Master Degree in Astrophysics and Cosmology

Wolf-Rayet – black hole binaries as progenitors of binary black holes

Supervisor:

Prof. Michela Mapelli

Co-supervisor:

Dr. Giuliano Iorio

Candidate:

Erika Korb

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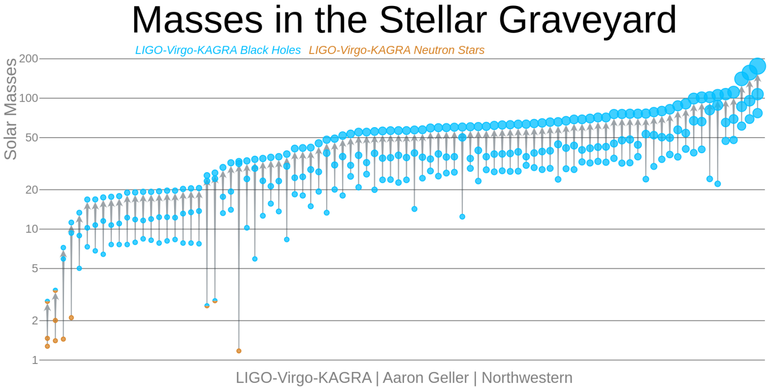
Which are the evolutionary channels of the $\sim$ 90 compact object binaries observed with gravitational wave detectors?

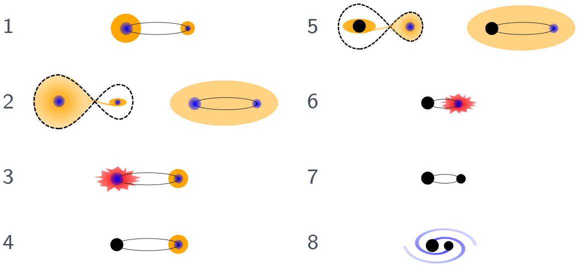


The LIGO-Virgo-KAGRA Collaboration 2021

Limited state-of-the-art models

Probable evolution:

1. Isolated binary
2. **Mass transfer (?)**
3. **Supernova**
4. Black hole + star
5. **Mass transfer**
6. **Supernova**
7. Binary black hole (BBH)
8. Merging via GW emission



Uncertainties:

- **Mass transfer**
- **Core-collapse supernova**
- **Supernova kick**

$\sim$ **80 merging BBHs detected...**

...can we observe their progenitors?

Wolf-Rayet – black hole binaries

Wolf-Rayet stars:

- Strong stellar winds ($\dot{M} \sim 10^4 - 10^5\ M_\odot\ \mathrm{yr}^{-1}$)
- **Little or no H envelope $\rightarrow$ mass transfer product?**
- $R_{\mathrm{WR}} \sim R_\odot$ $\rightarrow$ **allow close orbits** $a \gtrsim R_\odot$ $\rightarrow$ **merging?**

Time to merge only via GW emission

$$t_{\mathrm{GW}}{}^{*} \sim 12\ \mathrm{Gyr} \left(\frac{a}{20\ R_\odot}\right)^4$$

Peters 1964

Only 7 known Wolf-Rayet – black hole candidates

Host galaxy	Name	M_{BH} [$M_\odot$]	M_{WR} [$M_\odot$]	P [hours]	$t_{\mathrm{GW}}{}^{*}$ [Gyr]
Milky Way	**Cyg X-3**	**3-10**	**8-14**	**4.8**	**0.02**
IC 10	IC10 X-1	-	17-35	34.9	3.5
NGC 300	NGC300 X-1	13-21	15-26	32.8	2.9
NGC 253	CXOU J004732.0-251722.1	-	-	14.5	0.3
Circinus	CG X-1	-	-	7.2	0.05
M101	M101 ULX-1	8-46	17-19	196.8	348
NGC 4490	CXOU J123030.3+413853	-	-	6.4	0.04

* t_{GW} estimated with Peters 1964, assuming circular orbit and $M_1 = M_2 = 10\ M_\odot$

Esposito et al. 2015, Koljonen et al. 2017

Goals and methodology of the thesis

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Goals:

1. **Wolf-Rayet – black hole:** progenitors of merging BBHs at $Z_\odot$?
2. **Cyg X-3:** case-study for evolution of merging BBHs at $Z_\odot$

