

Widowed massive stars

Mathieu Renzo



with Y. Götberg, E. Zapartas, S. Justham, K. Breivik, M. Lau, R. Farmer, M. Cantiello, B. D. Metzger

Widowed massive stars

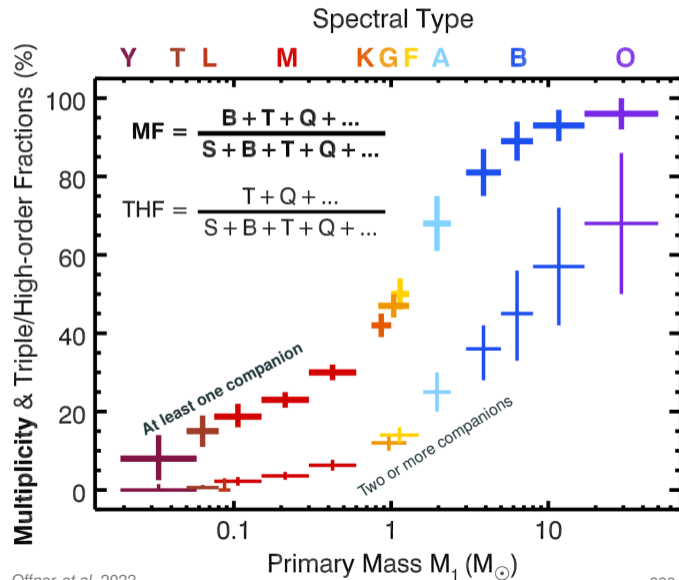
Mathieu Renzo



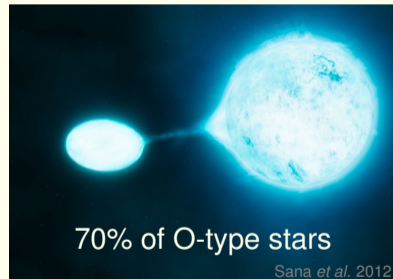
Take home point:

This is not a single star!

Massive stars are typically born with companions



Interactions are **common**



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

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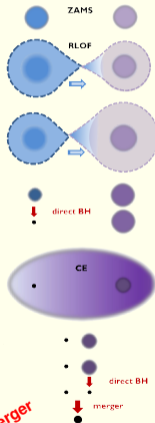
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Pols *et al.* 1991, Wang *et al.* 2021

Binary interactions



GW merger

Tutukov *et al.* 1993,

Belczynski *et al.* 2016, Renzo *et al.* 2022

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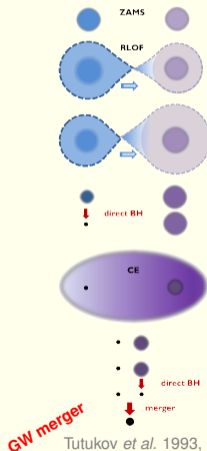
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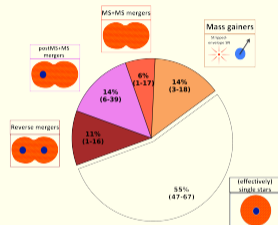
Binary interactions



Belczynski *et al.* 2016, Renzo *et al.* 2022

Transients

Common: H-rich SNe



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

+

Uncommon: H-rich/H-poor SNe

L-GRB, LBV, SNIIn ?

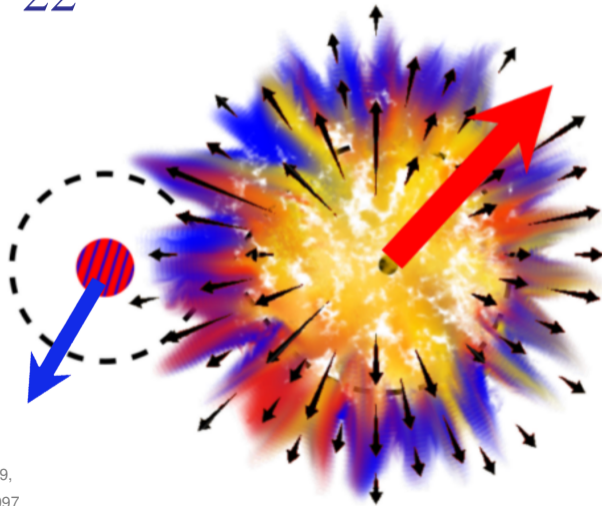
Petrovich *et al.* 2005, Cantiello *et al.* 2007

Most common massive binary evolution path: stable case B RLOF

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

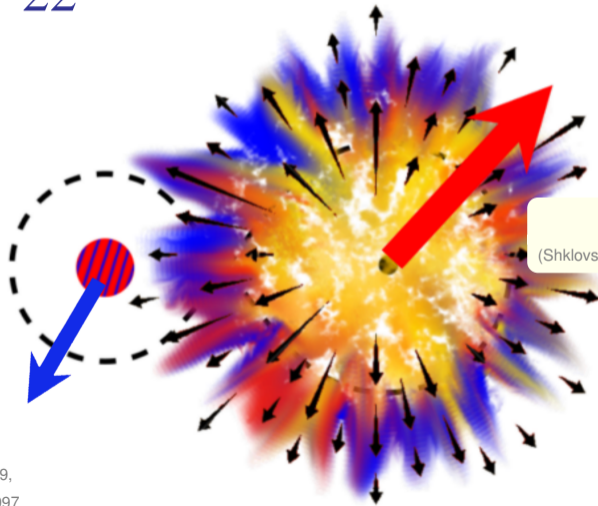
Accretors may live alone, **but they are *not* single stars**

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



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SN Natal kick

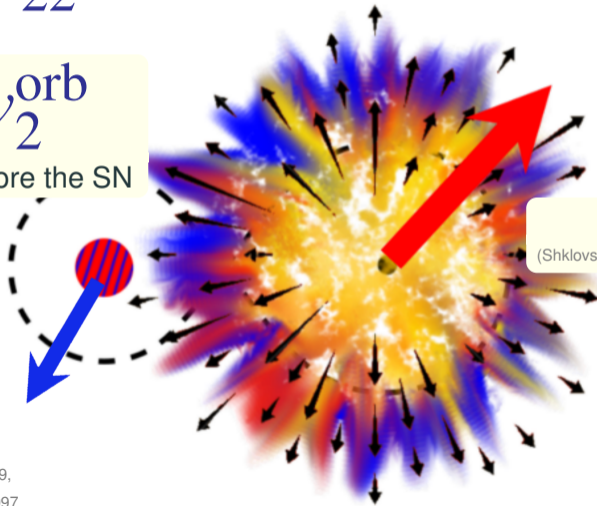
(Shklovskii 1970, Katz 1975, Janka 2013, 2017)

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

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

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

before the SN

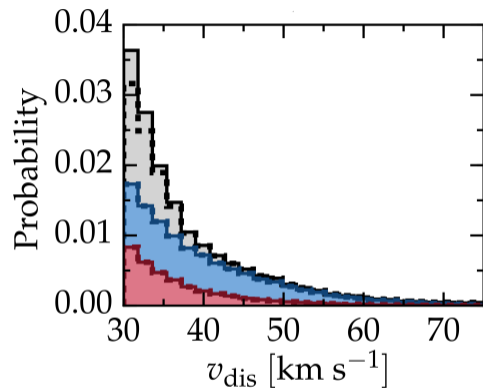


SN Natal kick

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

Kinematics of the widowed stars

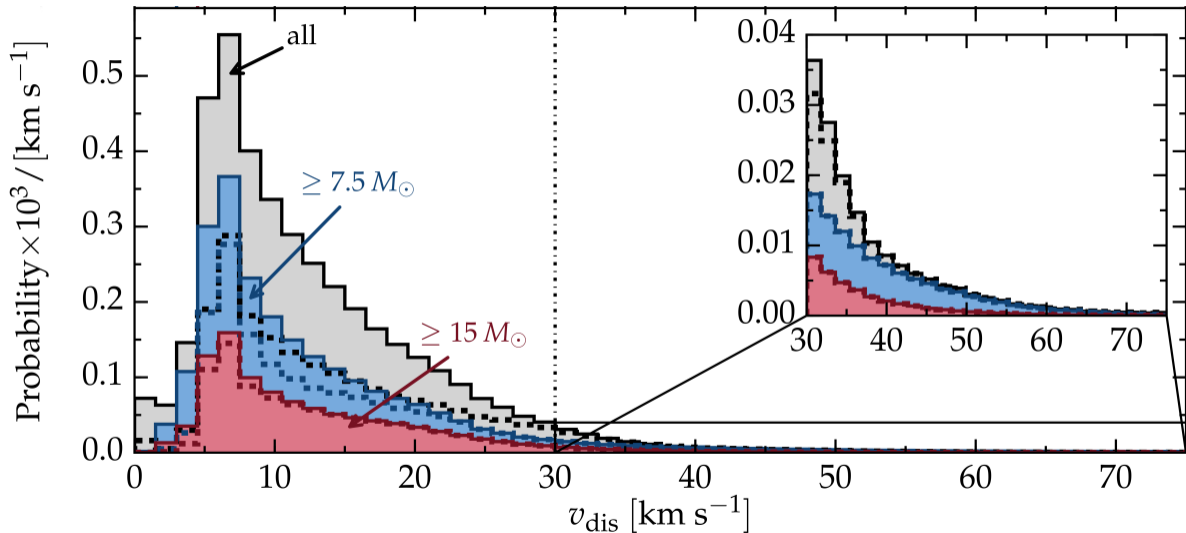
Accretor stars can be *runaways*...



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

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

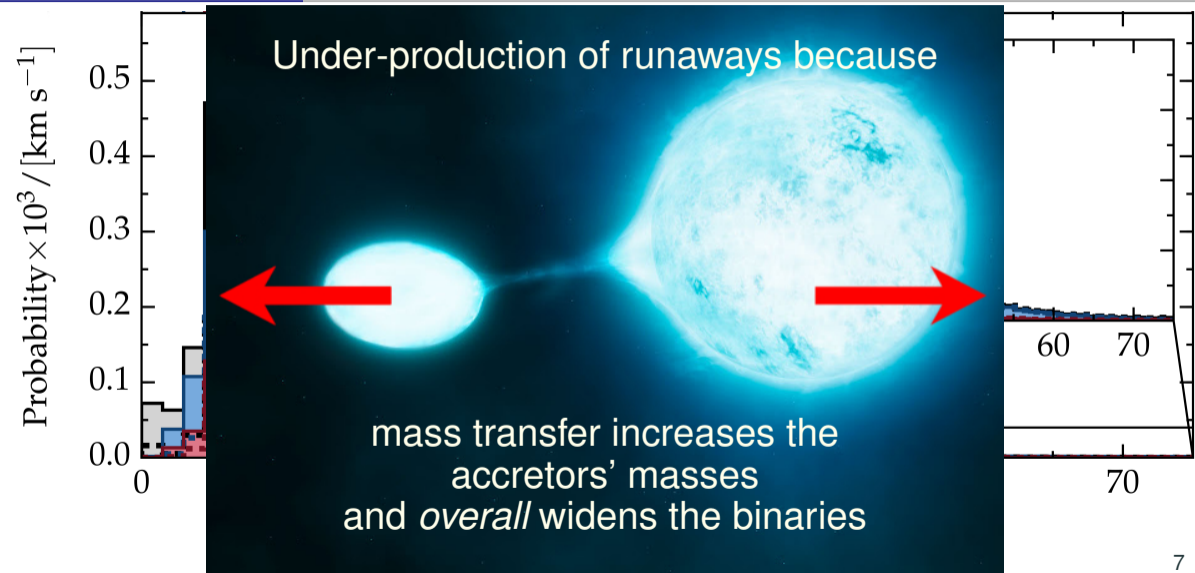
...but most are only *walkaways*



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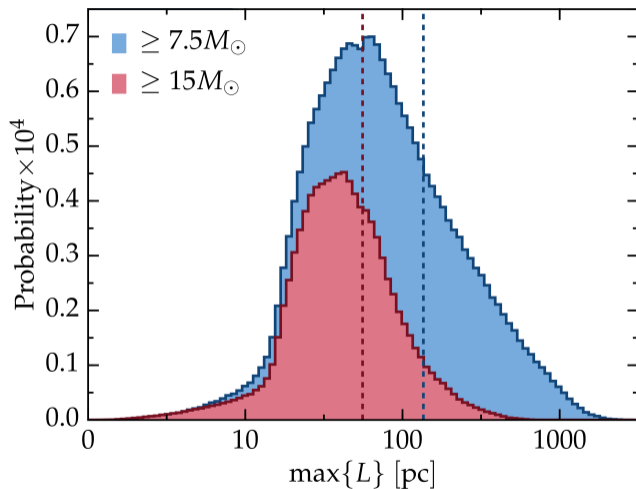
...but most are only *walkaways*



