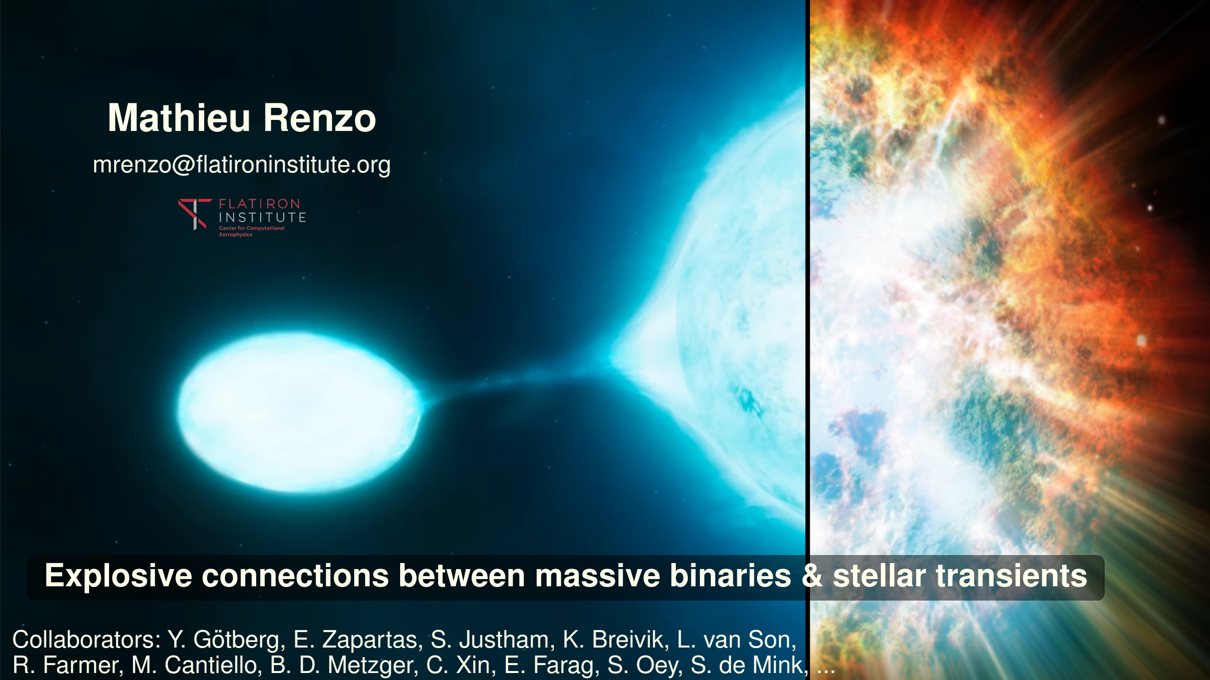

Mathieu Renzo

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FLATIRON INSTITUTE
Center for Computational Astrophysics

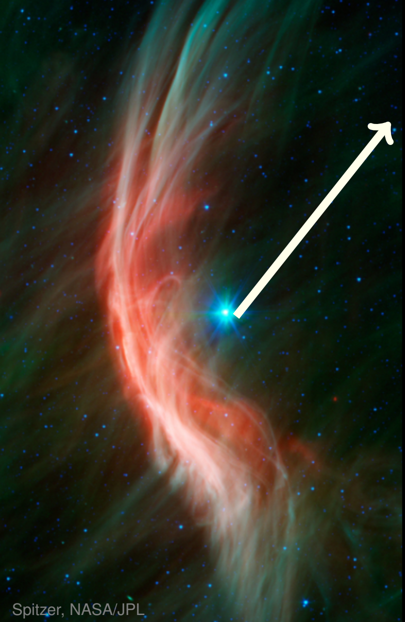
Explosive connections between massive binaries & stellar transients

Collaborators: Y. Götberg, E. Zapartas, S. Justham, K. Breivik, L. van Son, R. Farmer, M. Cantiello, B. D. Metzger, C. Xin, E. Farag, S. Oey, S. de Mink, ...

Why massive stars? ($M_{\rm initial} \gtrsim 7.5\,M_\odot$)

ζ **Ophiuchi is the nearest O-type star to Earth**

They are the progenitors of neutron stars & black holes

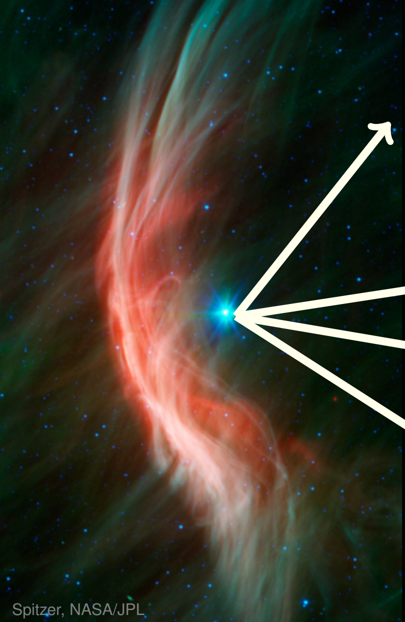


Compact objects
& transients
(incl. GW)

EM:
O'Connor & Ott 2011, Ertl *et al.* 2016, 2020, Farmer *et al.* 2016, **Morozova *et al.* (incl. Renzo) 2015, 2016, Renzo *et al.* 2017, 2020a, b, c, Laplace *et al.* (incl. Renzo) 2021, Vartanyan *et al.* (incl. Renzo) 2021, Zapartas *et al.* (incl. Renzo) 2017a, 2019, 2021a, b, Marchant *et al.* (incl. Renzo) 2019, Farmer *et al.* (incl. Renzo) 2019, 2020**, ...

GW:
LVK collaboration 2015-23, **Vigna-Gómez *et al.* (incl. Renzo) 2018, van Son *et al.* (incl. Renzo) 2020, 2021, Callister, Renzo, Farr 2021, Renzo *et al.* 2021**, ...

They shape their environment & the Universe as a whole



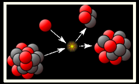
Spitzer, NASA/JPL

Compact objects
& transients
(incl. GW)

Stellar feedback

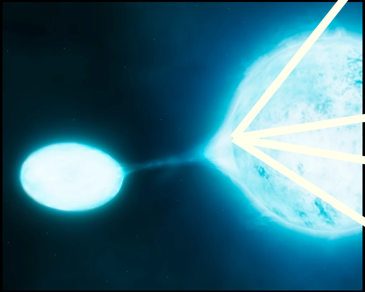
Ionizing rad.

Star Formation
& cluster evolution



Nucleosynthesis &
chemical evolution

Binary interactions *change* massive star feedback



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

Stellar feedback

Compact objects
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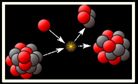
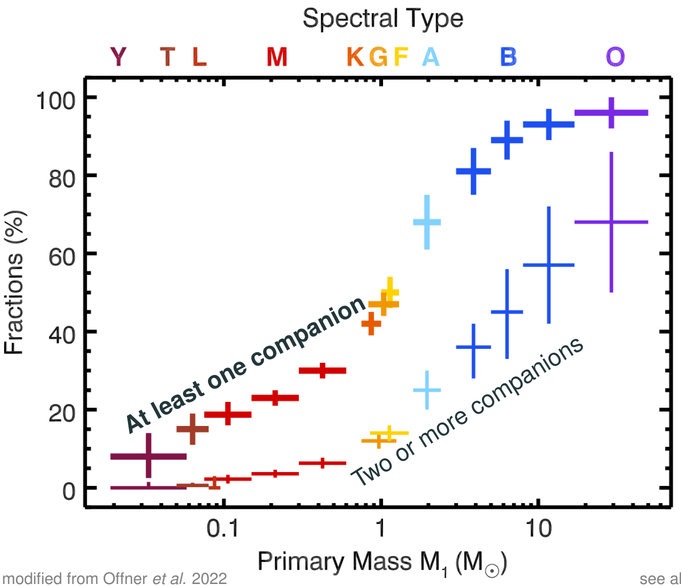


Nucleosynthesis &
chemical evolution

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



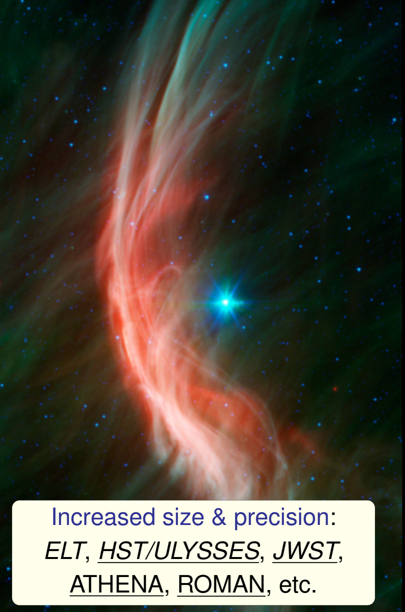
modified from Offner *et al.* 2022

Binary interactions are common

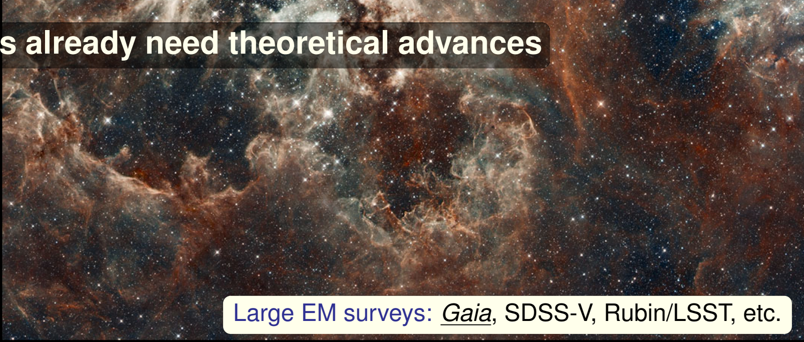
Sana *et al.* 2012

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

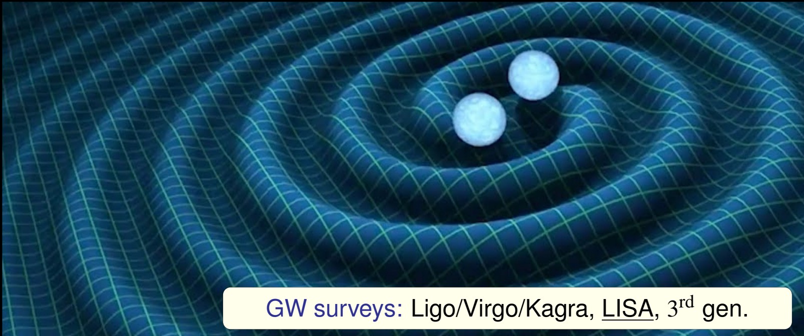
Rich and growing datasets already need theoretical advances



Increased size & precision: *ELT*, *HST/ULYSSES*, *JWST*, ATHENA, ROMAN, etc.



Large EM surveys: *Gaia*, SDSS-V, Rubin/LSST, etc.



GW surveys: Ligo/Virgo/Kagra, LISA, 3rd gen.

Detailed local obs. + Large populations (stars, explosions, mergers)

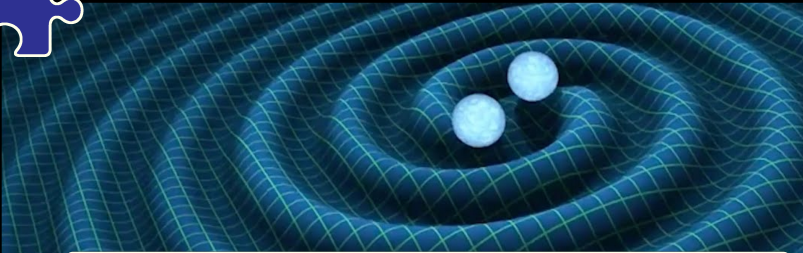
student-led papers

Examples co-authored studies on *observed* population of stars & transients:

Sana *et al.* 2022; **Chan, H.-S. *et al.* 2022**; **Evans, Renzo & Rossi 2020**; **Evans *et al.* 2020**; **Langer *et al.* 2020**; **Renzo *et al.* 2019b**; **Zapartas *et al.* 2017a, b, 2019, 2021a, b, 2022**; **Japelj *et al.* 2018**

Examples co-authored studies on individual sources:

Temim *et al.* 2022 on SNRG292.0+1.8
Renzo & Götberg 2021 on ζ Oph.
van der Meij *et al.* 2021 on HD153919
Renzo *et al.* 2020c on GW190521
Renzo *et al.* 2019a on VFTS682
Lennon *et al.* 2018 on VFTS16 and 72
Kerzendorf *et al.* 2017 on Cas A
Zapartas *et al.* 2017b on SN2002ap



Examples co-authored studies on GW populations:

van Son *et al.* 2022a, b; **Renzo *et al.* 2021a**; **Callister, Farr & Renzo 2021**; **Renzo *et al.* 2020a, b**; **Farmer *et al.* 2020, 2019**; **Marchant *et al.* 2019**; **van Son *et al.* 2020**; **Vigna-Gòmez *et al.* 2018**

Detailed local obs. + Large populations (stars, explosions, mergers)

MESA

Interior structure and evolution of stars

$\lesssim$ 100 CPUh per star/binary

Paxton *et al.* 2011, 2013, 2015, 2019, Jermyn *et al.* 2022

used since 2013, 19+ publications

COSMIC

Rapid population synthesis for studying distributions of stars and transients

$\lesssim$100 CPUh per $\sim 10^5$ binary population

Breivik *et al.* 2020

also used COMPAS, `binary_c` since 2017

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also used COMPAS, `binary_c` since 2017

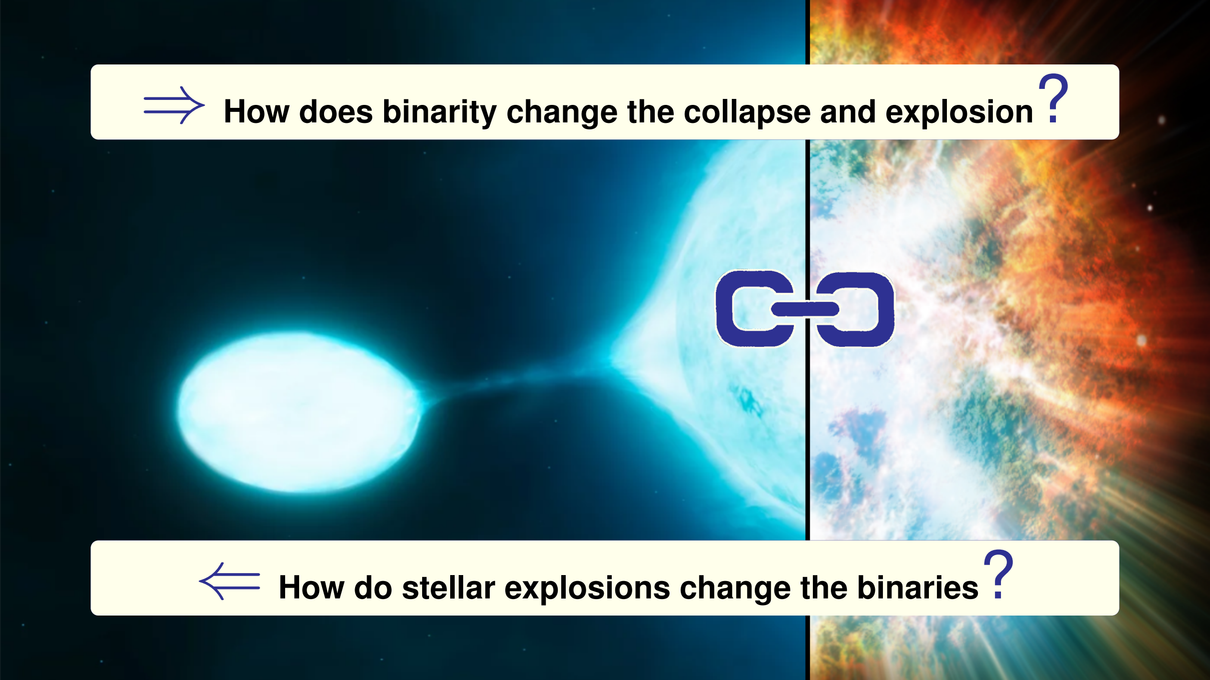
athena++

Multi-D radiation-hydro for selected phases

$10^5 - 10^6$ CPUh per dynamic timescale

Stone *et al.* 2020

presently exploring


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

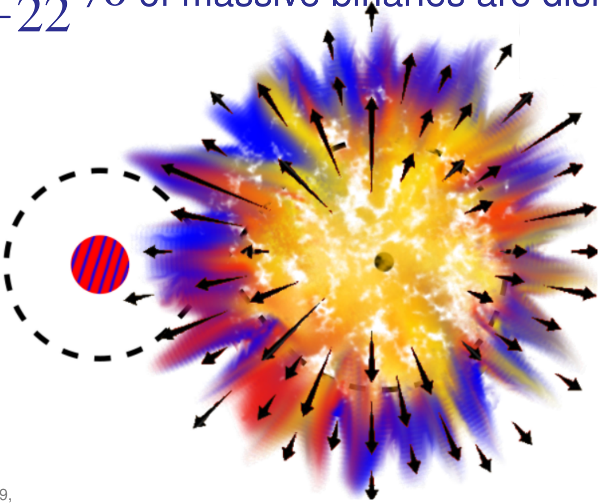
The most common binary interaction

Stable mass transfer after the donor's main sequence (case B RLOF)

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

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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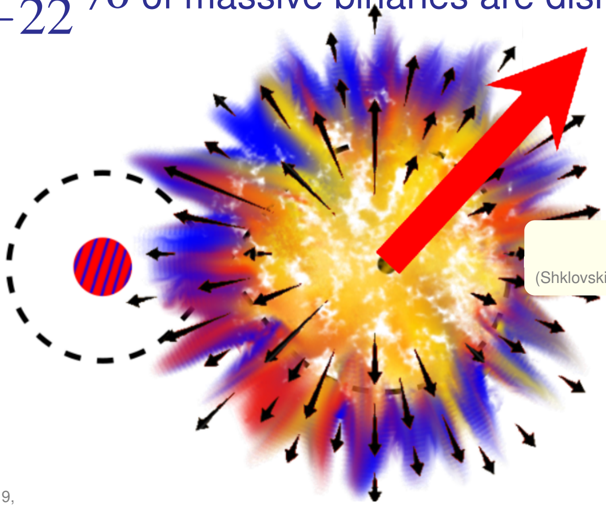
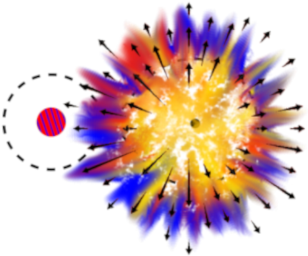


SN Natal kick

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

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

Outline: *Common, Uncommon*

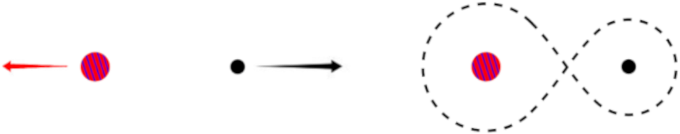


$86^{+11}_{-22}\%$

Disrupted binary

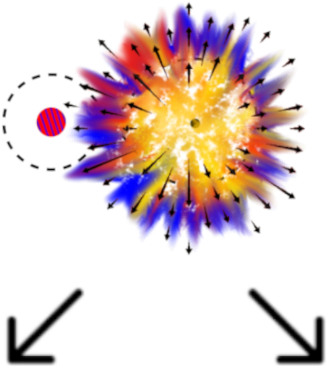
$14^{+22}_{-11}\%$

Surviving binaries



Renzo *et al.* 2019b

Outline: *Common*, *Uncommon*, and *Extreme*



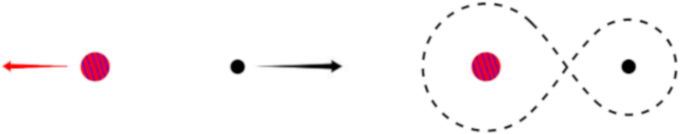
Pulsational Pair Instability

$86^{+11}_{-22}\%$

Disrupted binary

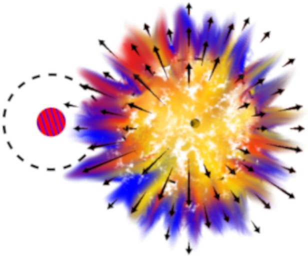
$14^{+22}_{-11}\%$

Surviving binaries



Renzo *et al.* 2019b

Common: Disrupted binaries



Pulsational Pair Instability

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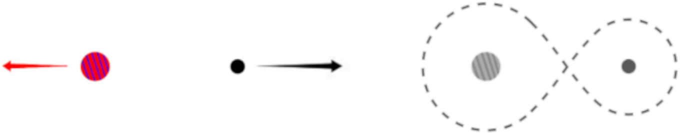

