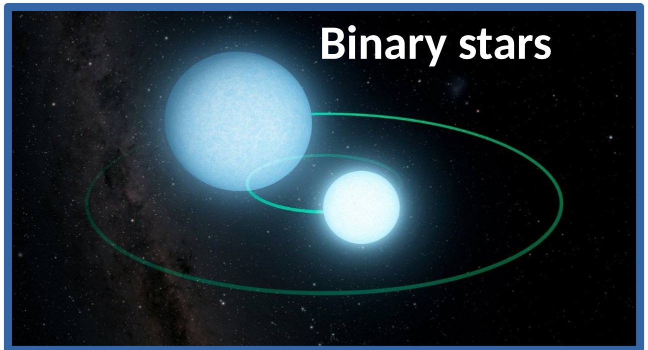
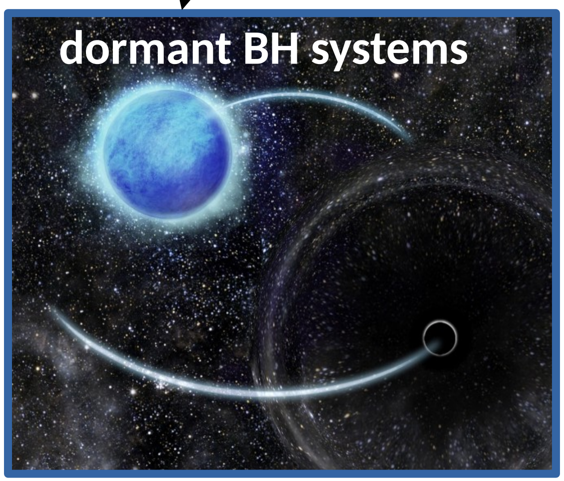
How binary mass transfer forms black hole mergers

Jakub Klencki

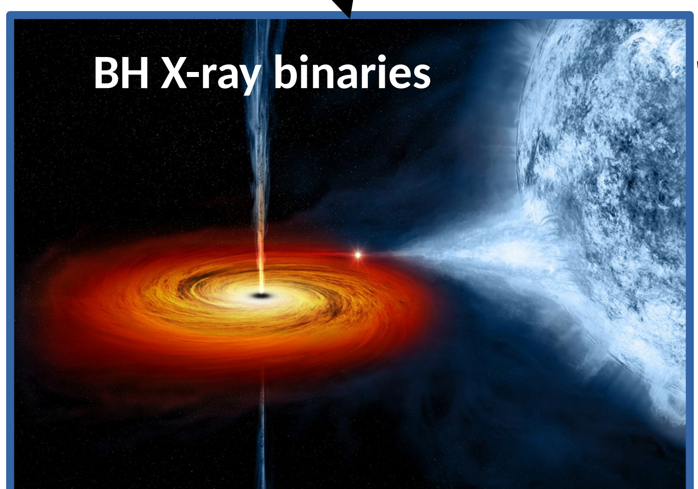
ESO Fellow

(incoming MPA Fellow)





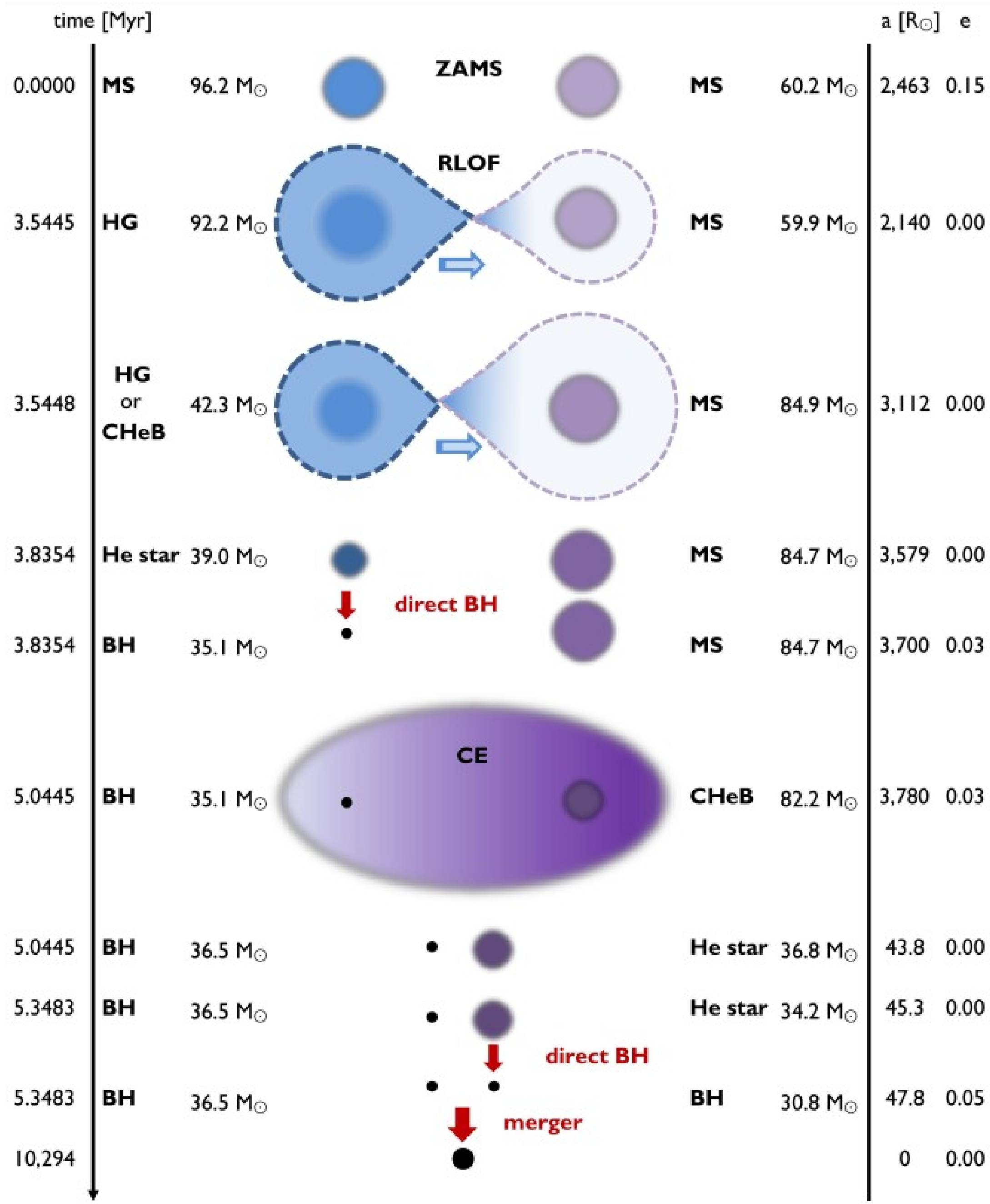
Credit: Shenar+(2022)/ I.Mayo / S.Pinilla



Credit: NASA/CXC/M.Weiss

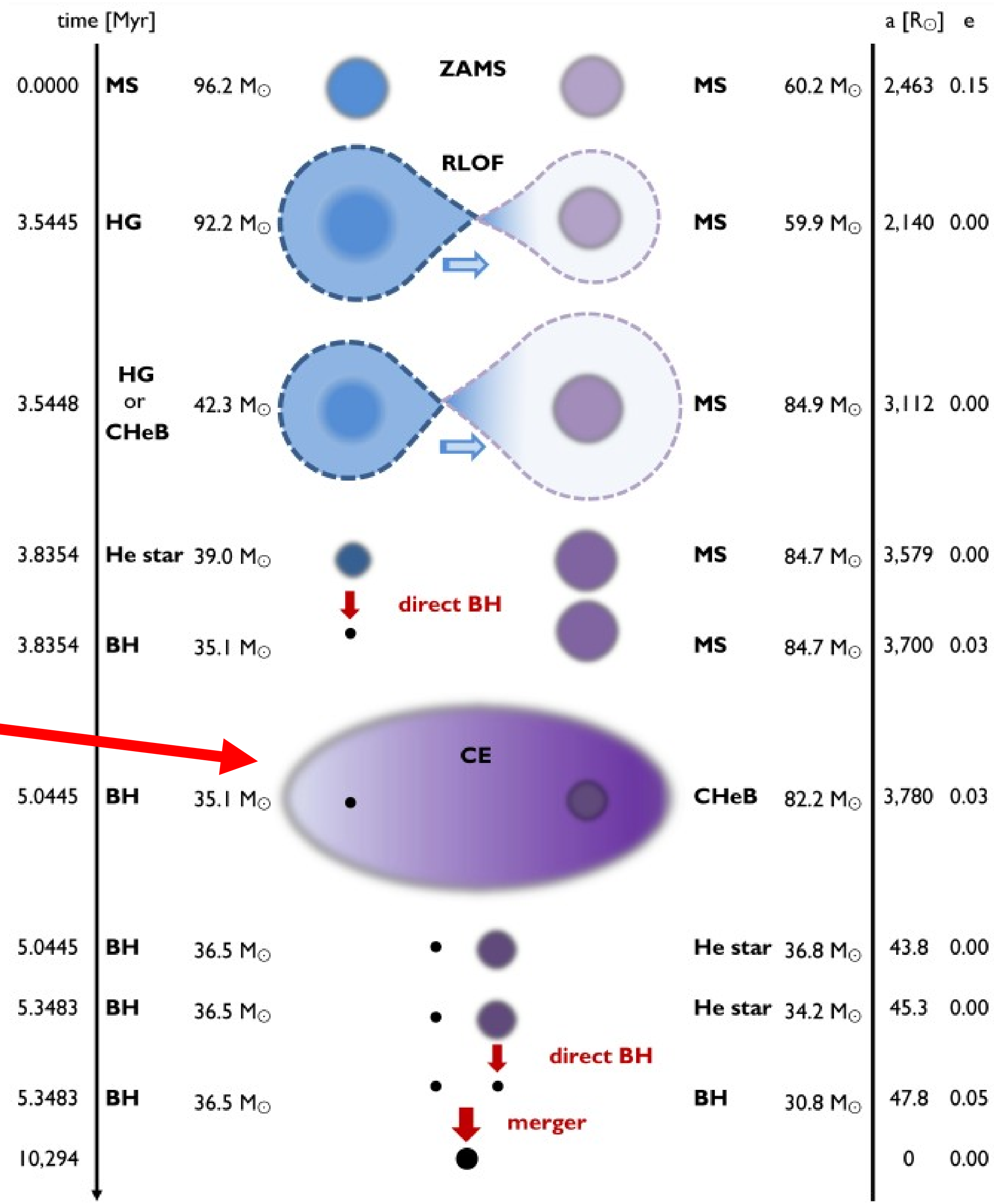
Artwork by Sandbox Studio Chicago with Corinne Mucha

Belczynski + 2016



graphic by Wojtek Gładysz & Belczynski+16

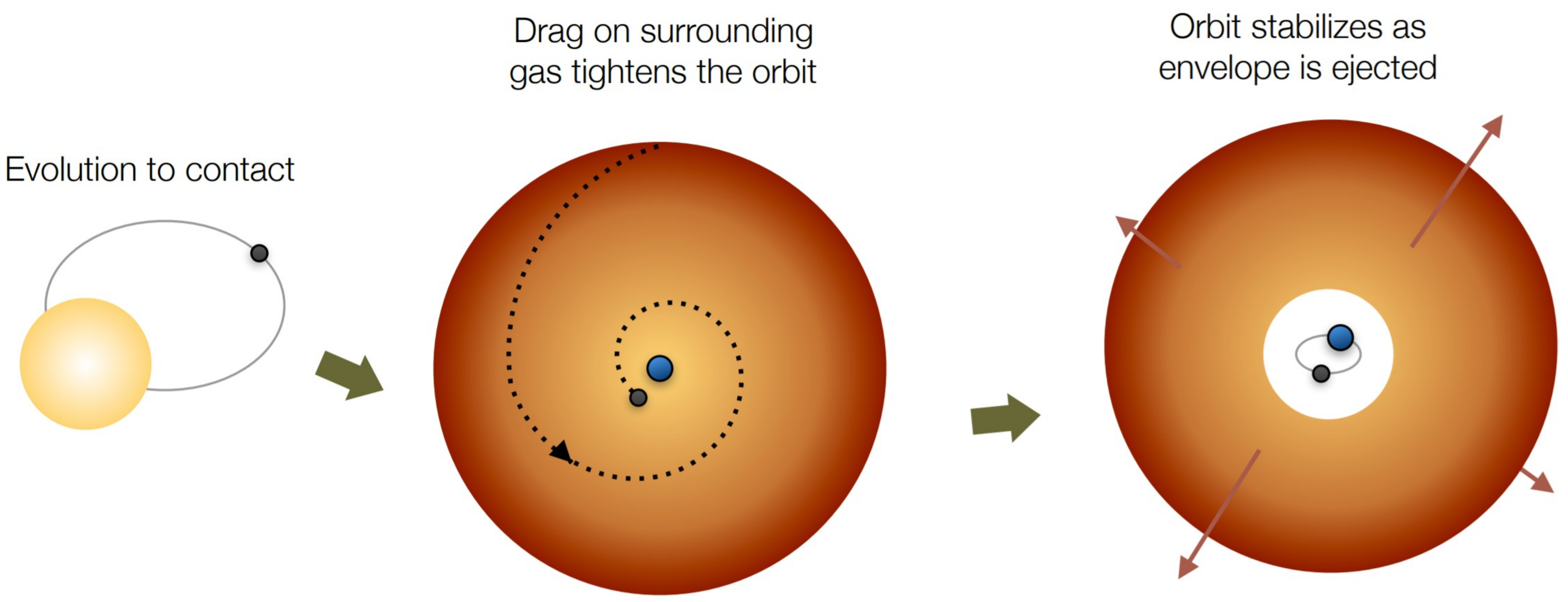
Belczynski + 2016



Common envelope

graphic by Wojtek Gładysz & Belczynski+16

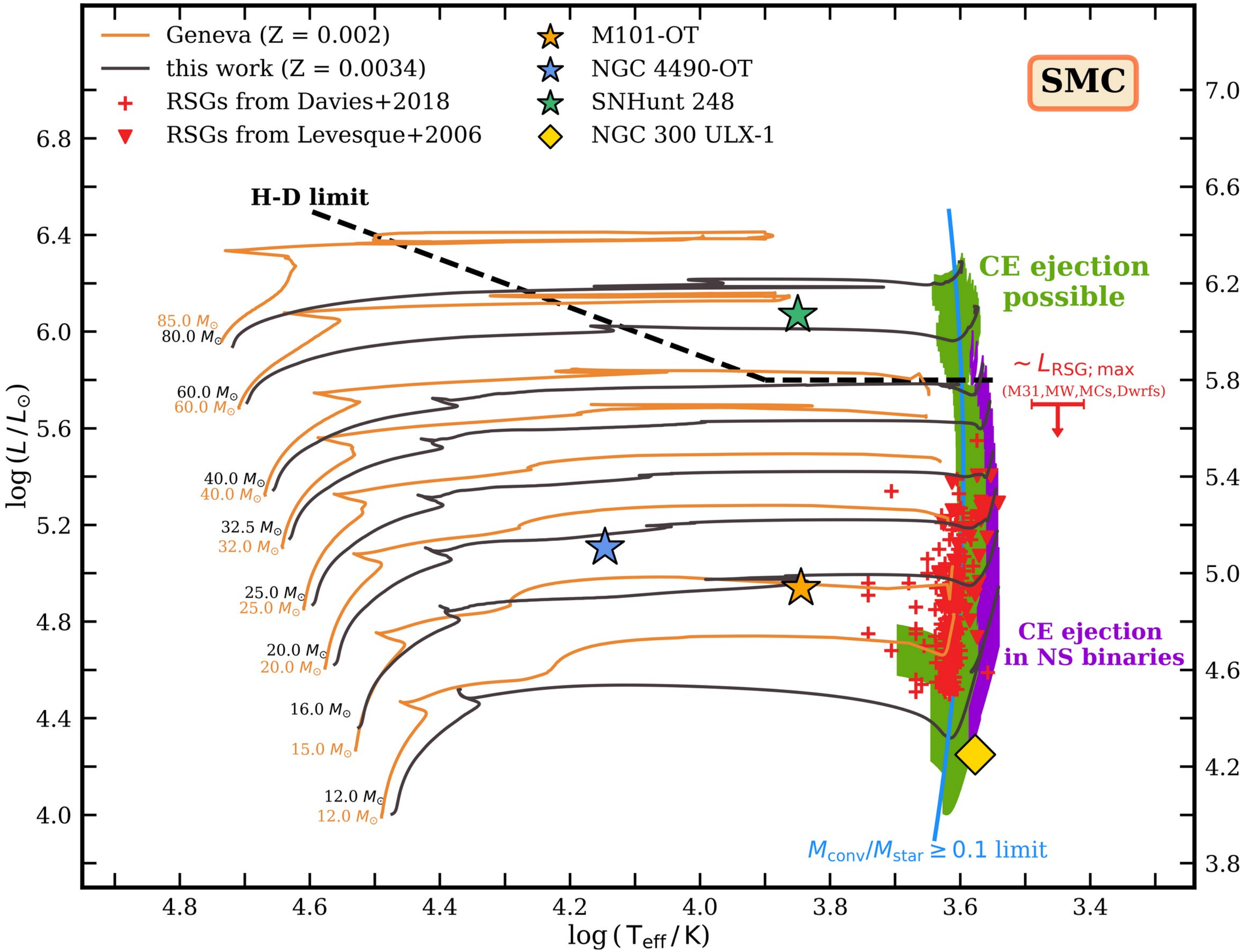
<u>Common-envelope</u> → a way to form close-orbit systems



Idea by Paczyński (1976), in communication with Webbink, Ostriker

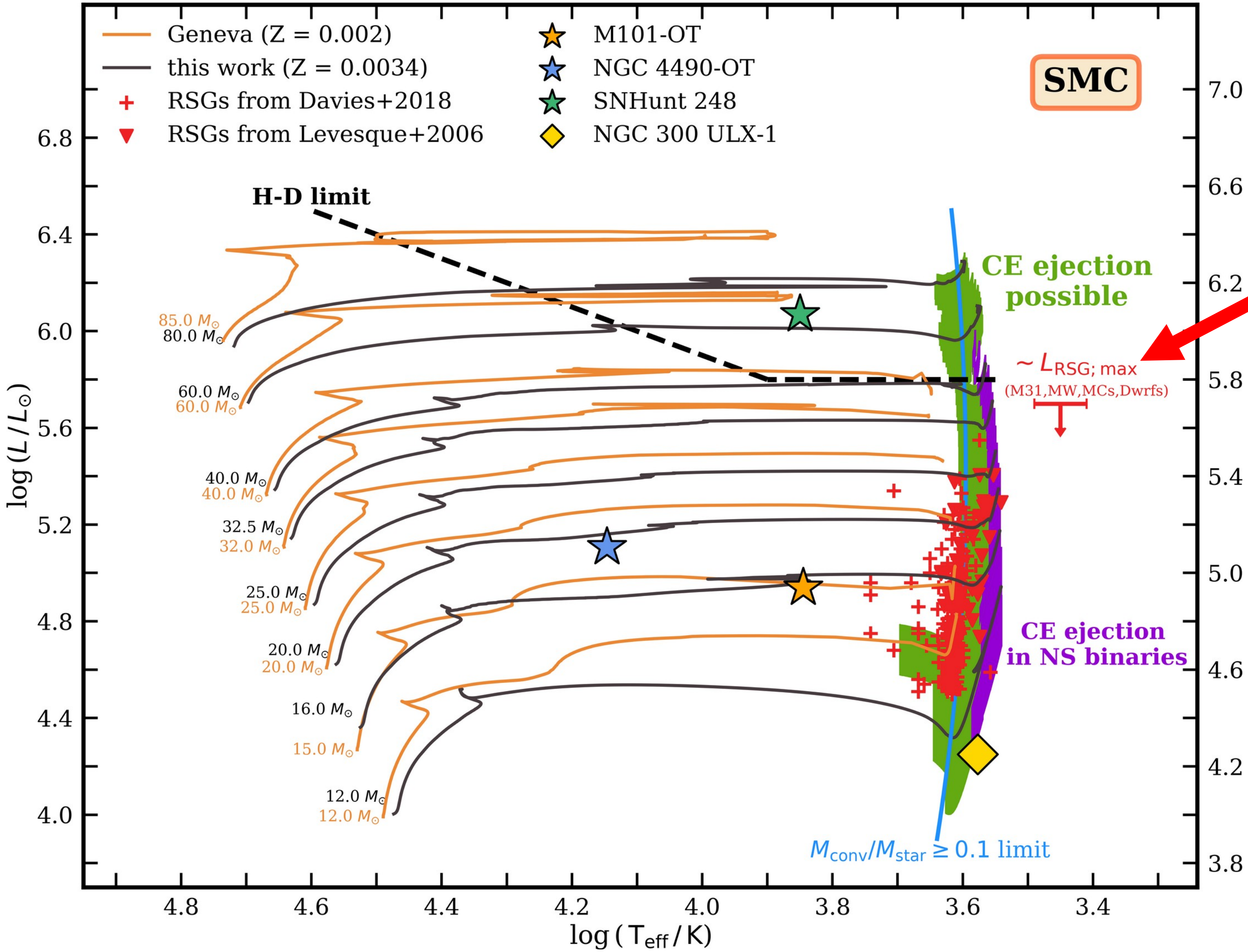
Sketch from MacLeod 2017, recent review: Ivanova, Justham, Ricker (2020)

Which stars do we need for CE? → **Convective-envelope giants (Red Supergiants)**



JK+20, 21, also Kruckow+16, Marchant+21

Which stars do we need for CE? → **Convective-envelope giants (Red Supergiants)**

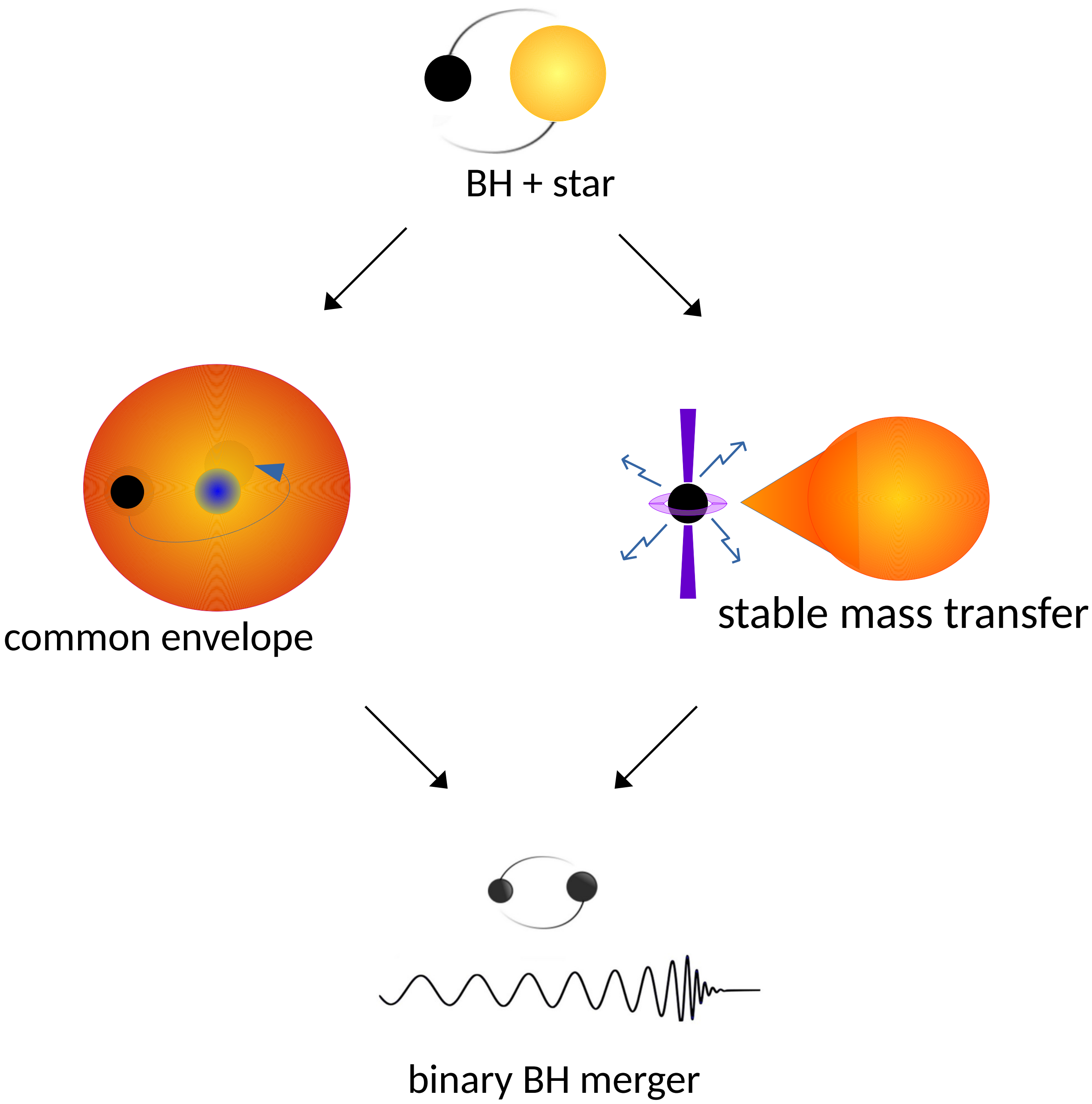


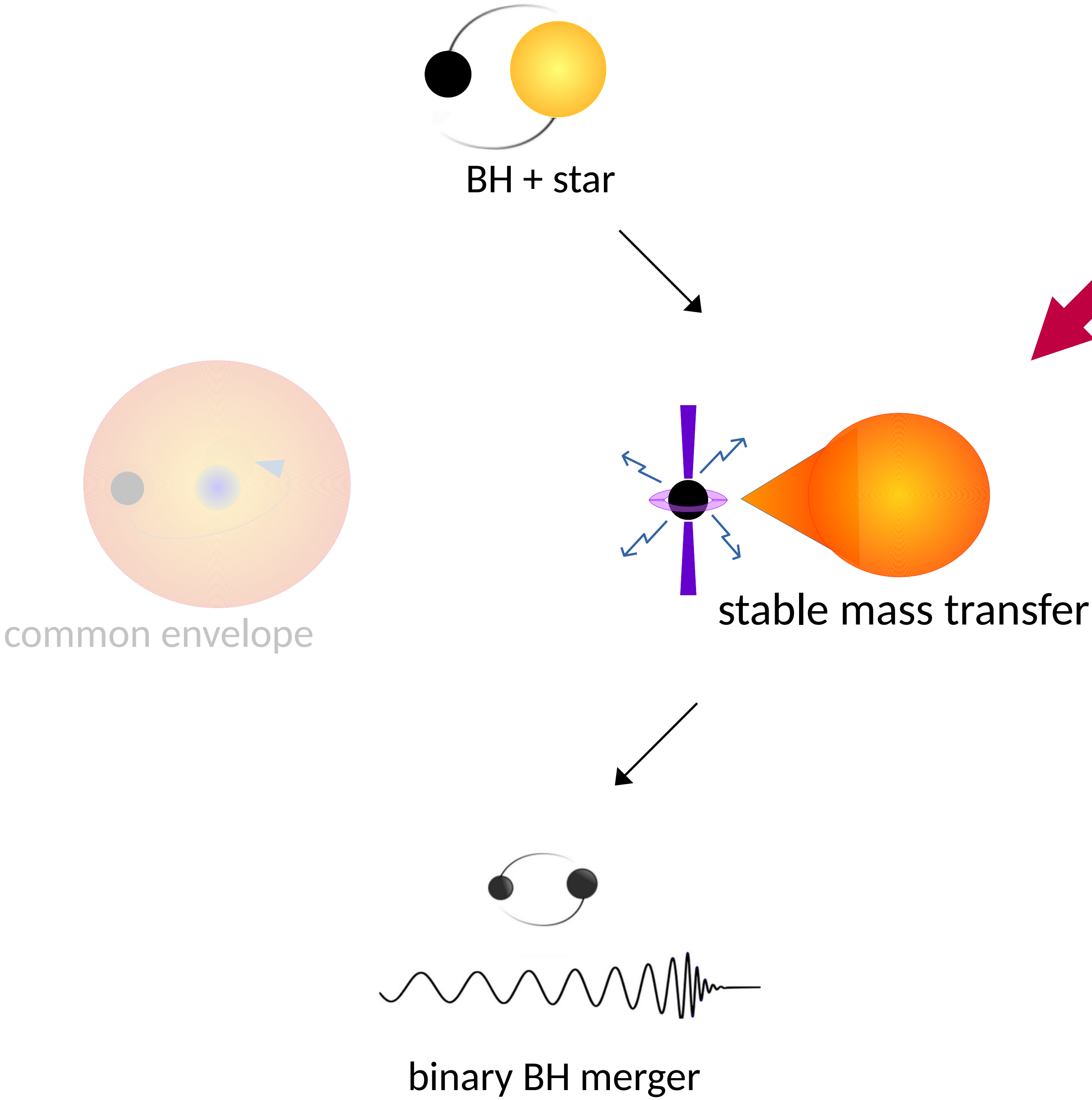
Problem:
no RSGs from $M > 40\, M_\odot$ stars