Model-independent results? → 24 combinations of parameters

Methodology:

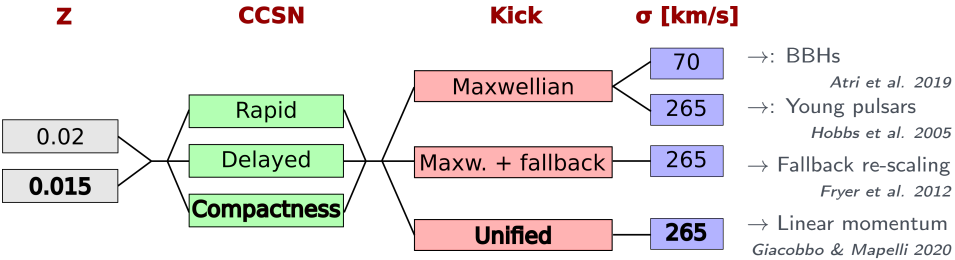
- I generated **24 sets of 10^6 binaries** → initial conditions **representative** of early-binaries observed in the Milky Way

  Sana et al. 2012, Moe & Di Stefano 2017

- **Simulations with the population-synthesis code** `SEVN` (*Stellar EVolution for N-body simulations*)

  Spera et al. 2019, Costa et al. 2021, Iorio et al. in prep.

Parameter space in SEVN



Core-collapse supernova (CCSN)

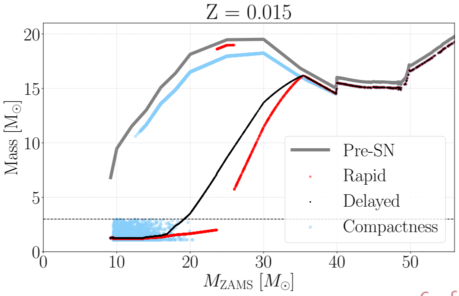
Preference for compact object masses:

- Light (Rapid/Delayed)

  Fryer et al. 2012

- Heavy (Compactness)

  Mapelli et al. 2020

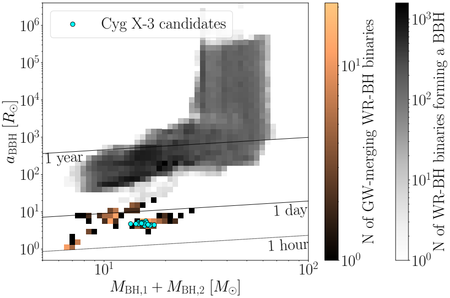


Main results:

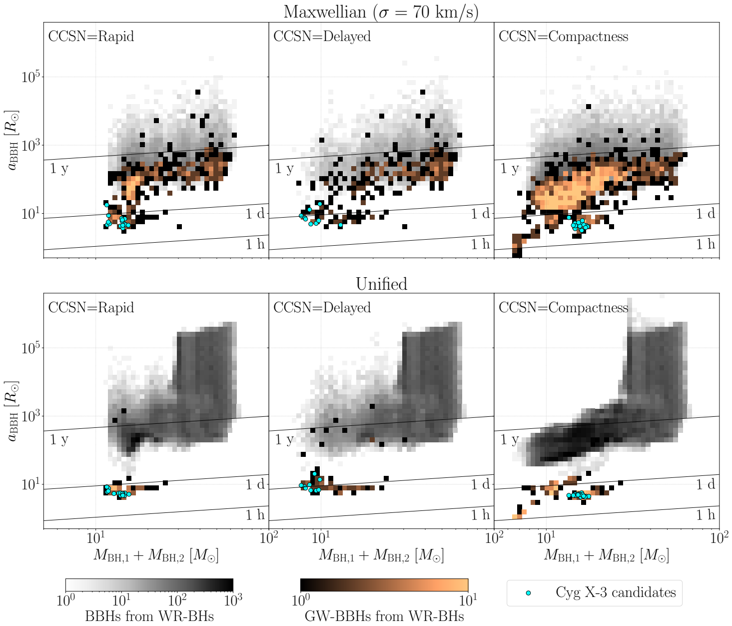
1. Wolf-Rayet – black hole: required for merging BBHs at $Z_\odot$ ($\gtrsim$ **90% probability**)
2. Cyg X-3: progenitor of merging BBHs ($\gtrsim$ **75% probability**)

In this parameter space:

