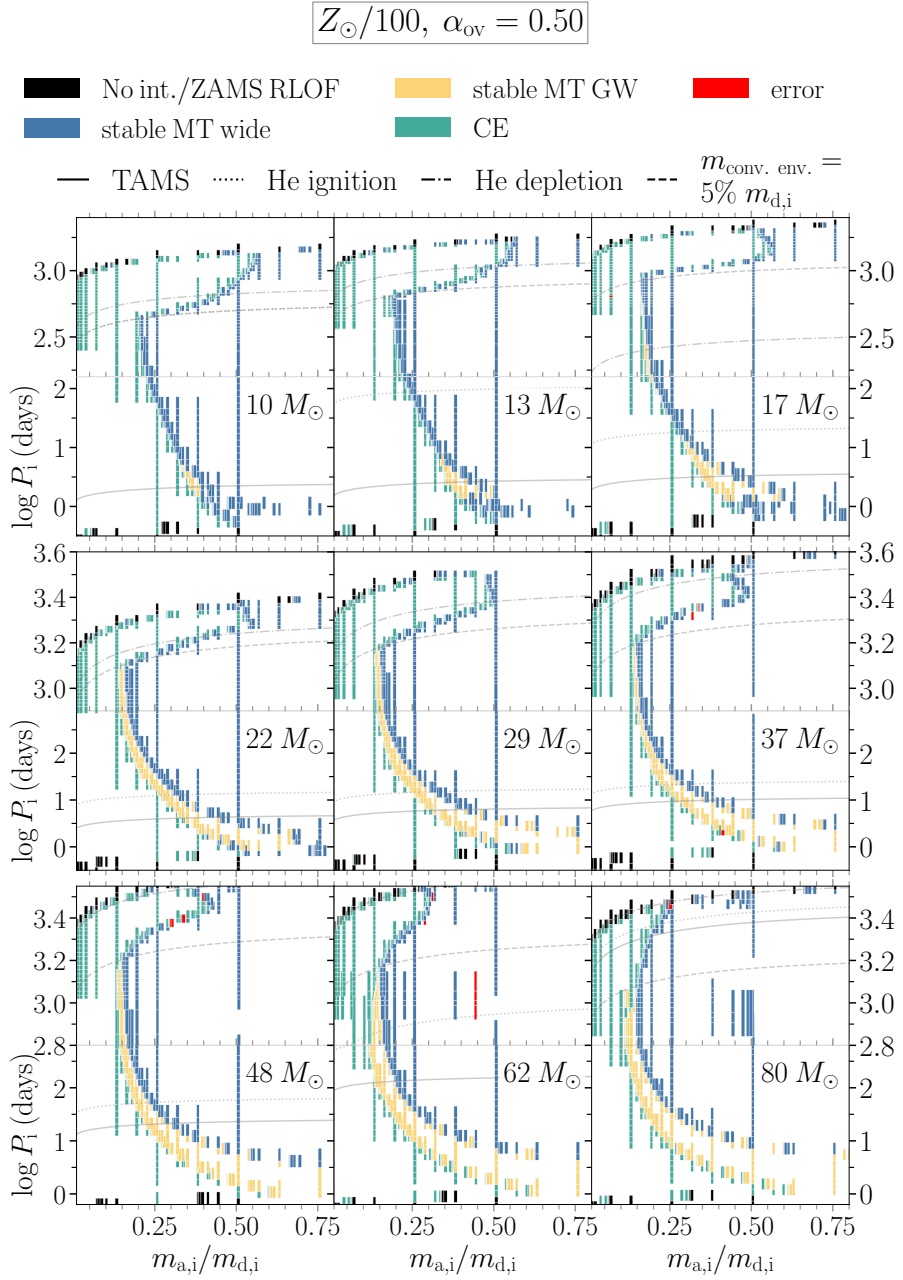


Figure D.9: Same as Fig. (D.1), for $Z = Z_{\odot}/100$ and $\alpha_{\text{ov}} = 0.50$.

in this work, see main text), more massive donors are more (less) stable in occurrence of case B (A) MT;

- b) the overshooting parameter α_{ov} in Fig. (D.11): stronger convective overshooting favors stability in radiative envelopes, as discussed in Sect. (5.3.1);
- c) the metallicity Z in Fig. (D.12): in presence of radiative envelopes, metal rich (poor) donors are more (less) stable in occurrence of case A and B MT, as discussed in Sect. (5.3.2) (and in agreement with Ge et al. 2023, 2024).

D.3 The stable MT mergers parameter window: dependence on α_{ov} and Z

In this section we show additional figures related to the stable MT mergers parameter window discussed in Sect. (5.3). In particular, we want to enable a direct comparison of the parameter window at different α_{ov} and Z , for different initial masses of the donor $m_{\text{d,i}}$. We show the results in Fig. (D.13) and Fig. (D.14). We see that 1) a higher overshooting leads to a stretch of the parameter window, enabling more unequal-mass progenitors to form GW sources; 2) a lower metallicity allows more massive progenitors to reside in tighter initial orbits, thereby stretching the parameter window towards more-equal initial mass ratios at lower initial periods.

D.4 Delayed dynamical instability

In this section we show additional figures related to the delayed dynamical instability (DDI) discussed in Sect. (5.3.3). In particular, we show:

- a) the dependence of the DDI on the initial masses of the donor in Fig. (D.15);
- b) the dependence of the DDI on the overshooting parameter α_{ov} and metallicity Z in Fig. (D.16);

DDI is robust, for donors with radiative envelopes, across different masses, metallicities and overshooting parameters. For donors with convective envelopes, we find prompt CE evolution, and little to no DDI (with a dependence on the initial mass ratio). At the instability boundary, DDI is the strongest, showing extreme values of 45% - 50% of mass lost before CE onset for case A MT. Core-helium burning donors also show enhanced DDI, in agreement with the physics discussion in Klencki et al. 2026.

