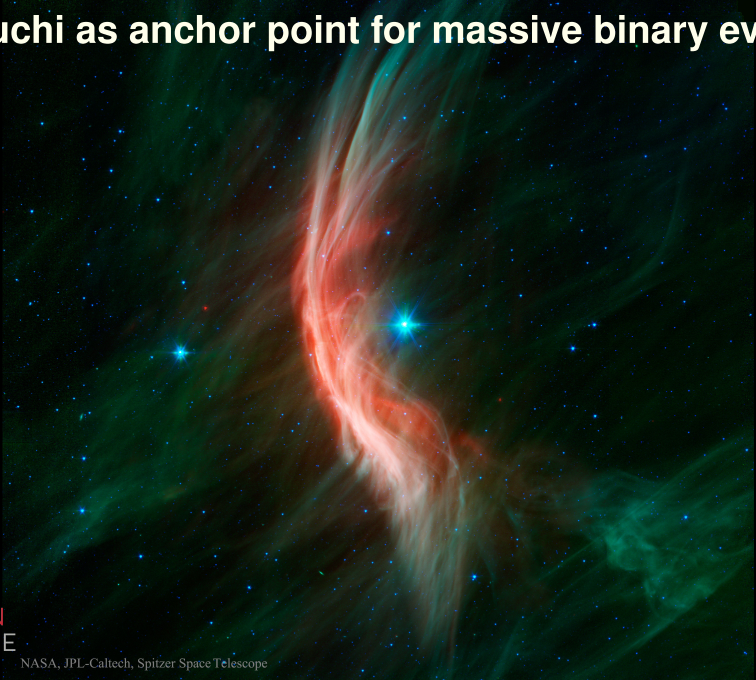
ζ Ophiuchi as anchor point for massive binary evolution



NASA, JPL-Caltech, Spitzer Space Telescope

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&

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Center for Computational Astrophysics

COLUMBIA UNIVERSITY

ζ Ophiuchi is the nearest O-type star to Earth: lots of data!

- Extreme surface rotation $v \sin(i) \gtrsim 350\,\mathrm{km\ s^{-1}}$
- (T_{eff}, L) position
- $Z \simeq Z_{\odot}$
- $^{4}\mathrm{He}$ and $^{14}\mathrm{N}$ rich
- Roughly solar $^{12}\mathrm{C}$ and $^{16}\mathrm{O}$
- High space velocity $20\,\mathrm{km\ s^{-1}} \lesssim v_{\mathrm{pec}} \lesssim 50\,\mathrm{km\ s^{-1}}$ $\Rightarrow$ bow shock

✗ Weak wind problem:

$$\log_{10}(|\dot{M}_{\mathrm{observed}}|) \simeq -8.8 \ll \log_{10}(|\dot{M}_{\mathrm{theory}}|) \simeq -6.8 \qquad [\mathrm{M_{\odot}\ yr^{-1}}]$$

Herrero *et al.* 92, Villamàriz & Herrero 05, Marcolino *et al.* 09, Lux *et al.* 20

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Rotational mixing does not seem to work!

Tested with Geneva and Brussels models

Villamàriz & Herrero 05, van Rensbergen *et al.* 96

Herrero *et al.* 92, Villamàriz & Herrero 05, Marcolino *et al.* 09, Lux *et al.* 20

Evolutionary path

Most common massive binary evolution path

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

Spin up, pollution, and rejuvenation

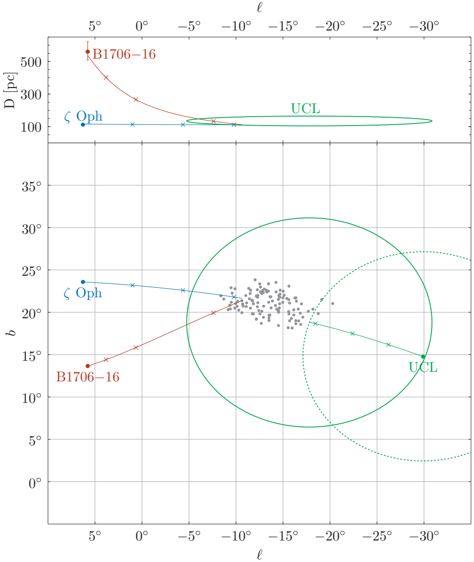
The binary disruption shoots out the accretor

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

Evolutionary path

Does this applies to ζ Ophiuchi?

We can trace it back to the neutron star formed by the companion explosion



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*

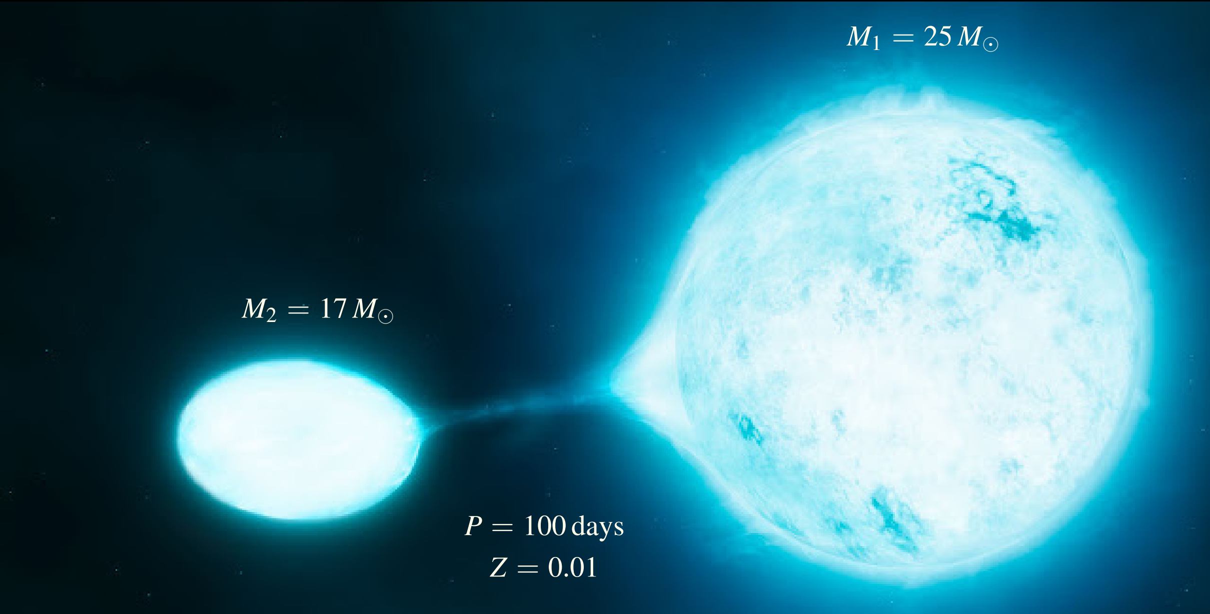
Accepted 2019 Sep 10. Received 2019 Sep 3; in original form 2019 July

