

# 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

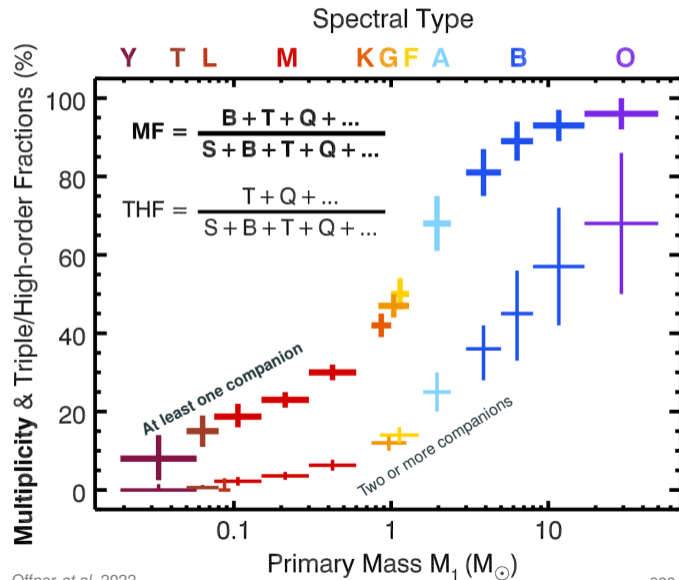


**Take home point:**

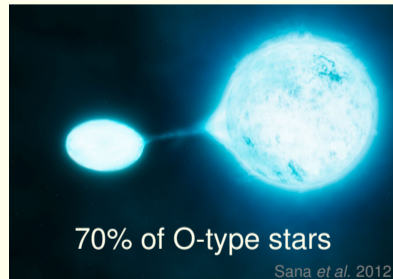
This is not a single star!



# 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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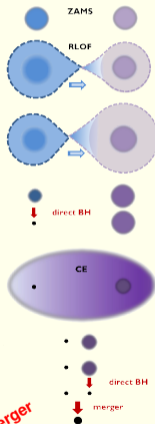
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Oe/Be stars, stragglers

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

## Binary interactions



GW merger

Tutukov *et al.* 1993,

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

# Why care about the accretor?

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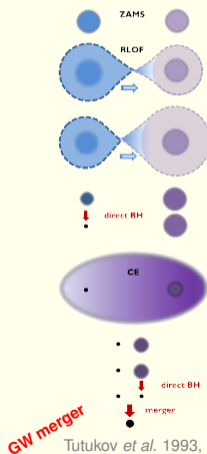
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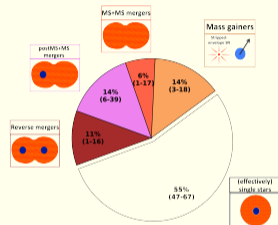
## Binary interactions



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

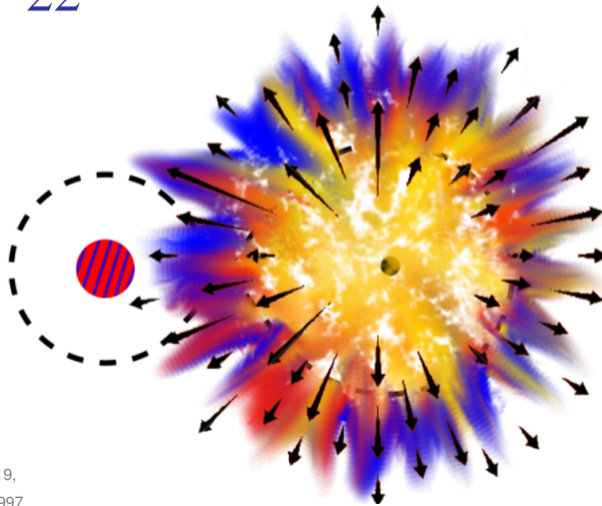
# Most common massive binary evolution path: stable case B RLOF

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

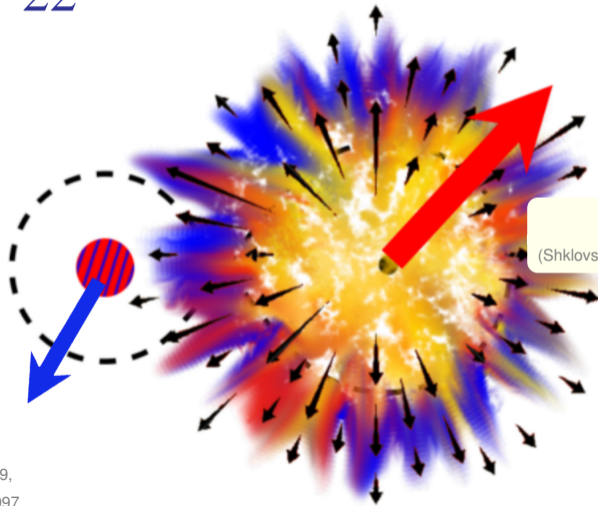
## Accretors may live alone, **but they are *not* single stars**

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



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**SN Natal kick**

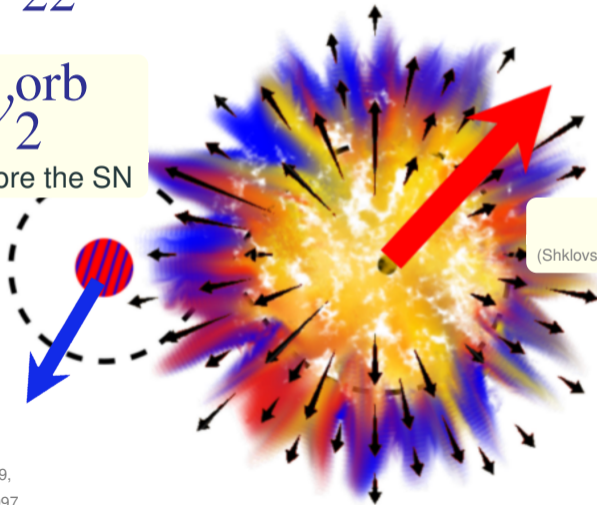
(Shklovskii 1970, Katz 1975, Janka 2013, 2017)

## 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**

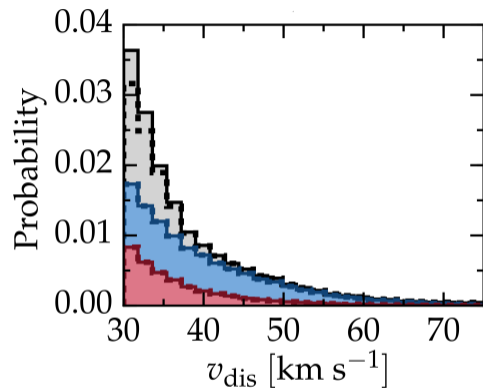
(Shklovskii 1970, Katz 1975, Janka 2013, 2017)



## **Kinematics of the widowed stars**

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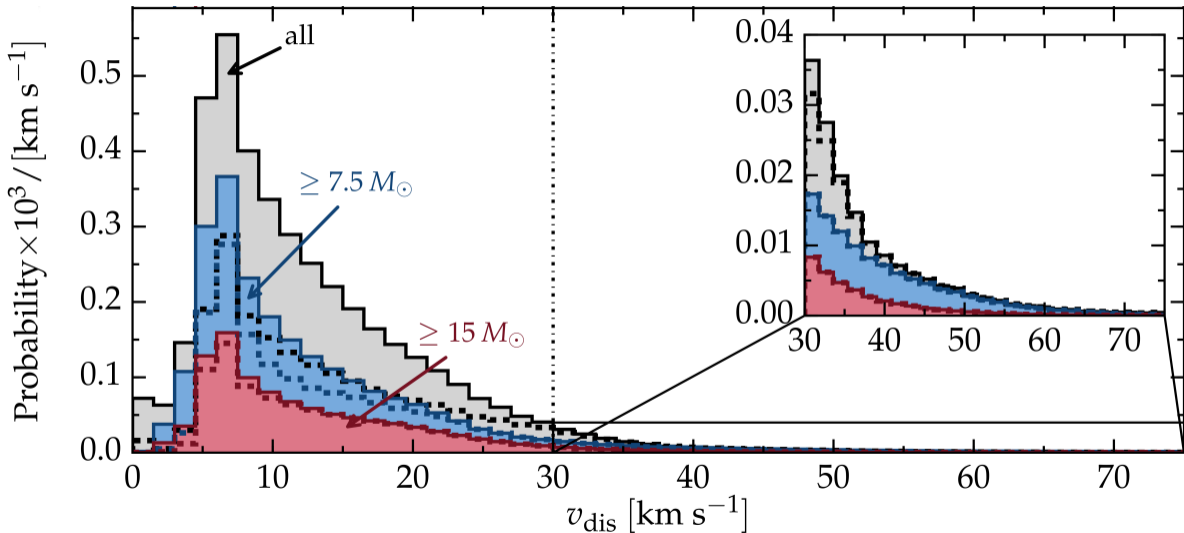
## Accretor stars can be *runaways*...



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

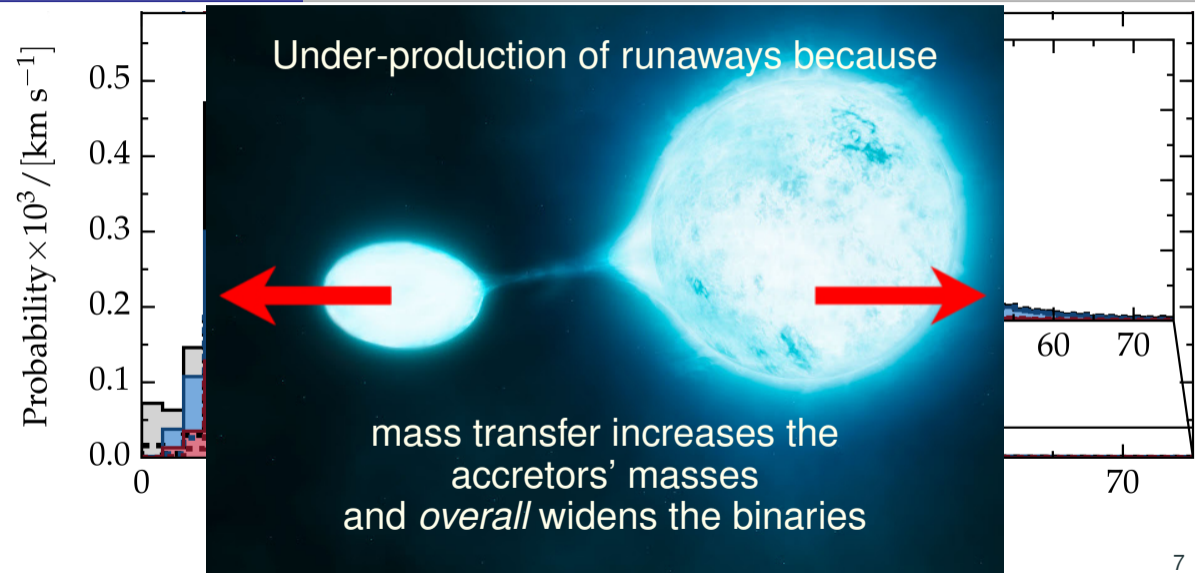
Numerical results: <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66>

