Mathieu Renzo

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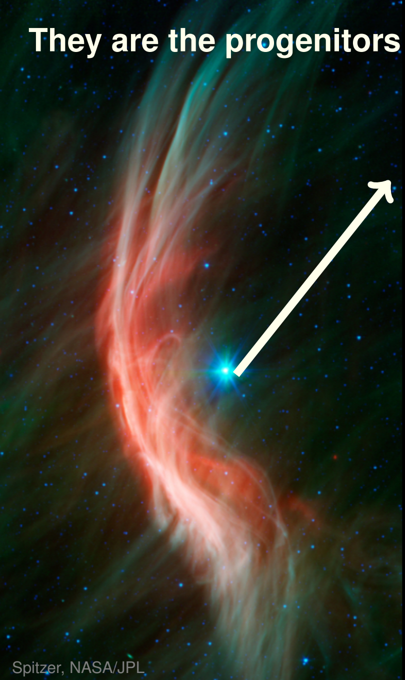
The explosive life of massive stellar binaries

Why massive stars? $(M \gtrsim 7.5\,M_\odot)$

Spitzer, NASA/JPL

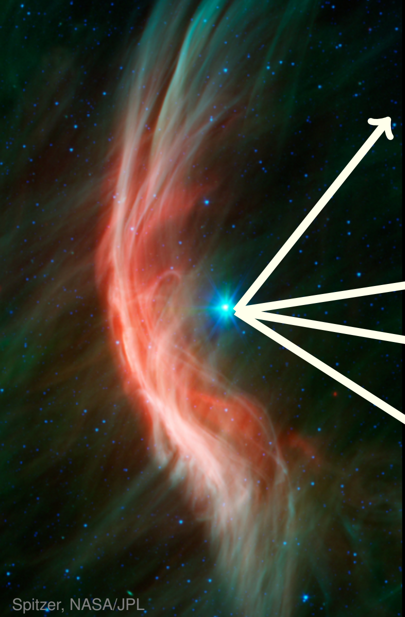
ζ **Ophiuchi is the nearest massive star to Earth**

They are the progenitors of neutron stars & black holes



BH or NS formation in Supernovae

They shape their environment & the Universe as a whole

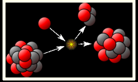


BH or NS formation in Supernovae

Their light can break atoms

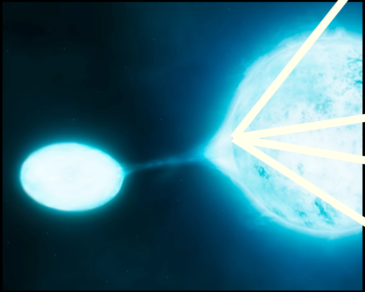
Stellar feedback

They drive star formation



They make lots of chemical elements

Binary interactions *change* massive star feedback



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

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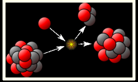
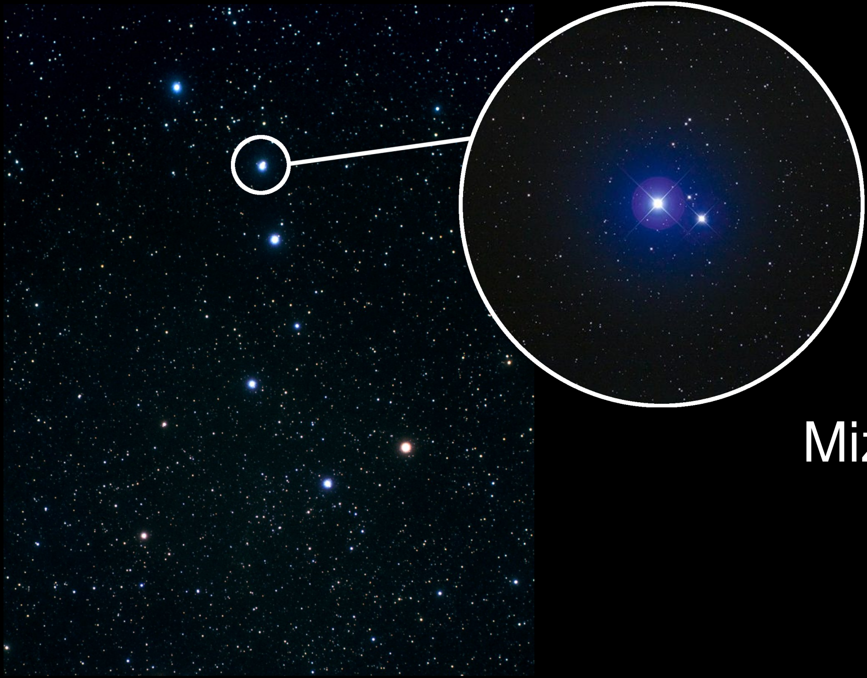