Mennekens & Vanbeveren (2014)

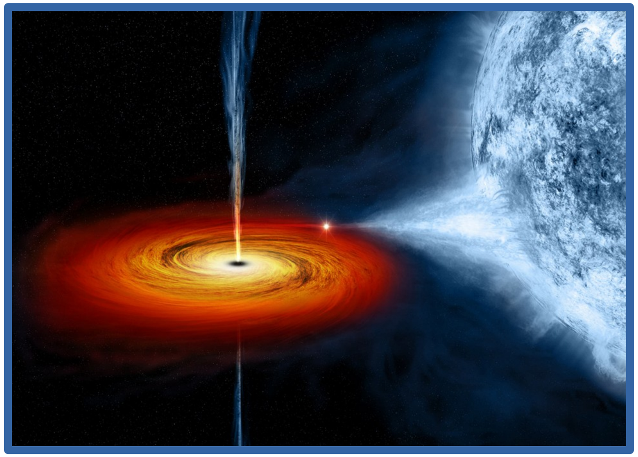
Impact on LVK sources:
Romagnolo,JK+24 (to be subm.)

JK+20, 21, also Kruckow+16, Marchant+21


BH + star
common envelope
stable mass transfer
binary BH merger



This talk:



Stable MT can also lead to BH-BH mergers

Van den Heuvel+17, Neijssel+19, Marchant+21, van Son+22, Olejak+21,24, Picco+24, Dorozsmai & Toonen 24

Q1: What are BH-BH orbital separation from stable MT?

→ delay times & host galaxy predictions

→ BH spins (very small separation => high spin)

Q1: What are BH-BH orbital separation from stable MT?

→ delay times & host galaxy predictions

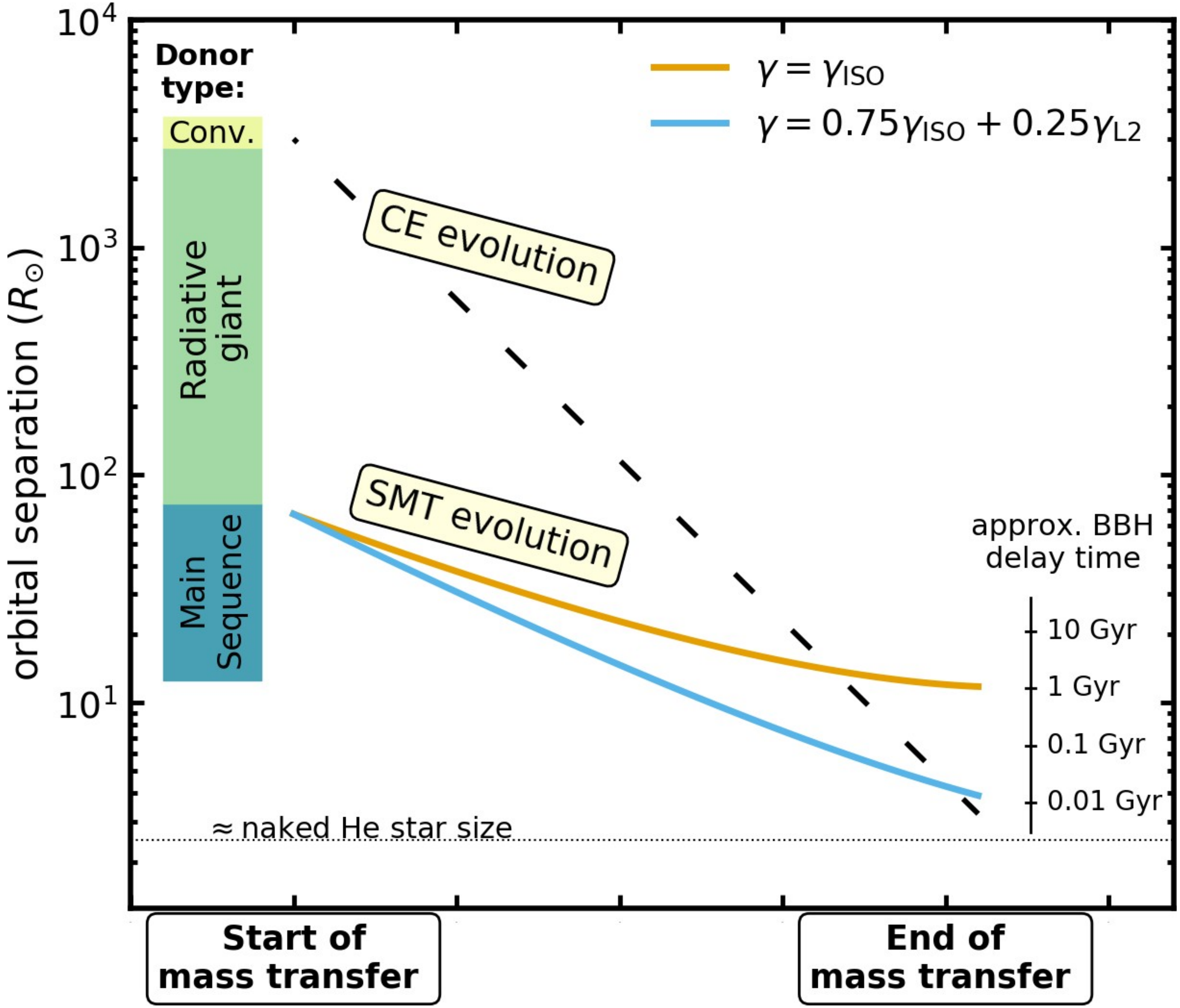
→ BH spins (very small separation => high spin)

Q2: Which stars do we need for the stable MT channel?

→ link to stellar astrophysics

→ BH mass range

Stable MT from $M_{donor} > M_{accretor}$ shrinks the orbit



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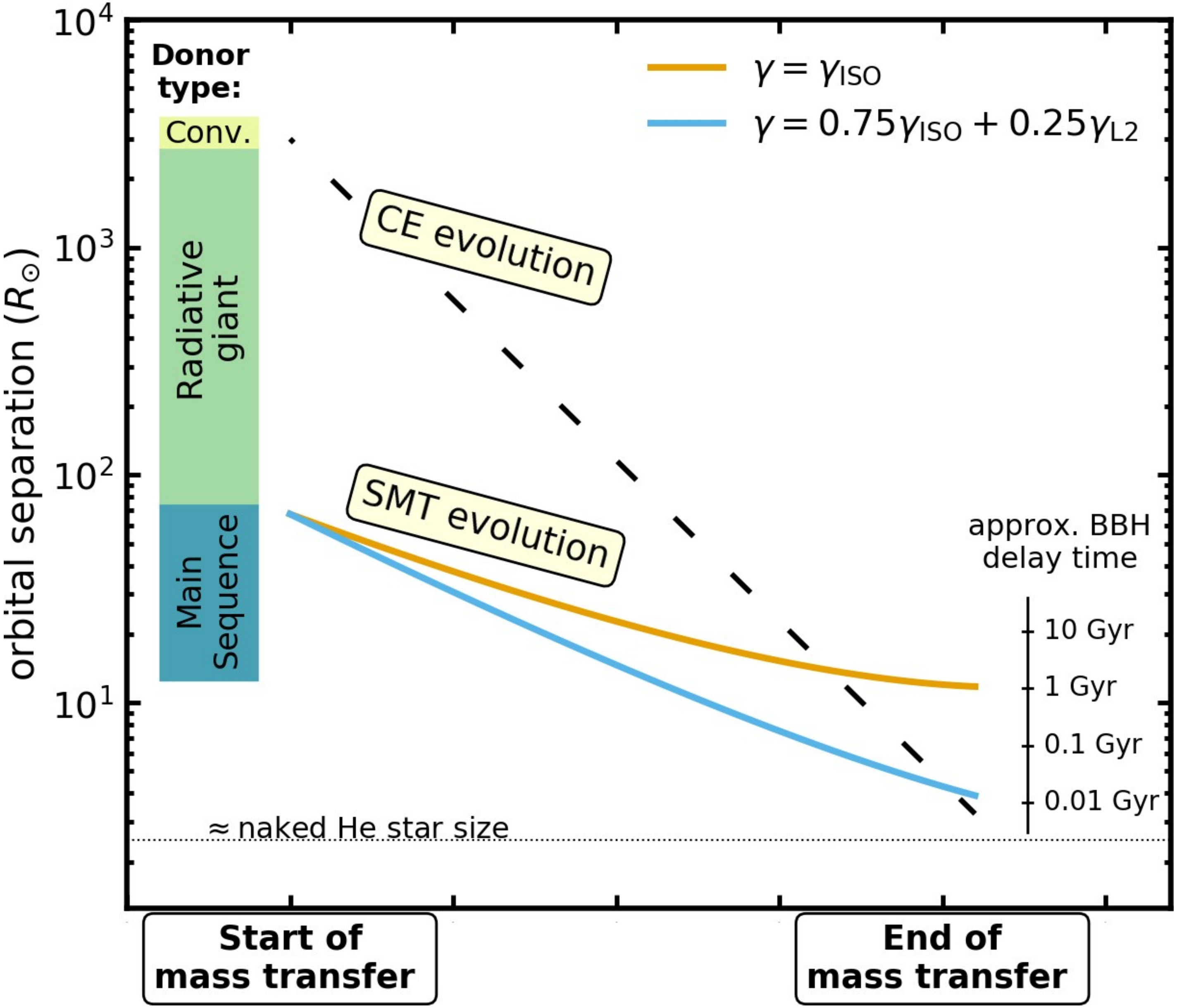
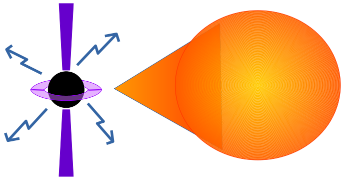
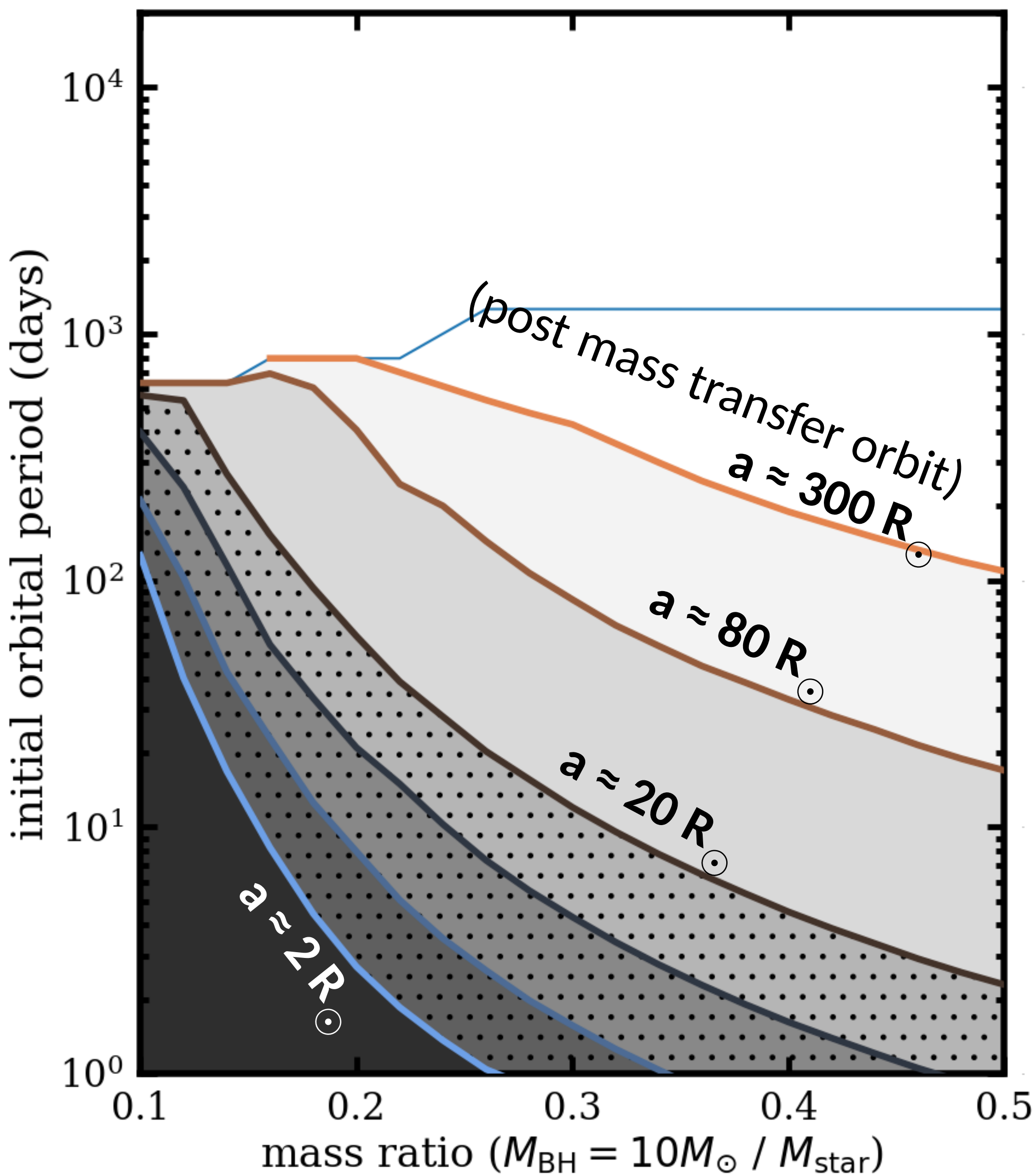


<u>Assume:</u>
→ accretion efficiency
→ angular momentum loss

<u>Get:</u>
→ orbital evolution

Post-mass transfer orbits? Analytical prediction





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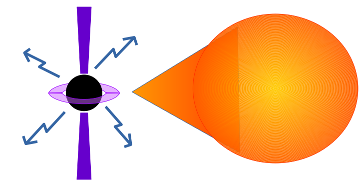
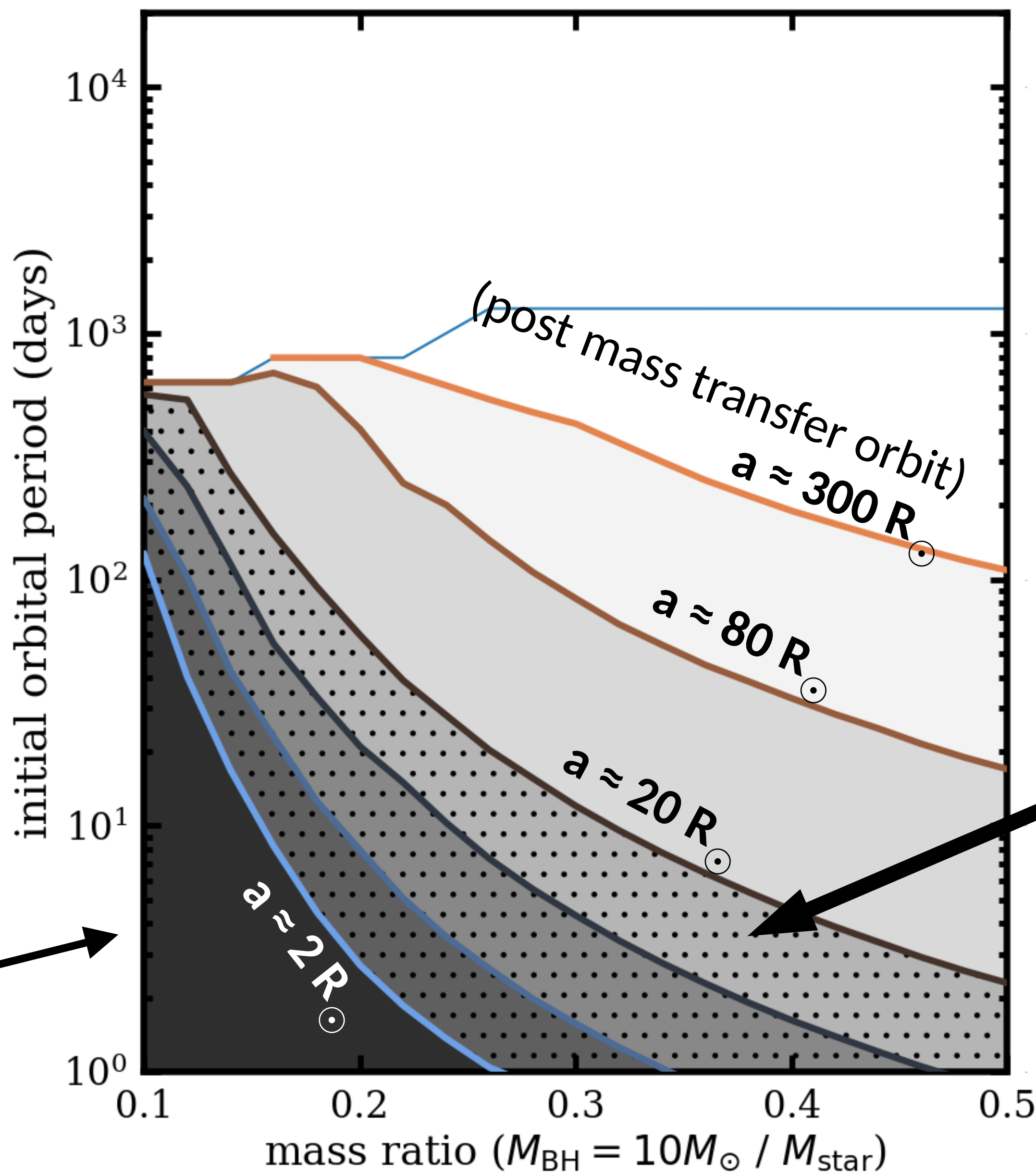
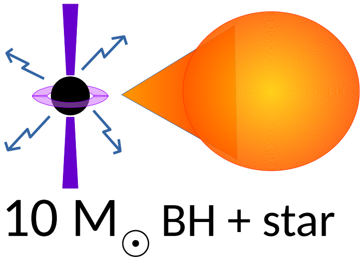


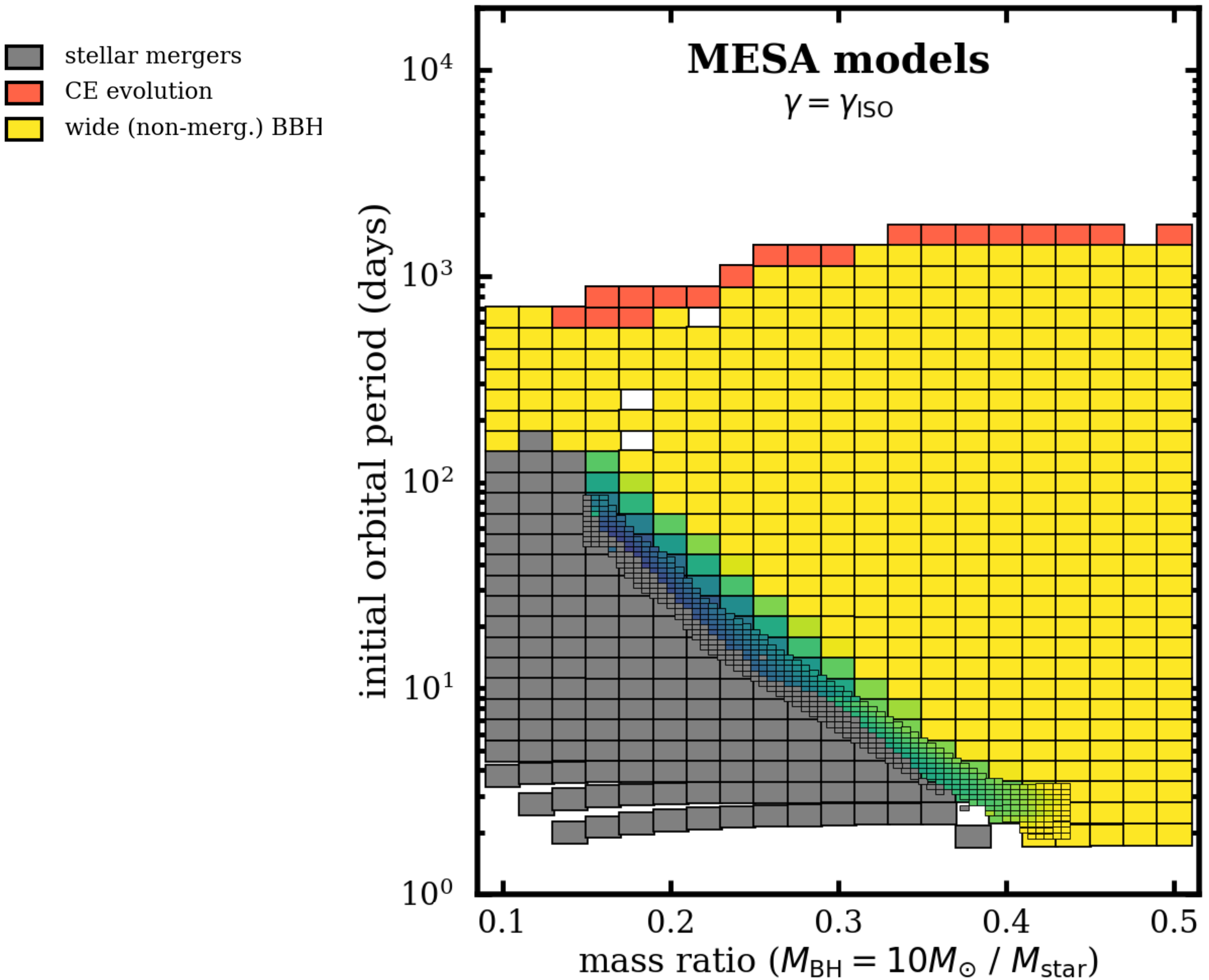


Dotted area:
~ BH-BH merger progenitors

Excluded region
(He core does not fit the orbit)