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

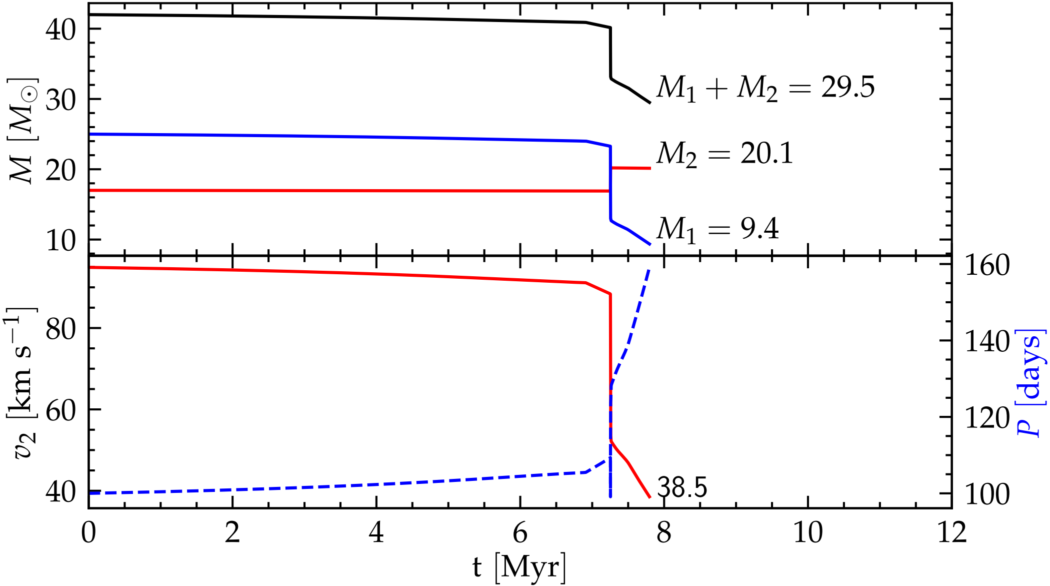
Neuhäuser *et al.* 19, see also van Rensbergen *et al.* 96, Hoogerwerf *et al.* 01, Lux *et al.* 20

Self-consistent binary model

Current best MESA model



Spatial peculiar velocity & mass



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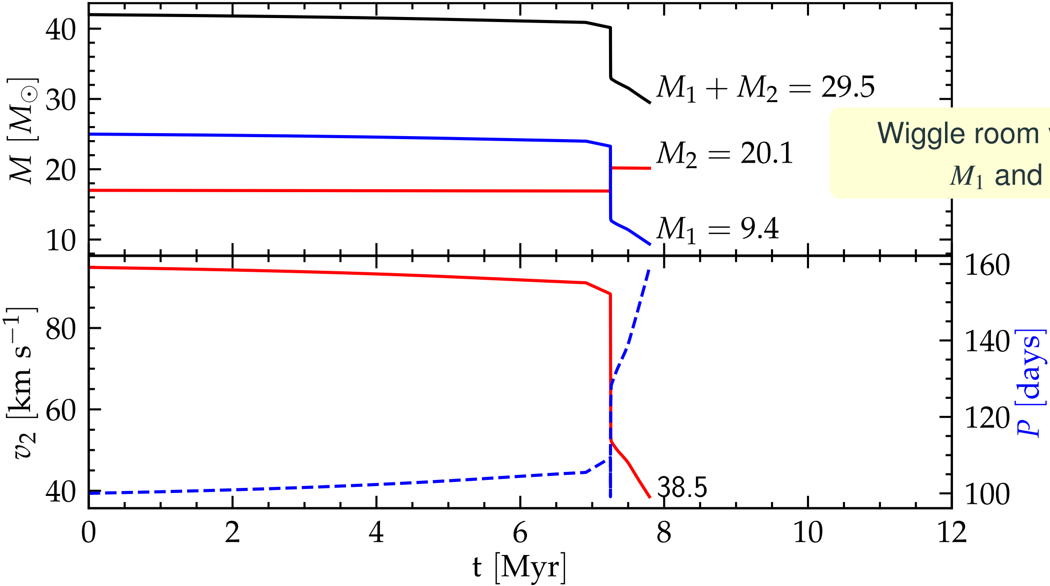
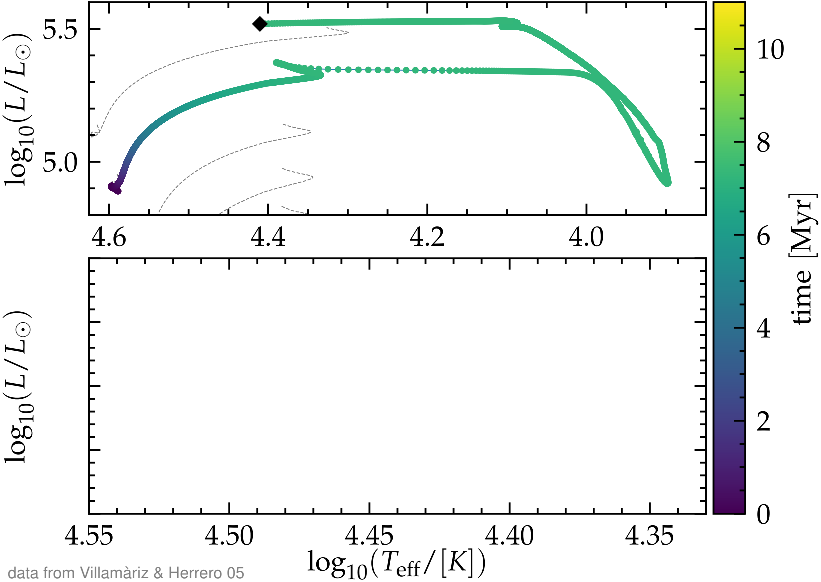


