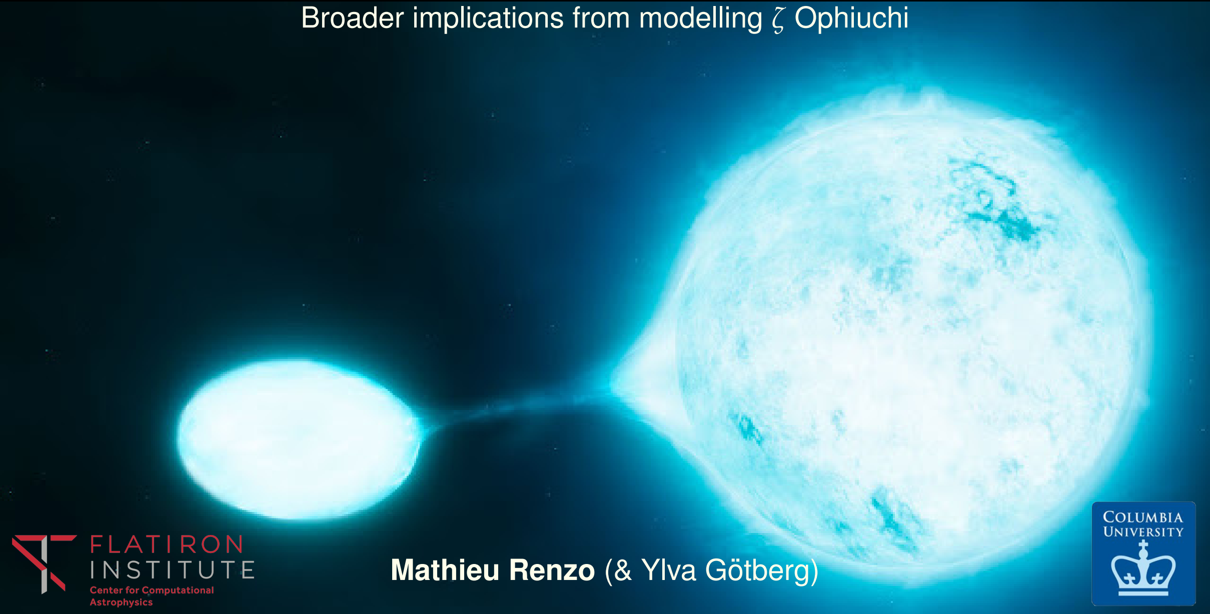
Accretors from massive binaries

Broader implications from modelling ζ Ophiuchi



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Center for Computational Astrophysics

Mathieu Renzo (& Ylva Götberg)

COLUMBIA UNIVERSITY

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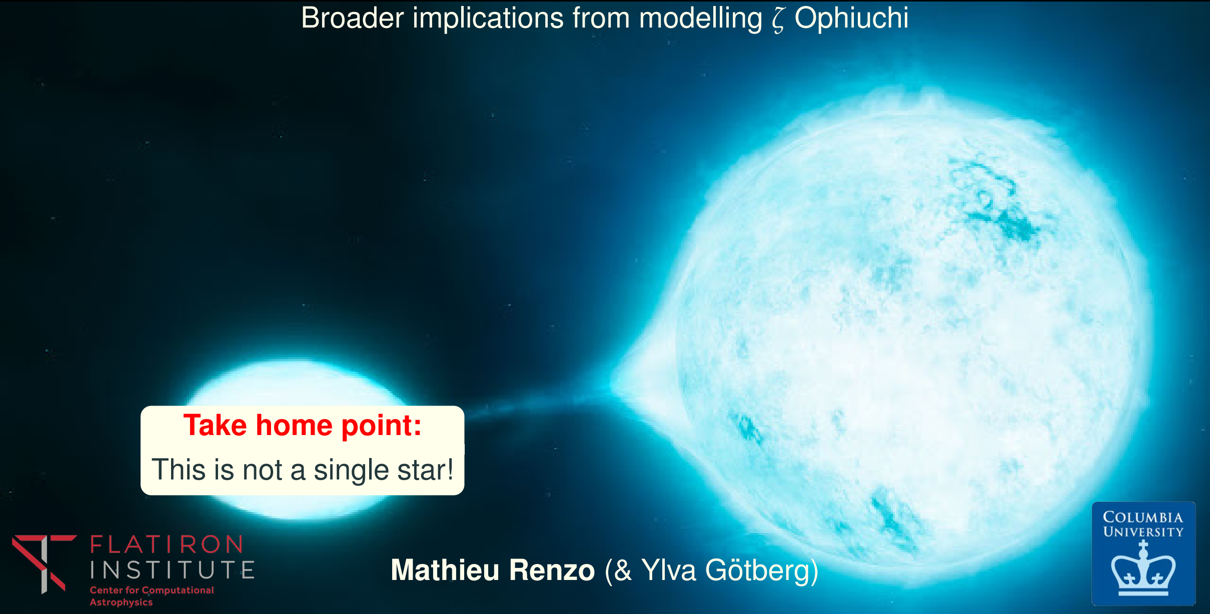
Broader implications from modelling ζ Ophiuchi



Take home point:

This is not a single star!

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Why care about the accretor?

Stellar populations

accretors lurk in samples

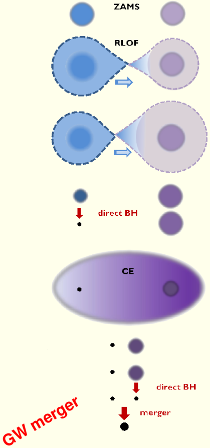
$(10-12\%)$ Renzo *et al.* 2019

+

Oe/Be stars, stragglers

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

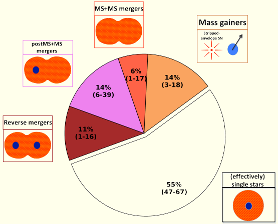
Binary interactions



Tutukov *et al.* 1993, Belczynski *et al.* 2016

Transients

Common: H-rich SNe



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

+

Uncommon: H-rich SNe

L-GRB, LBV, SNIIn **?**

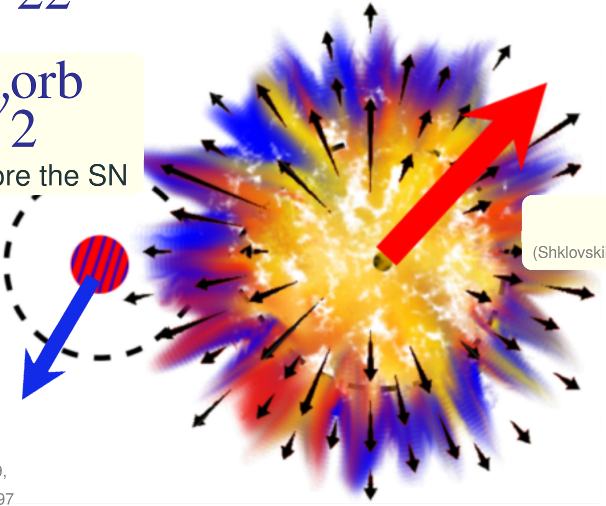
Petrovich *et al.* 2005, Cantiello *et al.* 2007