D.5 The GW mergers final mass ratios

We add similar figures to Fig. (5.8) in Sect. (5.3.4) for the final mass ratios of the GW mergers formed through stable MT, as discussed in Sect. (5.3). In particular, we highlight that these final mass ratios:

- a) vary with different overshooting parameters α_{ov} and metallicities Z , as shown in Fig. (D.17). In particular, the combination of a higher overshooting parameter and a lower metallicity leads to the most extreme (departing from unity) final mass ratios;
- b) are more extreme at higher initial masses of the donor, when α_{ov} and Z are fixed, as shown in Fig. (D.18).

D.6 The ζ -method for critical mass ratios

In Sect. (5.4.1) we discuss the ζ -method to compute critical mass ratios under different assumptions on the MT mode. In particular, we showed in Fig. (5.10) the stability boundaries from our time-dependent models for fully conservative and fully non-conservative MT (under the isotropic re-emission assumption), as compared to the analytical stability boundary derived from the ζ -method as done in population synthesis frameworks, i.e. as a direct translation from a fixed adiabatic mass-radius exponent, ζ_{ad} , computed for conservative MT.

In this Appendix we show the analytical curves (e.g. [Soberman et al. 1997](#); [Picco et al. 2024](#)) of the Roche lobe mass-radius exponents for fully conservative and fully non-conservative MT, $\zeta_{\text{RL}}^{\text{CONS}}$ and $\zeta_{\text{RL}}^{\text{ISO}}$, in Fig. (D.19). The response of the Roche-lobe radius to conservative MT is steeper than the response to non-conservative MT, at any mass ratio q (with more extreme differences at lower q , as seen also in Fig. (5.10) when compared the dashed blue with the solid gold curve). Therefore, when fixing an adiabatic ζ_{ad} and applying the ζ -method to determine critical mass ratios, q_{crit} , under different MT modes, one is effectively always shifting from the higher critical mass ratio of the conservative case to a lower critical mass ratio in the non-conservative case. As a consequence, the ζ -method determines that conservative MT should be always less stable than non-conservative MT, which is opposite to what our time-dependent models find (see Sect. (5.4.1) and Fig. (5.10)).

Fig. (D.19) also shows that the analytical curves for $\zeta_{\text{RL}}^{\text{CONS}}$ and $\zeta_{\text{RL}}^{\text{ISO}}$ become closer and closer as q decreases. As decreasing values of q_{crit} are approached at later evolutionary stages, the ζ -method predicts that the difference between the critical mass ratios in the conservative and non-conservative case becomes negligible for radiative donors approaching the base of the giant branch, and this was pointed out by [Ge et al. 2015](#) as an argument to use the conservative

ζ_{ad} to calculate q_{crit} under any MT mode assumption. However, this is in contrast with our time-dependent models that show a significant difference between the two cases at *all* evolutionary stages (Fig. (5.10)). Fig. (D.19) shows this inconsistency by showing example values of q_{crit} in the isotropic re-emission mode as calculated with the ζ -method, compared to those calculated with time-dependent models, at different evolutionary stages. The mapping is much less trivial than a simple vertical shift between the two curves, and critical mass ratios in the non-conservative case may be lower or higher than those in the conservative case, depending on the evolutionary stage.

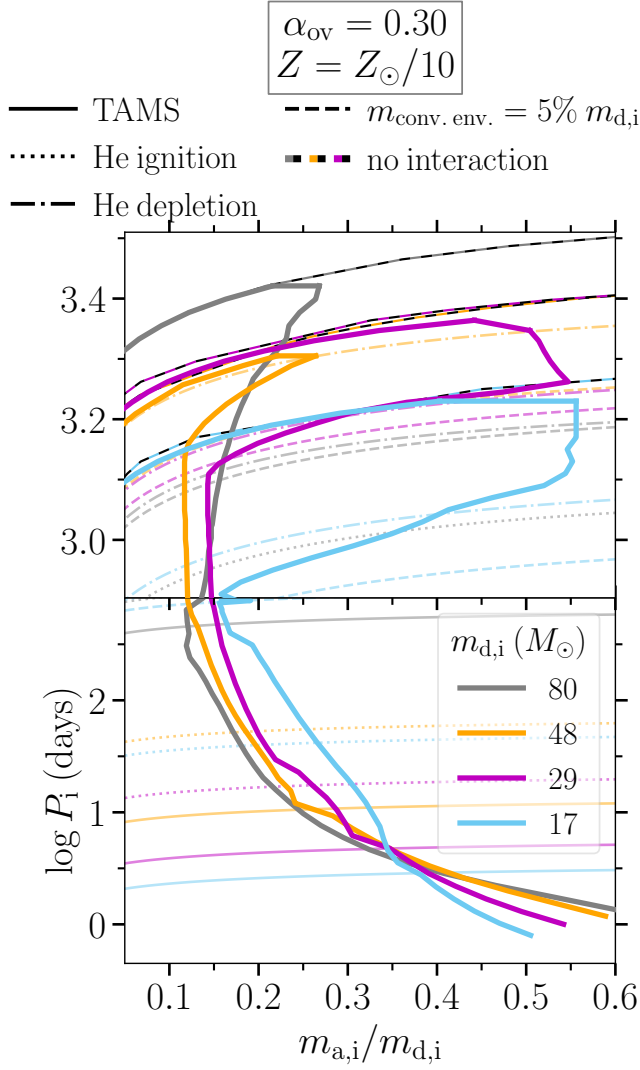


Figure D.10: Stability boundaries dependence on $m_{\text{d,i}}$ (color-coded), for fixed $\alpha_{\text{ov}} = 0.3$ and $Z = Z_{\odot}/10$. To the left of the curves, we expect CE evolution, while to the right of the curves we expect stable MT. The same convention on evolutionary stages as in Fig. (5.2) is used: each evolutionary stage is color-coded following the corresponding stellar mass.