- Results almost model-independent
- Cyg X-3 represents a sub-population of merging BBHs progenitors



Probing the parameter space at Z=0.015



Natal kicks

Pure Maxwellian

$\downarrow$

merging BBHs $a_{\rm BBH} \lesssim 1000\ R_\odot$

$\uparrow$

$t_{\rm GW} \propto (1-e^2)^{7/2}$

Peters 1964

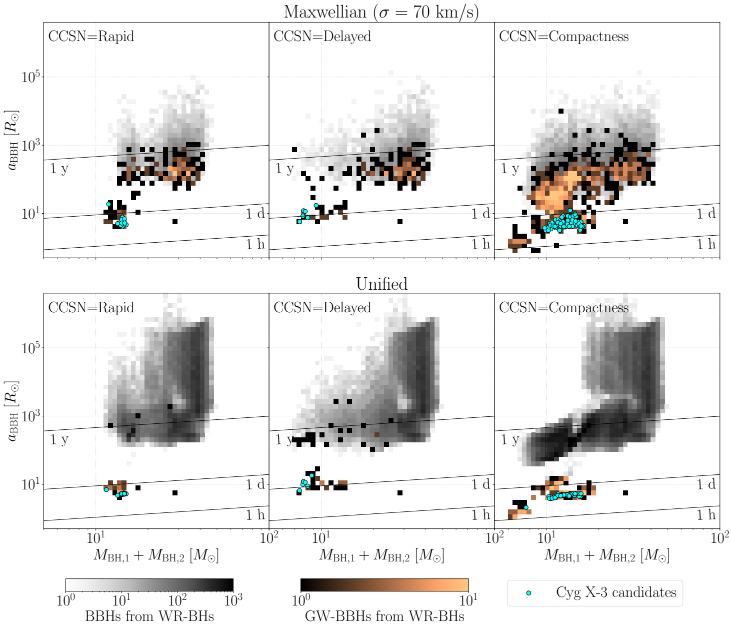
Maxwellian rescaled for

- Compact object mass
- Ejecta mass

$\downarrow$

merging BBHs $a_{\rm BBH} \lesssim 20\ R_\odot$

Probing the parameter space at Z=0.02



Metallicity

Negligible effect

↑

Mass variation

↓

Mass transfer selection

CCSN

Delayed CCSN: 2 common envelope

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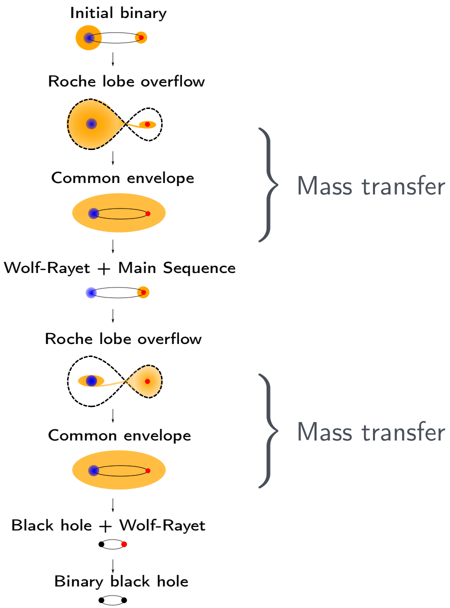
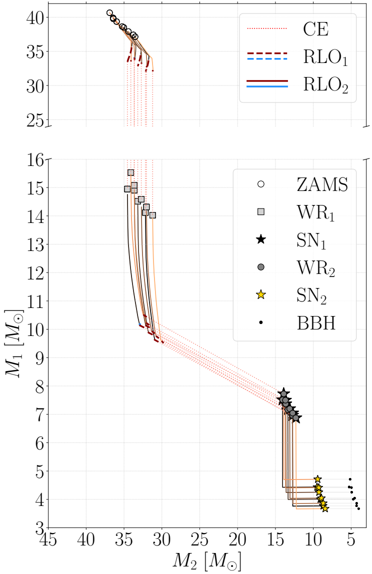
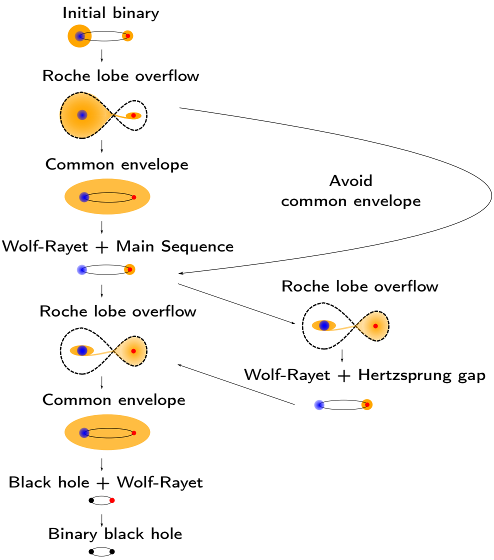
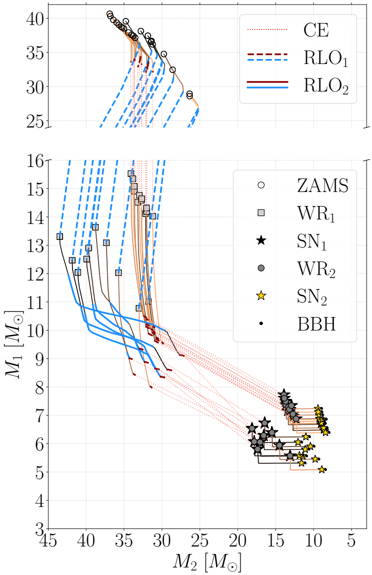