New: systematic binary grids with 1D stellar codes





also: Marchant+21, Gallegos-Garcia+21, Fragos+23, Picco+24

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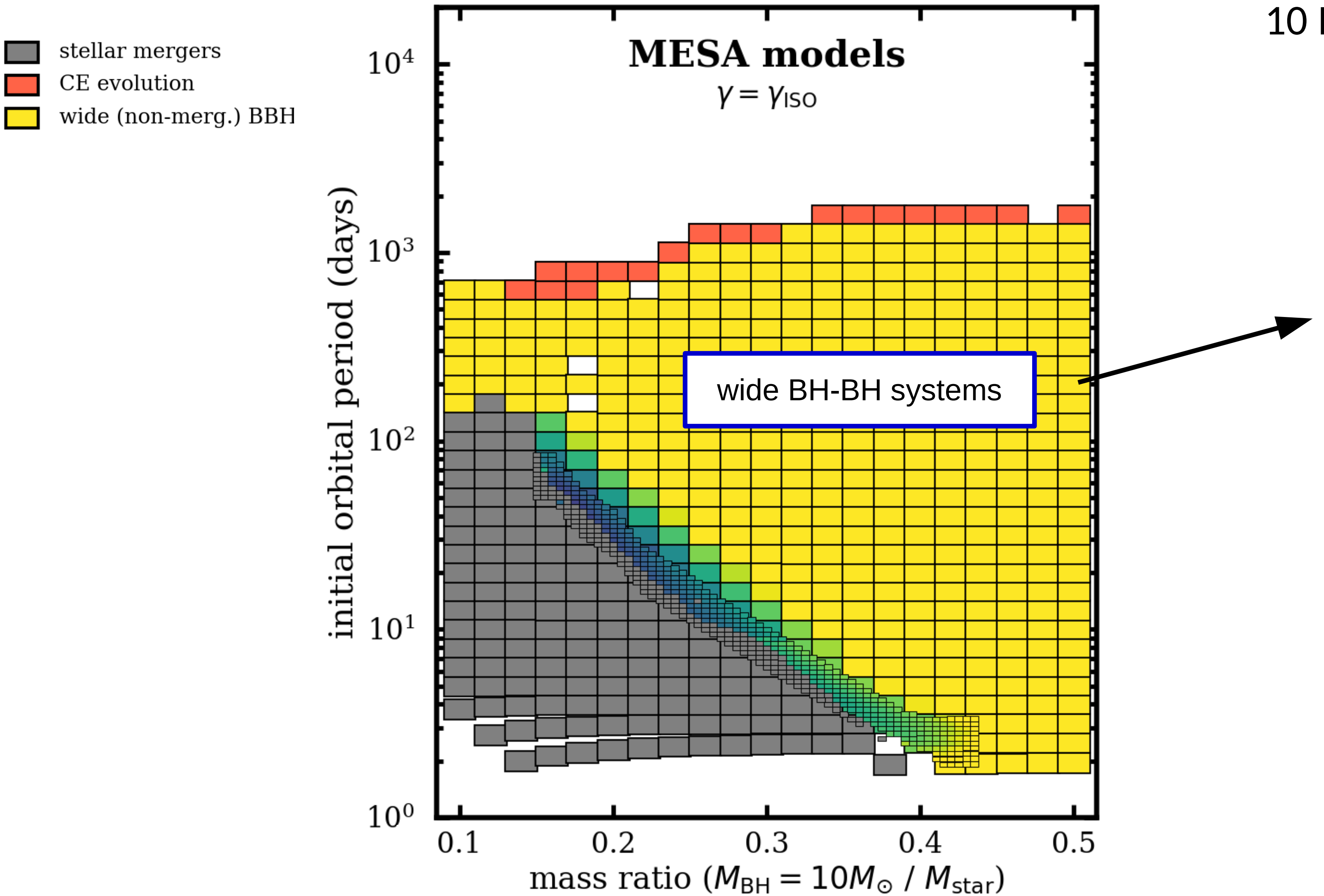

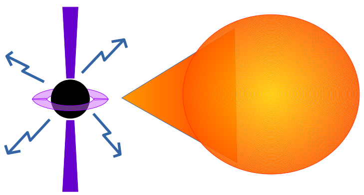

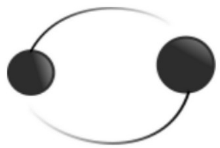

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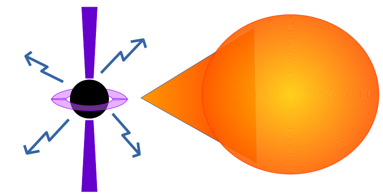

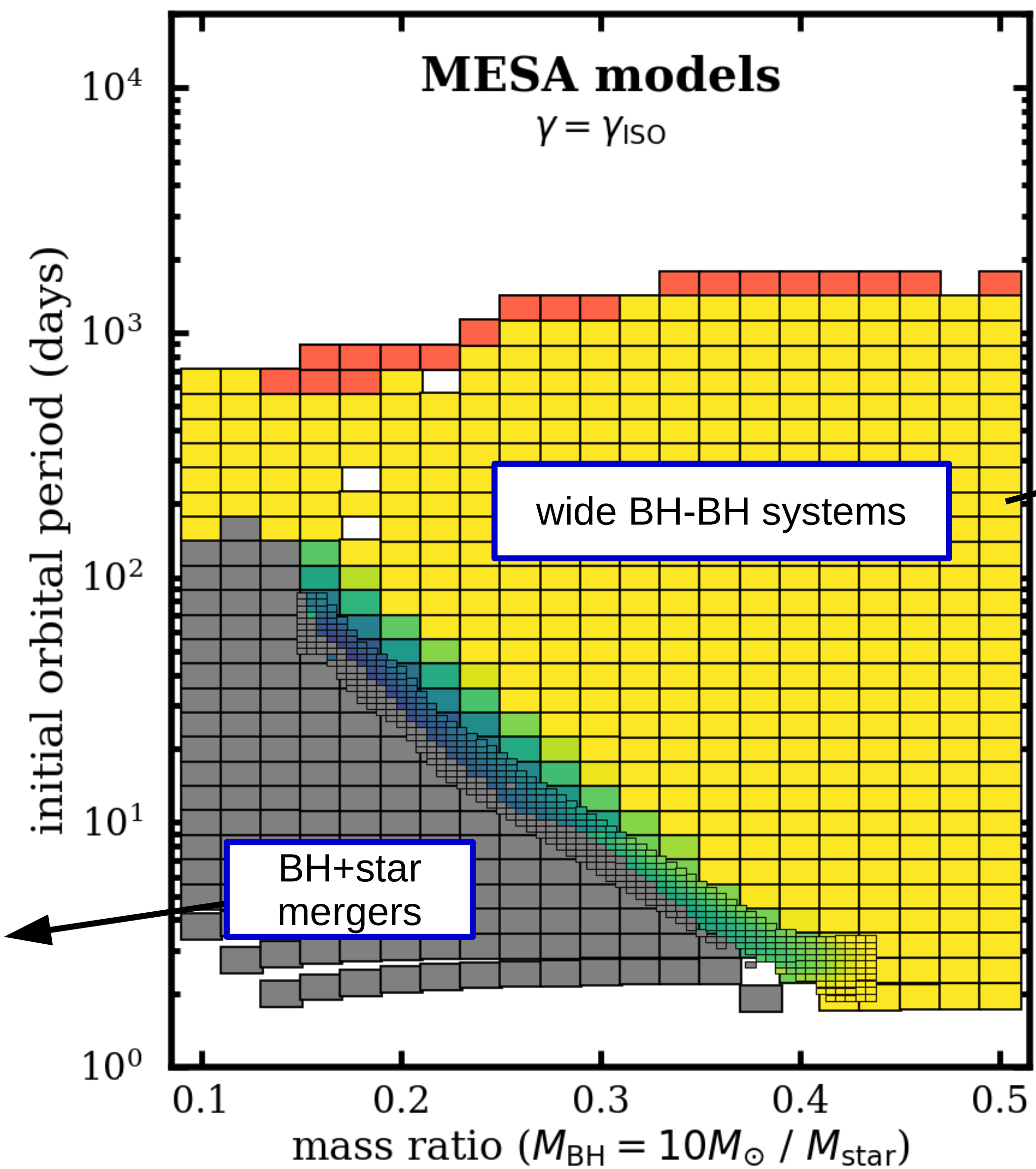

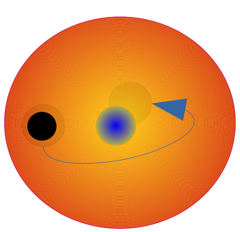

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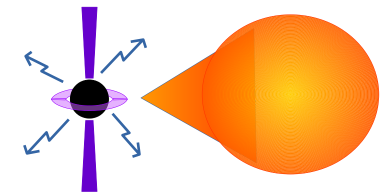
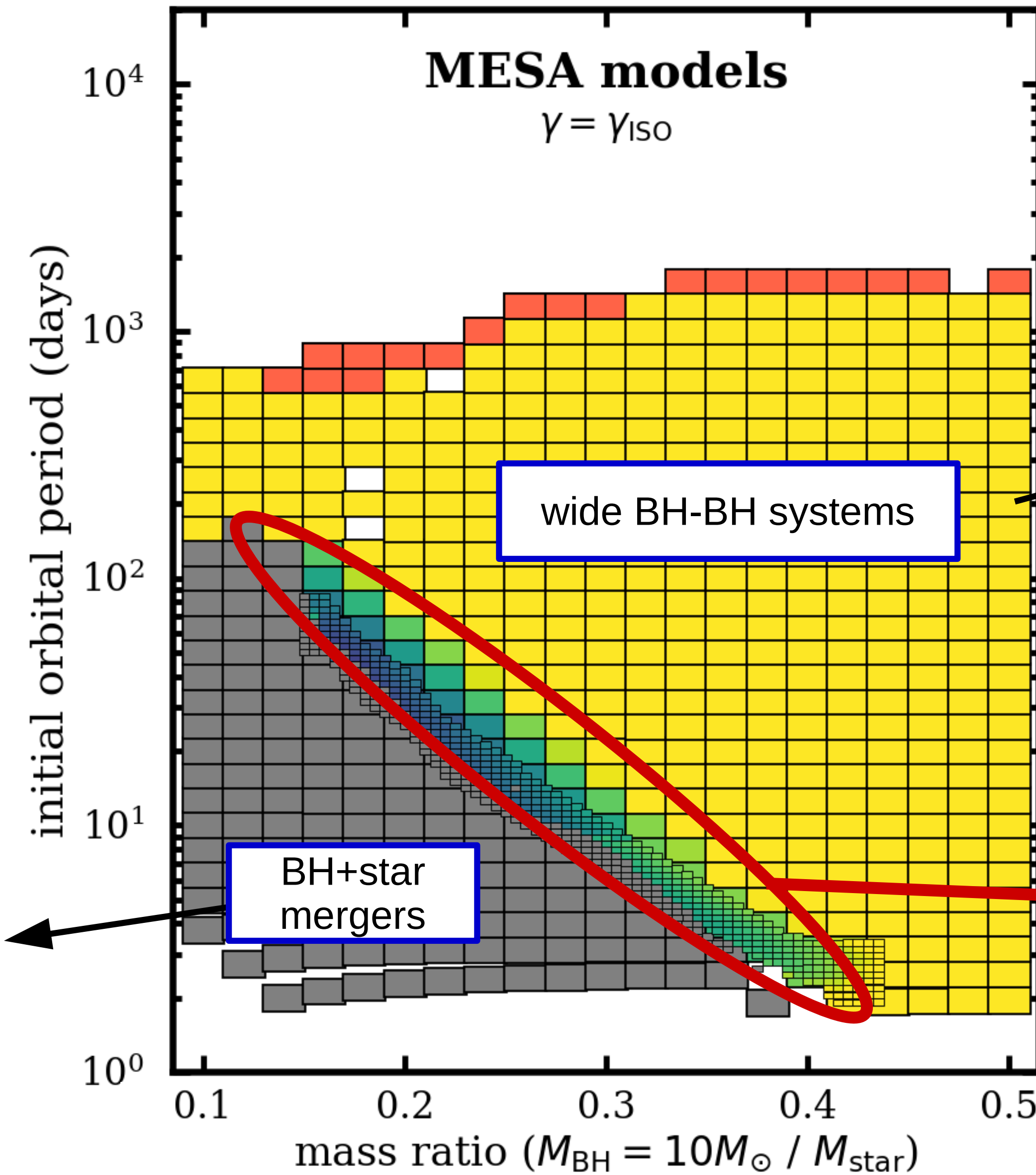
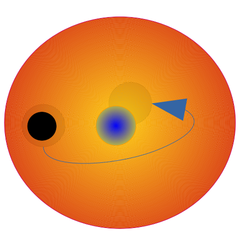
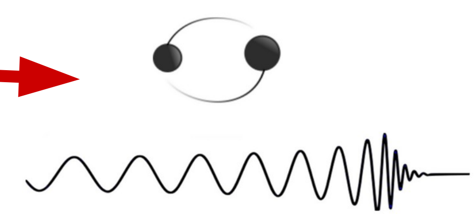






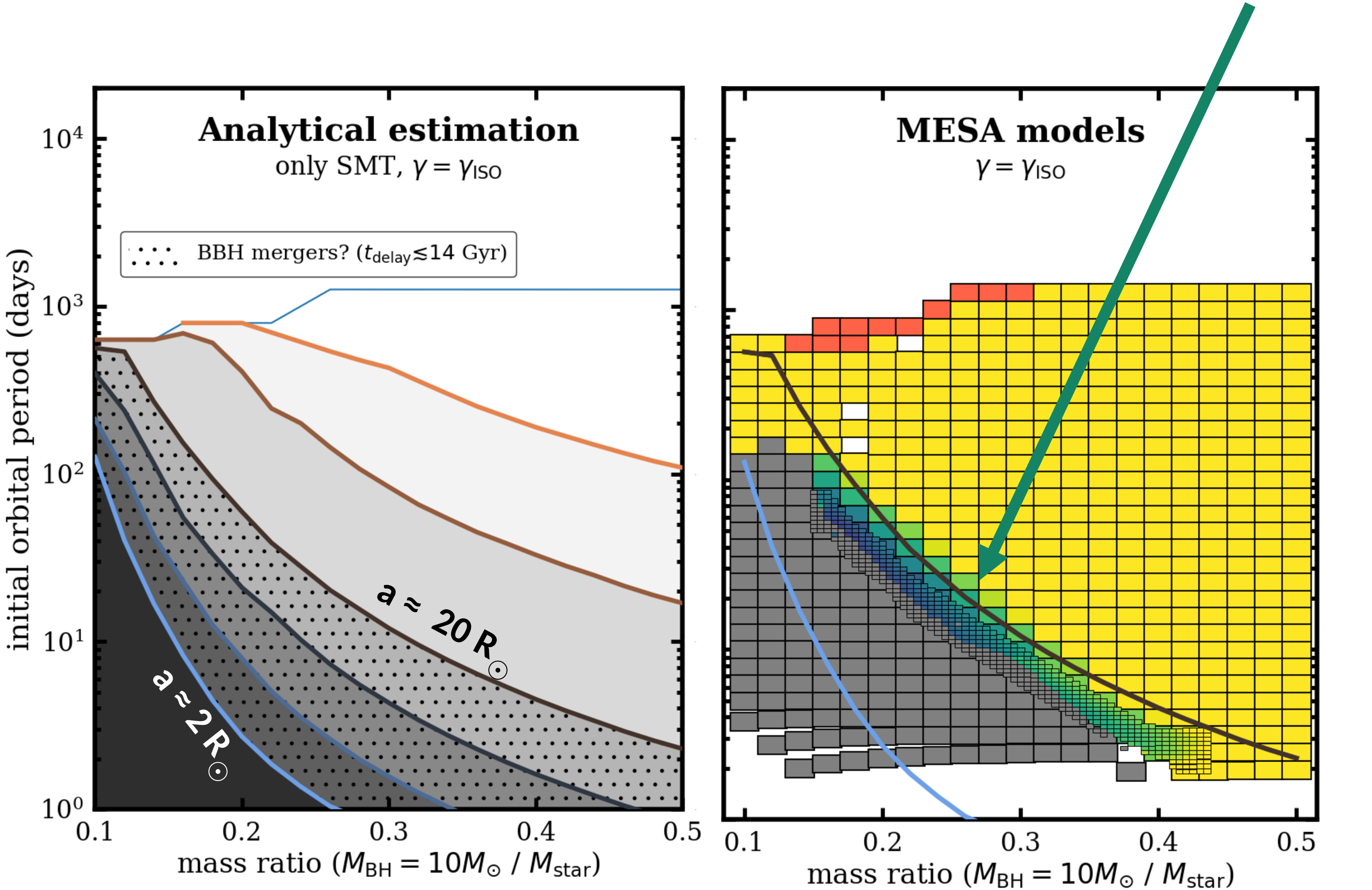
BH sinks
into the stellar core

($t_{tmerge} > t_{Hubble}$)

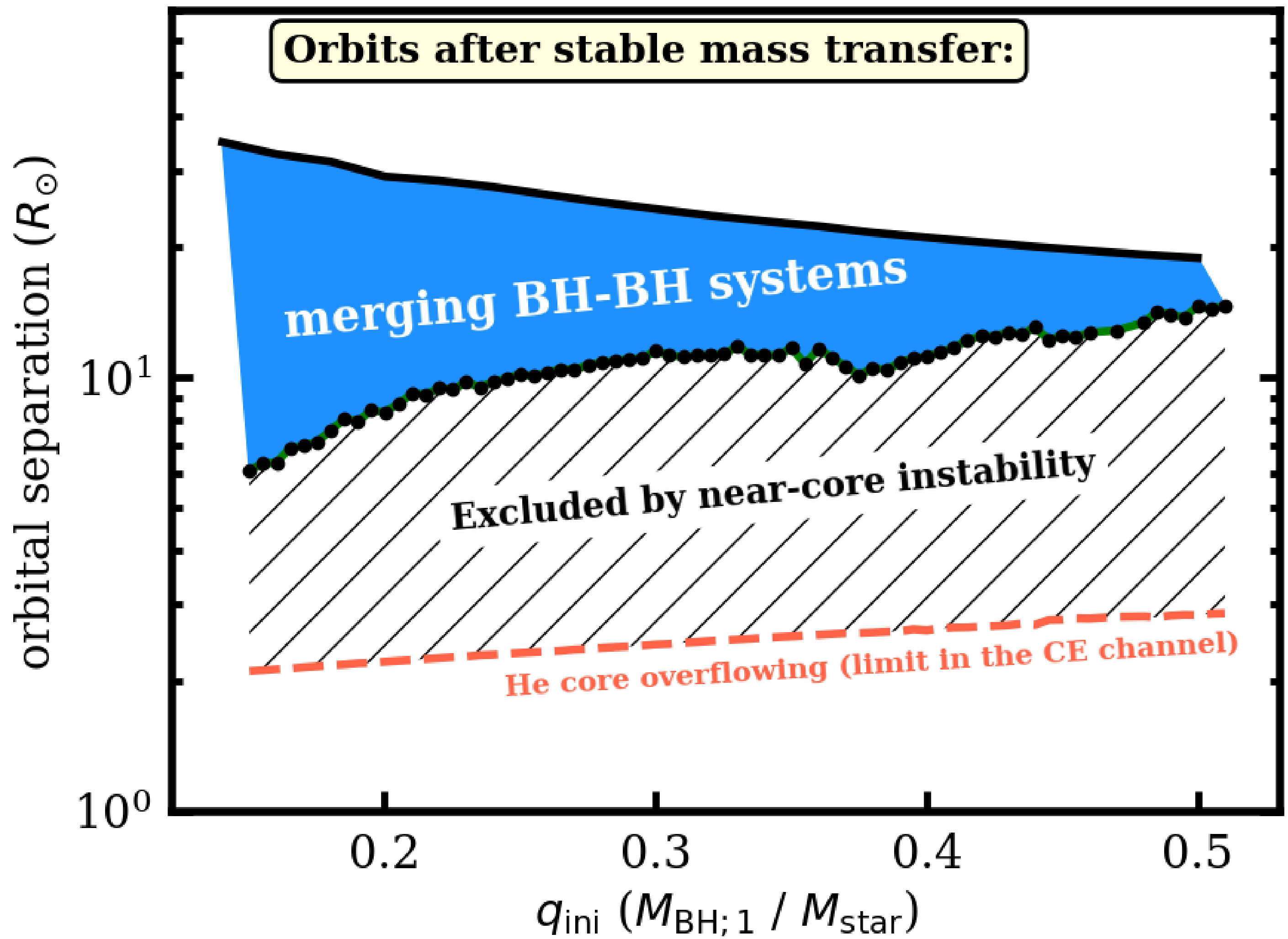


merging binary BH
($t_{tmerge} < t_{Hubble}$)

Comparison: narrow parameter space for BBH mergers in MESA



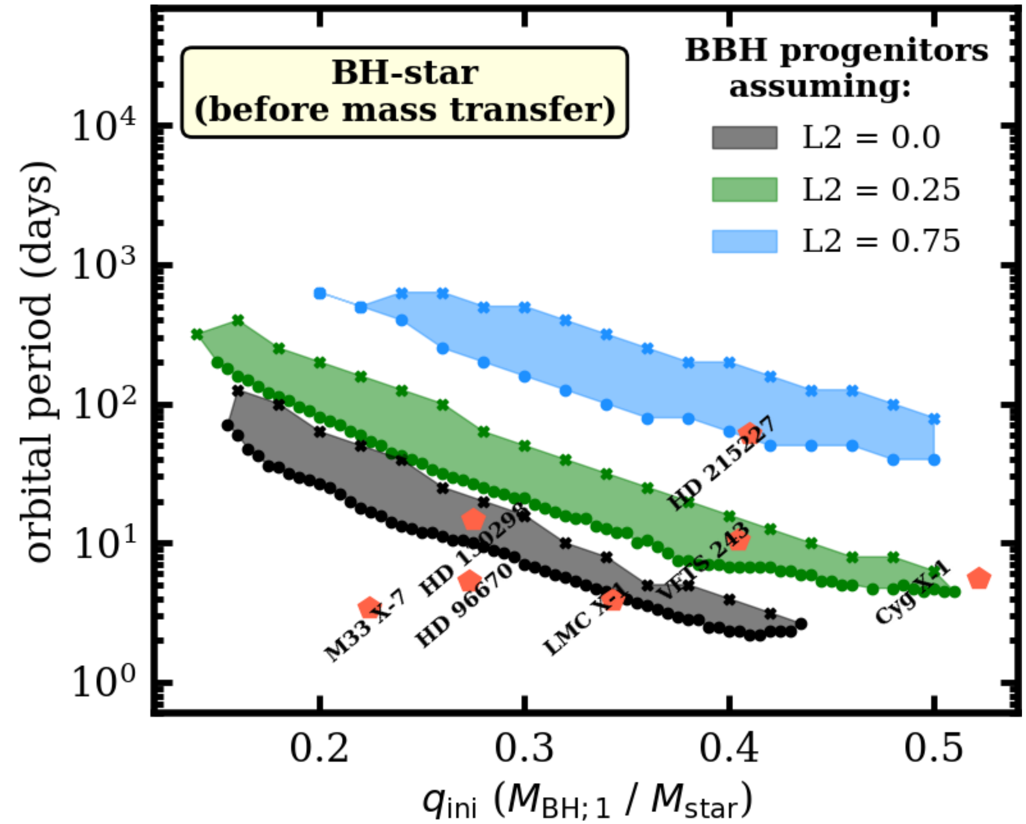
<u>There is a limit</u>: minimum separation from stable mass transfer ~ 10 $R_\odot$

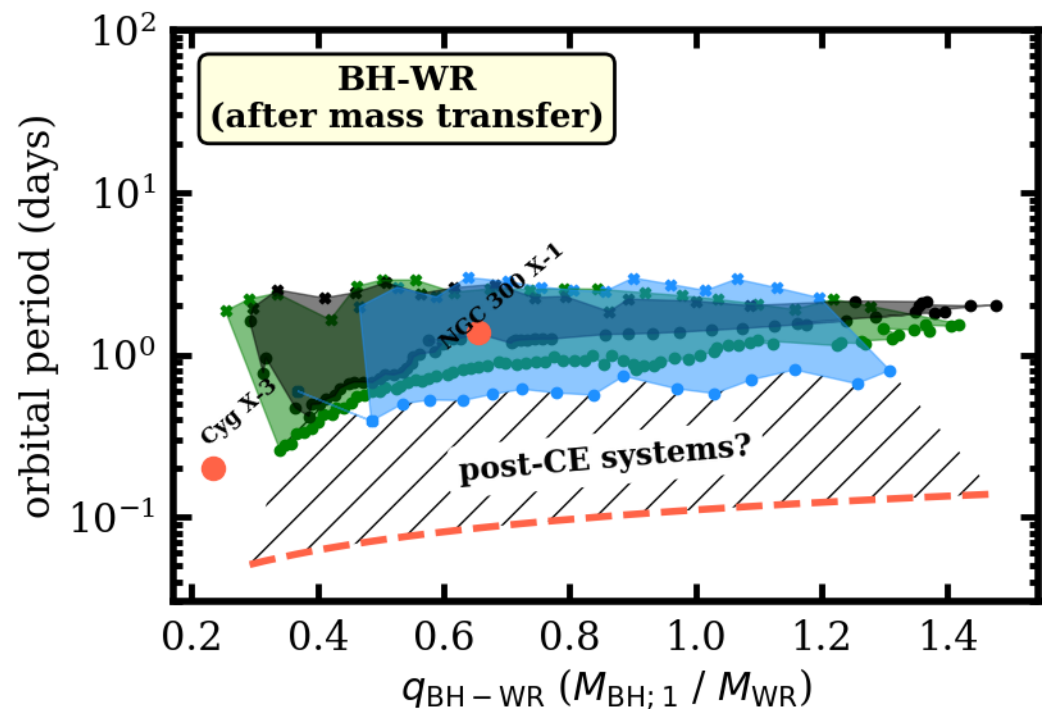


} Fast-merging (t_{del} ~ 100 Myr) + high spins

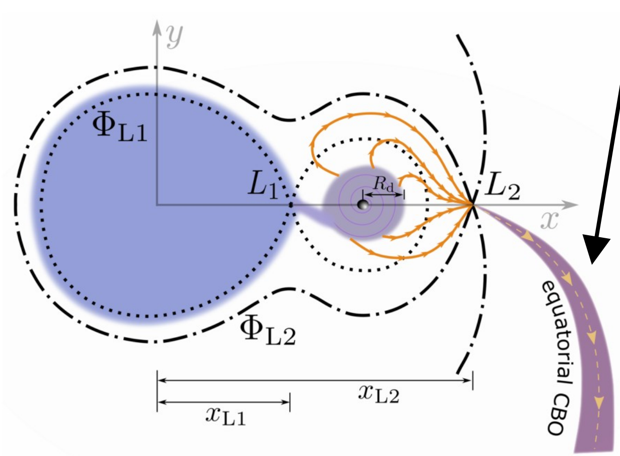
JK+(to be subm.)