Wiggle room varying M_1 and P

Hertzsprung-Russel diagram of both stars



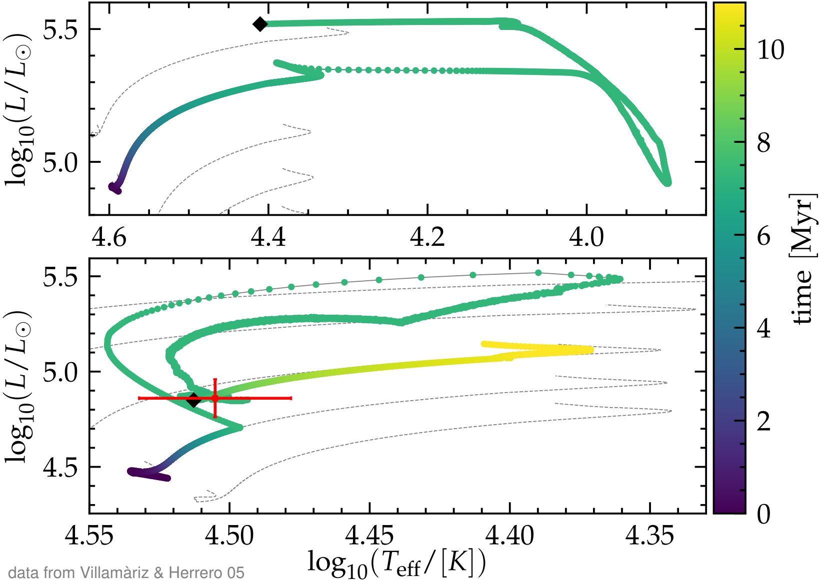
$Z = 0.01$

(Murphy *et al.* 21)

Features are sensitive to many free parameters

data from Villamàriz & Herrero 05

Hertzsprung-Russel diagram of both stars



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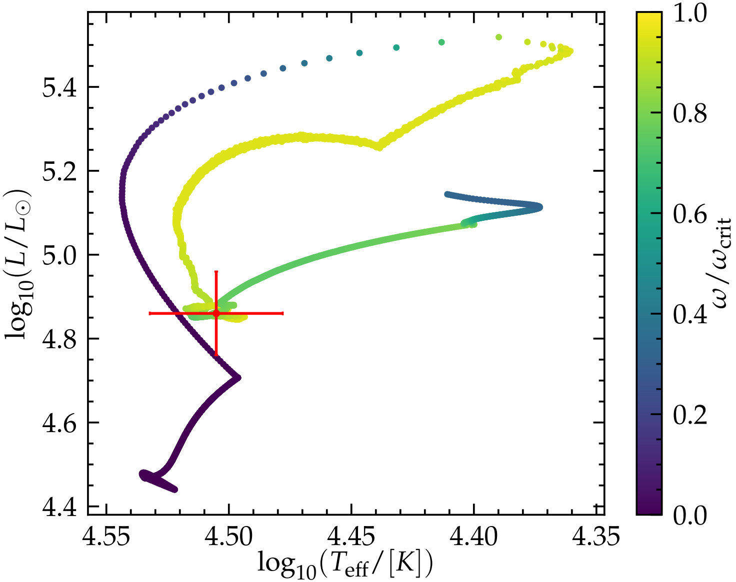
Self-consistent binary model

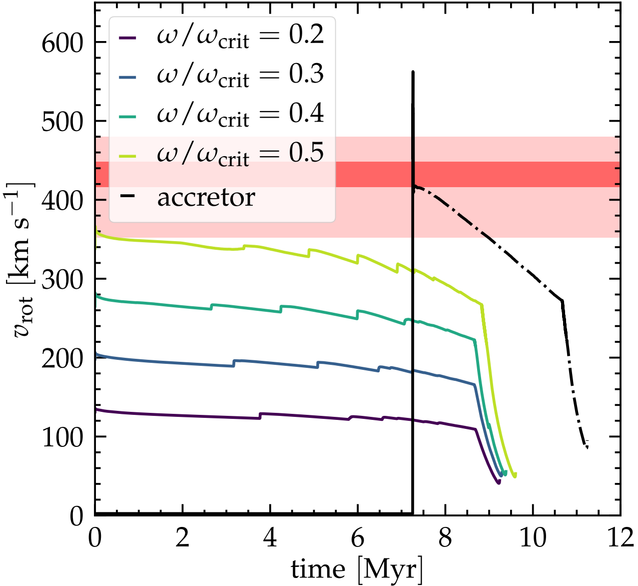
Rotation

Hertzsprung-Russel diagram: accretor rotation



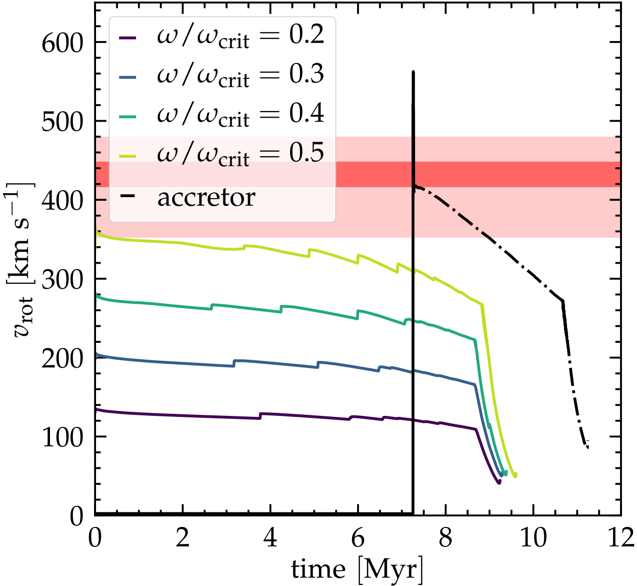
- Minimum $T_{\rm eff}$ during RLOF reached at onset of critical rotation.
- Rotation close to critical for large part of the main sequence.
- Redistribution of AM causes feature at $T_{\rm eff} \simeq 10^{4.4}$ K.

Surface rotation rate

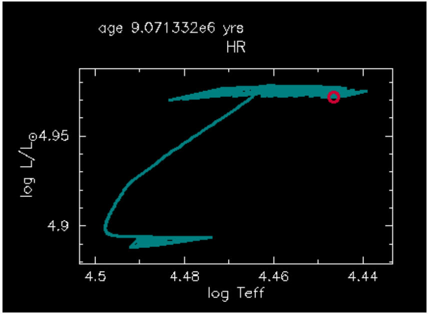


- but overestimating by $\sim 100\times$ wind mass loss!

