Mass transfer in binary systems

“Widowed” stars and “living” gravitational wave sources

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Center for Computational Astrophysics

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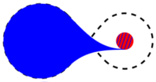
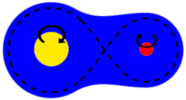
Mass transfer in binary systems can be

dynamically stable:



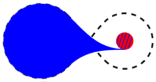
dynamically unstable:



Outline

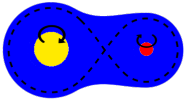
dynamically stable:

"Widowed" accretor stars



dynamically unstable:

can LISA detect GW from common envelope evolution?



Why care about the accretor?

Stellar populations

accretors hide in samples

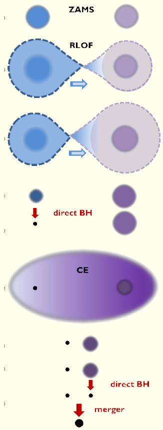
de Mink *et al.* 2013, Renzo *et al.* 2019b

+

Oe/Be stars, stragglers

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

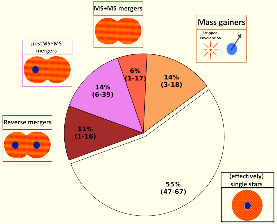
GW progenitors



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

Transients

type II supernovae



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

+

long GRB

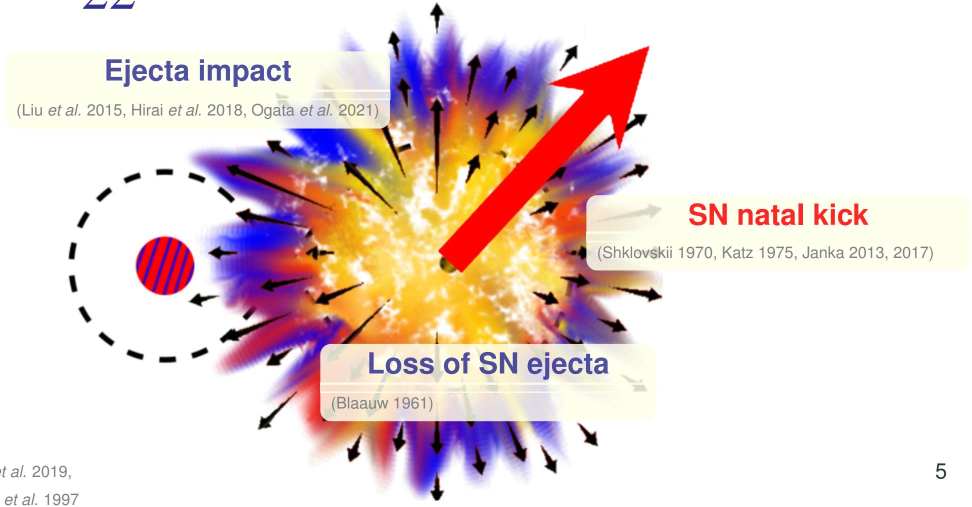
Cantiello *et al.* 2007, MR & Götberg 2021

Most common massive binary evolution path: stable case B RLOF

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

SN natal kicks disrupt the binary

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

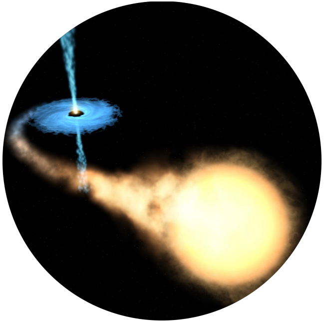


Renzo *et al.* 2019b, Kochanek *et al.* 2019,
Eldridge *et al.* 2011, De Donder *et al.* 1997

Do BHs receive kicks ?

NO

⇒ most remain bound to companion



YES

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

Do BHs receive kicks ?

NO

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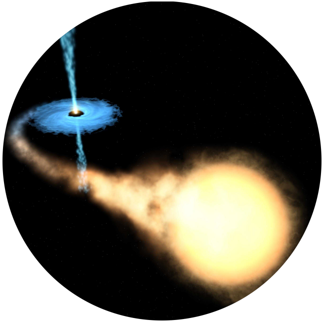
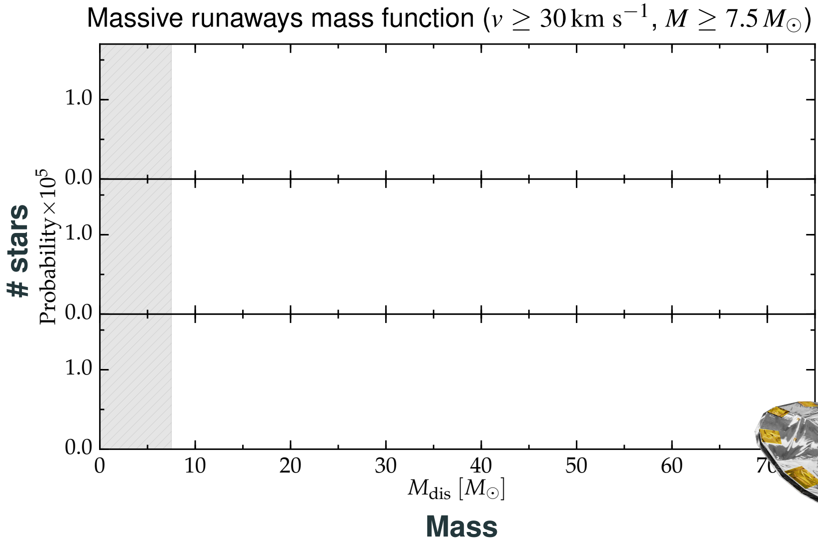


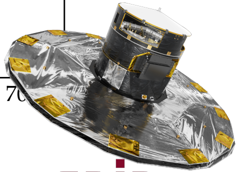
YES

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

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

Constrain BH kicks looking at the former companion with *Gaia*



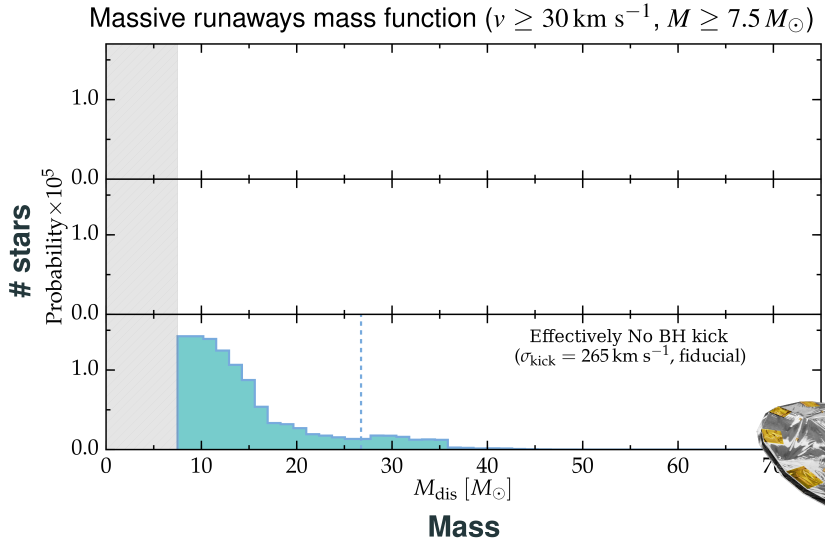


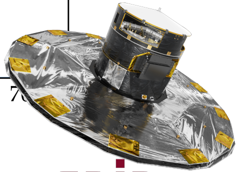
gaia

Renzo *et al.* 2019b

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

Constrain BH kicks looking at the former companion with *Gaia*





Renzo *et al.* 2019b

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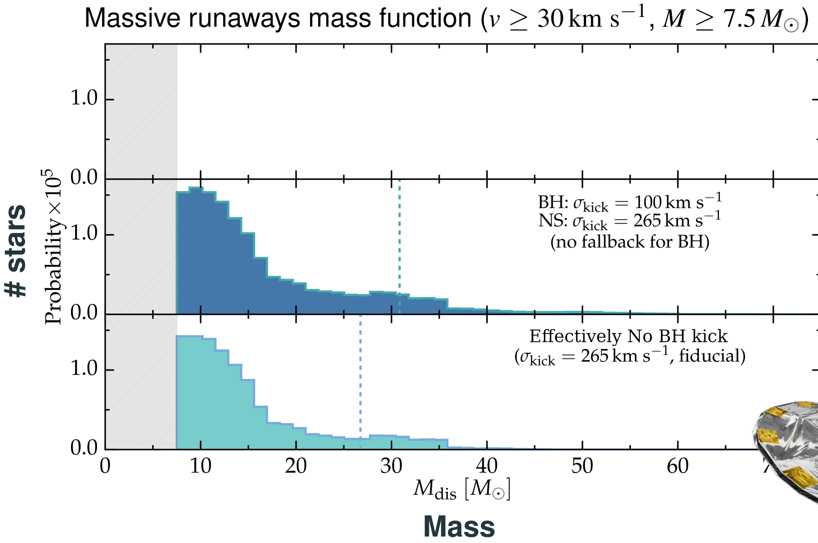

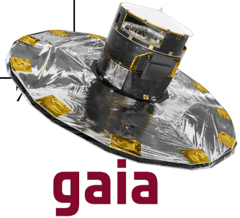

Renzo *et al.* 2019b

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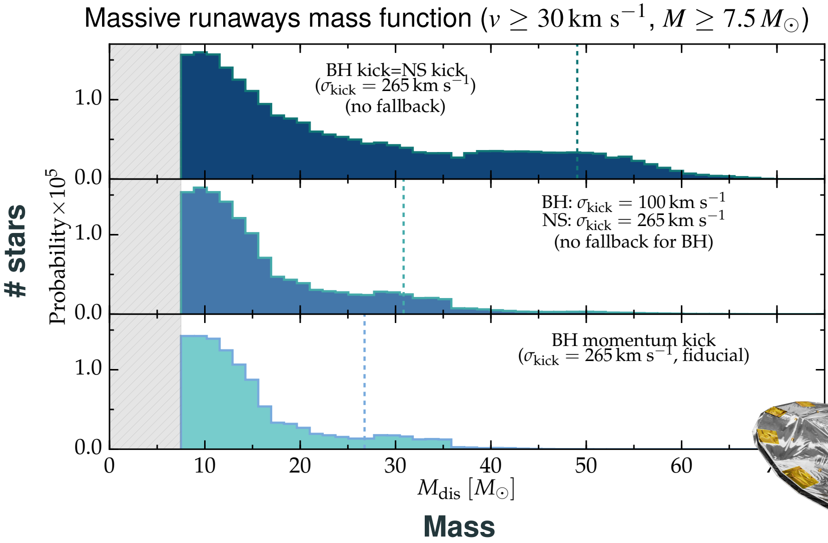
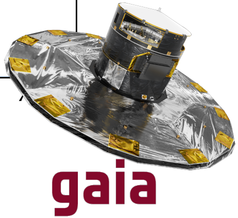




Renzo *et al.* 2019b

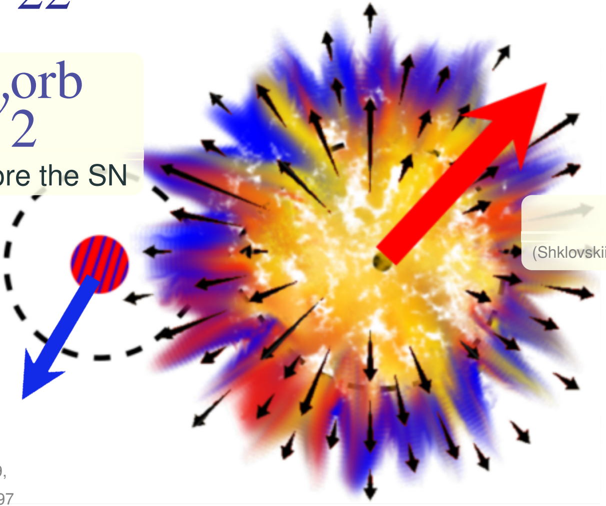
Numerical results: http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/624/A66

Kicks do not change the velocity of the widowed star

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

$$v_{\rm dis} \simeq v_2^{\rm orb}$$

before the SN



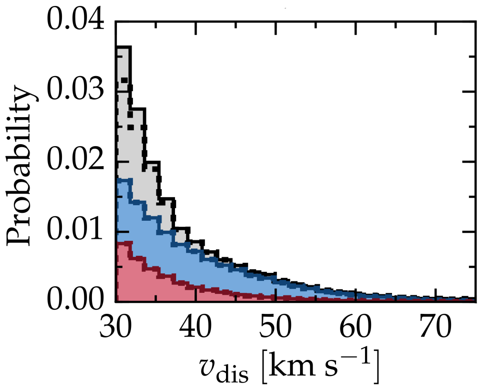
SN Natal kick

(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

Widowed stars can be *runaways*...

