Stable mass transfer

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with Y. Götberg, R. Farmer, S. Justham, S. E. de Mink, E. Laplace, L. van Son,
K. Breivik, E. Zapartas, M. Lau, M. Cantiello, B. D. Metzger, J. Goldberg, Y.-F. Jiang, D. Hendriks, R. Izzard, C. Xin

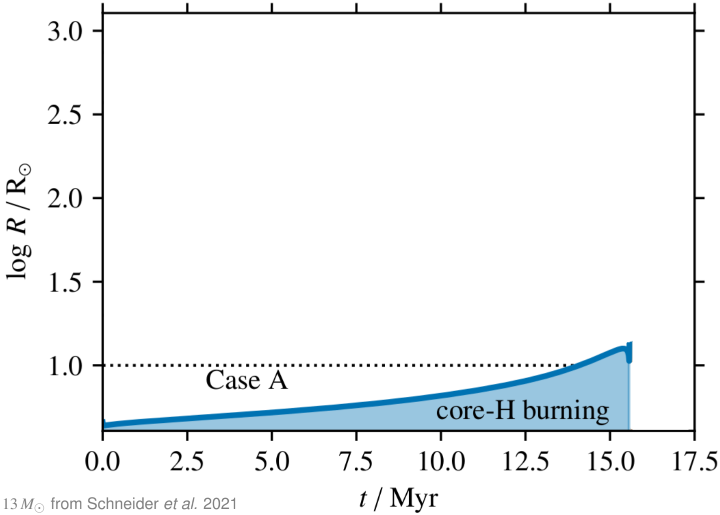
Stable mass transfer

A binary is much more than two stars!

highly non-linear interaction

Mandatory nomenclature

The evolutionary phase of the donor decides which RLOF "case"



$13\,M_\odot$ from Schneider *et al.* 2021

Very roughly for massive stars:

$P \lesssim 10$ days

see also Kippenhahn & Weigert 1967, Lauterborn 1970, Paczynski 1971, 1976, Ulrich & Burger 1976

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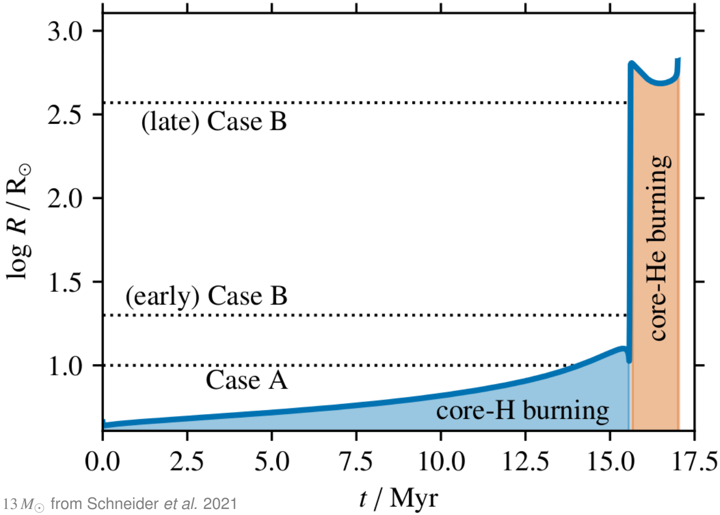


$13\,M_\odot$ from Schneider *et al.* 2021

Very roughly for massive stars:

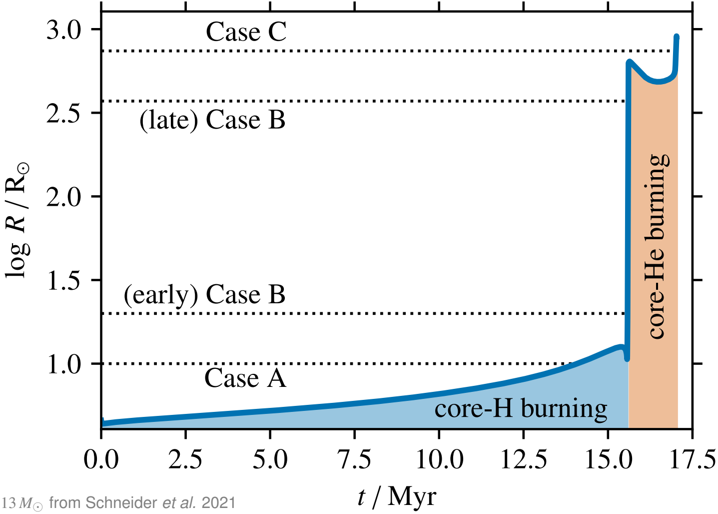
$P \lesssim 500$ days

$P \lesssim 100$ days

$P \lesssim 10$ days

see also Kippenhahn & Weigert 1967, Lauterborn 1970, Paczynski 1971, 1976, Ulrich & Burger 1976

The evolutionary phase of the donor decides which RLOF "case"



Very roughly for massive stars:

$P \lesssim 500 - 1000$ days

$P \lesssim 500$ days

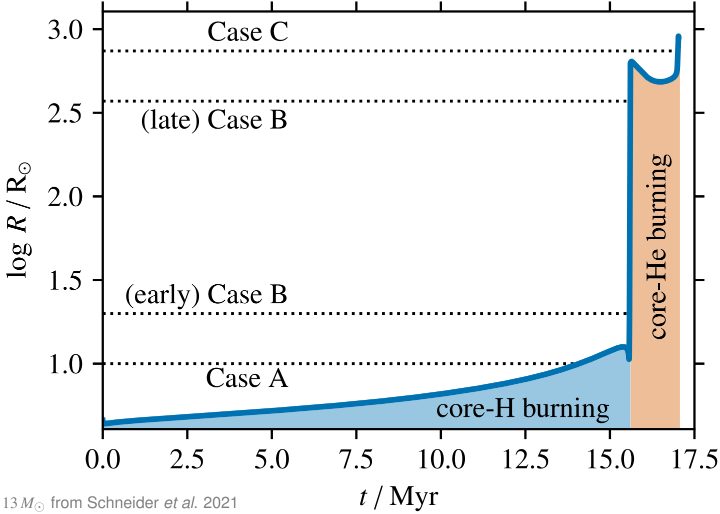
$P \lesssim 100$ days

$P \lesssim 10$ days

$13\,M_\odot$ from Schneider *et al.* 2021

see also Kippenhahn & Weigert 1967, Lauterborn 1970, Paczynski 1971, 1976, Ulrich & Burger 1976

The evolutionary phase of the donor decides which RLOF "case"



$13\,M_\odot$ from Schneider *et al.* 2021

The later, the faster

Timescales:

- **Case A:** thermal → nuclear
- **Case B:** thermal

(but see Klencki *et al.* 2022)

- **Case C:** thermal/dynamical

see also Kippenhahn & Weigert 1967, Lauterborn 1970, Paczynski 1971, 1976, Ulrich & Burger 1976

The most common massive binary evolution path

THE ASTRONOMICAL JOURNAL VOLUME 74, NUMBER 9 NOVEMBER 1969

The Expected Fraction of Evolved Close Binaries among Main-Sequence Stars of Spectral Type Earlier than A5*

E. P. J. van den Heuvel†
Lick Observatory, University of California, Santa Cruz, California

(Received 17 April 1969; revised 13 August 1969)

CBR formed by evolution according to KW's case B (in which the primary reaches the Roche lobe during the expansion following core-hydrogen exhaustion), since more than 80% of the observed B-type spectroscopic binaries are in this case (cf. Table I) as well as many A-type systems (cf. Conti 1968).

