Mass-gap & intermediate-mass BHs in dense star clusters:

The role of massive star binaries

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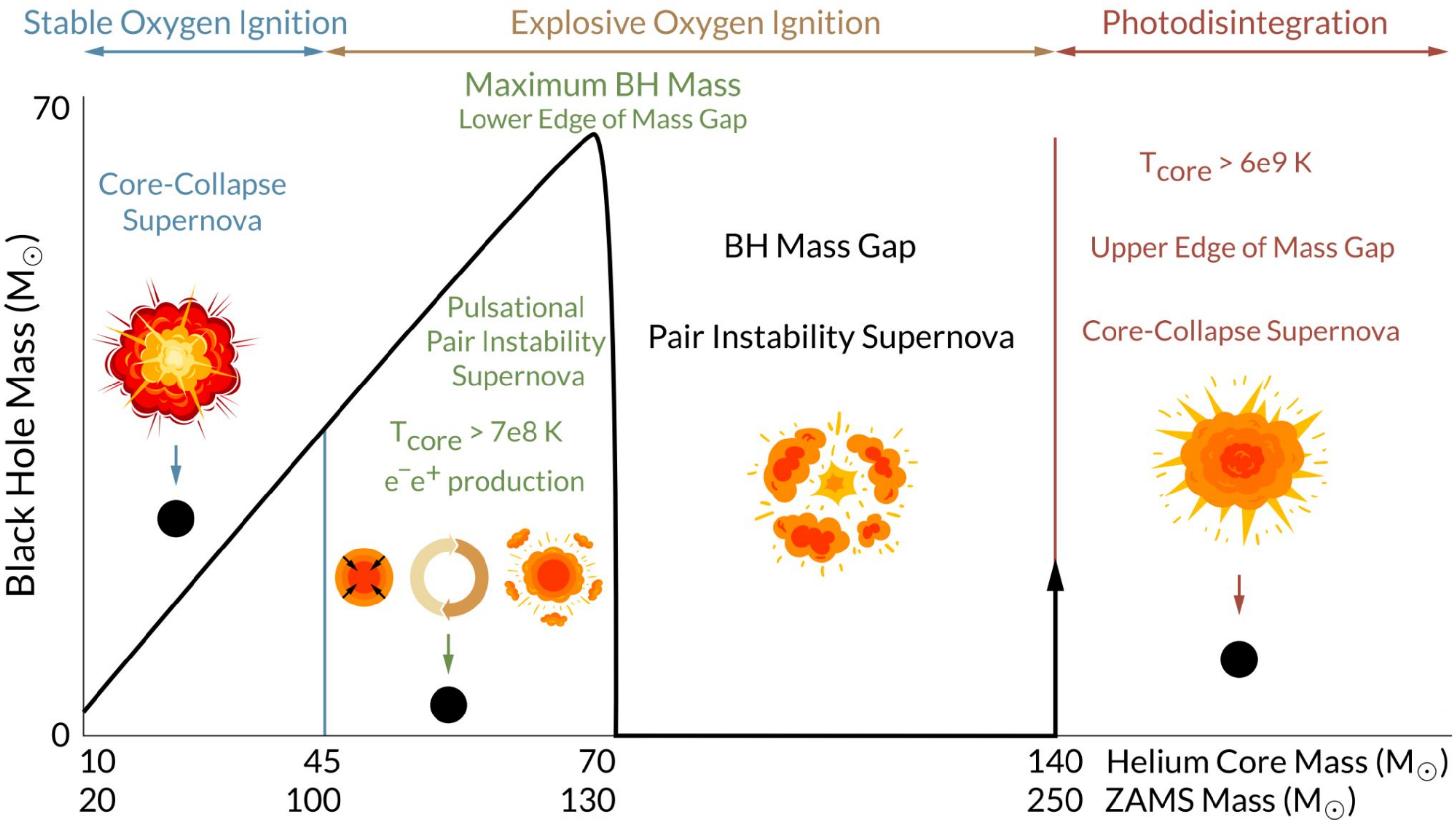
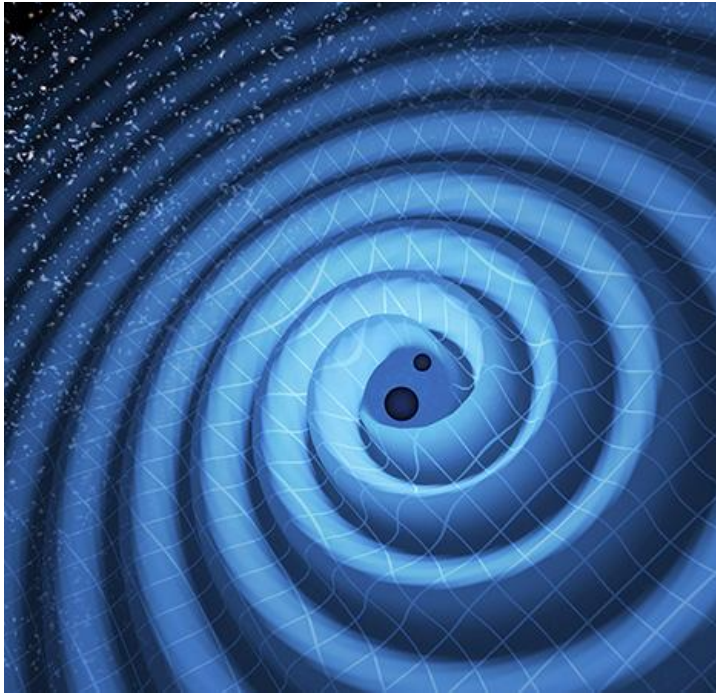
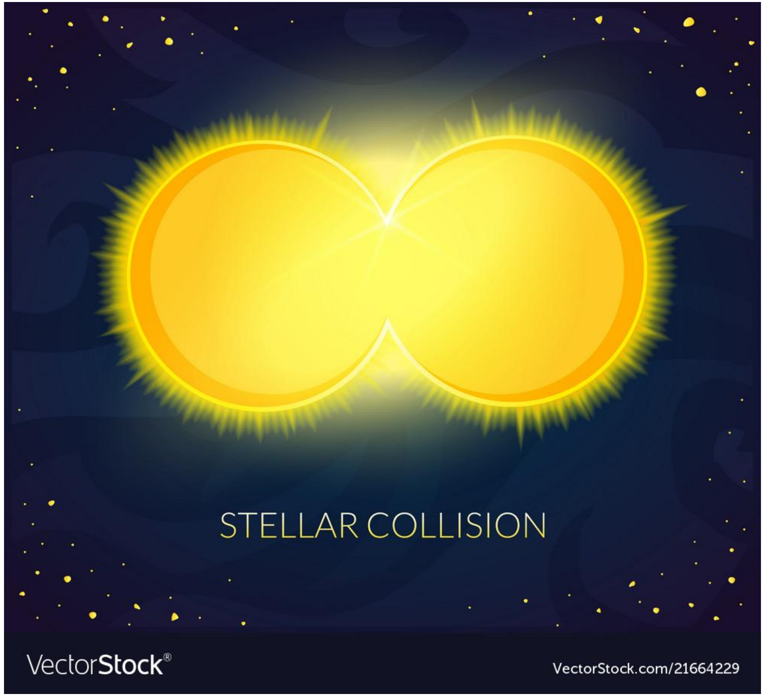
Upper mass-gap



Farag et al. 2022

Ways to form mass-gap BHs





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e.g., Ballone et al.2022

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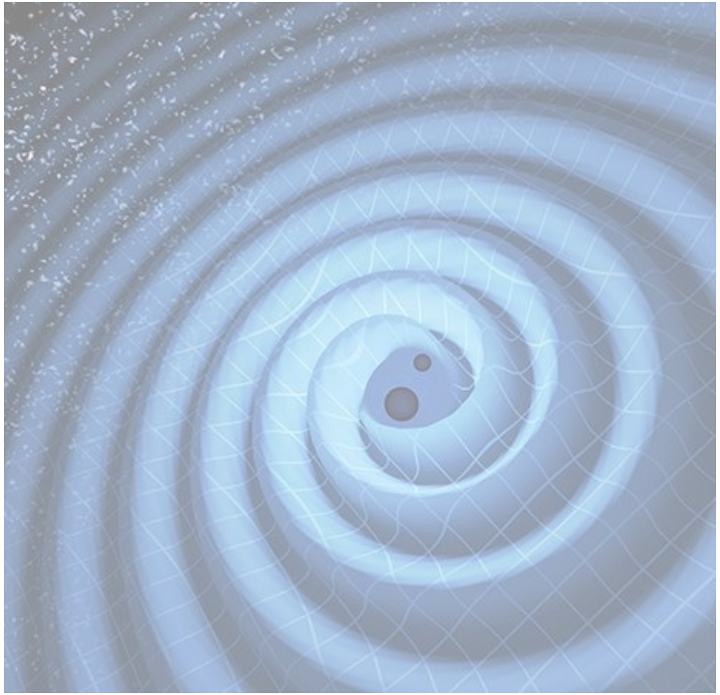