Example of large-scale implication: re-ionization

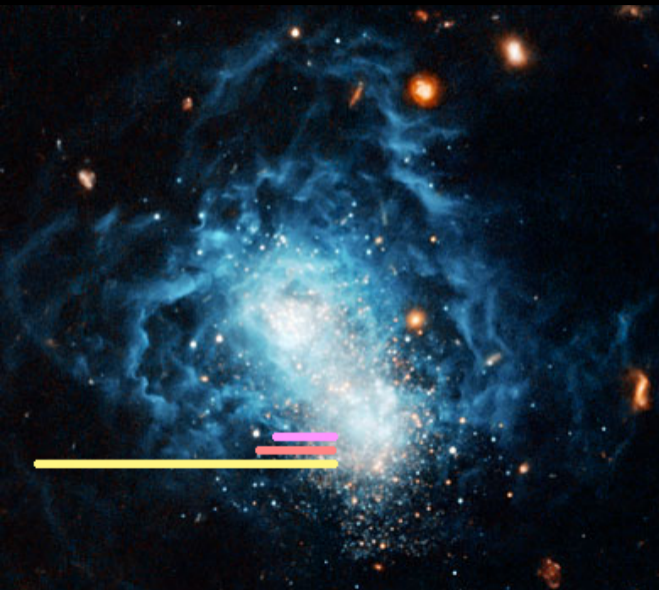
Ejected accretors & stripped donors

How far do widowed stars get?



“Distance traveled” = $v_{\text{dis}} \times \Delta t_{\text{left}}$
(No potential well)

Widowed stars can escape local dust clouds



for $M \geq 7.5 M_{\odot}$:

$$\langle D \rangle = 128 \text{ pc}$$

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

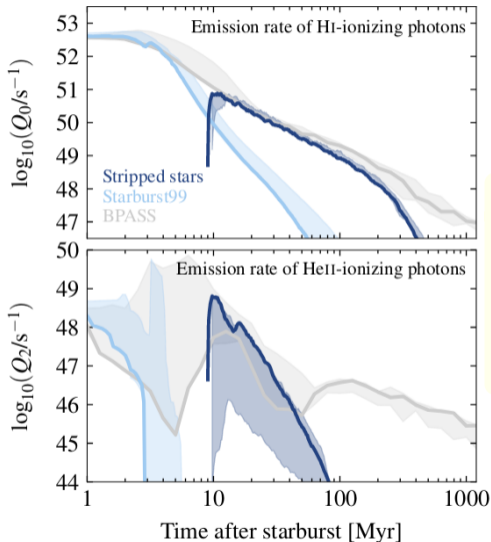
$$\langle D_{\text{walk}} \rangle = 103 \text{ pc}$$

Renzo *et al.* 19b

I Zw 18

Credits: ESA/Hubble & Nasa, A. Aloisi

Stripped donors likely contributed to cosmic reionization



Donors lose the H-rich envelope:

- Allows lower mass stars to produce hard photons
- Lower mass:
 - ⇒ slower evolution ⇒ delayed contribution
 - ⇒ fewer photons/star but many more stars

***How* does mass-transfer change
the accretor?**

The accretor is modified by the interaction

- Spin-up

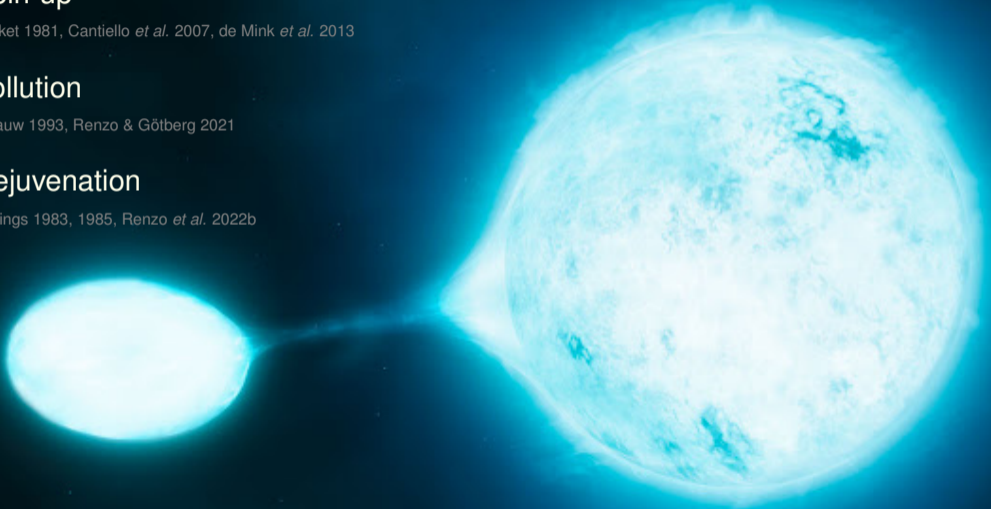
Packet 1981, Cantiello *et al.* 2007, de Mink *et al.* 2013

- Pollution

Blaauw 1993, Renzo & Götberg 2021

- Rejuvenation

Hellings 1983, 1985, Renzo *et al.* 2022b

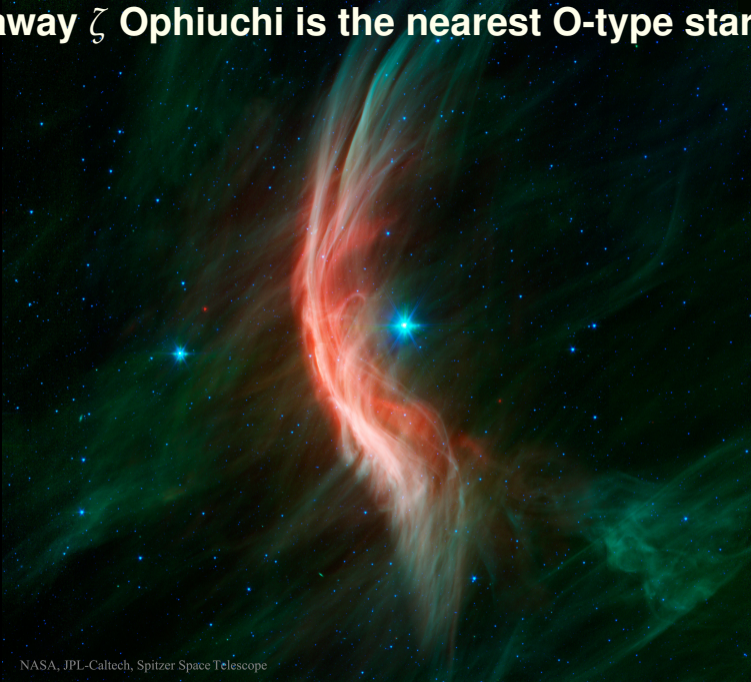


Constraints on widowed accretors

from the nearest O-type star

Renzo & Götberg 2021

The runaway ζ Ophiuchi is the nearest O-type star to Earth



see

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

NASA, JPL-Caltech, Spitzer Space Telescope

The runaway ζ Ophiuchi is the nearest O-type star to Earth

Many observational constraints!

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

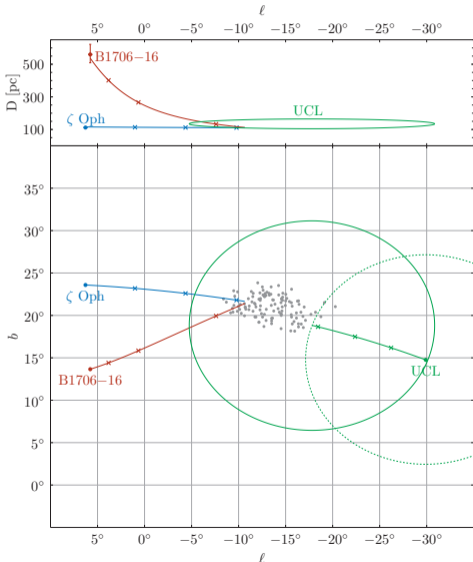
X Rotating single stars don't match

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

see

Walker *et al.* 1979,
Herrero *et al.* 1994,
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Renzo & Götberg 2021,
Shepard *et al.* 2022

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



A nearby recent supernova that ejected the runaway star ζ Oph, the pulsar PSR B1706-16, and ^{60}Fe found on Earth

R. Neuhäuser,^{1*} F. Gießler¹, and V.V. Hambaryan^{1,2}

¹ *Astrophysikalisches Institut und Universitäts-Sternwarte Jena, Schillergäßchen 2-3, 07745 Jena, Germany*

² *Byurakan Astrophysical Observatory, Byurakan 0213, Aragatsozn, Armenia*

Accepted 2019 Sep 10. Received 2019 Sep 3; in original form 2019 July

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

Self-consistent MESA model

$$M_1 = 25 M_\odot$$

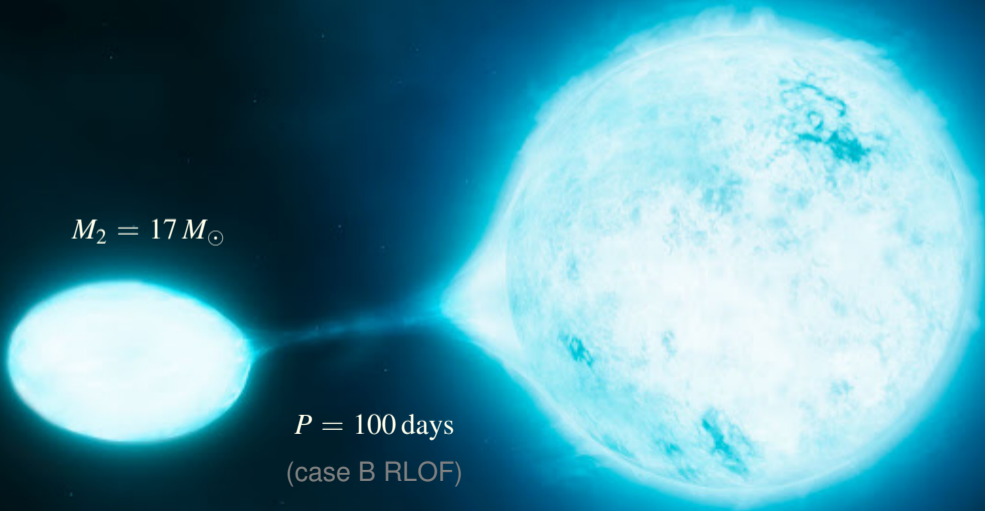
$$Z = 0.01$$

(Murphy *et al.* 2021)