Compactness CCSN: 2 or 3 mass transfer

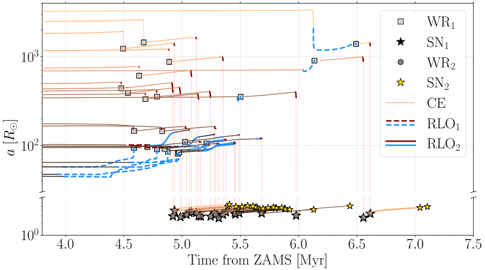


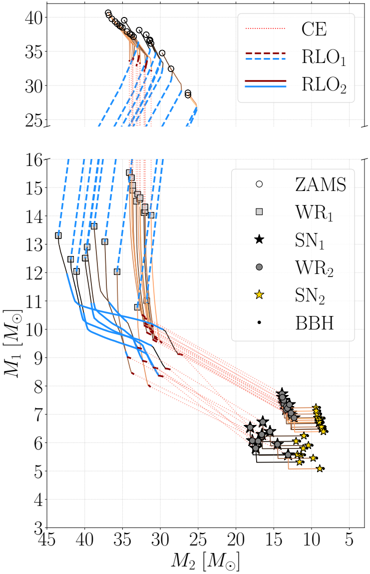


Cyg X-3 evolution and properties

For the fiducial model:

- $M_{\text{ZAMS},1,2} \sim 30 - 40\ M_\odot$
  $a_{\text{ZAMS}} \sim 50 - 3000\ R_\odot$
- 2 or 3 mass transfer episodes
  (1 common envelope needed)
- Wolf-Rayet – black hole for ~ 0.5 Myr
- **Wind-fed systems**
- BBHs merging in $\sim 50 - 200$ Myr

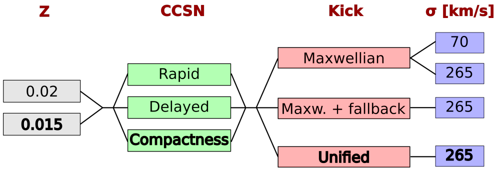




Conclusions

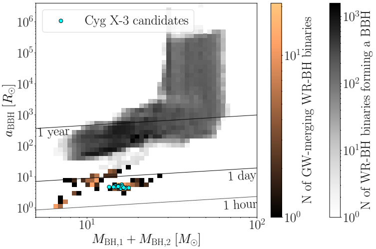
Results (almost) model-independent:

1. Wolf-Rayet – black hole: necessary stage to form merging BBHs at $Z_\odot$ ($\gtrsim$ **90% probability**)
2. Cyg X-3: progenitor of merging BBHs ($\gtrsim$ **75% probability**)



Cyg X-3:

- **Representative** of a **sub-population of merging BBHs progenitors**
- 2 or 3 mass transfer (**1 common envelope**)