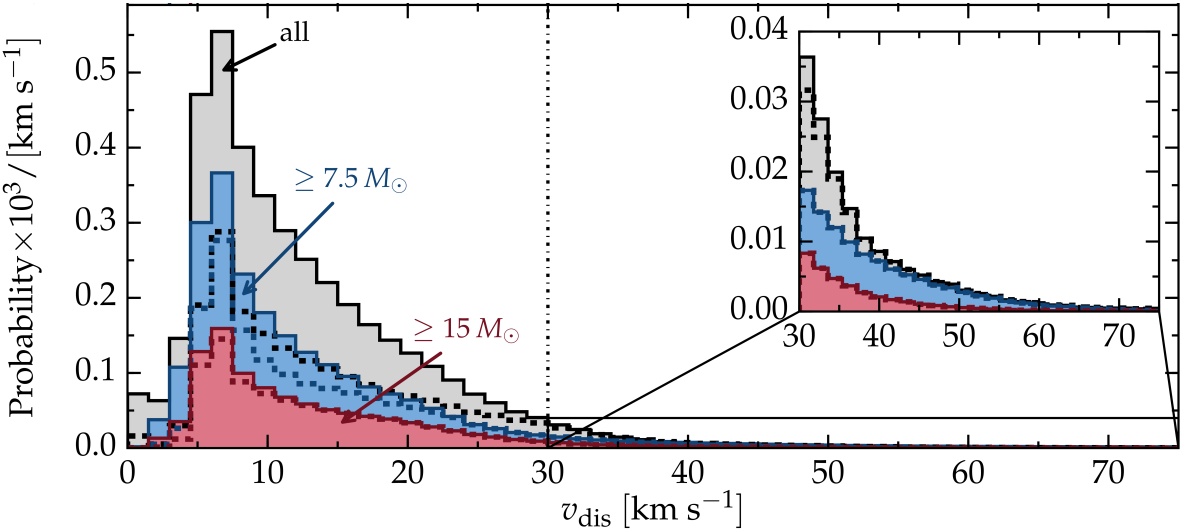


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

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

...but most widowed stars are only *walkaways*



Velocity respect to the 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

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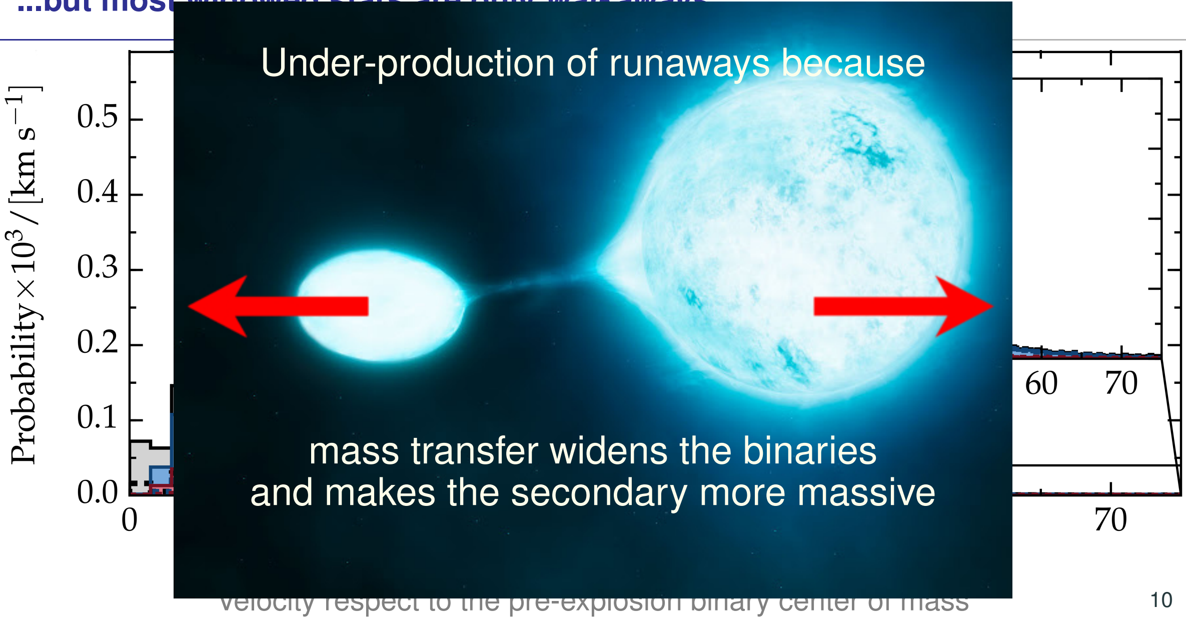


Renzo *et al.* 2019b

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

Appearance of “widowed” stars

Spin up, pollution, and rejuvenation of the second star

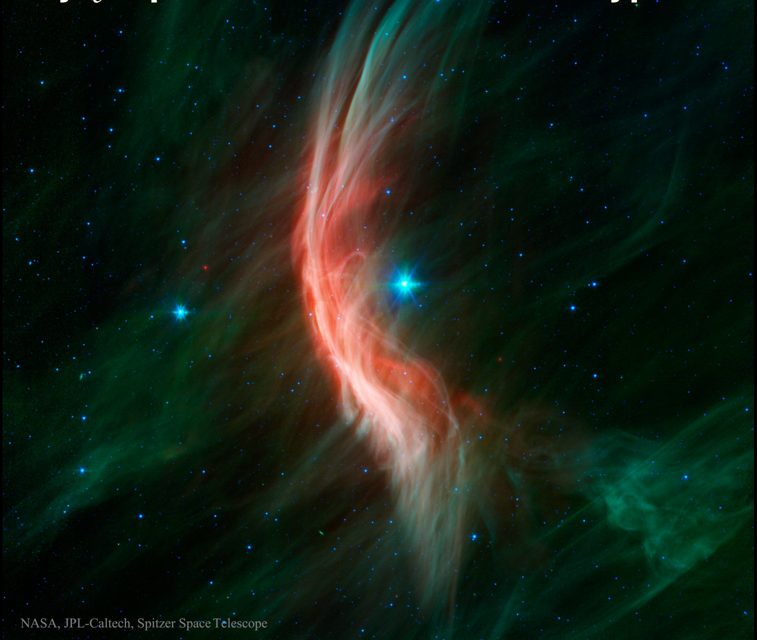
The binary disruption shoots out the accretor

Spin up: Packet 1981, Cantiello *et al.* 2007, de Mink *et al.* 2013
Pollution: Blaauw 1993
Rejuvenation: Hellings 1983, Schneider *et al.* 2015

Appearance of “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

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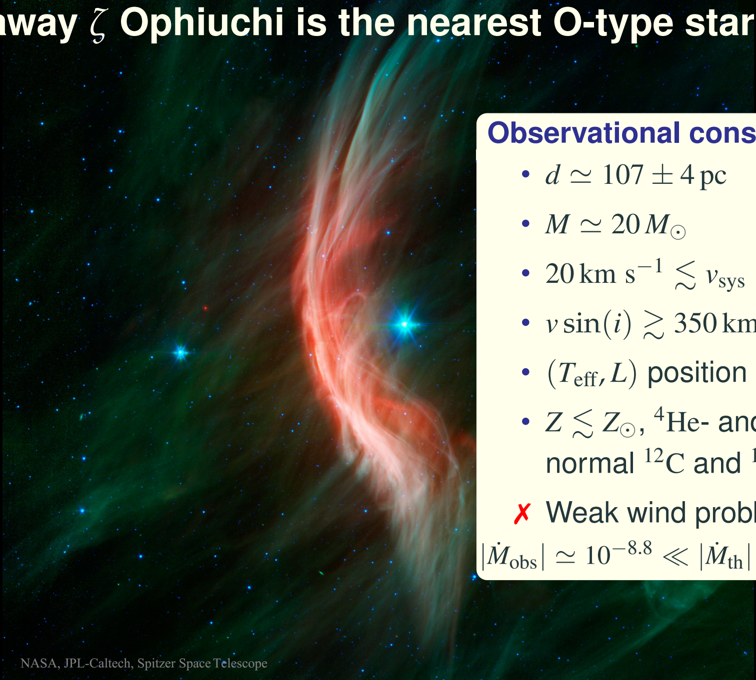


NASA, JPL-Caltech, Spitzer Space Telescope

Observational constraints

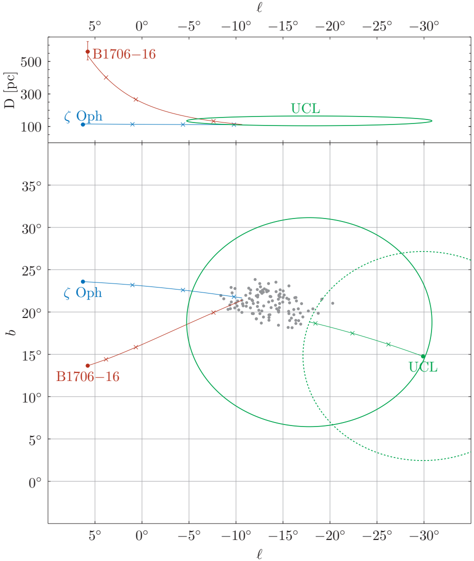
- $d \simeq 107 \pm 4\,\mathrm{pc}$
- $M \simeq 20\,M_\odot$
- $20\,\mathrm{km\ s^{-1}} \lesssim v_{\rm sys} \lesssim 50\,\mathrm{km\ s^{-1}}$
- $v\sin(i) \gtrsim 350\,\mathrm{km\ s^{-1}}$
- $(T_{\rm eff}, L)$ position
- $Z \lesssim Z_\odot$, ^{4}He- and ^{14}N-rich, normal ^{12}C and ^{16}O

✗ Weak wind problem:

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

e.g., Neuhäuser *et al.* 2020

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

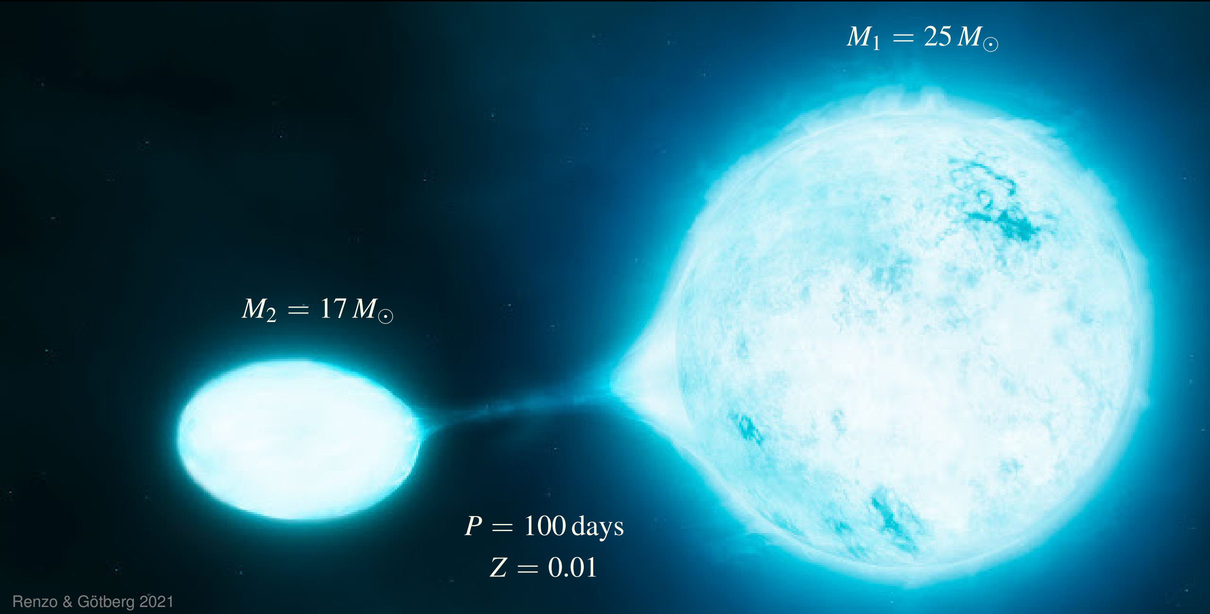
R. Neuhäuser,[1★], F. Gießler[1], and V.V. Hambaryan[1,2]
[1] *Astrophysikalisches Institut und Universitäts-Sternwarte Jena, Schillergäßchen 2-3, 07745 Jena, Germany*
[2] *Byurakan Astrophysical Observatory, Byurakan 0213, Aragatzotn, Armenia*