Stable post-donor-main-sequence RLOF (case B)

Credits: ESO, L. Calçada, M. Kornmesser, S.E. de Mink

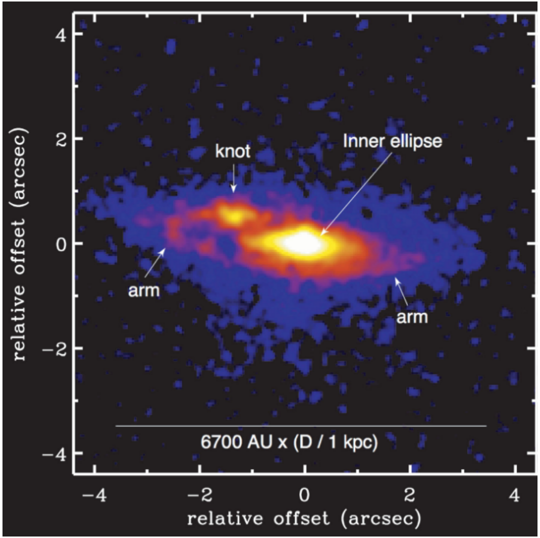
Known unknowns (for all cases)

Leaks from the system?

Disk or direct impact?

Dynamical stability $\Rightarrow$ talks tomorrow

Reality can be much messier...



Nebular structure around WR122/NaSt1
Mauerhan *et al.* 2015

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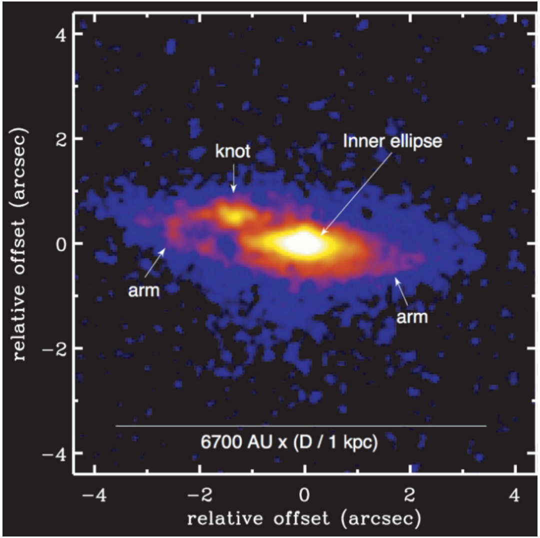
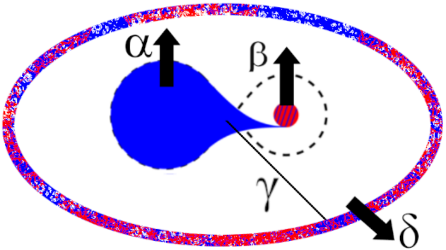


Nebular structure around WR122/NaSt1
Mauerhan *et al.* 2015

... so we parametrize unknowns



e.g., Sobermann *et al.* 1997

Same algorithms in 1D & pop. synth.

e.g., Renzo & Zapartas 2020

Known unknowns (for all cases)

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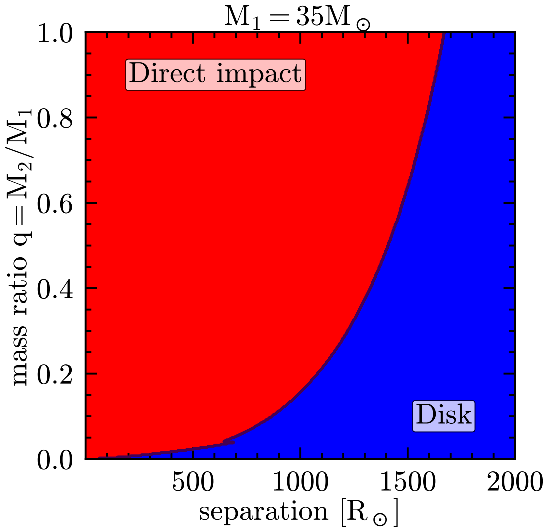
Disk or direct impact?

Dynamical stability $\Rightarrow$ talks tomorrow

Disk only if stream misses the accretor: $R_{\mathrm{min}} > R_2(t = t_{\mathrm{RLOF}})$

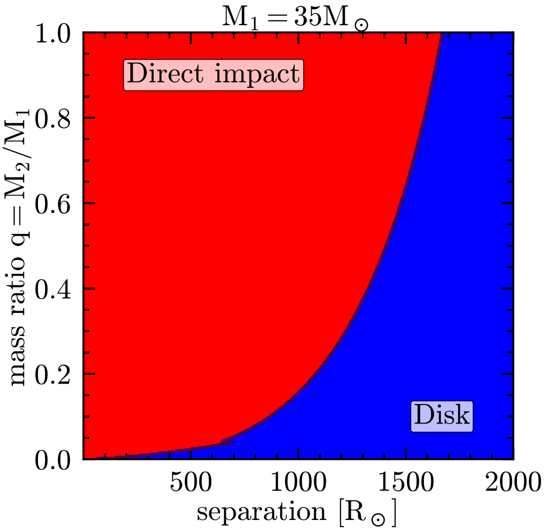


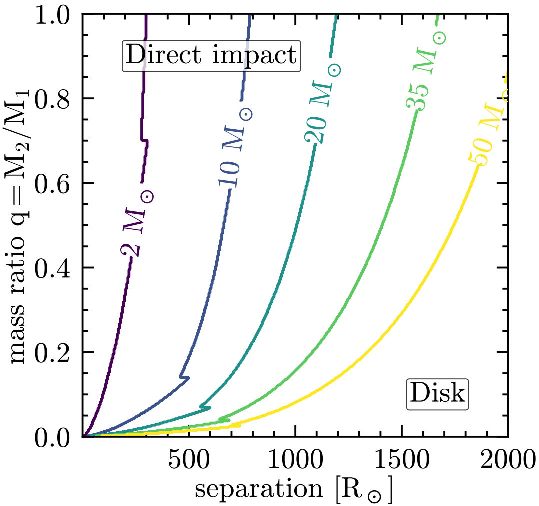
- ✗ Neglect evolution of $R_2 \equiv R_2(t)$
- Possibly different impact of accretion
- Favorable comparison with LMC eclipsing binaries Sen *et al.* 2022

https://github.com/mathren/disk_or_direct_impact

Lubow & Shu 1975, Ulrich & Burger 1976, de Mink *et al.* 2013, Hendriks & Izzard 2023

Massive binaries rarely make accretion disks during stable RLOF





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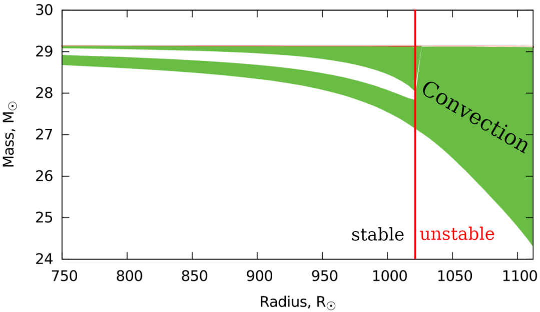
Disk or direct impact?

Dynamical stability $\Rightarrow$ talks tomorrow

Roche lobe overflow or common envelope? Donor star's opinion

$30\,M_\odot + 7\,M_\odot$ (point-mass)

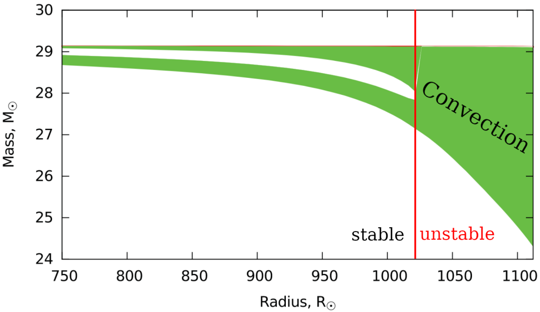


Pavlovskii *et al.* 2017

Convective donors expand as they lose mass

Roche lobe overflow or common envelope? Donor star's opinion

$30\,M_\odot + 7\,M_\odot$ (point-mass)



Pavlovskii *et al.* 2017

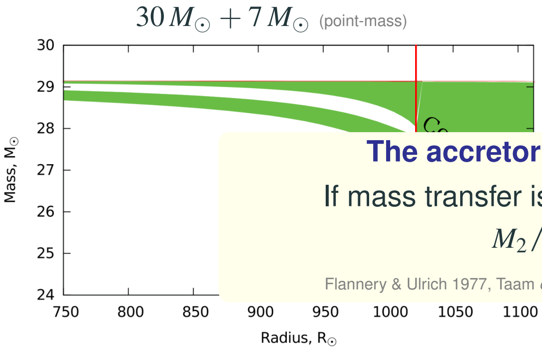
3D envelopes $\neq$ 1D envelopes

Turbulent v all the way to the "surface"

Chiavassa *et al.* 2011, Jiang *et al.* 2015, 2018, Goldberg *et al.* 2022, Schultz *et al.* 2023a,b, J.-Z. Ma *et al.*, in prep.

courtesy of J. Goldberg, see Goldberg *et al.* 2022

Roche lobe overflow or common envelope? Donor star's opinion



Pavlovskii *et al.* 2017

The accretor has an opinion too!

