

# Transients from massive binary progenitors: source formation

YKIS 2026, Kyoto, 13/2/26

Ilya Mandel



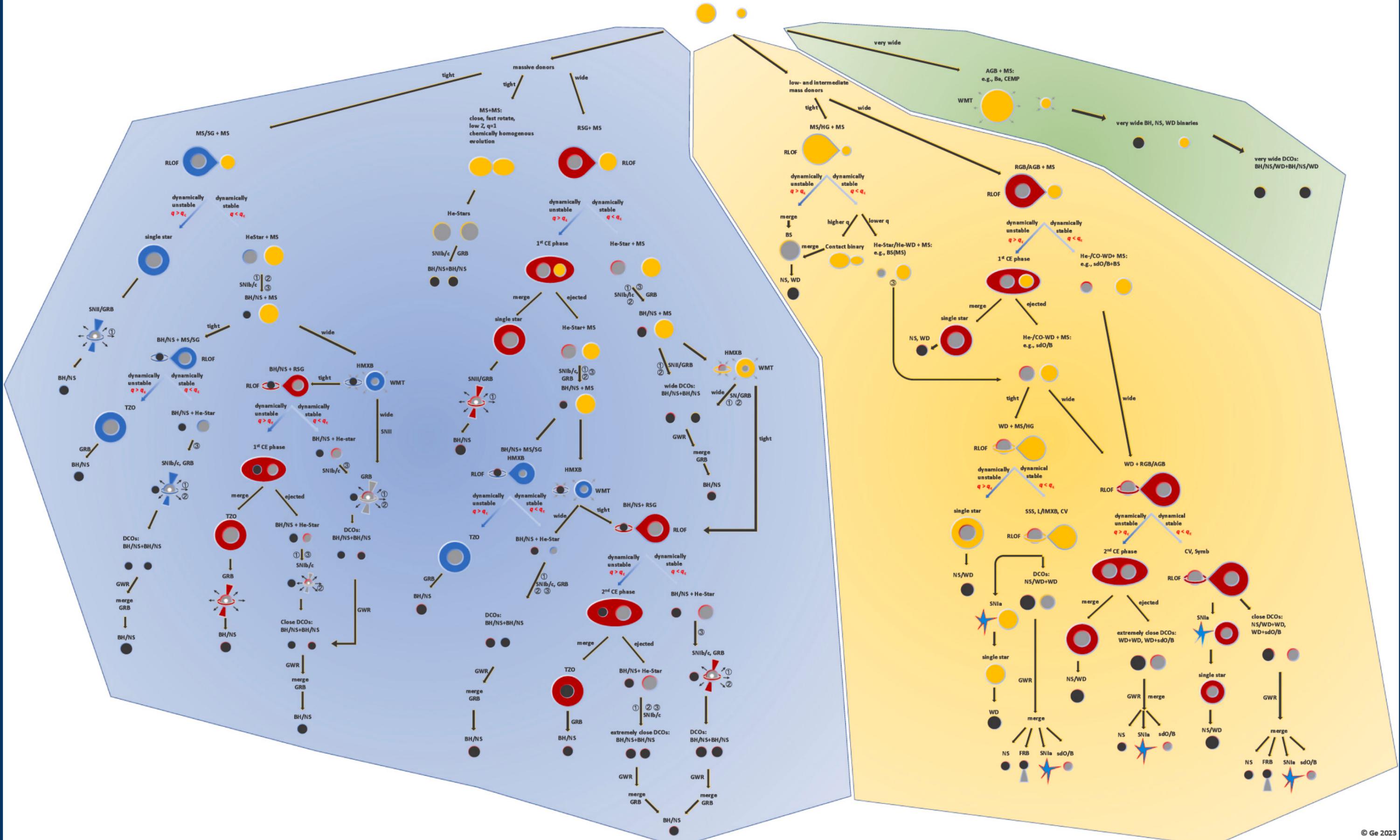
*This is the way the world ends  
Not with a bang but a whimper.*

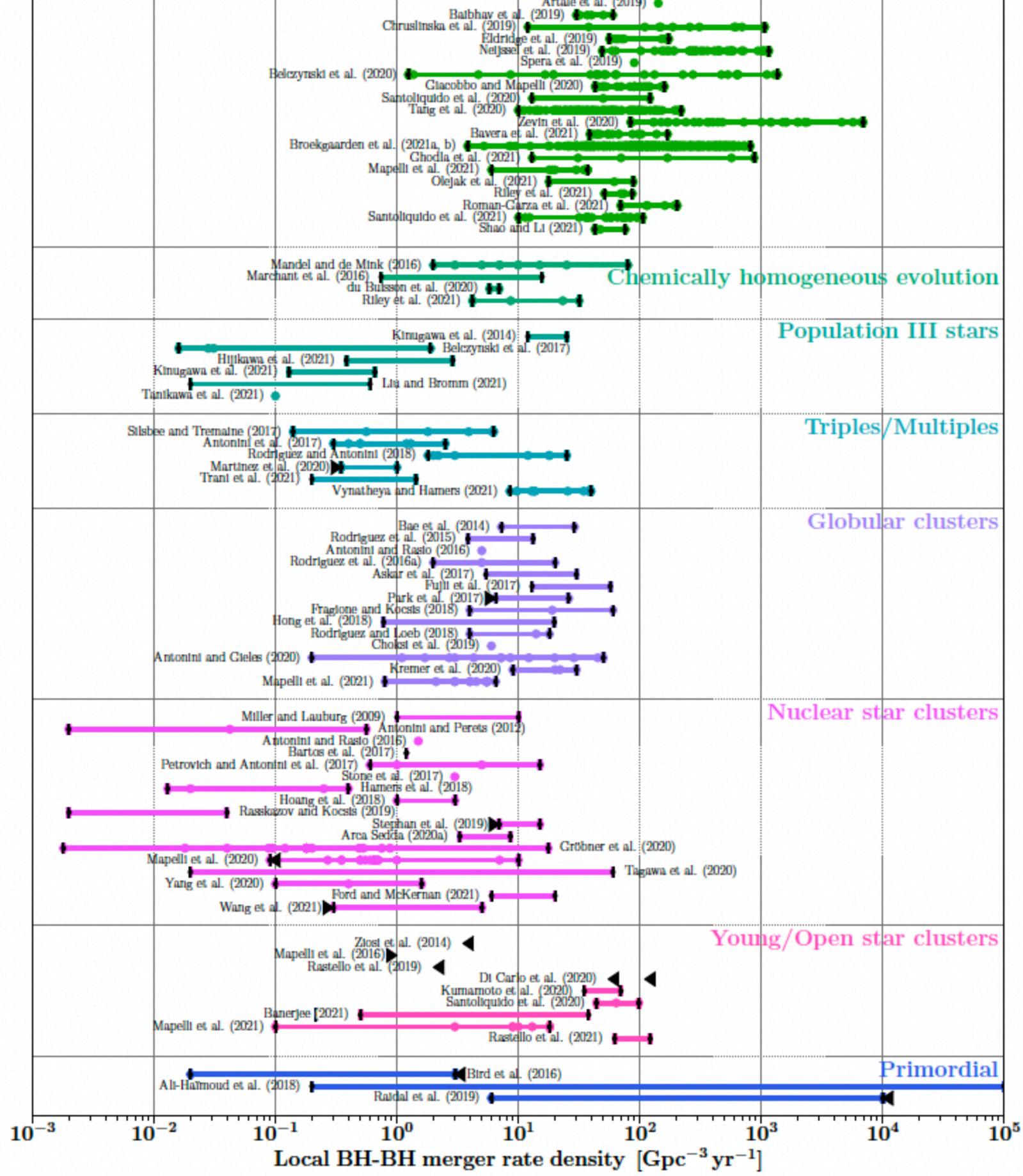
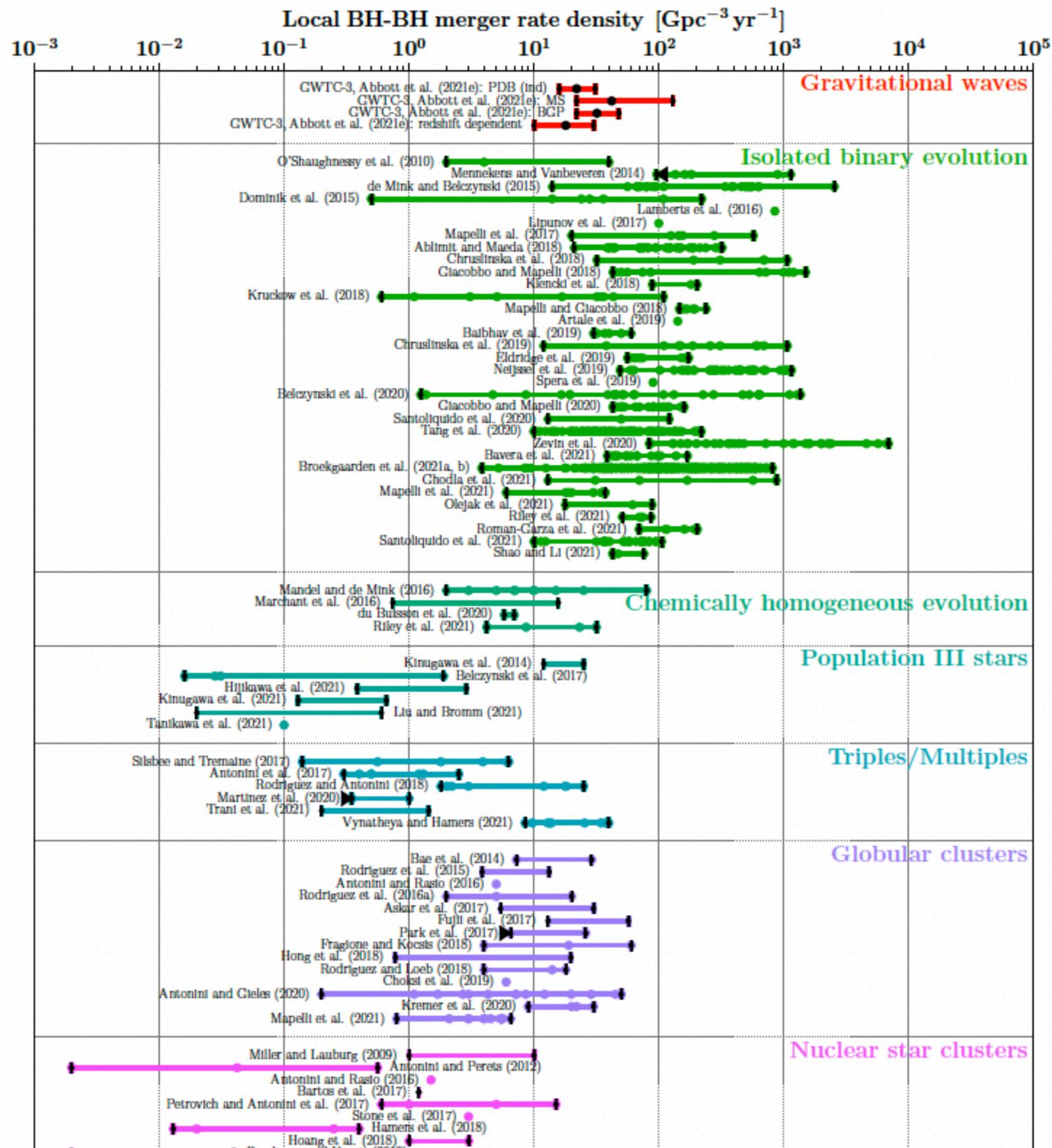
T. S. Eliot, The Hollow Men

# Transients of binary origin

- GW events
- Kilonovae
- GRBs
- (many) Supernovae
- Luminous red novae
- Tidal disruption events
- Not quite transients: HMXBs,  
Galactic double neutron stars, etc.

# binary evolution

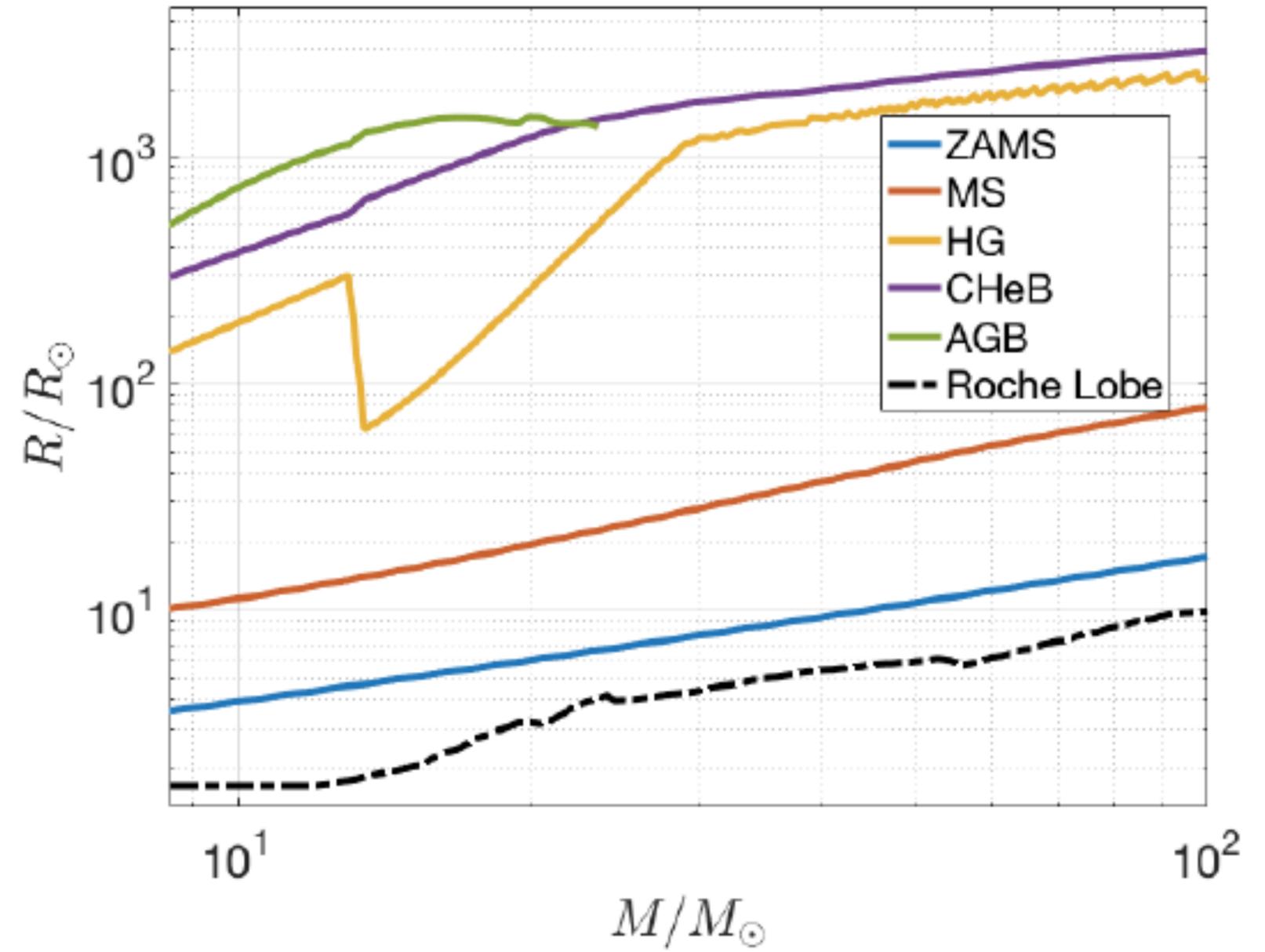
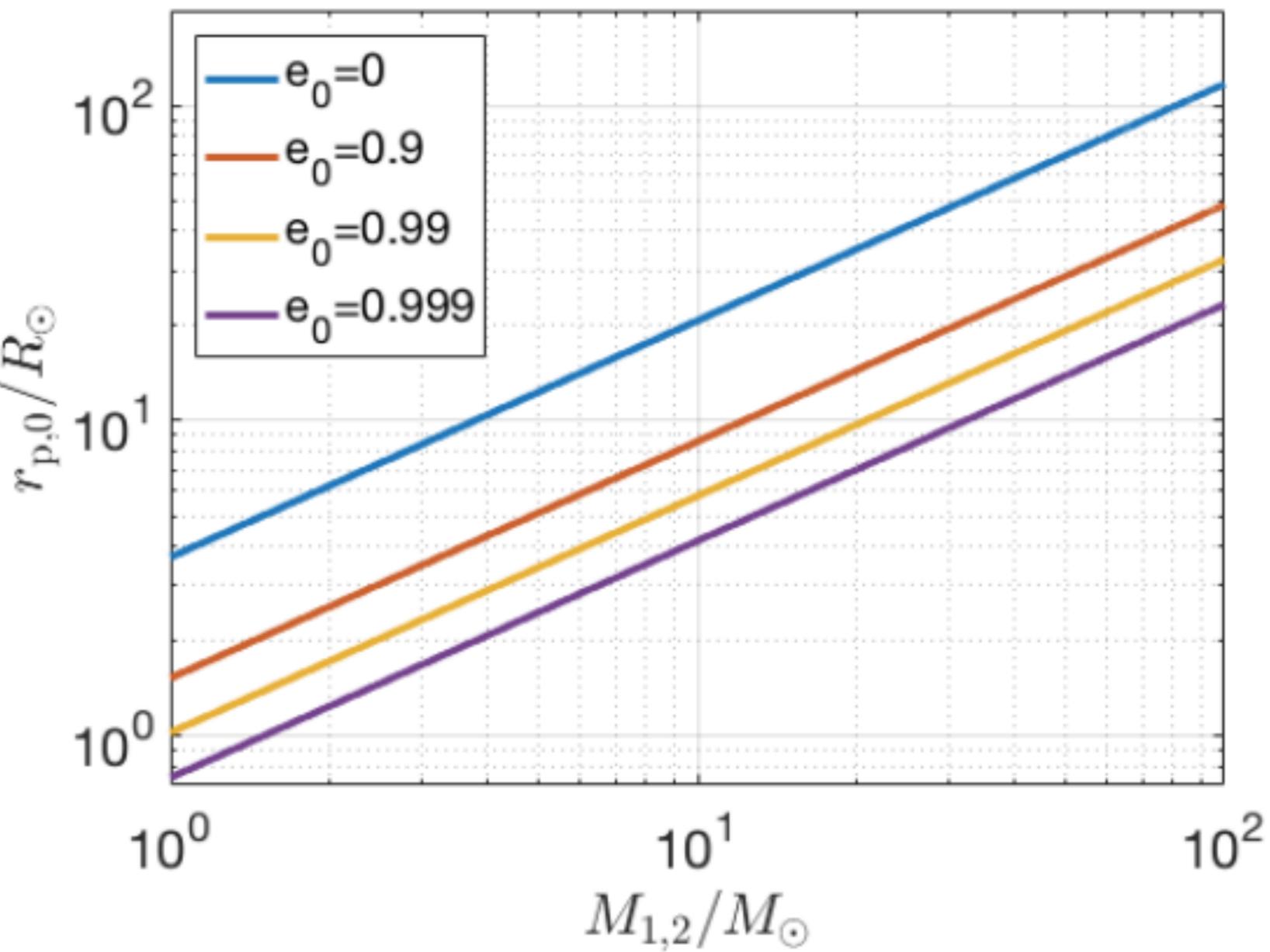




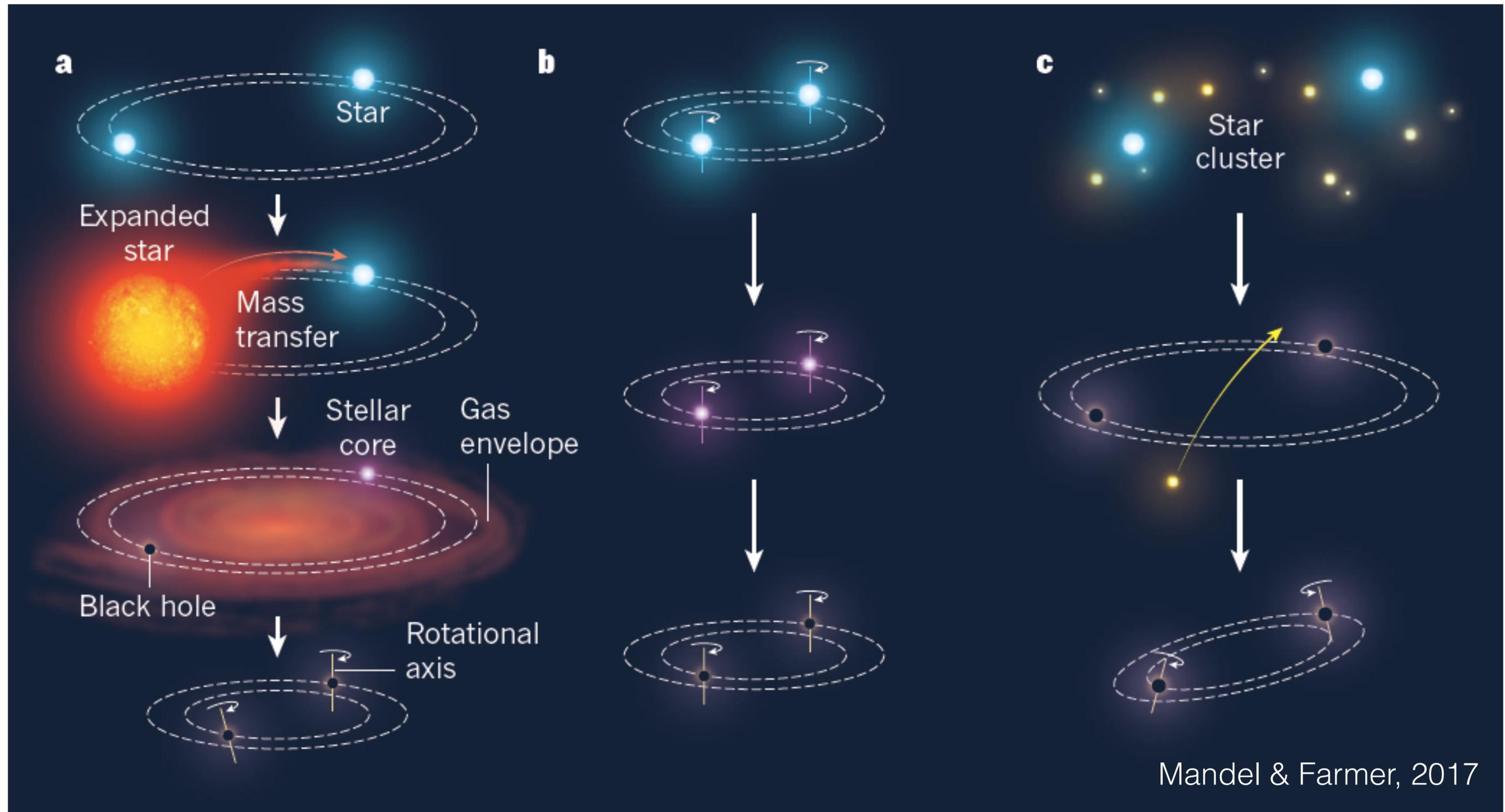
<b>Story elements</b>	<b>Puzzles</b>	<b>Partial solutions</b>	<b>Future tests?</b>
<b>Common Envelopes</b>	Why do GW sources merge?		

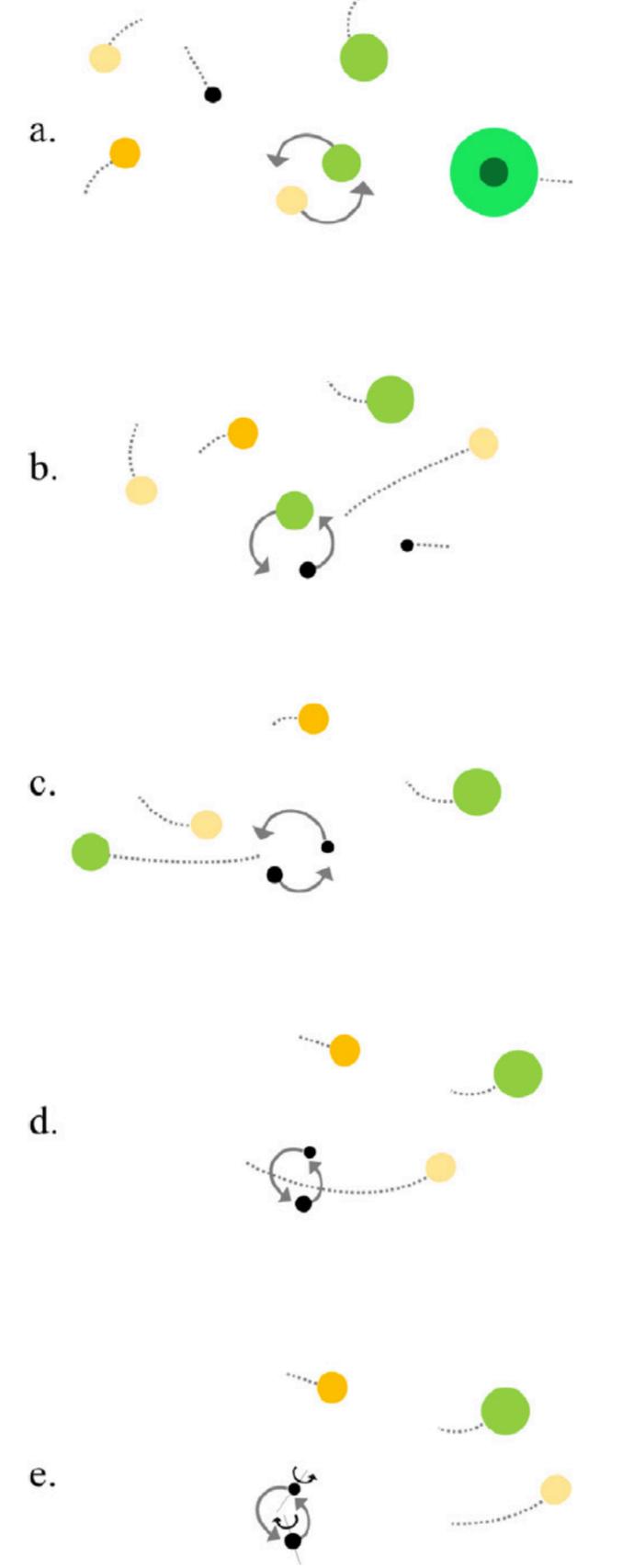
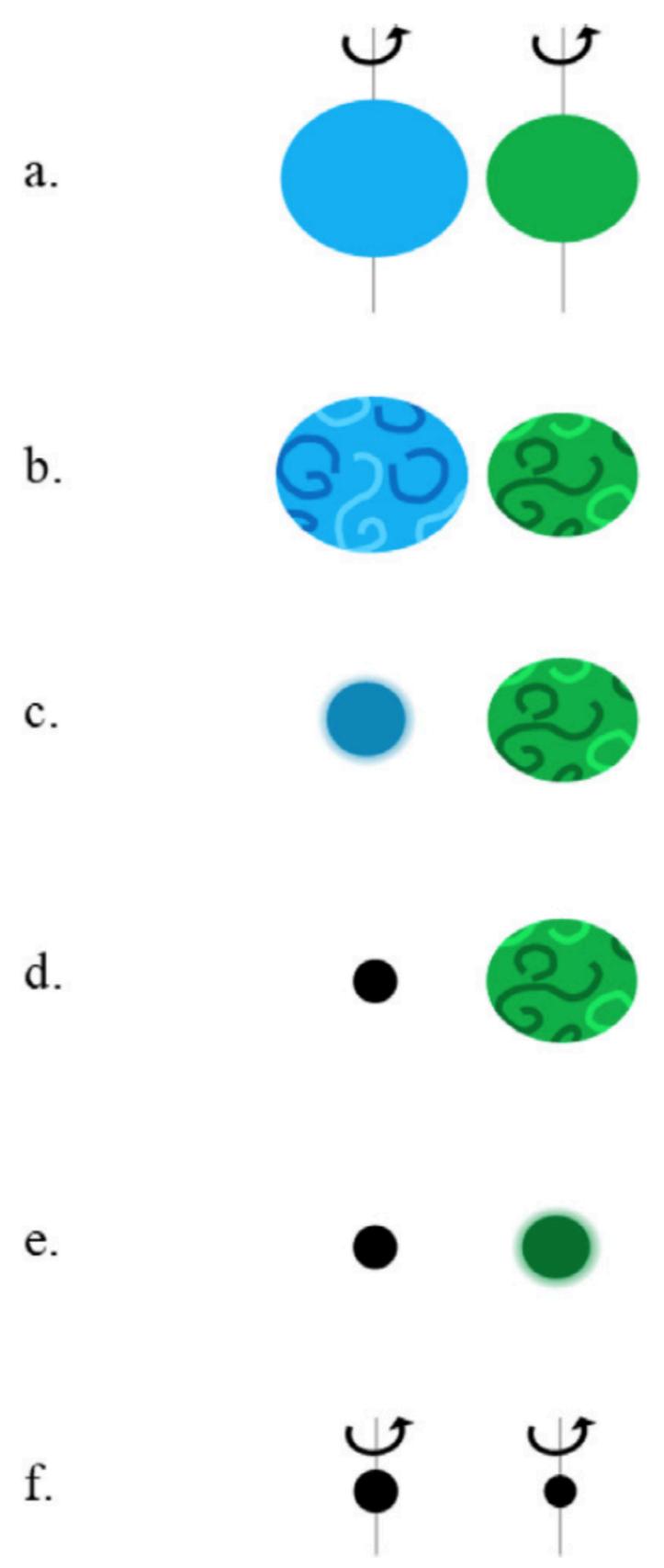
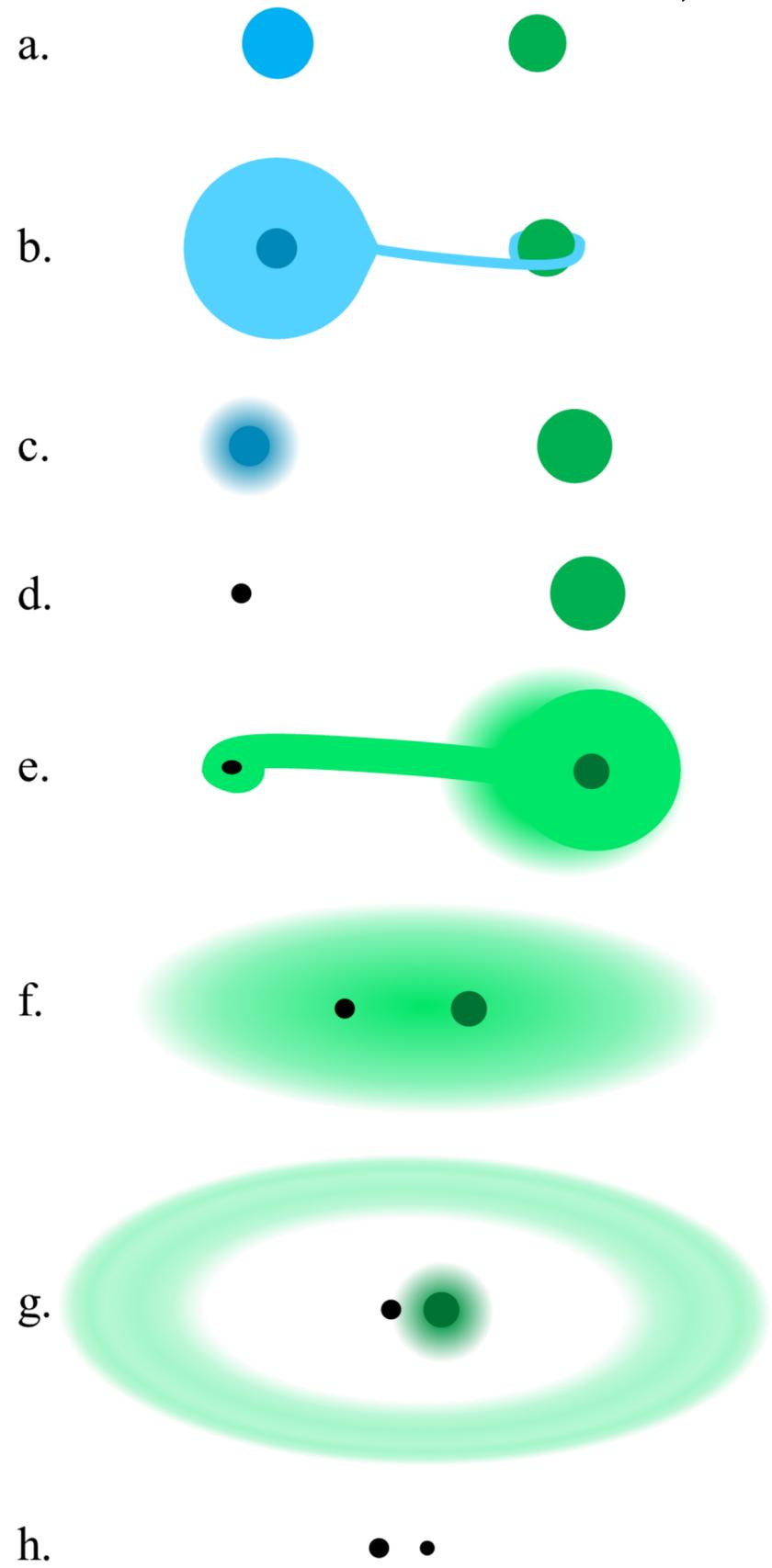
Story elements	Puzzles	Partial solutions	Future tests?
<b>Common Envelopes</b>	Why do GW sources merge?		
		<i>Two roads diverged in a yellow wood...</i>	
		Robert Frost, The Road not Taken	

