“Widowed stars” from massive binaries

Mathieu Renzo & Ylva Götberg

arXiv:2107.10933

github.com/mathren90/zeta_oph

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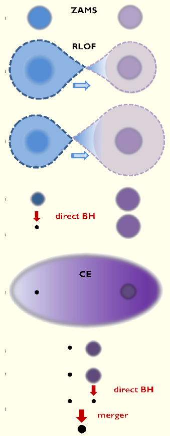
This might be on the low energy side for this group. There is a SN and I will connect to BH formation and long-GRBs at the end hopefully. I want to talk about some aspects of a paper that was recently accepted, where we studied binary interactions, but focusing on the accretor star, the underdog that will be widowed at the death of the companion

Why care about the accretor?

Binary interactions



e.g., Belczynski *et al.* 2016

Stellar populations

accretors lurk in samples

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

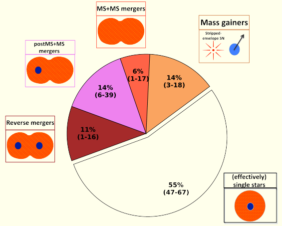
+

Oe/Be stars, stragglers

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

Transients

type II supernovae



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

+

long GRB

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

Binary:

$50-70\%$ of massive stars are in interacting binaries, the majority will go through stable mass transfer, meaning $25-35\%$ of massive stars are accretors. Need to understand them for GW progenitors. Also, those are relatively easy to see while stripped stars are elusive.

stellar populations:

∼10% of accretors shot out transients:

$\sim 14\%$ of type II SNe come from accretors, important for long-GRB

Most common massive binary evolution path: stable case B RLOF

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

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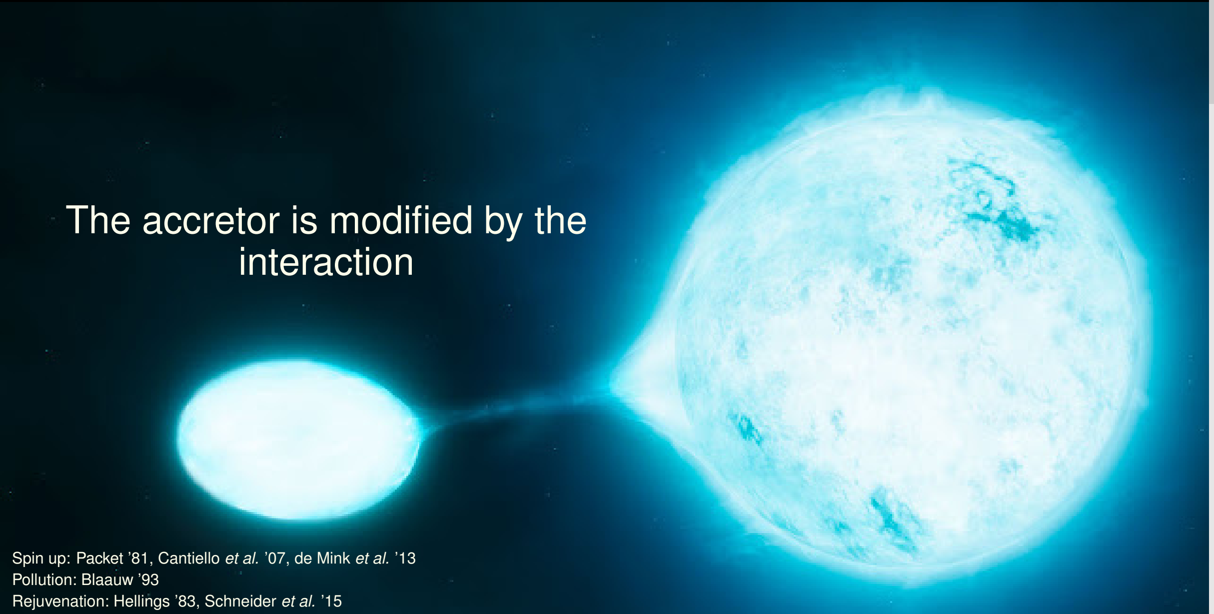
Most common massive binary evolution path: stable case B RLOF

Most common massive binary evolution path: stable case B RLOF

Spin up, pollution, and rejuvenation of the second star



The accretor is modified by the interaction

Spin up: Packet '81, Cantiello *et al.* '07, de Mink *et al.* '13
Pollution: Blaauw '93
Rejuvenation: Hellings '83, Schneider *et al.* '15

quantify $\sim 10-12\%$ **of field O type stars are accretors** but a tiny fraction can be runaway.

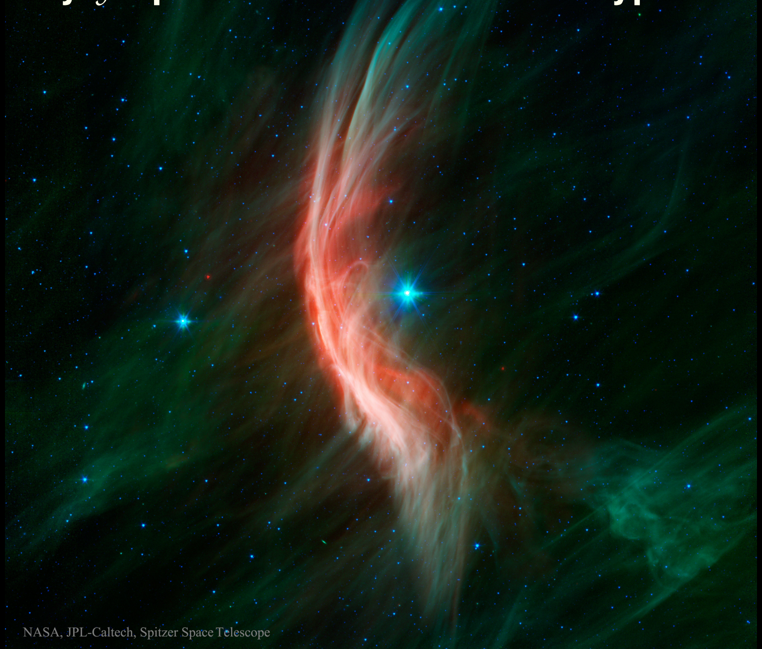
Need better models of accretor stars!