If mass transfer is too fast, accretor swells

$$M_2 / \dot{M}_2 \ll \tau_{\mathrm{KH},2}$$

Flannery & Ulrich 1977, Taam *et al.* 1978, Justham *et al.* 2011, Vigna-Gómez *et al.* 2020

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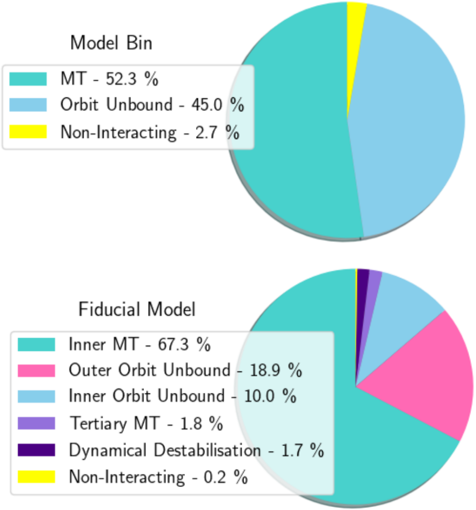
Stable mass transfer

3. Triples enhance binary interactions
2. *Both* stars and the orbit are modified
1. Presently single stars

(Initially stable, hierarchical) Triples lead to 15% more mass transfer overall



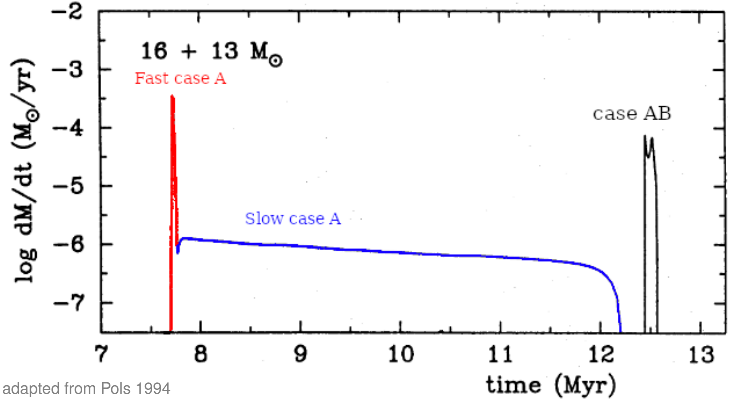
More case A RLOF because

- Tighter inner orbits
- von Zeipel-Kozai-Lidov oscillations $e_{\rm in} \leftrightarrow i_{\rm out}$

$\Rightarrow$ see F. Kummer's poster (P10)

Kummer *et al.* 2023, see also Toonen *et al.* 2016, 2020

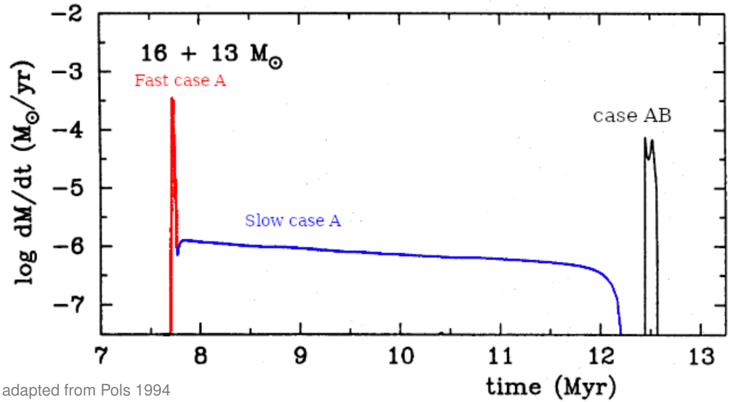
Stable RLOF during donor's main sequence (case A)



adapted from Pols 1994

- Fast case A ⇔ orbital evolution, $\sim \tau_{\text{thermal}}$
- Slow case A ⇔ donor expansion, $\sim \tau_{\text{nuc}}$
- case AB $\sim \tau_{\text{thermal}}$

Stable RLOF during donor's main sequence (case A)



adapted from Pols 1994

- Fast case A ⇔ orbital evolution, $\sim \tau_{\mathrm{thermal}}$
- Slow case A ⇔ donor expansion, $\sim \tau_{\mathrm{nuc}}$
- case AB $\sim \tau_{\mathrm{thermal}}$

1. Short period

⇓

Tides are important

⇒ see N. Britavskiy and L. Ma's talks

Zahn 1977, Hut 1981, Hurley *et al.* 2002, Qin *et al.* 2018

2. Mass loss before He core

⇓

∼ 4% reverse SN order
He WD, NS instead of BH

Pols 1994, Belczynski & Taam 2008, Renzo *et al.* 2019, van der Meij *et al.* 2021

Stable mass transfer

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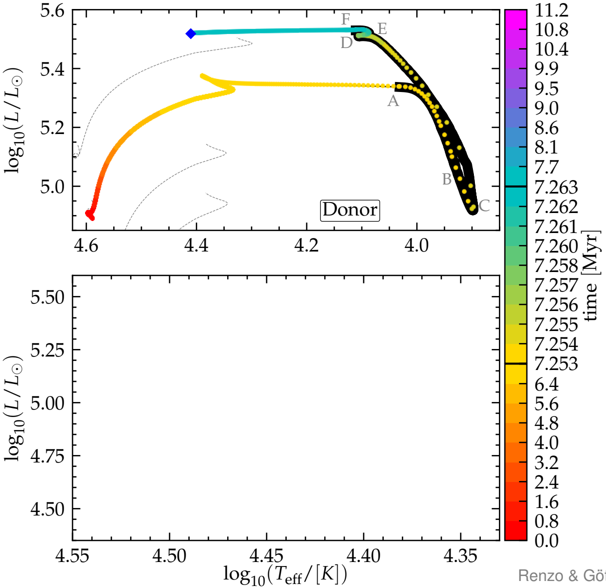
Hertzsprung-Russell diagrams of a case B binary



Renzo & Götberg 2021

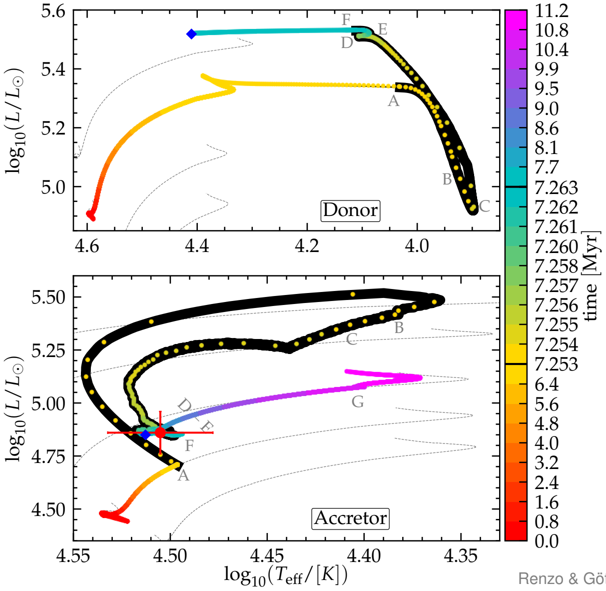
Donor star

⇒ B. Ludwig & V. Ramachandran's talk

- Loses (almost all) H-rich envelope
- Becomes a hot, stripped star
- Stripped envelope SN progenitors

Vanbeveren *et al.* 2007, Götberg *et al.* 2017, 2018, 2023, Gilkis *et al.* 2019, Laplace *et al.* 2020, 2021, Drout *et al.* 2023, ...