...but most are only *walkaways*



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

...but most are only *walkaways*



# The accretor is modified by the interaction

- Spin-up

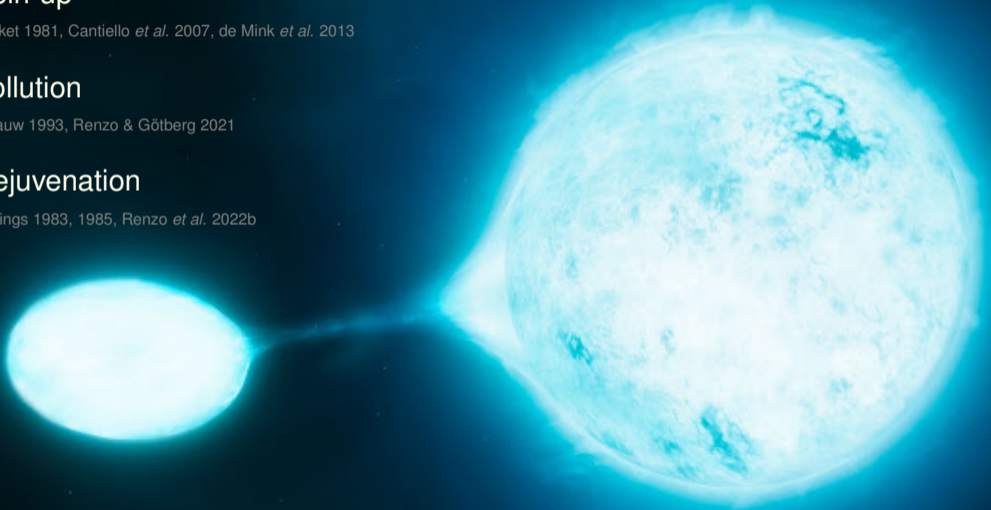
Packet 1981, Cantiello *et al.* 2007, de Mink *et al.* 2013

- Pollution

Blaauw 1993, Renzo & Götberg 2021

- Rejuvenation

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



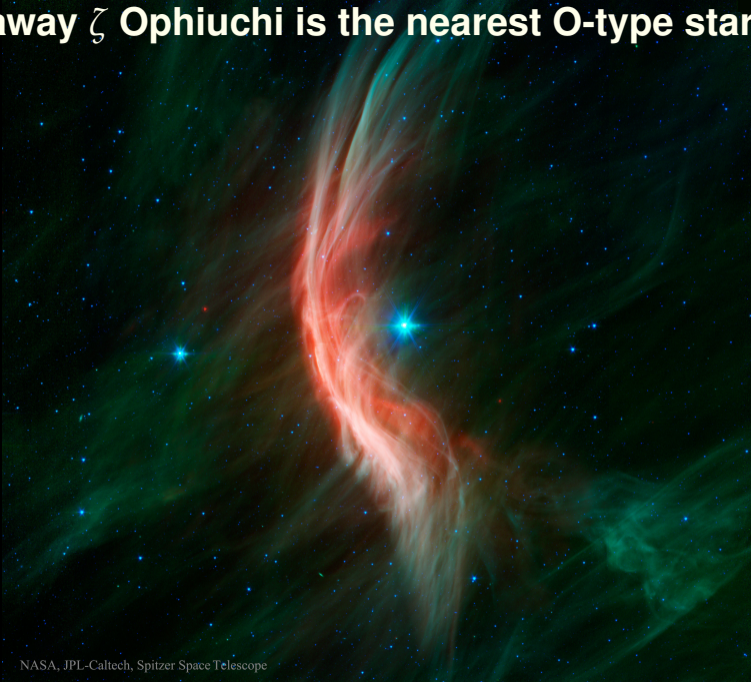
# Constraints on widowed accretors

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from the nearest O-type star

Renzo & Götberg 2021

# The runaway $\zeta$ 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 $\zeta$ Ophiuchi is the nearest O-type star to Earth

## Many observational constraints!

- $d \simeq 107 \pm 4$  pc
- $M \simeq 20 M_{\odot}$
- $20 \text{ km s}^{-1} \lesssim v_{\text{sys}} \lesssim 50 \text{ km s}^{-1}$
- $v \sin(i) \gtrsim 310 \text{ km s}^{-1}, i \gtrsim 56^{\circ}$
- $(T_{\text{eff}}, L)$  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**

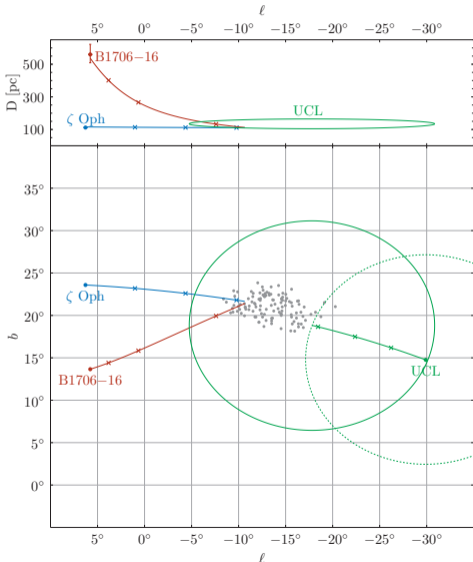
(van Rensbergen *et al.* 96, Howarth & Smith 01, Villamariz & Herrero 05)

see

Walker *et al.* 1979,  
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Neuhäuser *et al.* 2019, 2020,  
Renzo & Götberg 2021,  
Shepard *et al.* 2022



# $\zeta$ Oph is single today but we can trace it back to a neutron star



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

R. Neuhäuser,<sup>1\*</sup> F. Gießler<sup>1</sup>, and V.V. Hambaryan<sup>1,2</sup>

<sup>1</sup> *Astrophysikalisches Institut und Universitäts-Sternwarte Jena, Schillergäßchen 2-3, 07745 Jena, Germany*

<sup>2</sup> *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

$$M_1 = 25 M_{\odot}$$

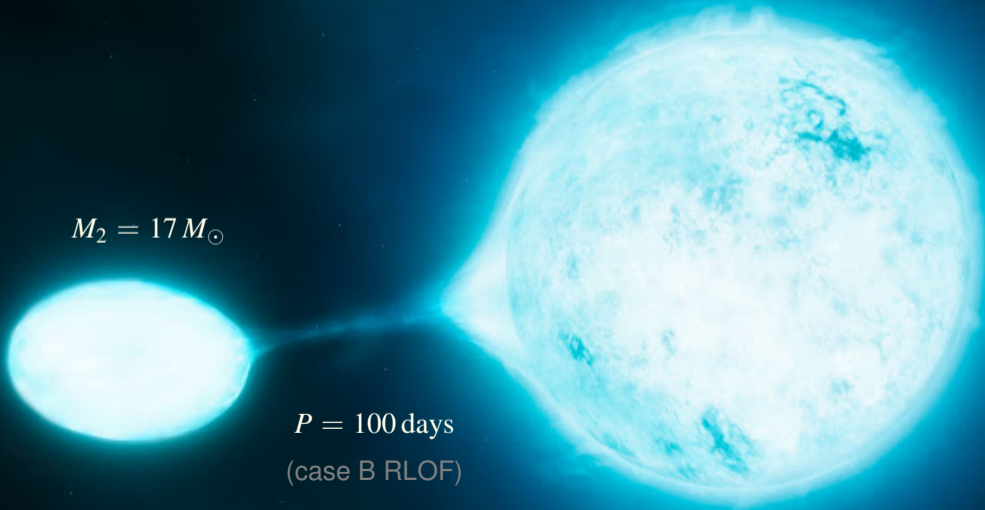
$$Z = 0.01$$

(Murphy *et al.* 2021)

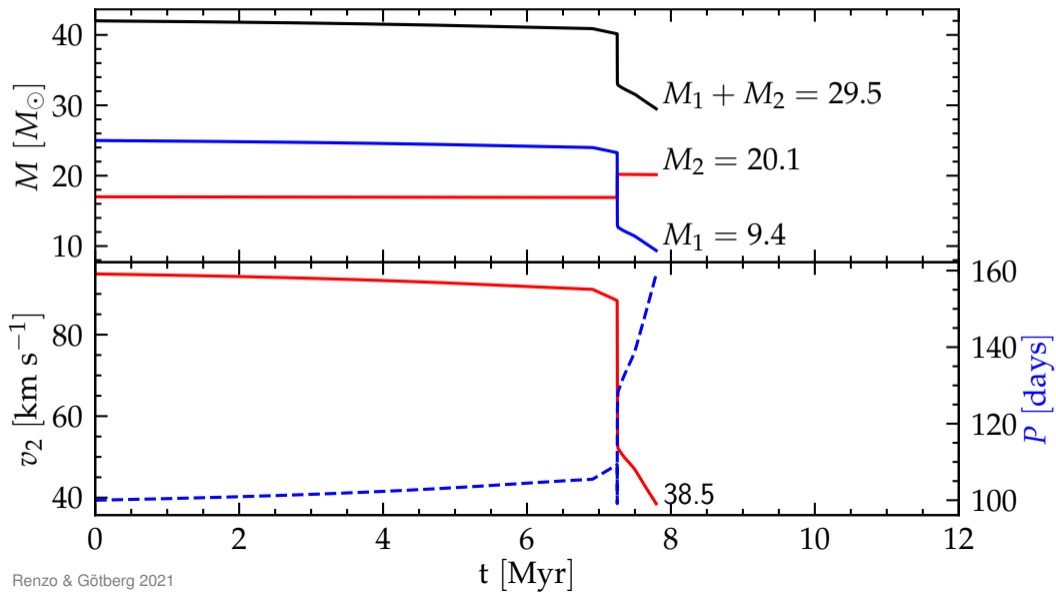
$$M_2 = 17 M_{\odot}$$

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

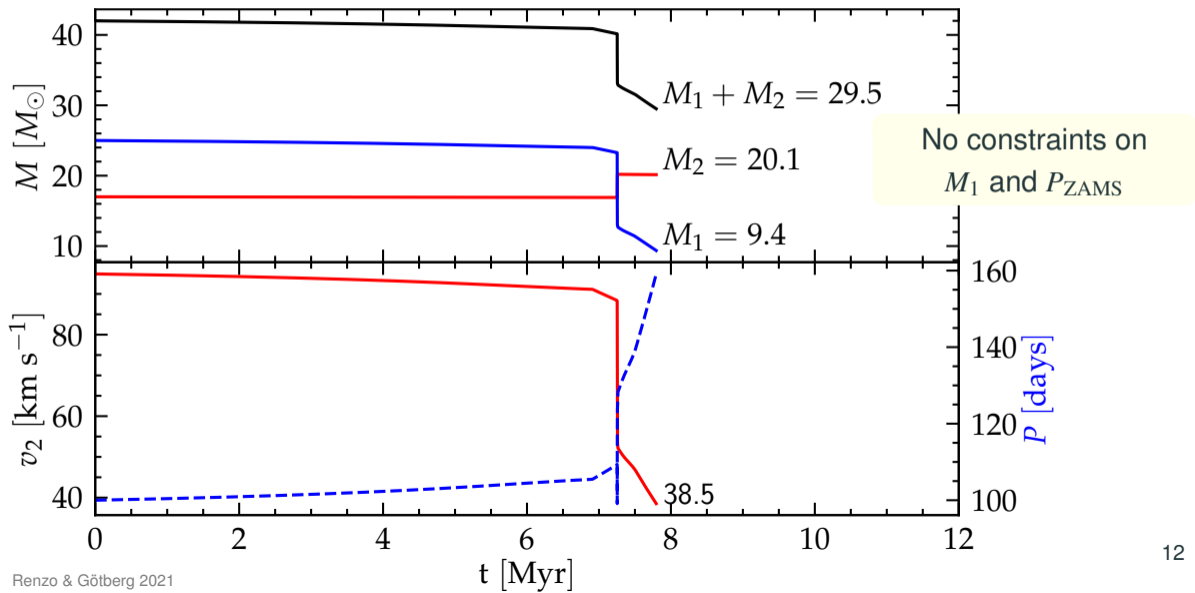
(case B RLOF)