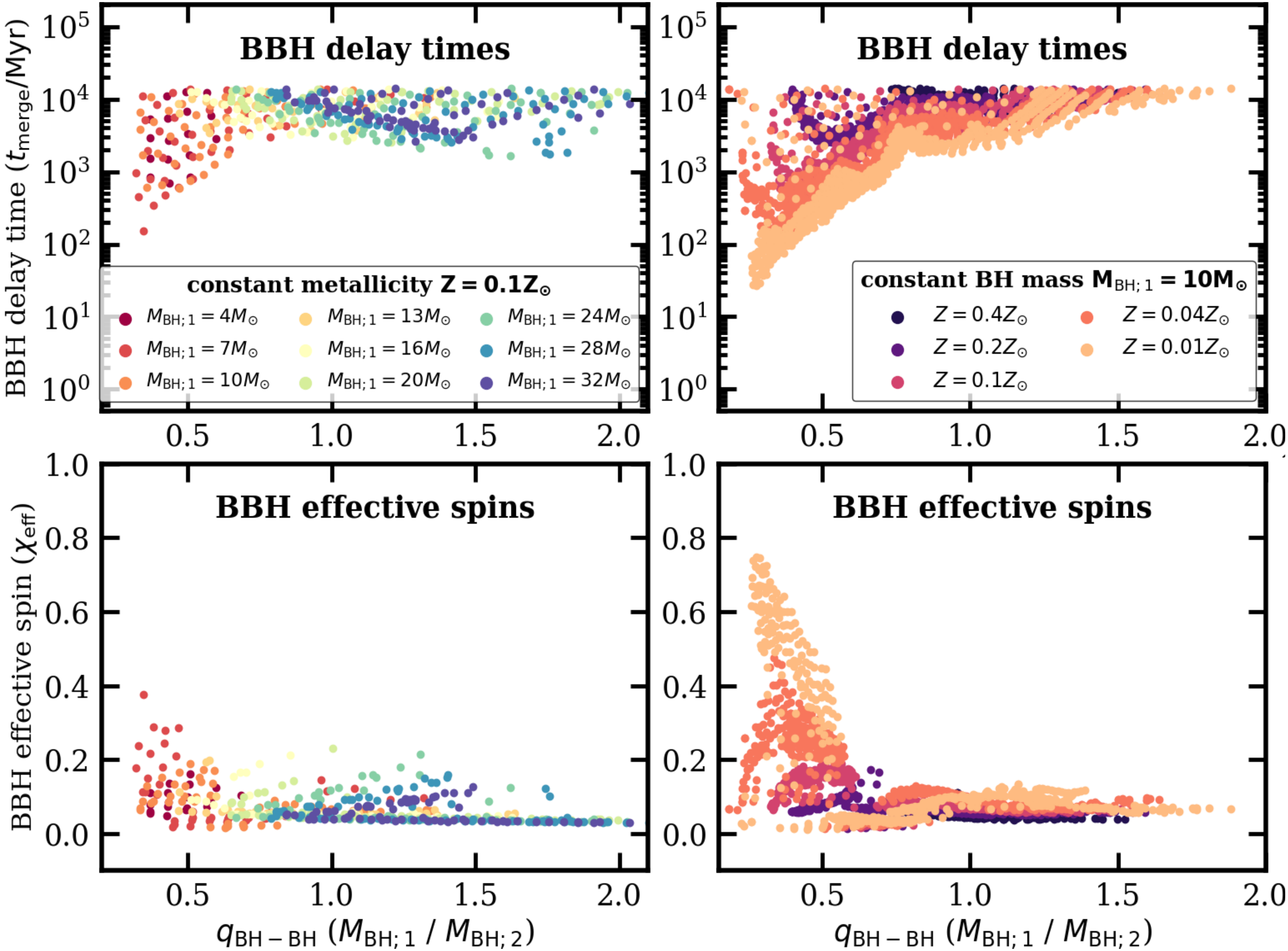
The limit does not disappear even if we significantly boost the orbital shrinkage!





<u>Example:</u>
by L2 outflows carrying lots of orbital angular momentum





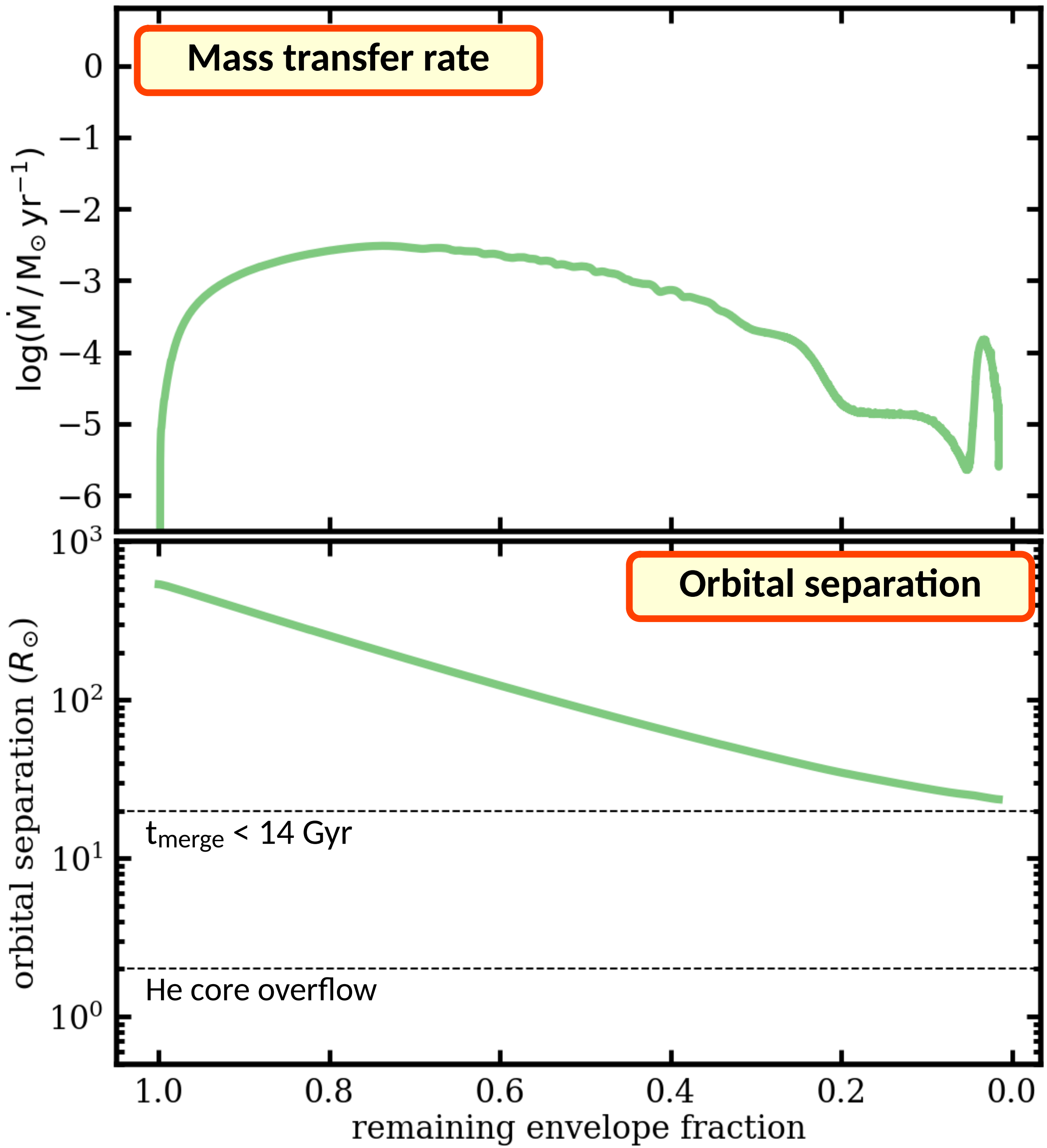
JK+ in prep, also Olejak, JK+24

Why is there a limit?

<u>Example:</u> **30 $M_\odot$ donor**
~250 $R_\odot$ at RLOF

initial mass ratio:

q = 5



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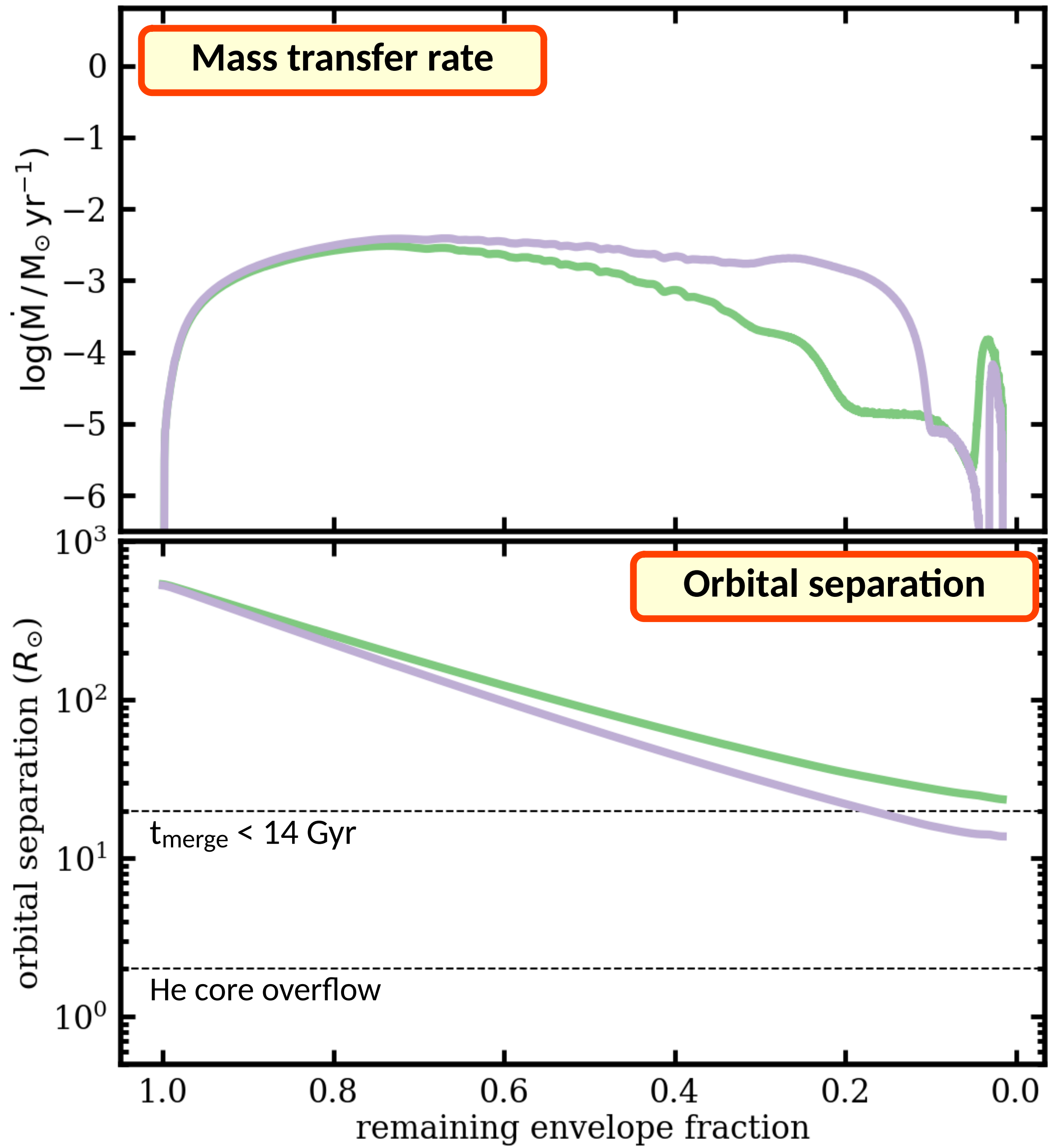


initial mass ratio:

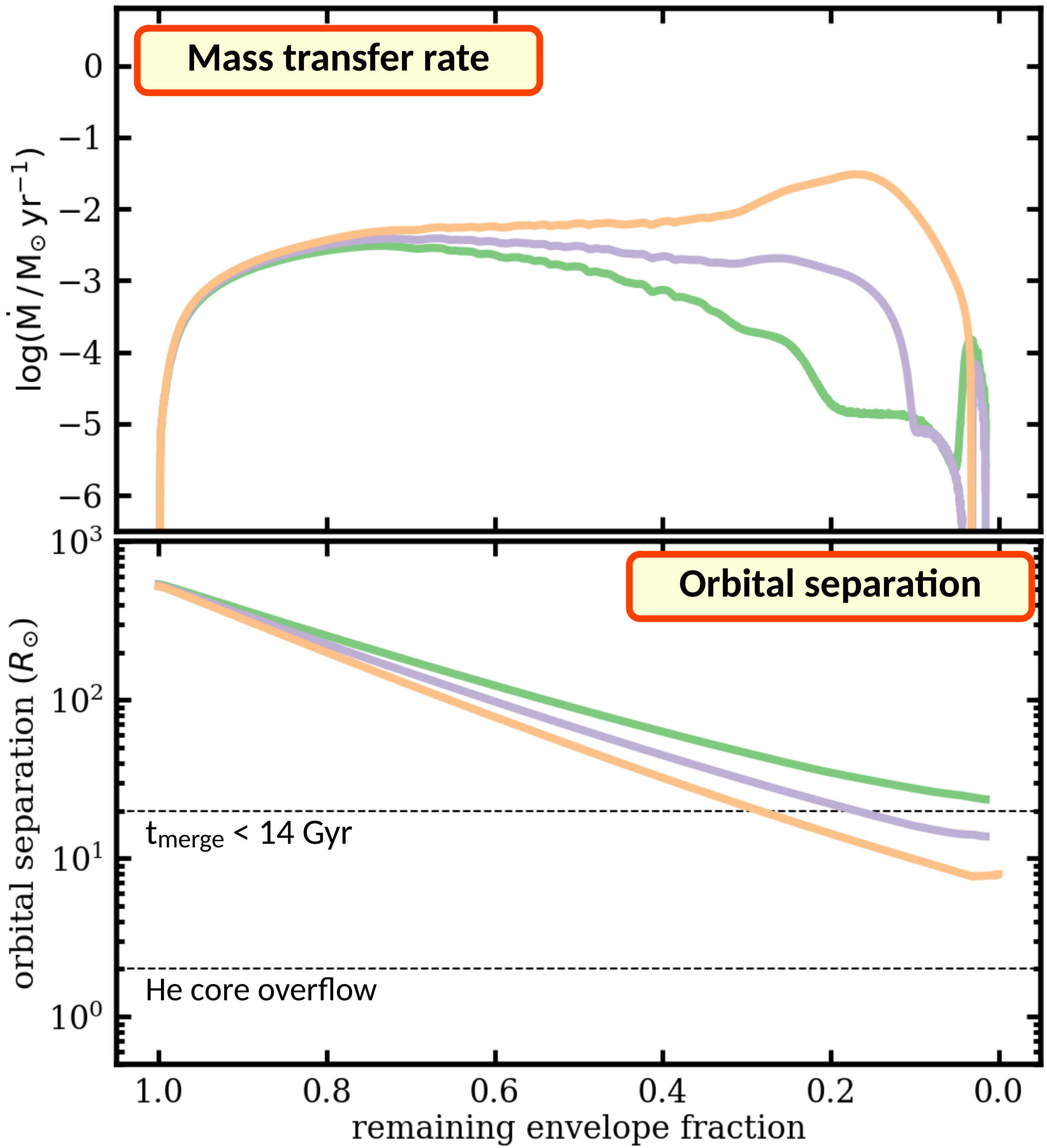
q = 5
q = 5.5

Why is there a limit?

Example: **30 $M_\odot$ donor**
~250 $R_\odot$ at RLOF

initial mass ratio:

- q = 5
- q = 5.5
- q = 6



Why is there a limit?

Example: **30 $M_\odot$ donor**
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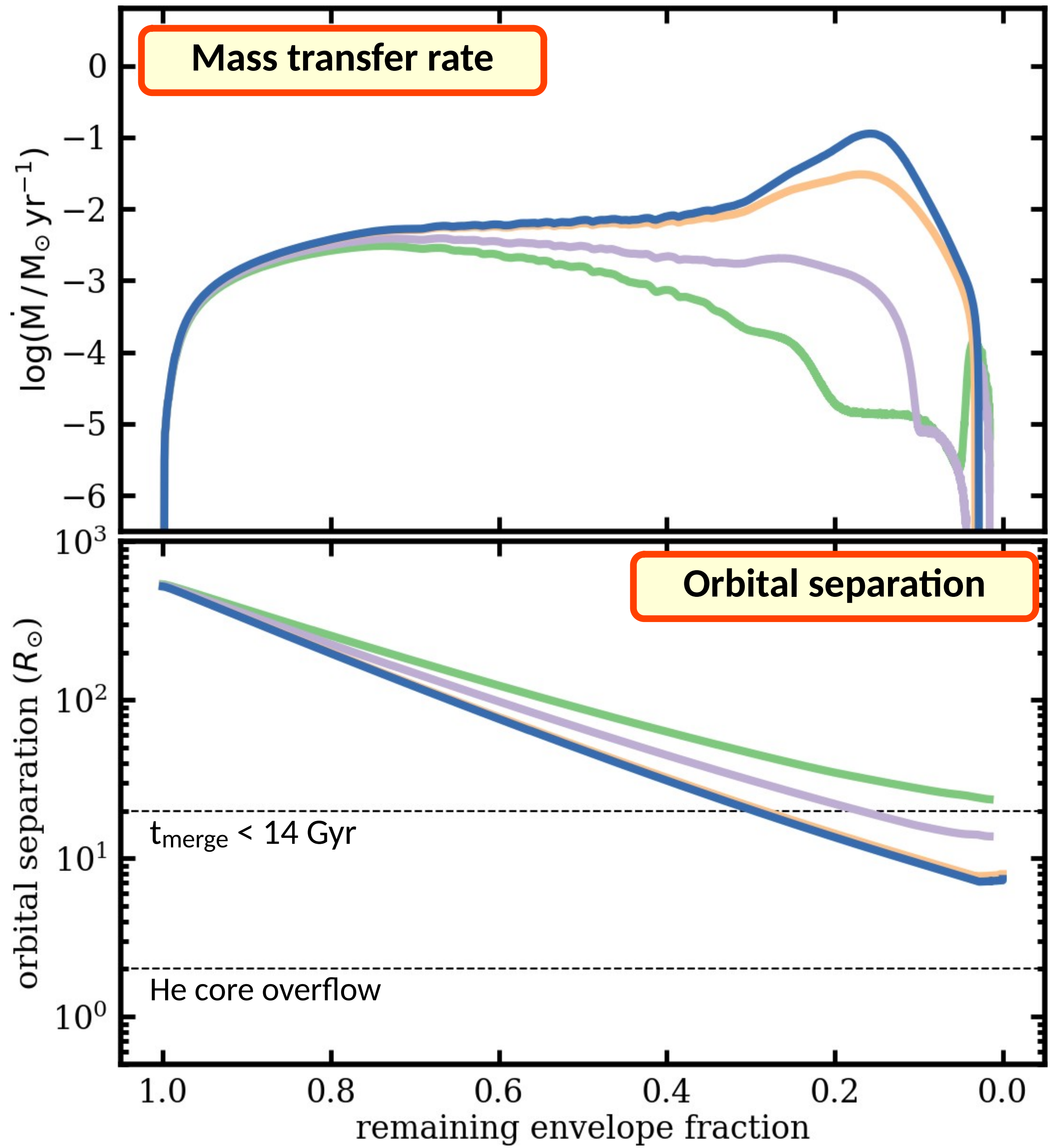
initial mass ratio:

q = 5
q = 5.5
q = 6
q = 6.06



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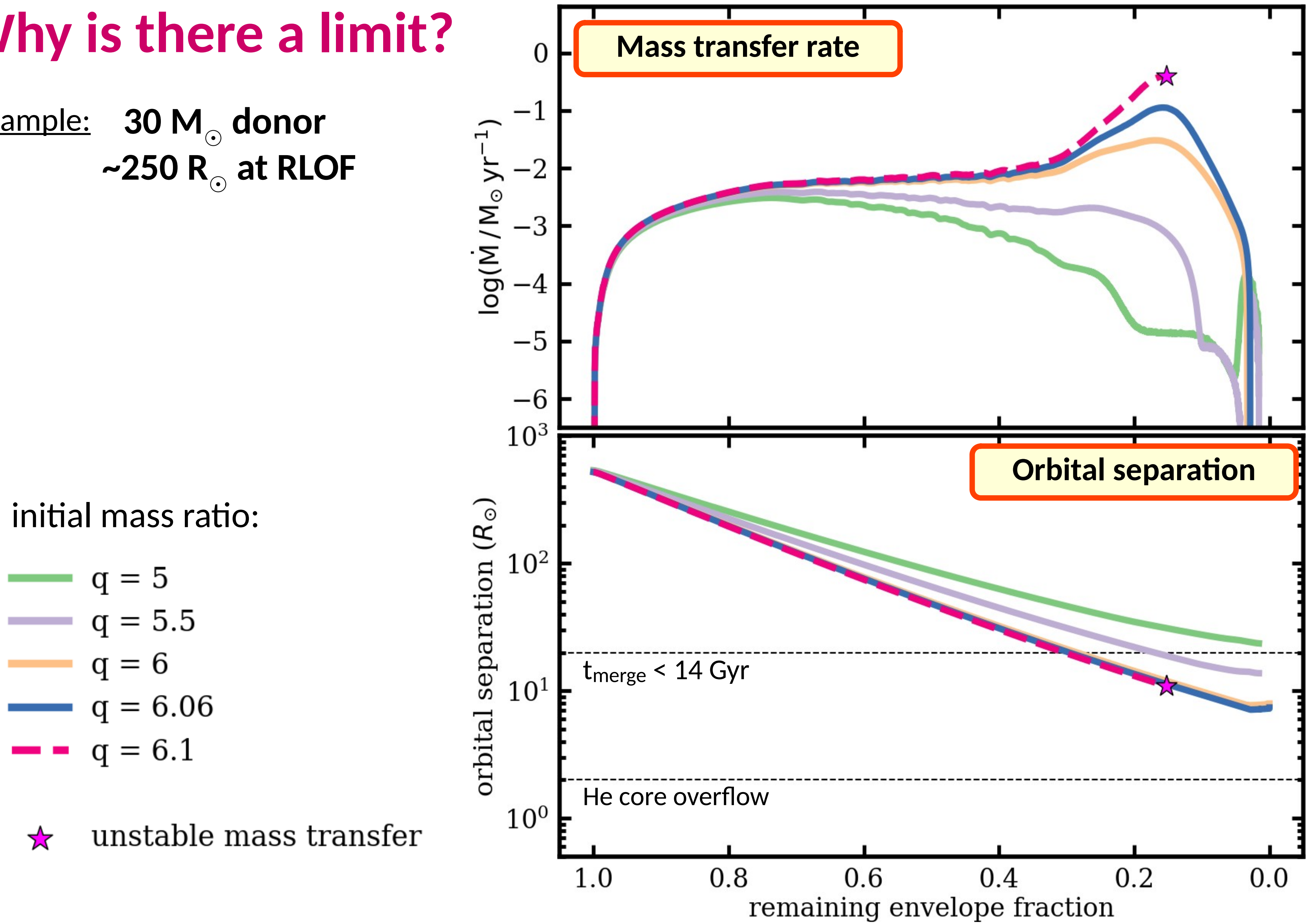
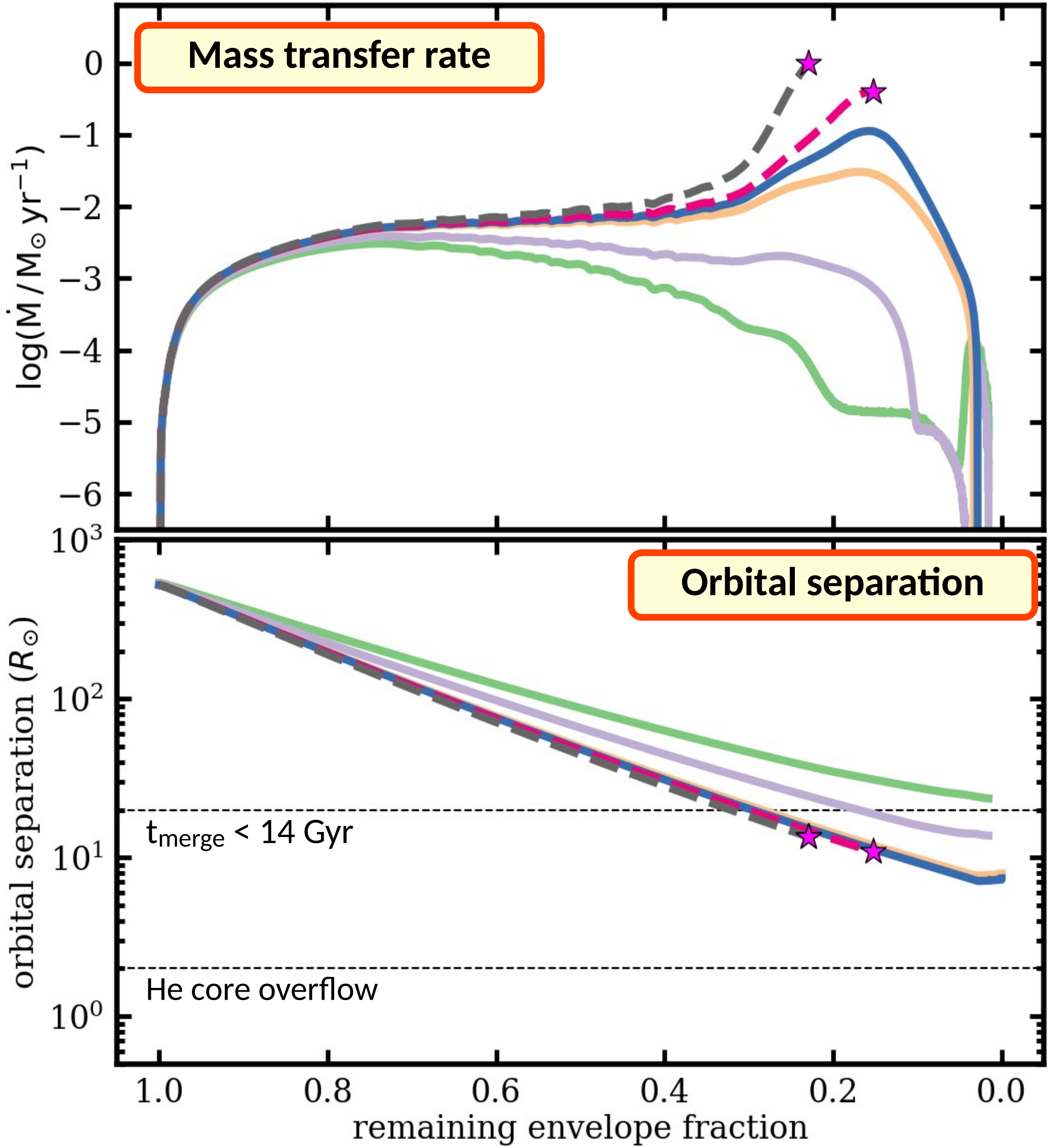


Why is there a limit?