Wolf-Rayet – black hole observations → "Rosetta stone" for merging BBHs

Thank you for the attention

Additional slides

Rapid

$$M_{\text{proto}} = 1.0\, M_\odot, \tag{15}$$

$$\begin{cases} M_{\text{fb}} = 0.2\, M_\odot & M_{\text{CO}} < 2.5\, M_\odot \\ M_{\text{fb}} = 0.286 M_{\text{CO}} - 0.514\, M_\odot & 2.5\, M_\odot \leqslant M_{\text{CO}} < 6.0\, M_\odot \\ f_{\text{fb}} = 1.0 & 6.0\, M_\odot \leqslant M_{\text{CO}} < 7.0\, M_\odot \\ f_{\text{fb}} = a_1 M_{\text{CO}} + b_1 & 7.0\, M_\odot \leqslant M_{\text{CO}} < 11.0\, M_\odot \\ f_{\text{fb}} = 1.0 & M_{\text{CO}} \geqslant 11.0\, M_\odot \end{cases} \tag{16}$$

with $a_1 = 0.25 - (1.275/M - M_{\text{proto}})$, $b_1 = -11a_1 + 1$, and $M_{\text{fb}} = f_{\text{fb}}(M - M_{\text{proto}})$ in the mass range for which f_{fb} is given.

The final baryonic mass of the remnant is then

$$M_{\text{rem,bar}} = M_{\text{proto}} + M_{\text{fb}} \tag{17}$$

Delayed

$$\begin{cases} M_{\text{proto}} = 1.2\, M_\odot & M_{\text{CO}} < 3.5\, M_\odot \\ M_{\text{proto}} = 1.3\, M_\odot & 3.5\, M_\odot \leqslant M_{\text{CO}} < 6.0\, M_\odot \\ M_{\text{proto}} = 1.4\, M_\odot & 6.0\, M_\odot \leqslant M_{\text{CO}} < 11.0\, M_\odot \\ M_{\text{proto}} = 1.6\, M_\odot & M_{\text{CO}} \geqslant 11.0\, M_\odot. \end{cases} \tag{18}$$

This assumes that the delay increases for more massive cores, causing more material to accrete onto the proto-NS during the explosion.

The amount of fallback is given by

$$\begin{cases} M_{\text{fb}} = 0.2\, M_\odot & M_{\text{CO}} < 2.5\, M_\odot \\ M_{\text{fb}} = 0.5 M_{\text{CO}} - 1.05\, M_\odot & 2.5\, M_\odot \leqslant M_{\text{CO}} < 3.5\, M_\odot \\ f_{\text{fb}} = a_2 M_{\text{CO}} + b_2 & 3.5\, M_\odot \leqslant M_{\text{CO}} < 11.0\, M_\odot \\ f_{\text{fb}} = 1.0 & M_{\text{CO}} \geqslant 11.0\, M_\odot \end{cases} \tag{19}$$

with $a_2 = 0.133 - (0.093/M - M_{\text{proto}})$, $b_2 = -11a_2 + 1$, and $M_{\text{fb}} = f_{\text{fb}}(M - M_{\text{proto}})$ in the mass range for which f_{fb} is given.

The final baryonic mass of the remnant is then

$$M_{\text{rem,bar}} = M_{\text{proto}} + M_{\text{fb}}, \tag{20}$$

Fryer et al. 2012

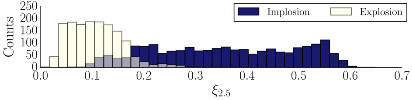
Compactness

$$\xi_{2.5} = \frac{2.5}{R(2.5\ M_\odot)}$$

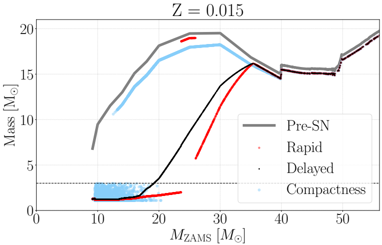
O'Connor et al. 2011

$$\xi_{2.5} = 0.55 - 1.1 \left(\frac{1\ M_\odot}{M_{\text{CO}}} \right)$$

Mapelli et al. 2020



Sukhbold et al. 2016



Kick models in SEVN

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Maxwellian

$$\boxed{v = f_\sigma}$$

- $\sigma = 70$ km/s $\rightarrow$ BBHs natal kicks

Atri et al. 2019

- $\sigma = 265$ km/s $\rightarrow$ young pulsars natal kicks

Hobbs et al. 2005

Maxwellian (+ fallback)

$$\boxed{v = f_\sigma \left(1 - f_{\rm fb}\right)} \qquad f_{\rm fb} = M_{\rm fb}/(M_{\rm rem} - M_{\rm proto}) \in [0, 1]$$

