Widowed massive stars

Mathieu Renzo

FLATIRON INSTITUTE
Center for Computational
Astrophysics

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

Widowed massive stars

Mathieu Renzo

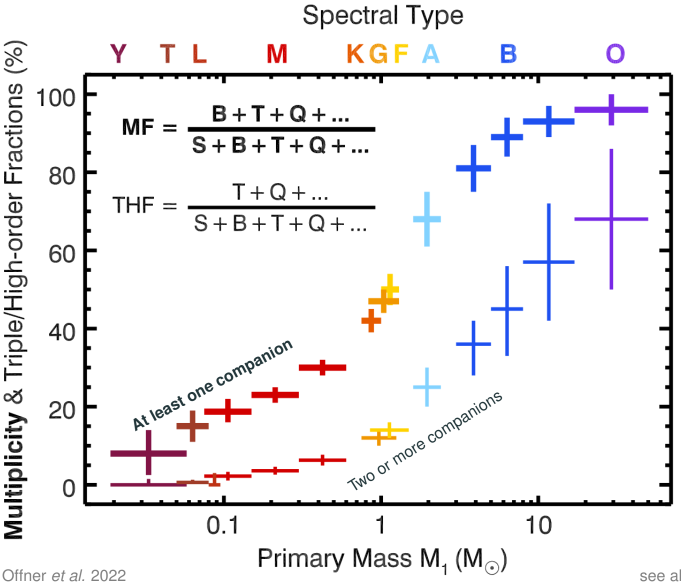
FLATIRON INSTITUTE
Center for Computational Astrophysics

Take home point:

This is not a single star!

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

Massive stars are typically born with companions



Offner *et al.* 2022

Interactions are **common**

70% of O-type stars

Sana *et al.* 2012

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

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

Why care about the accretor?

Stellar populations

accretors lurk in samples

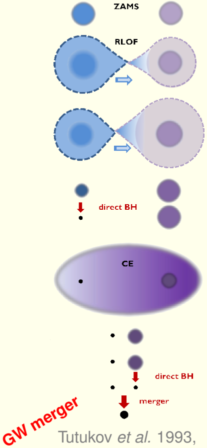
$(10 - 12\%)$ Renzo *et al.* 2019b

+

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.* 2022

Why care about the accretor?

Stellar populations

accretors lurk in samples

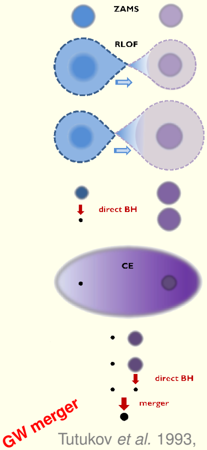
$(10-12\%)$ Renzo *et al.* 2019b

$+$

Oe/Be stars, stragglers

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

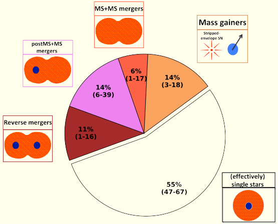
Binary interactions



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

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

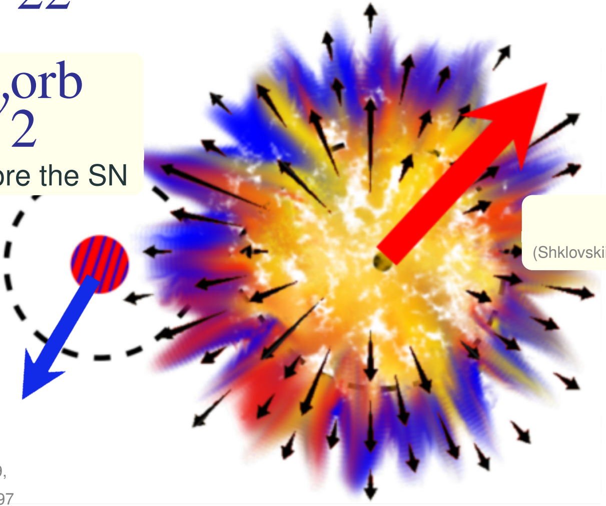
  Hellings 1983, 1985, Renzo *et al.* 2022b

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



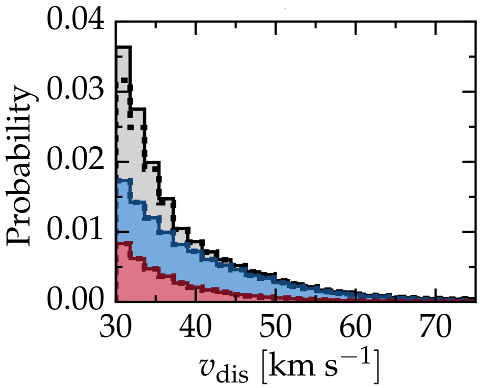
SN Natal kick

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

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

Kinematics of the widowed stars

Accretor stars can be *runaways*...

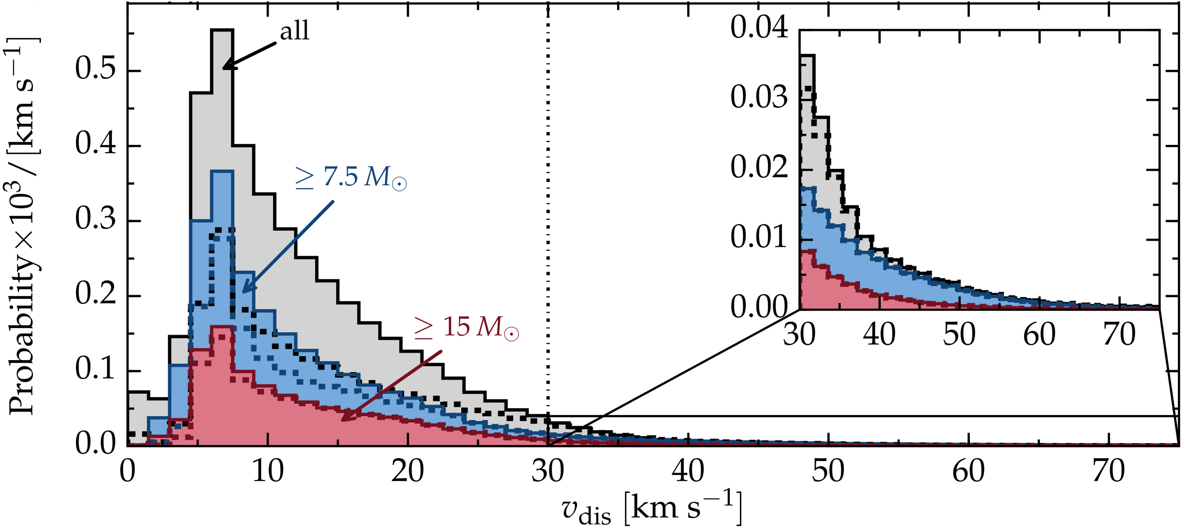


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

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

...but most are only *walkaways*

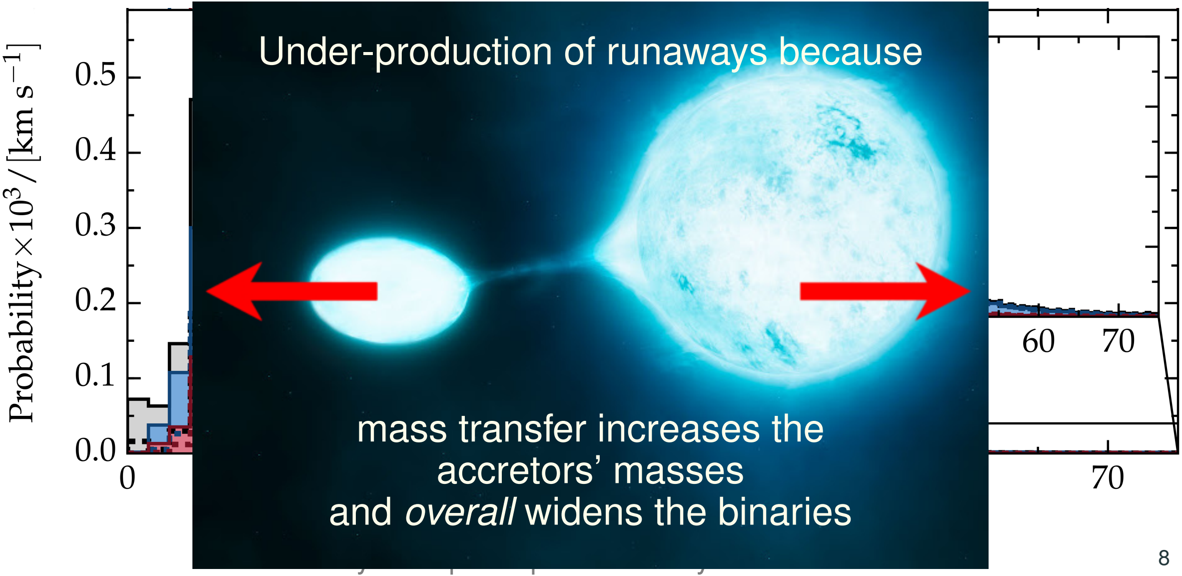


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

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

...but most are only *walkaways*



Under-production of runaways because

mass transfer increases the accretors' masses
and *overall* widens the binaries

Renzo *et al.* 2019b

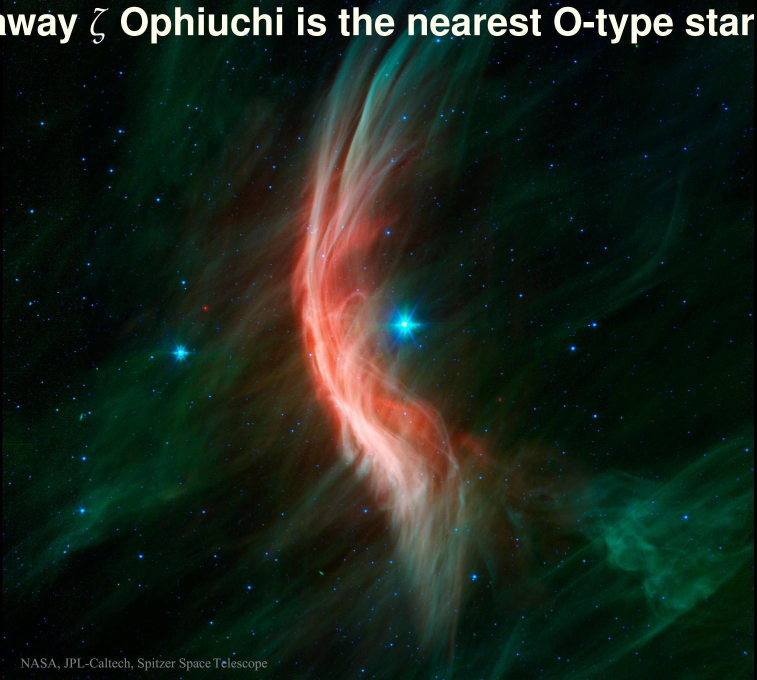
Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Constraints on widowed accretors

from the nearest O-type star

Renzo & Götberg 2021

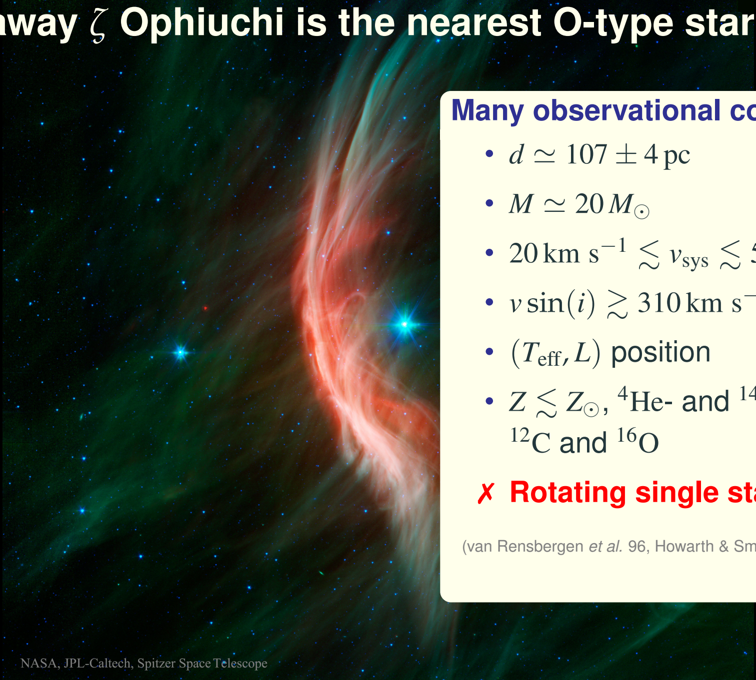
The runaway ζ Ophiuchi is the nearest O-type star to Earth



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

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



NASA, JPL-Caltech, Spitzer Space Telescope

Many observational constraints!