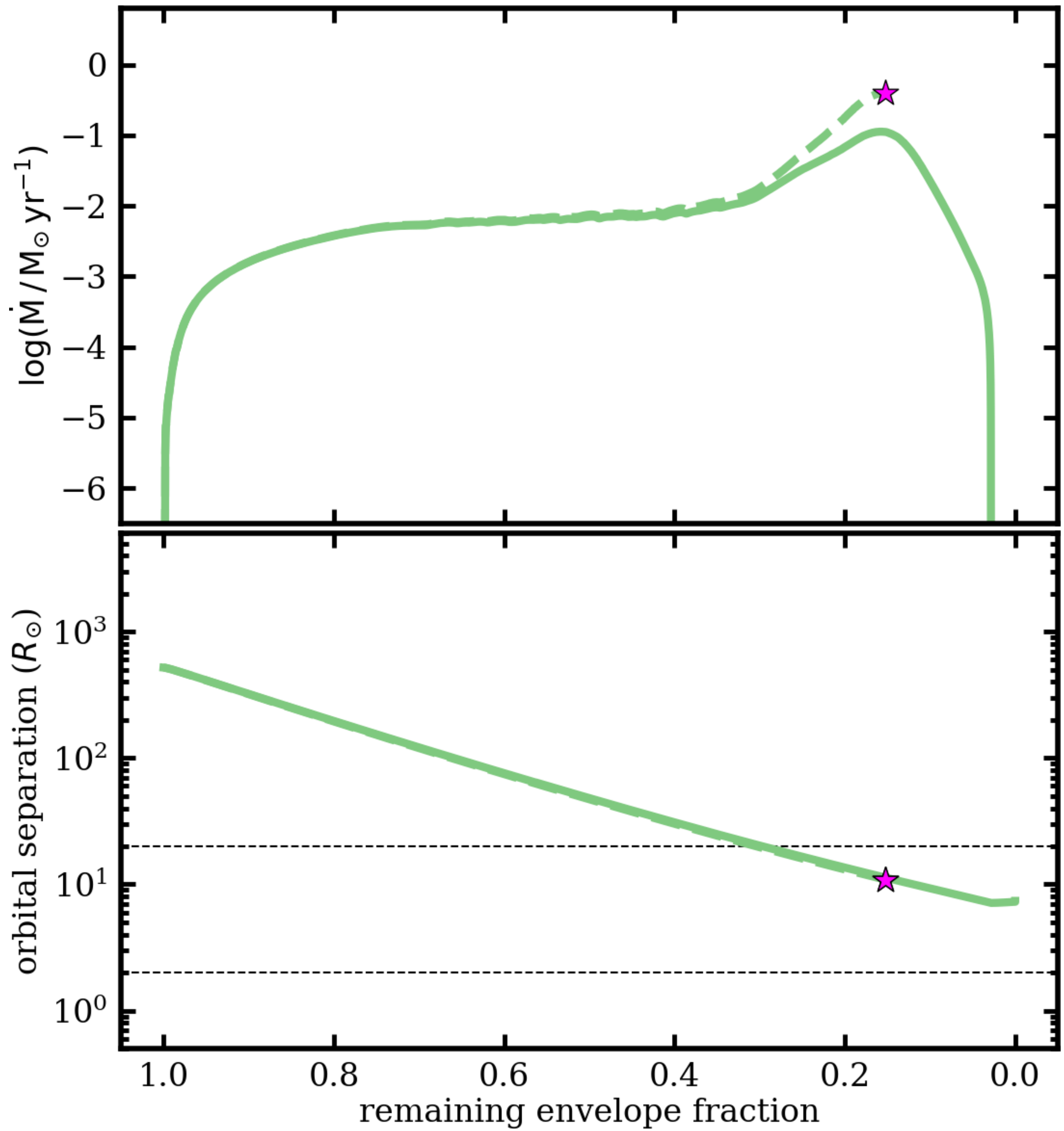
Example: **30 $M_\odot$ donor**
~250 $R_\odot$ at RLOF

initial mass ratio:

- q = 5
- q = 5.5
- q = 6
- q = 6.06
- q = 6.1
- q = 6.2
- ☆ unstable mass transfer



Minimum separation depends on the donor star



Donor star:

core-He burning blue supergiant

unstable mass transfer

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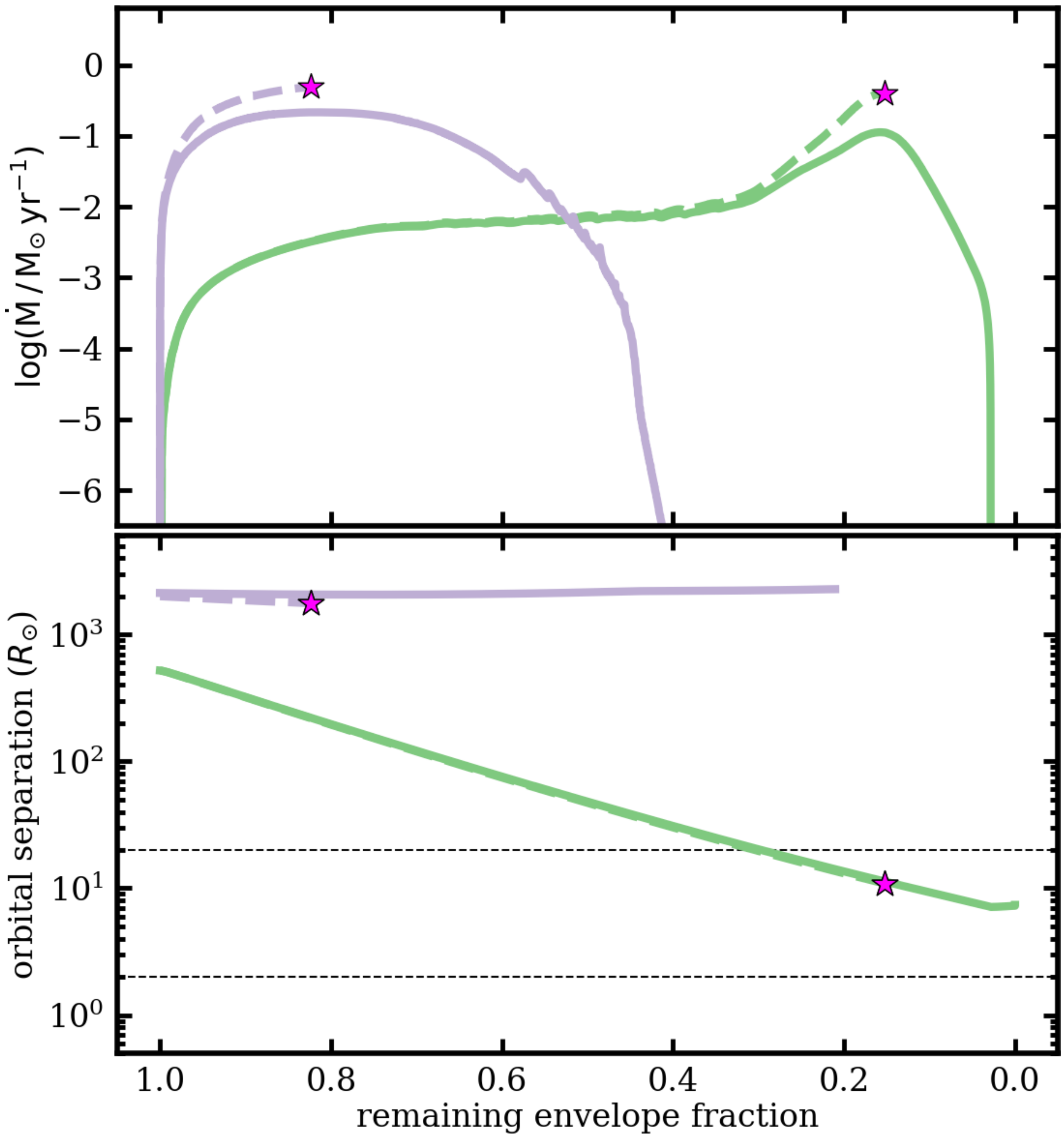


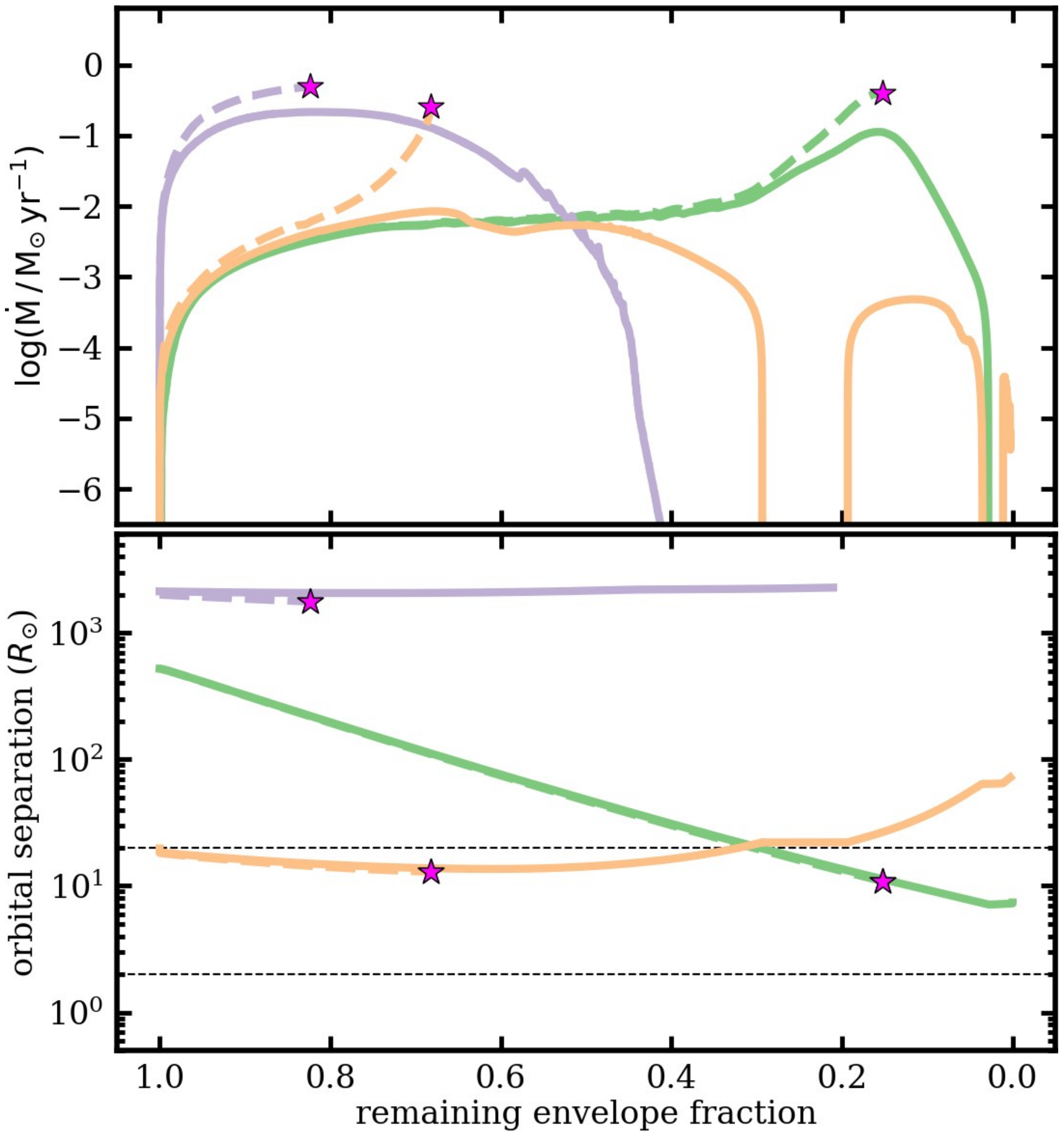
Donor star:

core-He burning blue supergiant

convective envelope red supergiant

★ unstable mass transfer

Minimum separation depends on the donor star

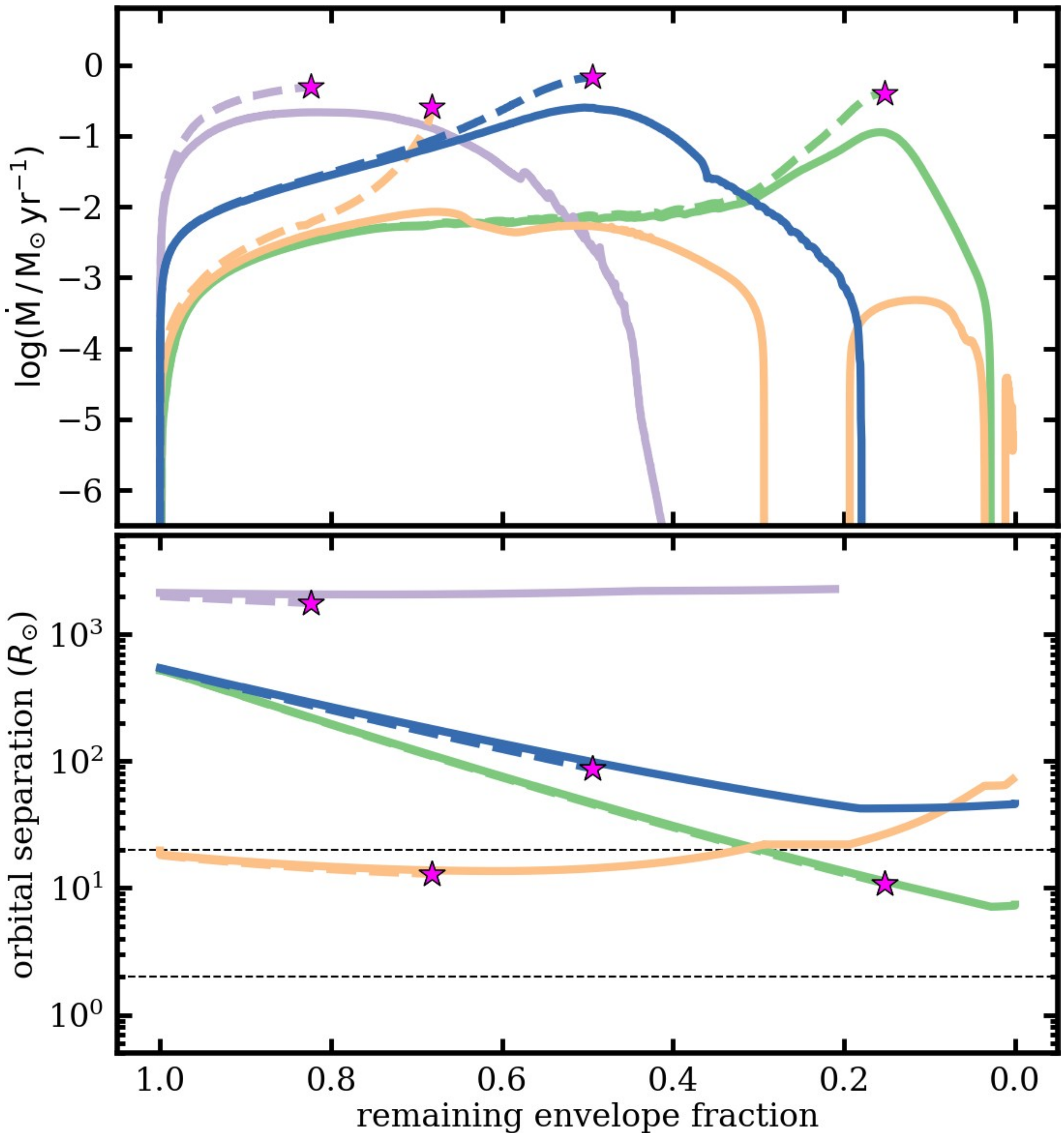


Donor star:

- core-He burning blue supergiant
- convective envelope red supergiant
- Main Sequence star

★ unstable mass transfer

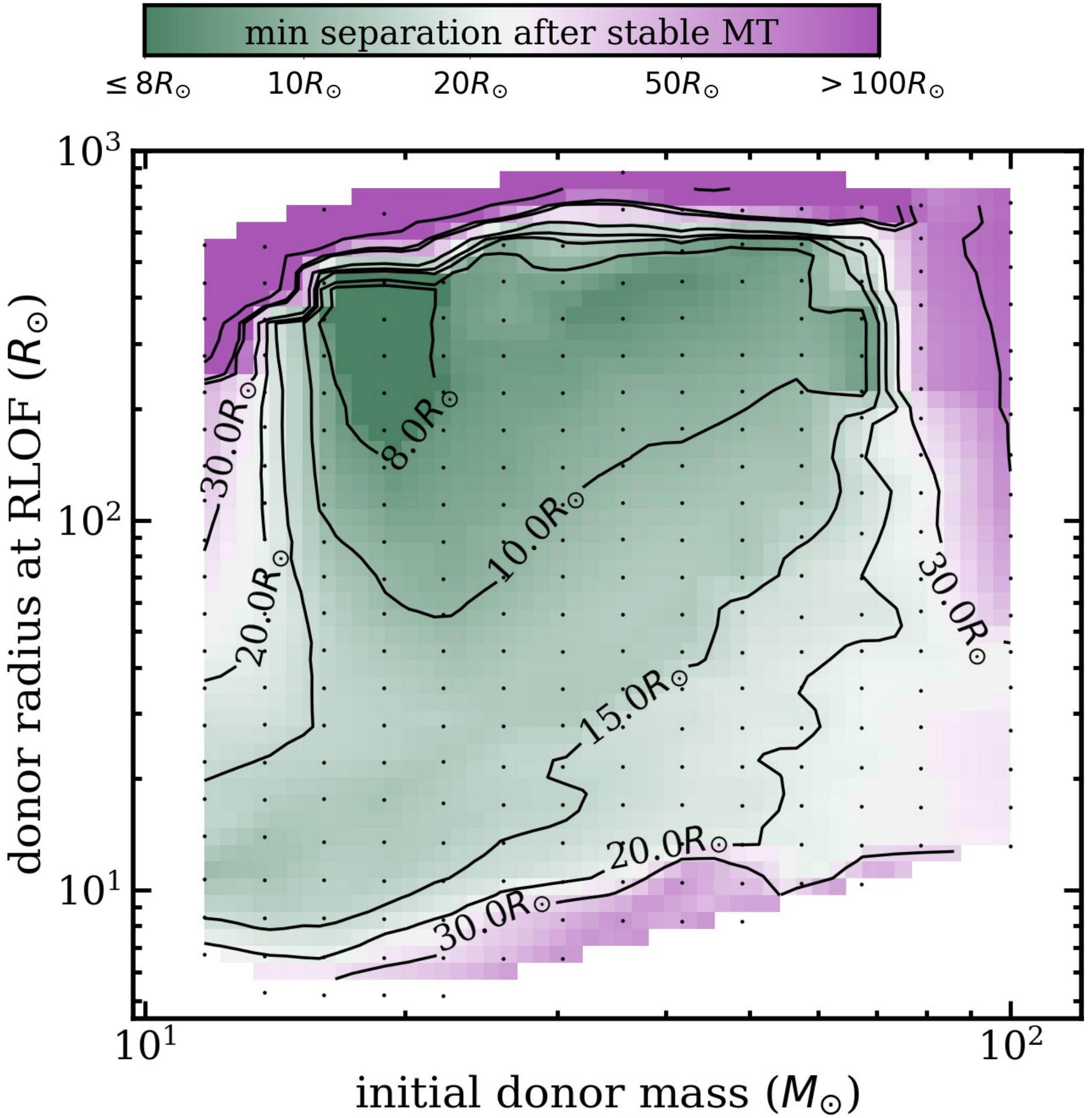
Minimum separation depends on the donor star



Donor star:

- core-He burning blue supergiant
- convective envelope red supergiant
- Main Sequence star
- Hertzprung Gap blue supergiant
- ★ unstable mass transfer

Which stars do we need for the stable MT channel?