Renzo *et al.* 2019b

Mass transfer occurs before the 1^{st} explosion

The “widowed” star carries signatures of its past in a binary

Renzo & Zapartas 2020

Mass transfer occurs before the 1^{st} explosion

- **Spin-up**

  Packet 1981, Cantiello *et al.* 2007, de Mink *et al.* 2013, **Renzo & Götberg 2021**

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- **Pollution**

  Blaauw 1993, **Renzo & Götberg 2021**

- **Rejuvenation**

  Hellings 1983, 1985, **Renzo *et al.* 2023**

The “widowed” star carries signatures of its past in a binary

Renzo & Zapartas 2020

Using the nearest O-type star to Earth to pin accretor’s 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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Gordon *et al.* 2018,
Neuhäuser *et al.* 2019, 2020,
Renzo & Götberg 2021,
Shepard *et al.* 2022

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

Using the nearest O-type star to Earth to pin accretor's models

Spitzer, NASA/JPL

Walker *et al.* 1979,
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Zee *et al.* 2018,
Gordon *et al.* 2018,
Neuhäuser *et al.* 2019, 2020,
Renzo & Götberg 2021,
Shepard *et al.* 2022

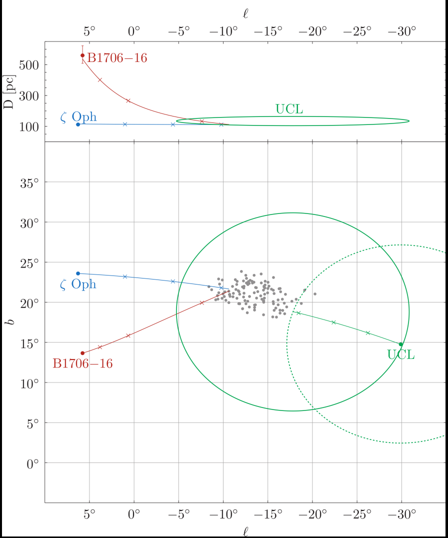
Observational constraints of ζ Oph.:

- $d \simeq 107 \pm 4\,\mathrm{pc}$
- $M \simeq 20\,M_\odot$
- $20\,\mathrm{km\ s^{-1}} \lesssim v_\mathrm{sys} \lesssim 50\,\mathrm{km\ s^{-1}}$
- $v\sin(i) \gtrsim 310\,\mathrm{km\ s^{-1}}$, $i \gtrsim 56^\circ$
- (T_eff, L) position
- $Z \lesssim Z_\odot$, $^4\mathrm{He}$- and $^{14}\mathrm{N}$-rich, normal $^{12}\mathrm{C}$ and $^{16}\mathrm{O}$

✗ **Rotating single stars**

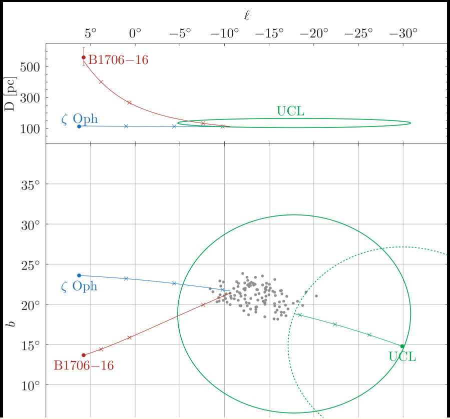
(e.g., van Rensbergen *et al.* 96, Howarth & Smith 01, Villamariz & Herrero 05)

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



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

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



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

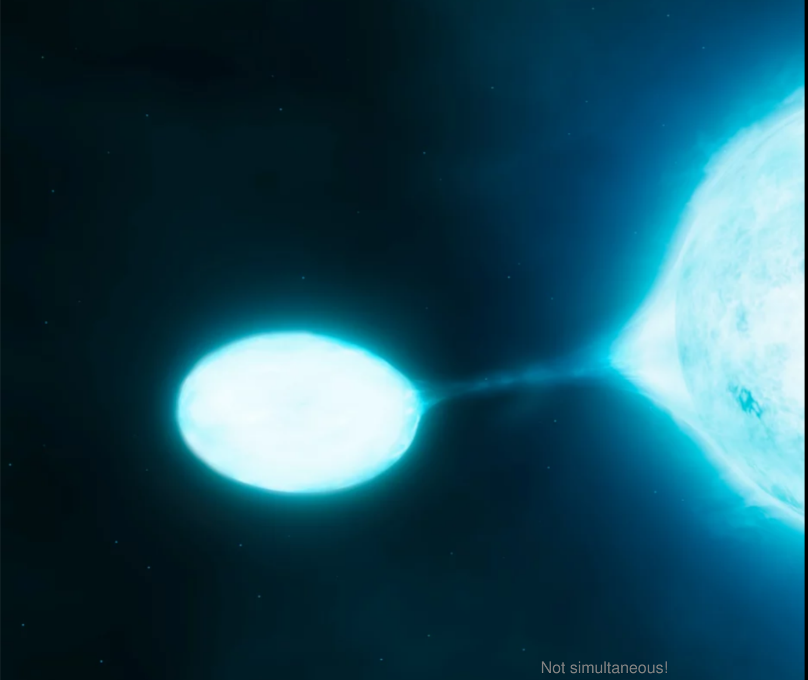
Neuhäuser *et al.* 2019, 2020 see also Blaauw 1952, 1961,
van Rensbergen *et al.* 1996, Hoogerwerf *et al.* 2001, Lux *et al.* 2020

Self-consistent MESA model

$Z = 0.01$

(Murphy *et al.* 2021)

Renzo & Götberg 2021



Not simultaneous!



Not simultaneous!

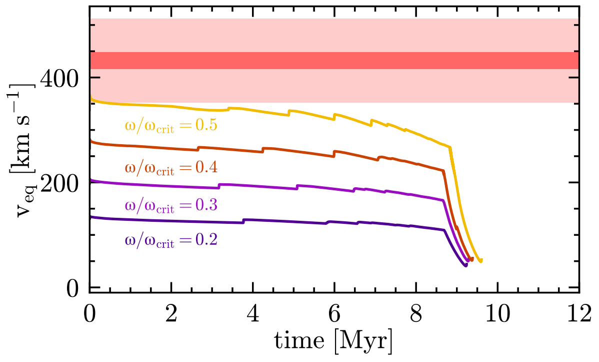
Does a binary past help with ζ Oph. ?

Spin-up – Pollution – Rejuvenation

Renzo & Götberg 2021

✗ Spin up:

Natal rotation would need to be extreme to match

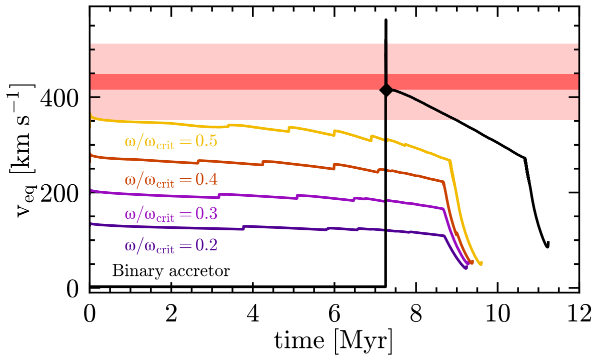


weak-wind problem, neglecting inclination

Renzo & Götberg 2021

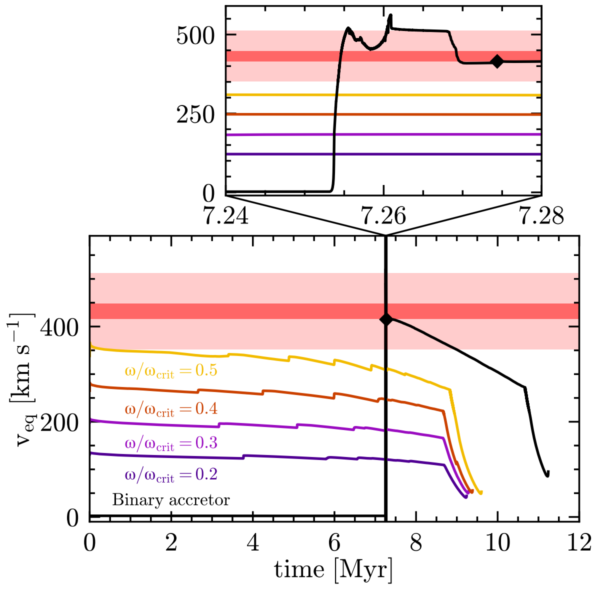
✓ Spin up:

late and to critical rotation



weak-wind problem, neglecting inclination

Renzo & Götberg 2021

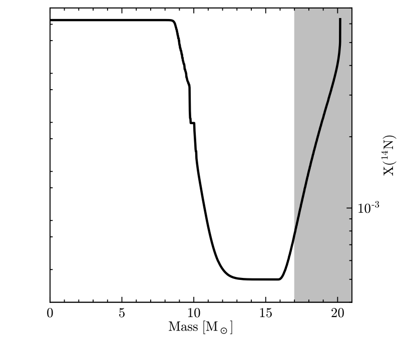


weak-wind problem, neglecting inclination

Renzo & Götberg 2021

✓ Pollution:

Surface composition partly comes from the donor's core



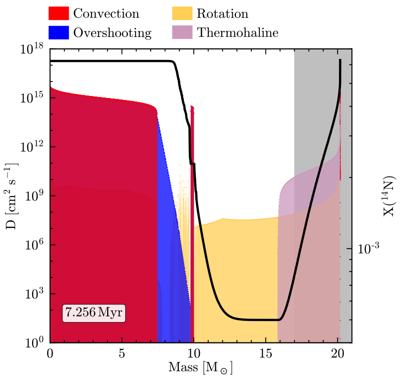
Nitrogen mass fraction

Joint constrain on accretion and internal mixing

Renzo & Götberg 2021

✓ Pollution:

Surface composition partly comes from the donor's core



"Mixing strength"

Nitrogen mass fraction

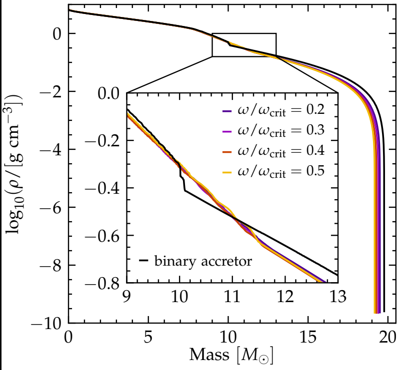
Joint constrain on accretion and internal mixing

Renzo & Götberg 2021

✓ Rejuvenation:

Core growth changes its outer boundary

"Density"



end of H-core burning,
later evolution amplifies differences
(e.g., **Renzo *et al.* 2017**)

Renzo & Götberg 2021, Renzo *et al.* 2023

MESA $\sim \zeta$ Oph $\Rightarrow$ Accretors $\neq$ Single (rotating) stars

Implications?

Pop.

- How to find "widowed" among stars & transients?

  Renzo *et al.* 2019, Renzo & Götberg 2021

Interior & evol.

- Do accretors show peculiar asteroseismology?

  Gade-Pedersen, Renzo *et* al., in prep.

- Rejuvenation impact on reverse mass-transfer?

  Renzo *et al.* 2023

Collapse & expl.

- Do accretors retain their spin? $\Rightarrow$ long GRBs?

  Lee 2006, Cantiello *et al.* 2007, Briel *et al.* 2022

- SNIIP plateau end as probe of rejuvenation?

  Zapartas *et al.*, (incl. Renzo) 2017, 2021, Goldberg & Renzo, in prep.

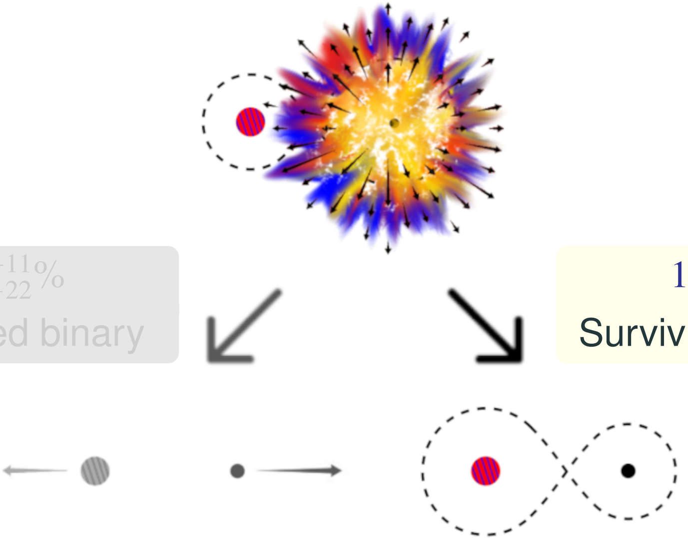
*Un*common: Compact objects with a companion are the *exception*

$86^{+11}_{-22}\%$

Disrupted binary

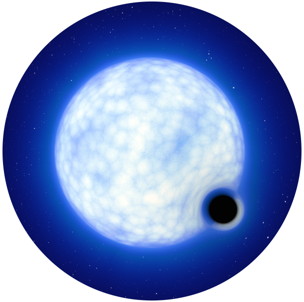
$14^{+22}_{-11}\%$

Surviving binaries



Renzo *et al.* 2019b

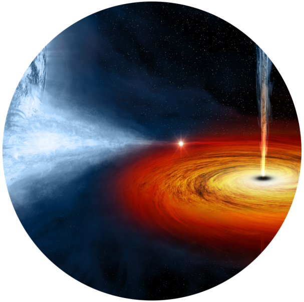
Often the only way to see stellar-mass compact objects†



Non-interacting

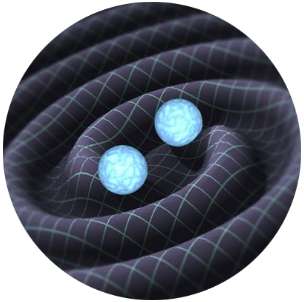
Shenar *et al.* 2022, El-Badry *et al.* 2022ab, 2023

Chawla *et al.* 2020, etc.



X-ray binaries

Webster & Murdin 1972, Bolton 1972,
van der Meij *et al.* (incl. Renzo) 2021,

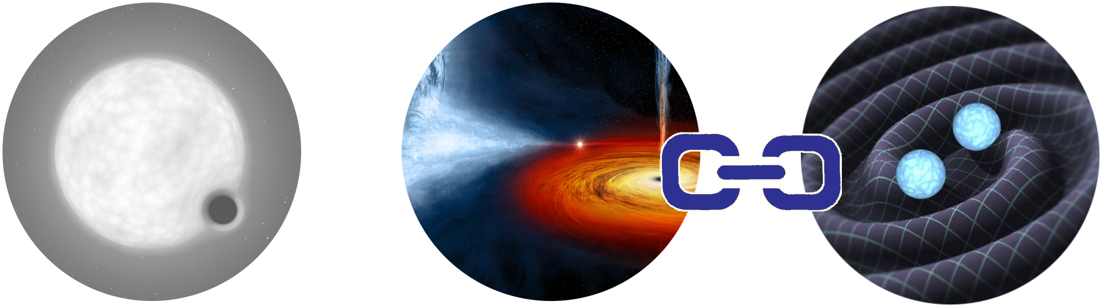


Gravitational waves

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

† Exceptions: pulsars beamed to Earth & serendipitous microlensing

Use *Galactic* X-ray binaries to constrain exceptional GW sources



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Chawla *et al.* 2020, etc.

X-ray binaries

Webster & Murdin 1972, Bolton 1972,
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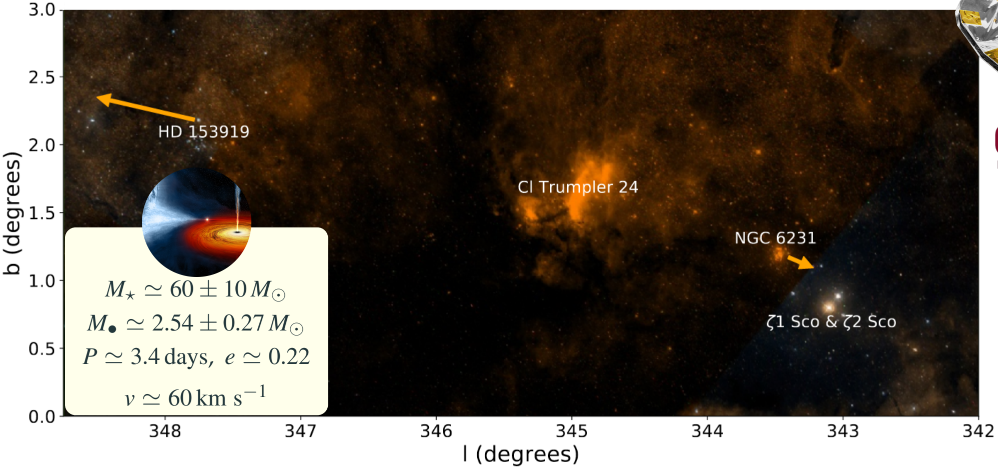
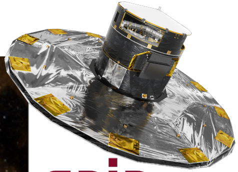
Gravitational waves

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

The X-ray binary HD153919/4U 1700-37



$$M_\star \simeq 60 \pm 10\, M_\odot$$
$$M_\bullet \simeq 2.54 \pm 0.27\, M_\odot$$
$$P \simeq 3.4\,\text{days},\ e \simeq 0.22$$
$$v \simeq 60\,\text{km s}^{-1}$$

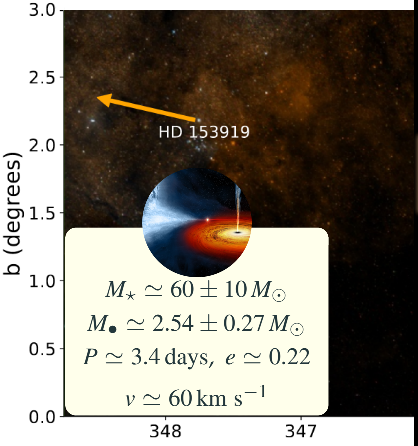


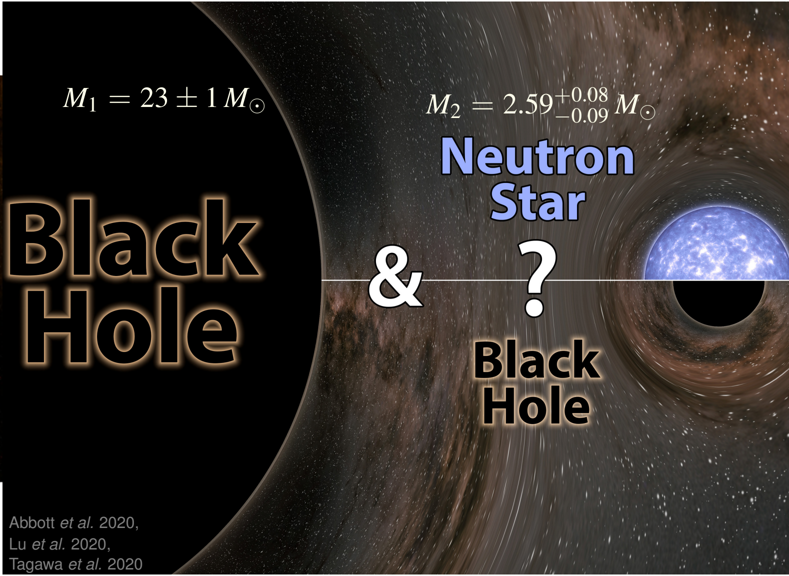
gaia

Vincent van der Meij

van der Meij *et al.* (incl. Renzo) 2021, see also Jones *et al.* 1973, Ankay *et al.* 2001, Hammerschlag-Hensberge *et al.* 2003

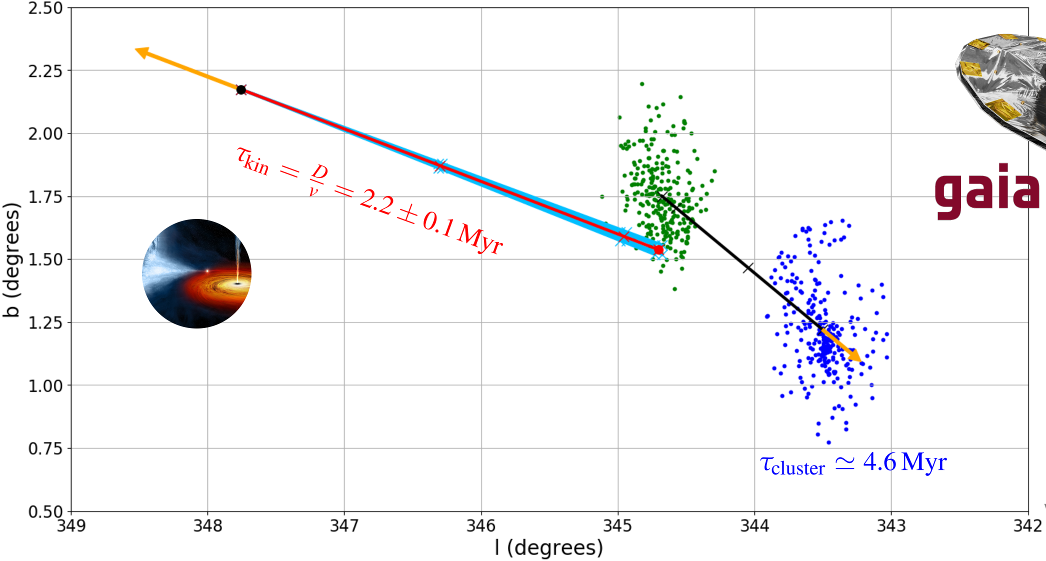
The X-ray binary HD153919: a Galactic analog of GW190814's progenitor?