“Widowed” stars

Constraints from the nearest O-type star

“Widowed” stars
Constraints from the nearest O-type star

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

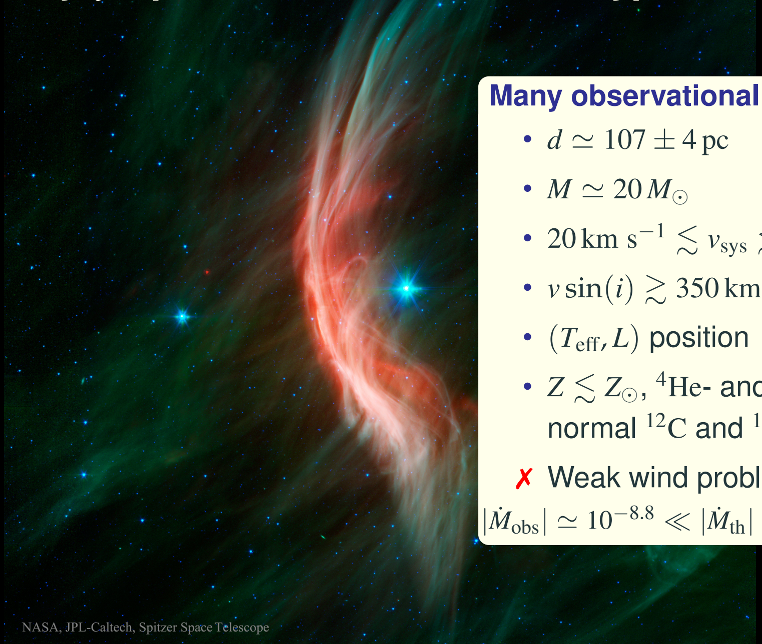

NASA, JPL-Caltech, Spitzer Space Telescope

e.g., Neuhäuser *et al.* 2020

ζ Ophiuchi is the **nearest O type star to Earth**
It is also a runaway star, spins extremely fast, and is well characterized observationally.

Up to 10% of single field stars, virtually all the OB companions to BHs, might be have a similar past to this particular star.

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



NASA, JPL-Caltech, Spitzer Space Telescope

Many observational constraints!

- $d \simeq 107 \pm 4\,\mathrm{pc}$
- $M \simeq 20\,M_\odot$
- $20\,\mathrm{km\ s^{-1}} \lesssim v_\mathrm{sys} \lesssim 50\,\mathrm{km\ s^{-1}}$
- $v\sin(i) \gtrsim 350\,\mathrm{km\ s^{-1}}$
- (T_eff, L) position
- $Z \lesssim Z_\odot$, ^{4}He- and ^{14}N-rich, normal ^{12}C and ^{16}O

✗ Weak wind problem:

$$|\dot{M}_\mathrm{obs}| \simeq 10^{-8.8} \ll |\dot{M}_\mathrm{th}| \simeq 10^{-6.8}\ [\mathrm{M_\odot yr^{-1}}]$$

e.g., Neuhäuser *et al.* 2020

ζ Ophiuchi is the **nearest O type star to Earth**

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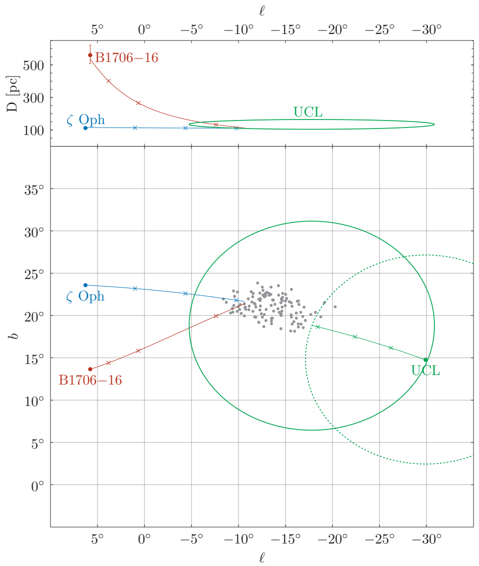
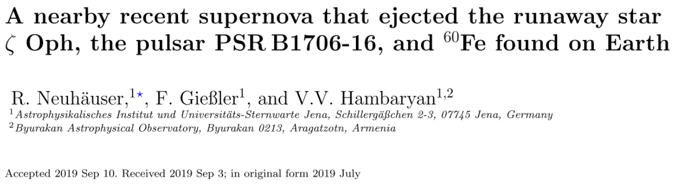
ζ Oph is a “widowed” star: we can trace it back to a neutron star





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.* 19, see also van Rensbergen *et al.* 96, Hoogerwerf *et al.* 01, Lux *et al.* 20

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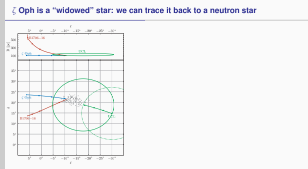
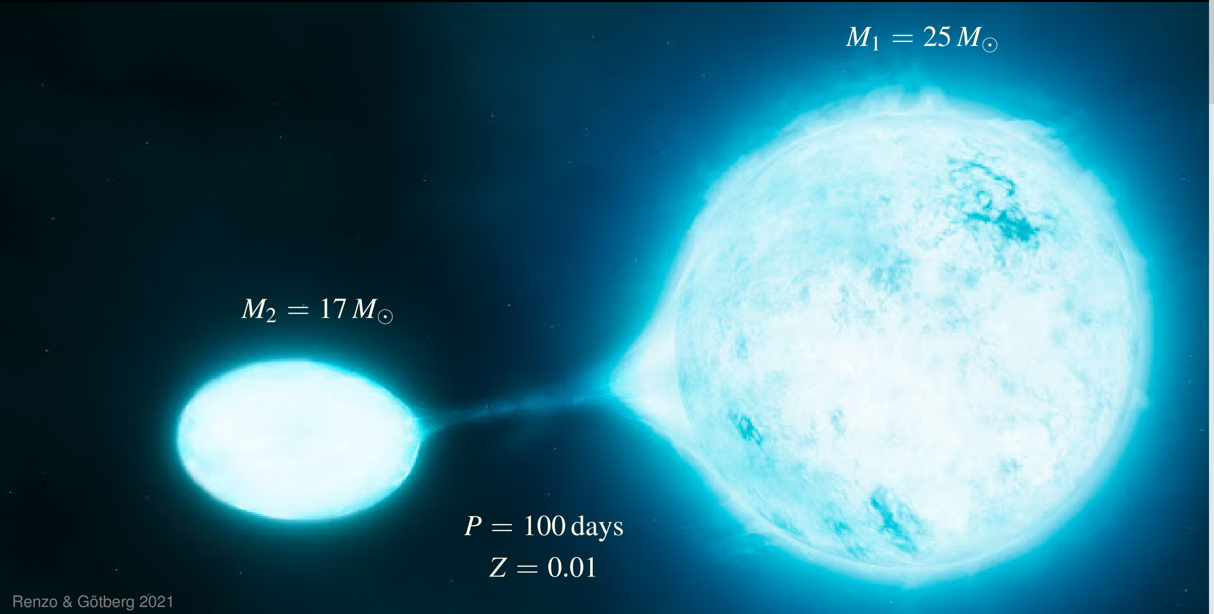
└“Widowed” stars
  └Constraints from the nearest O-type star
    └ζ Oph is a “widowed” star: we can trace it back to a neutron star