Hertzsprung-Russell diagrams of a case B binary



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Vanbeveren *et al.* 2007, Götberg *et al.* 2017, 2018, 2023, Gilkis *et al.* 2019,Laplace *et al.* 2020, 2021, Drout *et al.* 2023, ...

Accretor star

⇒ session after coffee

- No thermal equilibrium during RLOF
- Often neglected

Hellings 1983, 1985, van Resbergen*et al.* 1994, Braun & Langer 1995, Wang *et al.* 2020, 2022, 2023, Renzo *et al.* 2021, 2023

Renzo & Götberg 2021 (data-point ζ Ophiuchi from Villamàriz & Herrero 05)

Stable mass transfer

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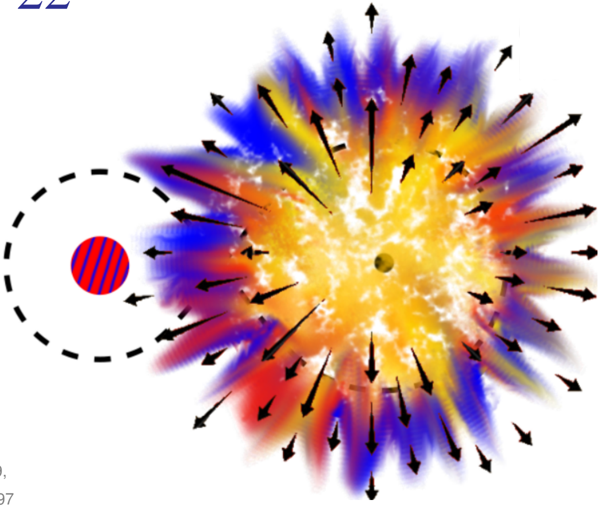
1. Presently single stars

Continuing the post-case B RLOF evolution: the donor explodes first

Credits: ESO, L. Calçada, M. Kornmesser, S.E. de Mink

Accretors may live alone, but they are *not* single stars

$86^{+11}_{-22}\%$ of massive binaries are disrupted



Renzo *et al.* 2019b, Kochanek *et al.* 2019,
Eldridge *et al.* 2011, De Donder *et al.* 1997

Mass transfer occurs before the 1^{st} explosion

- **Spin-up**

  Packet 1981, Cantiello *et al.* 2007, de Mink *et al.* 2013, Renzo & Götberg 2021

- **Pollution**

  Blaauw 1993, Renzo & Götberg 2021

- **Rejuvenation**

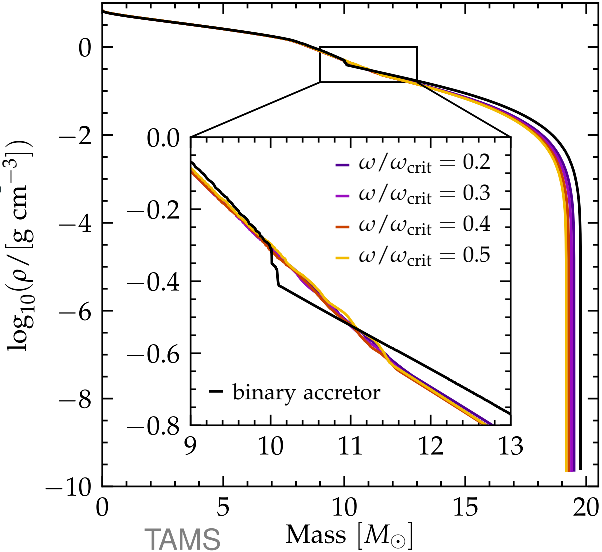
  Hellings 1983, 1985, Braun & Langer 1995, Renzo *et al.* 2023

The "widowed" star carries signatures of its past in a binary

Renzo & Zapartas 2020

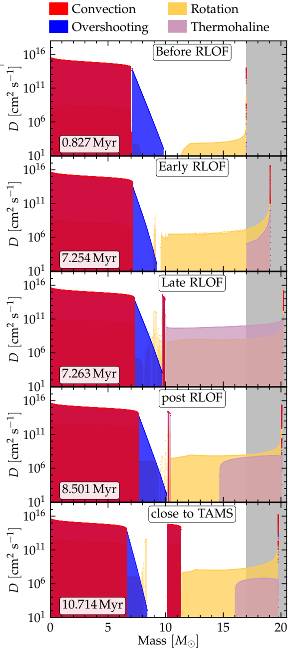
Rejuvenation changes the core/envelope boundary

"Density"



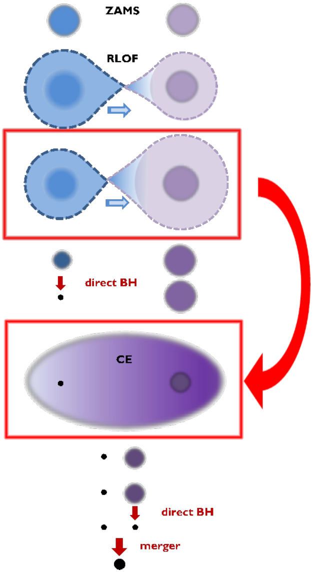
TAMS

"Diffusion coeff."



Renzo & Götberg 2021, Gade Pedersen, Renzo, *et al.* in prep., Wagg *et al.* in prep.

The common envelope in GW progenitors is initiated by the accretor



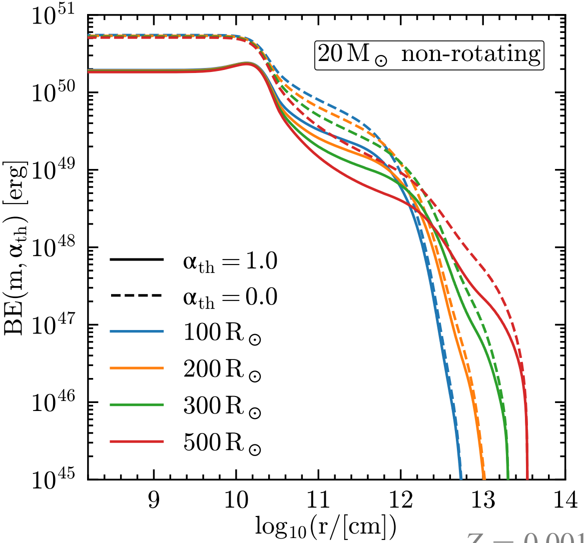
Does RLOF rejuvenation impact how easy it is to remove the envelope ?

Renzo *et al.* 2023

1. Binary evolution until detachment
2. Continue evolution of accretors as single
3. Compare binding energy of accretors and single stars of same total mass at given R

Belczynski *et al.* 2016

The binding energy is the cost to "dig" into the star



$$BE(m, \alpha_{th}) = -\int_m^M dm' \left(-\frac{Gm'}{r(m')} + \alpha_{th} u(m')\right)$$