Fryer et al. 2012

Unified

$$\boxed{v = f_\sigma \frac{M_{\rm ej}}{\langle M_{\rm ej} \rangle} \frac{\langle M_{\rm NS} \rangle}{M_{\rm rem}}} \qquad M_{\rm ej} = M_{\rm pre-SN} - M_{\rm rem}$$

with $\langle M_{\rm NS} \rangle \sim 1.30\ M_\odot \quad \langle M_{\rm ej} \rangle \sim 10.30\ M_\odot$ *Giacobbo & Mapelli 2020*

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Unstable Roche lobe overflow if $q \geq q_{\rm crit}$

Stellar phase	Burning	Condition	BSE phase	$q_{\rm crit}$
Main sequence	H-core	$M_{\rm ZAMS} \geq 0.7\ M_\odot$	1	3.0
Hertzsprung-gap	H-shell	$f_{\rm conv} < 0.33$	2	4.0
First giant branch	H-shell	$f_{\rm conv} \geq 0.33$	3	Equation 1
Core He burning	He-core	$f_{\rm conv} < 0.33$	4	3.0
Asymptotic giant branch	He-shell	$f_{\rm conv} \geq 0.33$	5	Equation 1
Wolf-Rayet	He-core	$M_{\rm He} > 0.979\ M$	7	3.0
Wolf-Rayet	He-shell	$M_{\rm He} > 0.979\ M$	8	0.784

$$q_{\rm crit} = 0.362 + \frac{1}{3\left(1 - \frac{M_{\rm He,d}}{M_{\rm d}}\right)}. \tag{1}$$

Hurley et al. 2002, Iorio et al. in prep.

Initial conditions with SEVN

Primary masses

$$\boxed{\xi(M_1) \propto M_1^{-2.3}} \qquad M_1 \in [10, 150]\ M_\odot$$

Sana et al. 2012

Mass ratios

$$\boxed{\xi(q) \propto q^{0.1}} \qquad q = M_2/M_1 \in [0.1, 1]$$

$$\xi(M_2) = \xi(M_1)\,\xi(q) \qquad M_2 \in [1\ M_\odot, M_1]$$

Sana et al. 2012

Periods

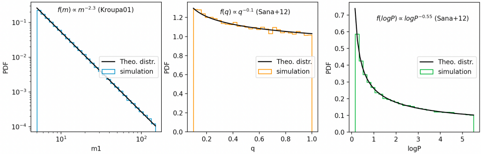
$$\boxed{\xi(\mathcal{P}) \propto \mathcal{P}^{-0.55}} \qquad \mathcal{P} = \log(P/\text{days}) \in [0.30, 5.5]$$

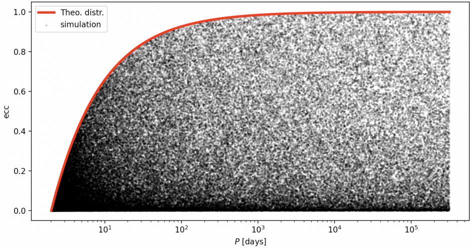
Sana et al. 2012

Eccentricities

$$\boxed{\xi(e(P)) \propto 1 - (P/\text{days})^{-2/3}} \qquad P \geq 2 \text{ days}$$

Moe & Di Stefano 2017





Results (1)