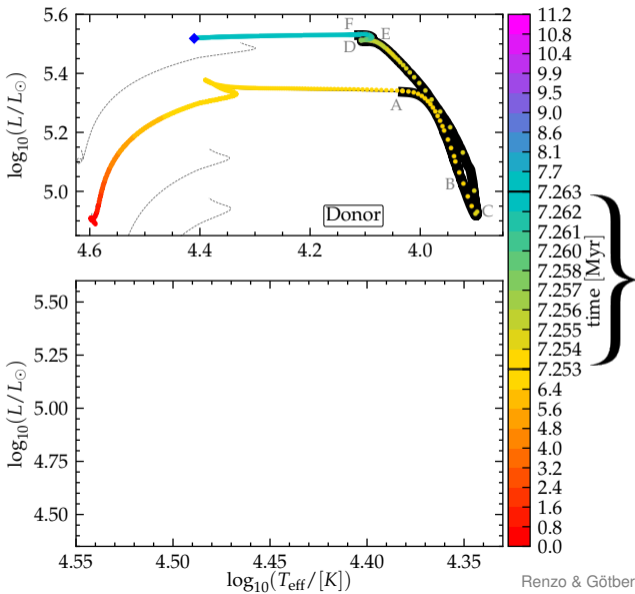
## Orbital evolution: ✓ Mass & ✓ spatial velocity



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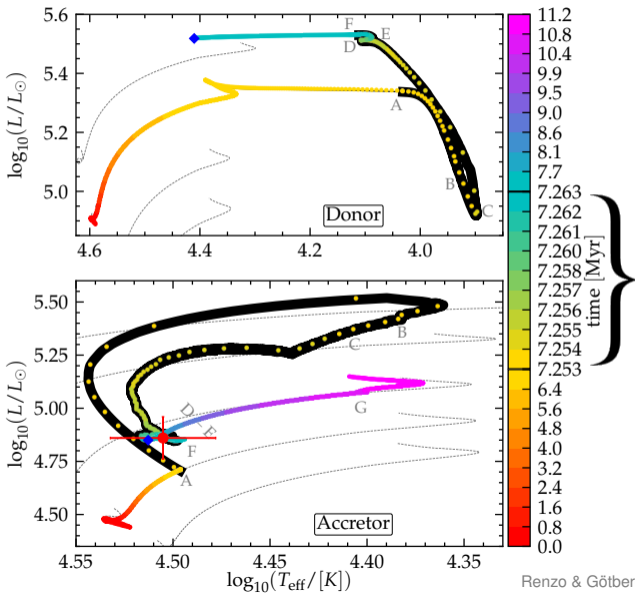
## HRD of both stars: the donor



### 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 ✓

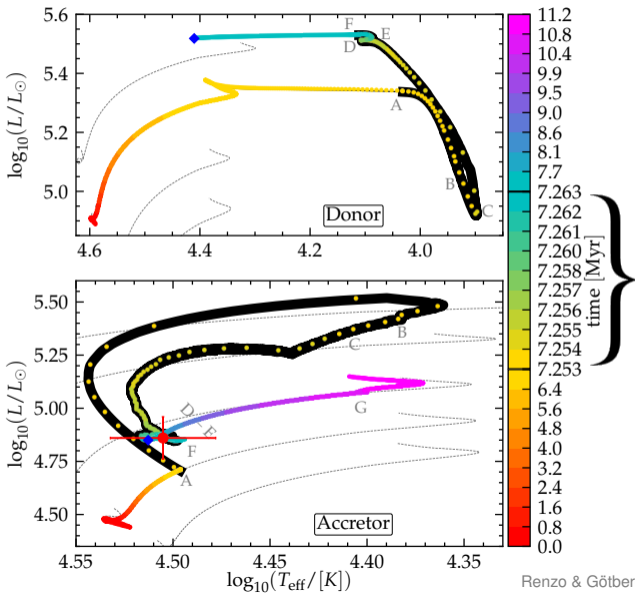


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✓ **Models match  $\zeta$  Oph.**

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

## Internal structure of the accretor

---

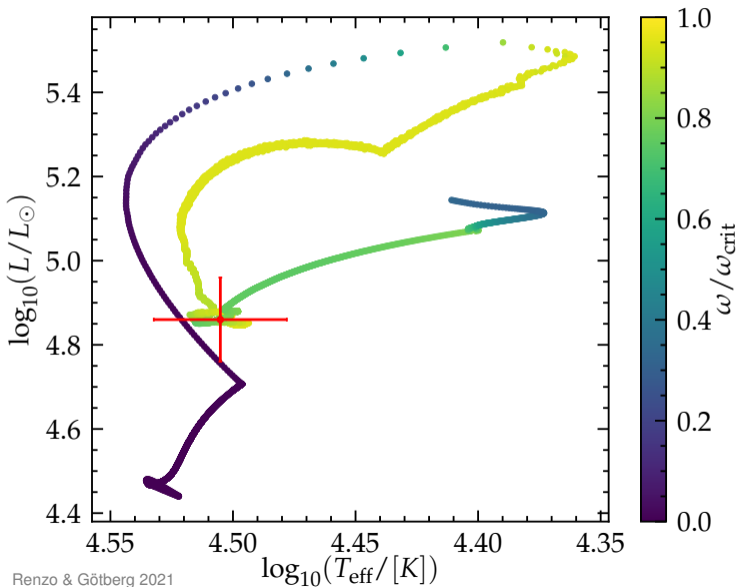
**Spin up:** surface and interior

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

**Rejuvenation:** core-envelope boundary

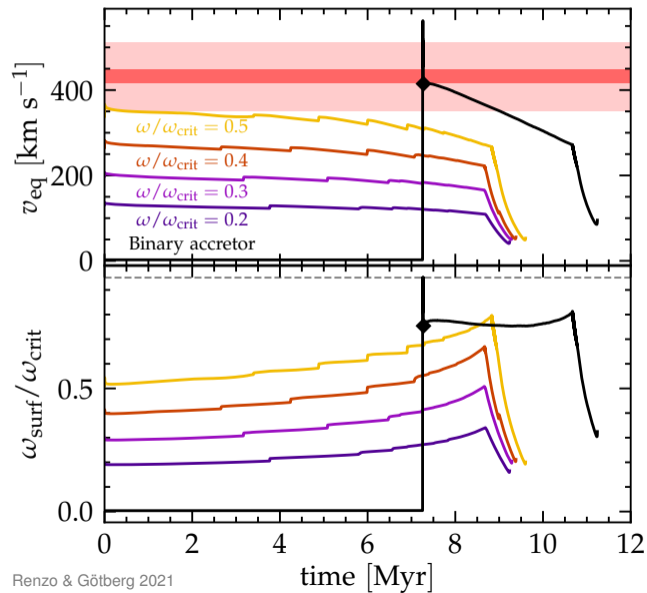


## HRD: accretor rotation

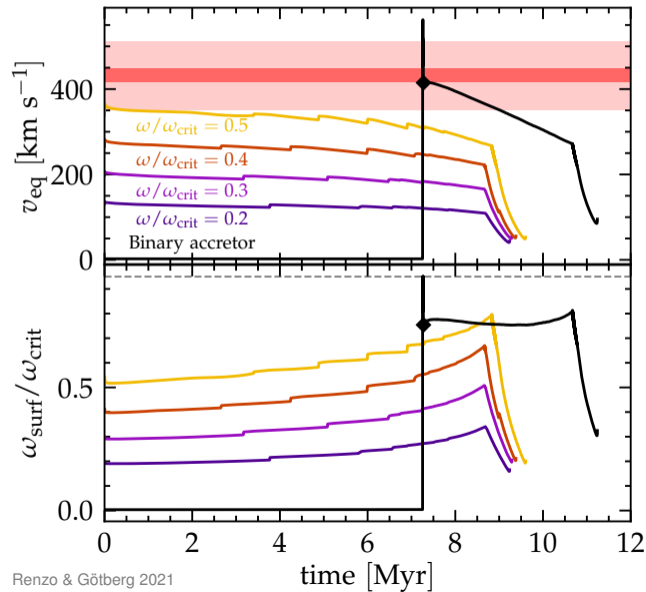


- Minimum  $T_{\text{eff}}$  during RLOF reached at onset of critical rotation.
- Rotation close to critical for large part of the main sequence.