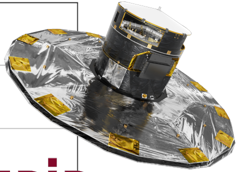




van der Meij *et al.* (incl. Renzo) 2021, see also Jones *et al.* 1973, Ankay *et al.* 2001, Hammerschlag-Hensberge *et al.* 2003

The motion on the sky constrains past evolution of the X-ray binary



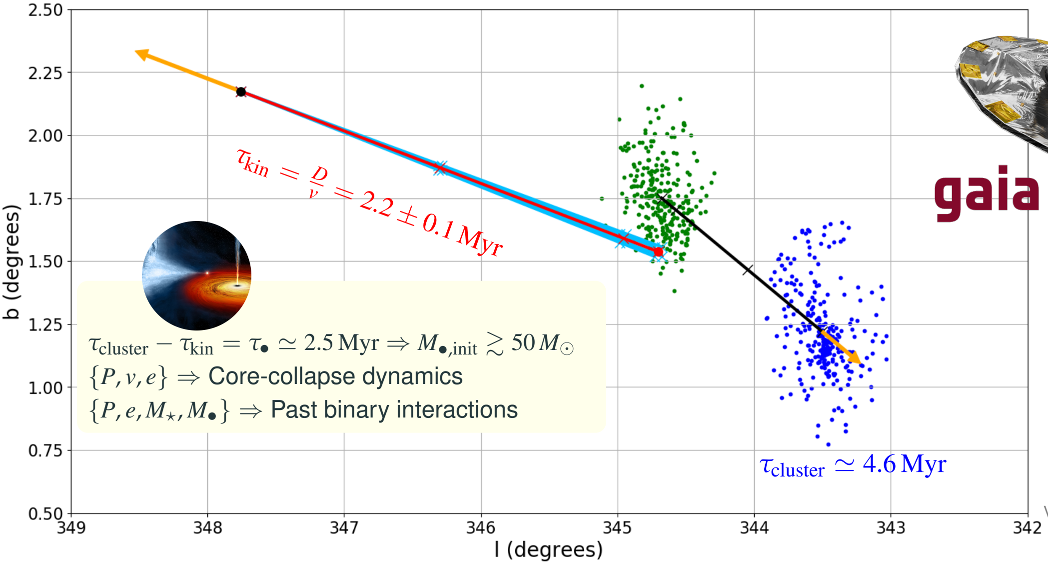


gaia

Vincent van der Meij

van der Meij *et al.* (incl. Renzo) 2021

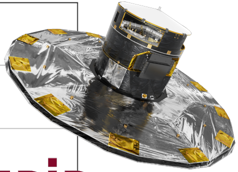
The motion on the sky constrains past evolution of the X-ray binary



$\tau_{\rm cluster} - \tau_{\rm kin} = \tau_{\bullet} \simeq 2.5\,{\rm Myr} \Rightarrow M_{\bullet,\rm init} \gtrsim 50\,M_{\odot}$

$\{P, v, e\} \Rightarrow$ Core-collapse dynamics

$\{P, e, M_{\star}, M_{\bullet}\} \Rightarrow$ Past binary interactions



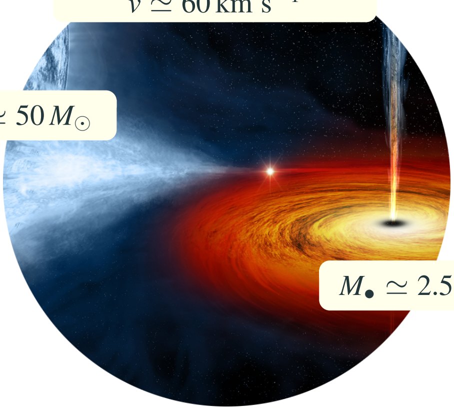
Vincent van der Meij

van der Meij *et al.* (incl. Renzo) 2021

How to make a small compact object from a big star?

$P \simeq 3.4\,\text{days},\ e \simeq 0.22,$
$v \simeq 60\,\text{km s}^{-1}$

$M_\star \simeq 50\,M_\odot$

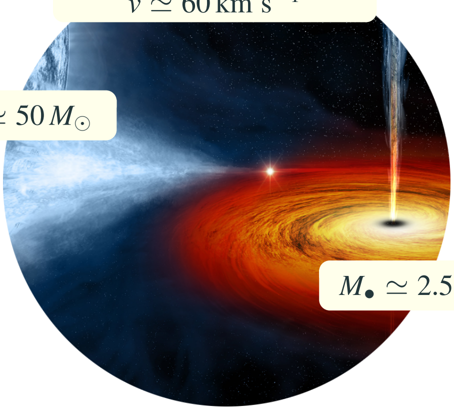


$M_\bullet \simeq 2.5\,M_\odot$

HD153919

van der Meij *et al.* (incl. Renzo) 2021, Nathalia Torres' summer project, see also Belczynski & Taam 2008

How to make a small compact object from a big star?



HD153919

$\Longrightarrow$

Need mass transfer *before* donor's He core formed

van der Meij *et al.* (incl. Renzo) 2021, Nathalia Torres' summer project, see also Belczynski & Taam 2008

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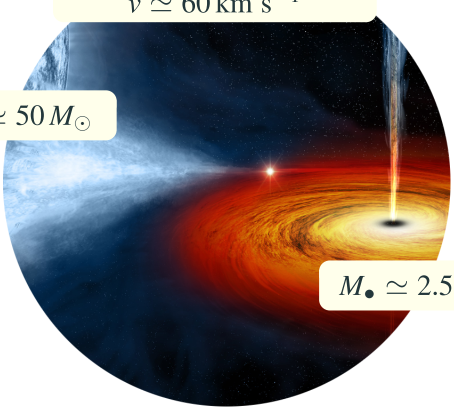


$M_\bullet \simeq 2.5\,M_\odot$

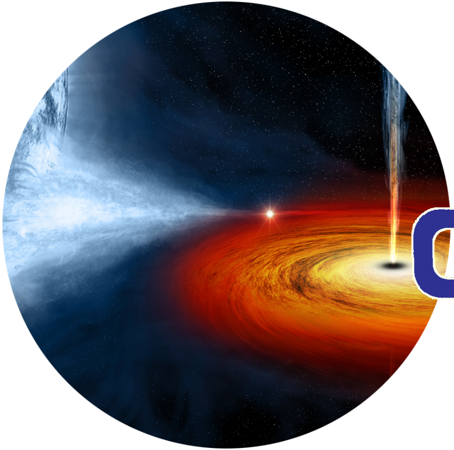
HD153919

$\Longrightarrow$

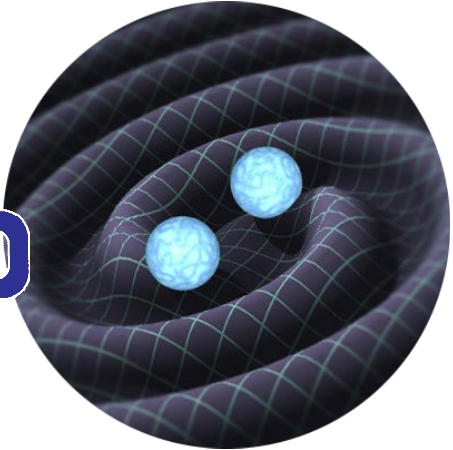
Need mass transfer *before* donor's He core formed
+
Lucky SN kick direction

van der Meij *et al.* (incl. Renzo) 2021, Nathalia Torres' summer project, see also Belczynski & Taam 2008

Future: build empirically anchored scenario for outstanding GW events



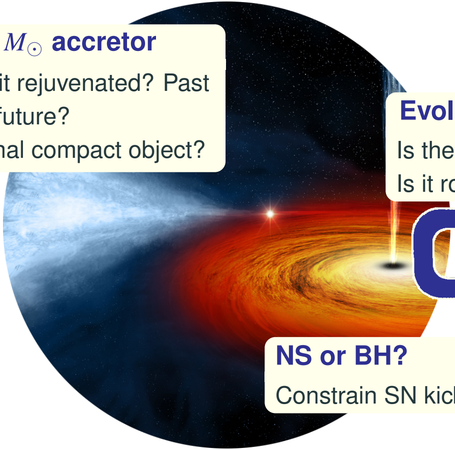
Galactic X-ray binaries



$M_2 \sim 2.5\, M_\odot$, $M_2 / M_1 \sim 0.1$

gravitational waves

Future: build empirically anchored scenario for outstanding GW events



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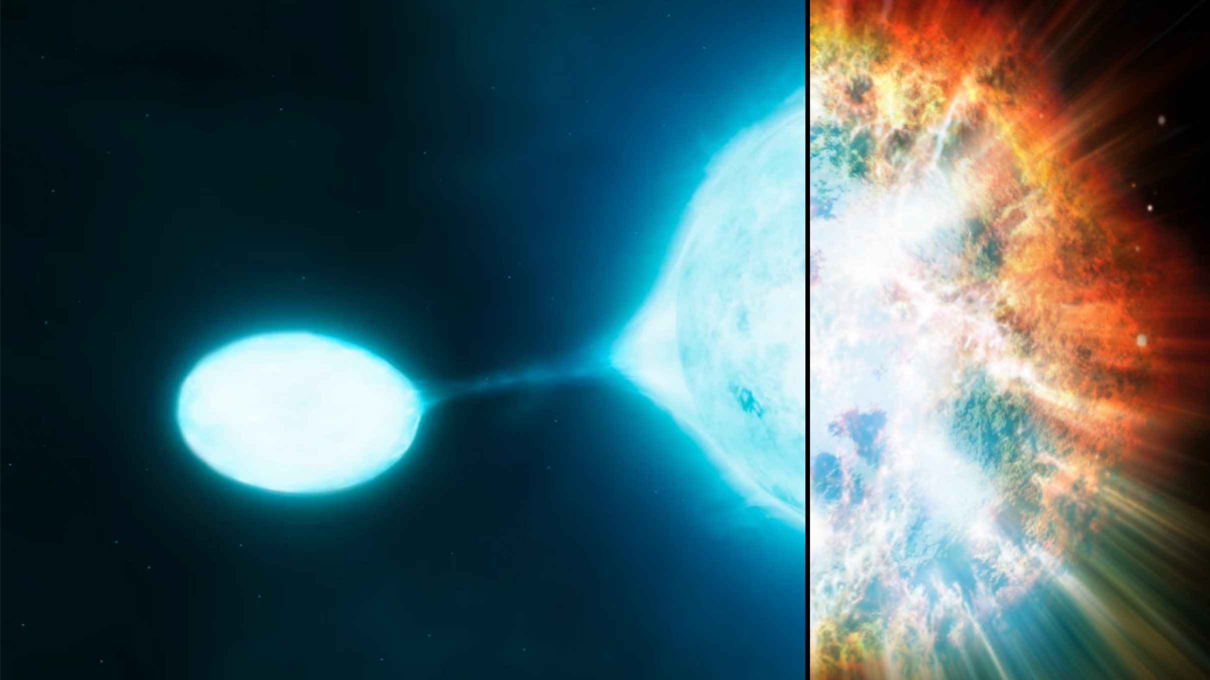


The most extreme stellar explosions: (Pulsational) pair instability SNe

Pair-instability SNe are the best understood supernovae

Radiation pressure dominated:

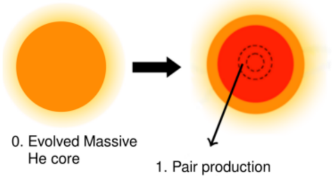
$$P_{\rm tot} \simeq P_{\rm rad}$$

$$M_{\rm He} \gtrsim 32\,M_{\odot}$$

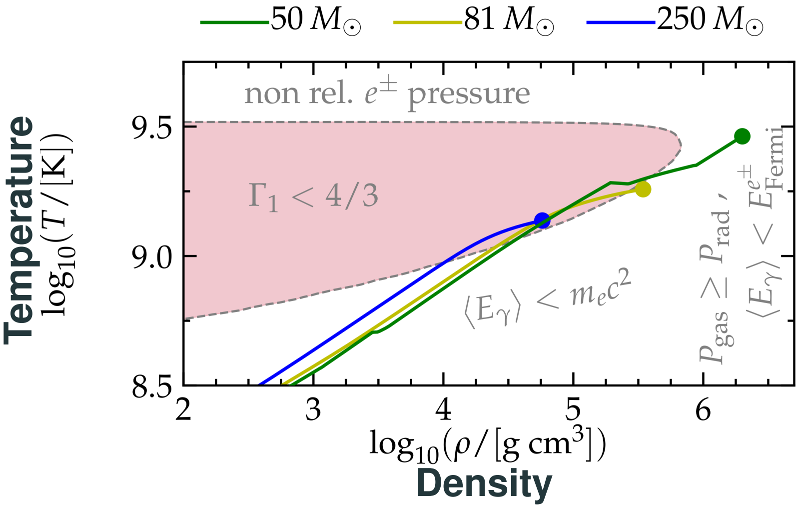
0. Evolved Massive He core

Renzo *et al.* 2020b

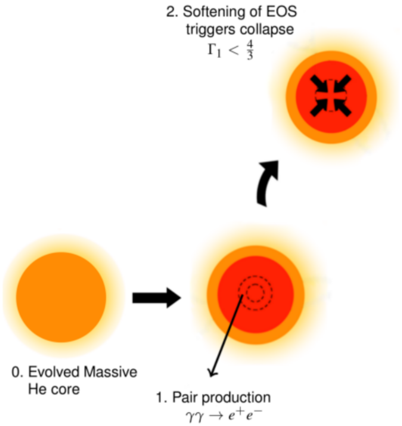
see Fowler & Hoyle 1964, Rakavy & Shaviv 1967, Barkat *et al.* 1967, 1968, Fraley 1968, Glatzel *et al.* 1985, **Woosley** *et al.* 2002, 2007, Langer *et al.* 2007, Chatzopoulos *et al.* 2012, 2013, Yoshida *et al.* 2016, Woosley 2017, 2019, **Marchant, Renzo *et al.* 2019, Farmer, Renzo *et al.* 2019, 2020,** Leung *et al.* 2019, 2020, **Renzo *et al.* 2020a, b, c** Croon *et al.* 2020a,b, Sakstein *et al.* 2020, 2022, Costa *et al.* 2021, Woosley & Heger 2021, **van Son *et al.* (incl. Renzo) 2020**, **Hendriks *et al.*, in prep.**, etc...



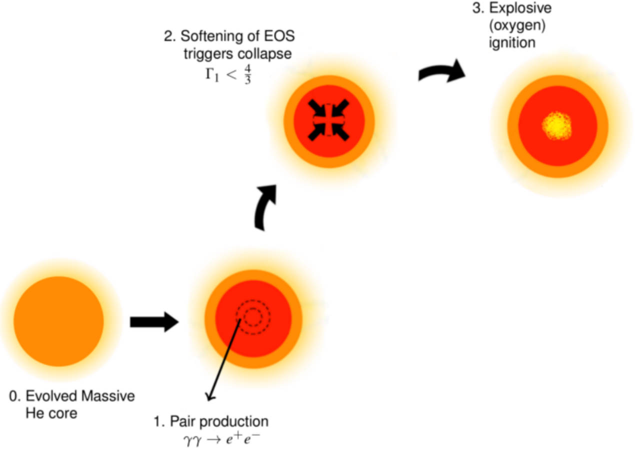
$$\gamma \, \gamma \rightarrow e^{+} \, e^{-}$$