Nucleosynthesis & chemical evolution

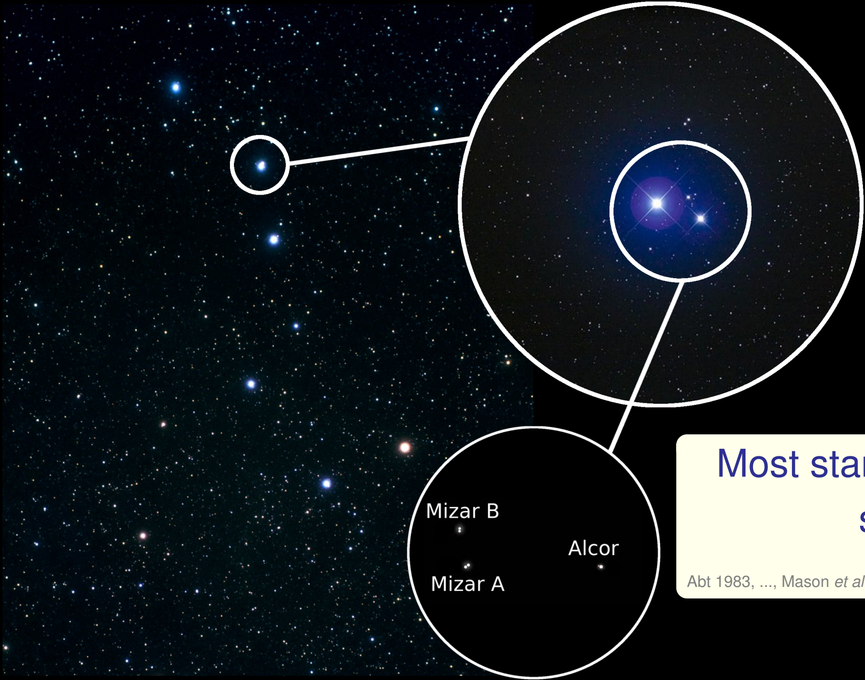
They drive star formation

Stellar feedback

The big dipper



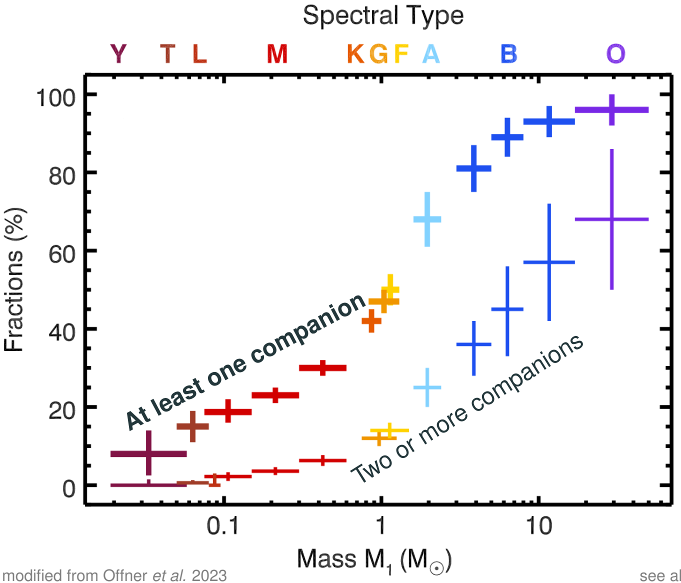
Mizar & Alcor



Most stars are in multiple systems

Abt 1983, ..., Mason *et al.* 2010, Sana *et al.* 2012, Offner *et al.* 2023

Why binaries? Most (massive) stars are born with companion(s)



modified from Offner *et al.* 2023

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

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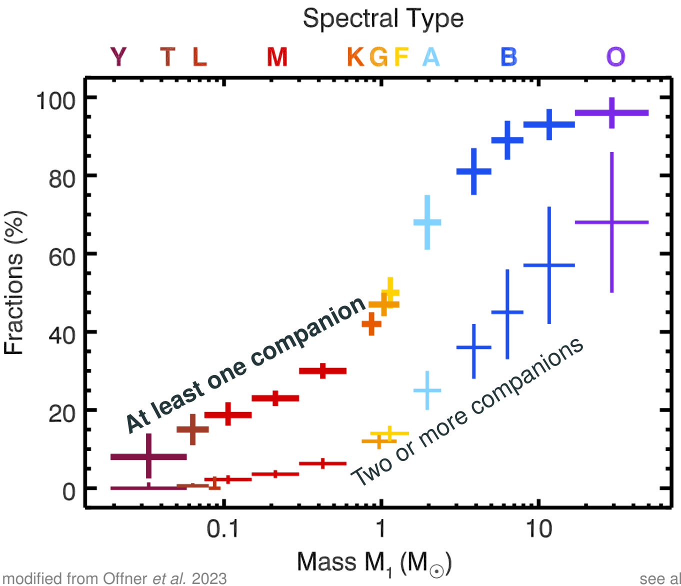
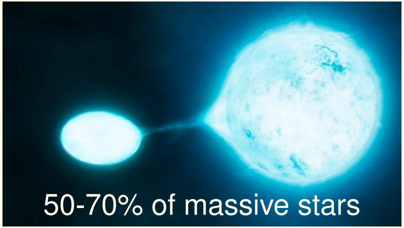


modified from Offner *et al.* 2023

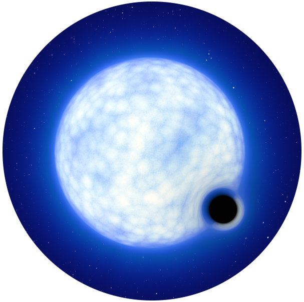
Mass transfer episodes are common



Sana *et al.* 2012

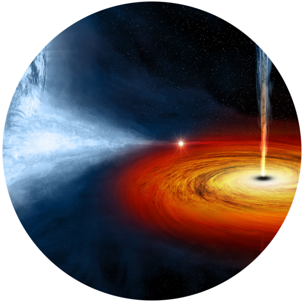
see also Mason *et al.* 2010, Kobulnicky & Fryer 2007, Moe & di Stefano 2017

Binaries are the only way to see (stellar-mass) black holes †



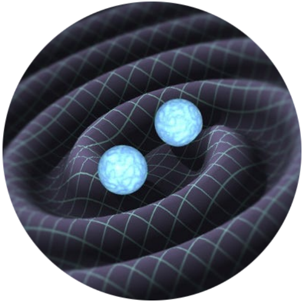
Non-interacting

Shenar *et al.* 2022, El-Badry *et al.* 2022ab, 2023
Vigna-Gómez *et al.* 2024, etc.



X-ray binaries

Webster & Murdin 1972, Bolton 1972,
Ankay *et al.* 2001, van der Meij *et al.* 2021, etc.



Gravitational waves

Including BBH, BHNS, BNS,
LIGO, Virgo, Kagra collaboration

† Exception: serendipitous microlensing, e.g. Sahu *et al.* 2022

What do I do with these?

as computational theorist

Can we "see inside" stars? "Fast-forward" their evolution?

Simulate stars to crack them open and speed them up!