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

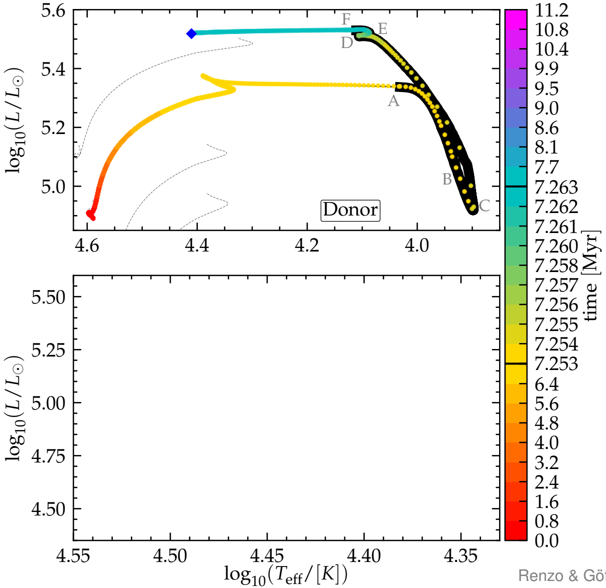
SN explosion $\sim 1.78 \pm 0.21$ Myr ago

Neuhäuser *et al.* 2019, see also van Rensbergen *et al.* 1996, Hoogerwerf *et al.* 2001, Lux *et al.* 2020

Self-consistent MESA model



Hertzsprung-Russel diagram of both stars: the donor

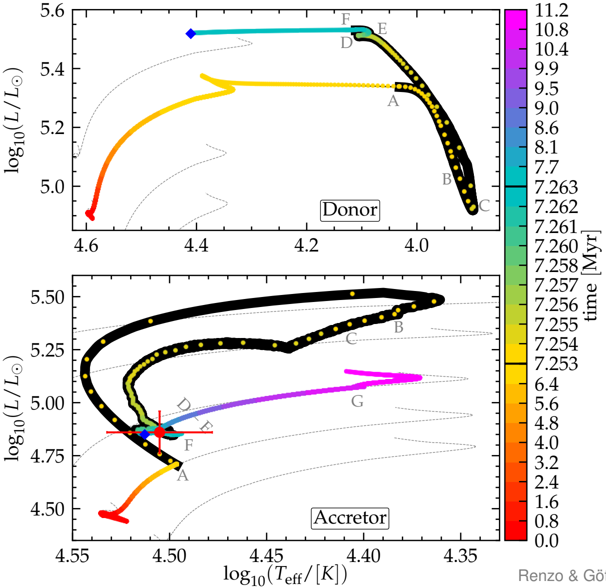


Renzo & Götberg 2021

Roche lobe overflow is short

But has long-lasting impact on both stars.

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



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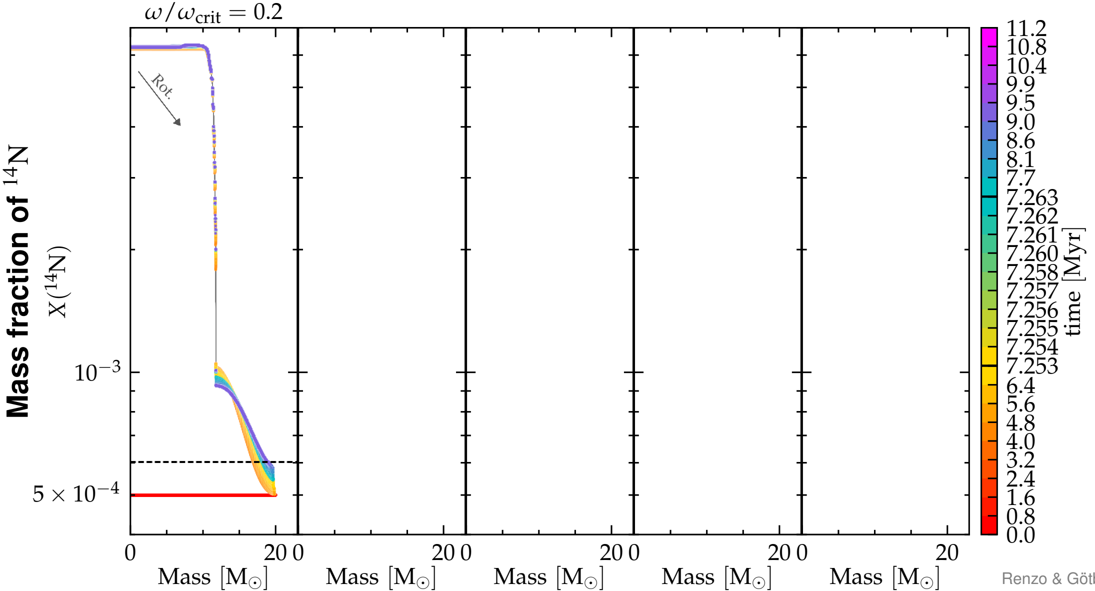
Renzo & Götberg 2021

data point from Villamàriz & Herrero 2005

Appearance of “widowed” stars

^{14}N as a tracer of chemical composition

Composition profile: comparison with rotating single stars



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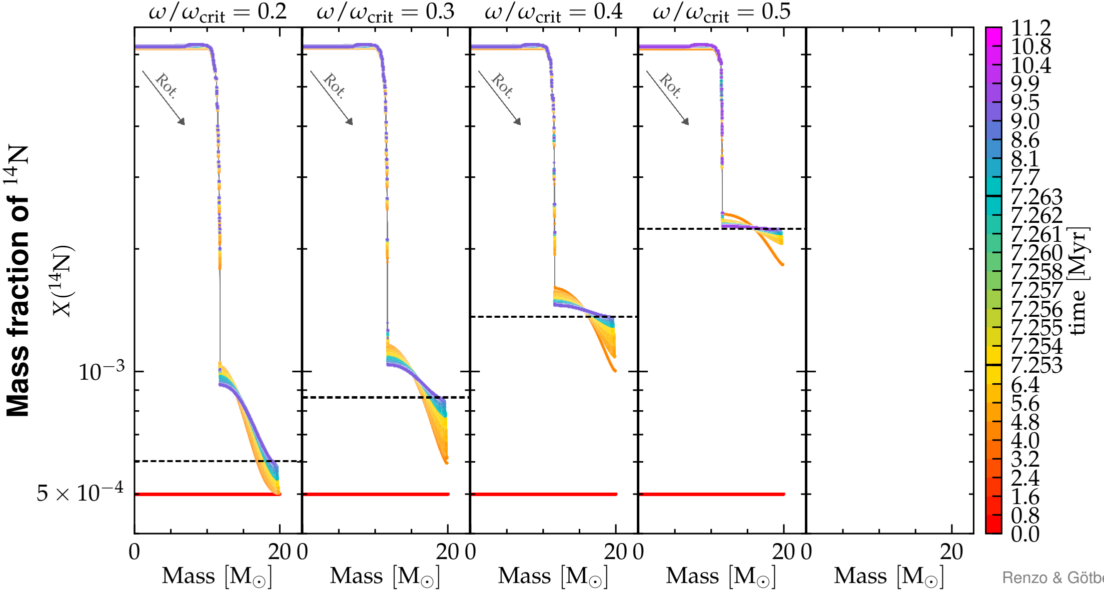
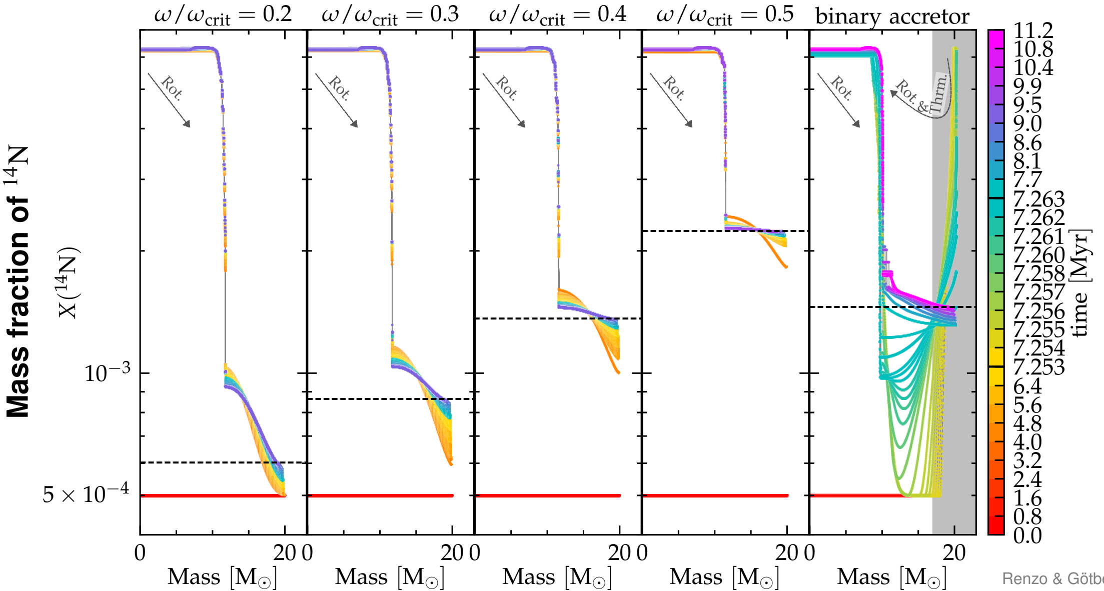


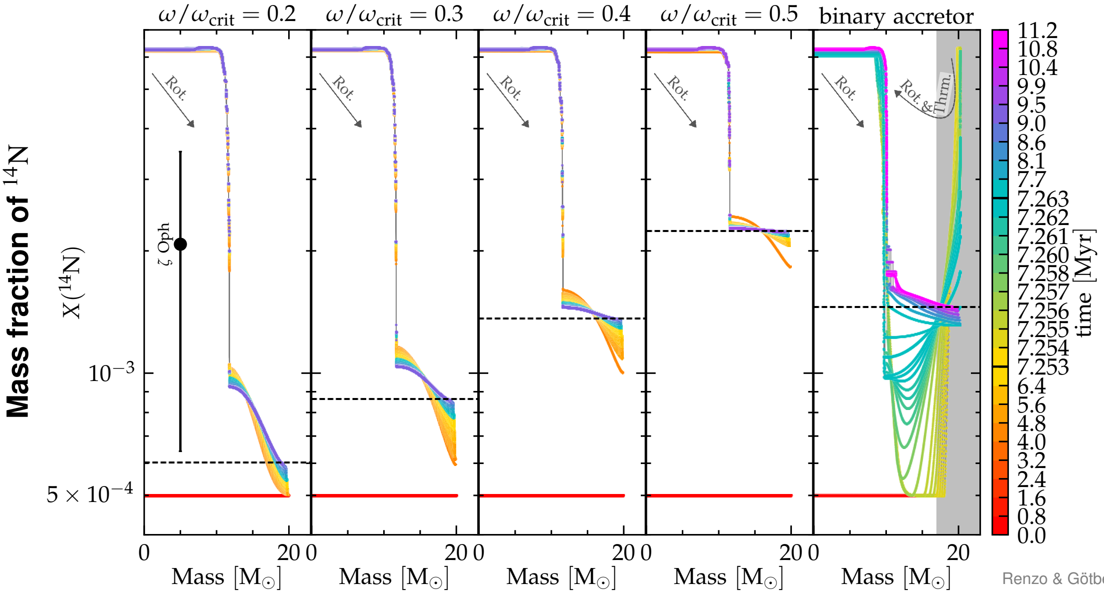
Renzo & Götberg 2021

Composition profile: comparison with rotating single stars



Renzo & Götberg 2021

Composition profile: comparison with rotating single stars

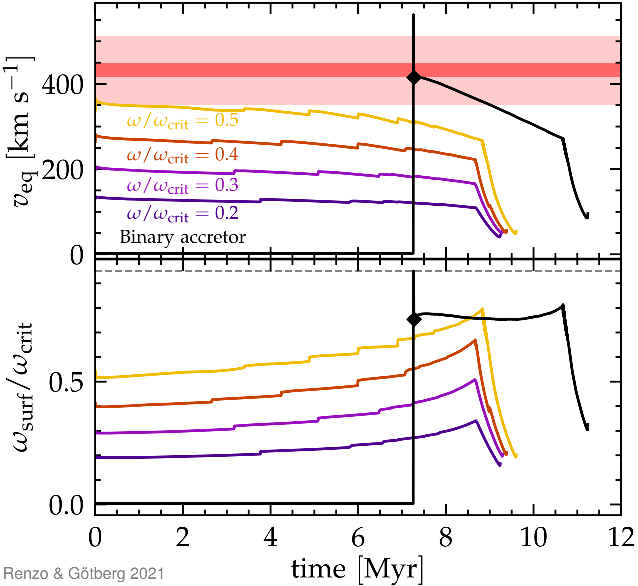


Renzo & Götberg 2021

Appearance of “widowed” stars

Rotation

Surface rotation rate



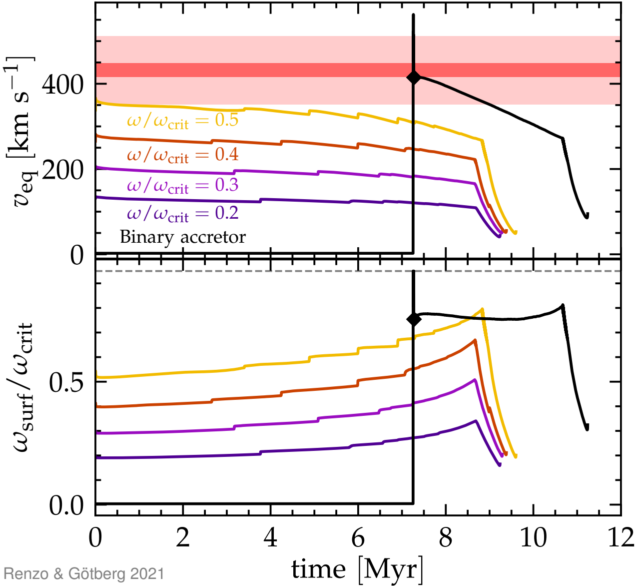
- but overestimating by $\sim$100$\times$ wind mass loss!