Self-consistent MESA model



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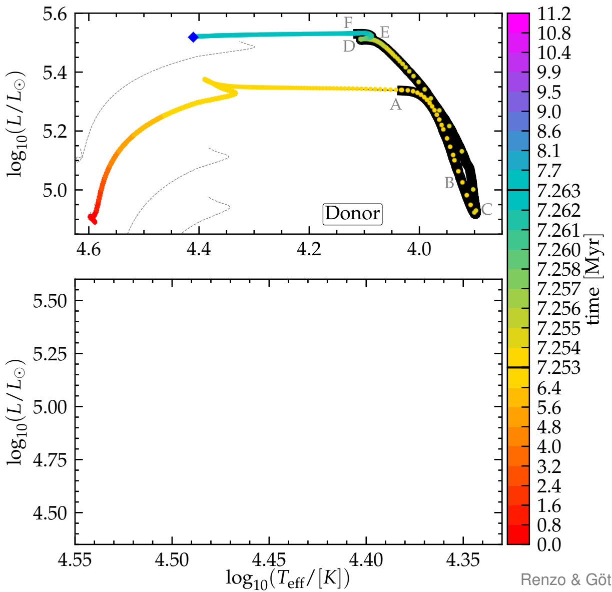
Hertzsprung-Russel diagram of both stars: the donor



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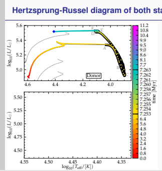
Roche lobe overflow is short

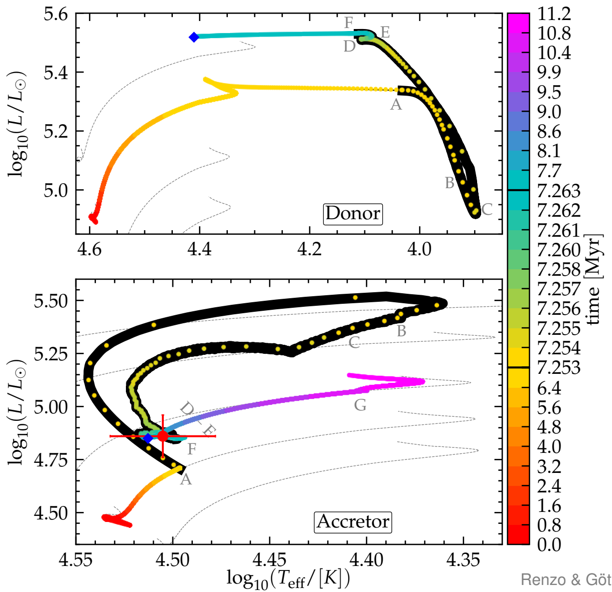
But has long-lasting impact on both stars.


Hertzsprung-Russel diagram of both stars: the donor

single non-rotating stars for reference in the background.

One dot each 50 years Note the different scales on the two panels.

Hertzsprung-Russel diagram of both stars: the donor & the accretor



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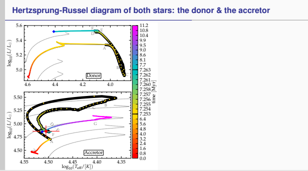
data from Villamàriz & Herrero 05



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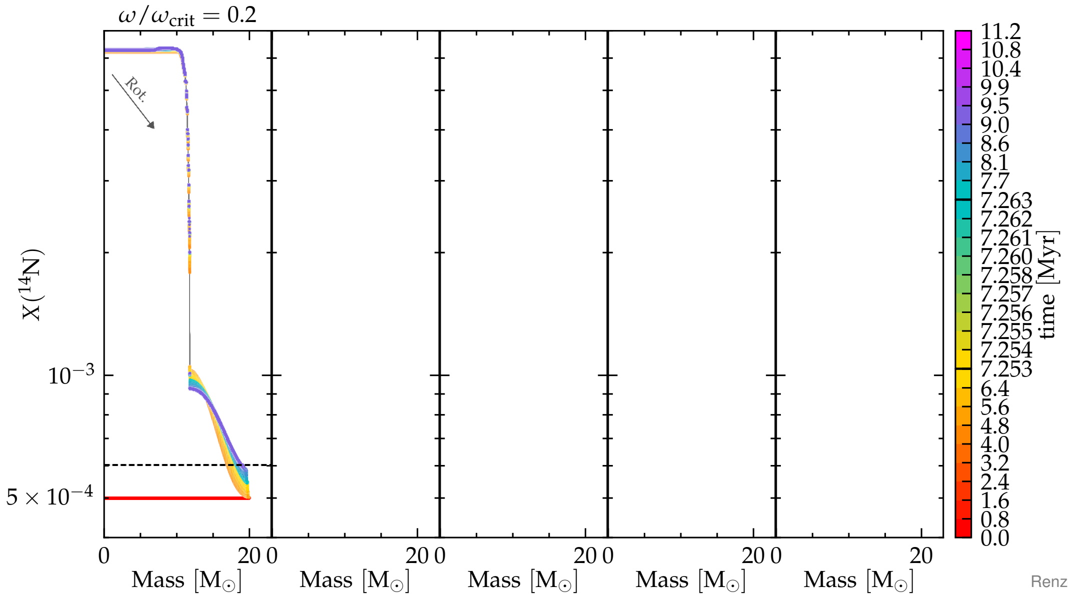
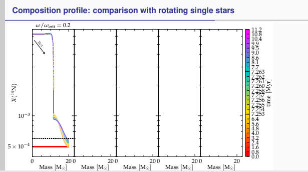
“Widowed” stars

^{14}N as a tracer for composition

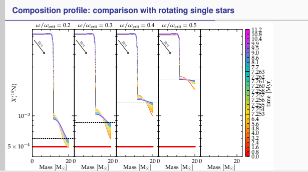
“Widowed” stars
^{14}N as a tracer for composition