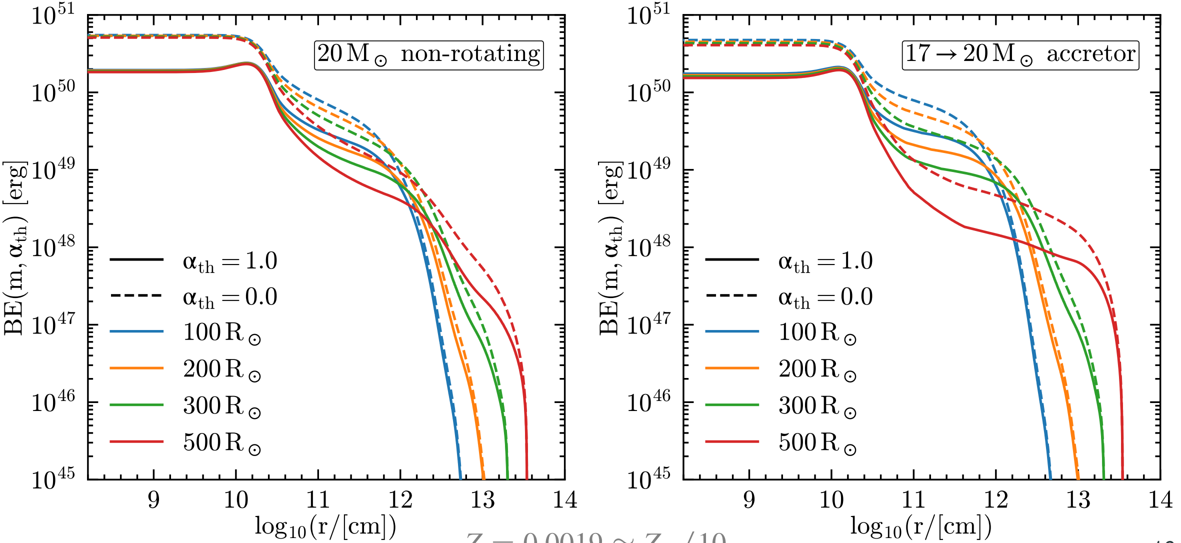
- Gravitational potential energy
- Internal energy
- α_{th} free parameter

fraction of internal energy usable to eject envelope

$Z = 0.0019 \simeq Z_\odot / 10$

Renzo *et al.* 2023

Comparing $20\,M_\odot$ non-rotating single star vs. accretor



$Z = 0.0019 \simeq Z_\odot/10$

Renzo *et al.* 2023

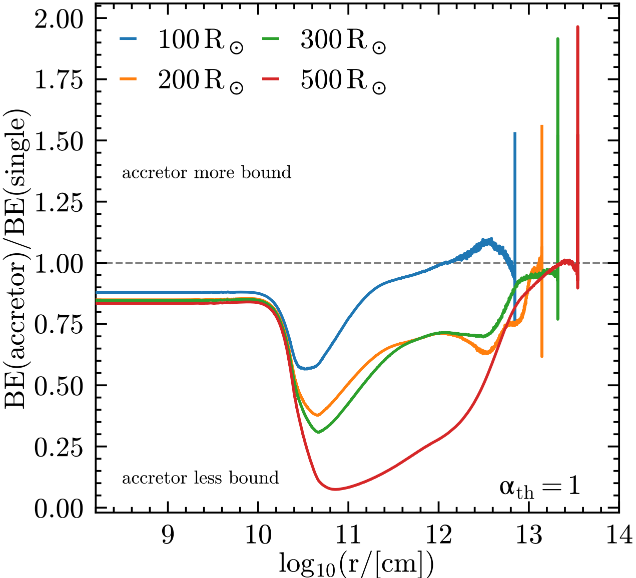
Ratio of binding energies: accretors are easier to unbind

NS progenitor

$15 \rightarrow 17\,M_\odot$

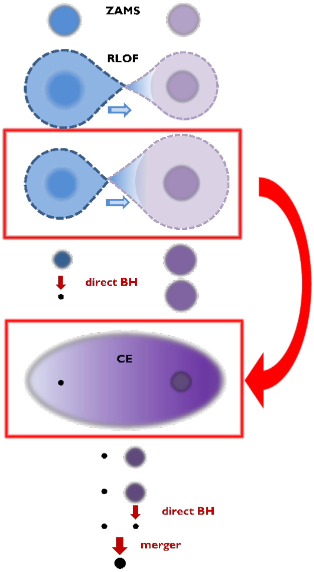
works up to

$\sim 30\,M_\odot$



Renzo *et al.* 2023

If the common-envelope donor is a former accretor

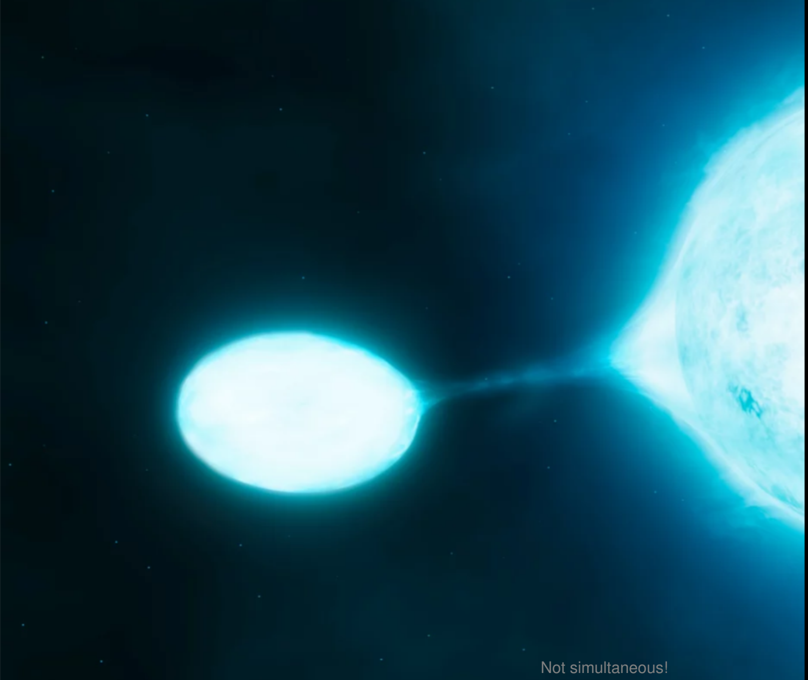


Implications for common-envelope

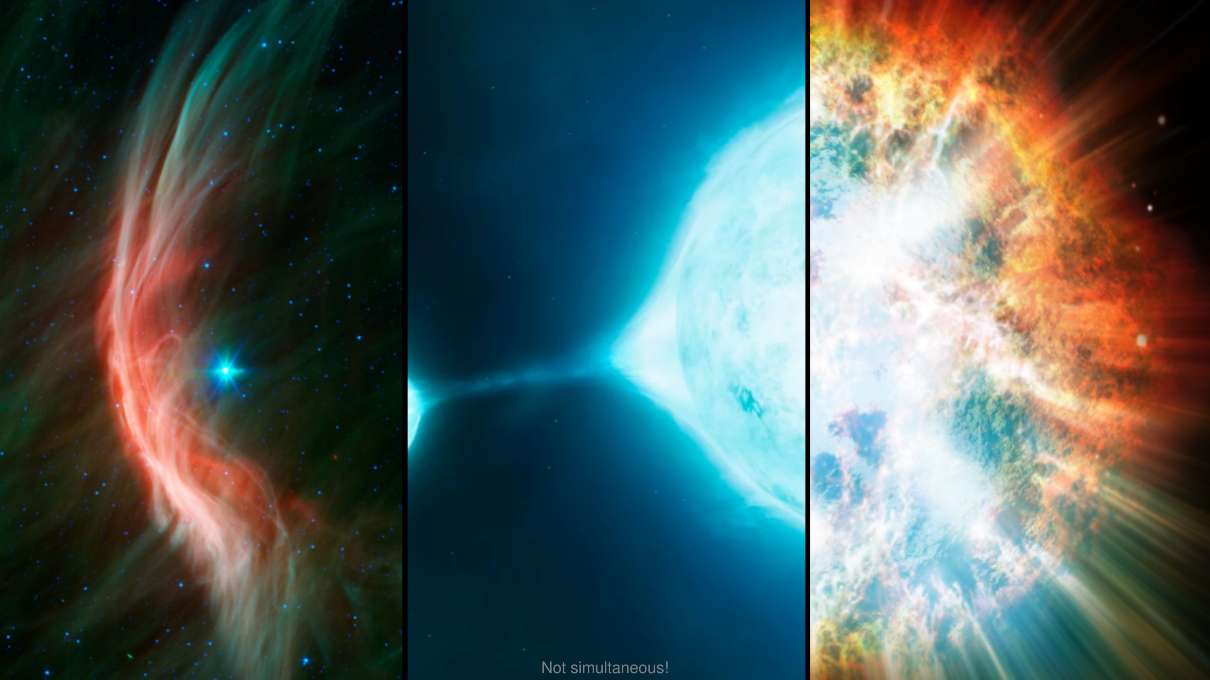
- Fewer “reverse” stellar merger
- Wider post-CE separation
- Mass-dependent (?) impact on GW merger rates

