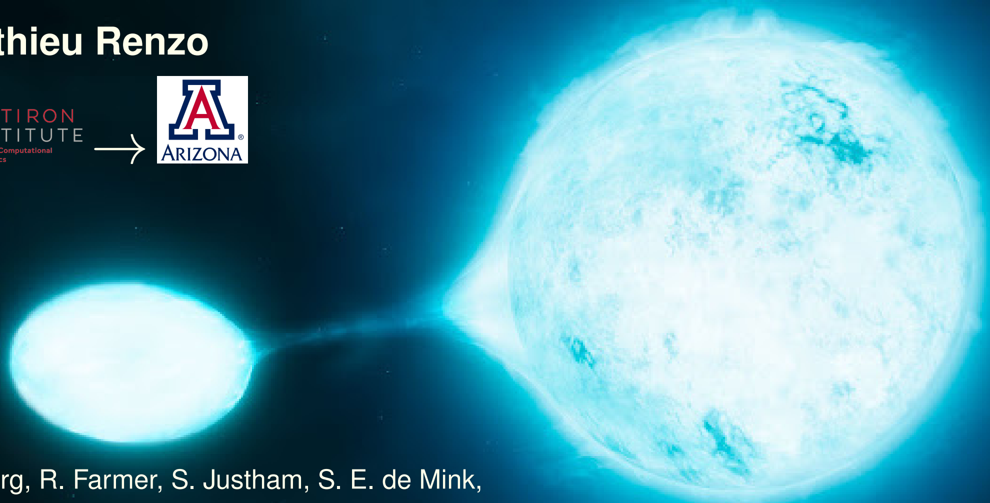
Widowed massive stars



Mathieu Renzo

FLATIRON INSTITUTE
Center for Computational Astrophysics → ARIZONA

with Y. Götberg, R. Farmer, S. Justham, S. E. de Mink,
K. Breivik, E. Zapartas, M. Lau, M. Cantiello, B. D. Metzger, J. Goldberg, Y.-F. Jiang, R. Izzard, ...

Widowed massive stars

Take home point:

This is not a single star!

The most common massive binary evolution path

Stable post donor main-sequence RLOF (case B)

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

Why care about the accretor?

Stellar populations

accretors lurk in samples

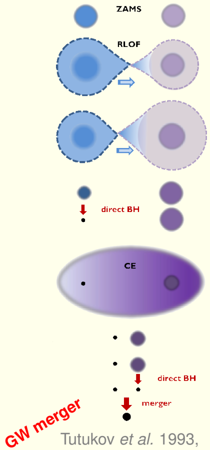
$(10 - 12\%)$ Renzo *et al.* 2019b

+

Oe/Be stars, stragglers

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

Binary interactions

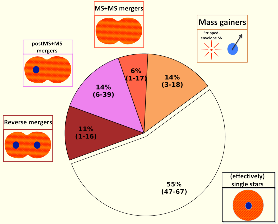


Tutukov *et al.* 1993,

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

Mass transfer occurs before the 1^{st} explosion

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

Renzo & Zapartas 2020

Mass transfer occurs before the 1^{st} explosion

- **Spin-up**

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

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Renzo & Zapartas 2020

Mass transfer occurs before the 1^{st} explosion

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- **Pollution**

  Blaauw 1993, Renzo & Götberg 2021

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Mass transfer occurs before the 1^{st} explosion

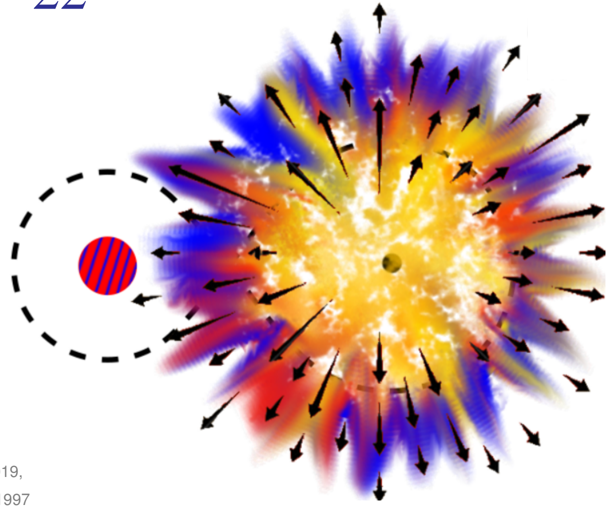
- **Spin-up**
  Packet 1981, Cantiello *et al.* 2007, de Mink *et al.* 2013, Renzo & Götberg 2021
- **Pollution**
  Blaauw 1993, Renzo & Götberg 2021
- **Rejuvenation**
  Hellings 1983, 1985, Braun & Langer 1995, Renzo *et al.* 2023

The “widowed” star carries signatures of its past in a binary

Renzo & Zapartas 2020

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

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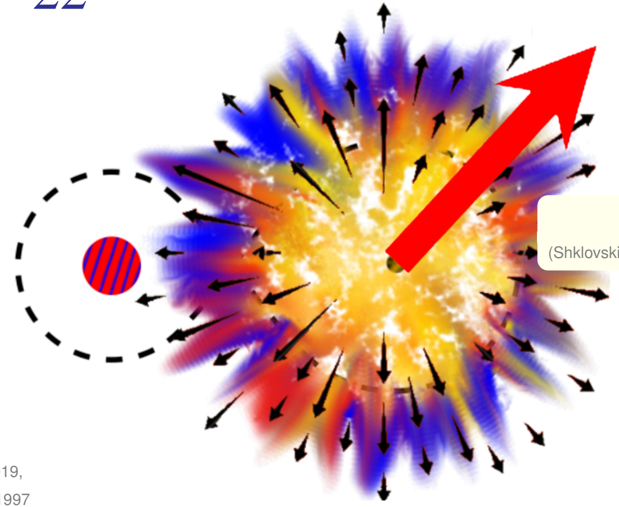

SN Natal kick

(Shklovskii 1970, Katz 1975, Janka 2013, 2017)

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

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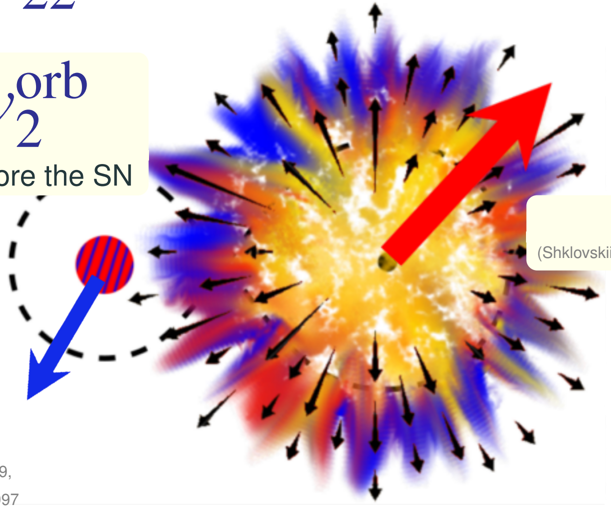
$86^{+11}_{-22}\%$ of massive binaries are disrupted

$$v_{\text{dis}} \simeq v_2^{\text{orb}}$$

before the SN



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(Shklovskii 1970, Katz 1975, Janka 2013, 2017)

Renzo *et al.* 2019b, Kochanek *et al.* 2019,
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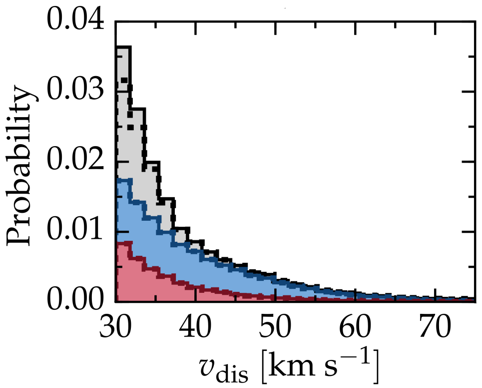
Kinematics of the widowed stars

Accretor stars can be *runaways*...

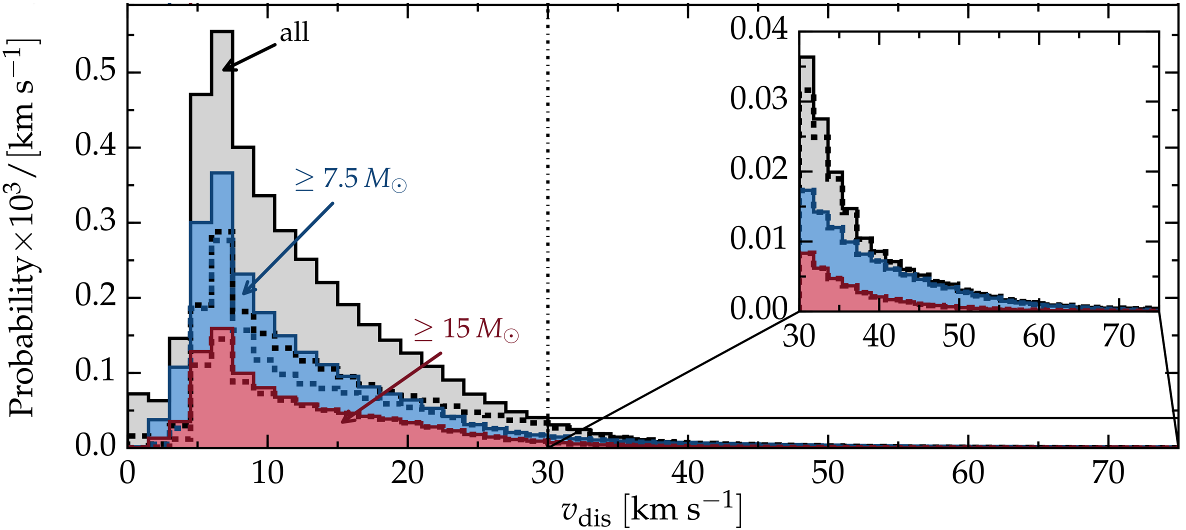


Velocity w.r.t. pre-explosion binary center of mass

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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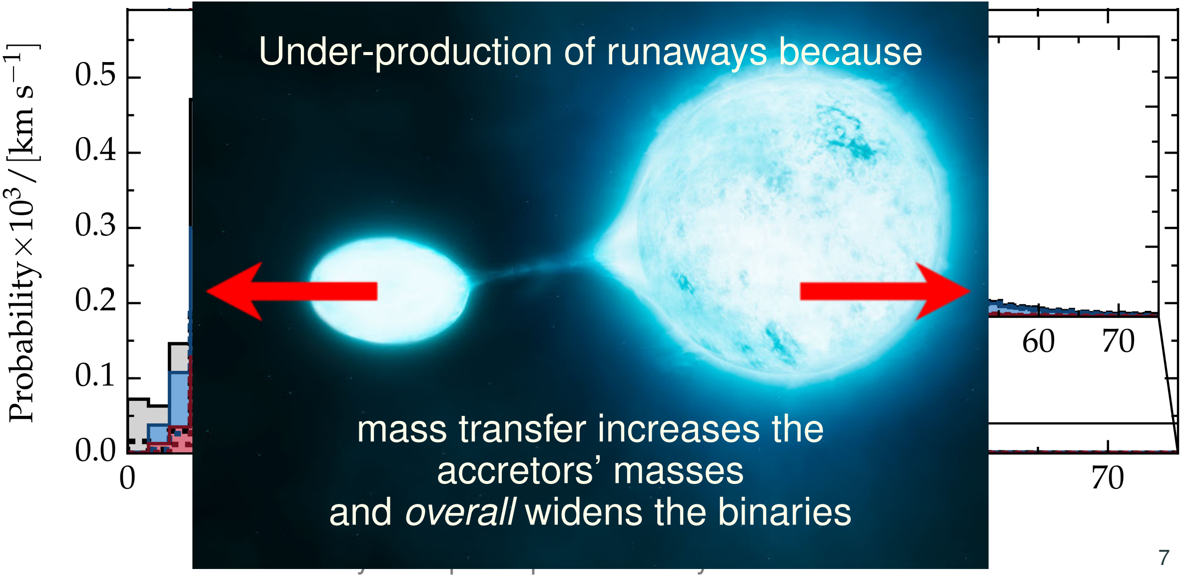