# How do compact binaries ever merge?

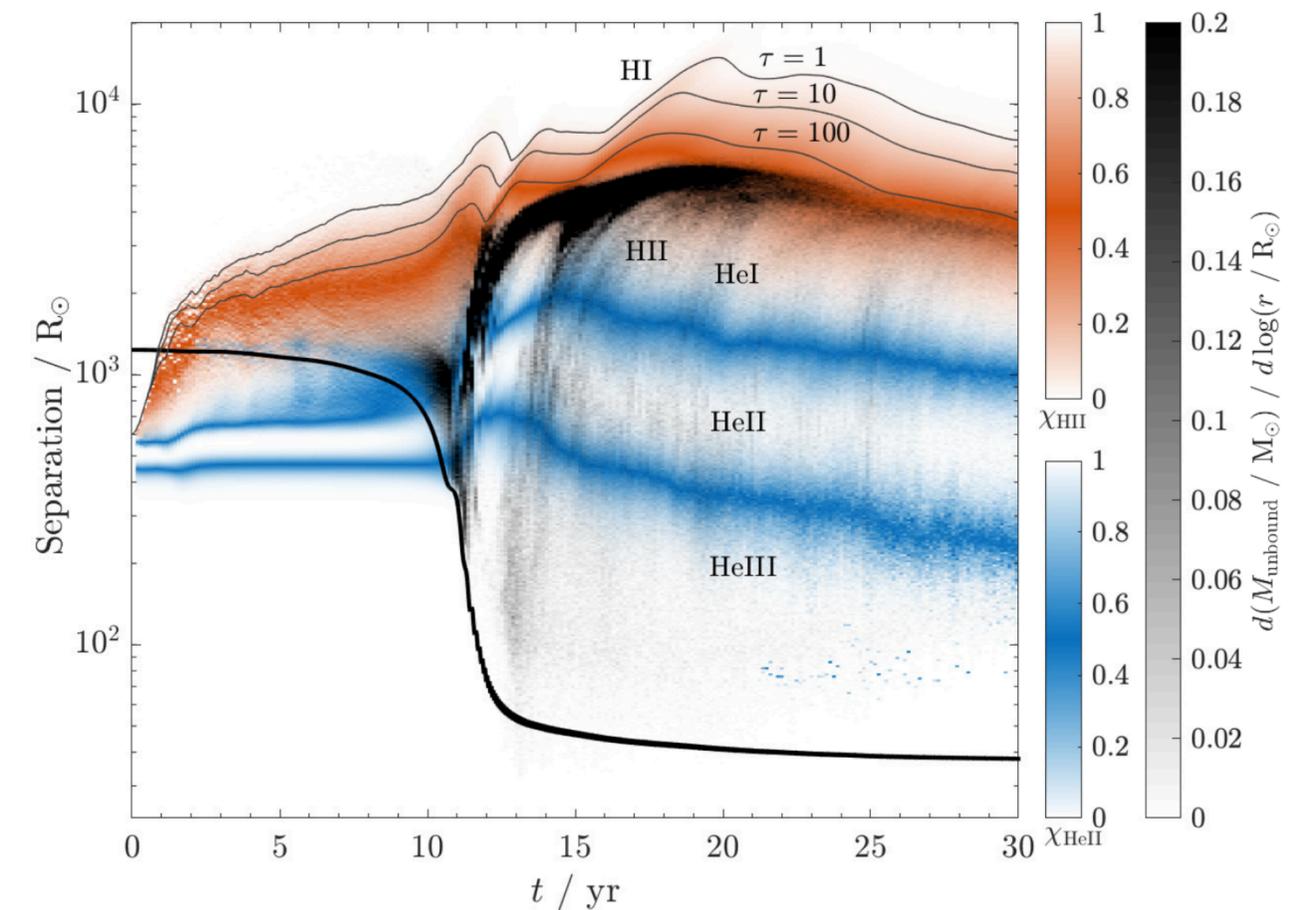
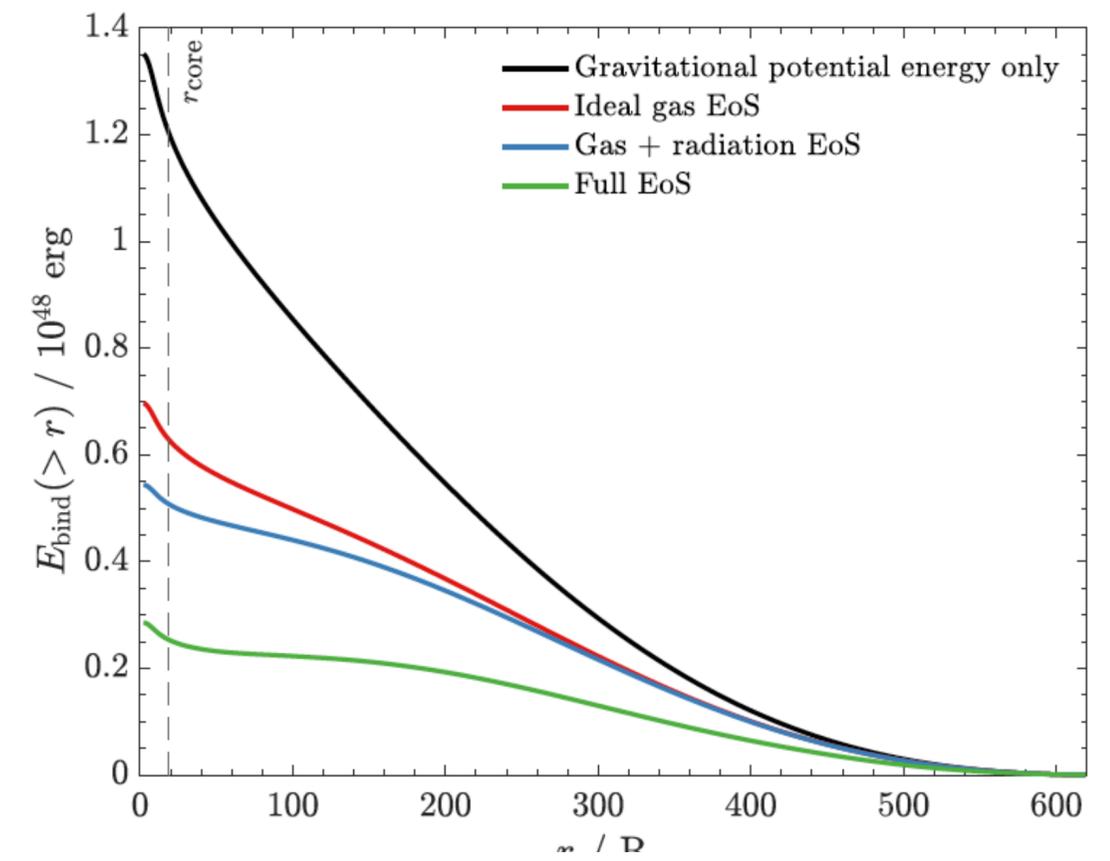
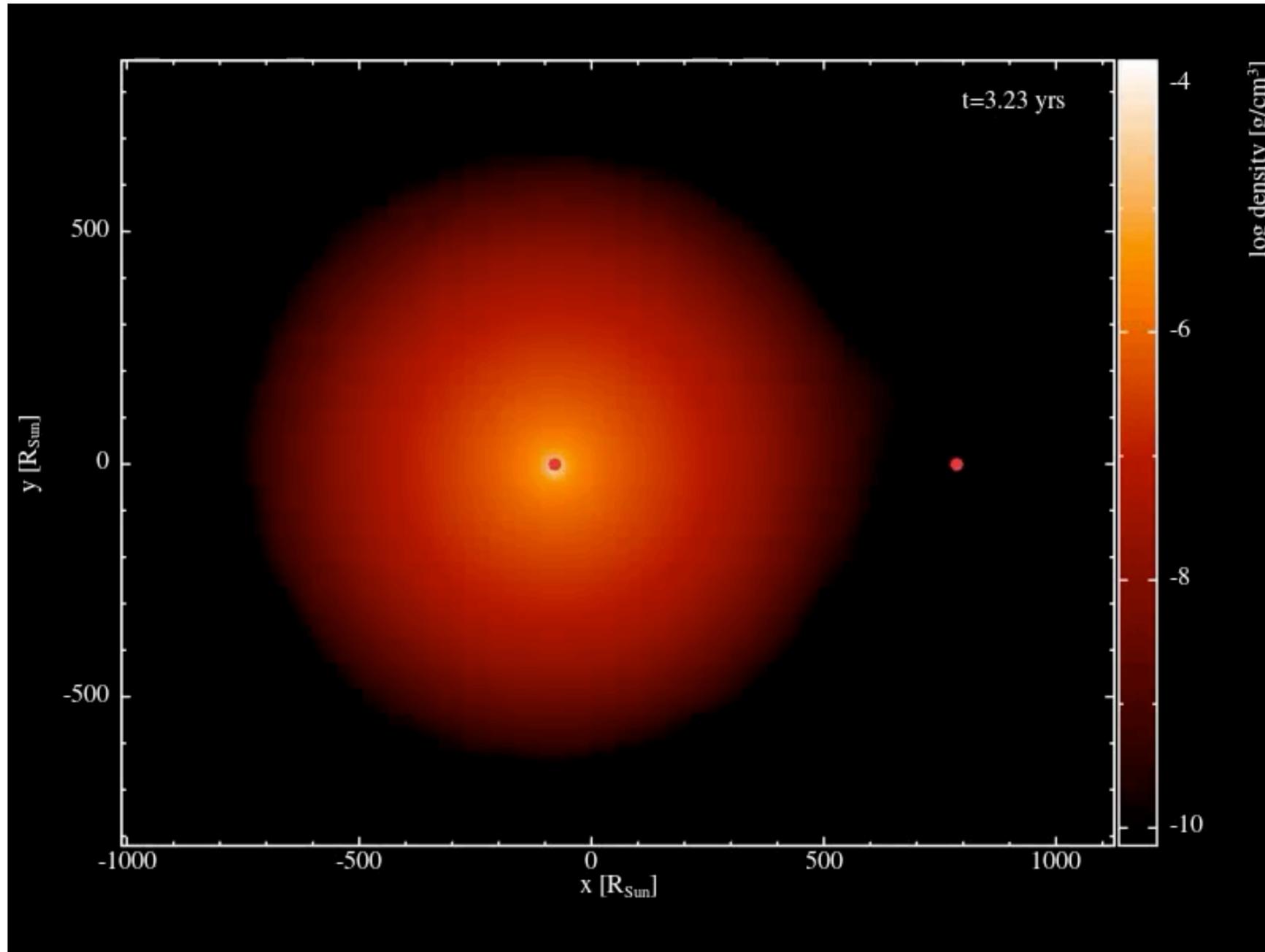


# So how do they merge?



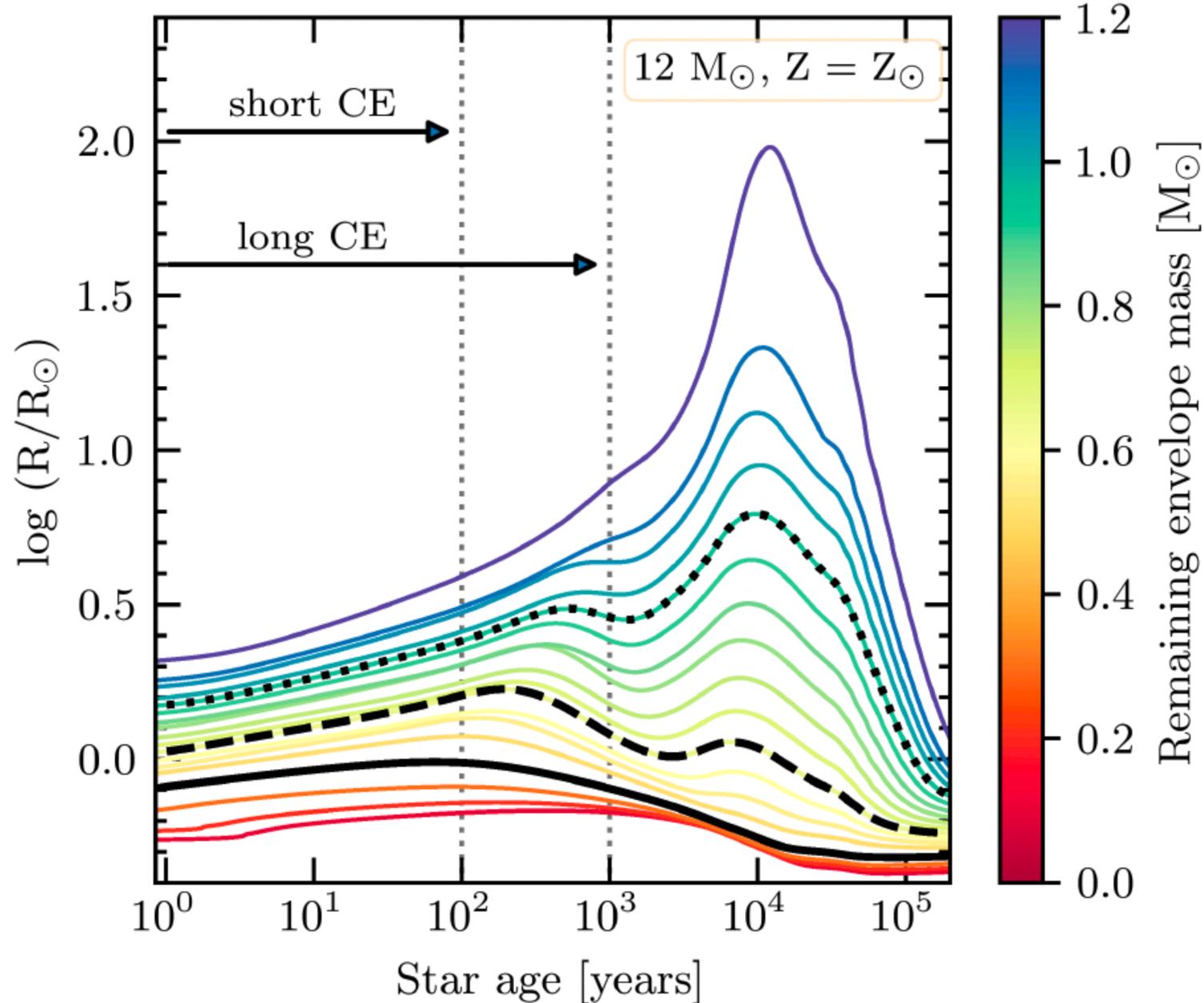


# Common-envelope evolution

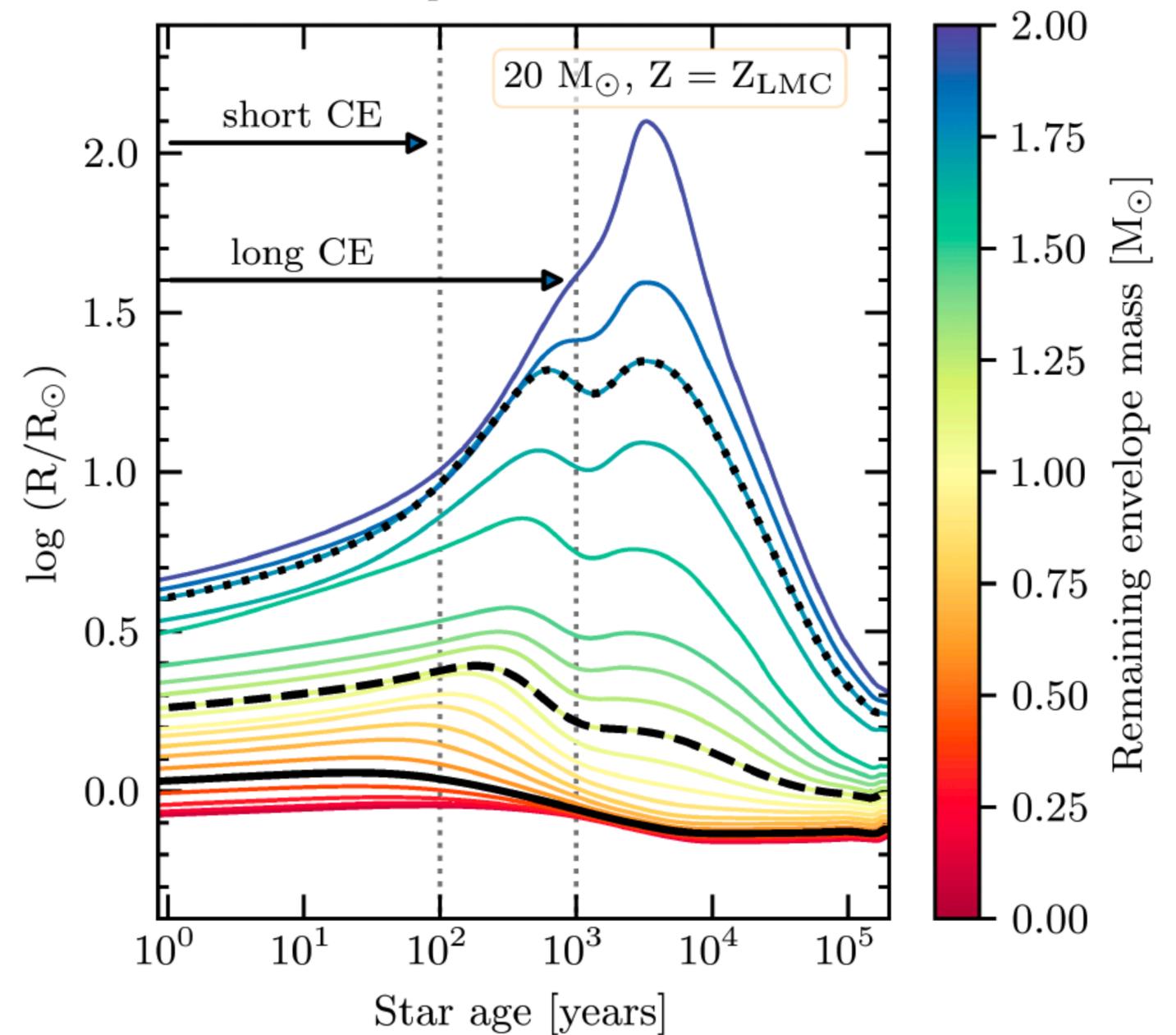


# How far does the CE strip a massive donor?

— maximum compression point    ··· upper bifurcation point  
 - - - lower bifurcation point



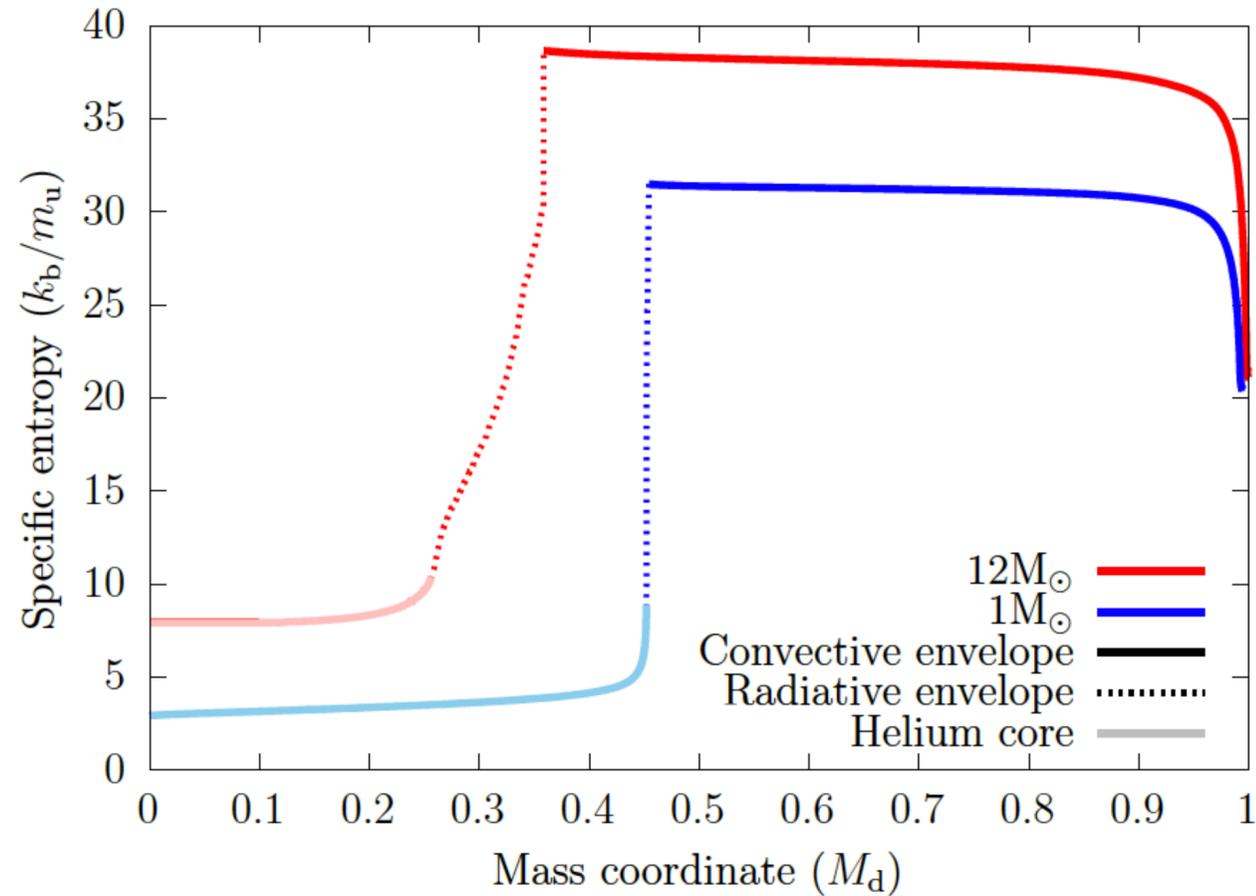
— maximum compression point    ··· upper bifurcation point  
 - - - lower bifurcation point



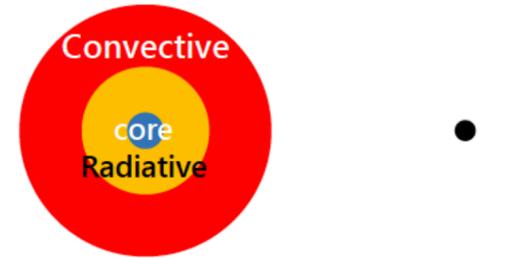
# Common envelope, analytics

$$E_{\text{env}} = \alpha_{\text{CE}} \left( -\frac{GM_{\text{d}}M_2}{2a_i} + \frac{GM_{\text{core}}M_2}{2a_f} \right)$$

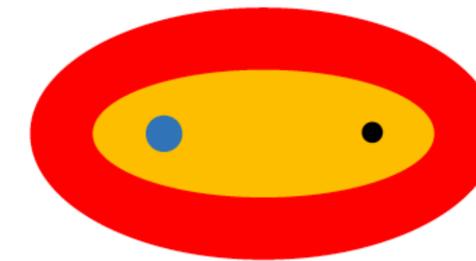
$$E_{\text{env}} = \frac{GM_{\text{d}}M_{\text{env}}}{\lambda R_{\text{d}}}$$



## Classical $\alpha$ -formalism



Massive donor + companion



Common-envelope phase

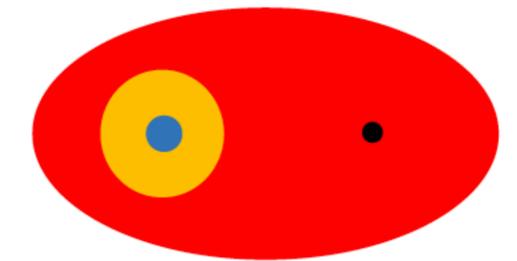


He star + companion

## Two-step formalism



Massive donor + companion



Stage I: Rapid in-spiral

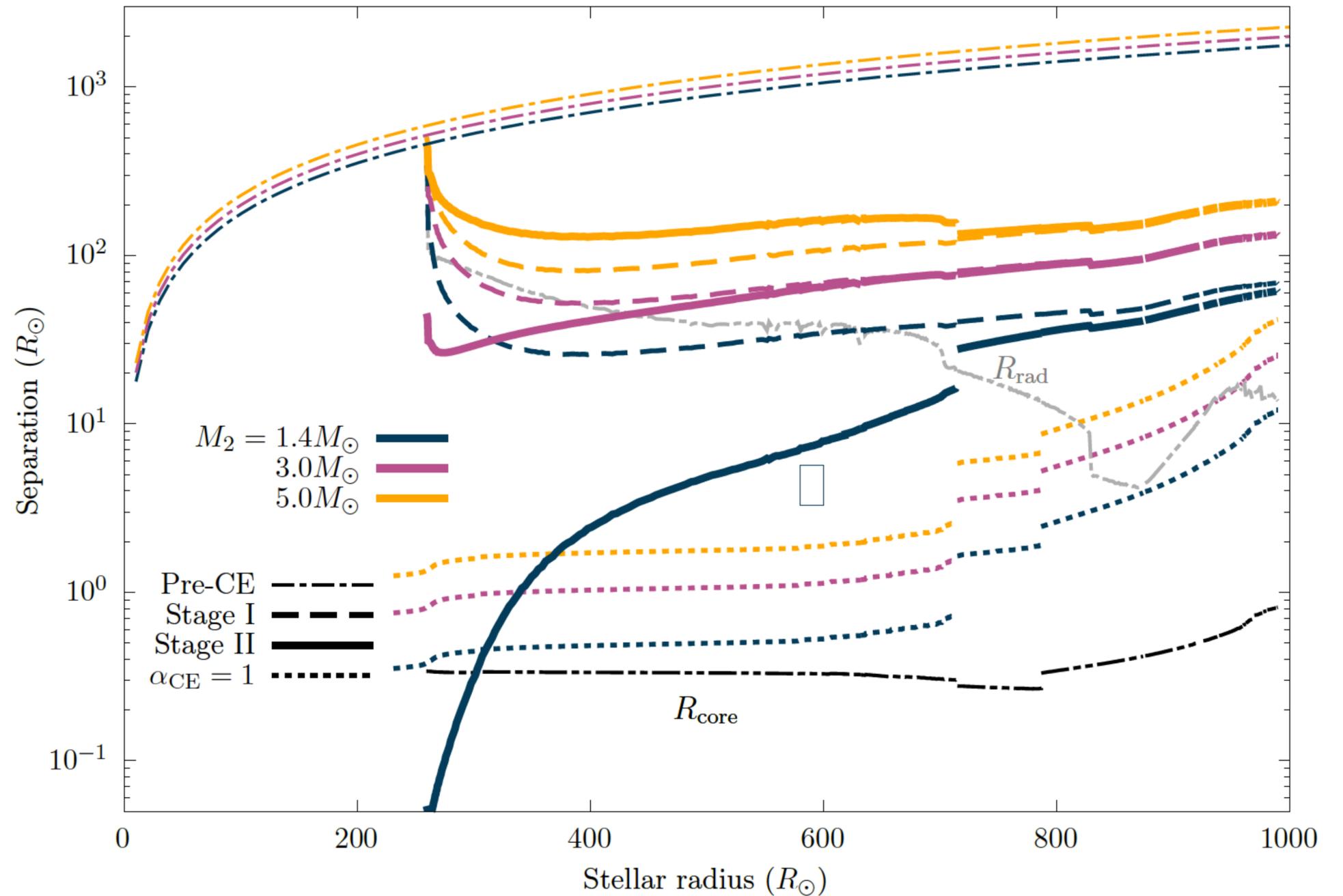
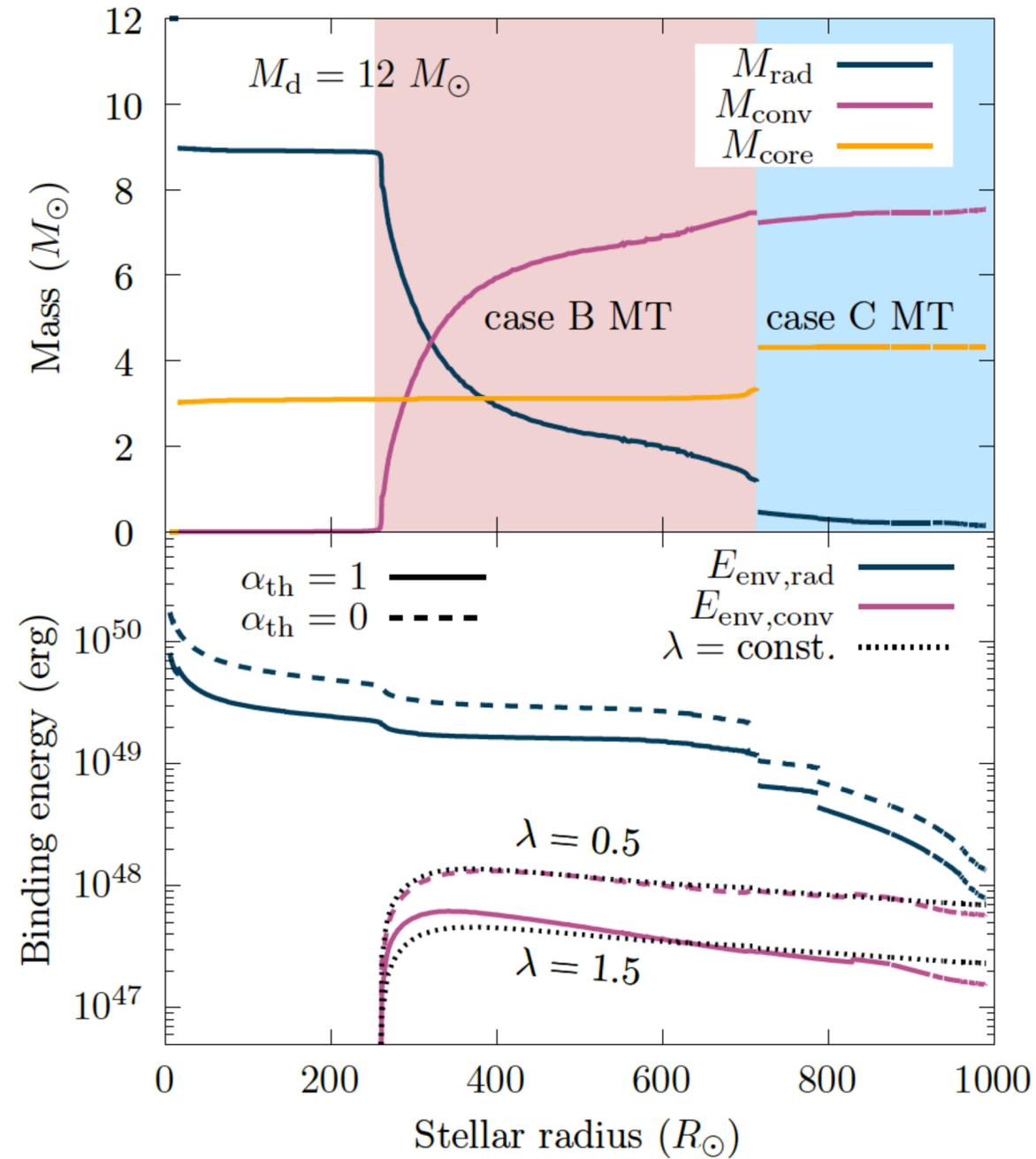


Stage II: Stable mass transfer

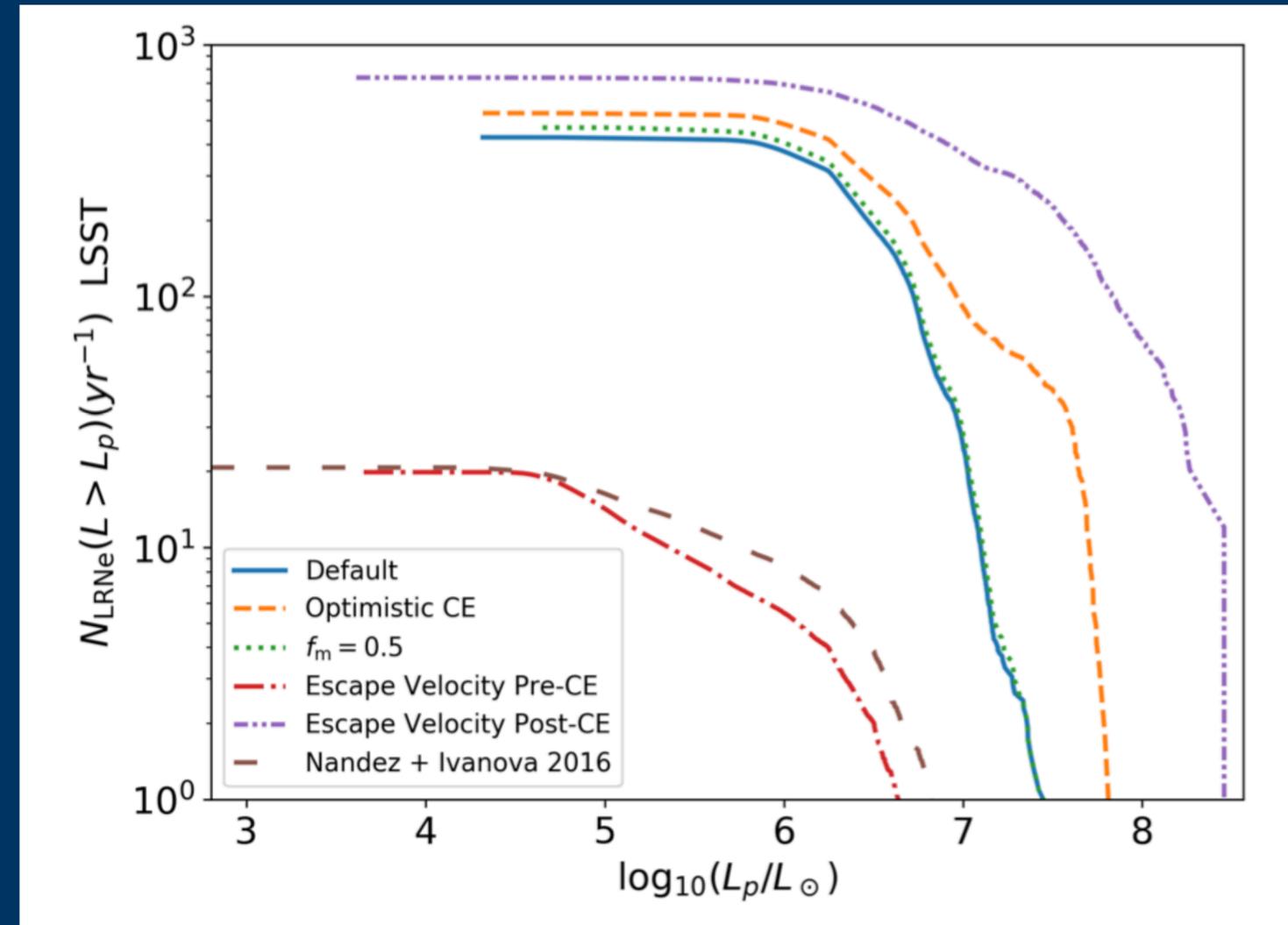
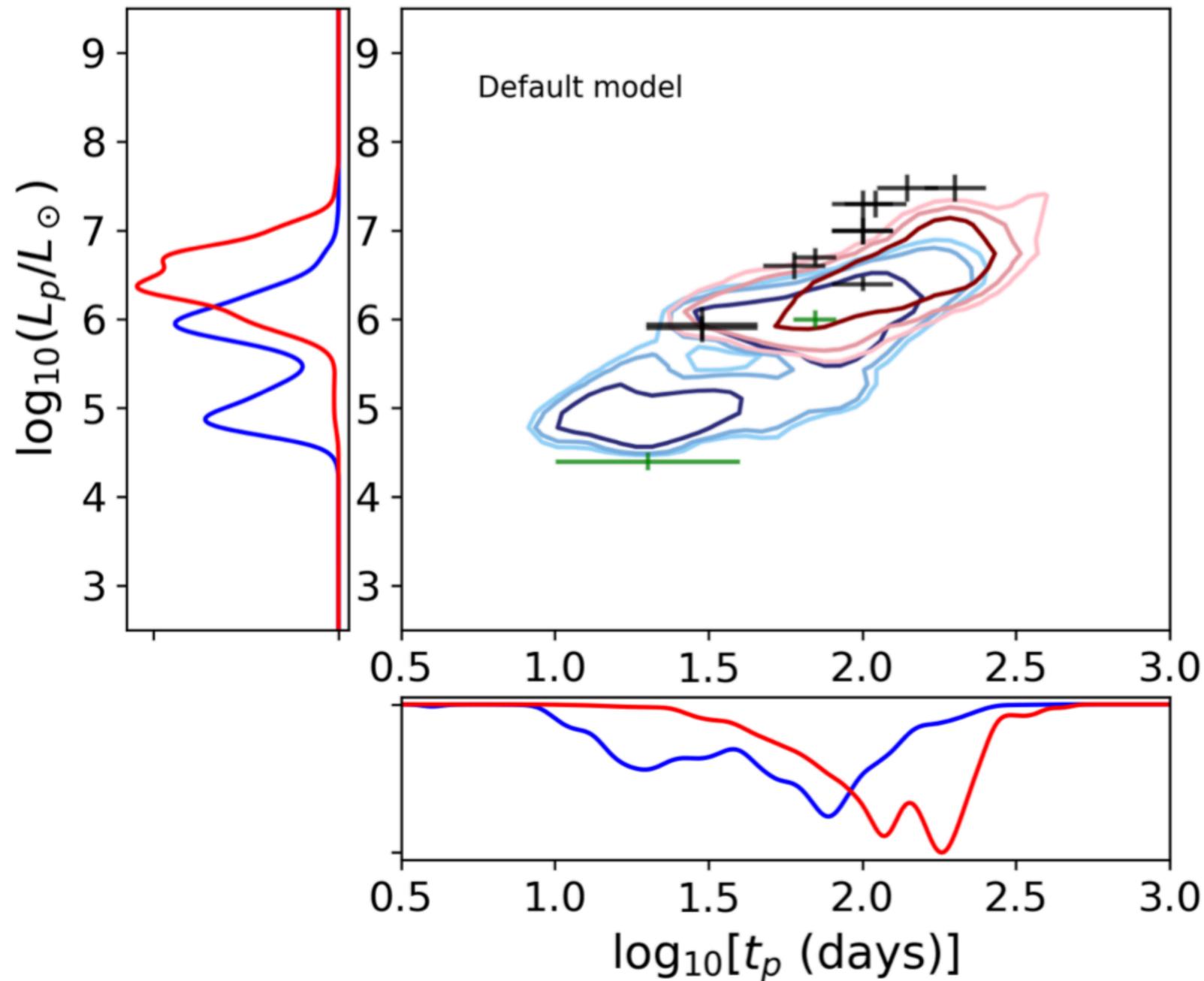
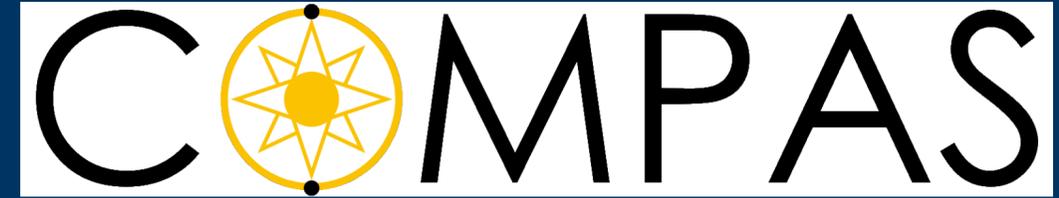


He star + companion

# Common envelope, analytics



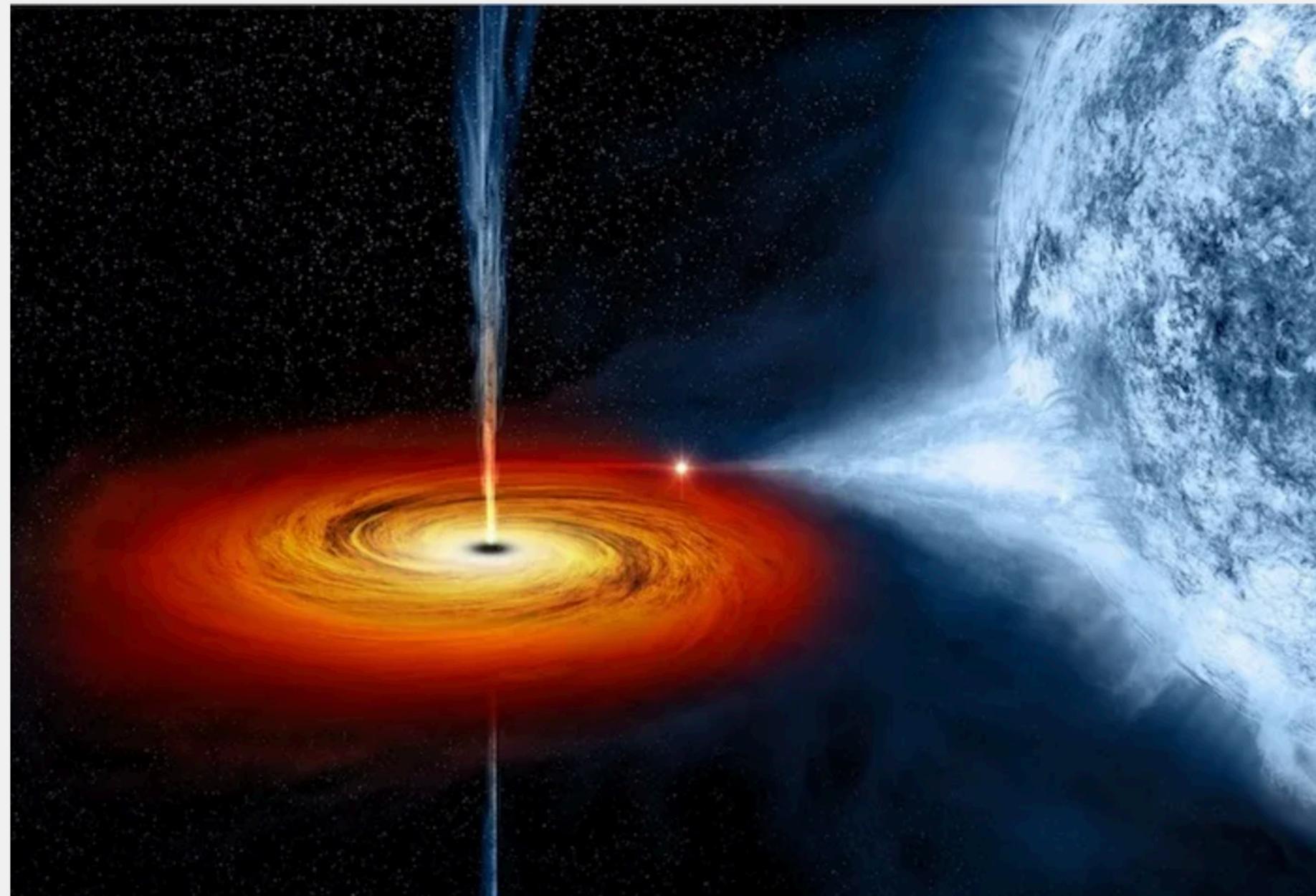
# LRN models & rates



Story elements	Puzzles	Partial solutions	Future tests?
<p><b>Common Envelopes</b></p>	<p>Why do GW sources merge?</p>	<p>Common envelope models: 3d, 1d, 0d...</p>	<p>Post-CE binaries, Vera Rubin Observatory LRNe, ...</p>
<p><b>Stable mass transfer</b></p>	<p>How do HMXBs form?</p>		<p><i>Early summer rain —</i></p>
			<p><i>houses facing the river,</i></p> <p><i>two of them.</i></p>
			<p>Yosa Buson</p>

# High-mass X-ray binaries

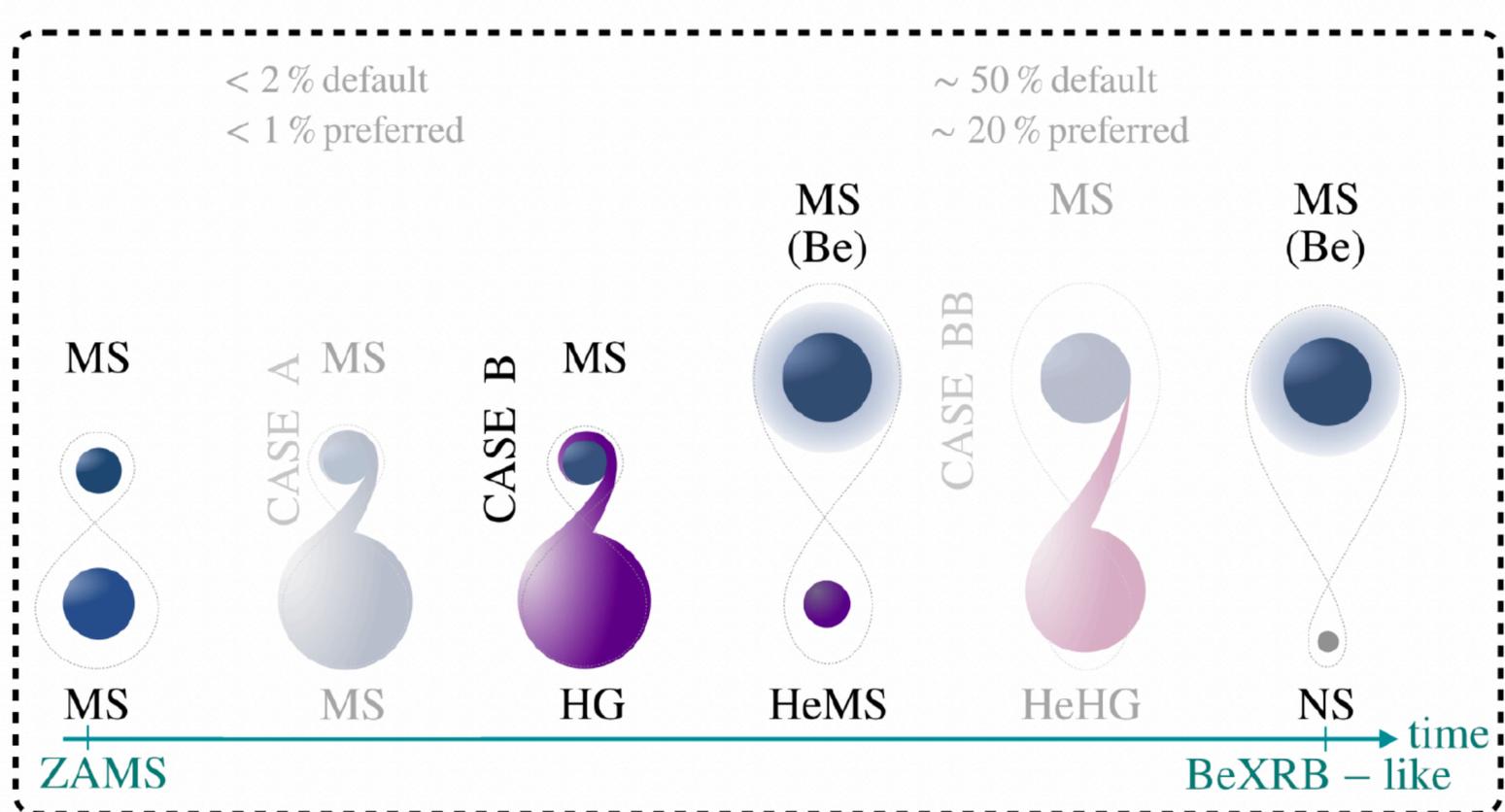
Not fed by Roche lobe overflow



An artist's impression of a High Mass X-ray Binary. Credit: NASA/CXC/M.Weiss.

