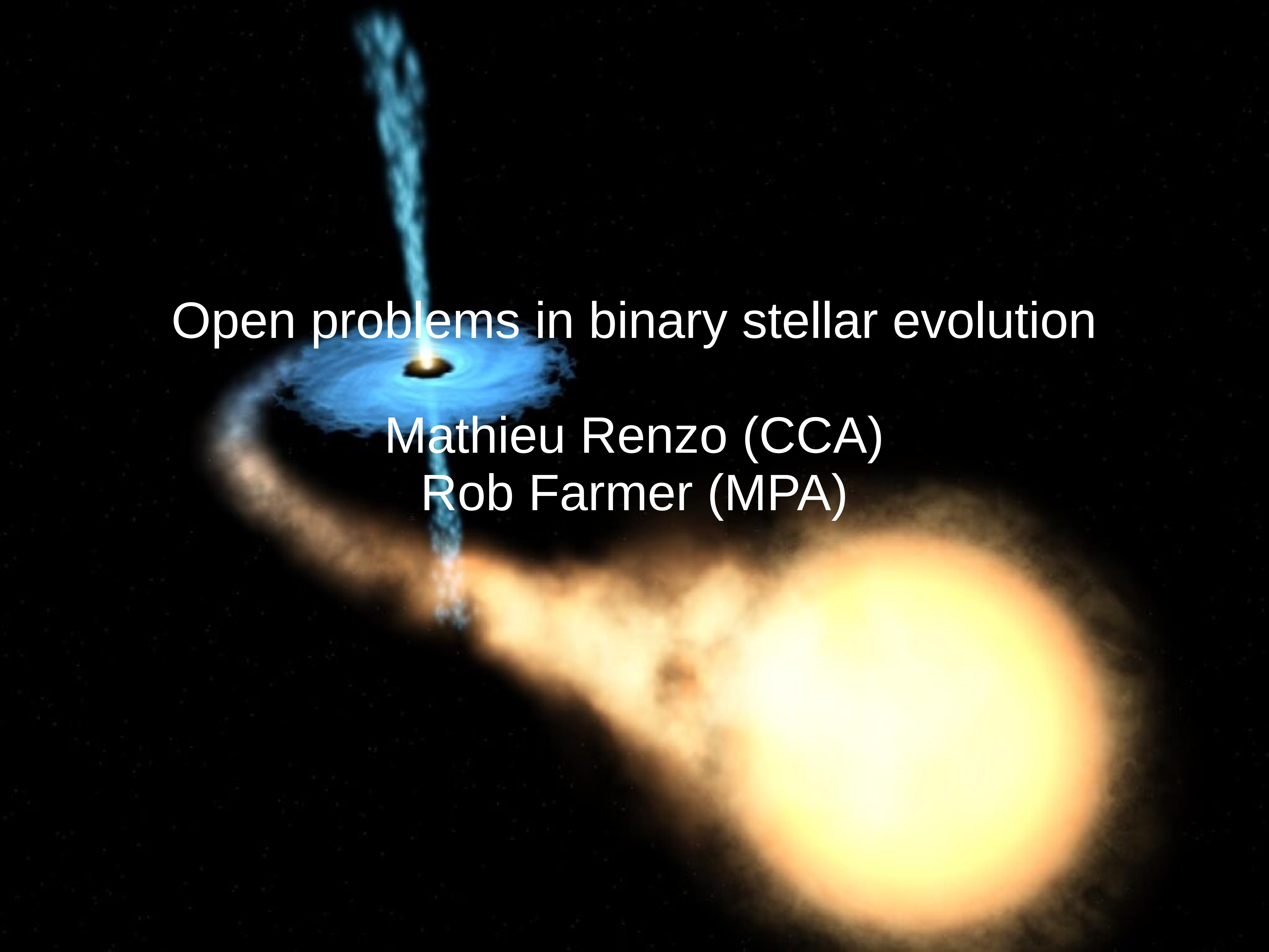
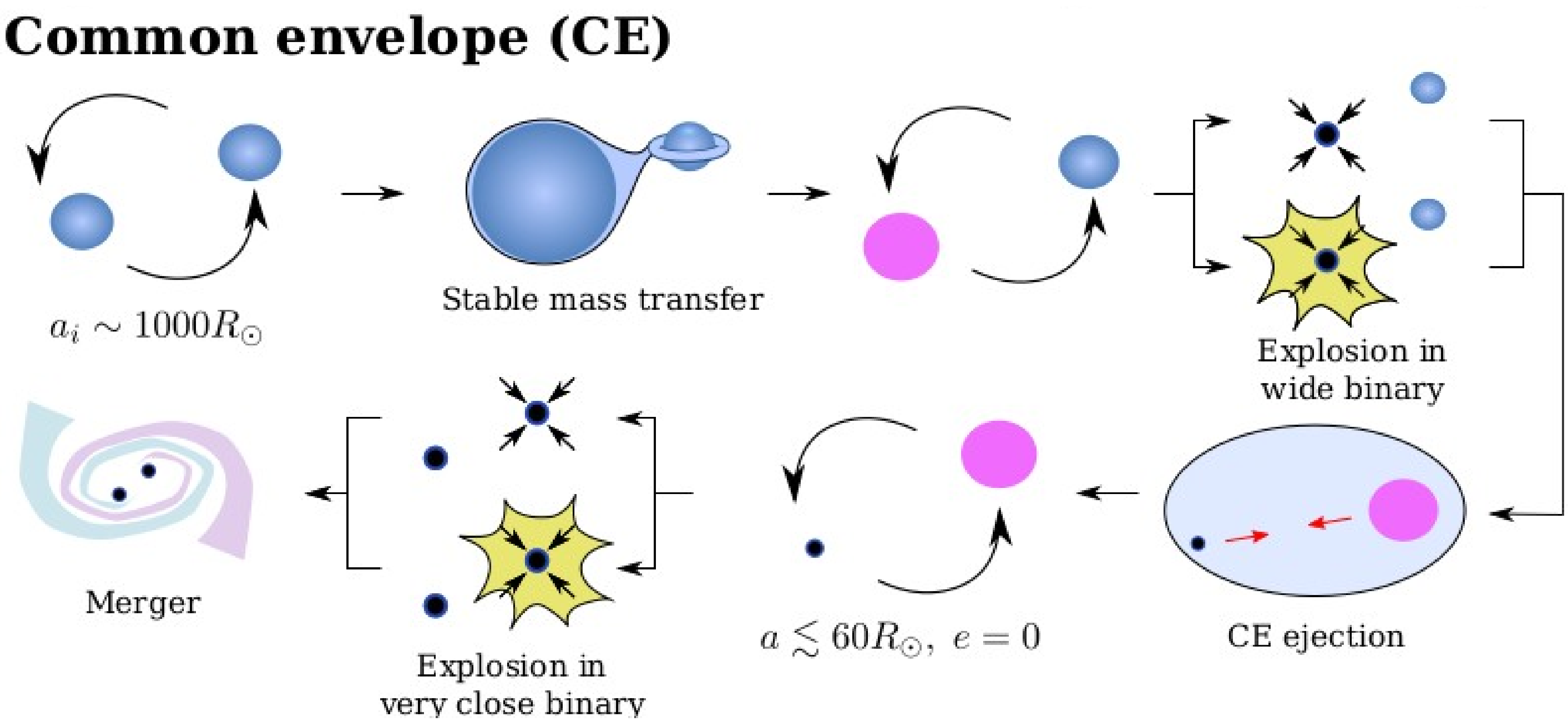


# Open problems in binary stellar evolution

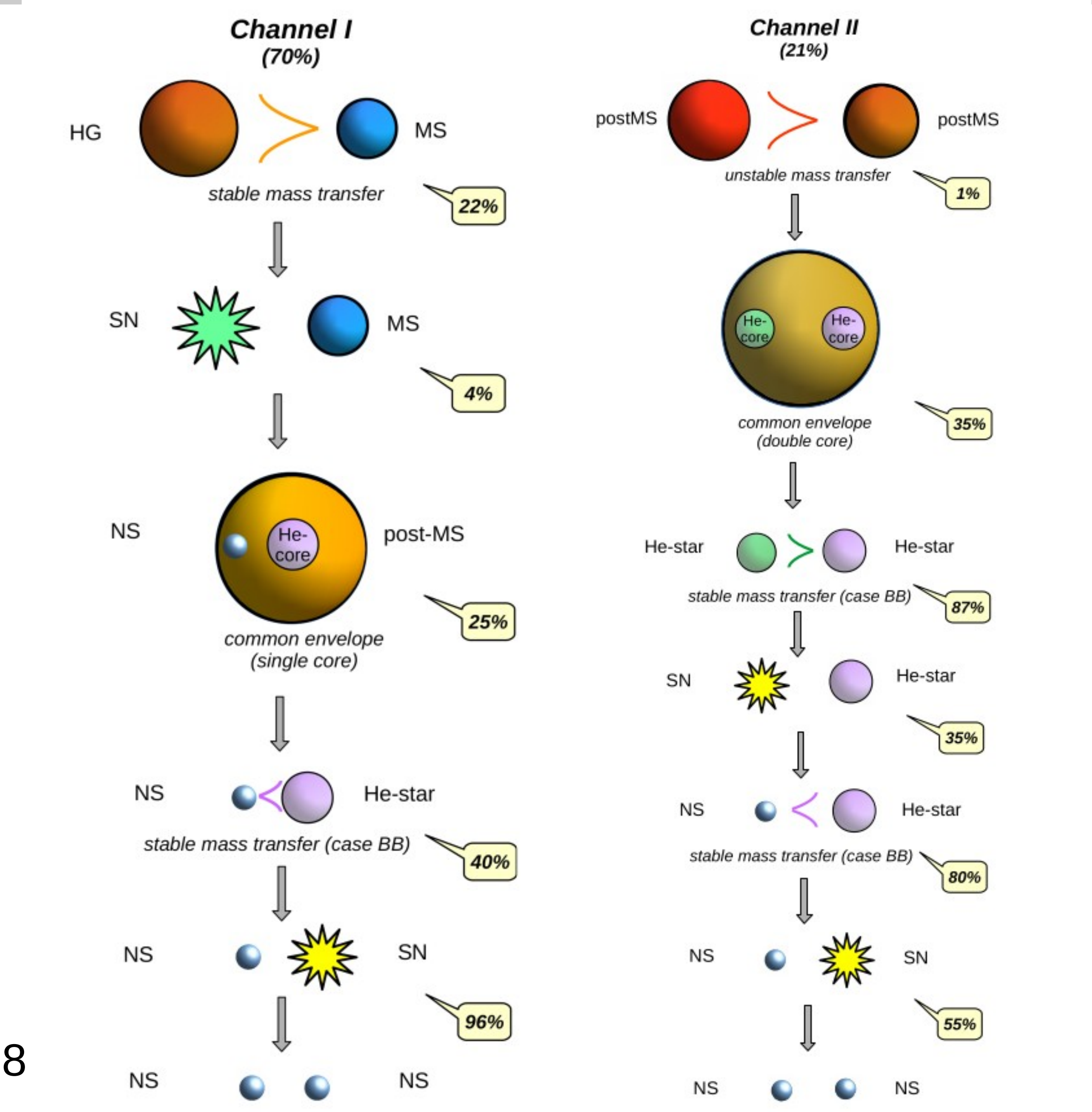

Mathieu Renzo (CCA)
Rob Farmer (MPA)