Renzo *et al.* 2019b

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

Using the nearest O-type star to Earth to understand accretors

Spitzer, NASA/JPL

Walker *et al.* 1979,
Herrero *et al.* 1994,
van Rensbergen *et al.* 1996,
Hoogerwerf *et al.* 2001,
Villamariz & Herrero 2005,
Walker & Koushnik 2005,
Zee *et al.* 2018,
Gordon *et al.* 2018,
Neuhäuser *et al.* 2019, 2020,
Lux *et al.* 2020,
Renzo & Götberg 2021,
Shepard *et al.* 2022

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Lux *et al.* 2020,
Renzo & Götberg 2021,
Shepard *et al.* 2022

e.g., Sexton *et al.* 2015, Kiminki *et al.* 2017,
Bodensteiner *et al.* 2018, Raga *et al.* 2022

Using the nearest O-type star to Earth to understand accretors

Spitzer, NASA/JPL

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Neuhäuser *et al.* 2019, 2020,
Lux *et al.* 2020,
Renzo & Götberg 2021,
Shepard *et al.* 2022

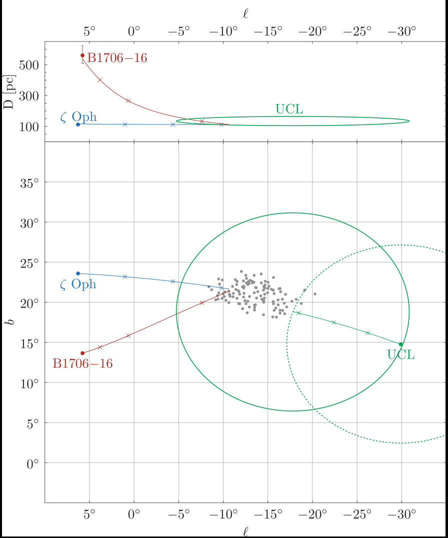
Observational constraints of ζ Oph.:

- $d \simeq 107 \pm 4\,\mathrm{pc}$
- $M \simeq 20\,M_\odot$
- $20\,\mathrm{km\ s^{-1}} \lesssim v_\mathrm{sys} \lesssim 50\,\mathrm{km\ s^{-1}}$
- $v \sin(i) \gtrsim 310\,\mathrm{km\ s^{-1}}$, $i \gtrsim 56°$
- (T_eff, L) position
- $Z \lesssim Z_\odot$, ^{4}He- and ^{14}N-rich, normal ^{12}C and ^{16}O

✗ **Rotating single stars**

(e.g., van Rensbergen *et al.* 96, Howarth & Smith 01, Villamariz & Herrero 05)

ζ Ophiuchi is single but we can trace it back to a neutron star



Neuhäuser *et al.* 2019, 2020 see also Blaauw 1952, 1961,
van Rensbergen *et al.* 1996, Hoogerwerf *et al.* 2001, Lux *et al.* 2020

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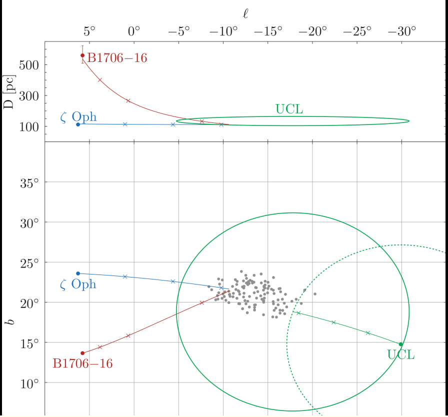


SN explosion $\sim 1.78 \pm 0.21$ **Myr ago**

$\Rightarrow$Radioactive iron rain on Earth

Benitez *et al.* 2002, Fry *et al.* 2016, Neuhäuser *et al.* 2020

Neuhäuser *et al.* 2019, 2020 see also Blaauw 1952, 1961,
van Rensbergen *et al.* 1996, Hoogerwerf *et al.* 2001, Lux *et al.* 2020

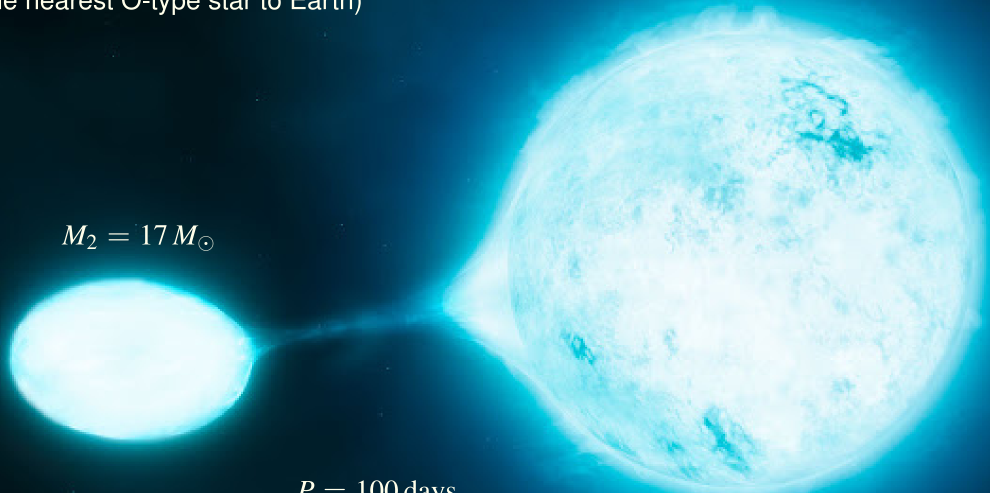
Self-consistent MESA model

(aiming at the nearest O-type star to Earth)

$Z = 0.01$

(Murphy *et al.* 2021)

$M_2 = 17\,M_\odot$

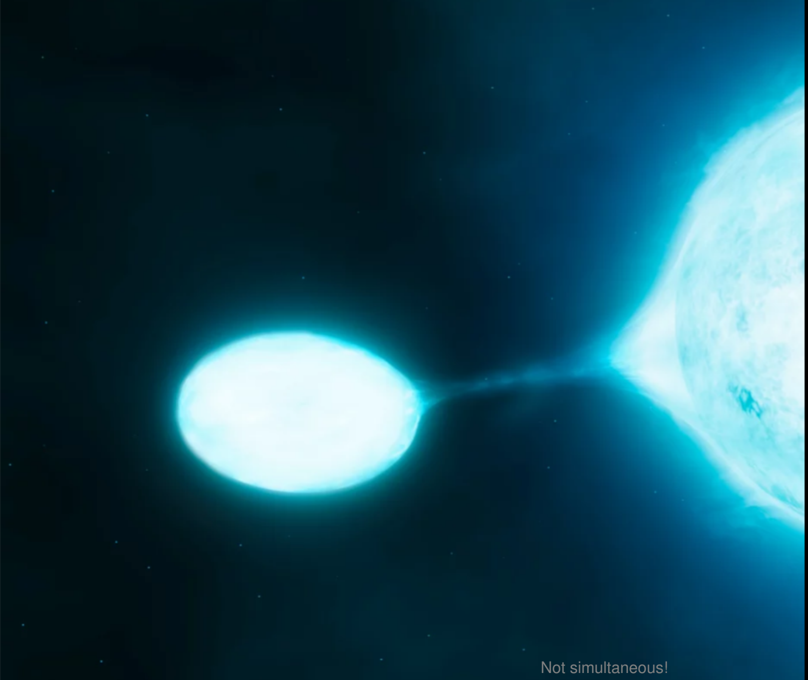


$P = 100$ days

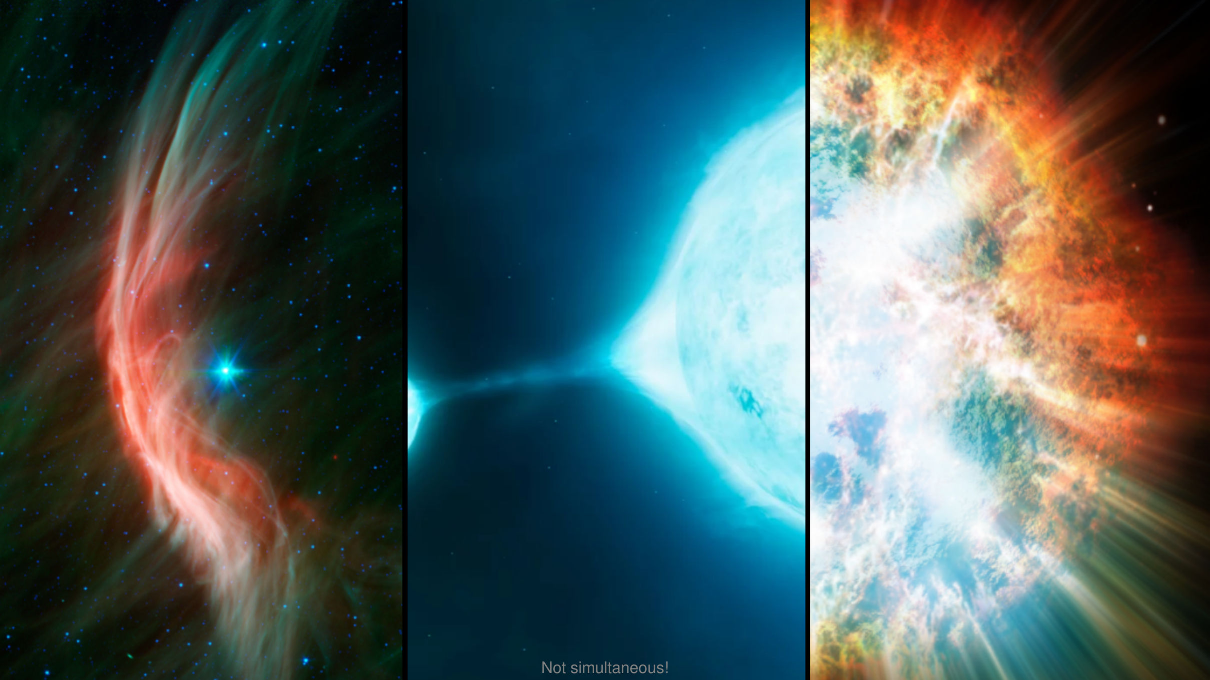
(case B RLOF)

$M_1 = 25\,M_\odot$

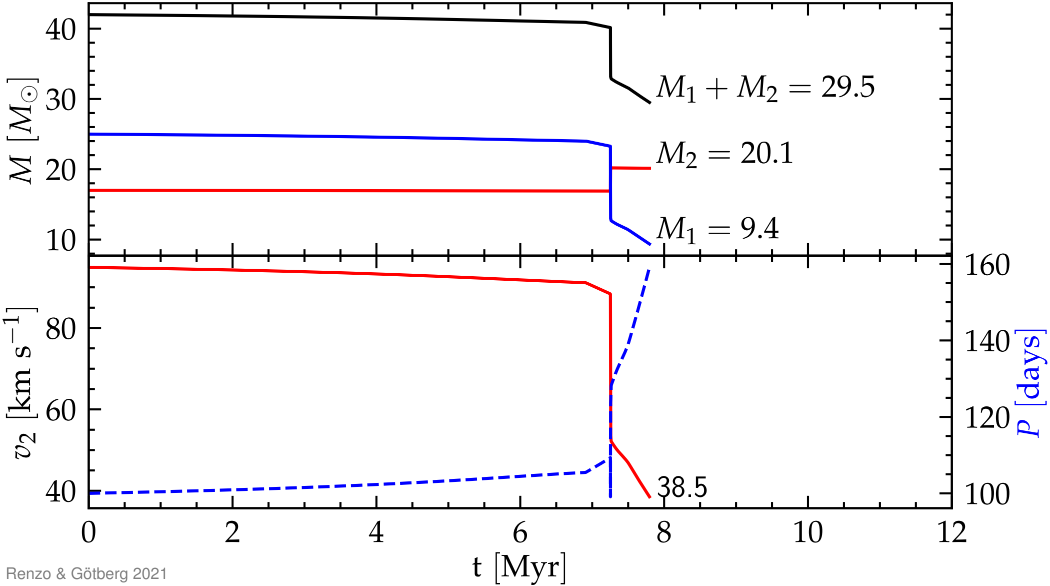
Renzo & Götberg 2021




Not simultaneous!