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

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

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

before the SN



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

The accretor is modified by the interaction

- Spin-up

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

- Pollution

  Blaauw 1993

- Rejuvenation

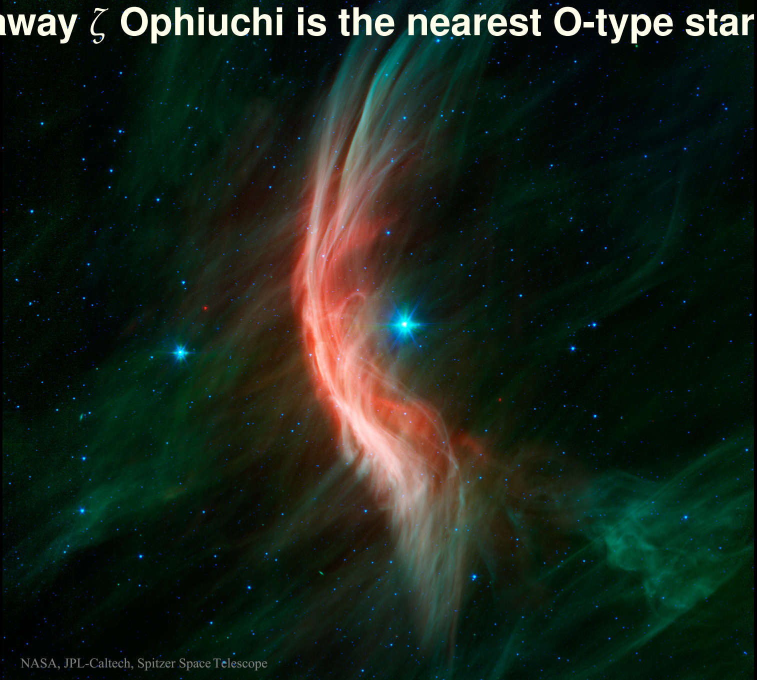
  Hellings 1983, 1985, Schneider *et al.* 2015

Constraints on accretors

from the nearest O-type star

Renzo & Götberg 2021, arXiv:2107.10933

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



NASA, JPL-Caltech, Spitzer Space Telescope

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

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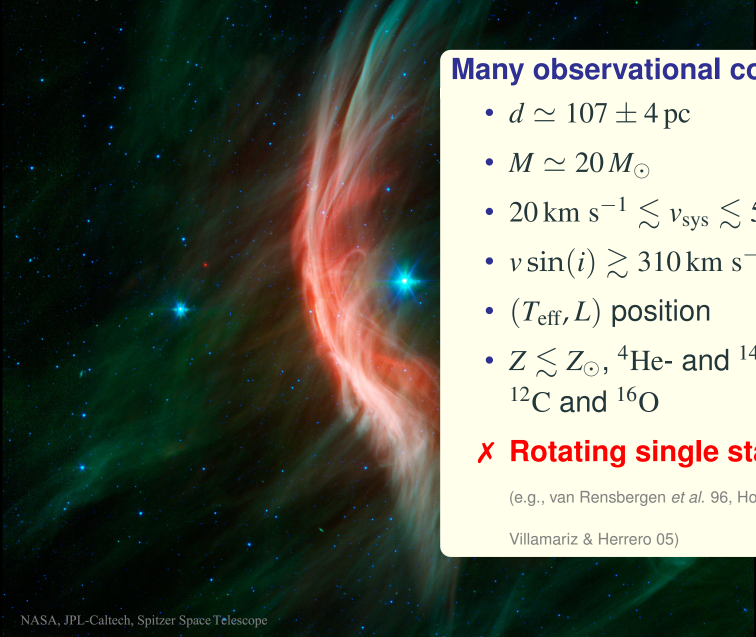


NASA, JPL-Caltech, Spitzer Space Telescope

Many observational constraints!

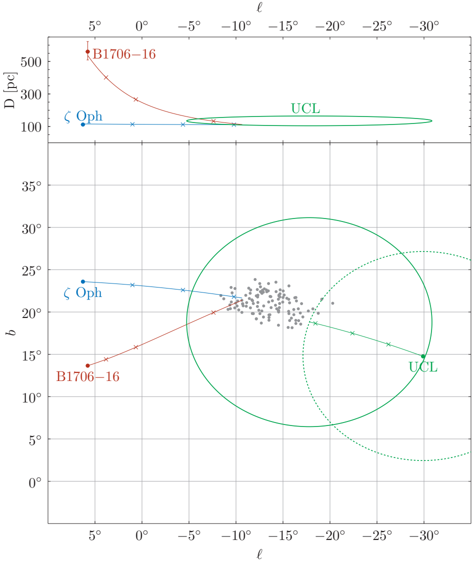
- $d \simeq 107 \pm 4\,\mathrm{pc}$
- $M \simeq 20\,M_{\odot}$
- $20\,\mathrm{km\ s^{-1}} \lesssim v_{\mathrm{sys}} \lesssim 50\,\mathrm{km\ s^{-1}}$
- $v\sin(i) \gtrsim 310\,\mathrm{km\ s^{-1}}$, $i \gtrsim 56^{\circ}$
- (T_{eff}, L) position
- $Z \lesssim Z_{\odot}$, $^{4}\mathrm{He}$- and $^{14}\mathrm{N}$-rich,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

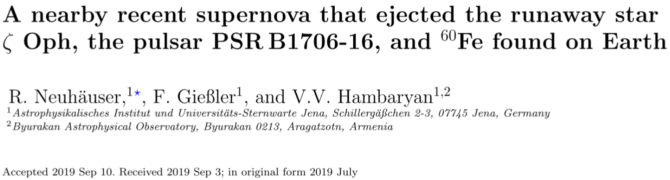
✗ Rotating single stars don't match

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

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

ζ Oph is single 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

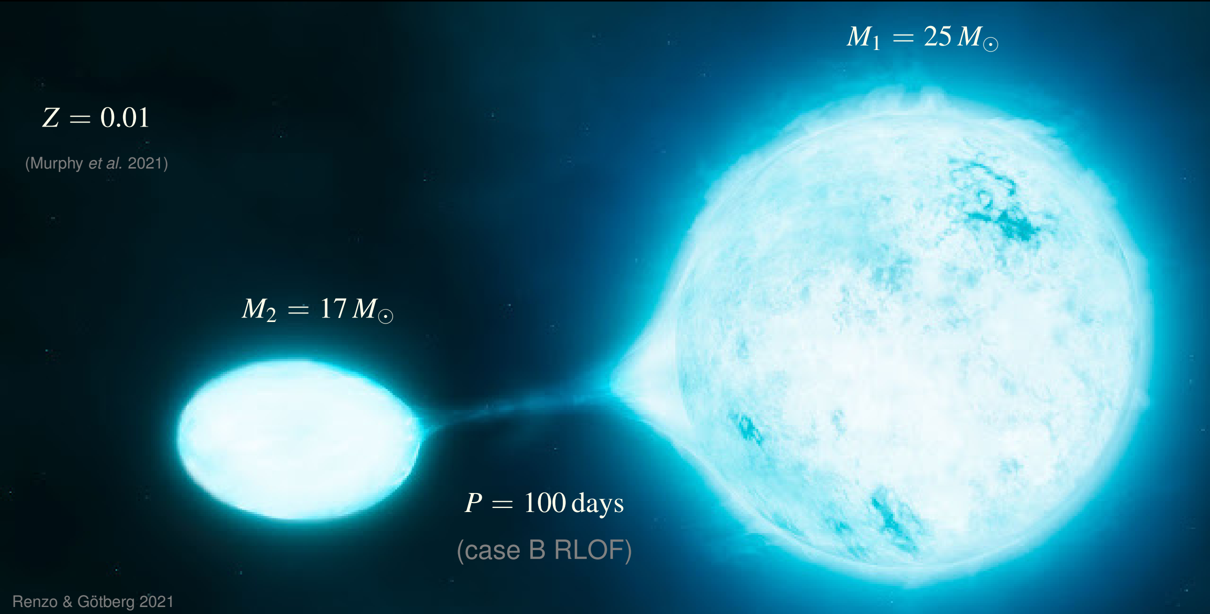
R. Neuhäuser,[1★], F. Gießler[1], and V.V. Hambaryan[1,2]
[1] *Astrophysikalisches Institut und Universitäts-Sternwarte Jena, Schillergäßchen 2-3, 07745 Jena, Germany*
[2] *Byurakan Astrophysical Observatory, Byurakan 0213, Aragatzotn, Armenia*