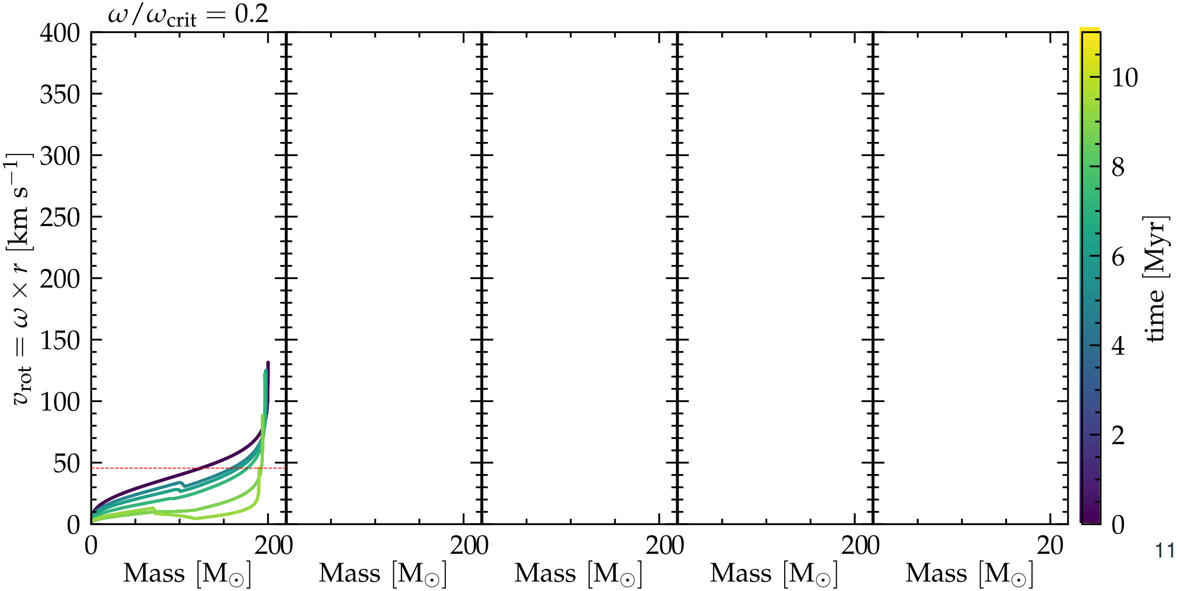
Surface rotation rate



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



Internal rotational structure



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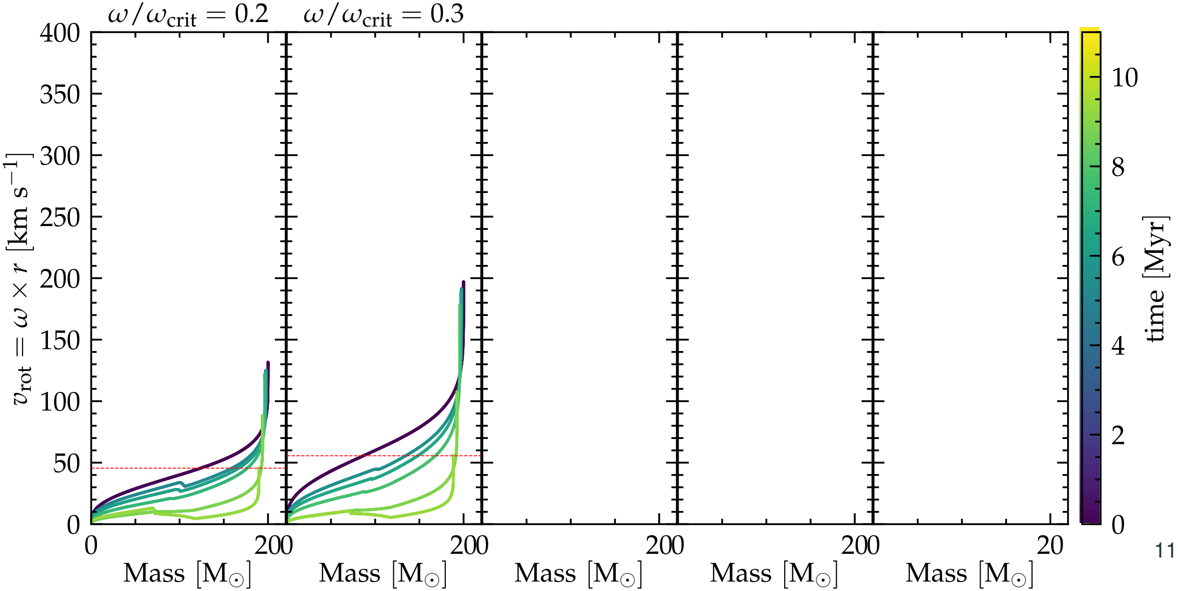

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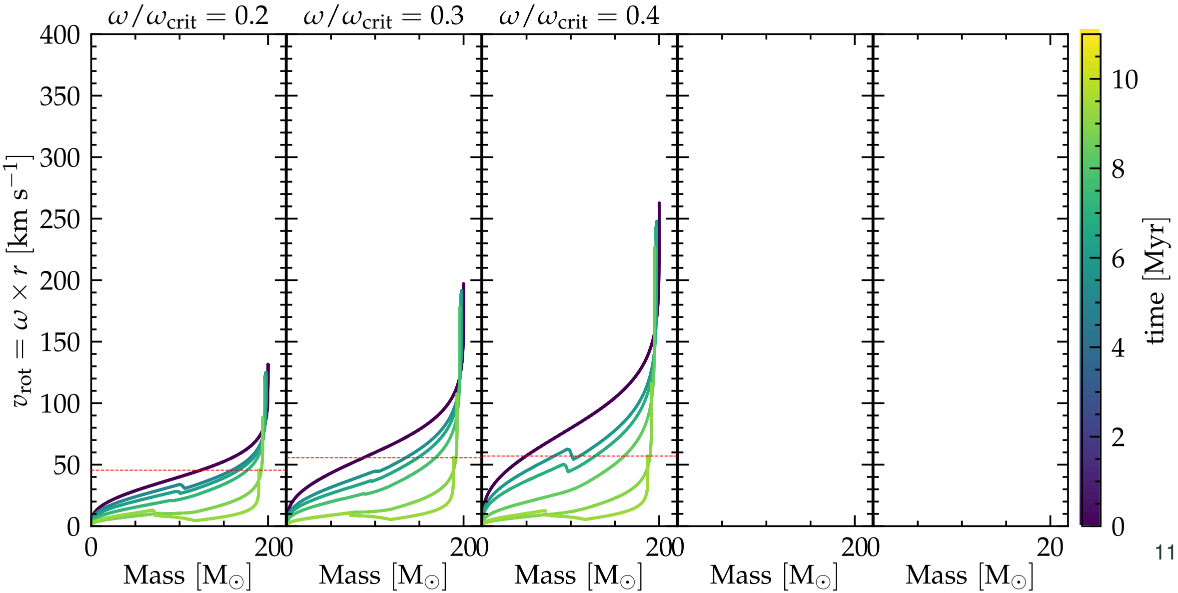