$$\omega_{crit} = \sqrt{\left(1 - \frac{L}{L_{Edd}}\right)\frac{GM}{R_{eq}^3}}$$

Gravity = Centrifugal forces at equator

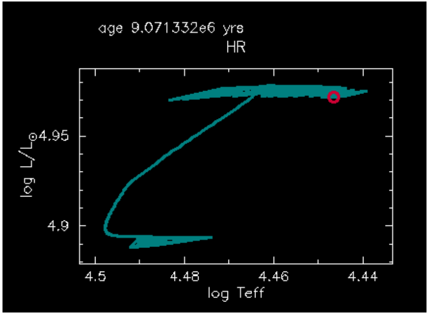
Renzo & Götberg 2021

Surface rotation rate

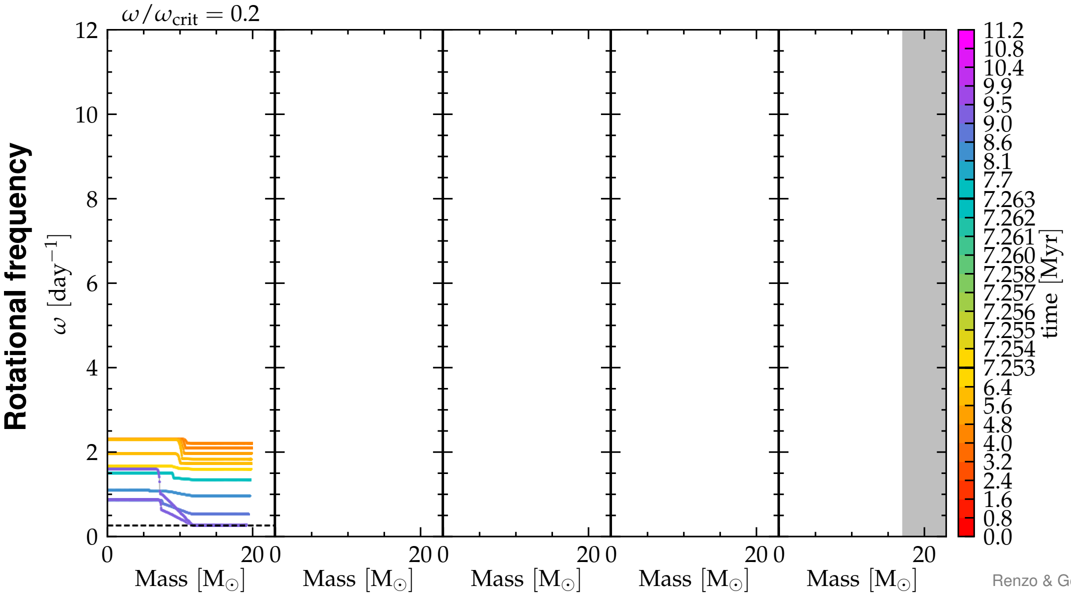


Renzo & Götberg 2021

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



Internal rotational profile: single stars



Renzo & Götberg 2021

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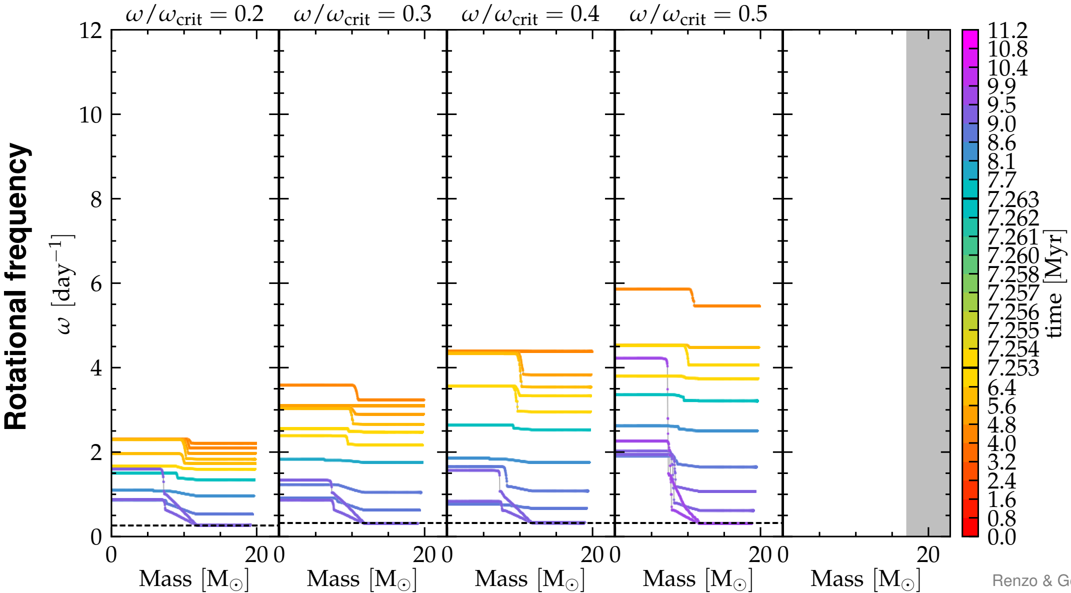
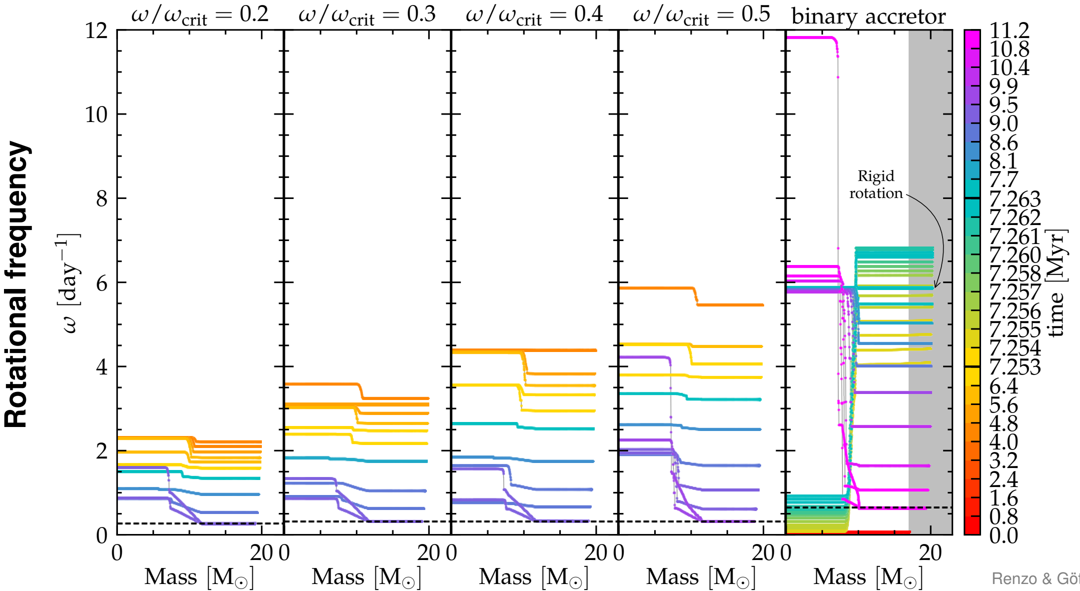


Renzo & Götberg 2021

Internal rotational profile: accretor

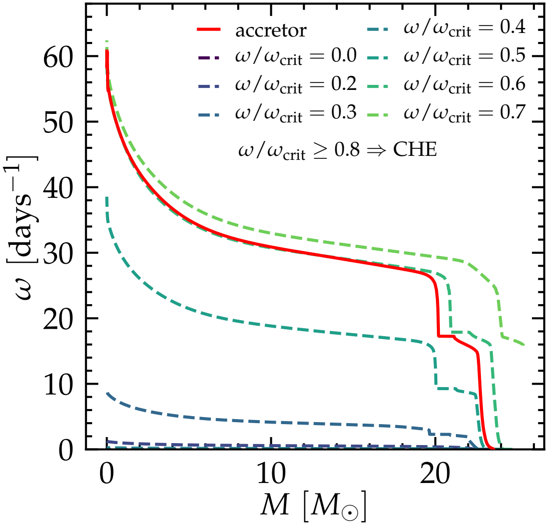


Renzo & Götberg 2021

Generalization to BH progenitors

Preliminary: accretion spin-up for BH progenitors

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



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

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

Conclusions

Stable mass transfer

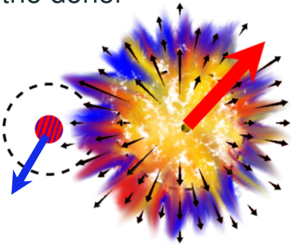
Take home points

Renzo *et al. 2019b*

- Most massive binaries disrupted at 1^{st} core-collapse
- Masses of widowed stars can inform BH kicks
- Most are slow moving walkaway, some are runaway

Renzo & Götberg 2021

- Widowed stars are modified by binary interactions
- Surface abundance influenced by matter from the donor
- Rotation profile of widowed stars unlike single rotating stars
  $\Rightarrow$ implications for long GRB and BH spins



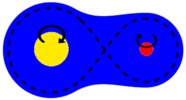
Mass transfer in binary systems can be

dynamically stable:

testing models of massive accretor stars with ζ Ophiuchi

dynamically unstable:

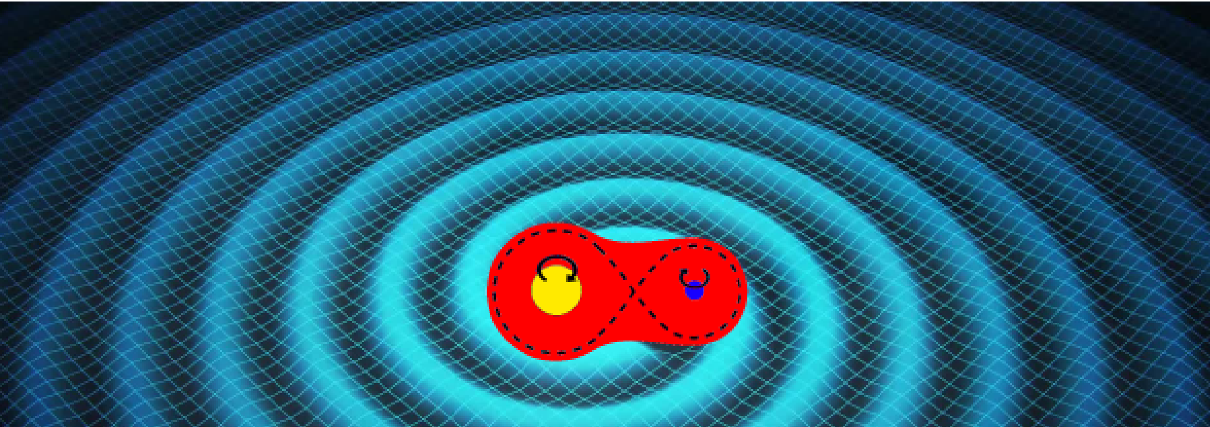
can LISA detect GW from common envelope evolution?