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

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

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



$M_1 = 25\,M_\odot$

$Z = 0.01$

(Murphy *et al.* 2021)

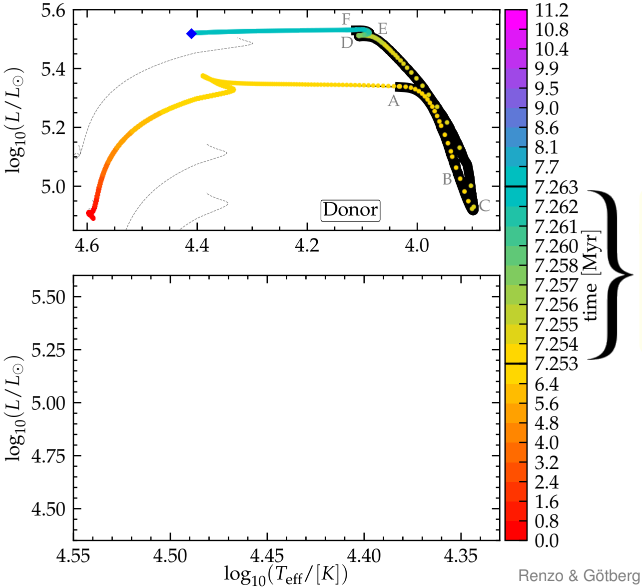
$M_2 = 17\,M_\odot$

$P = 100$ days

(case B RLOF)

Renzo & Götberg 2021

HRD of both stars: the donor



Renzo & Götberg 2021

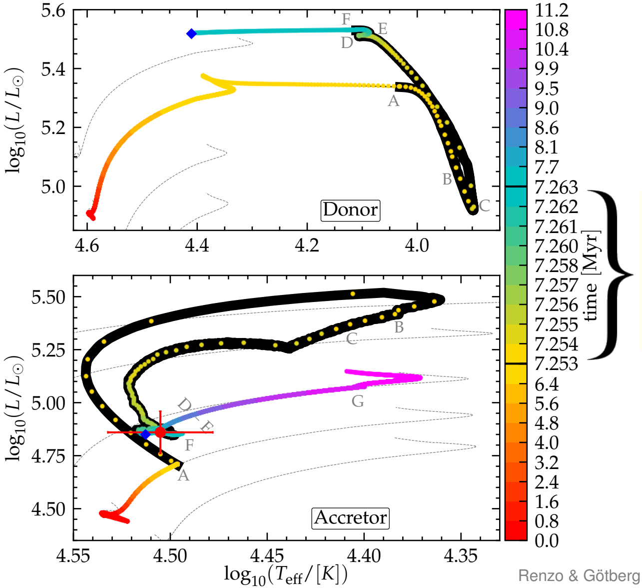
Case B mass transfer is short

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

but has long-lasting impact

on **both** stars.

HRD of both stars: the donor & the accretor ✓



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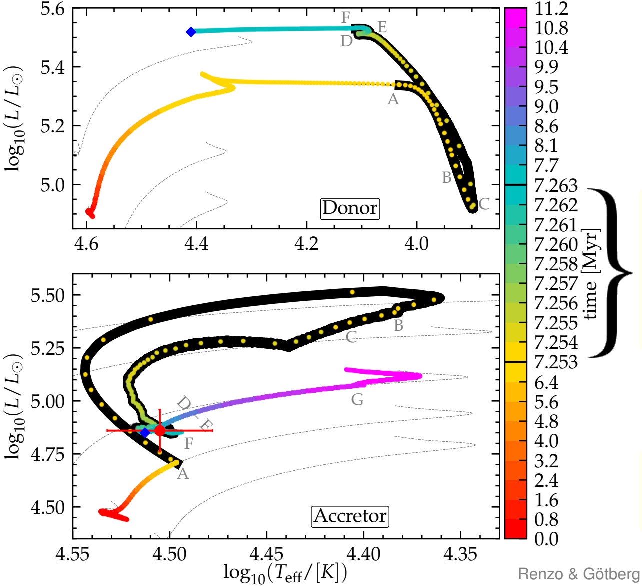
Renzo & Götberg 2021 (data from Villamàriz & Herrero 05)

HRD of both stars: the donor & the accretor ✓



Case B mass transfer is short

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but has long-lasting impact

on **both** stars.