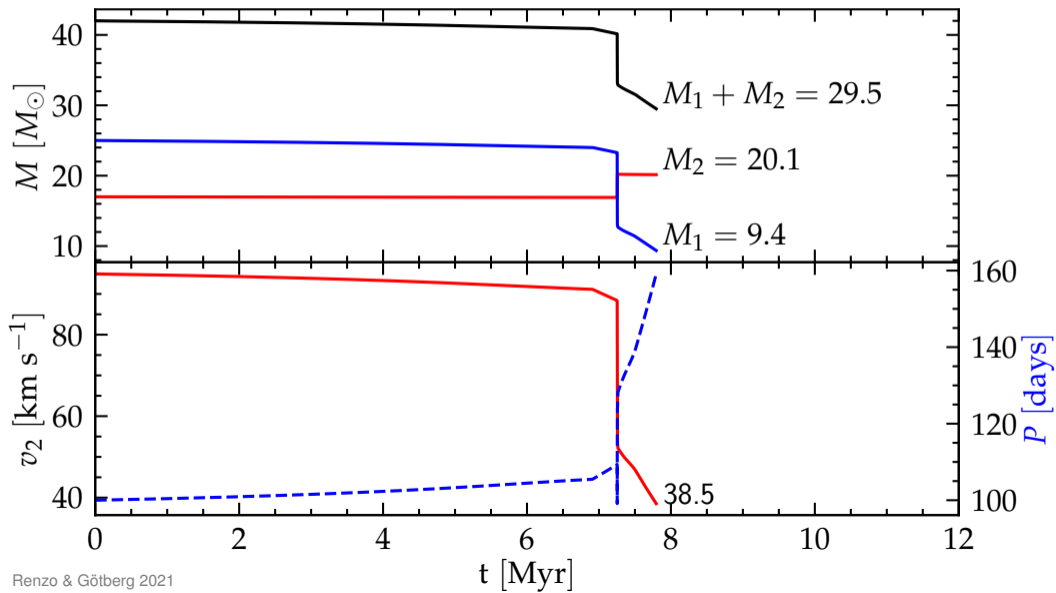
$$M_2 = 17 M_\odot$$

$$P = 100 \text{ days}$$

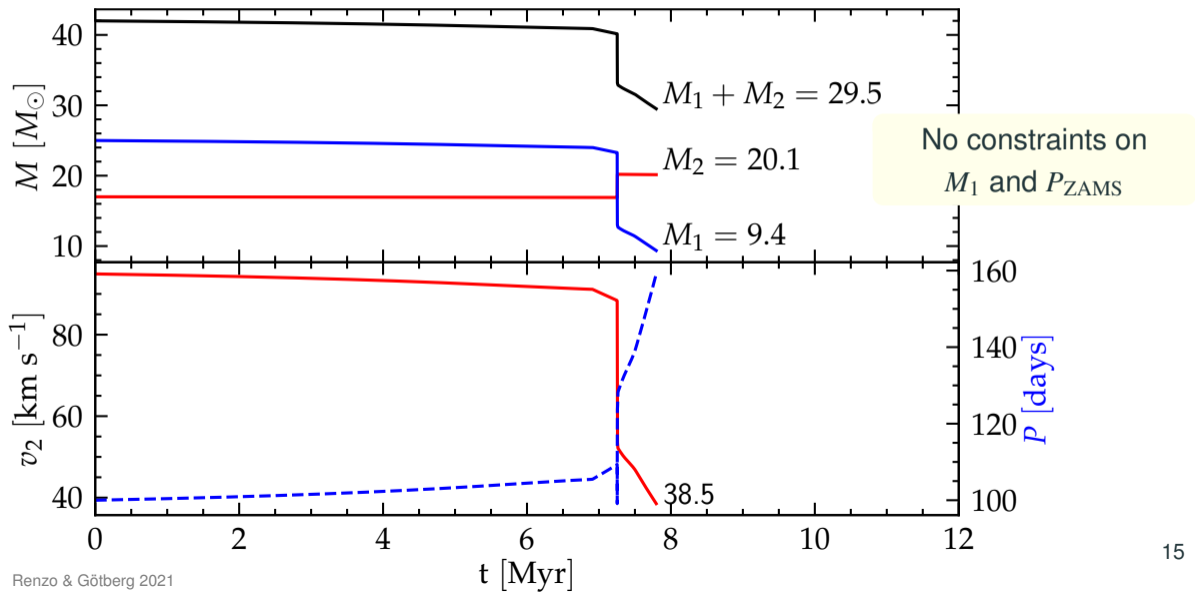
(case B RLOF)



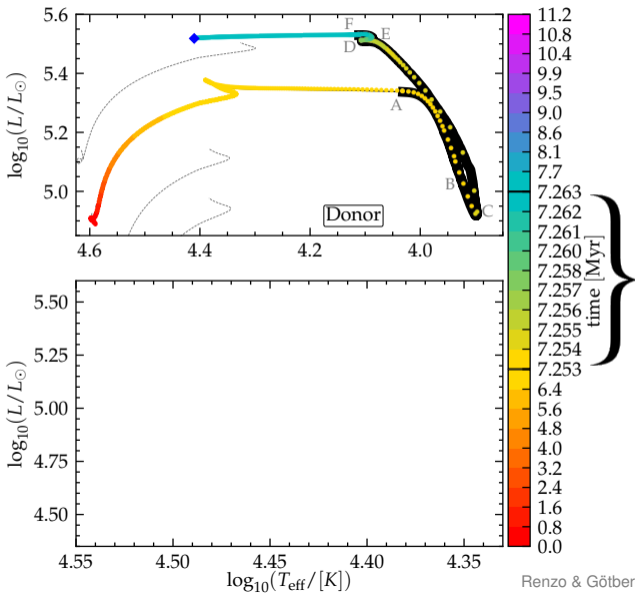
Orbital evolution: ✓ Mass & ✓ spatial velocity



Orbital evolution: ✓ Mass & ✓ spatial velocity



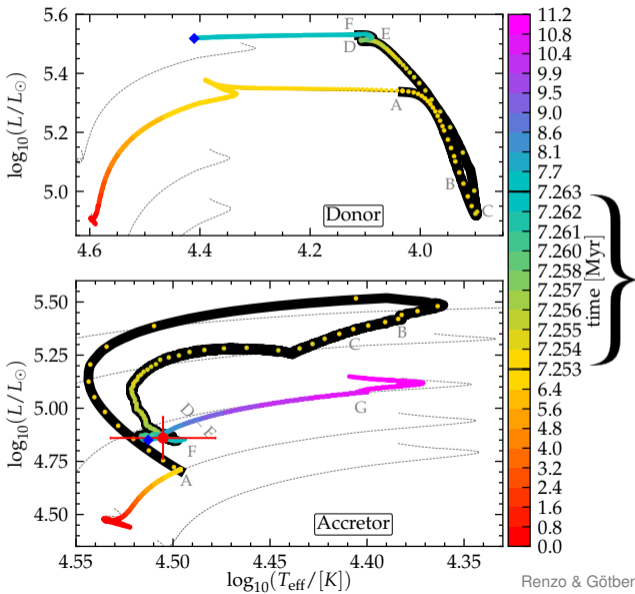
HRD of both stars: the donor



Case B mass transfer is short

$\Delta t_{\text{RLOF}} \sim 10^4 \text{ yr} \sim \tau_{\text{th}}$
but has long-lasting impact
on **both** stars.

HRD of both stars: the donor & the accretor ✓

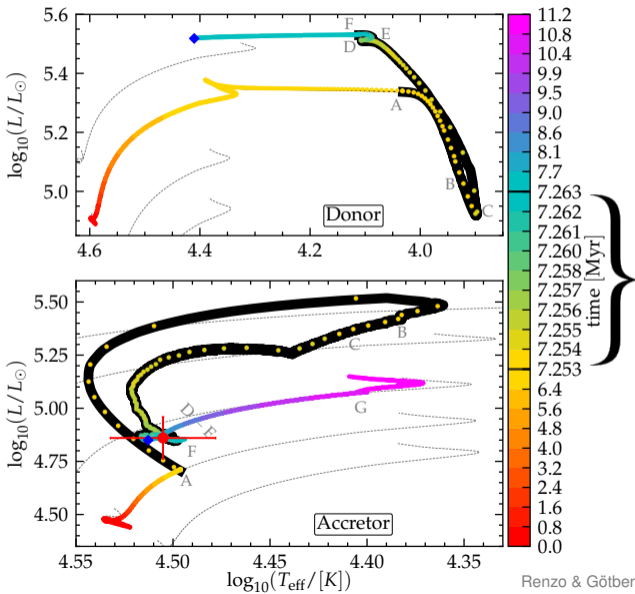


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✓ **Models match ζ Oph.**

L , T_{eff} , Mass, age, velocity

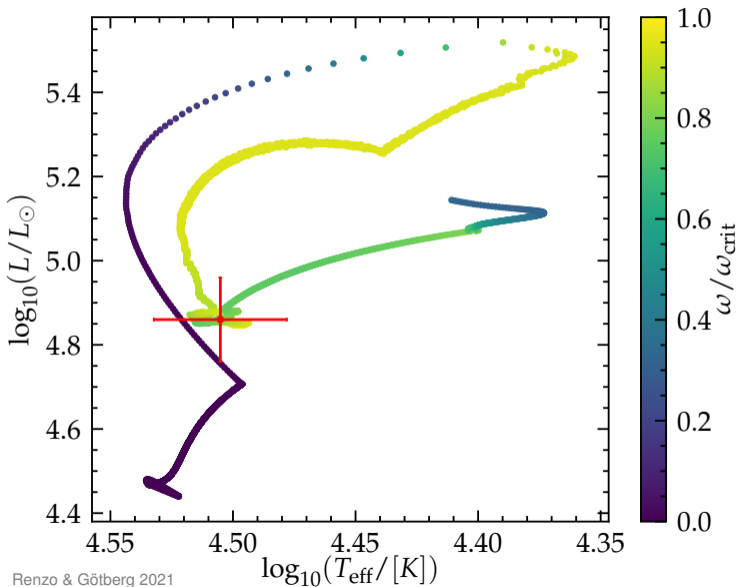
Internal structure of the accretor

Spin up: surface and interior

Pollution: ^4He and ^{14}N

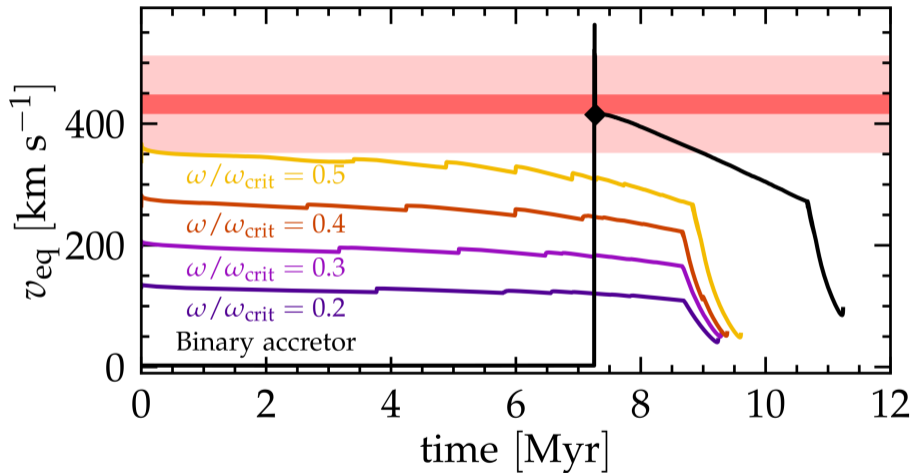
Rejuvenation: core-envelope boundary

HRD: accretor rotation

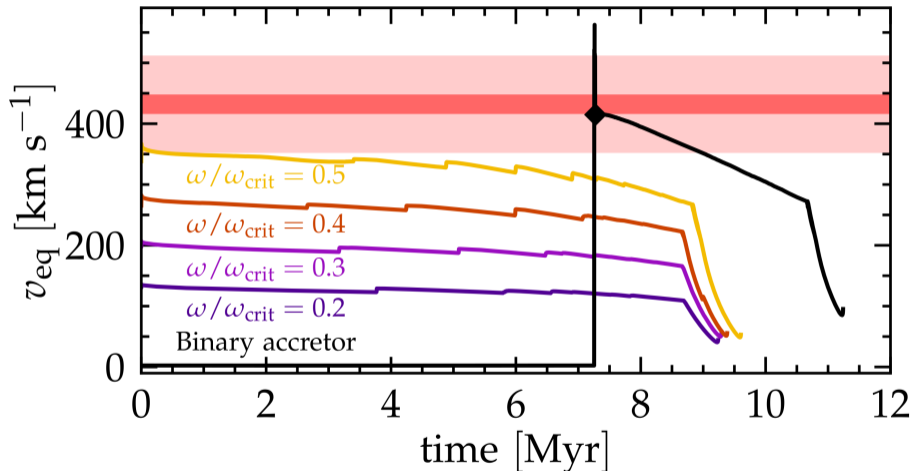


- Minimum T_{eff} during RLOF reached at onset of critical rotation.
- Rotation close to critical for large part of the main sequence.