Prospects of gravitational-waves detections from common-envelope evolution with LISA

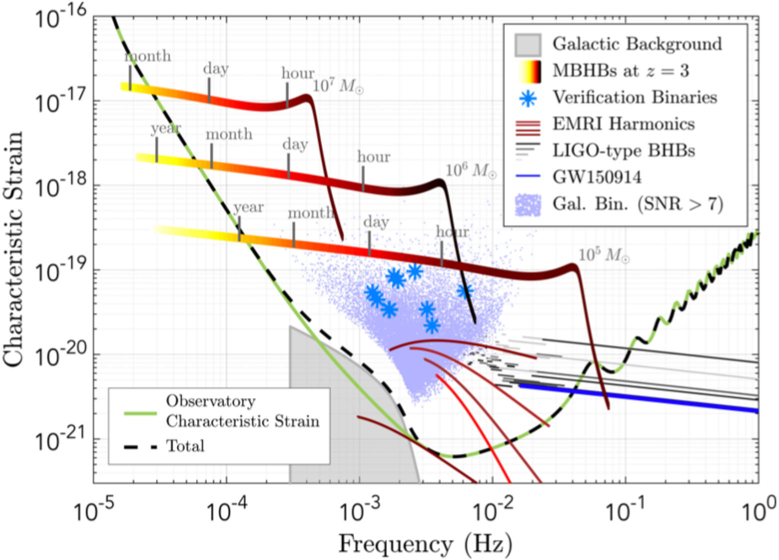
Mathieu Renzo, T. Callister, K. Chatziioannou, L. van Son, C. M. F. Mingarelli, M. Cantiello, K. E. S. Ford, B. McKernan, and G. Ashton

arXiv:2102.00078, accepted ApJ



LISA can see Galactic double white dwarfs formed via common envelope

⇐ PTA



LIGO/Virgo ⇒

Robson *et al.* 2019

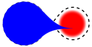
Common Envelope Evolution

Is *not* GW-driven!

But GW passively trace the dynamics

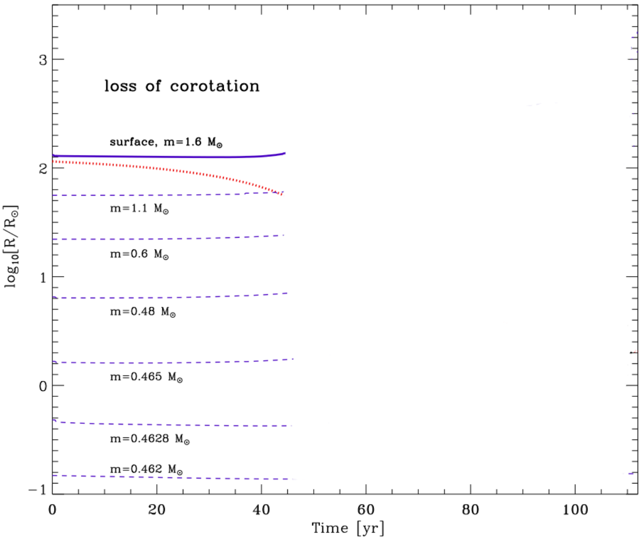
Common envelope evolution in one slide

Renzo *et al.* 2021

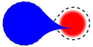


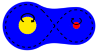
a. Mass transfer becomes dynamically unstable

Common envelope evolution in one slide



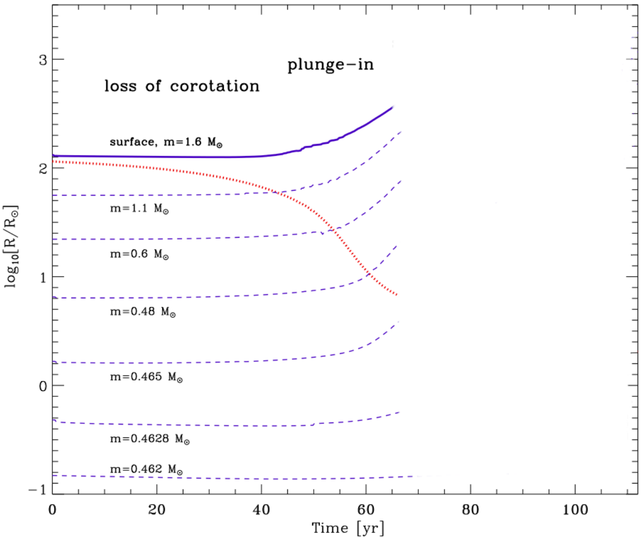
Example from Ivanova *et al.* 2013b





Common envelope evolution in one slide

Renzo *et al.* 2021



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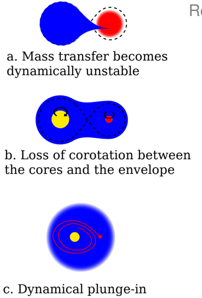

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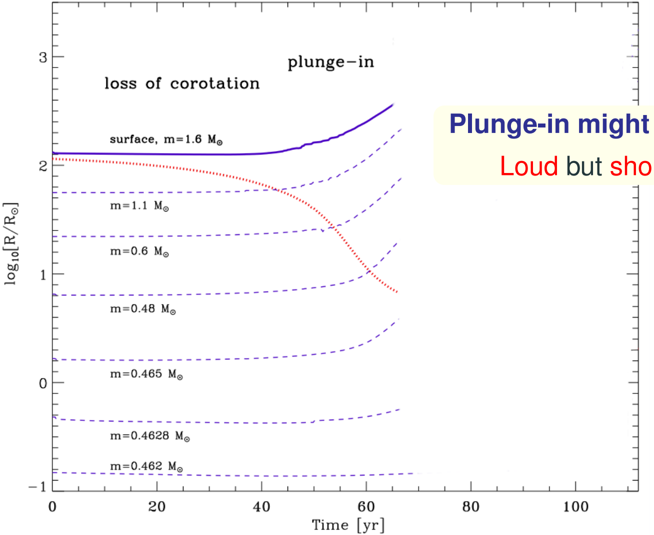
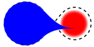


Example from Ivanova *et al.* 2013b

Plunge-in might be detectable

Loud but short and rare

Renzo *et al.* 2021



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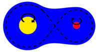
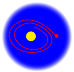
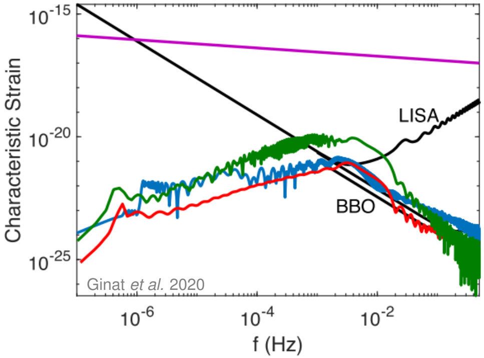


b. Loss of corotation between the cores and the envelope

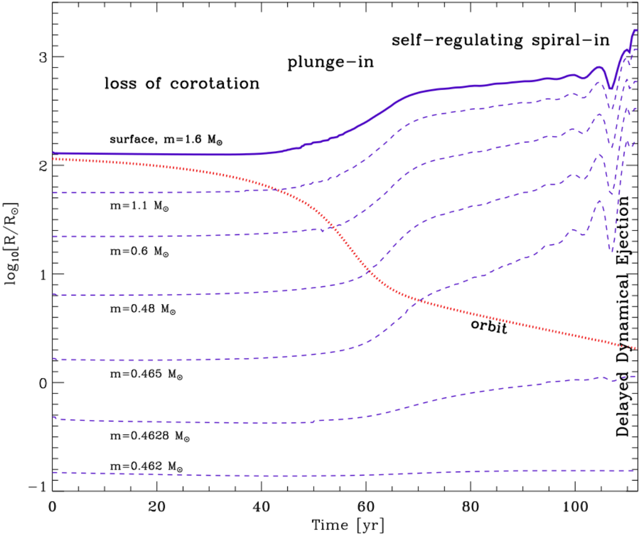


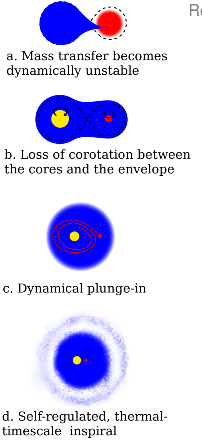
c. Dynamical plunge-in



Renzo *et al.* 2021

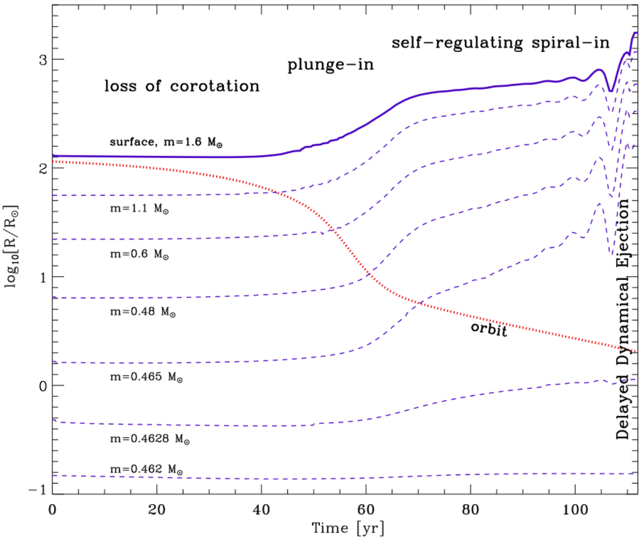
Common envelope evolution in one slide



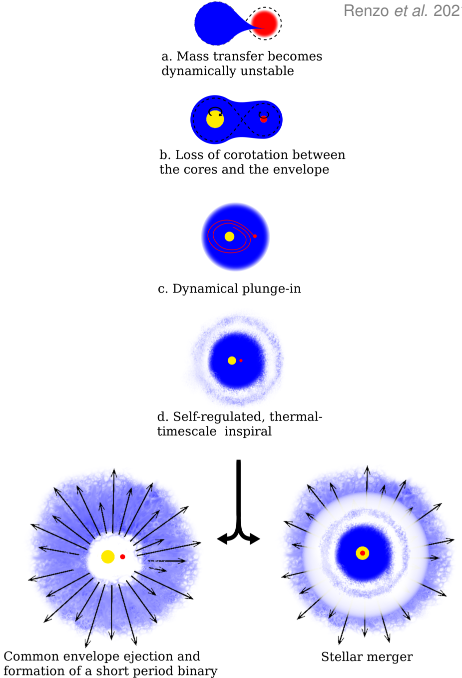


Example from Ivanova *et al.* 2013b

Common envelope evolution in one slide

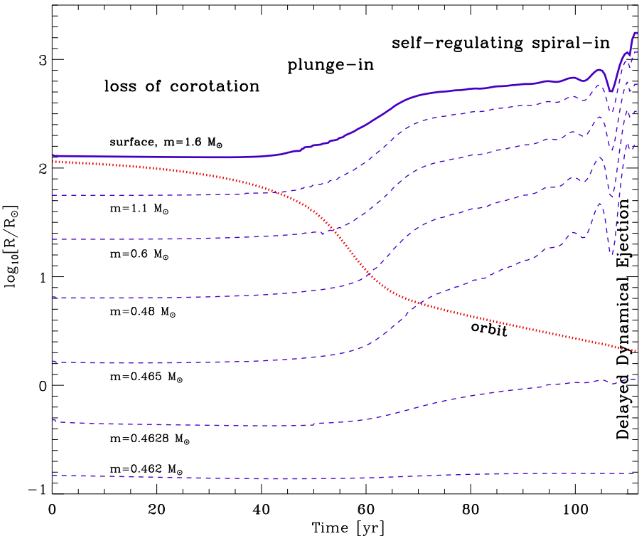


Example from Ivanova *et al.* 2013b

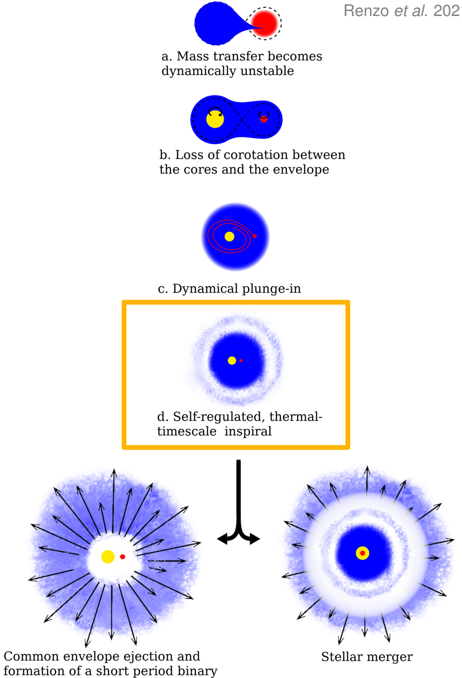


Common envelope evolution in one slide

Renzo *et al.* 2021



Example from Ivanova *et al.* 2013b



How many sources do we expect?