✓ **Models match ζ Oph.**

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

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

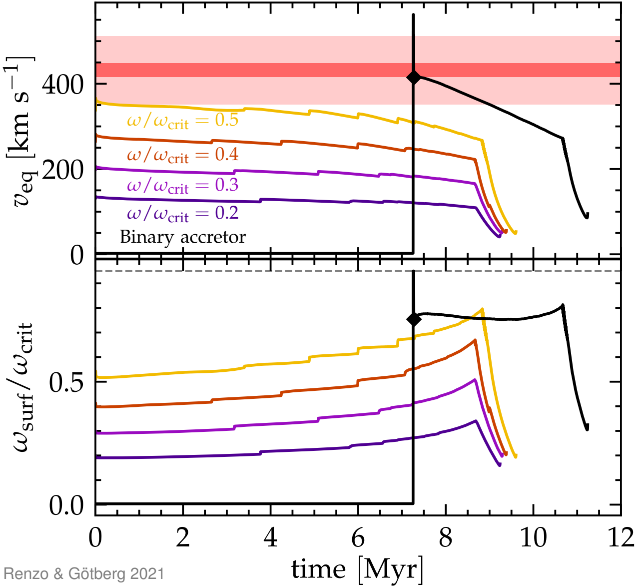
Internal structure of the accretor

Spin up: surface and interior

Pollution: ^{14}N as a tracer

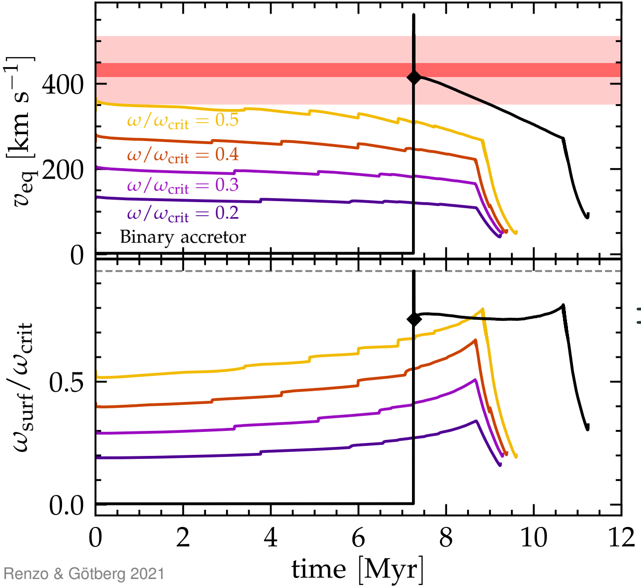
Rejuvenation: core-envelope boundary

✓ Surface rotation rate



Renzo & Götberg 2021

✓ Surface rotation rate



$\Longrightarrow$

Accretors are likely Oe/Be stars

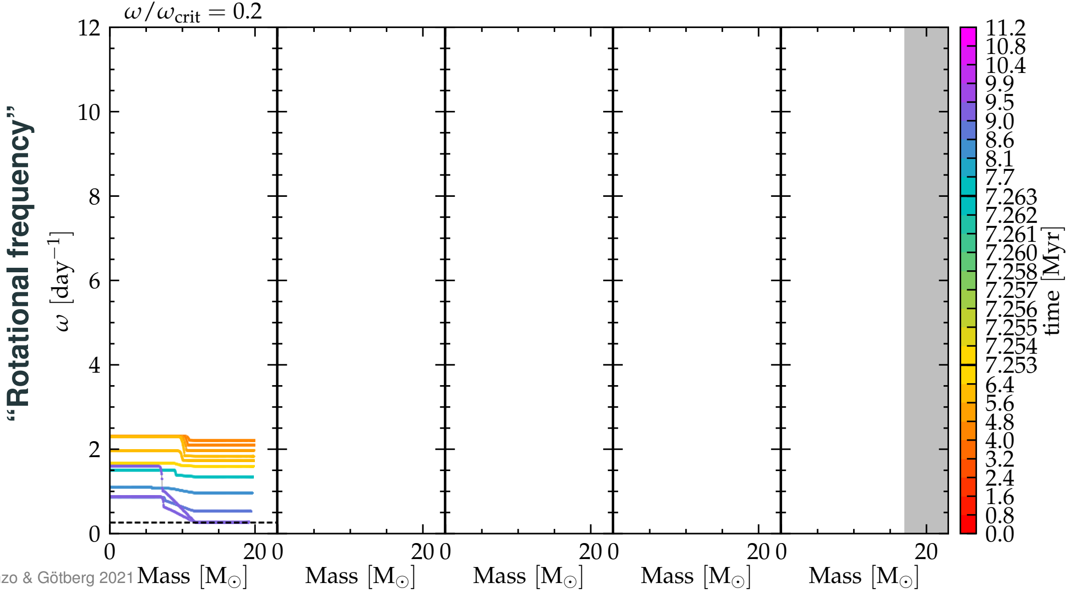
$$\omega_{\rm surf} \simeq 0.75\,\omega_{\rm crit}$$

decretion disk & emission lines

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

Renzo & Götberg 2021

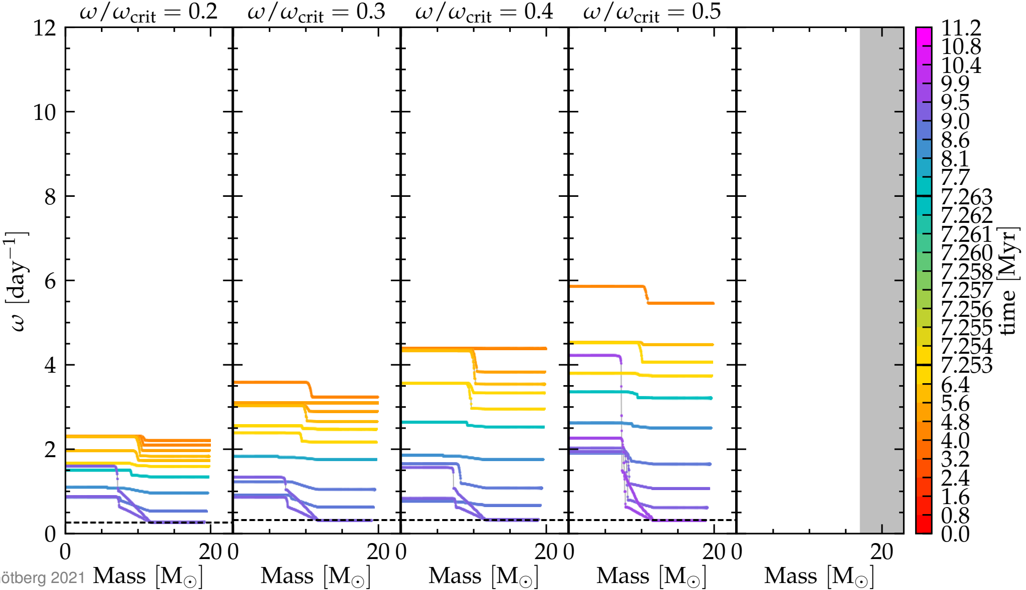
Internal rotational profile: single stars



Renzo & Götberg 2021

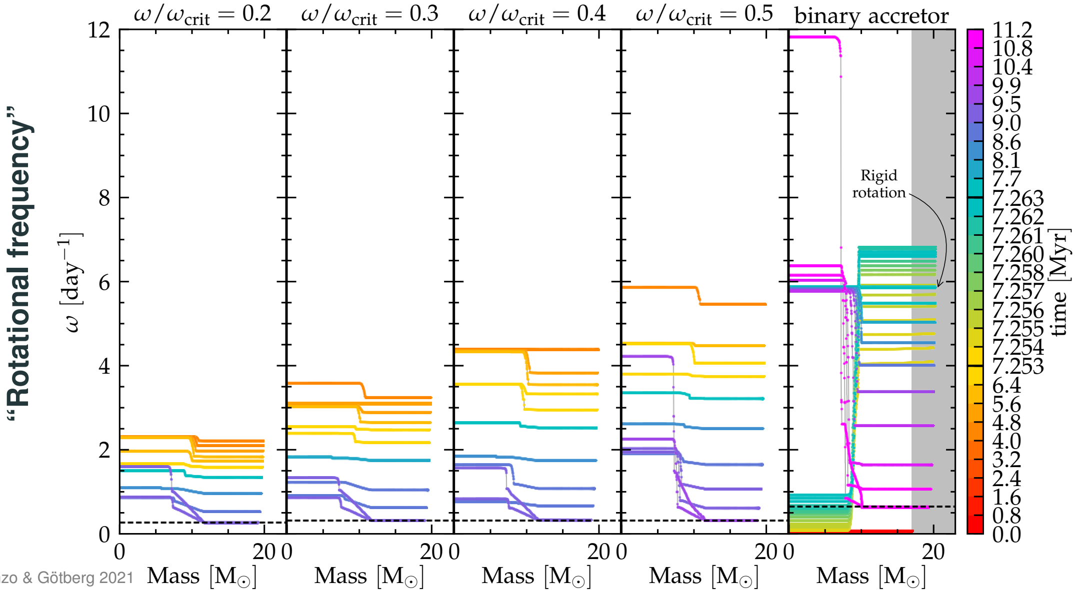
Internal rotational profile: single stars

“Rotational frequency”