Belczynski *et al.* 2016

Conclusions




Not simultaneous!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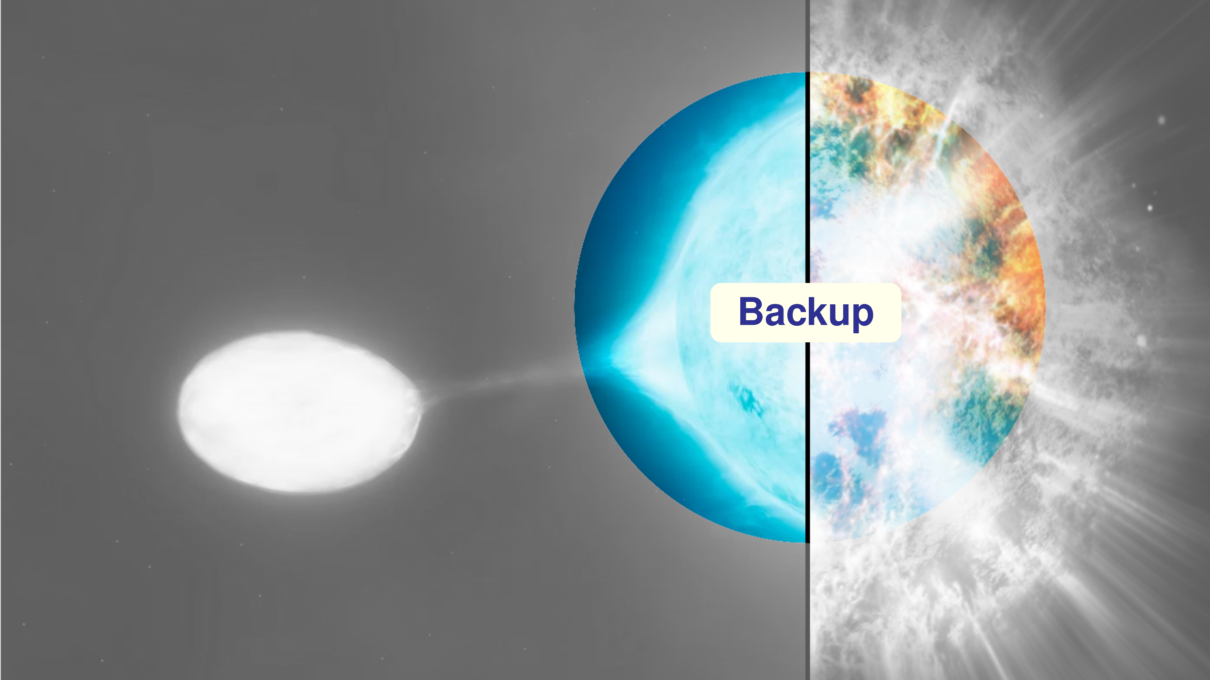
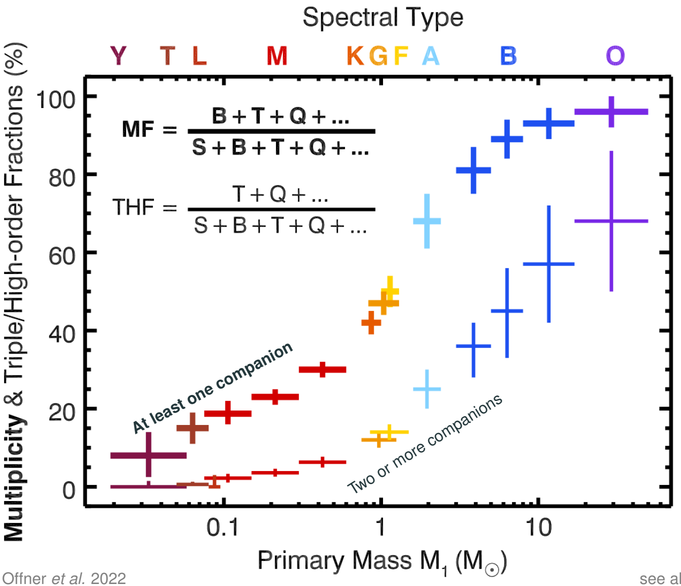

Backup

Massive stars are typically born with companions

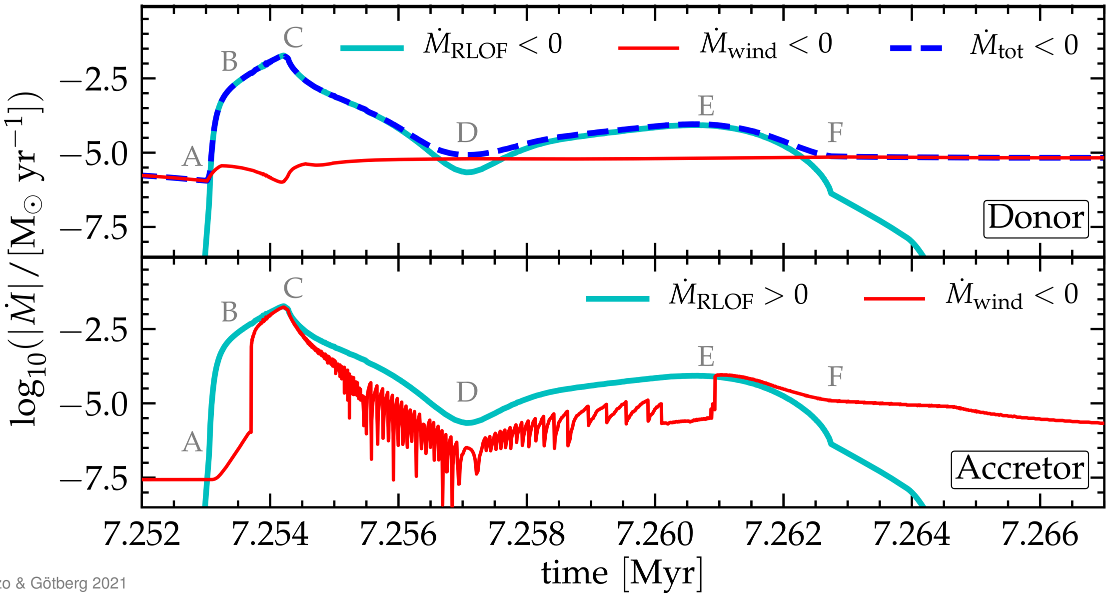


Offner *et al.* 2022

Interactions are common

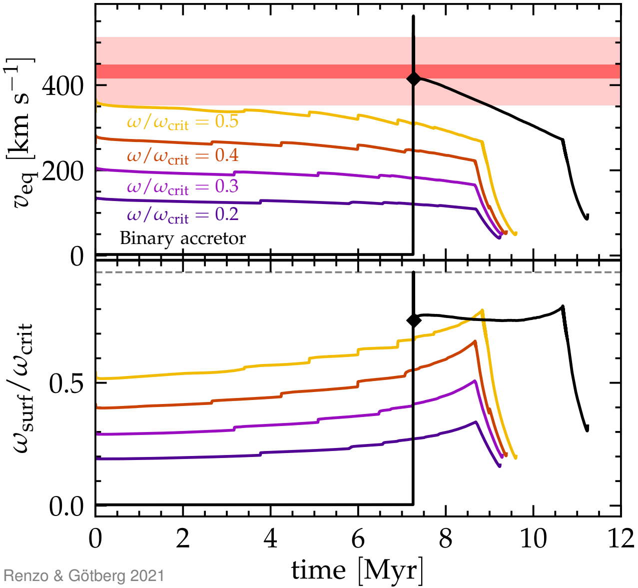
see also Mason *et al.* 2010, Kobulnicky & Fryer 2007, Moe & di Stefano 2017

Mass transfer history: $\Delta t_{\mathrm{RLOF}} \simeq 2 \times 10^4$ years



Renzo & Götberg 2021

✓ Surface rotation rate ?