# When is this important?



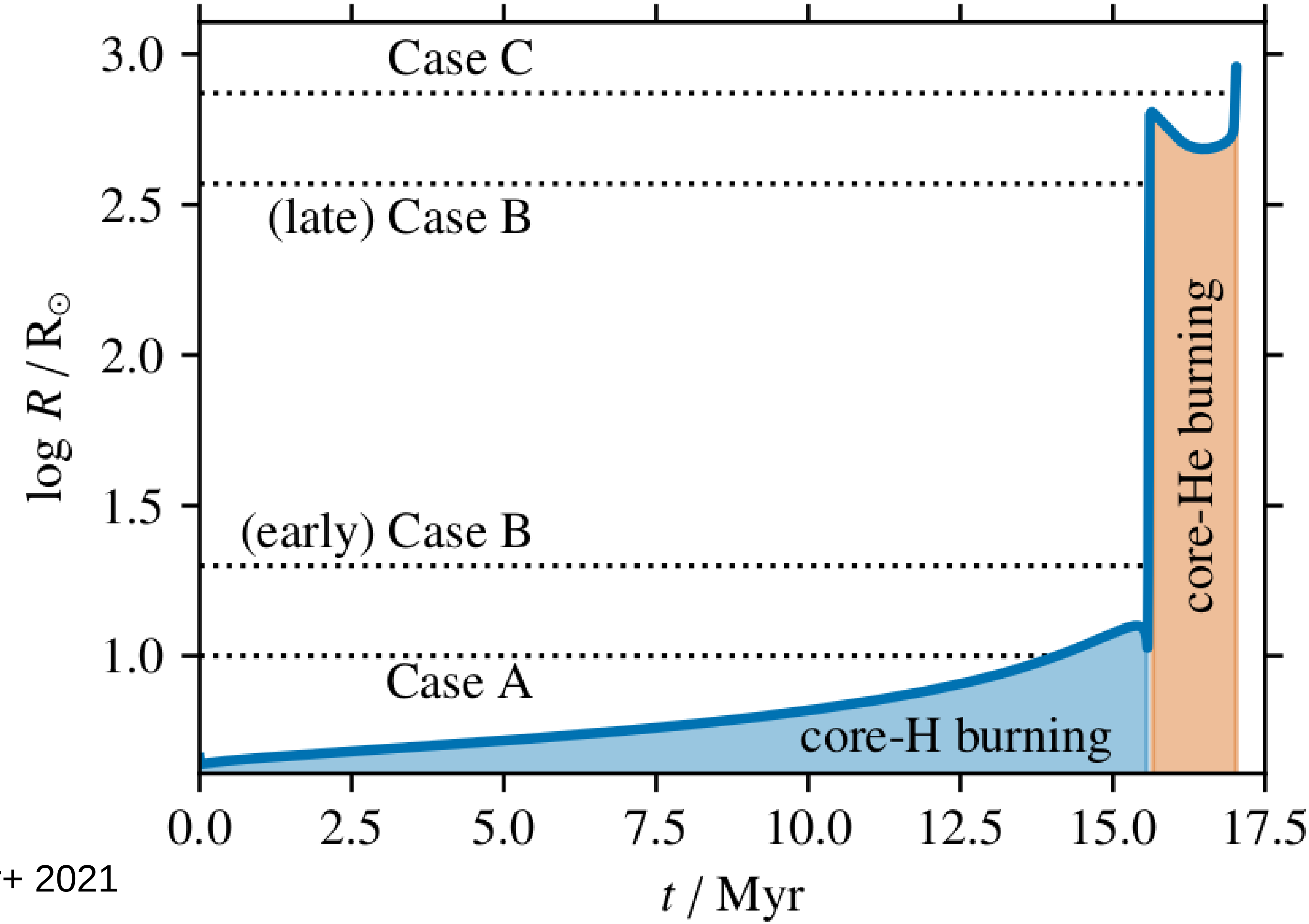

Marchant+ 2019

# When is this important?




Vigna-Gómez+ 2018

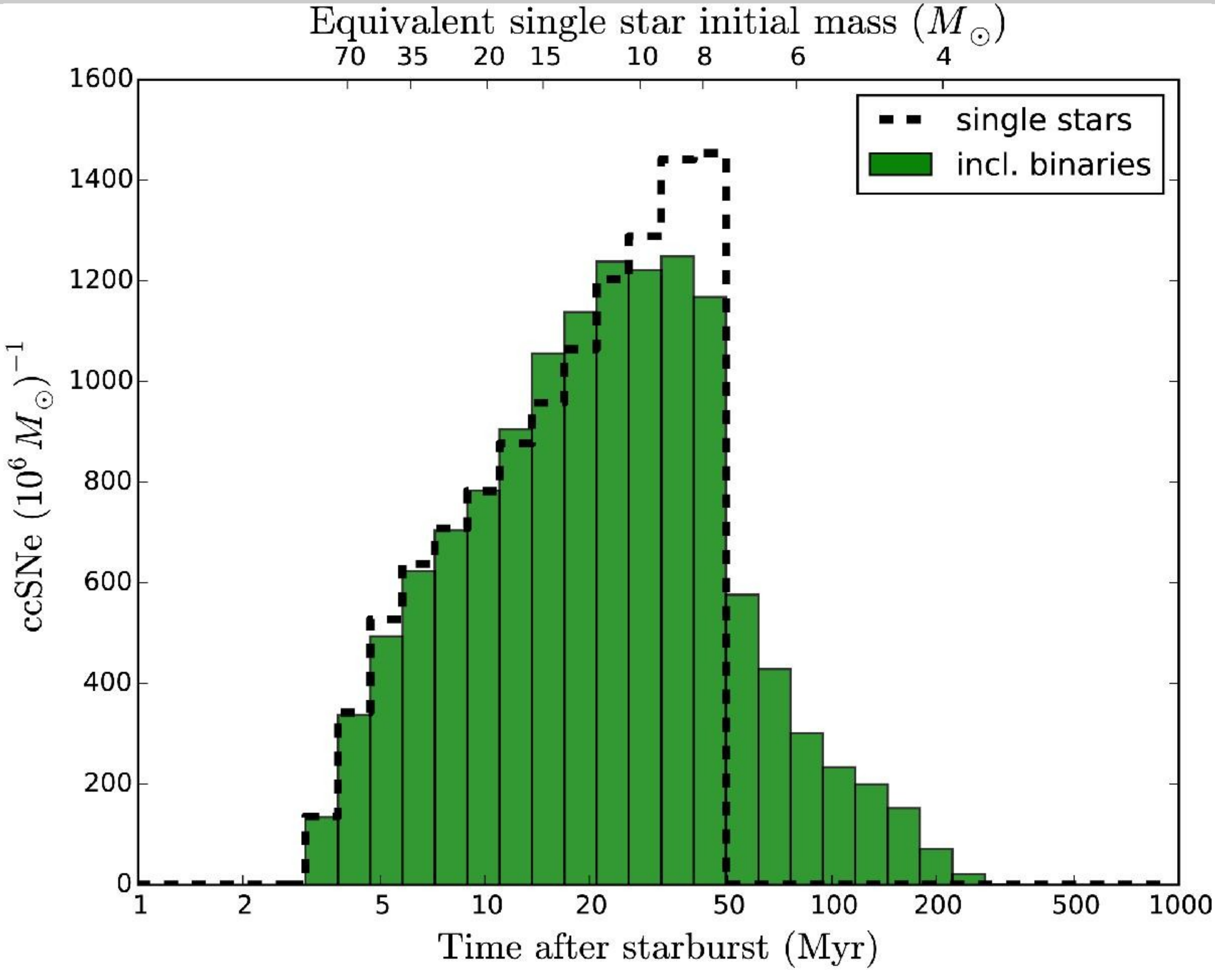
# Mass transfer




Schneider+ 2021

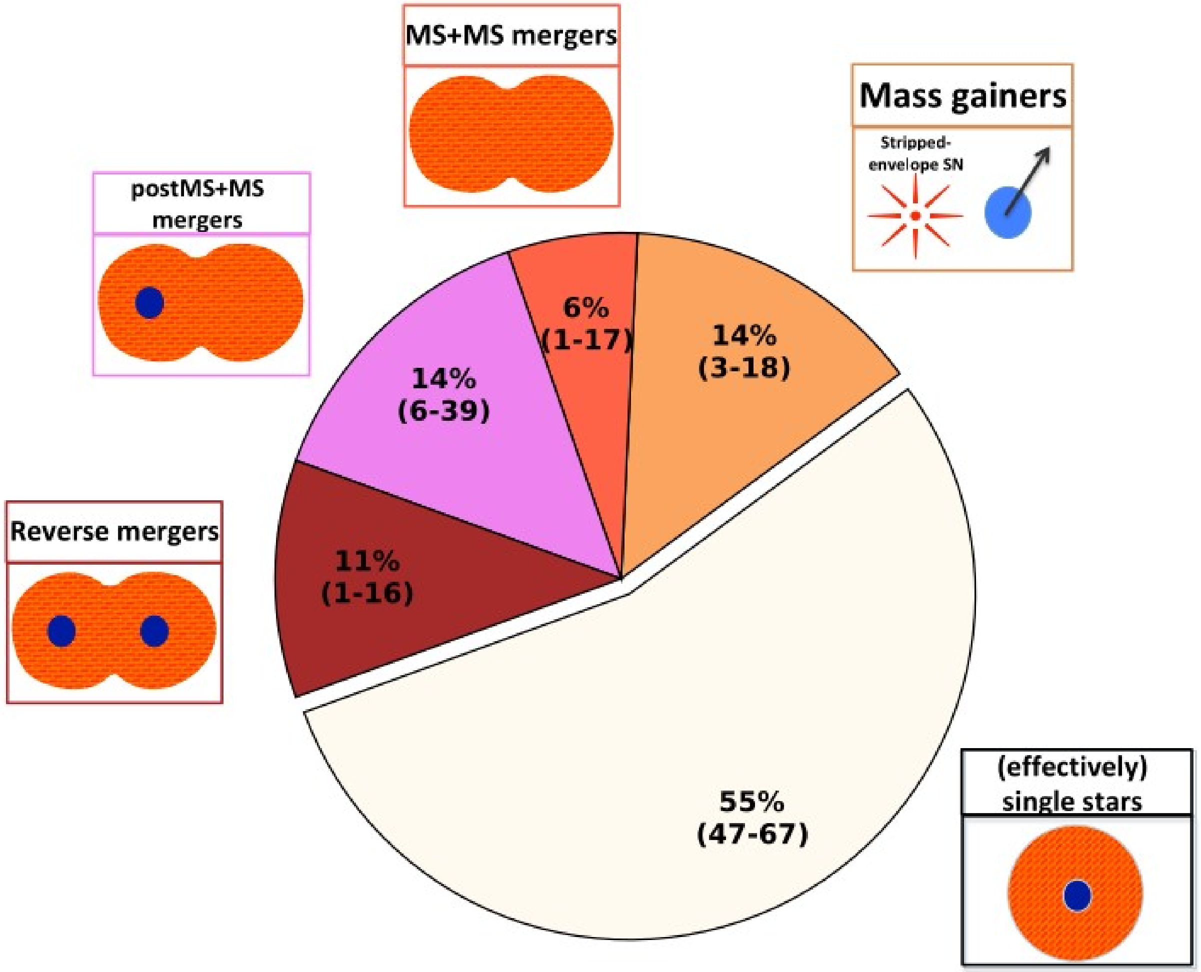
What happens to the accretor?