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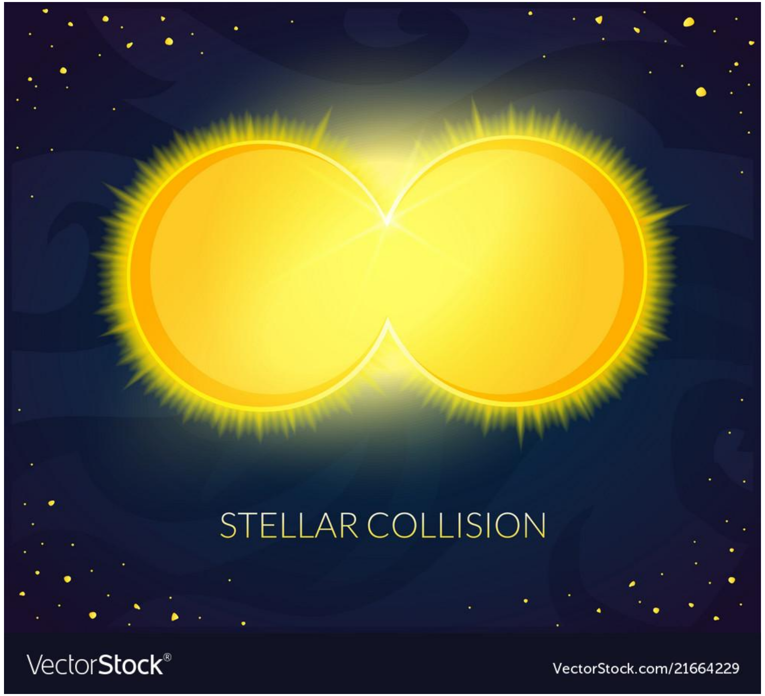
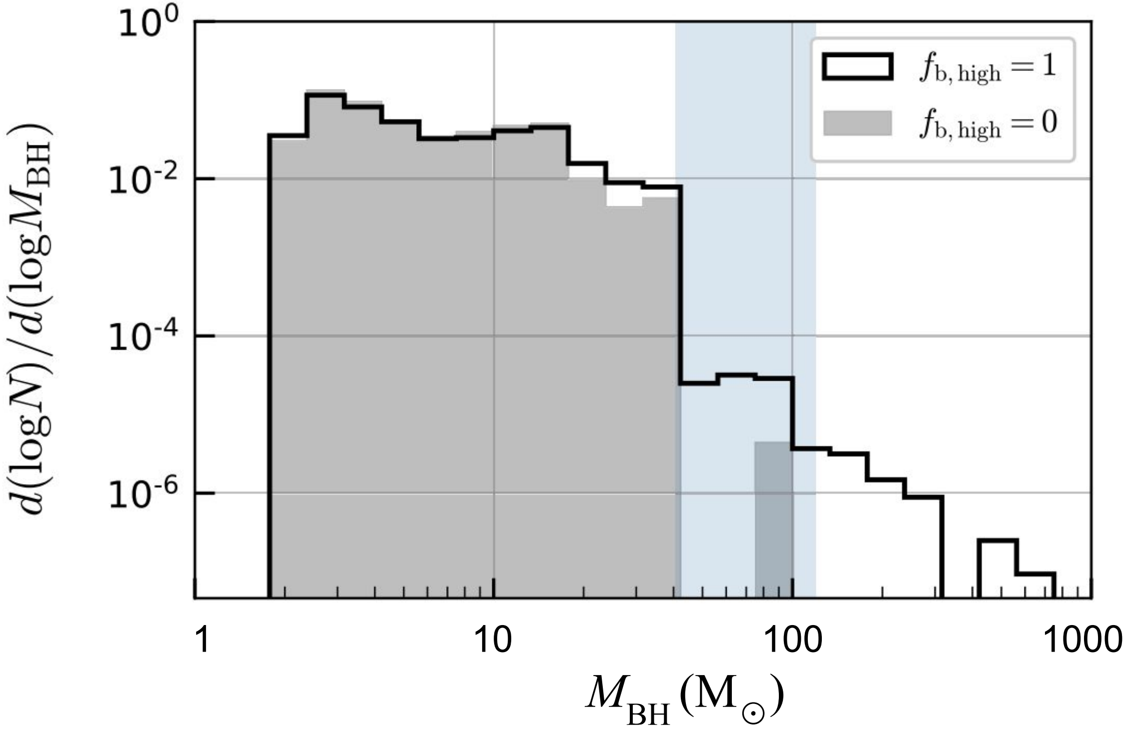


e.g., Ballone et al.2022

Massive star clusters with $f_{b,high}$=1 can create mass-gap BHs

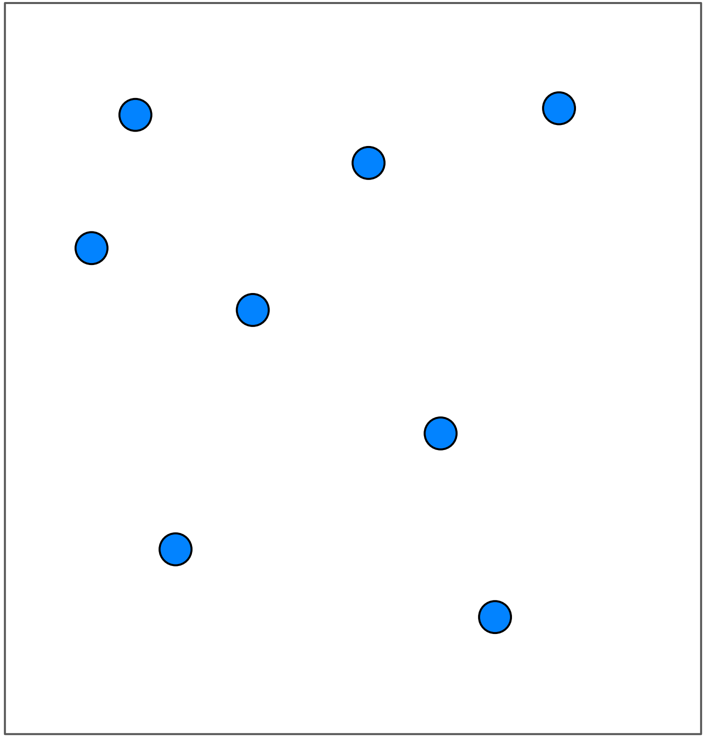


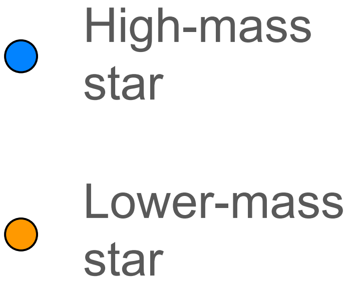
González et al. 2021

Differences between the models with $f_{b,high}$= 1 and 0

$f_{b,high}$= 1	$f_{b,high}$= 0
All high-mass stars are in binaries	All high-mass stars are singles
N_{high}	N_{high}

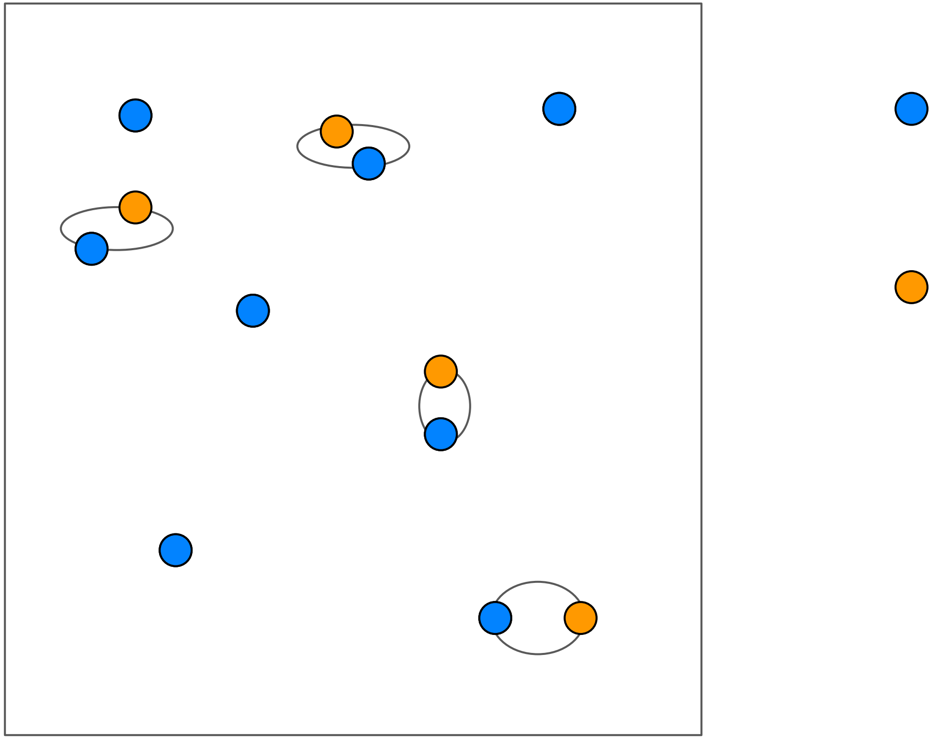
Differences between the models with $f_{b,high}$ = 1 and 0