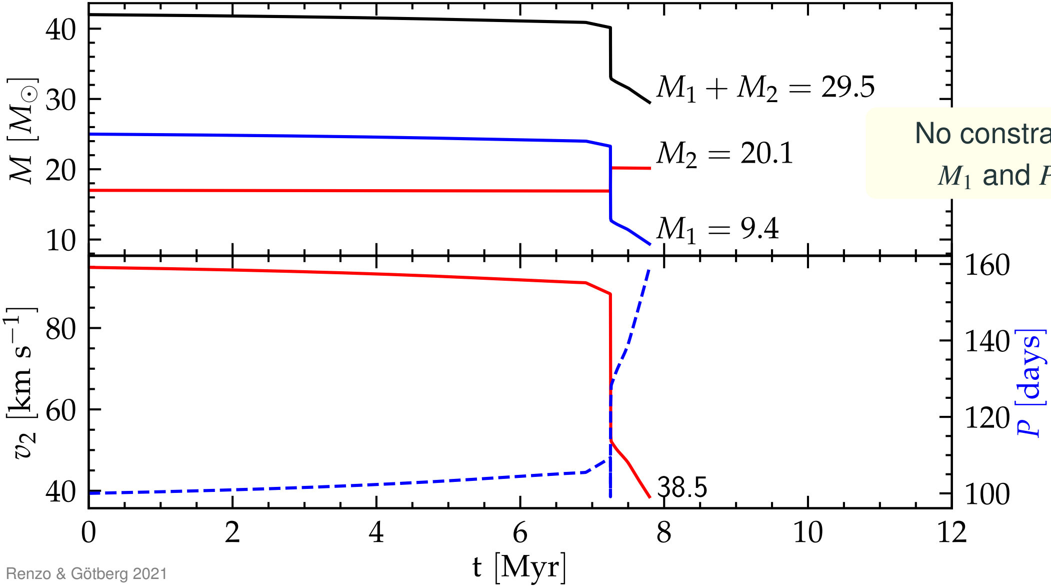

Not simultaneous!

Orbital evolution: ✓ Mass & ✓ spatial velocity



Renzo & Götberg 2021

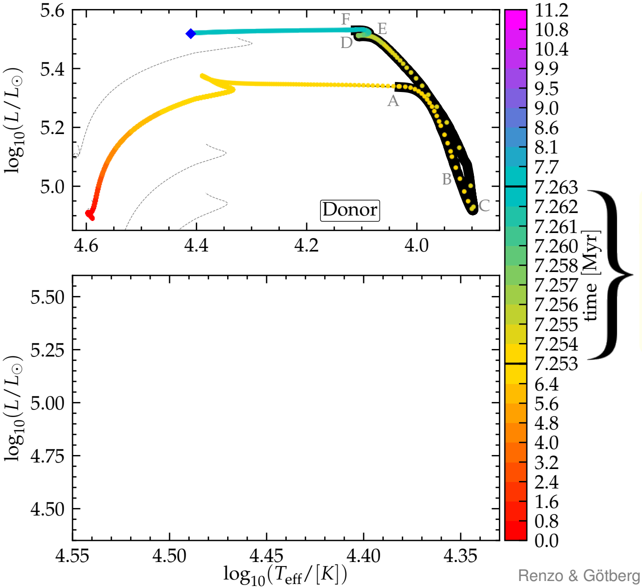
Orbital evolution: ✓ Mass & ✓ spatial velocity



No constraints on M_1 and P_{ZAMS}

Renzo & Götberg 2021

HRD of both stars: the donor



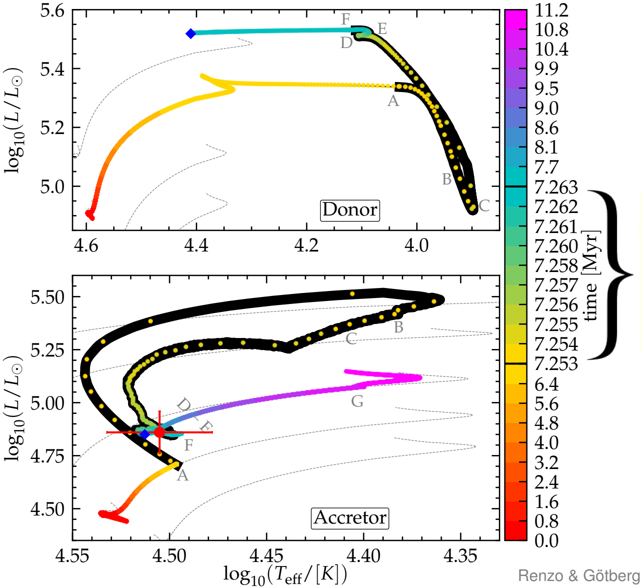
Case B mass transfer is short

$$\Delta t_{\mathrm{RLOF}} \sim 10^4\ \mathrm{yr}$$

but has long-lasting impact on **both** stars.

Renzo & Götberg 2021

HRD of both stars: the donor & the accretor ✓



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Renzo & Götberg 2021 (data from Villamàriz & Herrero 05)

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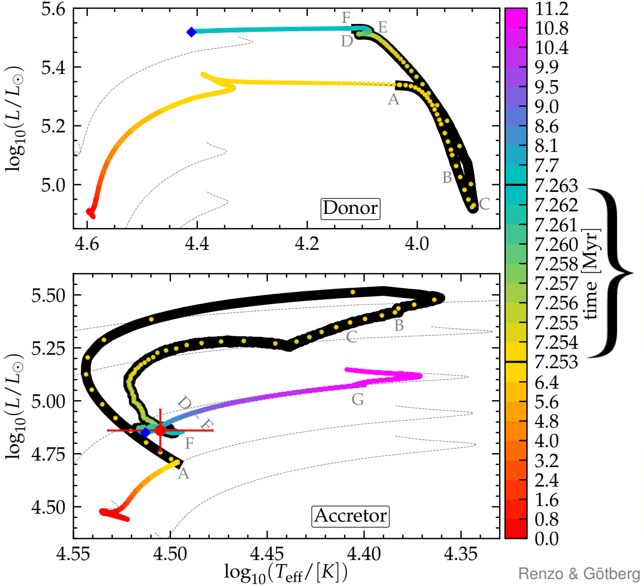


Case B mass transfer is short

$\Delta t_{\rm RLOF} \sim 10^4$ yr

but has long-lasting impact

on **both** stars.

✓ Models match ζ Oph.

L, $T_{\rm eff}$, Mass, age, velocity

Renzo & Götberg 2021 (data from Villamàriz & Herrero 05)

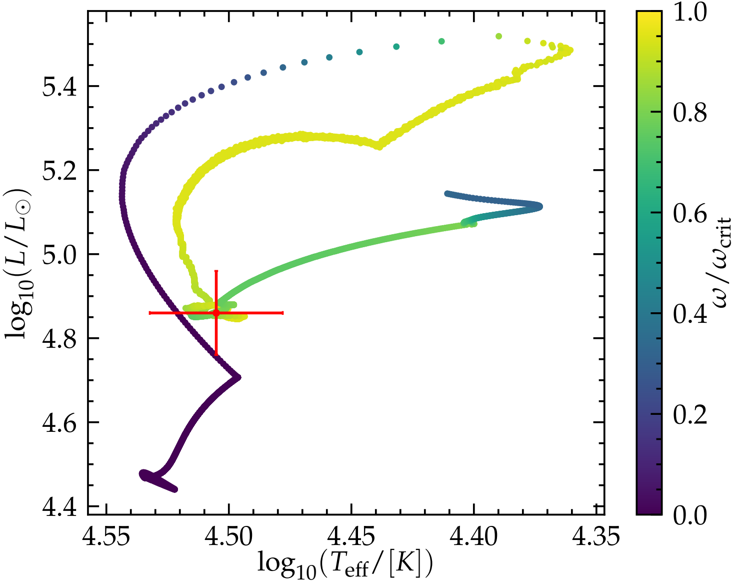
Internal structure of the accretor

Spin up: surface and interior

Pollution: ^{4}He and ^{14}N

Rejuvenation: core-envelope boundary

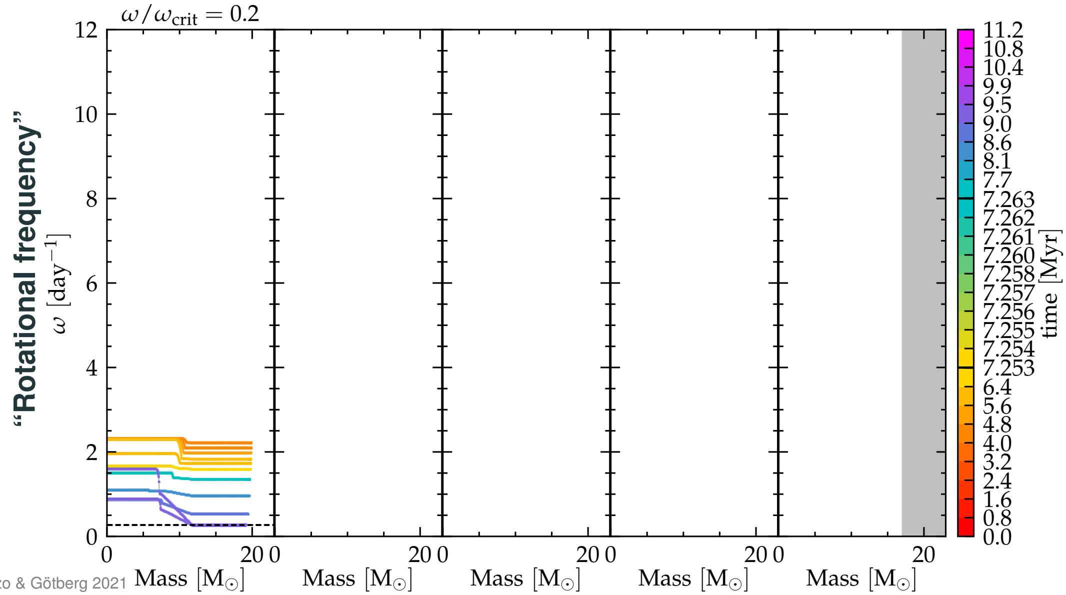
HRD: accretor rotation ✓



- Minimum $T_{\rm eff}$ during RLOF reached at onset of critical rotation.
- Rotation close to critical for large part of the main sequence.

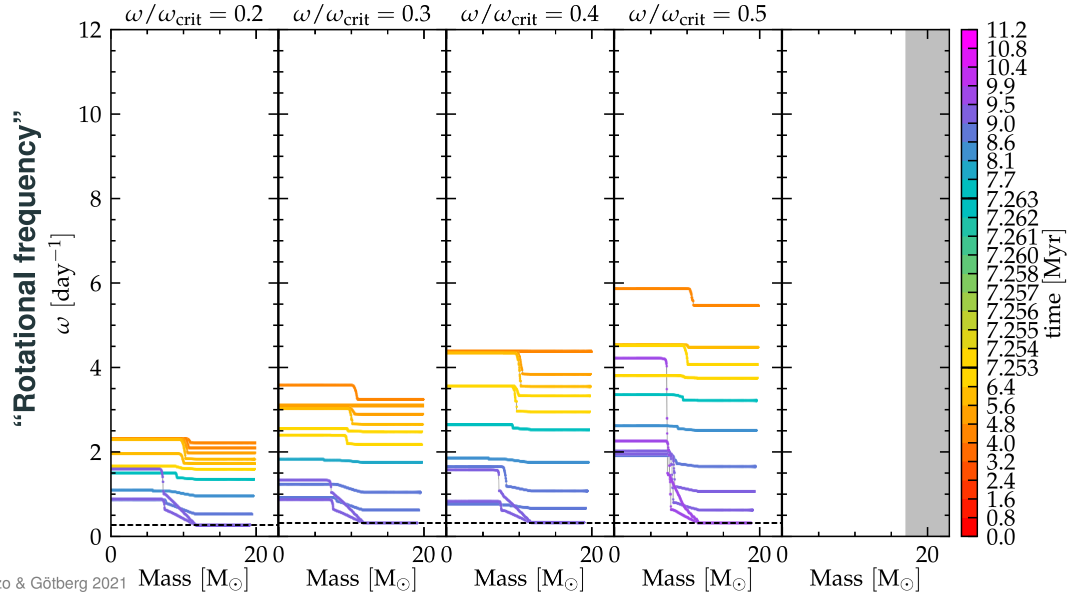
$$\omega \simeq \omega_{\rm crit} = \sqrt{\left(1 - \frac{L}{L_{\rm Edd}}\right)\frac{GM}{R^3}}$$