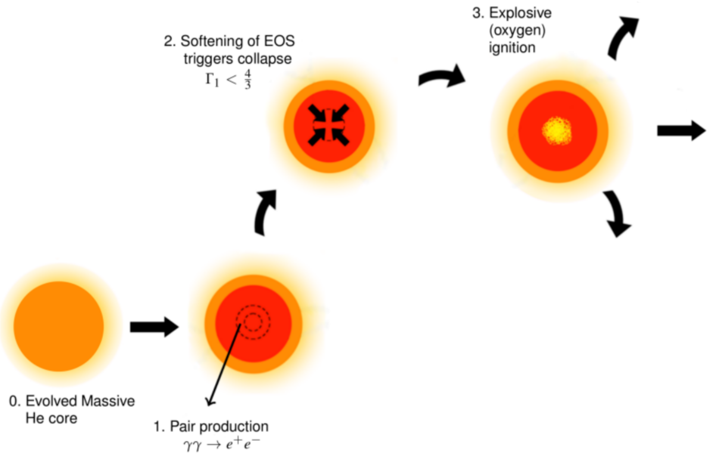
Renzo *et al.* 2020b



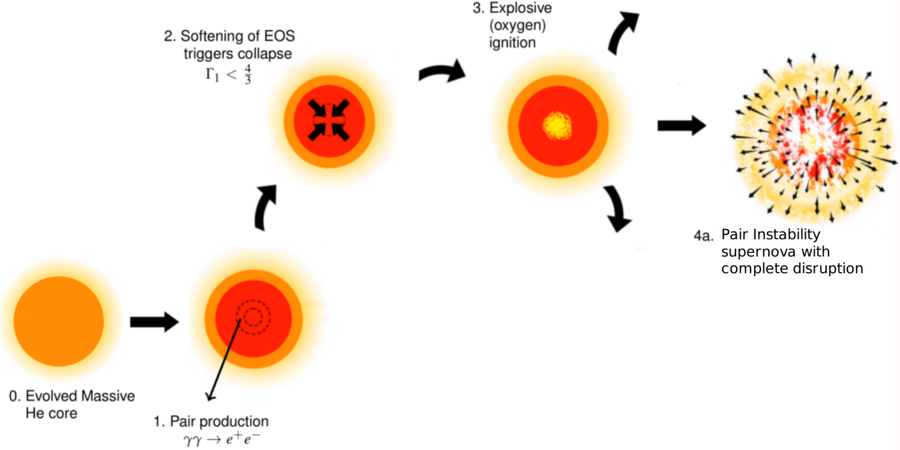
Renzo *et al.* 2020b



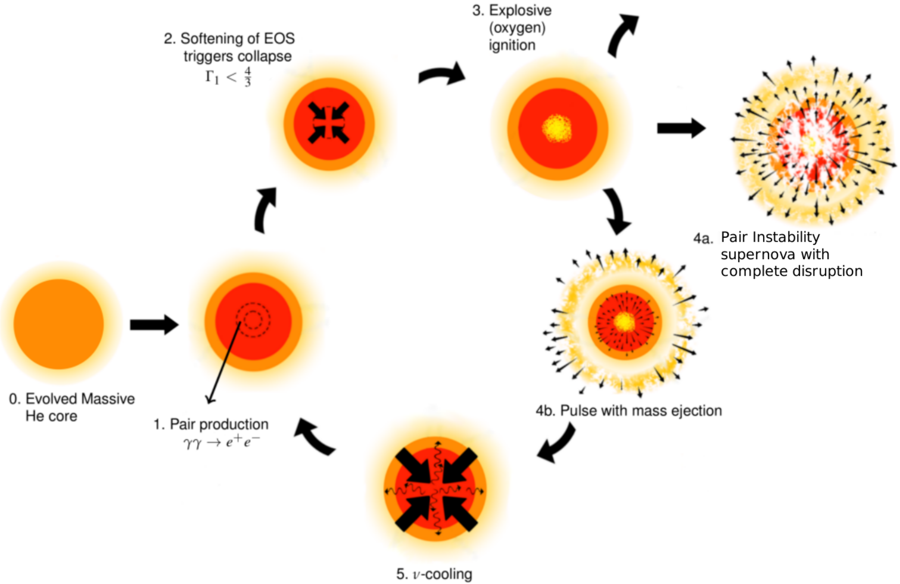
Renzo *et al.* 2020b



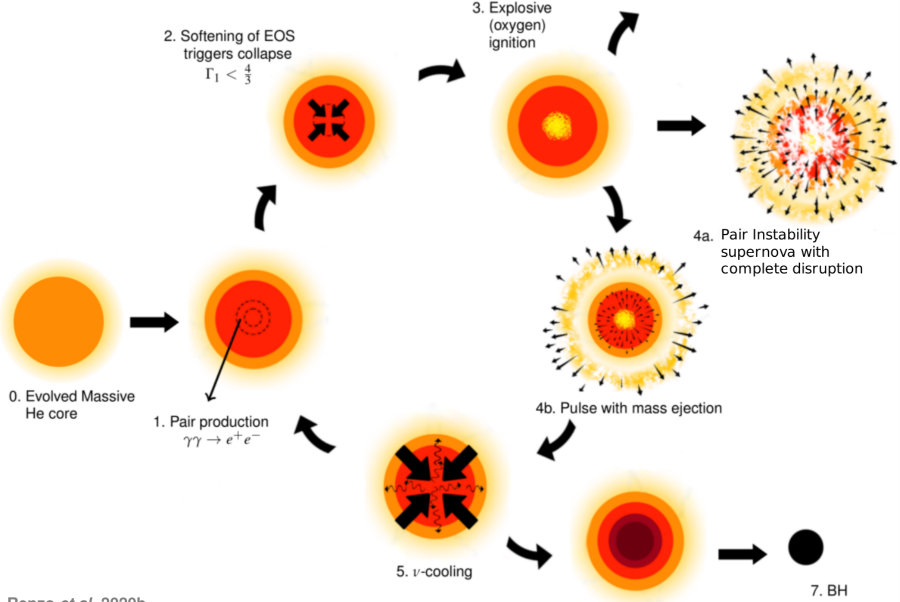
Renzo *et al.* 2020b



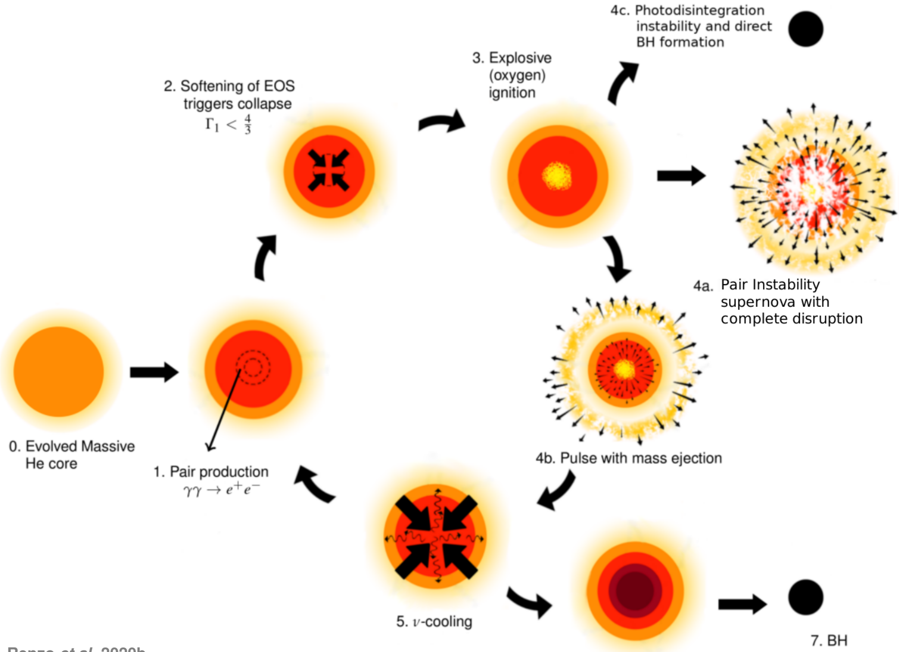
Renzo *et al.* 2020b



Renzo *et al.* 2020b



Renzo *et al.* 2020b

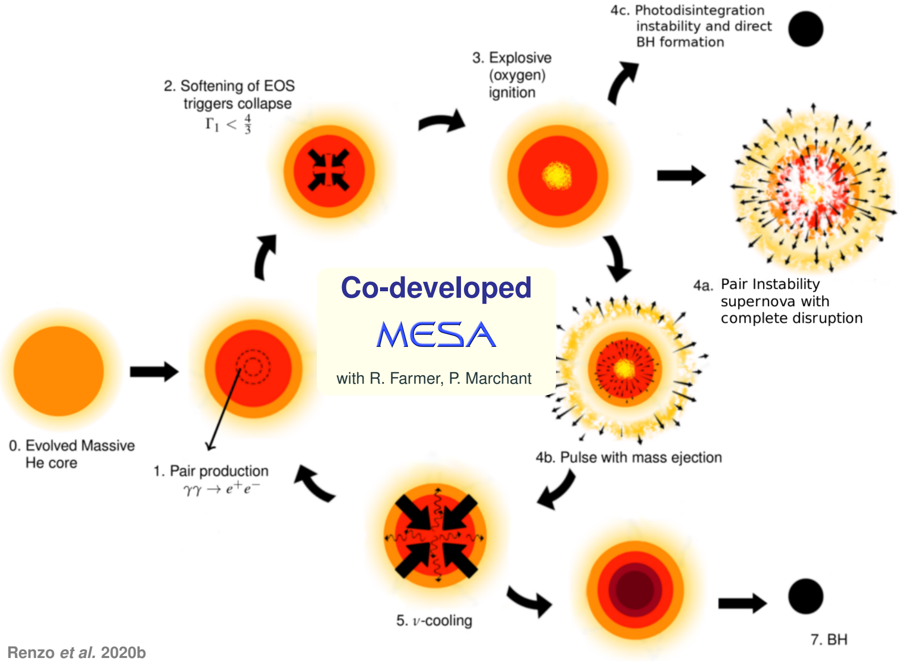


BH

no BH

BH

Renzo *et al.* 2020b



Renzo *et al.* 2020b

BH

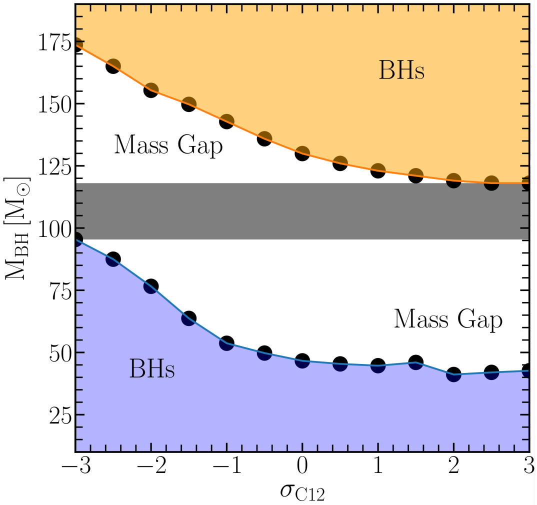
no BH

BH

Predicted PISN BH “mass gap”

Nuclear physics uncertainties

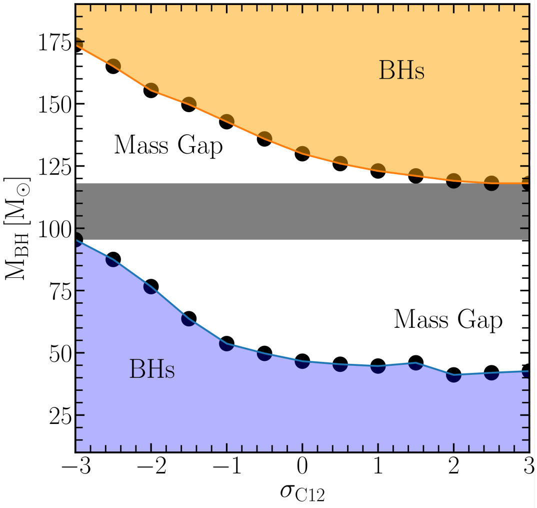
$^{12}C(\alpha,\gamma)^{16}O$ rate determines C/O ratio and thus how unstable cores are

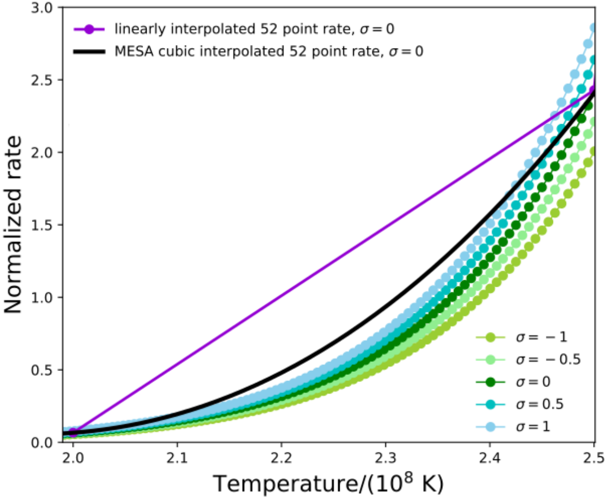


⇐ **lower** **Rate** **higher** ⇒

Farmer, Renzo *et al.* 2020, see also **Farmer, Renzo *et al.* 2019**, Costa *et al.* 2021, Woosley & Heger 2021, **Farag, Renzo *et al.* 2022**

$^{12}C(\alpha,\gamma)^{16}O$ reaction rate was undersampled in off-the-shelves tables

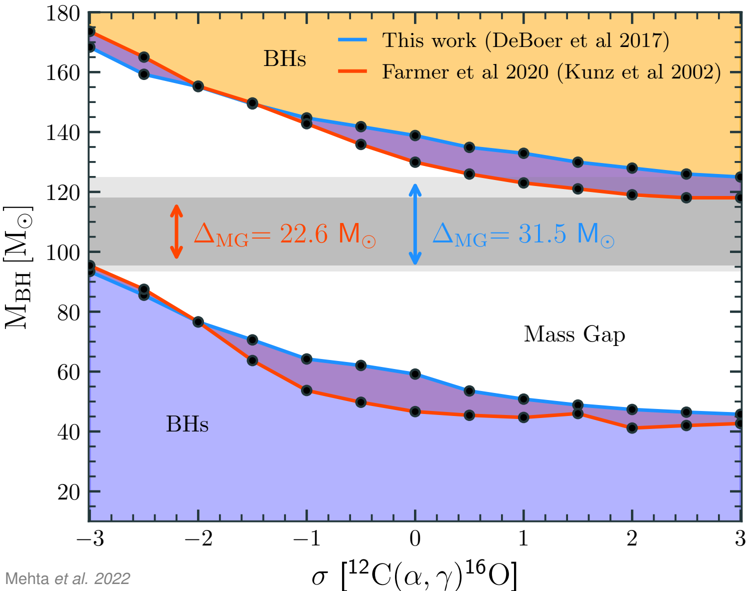




$\Leftarrow$ **lower** **Rate** **higher** $\Rightarrow$

Farmer, Renzo *et al.* 2020, see also **Farmer, Renzo *et al.* 2019**, Costa *et al.* 2021, Woosley & Heger 2021, **Farag, Renzo *et al.* 2022** Mehta *et al.* 2022

BH mass gap from single He cores with updated $^{12}C(\alpha,\gamma)^{16}O$ rate



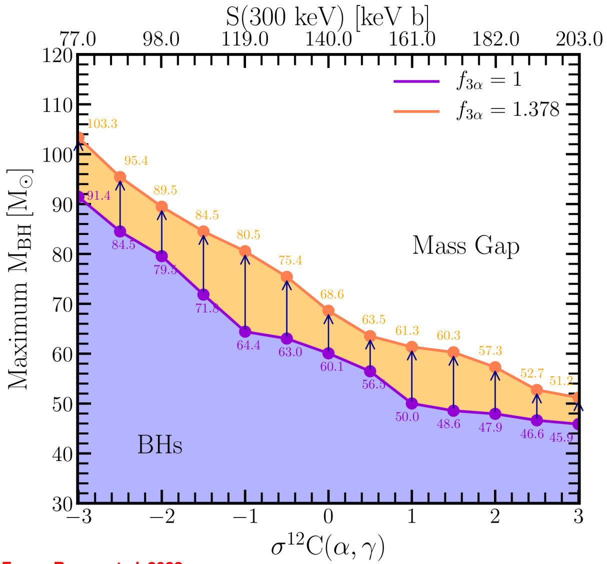
Mehta *et al.* 2022

Reproducibile results

show your work!

Luger *et al.* 2021, **Luger *et al.* (incl. Renzo), in prep.**

Pushing further up with 3α rate uncertainties



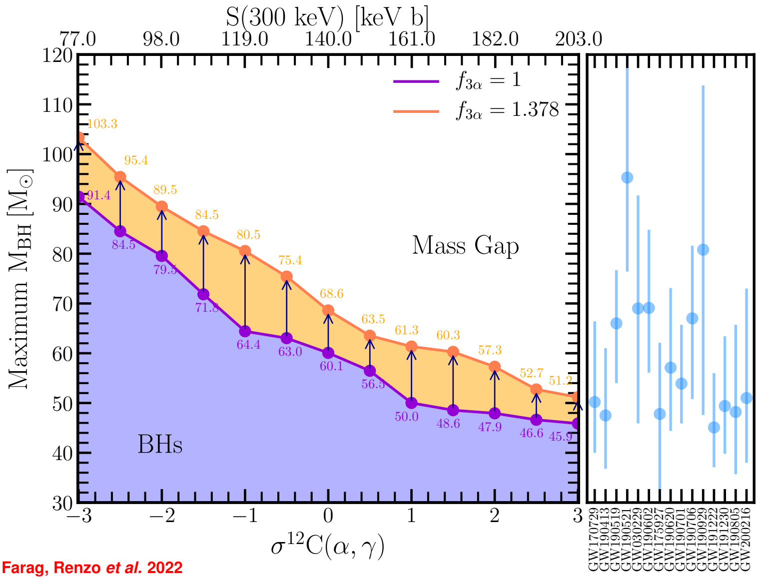
Ebrahim “Eb” Farag

New lower edge of the gap:

$$\max(M_{BH}) = 69^{+34}_{-18}\, M_\odot$$

Farag, Renzo *et al.* 2022

GW detection are populating the predicted “gap”



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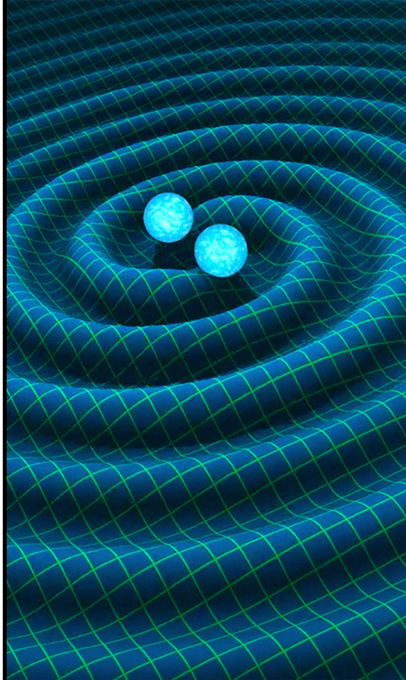
New lower edge of the gap:

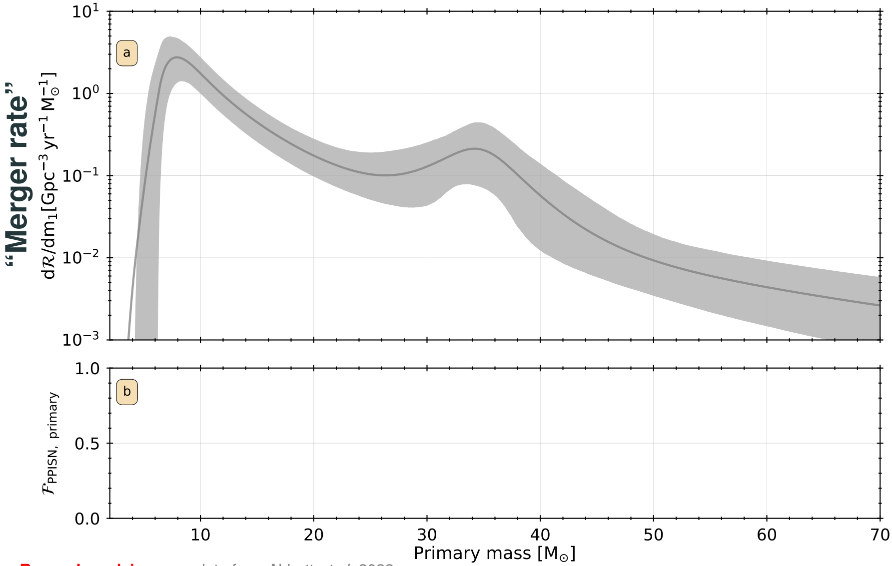
$$\max(M_{\rm BH}) = 69^{+34}_{-18}\, M_\odot$$

Farag, Renzo *et al.* 2022

Where are (P)PISN?