✓ Surface rotation rate



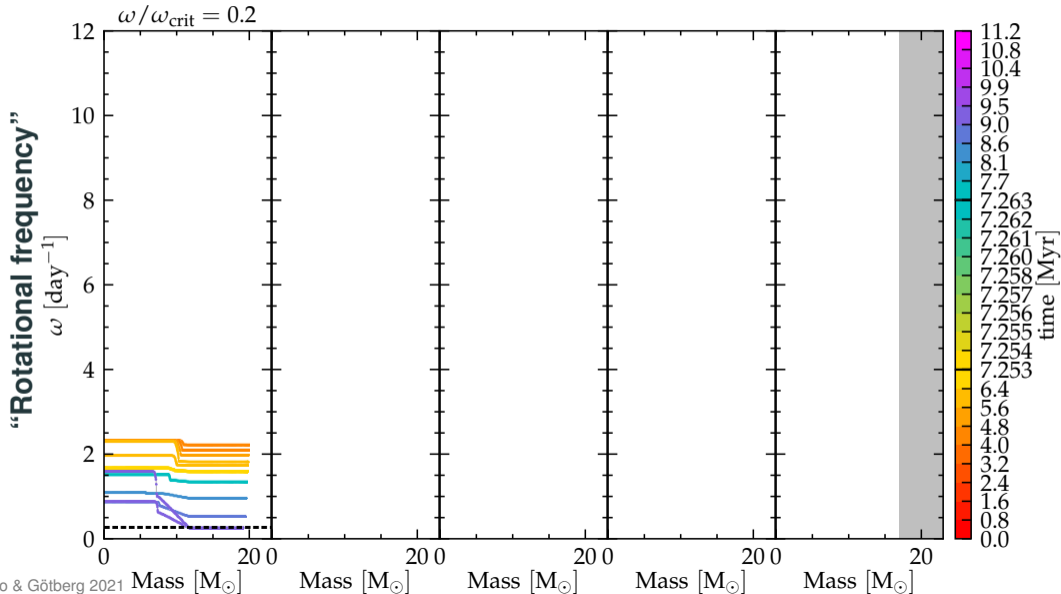
✓ Surface rotation rate



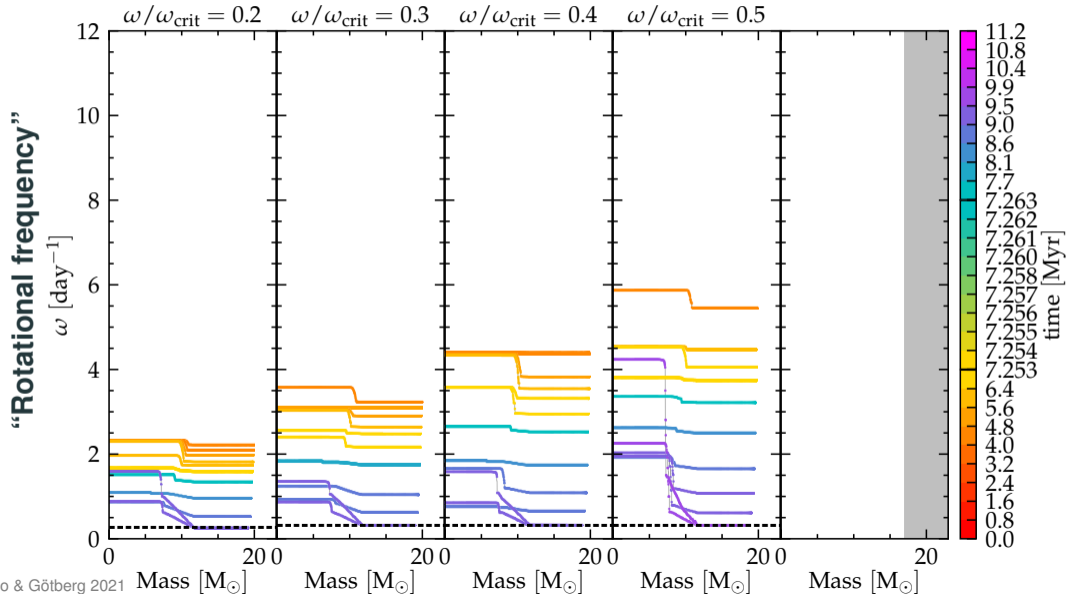
✓ Surface rotation at apparent age

Mass-transfer give a lot of angular momentum late

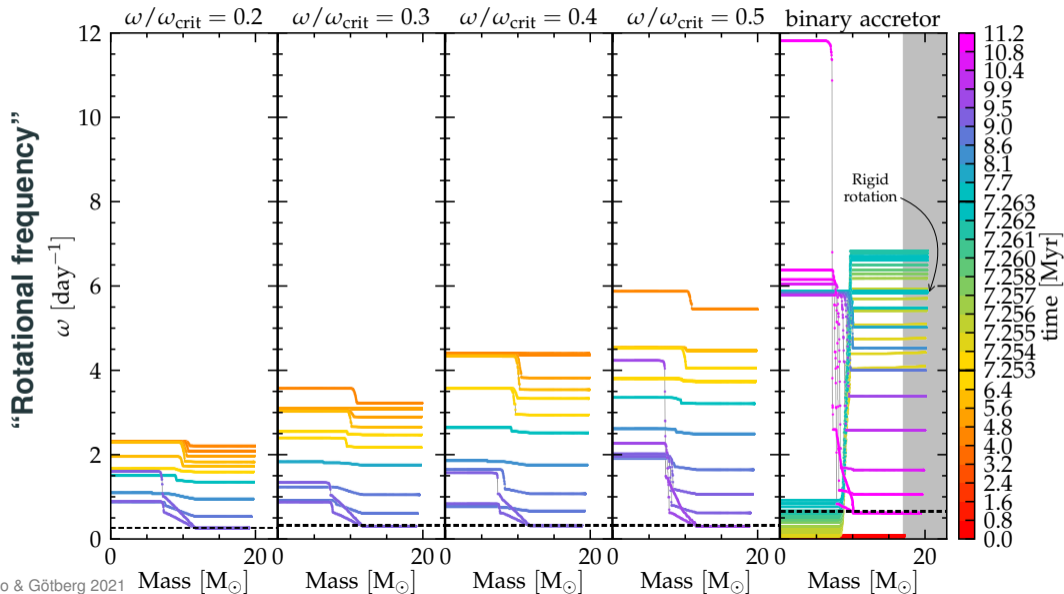
Internal rotational profile: single stars



Internal rotational profile: single stars



Internal rotational profile: accretor



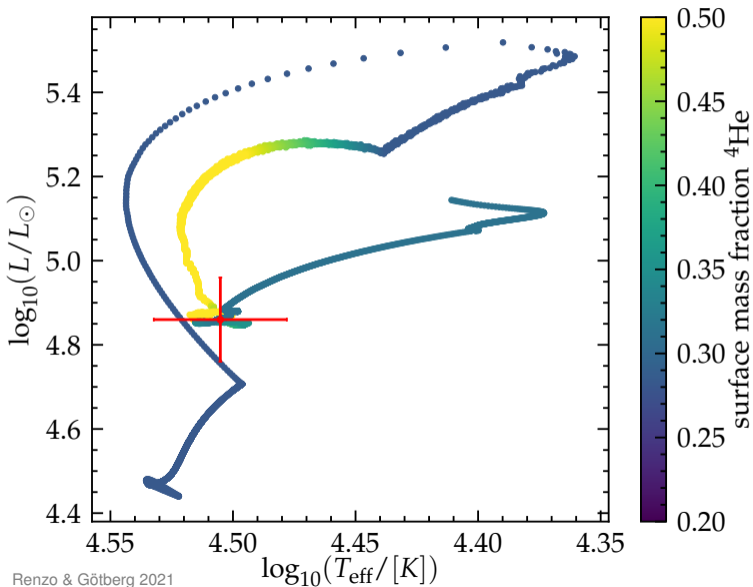
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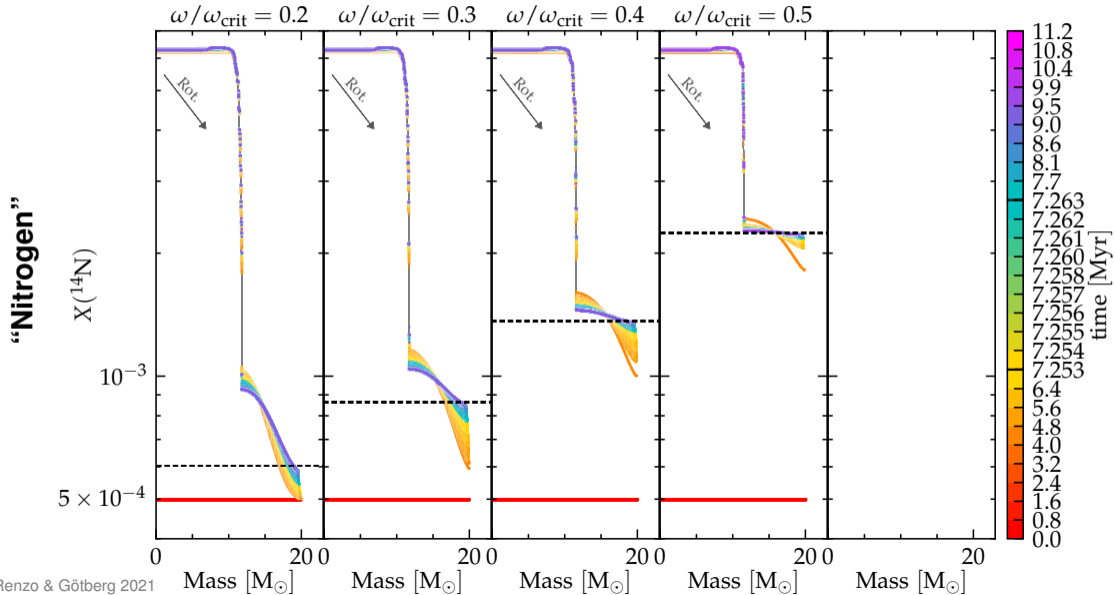
Rejuvenation: core-envelope boundary