# Mass change



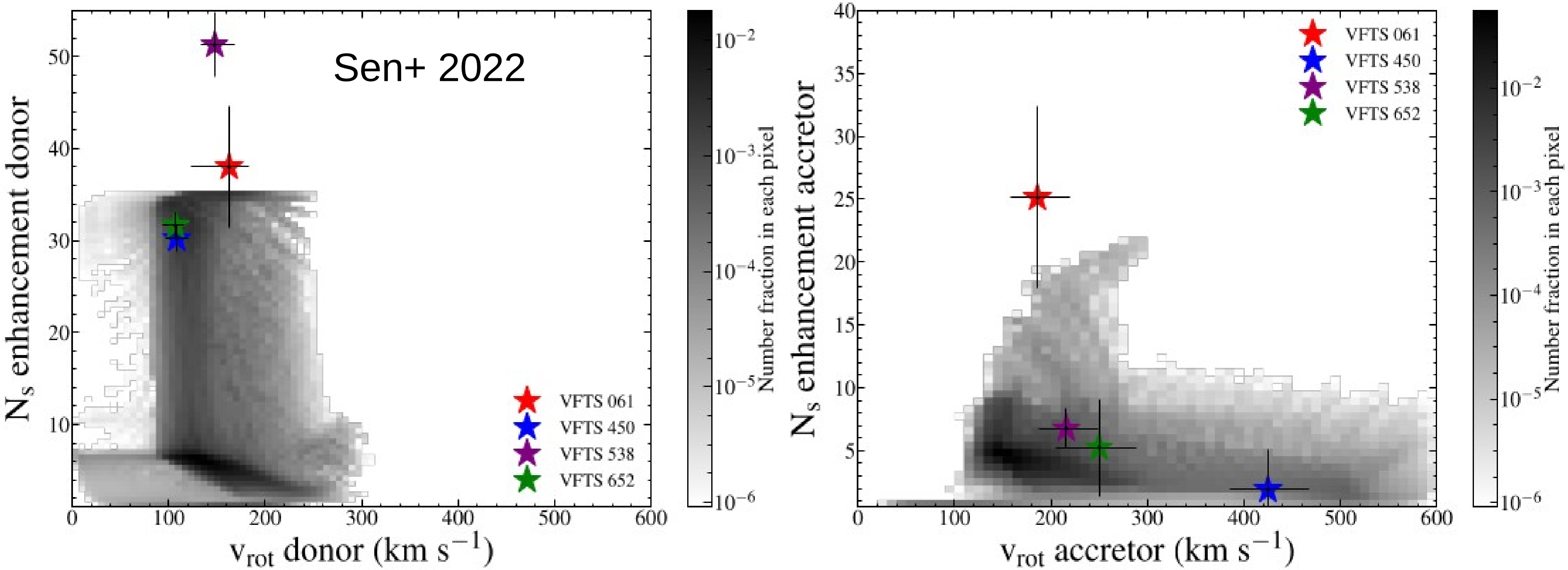

Zapartas+ 2017

# Fraction of H-rich SNe



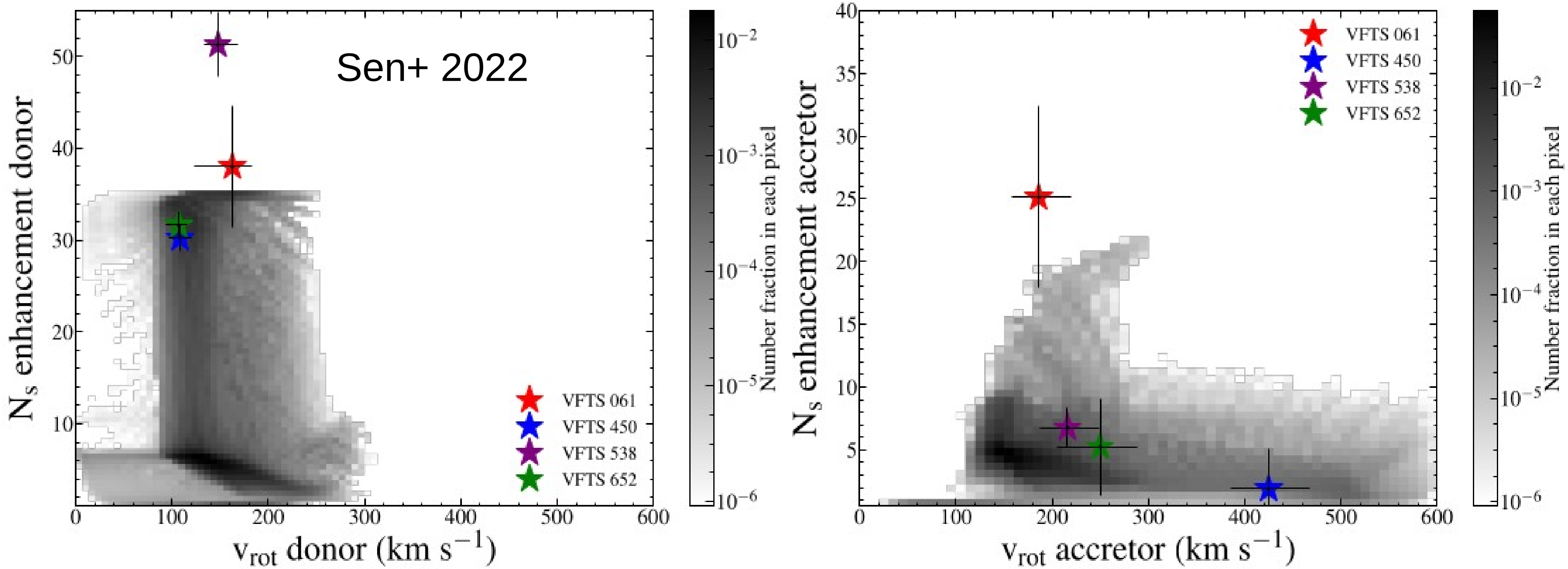

Zapartas+ 2019

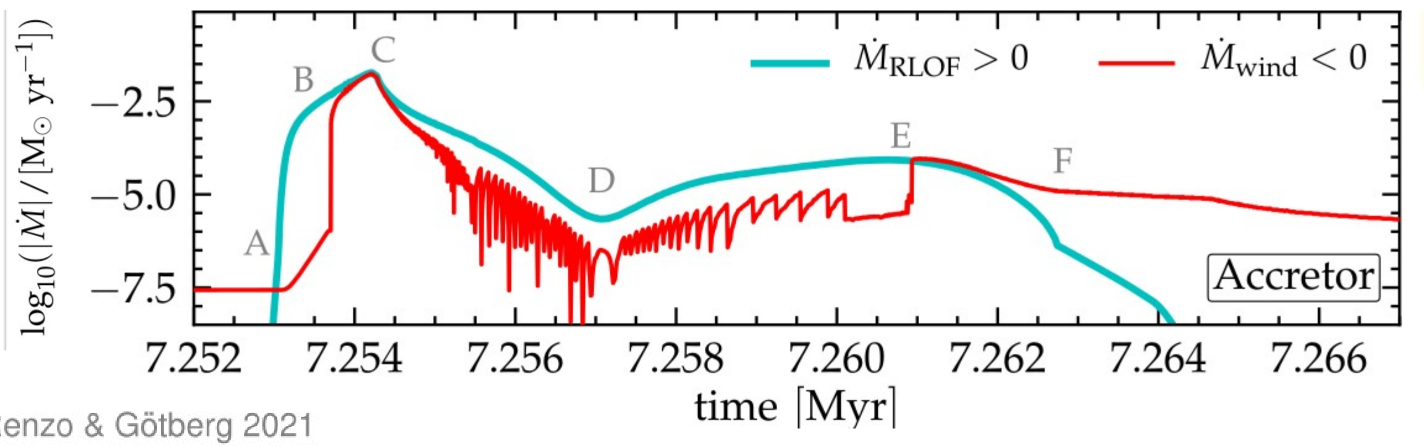
# Spin up



Sen+ 2022
$N_S$ enhancement donor
$v_{rot}$ donor (km $s^{-1}$)
VFTS 061
VFTS 450
VFTS 538
VFTS 652
Number fraction in each pixel
$N_S$ enhancement accretor
$v_{rot}$ accretor (km $s^{-1}$)

# Spin up




Renzo & Götberg 2021

# Rejuvenation

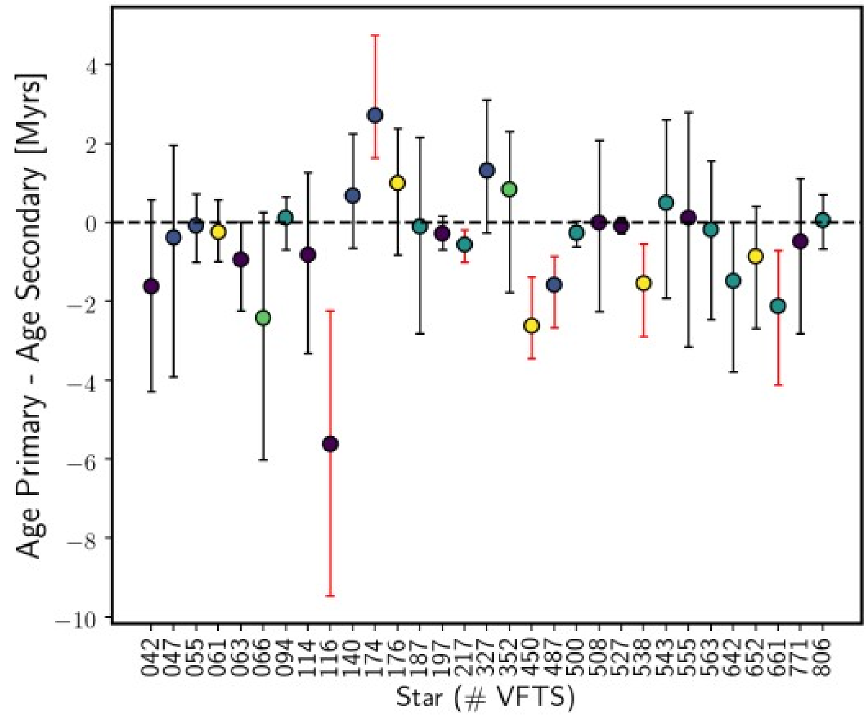
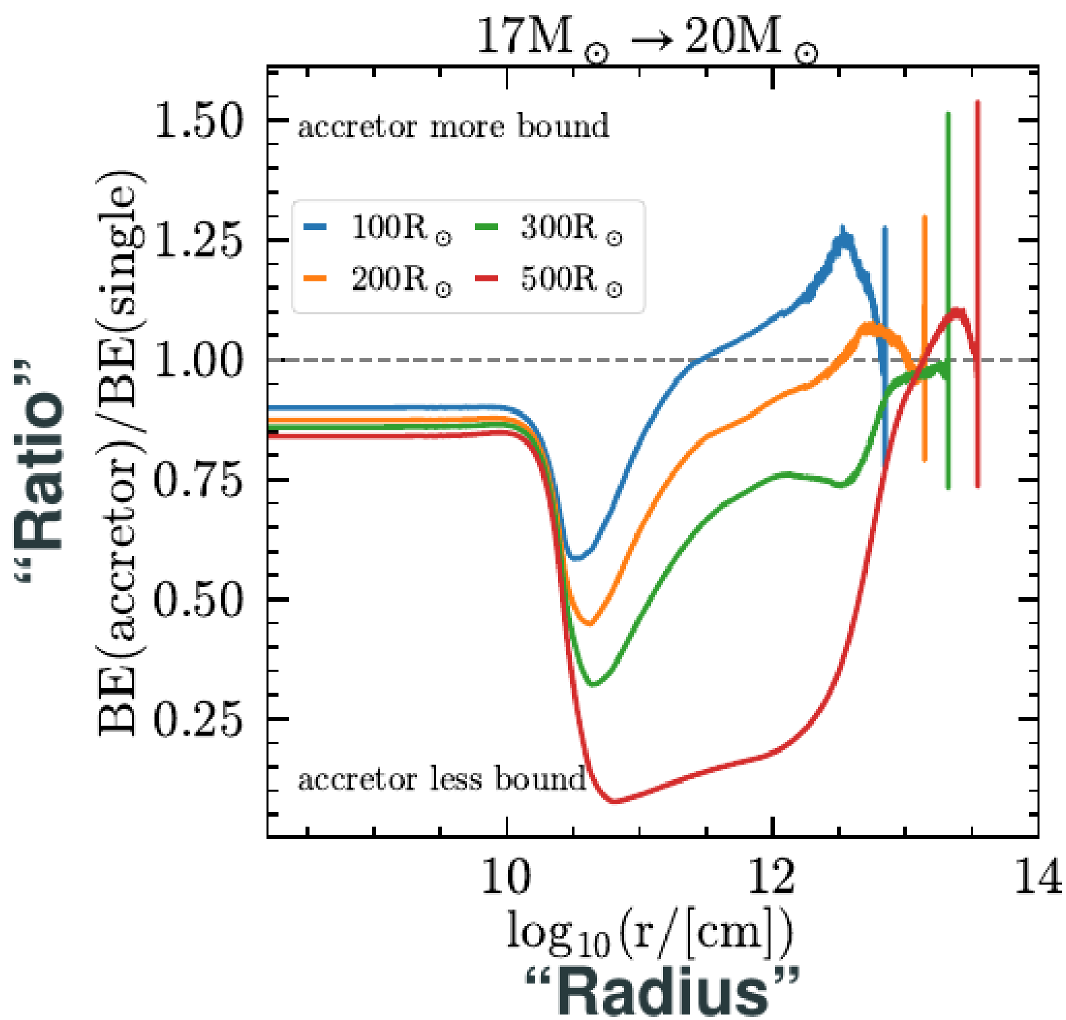



**Fig. 9.** Difference between the ages of the primary and secondary stars as a function of the system identification. The ages are from BONNSAI. The colour-code is given for the different subsamples given in Sect. 4, from dark blue for subsample 1 to yellow for group 5. The red error bars indicate that the systems are not coeval.