GW population challenges predictions

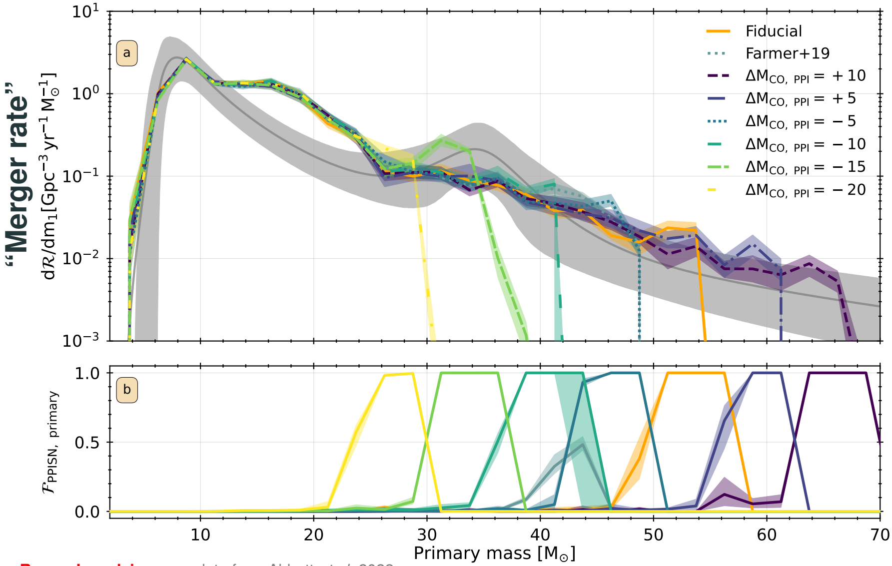


David D. Hendriks

Lieke van Son

Hendriks, van Son, Renzo, Izzard, in prep., data from Abbott *et al.* 2022

(P)PISN mass range and final BH masses as free parameters



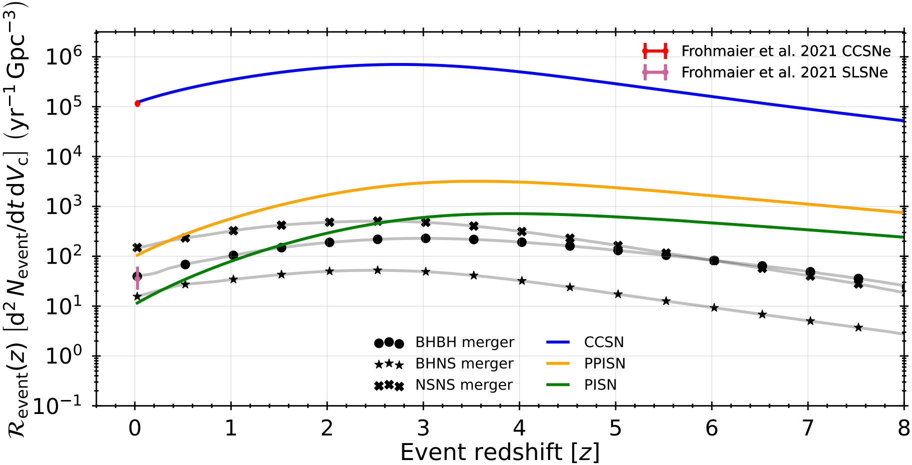
David D. Hendriks

Lieke van Son

Hendriks, van Son, Renzo, Izzard, in prep., data from Abbott *et al.* 2022

Combine constraint from EM and GW surveys

"Event rate"



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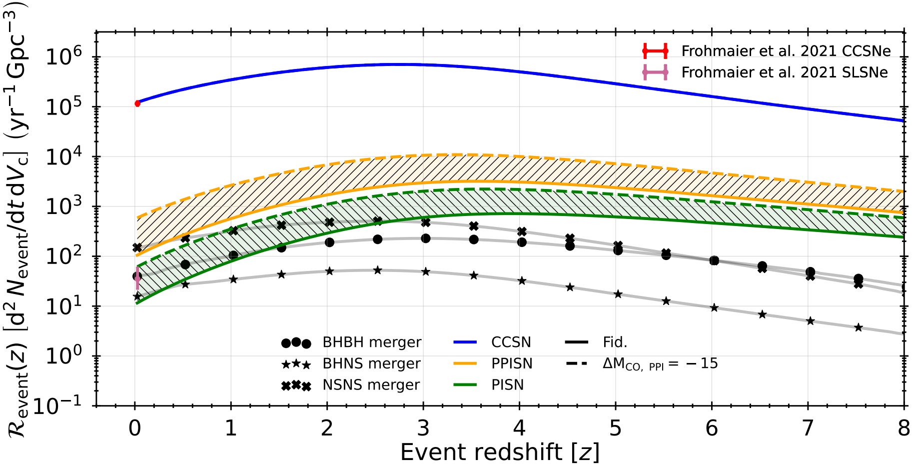
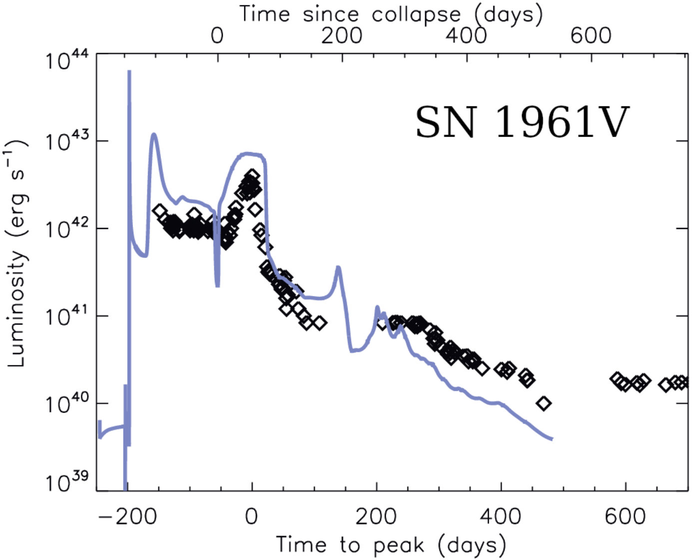


David D. Hendriks

Lieke van Son

Hendriks, van Son, Renzo, Izzard, in prep.

EM detections of (P)PISN and PISN exist but are controversial



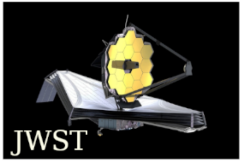
Woosley & Smith 2022

Other candidates

- SN2006gy — Gal-Yam *et al. 2007*
- SN2006jc — Foley *et al.* 2007
- PTF12dam — Tolstov *et al.* 2017
- iPTF16eh — Lunnan *et al.* 2018
- SN2016iet — Gomez *et al.* 2019
- PS15dpn — Wang & Li 2019

see **Renzo *et al.* 2020b** for short review

Upcoming constraints will elucidate the existence of (P)PISN



EM constraints

Rubin observatory

LSST

Legacy Survey of Space and Time

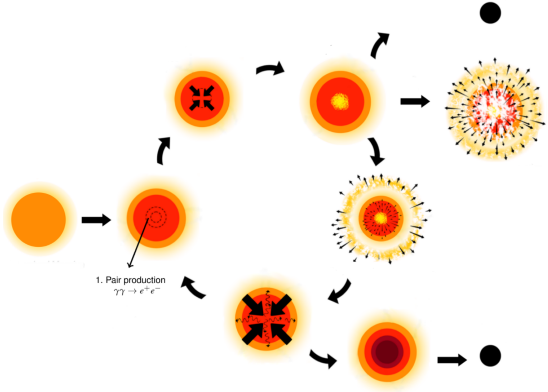
+

GW

LIGO
VIRGO
KAGRA

constraints

O4 starting this year!



e.g., Whalen *et al.* 2013, 2019, Regos *et al.* 2020, Tanikawa *et al.* 2021, 2022

The physics of (P)PISN is well understood, but ...

...new GW data challenge predictions and open new questions

- Envelope fate ?

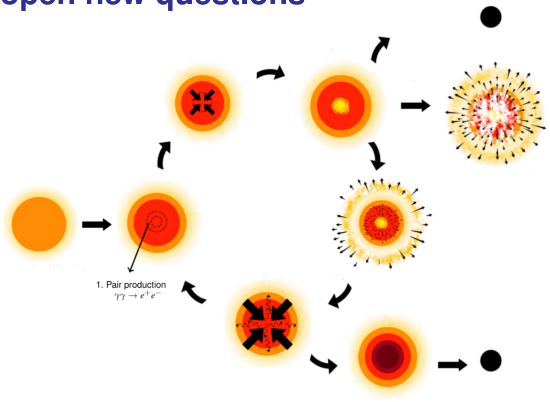
  Renzo *et al.* 2020c, Farrell *et al.* 2020, Vink *et al.* 2021

- Post-pulse BH formation ?

  Powell *et al.* 2021, Rahman *et al.* 2022, **Müller, Renzo *et al.*, in prep.**

- **Binary interactions** ?

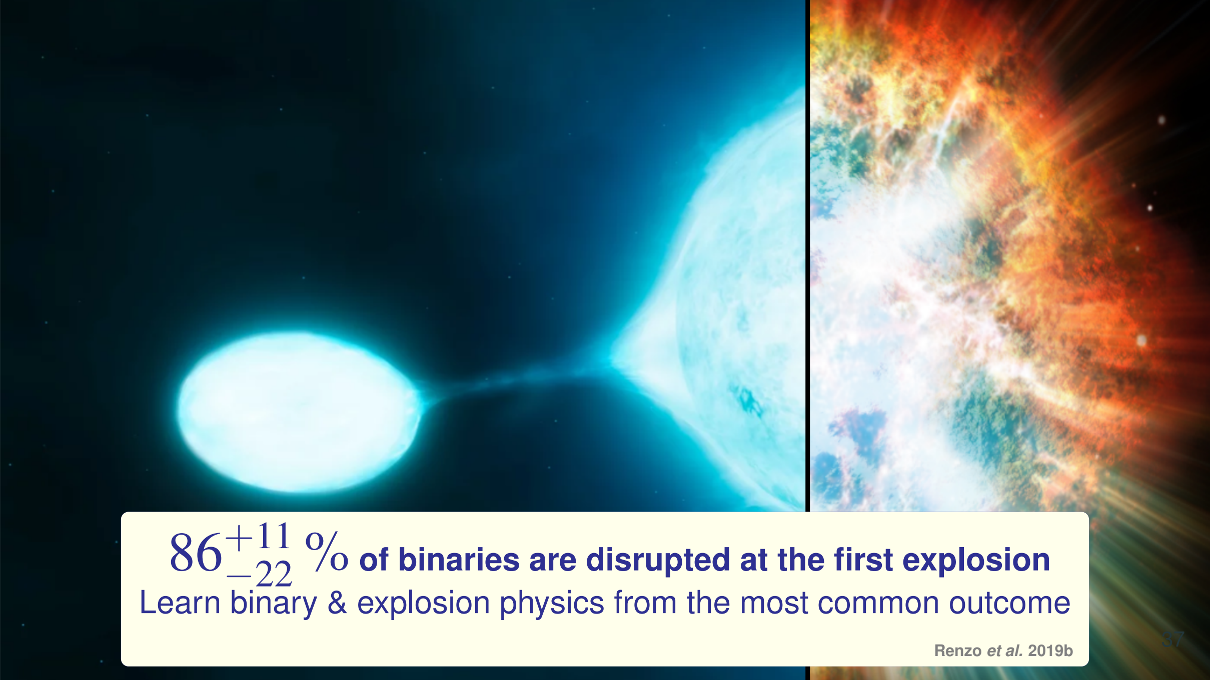
  Marchant, Renzo *et al.* 2019



Summary & Conclusions

Binary interactions modify the life and fate of *both* stars

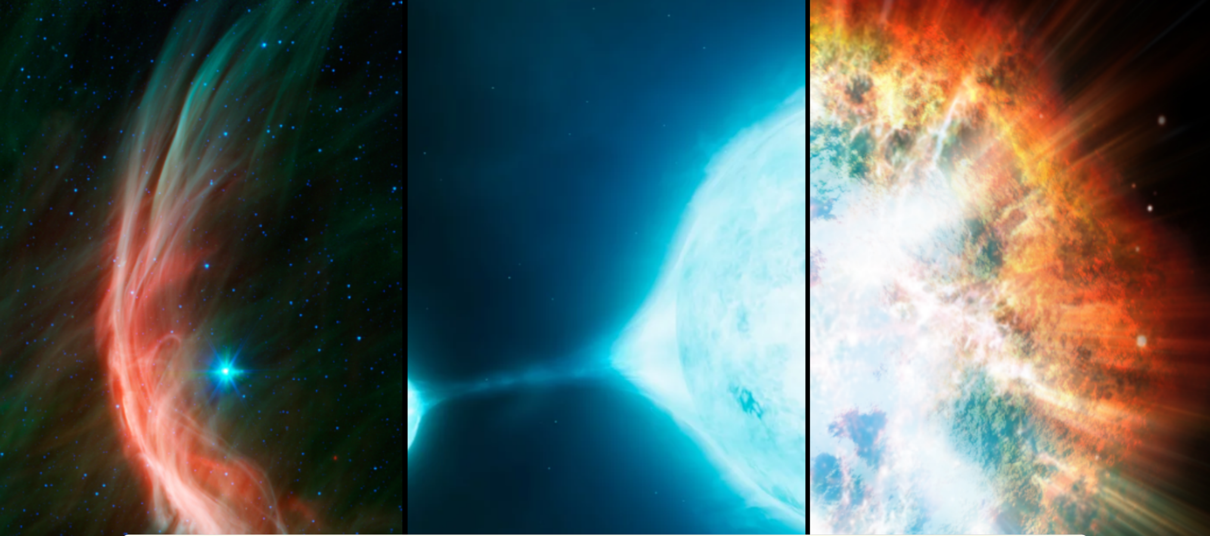
⇒ large influence on stellar feedback & explosions



$86^{+11}_{-22}\,\%$ **of binaries are disrupted at the first explosion**

Learn binary & explosion physics from the most common outcome

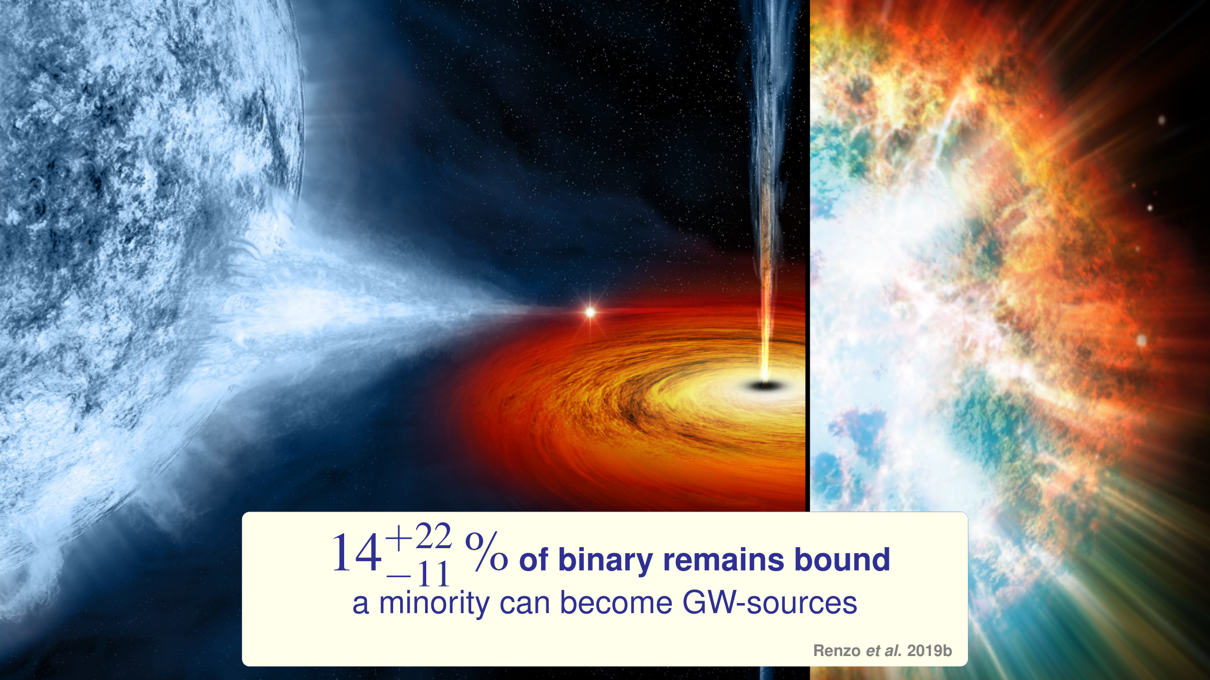
Renzo *et al.* 2019b



Ejected accretors carry information on their binary past

MESA $\sim \zeta$ Oph $\Rightarrow$ Accretors $\neq$ Single (rotating) stars

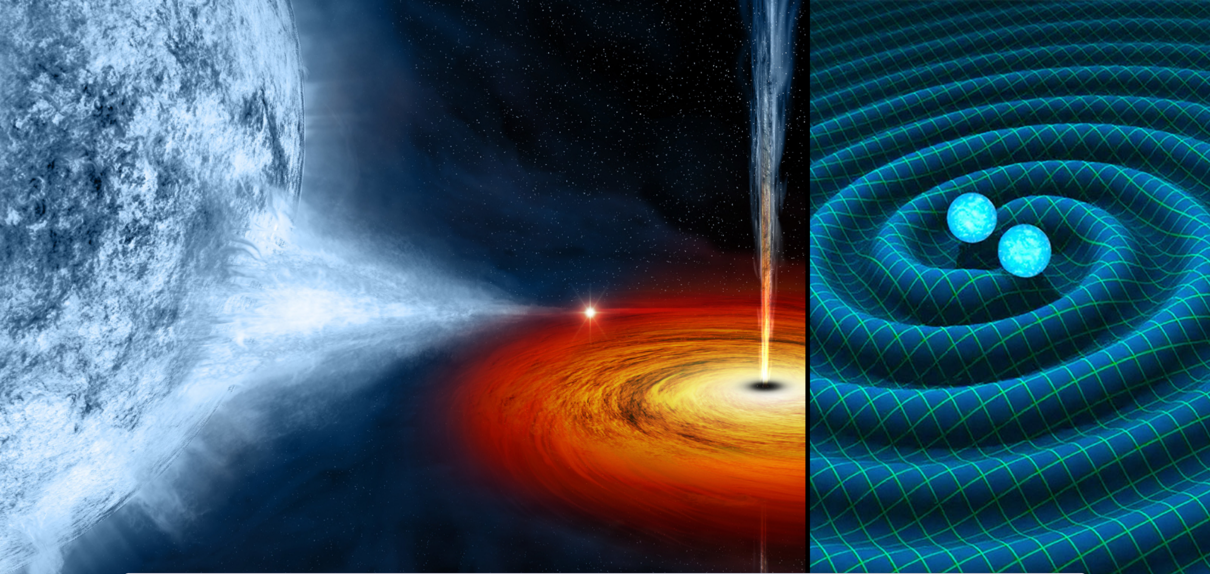
Renzo *et al.* 2019b, 2023, Renzo & Götberg 2021



$14^{+22}_{-11}\,\%$ **of binary remains bound**

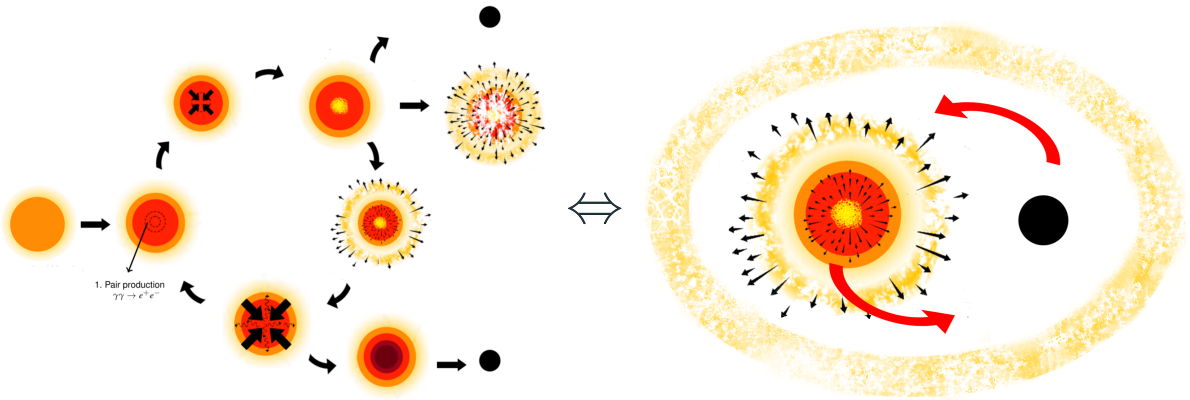
a minority can become GW-sources

Renzo *et al.* 2019b



Extreme sources probe the edge of physical distributions

Galactic systems provide context and physical insight

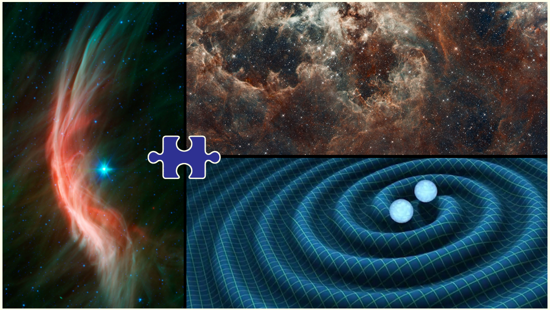


BH masses revealed by GW require studying binarity in (P)PISN progenitors

LVK collaboration 2022, see also **Marchant, Renzo *et al.* 2019, Renzo *et al.* 2020c, 2023**

Theory needs to keep up with new data

detailed obs. ⇔ large samples



Coming up: detailed & statistical view

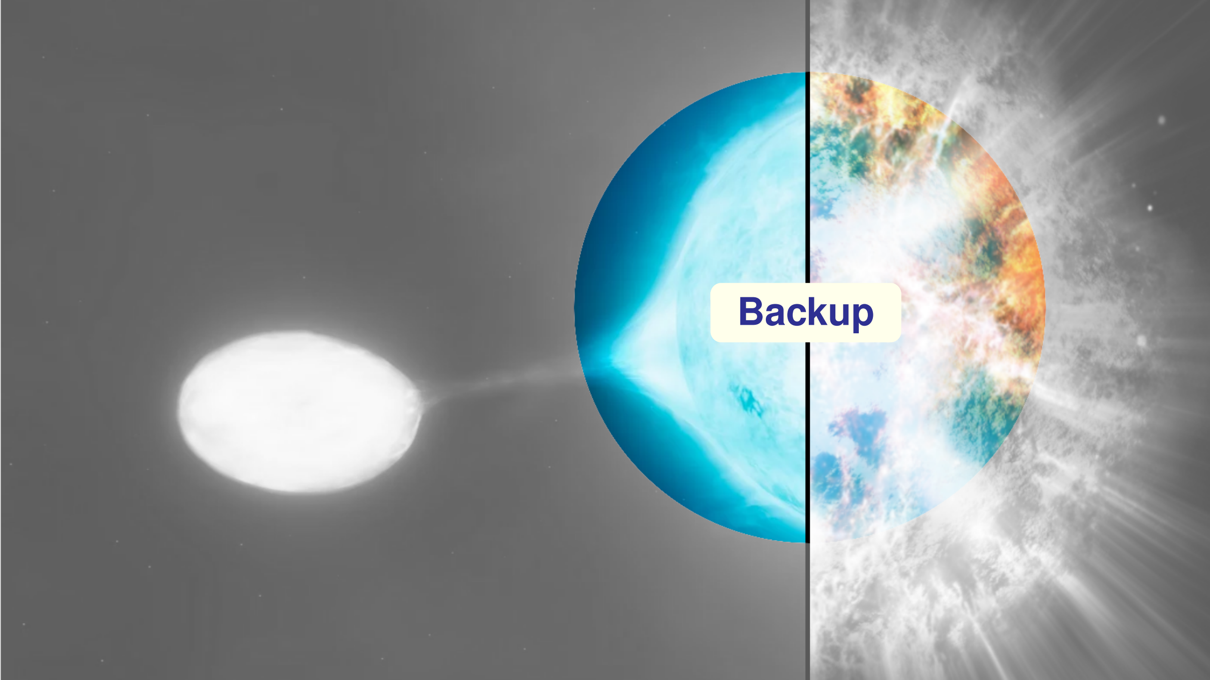
EM ground: SDSS-V, Rubin/LSST, SKA
EM space: *Gaia* DR4-5, *HST/ULYSSES*, *JWST*, ATHENA
GW: O4-5, LISA, TianQin, 3^{rd} generation
Neutrinos: Borexino, DUNE

Mathieu Renzo

mrenzo@flatironinstitute.org

FLATIRON INSTITUTE
Center for Computational Astrophysics

Explosive connections between massive binaries & stellar transients


Backup

Why understand widowed stars?