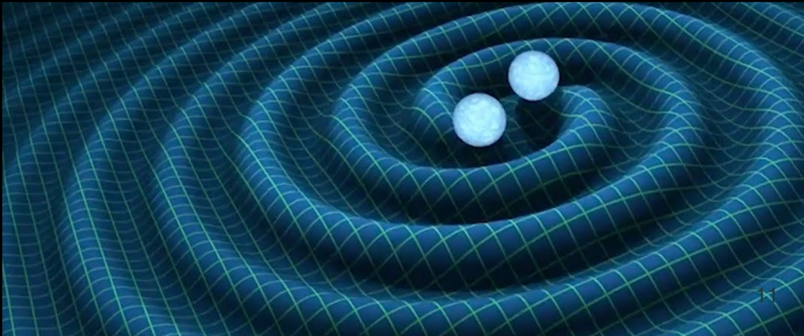
Physical model

(Equations and inputs)

+

(Super-)computers

Combine *local* sources and populations to validate numerical simulations



The most common binary evolution path

(Stable) Mass transfer

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

https://www.youtube.com/watch?v=pDDjEkGjV9U

Mass transfer occurs before the 1^{st} explosion

The donor star loses its H-rich envelope and becomes the least massive star

Kippenhahn & Weigert 1967, Götberg *et al.* 2017

Mass transfer occurs before the 1^{st} explosion

The donor star loses its H-rich envelope and becomes the least massive star

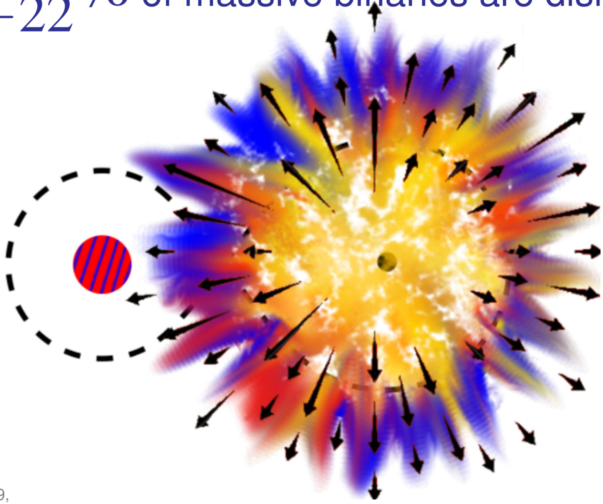
Kippenhahn & Weigert 1967, Götberg *et al.* 2017

The "widowed" star carries signatures of its past in a binary

Renzo & Zapartas 2020

Most massive binaries do not survive the 1st explosion

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



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

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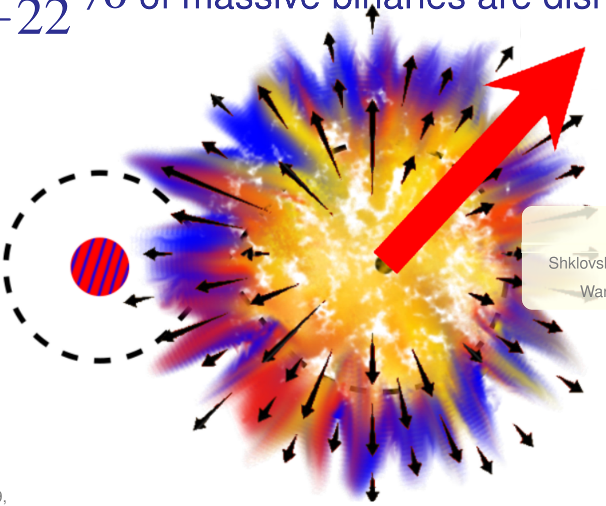
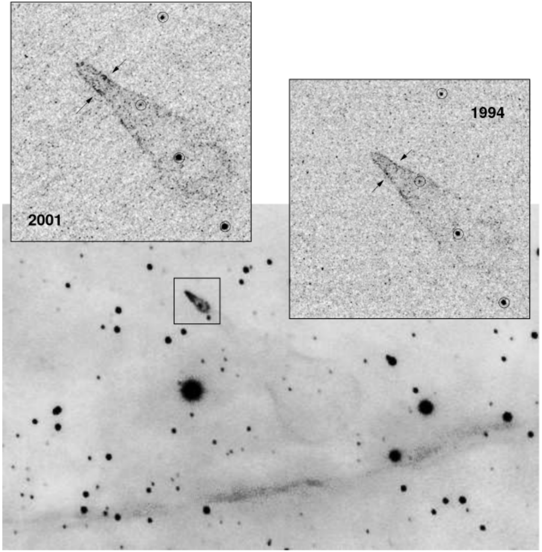


SN Natal kick

Shklovskii 1970, Katz 1975, Janka 2013, 2017, Wang *et al.* 2024, Burrows *et al.* 2025

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

Evidence for natal kicks: $v_{\rm NS} \gg v_{\rm progenitors}$



Chatterjee & Cordes 2003

Typically:

- $v_{\rm NS} \sim 100\,{\rm km\ s}^{-1}$ up to $\sim 1200\,{\rm km\ s}^{-1}$
- $v_{\rm progenitors} \sim 10\,{\rm km\ s}^{-1}$ up to $\sim 100\,{\rm km\ s}^{-1}$

NS speed up at birth

NS/ejecta momentum redistribution at explosion

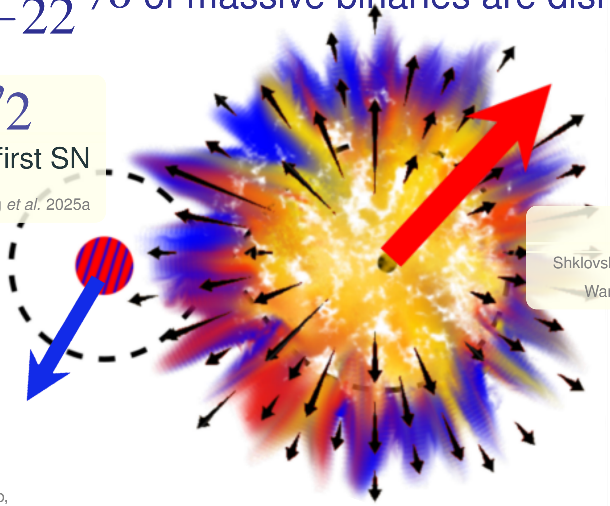
The velocity of the "widowed" star does **not** depend on the SN natal kick

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

$v \simeq v_2$

before the first SN

Boersma 1961, Wagg *et al.* 2025a



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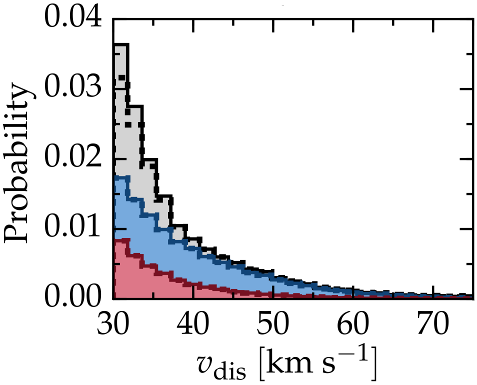
How fast are widowed stars?