## ✓ Surface rotation rate



## ✓ Surface rotation rate



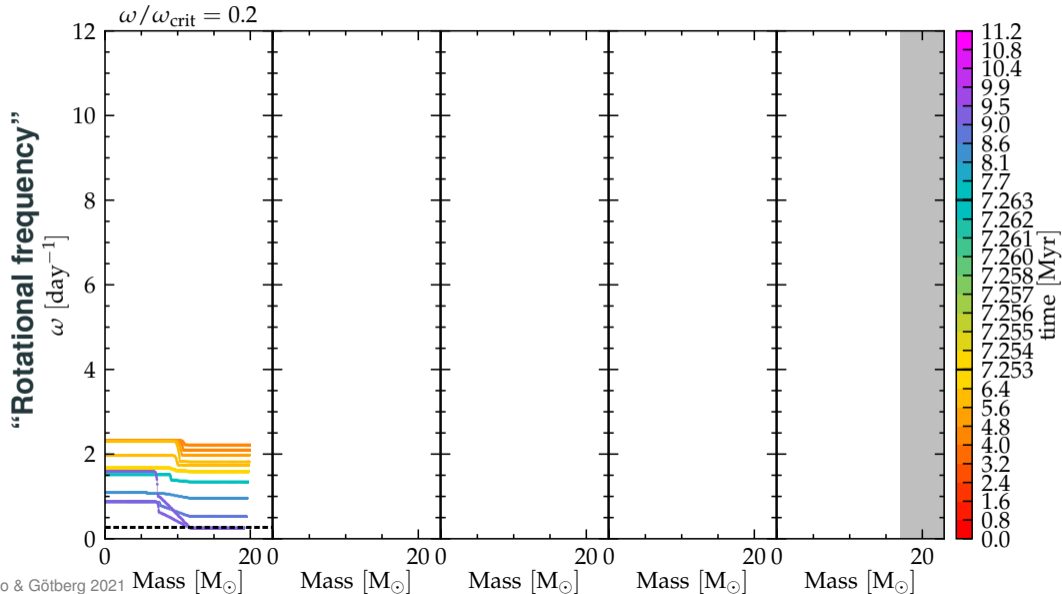
**Accretors are likely Oe/Be stars**

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

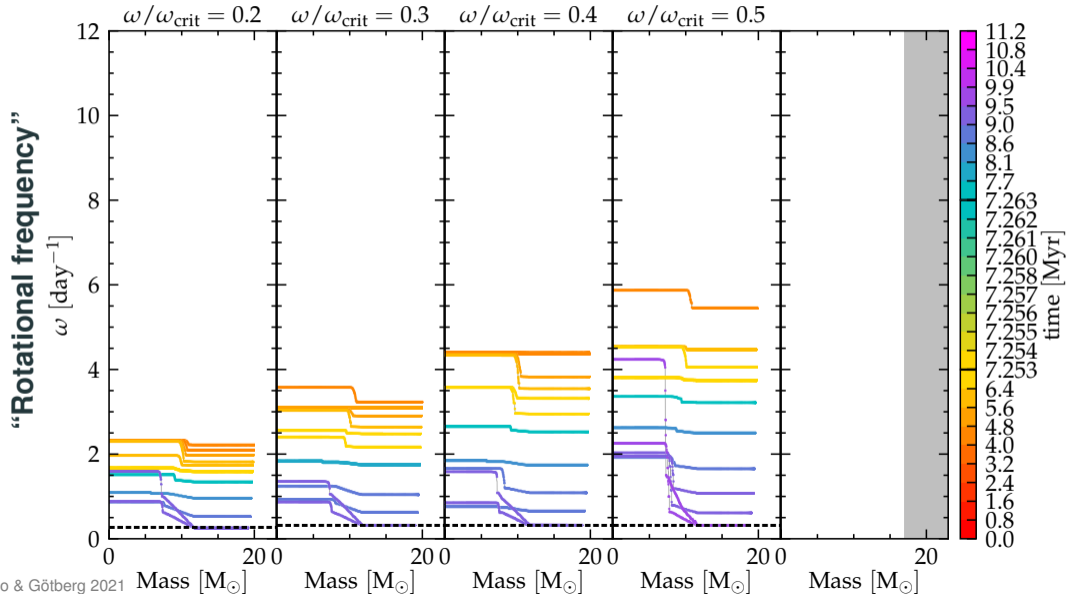
decretion disk & emission lines

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

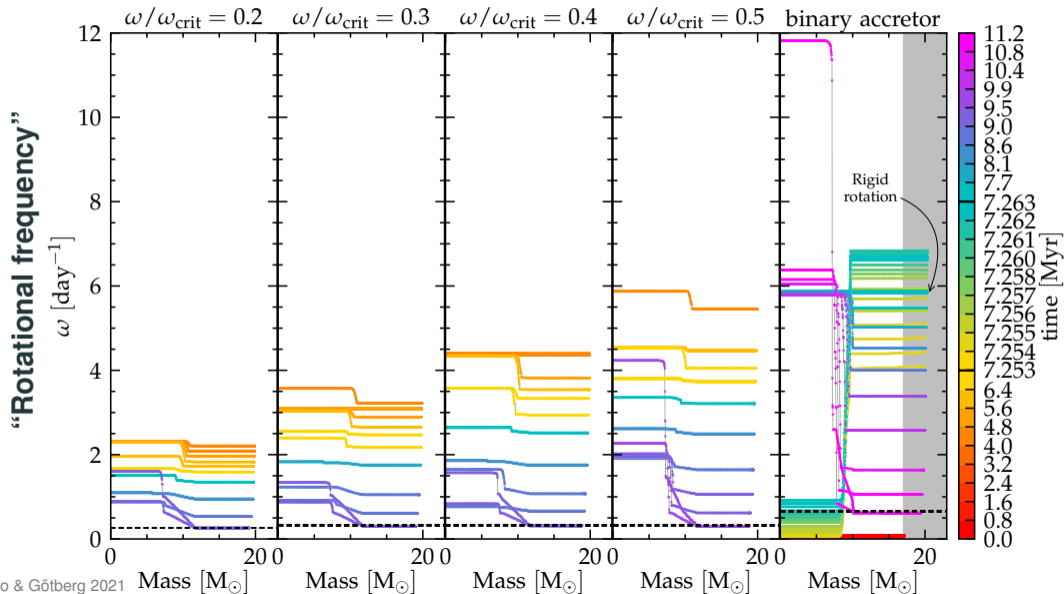
# Internal rotational profile: single stars



# Internal rotational profile: single stars



# Internal rotational profile: accretor



## Internal structure of the accretor

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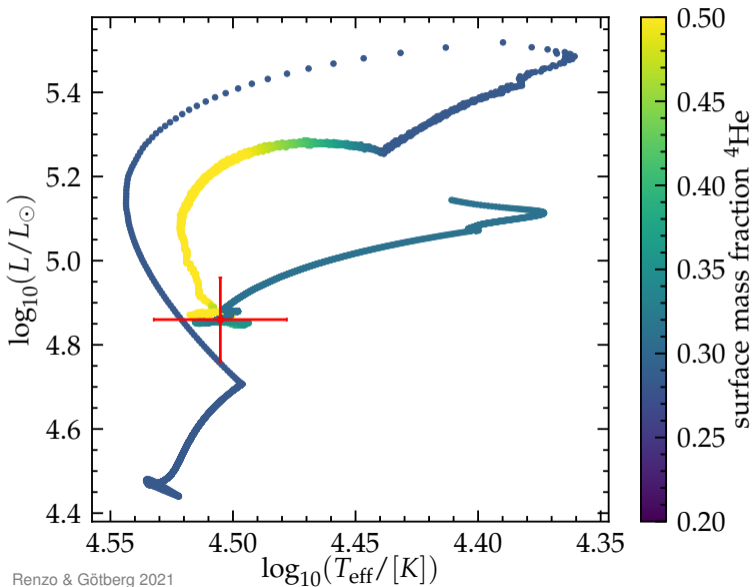
**Rejuvenation:** core-envelope boundary

## Internal mixing in the accretor

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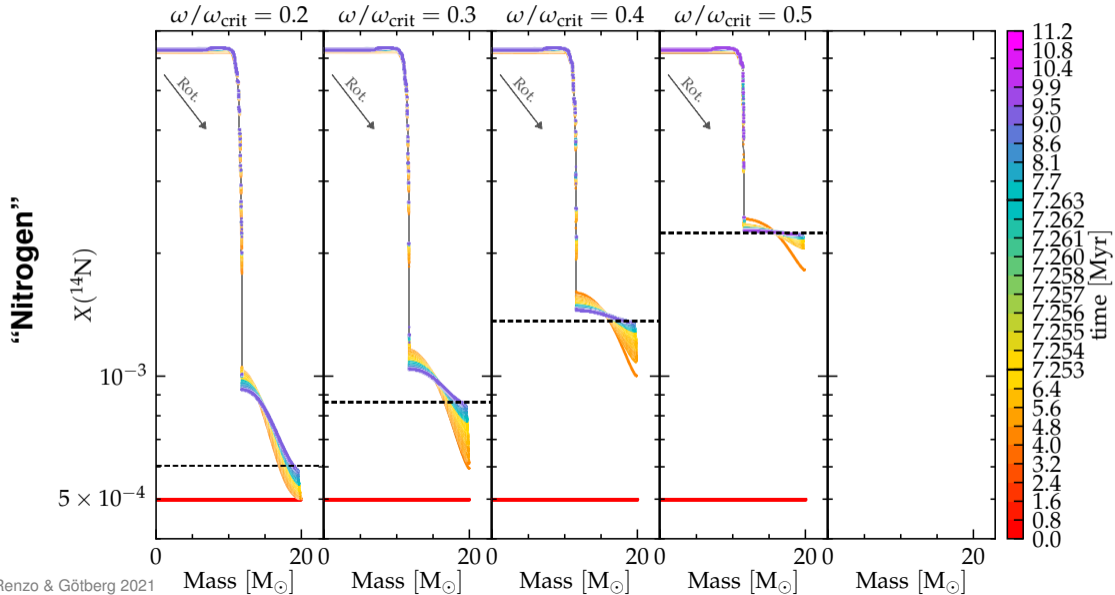


## HRD: Helium surface abundance

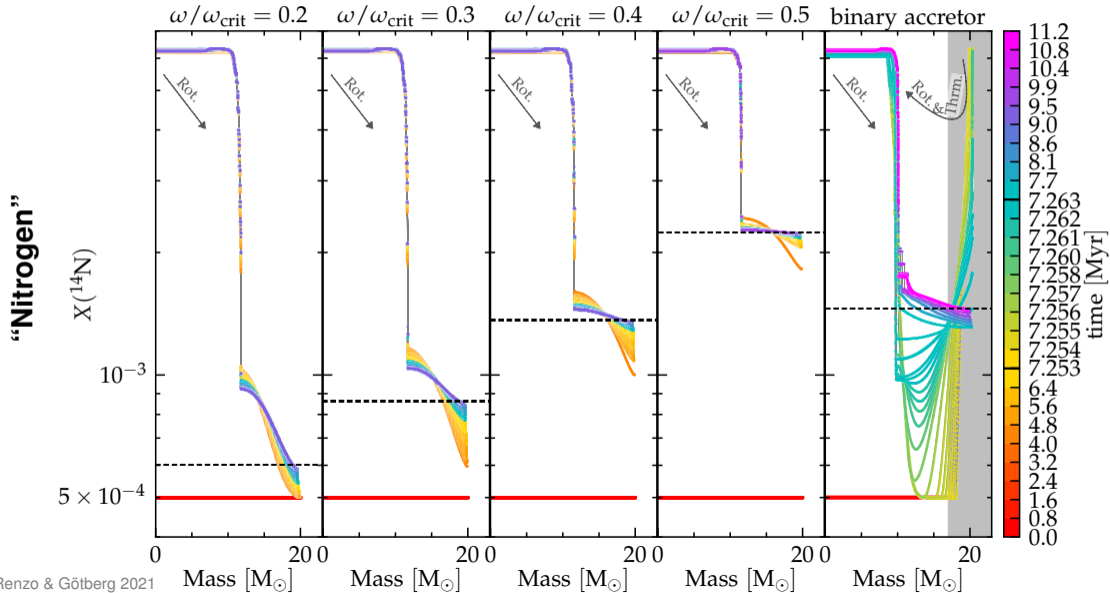


- Accretion of He-rich matter change morphology at  $T_{\text{eff}} \simeq 10^{4.44}$  K.
- Interplay between accretion, mixing and rotation causes “noisiness”.