# NS HMXBs

## Be XRBs

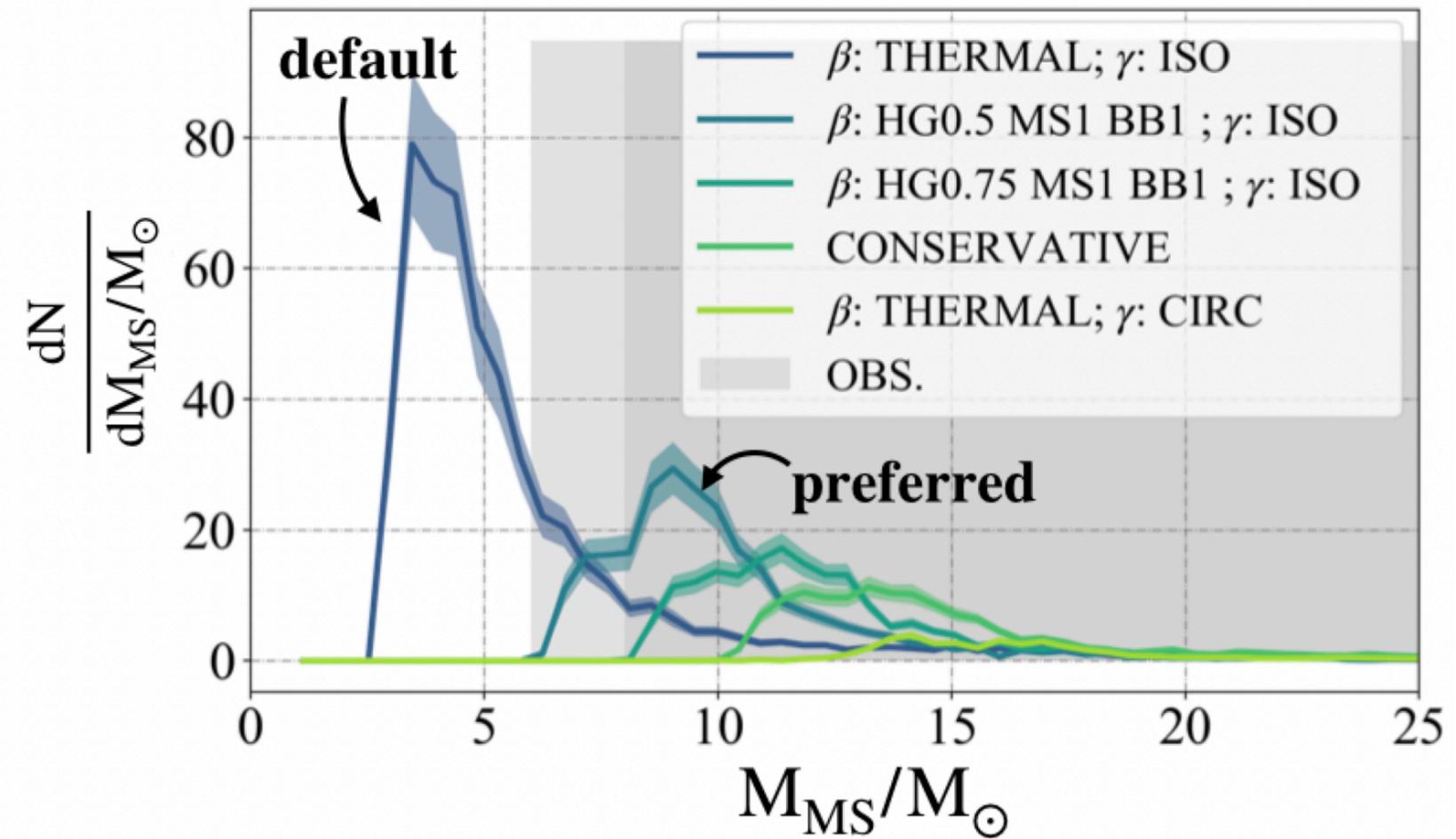
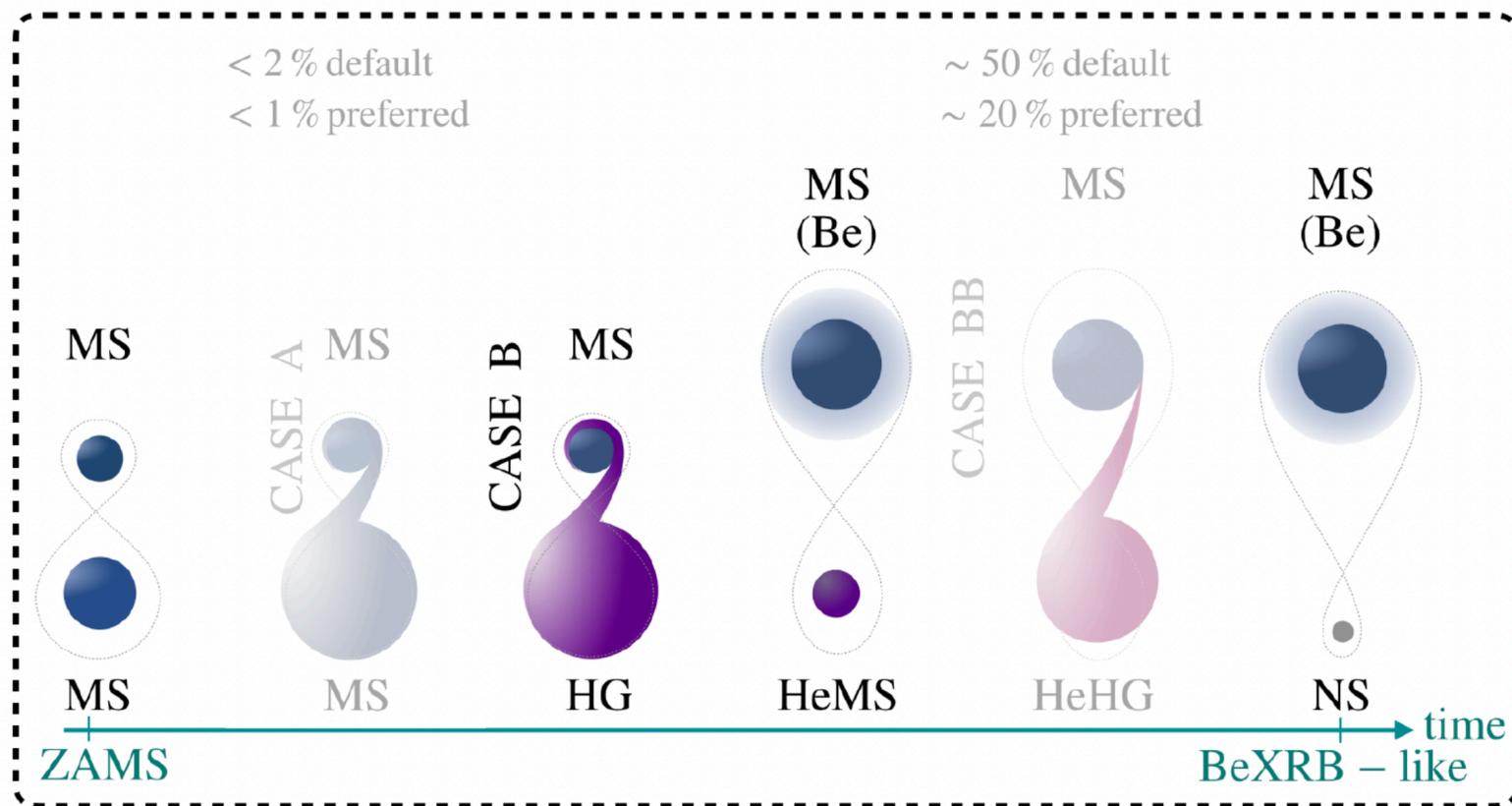


Vinciguerra+, 2020

(see also Knigge+ 2007; Shao & Li 2014, 2021; Rocha+ 2024; Liu+ 2024, ...)

# NS HMXBs

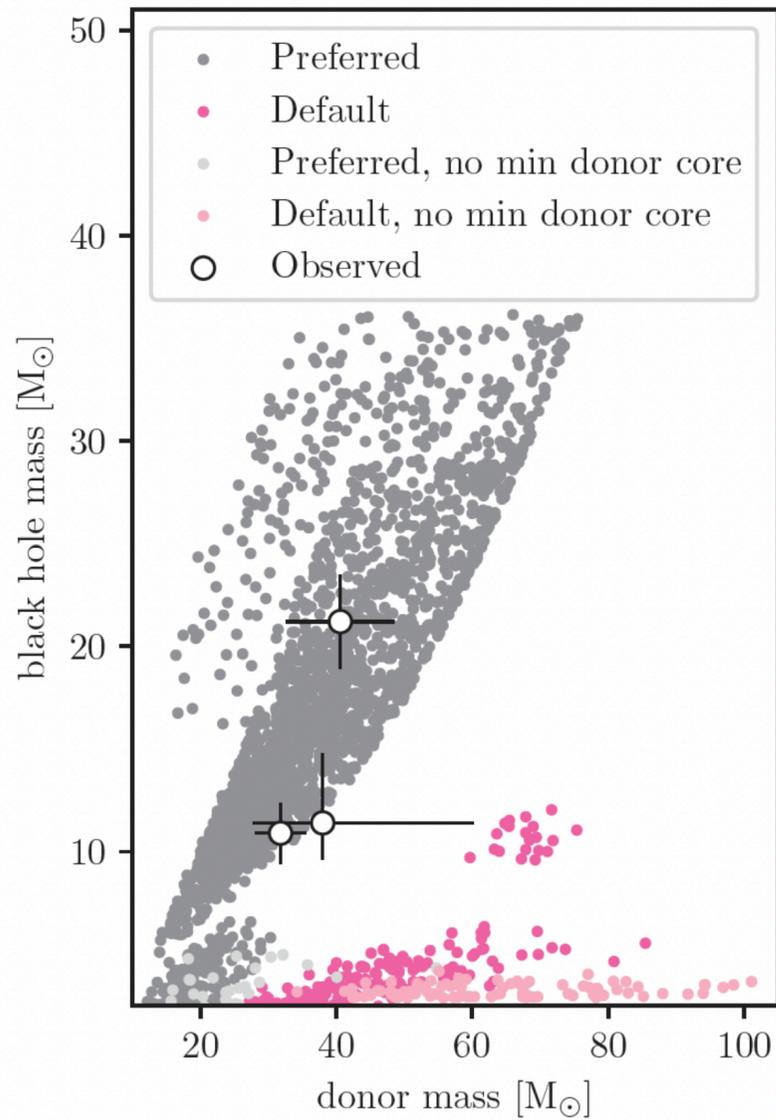
## Be XRBs



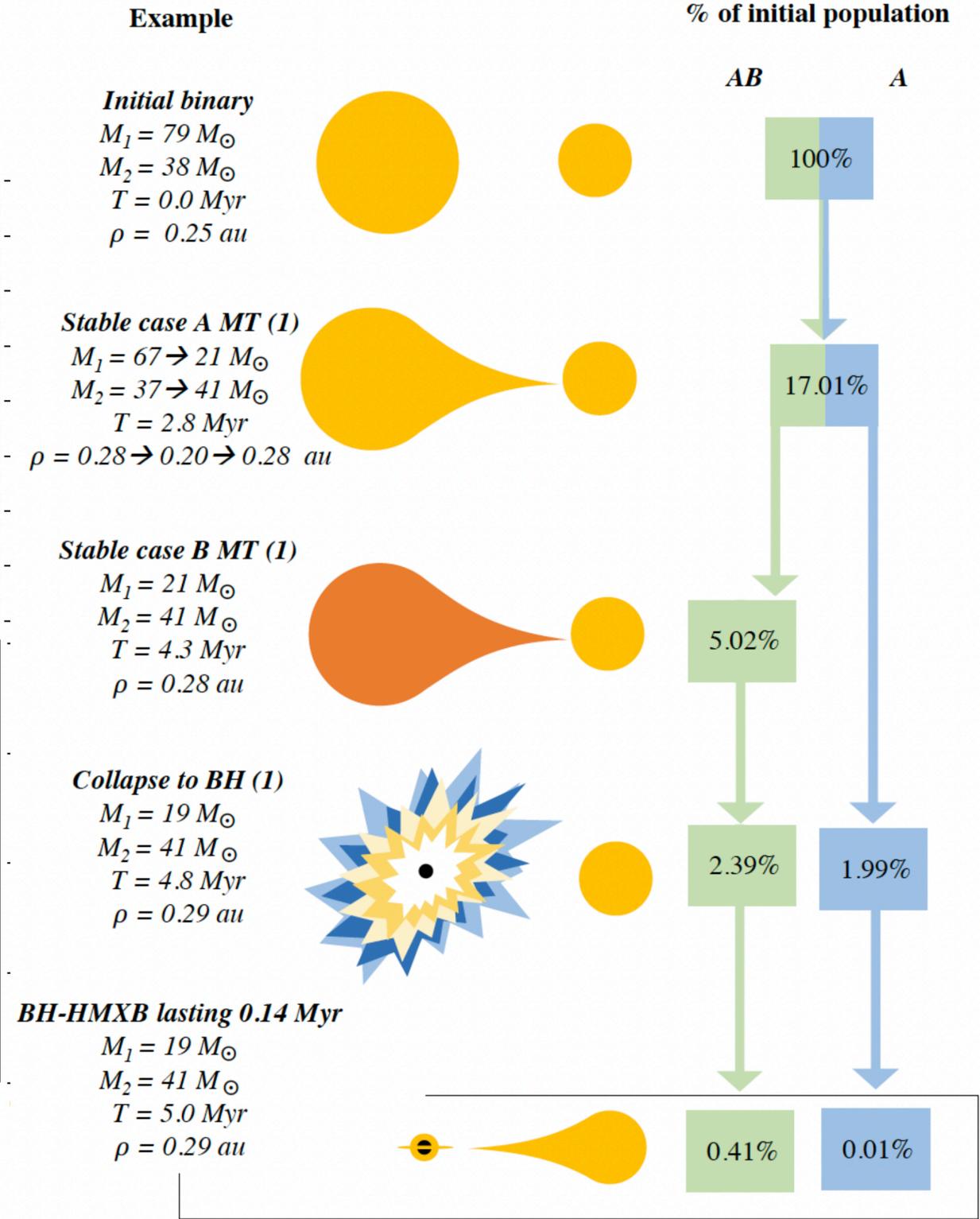
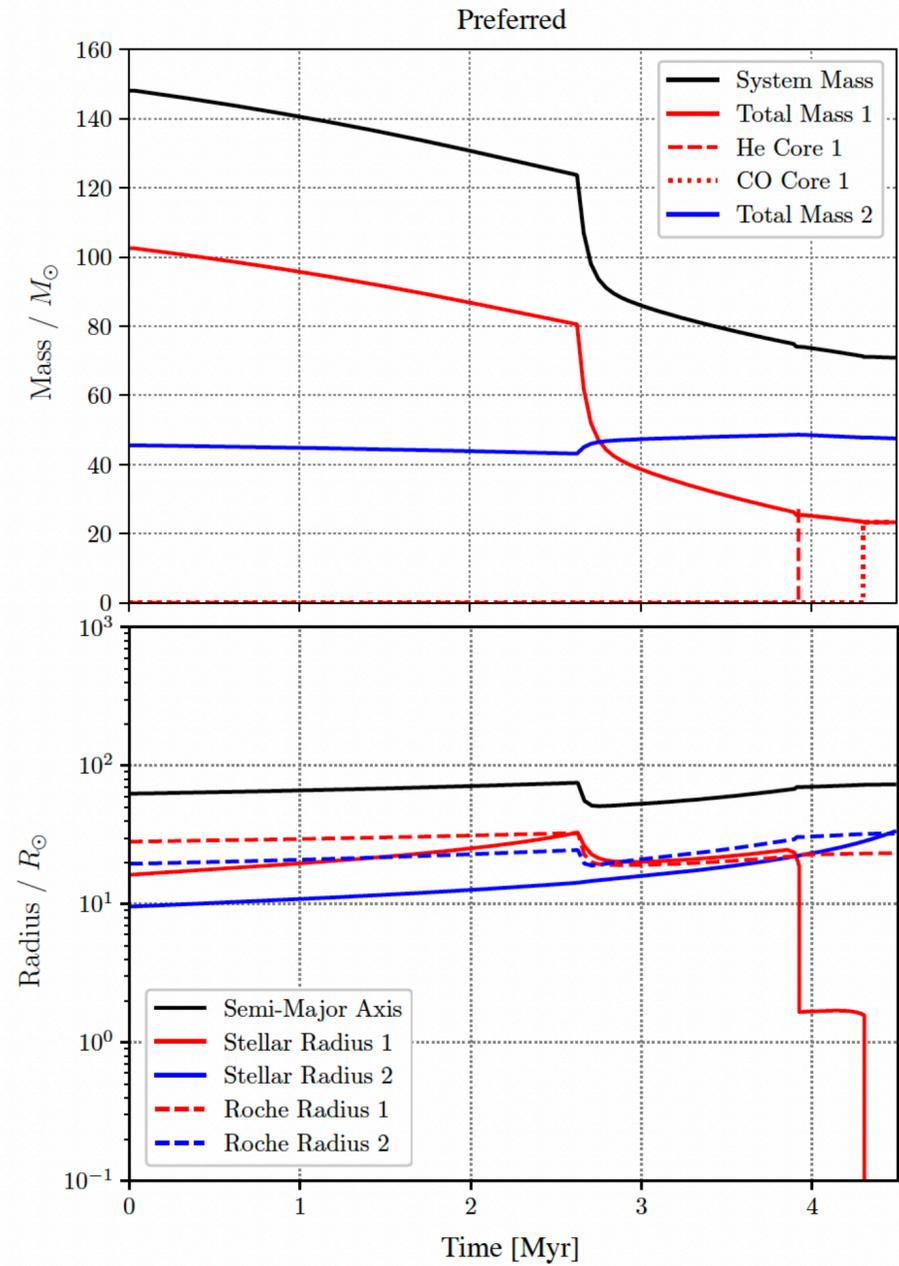
Vinciguerra+, 2020

(see also Knigge+ 2007; Shao & Li 2014; Rocha+ 2024; Liu+ 2024; Shao Yong's work, ...)

# BH HMXBs



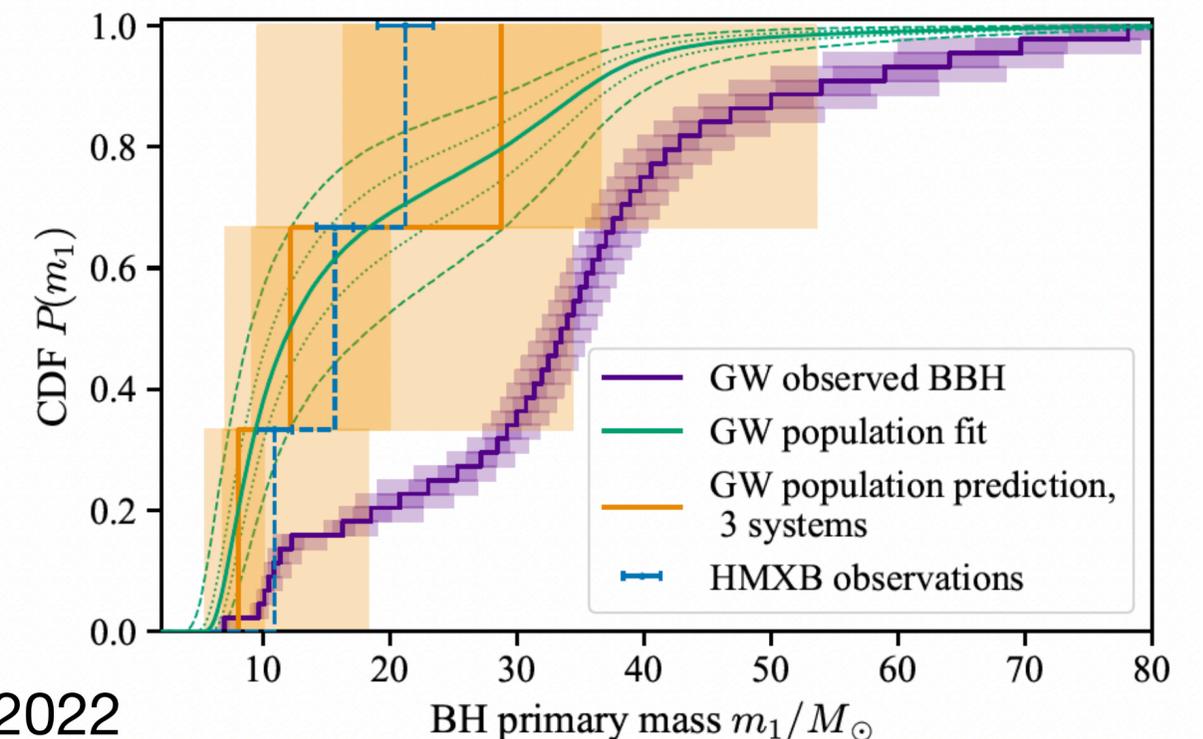
Romero-Shaw+, 2023



(see also Podsiadlowski+ 2002, 2003; Valsecchi+ 2009; Neijssel+ 2021; Sen+ 2022; Liotine+ 2022; Gallegos-Garcia+ 2022; Xing+ 2024 — see Zepei's talk!)

# Some BH HMXB takeaways

- Romero-Shaw+ (2023) need fairly non-conservative case A MT to reproduce the masses
- But we need fairly conservative case B MT to avoid too many case B HMXBs (with properties that don't match observations)
- No longer surprised that most observations are nearly RL filling — see below (and some could be post-MT-from-secondary systems, Xing+ 2024)
- Still surprised by very high observed spins
- Connection to LVK observations:
  - most BBHs not from BH HMXBs
- ULXs: are these HMXBs?

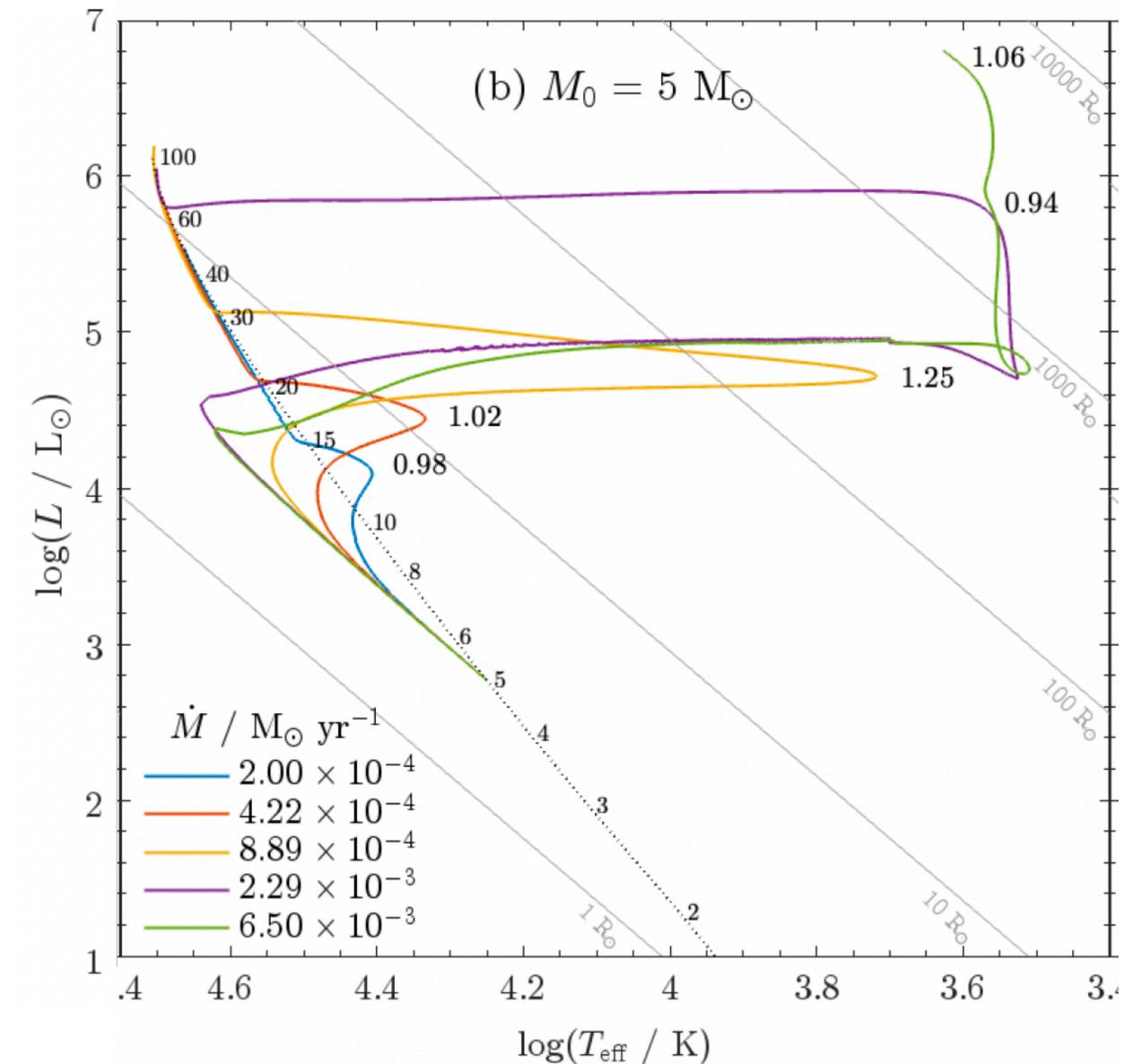


Fishbach & Kalogera, 2022



# XRBs as probes of Mass Transfer Physics

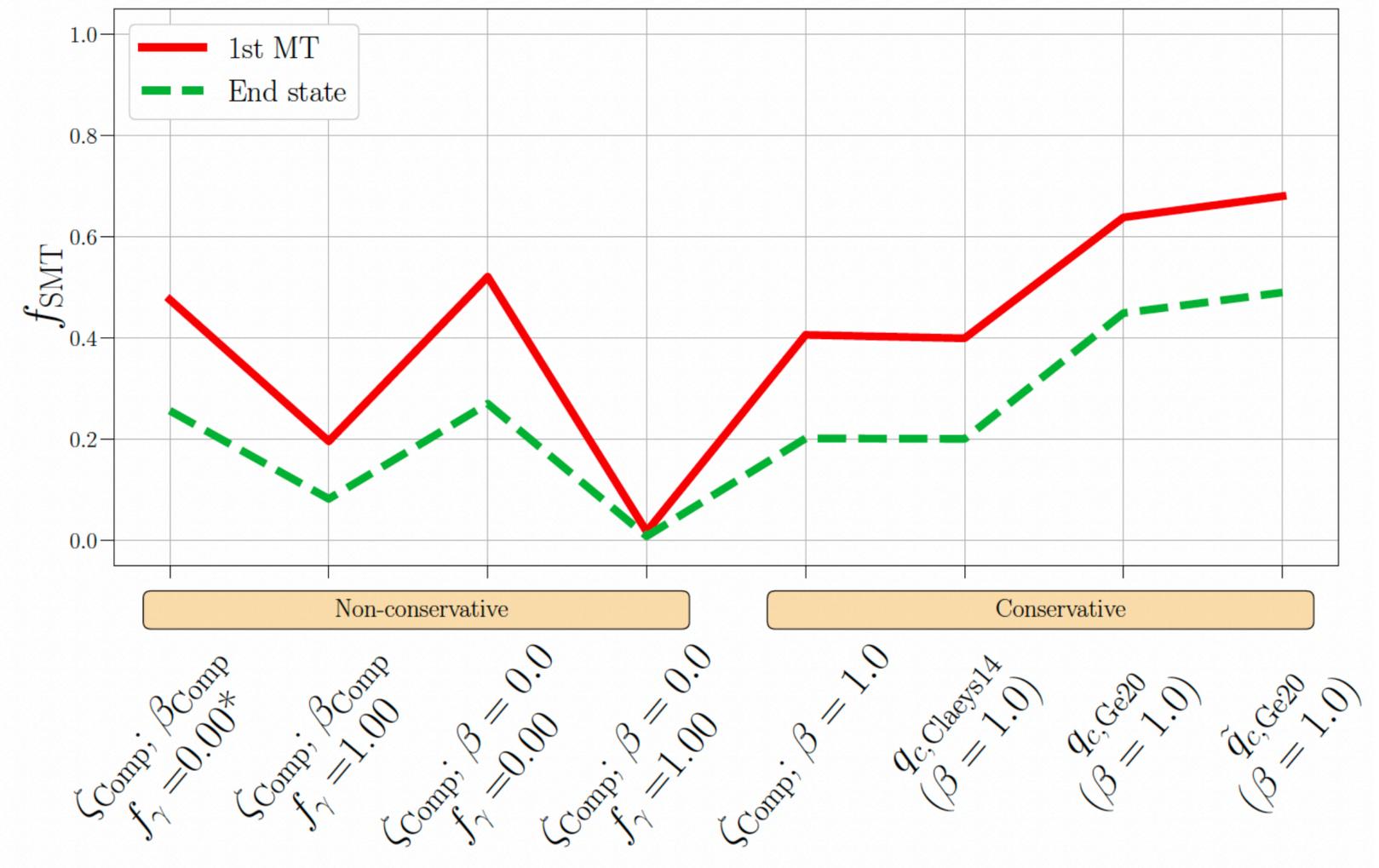
- Stability of Mass Transfer
- Conservativeness of mass transfer



Lau, Hirai, Mandel, Tout, 2024

# XRBs as probes of Mass Transfer Physics

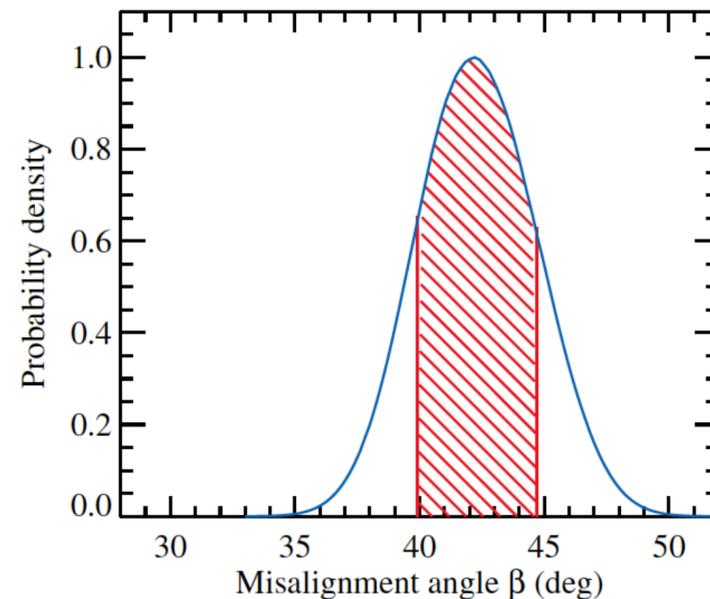
- Stability of Mass Transfer
- Conservativeness of mass transfer
- Angular momentum loss in non-conservative mass transfer



Willcox, MacLeod, Mandel, Hirai, 2023

# XRBs as probes of Mass Transfer Physics

- Stability of Mass Transfer
- Conservativeness of mass transfer
- Angular momentum loss in non-conservative mass transfer
- Rotation-limited accretion, stellar rotation and spin



Poutanen+, 2022

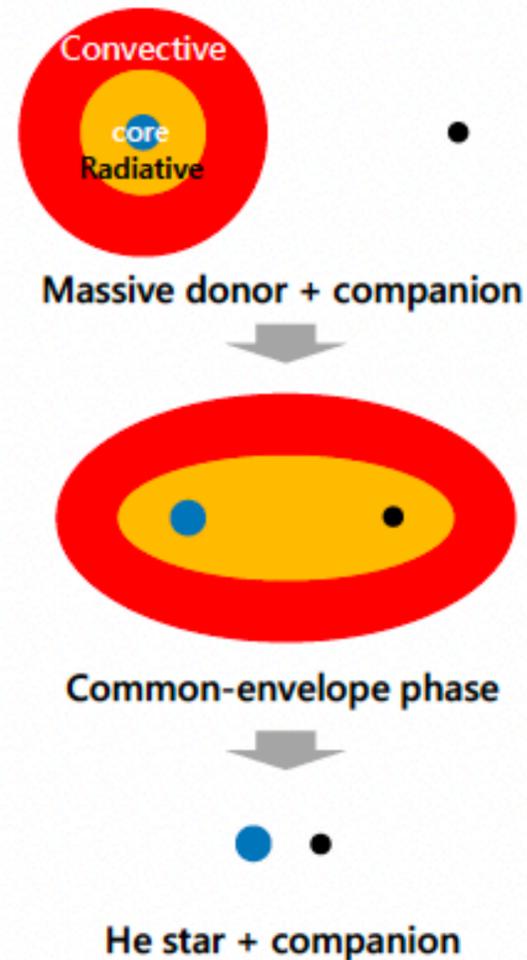
Object (by RA)	Disk Reflection	Disk Continuum	References
M33 X-7		$a = 0.84 \pm 0.05$	[302, 303]
LMC X-3		$0.21^{+0.18}_{-0.22}$	[222, 305]
LMC X-1	$0.97^{+0.02}_{-0.13}$	$0.92^{+0.05}_{-0.07}$	[343, 344]
A 0620-00		$0.12^{+0.19}_{-0.19}$	[345]
GS 1124-683		$-0.24^{+0.05}_{-0.64}$	[346]
4U 1543-475	$0.3 \pm 0.1$	$0.8 \pm 0.1$	[257], [347]
XTE J1550-654	$0.55 \pm 0.22$	$0.34^{+0.37}_{-0.45}$	[257, 348]
4U 1630-472	$0.985^{+0.005}_{-0.014}$		[349]
XTE J1650-500	$0.79 \pm 0.01$		[276, 257]
XTE J1652-453	$0.45 \pm 0.02$		[258]
GRO J1655-40	$0.98 \pm 0.01$	$0.7 \pm 0.1$	[257, 347]
GX 339-4	$0.94 \pm 0.02$		[257]
SAX J1711.6-3608	$0.6^{+0.2}_{-0.4}$		[257]
XTE J1752-223	$0.52 \pm 0.11$		[259]
Swift J1753.5-0127	$0.76^{+0.11}_{-0.15}$		[350]
MAXI J1836-194	$0.88 \pm 0.03$		[351]
XTE J1908+094	$0.75 \pm 0.09$		[350]
Swift J1910.2-0546	$\leq -0.32$		[352]
GRS 1915+105	$0.98 \pm 0.01$	$\geq 0.95$	[238, 275]
Cygnus X-1	$0.97^{+0.01}_{-0.02}$	$\geq 0.95$	[297, 296]