$$N_{\mathrm{CE}} = R_{\mathrm{CE,init}} \times \Delta t_{\mathrm{CE}}$$

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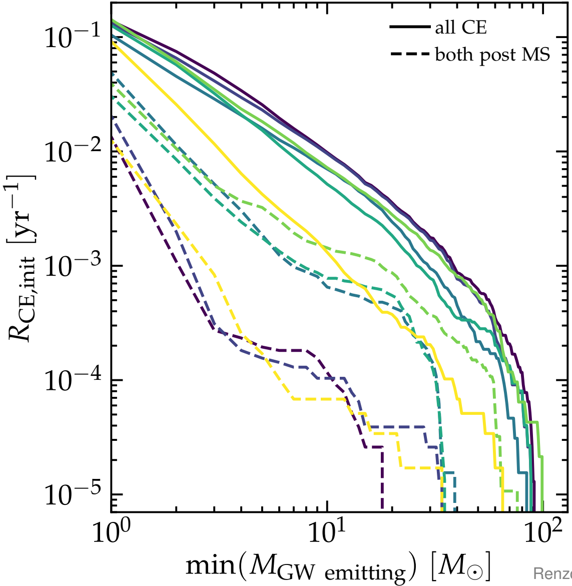


Renzo *et al.* 2021

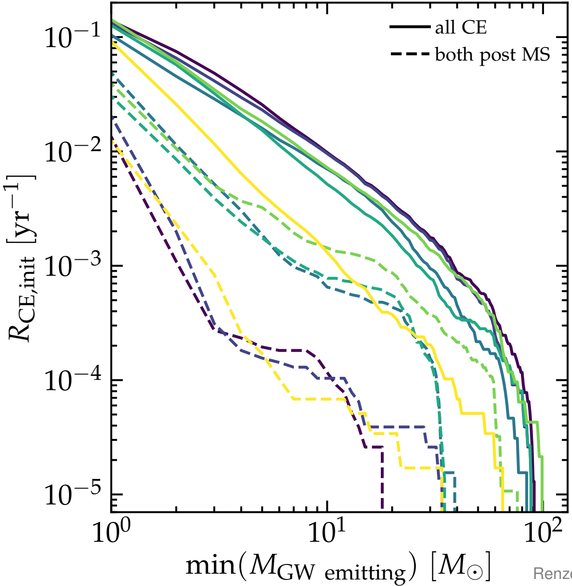
$$R_{\mathrm{CE,init}} = 0.18^{+0.02}_{-0.09} \quad (0.06^{+0.03}_{-0.02})$$

c.f. LRN rate $\sim$ 0.3 yr^{-1}

Kochaneck *et al.* 2014, see also Howitt *et al.* 2020

COSMIC
Breivik *et al.* 2020

How many sources do we expect? $N_{\rm CE} = R_{\rm CE,init} \times \Delta t_{\rm CE}$



Renzo *et al.* 2021

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Kochaneck *et al.* 2014, see also Howitt *et al.* 2020

Duration (in band) is very uncertain

$\Delta t_{\rm CE} \simeq 10^{-2} - 10^5$ years

(e.g., Meyer & Meyer-Hofmeister 1979, Fragos *et al.* 2019, Igoshev *et al.* 2020, Chamandy *et al.* 2020, Law-Smith *et al.* 2020)

$$\Downarrow$$

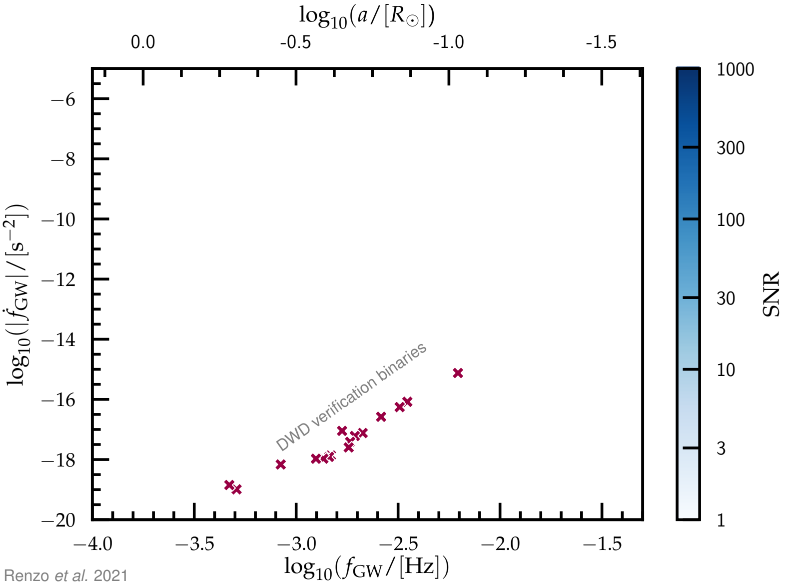
$$0 \lesssim N_{\rm CE} \lesssim 1000$$

COSMIC

Breivik *et al.* 2020

Could we detect something?

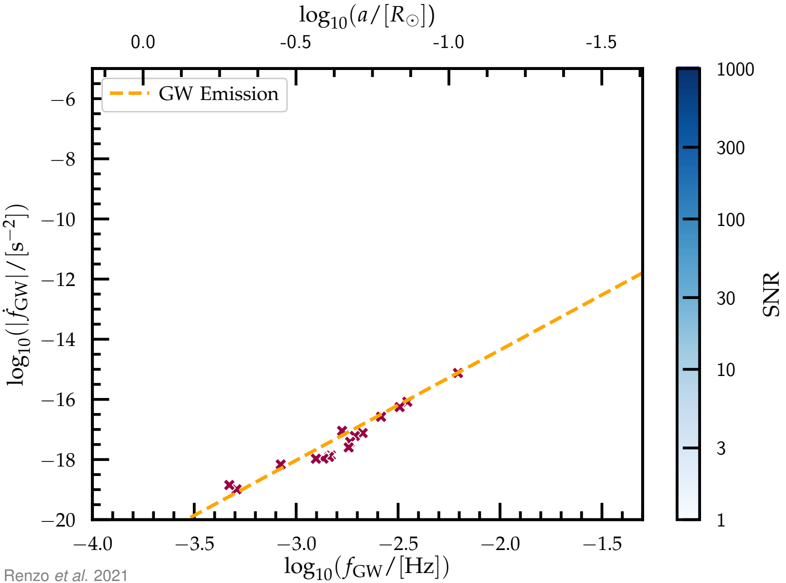
Could we see it? An answer not relying on a specific model



$M_{core} = 0.5\,M_\odot$, $M_2 = 0.3\,M_\odot$,
$D = 3\,\text{kpc}$, $T = 5$ years,
averaged over orientation and sky location

Renzo *et al.* 2021

Could we see it? An answer not relying on a specific model



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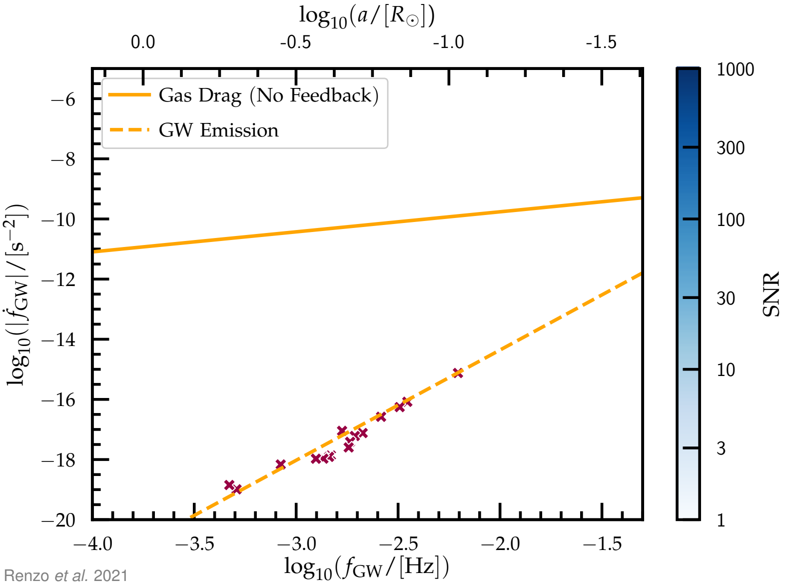

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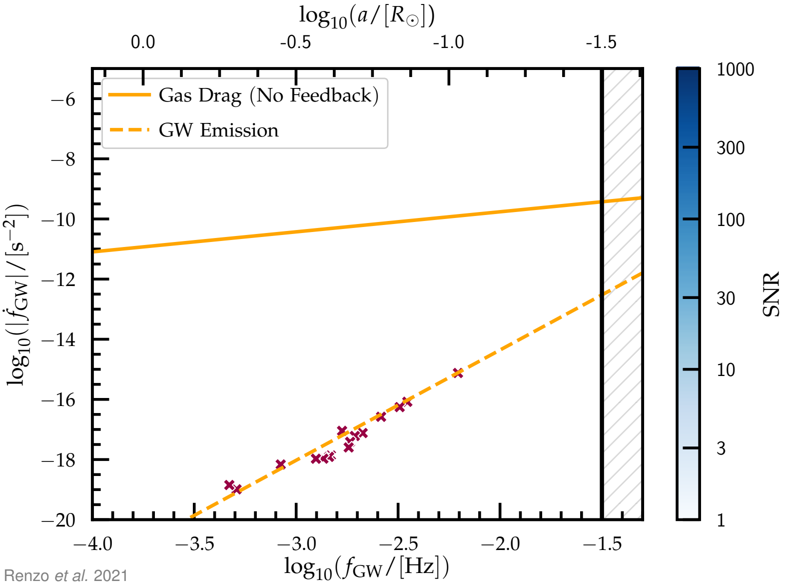

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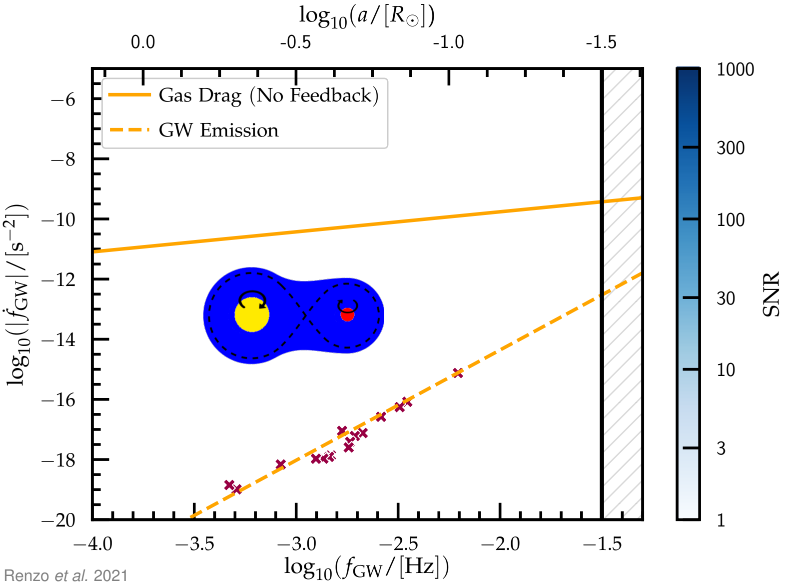

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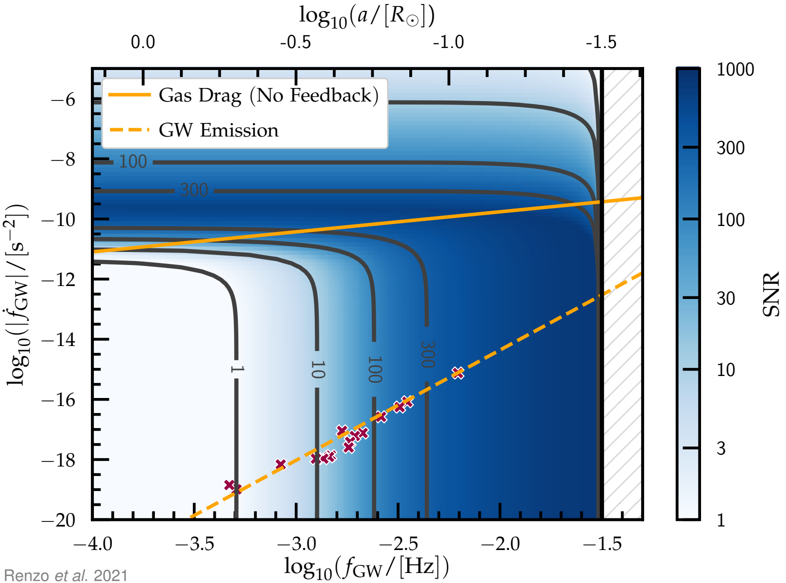