Internal rotational profile: single stars



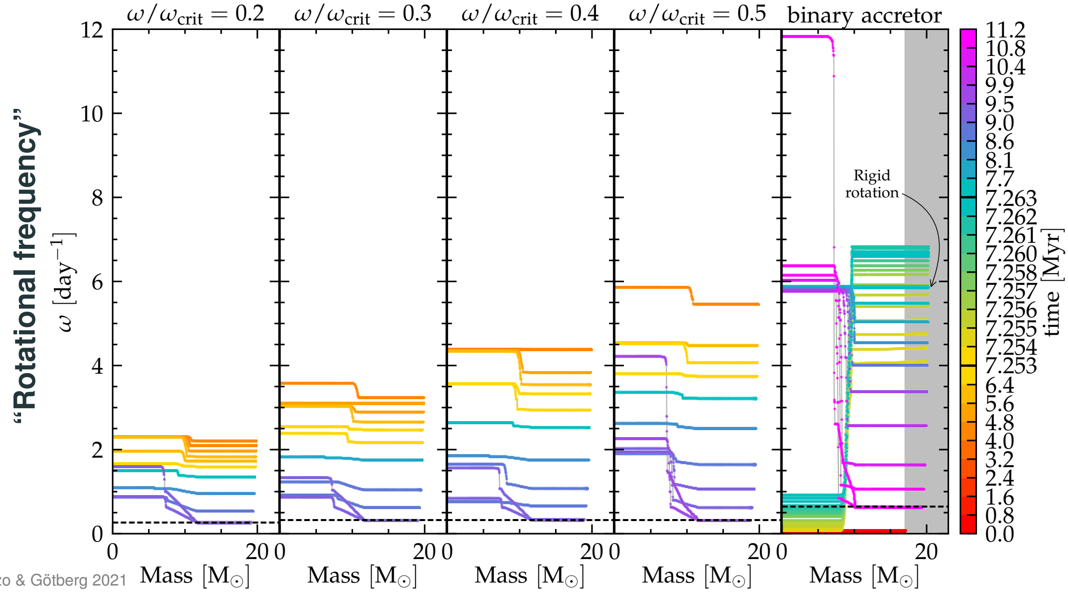
Renzo & Götberg 2021

Internal rotational profile: single stars



Renzo & Götberg 2021

Internal rotational profile: accretor

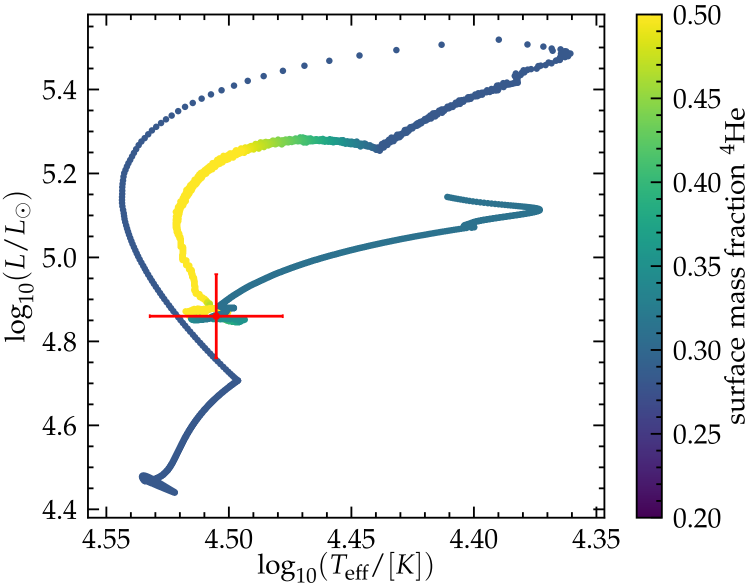


Renzo & Götberg 2021

Internal structure of the accretor

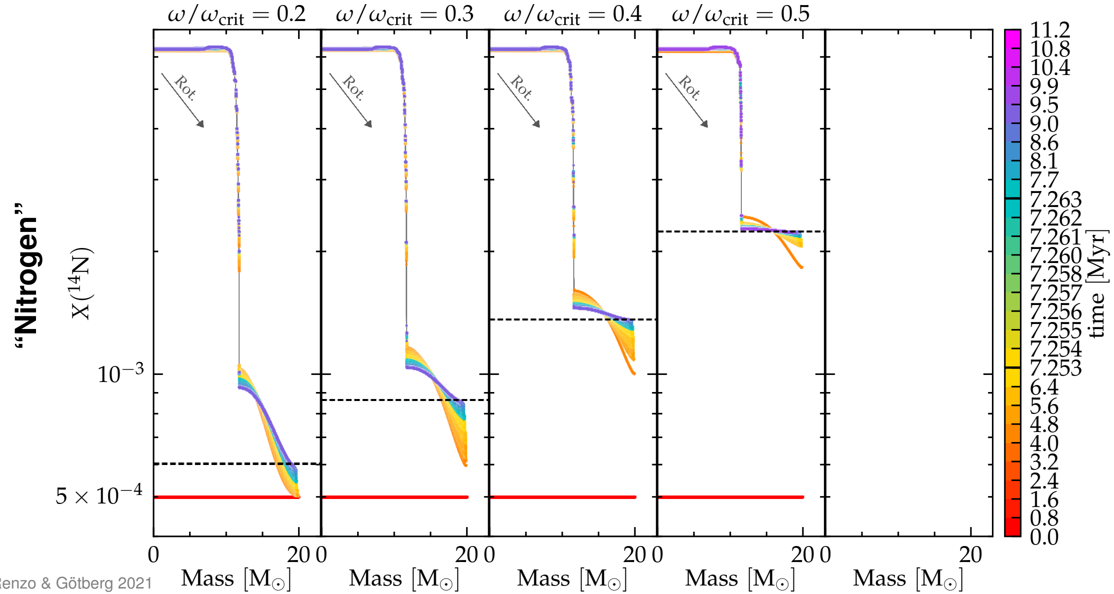
Spin up: surface and interior
Pollution: $^{4}\mathrm{He}$ and $^{14}\mathrm{N}$
Rejuvenation: core-envelope boundary

HRD: Helium surface abundance



- Accretion of He-rich matter change morphology at $T_{\rm eff} \simeq 10^{4.44}$ K.
- Interplay between accretion, mixing and rotation causes "noisiness".

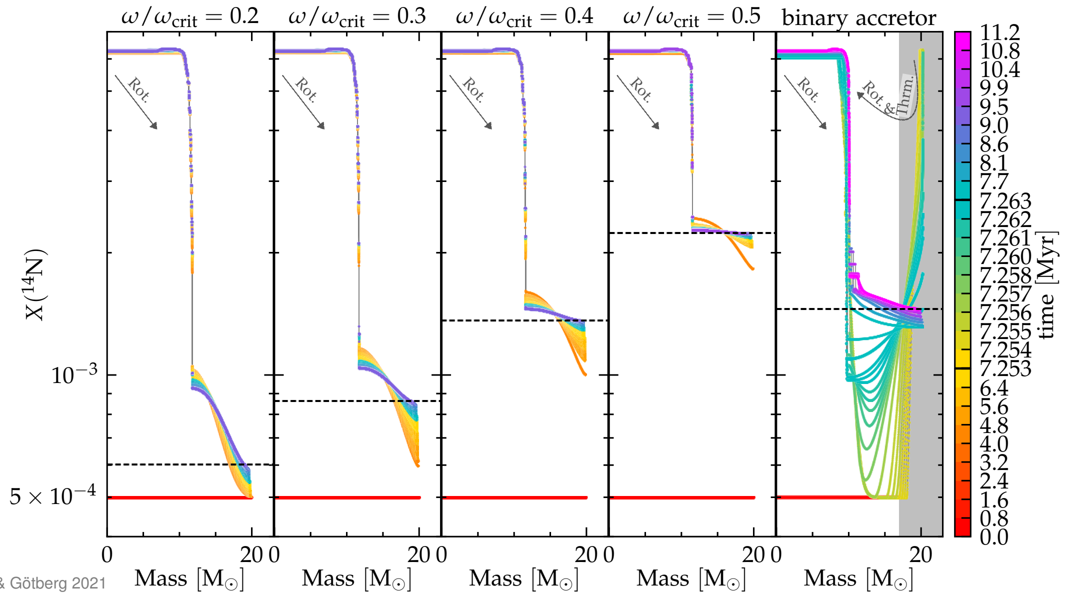
Composition profile: comparison with rotating single stars



Renzo & Götberg 2021

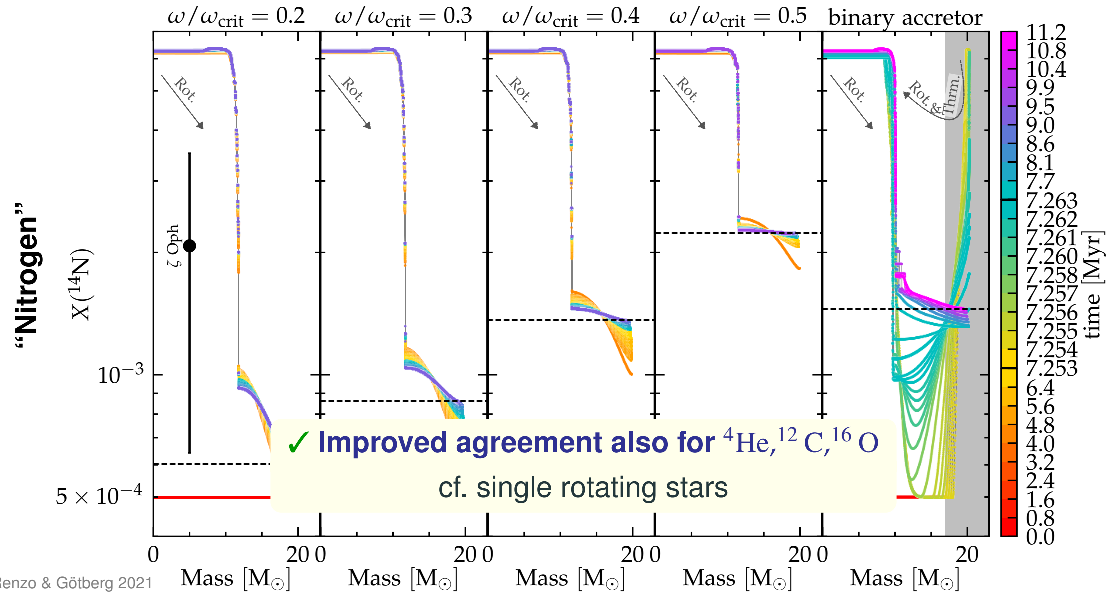
Composition profile: comparison with rotating single stars

"Nitrogen"



Renzo & Götberg 2021

Composition profile: accretor's surface is polluted by donor's core



✓ **Improved agreement also for $^{4}He, ^{12}C, ^{16}O$**

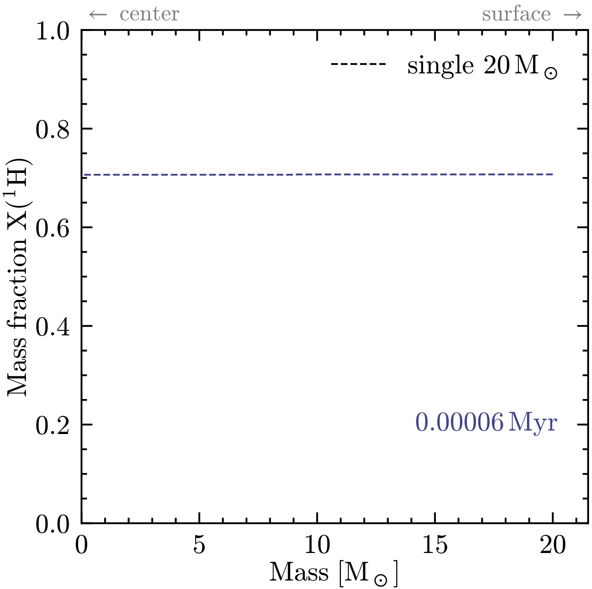
cf. single rotating stars

Renzo & Götberg 2021

Internal structure of the accretor

Spin up: surface and interior
Pollution: $^{4}\mathrm{He}$ and $^{14}\mathrm{N}$
Rejuvenation: core-envelope boundary