HRD: Helium surface abundance

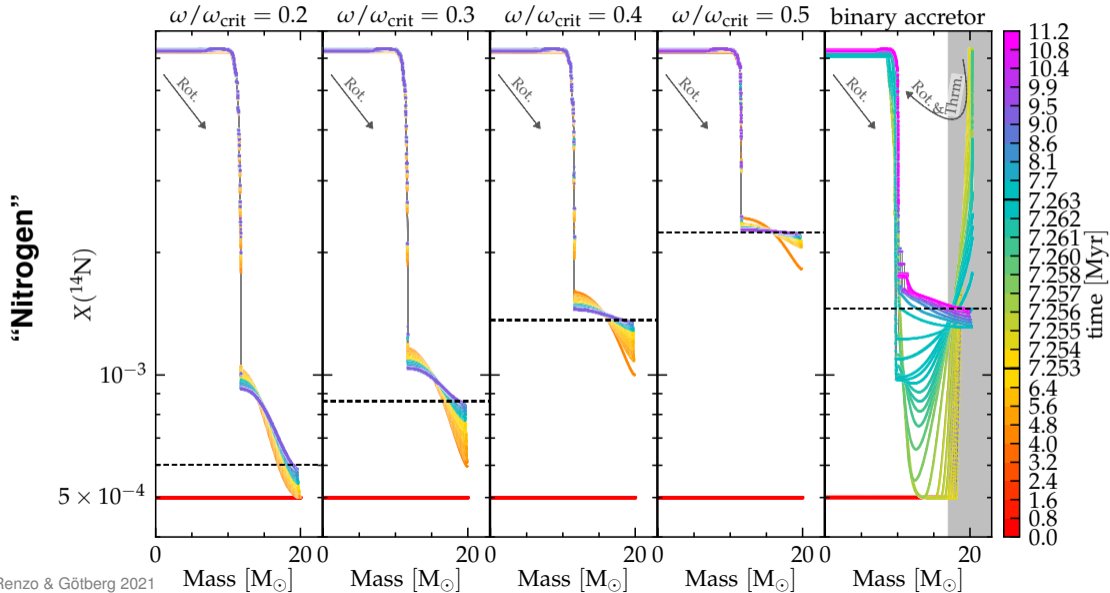


- Accretion of He-rich matter change morphology at $T_{\text{eff}} \simeq 10^{4.44}$ K.
- Interplay between accretion, mixing and rotation causes “noisiness”.

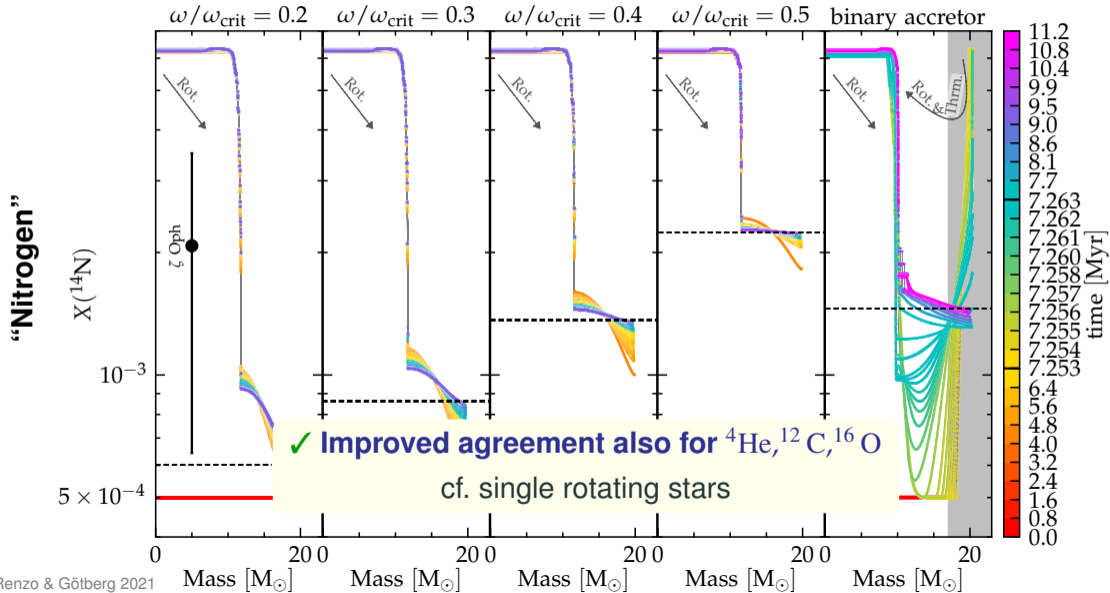
Composition profile: comparison with rotating single stars



Composition profile: comparison with rotating single stars



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



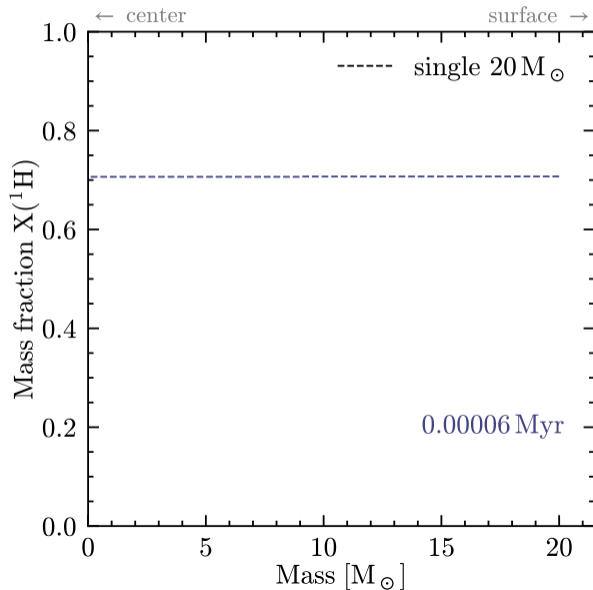
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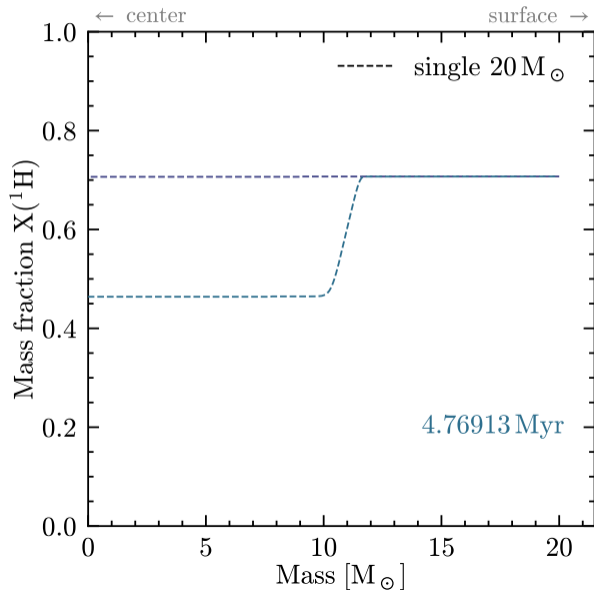
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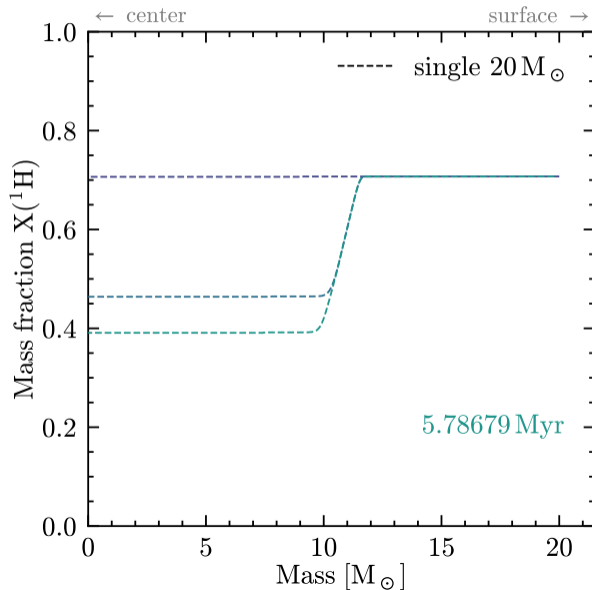
Refresher: formation of the helium core in single stars