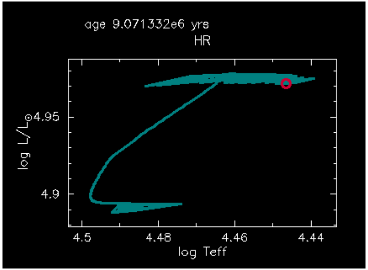
Renzo & Götberg 2021

- but "weak wind problem":

$$\frac{|\dot{M}_{obs}|}{M_\odot \mathrm{yr}^{-1}} \simeq 10^{-8.8} \ll \frac{|\dot{M}_{wind,theory}|}{M_\odot \mathrm{yr}^{-1}} \simeq 10^{-6.8}$$

(Marcolino *et al.* 2005, Lucy 2012, Lagae *et al.* 2021)

✗ Decreasing the wind: $\omega > \omega_{crit}$



Why care about the accretor?

Stellar populations

accretors lurk in samples

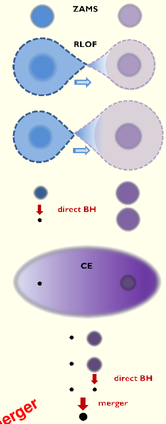
$(10 - 12\%)$ Renzo *et al.* 2019b

+

Oe/Be stars, stragglers

Pols *et al.* 1991, Wang *et al.* 2021

Binary interactions

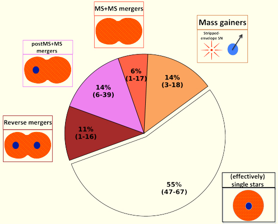


Tutukov *et al.* 1993,

Belczynski *et al.* 2016, Renzo *et al.* 2023

Transients

Common: H-rich SNe



Zapartas *et al.* (incl. MR) 2019

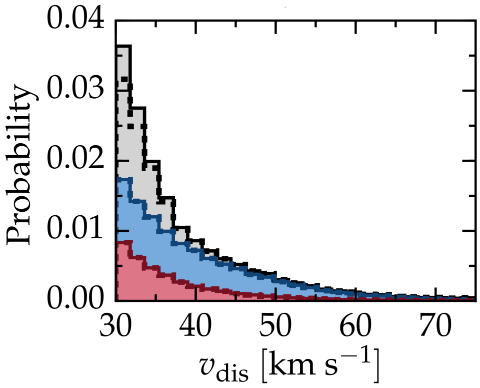
+

Uncommon: H-rich/H-poor SNe

L-GRB, LBV, SNIIn ?

Petrovich *et al.* 2005, Cantiello *et al.* 2007

Accretor stars can be *runaways*...

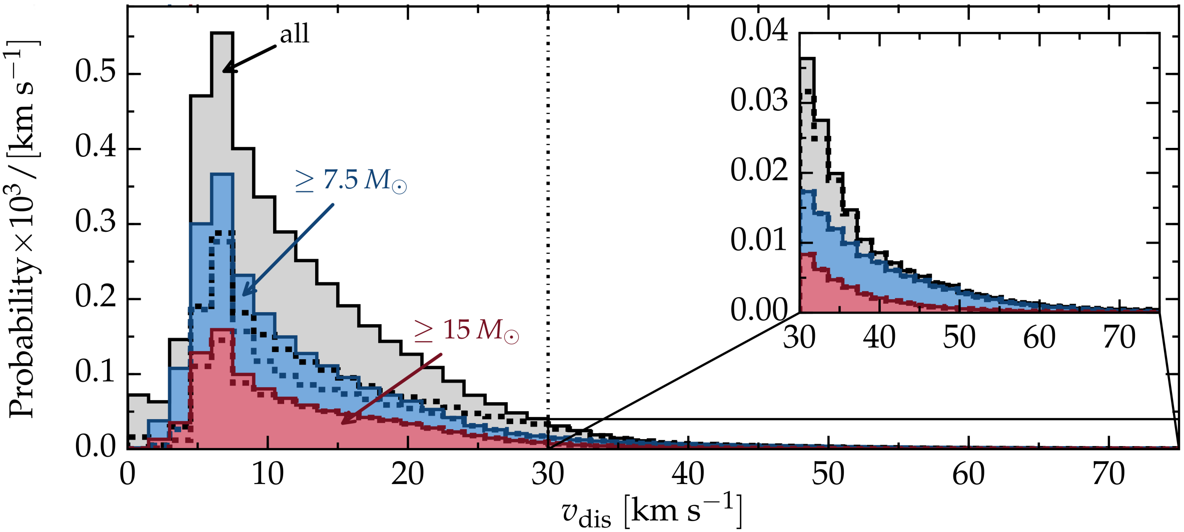


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

...but most are only *walkaways*



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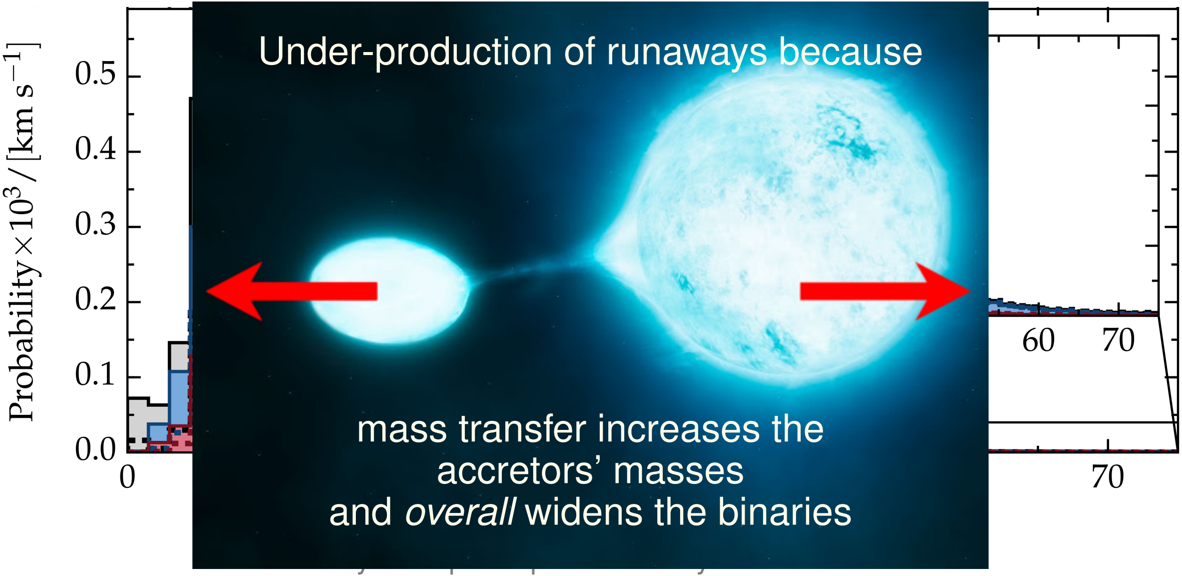
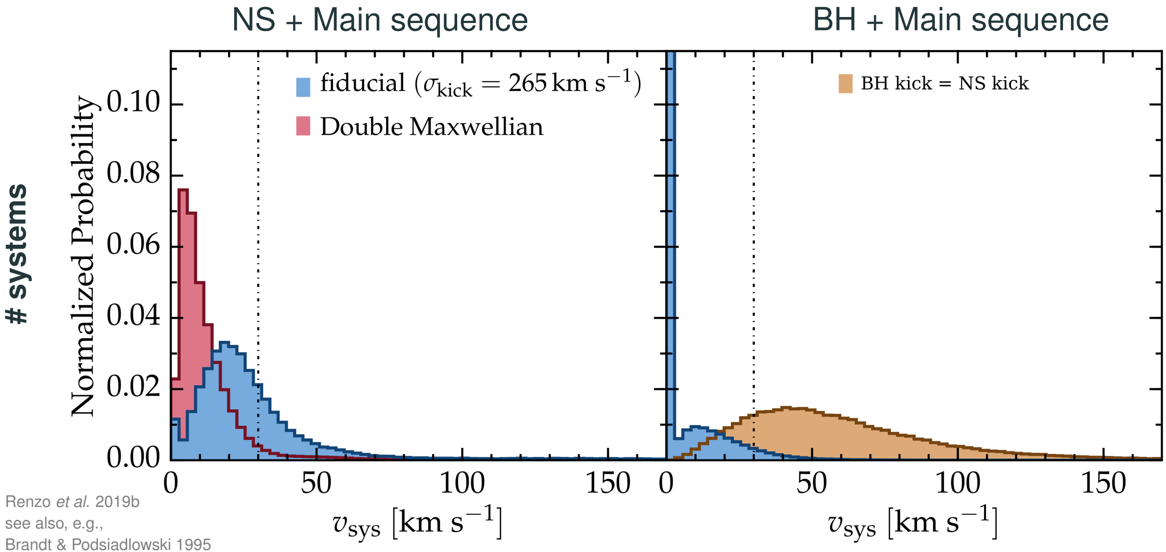