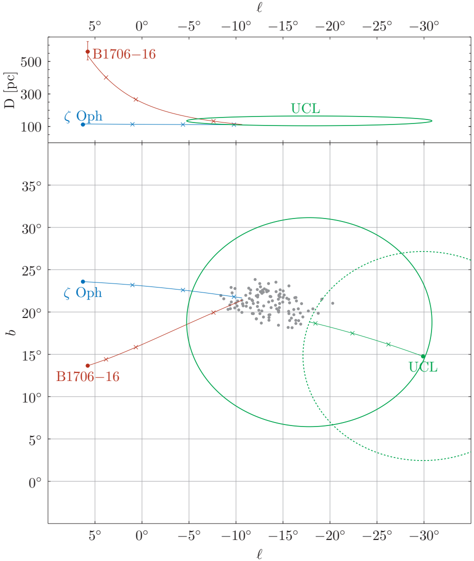
- $d \simeq 107 \pm 4\,\mathrm{pc}$
- $M \simeq 20\,M_\odot$
- $20\,\mathrm{km\ s^{-1}} \lesssim v_{\mathrm{sys}} \lesssim 50\,\mathrm{km\ s^{-1}}$
- $v\sin(i) \gtrsim 310\,\mathrm{km\ s^{-1}}$, $i \gtrsim 56^\circ$
- (T_{eff}, L) position
- $Z \lesssim Z_\odot$, $^4\mathrm{He}$- and $^{14}\mathrm{N}$-rich,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

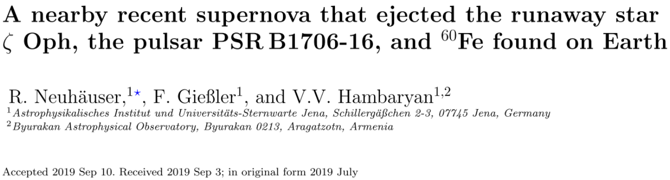
✗ **Rotating single stars don’t match**

(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 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

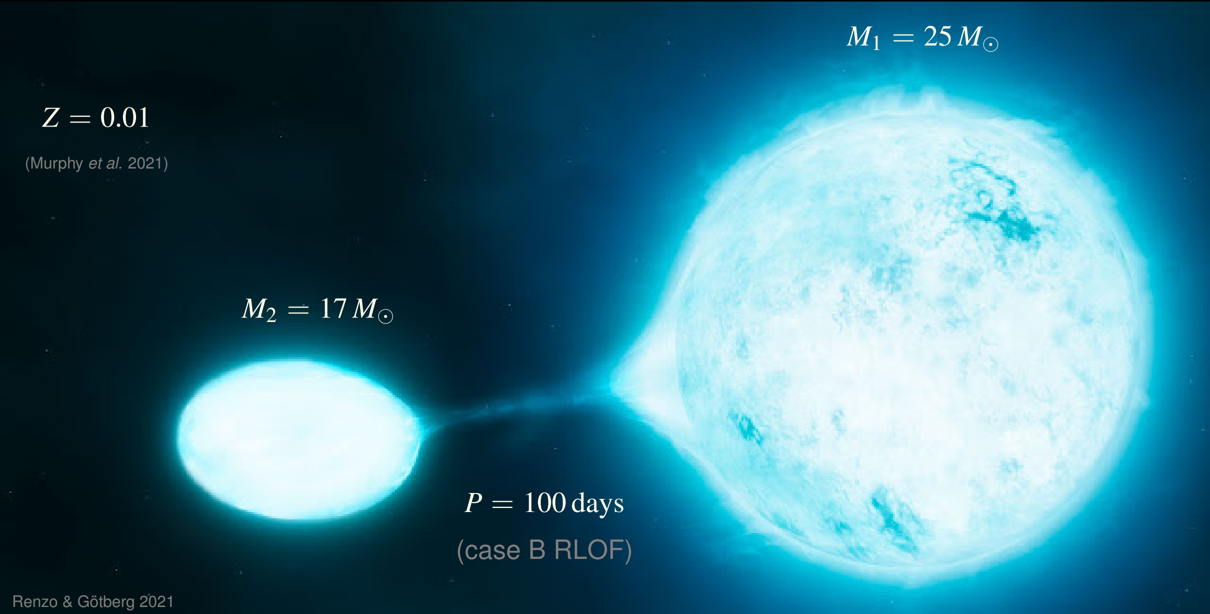
R. Neuhäuser,[1⋆], F. Gießler[1], and V.V. Hambaryan[1,2]
[1] *Astrophysikalisches Institut und Universitäts-Sternwarte Jena, Schillergäßchen 2-3, 07745 Jena, Germany*
[2] *Byurakan Astrophysical Observatory, Byurakan 0213, Aragatzotn, Armenia*

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, Benitez *et al.* 2002, Lux *et al.* 2020

Self-consistent MESA model



$M_1 = 25\,M_\odot$

$Z = 0.01$

(Murphy *et al.* 2021)

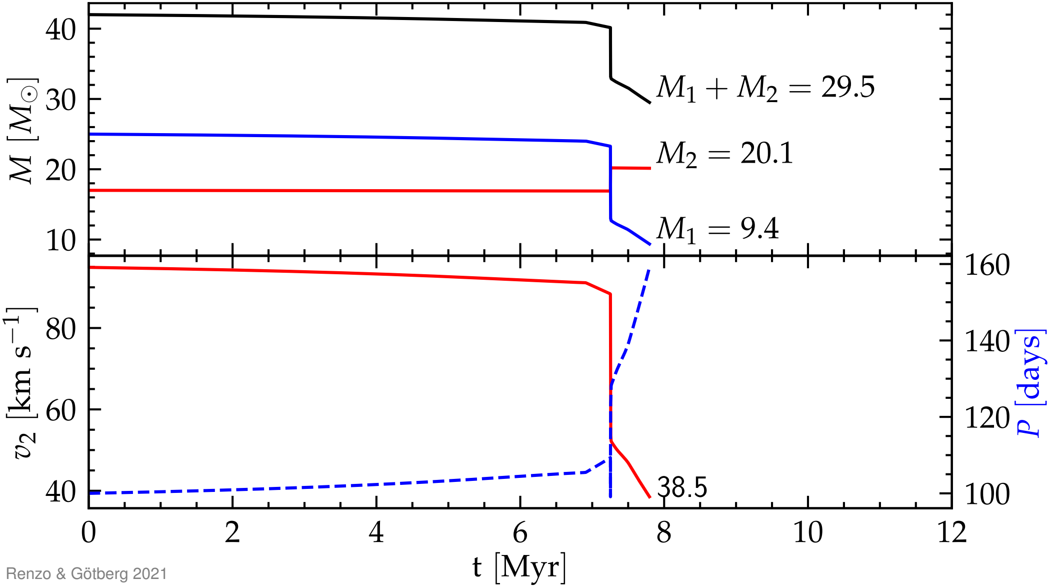
$M_2 = 17\,M_\odot$

$P = 100$ days

(case B RLOF)

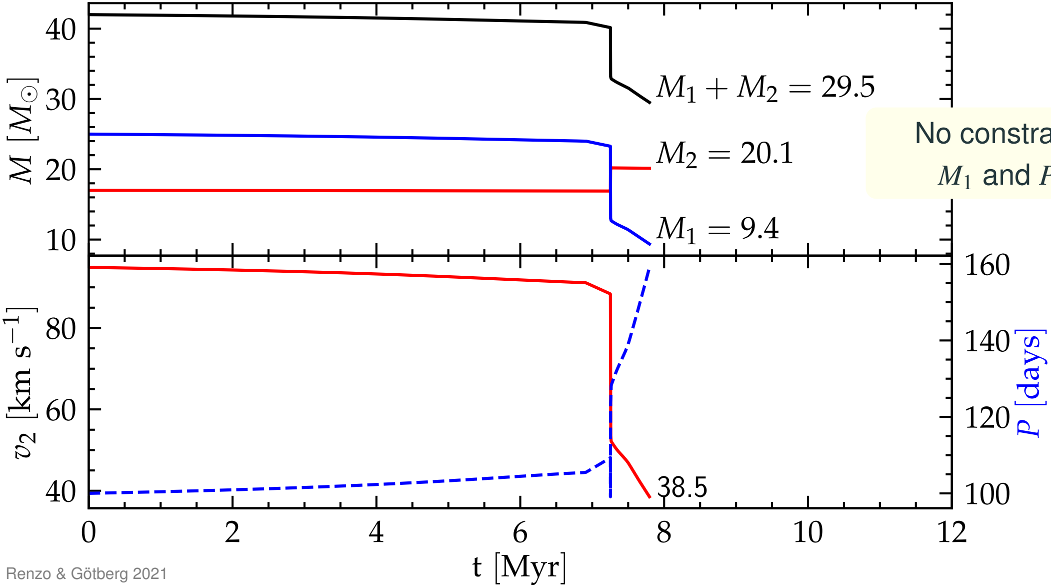
Renzo & Götberg 2021

Orbital evolution: ✓ Mass & ✓ spatial velocity



Renzo & Götberg 2021

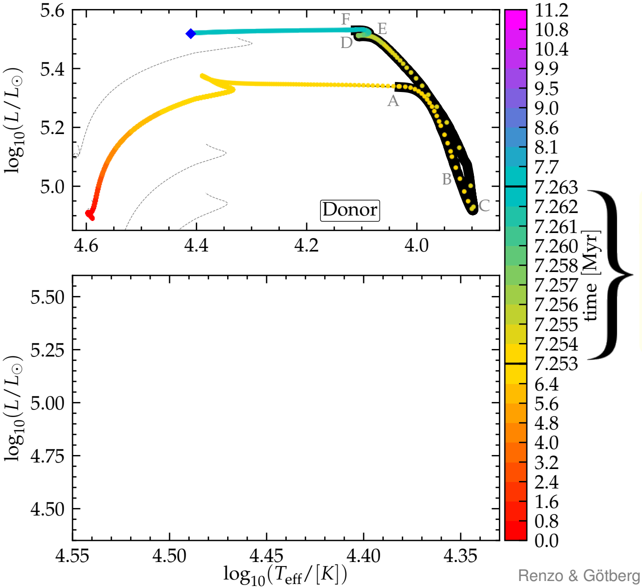
Orbital evolution: ✓ Mass & ✓ spatial velocity