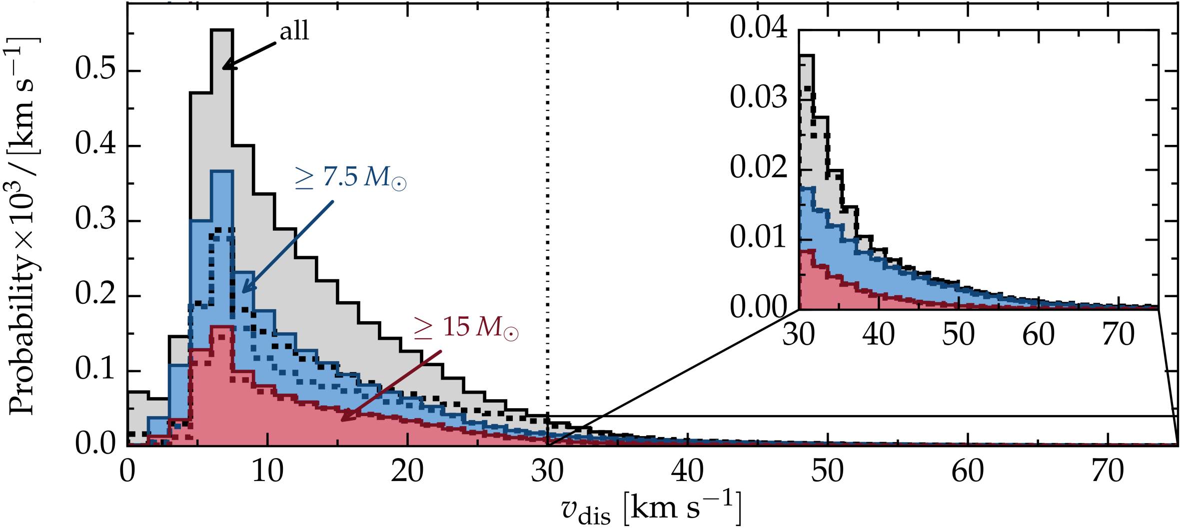
Widowed stars can be *runaways*...



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

Renzo *et al.* 2019b

...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

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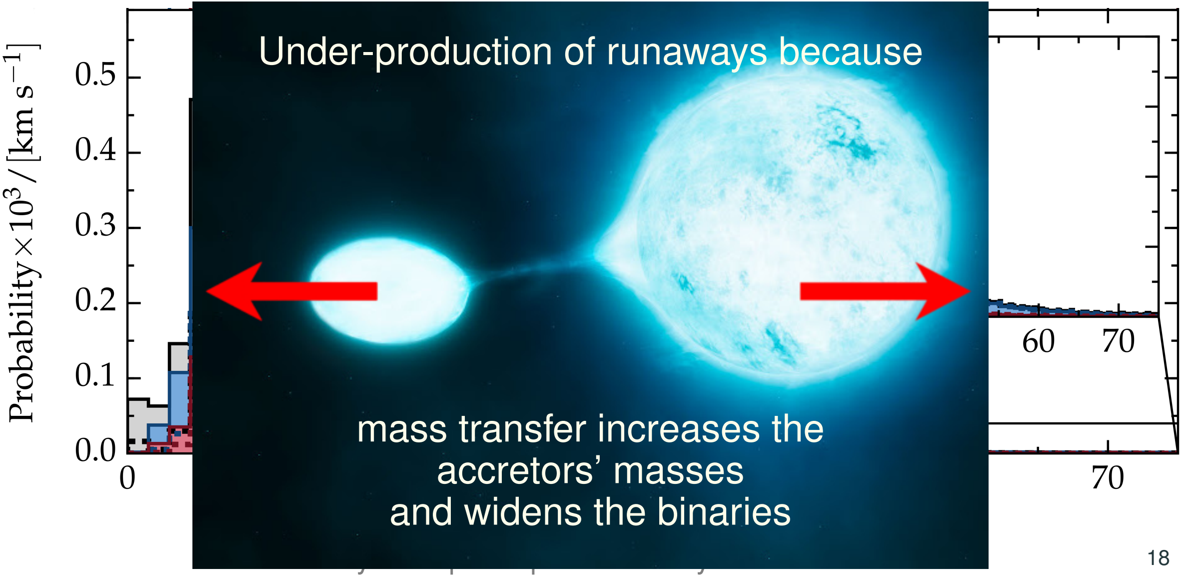

Renzo *et al.* 2019b

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Models of widowed stars...

... and their validation

Using the nearest massive star to pin models

Spitzer, NASA/JPL

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

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Shepard *et al.* 2022

e.g., Sexton *et al.* 2015, Kiminki *et al.* 2017,
Bodensteiner *et al.* 2018, Raga *et al.* 2022

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Observational constraints of ζ Oph.:

- $d \simeq 300$ light years $(107 \pm 4\,\mathrm{pc})$
- $M \simeq 20\,M_\odot$
- Luminosity and color
- **Fast "runaway" star**

  $20\,\mathrm{km\ s^{-1}} \lesssim v_{sys} \lesssim 50\,\mathrm{km\ s^{-1}}$

- **Fastest rotating star known**

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- **Weird surface composition**