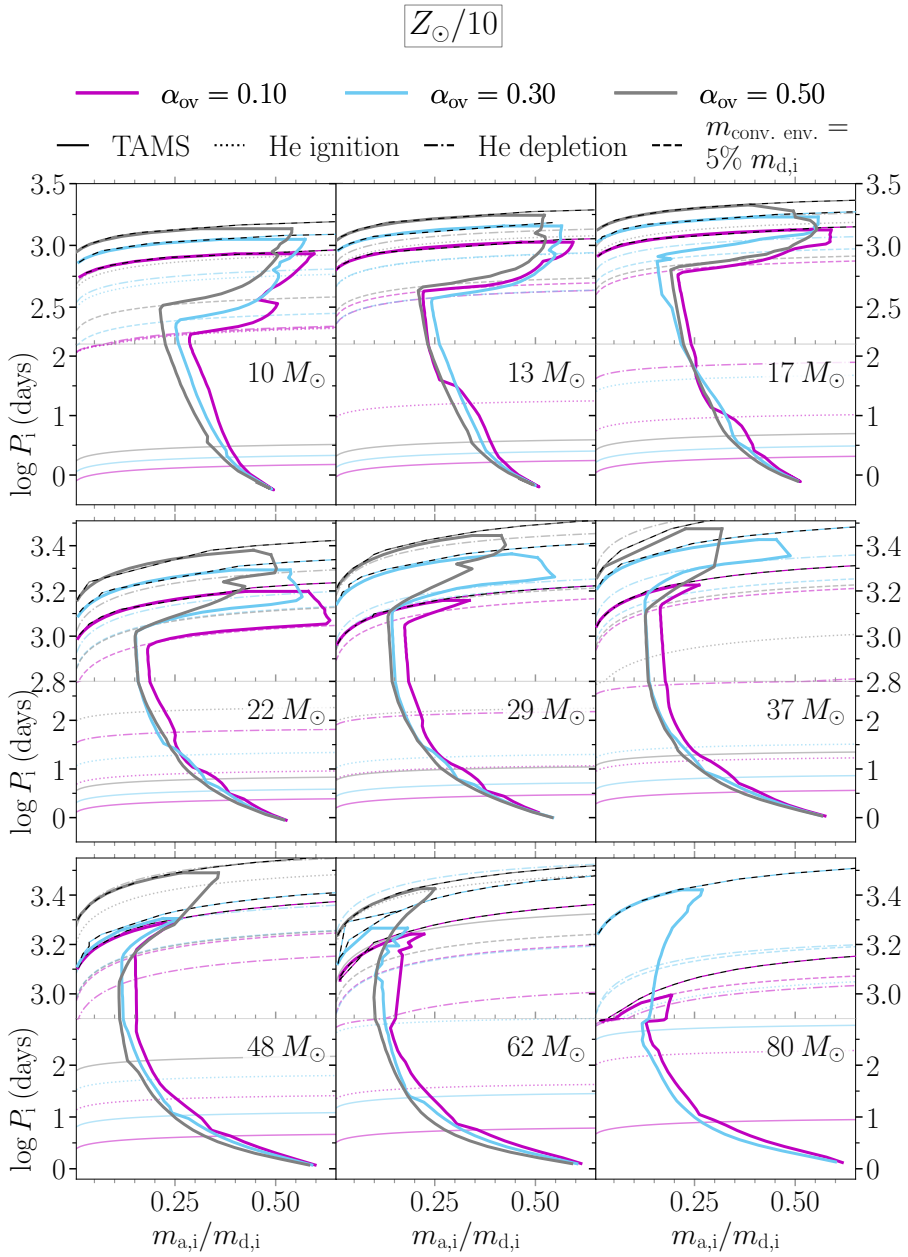


Figure D.11: Stability boundaries dependence on α_{ov} (color-coded), for different $m_{\text{d,i}}$ and at fixed $Z = Z_{\odot}/10$. Same conventions as Fig. (D.10) are adopted.