Composition profile: comparison with rotating single stars





the abundances from Villamariz & Herrero depend on the surface H abundance



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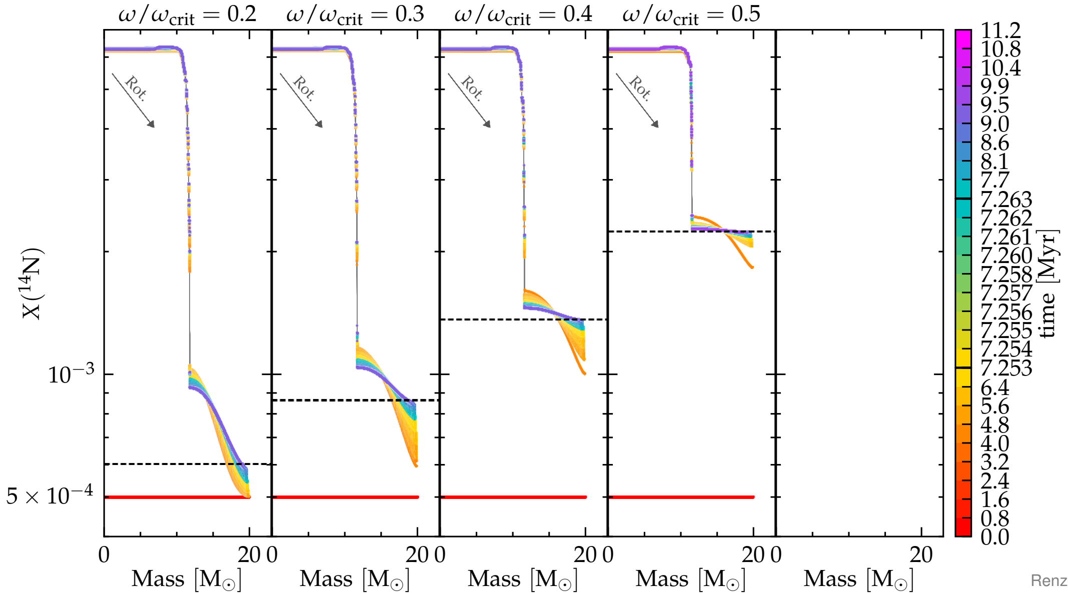

Renzo & Götberg 2021

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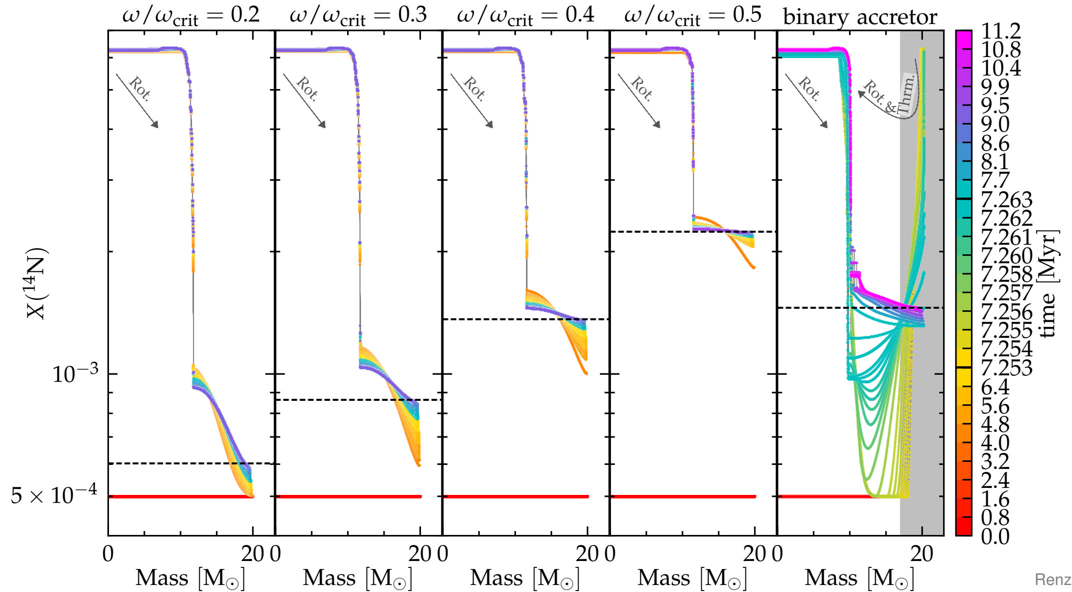
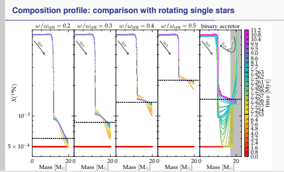


Renzo & Götberg 2021



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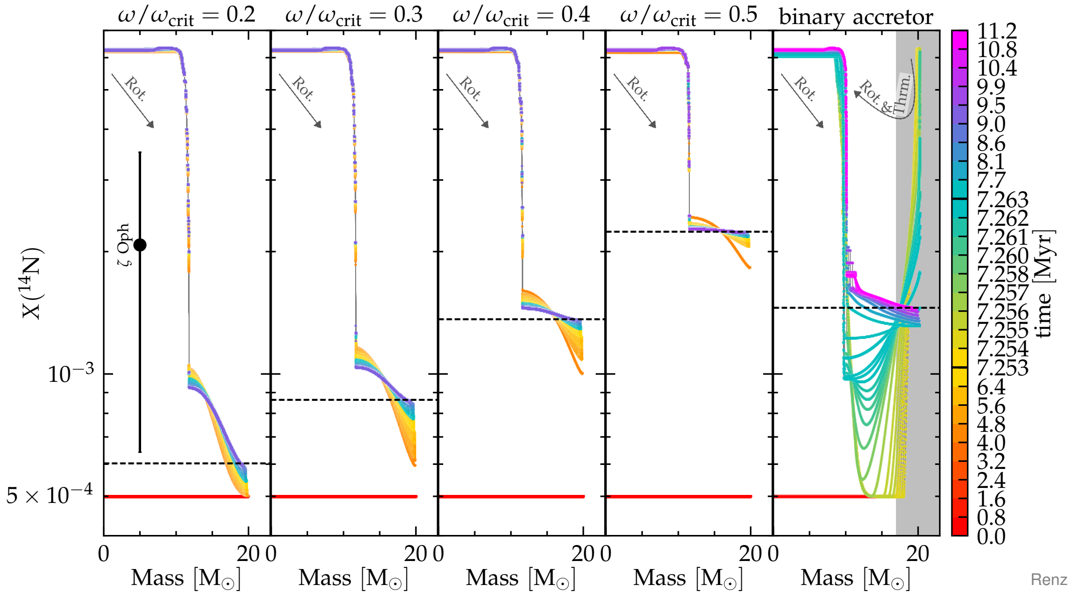
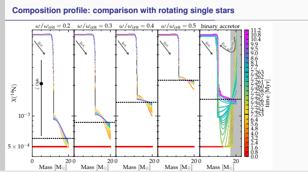