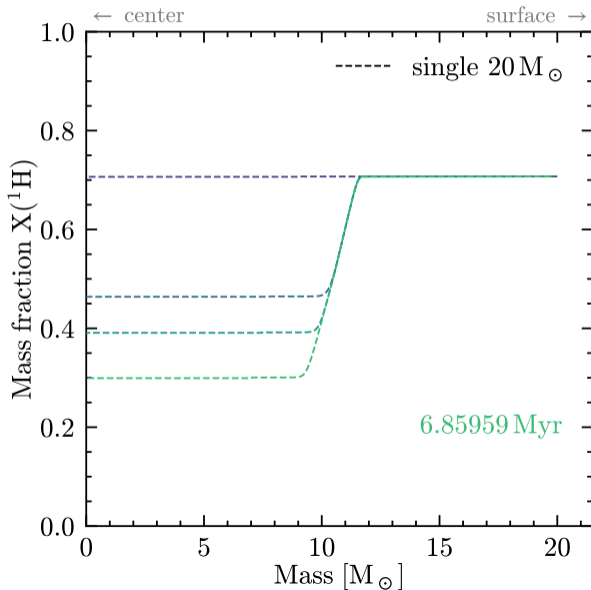
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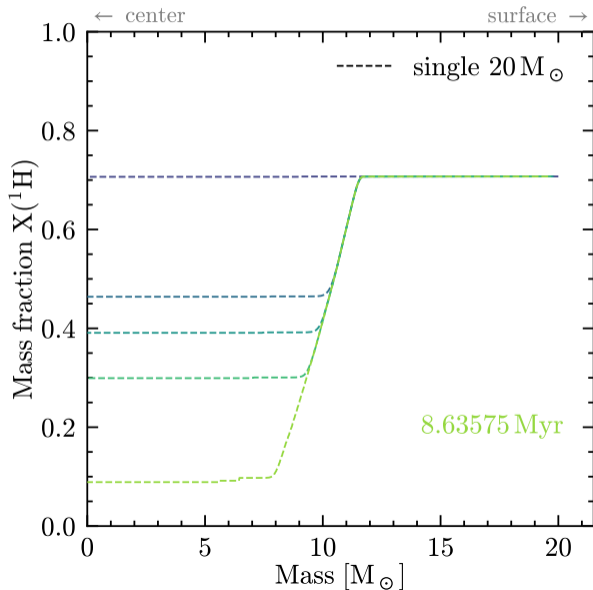
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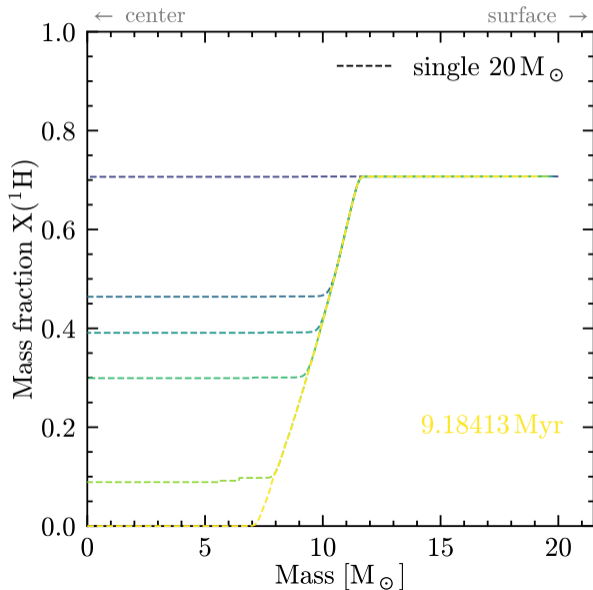
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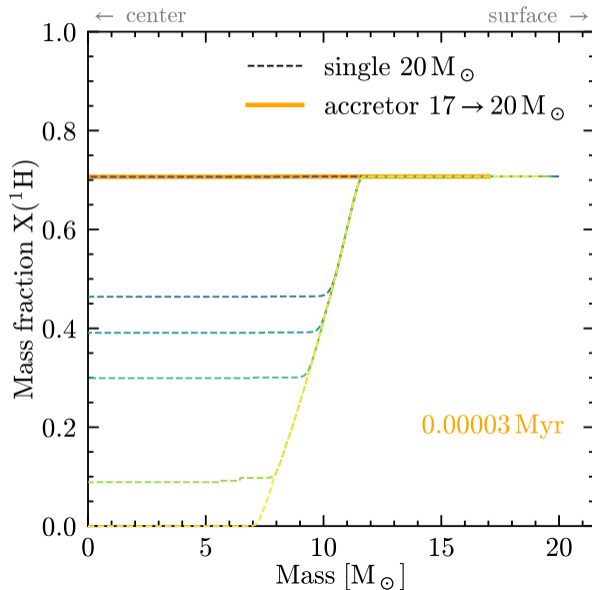
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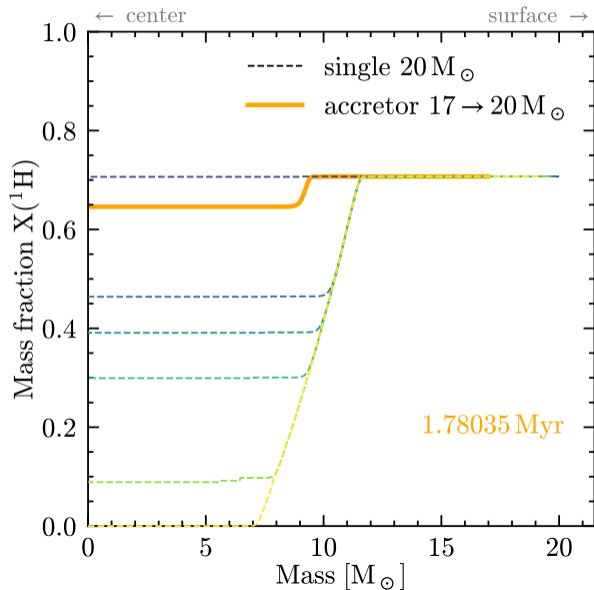
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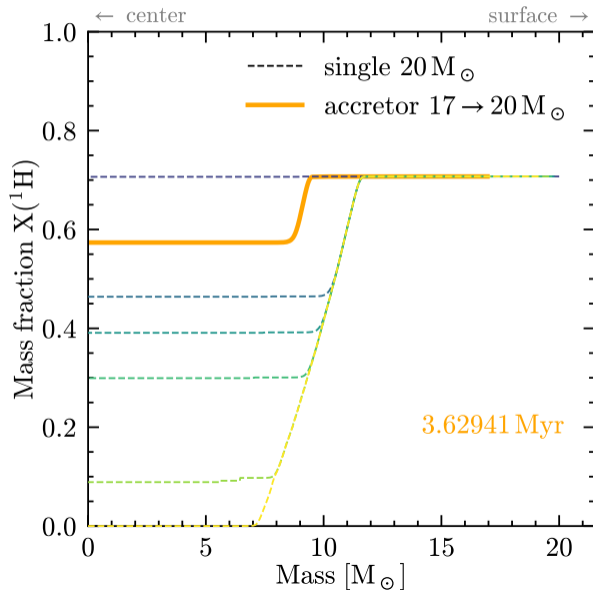
Evolution of the accretor's core through RLOF



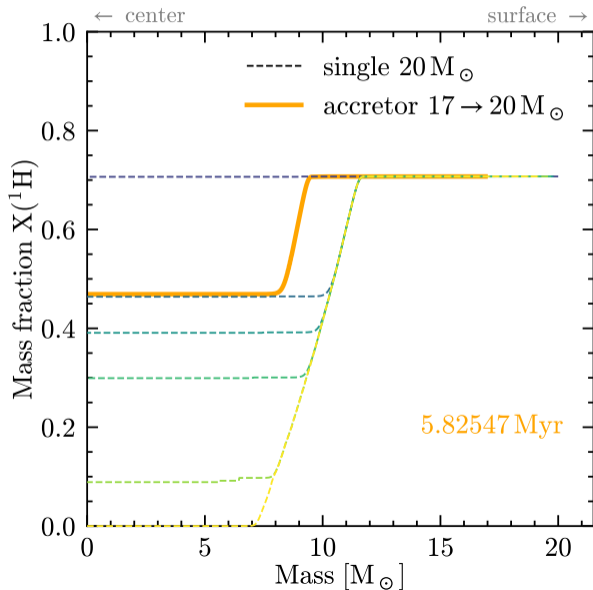
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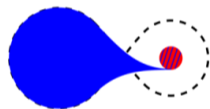
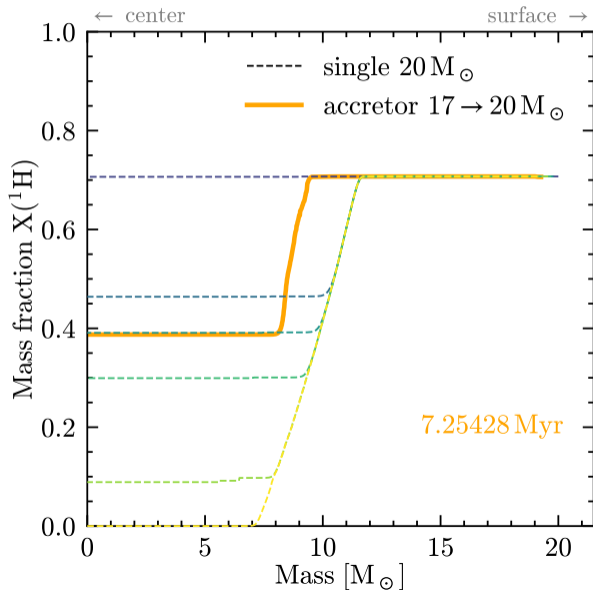
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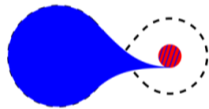
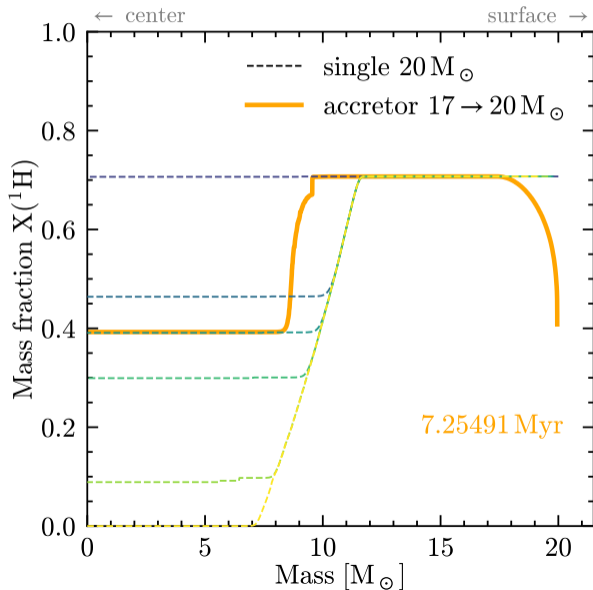
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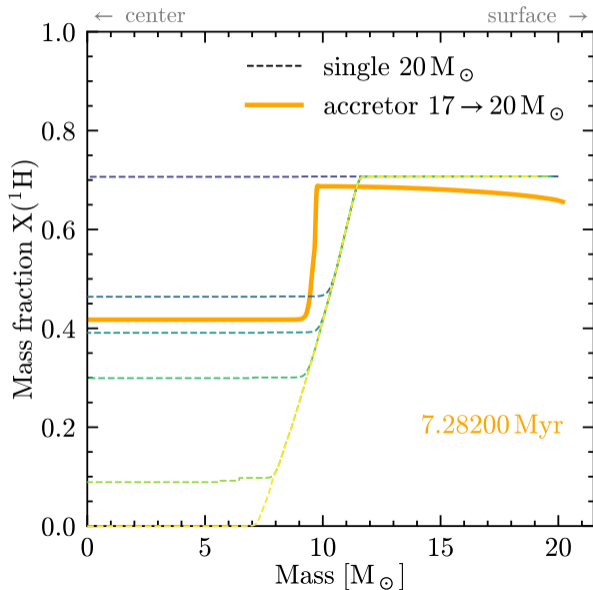
Evolution of the accretor's core through RLOF



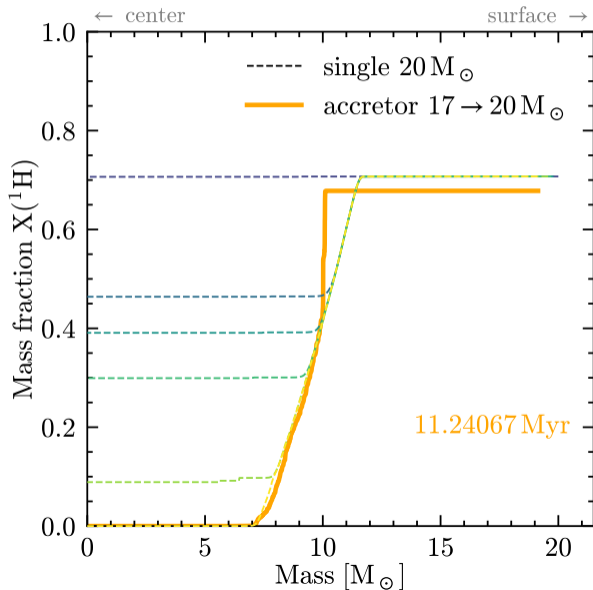
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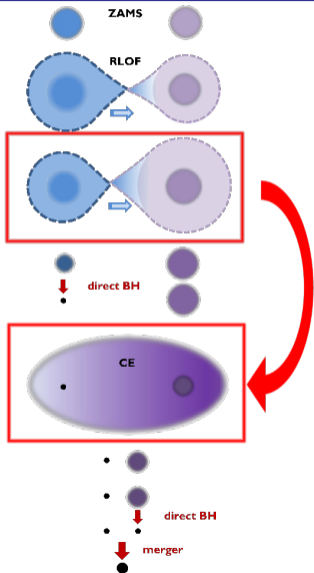
Evolution of the accretor's core through RLOF



Consequences of rejuvenation

Easier to unbind the envelope

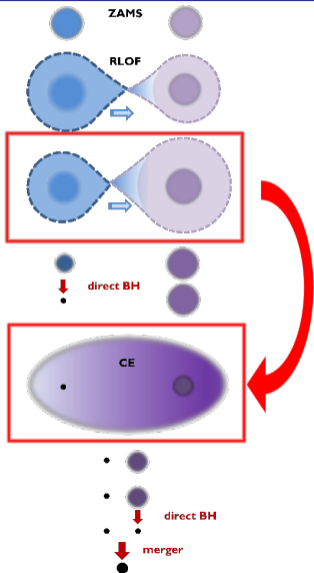
The common envelope in GW progenitors is initiated by the accretor



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

Renzo *et al.* 2022b

The common envelope in GW progenitors is initiated by the accretor

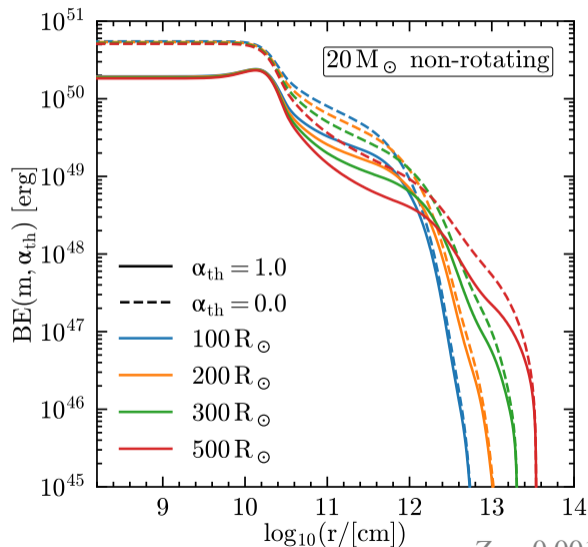


Does RLOF rejuvenation impact how easy it is to remove the envelope ?