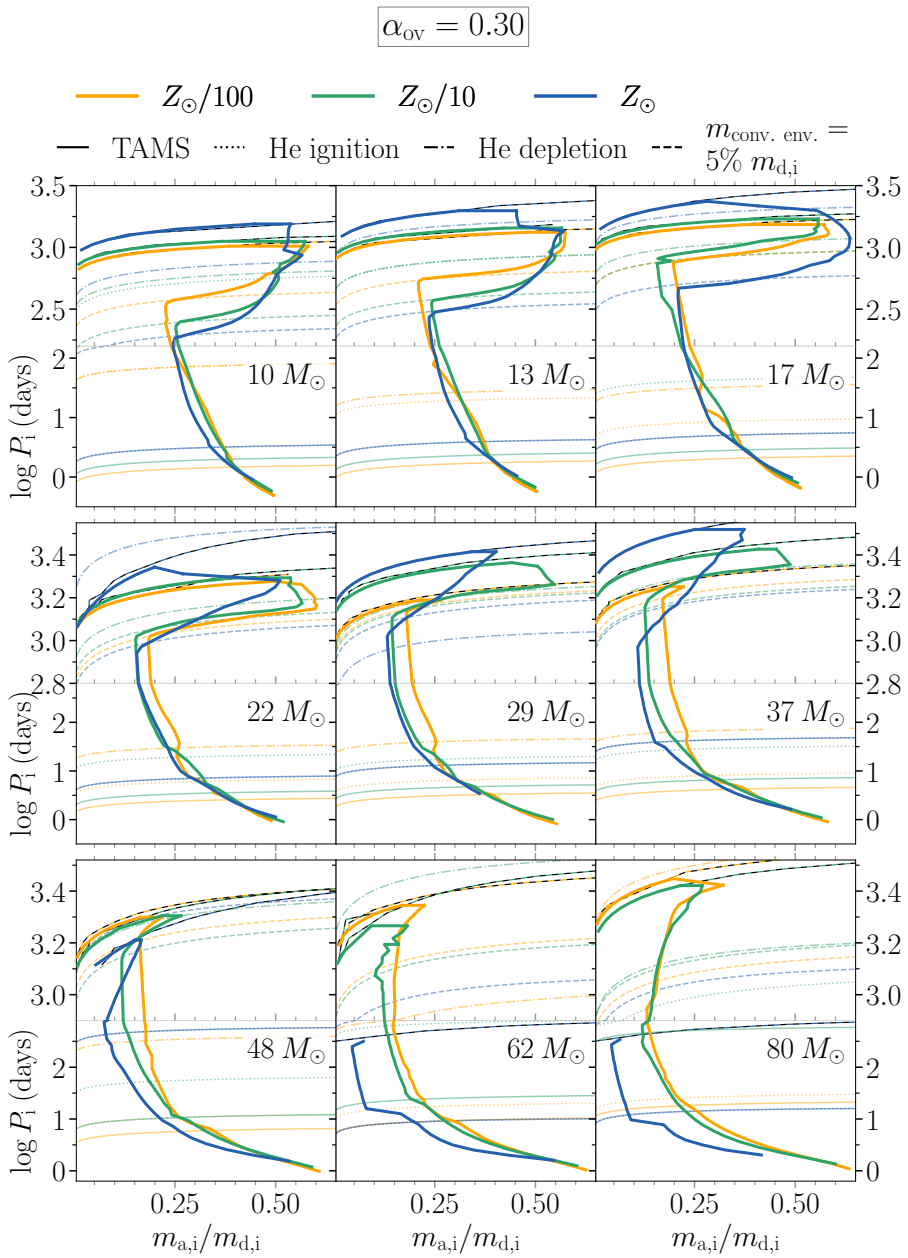


Figure D.12: Stability boundaries dependence on Z (color-coded), for different $m_{\text{d,i}}$ and at fixed $\alpha_{\text{ov}} = 0.30$. Same conventions as Fig. (D.10) are adopted.

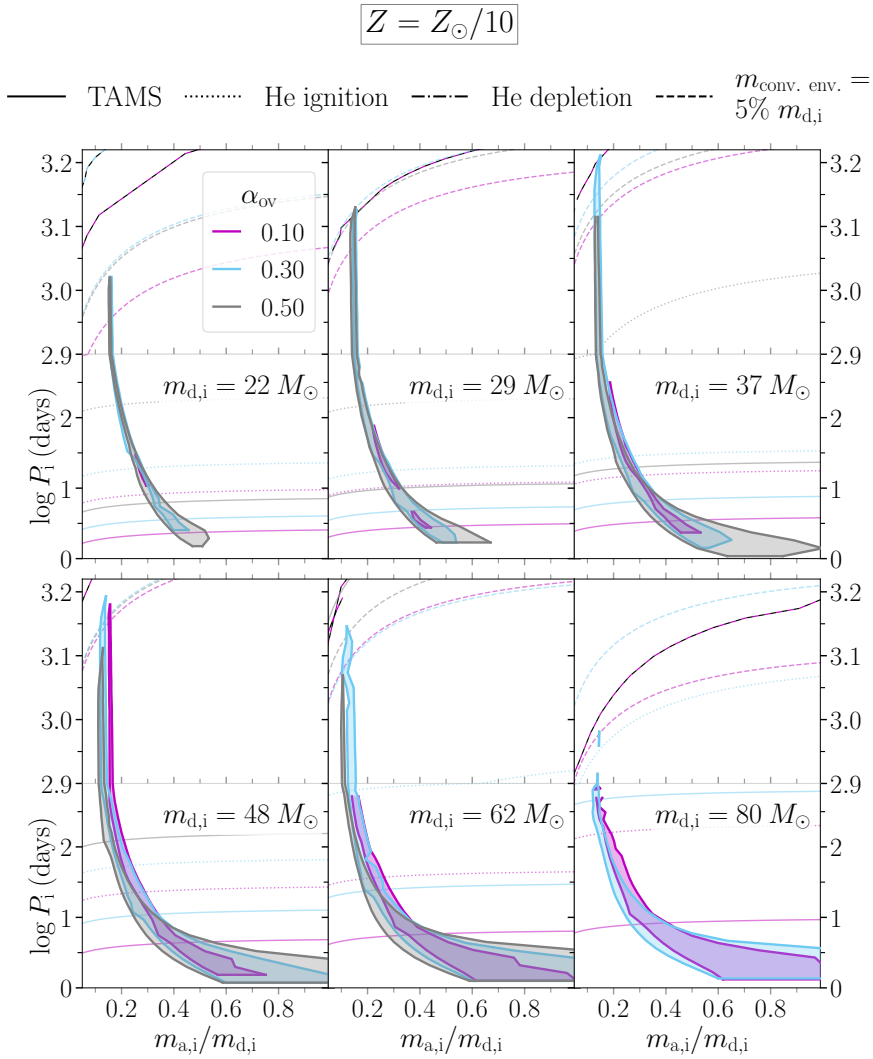


Figure D.13: Boundaries for stable MT mergers at different $m_{\text{d,i}}$ and at fixed $Z = Z_{\odot}/10$, for different α_{ov} (color-coded). Same conventions as Fig. (5.3) in the main text are adopted. We only show masses from $m_{\text{d,i}} = 22 M_{\odot}$ above, as the stable MT mergers parameter window is very small for lower masses at this metallicity (see Fig. (D.2)).