No constraints on M_1 and P_{ZAMS}

Renzo & Götberg 2021

HRD of both stars: the donor



Case B mass transfer is short

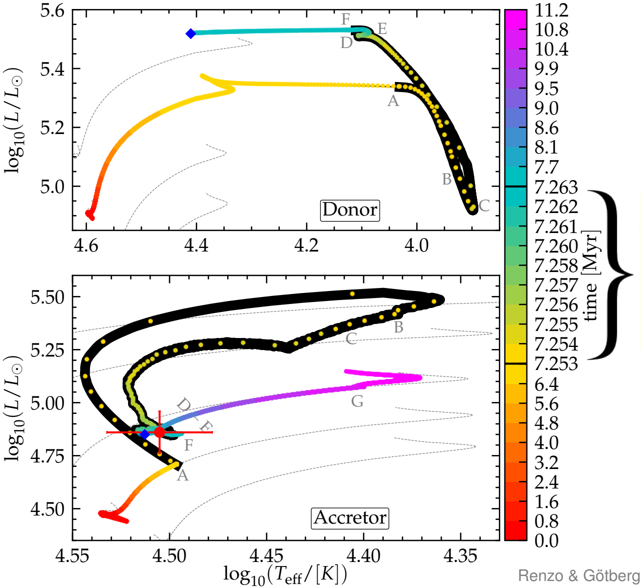
$\Delta t_\mathrm{RLOF} \sim 10^4\ \mathrm{yr} \sim \tau_\mathrm{th}$

but has long-lasting impact

on **both** stars.

Renzo & Götberg 2021

HRD of both stars: the donor & the accretor ✓



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

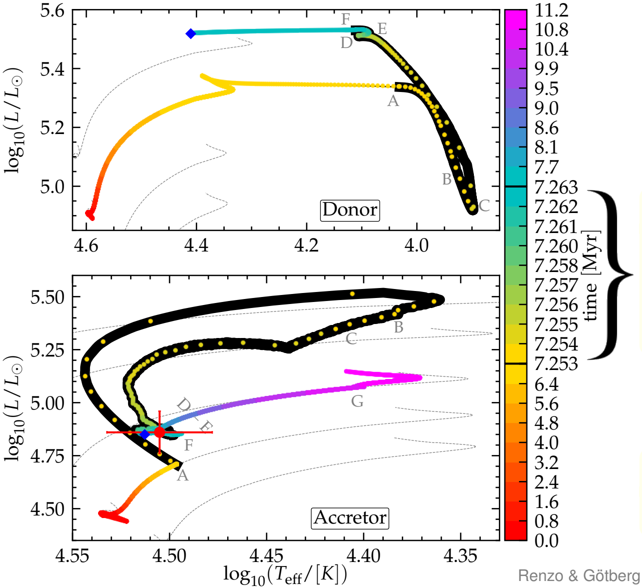
Case B mass transfer is short

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

but has long-lasting impact

on **both** stars.

HRD of both stars: the donor & the accretor ✓



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.

✓ Models match ζ Oph.

L, T_eff, Mass, age, velocity

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

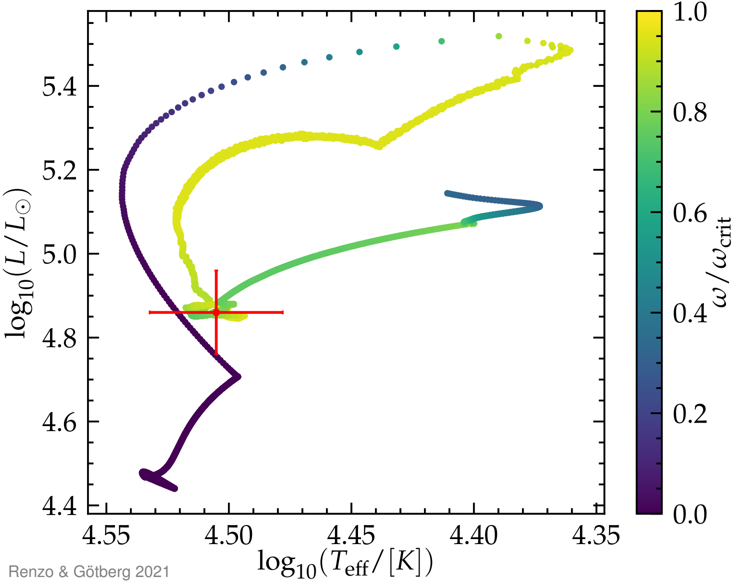
Internal structure of the accretor

Spin up: surface and interior

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

Rejuvenation: core-envelope boundary

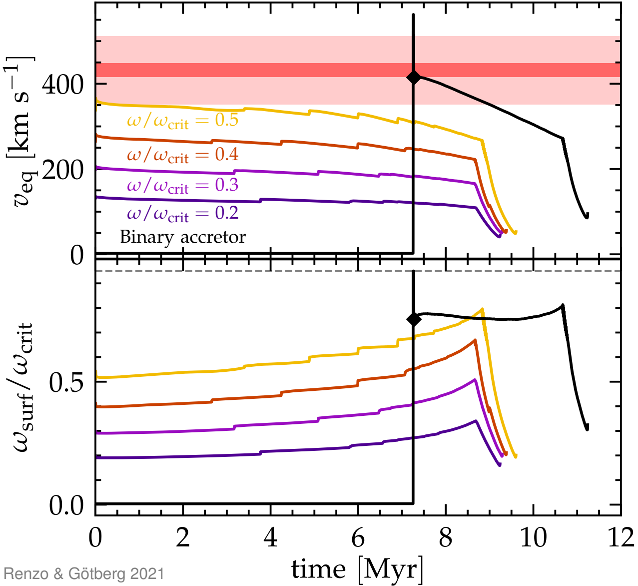
HRD: accretor rotation



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

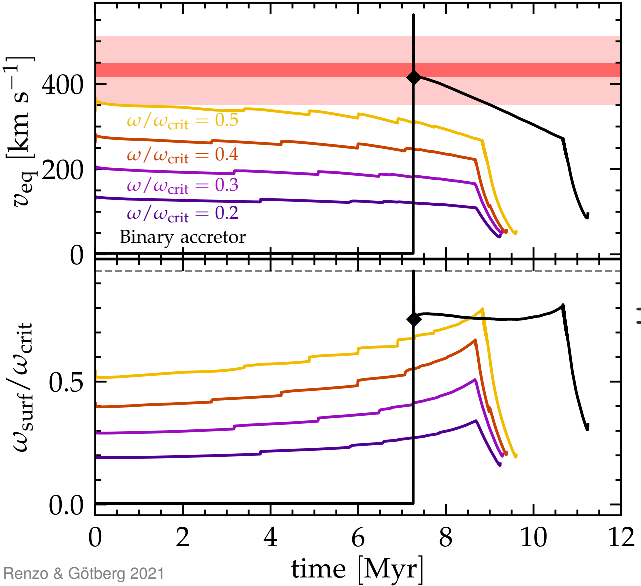
Renzo & Götberg 2021

✓ Surface rotation rate



Renzo & Götberg 2021

✓ Surface rotation rate



Renzo & Götberg 2021

$\Longrightarrow$

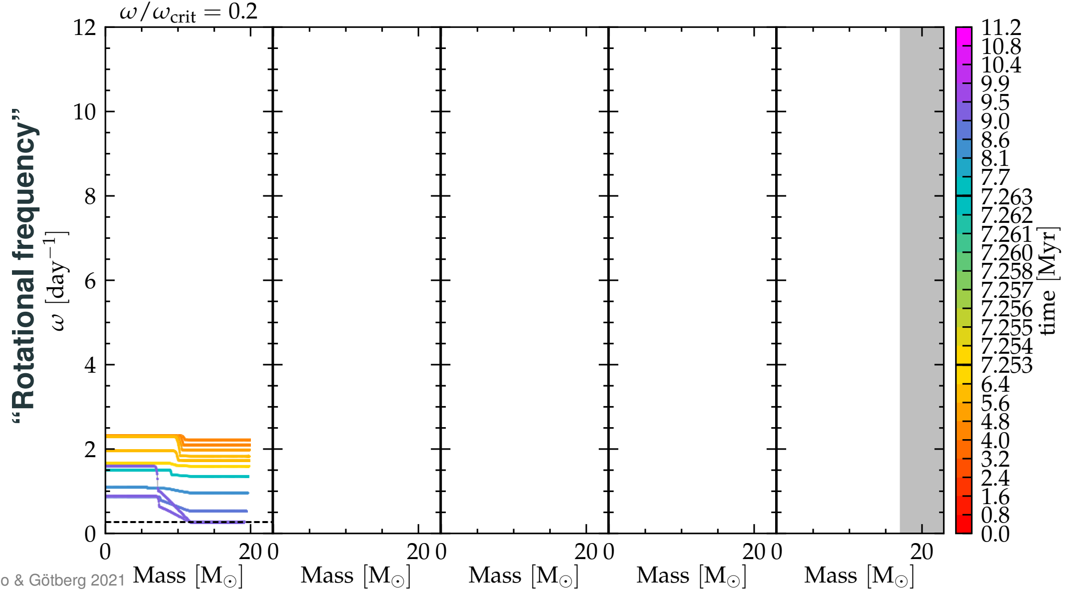
Accretors are likely Oe/Be stars

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

decretion disk & emission lines

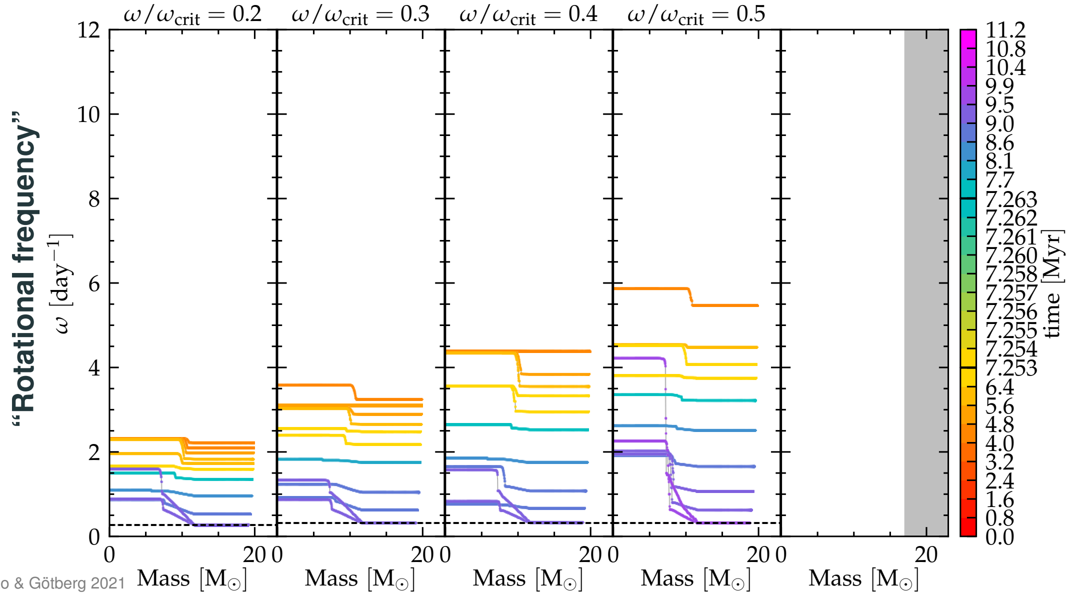
(Pols & Marinus 94, Vinciguerra *et al.* 20, Bodensteiner *et al.* 20)