Renzo & Götberg 2021

Internal rotational profile: accretor



Renzo & Götberg 2021

Internal structure of the accretor

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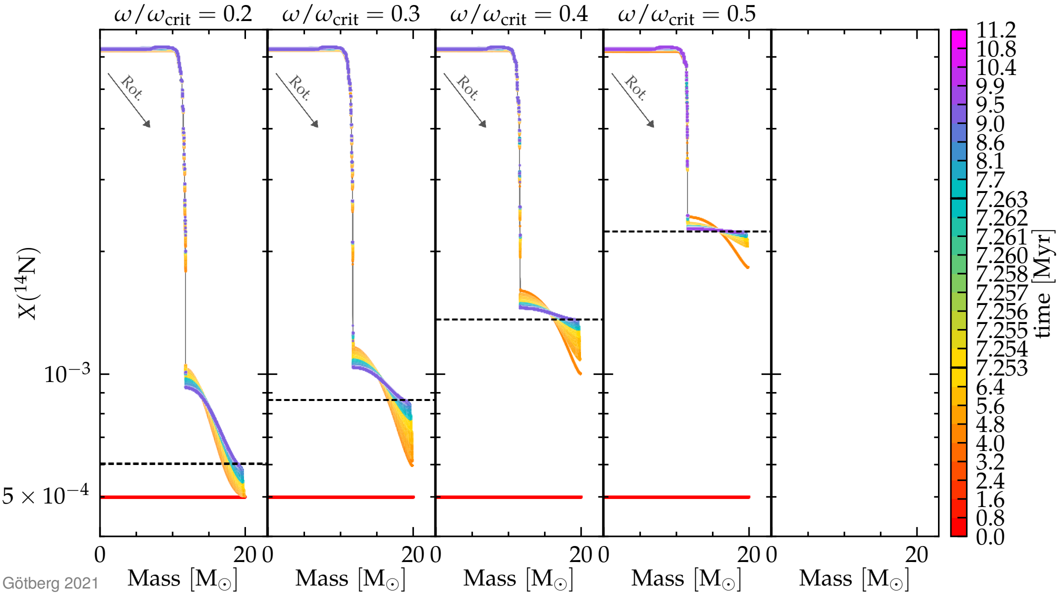
Composition profile: comparison with rotating single stars

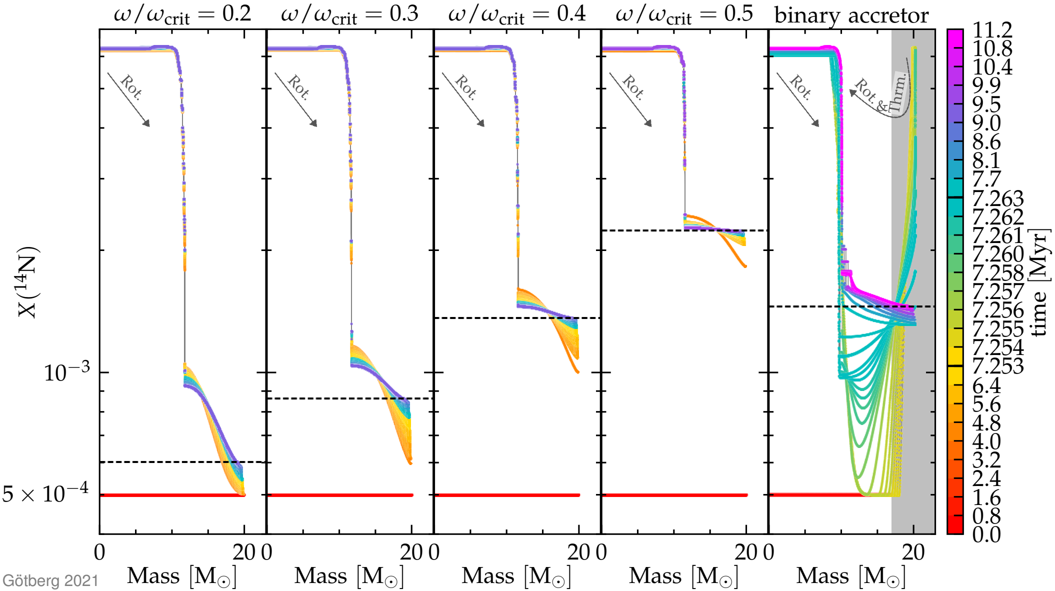
“Nitrogen”



Renzo & Götberg 2021

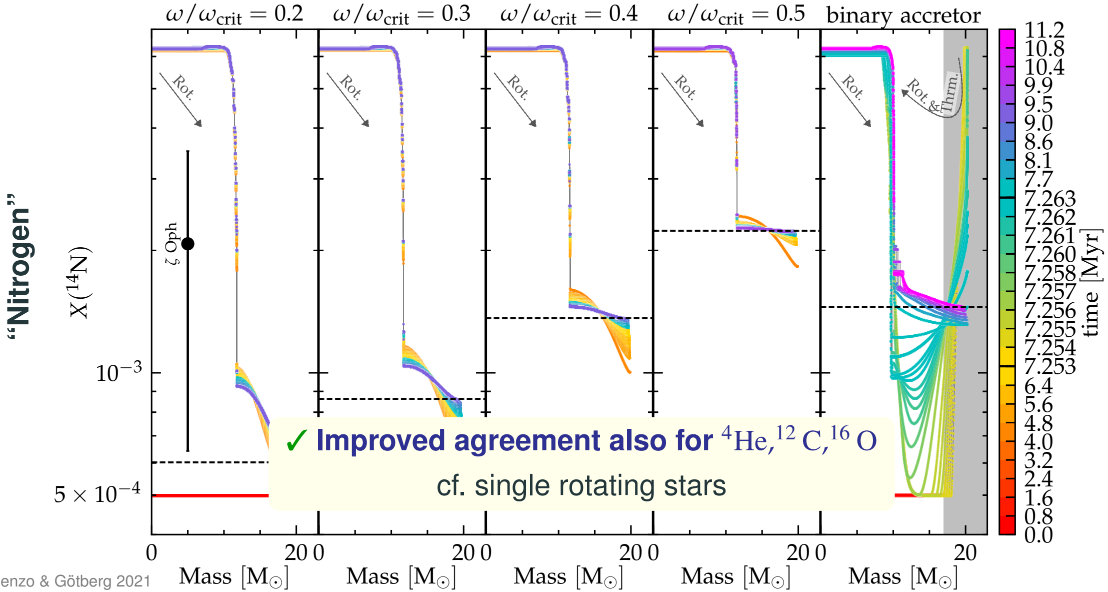
Composition profile: comparison with rotating single stars