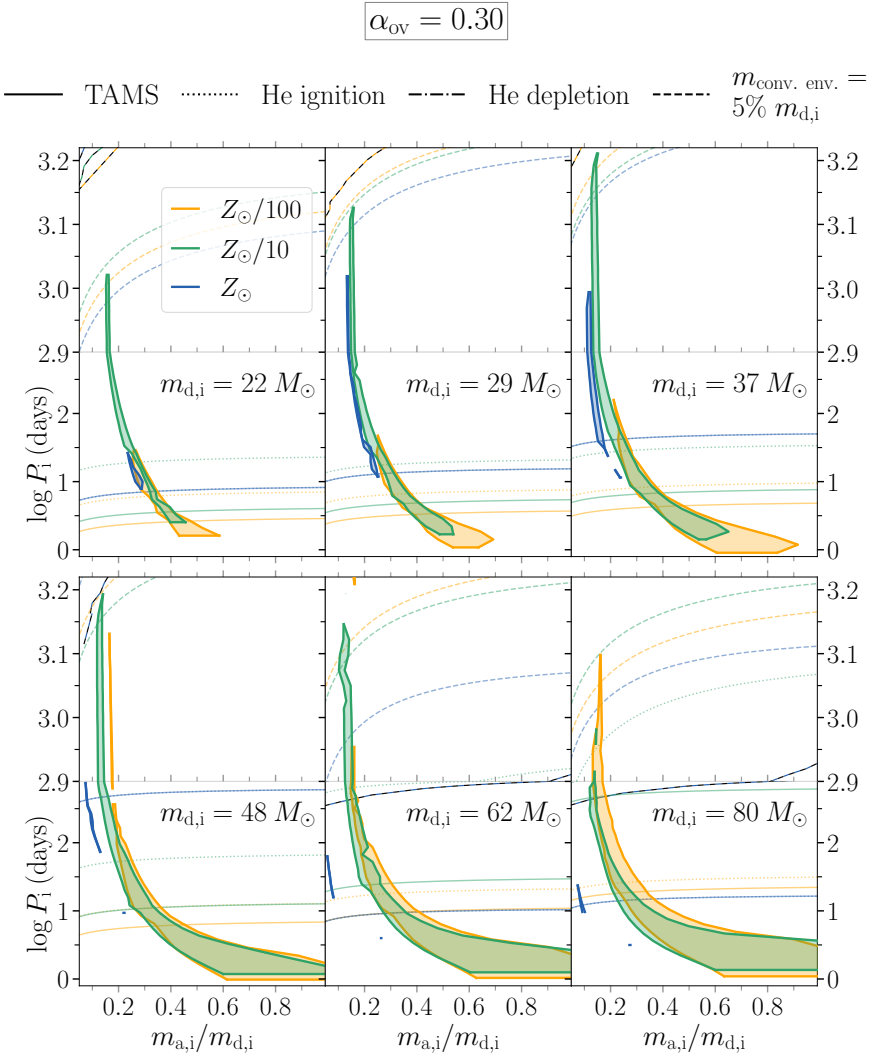


Figure D.14: Boundaries for stable MT mergers at different $m_{\text{d,i}}$ and at fixed $\alpha_{\text{ov}} = 0.30$, for different Z (color-coded). Same conventions as Fig. (5.4) in the main text are adopted. Similarly as for Fig. (D.13), we only show masses from $m_{\text{d,i}} = 22 M_{\odot}$ above.

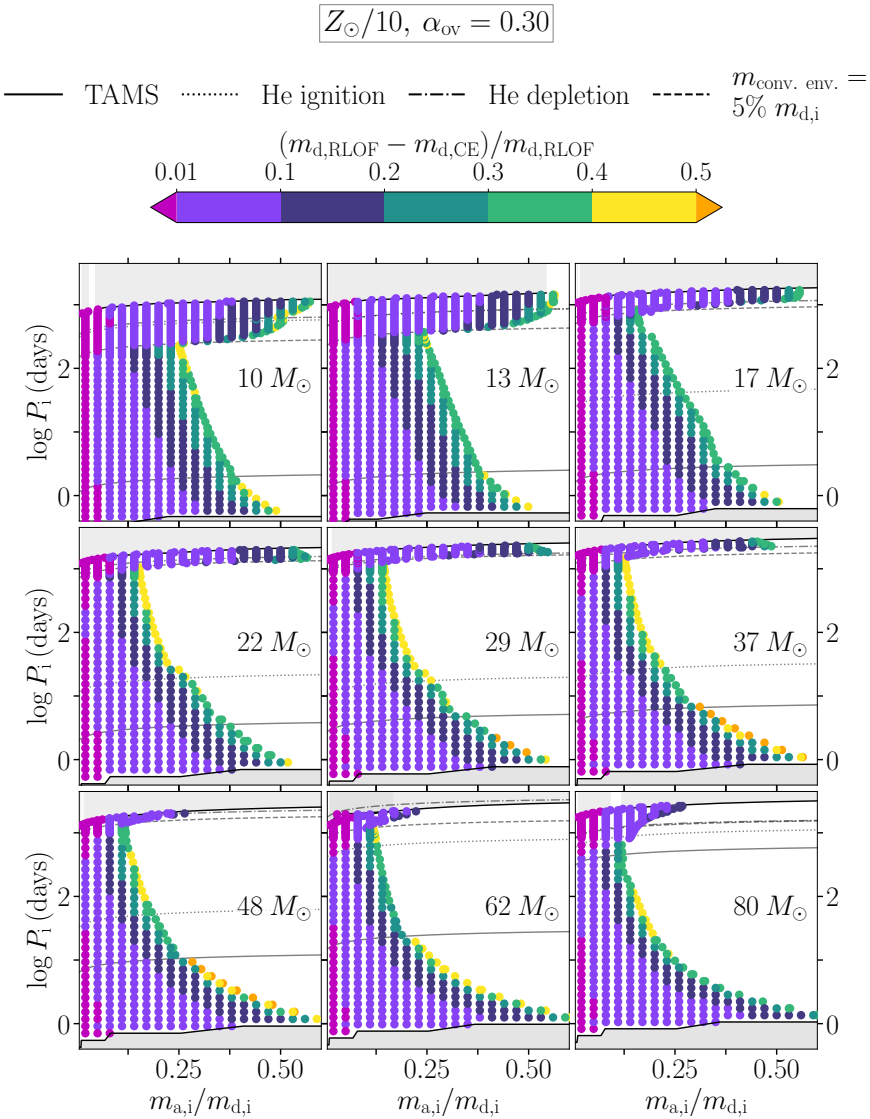


Figure D.15: Grids of simulations showing the amount of mass lost before the onset of CE evolution (color-coded), referred to as delayed dynamical instability, for different initial masses of the donor $m_{\text{d,i}}$, at fixed metallicity $Z = Z_{\odot}/10$ and overshooting parameter $\alpha_{\text{ov}} = 0.30$. The same convention on evolutionary stages as in Fig. (5.1) is used.