Miller & Miller, 2015

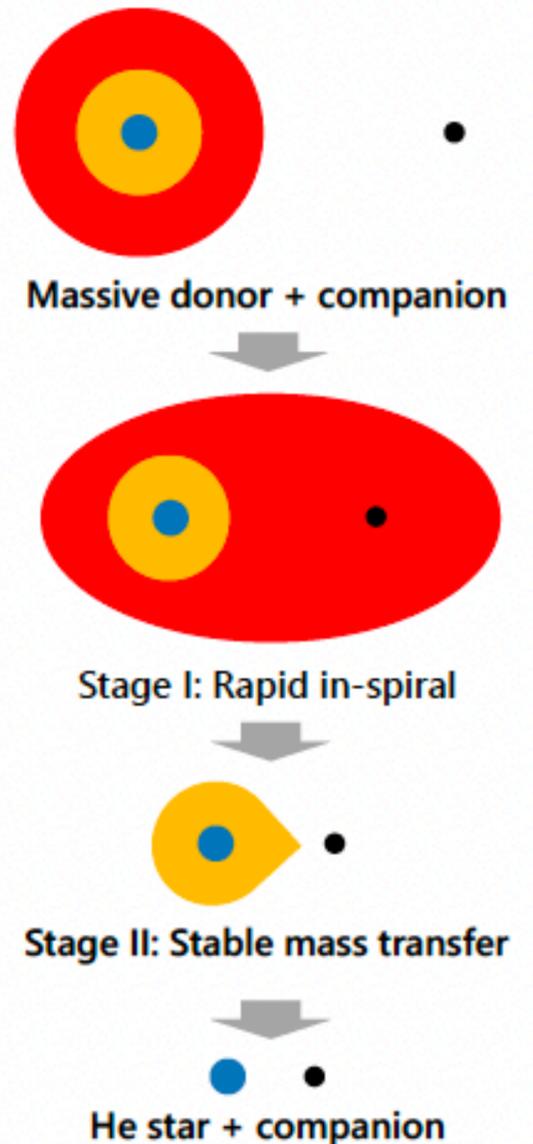
# XRBs as probes of Mass Transfer Physics

- Stability of Mass Transfer
- Conservativeness of mass transfer
- Angular momentum loss in non-conservative mass transfer
- Rotation-limited accretion, stellar rotation and spin
- Outcomes of common envelopes

Classical  $\alpha$ -formalism

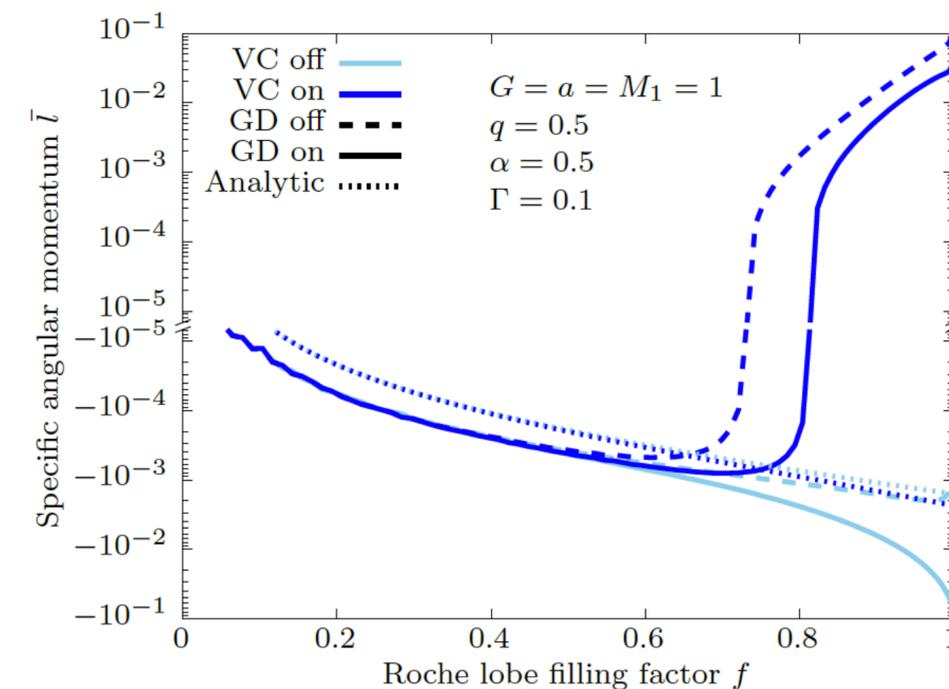
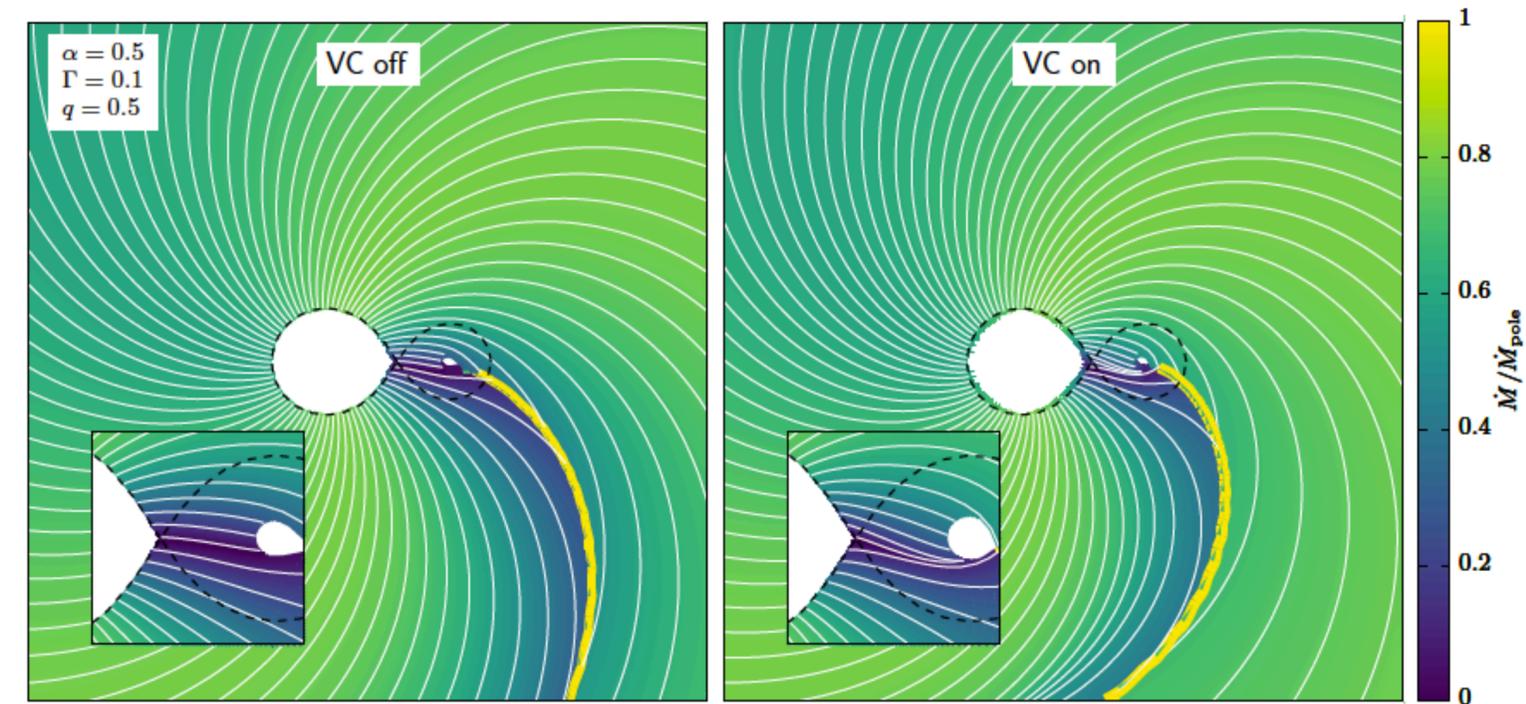


Two-step formalism



# XRBs as probes of Mass Transfer Physics

- Stability of Mass Transfer
- Conservativeness of mass transfer
- Angular momentum loss in non-conservative mass transfer
- Rotation-limited accretion, stellar rotation and spin
- Outcomes of common envelopes
- Wind RLOF



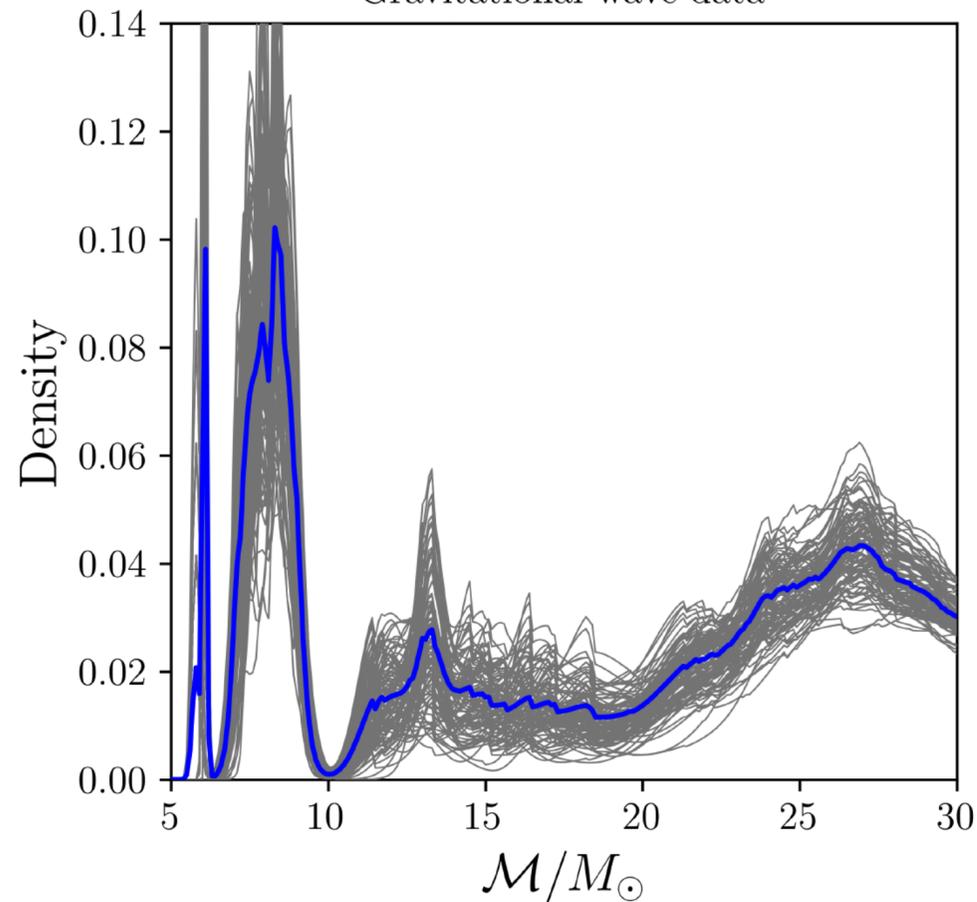
Hirai & Mandel, 2021

# Takeaways

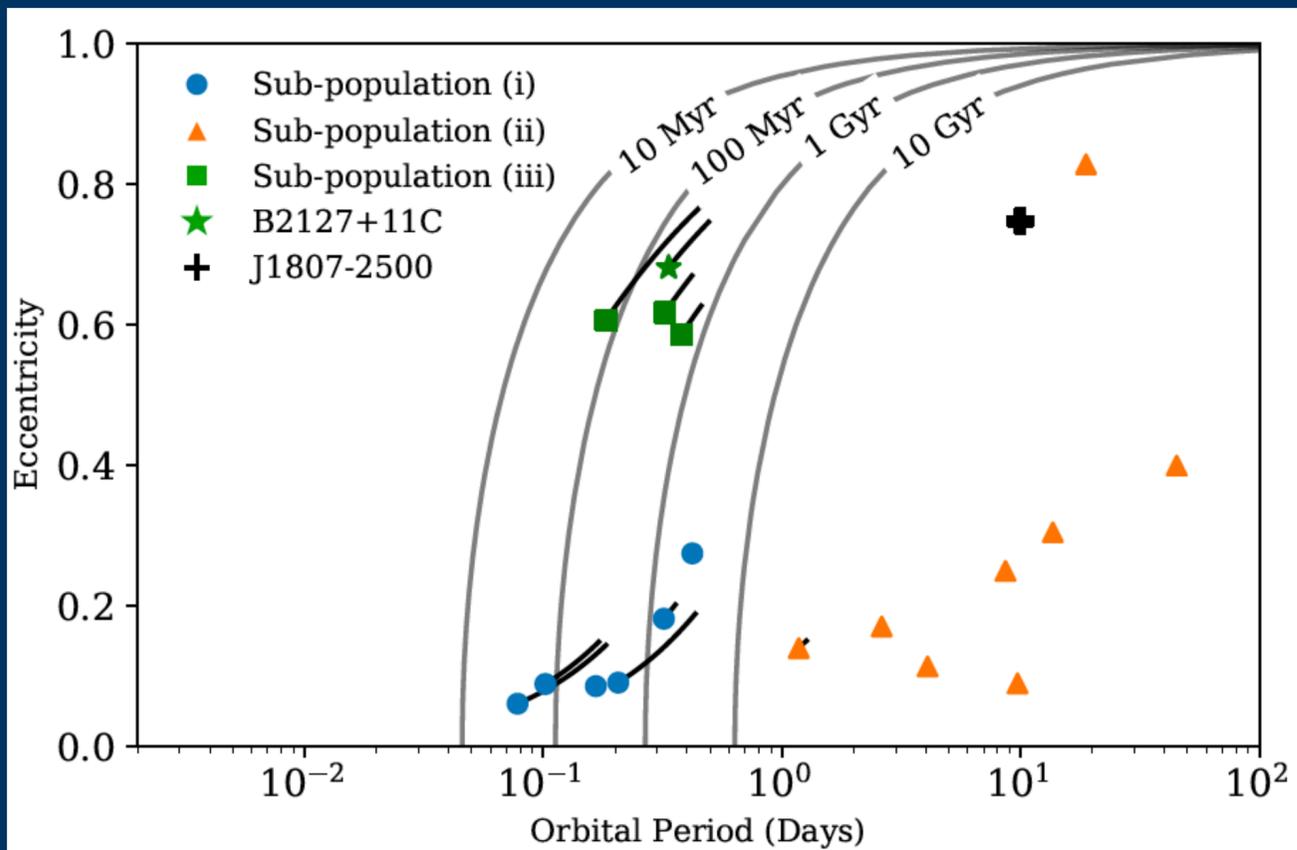
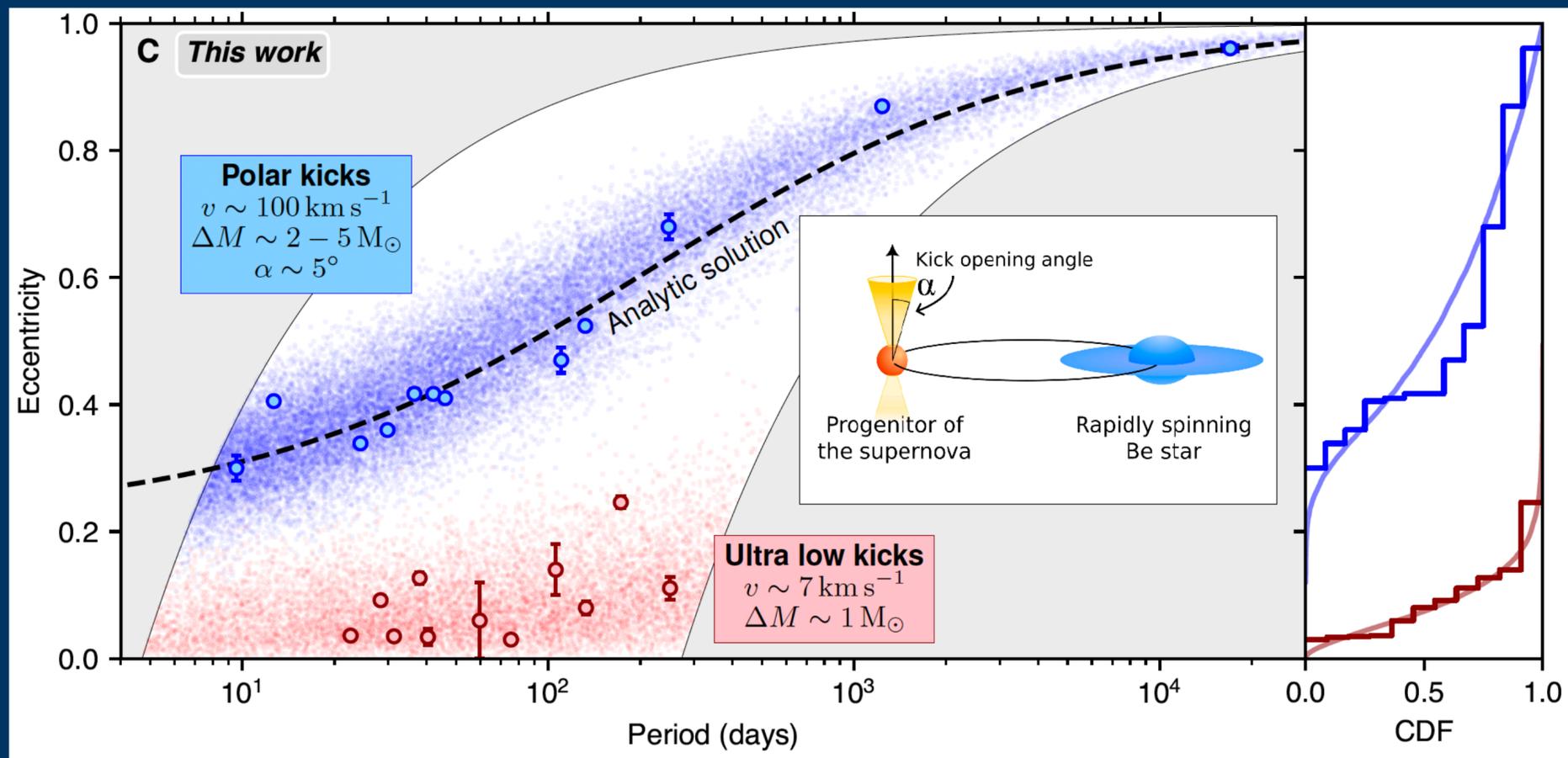
- Massive binaries, including HMXBs, are providing some of the best constraints on:
  - Supernova physics, including outcomes, remnant masses, natal kicks
  - Mass transfer physics, including stability, conservativeness, outcomes
  - Rotation, tides (e.g., orbital period evolution of classical NS HMXBs), chemically homogeneous evolution (?), spin-up

Story elements	Puzzles	Partial solutions	Future tests?
<b>Common Envelopes</b>	Why do GW sources merge?	Common envelope models: 3d, 1d, 0d...	Post-CE binaries, Vera Rubin Observatory LRNe, ...
<b>Stable mass transfer</b>	How do HMXBs form?	Stability and conservativeness of mass transfer?	WR binaries, post-MT systems, Be XRB dynamical masses, ...
<b>SN remnant masses and kicks</b>	GW masses, NS binary eccentricities, rotation rates?		<i>Things fall apart, the centre cannot hold;</i>
			<i>Mere anarchy is loosed upon the world</i> W.B. Yeats, The Second Coming

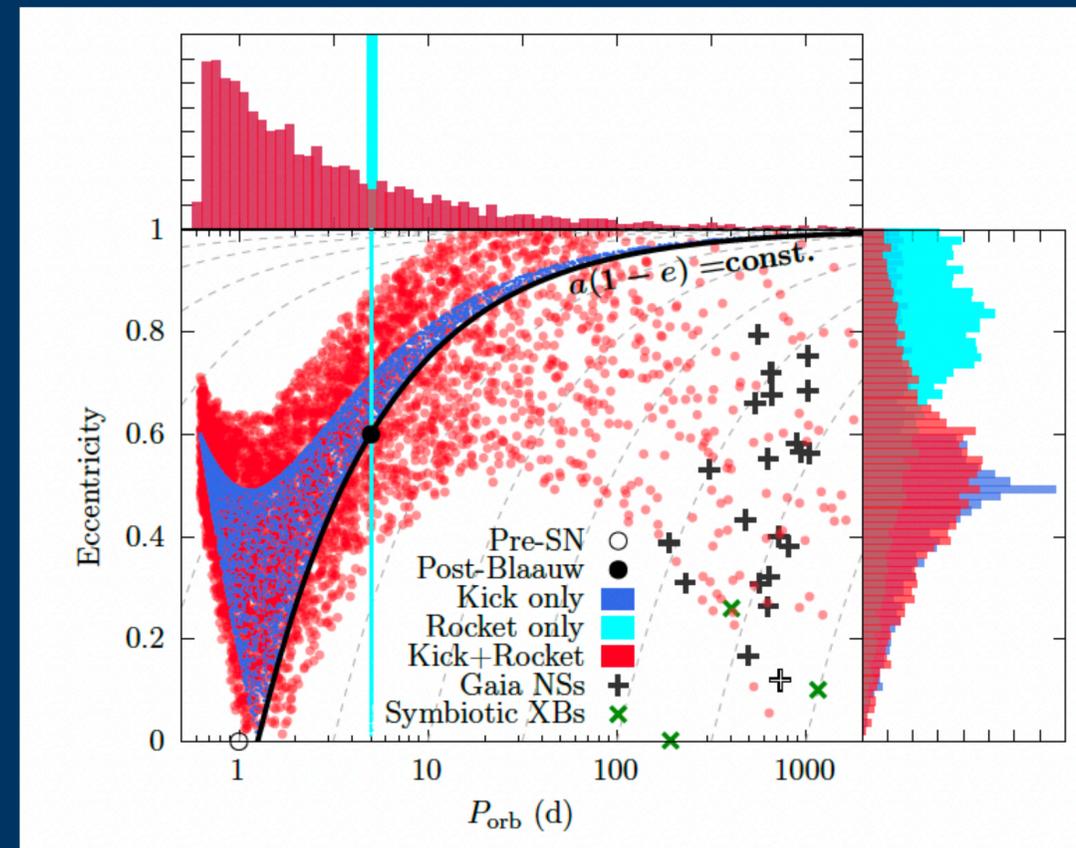
Gravitational-wave data



Willcox+,  
2025



Andrews  
&  
Mandel,  
2019

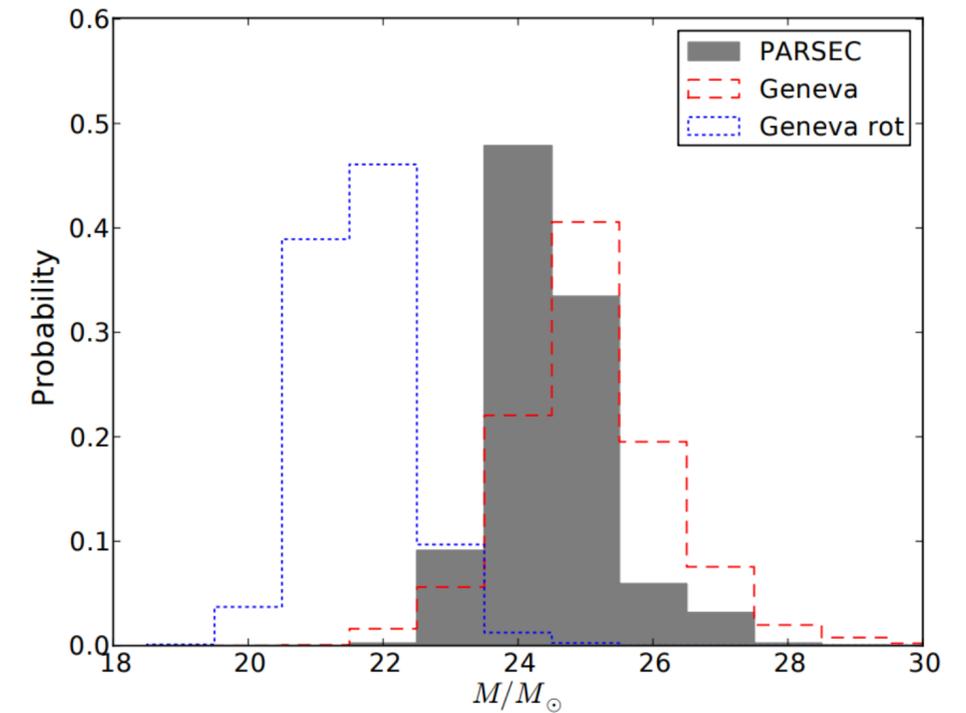


Valli+, 2025

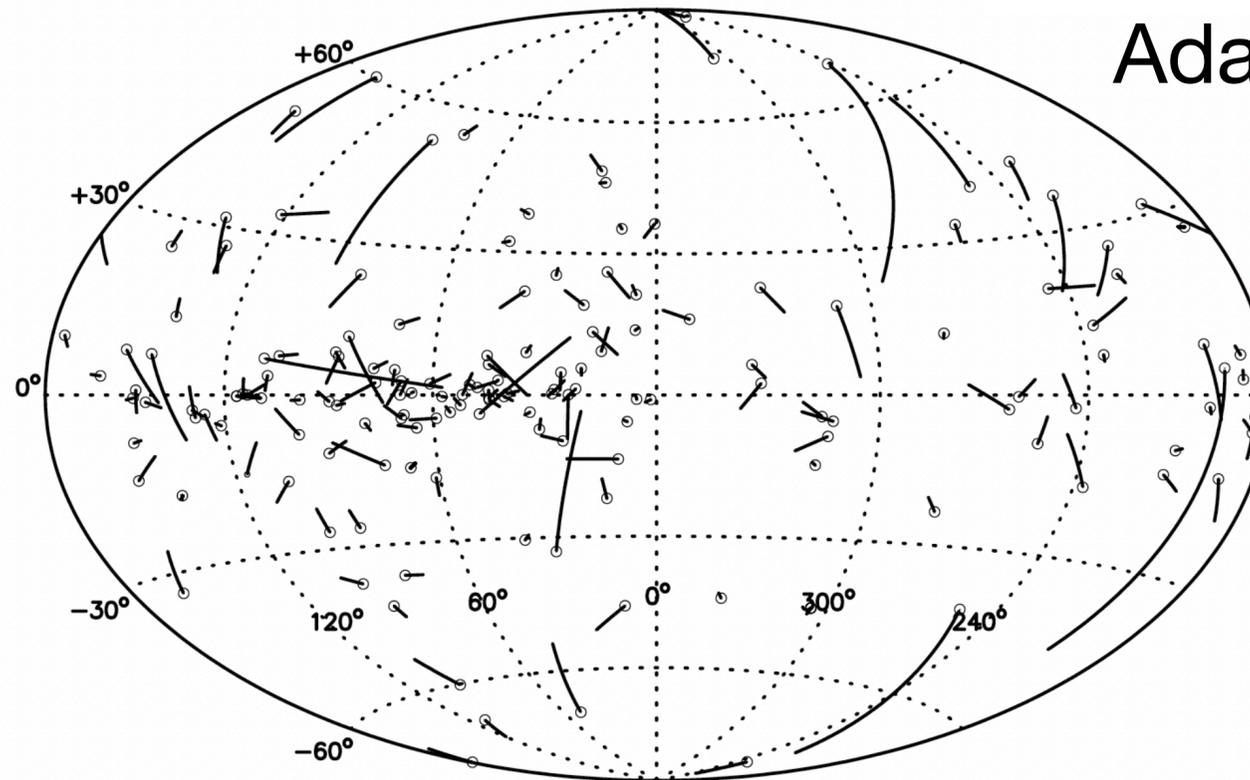
Hirai+, 2024

# What do massive stars leave behind?

- $< 8 M_{\text{sun}}$  @ ZAMS  $\rightarrow$  White Dwarf
- $8\text{-}20 M_{\text{sun}}$  @ ZAMS  $\rightarrow$  Neutron Star
- $20+ M_{\text{sun}}$  @ ZAMS  $\rightarrow$  Black Hole
- Natal kicks?
- Initial rotation?