“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**

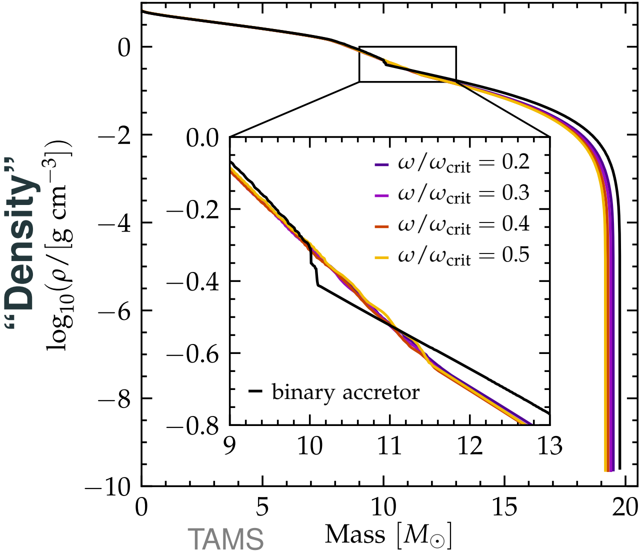
cf. single rotating stars

Renzo & Götberg 2021

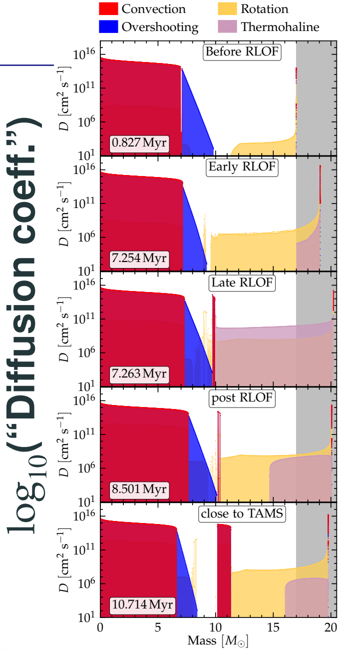
Internal structure of the accretor

Rejuvenation: core-envelope boundary

Effect of mixing processes in the accretor



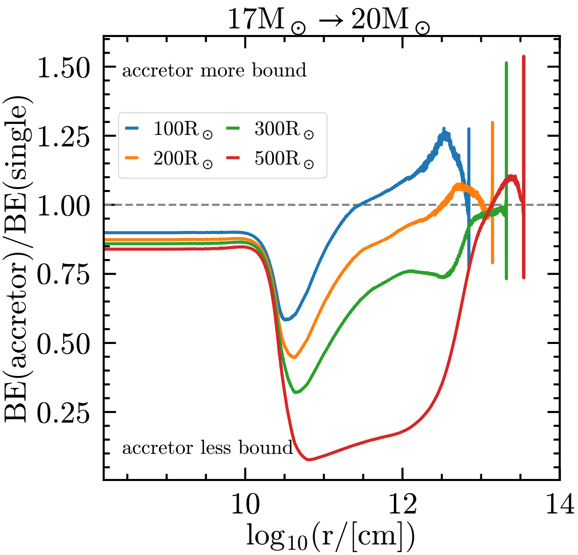
TAMS



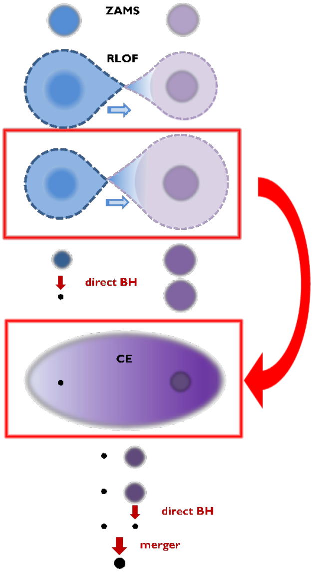
Renzo & Götberg 2021, Gade Pedersen, Renzo, *et al.* in prep.

RLOF-accretors are “better” CE-donors: easier to unbind

“Ratio of Binding energies”



“Radius”



Renzo *et al.*, in prep.

Conclusions

Accretors are *not* single stars

- MESA accretor models successful with “standard” assumptions

  $\Rightarrow$ ✓ ζ Oph age, L, T_{eff}, velocity, rotation, mass, composition

- Surface $^{10}\mathrm{N}$ and $^{4}\mathrm{He}$ from the donor, not own core

  $\Rightarrow$ Observed composition constrain mixing & RLOF accretion efficiency

  $\Rightarrow$ v_∞ measurements affected?

- Long time $\omega_{\mathrm{surf}} \simeq 0.75\,\omega_{\mathrm{crit}}$

  $\Rightarrow$ Oe/Be run/walkaway stars, (non-interacting) companions to NS/BHs

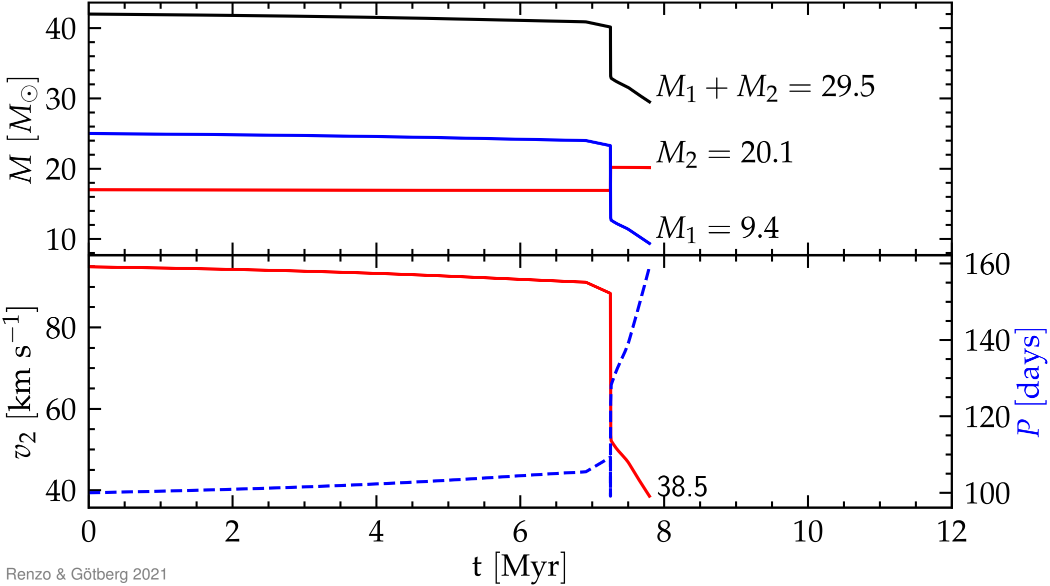
- Core-envelope boundary changed by rejuvenation

  $\Rightarrow$ Implications for asteroseismology & common envelope in GW progenitors ?