Internal rotational profile: single stars



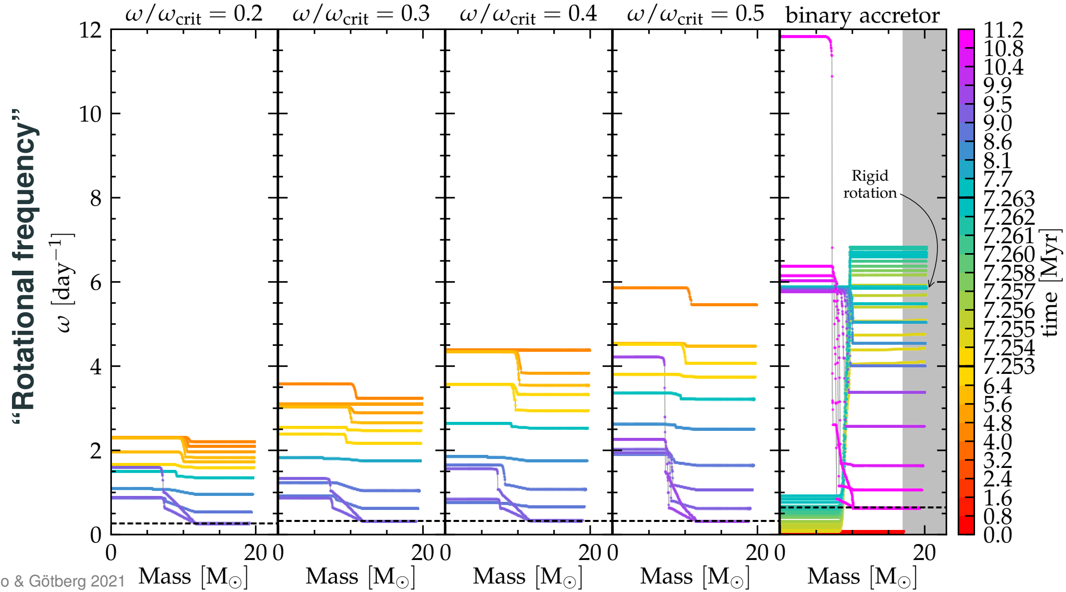
Renzo & Götberg 2021

Internal rotational profile: single stars



Renzo & Götberg 2021

Internal rotational profile: accretor



Renzo & Götberg 2021

Internal structure of the accretor

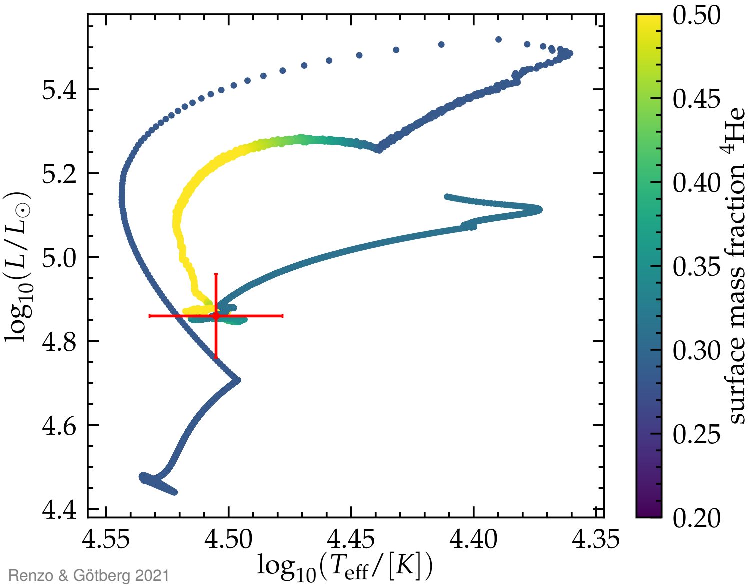
Spin up: surface and interior

Pollution: $^{4}\mathrm{He}$ and $^{14}\mathrm{N}$

Rejuvenation: core-envelope boundary

Internal mixing in the accretor

HRD: Helium surface abundance

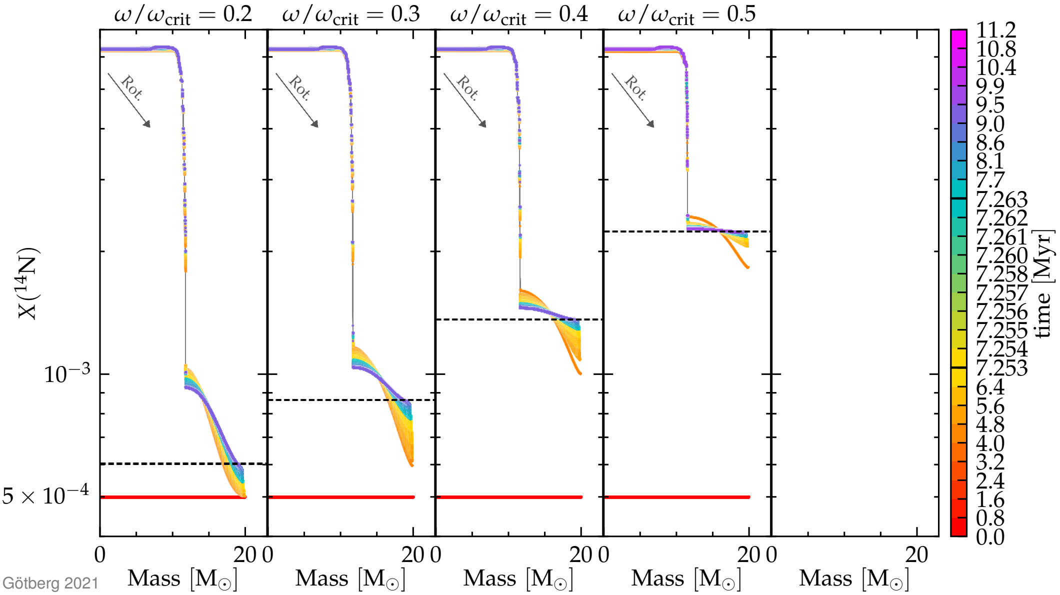


Renzo & Götberg 2021

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

Composition profile: comparison with rotating single stars

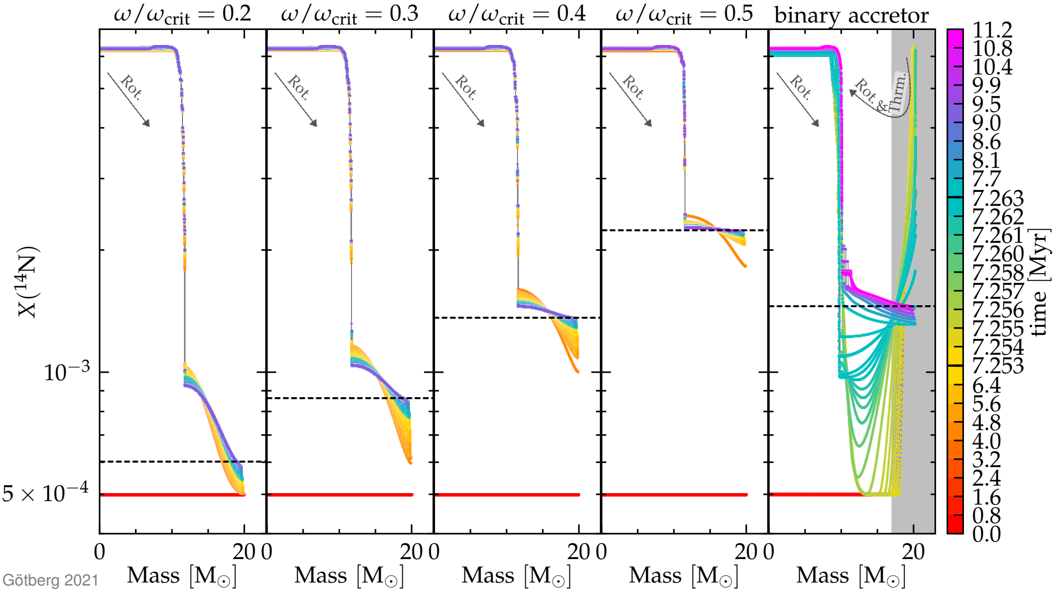
“Nitrogen”



Renzo & Götberg 2021

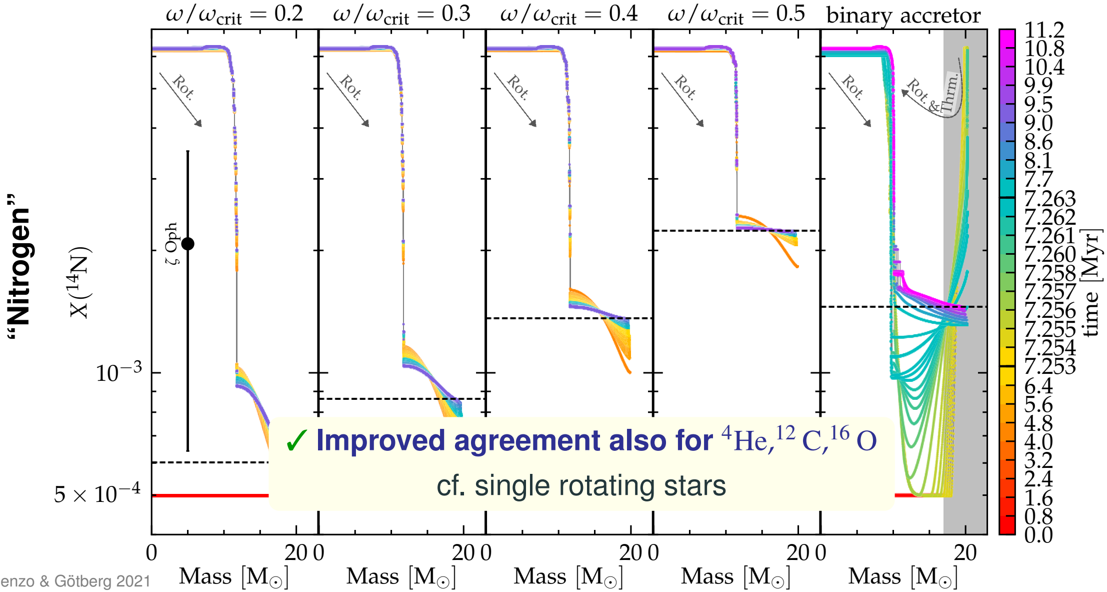
Composition profile: comparison with rotating single stars