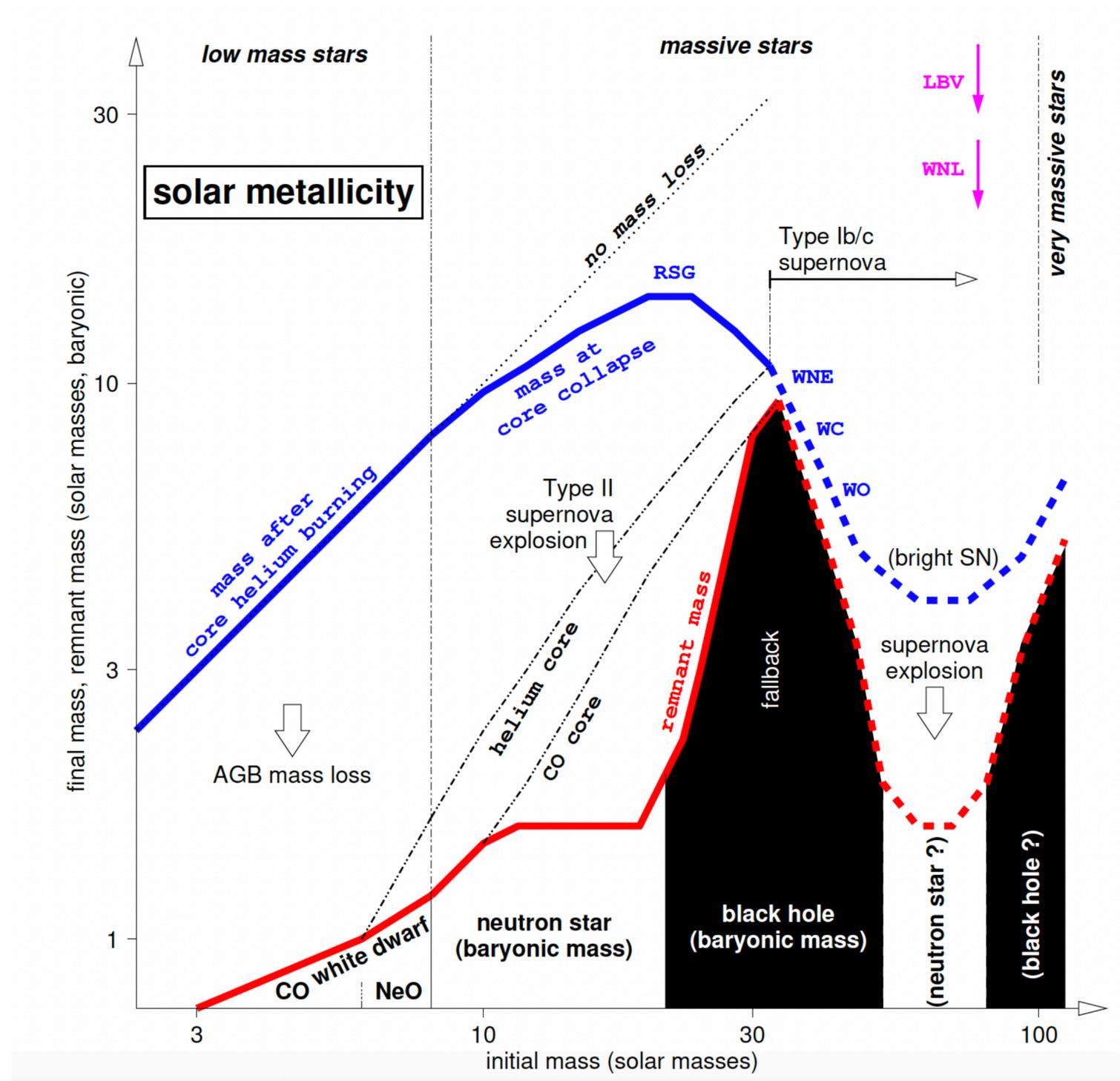


Adams, Kochanek+, 2017



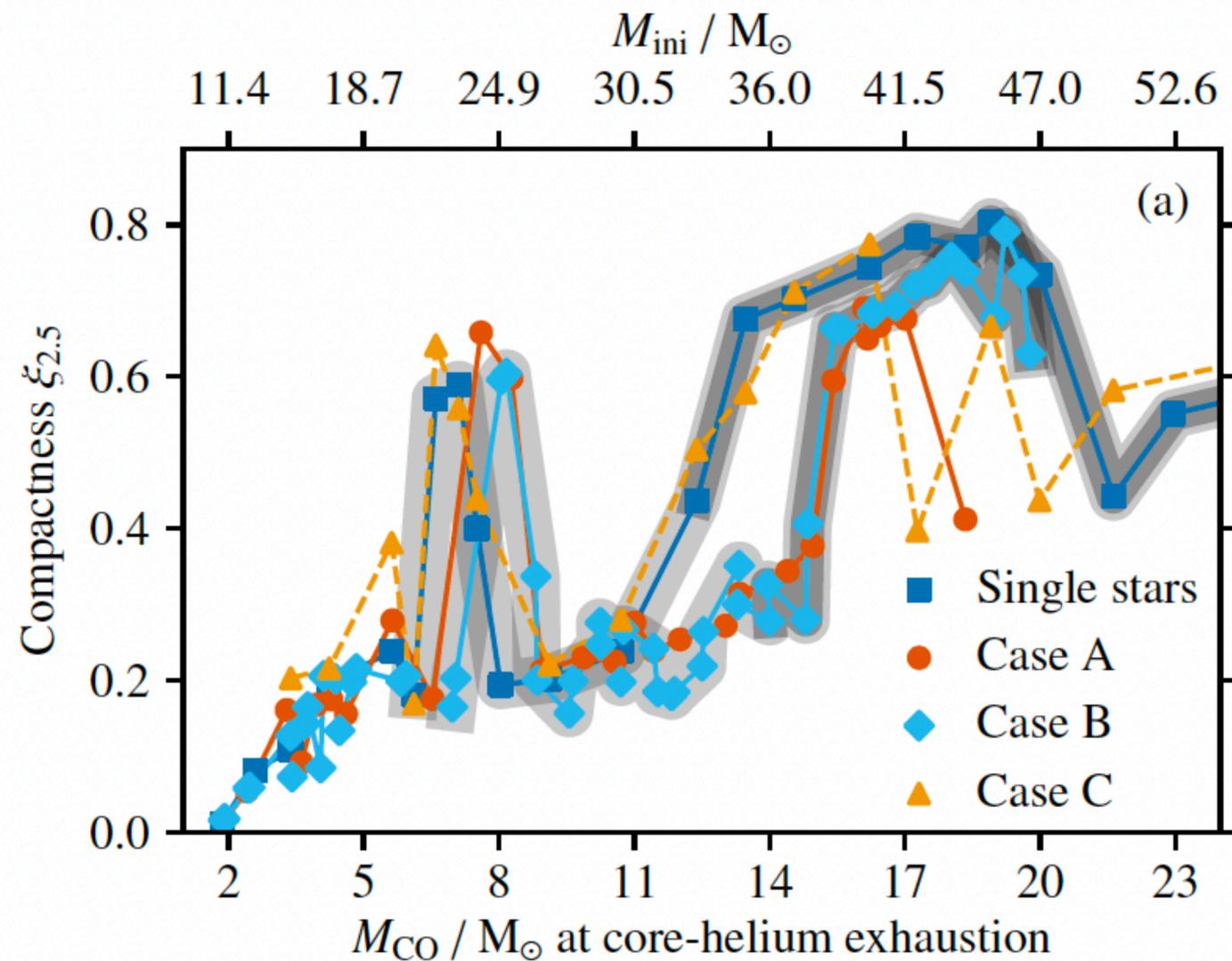
Hobbs+, 2005

# Could it be a tad more complicated?



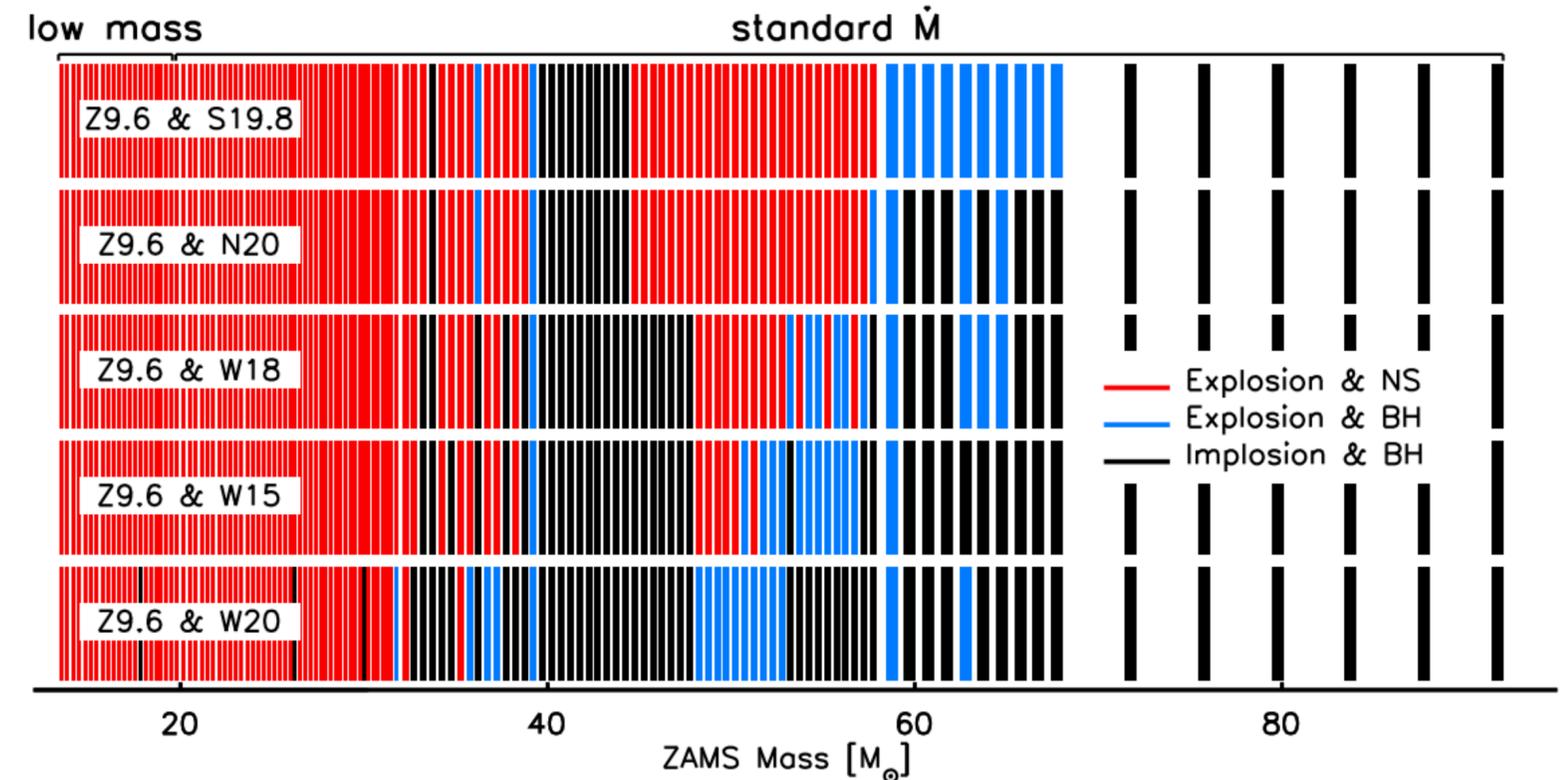
Heger, Müller,  
Mandel, 2023

# Why are things so messy?



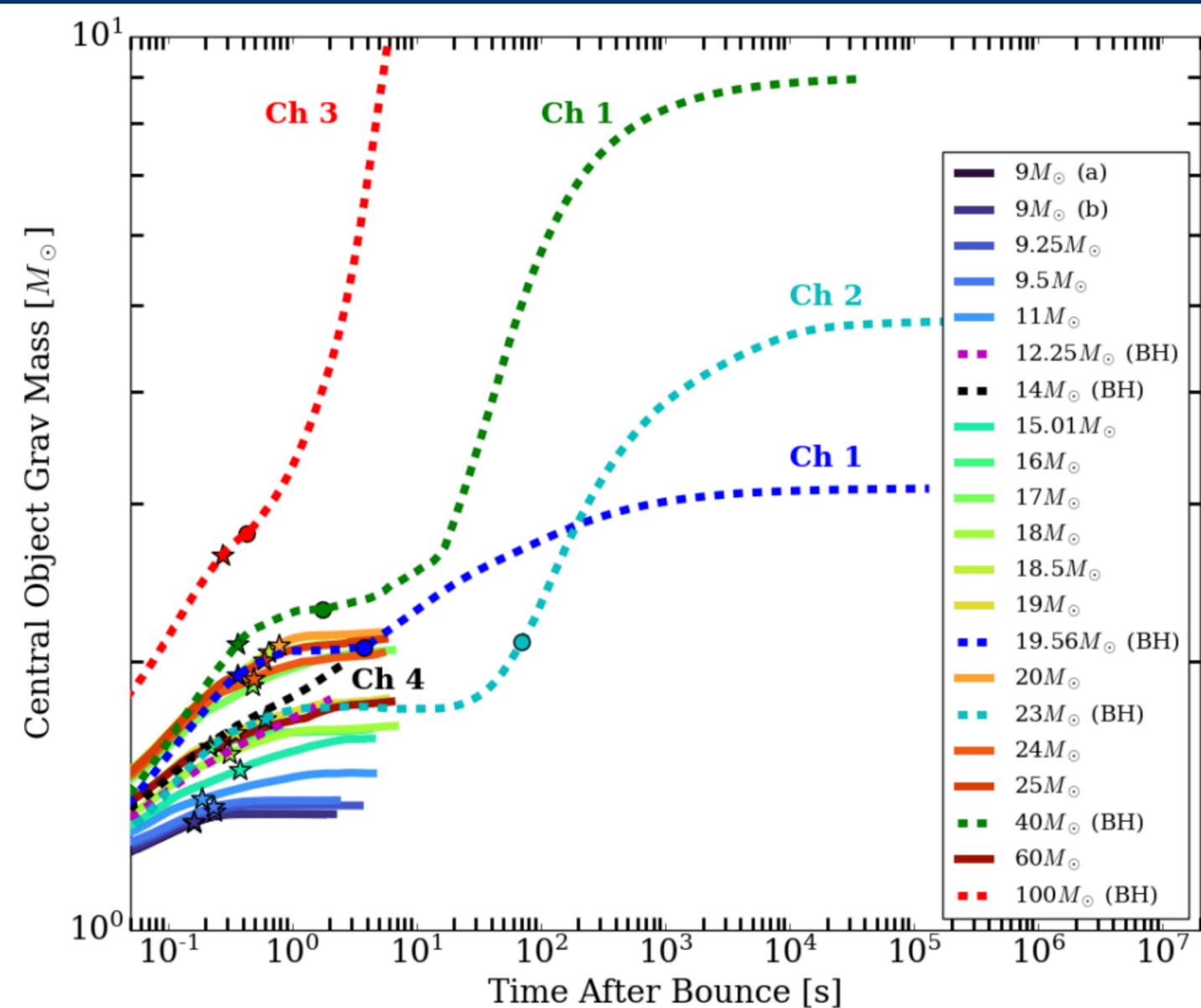
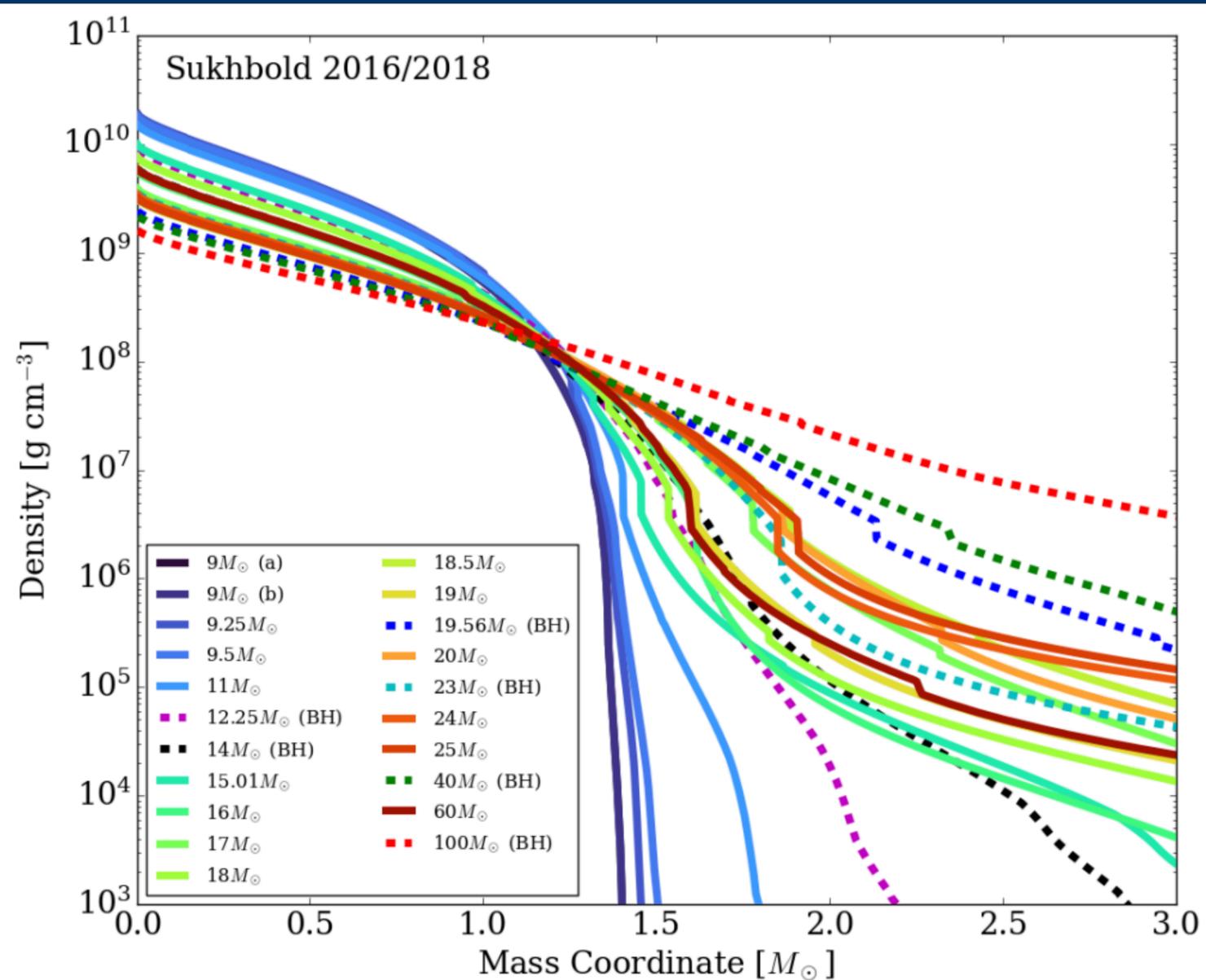
Schneider+ 2021

$$\xi_M = \frac{M/M_{\odot}}{R(M)/1000 \text{ km}}, \quad \text{O'Connor \& Ott, 2011}$$



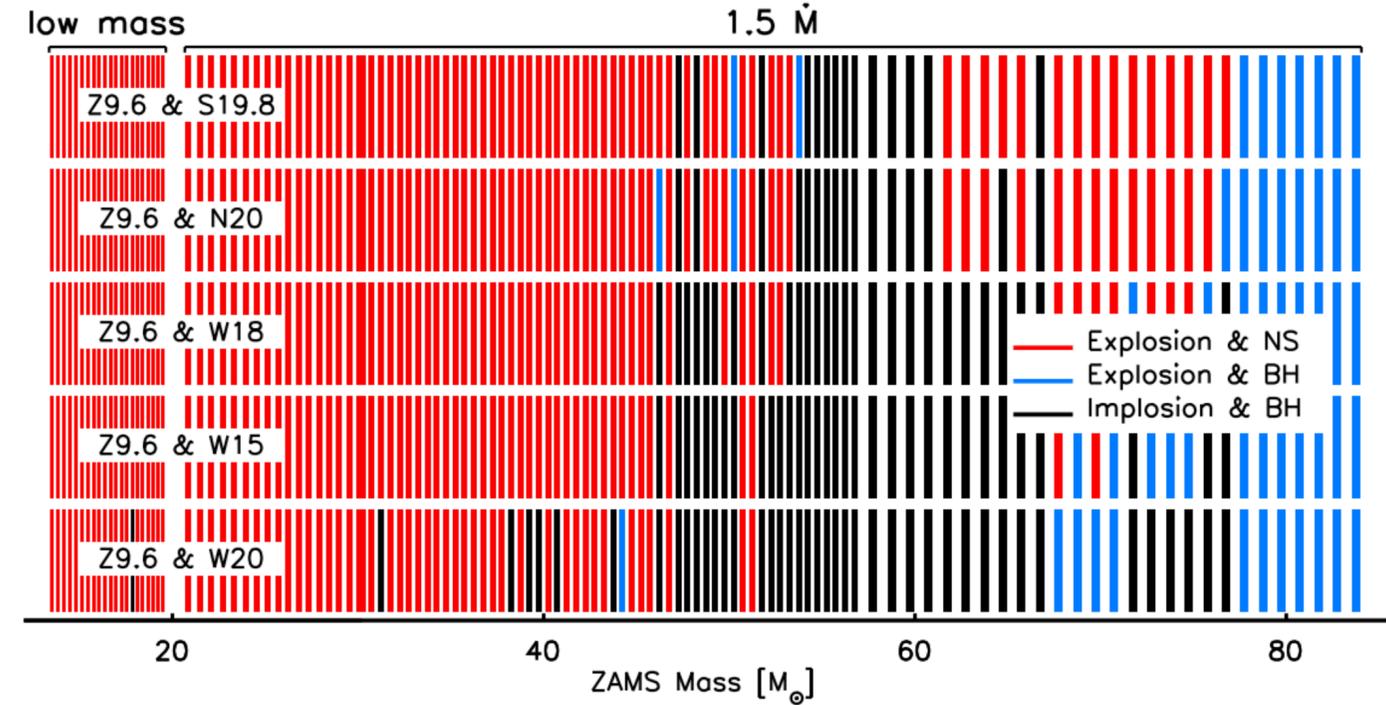
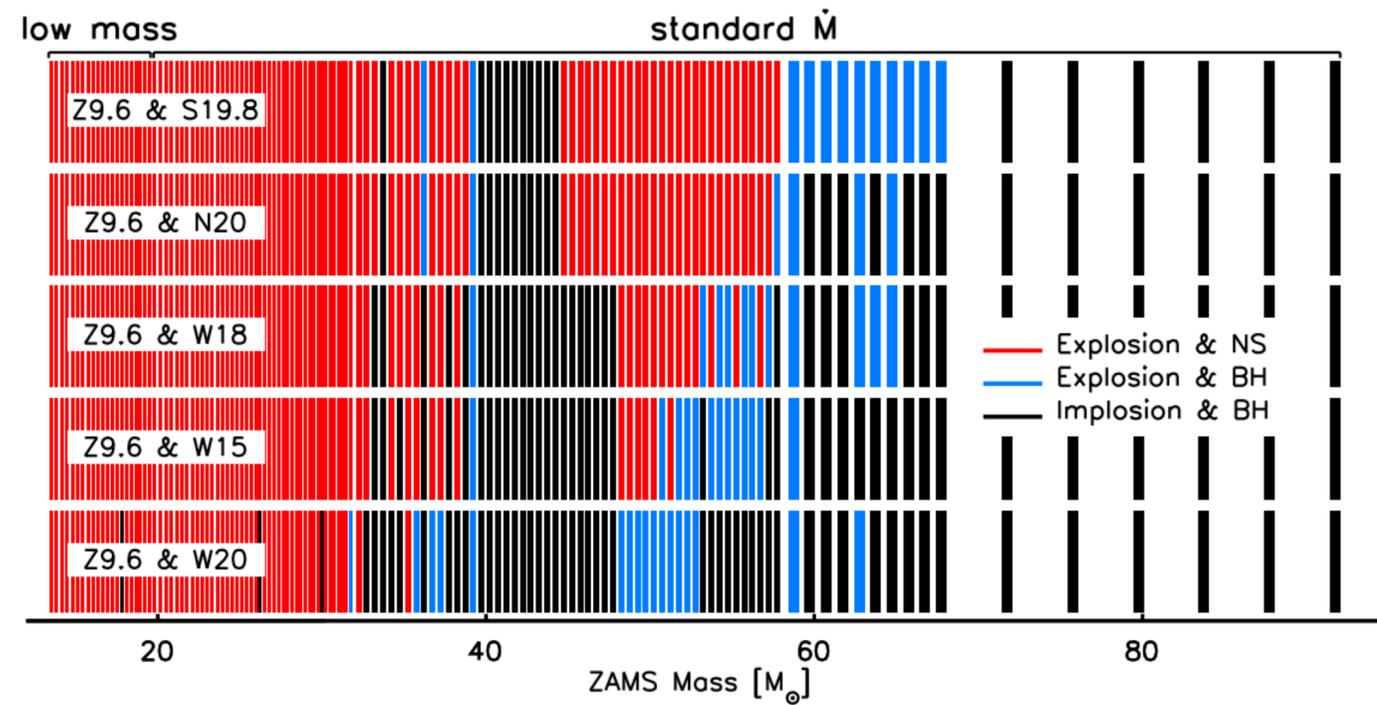
Ertl+, 2019

Also see work by Burrows, Janka, Müller, Sukhbold, and collaborators...



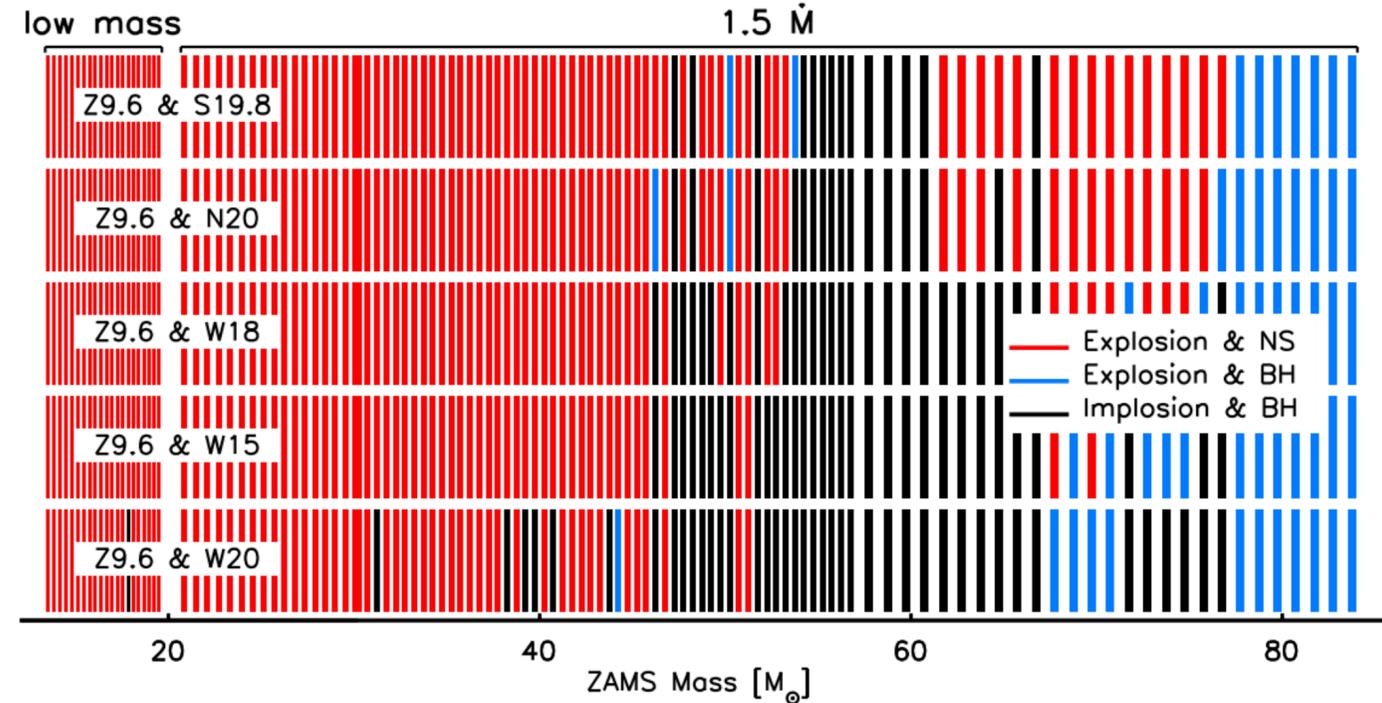
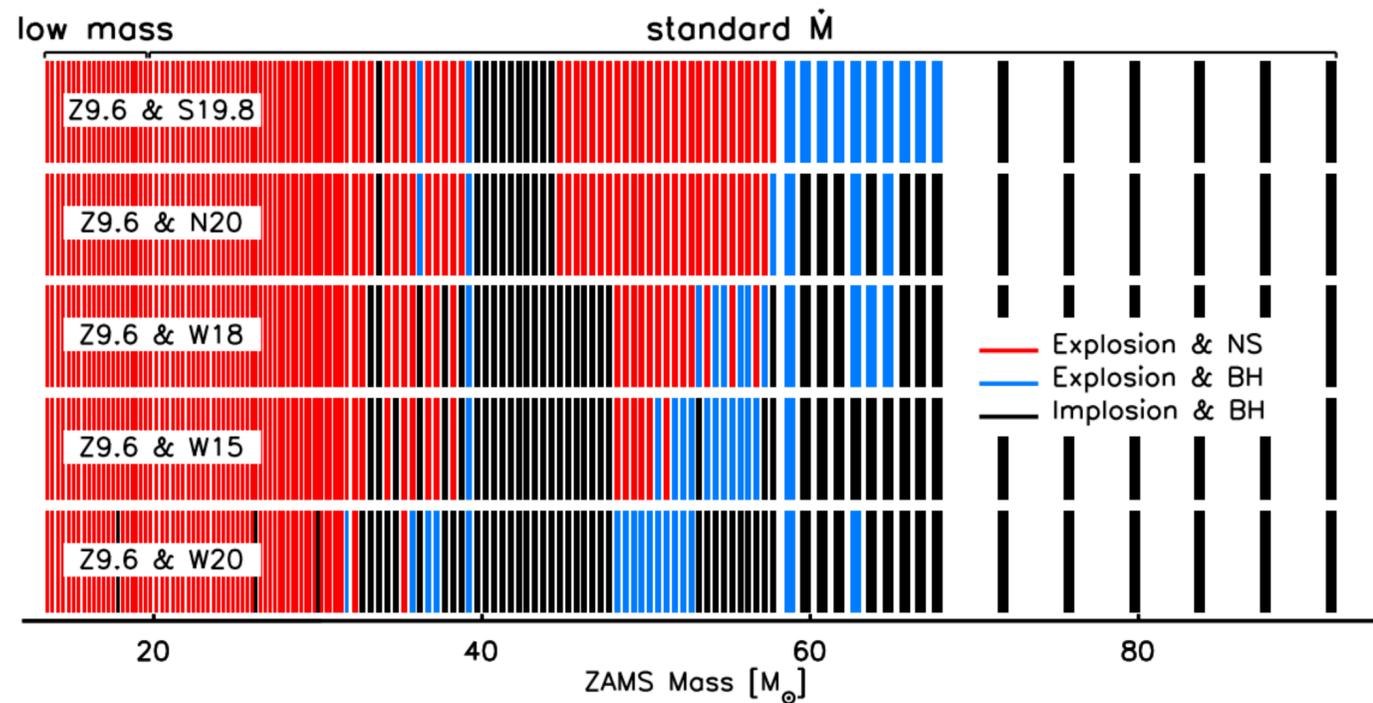
Burrows+, 2025

# Mass loss, metallicity, MT history, stochasticity?...

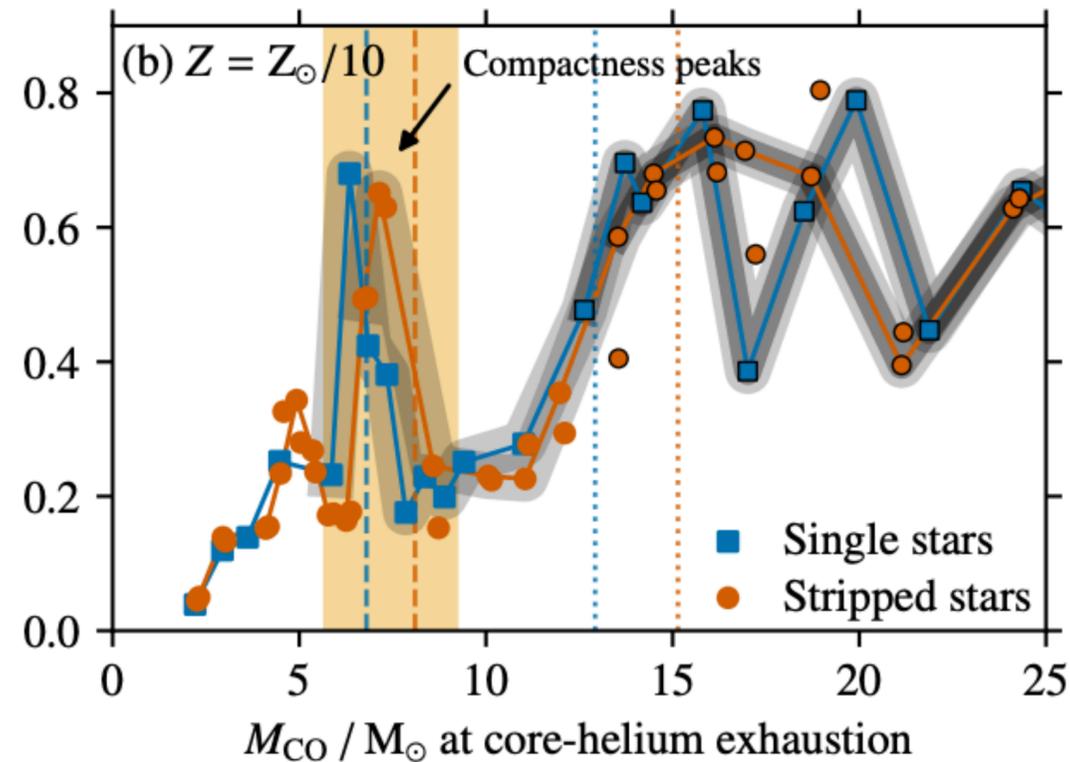
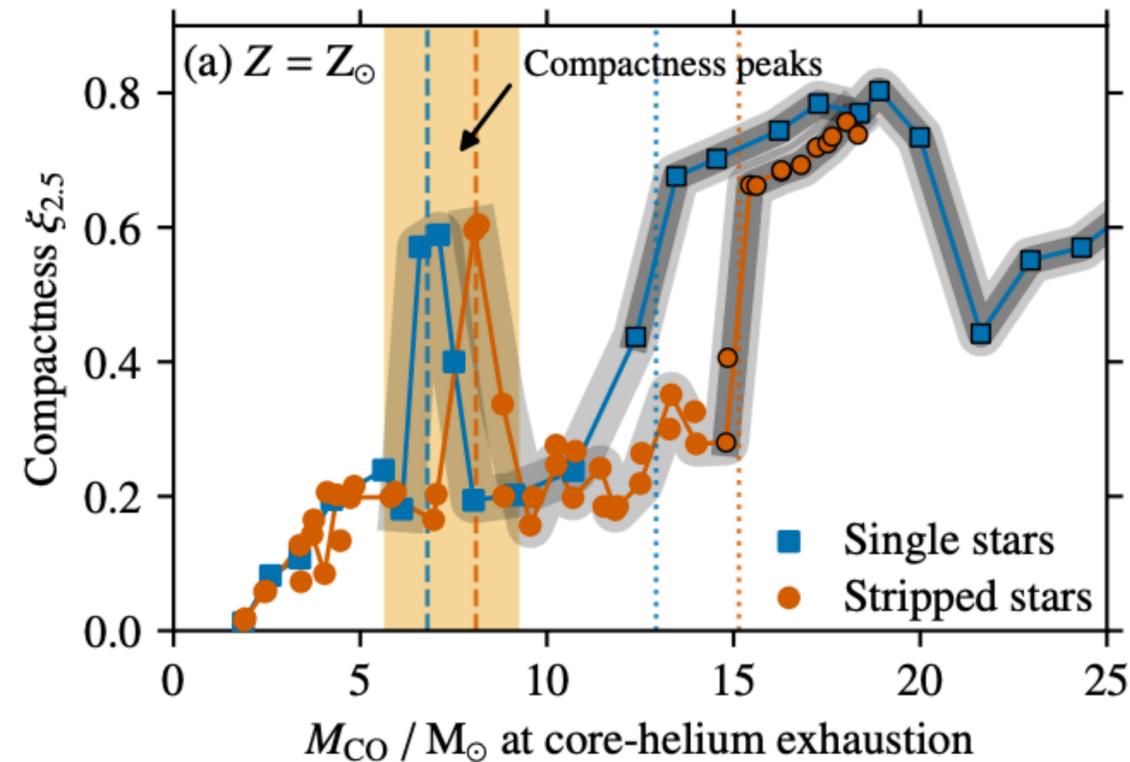


Ertl+, 2019

# Mass loss, metallicity, MT history, stochasticity?...

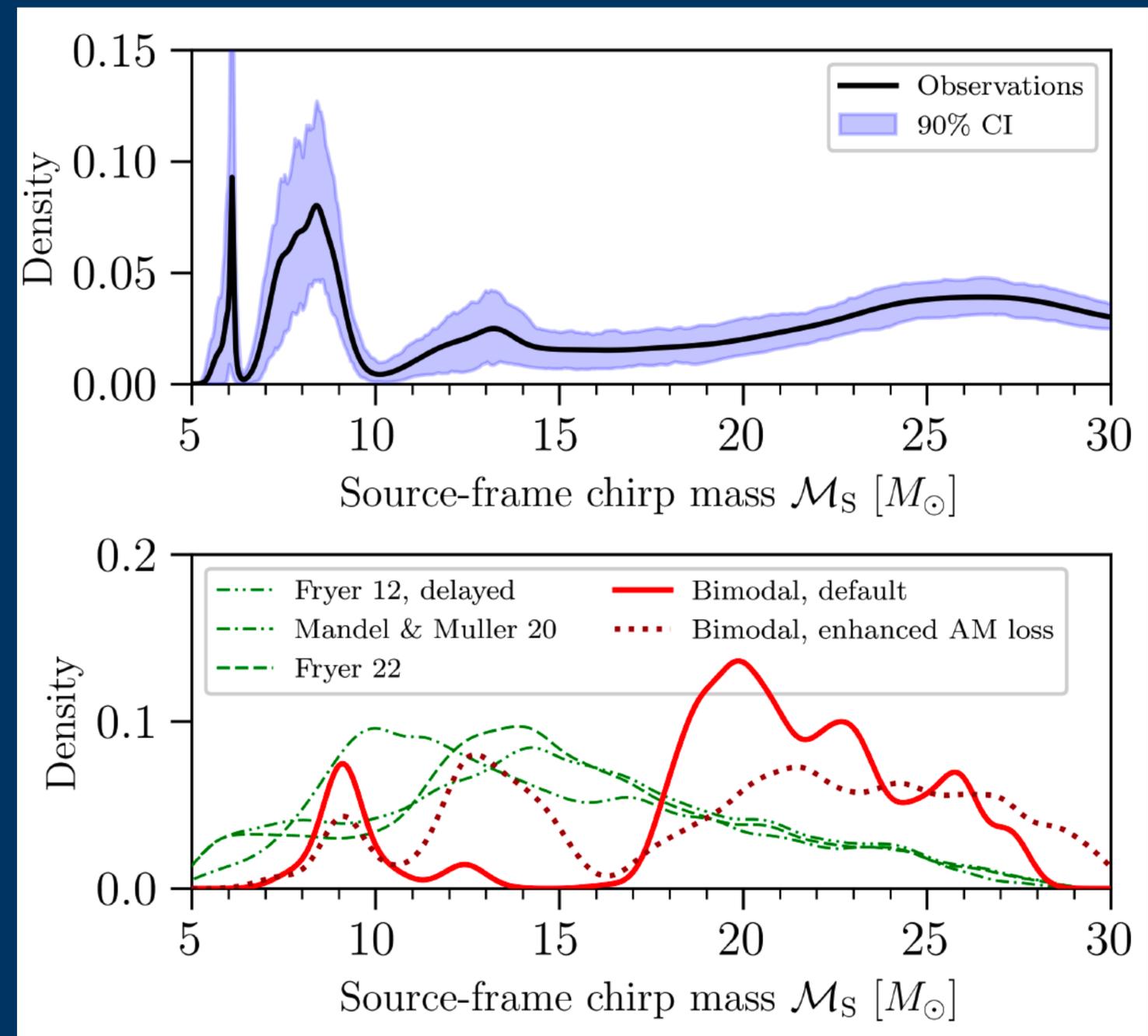
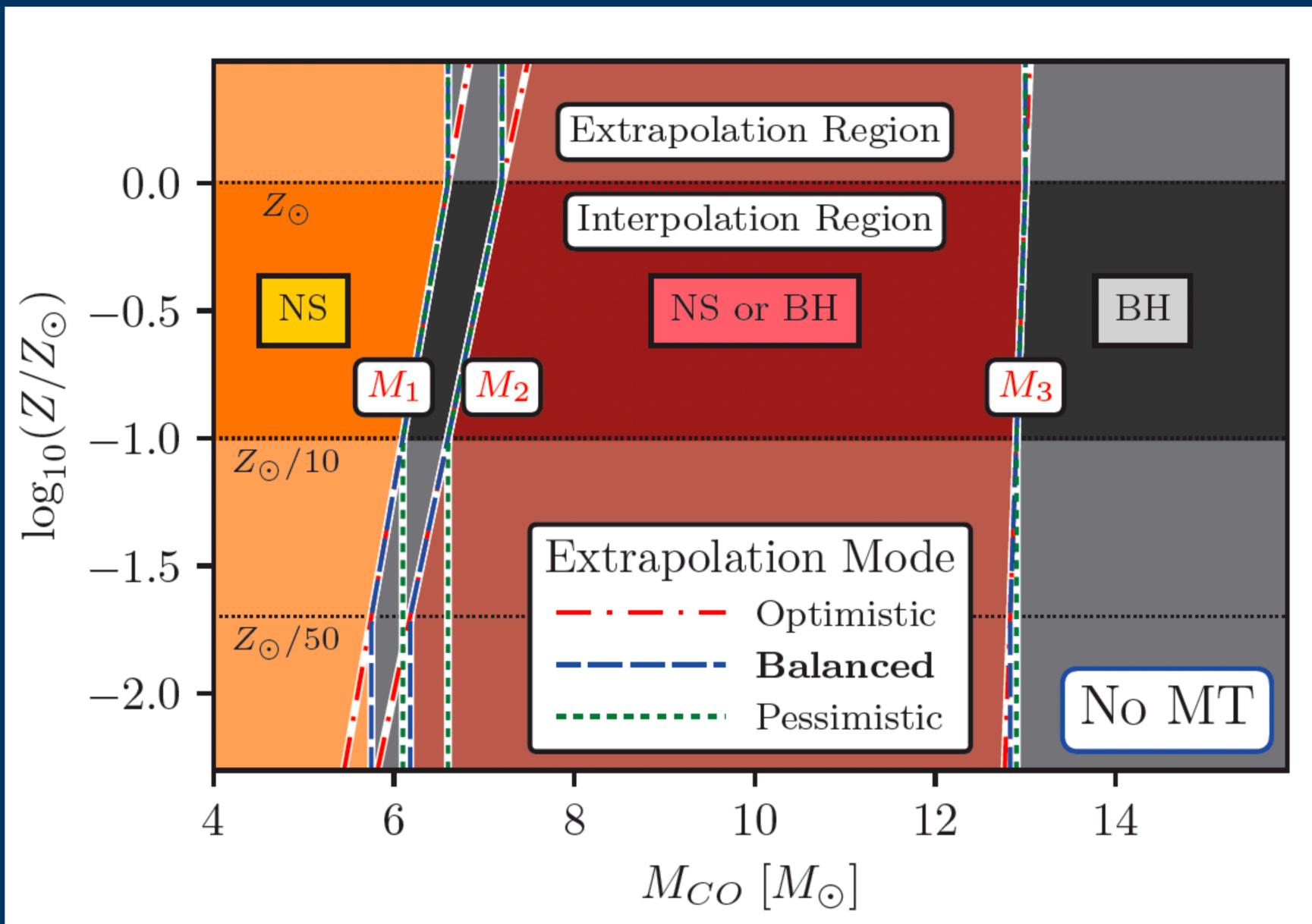


Ertl+, 2019



Schneider,  
Podsiadlowski,  
Laplace, 2023

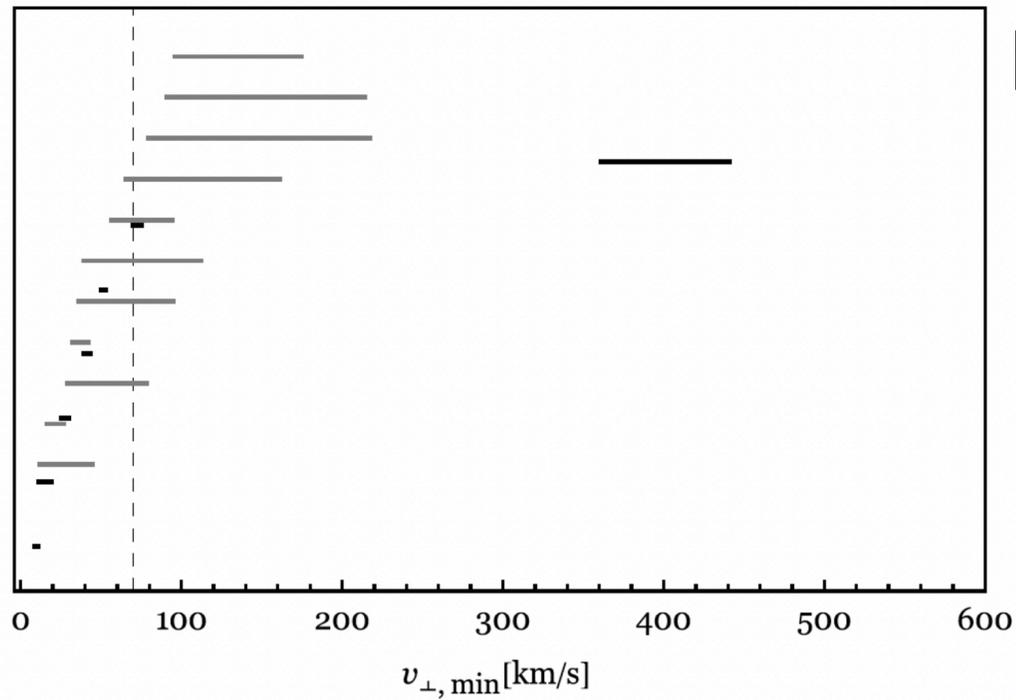
# BH mass distribution?