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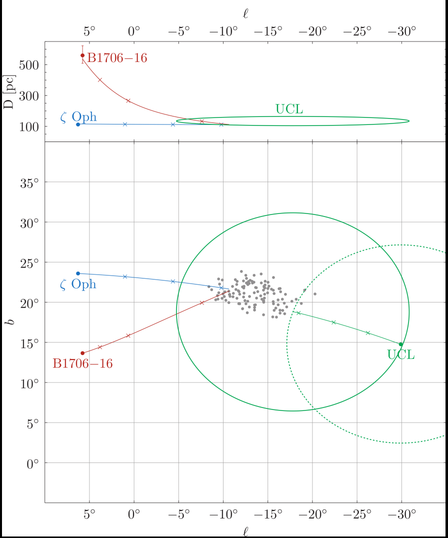
✗ **Rotating single stars**

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

ζ Ophiuchi is single but we can trace it back to a neutron star



Neuhäuser *et al.* 2019, 2020 see also Blaauw 1952, 1961,
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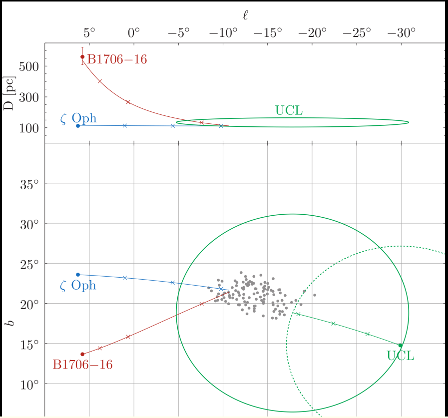


SN explosion $\sim 1.78 \pm 0.21$ **Myr ago**

$\Rightarrow$Radioactive iron rain on Earth

Benitez *et al.* 2002, Fry *et al.* 2016, Neuhäuser *et al.* 2020

Neuhäuser *et al.* 2019, 2020 see also Blaauw 1952, 1961,
van Rensbergen *et al.* 1996, Hoogerwerf *et al.* 2001, Lux *et al.* 2020

Numerical model of ζ Ophiuchi

$Z = 0.01$

(Murphy *et al.* 2021)

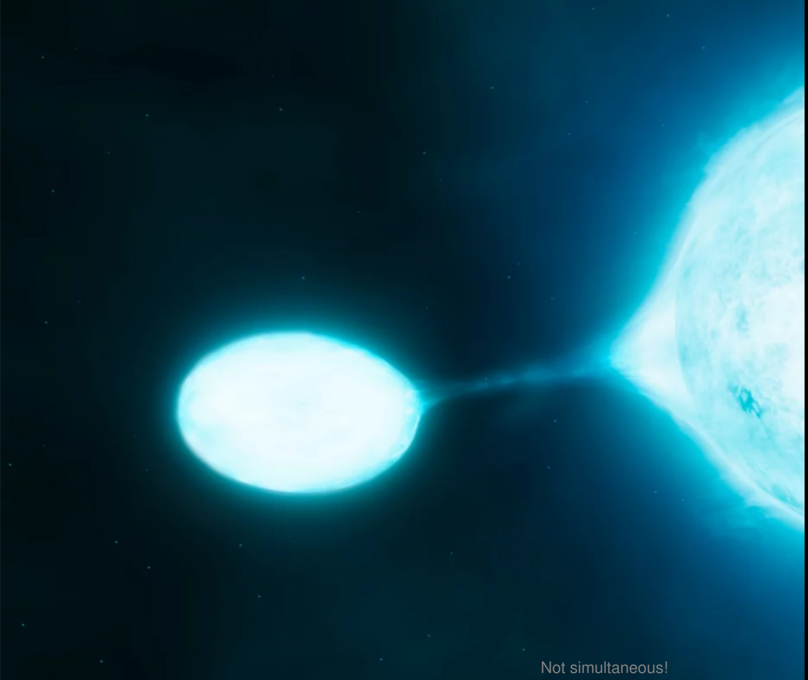
$M_2 = 17\,M_\odot$

$P = 100\,\mathrm{days}$

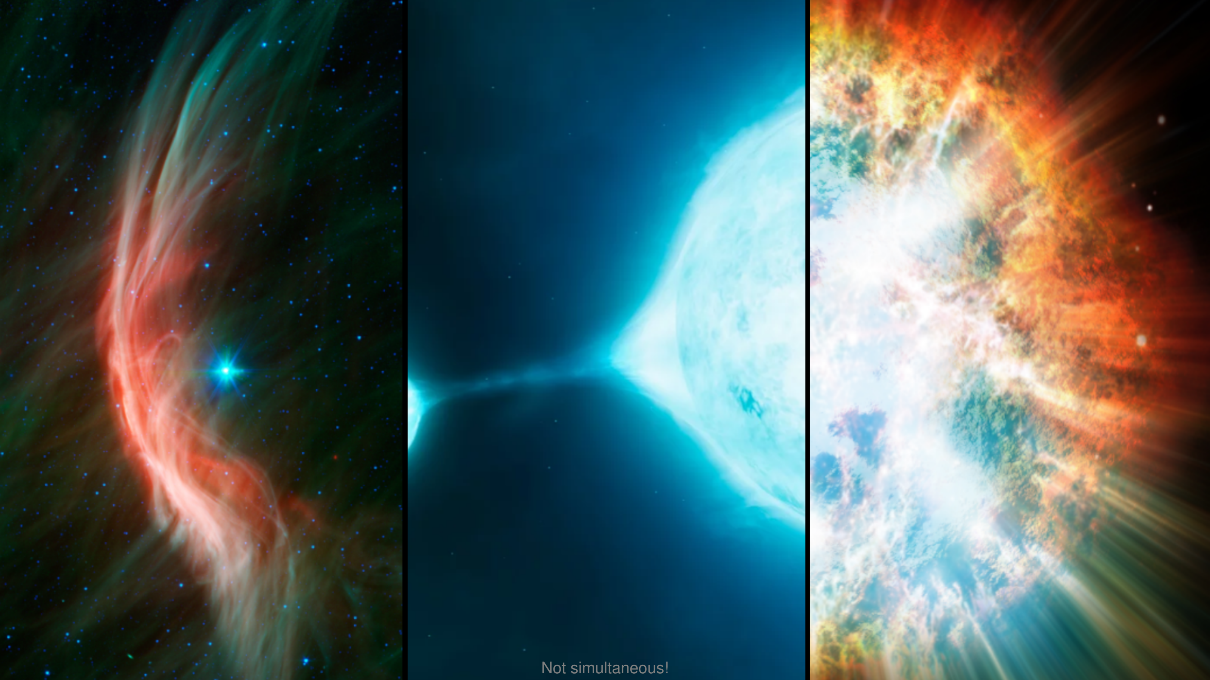
(case B RLOF)

$M_1 = 25\,M_\odot$

Renzo & Götberg 2021



Not simultaneous!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Does a binary past help with ζ Oph. ?