$M_{core} = 0.5\,M_\odot$, $M_2 = 0.3\,M_\odot$,
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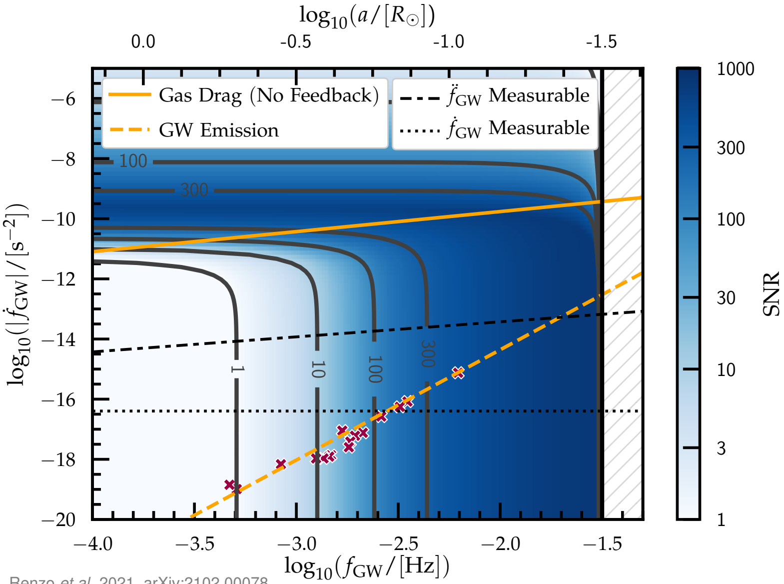
Renzo *et al.* 2021

Conclusions

Unstable mass transfer

Can LISA see common-envelope events? Maybe!



Renzo *et al.* 2021, arXiv:2102.00078

- $\sim$ One CE-begin per 10 yr
- $0 \lesssim N_{CE} \lesssim 1000$
- if stalls at short separation they might detectable

$\Downarrow$

Direct window on the inside

If non-detection

- stalls at large separation

and/or

- stalling phase is short

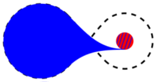
Conclusions

for real!

Mass transfer makes binaries different than single stars

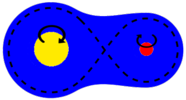
dynamically stable:

common, widens the orbit, changes *significantly* both stars



dynamically unstable:

rare, shrinks the orbit, necessary for *most* compact binary formations



Backup slides

Summary of ejection mechanisms

Binary SN disruption

- Ejects initially less massive star
- Requires SN kick
- Final $v \simeq v_2^{\rm orb}$
- Most binaries are disrupted
- Leaves binary signature

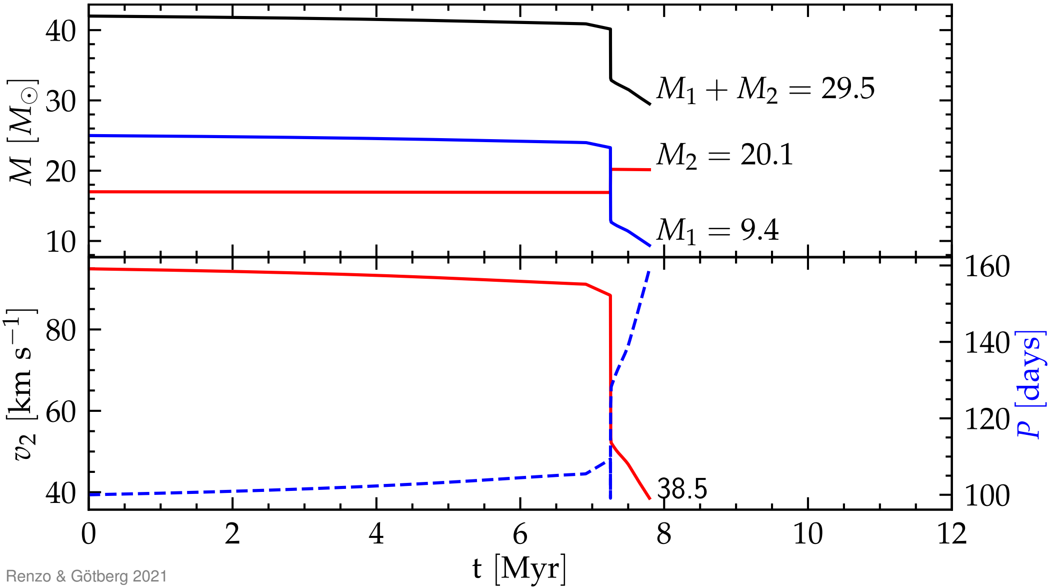
fast rotation, He/N enrichment, lower apparent age

Cluster ejections

- Happen early on, before SNe
- Can produce faster stars
- Least massive thrown out
- *Gaia* hint: high efficiency dynamical ejection

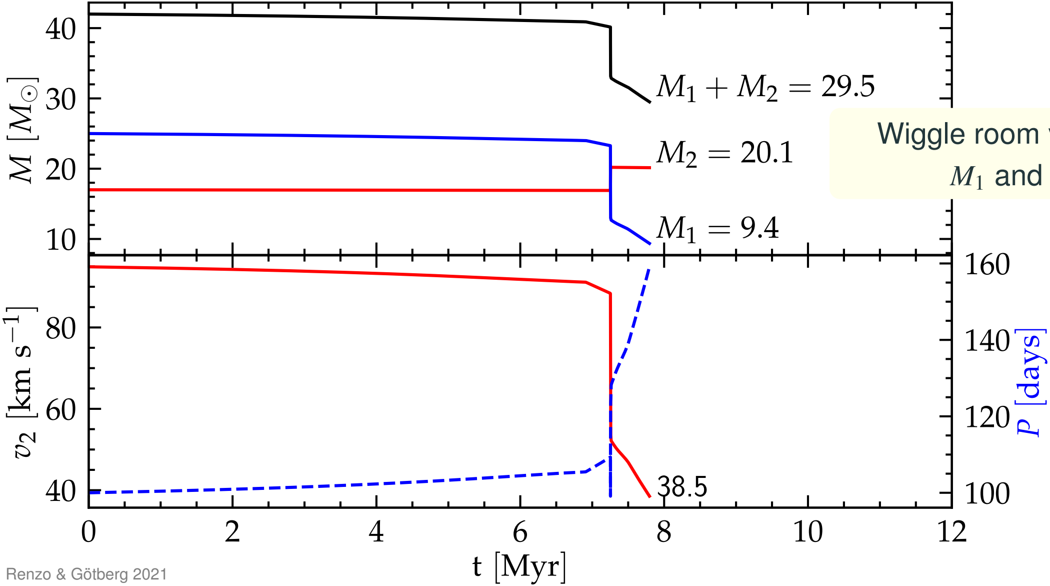
...Binaries are still important! but might not leave signature

Spatial velocity & mass



Renzo & Götberg 2021

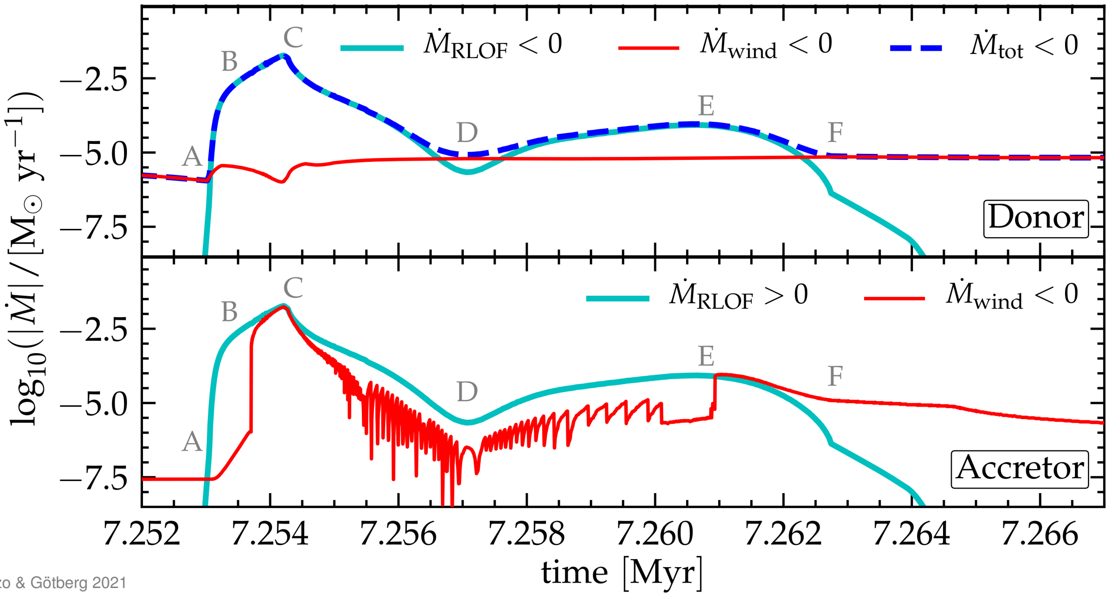
Spatial velocity & mass



Wiggle room varying M_1 and P

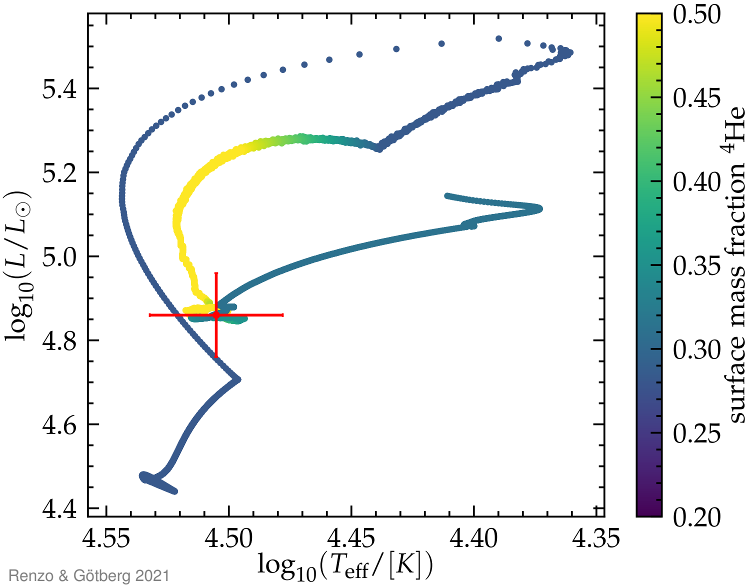
Renzo & Götberg 2021

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



Renzo & Götberg 2021

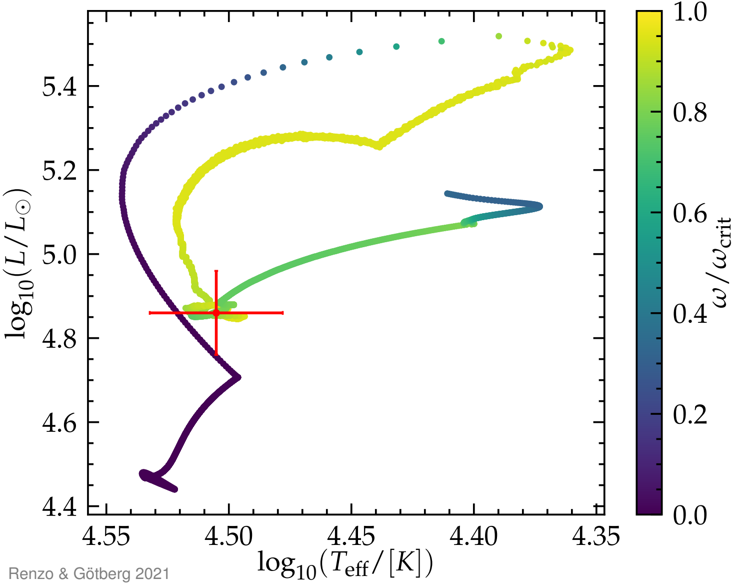
Hertzsprung-Russel diagram: helium surface abundance