Mahy+ 2020

## RLOF-accretors are better CE-donors: easier to unbind at given $R$




Renzo *et al.*, in prep.

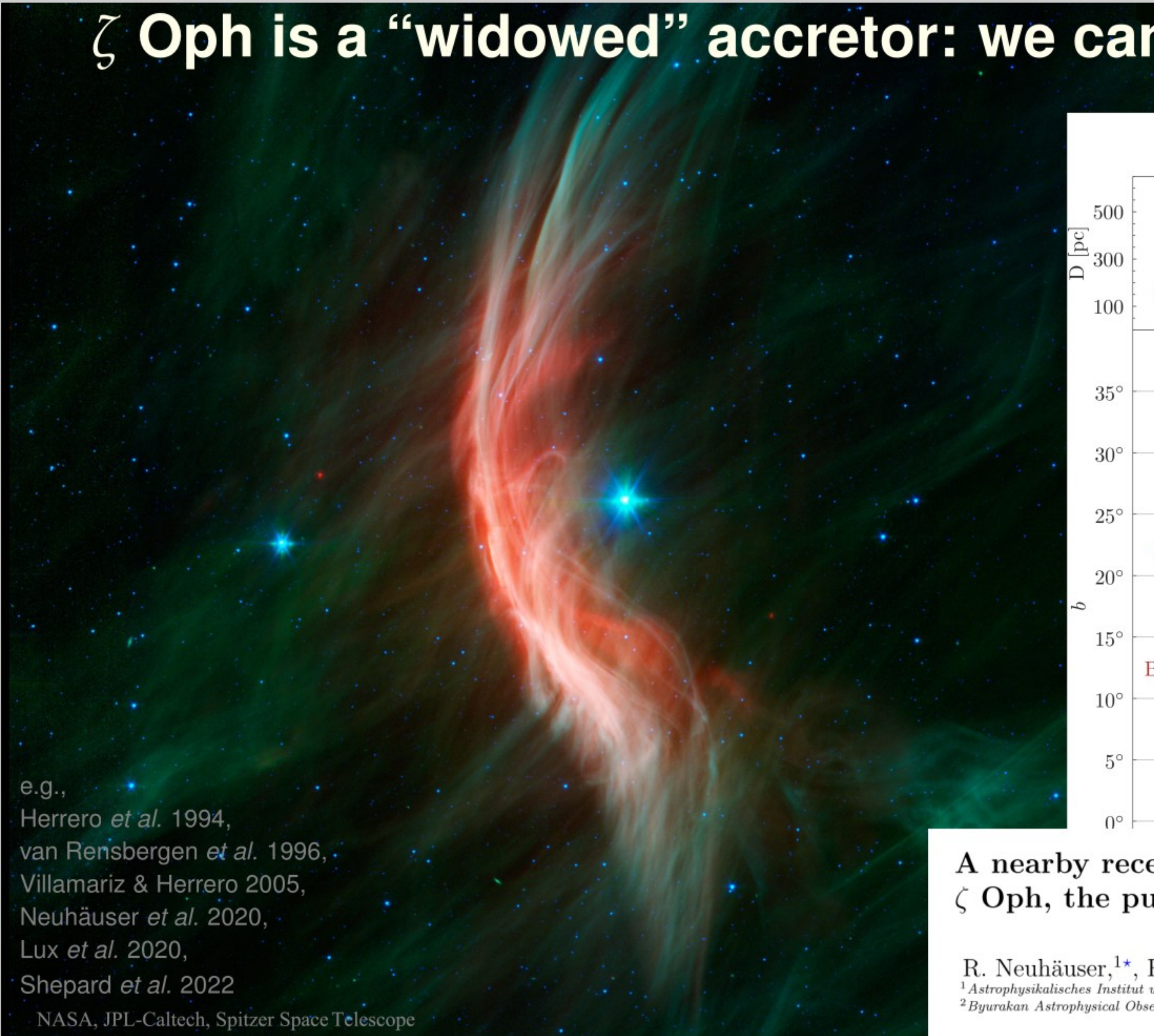
# Case study

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

e.g.,
Herrero *et al.* 1994,
van Rensbergen *et al.* 1996,
Villamariz & Herrero 2005,
Neuhäuser *et al.* 2020,
Lux *et al.* 2020,
Shepard *et al.* 2022

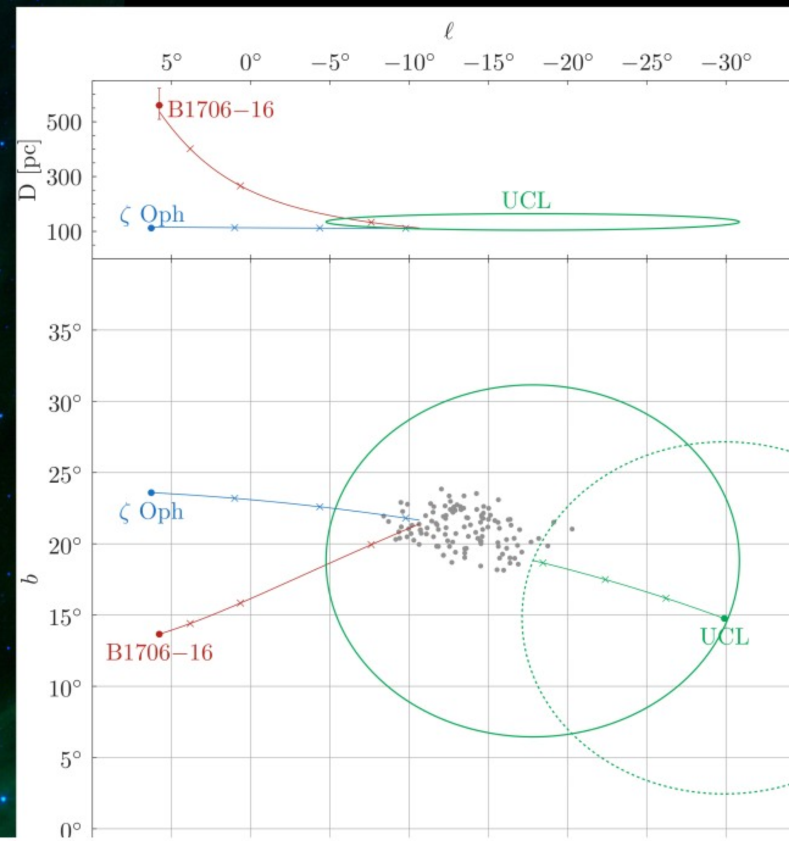
NASA, JPL-Caltech, Spitzer Space Telescope

# $\zeta$ Oph is a “widowed” accretor: we can trace it back to a NS



e.g.,
Herrero *et al.* 1994,
van Rensbergen *et al.* 1996,
Villamariz & Herrero 2005,
Neuhäuser *et al.* 2020,
Lux *et al.* 2020,
Shepard *et al.* 2022

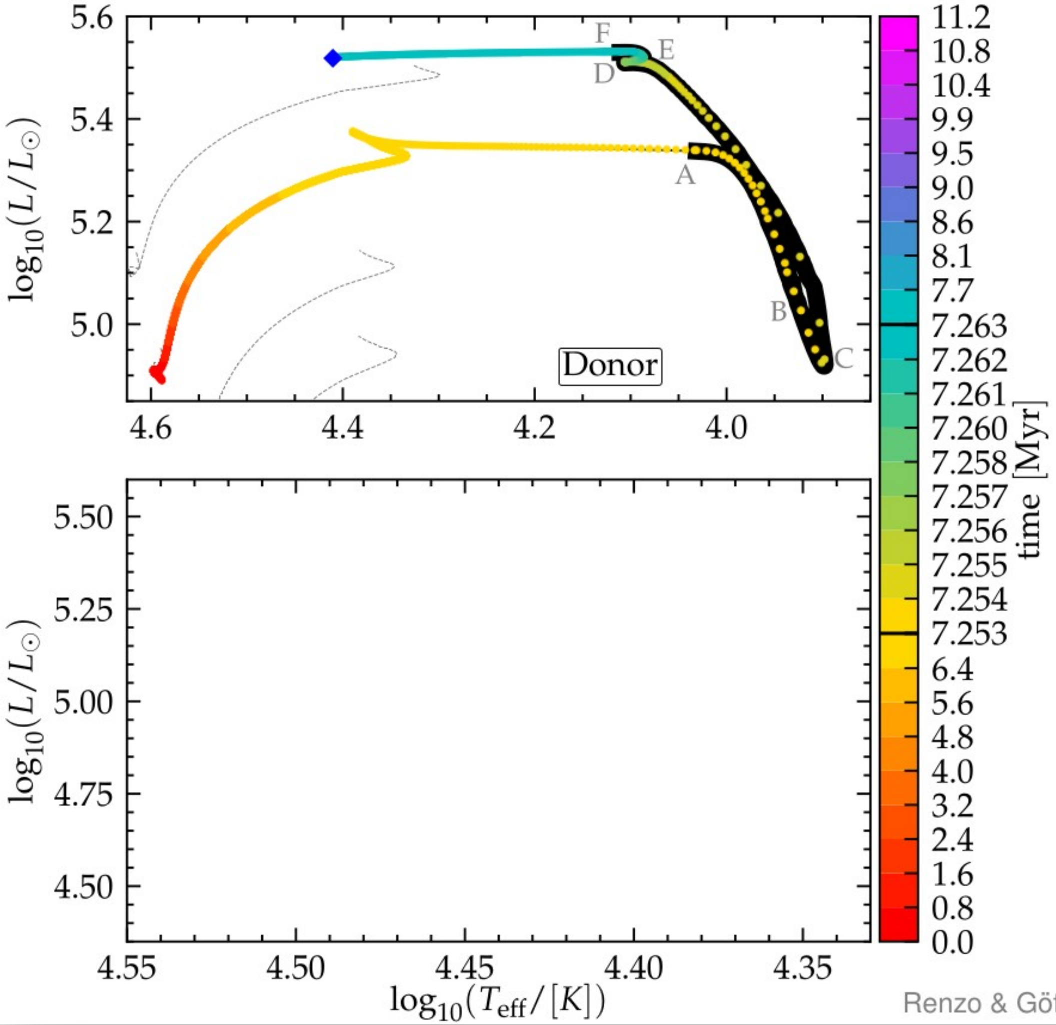
NASA, JPL-Caltech, Spitzer Space Telescope