Renzo & Götberg 2021

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Spitzer, NASA/JPL

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

It's fast moving because it was ejected from a binary

Spitzer, NASA/JPL

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It's fast rotating because it was spun up by accretion

Renzo & Götberg 2021

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The composition is a mixture of both stars

Spitzer, NASA/JPL

Renzo & Götberg 2021

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A binary past does help with ζ Oph. !

and the effects of accretion are long-lasting

Renzo & Götberg 2021

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Renzo & Götberg 2021

Ongoing work:

- Does mass transfer change the interior structure?

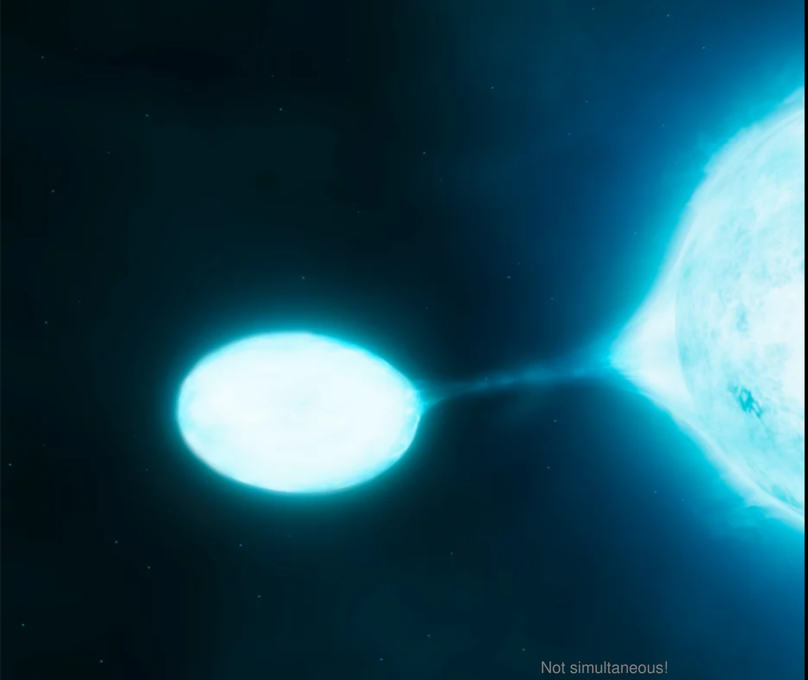
  Renzo *et al.* 2023, Wagg *et al.* 2024, Lau *et al.* 2024, Schürmann & Langer 2024, Landri *et al.* 2025

- Use telescopes to find more widowed stars!

  First remote observation one month ago!

Question

Which star explodes first? (and why?)


Not simultaneous!


Not simultaneous!

Take home points:

- Massive stars are born with companion(s)

  Interactions are common

- Most binaries break at the 1st supernova

  Donor explodes, “widowed” accretor is ejected

- Binaries with a NS or BH are <u>rare</u>

  though that’s typically the only way to study BHs

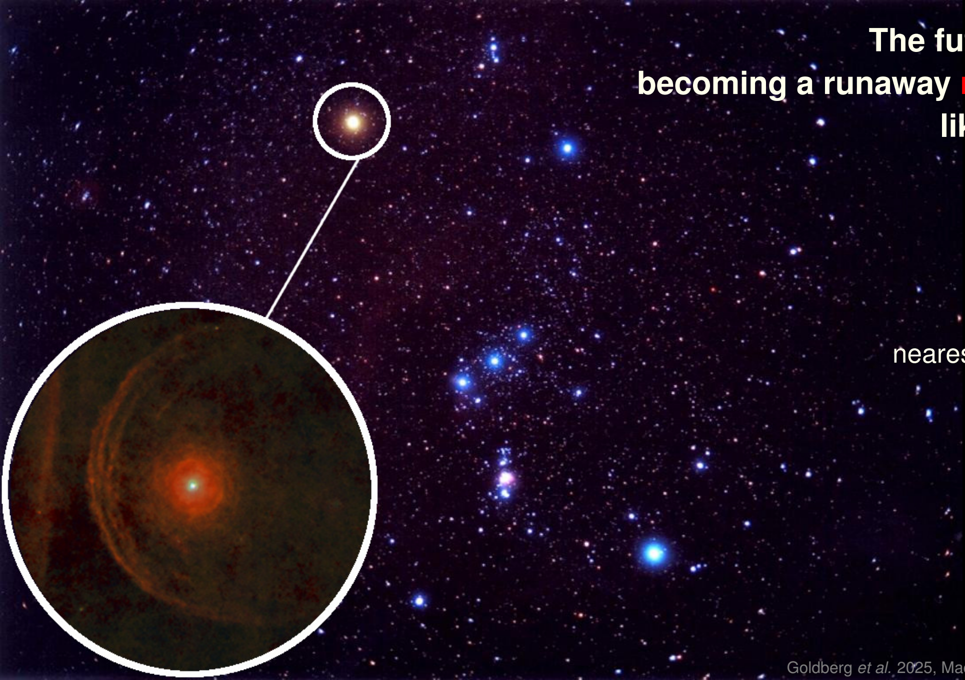
- ζ Ophiuchi is a “widowed” star

  the nearest massive star to Earth ($\sim$ 300 ly)