Stellar populations

accretors lurk in samples

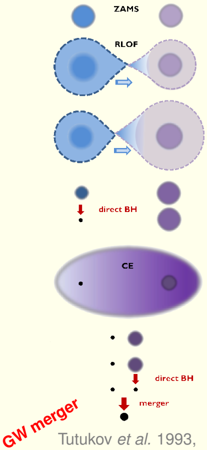
$(10 - 12\%)$ Renzo *et al.* 2019b

+

Oe/Be stars, stragglers

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

Binary interactions

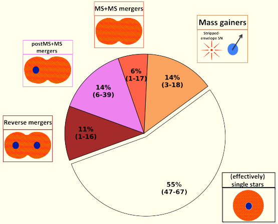


Tutukov *et al.* 1993,

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

Transients

Common: H-rich SNe



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

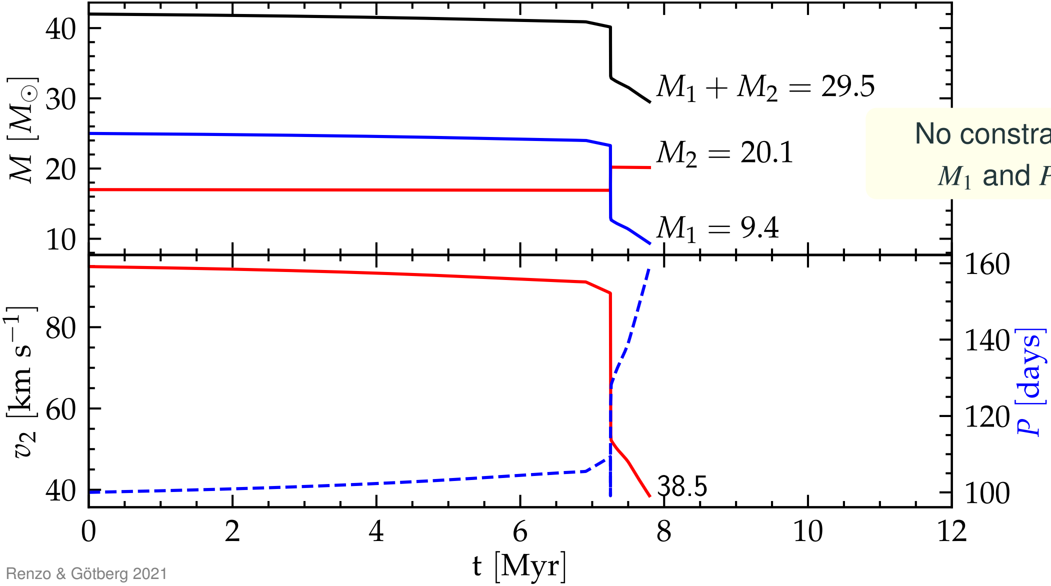
+

Uncommon: H-rich/H-poor SNe

L-GRB, LBV, SNIIn ?

Petrovich *et al.* 2005, Cantiello *et al.* 2007

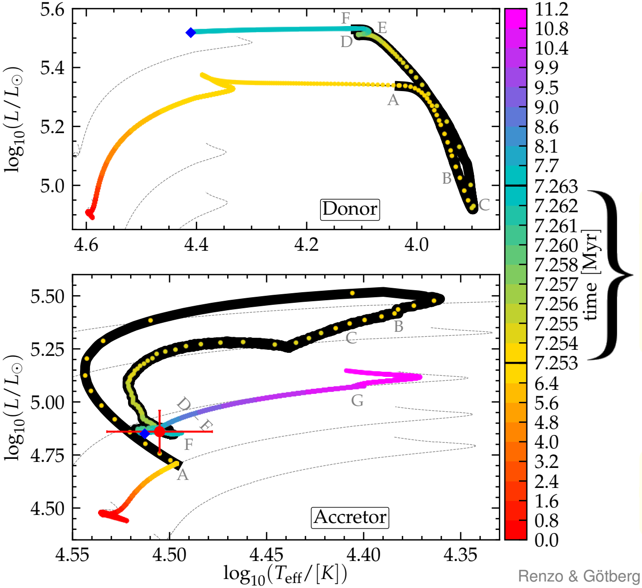
Orbital evolution: ✓ Mass & ✓ spatial velocity



No constraints on M_1 and P_{ZAMS}

Renzo & Götberg 2021

HRD of both stars: the donor & the accretor ✓



Case B mass transfer is short

$\Delta t_{RLOF} \sim 10^4$ yr $\sim \tau_{th}$

but has long-lasting impact

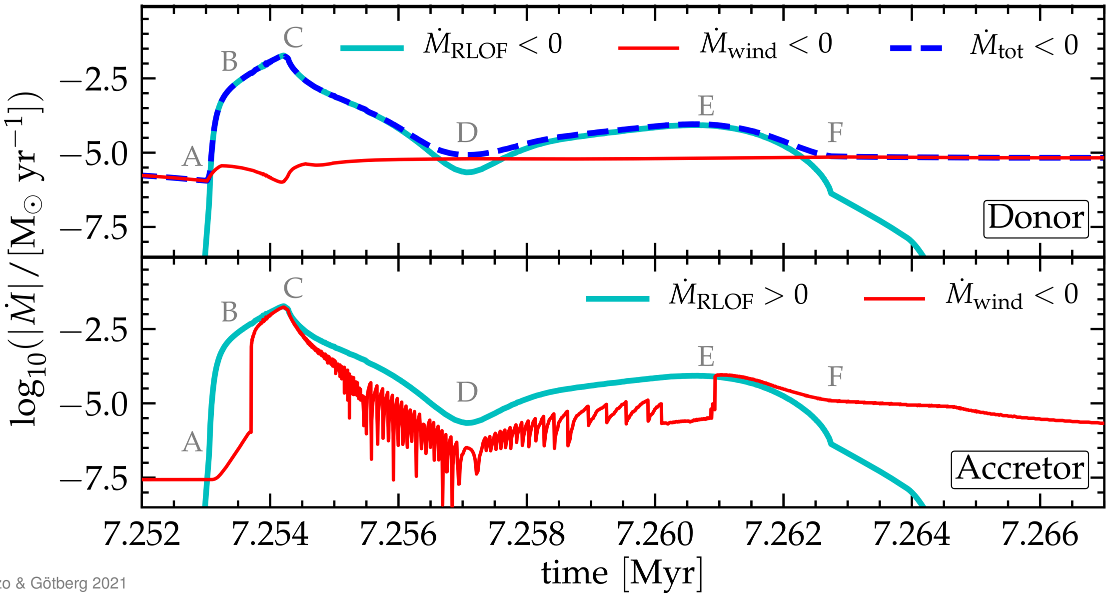
on **both** stars.

✓ **Models match ζ Oph.**

L, T_{eff}, Mass, age, velocity

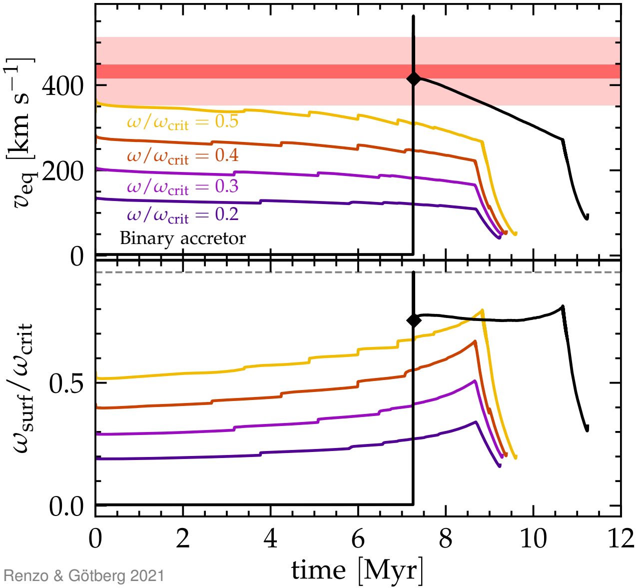
Renzo & Götberg 2021 (data from Villamàriz & Herrero 05)

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



Renzo & Götberg 2021

✓ Surface rotation rate ?

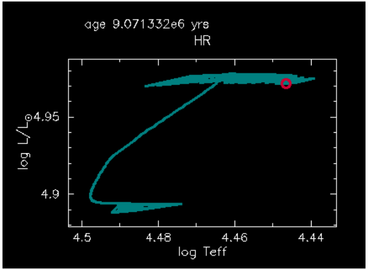


- but "weak wind problem":

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

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

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



Renzo & Götberg 2021

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 ζ Ophiuchi ✓

  ⇒ ^{14}N and ^{4}He from the donor, inward angular momentum transport

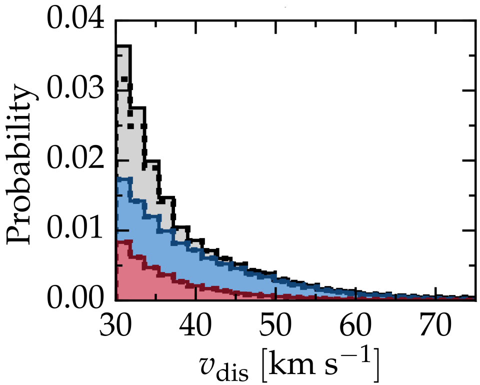
  ⇒ Observed composition constrains mixing & accretion efficiency

- Evolved accretor's core boundary results in easier to eject envelopes

  ⇒ Implications for asteroseismology & common envelope in GW progenitors

Renzo & Götberg 2021, Renzo *et al.* 2022

Accretor stars can be *runaways*...

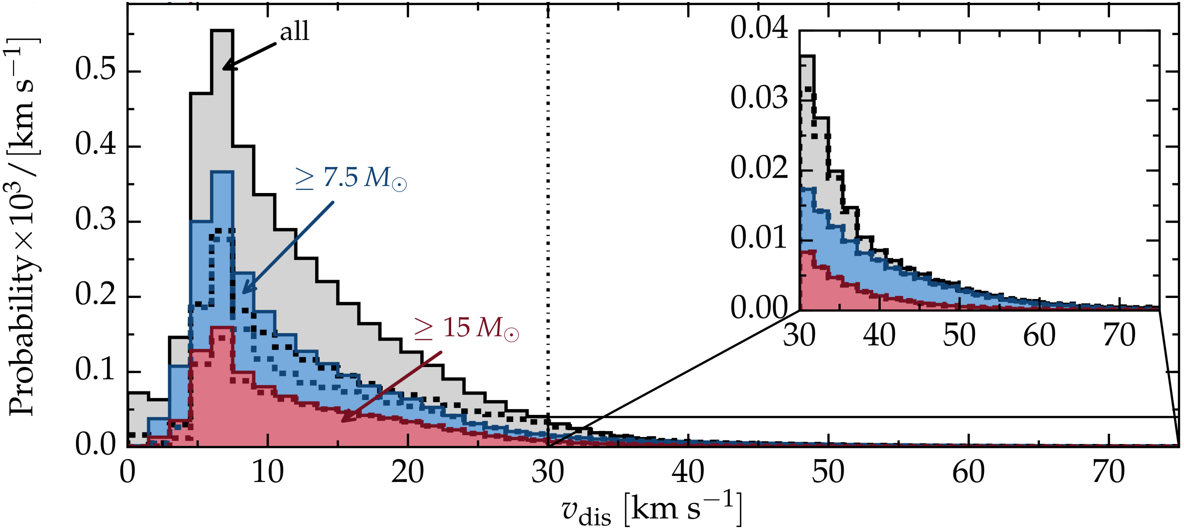


Velocity w.r.t. pre-explosion binary center of mass

Renzo *et al.* 2019b

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

...but most are only *walkaways*



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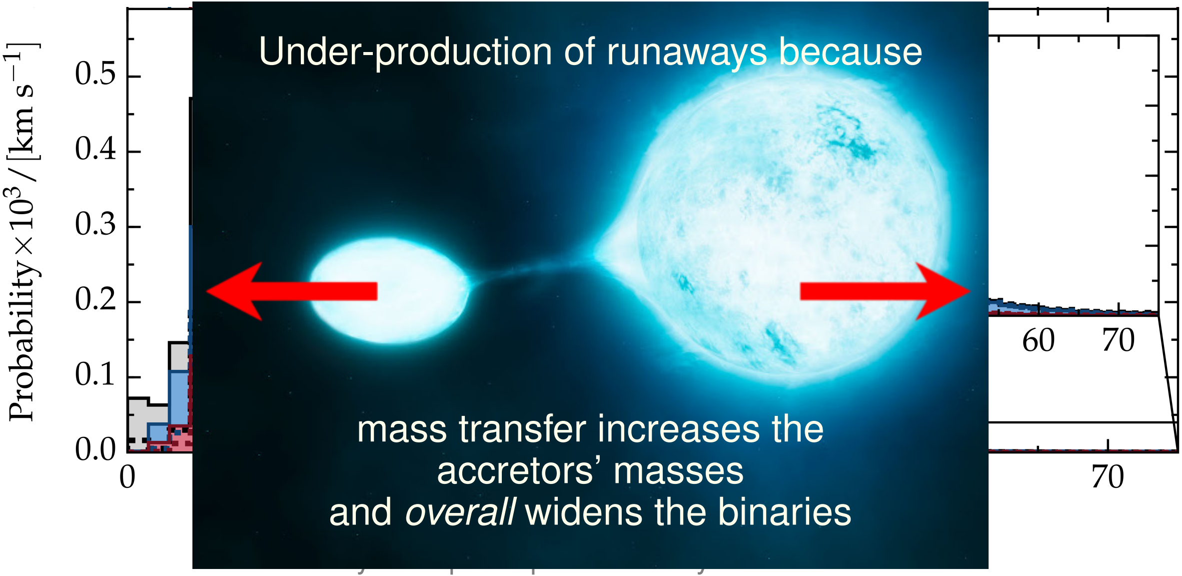
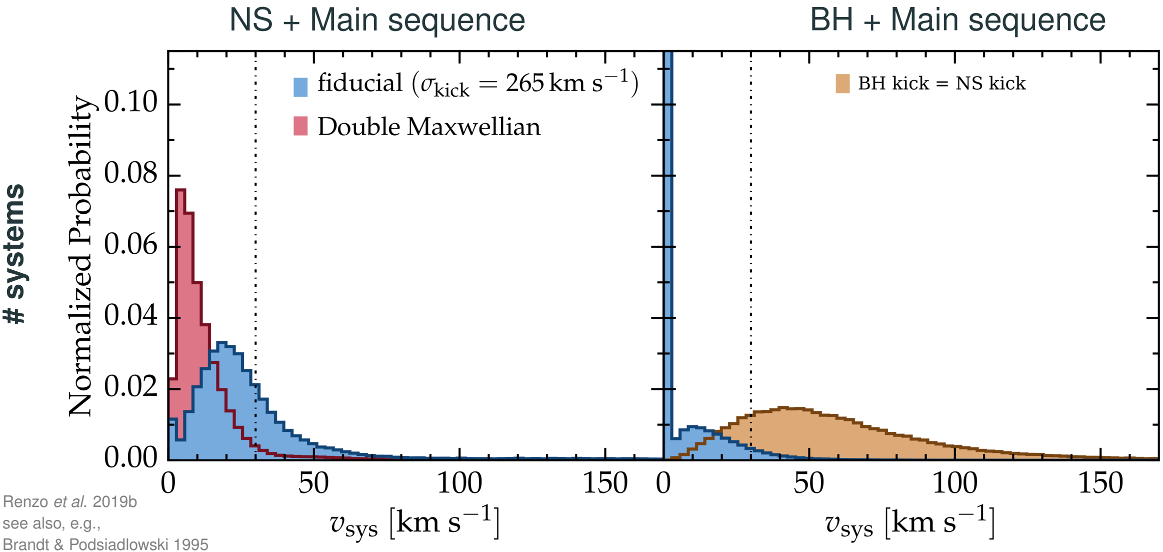


Renzo *et al.* 2019b

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

Post-SN velocity of surviving binaries

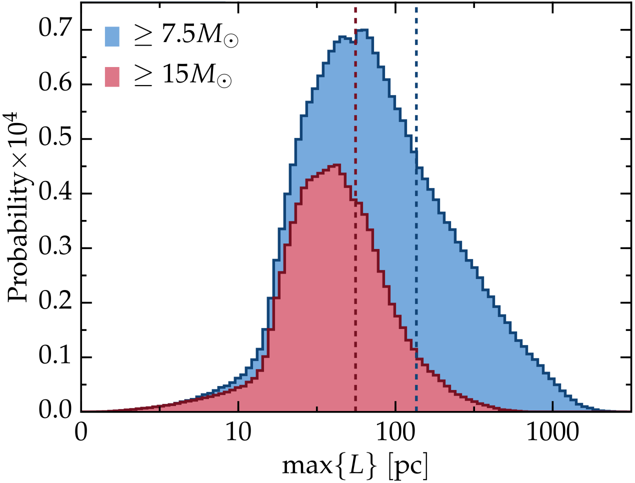


Renzo *et al.* 2019b
see also, e.g.,
Brandt & Podsiadlowski 1995
Kalogera 1996
Tauris & Takens 1998

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

How far do they get?