Renzo & Götberg 2021, arXiv:2107.10933, https://zenodo.org/record/4701565

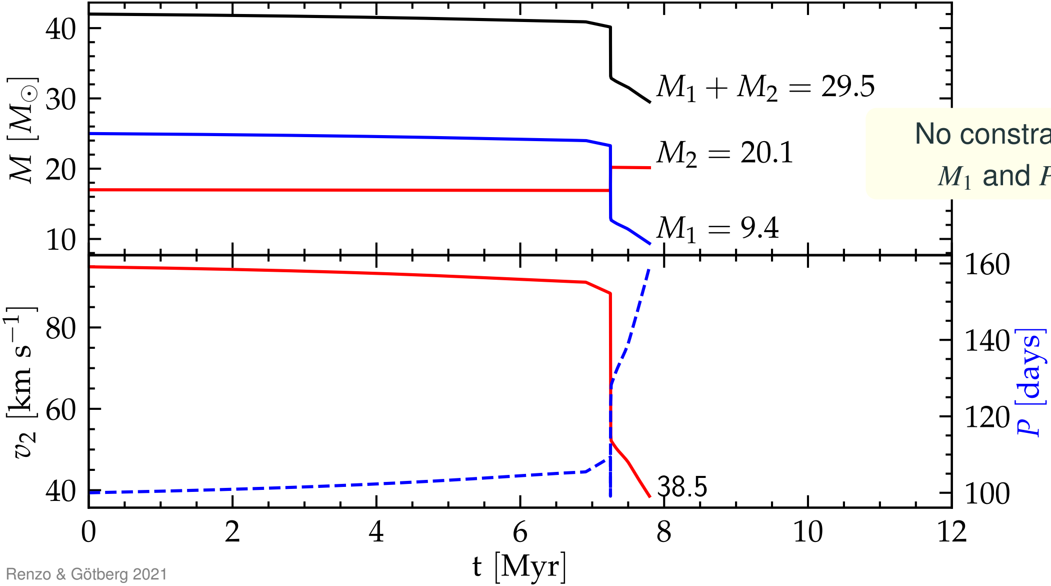
Backup slides

✓ Mass, ✓ orbital evolution & ✓ spatial velocity



Renzo & Götberg 2021

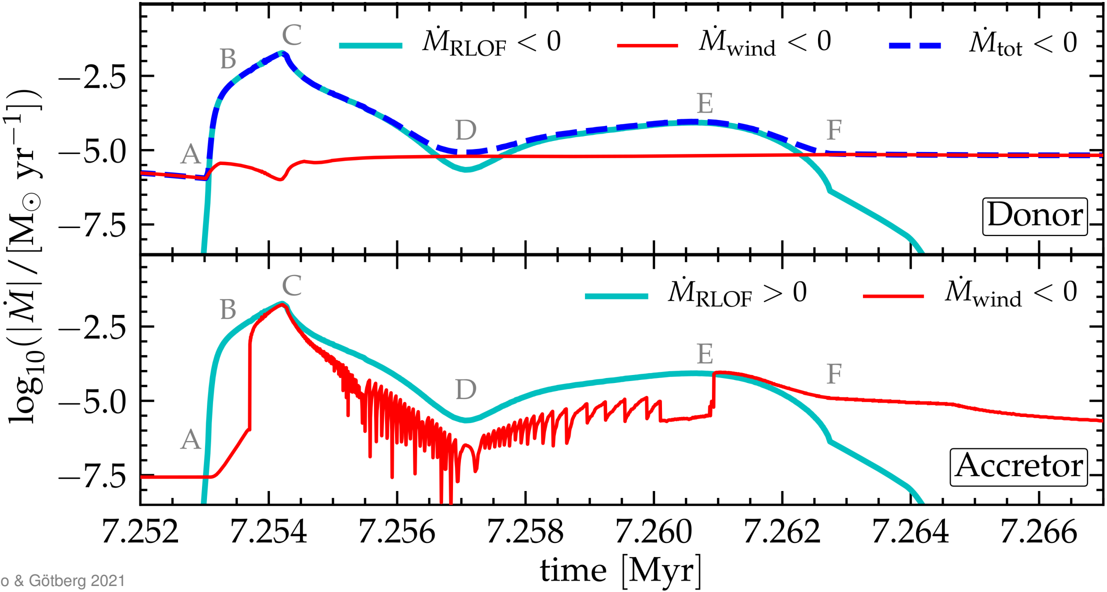
✓ Mass, ✓ orbital evolution & ✓ spatial velocity



No constraints on M_1 and P_{ZAMS}

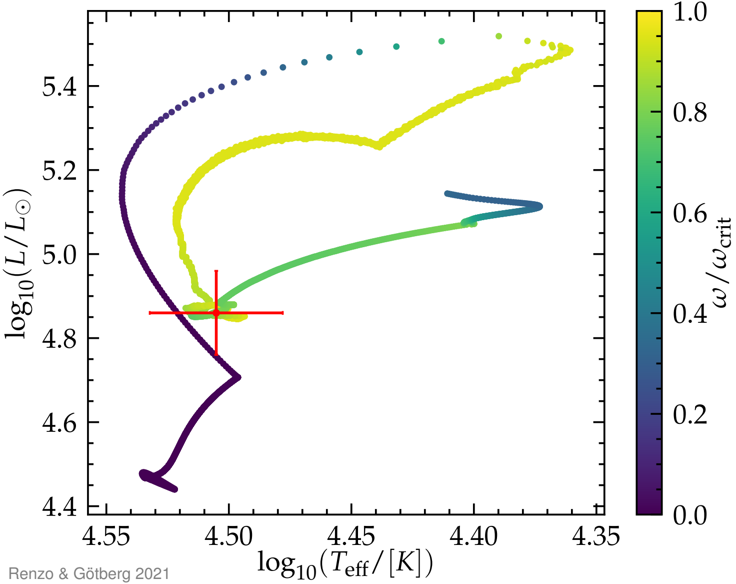
Renzo & Götberg 2021

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



Renzo & Götberg 2021

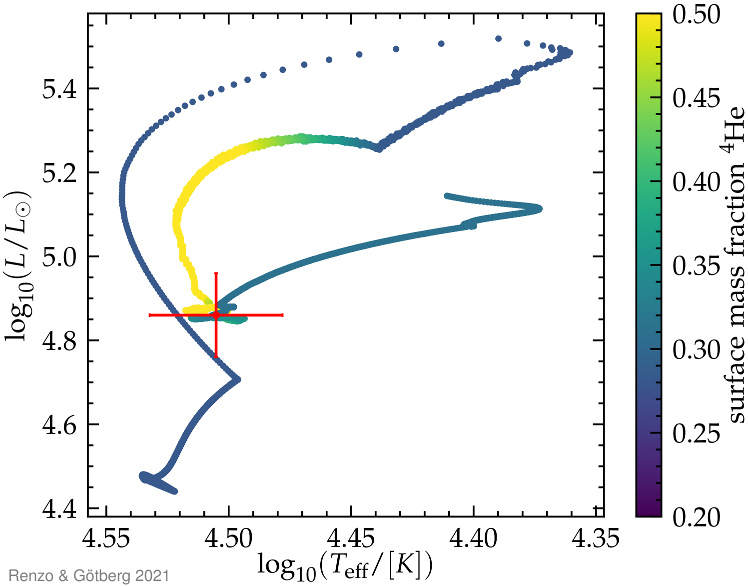
HRD: accretor rotation



Renzo & Götberg 2021

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

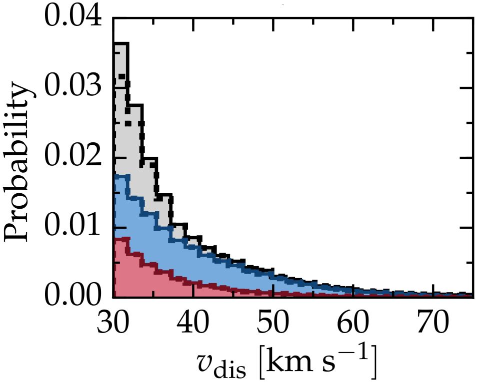
HRD: Helium surface abundance



Renzo & Götberg 2021

- Accretion of He-rich matter change morphology at $T_{\mathrm{eff}} \simeq 10^{4.44}$ K.
- Interplay between rotational and thermohaline mixing causes "noisiness" in the track.

Accretor stars can be *runaways*...