The future of ζ Oph.: becoming a runaway red supergiant

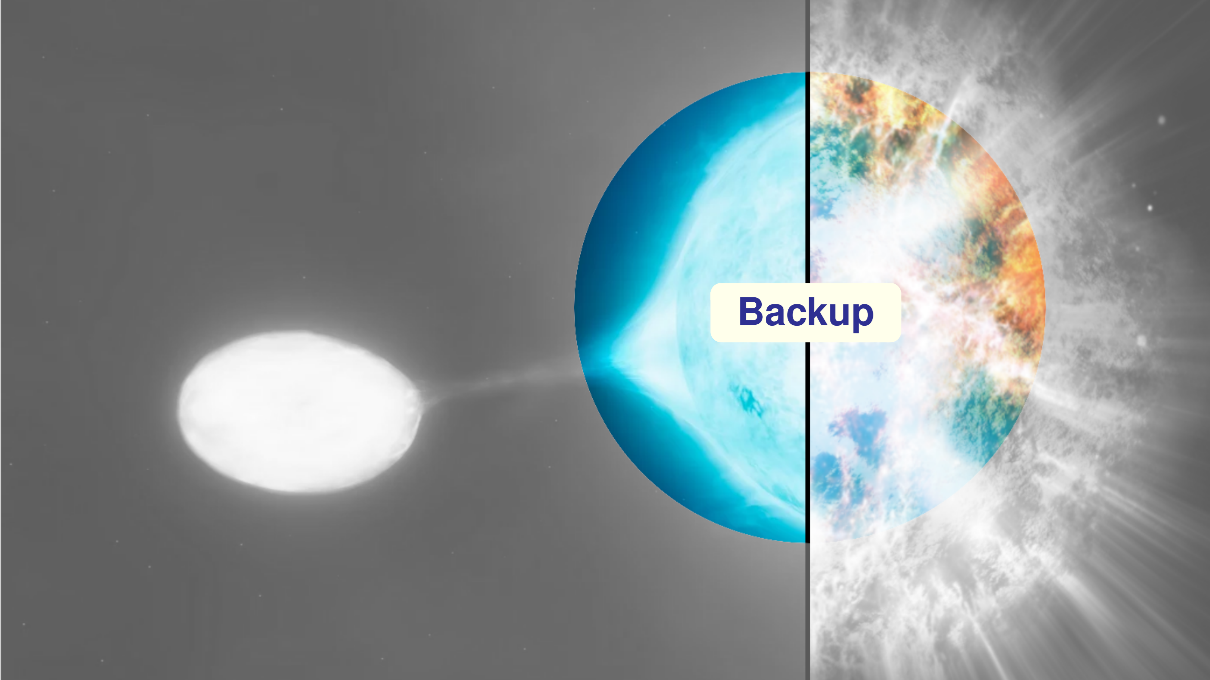
Goldberg *et al.* 2025, MacLeod *et al.* 2025, O'Grady 2025

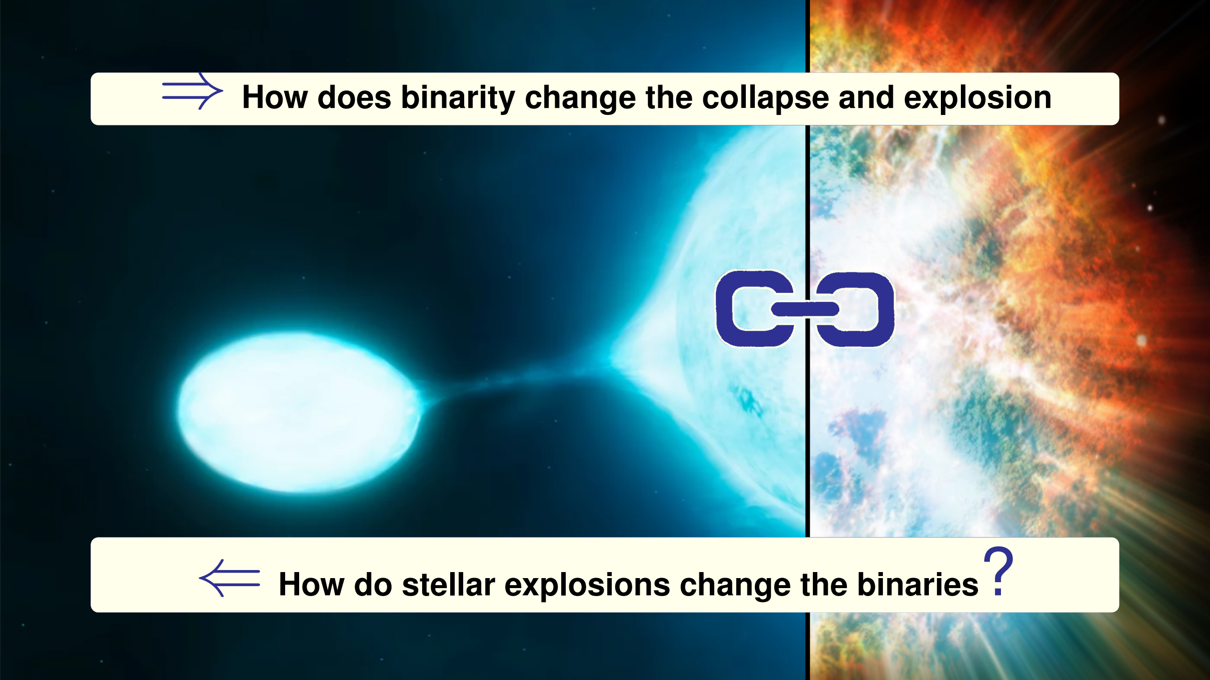
The future of ζ Oph.: becoming a runaway red supergiant like Betelgeuse



nearest "old" massive star
also runaway
recently claimed
to still be in binary

Goldberg *et al.* 2025, MacLeod *et al.* 2025, O'Grady 2025

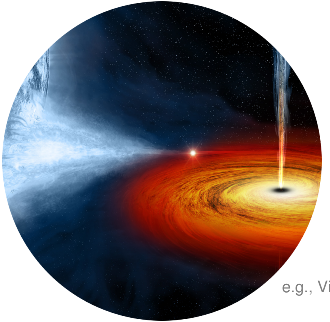

Backup


⇒ How does binarity change the collapse and explosion
⇐ How do stellar explosions change the binaries ?

Do BHs receive kicks ?