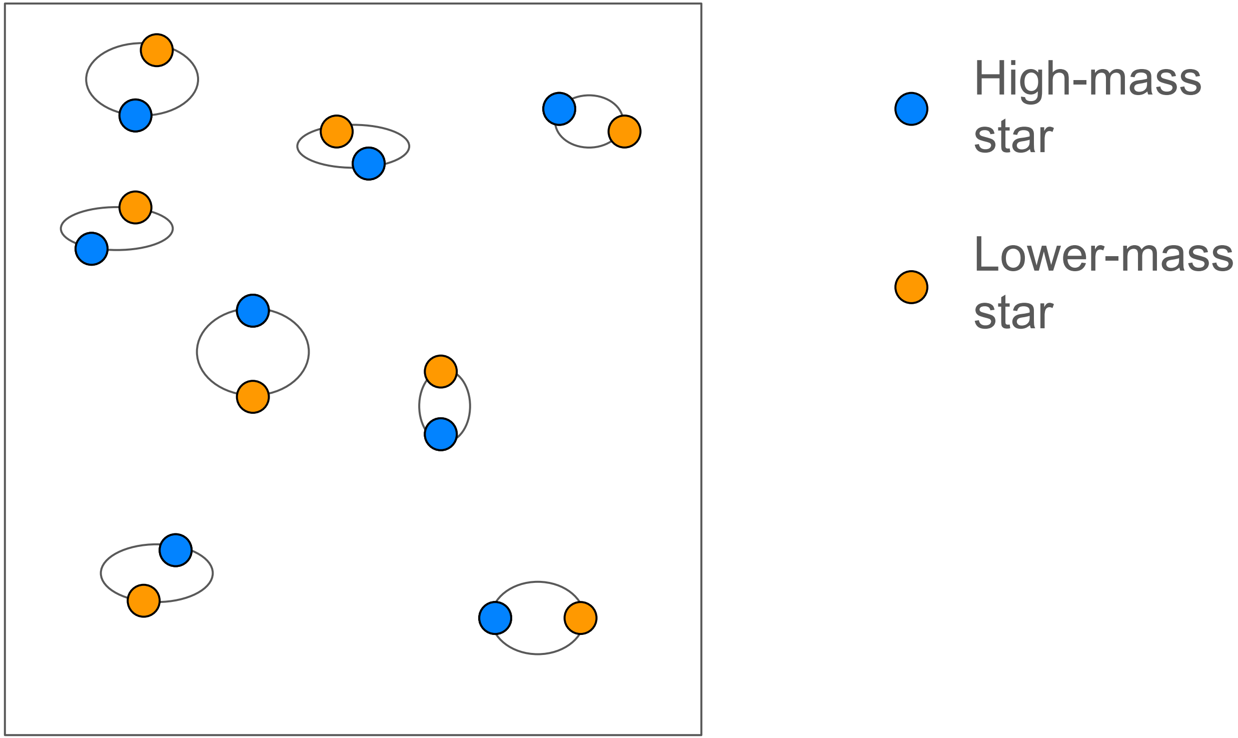
Differences between the models with $f_{b,high}$ = 1 and 0

$f_{b,high}$ = 0.5



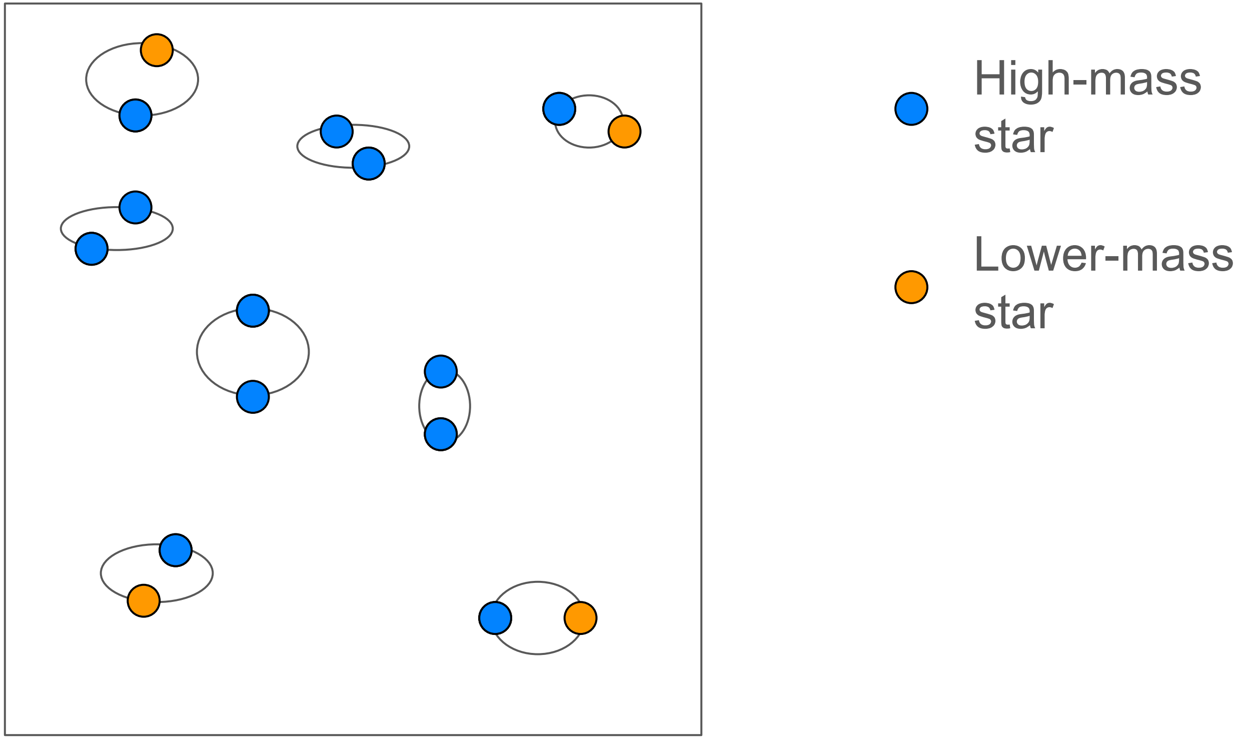
Differences between the models with $f_{b,high}$= 1 and 0

$f_{b,high}$= 1.0



Differences between the models with $f_{b,high}$ = 1 and 0

$f_{b,high}$ = 1.0



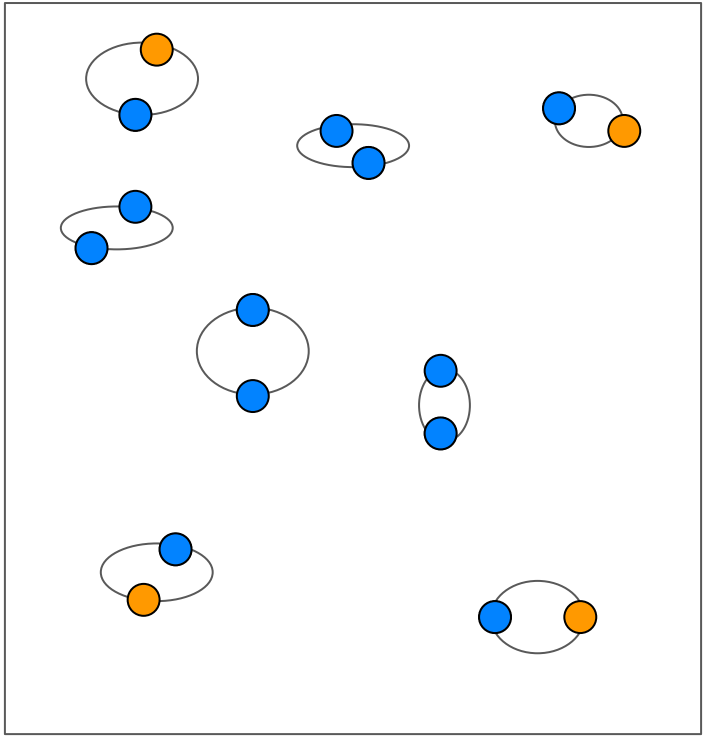
Differences between the models with $f_{b,high}$= 1 and 0

$f_{b,high}$= 1	$f_{b,high}$= 0
All high-mass stars are in binaries	All high-mass stars are singles
$N_{high} \approx 3800$	$N_{high} \approx 2200$

Our aim is to disentangle the roles of N_{high} and the state of high-mass stars being in a binary.

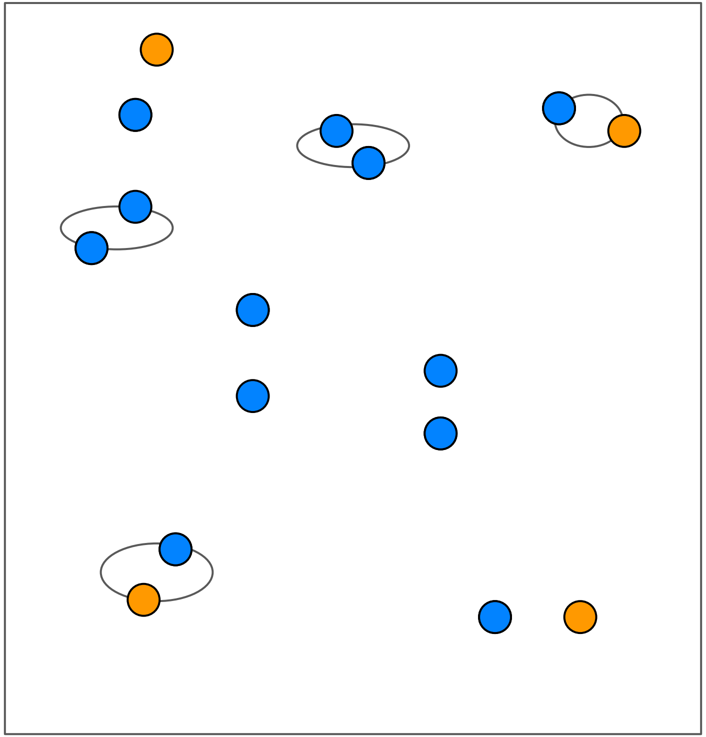
Methods

- Initialise a model with $f_{b,high}$=1.
- Extract all massive binaries.