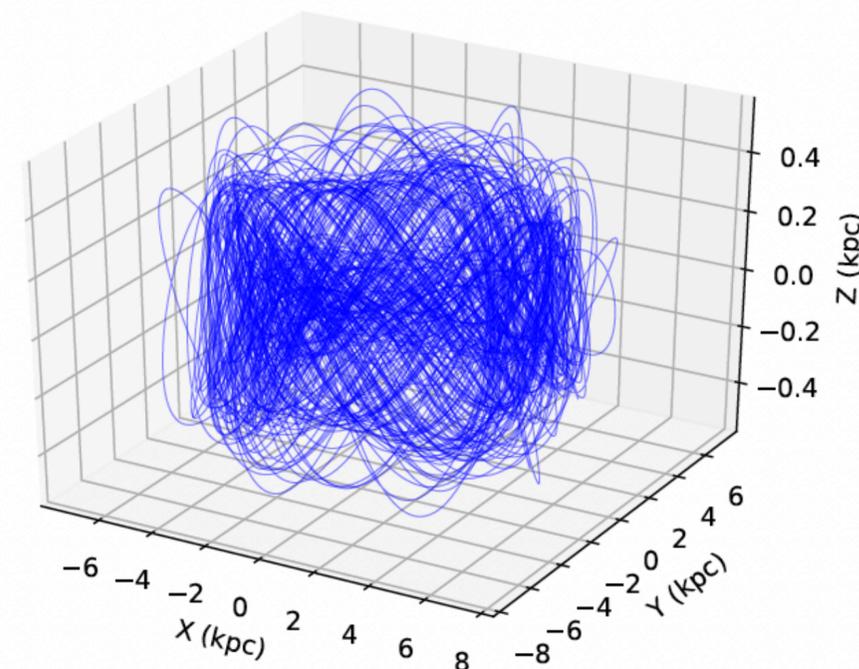
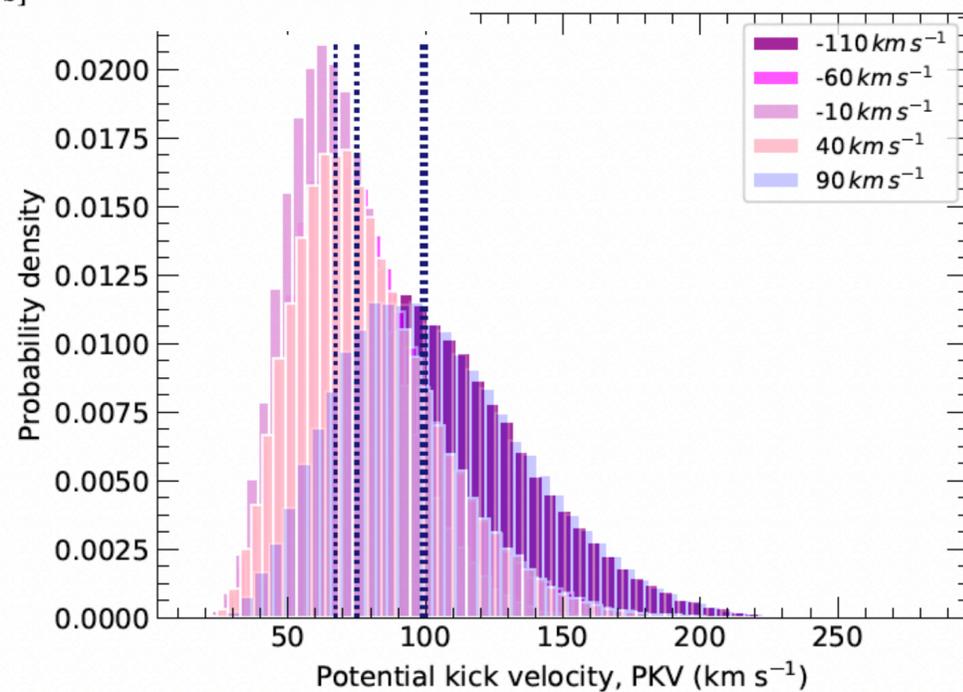
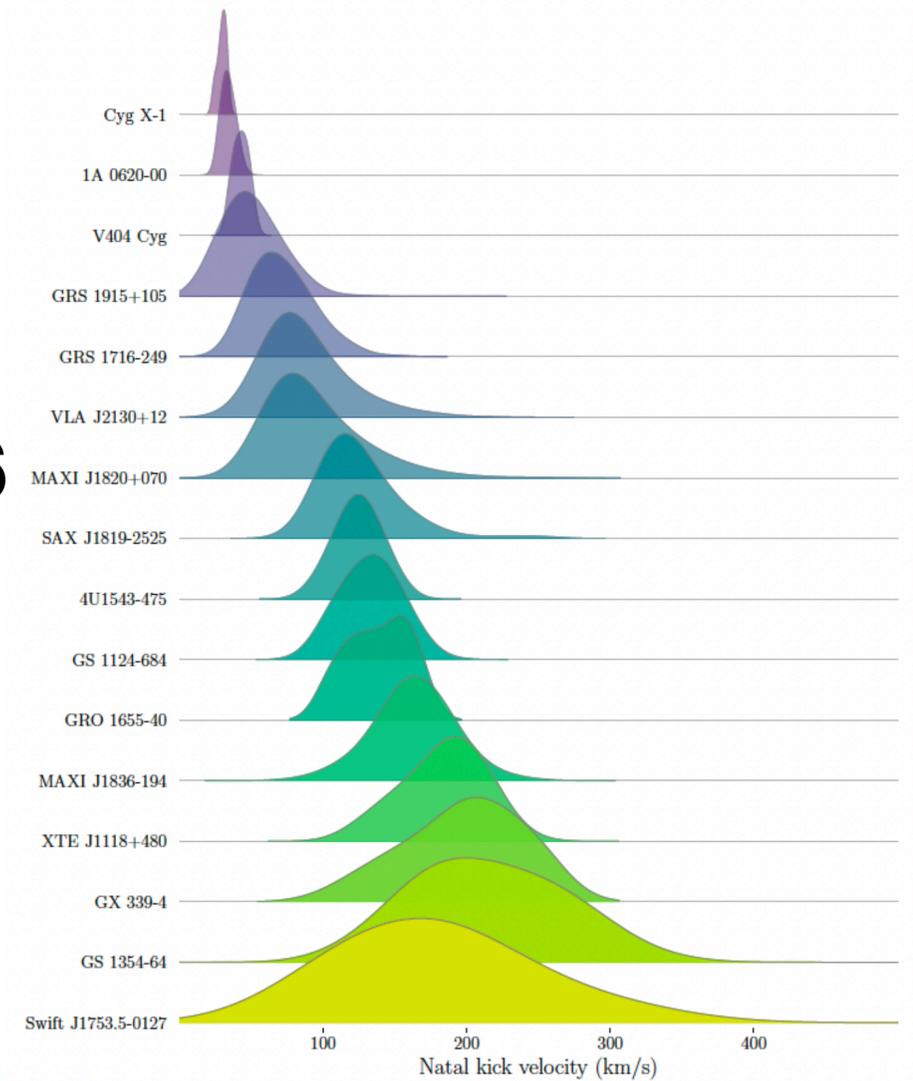
Maltsev+, 2025; Willcox+, 2025

# Natal kicks

## Black holes



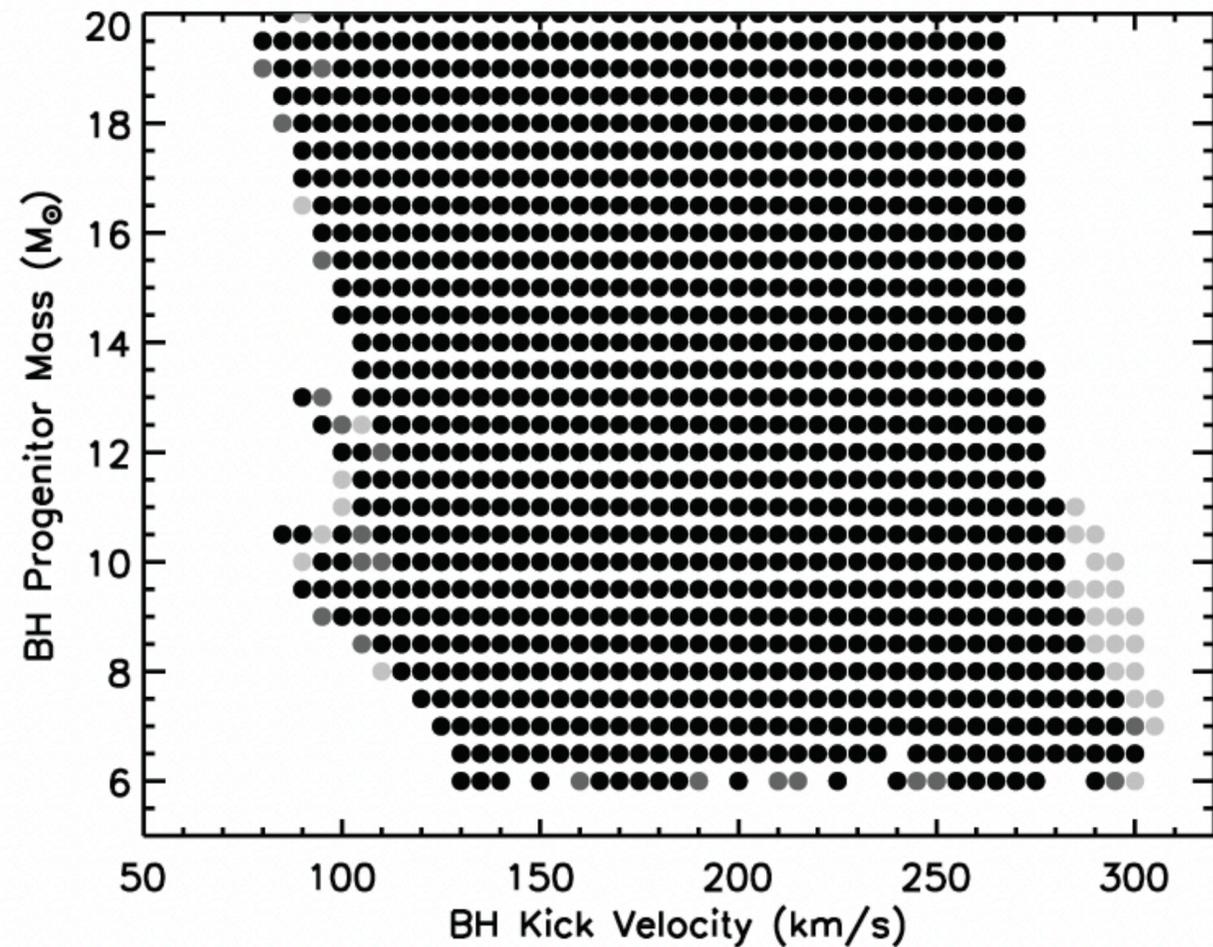
Repetto & Nelemans, 2016



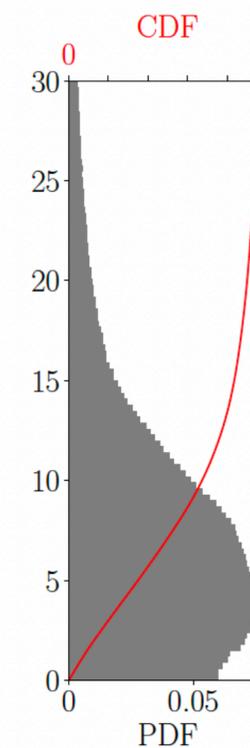
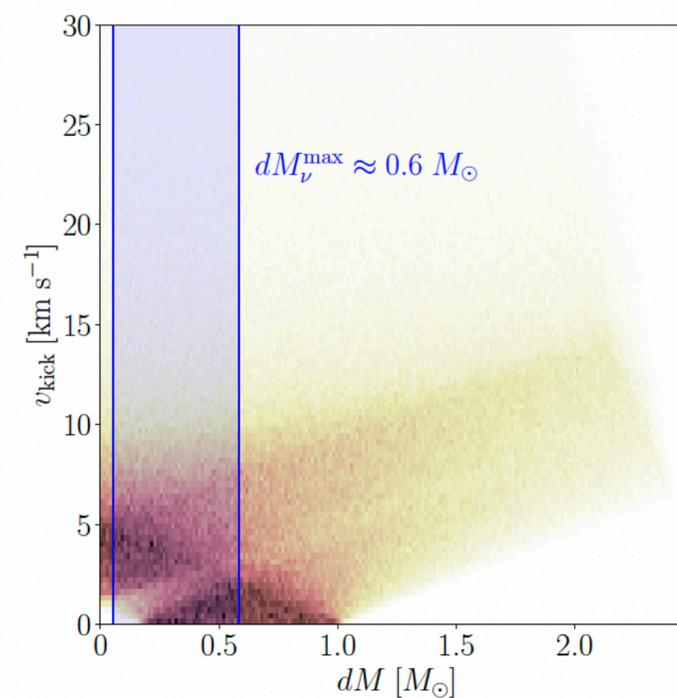
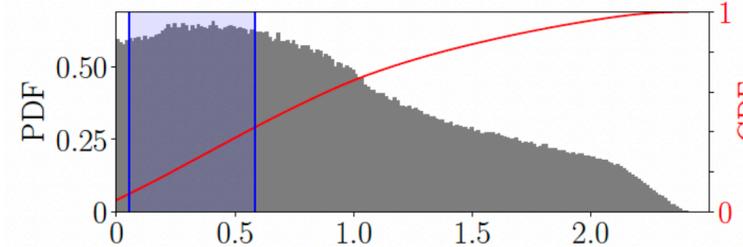
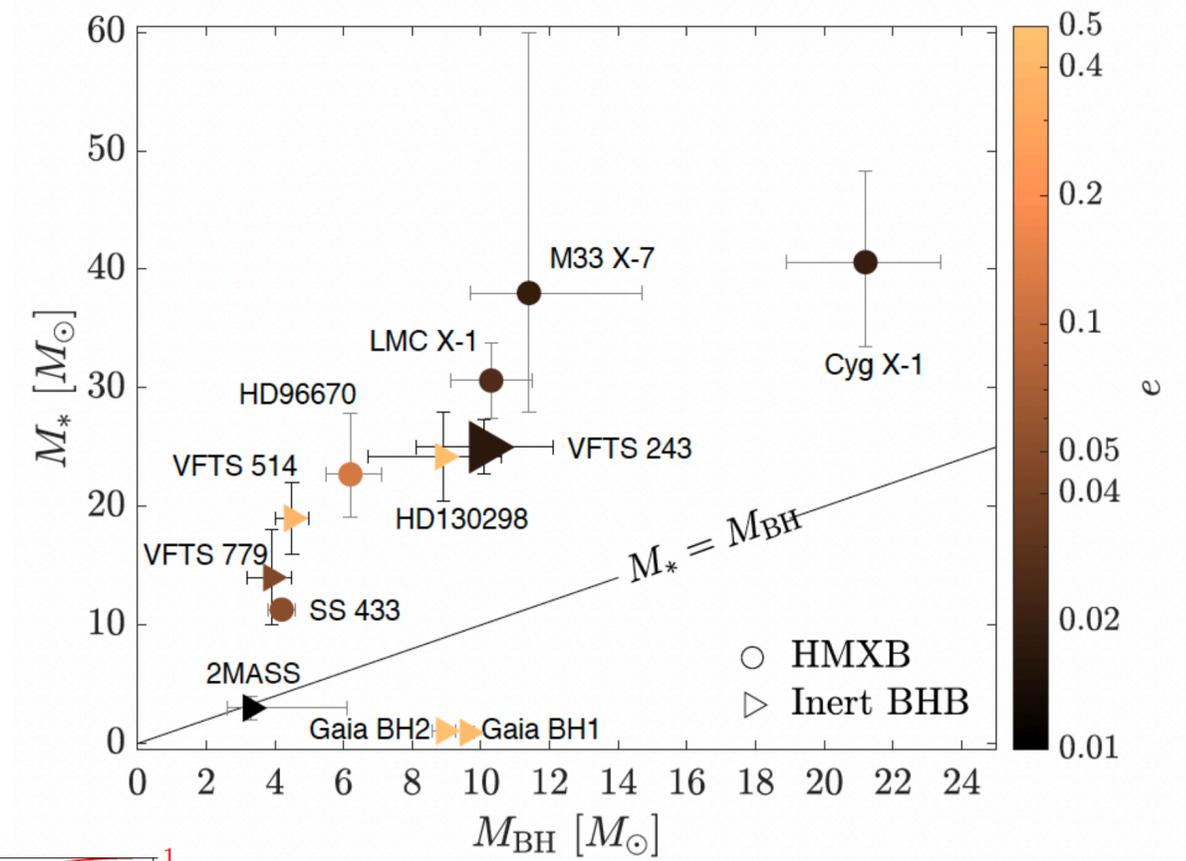
Atri+, 2021

# Natal kicks

## Black holes



Fragos+ 2009 for XTE J1118 + 480



Vigna-Gomez+ 2024

(see also Shenar+ 2022,

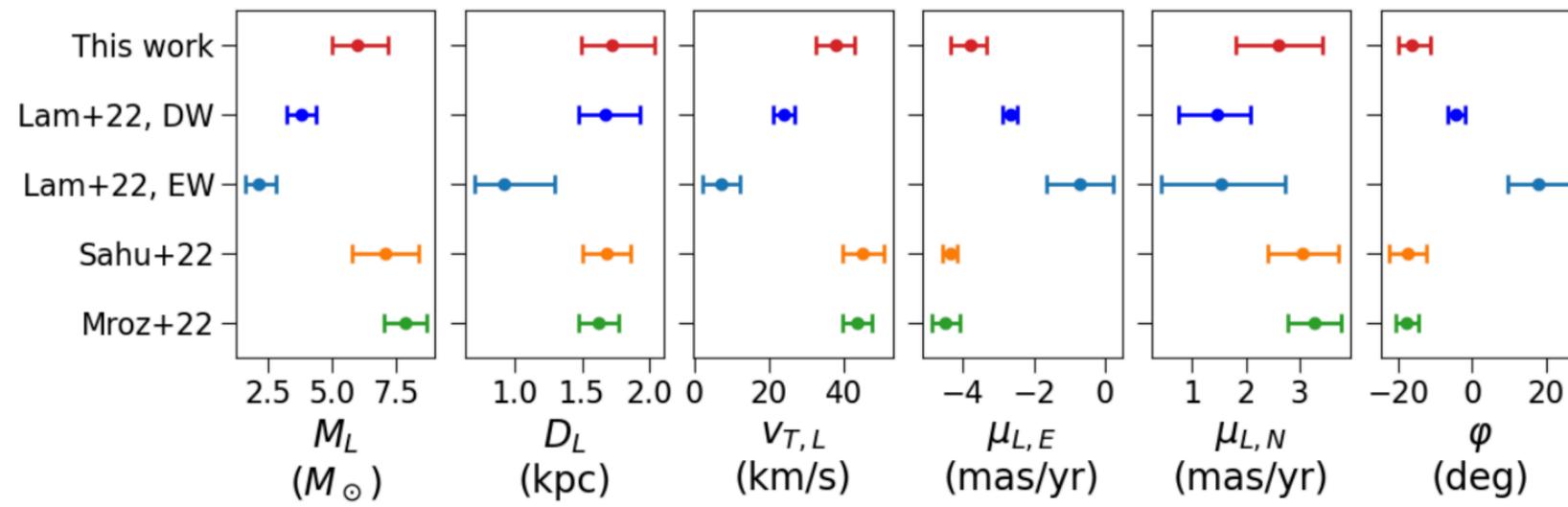
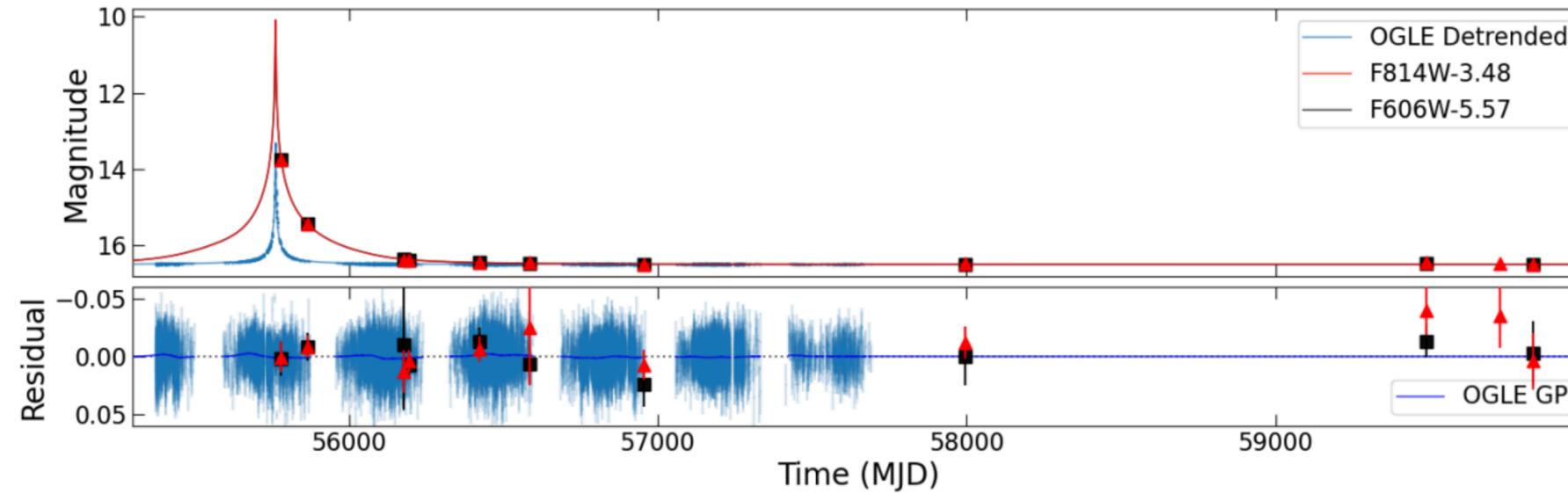
Stevance+ 2022, Banagiri+ 2022

for VFTS243

and e.g. Neijssel+ (2021) for Cygnus X-1)

# Natal kicks

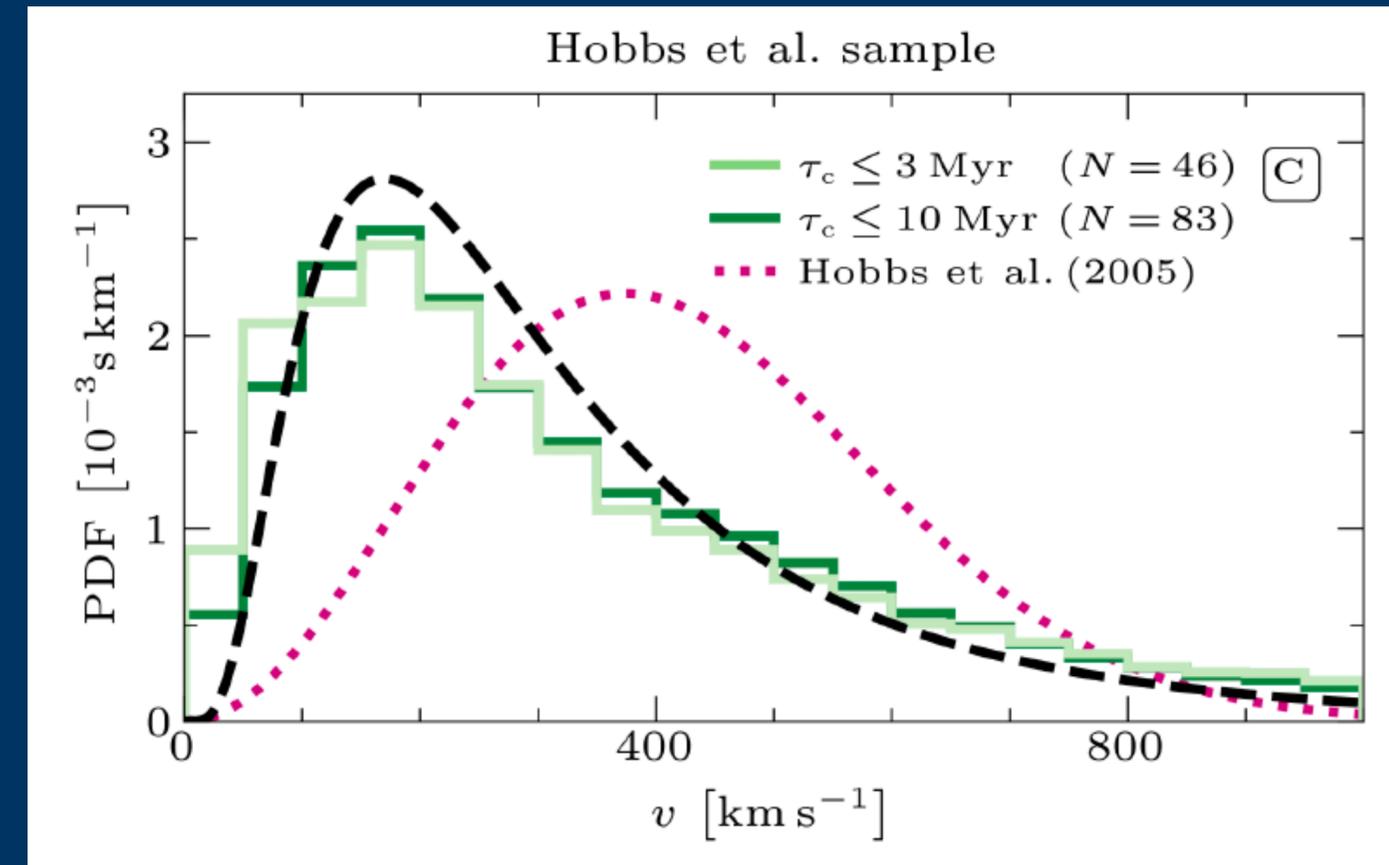
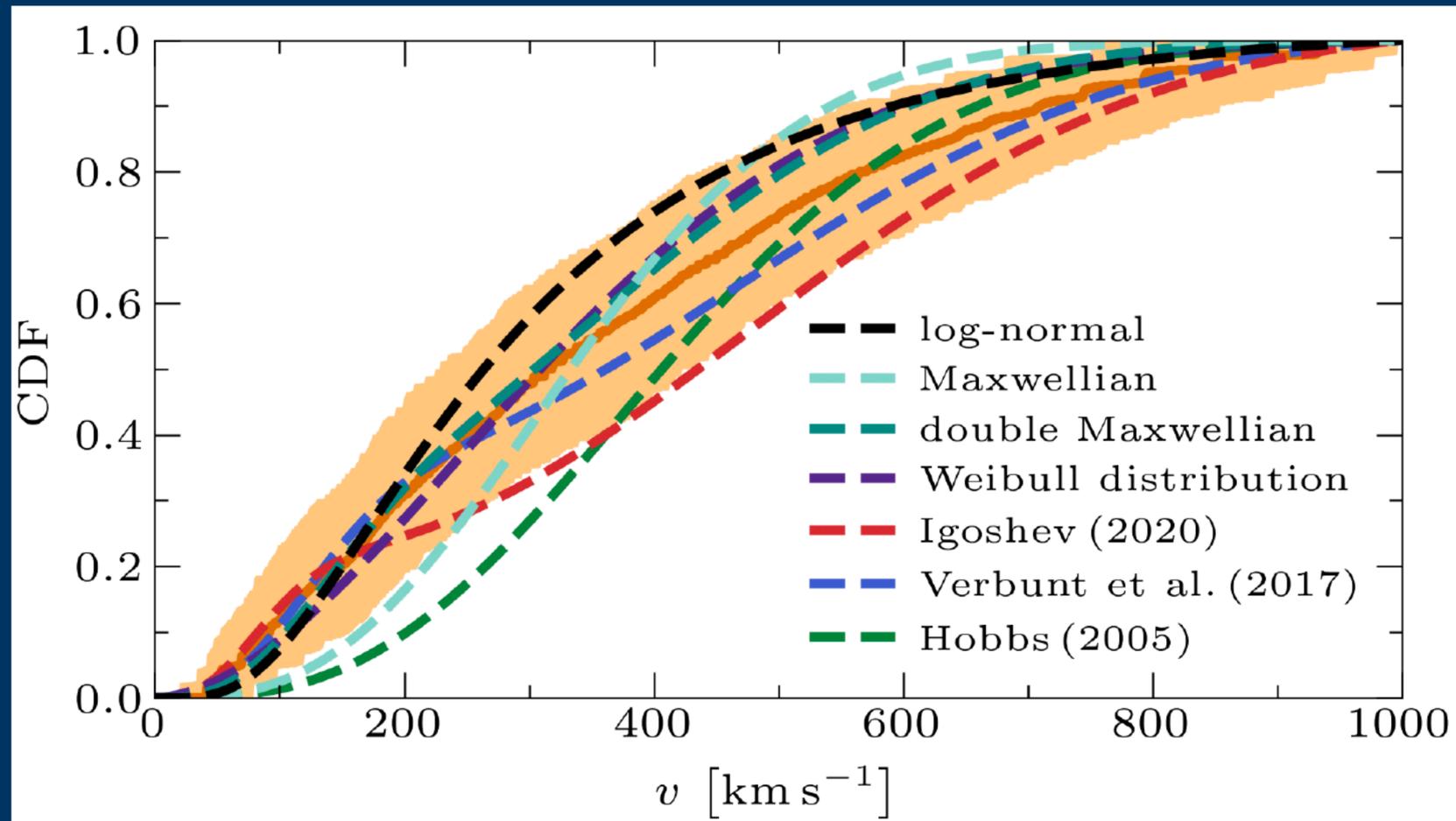
## Black holes



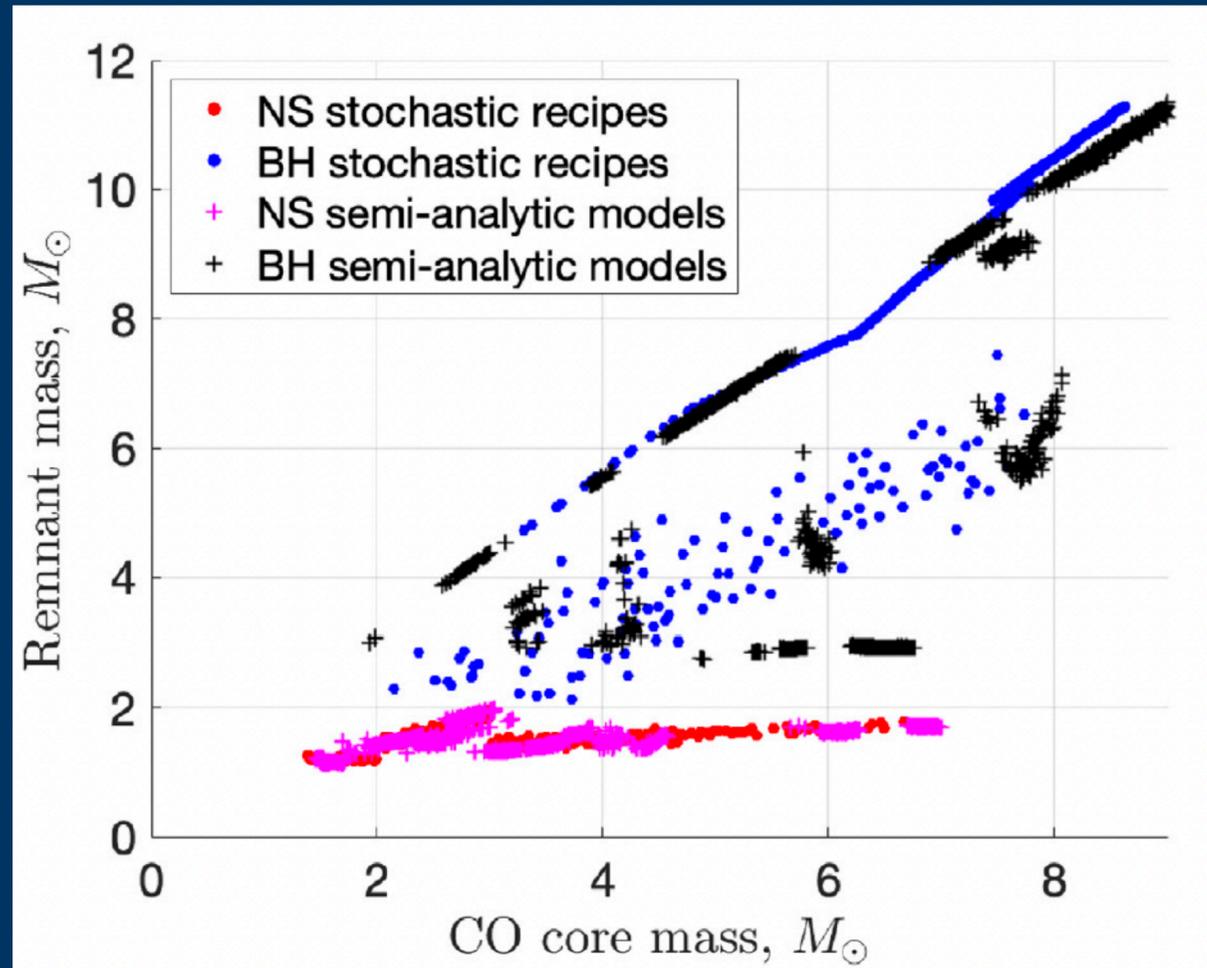
**Figure 10.** Comparison of lens mass  $M_L$ , distance  $D_L$ , transverse velocity  $v_{T,L}$ , proper motion vector  $(\mu_{L,E}, \mu_{L,N})$ , and lens-source relative proper motion direction  $\phi$  inferred from various studies of OB110462.

Lam & Lu, 2023

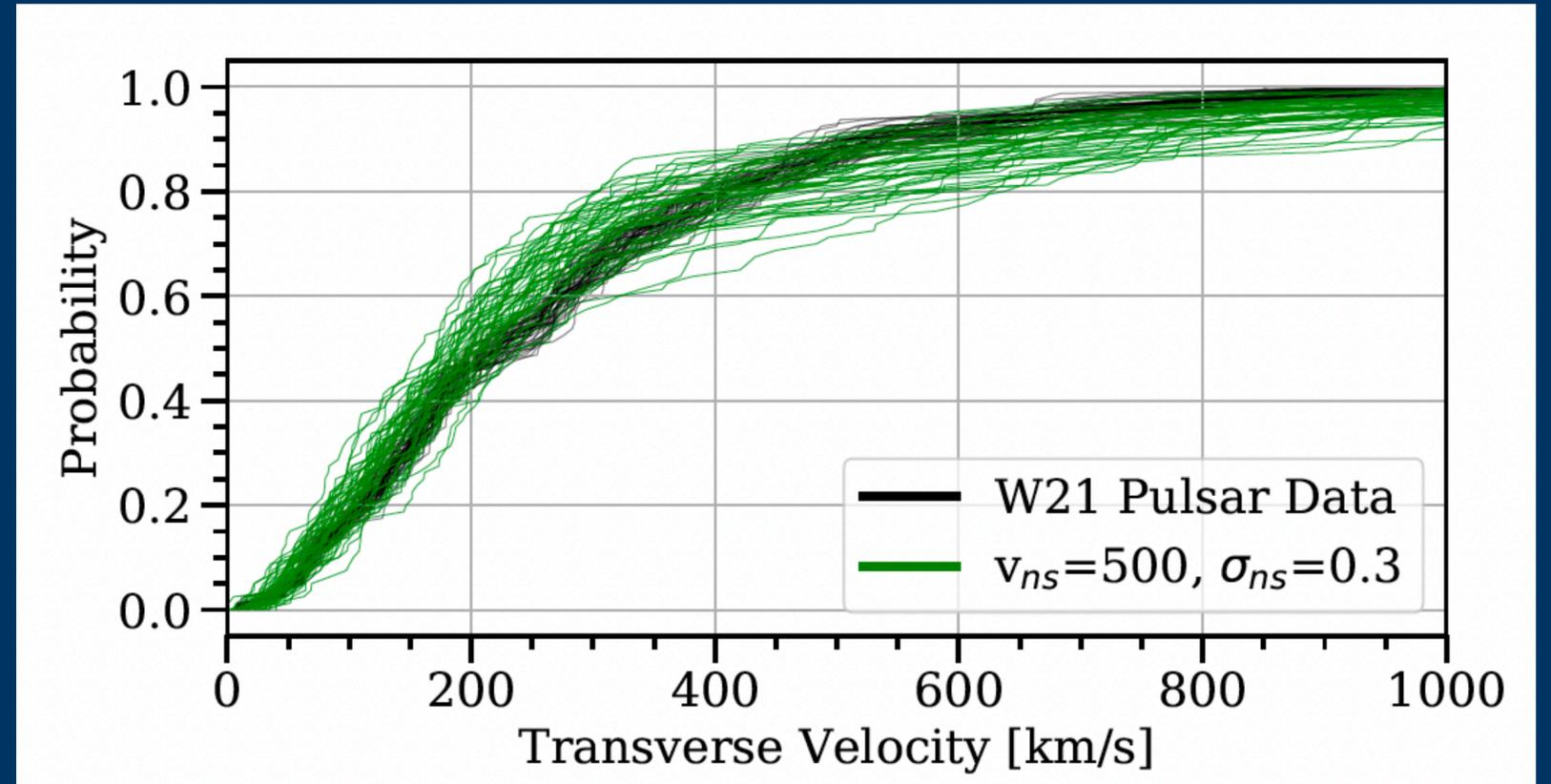
# Isolated NS kicks



# Physical model



Mandel & Mueller, 2020



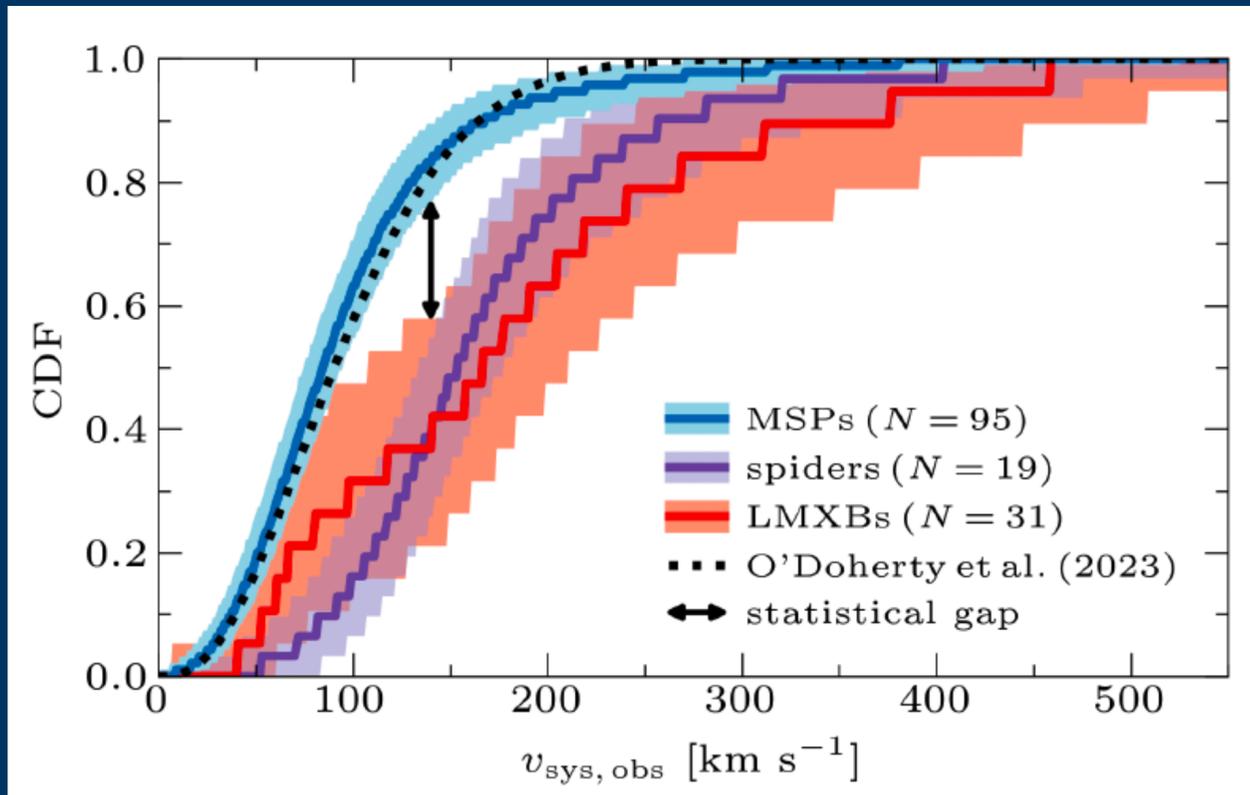
$$\mu_{\text{kick}} = v_{\text{NS}} \frac{M_{\text{CO}} - M_{\text{NS}}}{M_{\text{NS}}}$$