**A nearby recent supernova that ejected the runaway star $\zeta$ 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*

# Hertzsprung-Russel diagram of both stars: the donor

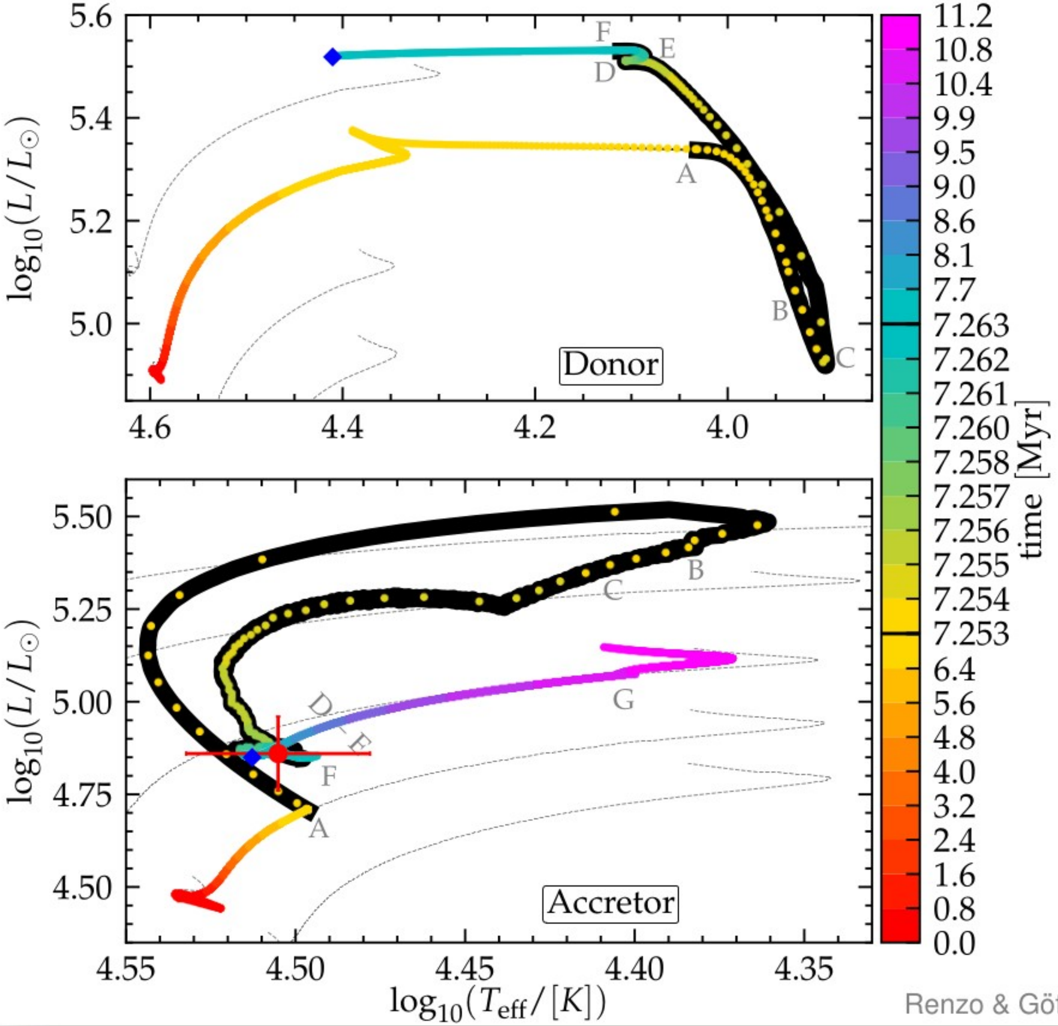



Renzo & Götberg 2021

**Roche lobe overflow is short**

But has long-lasting impact on both stars.

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



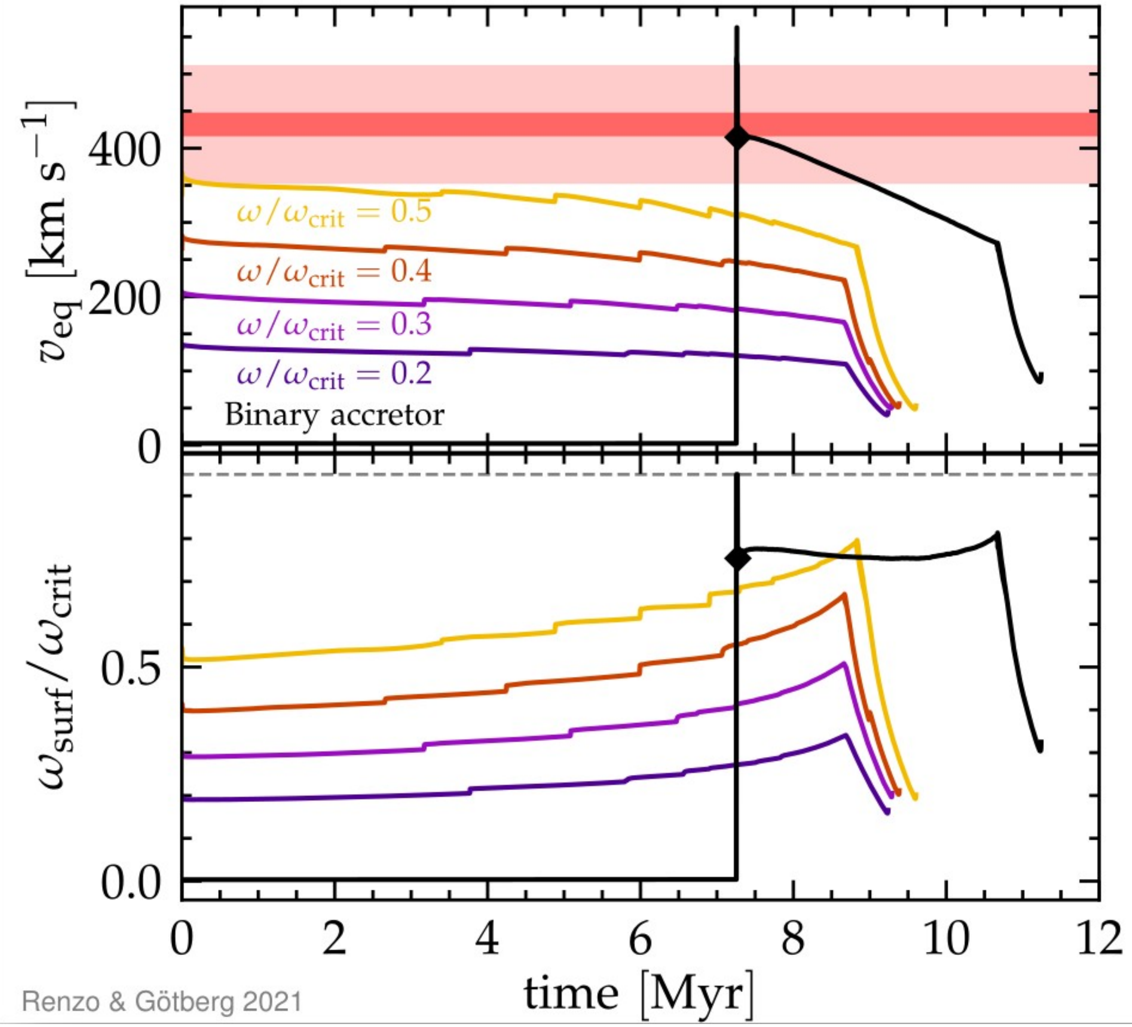

Renzo & Götberg 2021

**Roche lobe overflow is short**

But has long-lasting impact on both stars.

data from Villamàriz & Herrero 05

## Surface rotation rate: Be/Oe stars from binaries



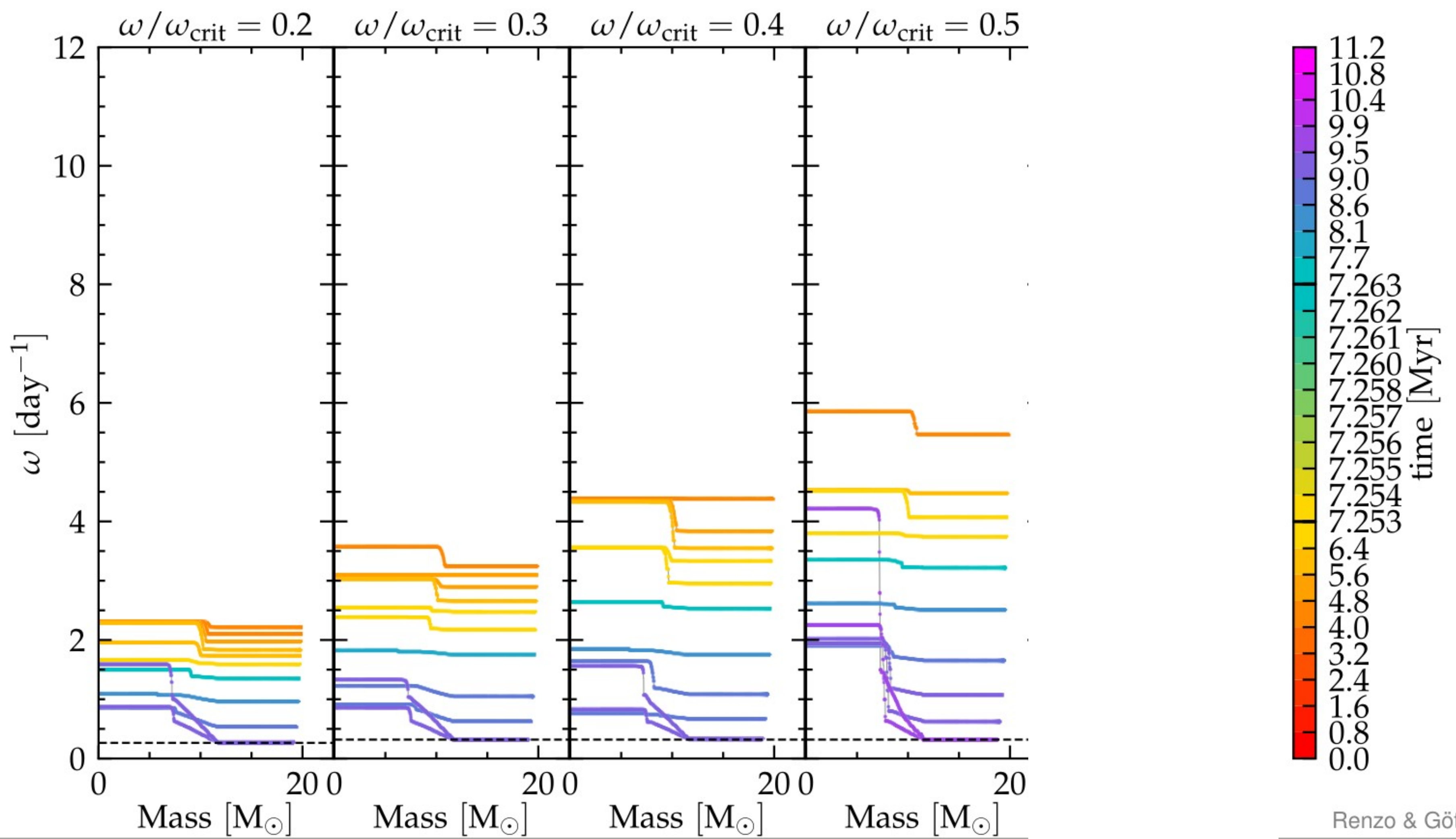

- but overestimating by $\sim 100\times$ wind mass loss!