Methods

- Initialise a model with $f_{b,high}$=1.
- Extract all massive binaries.
- Randomly select a fraction of them and break them into single stars.



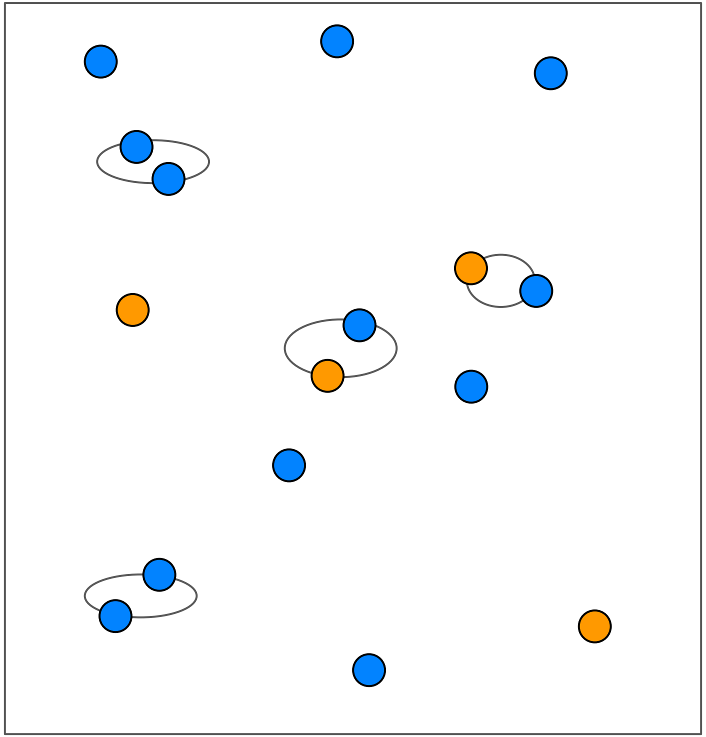
Methods

- Initialise a model with $f_{b,high}$=1.
- Extract all massive binaries.
- Randomly select a fraction of them and break them into single stars.
- Spatially redistribute all objects in the cluster.

↓

Cluster models with identical individual stars but different fraction of massive stars in binaries, i.e., " $\boldsymbol{f'_{b,15}}$ ".

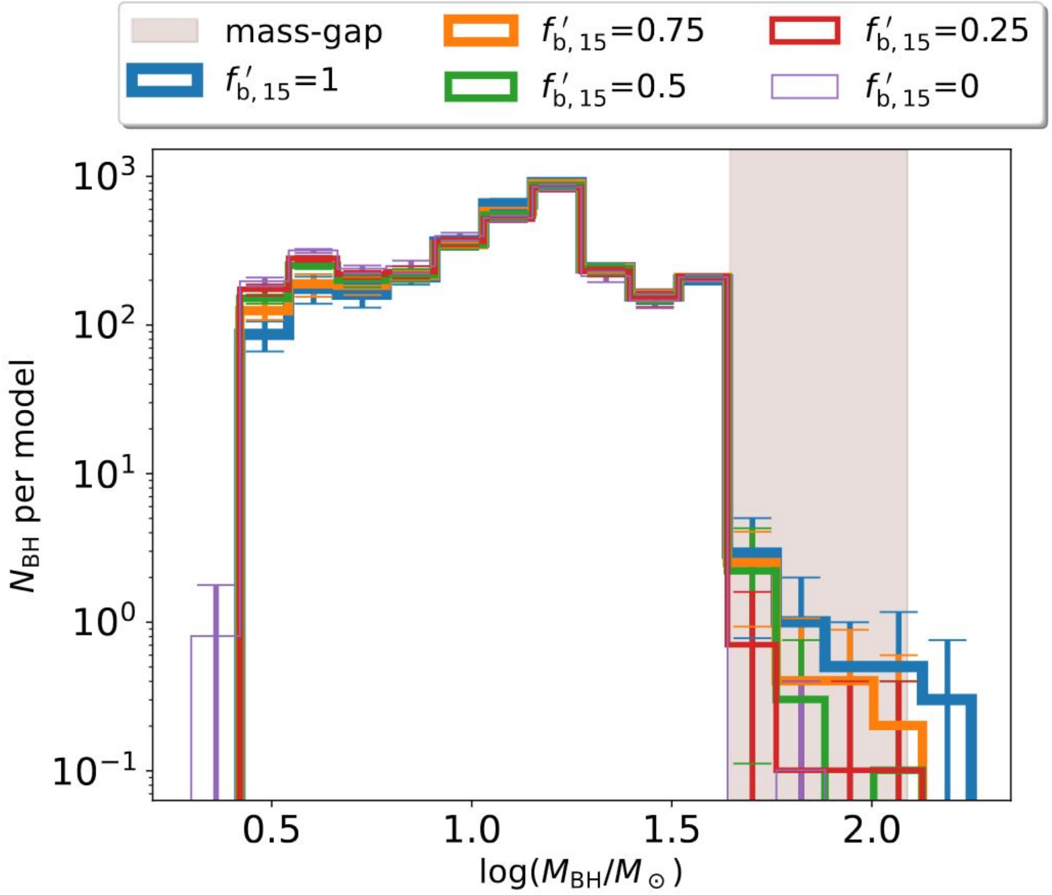
We simulate the evolution using **CMC** (Rodriguez et al. 2022).