Renzo *et al.* 2022b

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

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



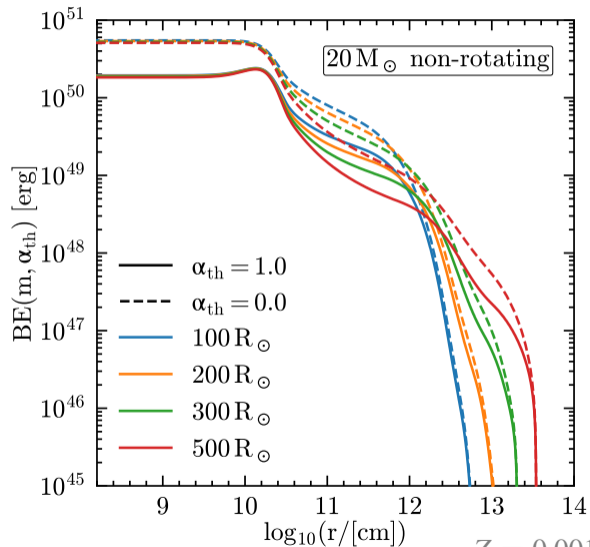
$$BE(m, \alpha_{\text{th}}) = - \int_m^M dm' \left(-\frac{Gm'}{r(m')} + \alpha_{\text{th}} u(m') \right)$$

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

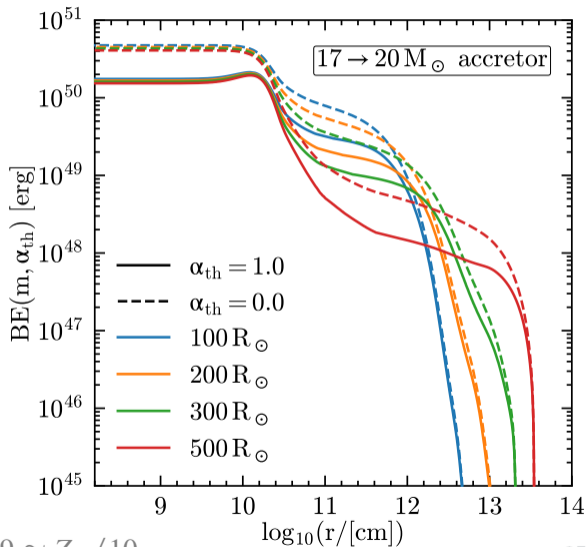
fraction of internal energy usable to eject envelope

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

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



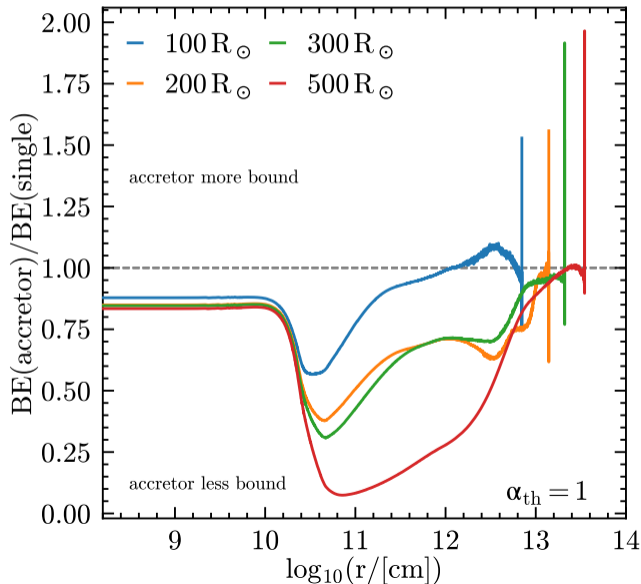
$Z = 0.0019 \simeq Z_{\odot}/10$



25

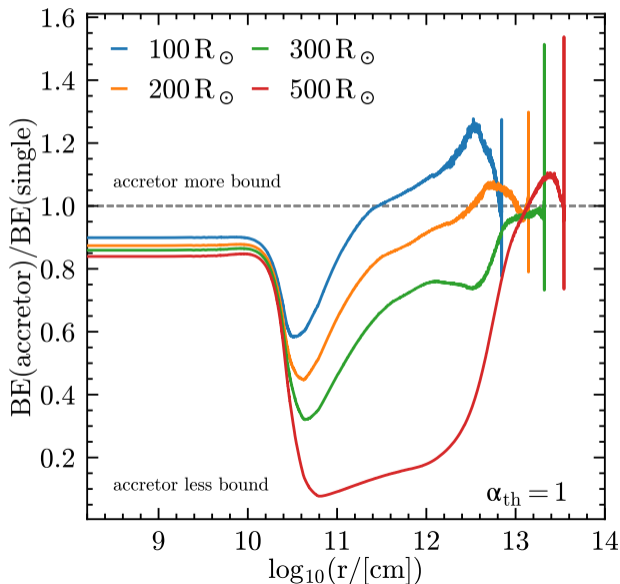
Taking the ratio: accretors are easier to unbind

NS progenitor
 $15 \rightarrow 17 M_{\odot}$



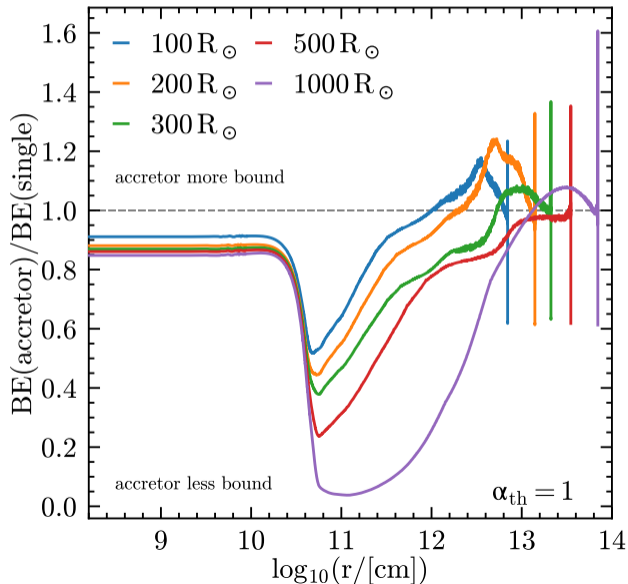
Taking the ratio: accretors are easier to unbind

NS or BH progenitor
 $17 \rightarrow 20 M_{\odot}$

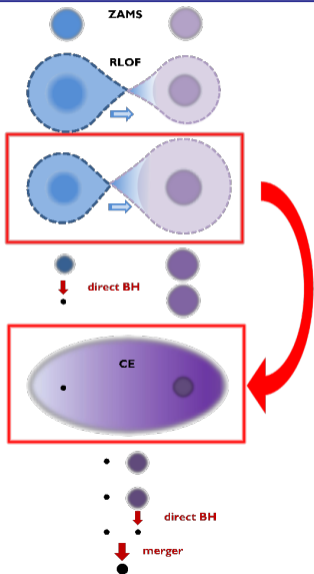


Taking the ratio: accretors are easier to unbind

BH progenitor
 $30 \rightarrow 36 M_{\odot}$



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

Conclusions

Small scale binary interactions influence large scale

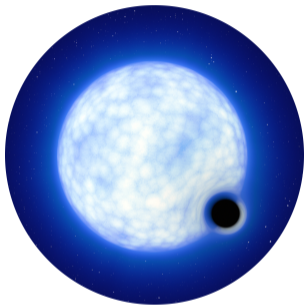
Accretors are *not* single stars

- Most common product 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 ^4He 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

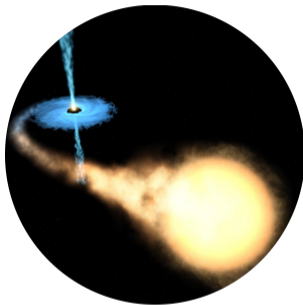
Internal mixing in the accretor

Some binaries do survive the 1st core-collapse



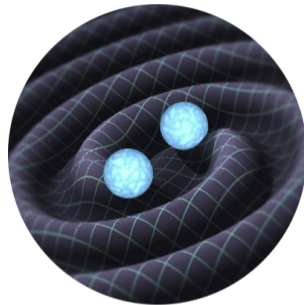
Non-interacting

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.