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

Renzo & Götberg 2021

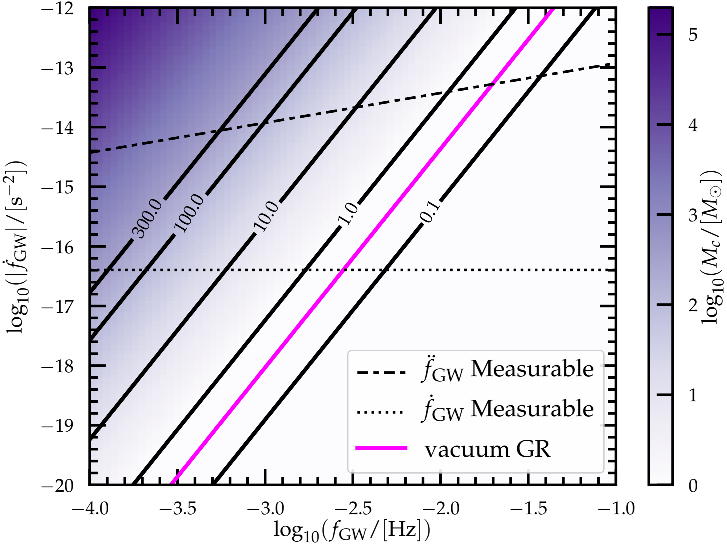
Hertzsprung-Russel diagram: accretor rotation



Renzo & Götberg 2021

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

"Stealth bias" assuming GR in vacuum: chirp mass

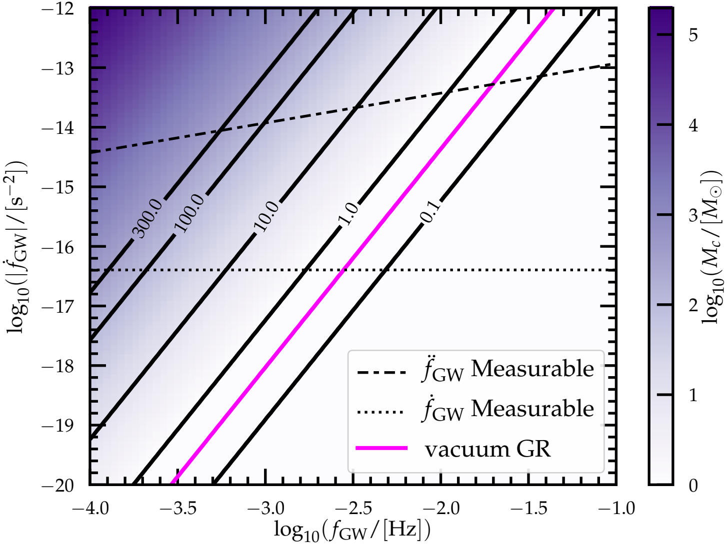


Renzo *et al.* 2021

“Stealth bias” assuming GR in vacuum: chirp mass

“Braking index”

$$n = f\ddot{f}/\dot{f}^2$$
$$\Downarrow$$
$$n_{\rm GR} = \frac{11}{3}$$



Renzo *et al.* 2021

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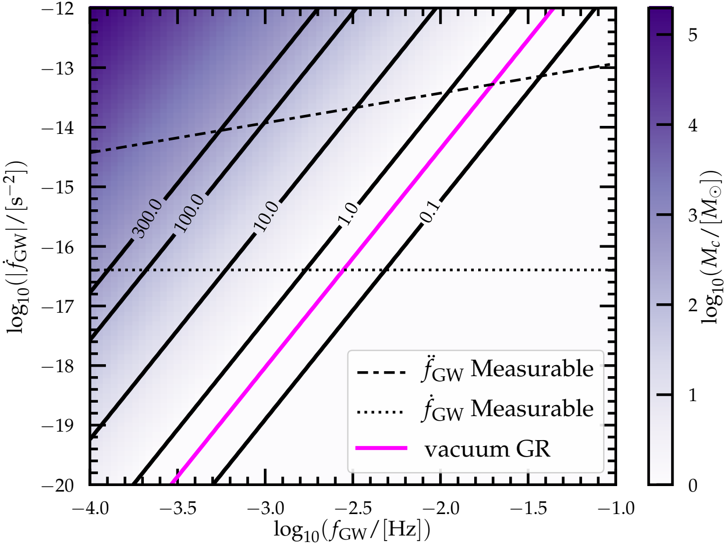
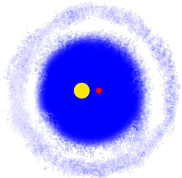




EM counterparts:

- Optical/IR transients

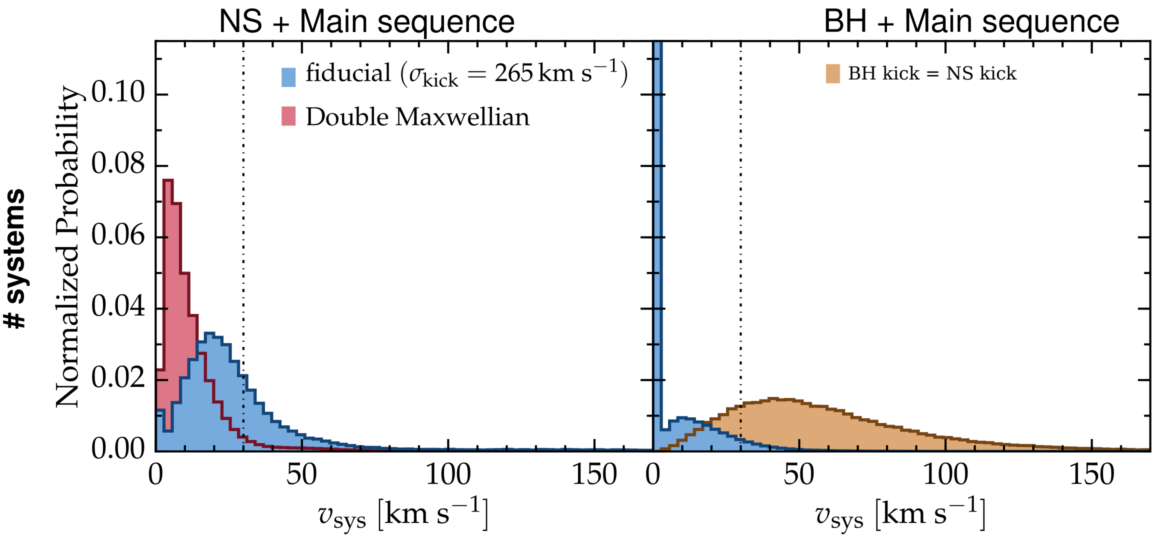
  (Blagorodnova *et al.* 2020)

- “weird” red giant star

  (Clayton *et al.* 2017)

Renzo *et al.* 2021

Post-SN velocity of surviving binaries



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

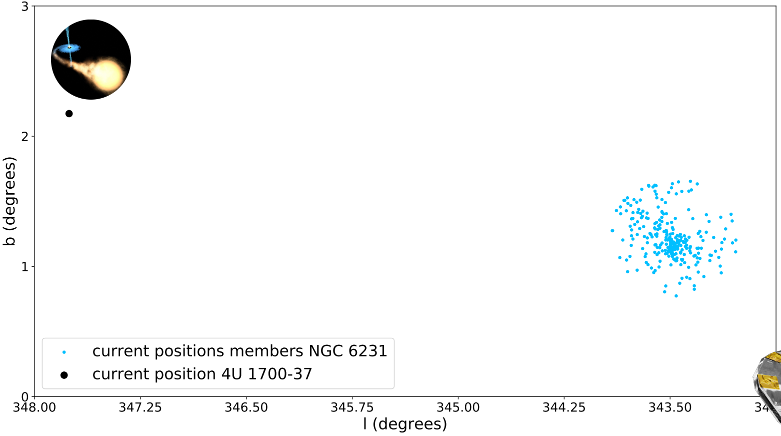
Renzo *et al.* 2019b

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

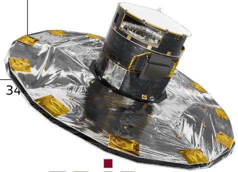
Preliminary: The case of 4U1700-37

$$M \simeq 2.5\,M_\odot\ ,\ M_* \simeq 60 \pm 10\,M_\odot\ ,\ P \simeq 3.4\,\text{days}\ ,\ e \simeq 0.22\ , v \simeq 60\,\text{km s}^{-1}$$

Galactic longitude



Galactic latitude



gaia

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

Preliminary: *Gaia* corroborates cluster of origin

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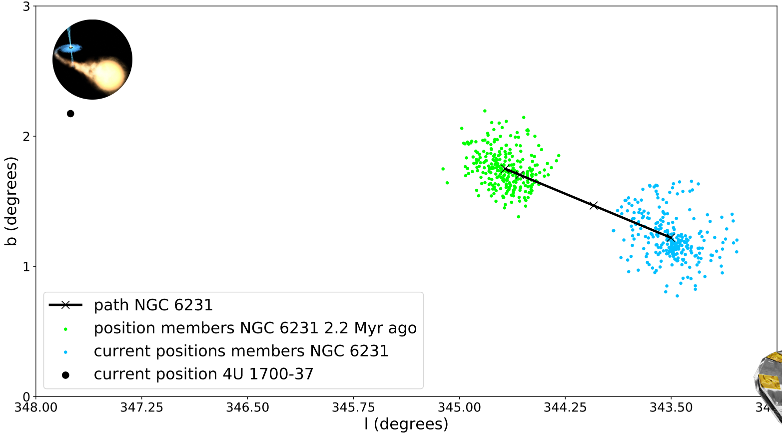
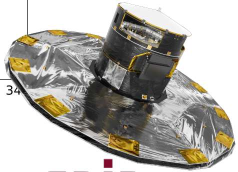


Galactic latitude



gaia

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

Preliminary: Cluster of origin constrains past evolution

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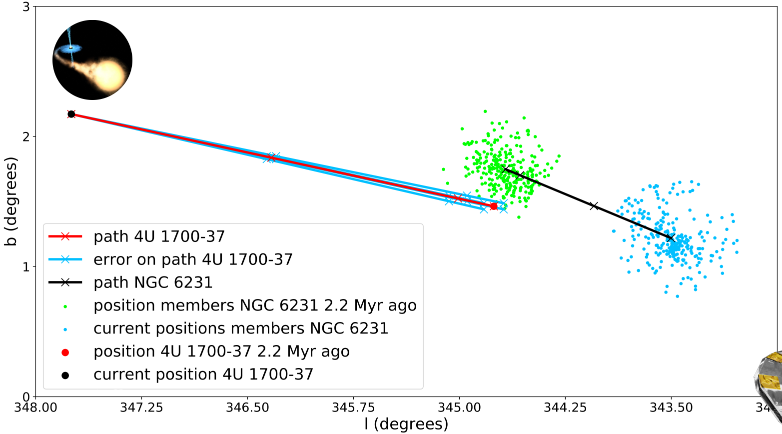

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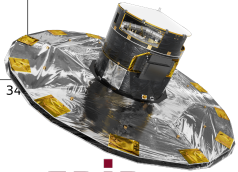
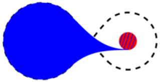
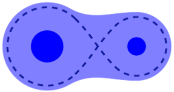


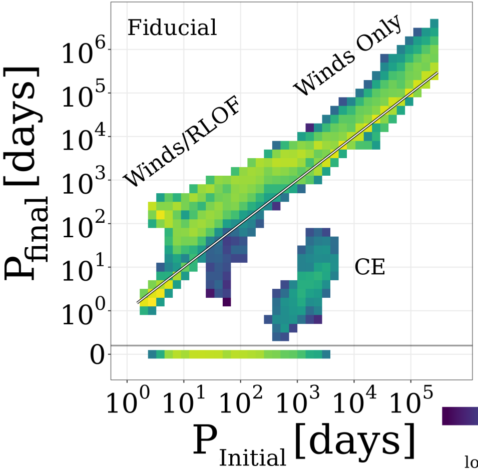
gaia

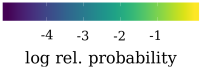
van der Meij, *et al.* (incl. MR), 2021

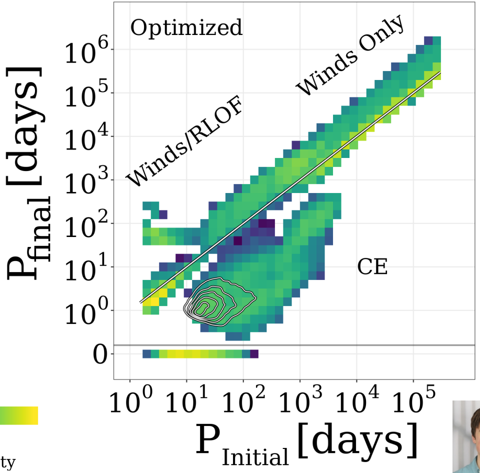
Period evolution depends on uncertain free parameters











Evans, MR, Rossi 2020