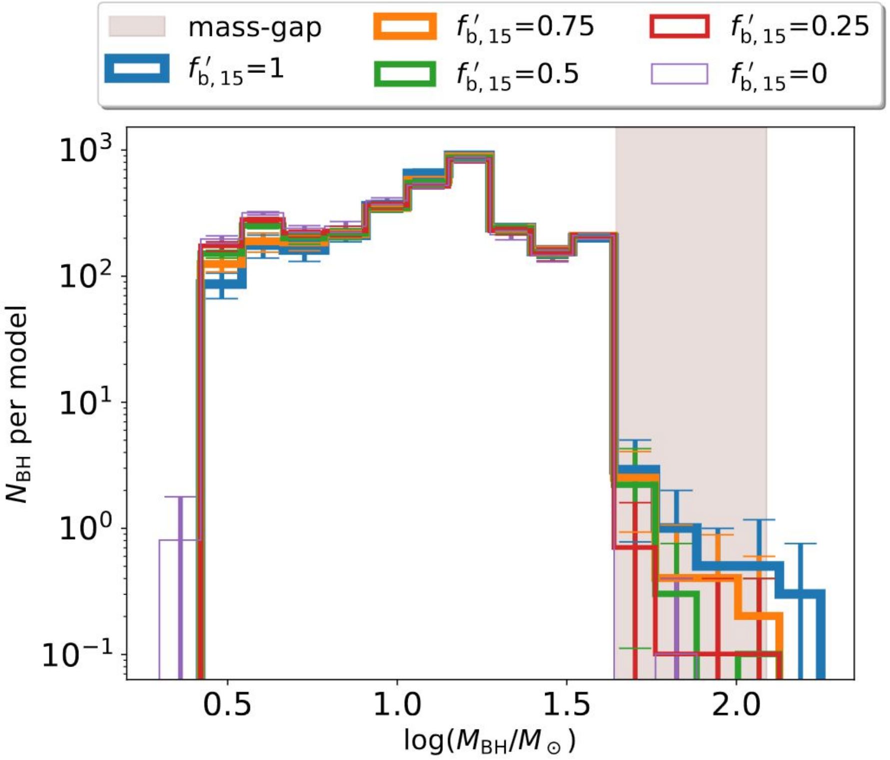
Methods: Simulations performed

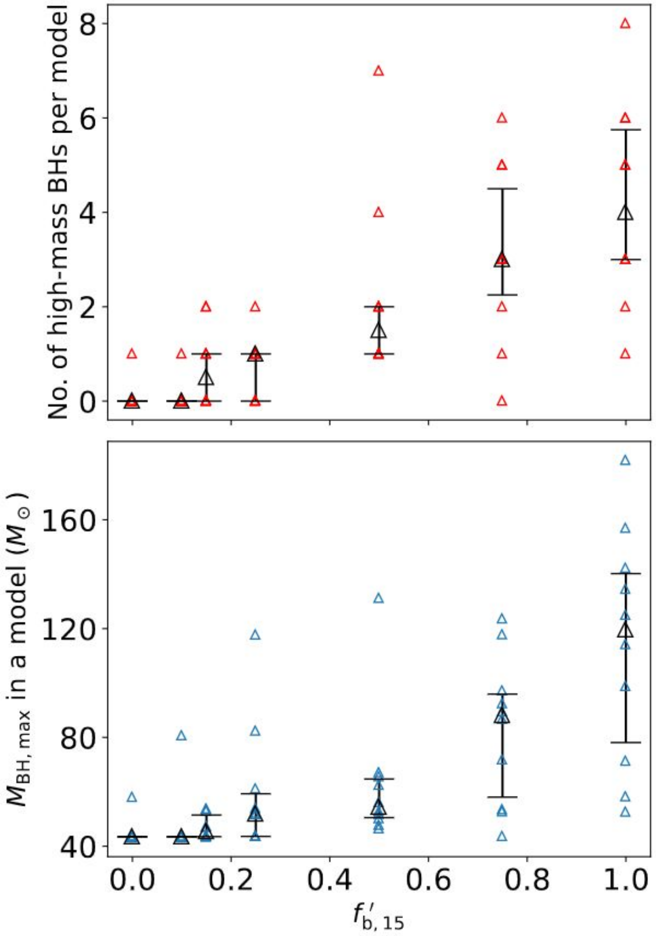
- $\boldsymbol{f'_{b,15}}$ - 0, 0.25, 0.5, 0.75, 1 (10 realisations each).
- f_b for lower-mass stars - 0.05.
- Eccentricity distribution of binaries - thermal [Jeans 1919].
- Orbital period distribution of binaries - $dN/d \log P \propto P^{-0.55}$ [Sana 2012].
- Uniform mass ratio for binaries between 0.1 and 1 for lower-mass primaries and between 0.6 and 1 for high-mass primaries.
- Stellar IMF - Kroupa01 [Kroupa 2001].
- Cluster profile - King [King 1966].
- Virial radius, r_v - 1 pc.
- Metallicity, z = 0.002.
- Number of objects - 8 x 10^5.

So, do we need massive stars to be in a binary? YES.



Number of massive BHs as well as mass of the most massive BH depend on $f'_{b,15}$





The role of binaries: mass segregation

$$t_{\rm seg,i} \sim \frac{< M >}{M_i} t_{\rm relax}$$

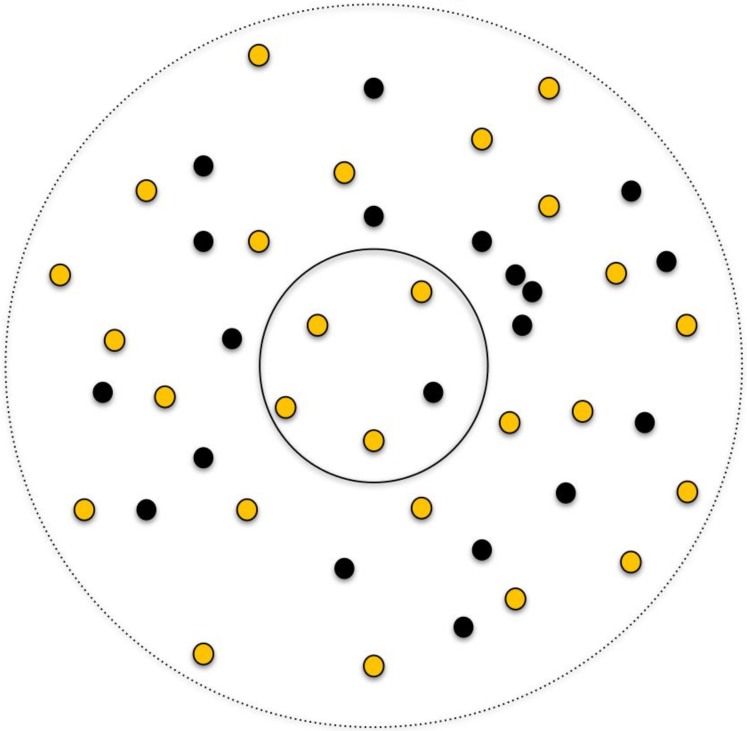


Diagram credit: Sourav Chatterjee

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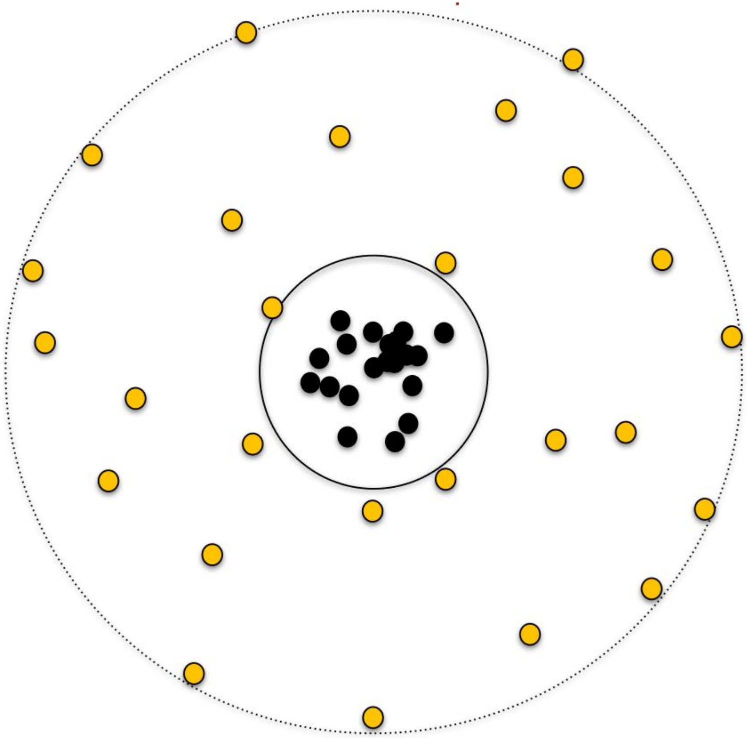