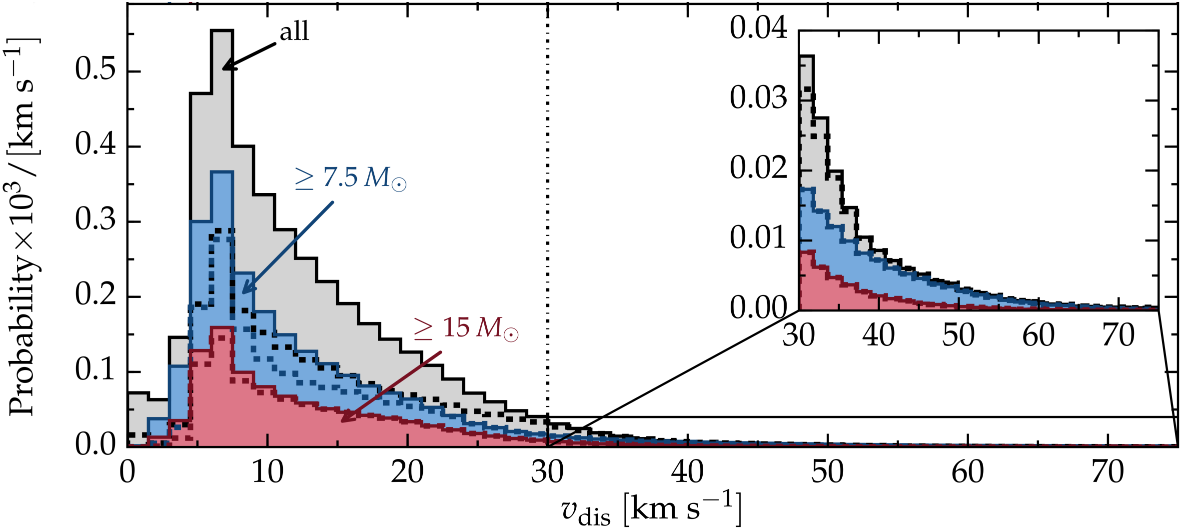


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

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

...but most are only *walkaways*

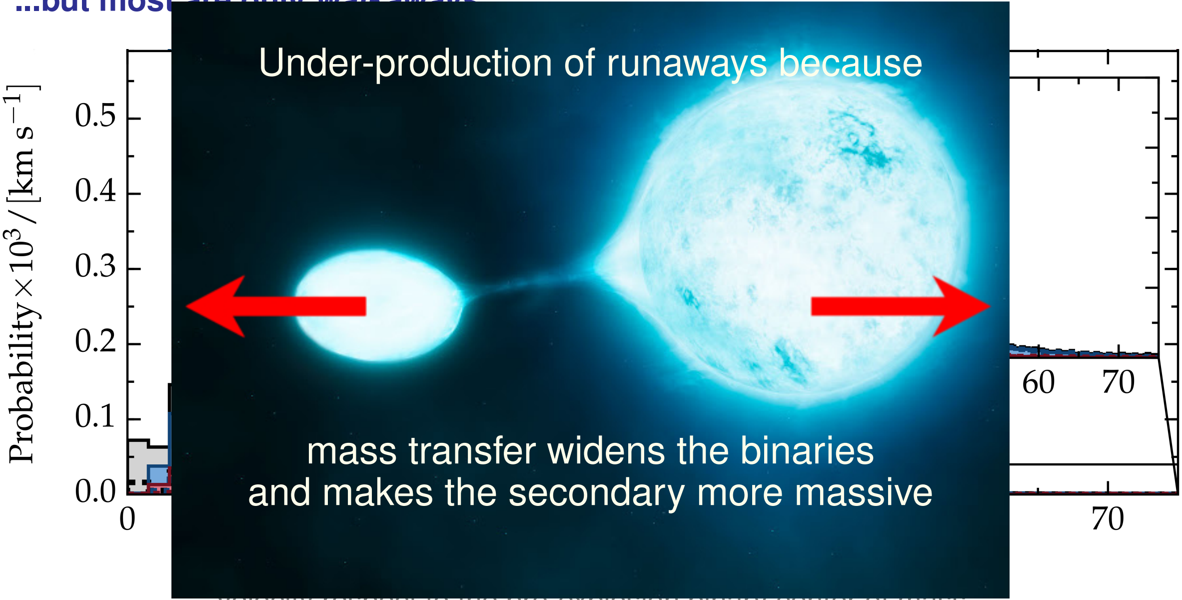


Velocity respect to the pre-explosion binary center of mass

Renzo *et al.* 2019b

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

...but most are only *walkaways*



Under-production of runaways because

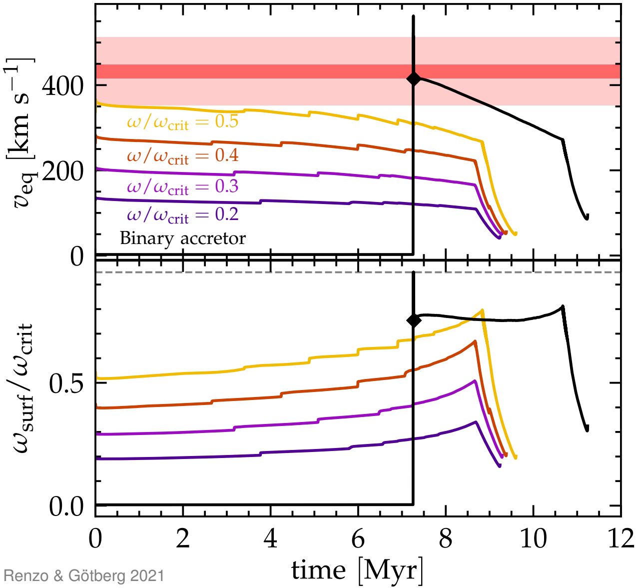
mass transfer widens the binaries
and makes the secondary more massive

velocity respect to the 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

✓ Surface rotation rate ?



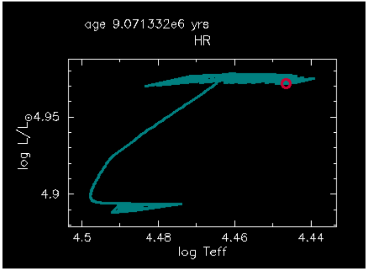
Renzo & Götberg 2021

- but "weak wind problem":

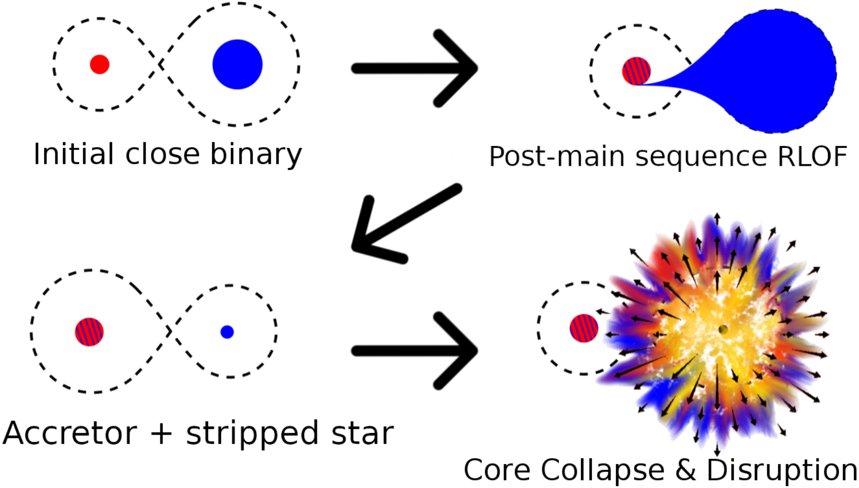
$$\frac{|\dot{M}_\mathrm{obs}|}{M_\odot \mathrm{yr}^{-1}} \simeq 10^{-8.8} \ll \frac{|\dot{M}_\mathrm{wind,theory}|}{M_\odot \mathrm{yr}^{-1}} \simeq 10^{-6.8}$$

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

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



Most common massive binary evolution path: stable case B RLOF



e.g., van den Heuvel 1969, de Mink *et al.* 2013, Renzo *et al.* 2019b

see also https://www.youtube.com/watch?v=qmfJNI0PXbo