Renzo *et al.* 2019b

Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Post-SN velocity of surviving binaries



Renzo *et al.* 2019b
see also, e.g.,
Brandt & Podsiadlowski 1995
Kalogera 1996
Tauris & Takens 1998

Velocity respect to the pre-explosion binary center of mass

Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

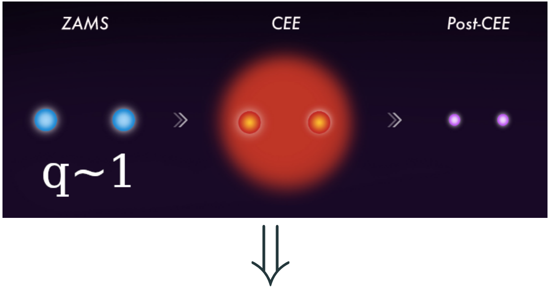
Roche lobe overflow or common envelope? Accretor's reaction

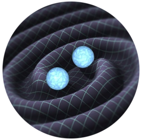
If mass transfer too fast for accretor to accept

$$M_2/\dot{M}_2 \ll \tau_{\mathrm{KH},2}$$

$$\Downarrow$$

Accretor swells

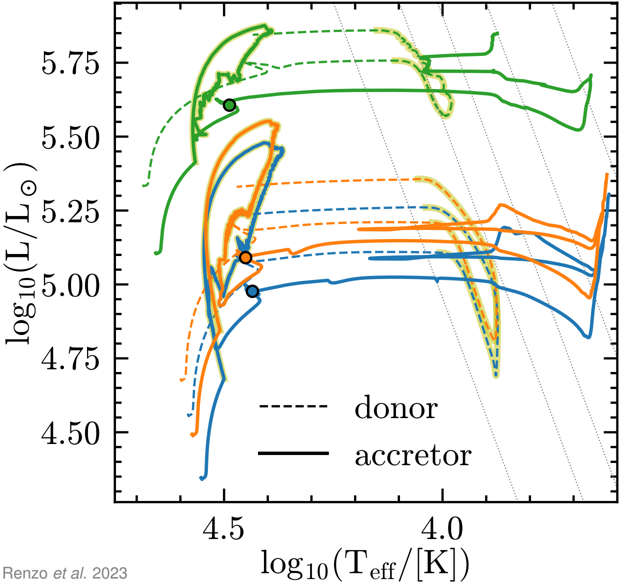




adapted from Vigna-Gómez *et al.* 2020

e.g., Flannery & Ulrich 1977, Justham *et al.* 2011, Vigna-Gómez *et al.* 2020

Low-Z massive accretors



$Z = 0.0019 \simeq Z_\odot/10$

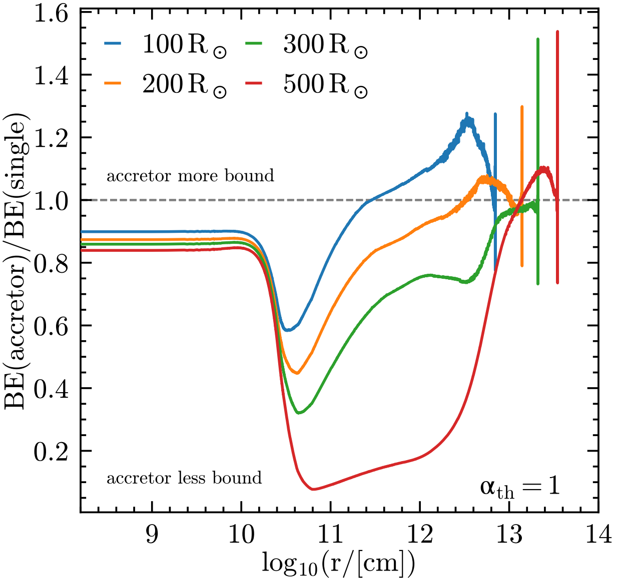
(to focus on GW merger progenitors)

Renzo *et al.* 2023

Taking the ratio: accretors are easier to unbind

NS or BH progenitor

$17 \rightarrow 20\, M_\odot$

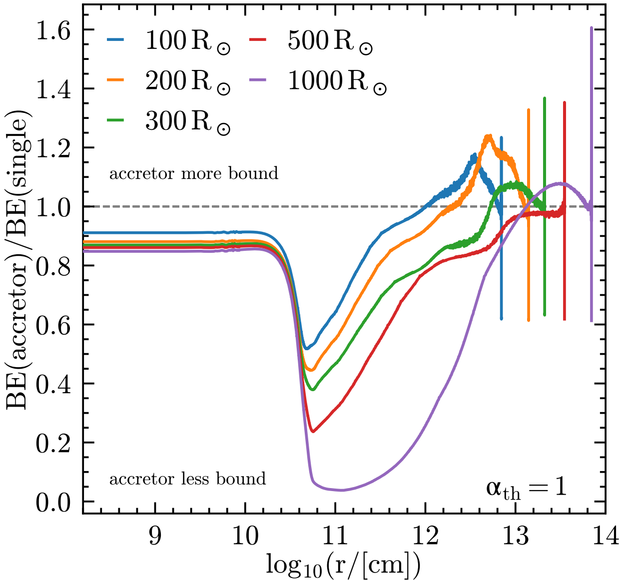


Renzo *et al.* 2023

Taking the ratio: accretors are easier to unbind

BH progenitor

$30 \rightarrow 36\,M_\odot$



Renzo *et al.* 2023

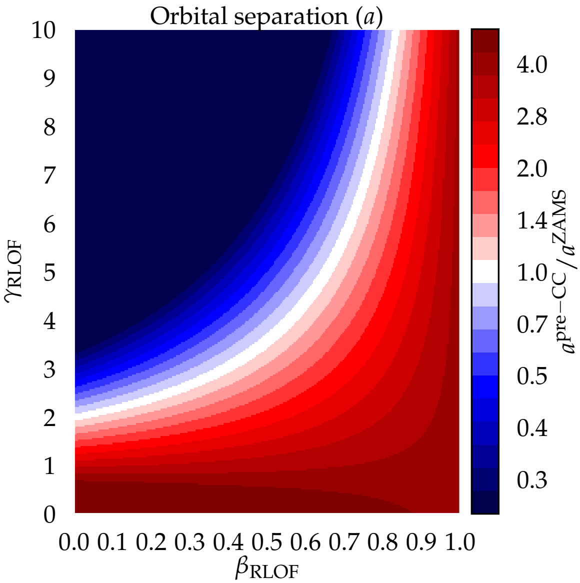
M_2 increase $\Rightarrow$ T_c increase $\Rightarrow$ core tries to grow

"Mixing strength"

Diffusion coefficients

Renzo & Götberg 2021, see also Hellings 1983, 1985, Braun & Langer 1995, Wang *et al.* 2020, Renzo *et al.* 2023

Overall widening of the orbits



Renzo *et al.* 2019b