Refresher: formation of the helium core in single stars



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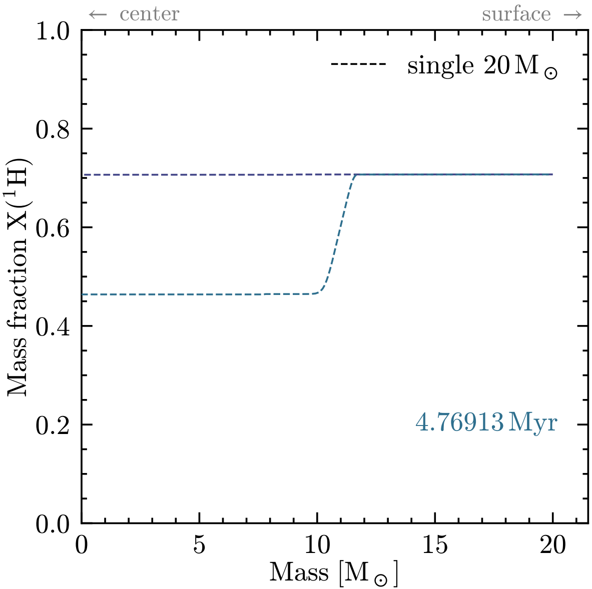

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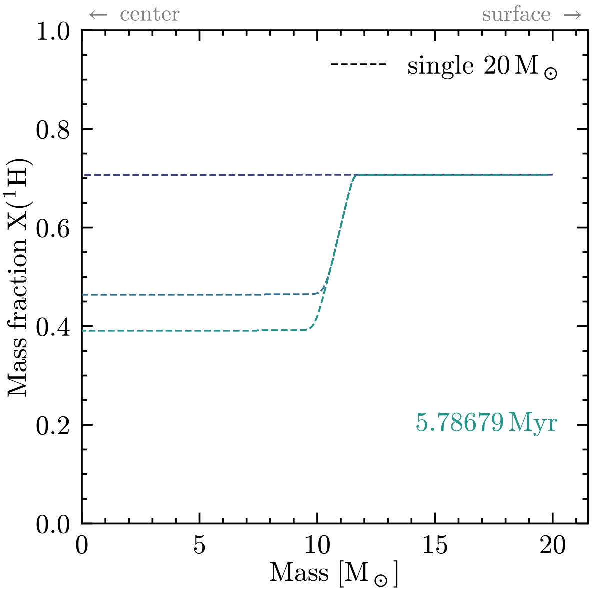

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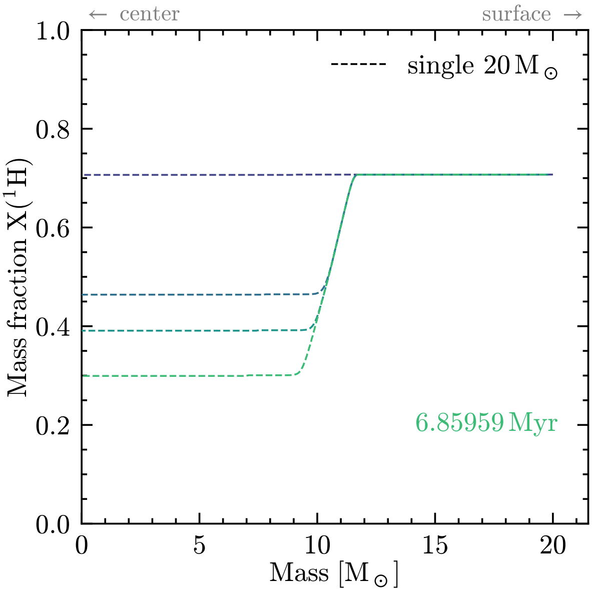

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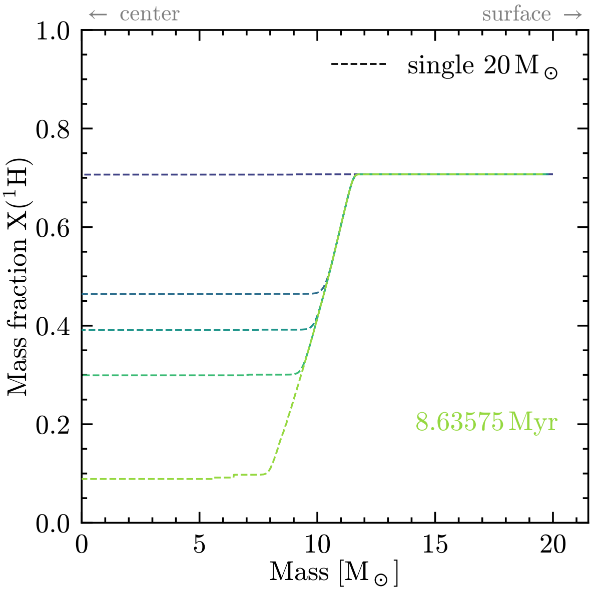

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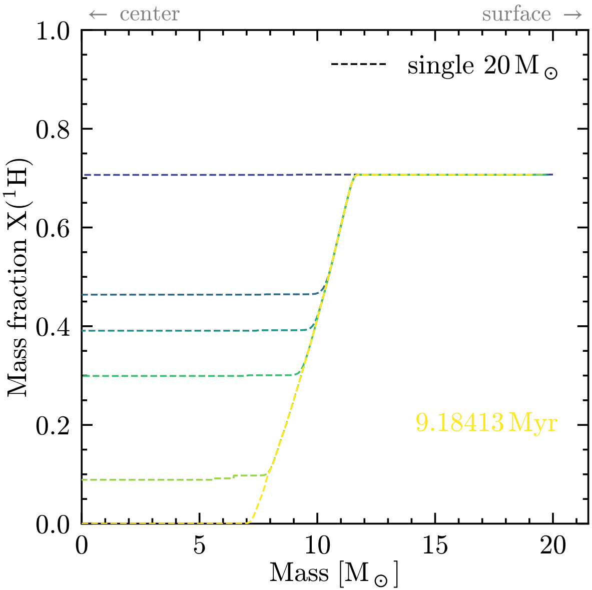
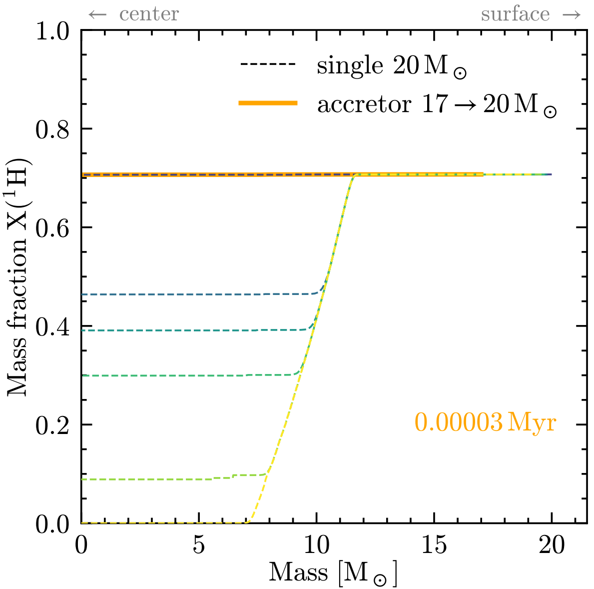


Evolution of the accretor's core through RLOF



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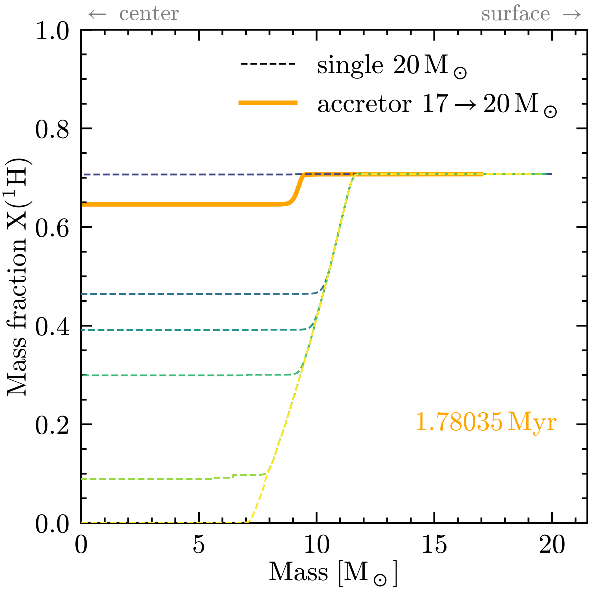

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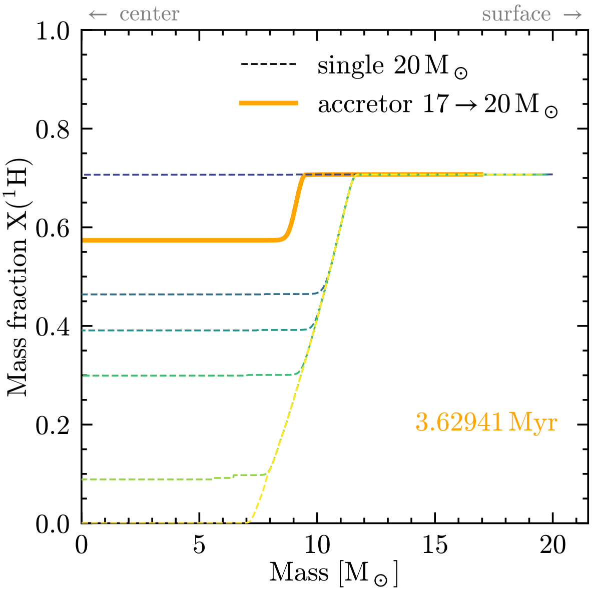

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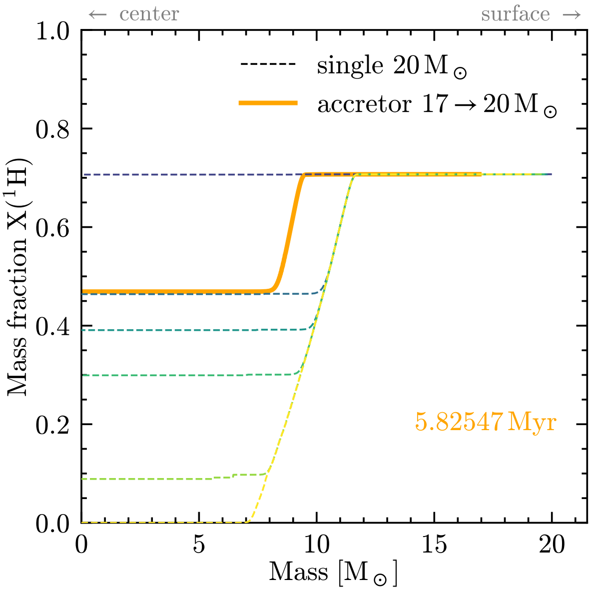

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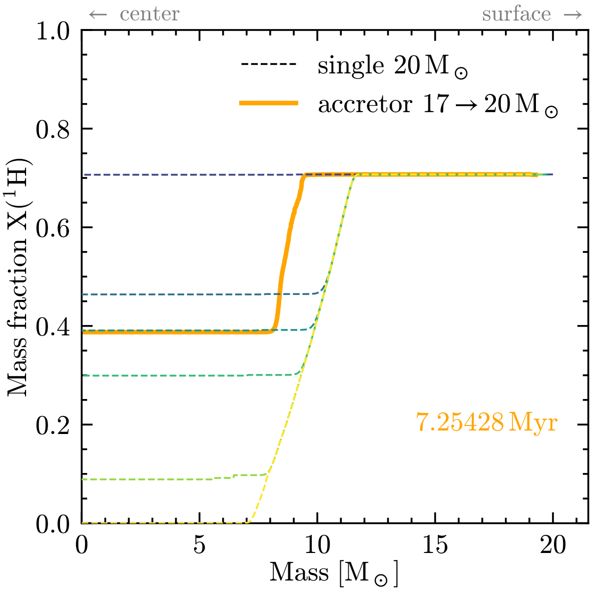