Renzo & Götberg 2021



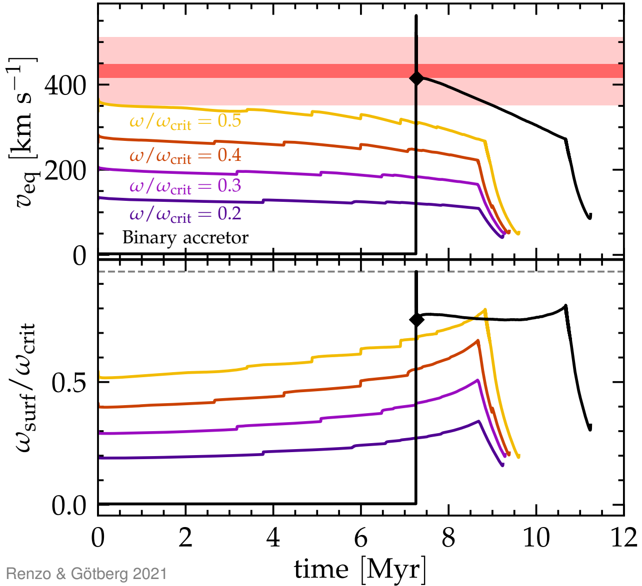
the abundances from Villamariz & Herrero depend on the surface H abundancen14 alone is not a smoking gun, but most of the n14 for accretors come from the core of the companion

“Widowed” stars

Rotation

“Widowed” stars
Rotation

Surface rotation rate



Renzo & Götberg 2021

- but overestimating by $\sim 100\times$ wind mass loss!

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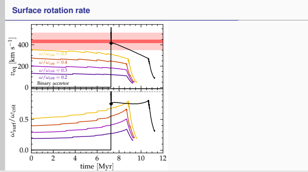
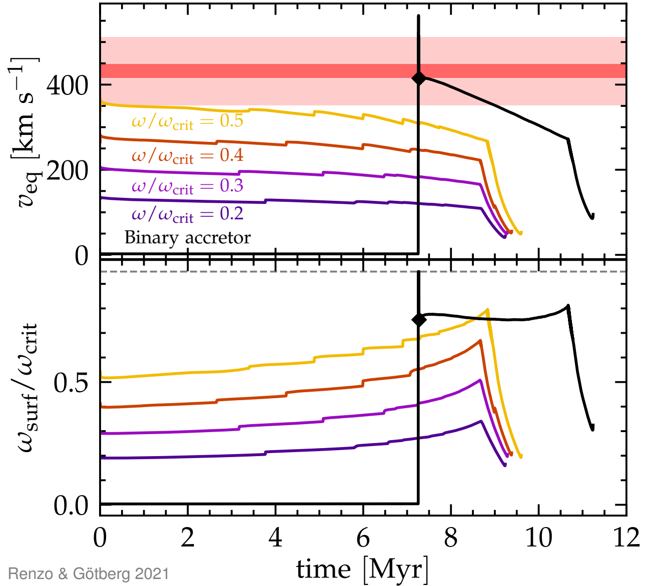
└"Widowed" stars
  └Rotation
    └Surface rotation rate

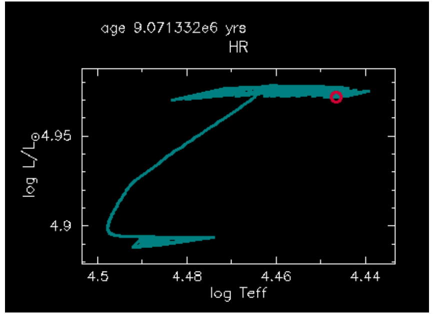


Surface rotation rate



Renzo & Götberg 2021

- but overestimating by $\sim 100\times$ wind mass loss!
- Decreasing the wind yields $\omega/\omega_{\rm crit} > 1$



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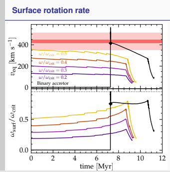
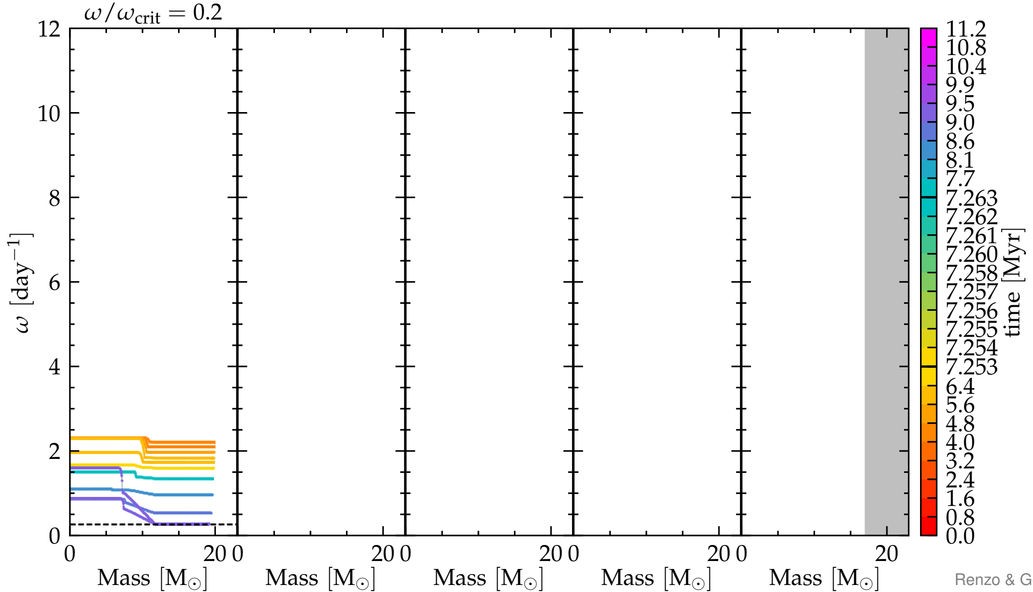
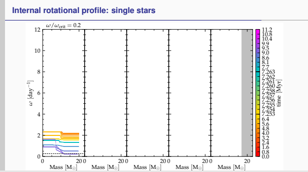
└"Widowed" stars
  └Rotation
    └Surface rotation rate