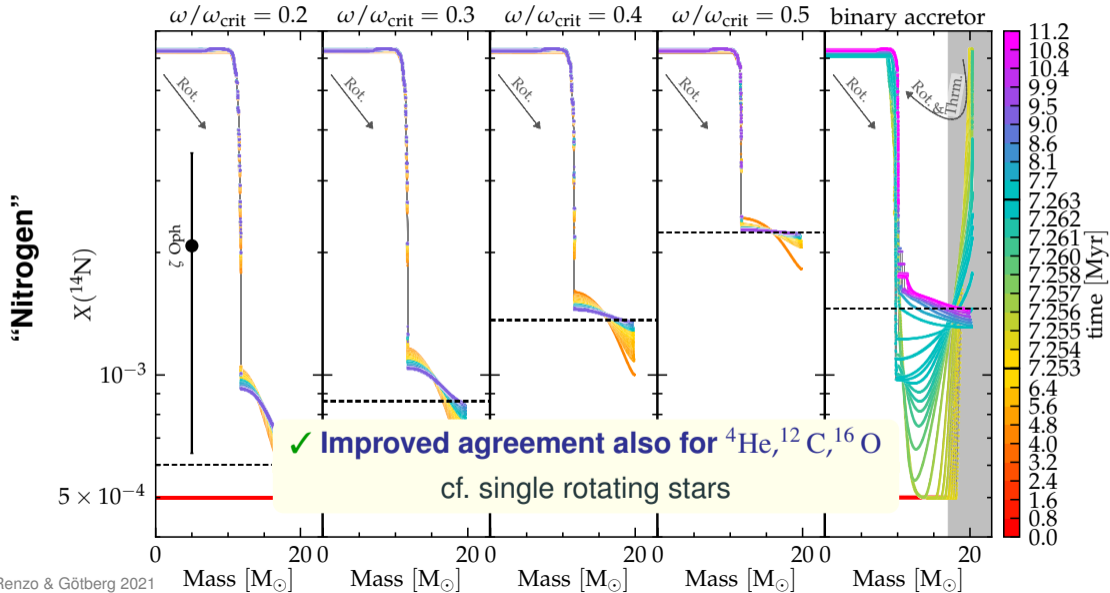
# Composition profile: comparison with rotating single stars



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



## Internal structure of the accretor

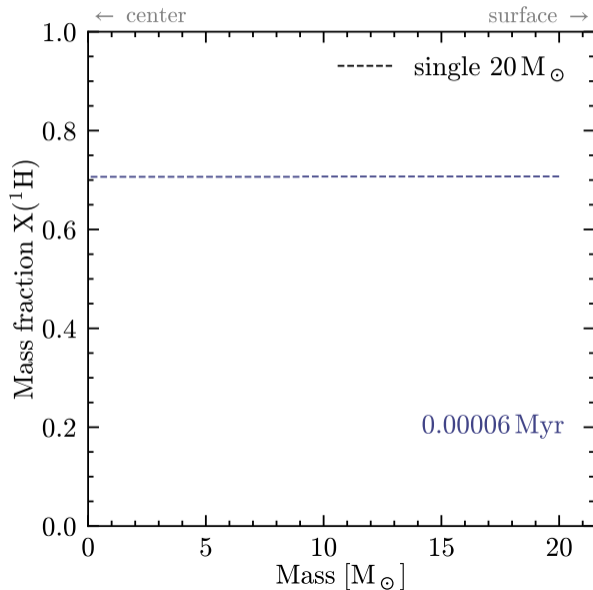
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**Spin up:** surface and interior

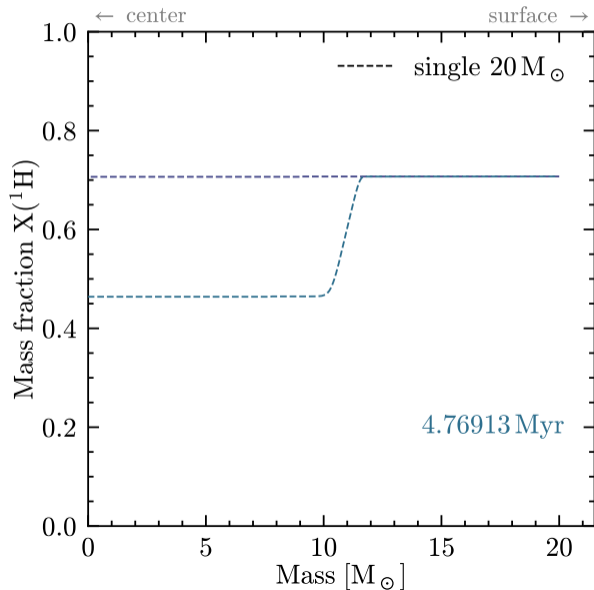
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**Rejuvenation:** core-envelope boundary

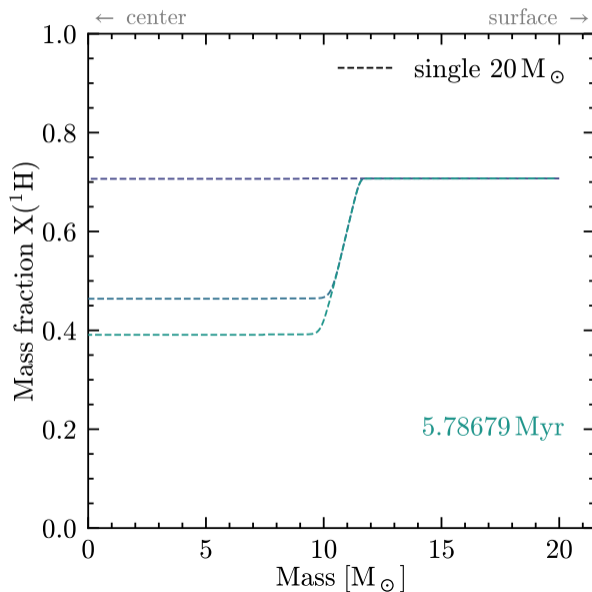
## Refresher: formation of the helium core in single stars



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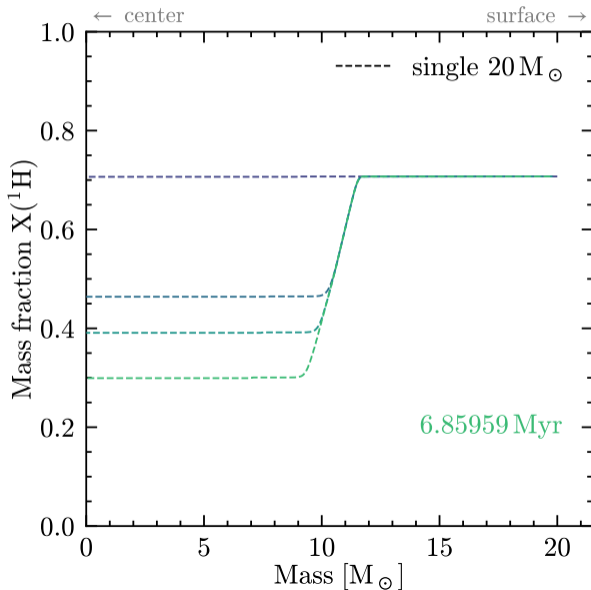


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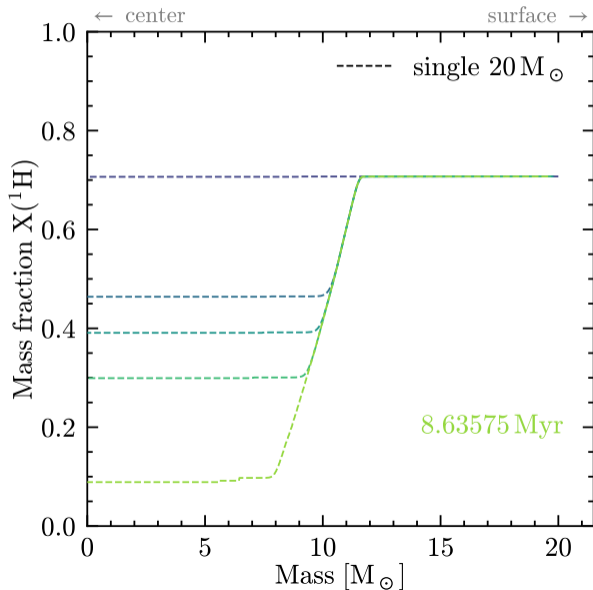




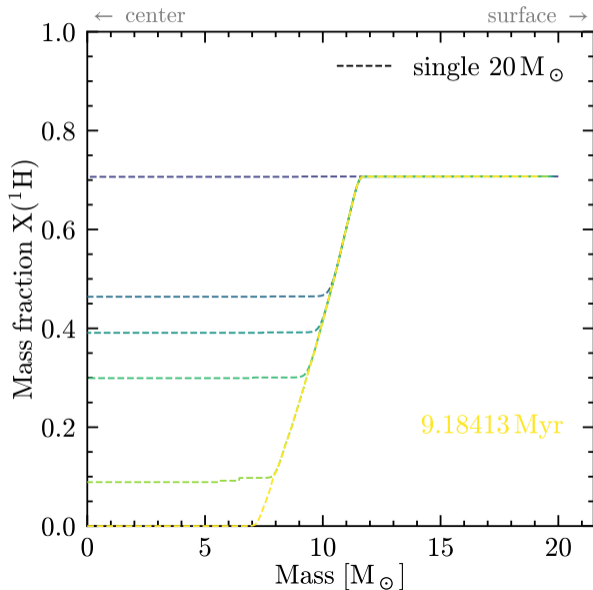
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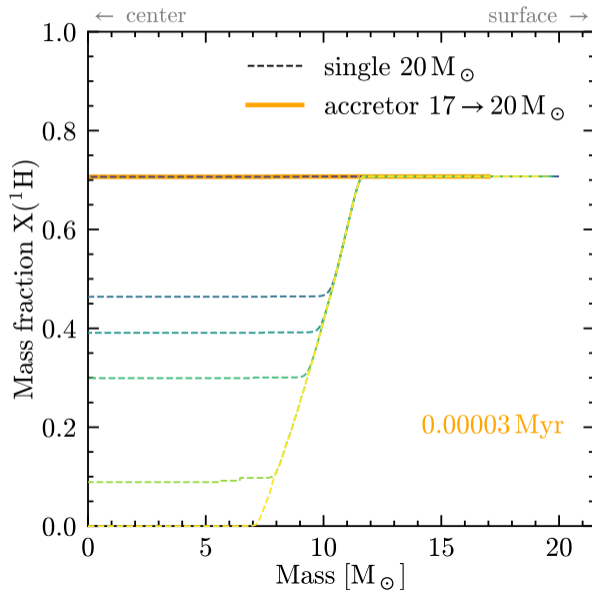
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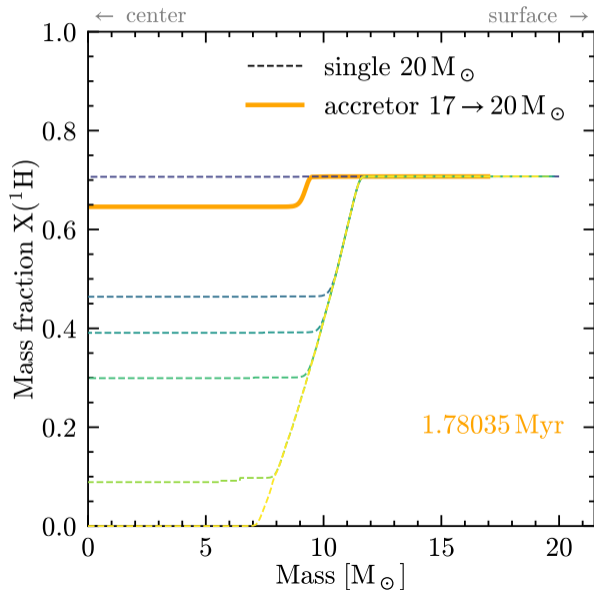
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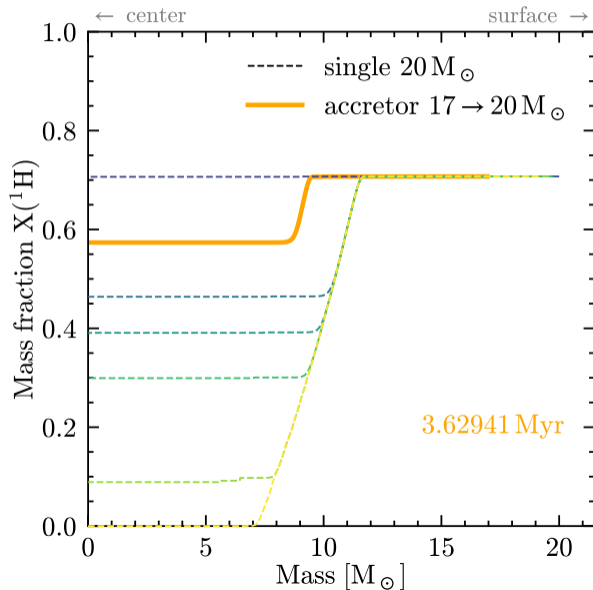
## Evolution of the accretor's core through RLOF