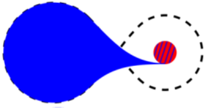

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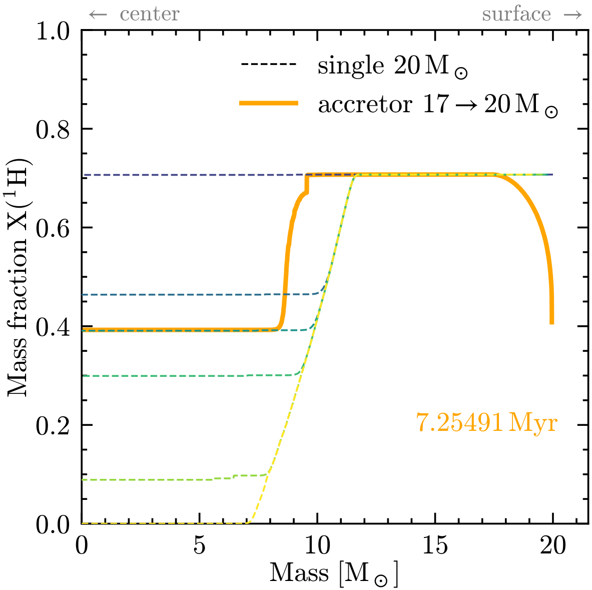

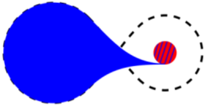

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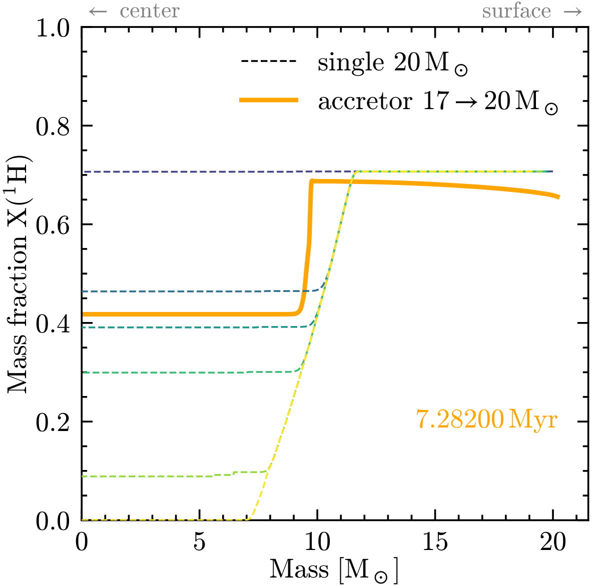

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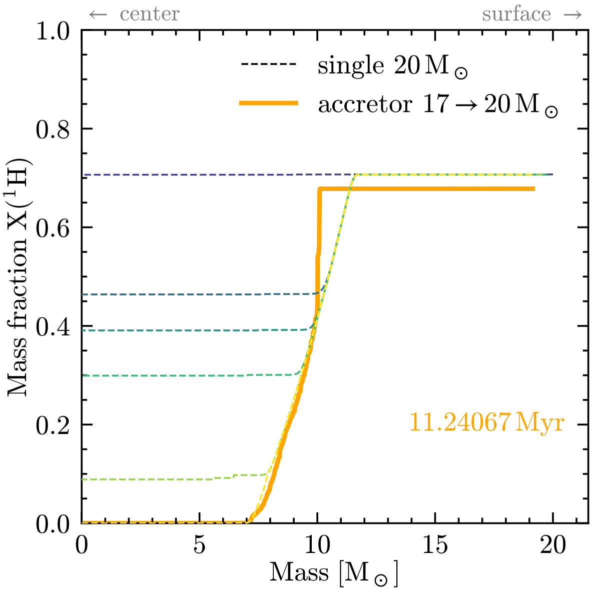
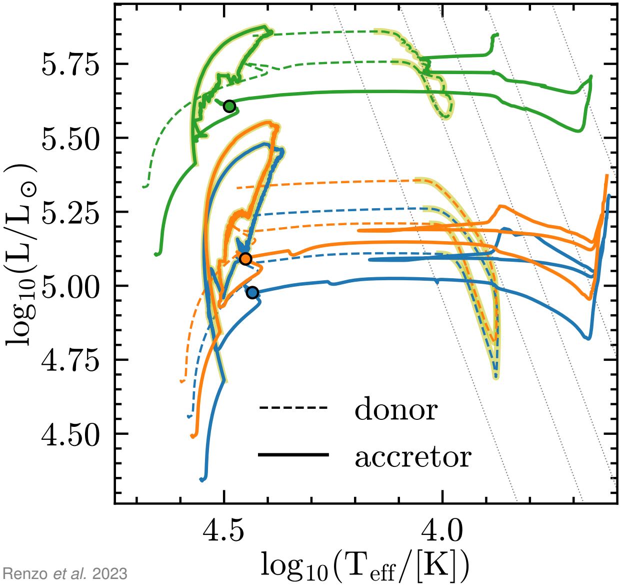


Consequences of rejuvenation

Blue loops in high-mass stars?

Easier to unbind the envelope

Low-Z massive accretors



Renzo *et al.* 2023

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

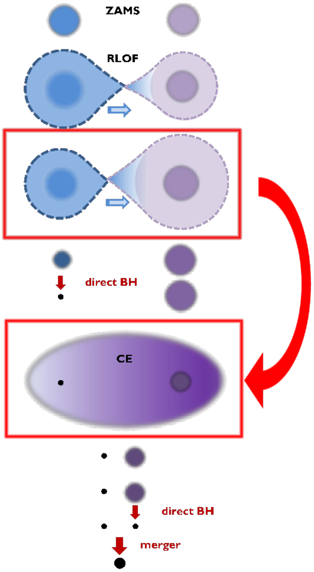
(to focus on GW merger progenitors)

Consequences of rejuvenation

Blue loops in high-mass stars?

Easier to unbind the envelope

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

Project with Paul Ricker!

Belczynski *et al.* 2016

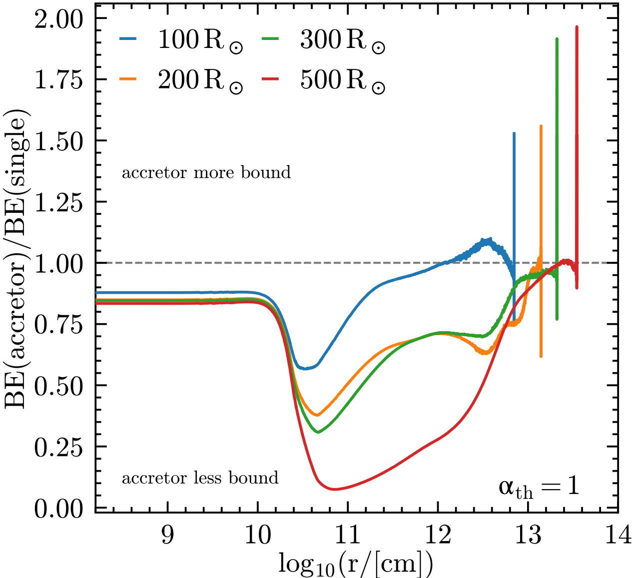
Ratio of binding energies: accretors are easier to unbind

NS progenitor

$15 \rightarrow 17\,M_\odot$

works up to

$\sim 30\,M_\odot$



Renzo *et al.* 2023

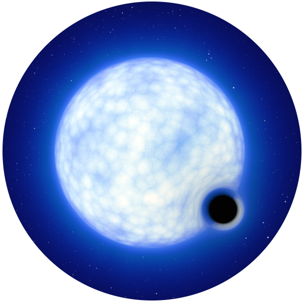
Conclusions

Accretors are *not* single stars

- One of the most common products of massive binary evolution
  - ⇒ important contaminants of populations of stars and transients
- Binary SN disruption produces more walkaways than runaways
  - ⇒ kinematics, appearance, and structure probe binary interactions
- Mass transfer modifies accretors **spin-up**, **pollution**, and **rejuvenation**
  - ⇒ MESA binary models of ζ Ophiuchi ✓
  - ⇒ ^{14}N and ^{4}He from the donor, inward angular momentum transport
  - ⇒ Observed composition constrains mixing & accretion efficiency
- Evolved accretor's core boundary results in easier to eject envelopes (?)
  - ⇒ Implications for asteroseismology & common envelope in GW progenitors

Backup slides

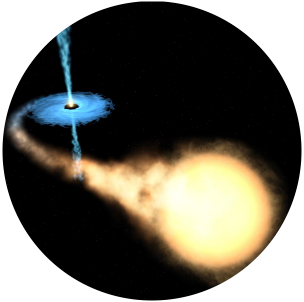
Some binaries do survive the 1^{st} core-collapse



Non-interacting

Shenar *et al.* 2022, El-Badry *et al. 2022ab*,

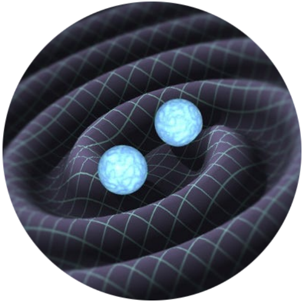
Chawla *et al.* 2020, etc.



X-ray binaries

Webster & Murdin 1972, Bolton 1972,

van der Meij *et al.* (incl. MR) 2021, etc.

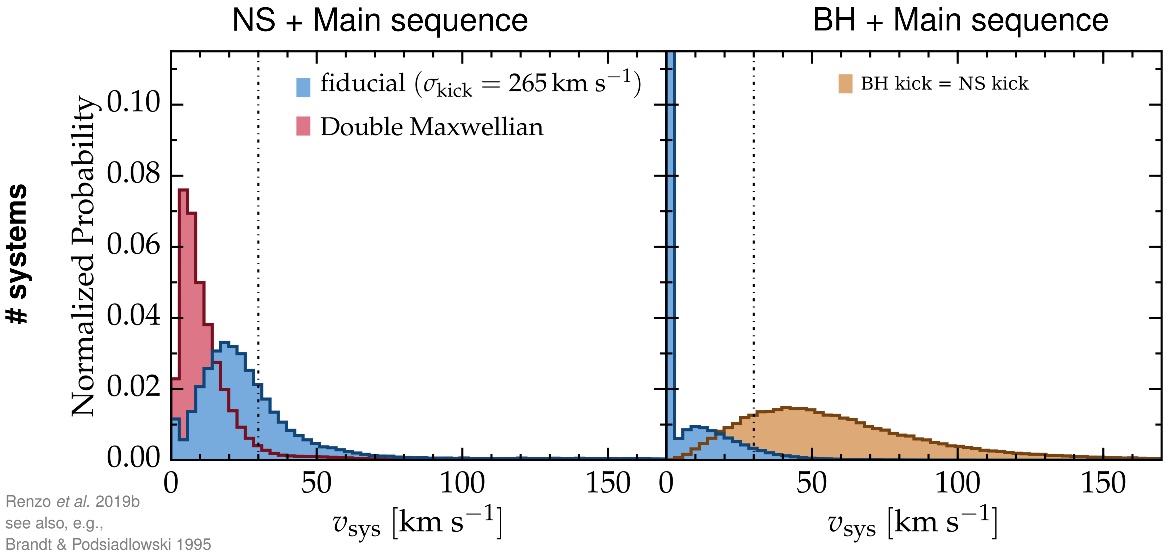


Gravitational waves

Including BBH, BHNS, BNS,

LIGO, Virgo, Kagra collaboration

Post-SN velocity of surviving binaries

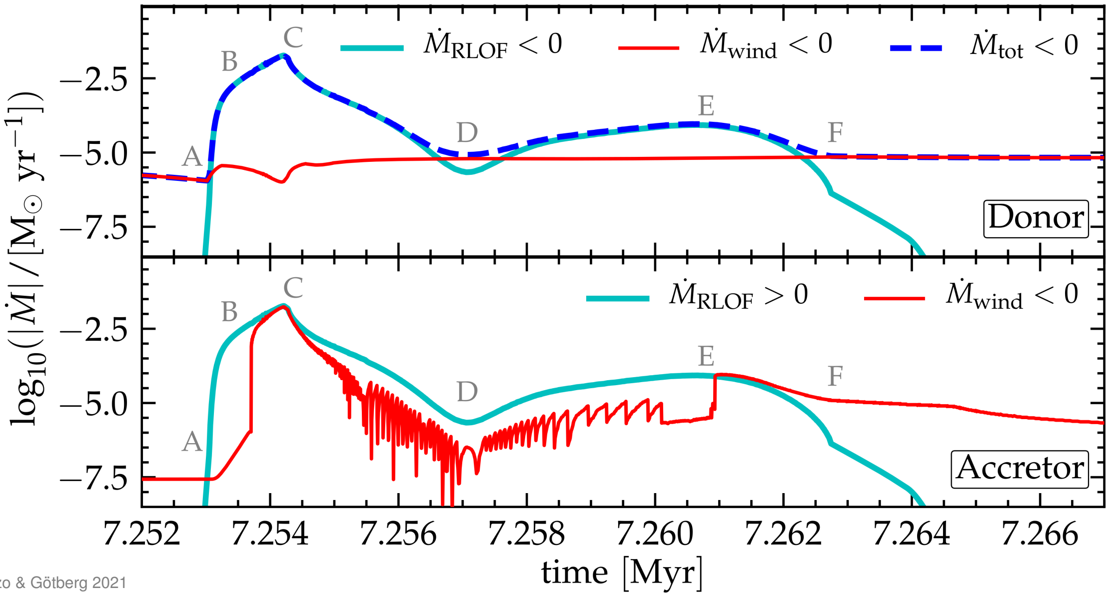


Renzo *et al.* 2019b
see also, e.g.,
Brandt & Podsiadlowski 1995
Kalogera 1996
Tauris & Takens 1998