NO

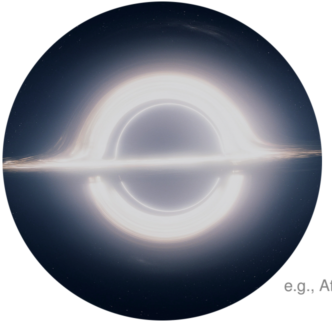
⇒ most remain with their companion



e.g., Vigna-Gómez et al. 2024

YES

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



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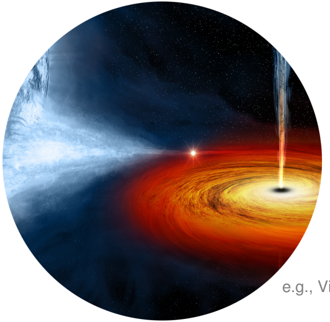

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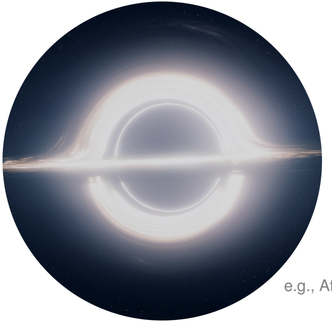
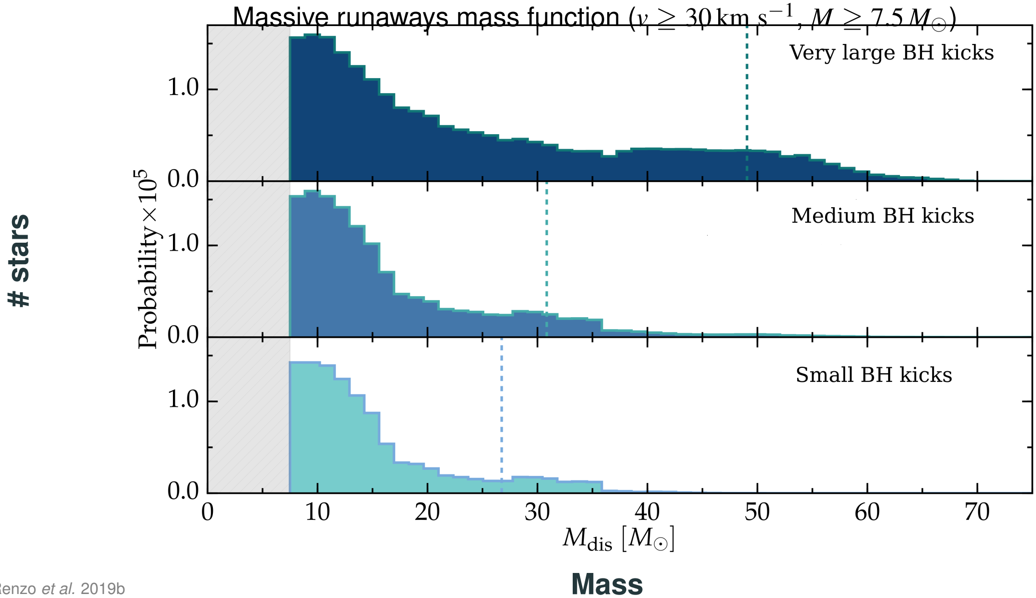


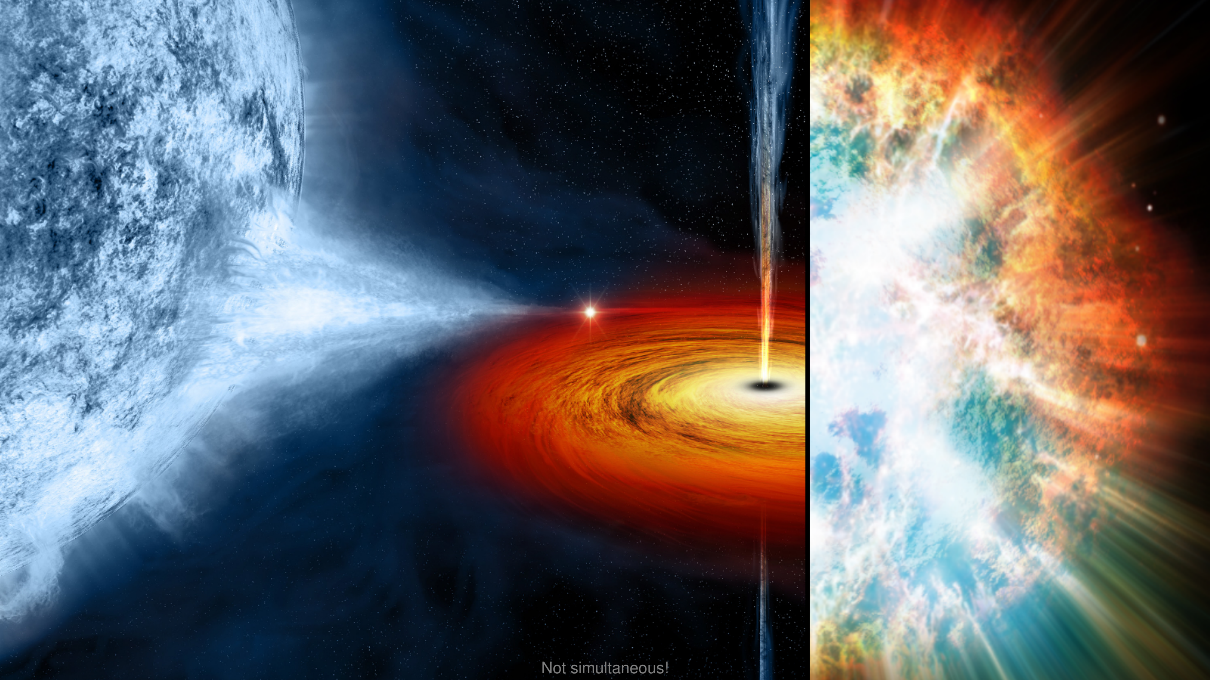
e.g., Atri *et al.* 2019

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

Constraining BH kicks with the mass distribution of "widowed" stars



Renzo *et al.* 2019b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