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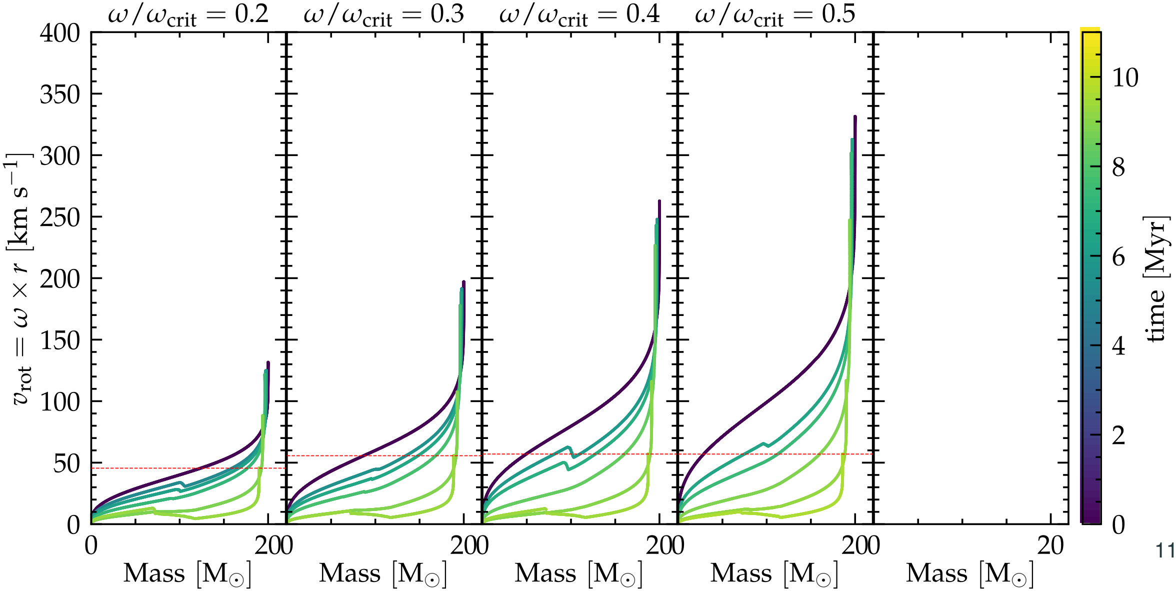

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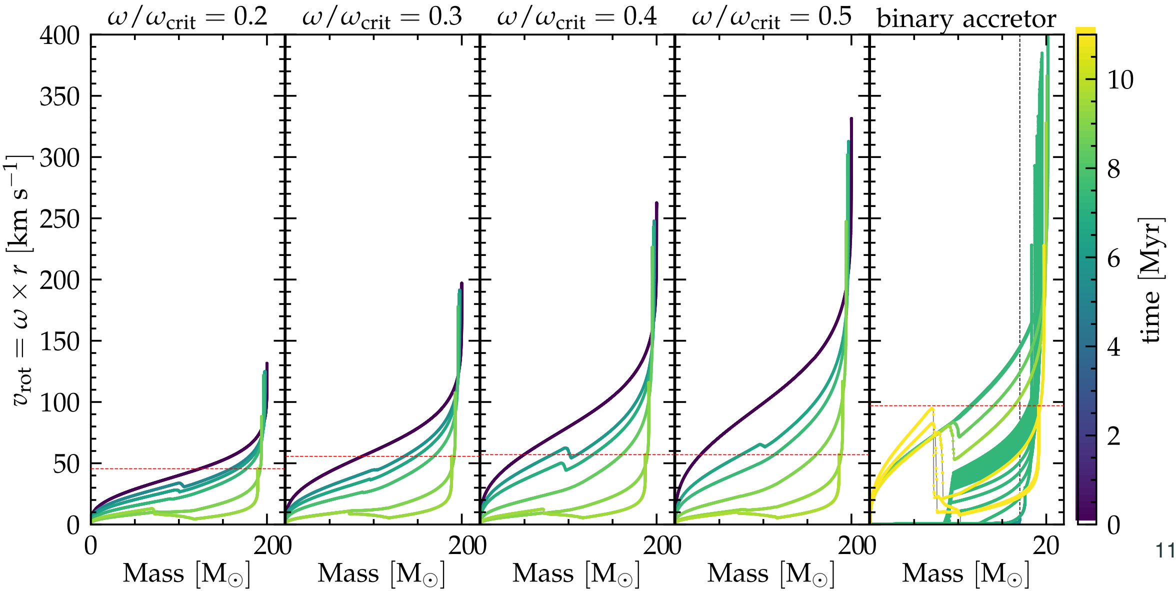
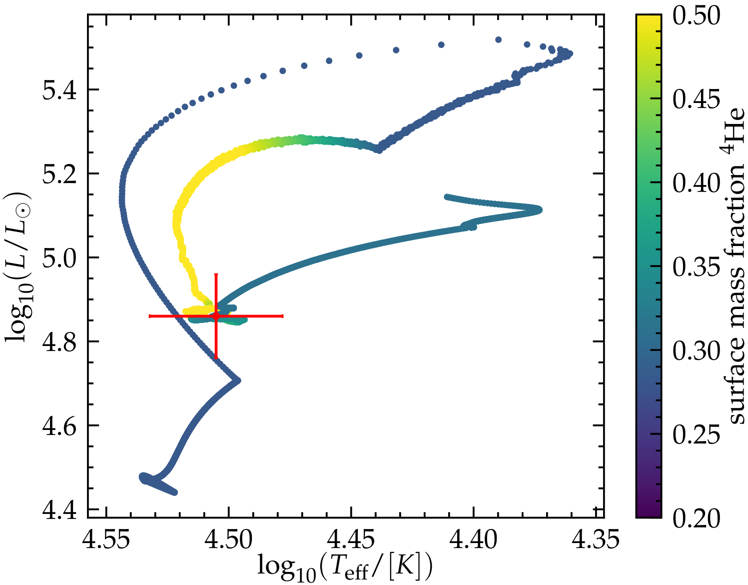