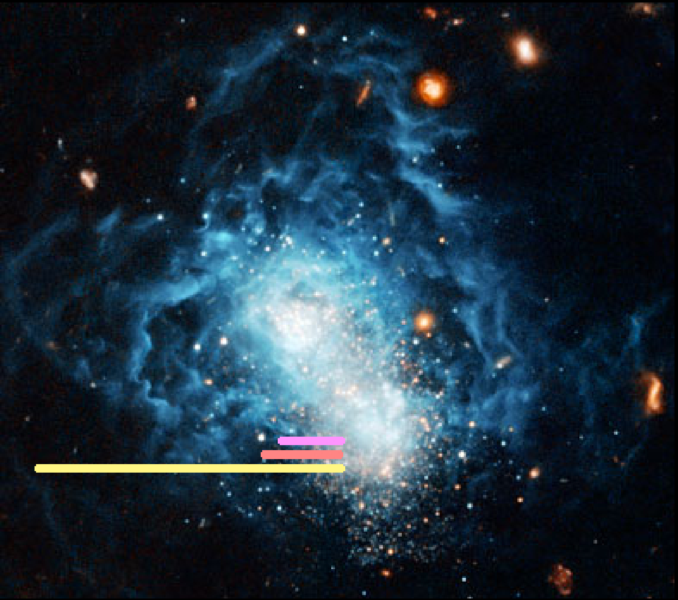


“Distance traveled”

(No potential well)

Renzo *et al.* 2019b

Nevertheless: widowed stars can escape local dust clouds



for $M \geq 7.5\,M_\odot$:

$\langle D \rangle$ = 128 pc

$\langle D_{\mathrm{run}} \rangle$ = 525 pc

$\langle D_{\mathrm{walk}} \rangle$ = 103 pc

Renzo *et al.* 19b

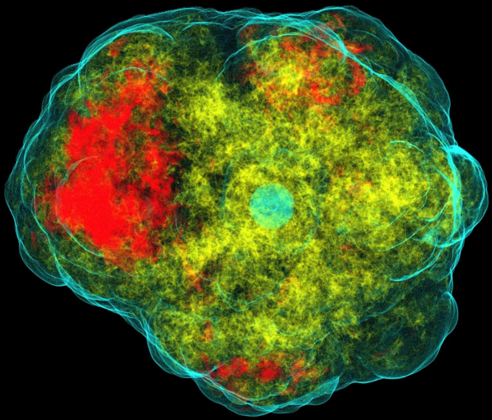
I Zw18

Credits: ESA/Hubble & Nasa, A. Aloisi

SN natal kick

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

Physically: ν emission and/or ejecta anisotropies



Credits: C. D. Ott, S. Drasco

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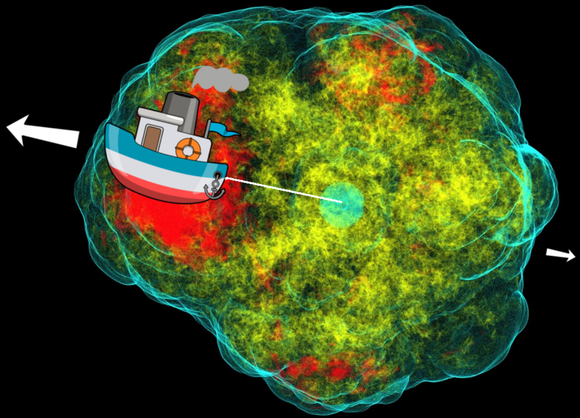
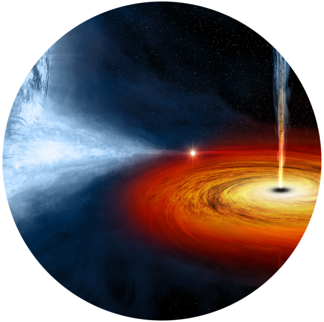


Credits: C. D. Ott, S. Drasco

Do BHs receive kicks ?

NO

⇒ most remain together with their widowed companion

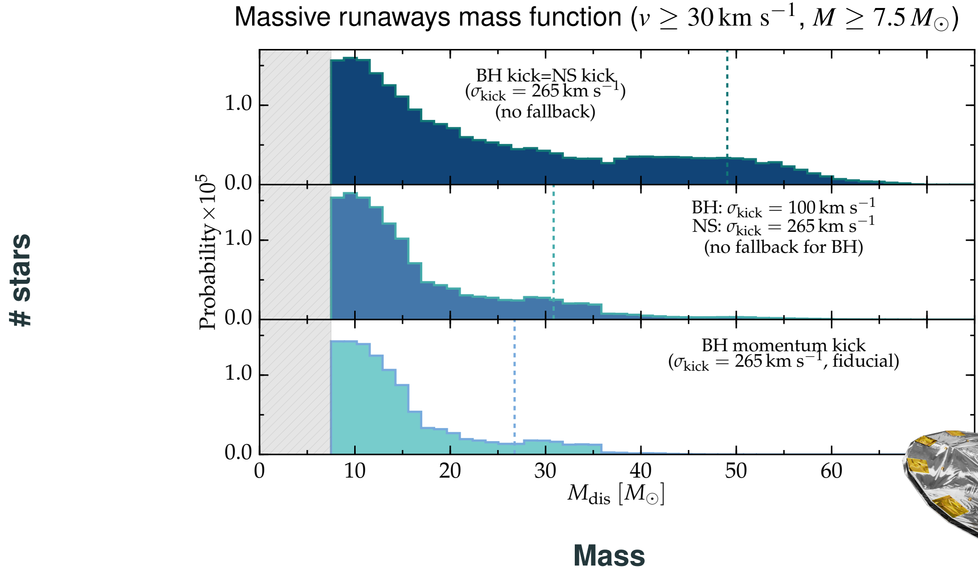


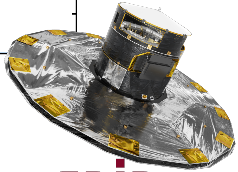
YES

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

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

A way to constrain BH kicks with Gaia



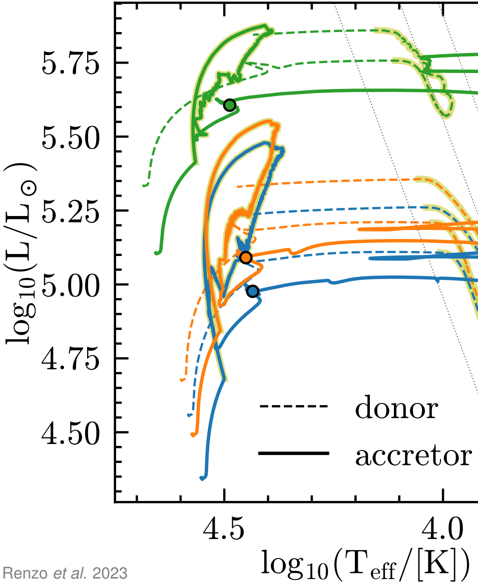


Numerical results publicly available at:

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

Renzo *et al.* 19b

Low-Z massive accretors



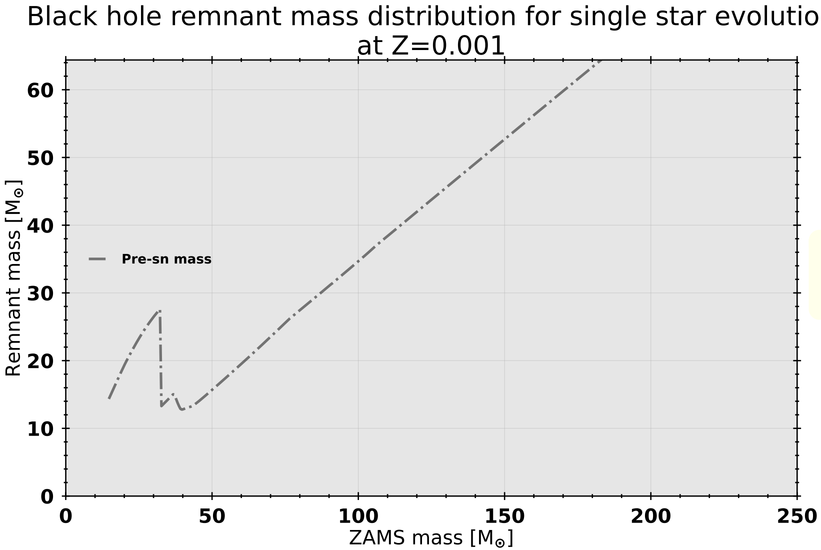
$Z = 0.0019 \simeq Z_\odot/10$

(to focus on GW merger progenitors)

Renzo *et al.* 2023

$M_{\text{initial}} \xrightarrow{\dagger}$ CO core mass† → BH mass

† and composition! (Patton & Sukhbold 2020)



"Initial mass"

David D. Hendriks

Univ. Surrey

Fryer *et al.* 2012

Fryer *et al.* 22, Olejak *et al.* 22

see also:
Belczynski *et al.* 2016,
Spera & Mapelli 2017,
Stevenson *et al.* 2019,
van Son *et al.* (incl. Renzo) 2022, ...

Hendriks, van Son, Renzo, Izzard, in prep.

$M_{\text{initial}} \rightarrow$ CO core mass† $\rightarrow$ BH mass

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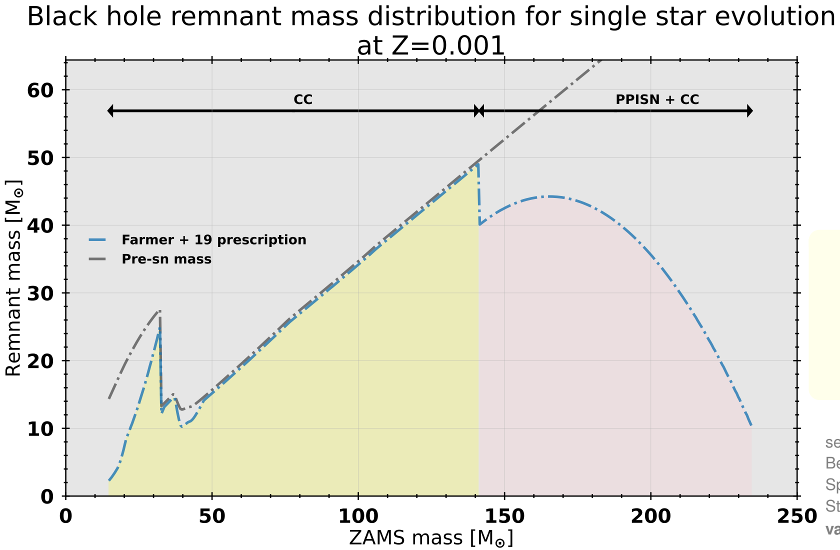

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+
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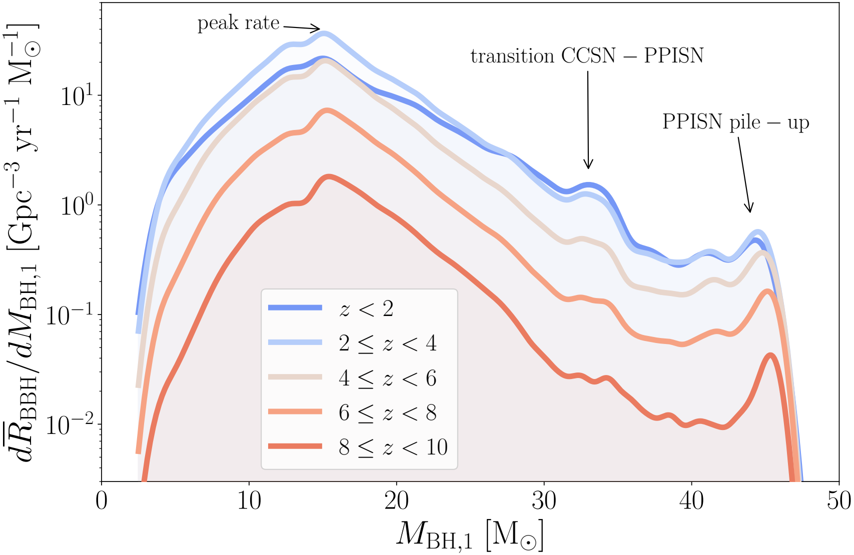
Hendriks, van Son, Renzo, Izzard, in prep.

Using “recipes” out-of-the-box leads to artificial features



“Binary BH merger rate”

“biggest BH mass”

Lieke van Son

van Son *et al.* (incl. Renzo) 2022

see also Tanikawa *et al.* 2020, 2021, 2022

Pair-instability mass loss for top-down compact object mass calculations

M. Renzo,[1,2] D. D. Hendriks,[3] L. A. C. van Son,[4,5,6] and R. Farmer[6]

[1] *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*
[2] *Department of Physics, Columbia University, New York, NY 10027, USA*
[3] *Department of Physics, University of Surrey, Guildford, GU2 7XH, Surrey, UK*
[4] *Center for Astrophysics | Harvard & Smithsonian,60 Garden St., Cambridge, MA 02138, USA*
[5] *Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098XH Amsterdam, The Netherlands*
[6] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85741 Garching, Germany*

$$M_{\rm BH} = M_{\rm proto-NS} + M_{\rm fallback}$$

(Fryer *et al.* 2012, 2022)

$$\Downarrow$$

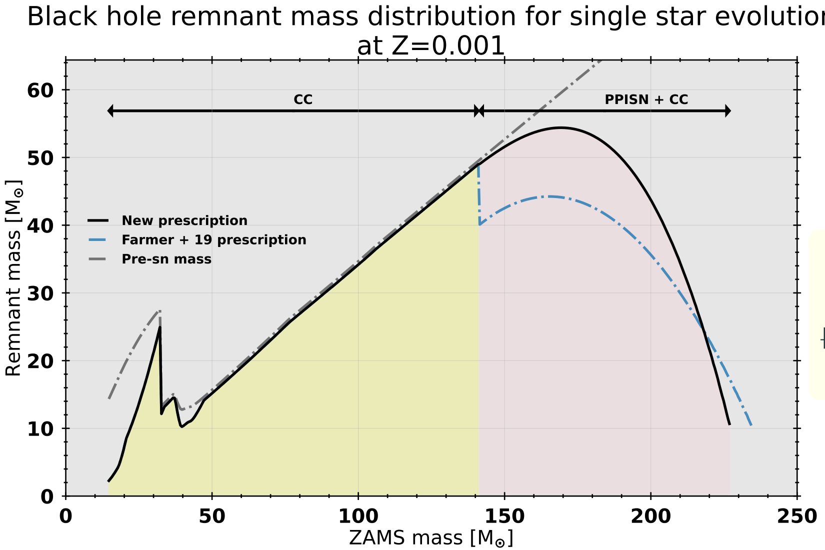
$$M_{\rm BH} = M_{\rm pre-explosion} - \left(\Delta M_{\rm SN} + \Delta M_{\nu,\rm core} + \Delta M_{\rm env} + \Delta M_{\rm PPI} + \cdots\right)$$

New fit to **Farmer, Renzo *et al.* 2019**

Renzo *et al.* 2022, RNAAS

$M_{\rm initial} \rightarrow$ CO core mass† $\rightarrow$ BH mass

† and composition! (Patton & Sukhbold 2020)



"Initial mass"

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Fryer *et al.* 2012

+

~~Farmer, MR *et al.* 2019~~

Renzo *et al.* 2022

Hendriks, van Son, MR *et al.*, in prep.

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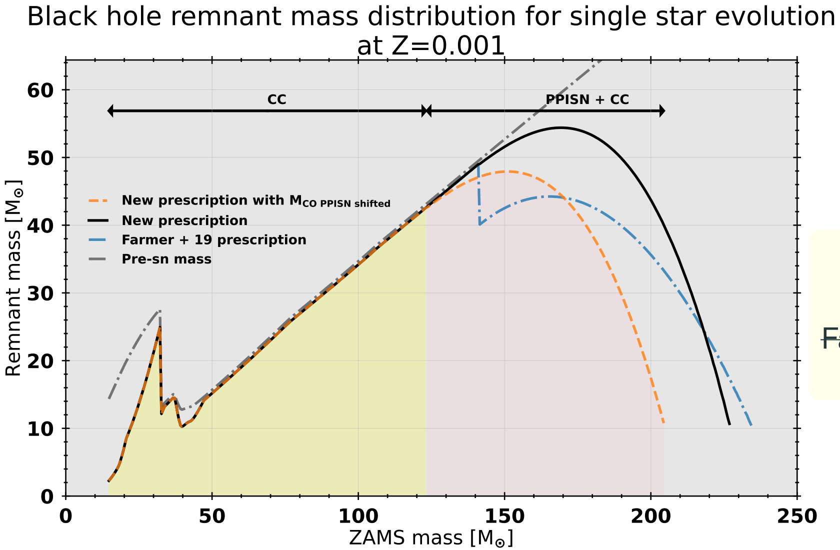

"Initial mass"

David D. Hendriks

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Fryer *et al.* 2012

+

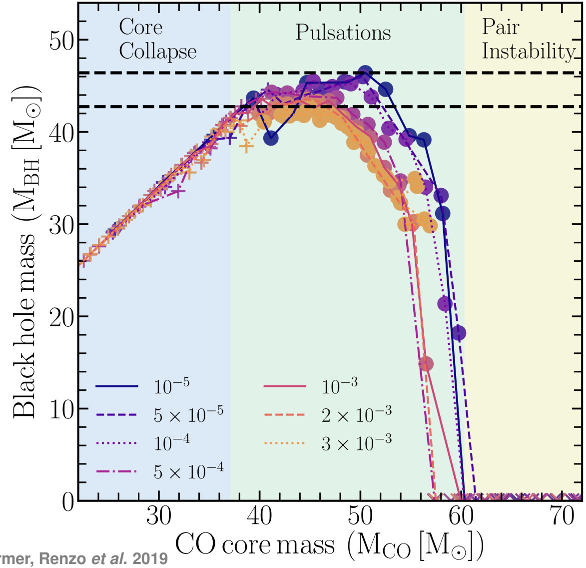
~~Farmer, MR *et al.* 2019~~

Renzo *et al.* 2022

Hendriks, van Son, MR *et al.*, in prep.

Metallicity? Small effect

Focus on lower edge of the gap



Farmer, Renzo *et al.* 2019

Metallicity shift

$\Delta \max\{M_{BH}\} \sim 7\%$

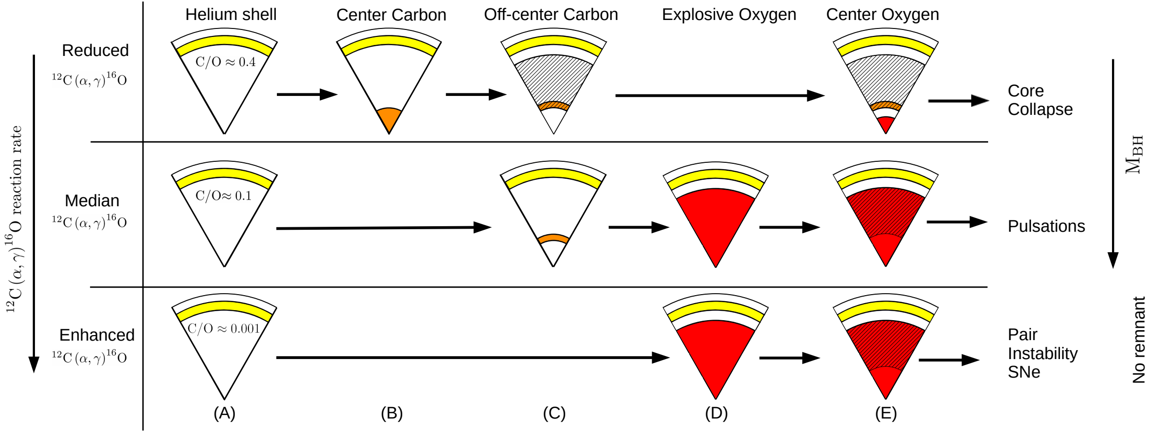
over 2.5 orders of magnitude

Comparable or smaller effects:
mixing, winds, nuclear reaction network size, rotation, code used, etc...