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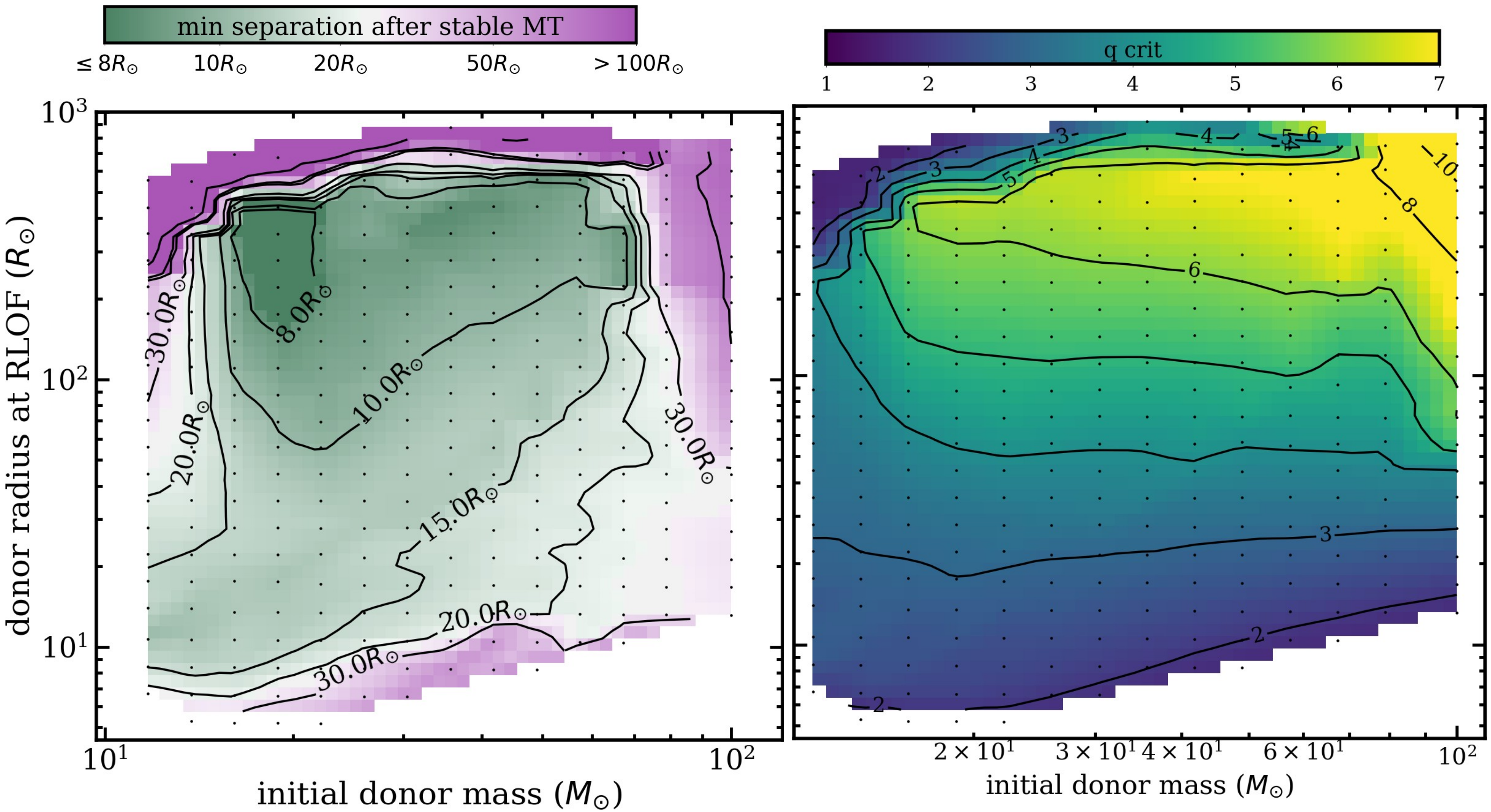
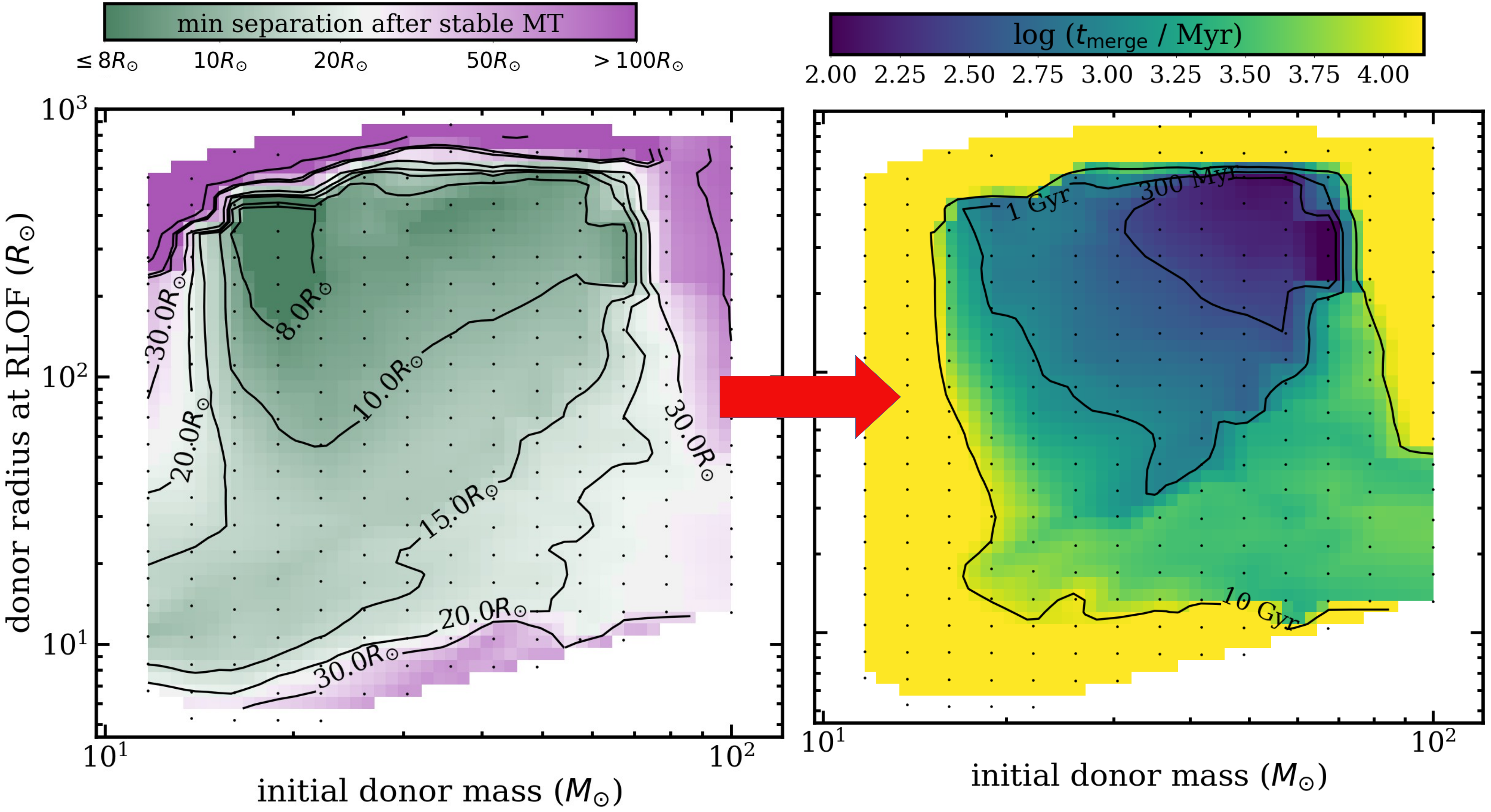
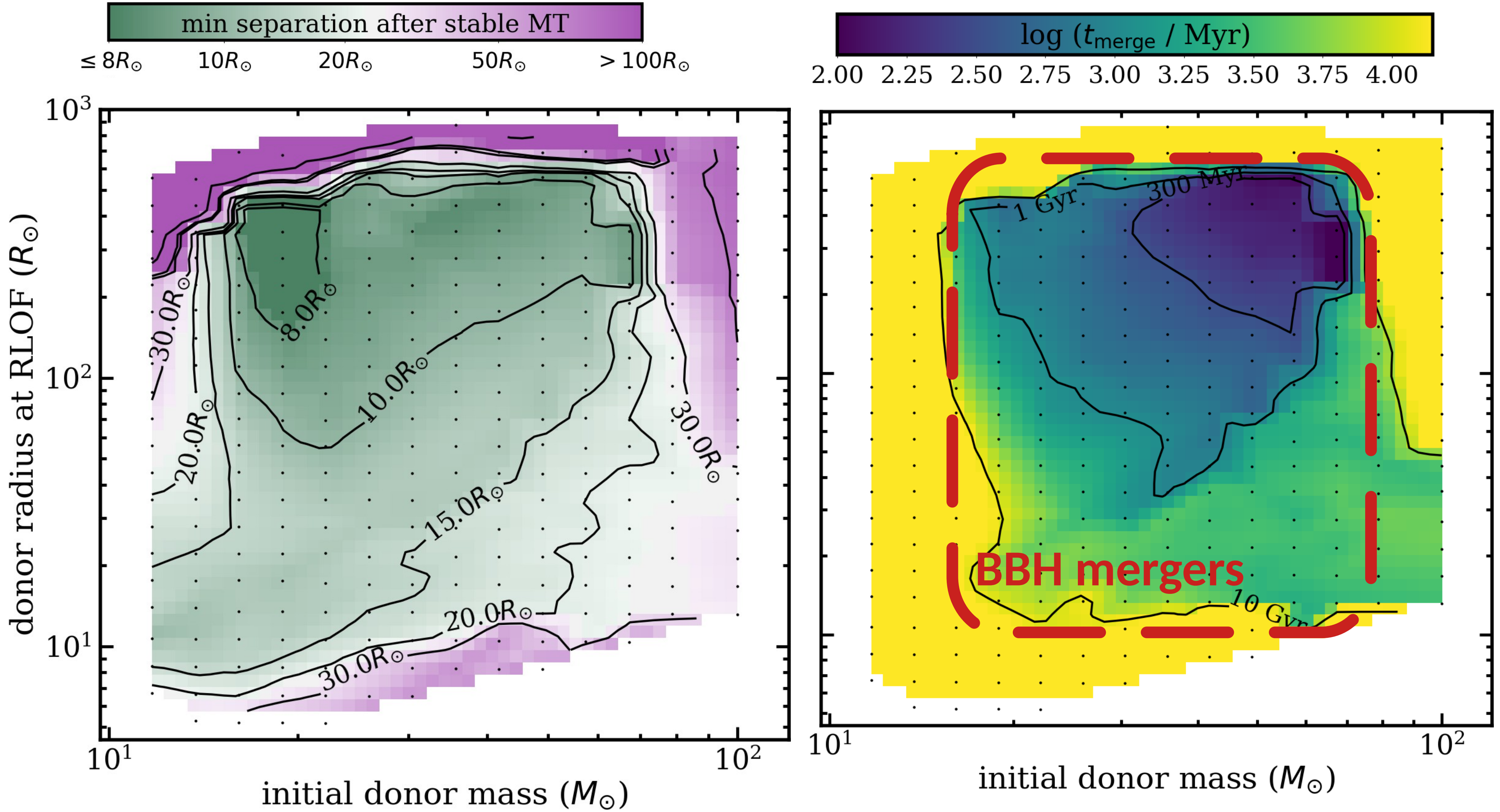


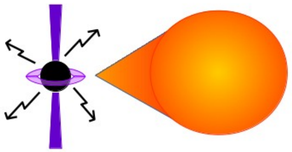
Which stars do we need for the stable MT channel?

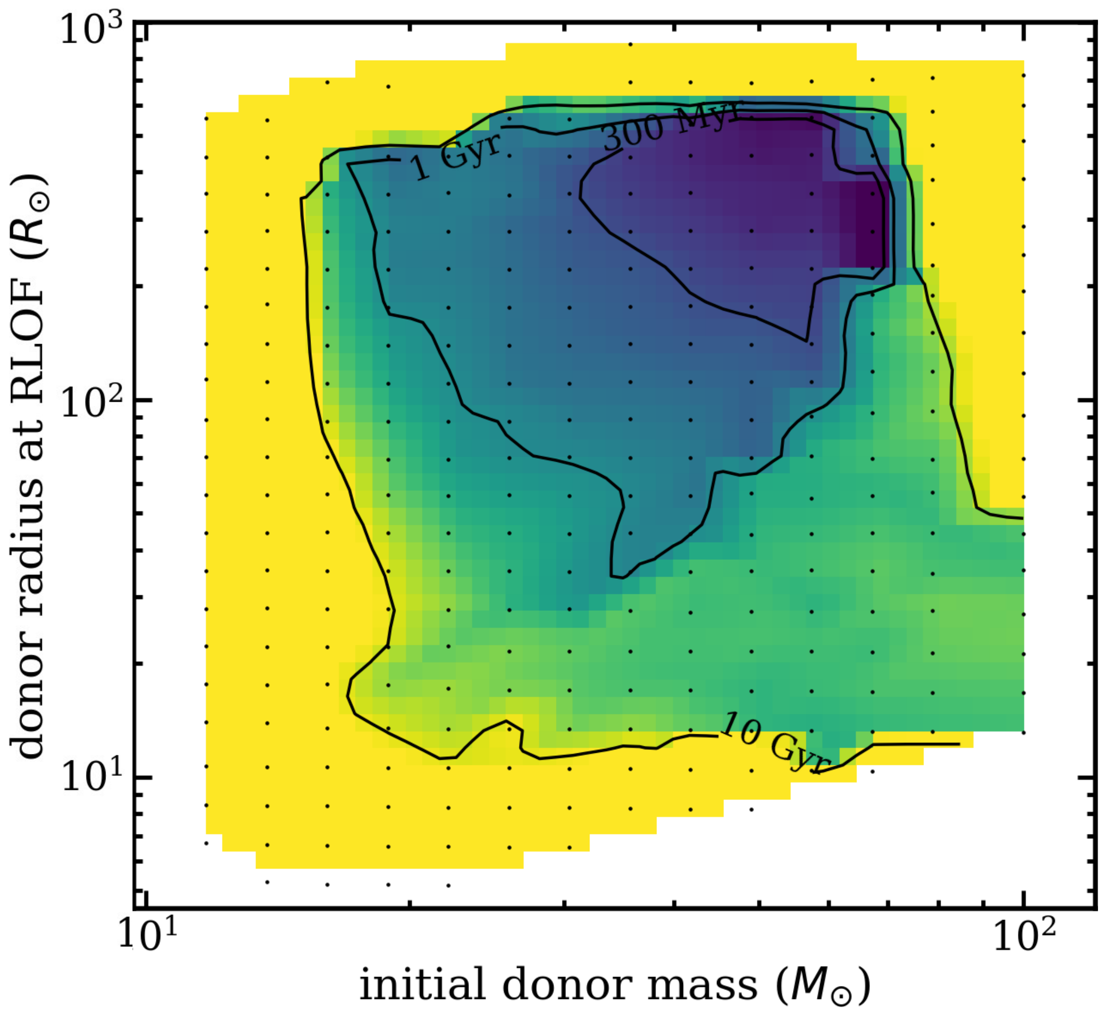


Which stars do we need for the stable MT channel?



Stars that do not work? (yellow)





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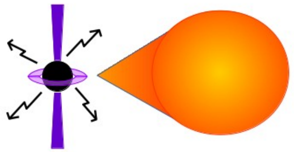
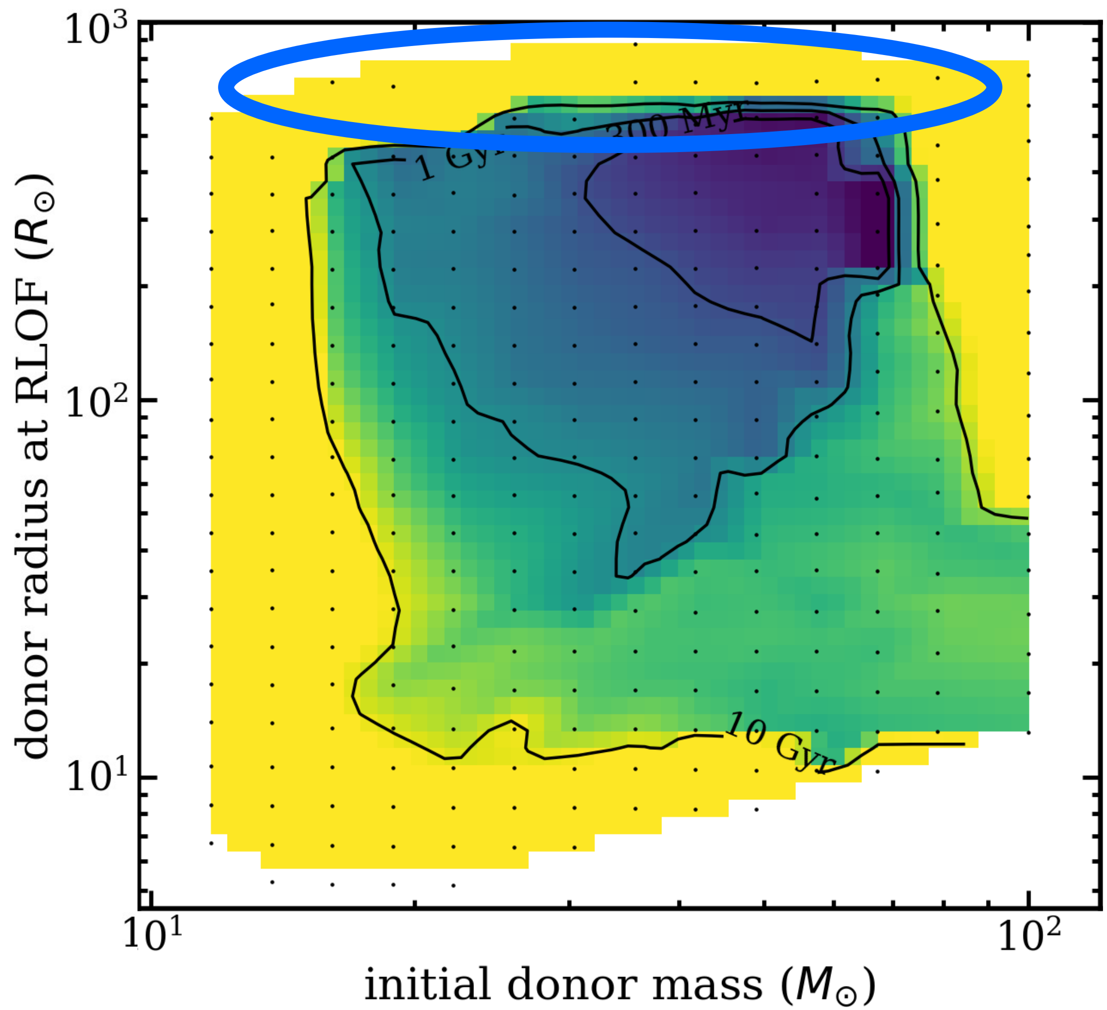


Convective-envelope stars



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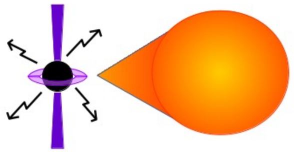
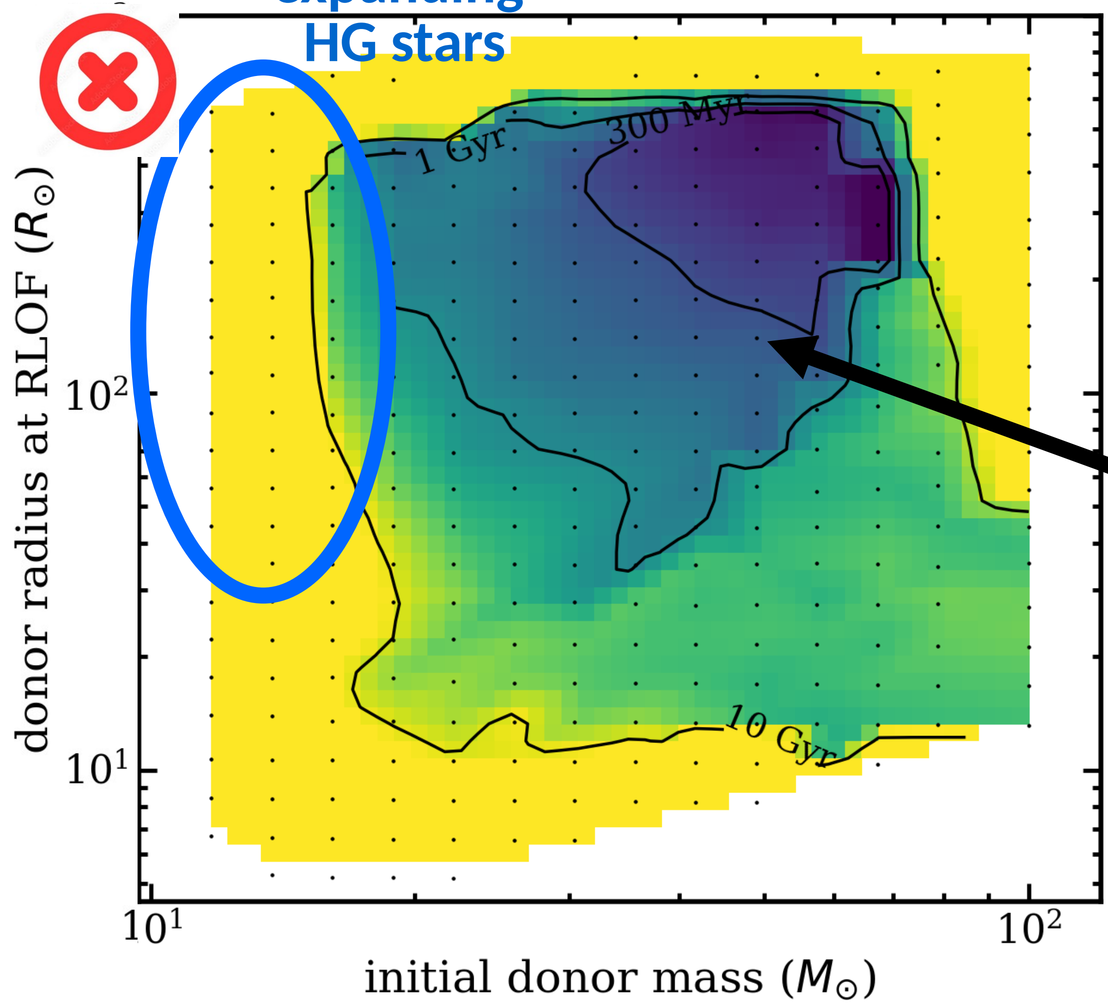
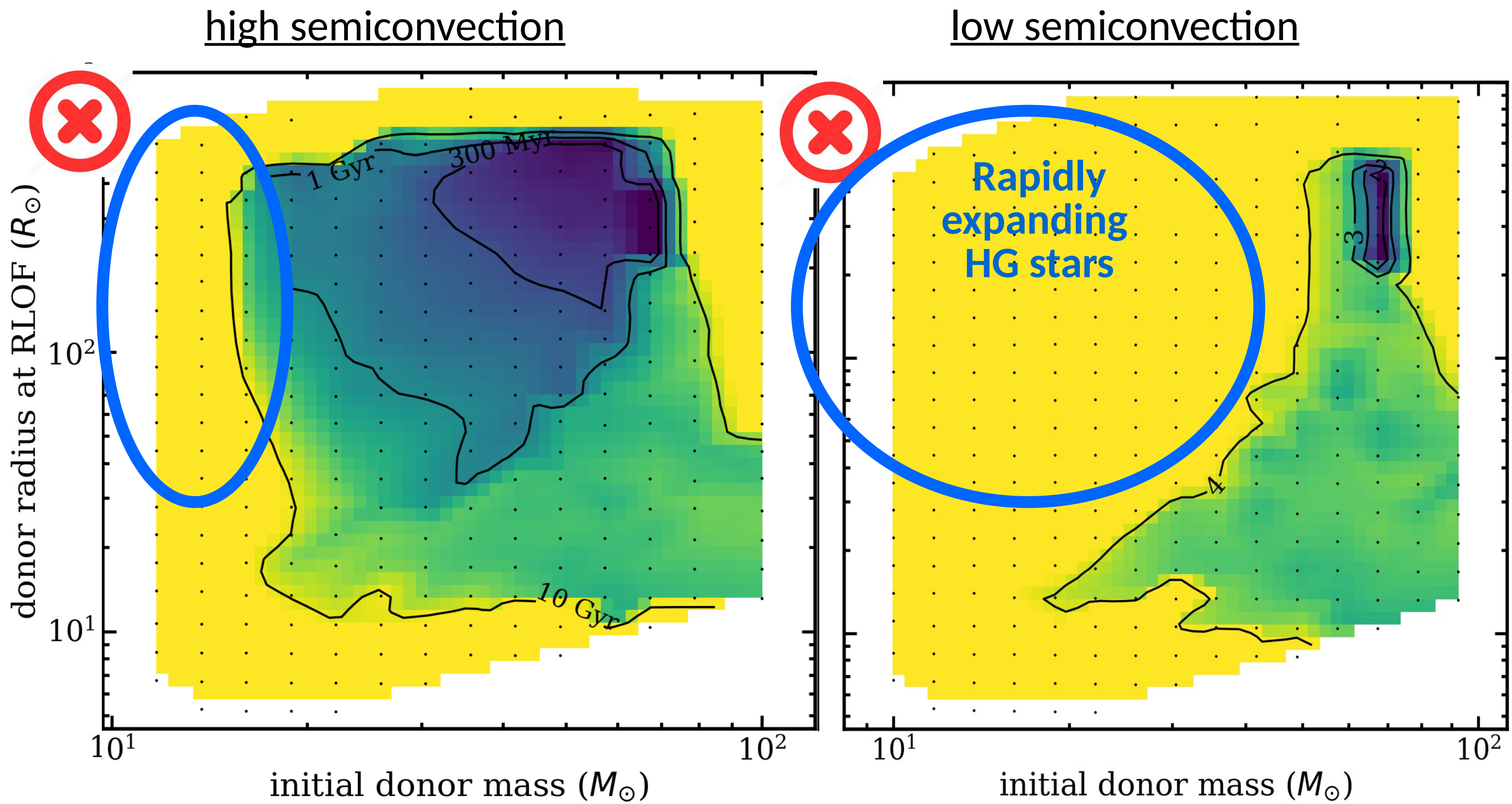


Rapidly expanding HG stars



Core-He burning stars

Huge variation with stellar models(!)