Self-consistent binary model

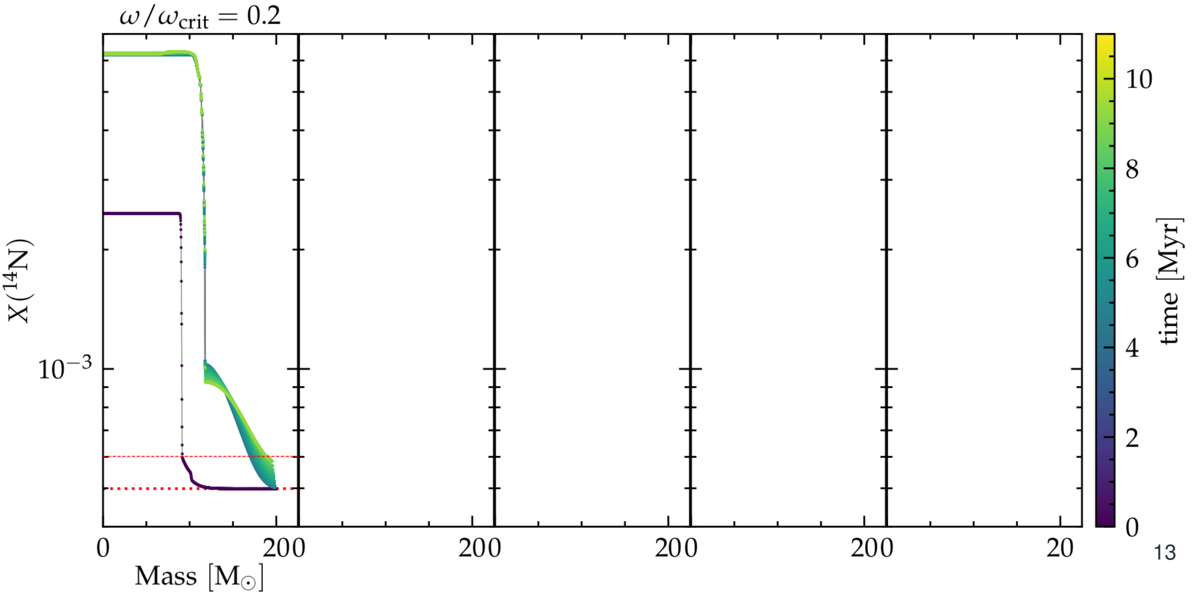
Surface composition

Hertzsprung-Russel diagram: helium surface abundance

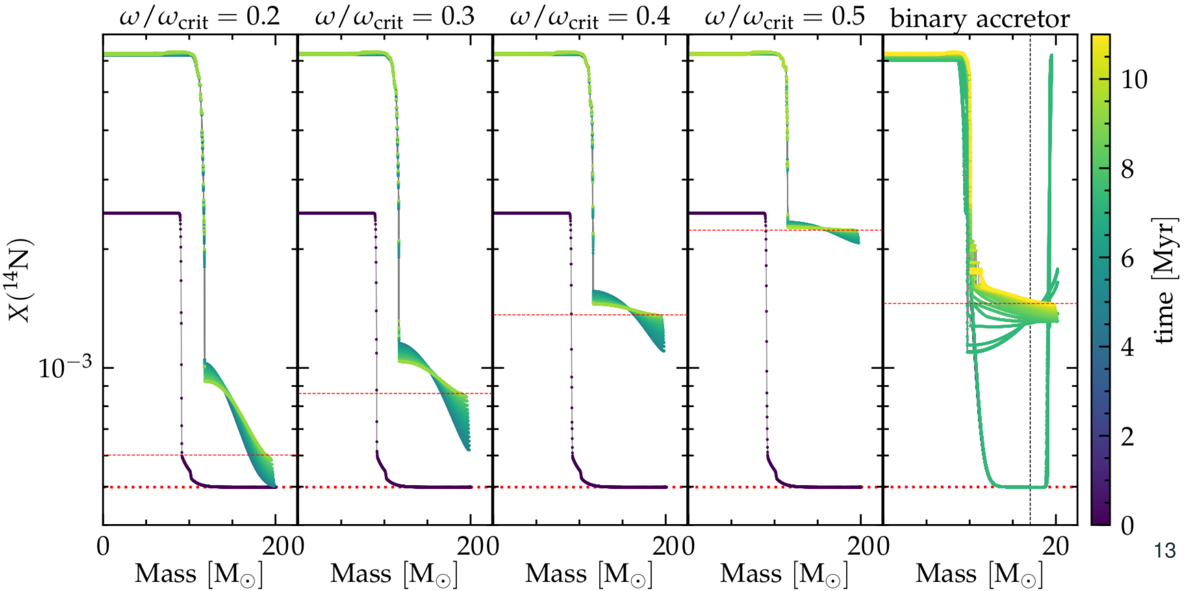


- Accretion of He-rich matter change morphology at $T_\mathrm{eff} \simeq 10^{4.44}$ K.
- Interplay between rotational and thermohaline mixing causes “noisiness” in the track.