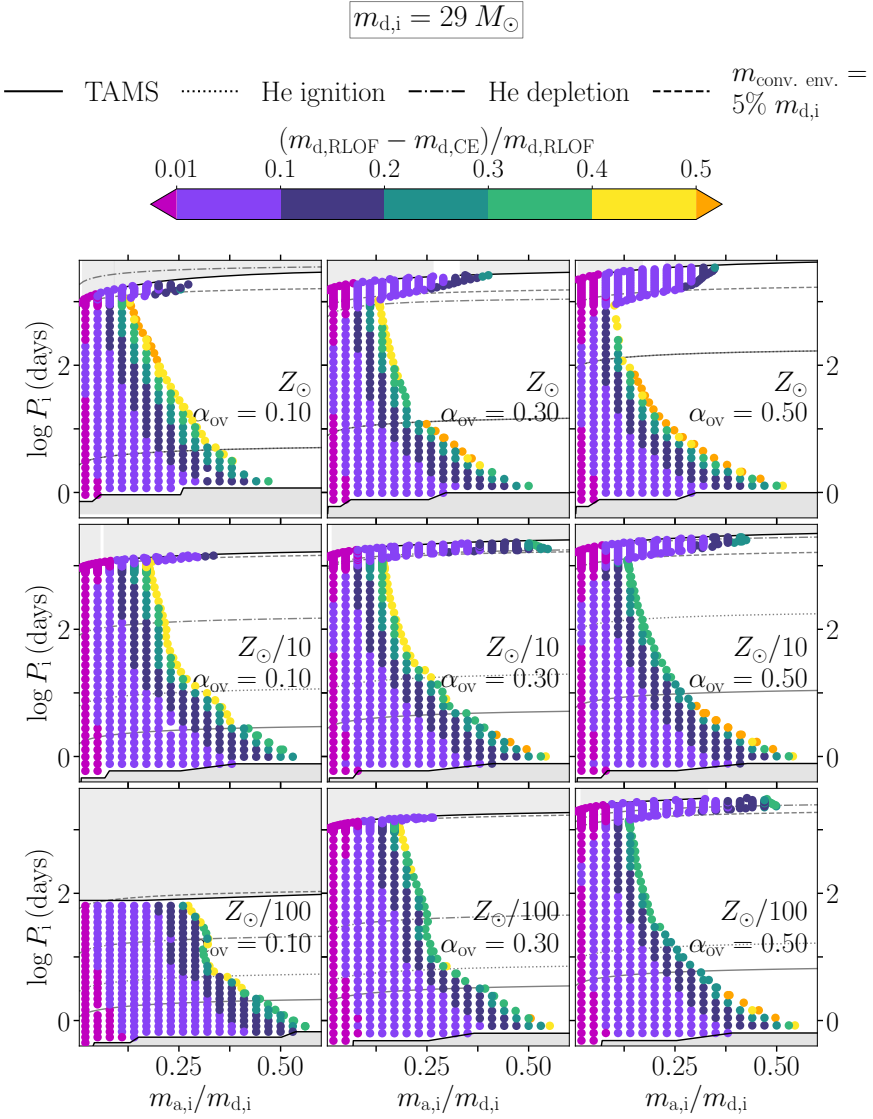


Figure D.16: As in Fig. (D.15), grids of simulations showing the delayed dynamical instability (color-coded), for different overshooting parameters α_{ov} and metallicities Z , at fixed initial mass of the donor $m_{d,i} = 29 M_{\odot}$.