Renzo *et al.* 2020a, Farmer, Renzo *et al.* 2019, 2020,
Marchant & Moryia 2020, Costa *et al.* 2021, Woosley & Heger 2021

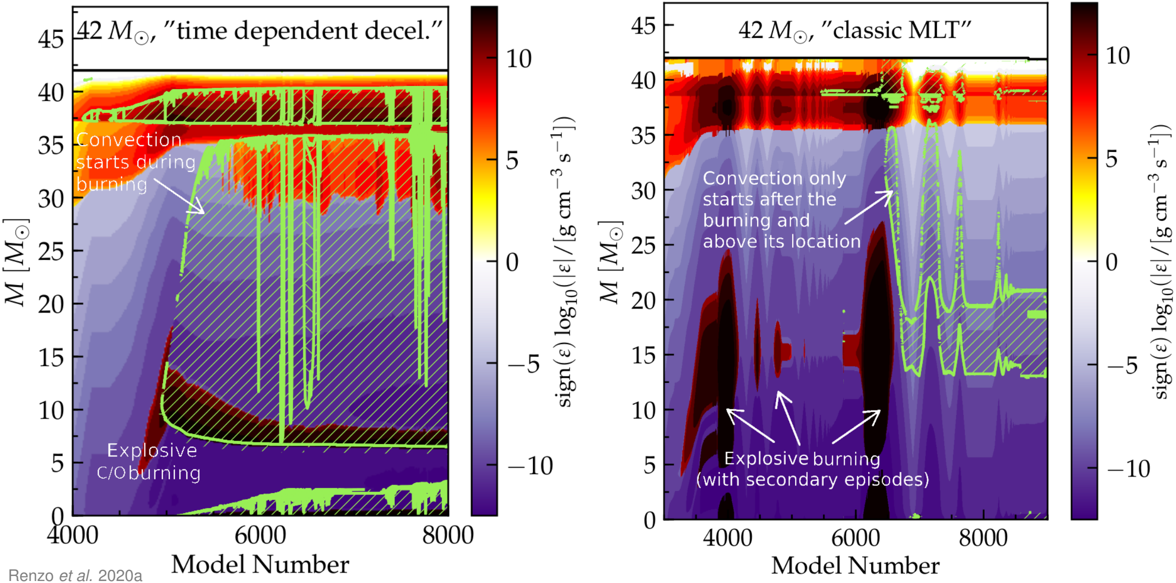
The $^{12}C(\alpha,\gamma)^{16}O$ ends He core burning

More $^{12}C \Rightarrow$ C shell burning delays ^{16}O ignition to higher ρ



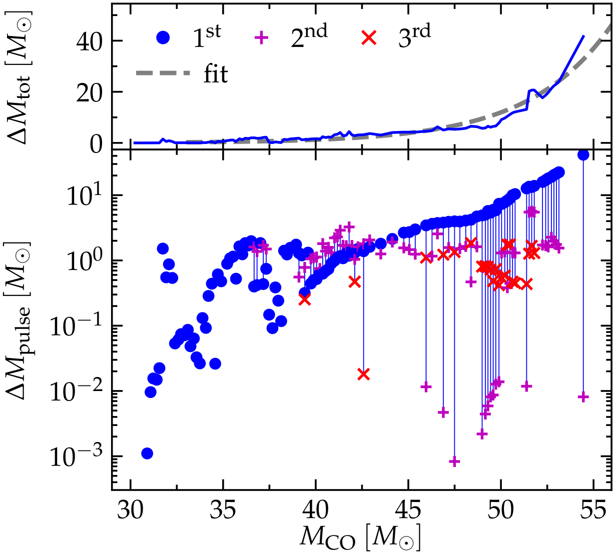
Farmer, Renzo *et al.* 2020

Convection during the pulses quenches the PPI mass loss



Renzo *et al.* 2020a

Amount of mass lost per pulse



Larger cores

⇓

More energetic pulses

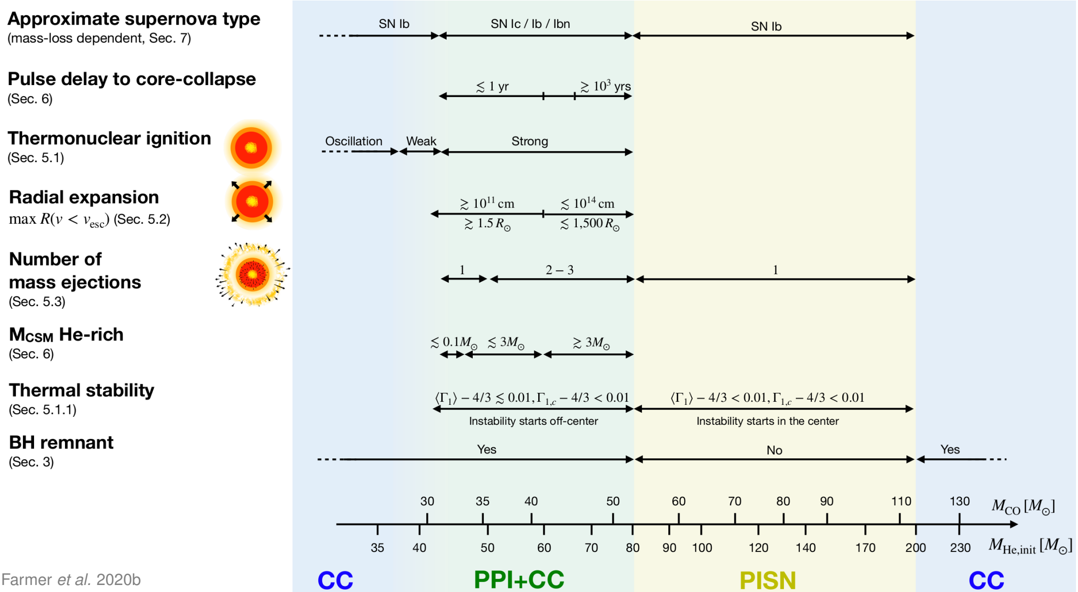
⇓

More mass loss

(and longer delays)

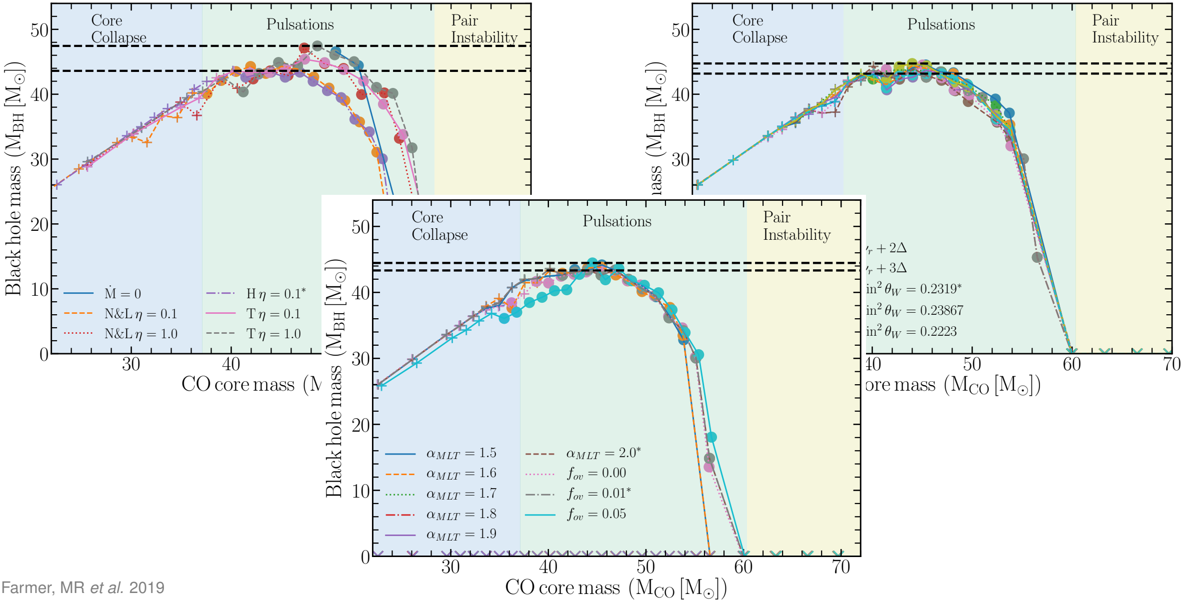
Renzo, Farmer *et al.* 2020b

Summary of EM transients



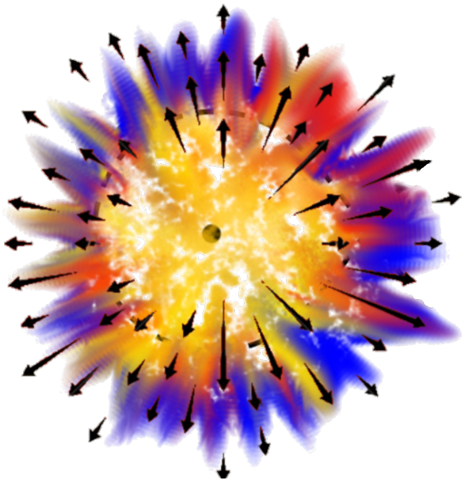
Renzo, Farmer *et al.* 2020b

Winds, mixing, ν physics? Also small effects



Farmer, MR *et al.* 2019

What is the fate of the H-rich envelope at BH formation?



$$\Delta E_\nu \simeq 10^{53}\ \mathrm{erg}$$

Possible causes for mass ejection:

- ν-driven shocks

  Nadhezin 80, Lovegrove & Woosley 13, Piro 13, Fernandez *et al.* 18, Ivanov & Fernandez 21

- Jets (even without net rotation)

  Gilkis & Soker 2014, Perna *et al.* 18, Quataert *et al.* 19, Antoni & Quataert 22

- weak fallback powered explosion

  Ott *et al.* 18, Kuroda *et al.* 18, Chan *et al.* 20, 21

see also Adams *et al.* 17 & Basinger *et al.* 20 for possible EM counterpart to BH formation

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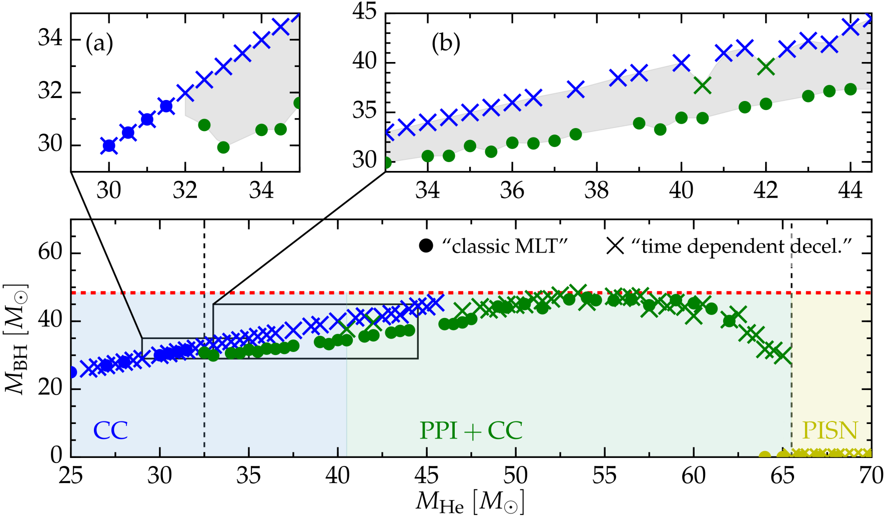
Different predicted outcomes for RSG/BSG

$\Rightarrow$ Z-dependence

see also Adams *et al.* 17 & Basinger *et al.* 20 for possible EM counterpart to BH formation

Treatment of time-dependent convection? Not the edge

Matters for least massive PPI, not for the most massive BH progenitors



Renzo *et al.* 2020a

Treatment of time-dependent convection? Not the edge

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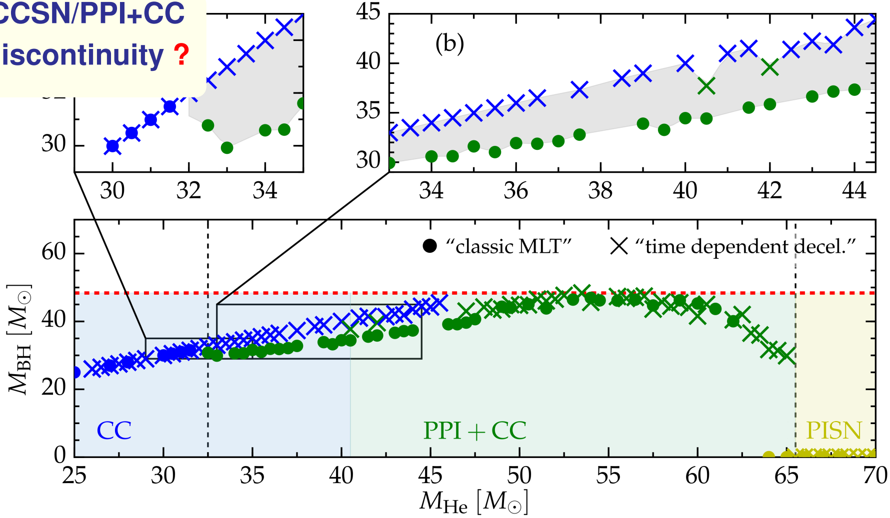
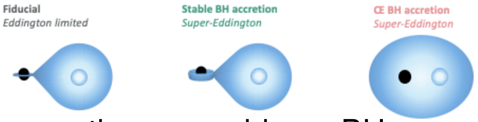
CCSN/PPI+CC discontinuity ?



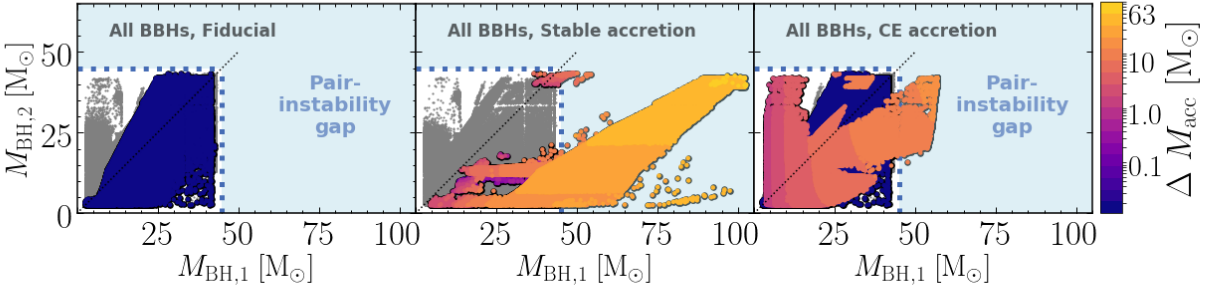
Renzo *et al.* 2020a

Can isolated binary evolution “pollute” the gap?

van Son *et al.*, incl. MR, 2020



With unlimited accretion, some binary BHs can enter the gap...



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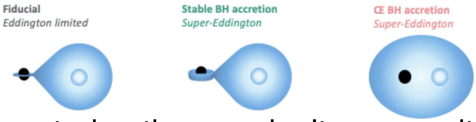
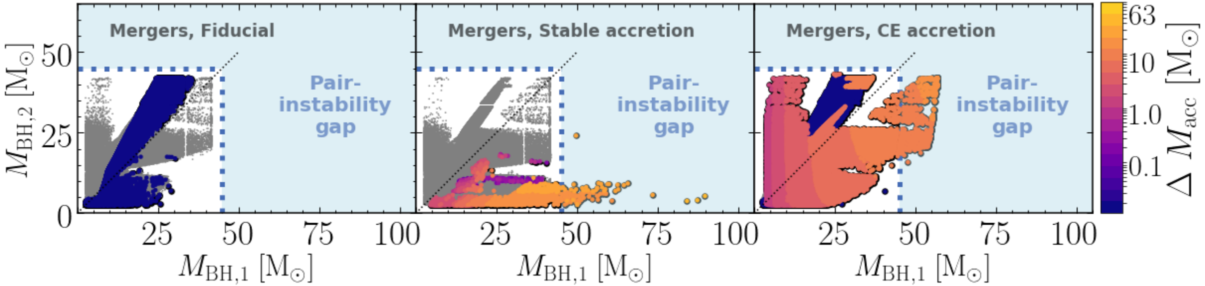
van Son *et al.*, incl. MR, 2020



... but those entering the gap don't merge within 13.7 Gyr



Mass accretion leads to orbital widening

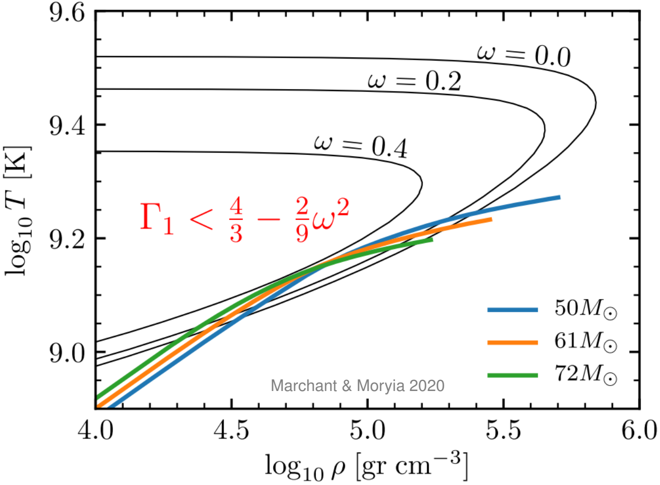
even with the most optimistic assumptions:

- $\lesssim 1\%$ systems with $M_{\rm tot} \gtrsim 90\,M_\odot$
- No systems with $M_{\rm tot} > 100\,M_\odot$

Can rotation move the gap? Barely...

Rotation $\Rightarrow$ **bigger** M_{He} $\Rightarrow$ can increase the rates

Chatzopoulos *et al.* 2012, 2013



Rotation stabilizes only for *very* extreme assumption:

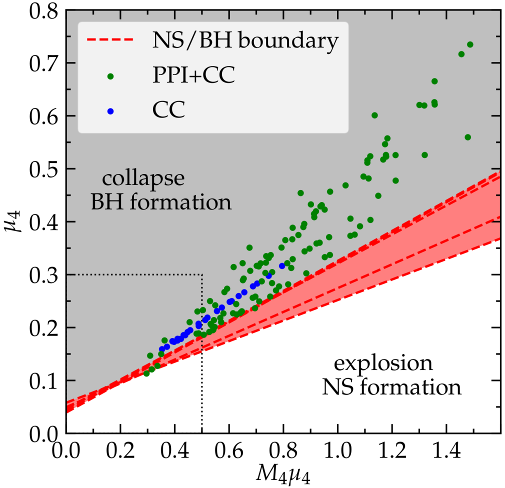
- No core-envelope coupling
- large initial rotation
- low Z ($\simeq$ no winds)

only $\sim$20% shift of instability
$\lesssim$4% for "realistic" coupling

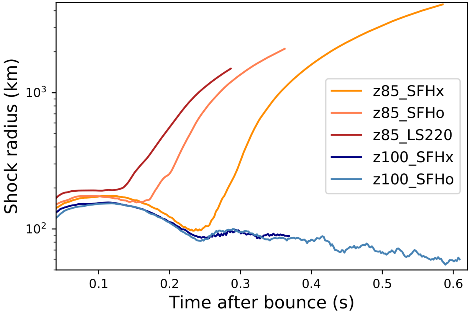
see also Glatzel *et al.* 1985

Can the final core-collapse result in an explosion?

Parametric 1D explodability criteria are not really applicable.



3D simulations not conclusive yet



Powell, Muëller, Heger 2021

$$\max \Delta M_{CC} \lesssim 3.5\, M_\odot$$

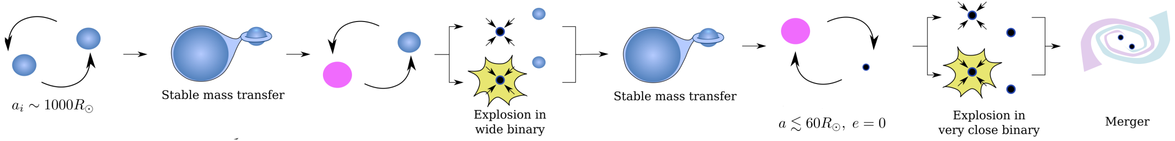
from ν-driven engines

Rahman *et al.*, 2021

Renzo, Farmer, *et al.* 2020b, see also Ertl *et al.* 2016,2020, O'Connor & Ott 2011, Müller & Mandel 2020, Couch *et al.* 2020

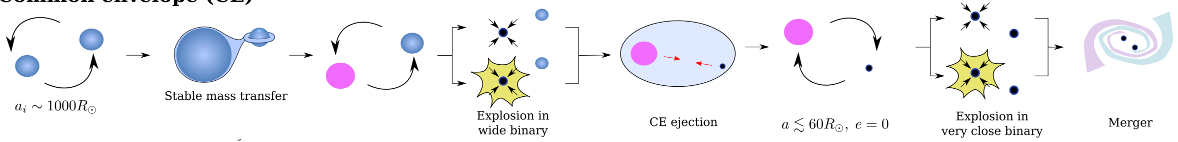
Isolated binary evolution removes the H-envelope anyways

Stable mass transfer (RLOF)

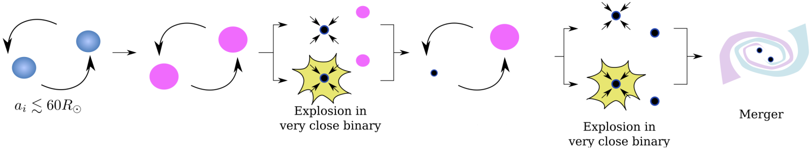


e.g., Klencki *et al.* 2021, van Son *et al.* (incl. MR) 2021, Marchant *et al.* 2021, Gallegos-Garcia *et al.* 2022

Common envelope (CE)



Chemically homogeneous evolution (CHE)



Marchant, MR *et al.* 2019