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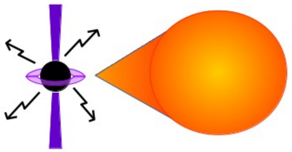

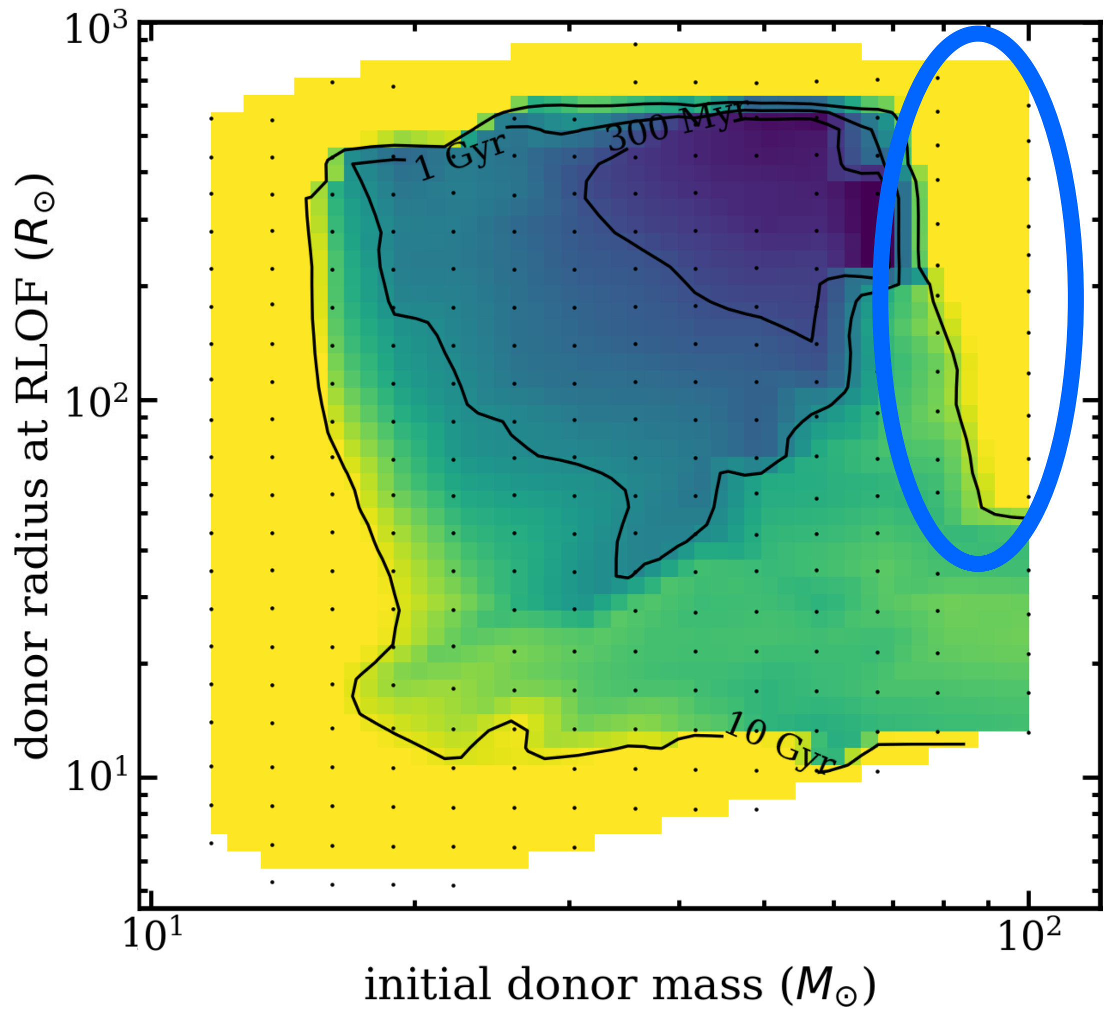

He-enriched envelopes

Very massive stars transfer ~20-40% of the envelope and then contract

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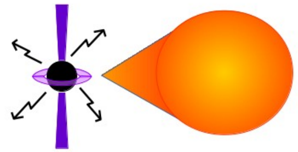
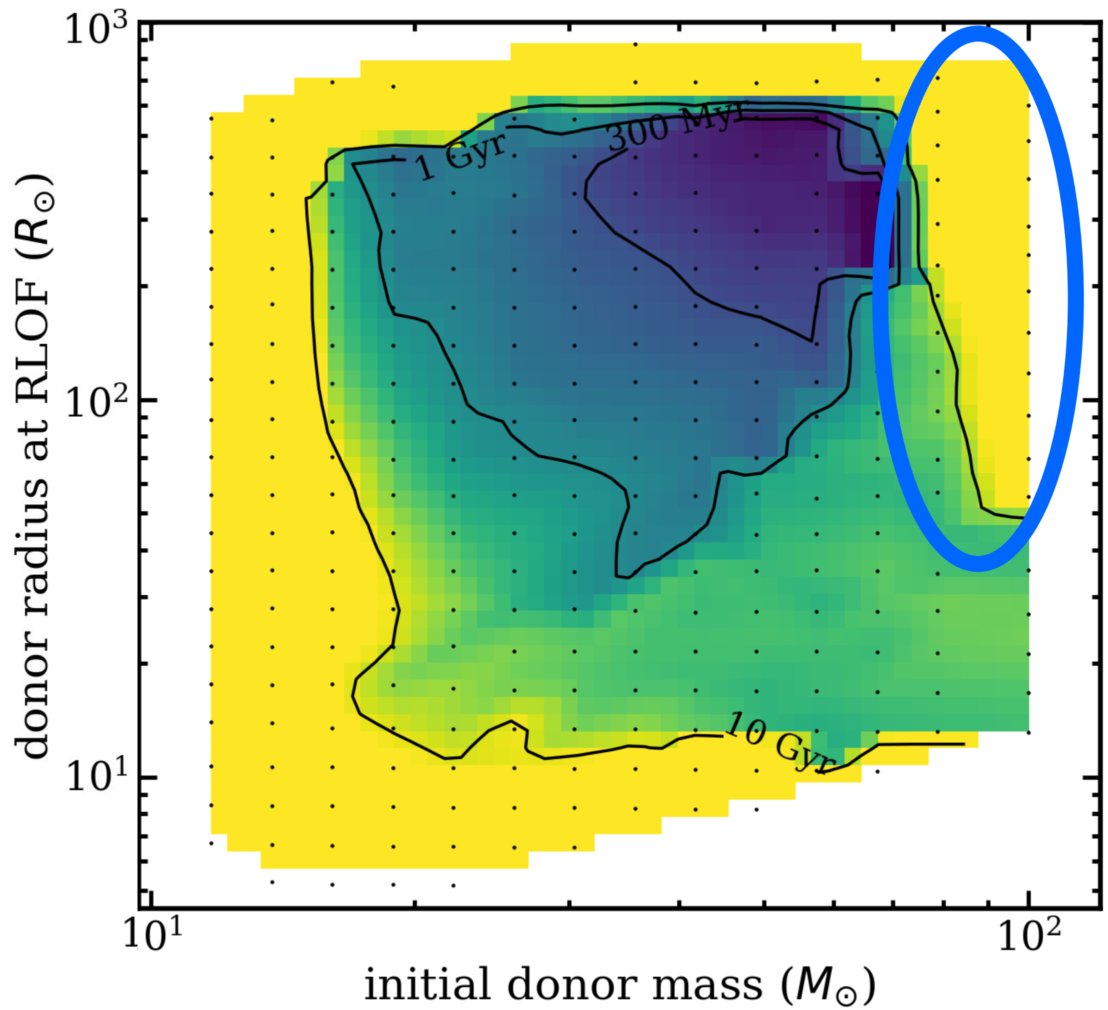




He-enriched envelopes ❌

↓

Very massive stars transfer ~20-40% of the envelope and then contract

↓

Mass transfer channels may fall off for >30 $M_\odot$ BH

hence no PPISN pile-up?

XShootU
The ULLYSES and X-Shooter massive stars collaboration

- Stellar winds at low metallicity
- Spectra & ionizing feedback of massive hot stars
- Chemically homogeneous evolution?

Vink et al. 2023

BLOEM
Binarity at LOw Metallicity

- Stellar multiplicity at subsolar metallicity (SMC)
- Mass transfer & stellar interaction products

Shenar, Bodensteiner et al. 2024

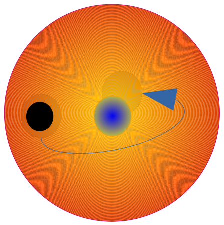
'Hotberg' collaboration
- Discovering helium stars across environments
- He stars in X-ray binaries, supernovae, GW sources, high-z Universe

Klencki, Laplace, Gotberg, Simon-Diaz, Degenaar

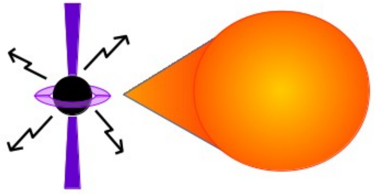
Summary

Binary mass transfer channels may drop off going to higher masses

→ common envelope: M_{BH} <~ 15 $M_\odot$



→ stable mass transfer M_{BH} <~ 30-40 $M_\odot$ (JK+in prep.)

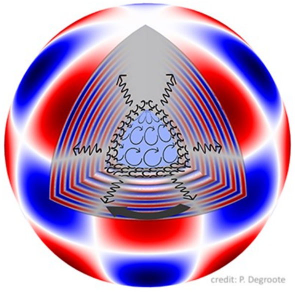


Minimum orbital separation from stable MT ~10 $R_\odot$

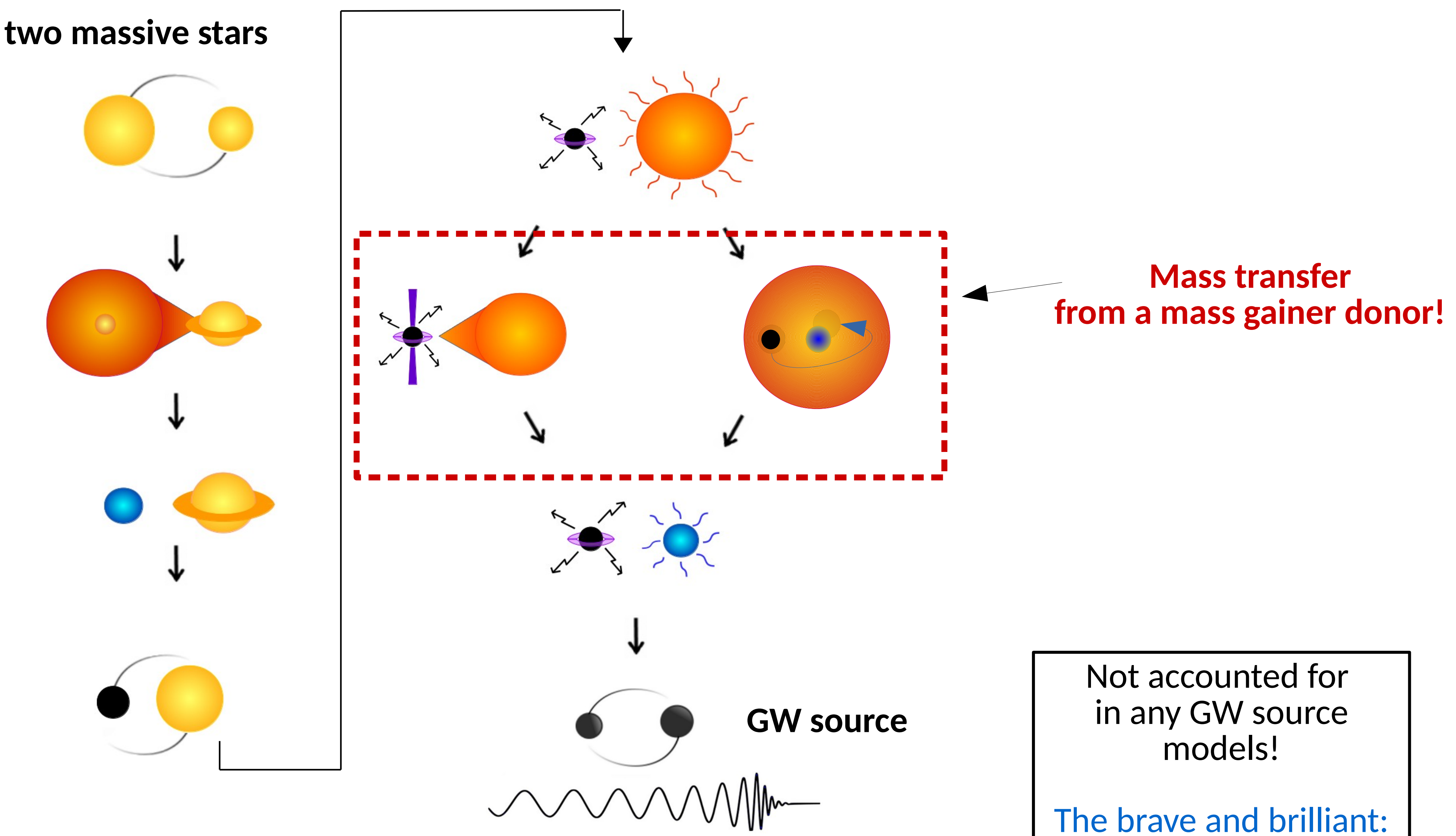
→ determined by the <u>internal structure of the star,</u> not AM loss

→ long BBH delay times (>1-5 Gyr), small effective spins

possible exception: unequal mass BBHs (q ~ 0.5)

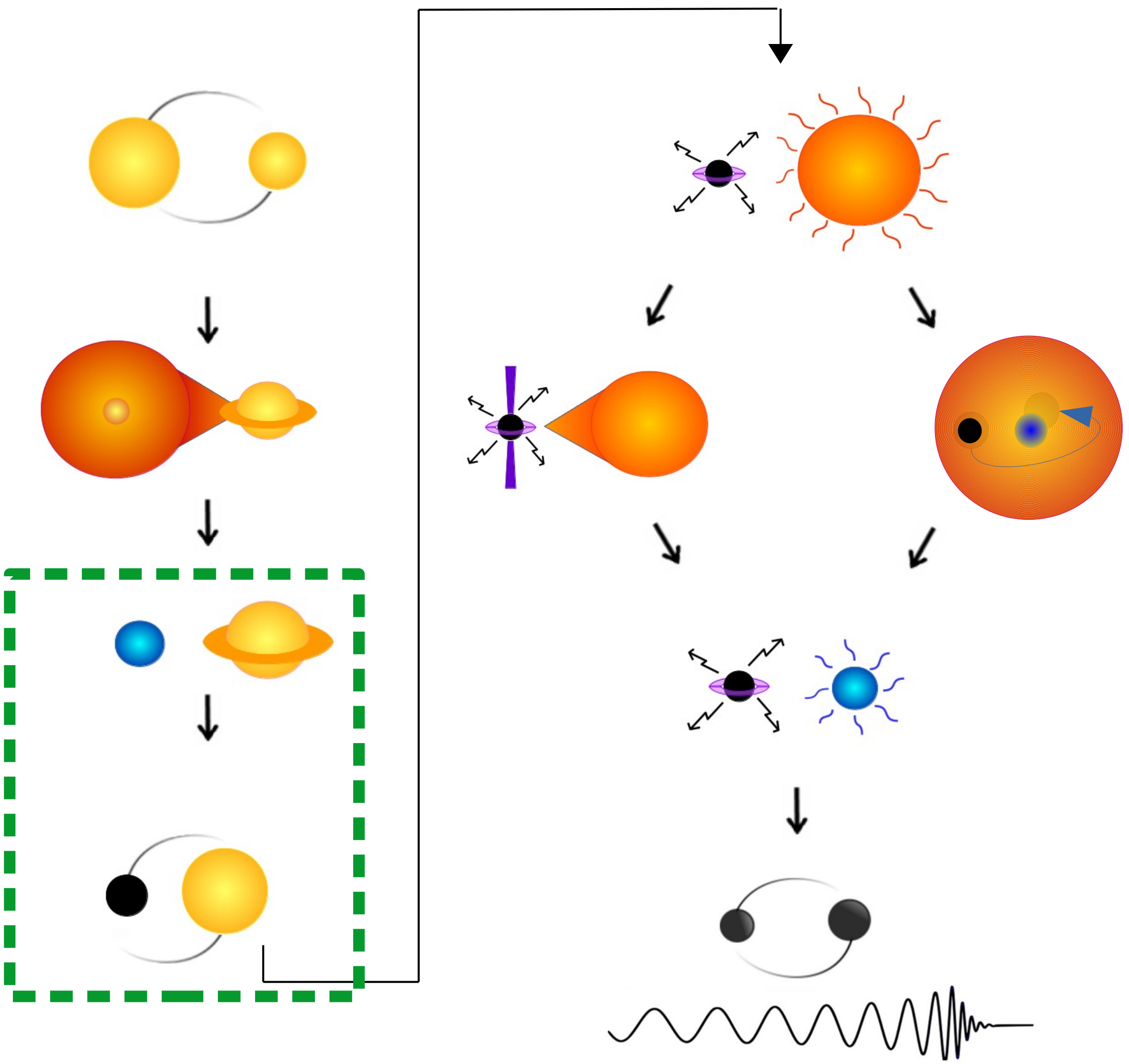


Extra slides



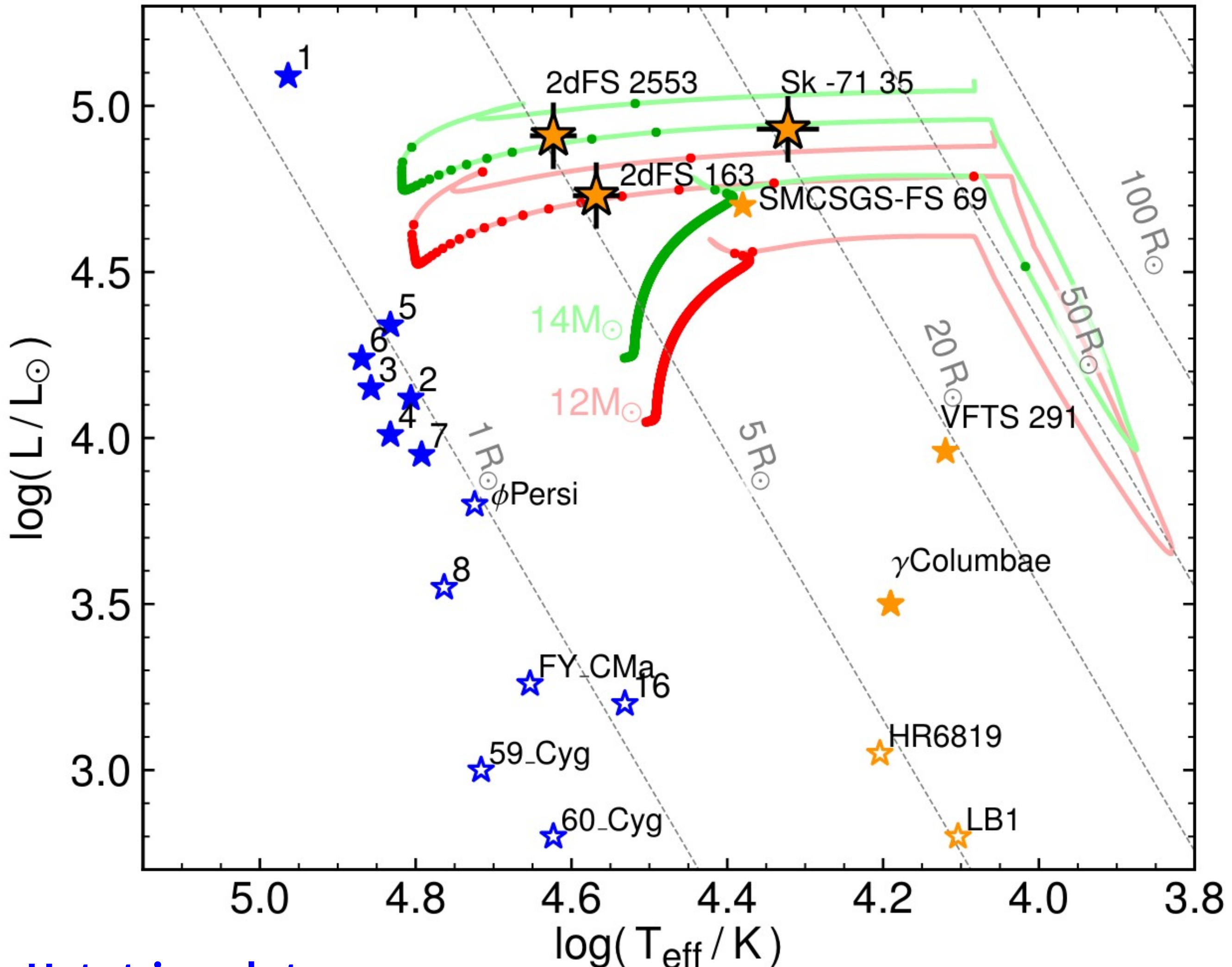
Not accounted for
in any GW source
models!

The brave and brilliant:
Renzo+23



This is where we can learn about <u>mass gainers</u>

Post-interaction binaries



Hot stripped stars & subdwarfs
(Götberg+2023, Drout+2023, Wang+21)

Cool partially-stripped stars
Ramachandran+ (2024)

Also: Bodensteiner+20, El-Badry+22ab, Shenar+20, Villaseñor+23, Ramachandran+23, Pauli+22, Irrgang+22

Just the tip of the iceberg?

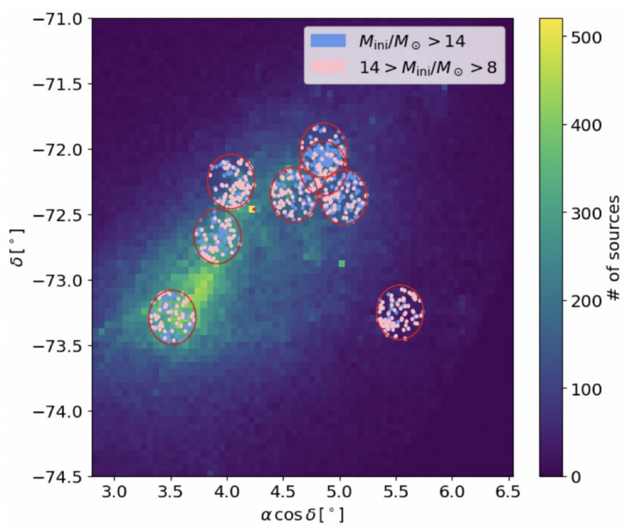
Prediction:

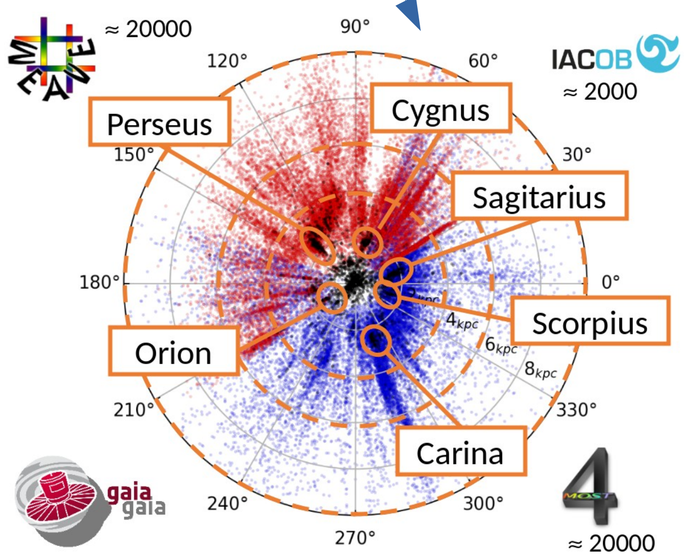
~ 1% of the Main Sequence are partially-stripped stars (Dutta & JK 24)
(more at low Z & beyond TAMS? JK+22)

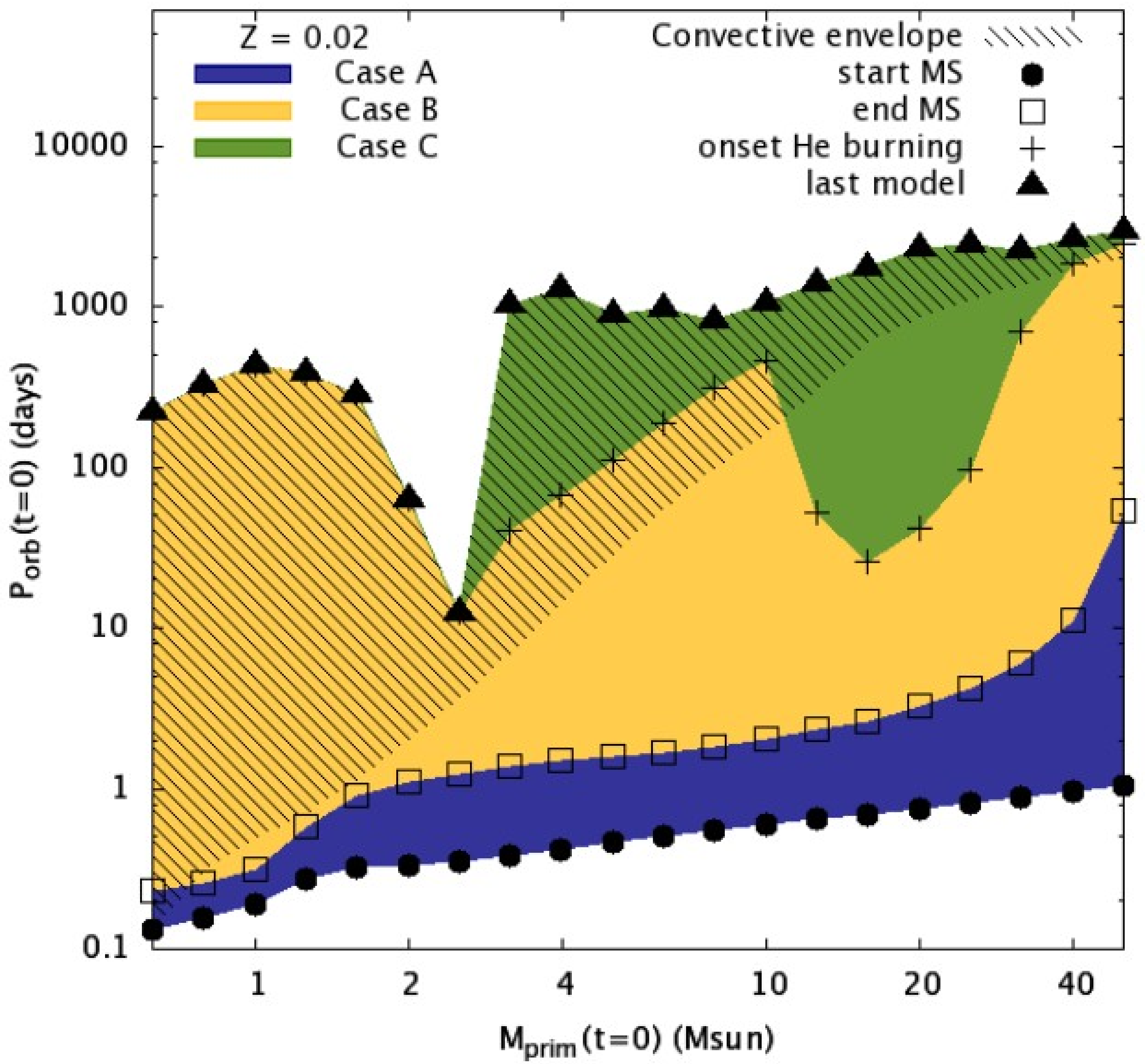
Debasish Dutta
(IITP, India
→ ISTA 09/24)

Need: large spectroscopic samples

→ 40000 massive stars in the Milky Way (<2030, IACOB, WEAVE, 4MOST)
→ 1000 massive stars in the SMC (BLOeM collaboration)