Kapil, Mandel,  
Berti, Müller, 2023

**Very low-kick SNe**

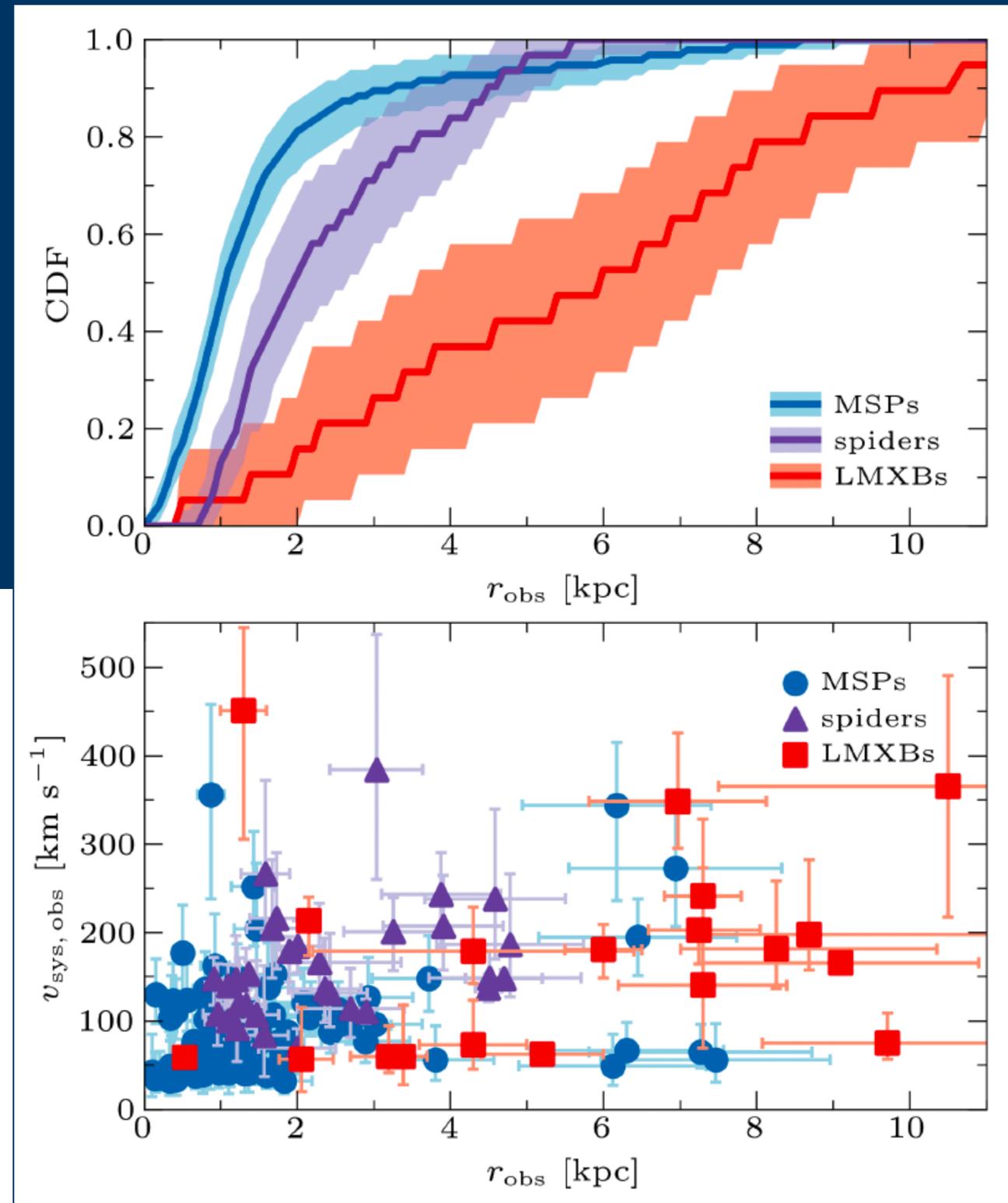
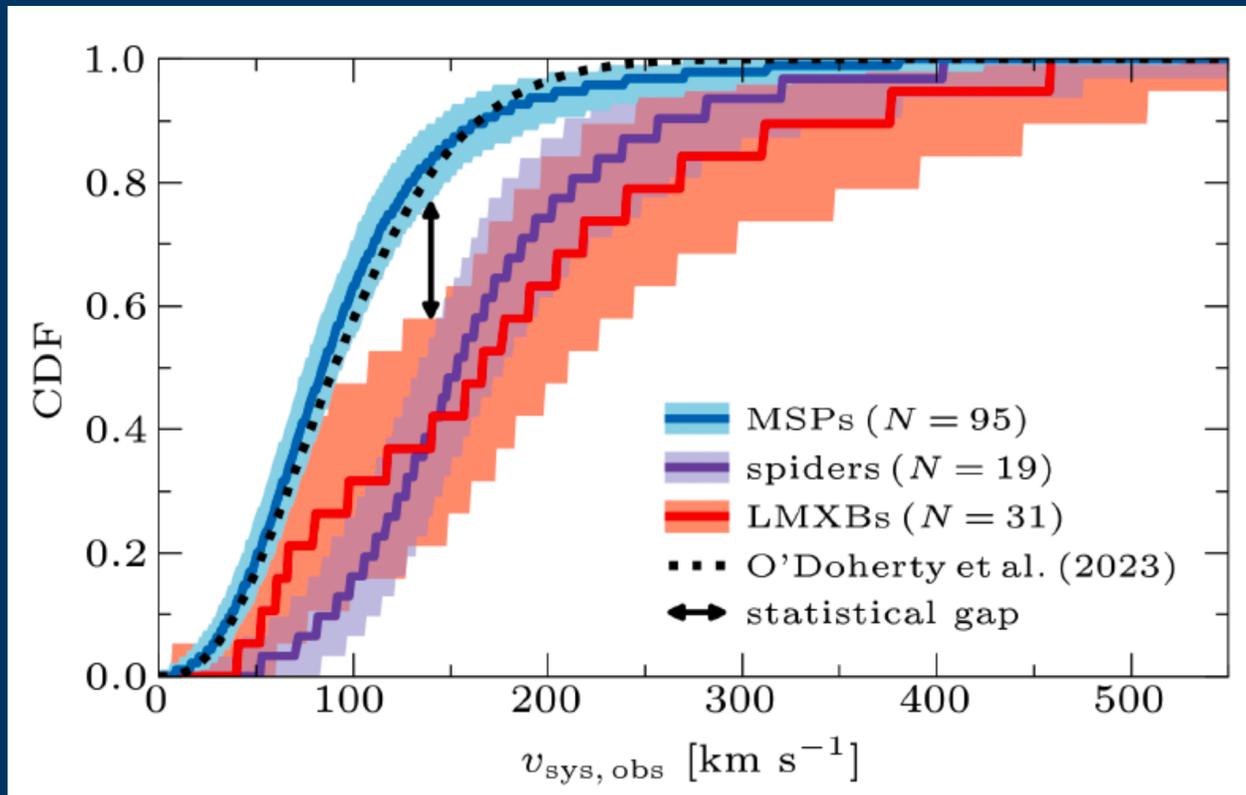
**(e.g., electron capture SNe) Willcox+, 2021**  
**happen only for mass donors...**

# NS binary kicks

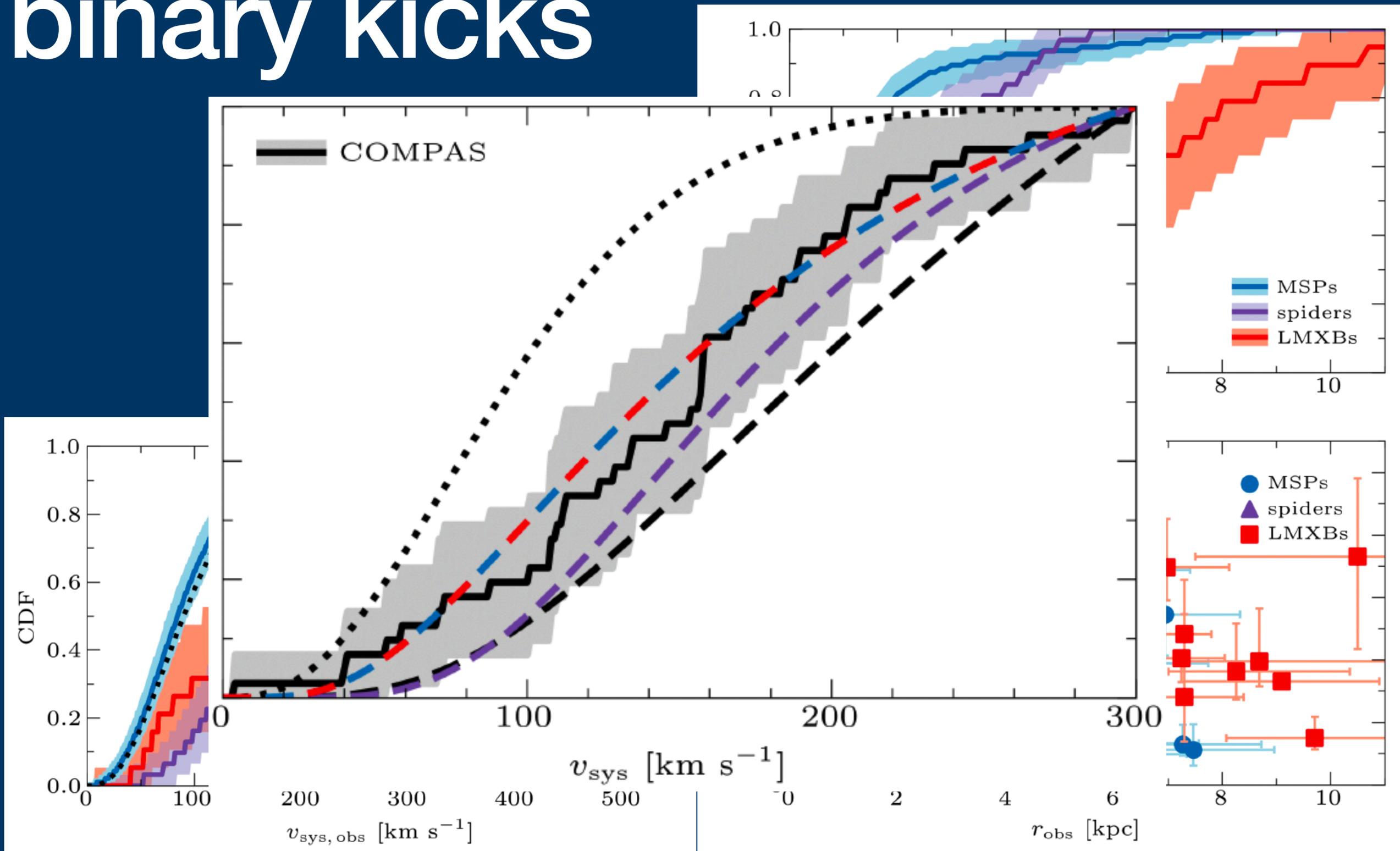


O'Doherty+, 2023; Disberg, Bahramian, Mandel, 2026

# NS binary kicks



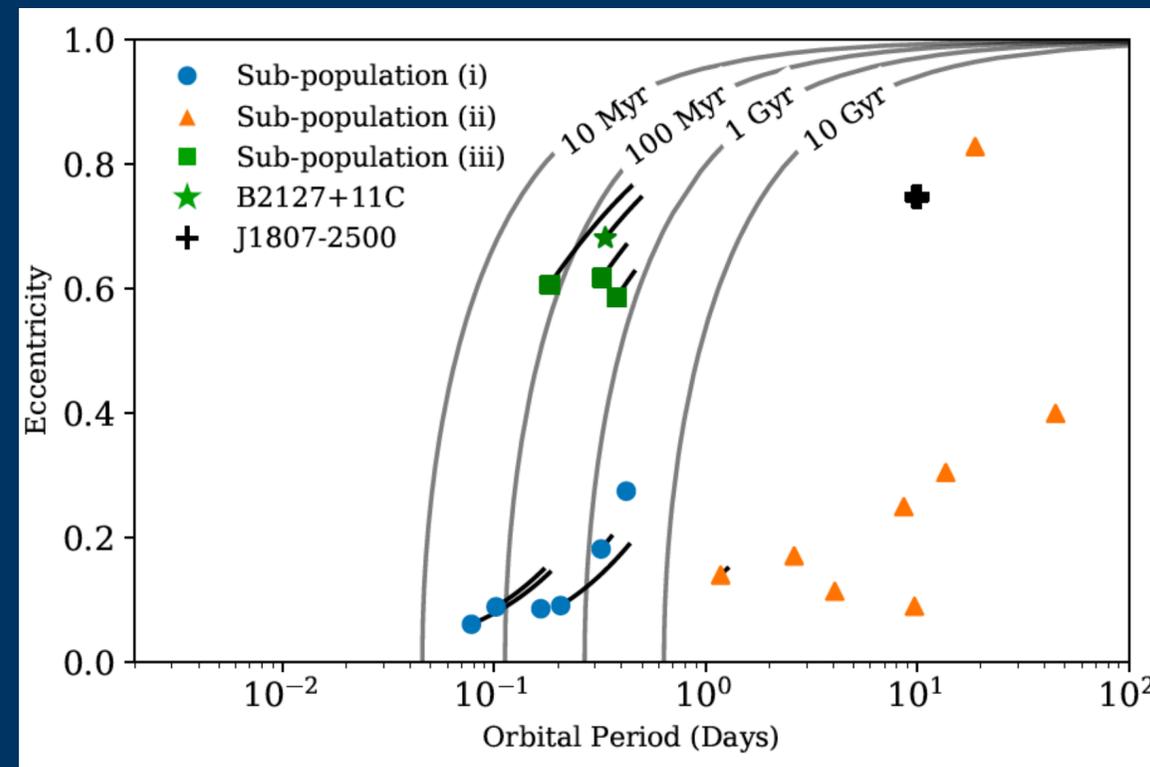
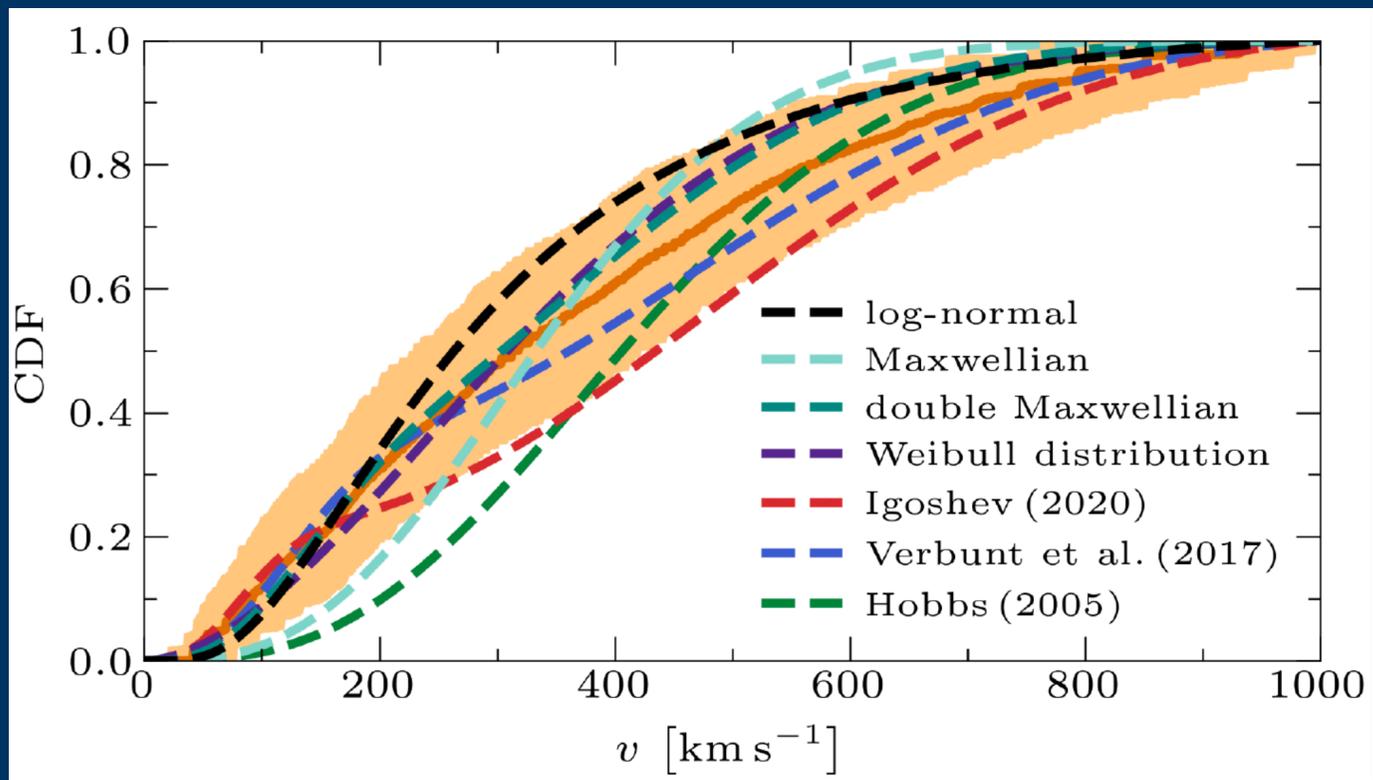
# NS binary kicks



# NS Kicks — Ilya Mandel



MONASH University

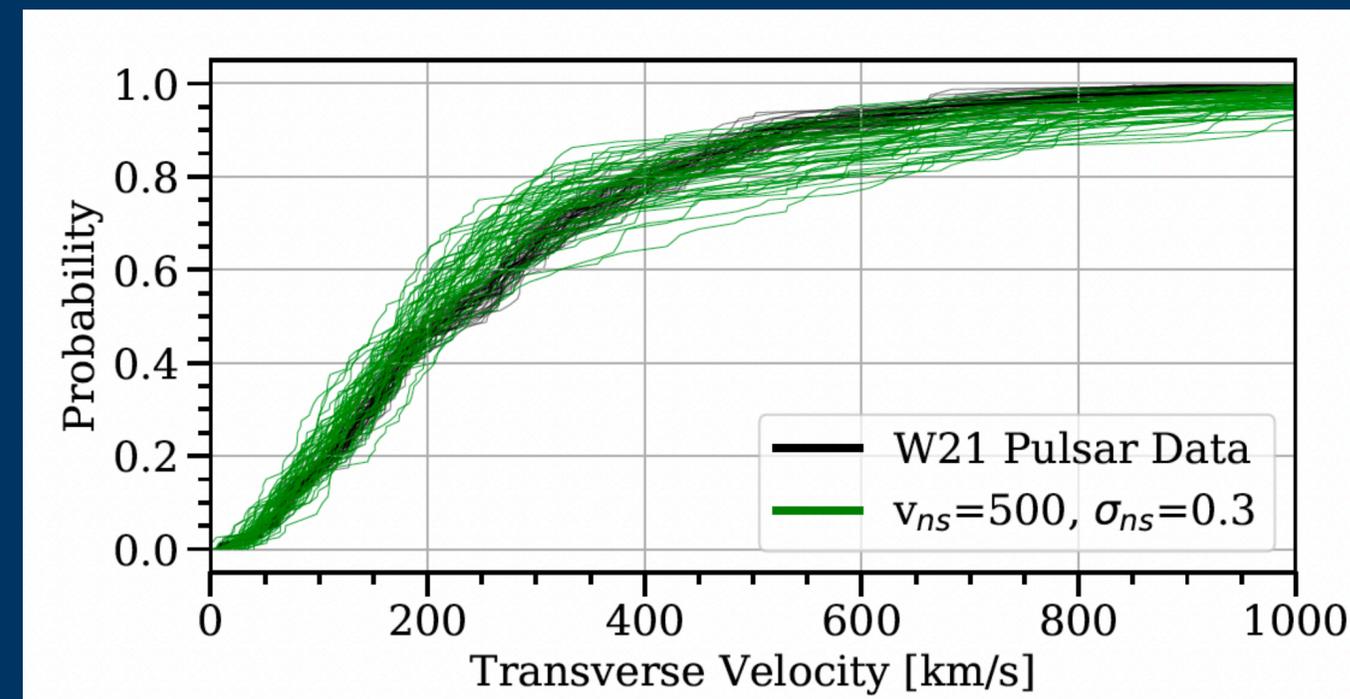
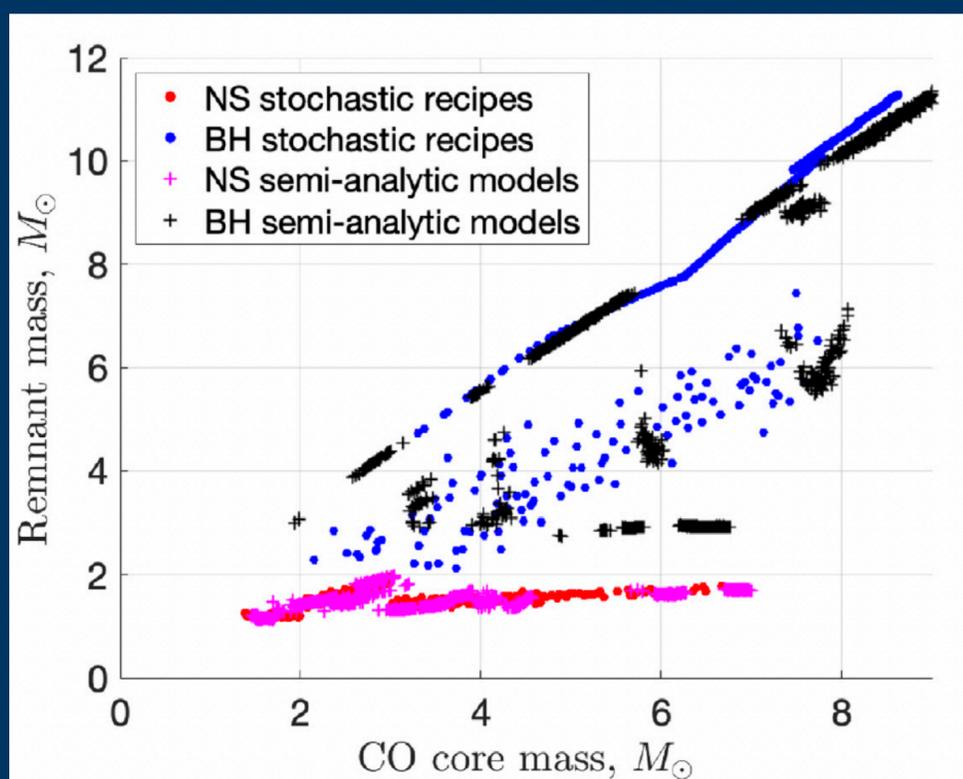


Andrews & Mandel, 2019

Kapil, Mandel, Berti, Müller, 2023

Disberg & Mandel, 2025

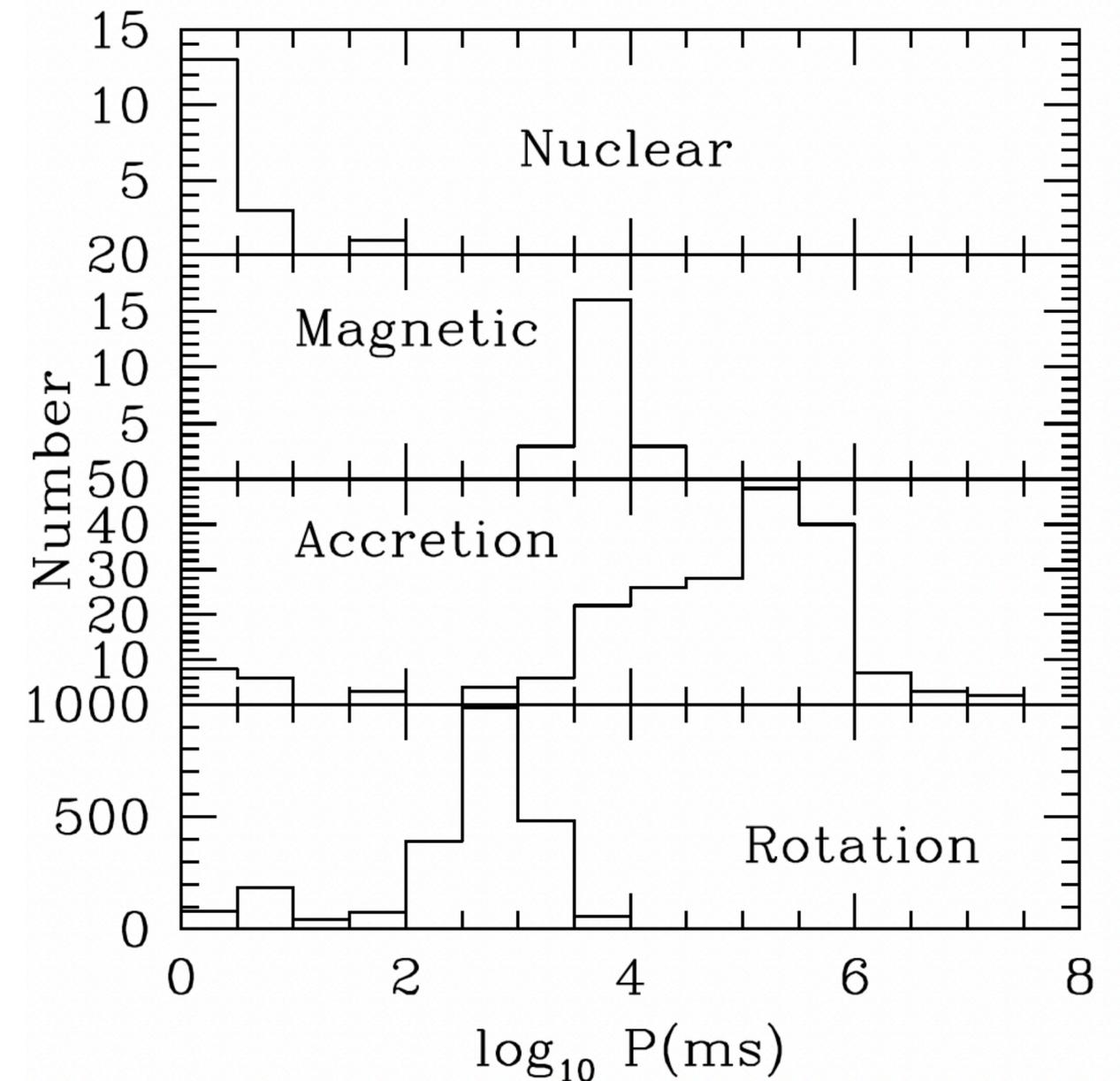
Mandel & Mueller, 2020



# Rotation

## Neutron stars

- Initial spins difficult to infer — or model
- Unclear correlation between pre-SN and post-SN spin and even spin direction (e.g., J0737 B pulsar)
- Rotation direction observed to be aligned with kick (?), but don't know why [Janka+2022 vs. Müller 2023]

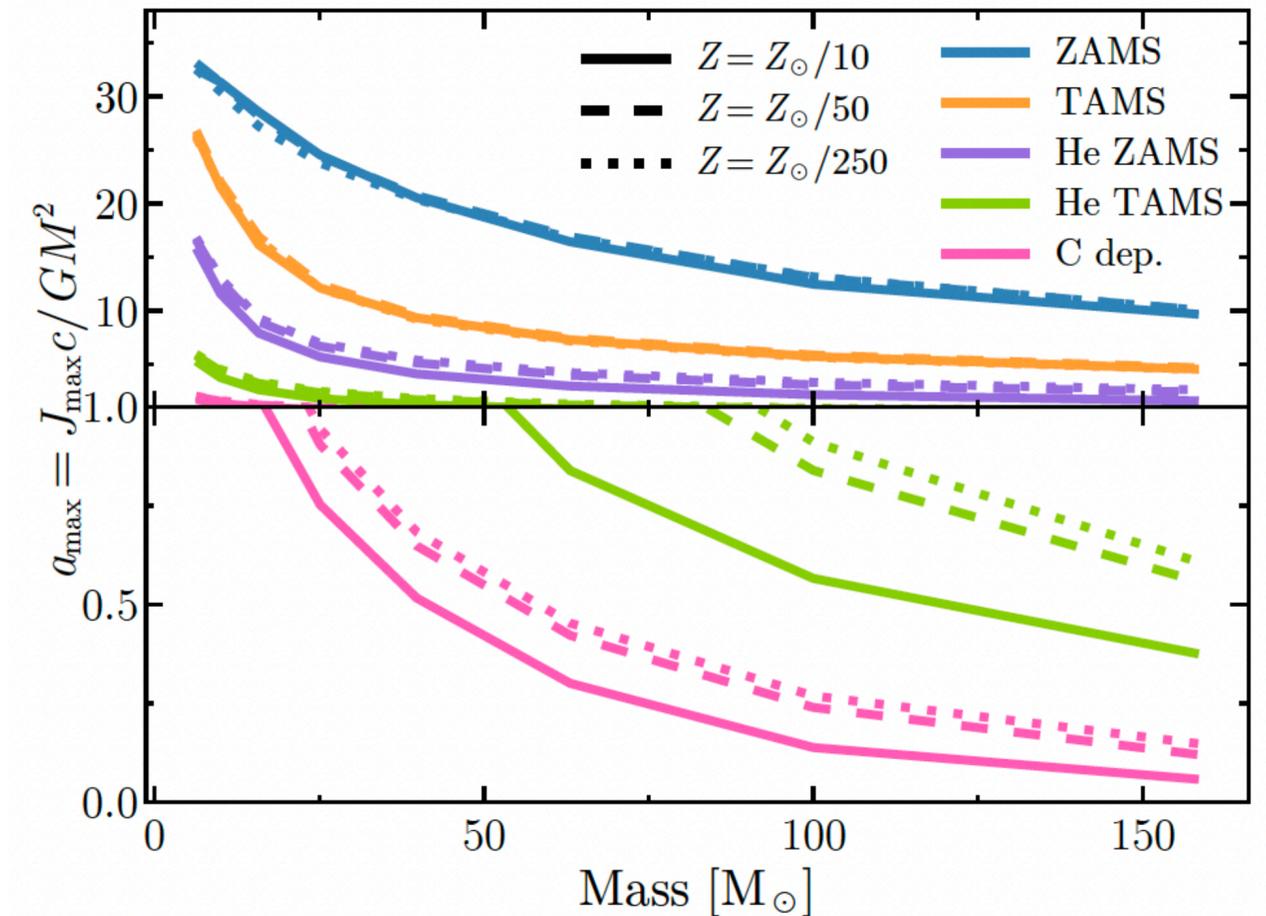


Miller & Miller, 2015

# Rotation

## Black holes

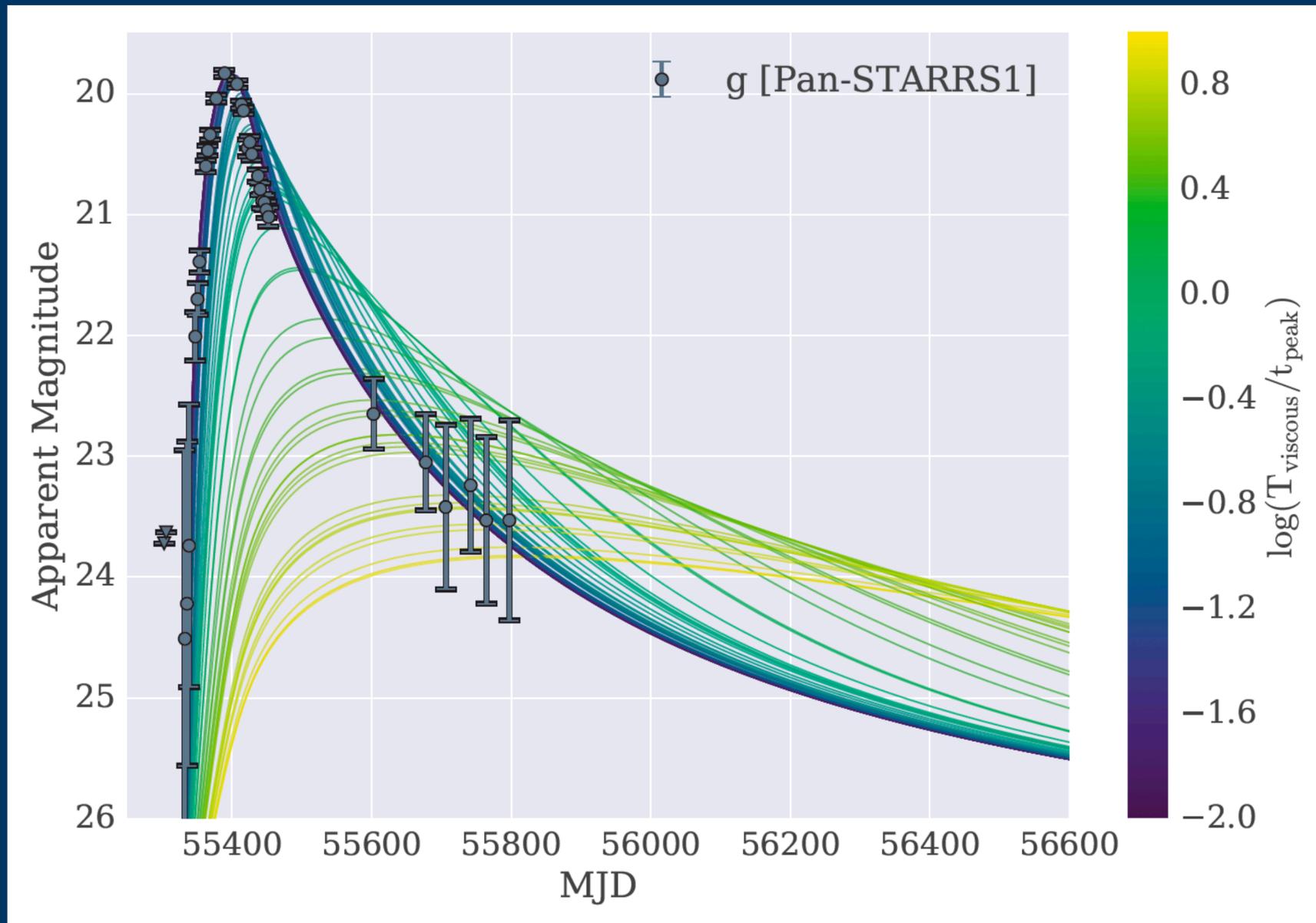
- Do LGRBs point to excess spin? Do we trust XRB spin observations? GW spins?
- If accretion is Eddington-limited, has to come from birth
- Plenty of angular momentum in the envelope, but is it lost? [Nadezhin 1980, Lovegrove & Woosley 2013, Antoni & Quataert 2022...]
- Spin-up during SN? [Batta+ 2017, Schroeder+ 2018]
- Chemically homogeneous evolution? Tidal spin-up of core? [e.g., Qin+, 2019]



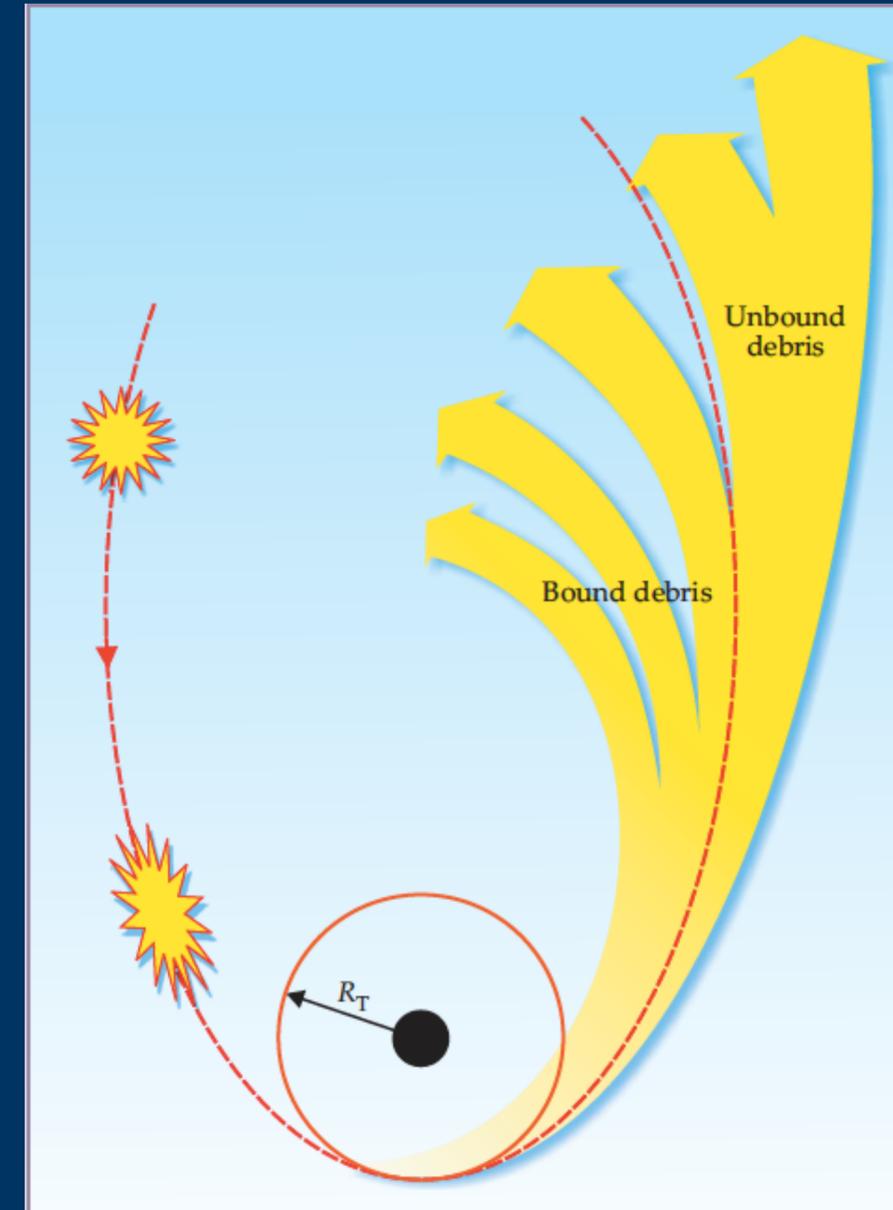
Marchant, Podsiadlowski, Mandel, 2024

Story elements	Puzzles	Partial solutions	Future tests?
<b>Common Envelopes</b>	Why do GW sources merge?	Common envelope models: 3d, 1d, 0d...	Post-CE binaries, Vera Rubin Observatory LRNe, ...
<b>Stable mass transfer</b>	How do HMXBs form?	Stability and conservativeness of mass transfer?	WR binaries, post-MT systems, Be XRB dynamical masses, ...
<b>SN remnant masses and kicks</b>	GW masses, NS binary eccentricities, rotation rates?	Physically motivated models + observational constraints (NB: selection effects!)	Gaia detached binaries
<b>Tidal disruption events</b>	Prompt emission? Impact of stellar binaries?		