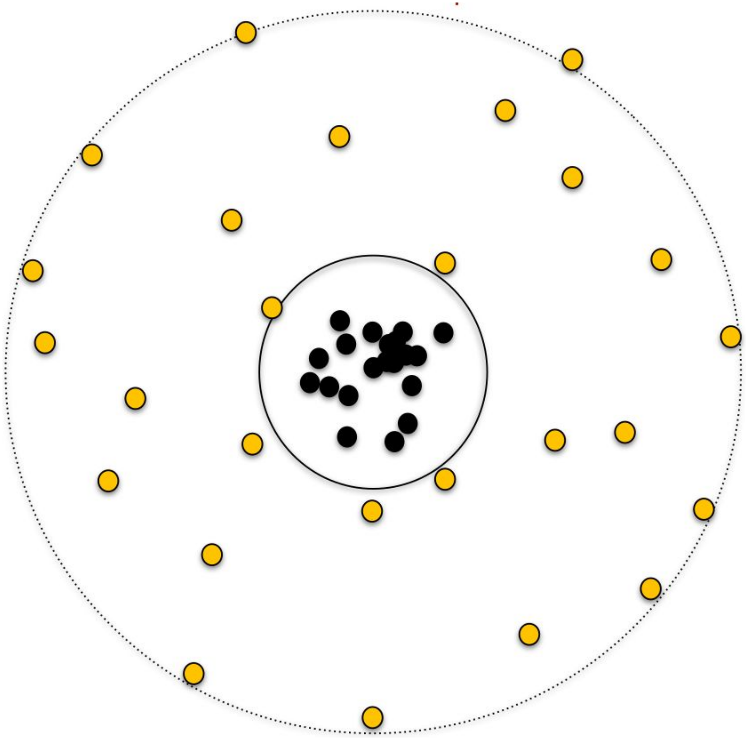
Diagram credit: Sourav Chatterjee

The role of binaries: mass segregation

$$t_{\rm seg,i} \sim \frac{<M>}{M_i} t_{\rm relax}$$

$$M_{\rm bin} = (1 + q)\, M_{\rm prim}$$

$$t_{\rm seg} < t_{\rm MS}$$



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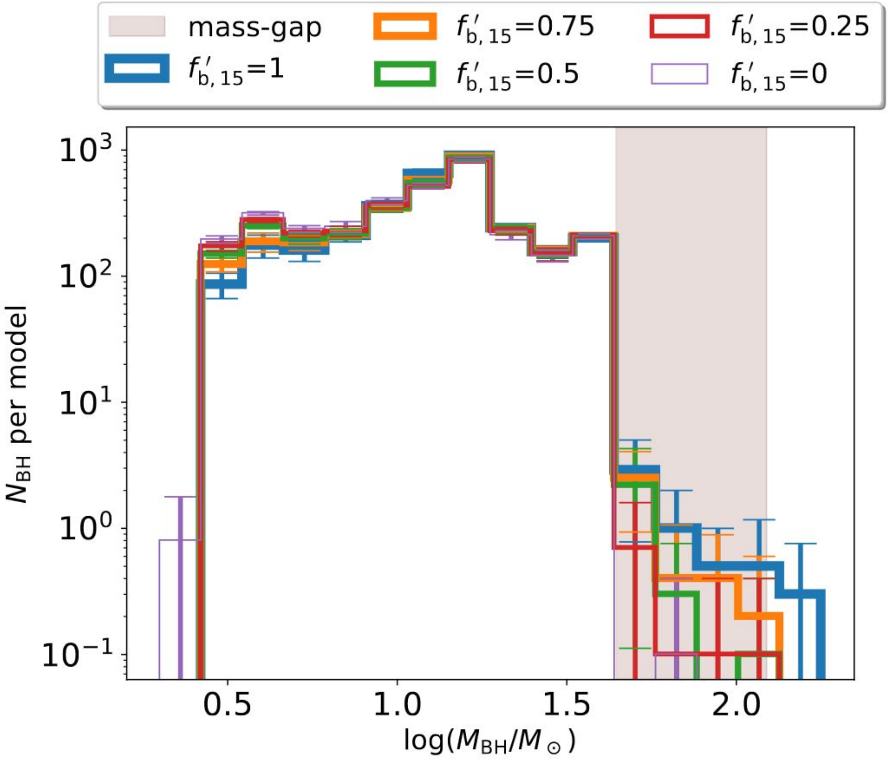
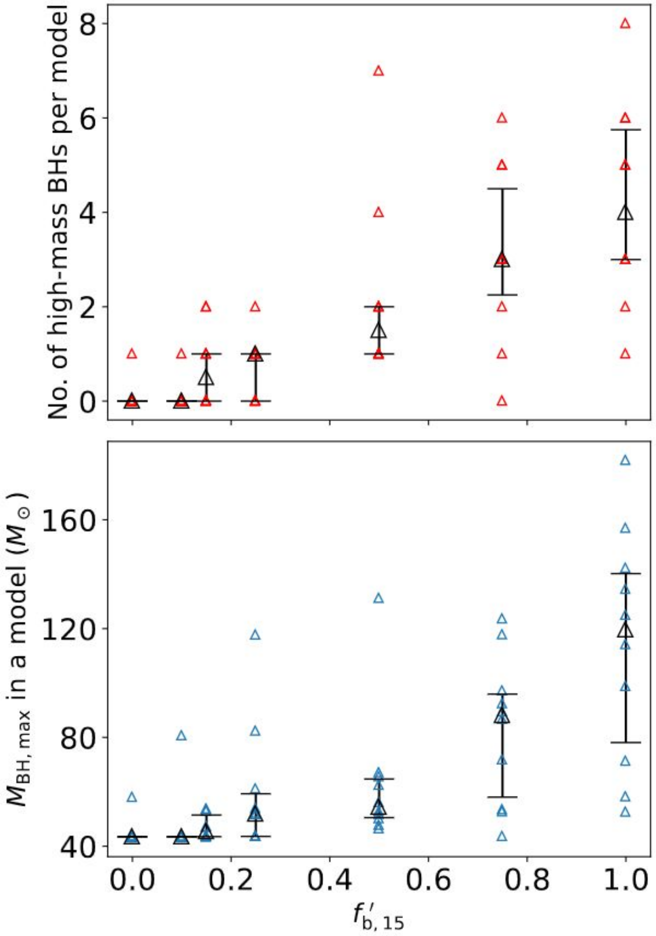
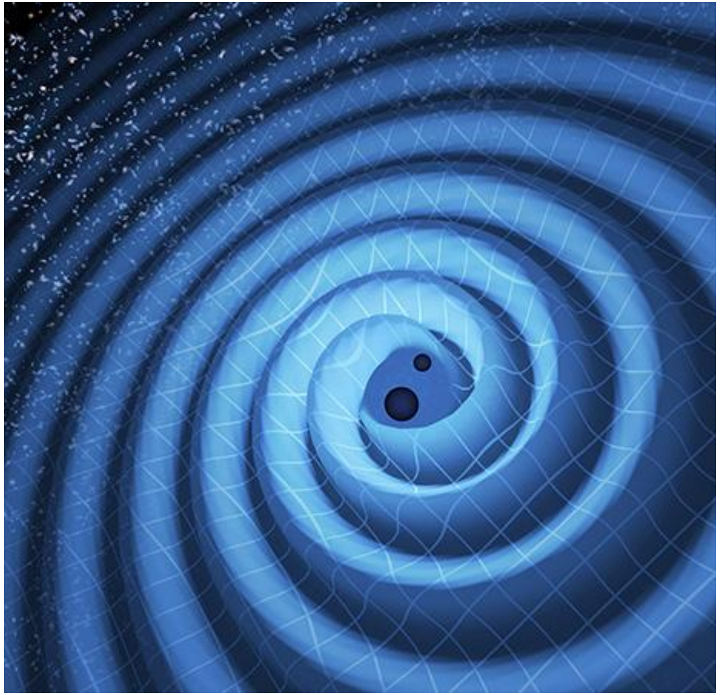
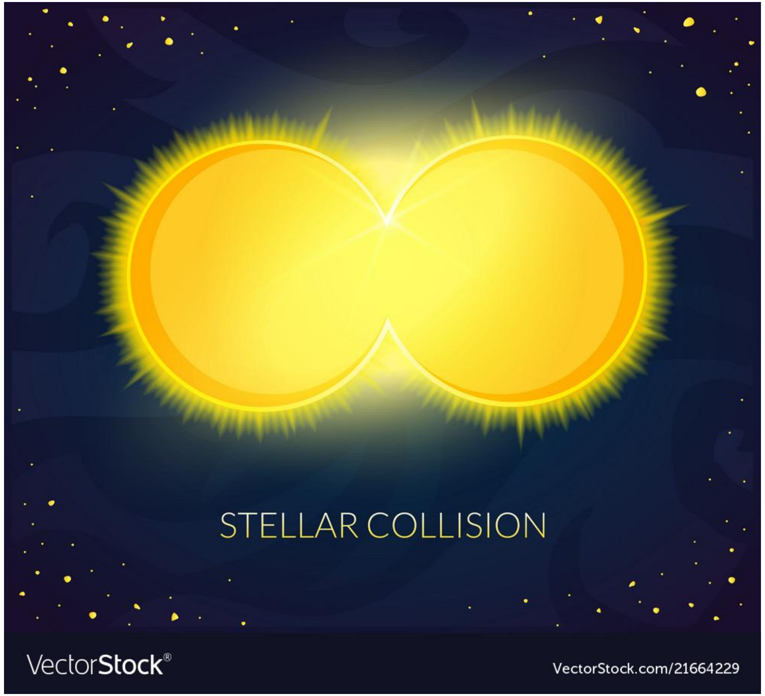




Ways to form mass-gap BHs





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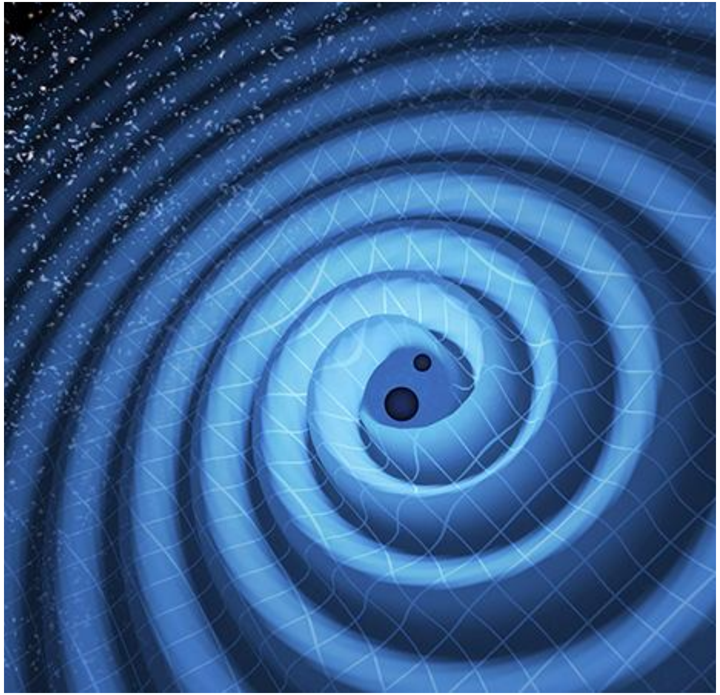

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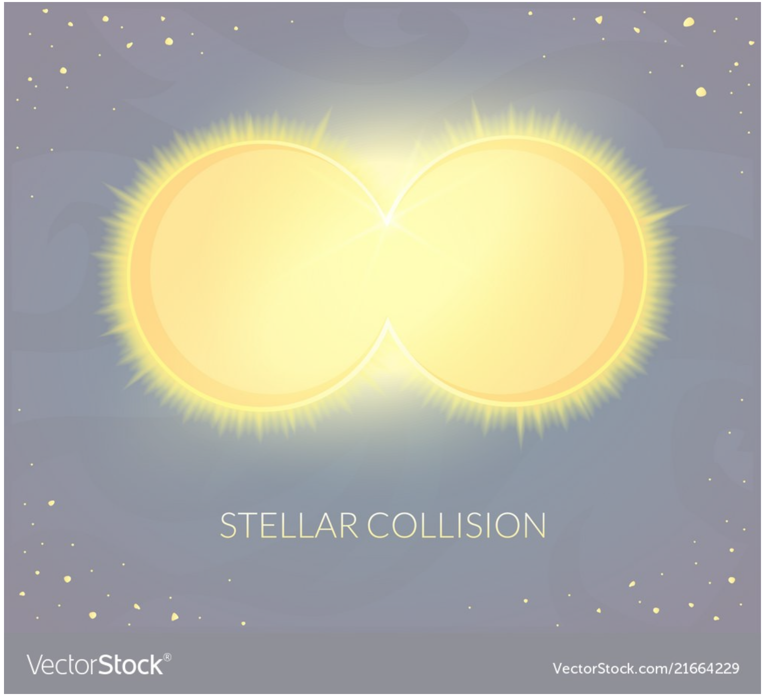