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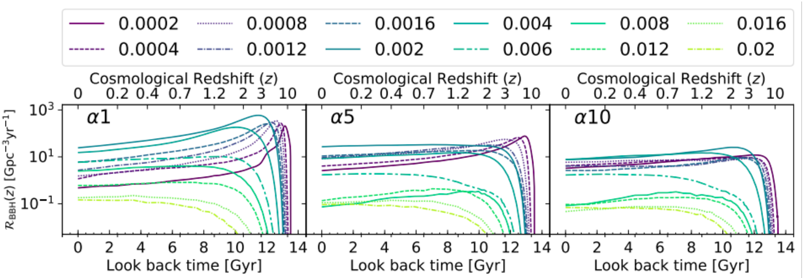
Metallicity	$Z = 0.02$			$Z = 0.015$		
CCSN model	Rap	Del	Com	Rap	Del	Com
Natal kick model	Maxwellian ($\sigma = 70$ km/s)					
BBHs	5626	5248	18425	10350	7564	27740
after a WR–BH	100%	100%	100%	99%	99%	100%
GW–BBHs	207	171	949	418	282	1287
after a WR–BH	207	171	948	418	281	1285
Cyg X-3 candidates	14	8	76	16	10	18
becoming GW–BBHs	14	6	76	16	9	18
Natal kick model	Maxwellian ($\sigma = 265$ km/s)					
BBHs	166	156	727	416	260	1420
after a WR–BH	100%	100%	100%	99%	99%	100%
GW–BBHs	34	21	221	101	67	392
after a WR–BH	34	21	221	101	67	392
Cyg X-3 candidates	4	2	29	6	4	7
becoming GW–BBHs	4	0	23	5	3	7

Results (2)

Metallicity	$Z = 0.02$			$Z = 0.015$		
CCSN model	Rap	Del	Com	Rap	Del	Com
Natal kick model	Maxwellian + fallback					
BBHs	44307	35029	96557	55986	45701	109935
after a WR–BH	100%	100%	96%	92%	96%	94%
GW–BBHs	70	108	271	230	173	201
after a WR–BH	70	108	257	225	168	189
Cyg X-3 candidates	15	6	70	19	12	22
becoming GW–BBHs	15	5	70	19	9	22
Natal kick model	Unified					
BBHs	55655	46373	142613	71016	61257	157671
after a WR–BH	90%	95%	68%	87%	88%	69%
GW–BBHs	45	62	246	74	76	177
after a WR–BH	45	57	244	73	73	177
Cyg X-3 candidates	16	7	70	19	9	22
becoming GW–BBHs	16	6	70	19	9	22

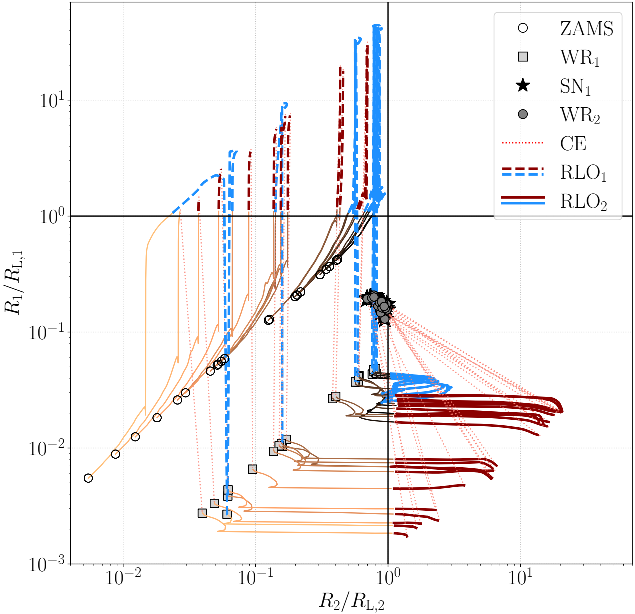
Merger redshift and metallicity

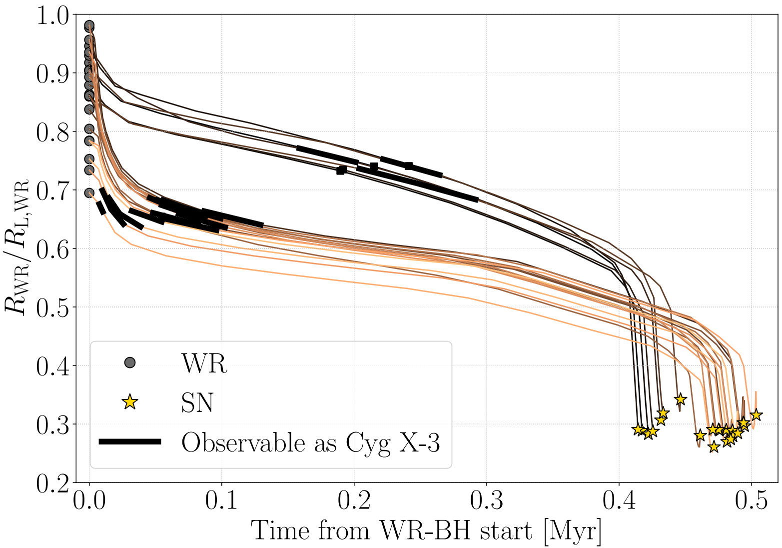
$\sim 10\%$ of today's BBH mergers have solar metallicity