Renzo & Götberg 2021

# Internal rotational profile: accretor

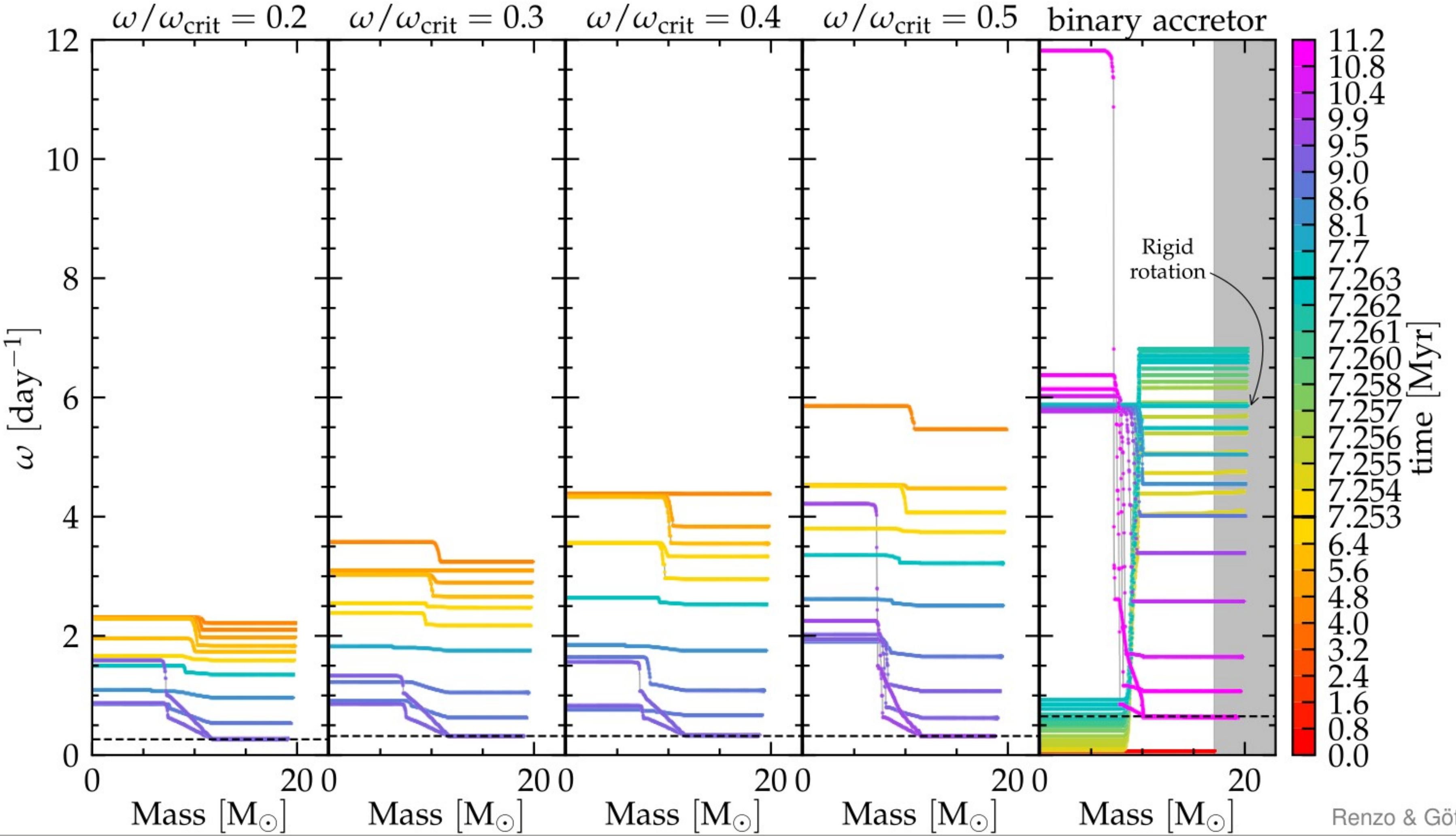

Renzo & Götberg 2021

# Internal rotational profile: accretor




Renzo & Götberg 2021

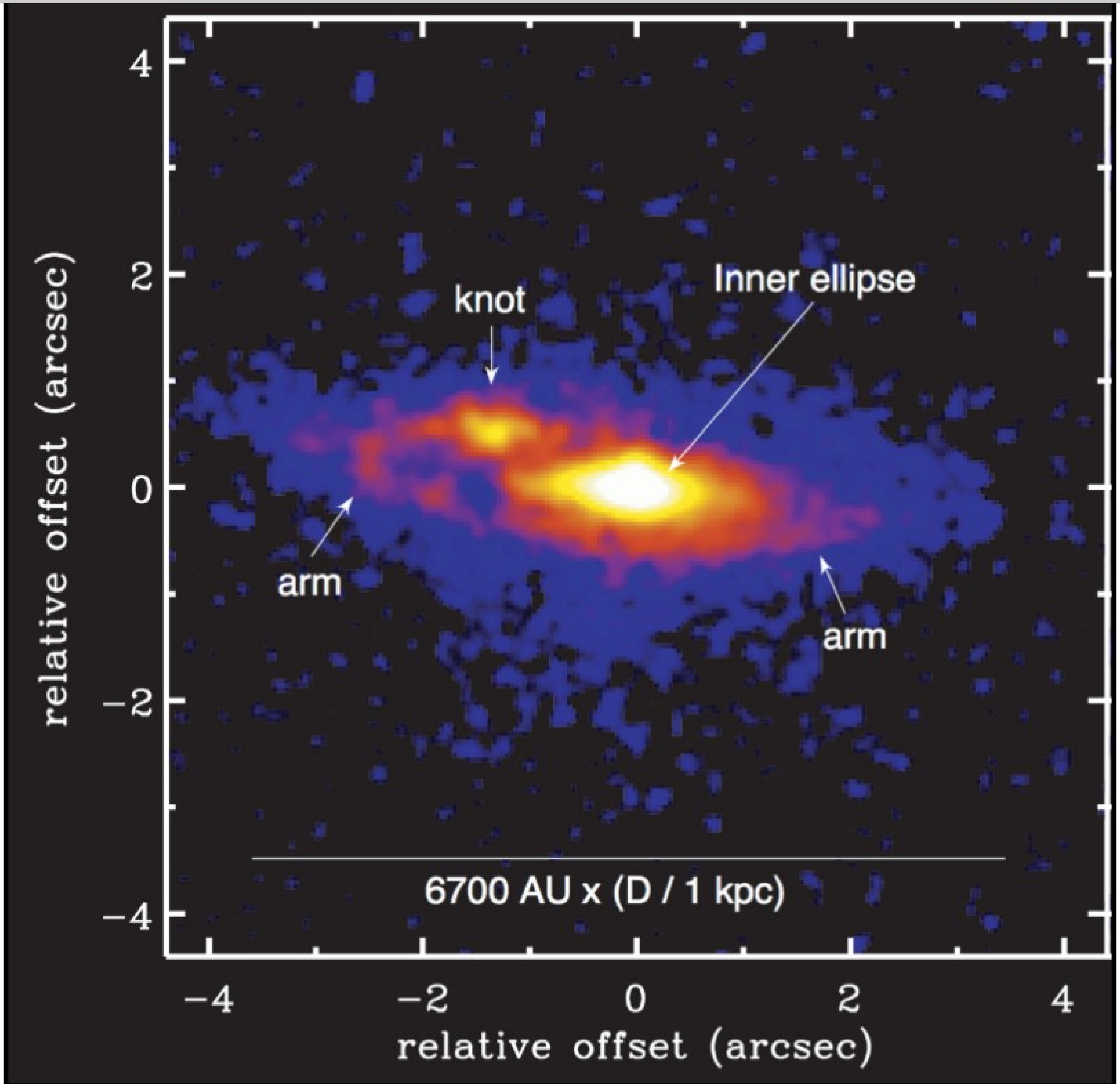
# Internal rotational profile: accretor




Renzo & Götberg 2021

What about disks?

# What are we modelling?




Mauerhan+ 2015

NaSt1 (WR 122)

# What do we do?

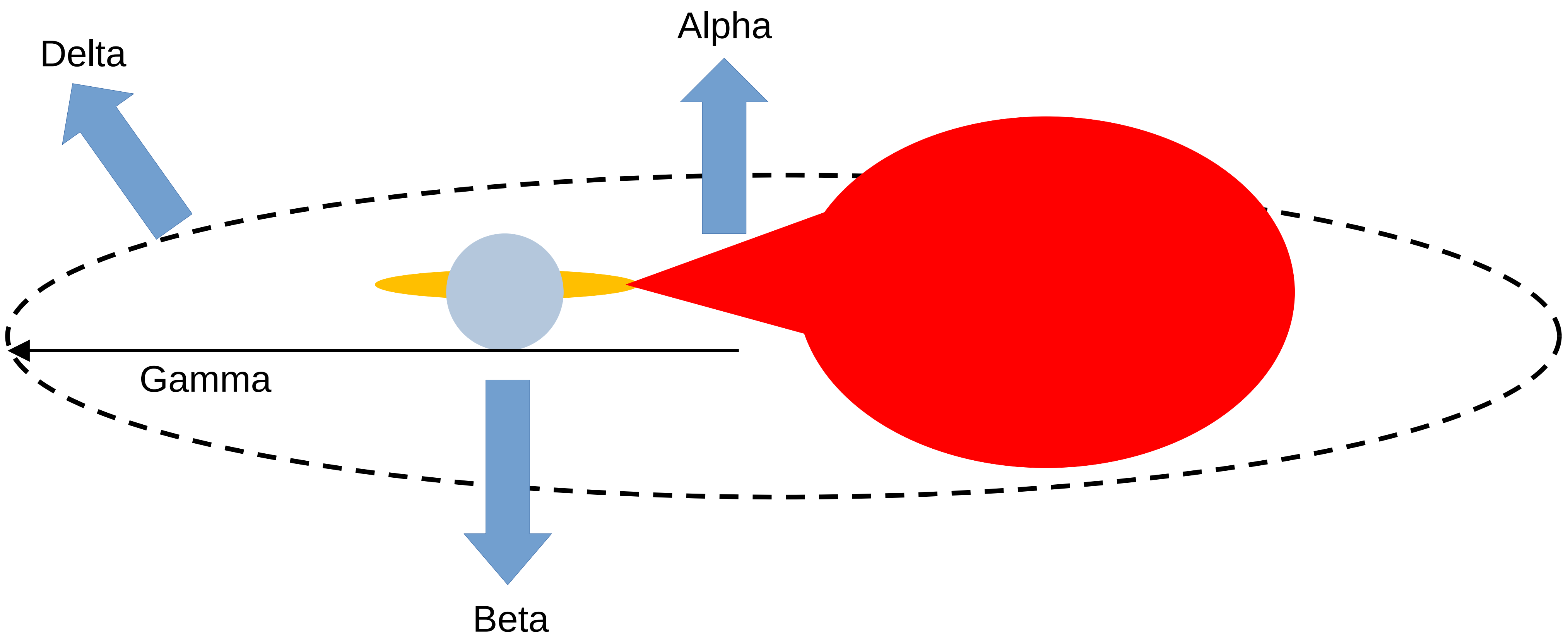
where $\alpha_{\mathrm{mt}}$, $\beta_{\mathrm{mt}}$, and $\delta_{\mathrm{mt}}$ are respectively the fractions of mass transferred that is lost from the vicinity of the donor, accretor and circumbinary toroid, and $\gamma_{\mathrm{mt}}^2 a$ is the radius of the toroid. Ignoring winds, the efficiency of mass transfer is then given by $f_{\mathrm{mt}} = 1 - \alpha_{\mathrm{mt}} - \beta_{\mathrm{mt}} - \delta_{\mathrm{mt}}$. When accretion is limited to $\dot{M}_{\mathrm{Edd}}$, efficiency of accretion is given by

$$f_{\mathrm{mt}} = \min\left(1 - \alpha_{\mathrm{mt}} - \beta_{\mathrm{mt}} - \delta_{\mathrm{mt}}, \left|\dot{M}_{\mathrm{Edd}}/\dot{M}_{\mathrm{RLOF}}\right|\right), \quad (6)$$

and the additional mass being lost is added to the $\beta_{\mathrm{mt}}\dot{M}_{\mathrm{RLOF}}$ term in Equation (5), i.e., it is assumed to leave the system carrying the specific orbital angular momentum of the accretor.