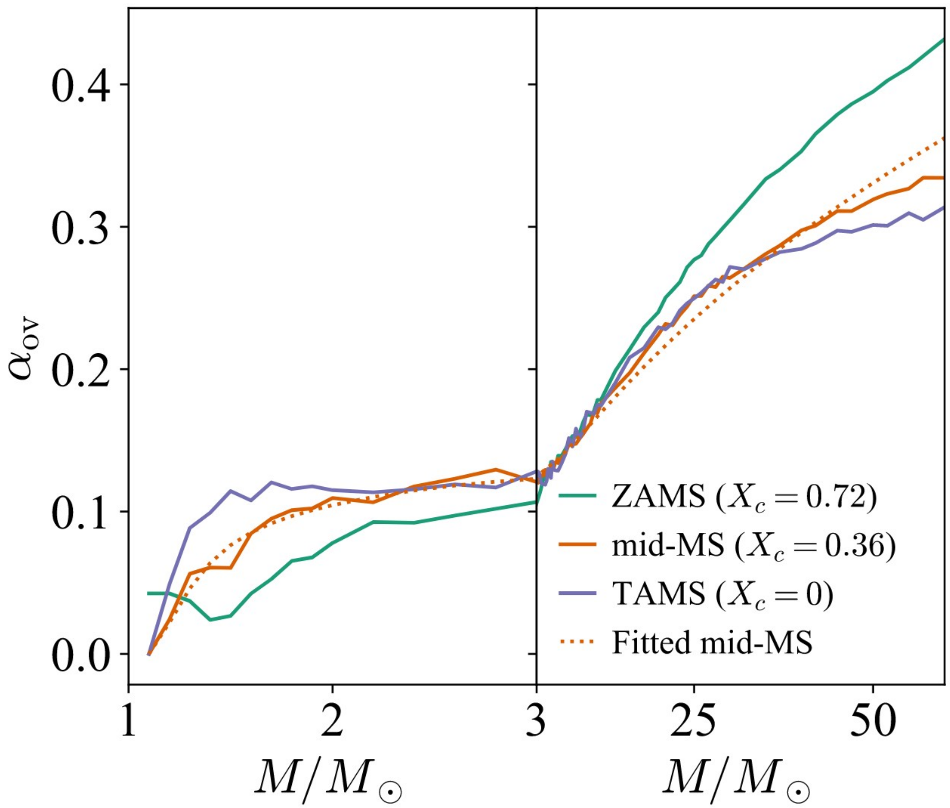




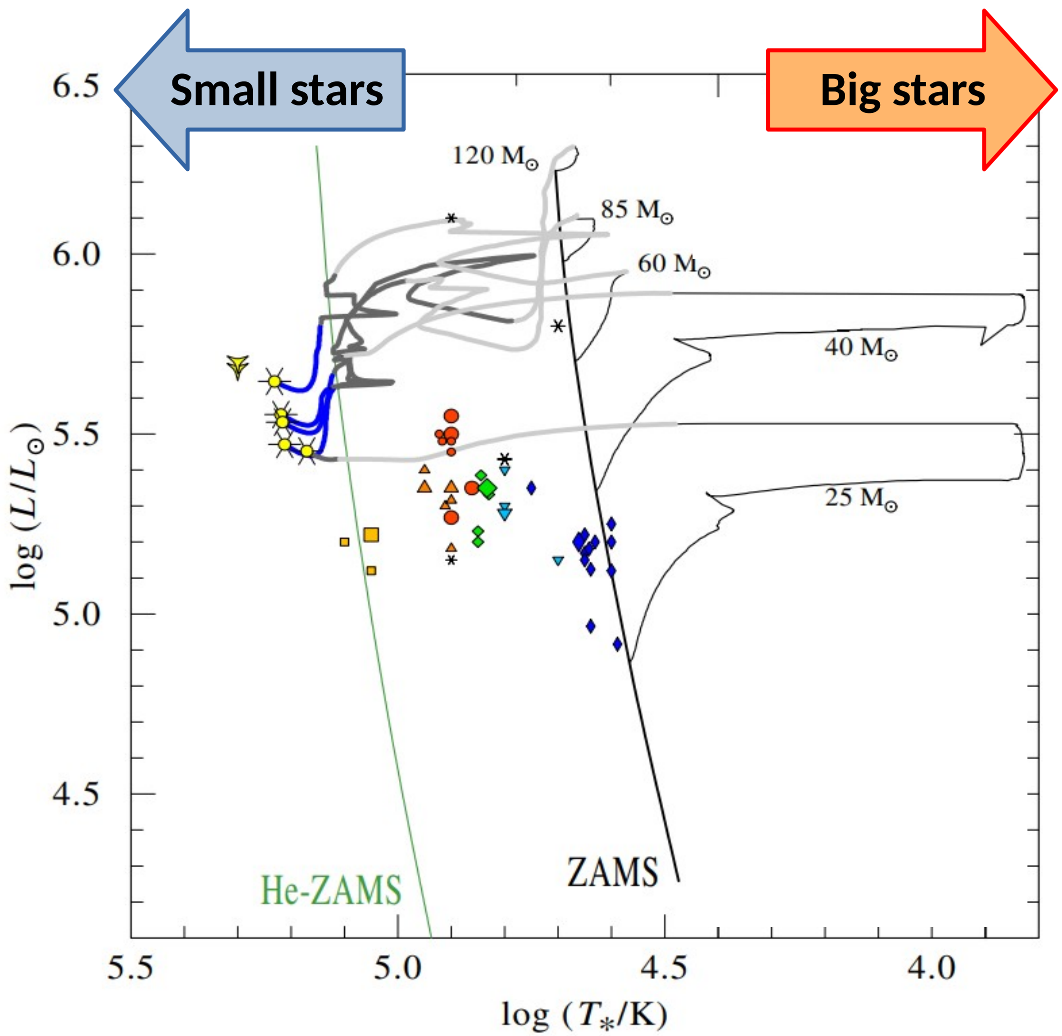

Z = 0.02
Case A
Case B
Case C
Convective envelope
start MS
end MS
onset He burning
last model
10000
1000
100
10
1
0.1
1
2
4
10
20
40
P_orb(t=0) (days)
M_prim(t=0) (Msun)

Various evidence:
mixing increases with mass

Effect:
very massive stars never expand



Jermyn et al. (2022)
3D simulations by Evan Anders
also Johnston et al. (2023)

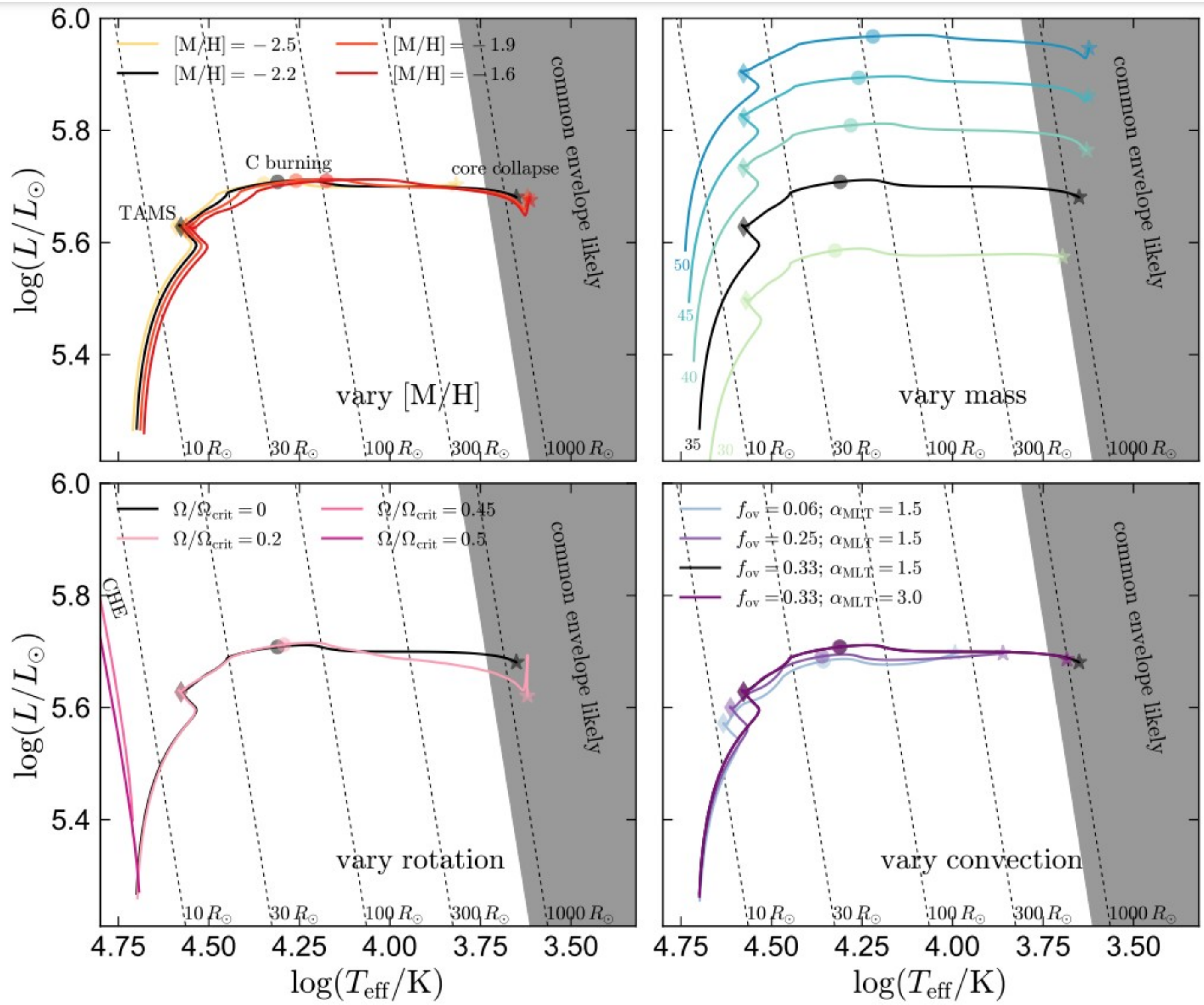


Sander+2012

Formation of Gaia BH3

Problem for binary evolution only if common envelope cannot be avoided

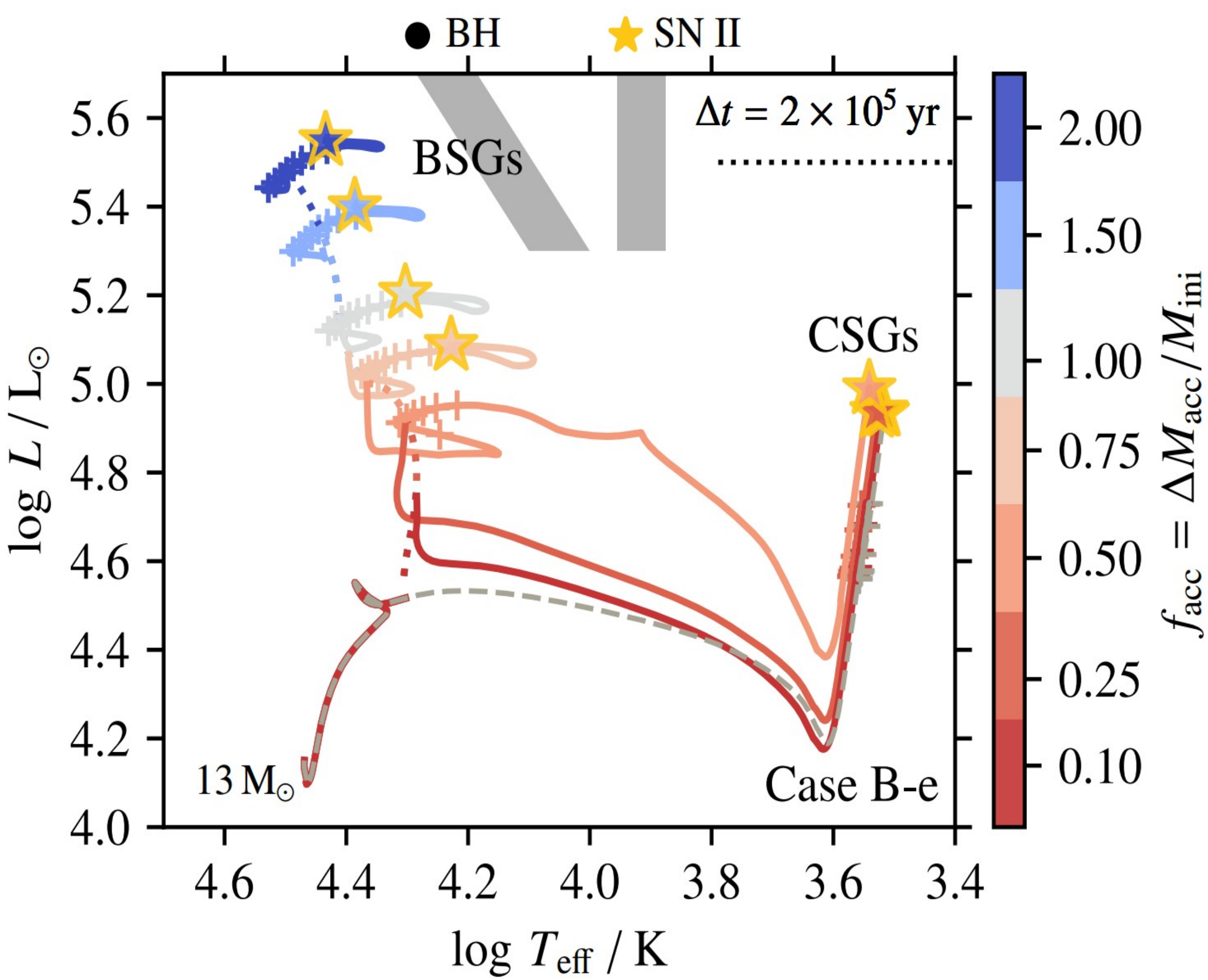
El-Badry 2024



It can be solved if the BH progenitor star stayed compact < 300 Rsun

(mixing, case B merger)

Giant stellar mergers products do not expand

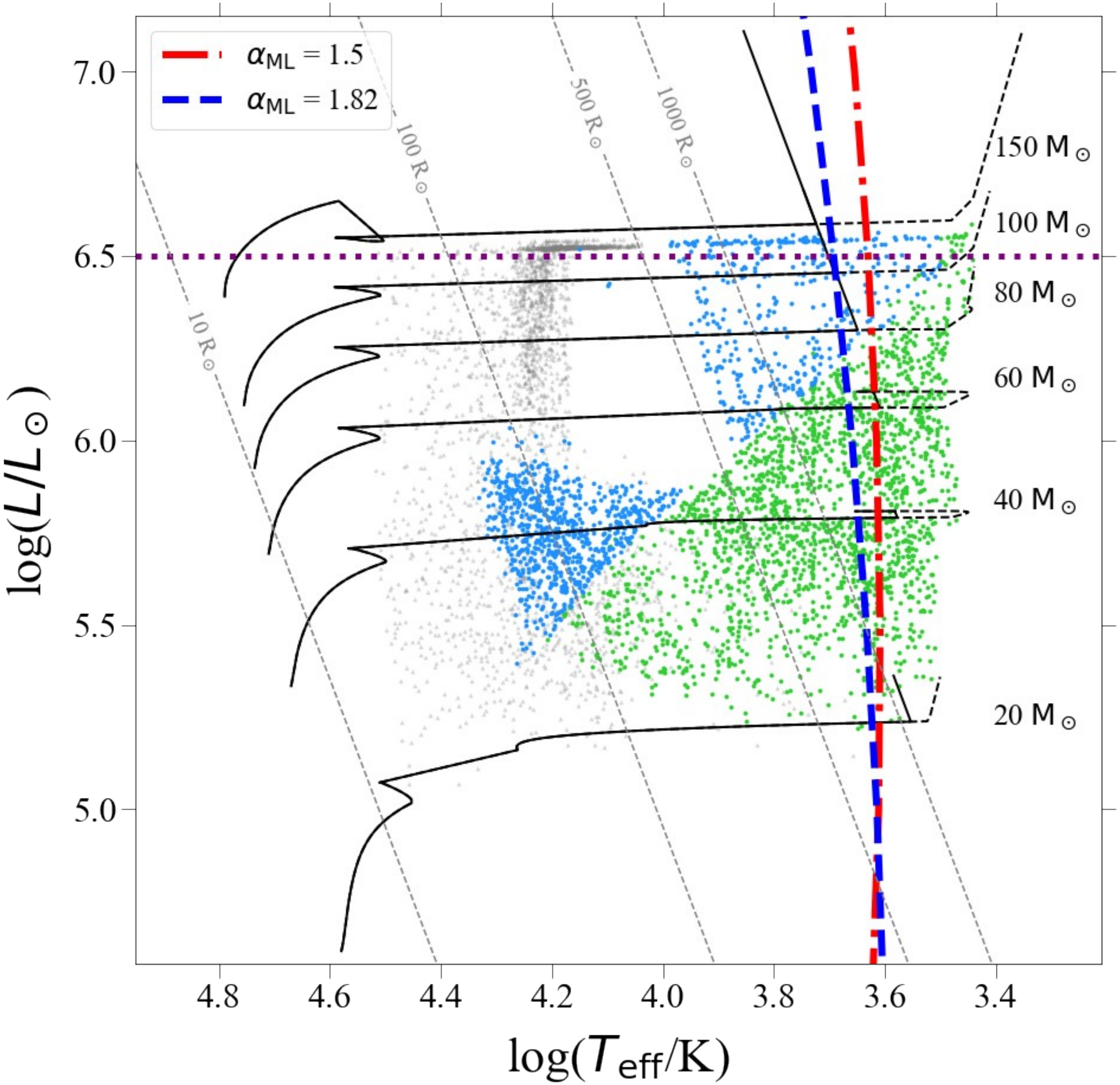


Similar to a MS star but it has a hidden He core

envelope:
L, Teff, radius
(~ of a MS star)

core:
lifetime,
BH/NS fate

Schneider, Podsiadlowski, Laplace (2024) ← systematic 1D models of accretors/stellar mergers



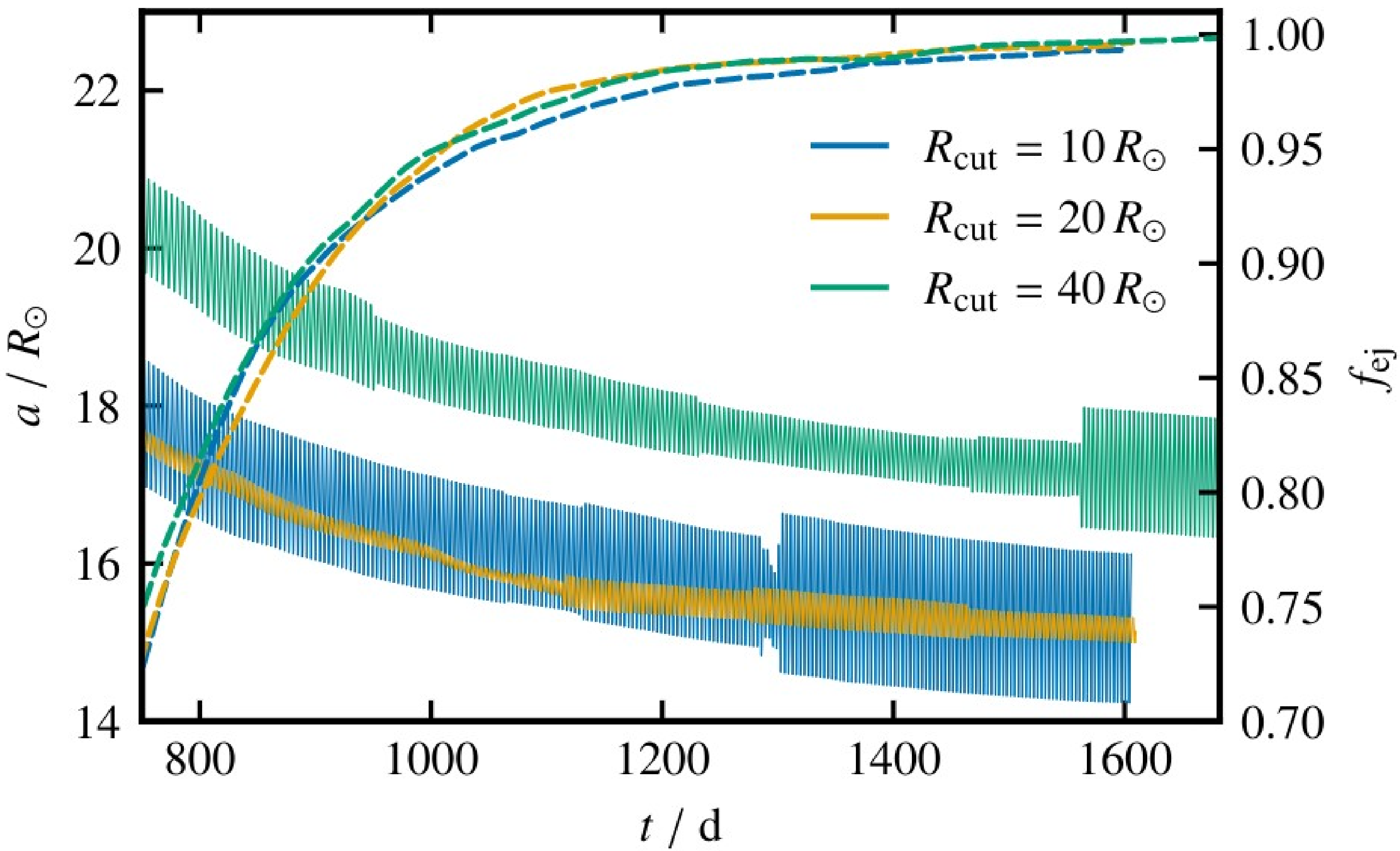
Amedeo Romagnolo

GW population models likely overpredict the CE channel

Romagnolo+ (2022, 2024 in prep), also Marchant+21, Gallegos-Garcia+21

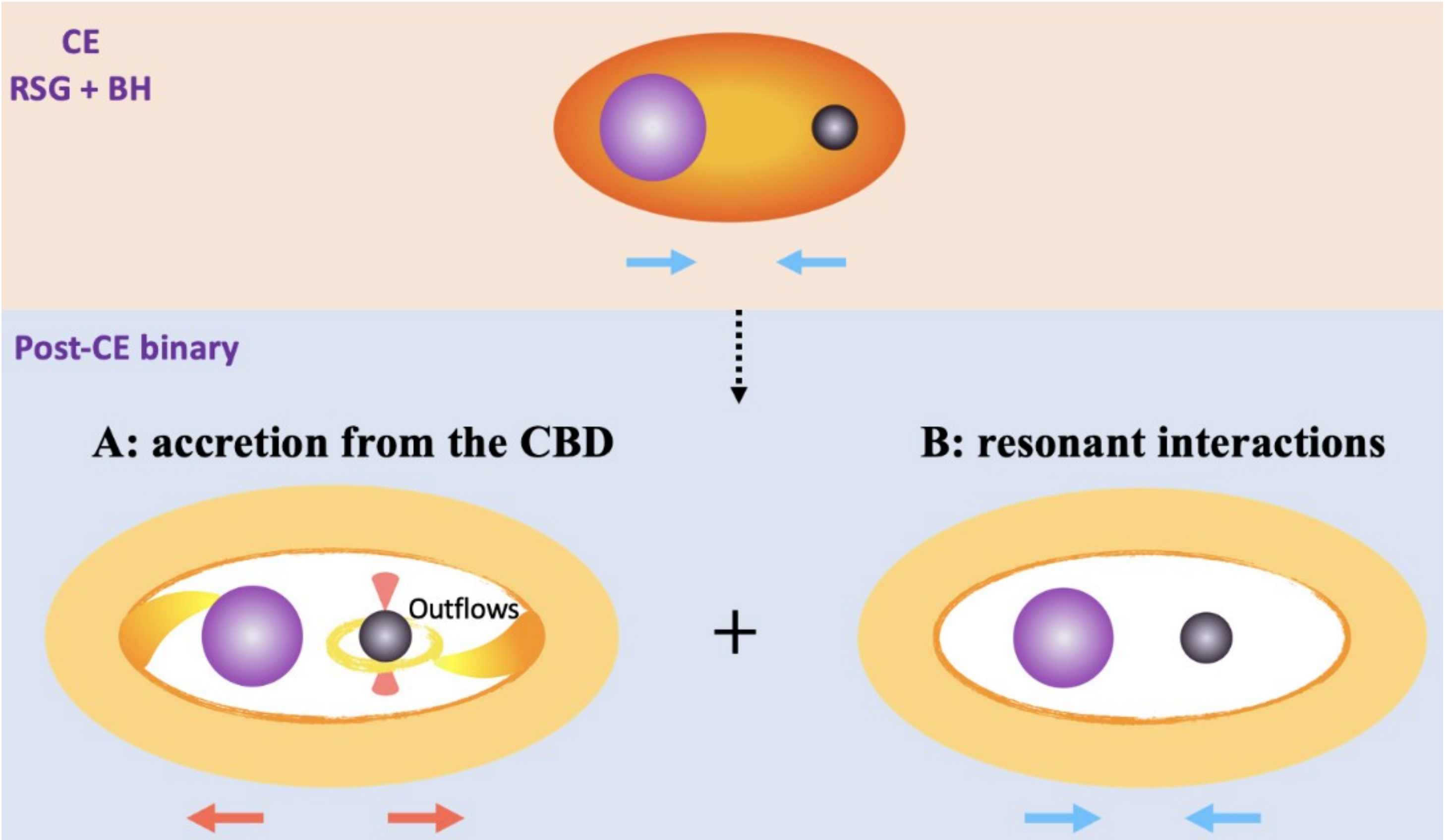
Major question for CE: what is the final separation?

Simulation: no real answer
Observations: no massive post-CE systems (yet)



Moreno+22

Major question for CE: what is the final separation?



Wei+2023 : **depending on the disk mass & lifetime,**
a circumbinary disk can completely change the post-CE orbit

also: Gagnier+23,24, Tuna & Metzger+23