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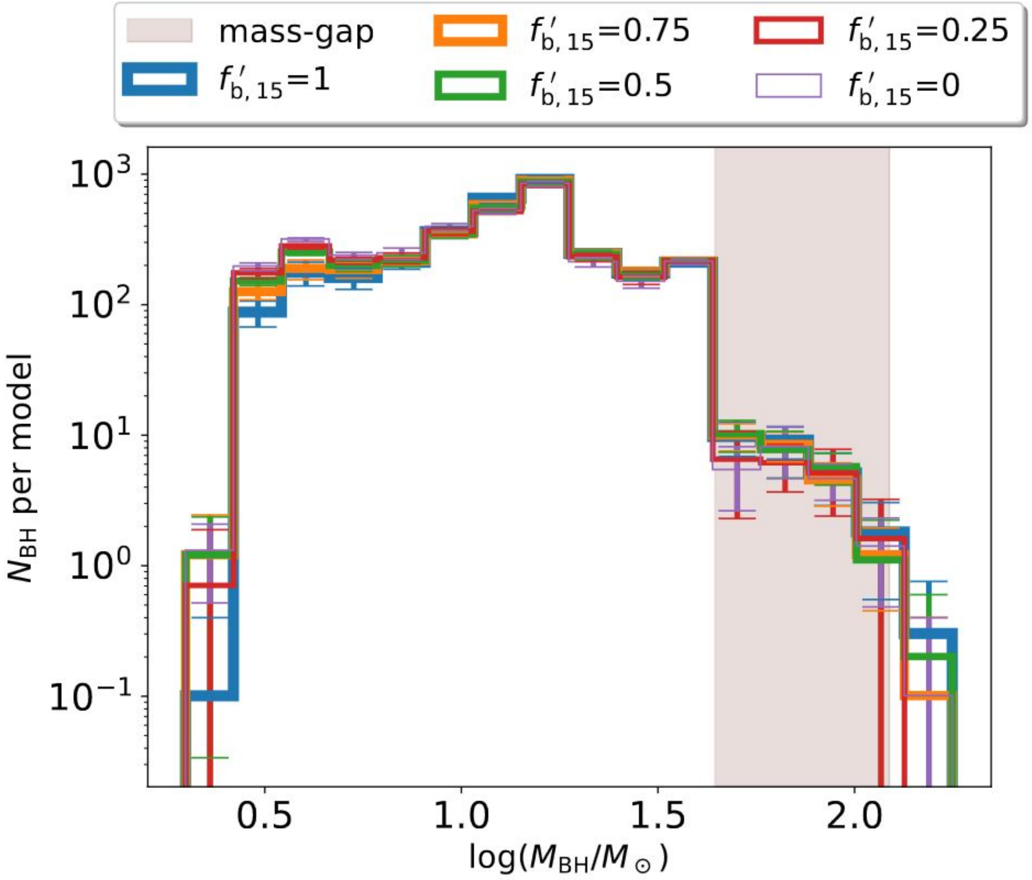
BHs formed during a ~Hubble time.



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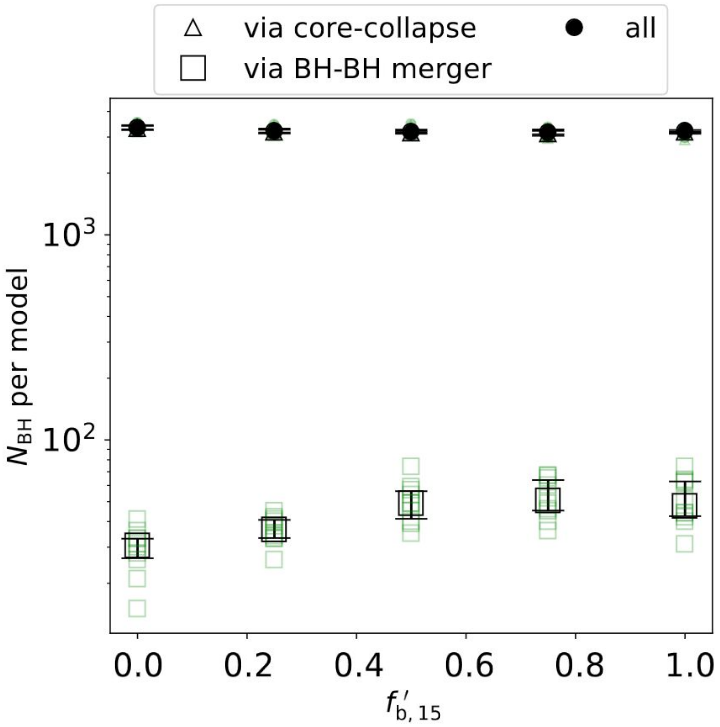