Santoliquido et al. 2021

Fiducial evolution of Cyg X-3





1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
$R_{\mathrm{WR}}/R_{\mathrm{L,WR}}$
0.0
0.1
0.2
0.3
0.4
0.5
Time from WR-BH start [Myr]
WR
SN
Observable as Cyg X-3

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Metallicity:

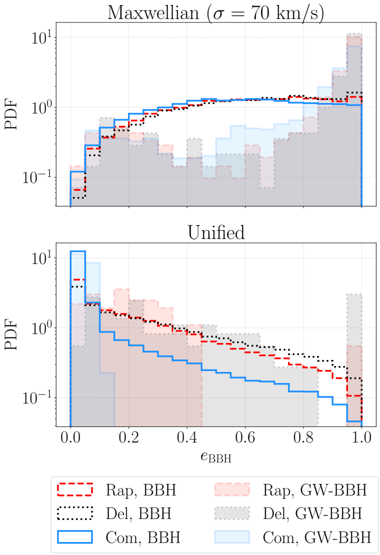
- **Negligible impact** ($Z_\odot$=0.02 vs $Z_\odot$=0.015)
- $\neq$ number of systems, $\approx$ probability

Kick

- **Strong kicks $\rightarrow e_{\mathrm{BBH}} \sim 1$ probable** $t_{\mathrm{GW}} \propto (1-e^2)^{7/2}$ *Peters 1964*
- Merging BBHs for $a_{\mathrm{BBH}} \lesssim 1000\ R_\odot$

Core-collapse supernova:

- **Compact object mass and nature**
- **Selects mass transfer evolution**



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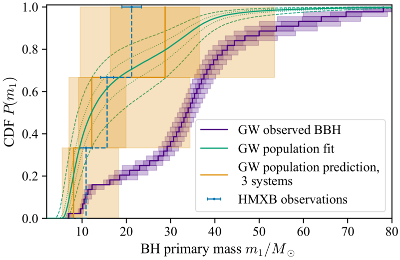
High Mass X-ray binaries:

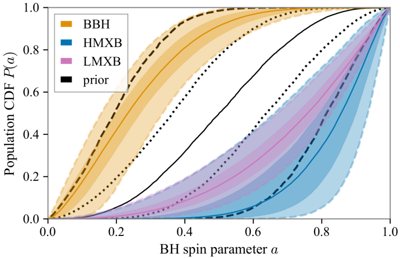
- accreting **black hole**
- **massive donor** ($\gtrsim 5\ M_\odot$)

Are progenitors of binary black holes?:

- Difficult to characterize (mass, spin)
- Compatible in the mass distribution
- **Tension in the spin distribution**

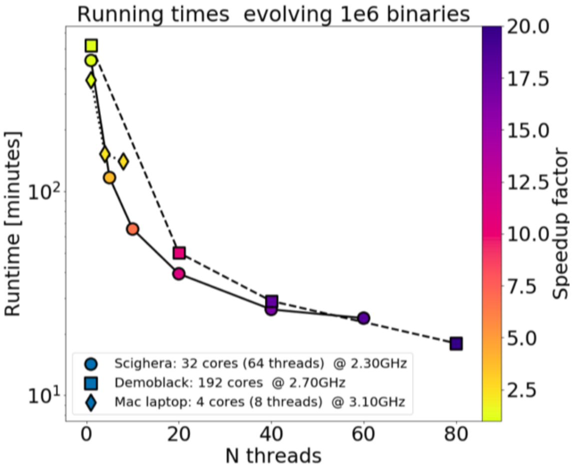
The debate is still open!





Fishbach & Kalogera 2022

SEVN speed



Running times evolving 1e6 binaries
Runtime [minutes]
10^2
10^1
0
20
40
60
80
N threads
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
Speedup factor
Scighera: 32 cores (64 threads) @ 2.30GHz
Demoblack: 192 cores @ 2.70GHz
Mac laptop: 4 cores (8 threads) @ 3.10GHz