# Prompt emission from TDEs?

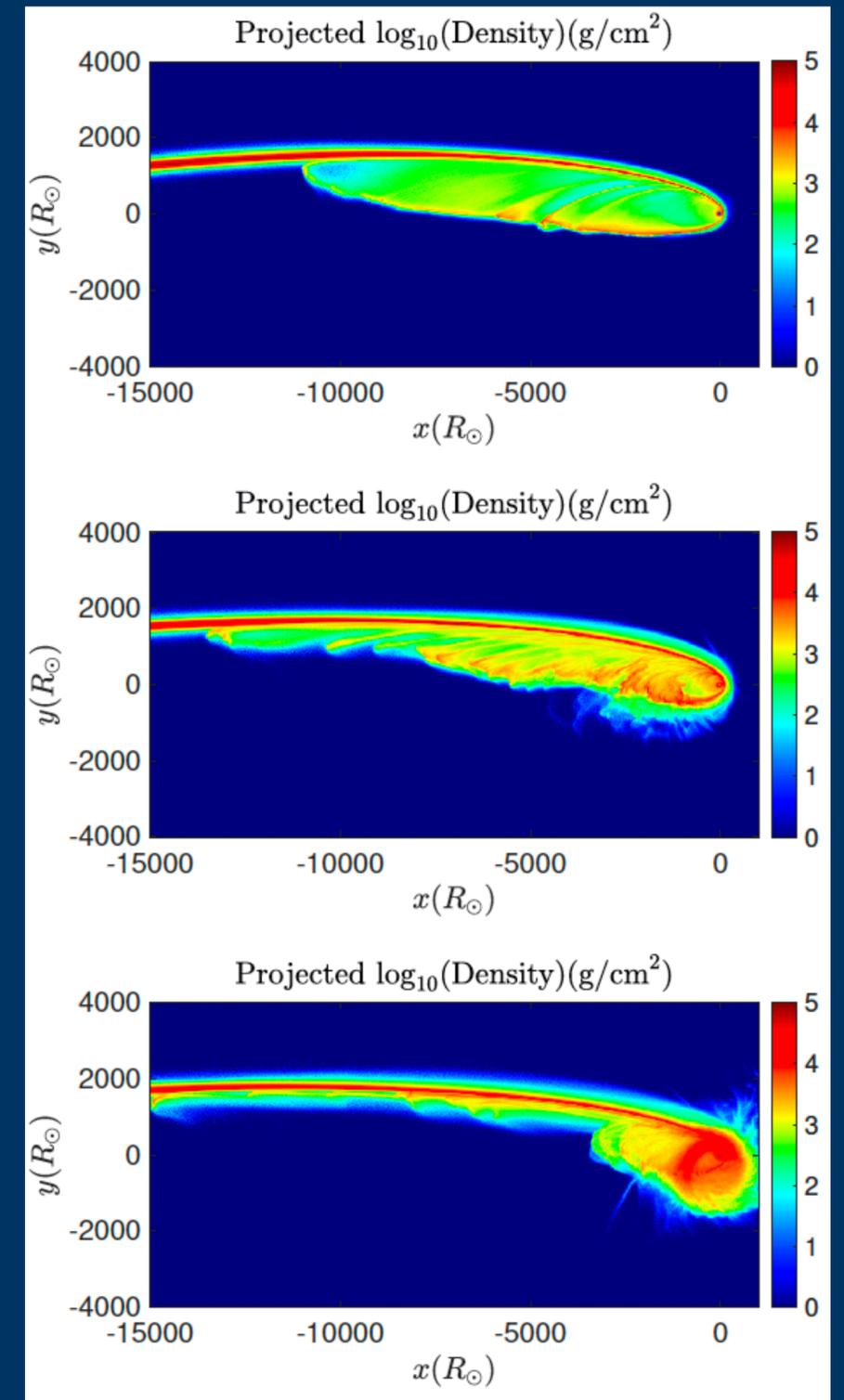


Mockler+, 2018



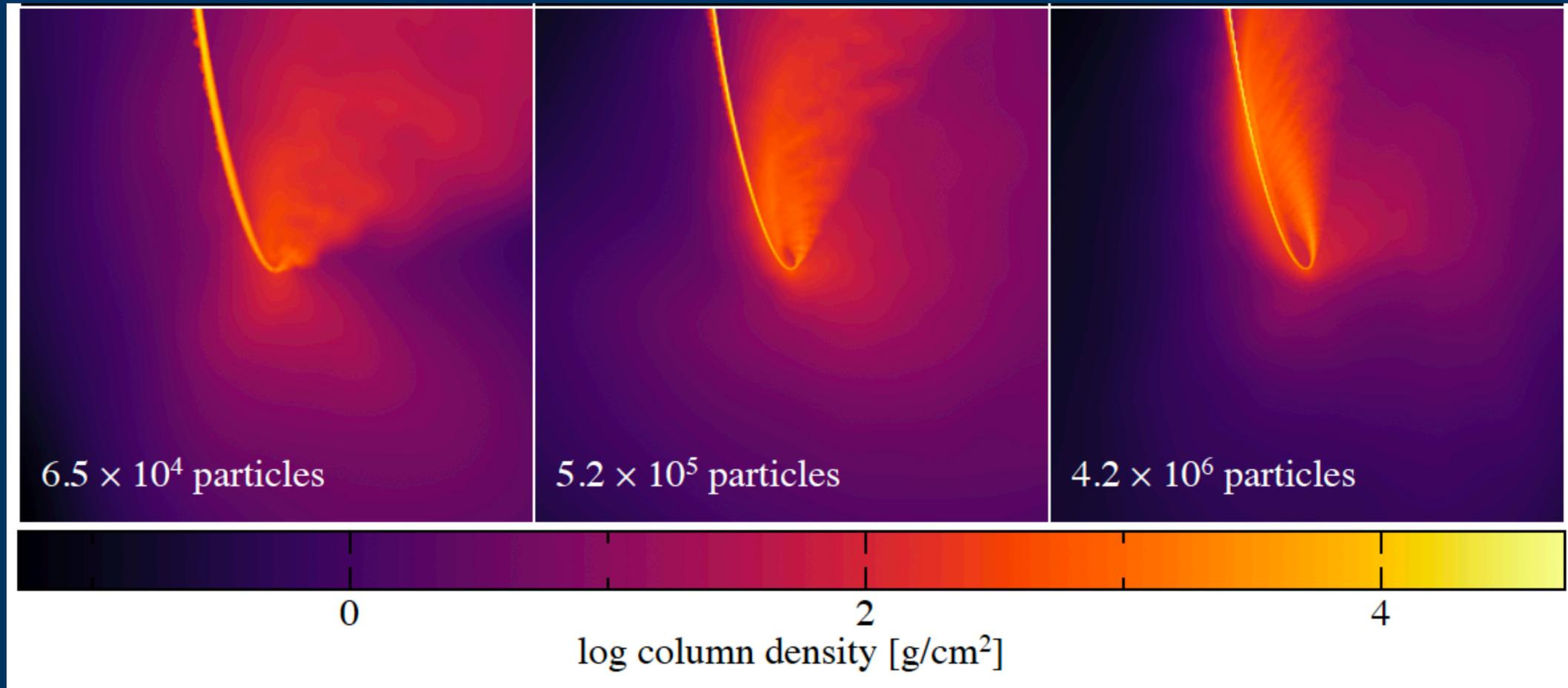
Gezari, 2014

# Nozzle shocks?

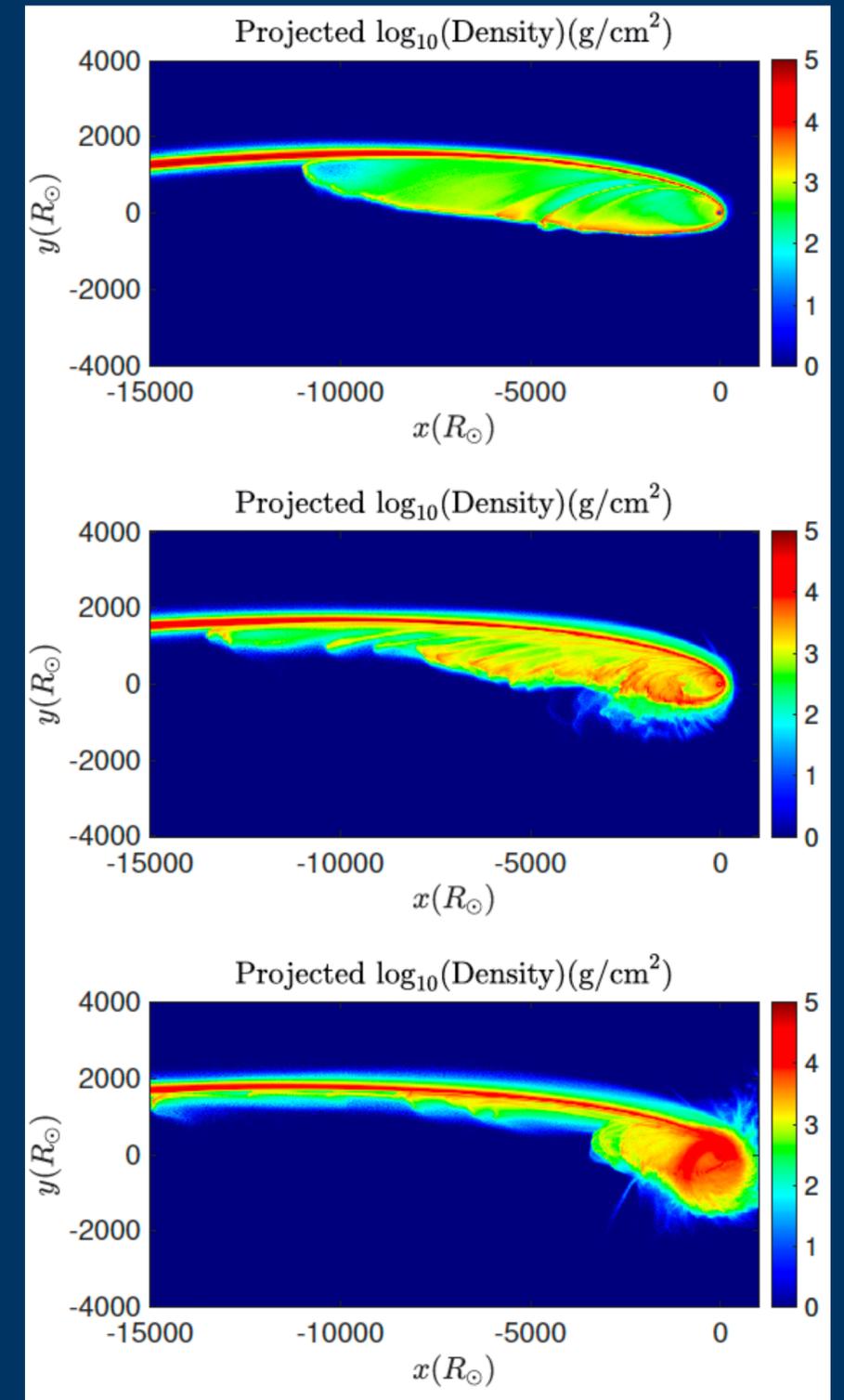


Steinberg & Stone, 2023

# Nozzle shocks?

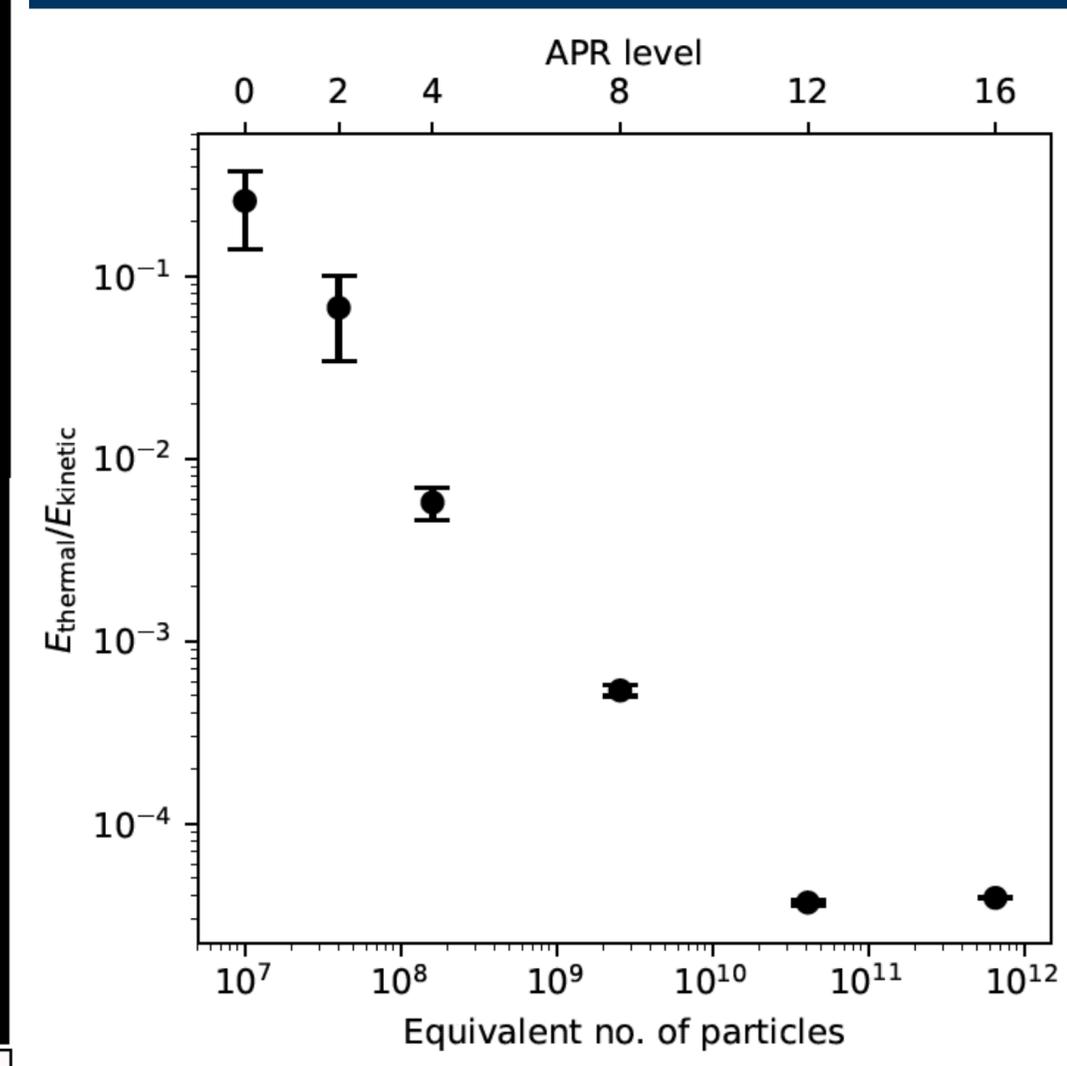
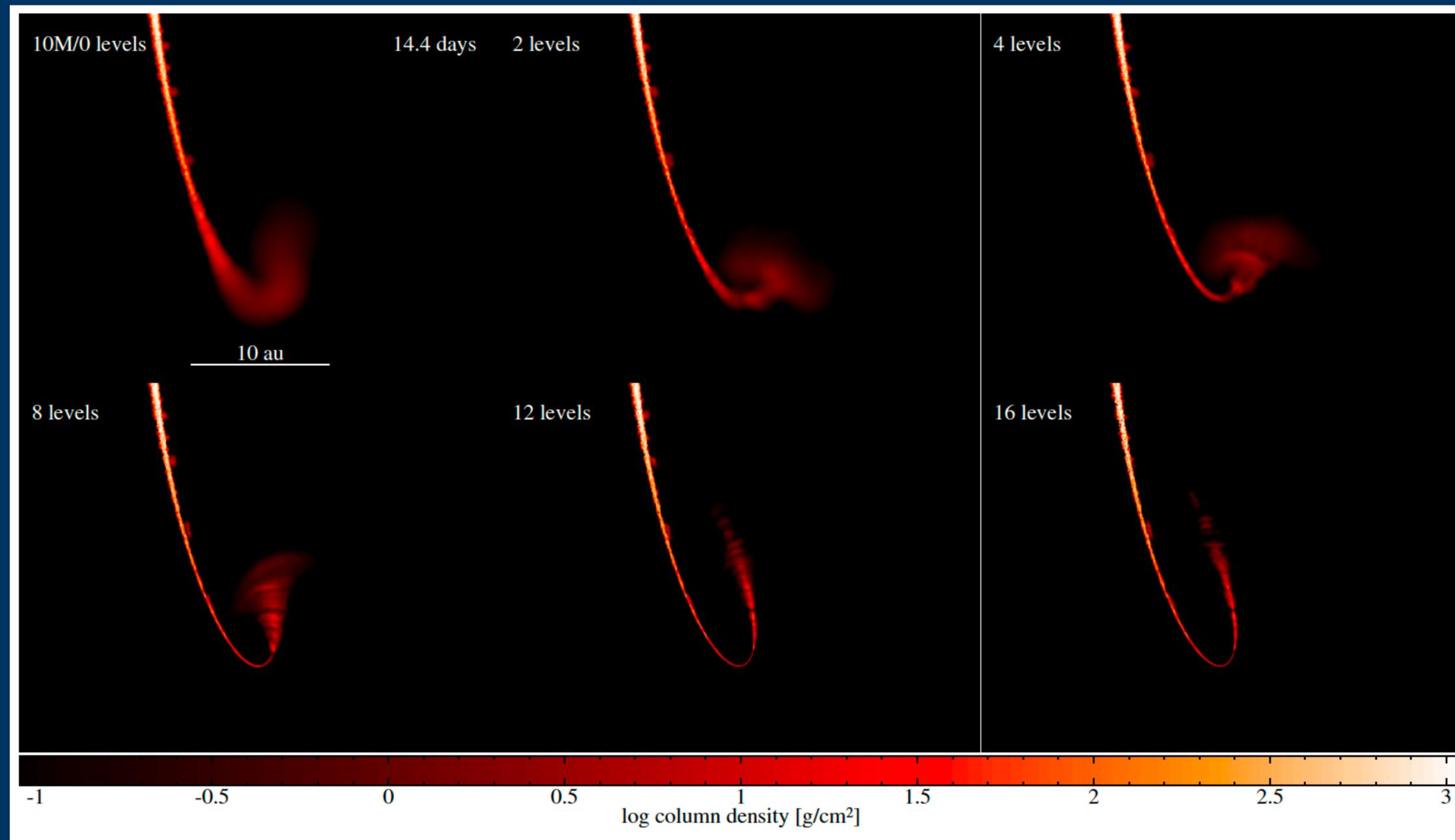


Price+, 2024



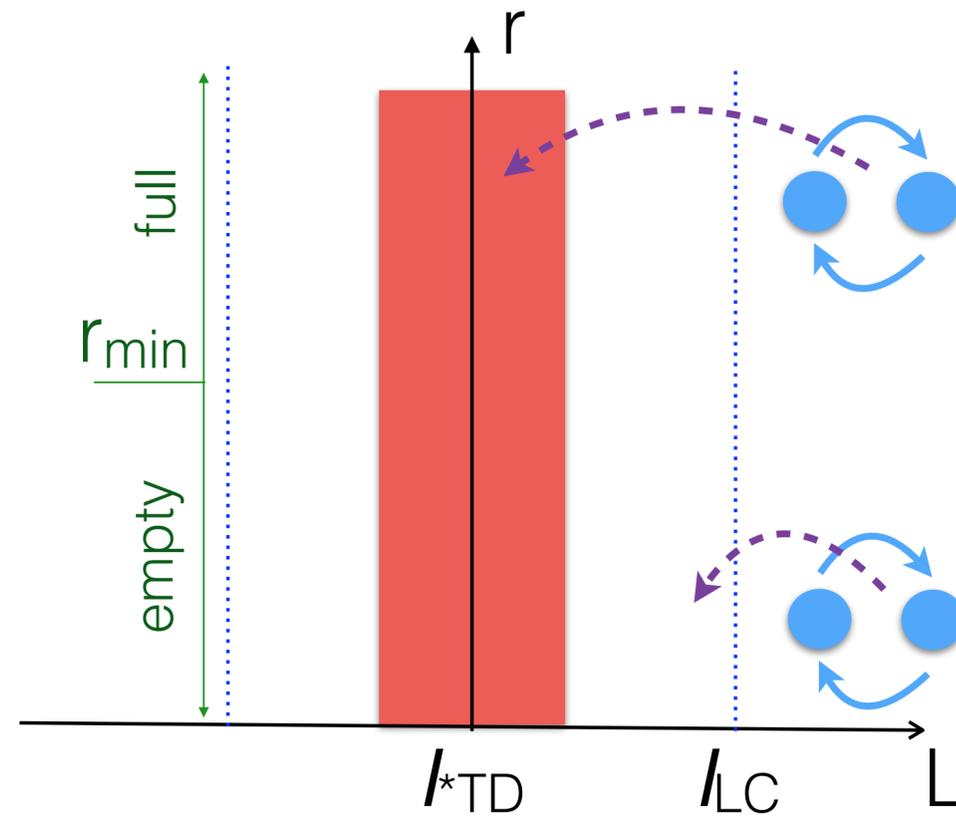
Steinberg & Stone, 2023

# Nozzle shocks? Stream-stream collisions



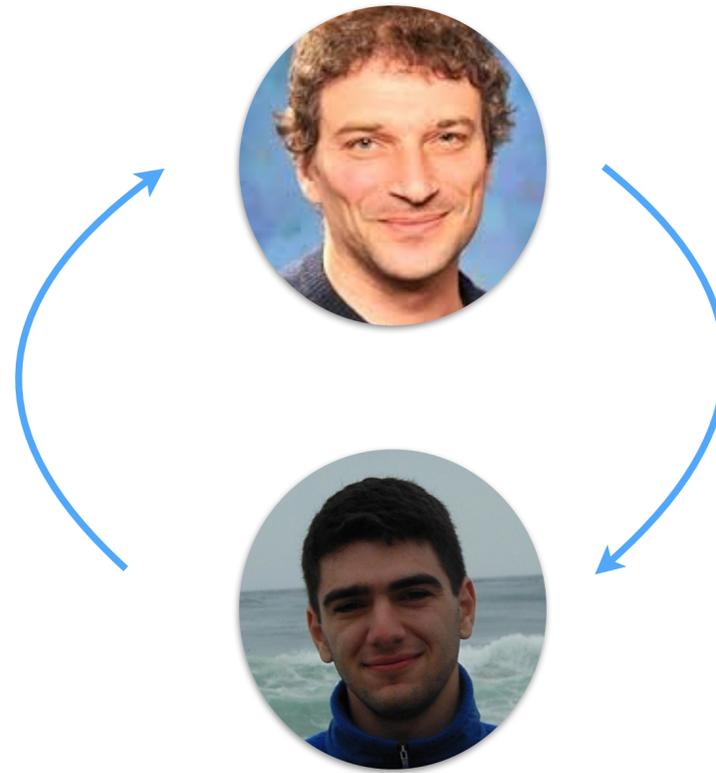
# Loss cone physics

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# Binary tidal disruptions

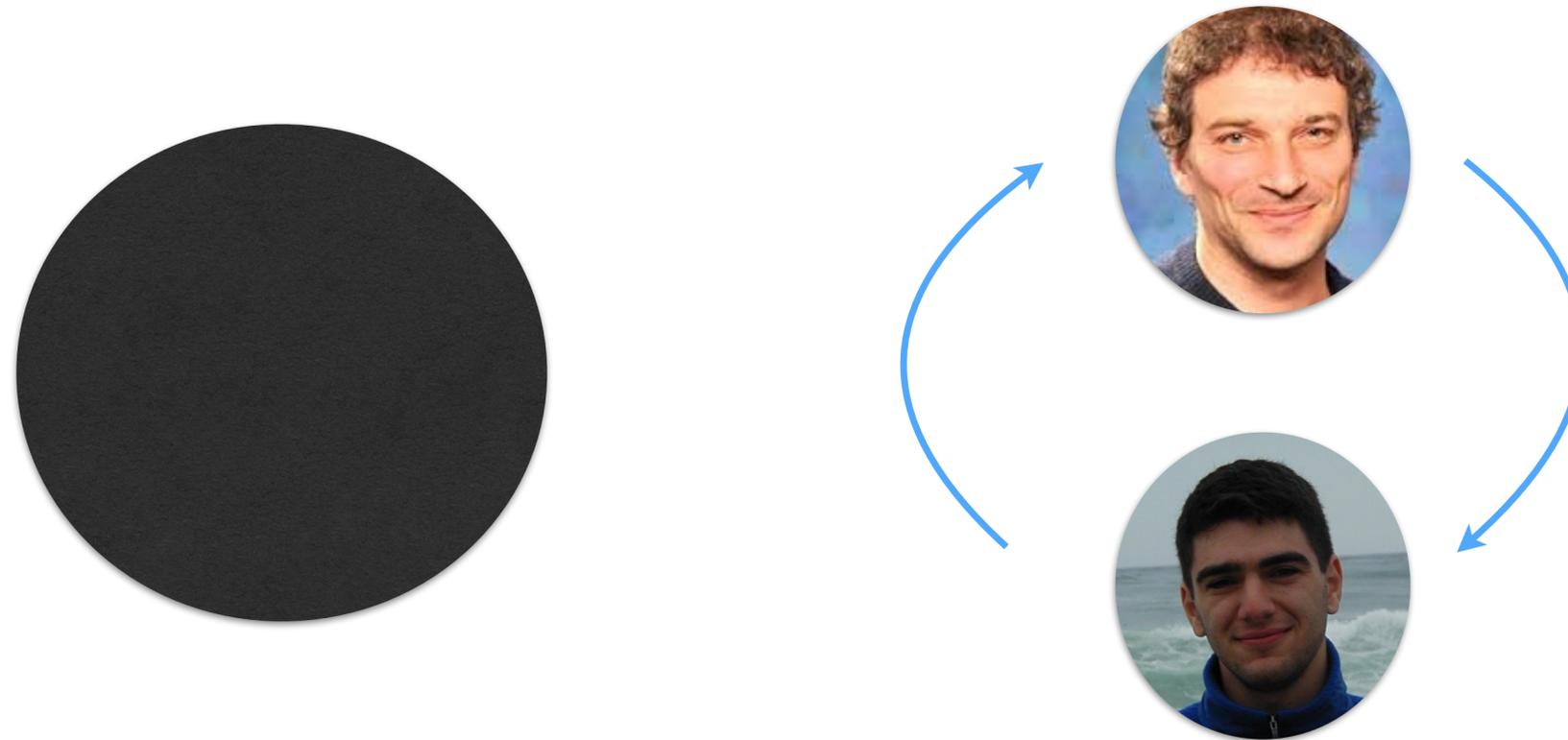
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Mandel & Levin, 2015

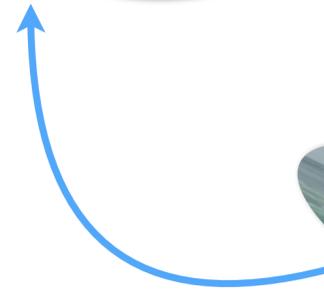
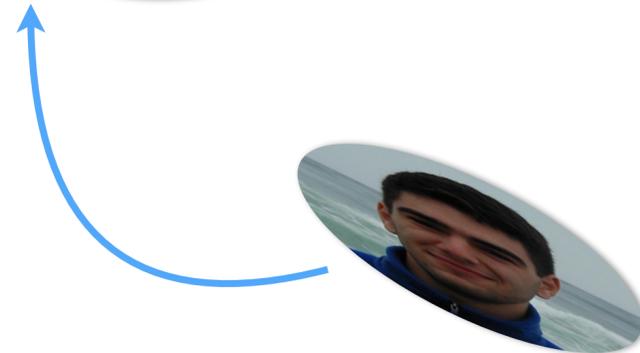
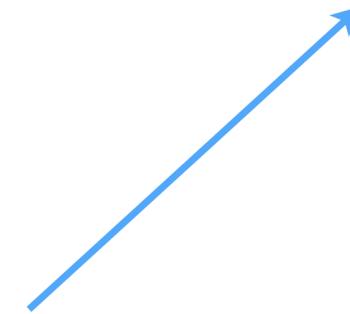
# Binary tidal disruptions

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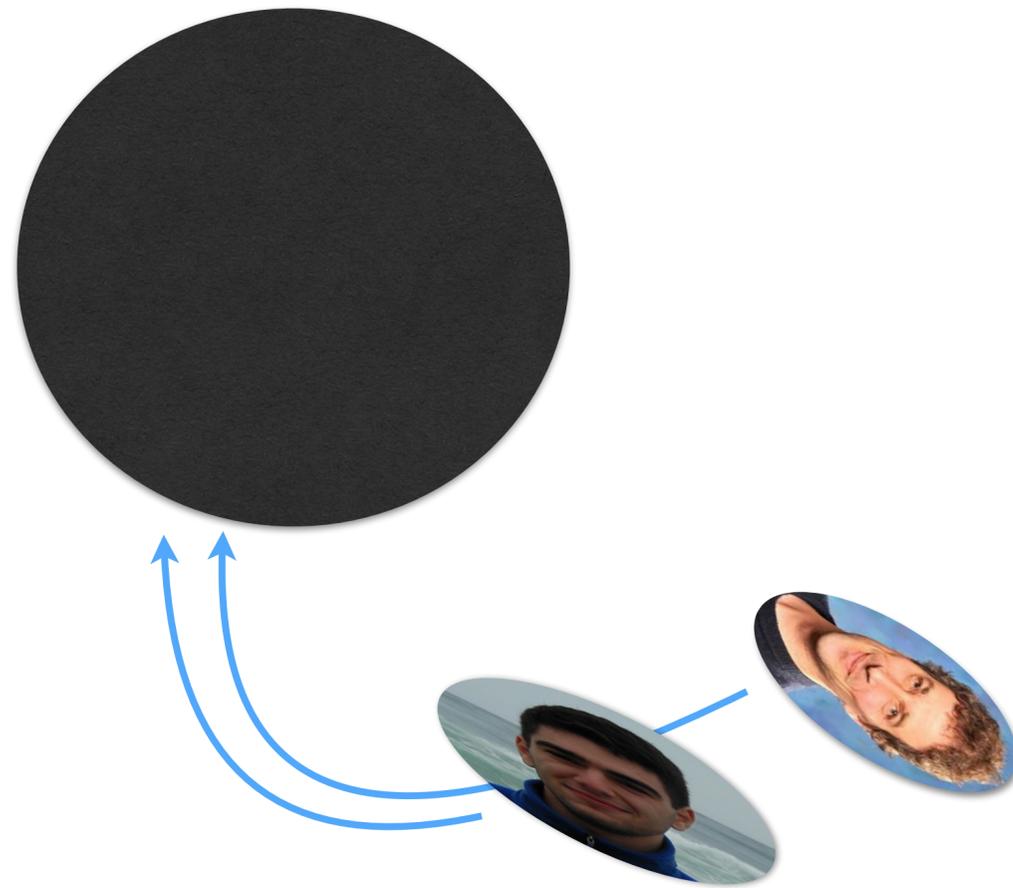
# Binary tidal disruptions

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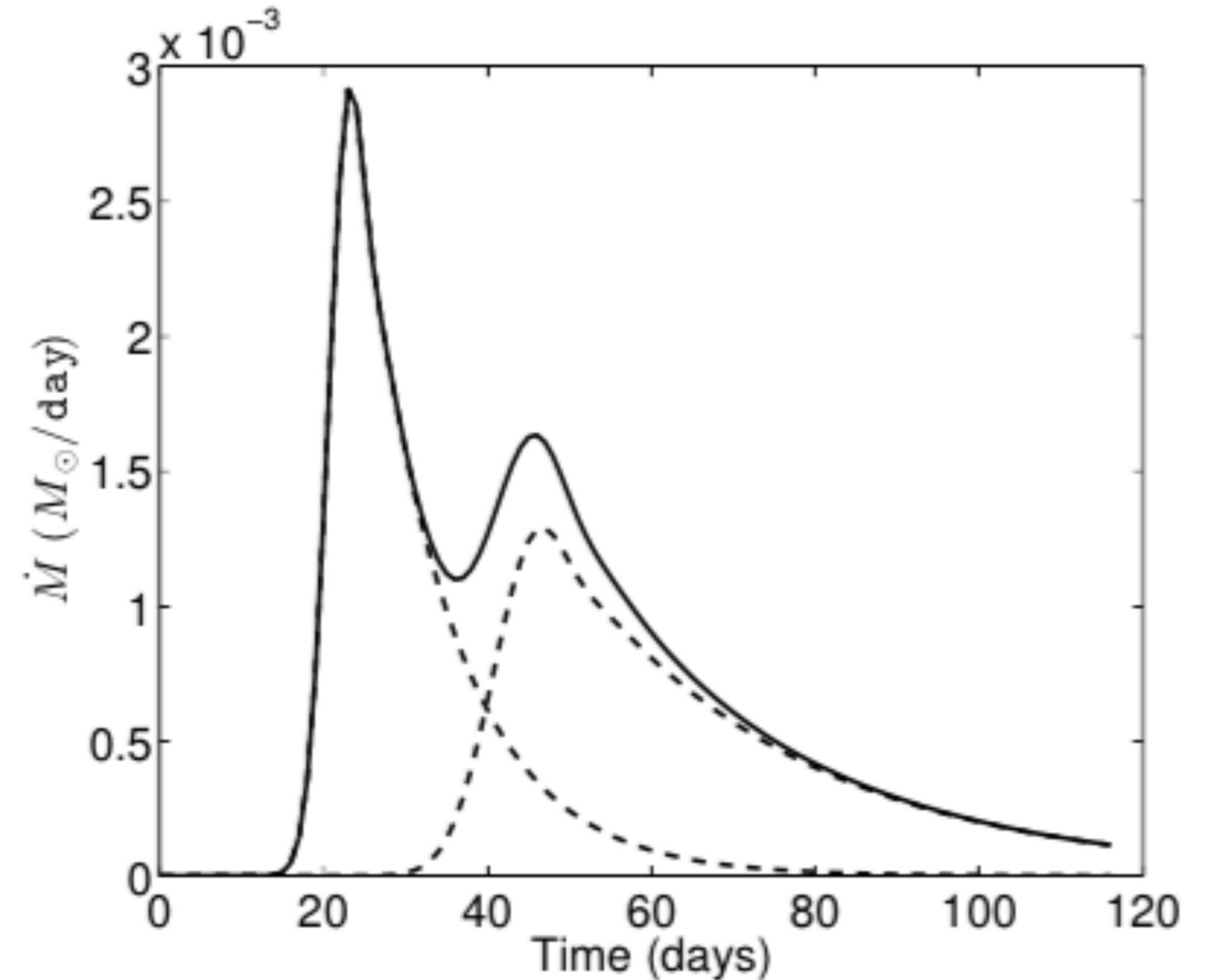
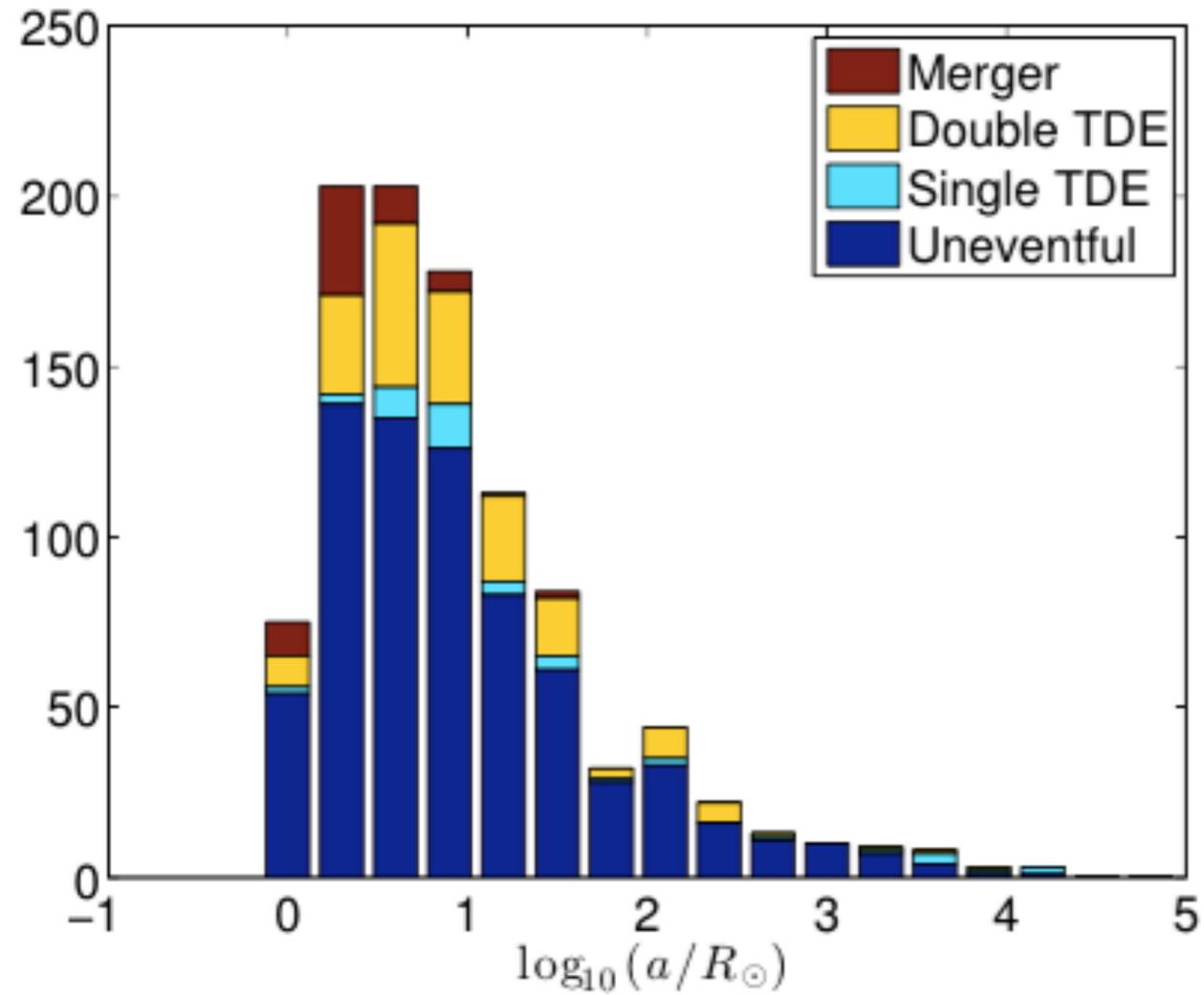


# Binary tidal disruptions

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# Double tidal disruptions



Story elements	Puzzles	Partial solutions	Future tests?
<b>Common Envelopes</b>	Why do GW sources merge?	Common envelope models: 3d, 1d, 0d...	Post-CE binaries, Vera Rubin Observatory LRNe, ...
<b>Stable mass transfer</b>	How do HMXBs form?	Stability and conservativeness of mass transfer?	WR binaries, post-MT systems, Be XRB dynamical masses, ...
<b>SN remnant masses and kicks</b>	GW masses, NS binary eccentricities, rotation rates?	Physically motivated models + observational constraints (NB: selection effects!)	Gaia detached binaries
<b>Tidal disruption events</b>	Prompt emission? Impact of stellar binaries?	Modelling full and empty loss cone dynamics; higher resolution models	More telescope time for Matt, Iair and collaborators :-)

## The Roads Not Taken

The clock hands spin in silent dance,  
Inexorably playing twister.  
With every turn the walls advance,  
Obstructing paths, destroying vistas.

I am hemmed in by mural tricks.  
My every choice forbids a hundred.  
Decisions mutate into bricks  
That indecision binds harder.

I do not dwell on past mistakes,  
On choices made, or those forsaken.  
But I'm the sum of future stakes --  
Reduced by every road not taken.

The options narrow. I diminish.  
I walk along a tunnel. Finish.