"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

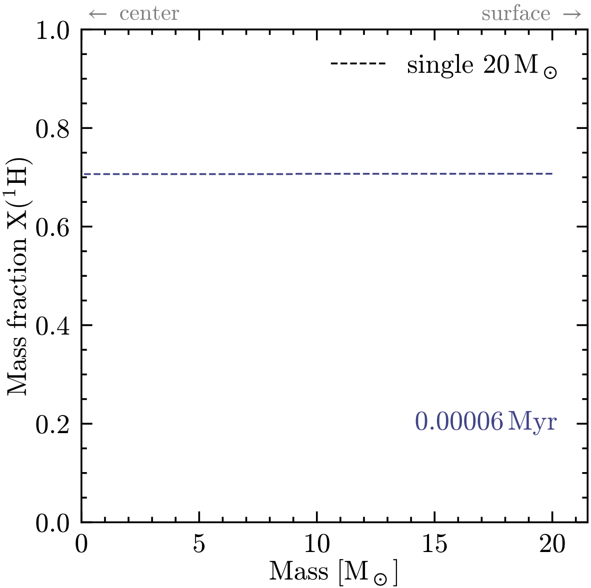
Internal structure of the accretor

Spin up: surface and interior

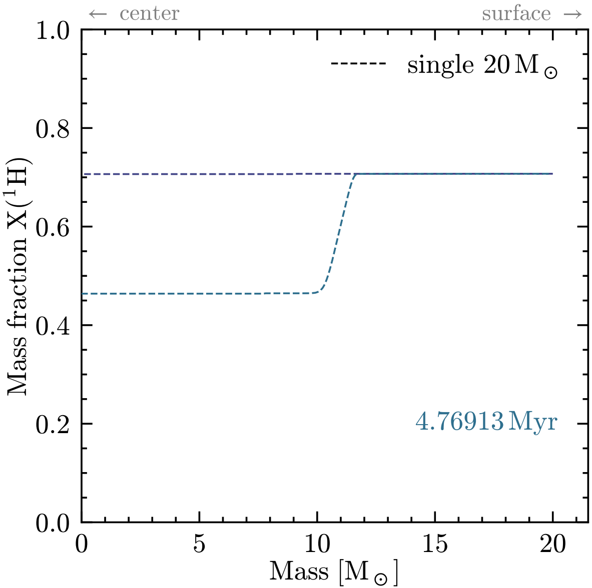
Pollution: ^{4}He and ^{14}N

Rejuvenation: core-envelope boundary

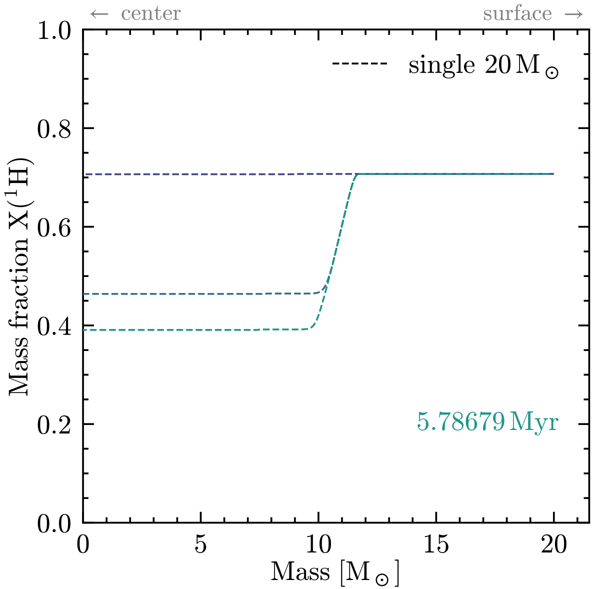
Refresher: formation of the helium core in single stars



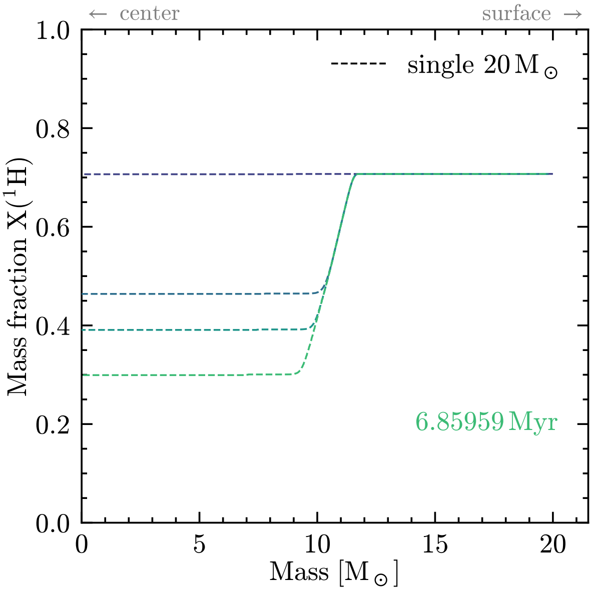
Refresher: formation of the helium core in single stars



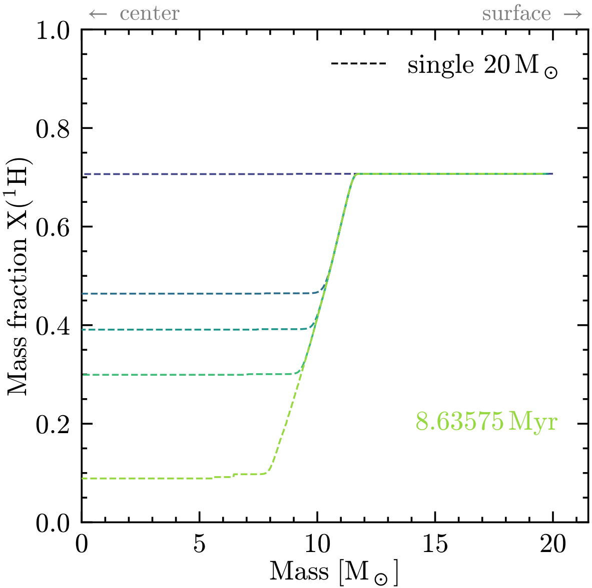
Refresher: formation of the helium core in single stars



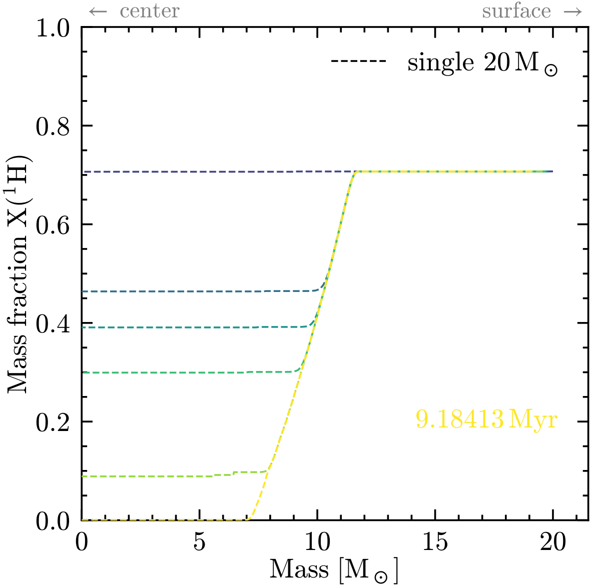
Refresher: formation of the helium core in single stars



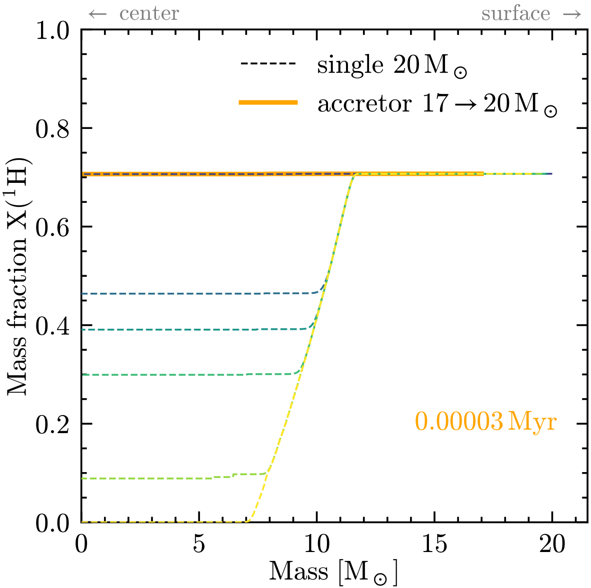
Refresher: formation of the helium core in single stars



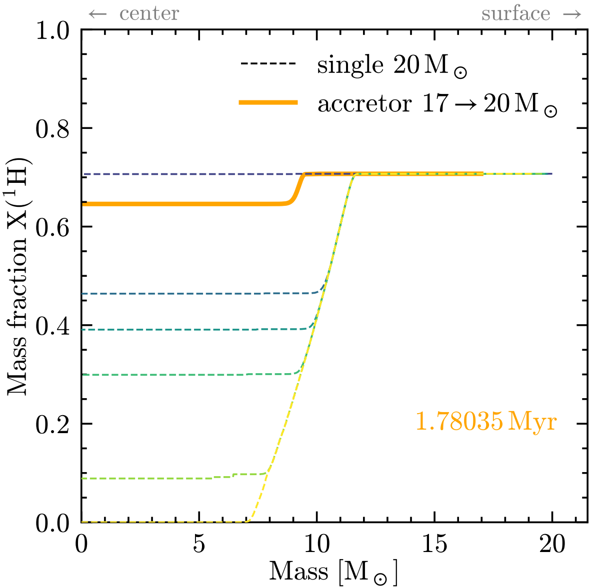
Refresher: formation of the helium core in single stars



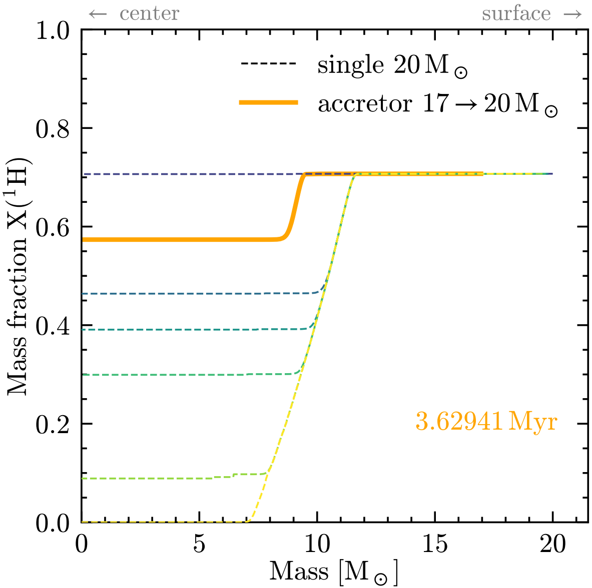
Evolution of the accretor’s core through RLOF