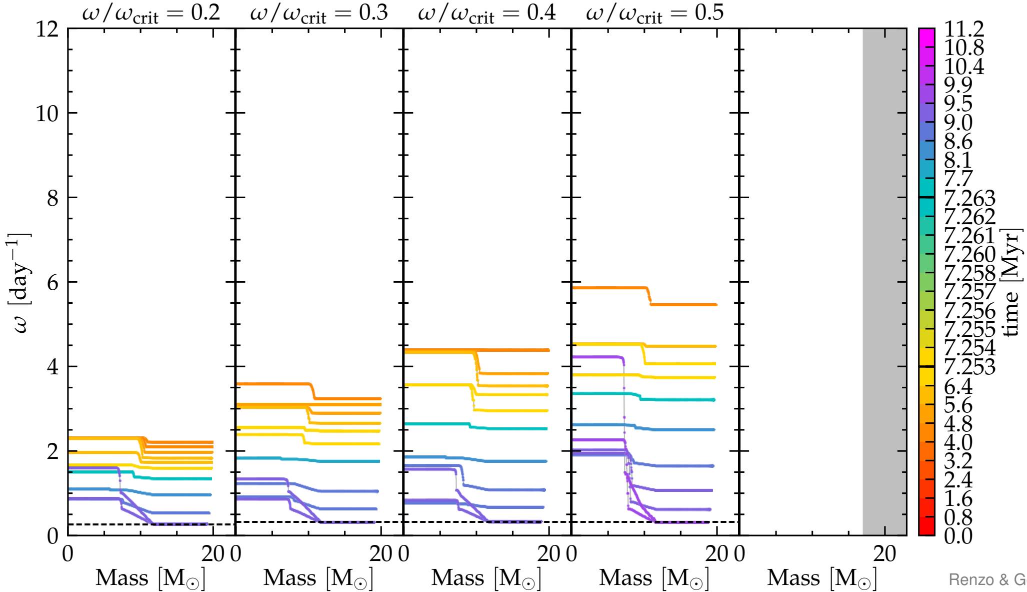
Internal rotational profile: single stars





Let me start by showing a normal, mildly rotating single star. Here you see the rotational frequency omega, as a function of mass coordinate, the core is on the left and the surface on the right. As the star evolves, the surface spins down due to wind mass loss, and the core contracts and tries to spin up.

Internal rotational profile: single stars



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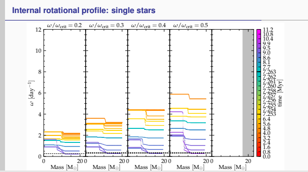
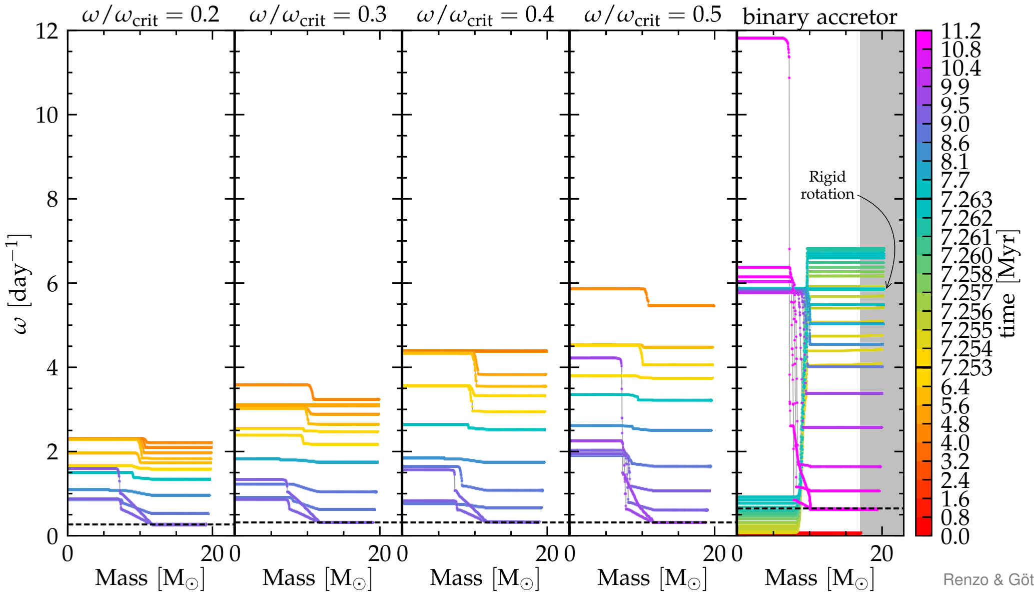
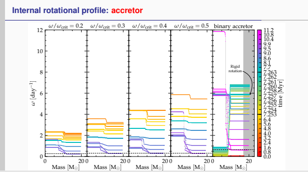


Of course, the faster you spin initially, the more angular momentum there is and can be retained at the end of the evolution, and the details of its distribution depend on angular momentum transport mechanisms which are highly debated still.

Internal rotational profile: accretor



Renzo & Götberg 2021



In this last panel instead I'm going to show you an accretor in a binary. All the gray area corresponds to matter that is accreted during the mass transfer. As you can see, the morphology here is quite different:

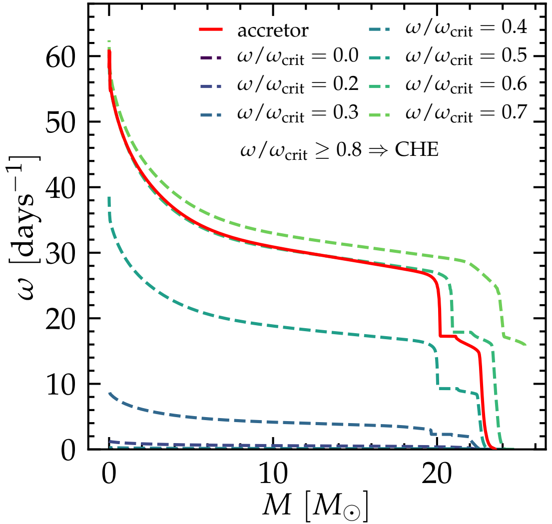
- initially the star is basically non-rotating
- during mass transfer, first the surface spins up rapidly, and then angular momentum is transported inwards until rigid rotation is achieved (in this particular model)
- since this happens later in the evolution, the core now doesn't have much time left to give back angular momentum to the envelope and spin down, and as it contracts and evolves this leads to a much faster spinning core at the end of the main sequence.