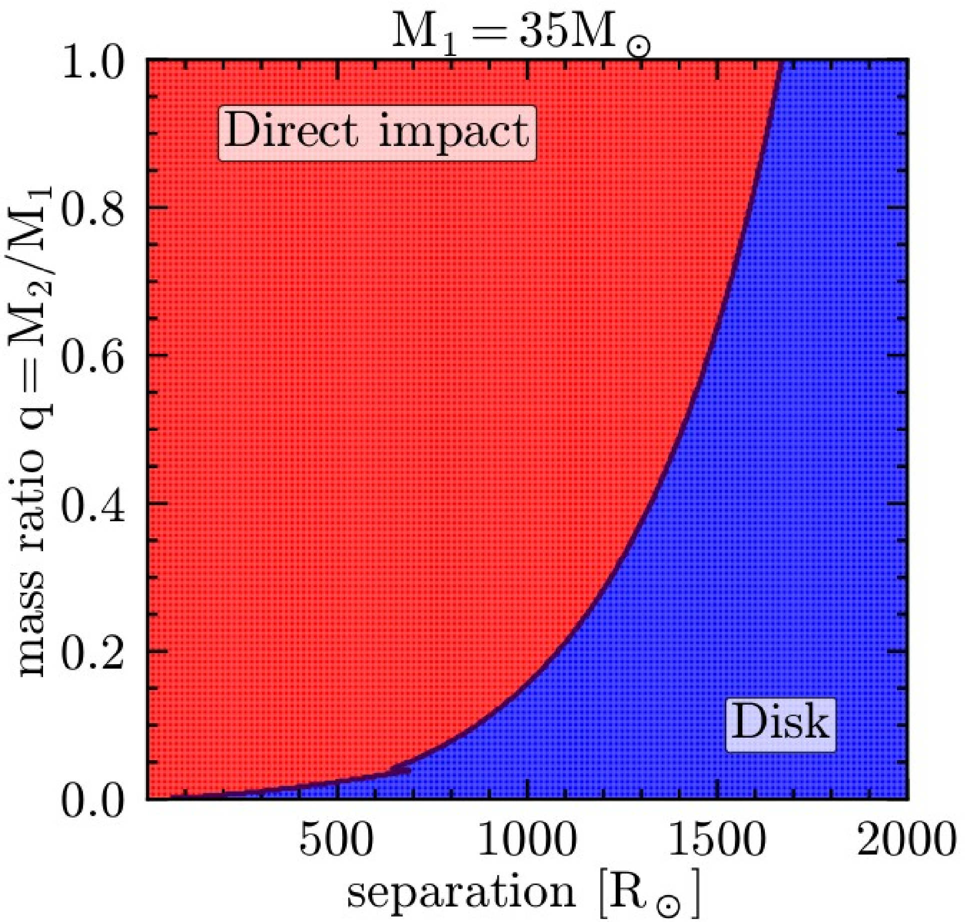
Paxton+2015 (BEC, BPASS, Pop Syn, +others)

# What do we do?




$$f_{\rm mt} = \min\Big(1 - \alpha_{\rm mt} - \beta_{\rm mt} - \delta_{\rm mt}, \left|\dot{M}_{\rm Edd}/\dot{M}_{\rm RLOF}\right|\Big),$$

## Disk only if the stream misses the accretor: $R_{\min} > R_2(t = t_{\rm RLOF})$

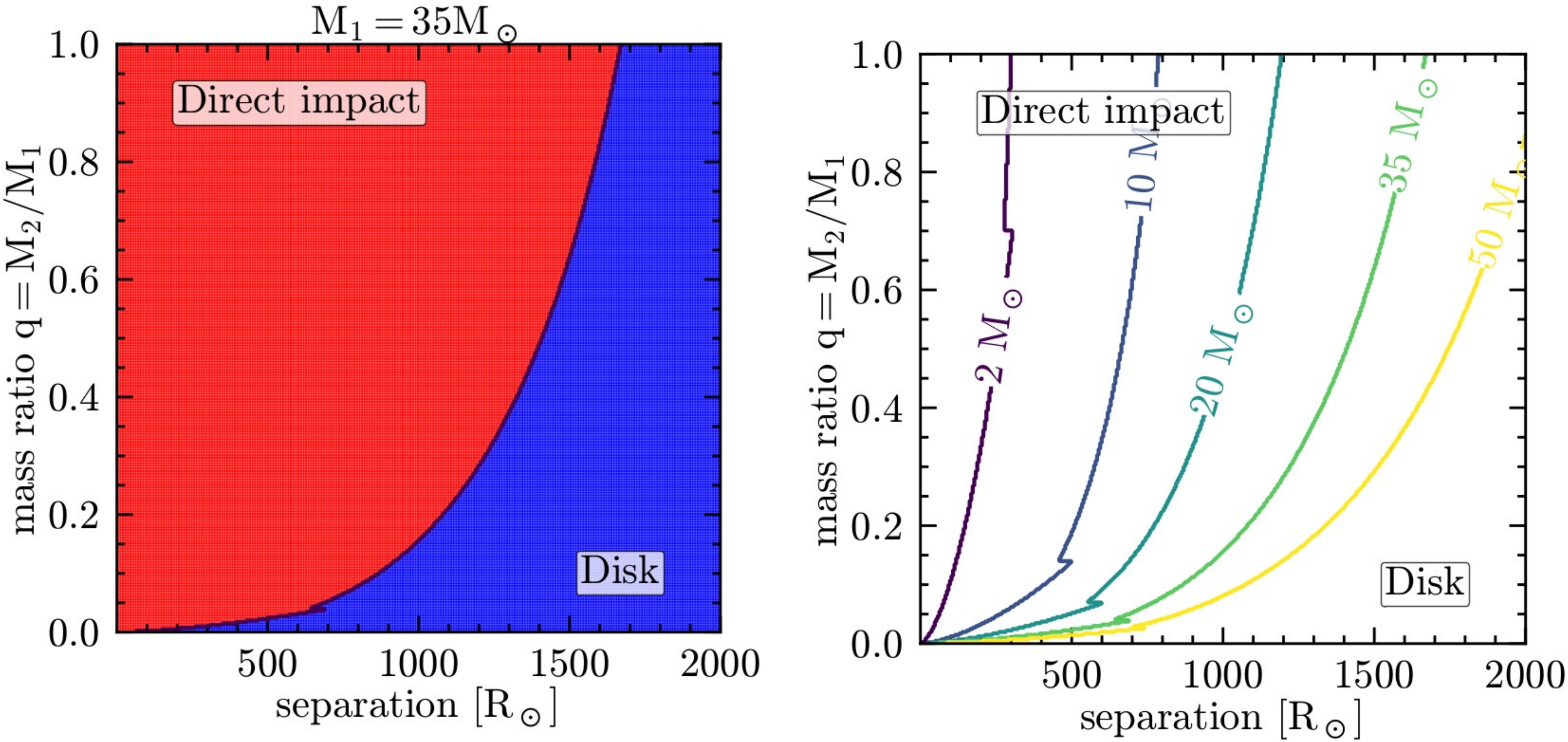



- Neglect evolution of $R_2 \equiv R_2(t)$
- Likely different accretion and spin-up
- Differences compare favorably to LMC eclipsing binaries

Sen *et al.* 2022

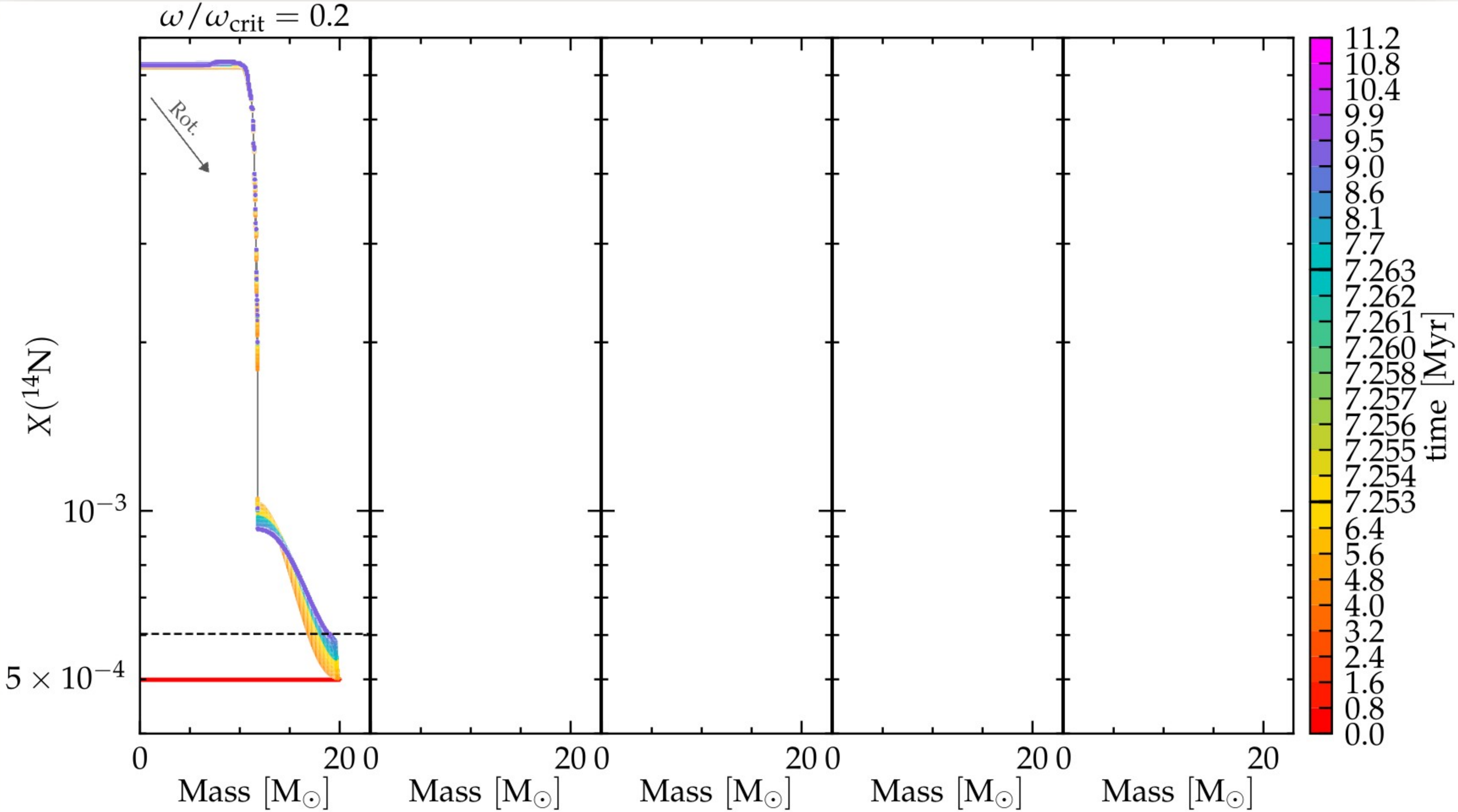
see also Lubow & Shu 1975, Ulrich & Burger 1976, de Mink *et al.* 2013