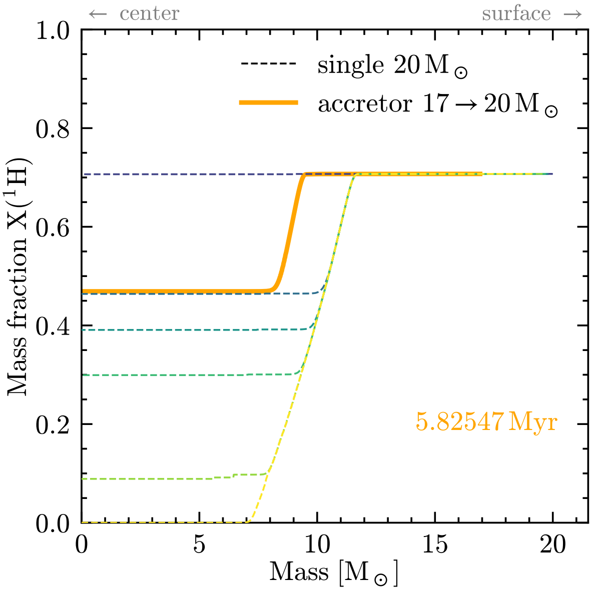
Evolution of the accretor's core through RLOF



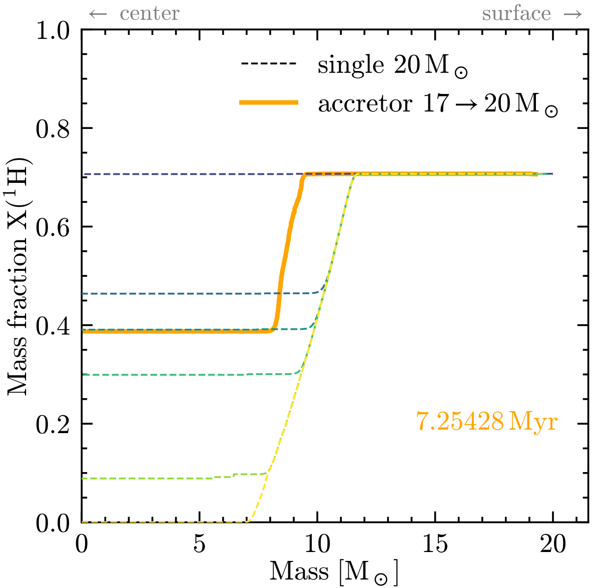
Evolution of the accretor’s core through RLOF

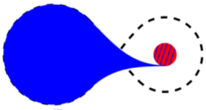


Evolution of the accretor’s core through RLOF

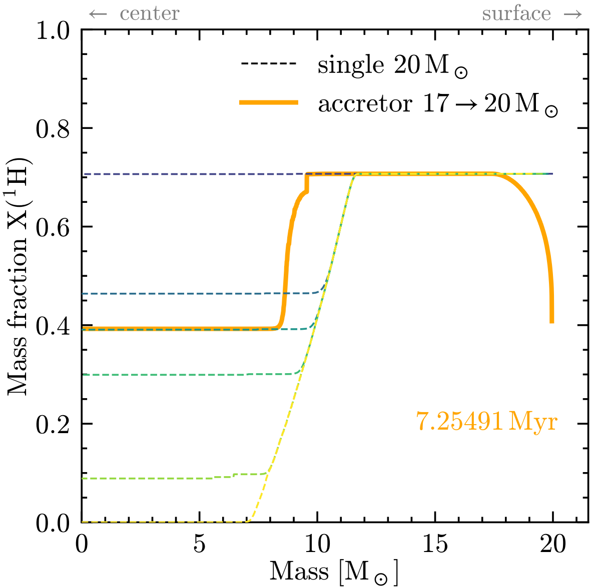


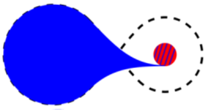
Evolution of the accretor’s core through RLOF



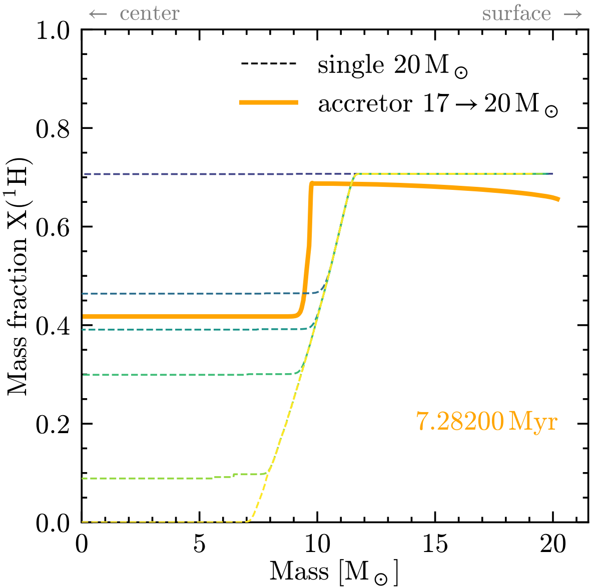


Evolution of the accretor's core through RLOF

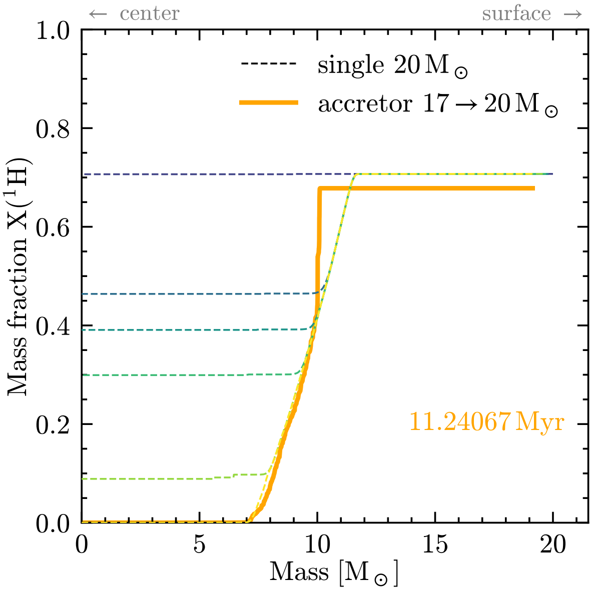




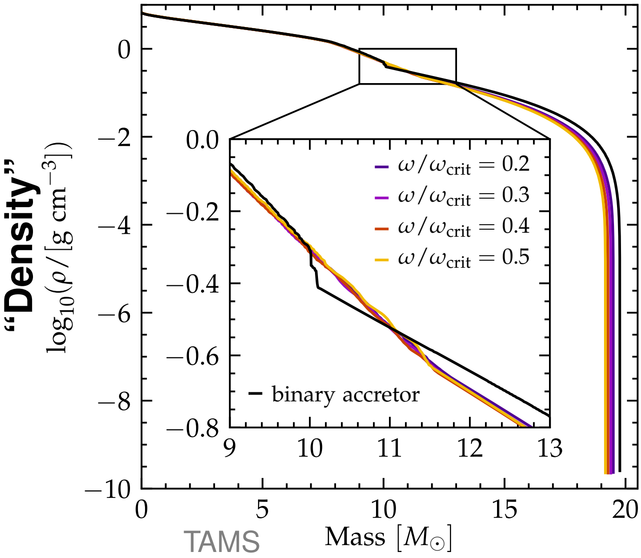
Evolution of the accretor's core through RLOF

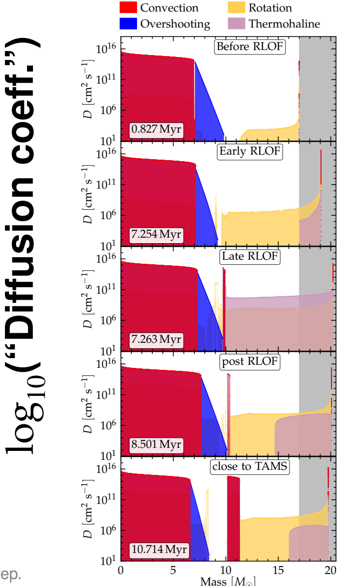


Evolution of the accretor's core through RLOF



Rejuvenation changes the core/envelope boundary





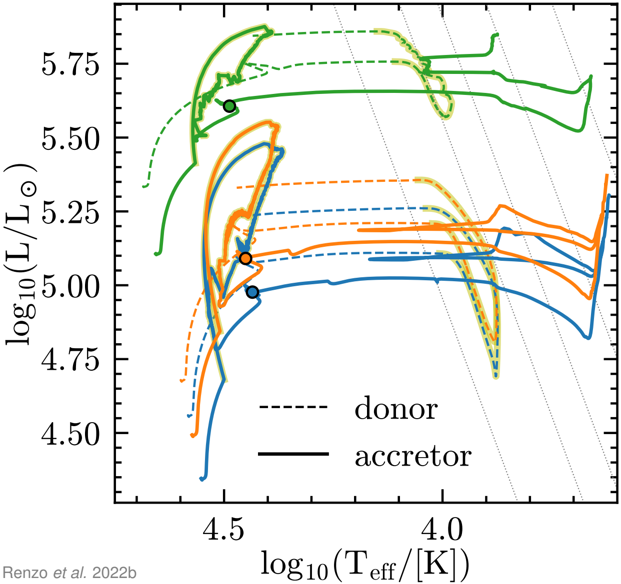
Renzo & Götberg 2021, Gade Pedersen, Renzo, *et al.* in prep.

Consequences of rejuvenation

Blue loops in high-mass stars?

Easier to unbind the envelope

Low-Z massive accretors



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

(to focus on GW merger progenitors)