Generalization to BBH progenitors

Generalization to BBH progenitors

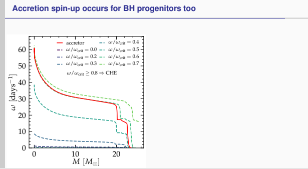
Accretion spin-up occurs for BH progenitors too

$40\,M_\odot$ stars at $Z = Z_\odot/10$ evolved until carbon depletion with Spruit-Tayler dynamo



$50\,M_\odot + 40\,M_\odot$, initial separation $200\,R_\odot$

The 2$^{\rm nd}$ BH might be fast spinning even without tidal interactions



Accretion spin-up occurs for BH progenitors too

Conclusions

Conclusions

Take home points

- *Both* stars are modified by binary interactions
- Accretors and “widowed” stars are common
- We can “calibrate” models of accretors on the nearest O-type star
- Standard assumptions reproduce reasonably ζ Ophiuchi
- $^{14}\mathrm{N}$ and $^{4}\mathrm{He}$ come from the former companion, not the core!
- Rotation profile of “widowed” stars unlike single rotating stars
  ⇒ implications for long-GRBs and BH spins

Renzo & Götberg 21, arXiv:2107.10933

Massive stars are predominantly born in multiple systems
Binary interactions modify *both* stars
Most binaries are broken because of a SN kick
The mass distribution of accretors might reveal BH kicks
The velocity distribution says something about the orbital evolution, but hard to find
Detail modeling reveals interesting features in the rotational profile

Backup slides

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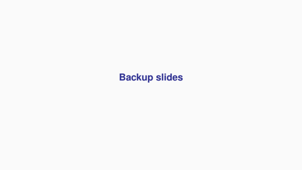
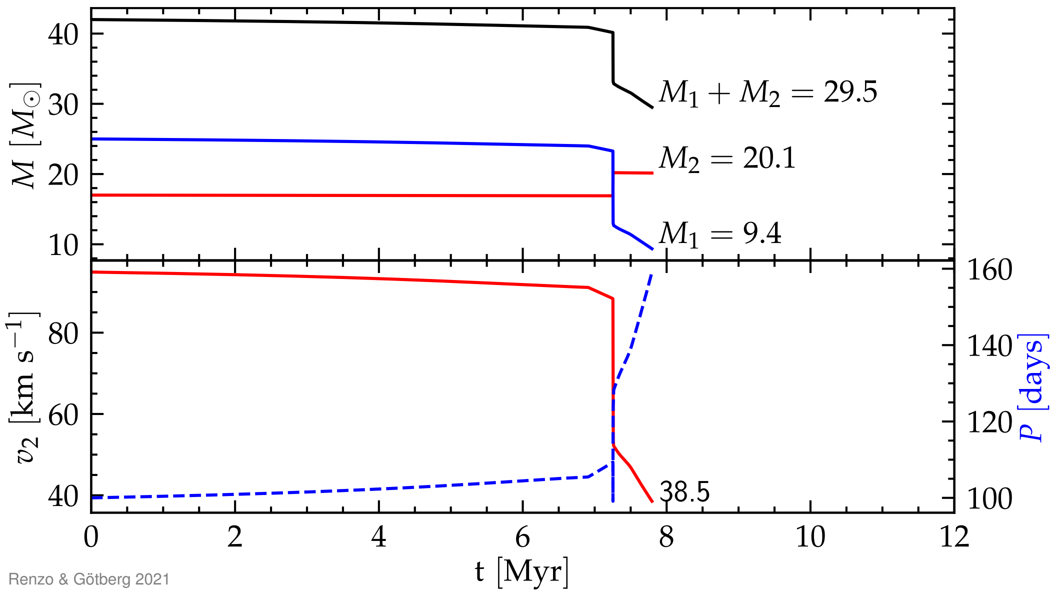


Backup slides

Spatial velocity & mass



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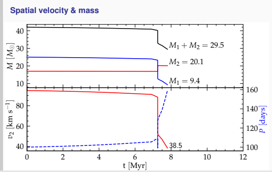
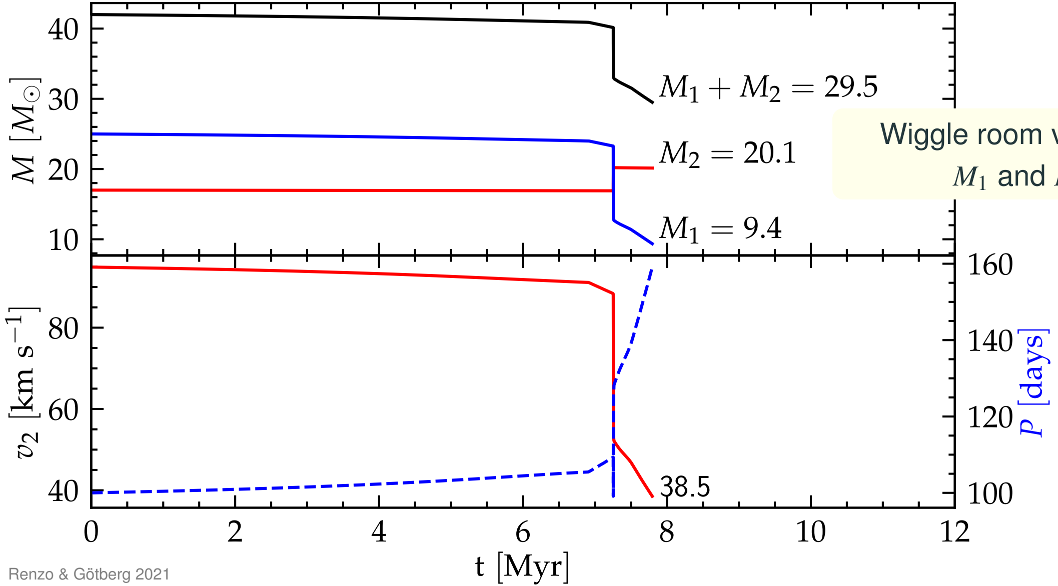
└Spatial velocity & mass



At donor He depletion

Spatial velocity & mass



Wiggle room varying
M_1 and P

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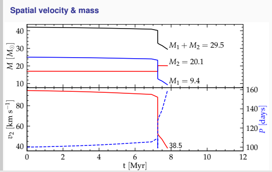
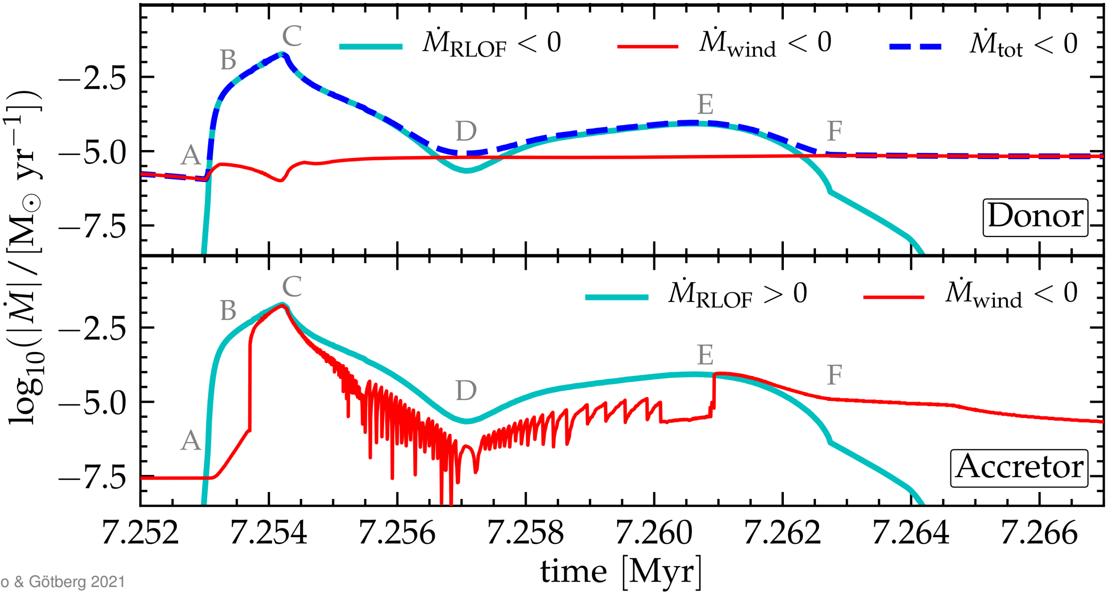
└Spatial velocity & mass