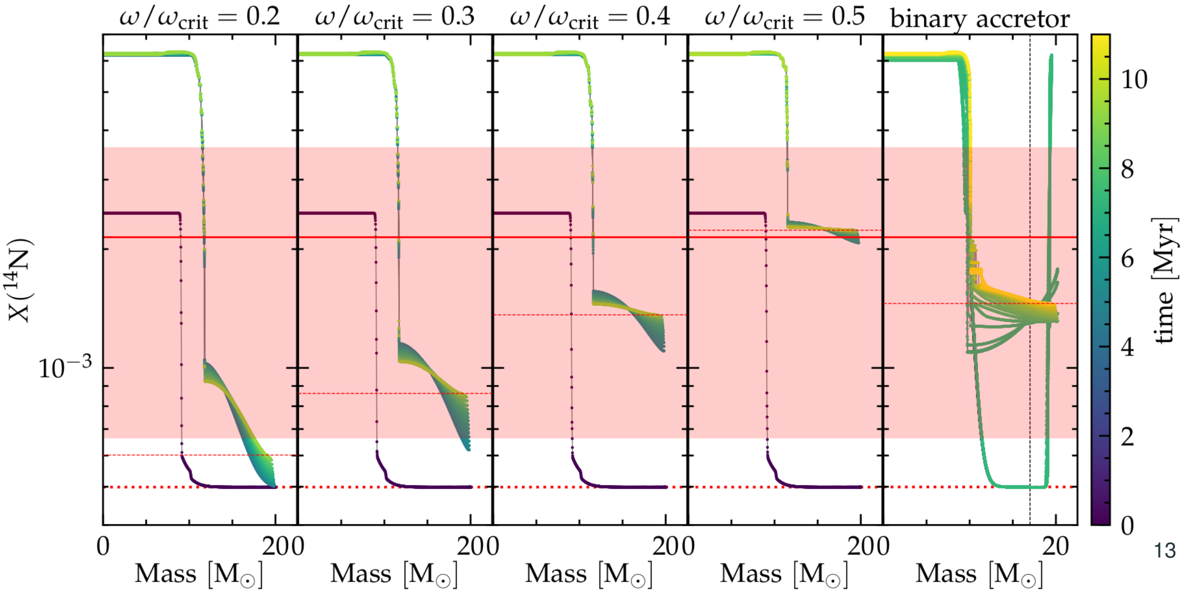
Composition profile: comparison with rotating single stars



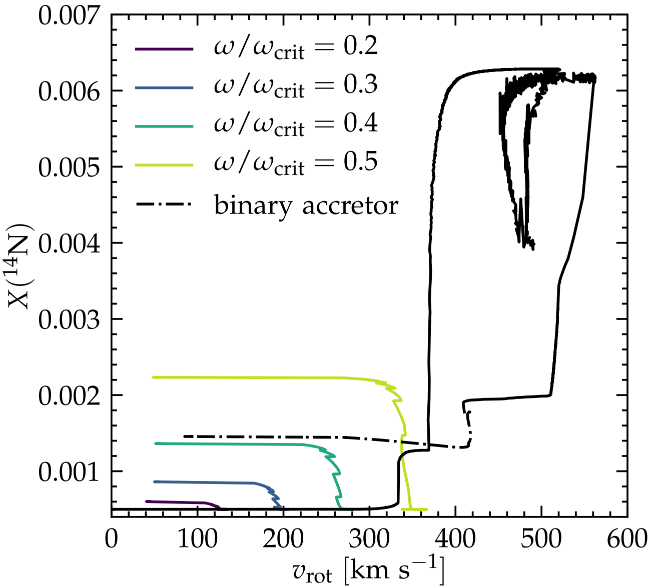
Composition profile: comparison with rotating single stars



Composition profile: comparison with rotating single stars



“Hunter” diagram

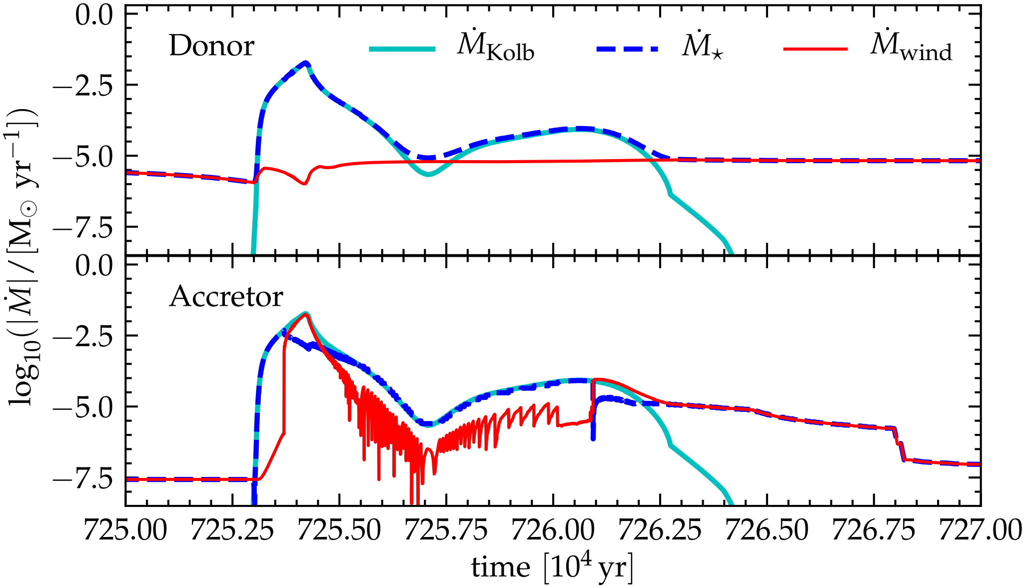


Dot-dashed line = post-RLOF evolution

Self-consistent binary model

Mass transfer rate

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



Outlook and Todos

Take home points

- ζ Oph is a runaway from the binary SN scenario

  we know the associated pulsar, birth location, kinematic age

- Accretor $\neq$ single star rotating since ZAMS

  composition and rotational profiles very different

- Modeling accretors is difficult

  because of rotation and mixing in *both* stars, and mass transfer

Ongoing and future steps

Parameter variations:

- Vary M_1, M_2, P and Z at fixed physics assumptions
- Vary J-transport e.g., Langer *et al.* 98, Zhao & Fuller 20
- Vary RLOF-parameters?