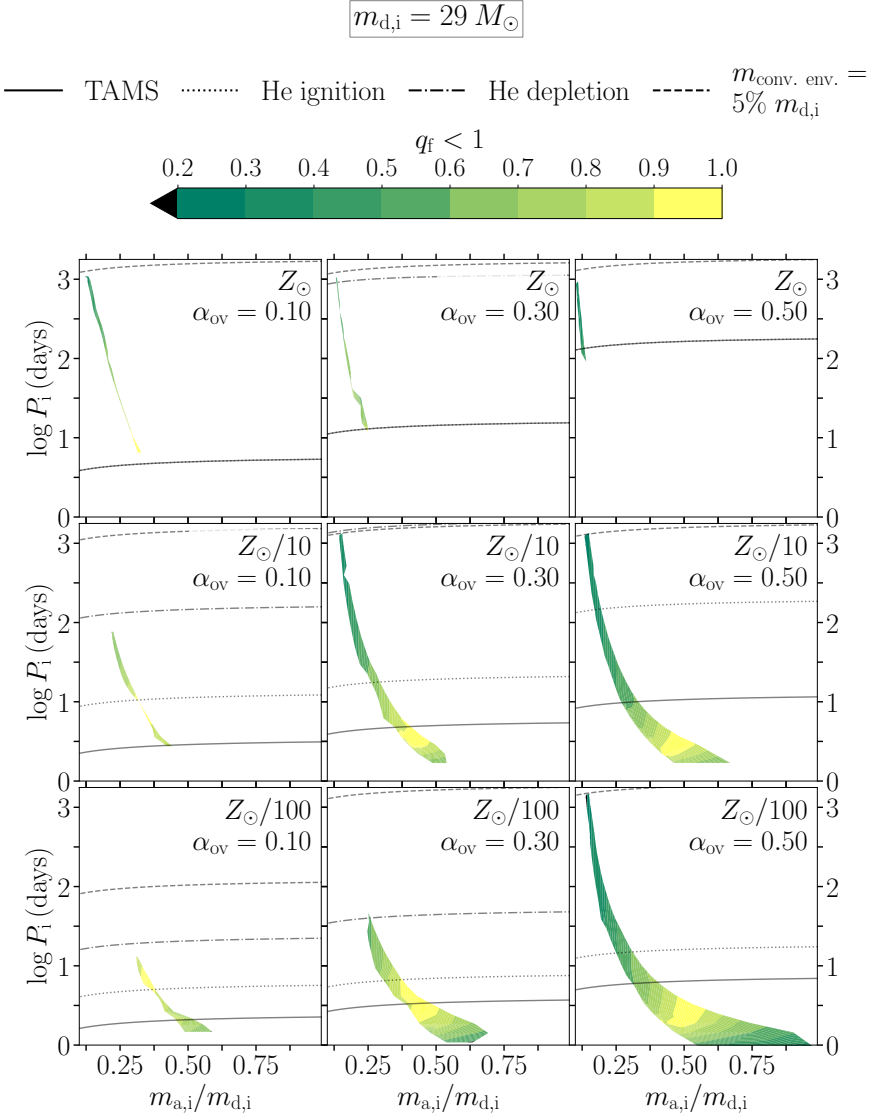


Figure D.17: Parameter space of stable MT GW mergers at different α_{ov} and Z , at fixed $m_{d,i} = 29 M_{\odot}$. The final mass ratios of the GW mergers are color-coded and they are computed as the ratio between the less massive and the more massive component, such that $q_f < 1$, following the same convention as in Fig. (5.8).

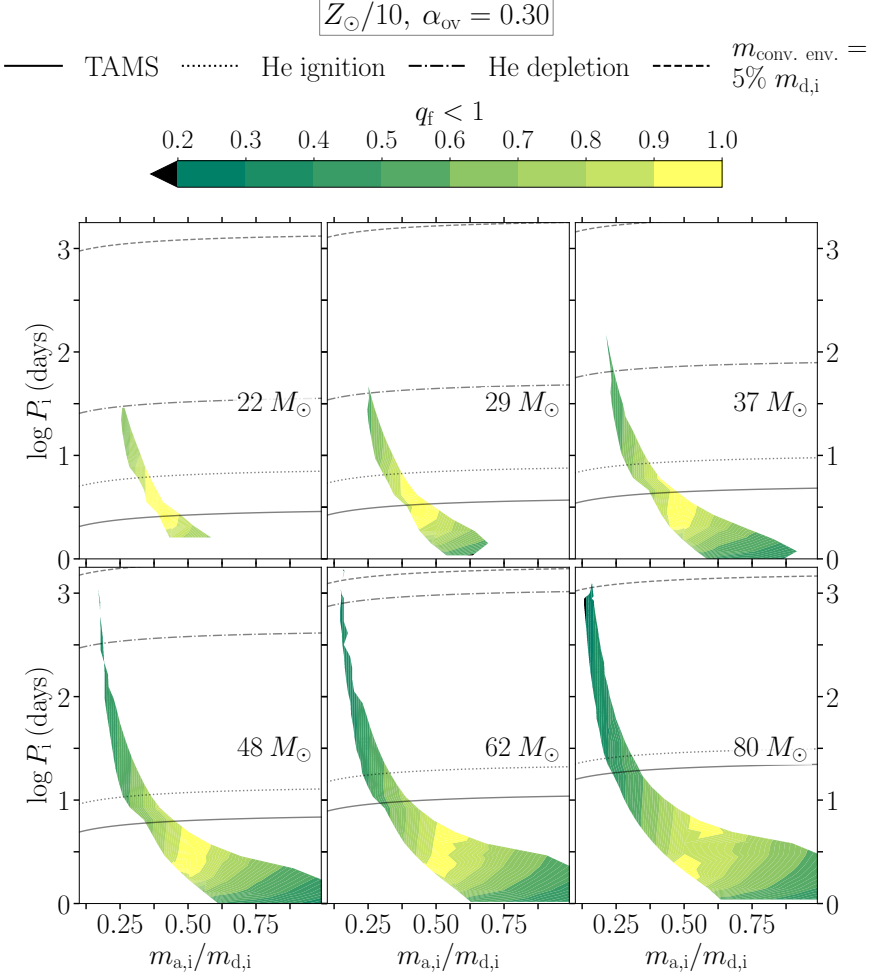


Figure D.18: Parameter space of stable MT GW mergers at different $m_{\text{d,i}}$, but fixed α_{ov} and Z . We adopt the same conventions as in Fig. (D.17).

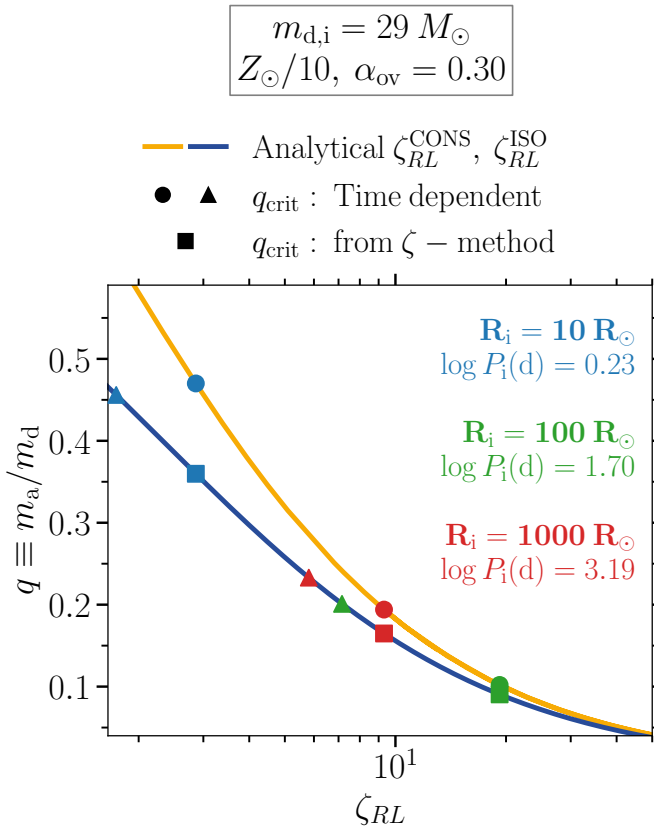


Figure D.19: Analytical dependence, on the mass ratio q , of the Roche lobe mass-radius exponents, in the case of fully conservative and fully non-conservative MT under the isotropic re-emission assumption, ζ_{RL}^{CONS} (solid orange line) and ζ_{RL}^{ISO} (solid indigo line), respectively. Along the analytical curve of ζ_{RL}^{CONS} , we highlight three critical mass ratio values, q_{crit} (circular markers), at different evolutionary stages (and at reported donor radius and RLOF period), as computed from our time-dependent models. Specifically, Main Sequence (blue), after helium-burning ignition (green), and donor with convective envelope (red). Analogously, we show the critical mass ratio values computed from our time-dependent models for fully non-conservative MT, q_{crit}^{ISO} (triangular markers), at the same evolutionary stages. Along the curve of ζ_{RL}^{ISO} , we add the critical mass ratios (rectangular markers) that result from the analytical ζ method, which compares the mass-radius exponents in the *conservative case* to translate directly into critical mass ratios in the *non-conservative case* (that is, a vertical shift between the two curves).