## Disk only if the stream misses the accretor: $R_{\min} > R_2(t = t_{\rm RLOF})$

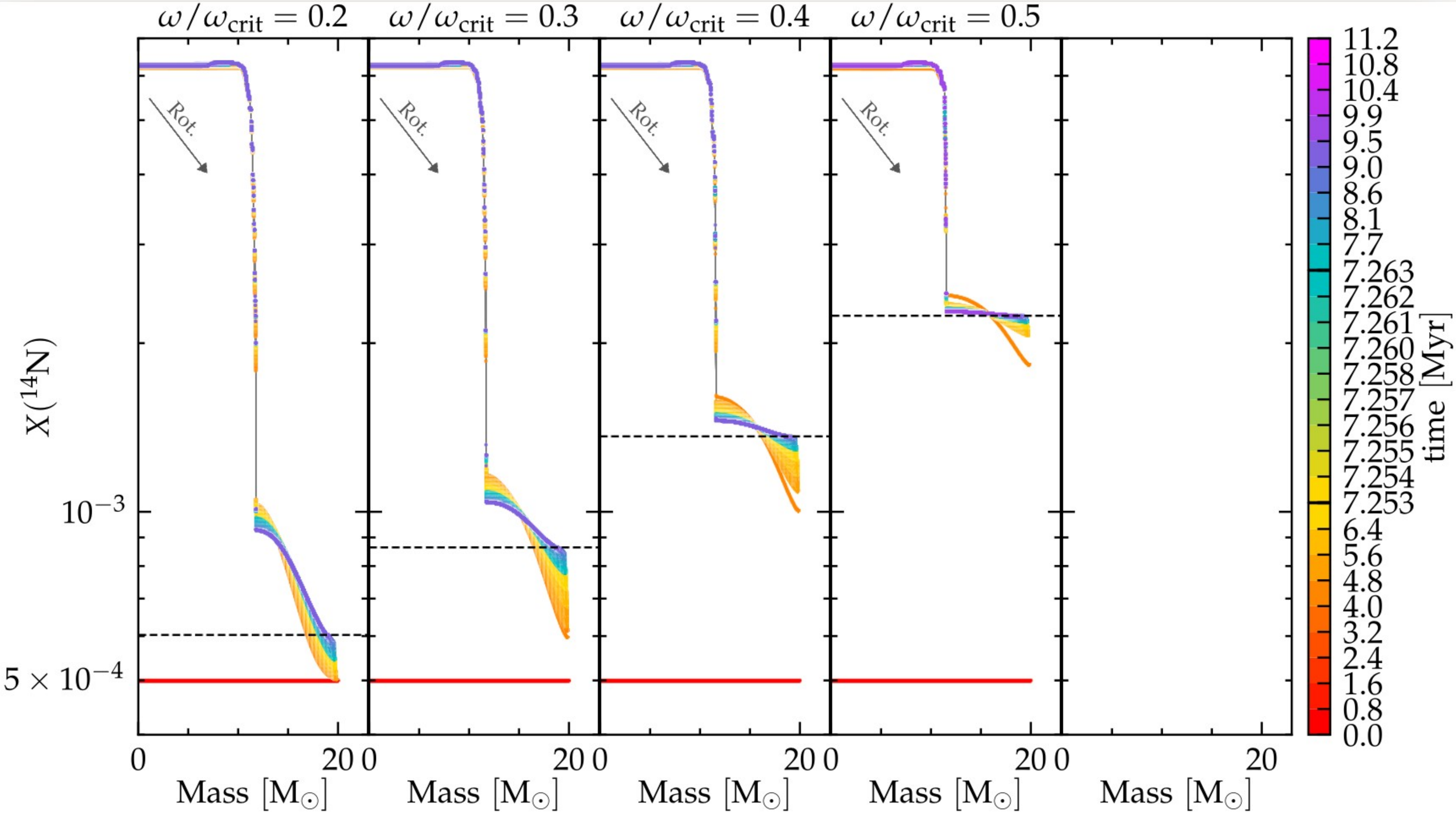



see also Lubow & Shu 1975, Ulrich & Burger 1976, de Mink *et al.* 2013

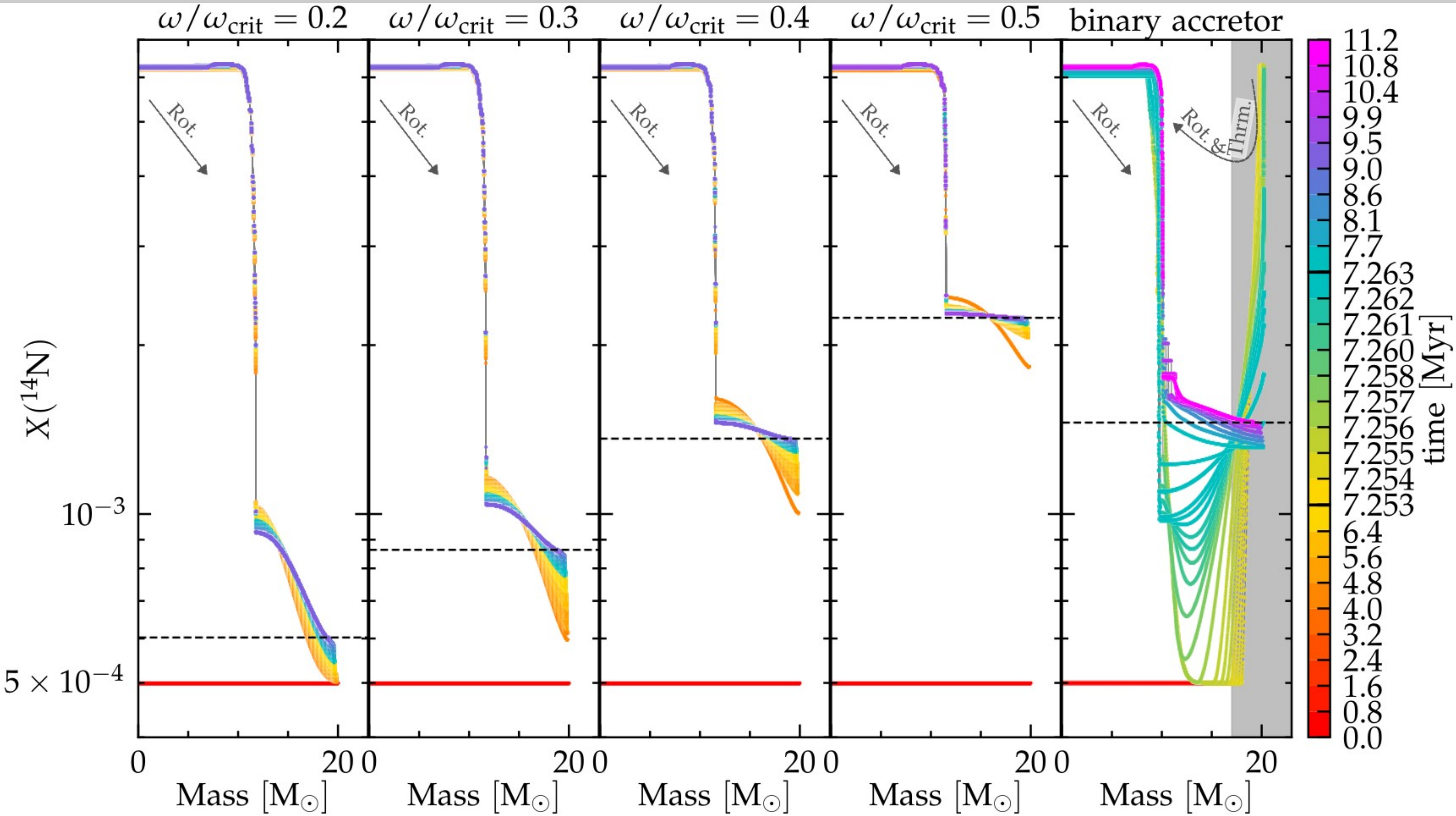
# Backup slides



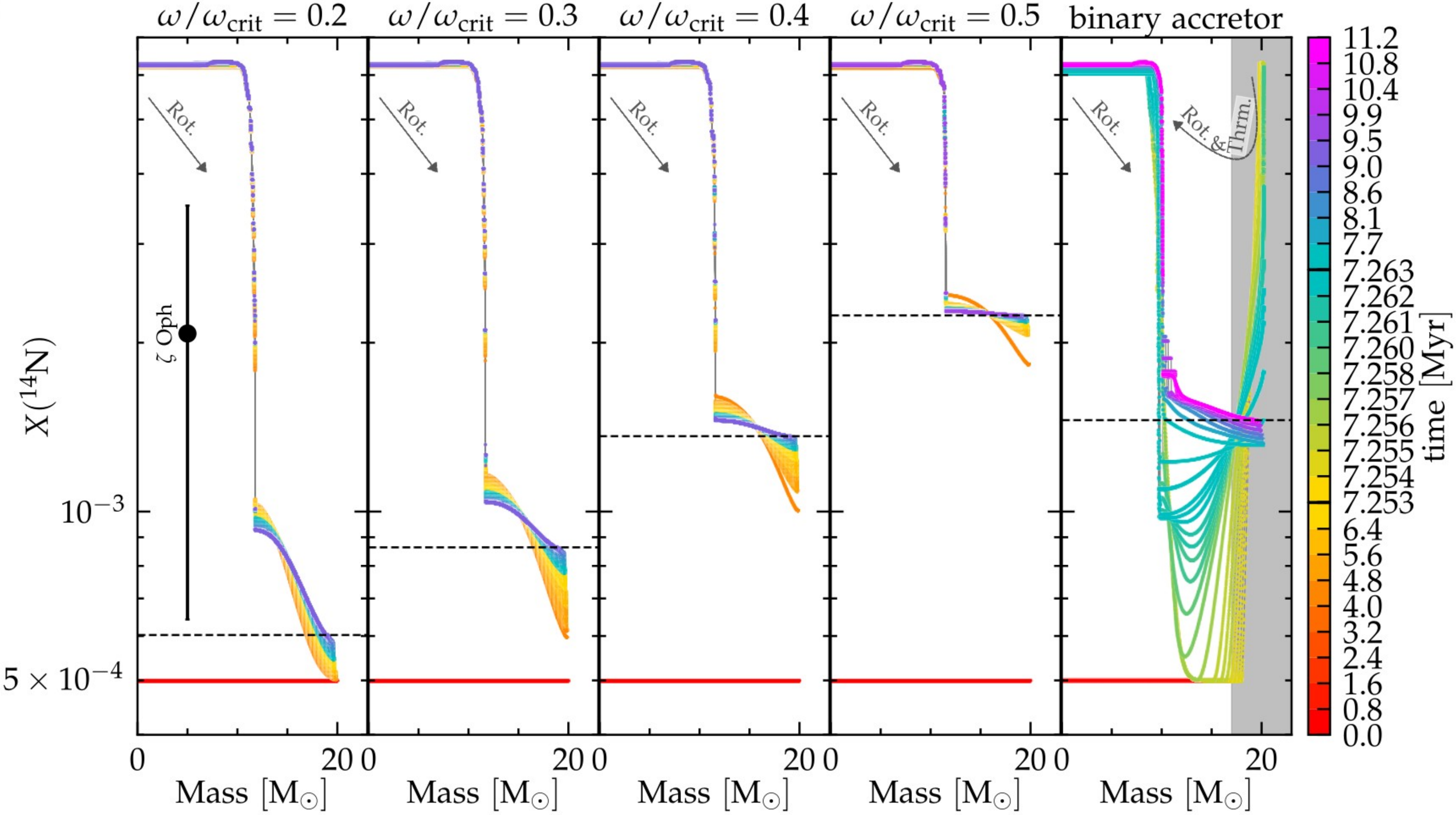
$\omega/\omega_{\rm crit} = 0.2$
Rot.
$X(^{14}N)$
$10^{-3}$
$5 \times 10^{-4}$
0
20
Mass [M$_\odot$]
time [Myr]
11.2
10.8
10.4
9.9
9.5
9.0
8.6
8.1
7.7
7.263
7.262
7.261
7.260
7.258
7.257
7.256
7.255
7.254
7.253
6.4
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0



$\omega/\omega_{crit} = 0.2$
$\omega/\omega_{crit} = 0.3$
$\omega/\omega_{crit} = 0.4$
$\omega/\omega_{crit} = 0.5$
Rot.
$X(^{14}N)$
$10^{-3}$
$5 \times 10^{-4}$
0
20
Mass [$M_\odot$]
time [Myr]
11.2
10.8
10.4
9.9
9.5
9.0
8.6
8.1
7.7
7.263
7.262
7.261
7.260
7.258
7.257
7.256
7.255
7.254
7.253
6.4
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0



$\omega/\omega_{\rm crit} = 0.2$
$\omega/\omega_{\rm crit} = 0.3$
$\omega/\omega_{\rm crit} = 0.4$
$\omega/\omega_{\rm crit} = 0.5$
binary accretor
Rot.
Rot.&Thrm.
$X(^{14}N)$
$10^{-3}$
$5 \times 10^{-4}$
0
20
Mass [$M_\odot$]
time [Myr]
11.2
10.8
10.4
9.9
9.5
9.0
8.6
8.1
7.7
7.263
7.262
7.261
7.260
7.258
7.257
7.256
7.255
7.254
7.253
6.4
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0



ω/ω_crit = 0.2
ω/ω_crit = 0.3
ω/ω_crit = 0.4
ω/ω_crit = 0.5
binary accretor
Rot.
Rot. & Thrm.
ζ Oph
X(14N)
10−3
5 × 10−4
0
20
Mass [M⊙]
time [Myr]
11.2
10.8
10.4
9.9
9.5
9.0
8.6
8.1
7.7
7.263
7.262
7.261
7.260
7.258
7.257
7.256
7.255
7.254
7.253
6.4
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0