Velocity respect to the pre-explosion binary center of mass

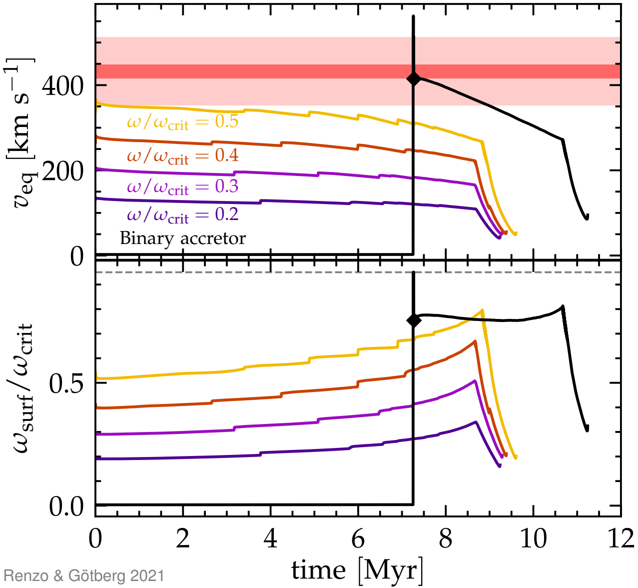
Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

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



Renzo & Götberg 2021

✓ Surface rotation rate ?



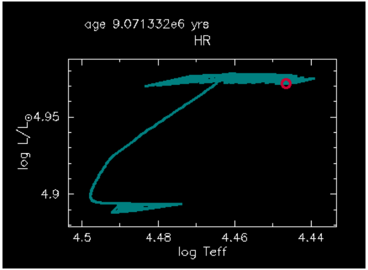
Renzo & Götberg 2021

- 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)

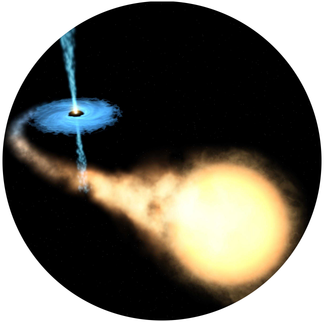
✗ Decreasing the wind: $\omega > \omega_{crit}$



Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion



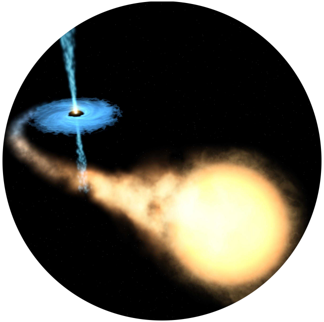
YES

⇒ most are single and we can't see them...

Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion

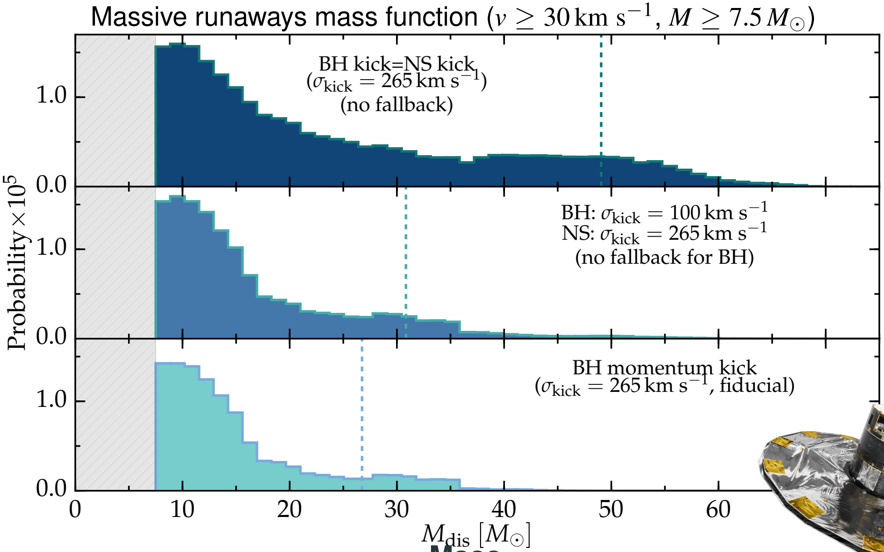


YES

⇒ most are single and we can't see them...

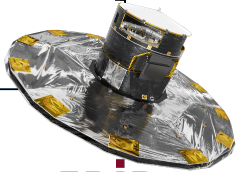
...but we can see the "widowed" companions

A way to constrain BH kicks with Gaia



stars

Mass



Numerical results publicly available at:

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

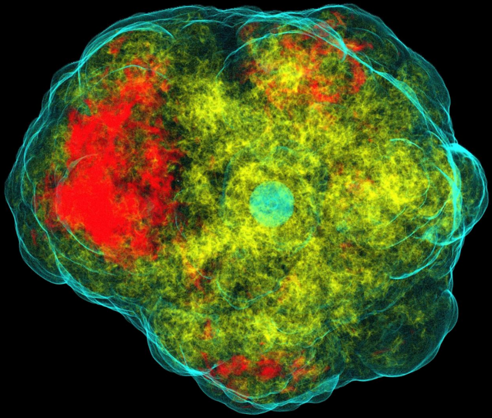
Renzo *et al.* 19b

gaia

SN natal kick

Observationally: $v_{\rm pulsar} \gg v_{\rm OB-stars}$

Physically: ν emission and/or ejecta anisotropies



Credits: C. D. Ott, S. Drasco

SN natal kick

Observationally: $v_{\mathrm{pulsar}} \gg v_{\mathrm{OB-stars}}$

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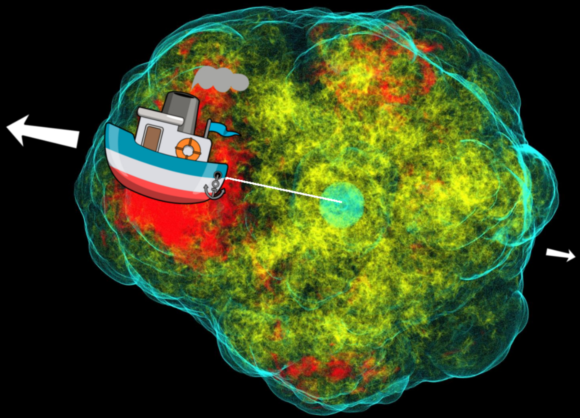
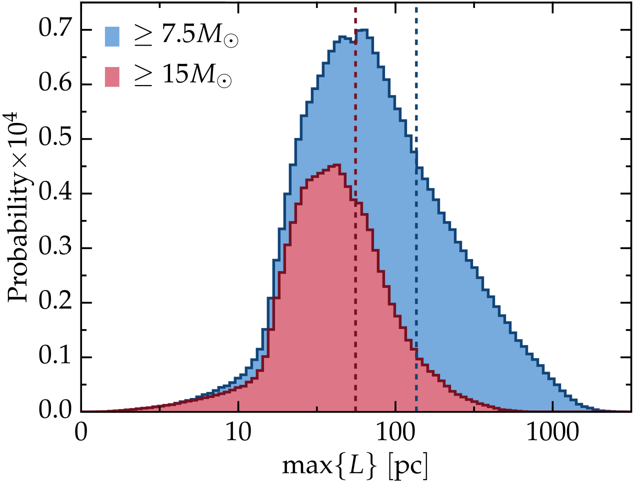


Credits: C. D. Ott, S. Drasco

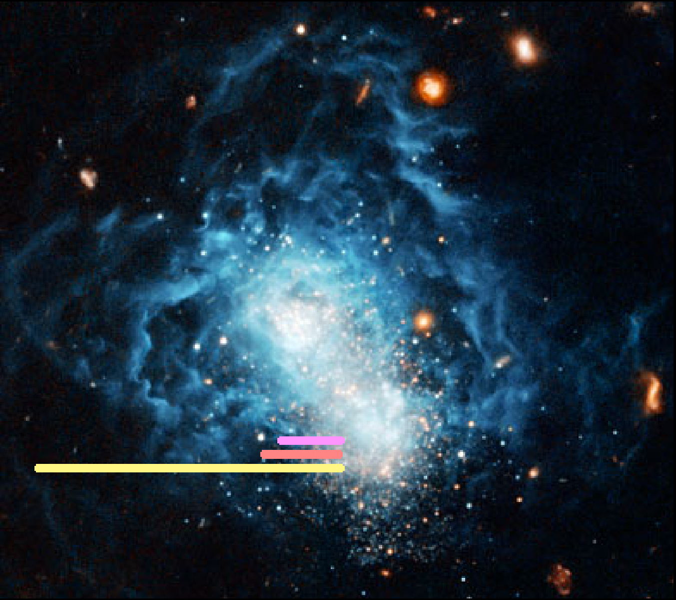
How far do they get?



"Distance traveled"
(No potential well)

Renzo *et al.* 19b

Nevertheless: widowed stars can escape local dust clouds



for $M \geq 7.5\,M_\odot$:

$\langle D \rangle$ = 128 pc

$\langle D_{\rm run} \rangle$ = 525 pc

$\langle D_{\rm walk} \rangle$ = 103 pc

Renzo *et al.* 19b

I Zw18

Credits: ESA/Hubble & Nasa, A. Aloisi

Thermohaline mixing = double diffusion

Stable thermal gradient

+

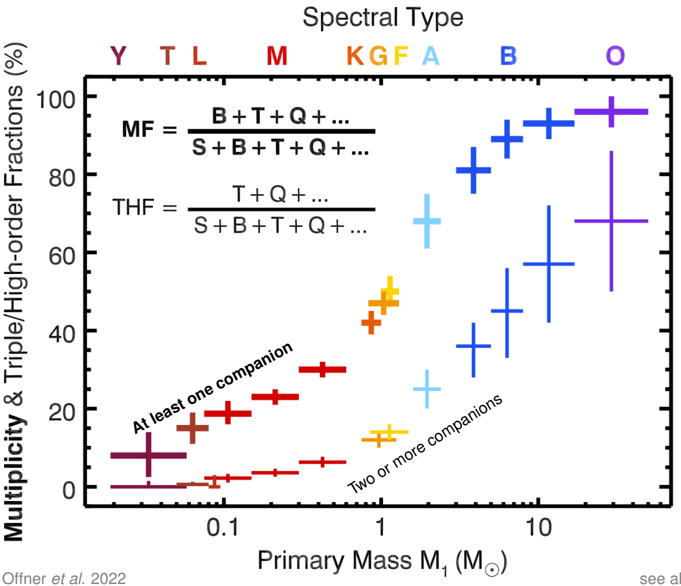
Unstable composition gradient

=

Heat needs to diffuse for mixing to happen

credits: M. Cantiello

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

Internal mixing in the accretor

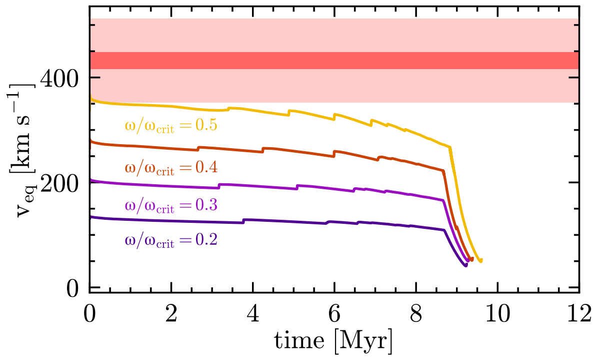
Does a binary past help with ζ Oph. ?