✗ Vary J-accretion: extremely noisy tracks

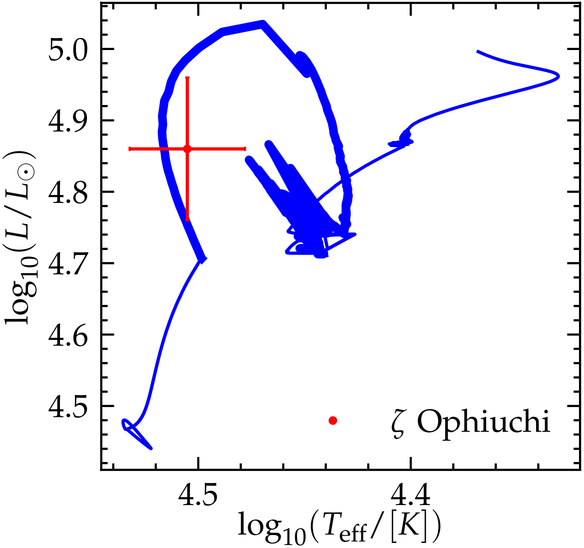
✗ Decrease $\dot{M}$

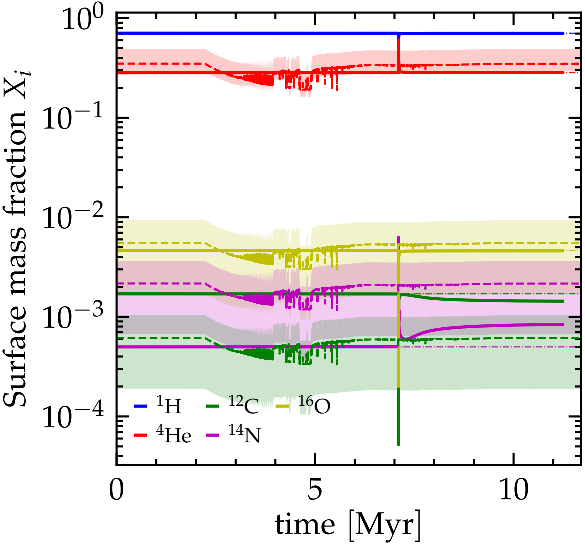
- ... more?

What would observers want to have from such models?

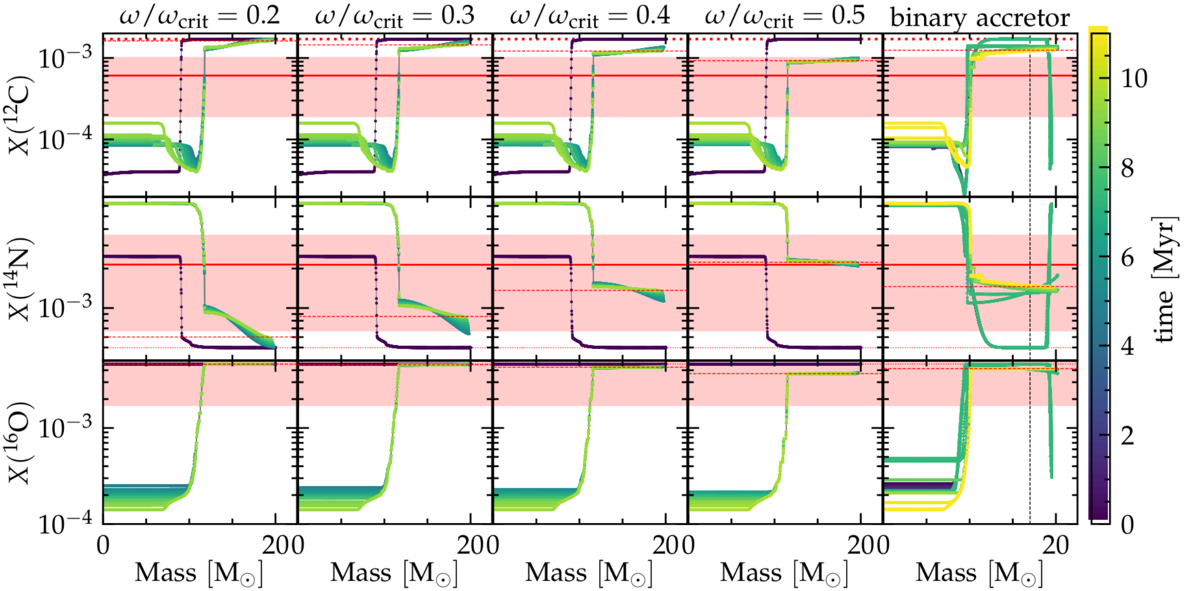
Backup slides

Accreting angular momentum from a disk

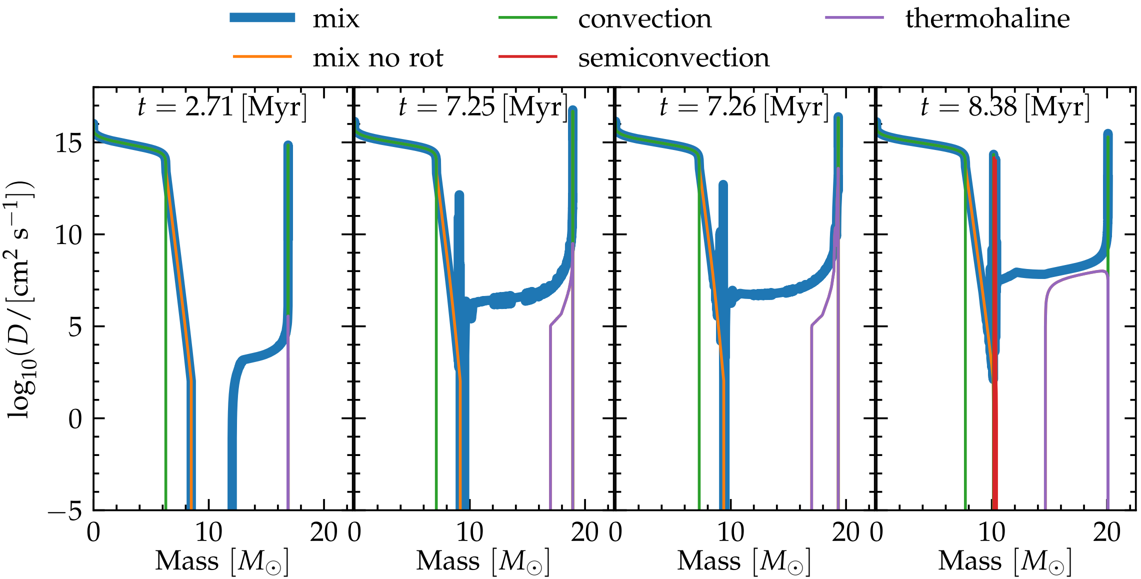




Evolution of composition profile



Internal mixing at selected times



Spatial resolution test