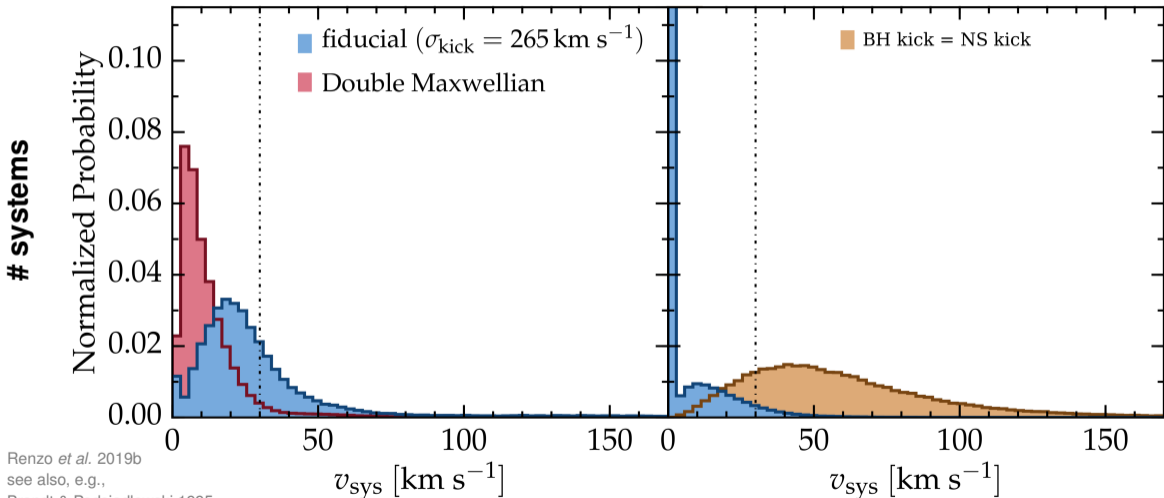
Gravitational waves

Including BBH, BHNS, BNS,
LIGO, Virgo, Kagra collaboration

Post-SN velocity of surviving binaries

NS + Main sequence

BH + Main sequence



Renzo *et al.* 2019b

see also, e.g.,

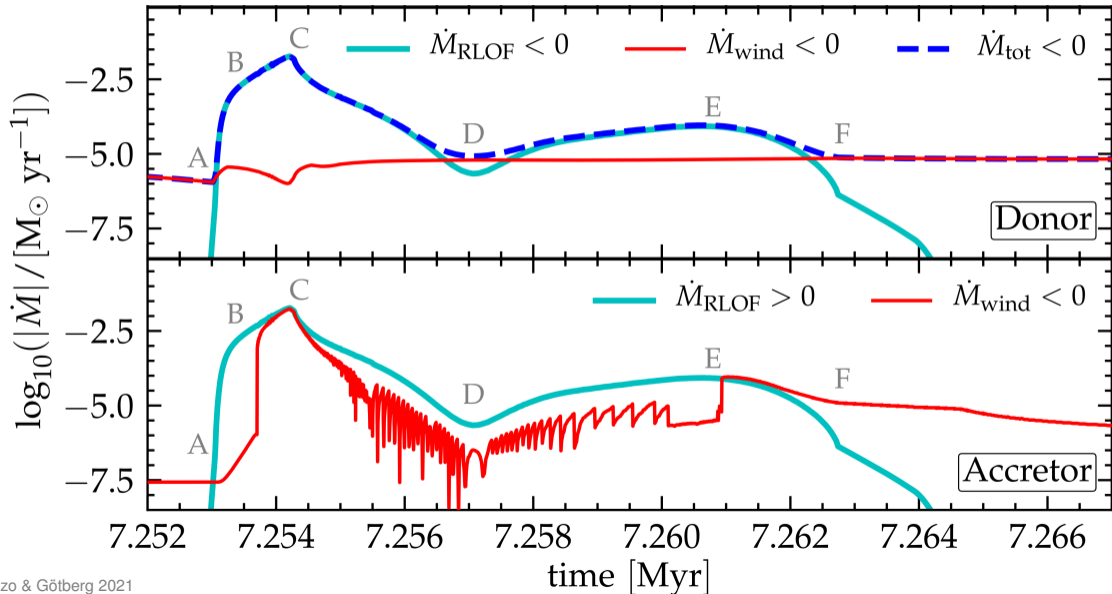
Brandt & Podsiadlowski 1995

Kalogera 1996

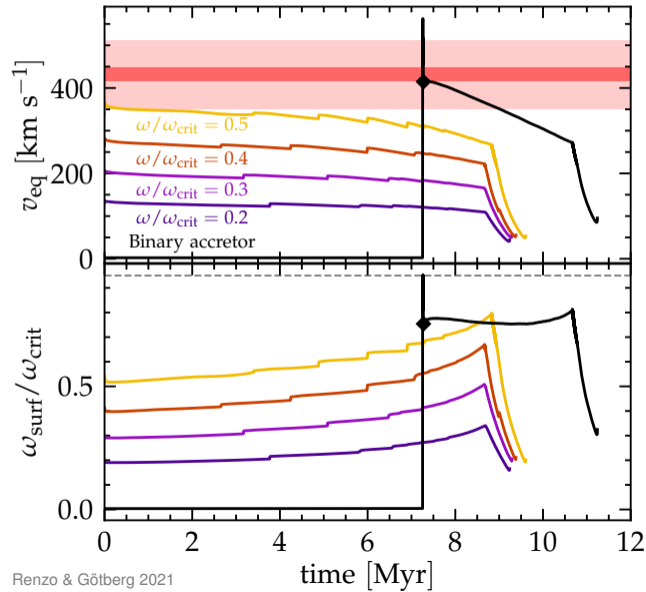
Tauris & Takens 1998

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

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



✓ Surface rotation rate ?

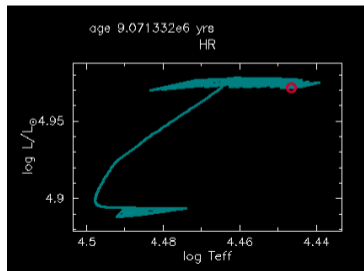


- but “weak wind problem”:

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

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

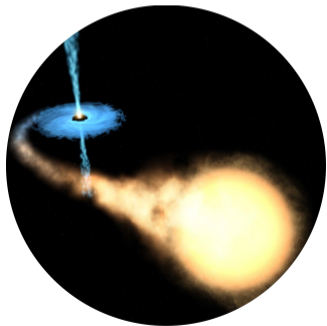
- ✗ Decreasing the wind: $\omega > \omega_{\text{crit}}$



Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion



YES

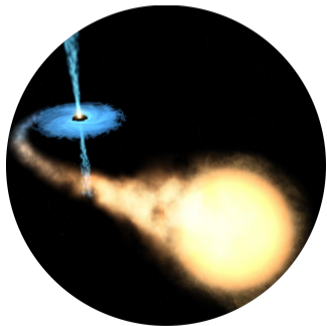
⇒ most are single and we can't see them...



Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion



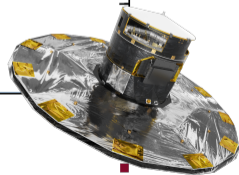
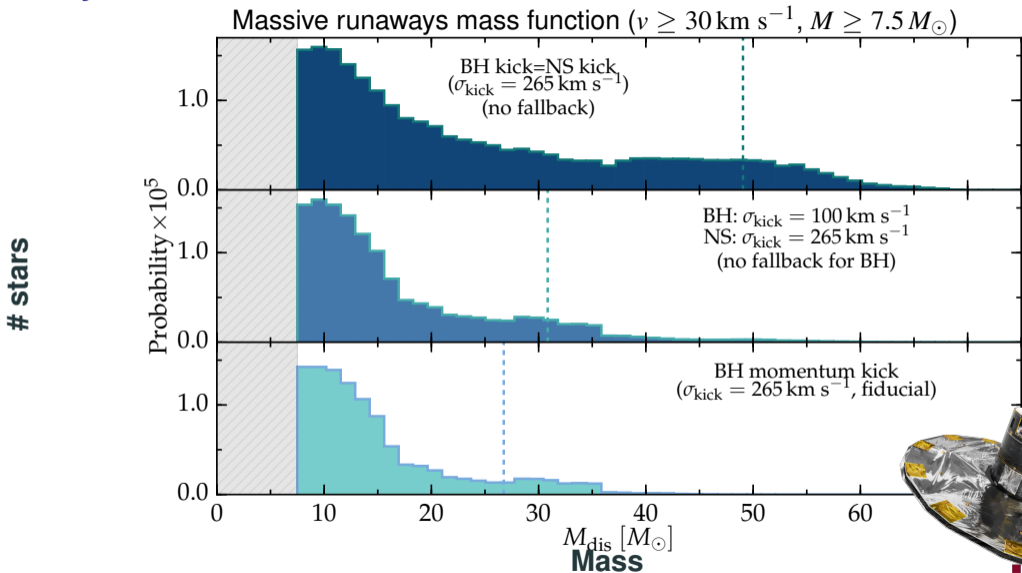
YES

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



...but we can see the
“widowed” companions

A way to constrain BH kicks with Gaia



gaia

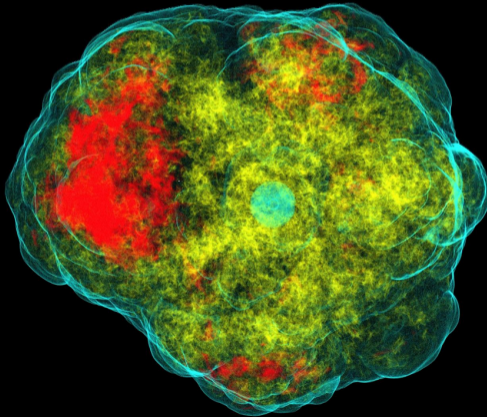
Numerical results publicly available at:

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

SN natal kick

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

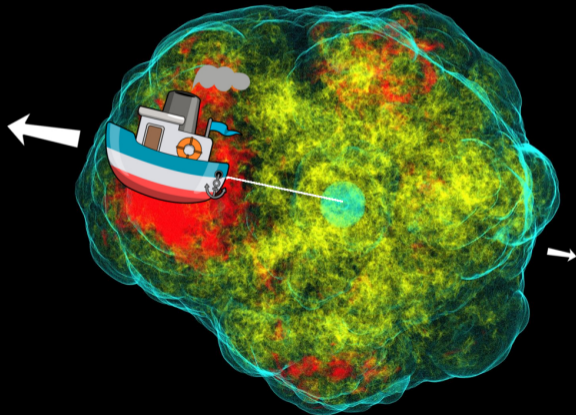
Physically: ν emission and/or ejecta anisotropies



SN natal kick

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

Physically: ν emission and/or ejecta anisotropies



Thermohaline mixing = double diffusion



Stable thermal gradient

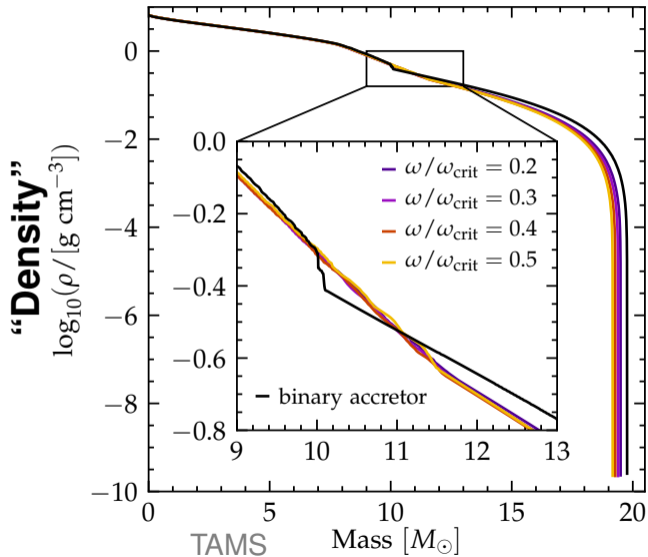
+

Unstable composition gradient

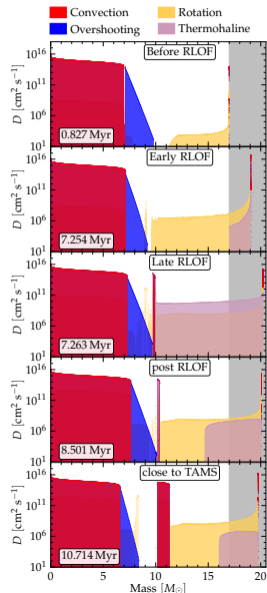
=

Heat needs to diffuse for mixing to happen

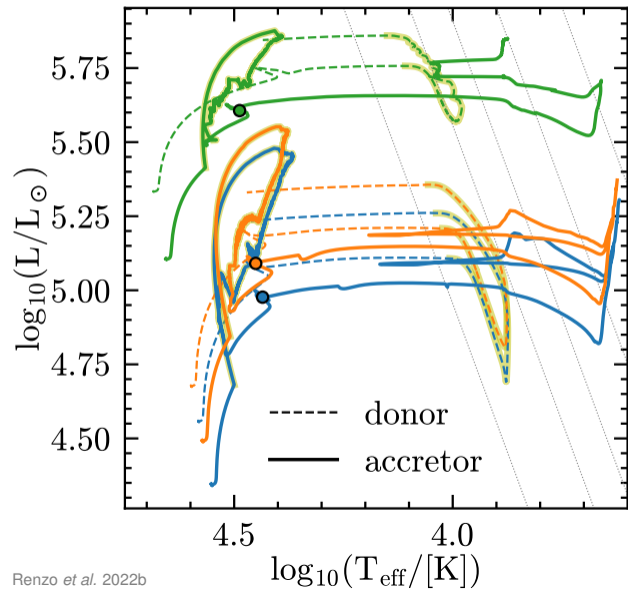
Rejuvenation changes the core/envelope boundary



log₁₀(“Diffusion coeff.”)



Low-Z massive accretors



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

(to focus on GW merger progenitors)