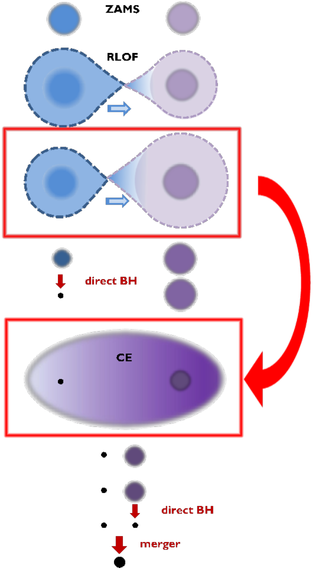
Renzo *et al.* 2022b

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

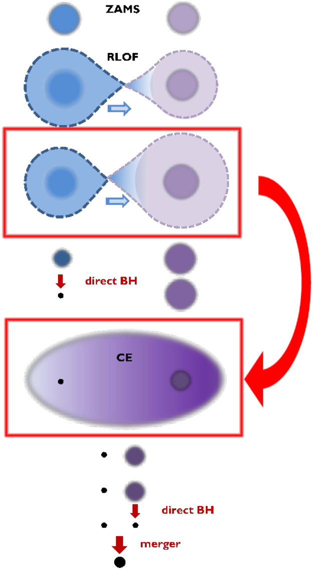


Belczynski *et al.* 16

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



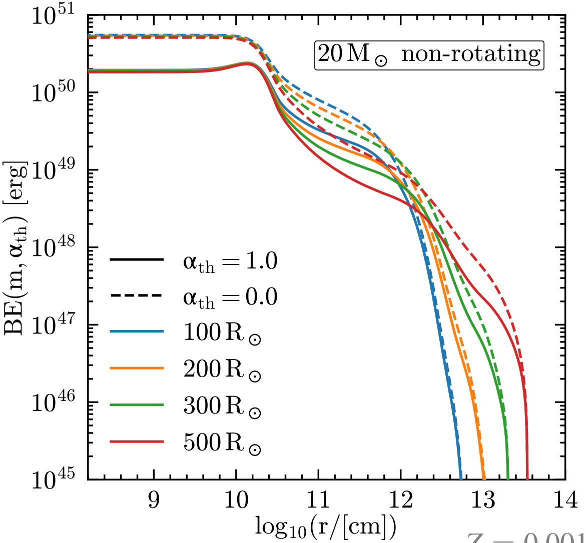
Belczynski *et al.* 16

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



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

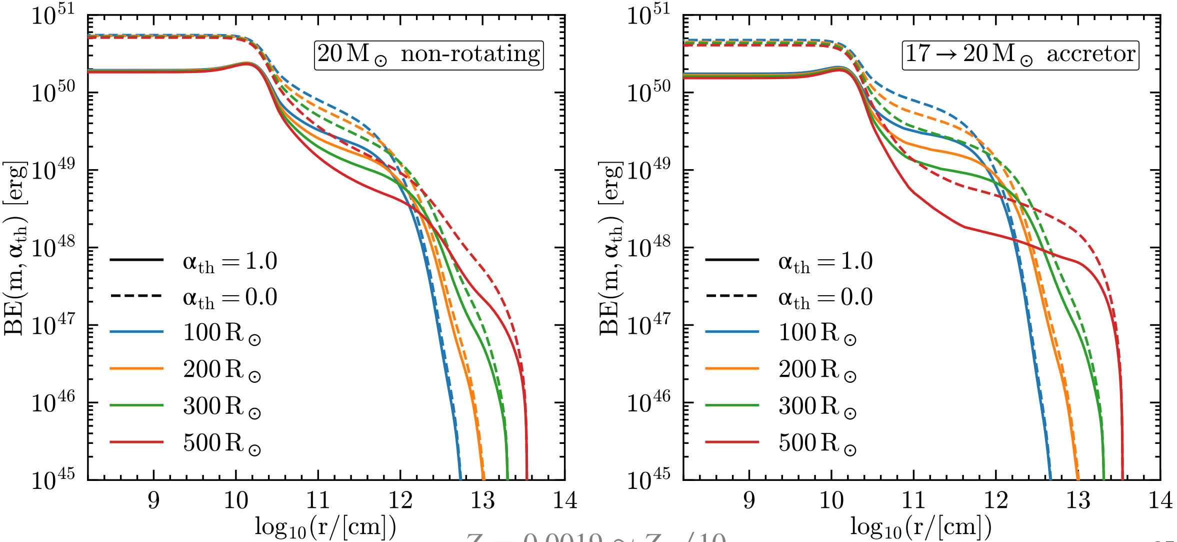
- Gravitational potential energy
- Internal energy
- α_{th} free parameter

fraction of internal energy usable to eject envelope

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

Renzo *et al.* 2022b

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



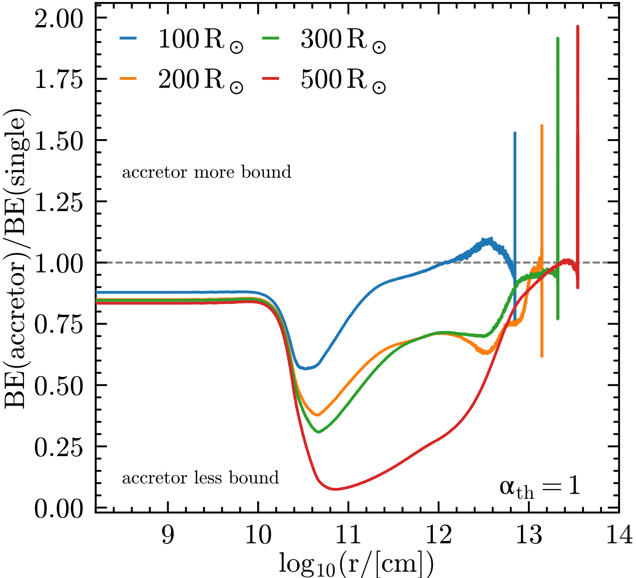
$Z = 0.0019 \simeq Z_\odot/10$

Renzo *et al.* 2022b

Taking the ratio: accretors are easier to unbind

NS progenitor

$15 \rightarrow 17\,M_\odot$

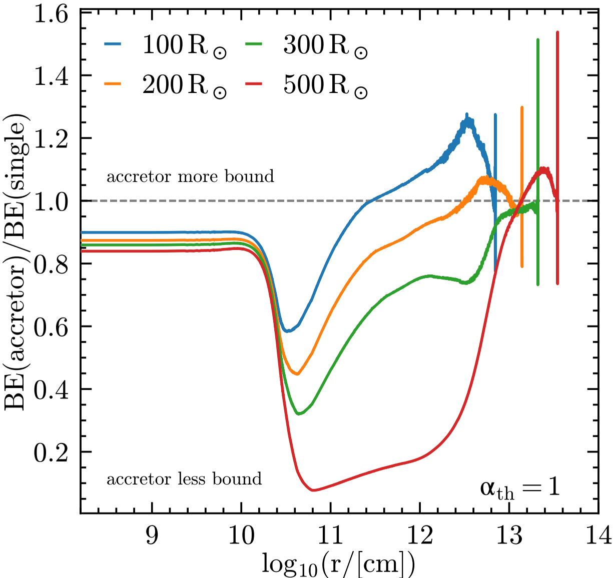


Renzo *et al.* 2022b

Taking the ratio: accretors are easier to unbind

NS or BH progenitor

$17 \rightarrow 20\,M_{\odot}$

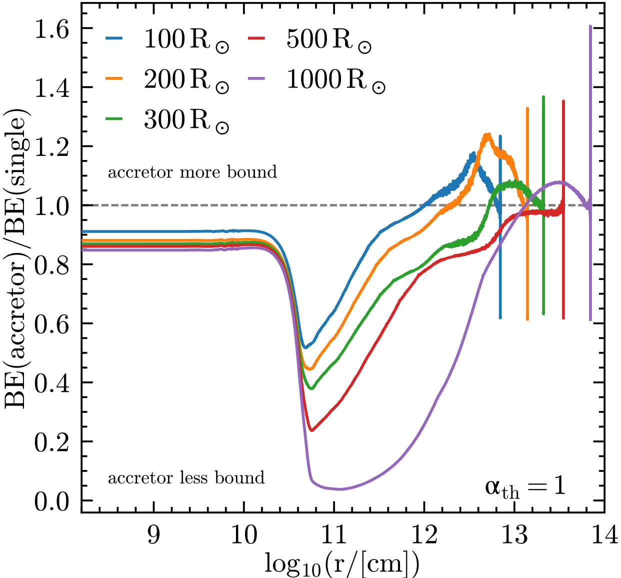


Renzo *et al.* 2022b

Taking the ratio: accretors are easier to unbind

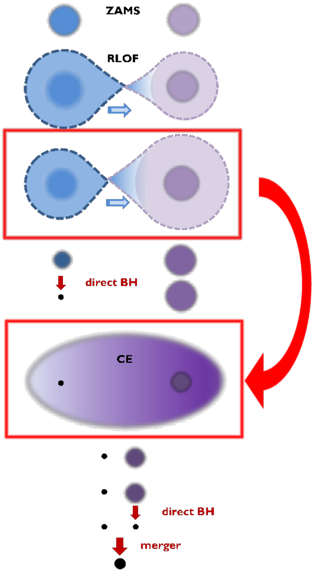
BH progenitor

$30 \rightarrow 36\,M_{\odot}$



Renzo *et al.* 2022b

If the common-envelope donor is a former accretor



Belczynski *et al.* 16

Implications for common-envelope

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

Conclusions

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 ✓

  ⇒ $^{14}\mathrm{N}$ and $^{4}\mathrm{He}$ from the donor, inward angular momentum transport

  ⇒ Observed composition constrains mixing & accretion efficiency

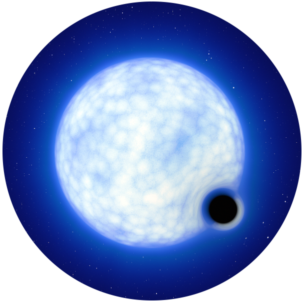
- Evolved accretor's core boundary results in easier to eject envelopes

  ⇒ Implications for asteroseismology & common envelope in GW progenitors

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

Backup slides

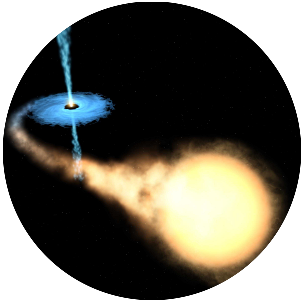
Some binaries do survive the 1^{st} core-collapse



Non-interacting

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

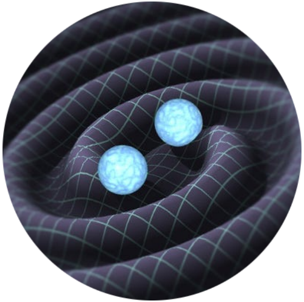
Chawla *et al.* 2020, etc.