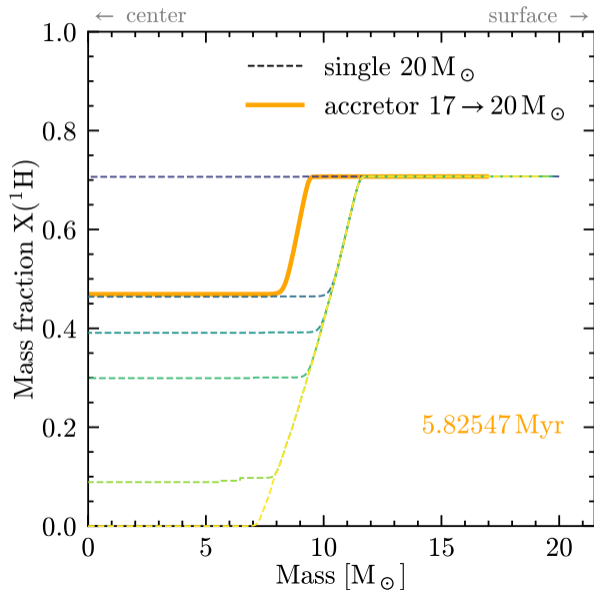
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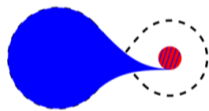
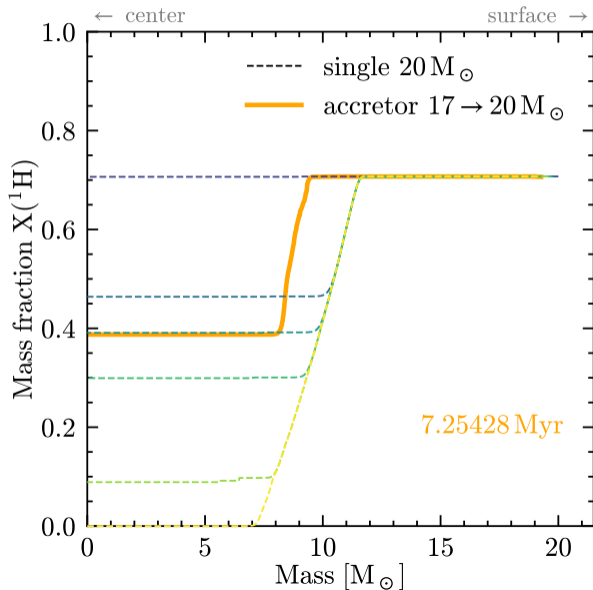
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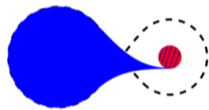
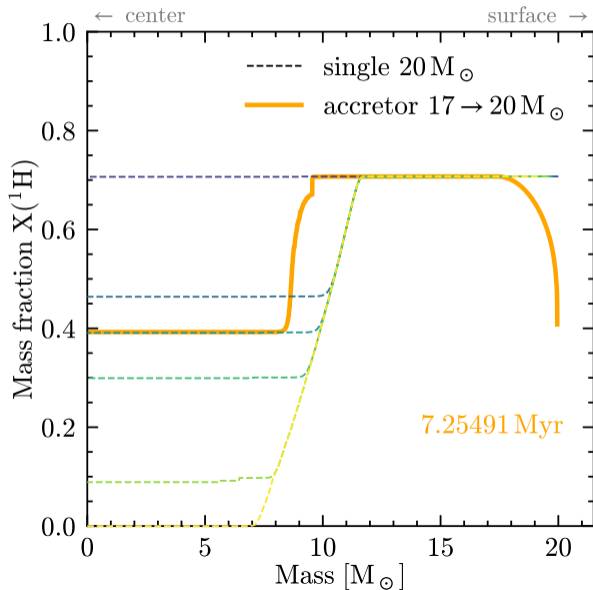


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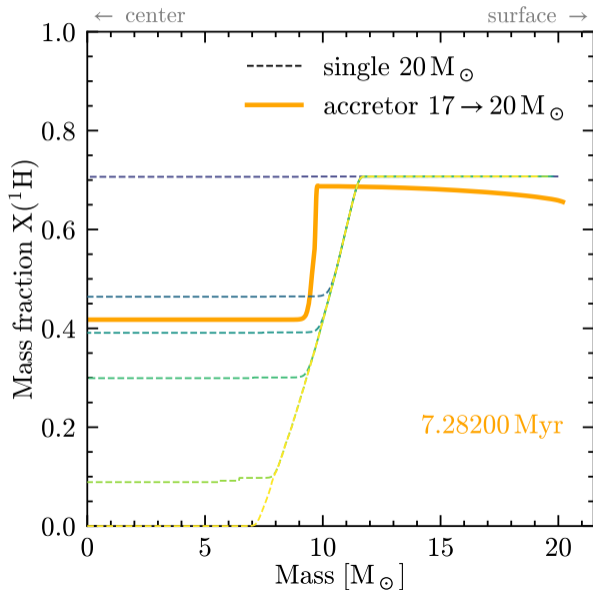




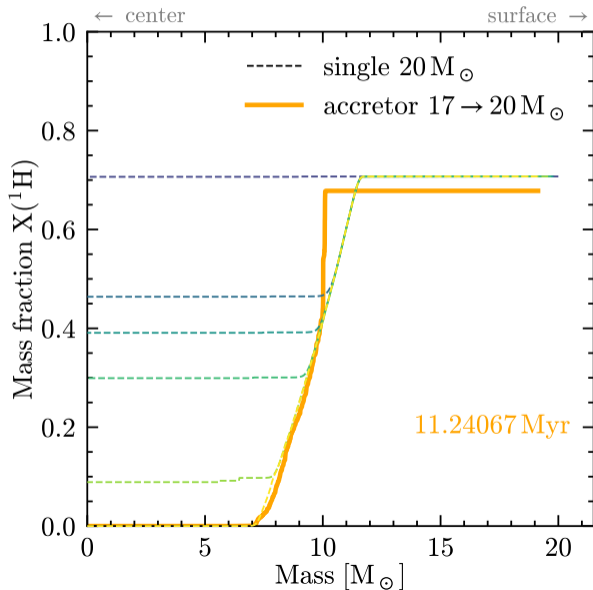
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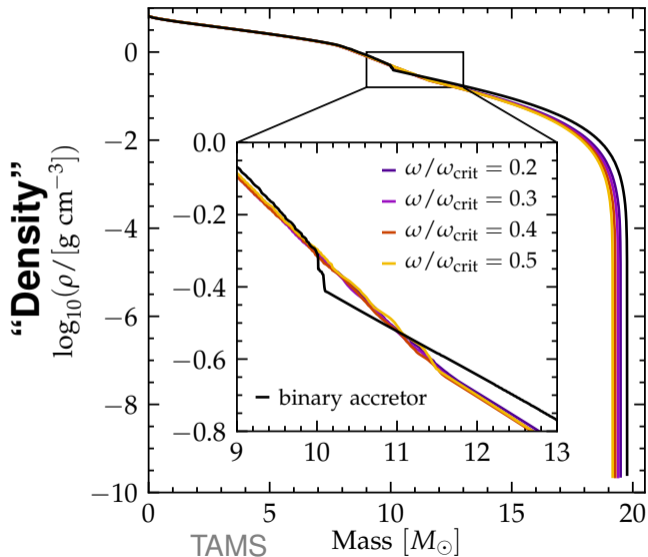
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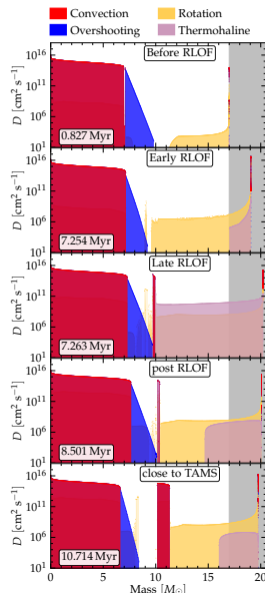
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# Rejuvenation changes the core/envelope boundary



**log<sub>10</sub>(“Diffusion coeff.”)**



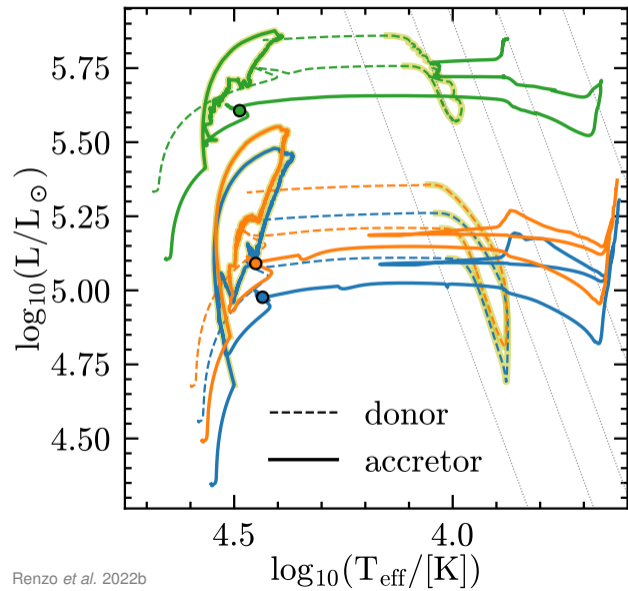
## Consequences of rejuvenation

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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)

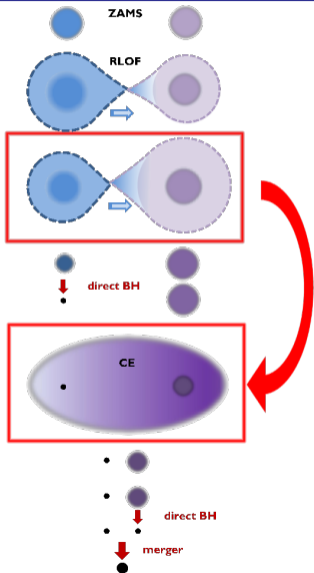
## Consequences of rejuvenation

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Blue loops in high-mass stars?

Easier to unbind the envelope

# The common envelope in GW progenitors is initiated by the accretor

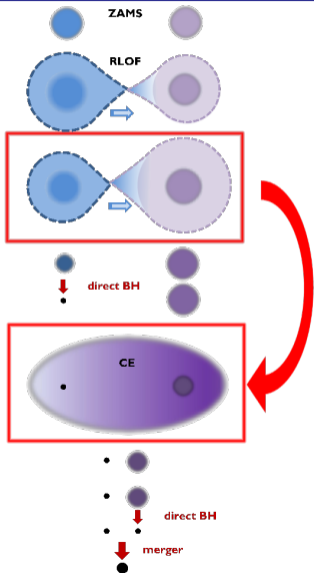


Does RLOF rejuvenation impact how easy it is to remove the envelope ?