Spin-up – Pollution – Rejuvenation

Renzo & Götberg 2021

✗ Spin up:

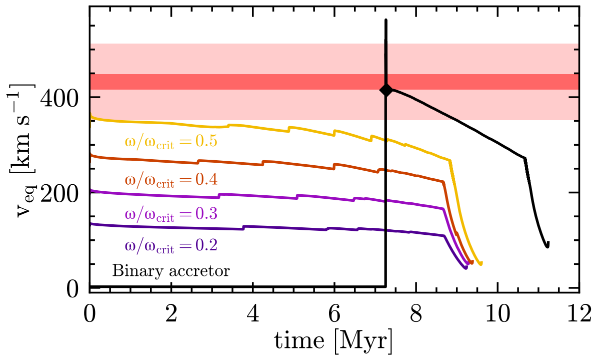
Natal rotation would need to be extreme to match



weak-wind problem, neglecting inclination

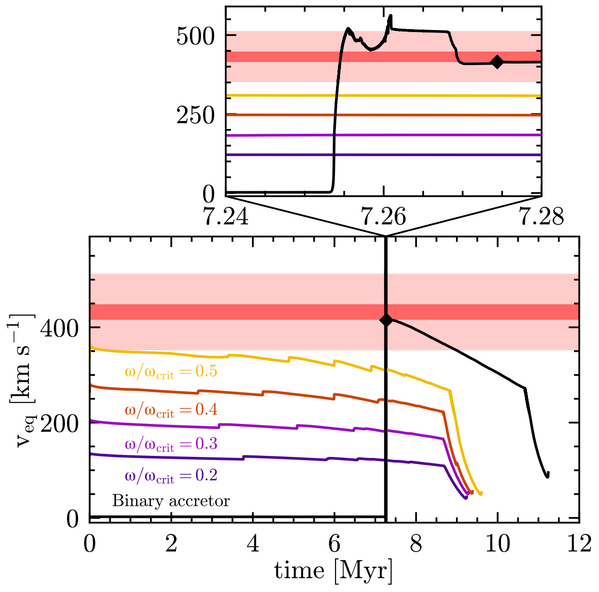
Renzo & Götberg 2021

✓ Spin up:
late and to critical rotation



weak-wind problem, neglecting inclination

Renzo & Götberg 2021

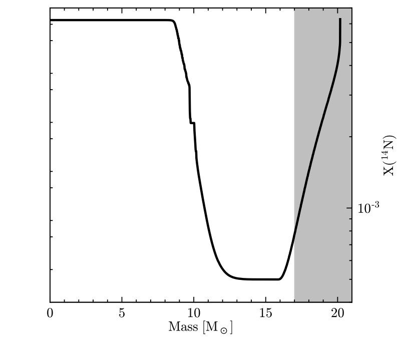


weak-wind problem, neglecting inclination

Renzo & Götberg 2021

✓ Pollution:

Surface composition partly comes from the donor's core



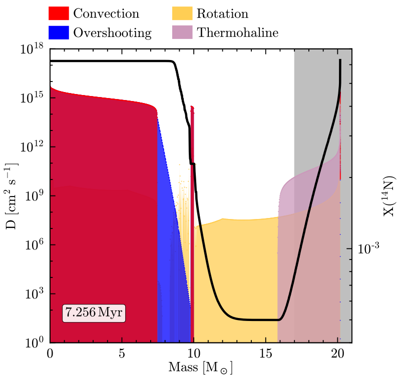
Nitrogen mass fraction

Joint constrain on accretion and internal mixing

Renzo & Götberg 2021

✓ Pollution:

Surface composition partly comes from the donor's core



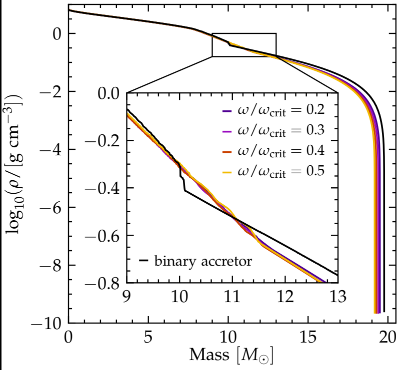
Joint constrain on accretion and internal mixing

Renzo & Götberg 2021

✓ Rejuvenation:

Core growth changes its outer boundary

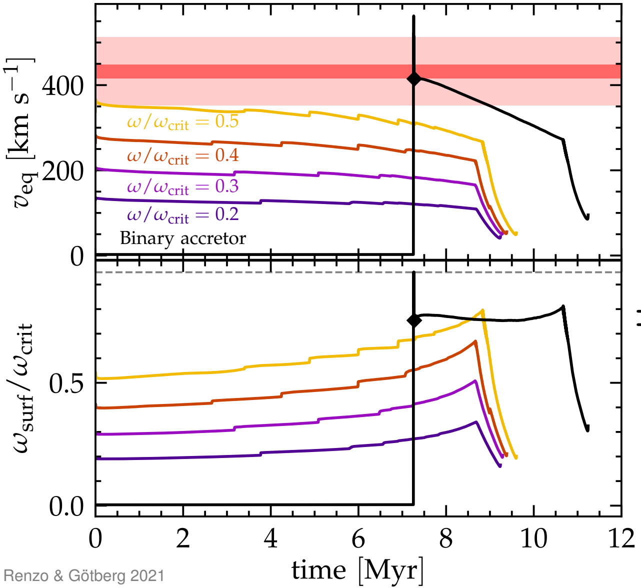
"Density"



end of H-core burning,
later evolution amplifies differences
(e.g., **Renzo *et al.* 2017**)

Renzo & Götberg 2021, Renzo *et al.* 2023

✓ Surface rotation rate



Renzo & Götberg 2021

$\Rightarrow$

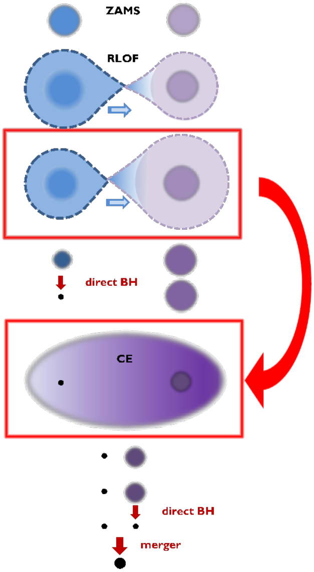
Accretors are likely Oe/Be stars

$$\omega_{surf} \simeq 0.75\,\omega_{crit}$$

decretion disk & emission lines

(Pols & Marinus 94, Vinciguerra *et al.* 20, Bodensteiner *et al.* 20)

If the common-envelope donor is a former accretor

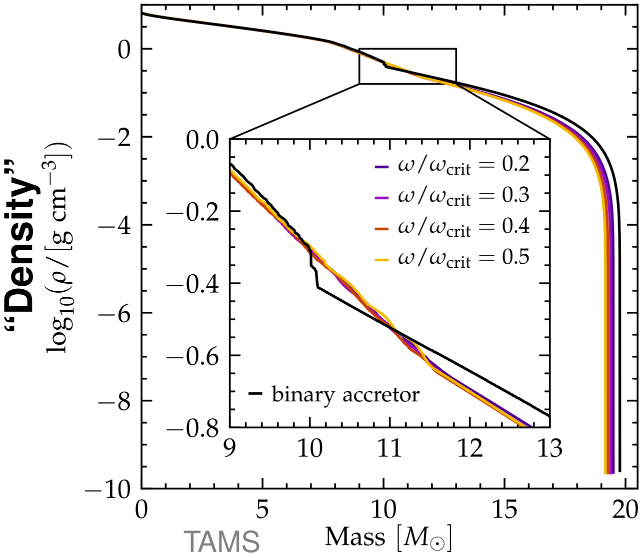


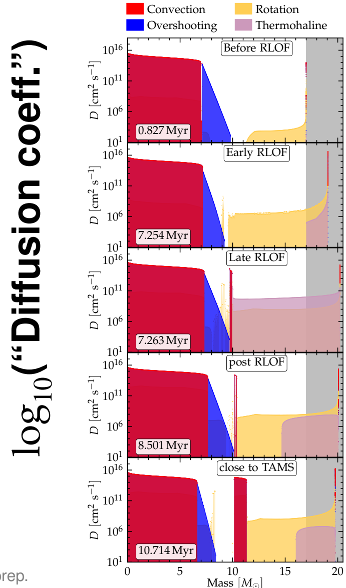
Belczynski *et al.* 2016

Implications for common-envelope

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

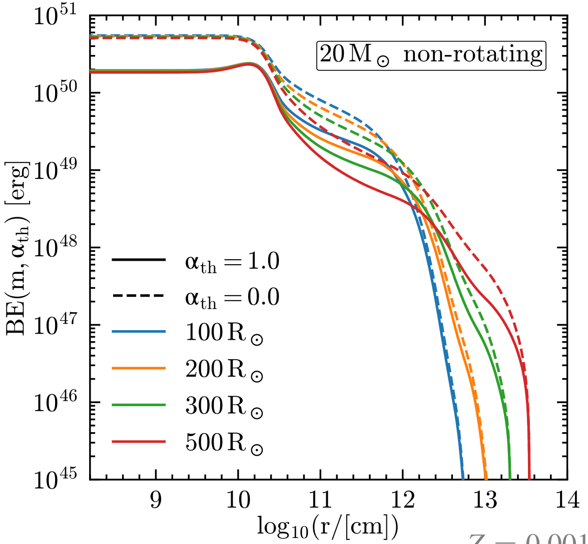
Rejuvenation changes the core/envelope boundary





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

The binding energy is the cost to “dig” into the star



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

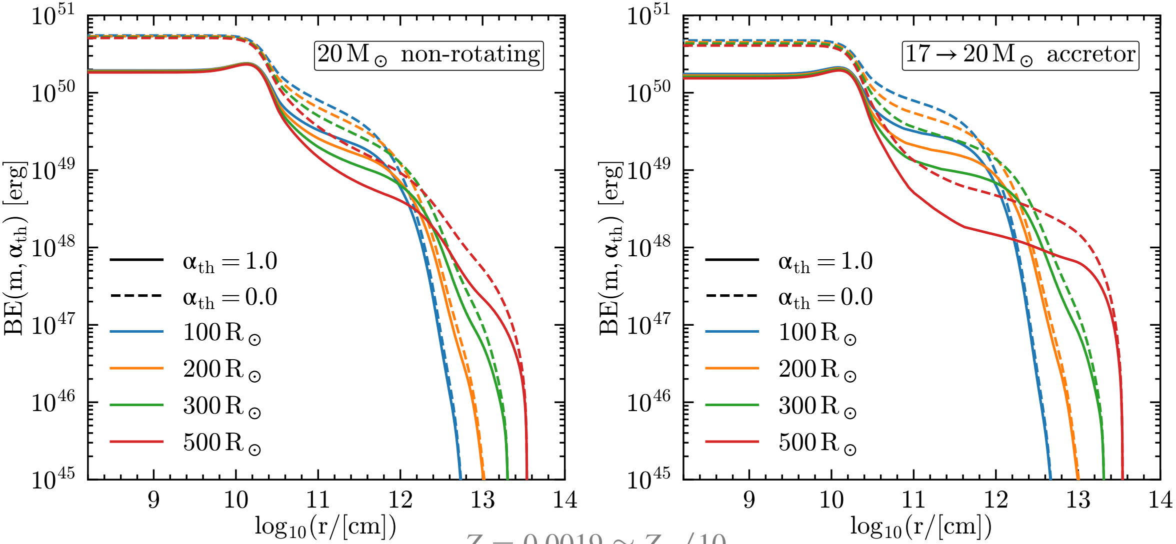
- Gravitational potential energy
- Internal energy
- α_{th} free parameter

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