X-ray binaries

Webster & Murdin 1972, Bolton 1972,

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



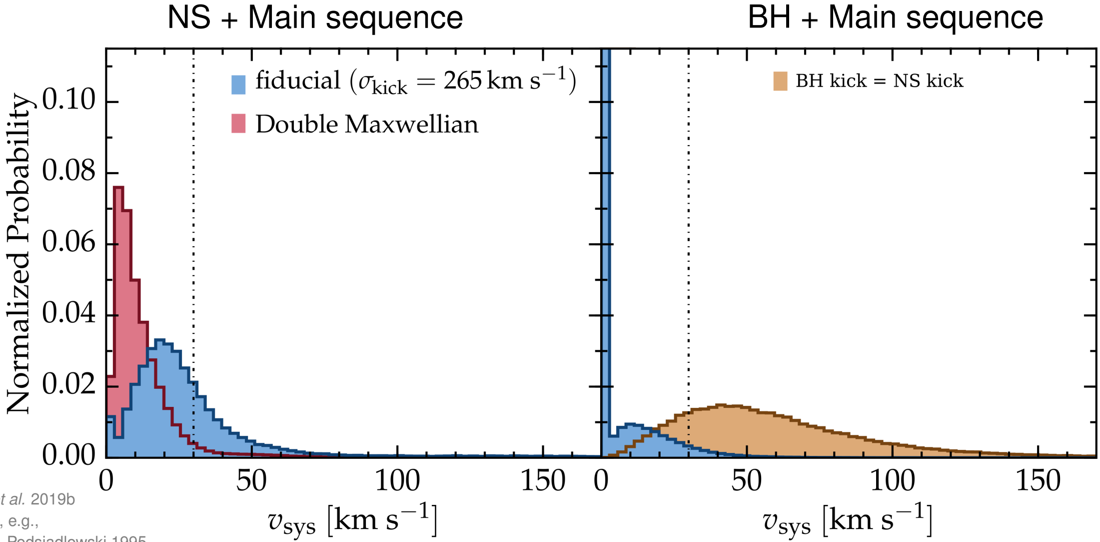
Gravitational waves

Including BBH, BHNS, BNS,

LIGO, Virgo, Kagra collaboration

Post-SN velocity of surviving binaries

 # systems

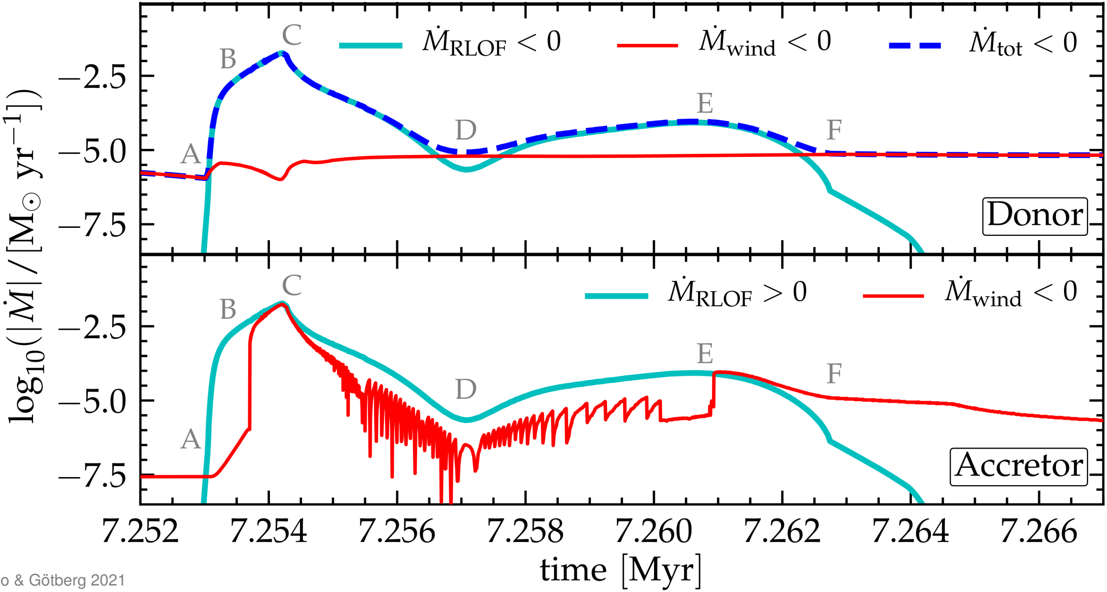


Renzo *et al.* 2019b
see also, e.g.,
Brandt & Podsiadlowski 1995
Kalogera 1996
Tauris & Takens 1998

Velocity respect to the pre-explosion binary center of mass

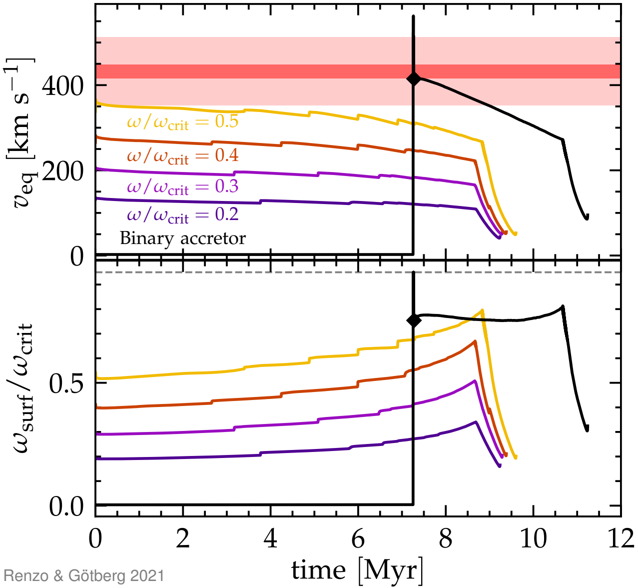
Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Mass transfer history: $\Delta t_{\mathrm{RLOF}} \simeq 2\times10^4$ years



Renzo & Götberg 2021

✓ Surface rotation rate ?



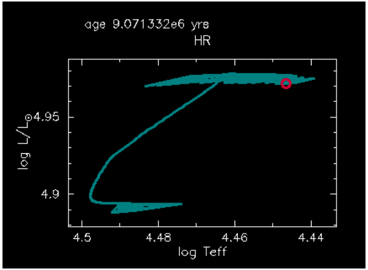
Renzo & Götberg 2021

- but "weak wind problem":

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

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

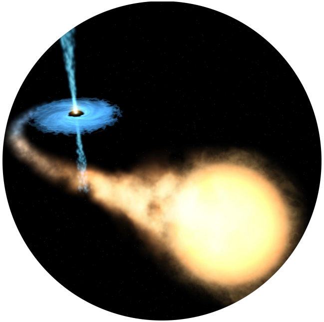
✗ Decreasing the wind: $\omega > \omega_{\rm crit}$



Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion



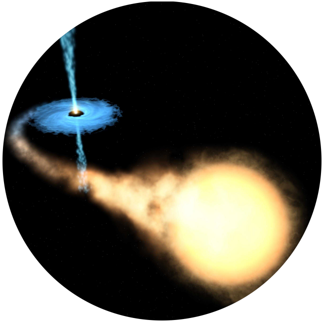
YES

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

Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion

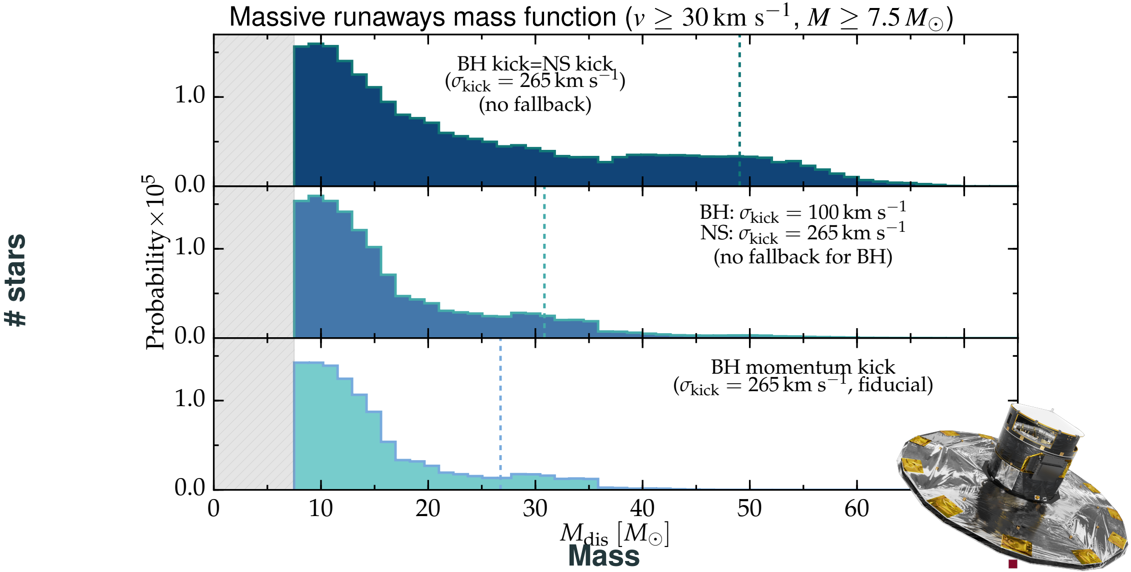


YES

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

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

A way to constrain BH kicks with Gaia


Massive runaways mass function ($v \geq 30\,\mathrm{km\ s^{-1}}$, $M \geq 7.5\,M_\odot$)

Numerical results publicly available at:

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

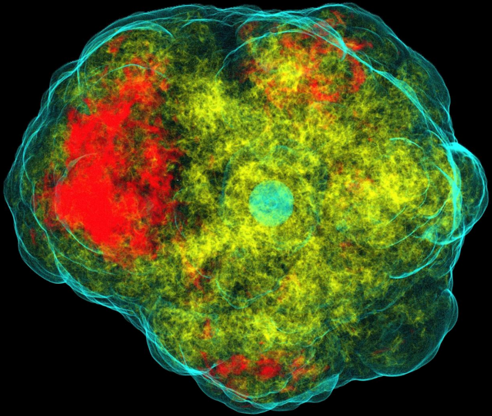
Renzo *et al.* 19b

gaia

SN natal kick

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

Physically: ν emission and/or ejecta anisotropies

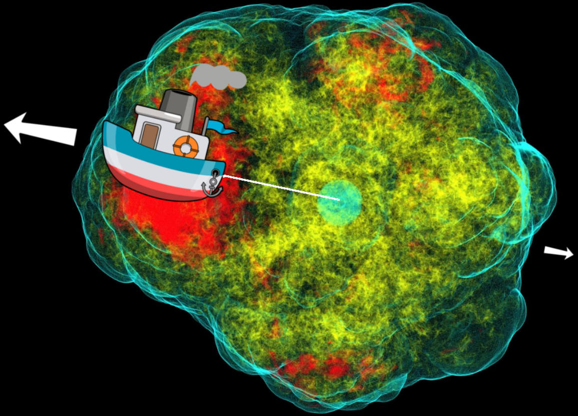


Credits: C. D. Ott, S. Drasco

SN natal kick

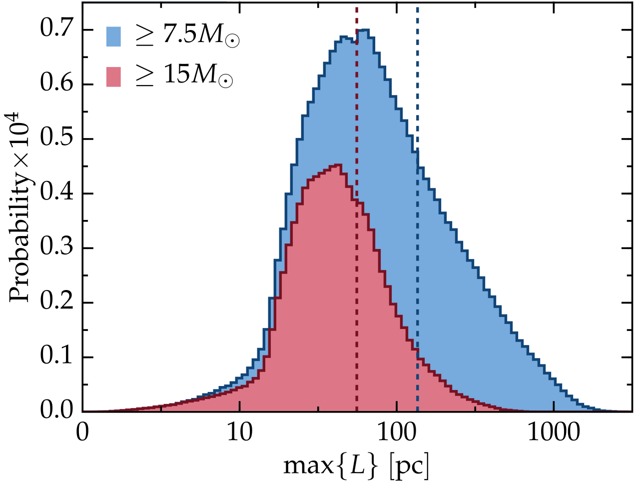
Observationally: $v_{\rm pulsar} \gg v_{\rm OB-stars}$

Physically: ν emission and/or ejecta anisotropies



Credits: C. D. Ott, S. Drasco

How far do they get?

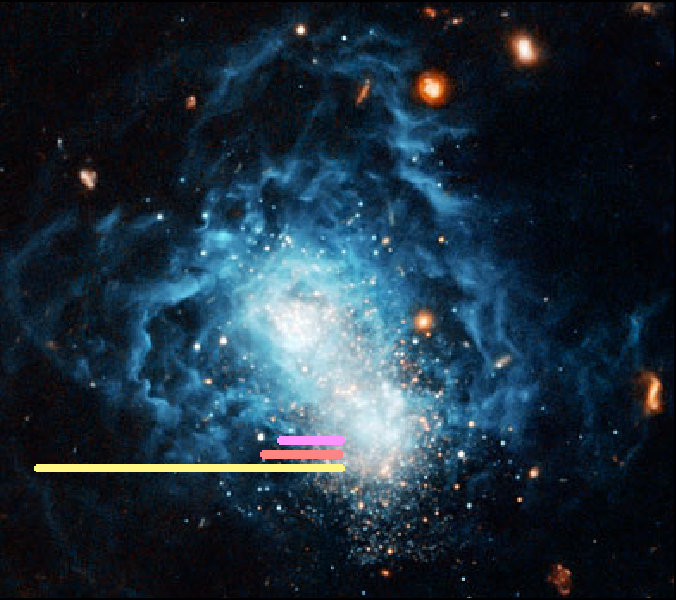


“Distance traveled”

(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

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

$\langle D_\mathrm{walk} \rangle$ = 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