Renzo *et al.* 2022b



# The common envelope in GW progenitors is initiated by the accretor

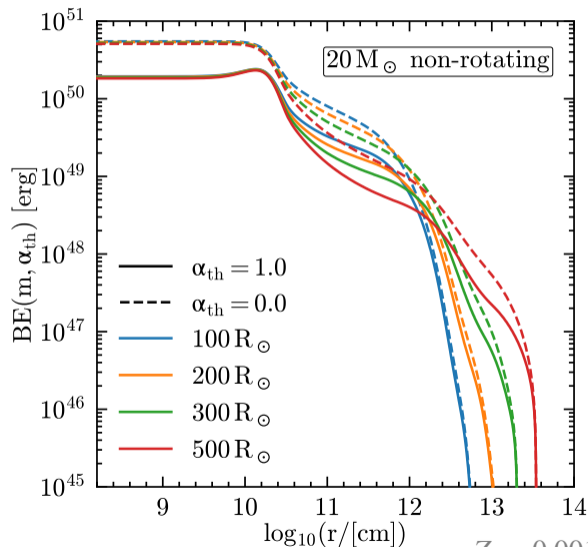


Does RLOF rejuvenation impact how easy it is to remove the envelope ?

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



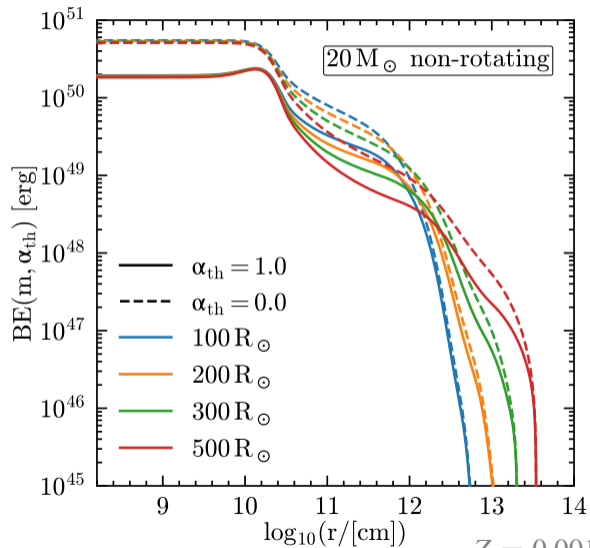
$$BE(m, \alpha_{\text{th}}) = - \int_m^M dm' \left( -\frac{Gm'}{r(m')} + \alpha_{\text{th}} u(m') \right)$$

- Gravitational potential energy
- Internal energy
- $\alpha_{\text{th}}$  free parameter

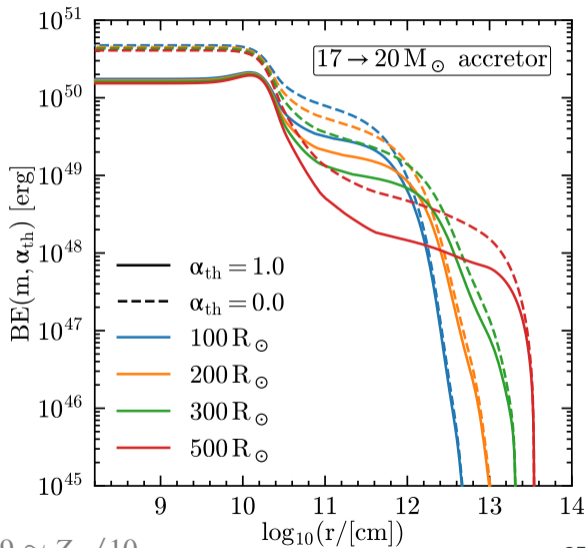
fraction of internal energy usable to eject envelope

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

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



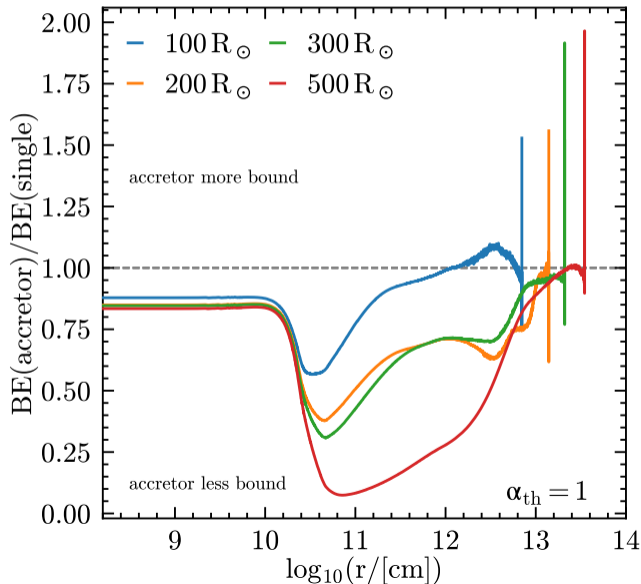
$Z = 0.0019 \simeq Z_{\odot}/10$



25

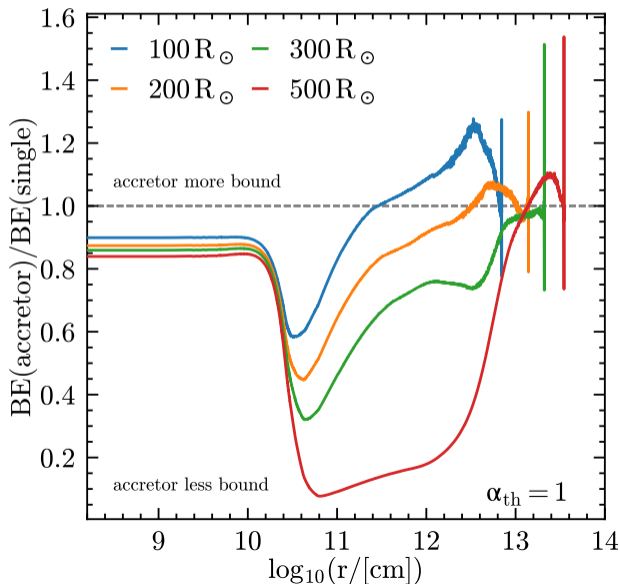
## Taking the ratio: accretors are easier to unbind

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



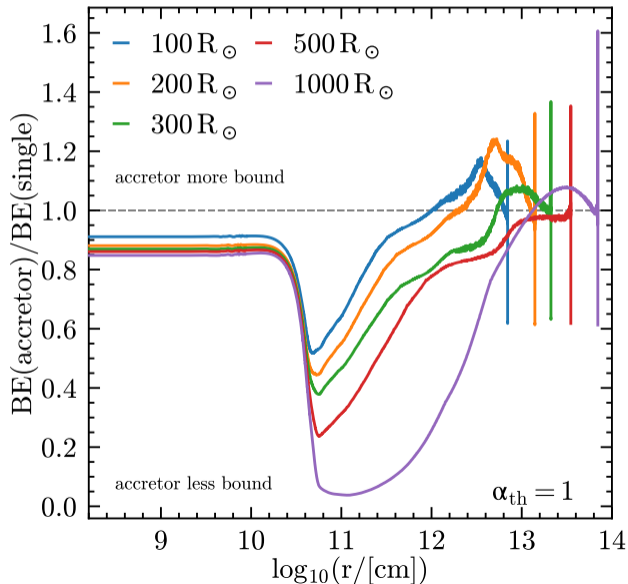
## Taking the ratio: accretors are easier to unbind

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

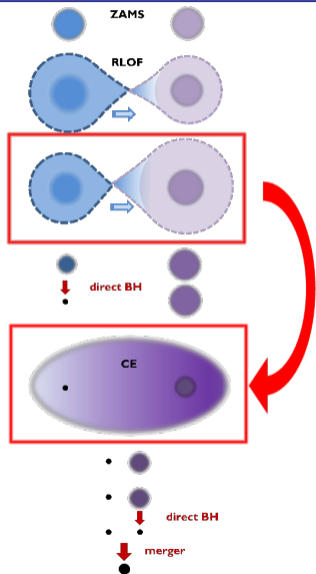


## Taking the ratio: accretors are easier to unbind

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

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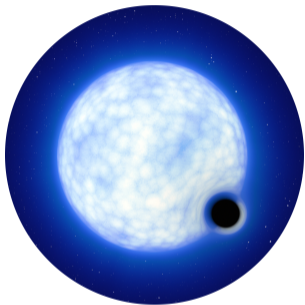


## Accretors are *not* single stars

- 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  $\zeta$  Ophiuchi ✓  
⇒  $^{14}\text{N}$  and  $^4\text{He}$  from the donor, inward angular momentum transport  
⇒ Observed composition constrains mixing & accretion efficiency
- Evolved accretor's core boundary results in easier to eject envelopes  
⇒ Implications for asteroseismology & common envelope in GW progenitors

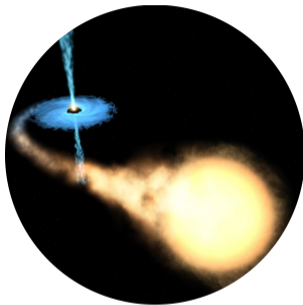
**Backup slides**

## Some binaries do survive the 1<sup>st</sup> core-collapse



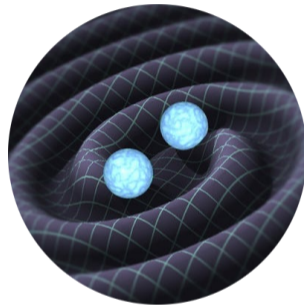
### Non-interacting

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.