At donor He depletion

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



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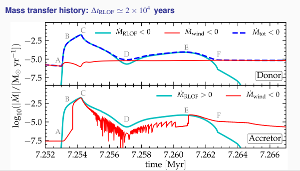
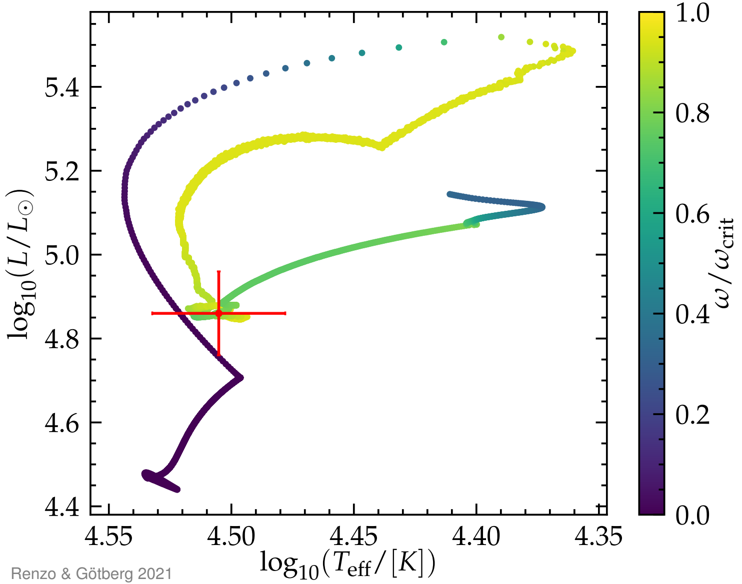


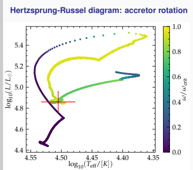
most of the mass is transferred between A and C

Hertzsprung-Russel diagram: accretor rotation

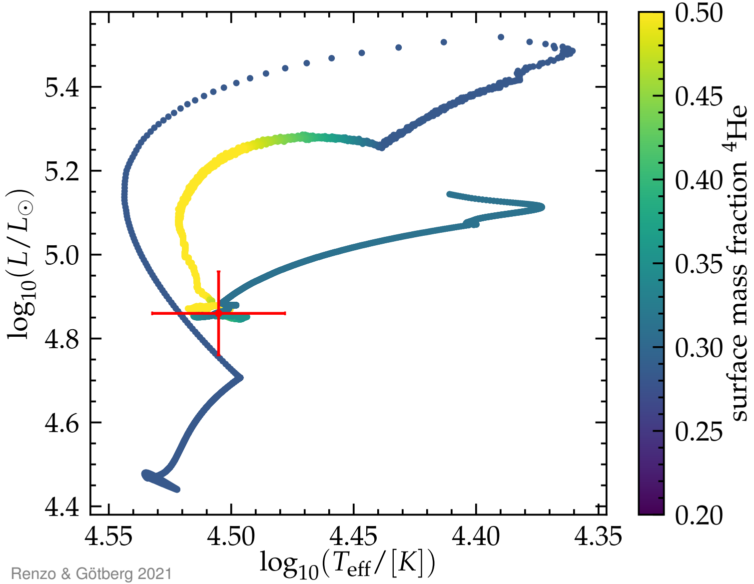


- Minimum T_eff during RLOF reached at onset of critical rotation.
- Rotation close to critical for large part of the main sequence.

Renzo & Götberg 2021



Hertzsprung-Russel diagram: helium surface abundance



- 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.

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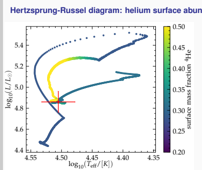
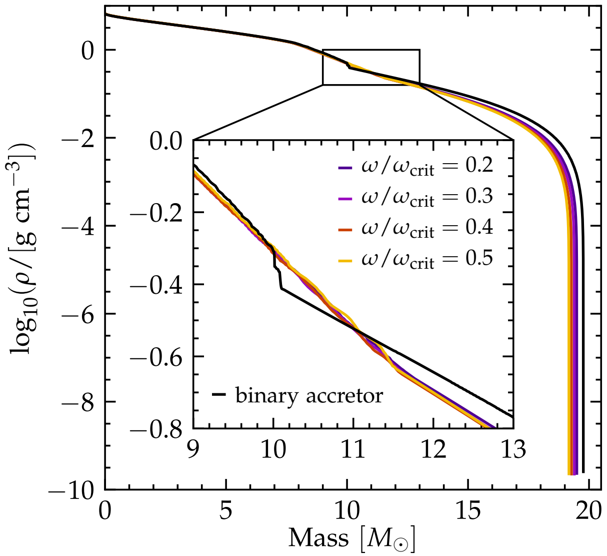
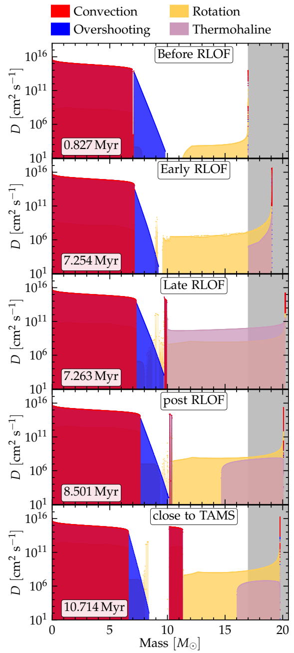
└Hertzsprung-Russel diagram: helium surface abundance



Effect of mixing processes in the accretor





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Effect of mixing processes in the accretor