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Statement on the use of Generative AI

I have used the generative AI assistance tools ChatGPT, Consensus, and NotebookLM. Generative AI was primarily used for language assistance, including improving grammar, readability, and the overall flow of the text. In addition, it was used for assistance with Python programming for generating plots and visualizations.

The text, code, and images in this thesis are my own (unless otherwise specified). Generative AI has only been used in accordance with the KU Leuven guidelines and appropriate references have been added. I have reviewed and edited the content as needed and I take full responsibility for the content of the thesis.

List of publications and Curriculum Vitae

First-author publications

1. **Picco, A.**, Marchant, P., Sana, H., *No hard boundaries: the mass transfer stability depends on overshooting and metallicity*, *Astronomy & Astrophysics*, (2026, to be submitted)
2. **Picco, A.**, Marchant, P., Pauli, D., Sana, H., *Helium stars mergers as a route towards intermediate mass stripped stars*, *Astronomy & Astrophysics*, Volume 710, L12 (2026)
3. **Picco, A.**, Marchant, P., Sana, H., J. Bodensteiner, T. Shenar, A. J. Frost, K. Deshmukh, J. S. G. Mombarg, D. Pauli, R. Willcox, A. Kemp, *HR6819: a puffed-up stripped star system challenging stable mass transfer theory*, *Astronomy & Astrophysics*, Volume 705, A225 (2025)
4. **Picco, A.**, Marchant, P., Sana, H., and Nelemans, G., *Forming merging double compact objects with stable mass transfer*, *Astronomy & Astrophysics*, Volume 681, A31 (2024)

Co-author publications

1. K. Deshmukh, S. Geier, H. Sana, H. Dawson, M. Dorsch, A. J. Frost, U. Heber, T. Kupfer, **A. Picco**, and M. Vučković, *Toward 3D orbits of wide hot subdwarf binaries. I. Five composite systems spatially resolved with VLTI/GRAVITY*, *Astronomy & Astrophysics Letters*, Volume 712, L19 (2026)

2. Stringer, E., Kupfer, T., Deshmukh, K., Maccarone, T., Jackson, I., Kosakowski, A. C., Bradshaw, W., Brown, A., Dorsch, M., **Picco, A.**, Dhillon, V. S., *Discovery of the First Outbursting Hot Subdwarf Binary: ZTFJ0007+4804*, *Astronomy & Astrophysics*, Volume 710, A253 (2026)
3. Shenar, T., Bodensteiner, J., Abdul-Masih, M., Backs, F., Berlanas, S. R., Bestenlehner, J. M., Bobrick, A., Bowman, D. M., Britavskiy, N., Bronner, V. A., Crowther, P. A., Deshmukh, K., Fabry, M., Gieles, M., Gilkis, A., González-Torà, G., Gräfener, G., Gull, M., Götberg, Y., Hawcroft, C., Hénault-Brunet, V., Herrero, A., Holgado, G., Izzard, R. G., Janssens, S., Jin, H., Kalari, V. M., Katabi, Z., de Koter, A., Klencki, J., Kubátová, B., Kubát, J., Langer, N., Lechien, T., Lennon, D., Lefever, R., Ludwig, B., Mahy, L., Maíz Apellániz, J., Mandel, I., Mang Román, A., Maravelias, G., Marchant, P., Menon, A., Najarro, F., O'Grady, A., Oskinova, L., Ovardia, R., Patrick, L. R., Pauli, D., Bernini Peron, M., **Picco, A.**, Ramachandran, V., Renzo, M., Rocha, D. F., Sana, H., Sander, A. A. C., Sayada, T., Schootemeijer, A., Schneider, F. R. N., Seeburger, R., Sen, K., Shahaf, S., Simón-Díaz, S., Stoop, M., Toonen, S., Tramper, F., Valli, R., Van Daele, P., van Loon, J. Th., van Son, L., Vigna-Gómez, A., Villaseñor, J. I., Vink, J. S., Wang, C., Xu, X.-T., *Multiplicity of massive stars at low metallicity: early results from the BLOeM campaign*, *The Messenger*, No. 196 (2026)
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5. Villaseñor, J. I., Lennon, D. J., **Picco, A.**, Shenar, T., Marchant, P., Langer, N., Dufton, P. L., Nardini, F., Evans, C. J., Bodensteiner, J., de Mink, S. E., Götberg, Y., Soszyński, I., Taylor, W. D., and Sana, H., *The B-type Binaries Characterisation Programme II. VFTS 291: a stripped star from a recent mass transfer phase*, *Monthly Notices of the Royal Astronomical Society*, Volume 525, Issue 4 (2023)
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Supervision of Master’s theses

1. Graulus, S., **Picco, A.**, Marchant, P., *Mass transfer stability of massive binaries: the role of stellar structure in forming merging double compact objects*, Master’s thesis, KU Leuven (2025)
2. Taşkın, I., Kemp, A., and **Picco, A.**, *Investigating asteroseismic post-mass transfer candidates using population synthesis*, Master’s thesis, KU Leuven (2024)

Curriculum Vitae

The latest version of the author’s CV can be found on
<https://annachiarapicco.github.io/> .

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