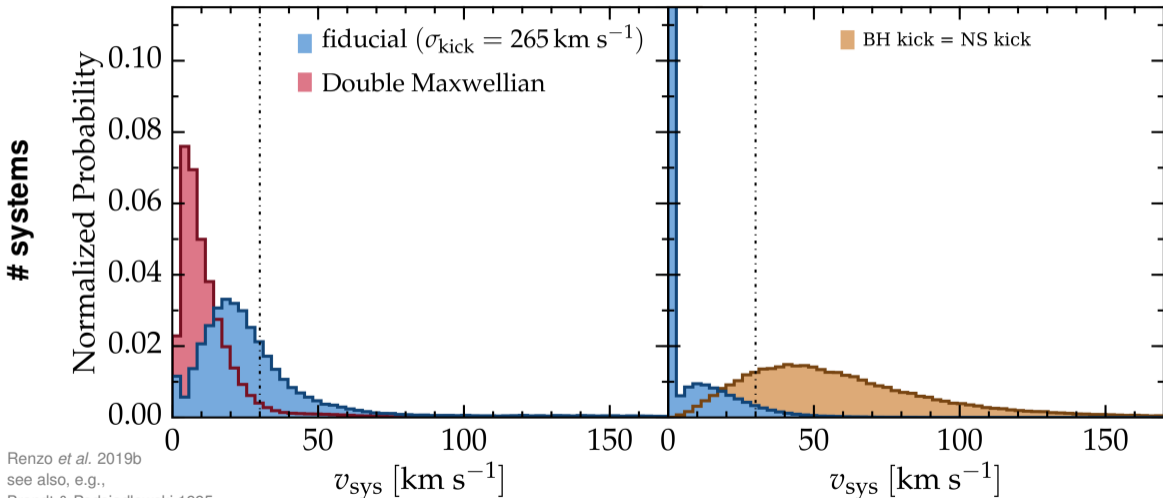
### Gravitational waves

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

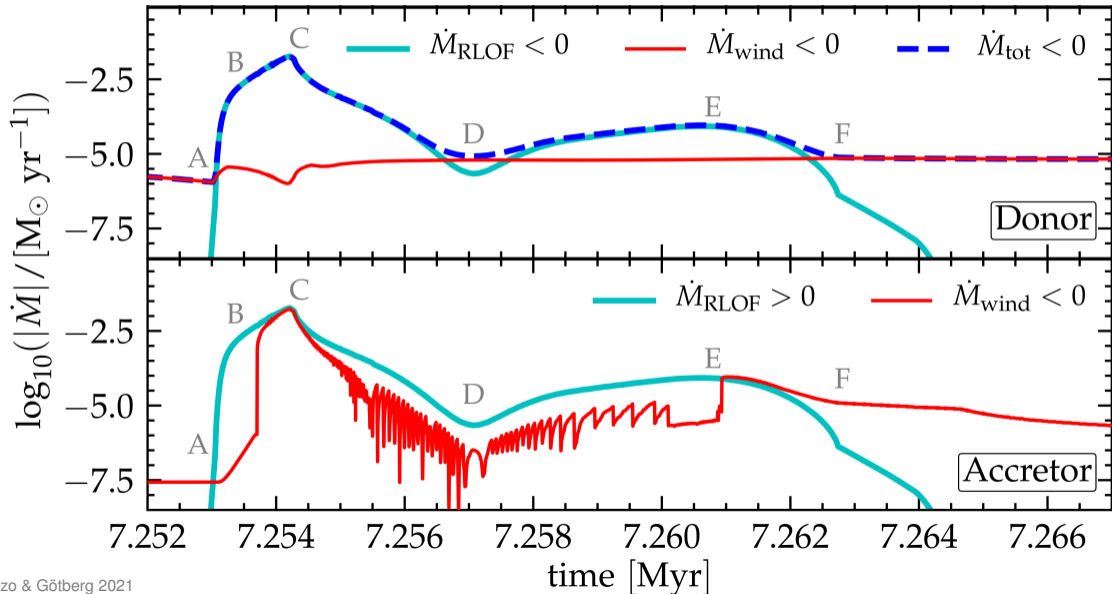
Kalogera 1996

Tauris & Takens 1998

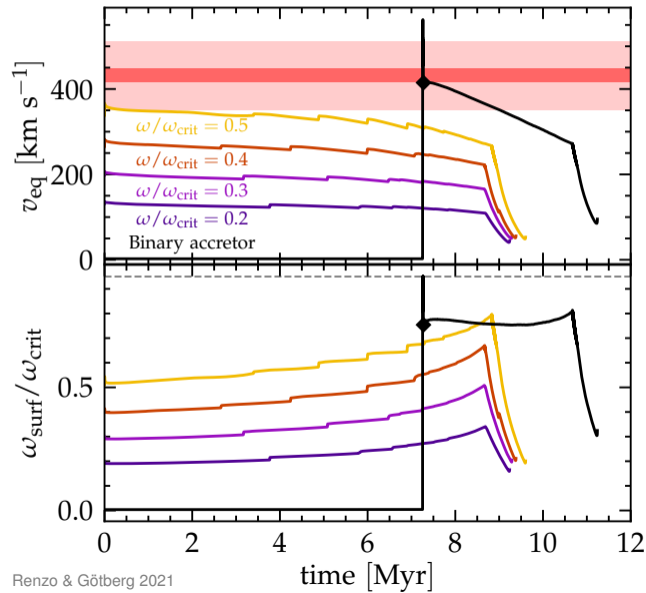
Velocity respect to the pre-explosion binary center of mass

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

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



## ✓ Surface rotation rate ?

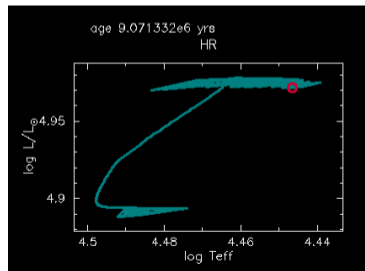


• but “weak wind problem”:

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

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

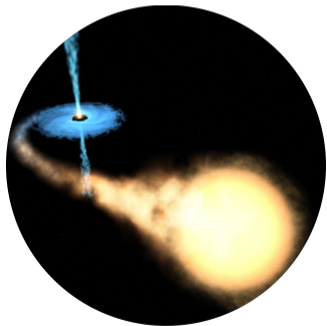
✗ Decreasing the wind:  $\omega > \omega_{\text{crit}}$



Do BHs receive kicks ?

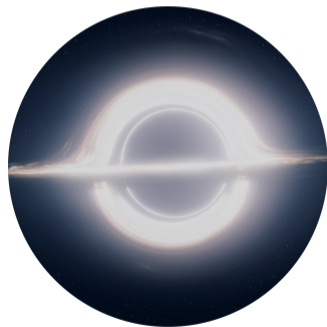
NO

⇒ most remain together with their widowed companion



YES

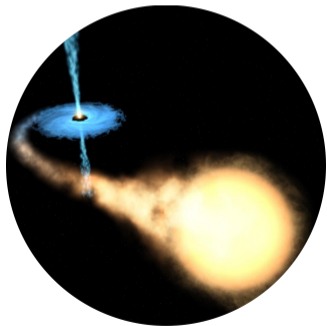
⇒ most are single and we can't see them...



Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion



YES

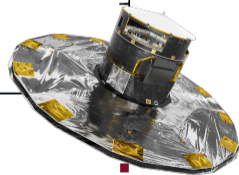
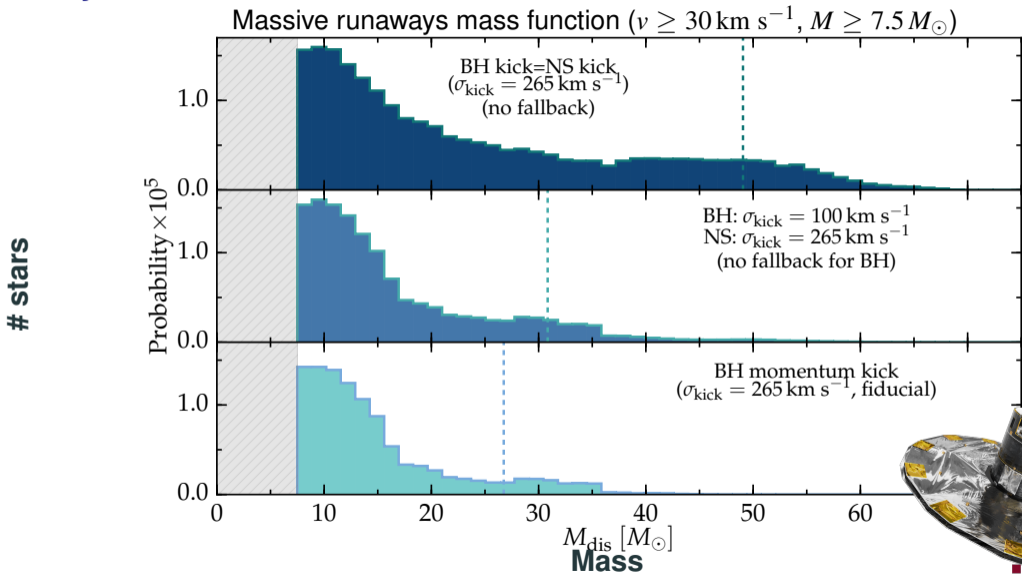
⇒ most are single and we can't see them...



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



# A way to constrain BH kicks with Gaia



gaia

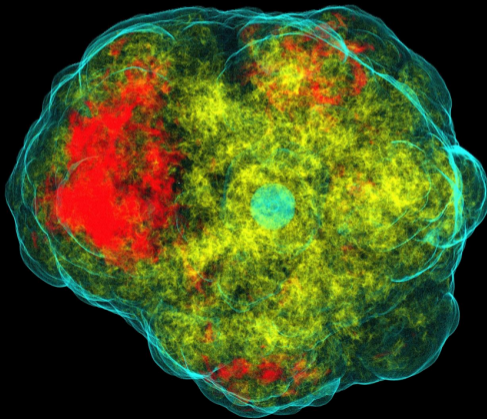
Numerical results publicly available at:

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

# SN natal kick

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

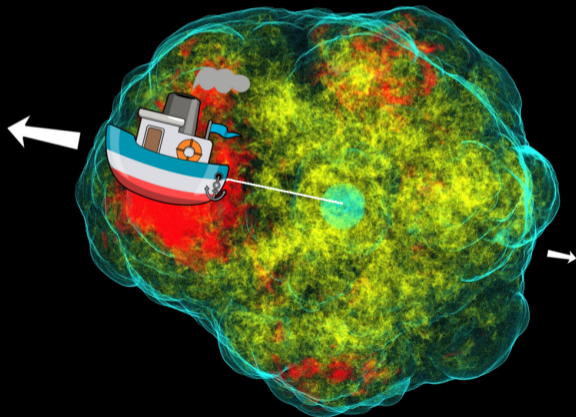
Physically:  $\nu$  emission and/or ejecta anisotropies



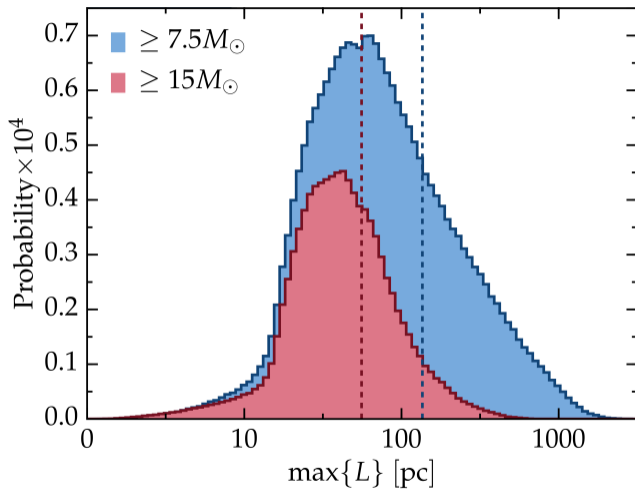
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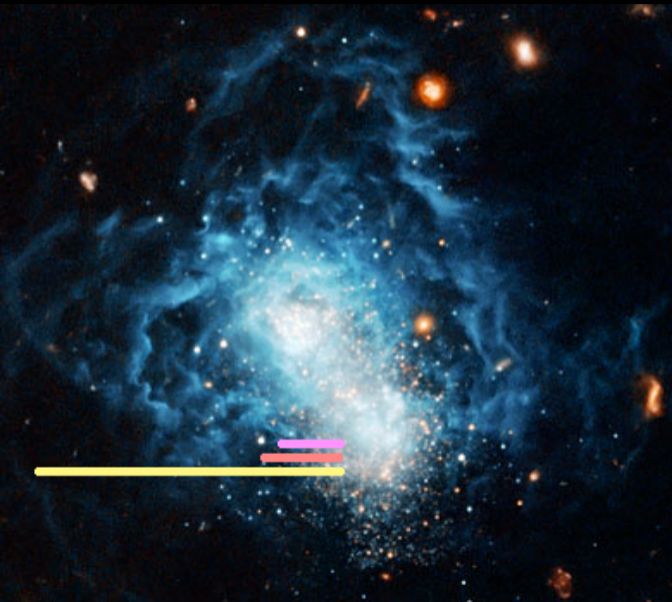


## How far do they get?



“Distance traveled”  
(No potential well)

# Nevertheless: 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

## Thermohaline mixing = double diffusion



Stable thermal gradient

+

Unstable composition gradient

=

**Heat needs to diffuse for mixing to happen**