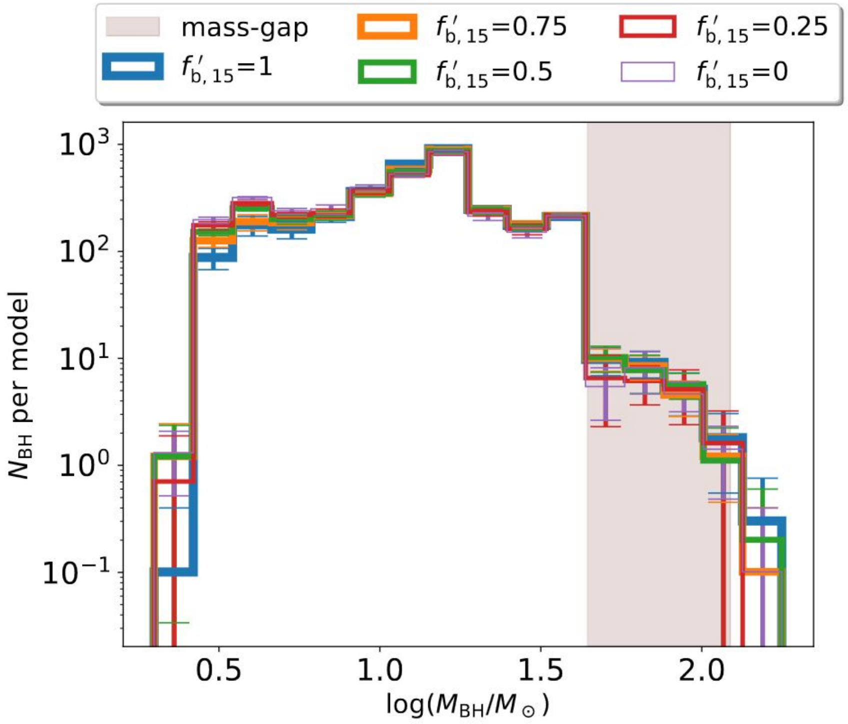

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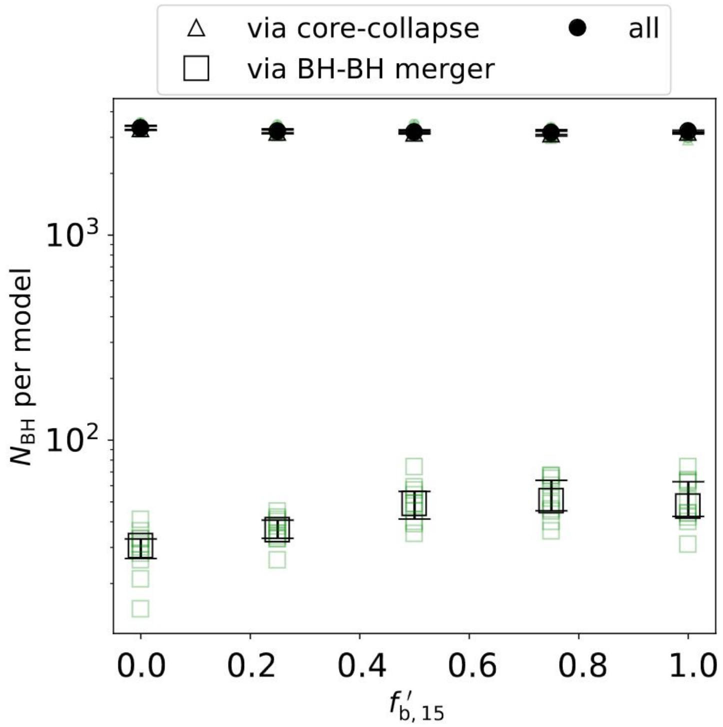
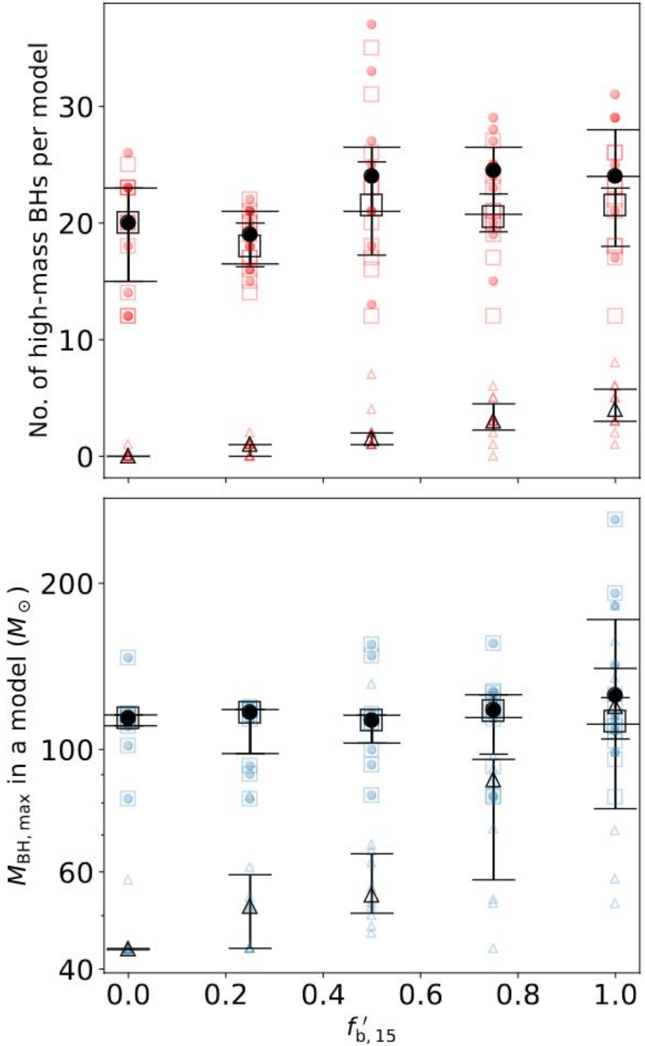
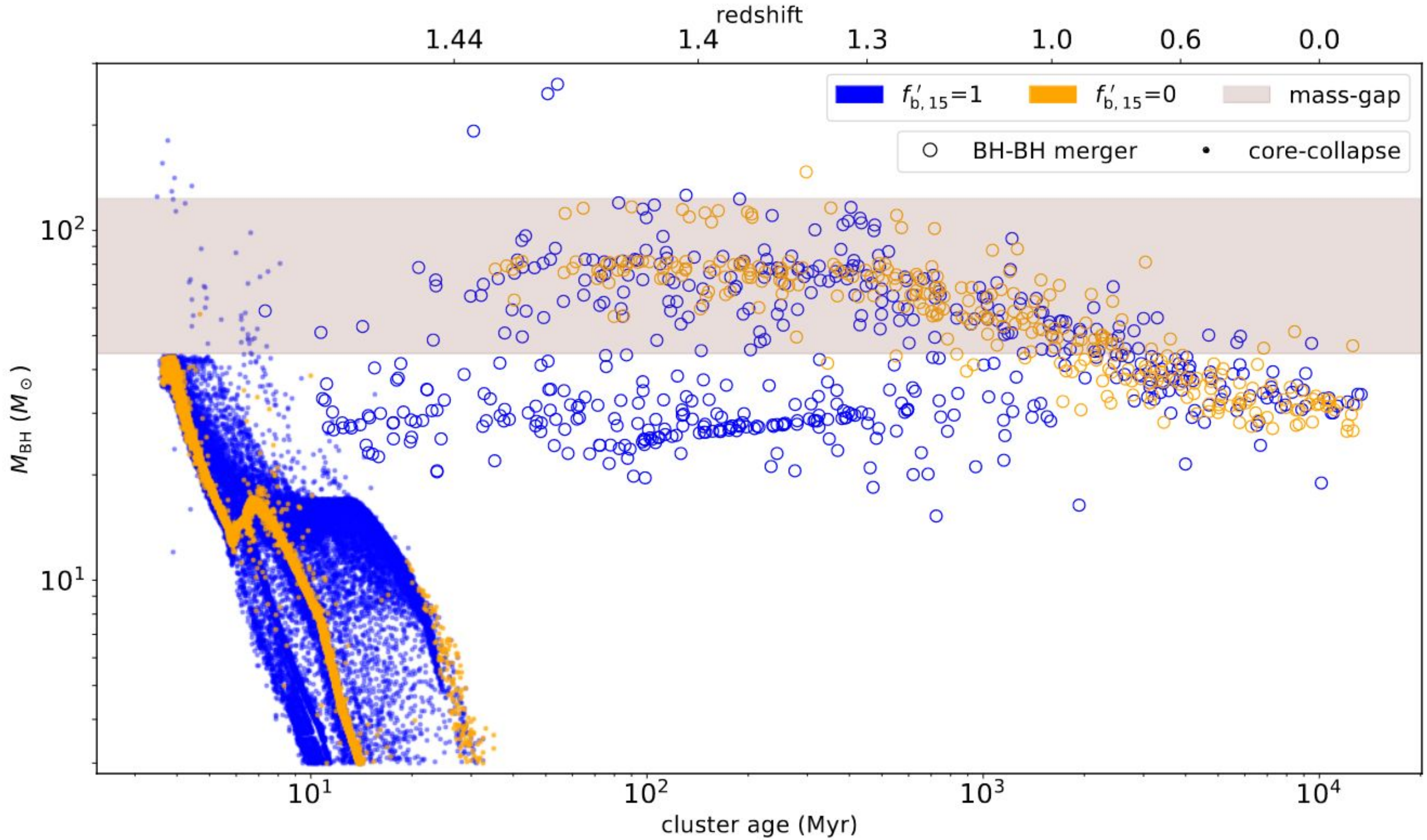
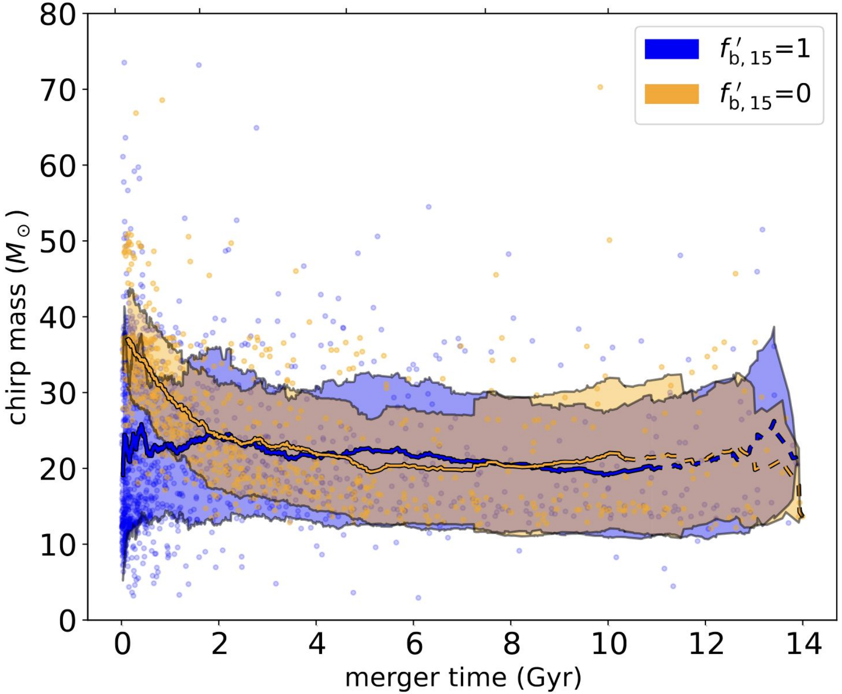


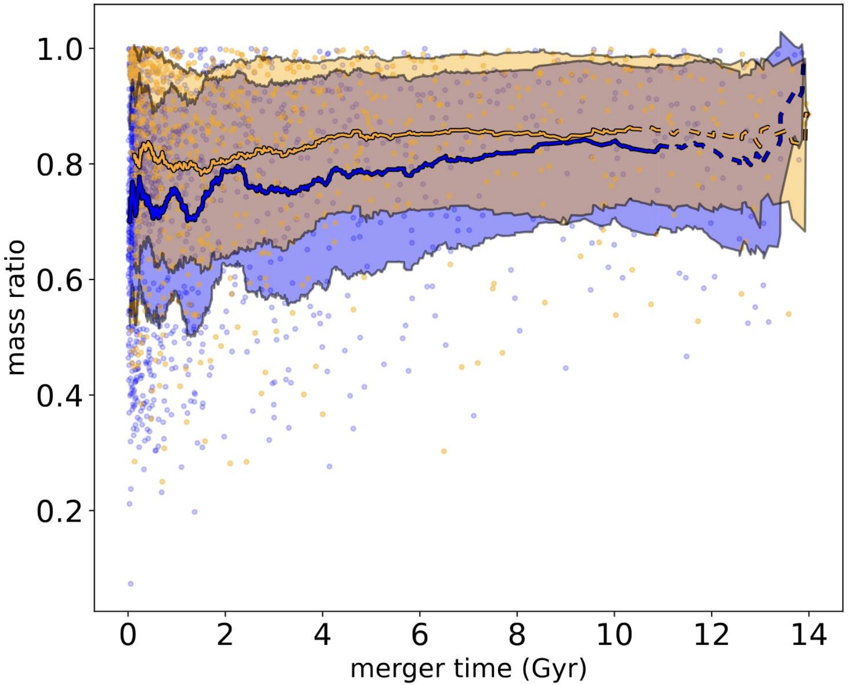


BH formation demographics



BH-BH mergers’ properties





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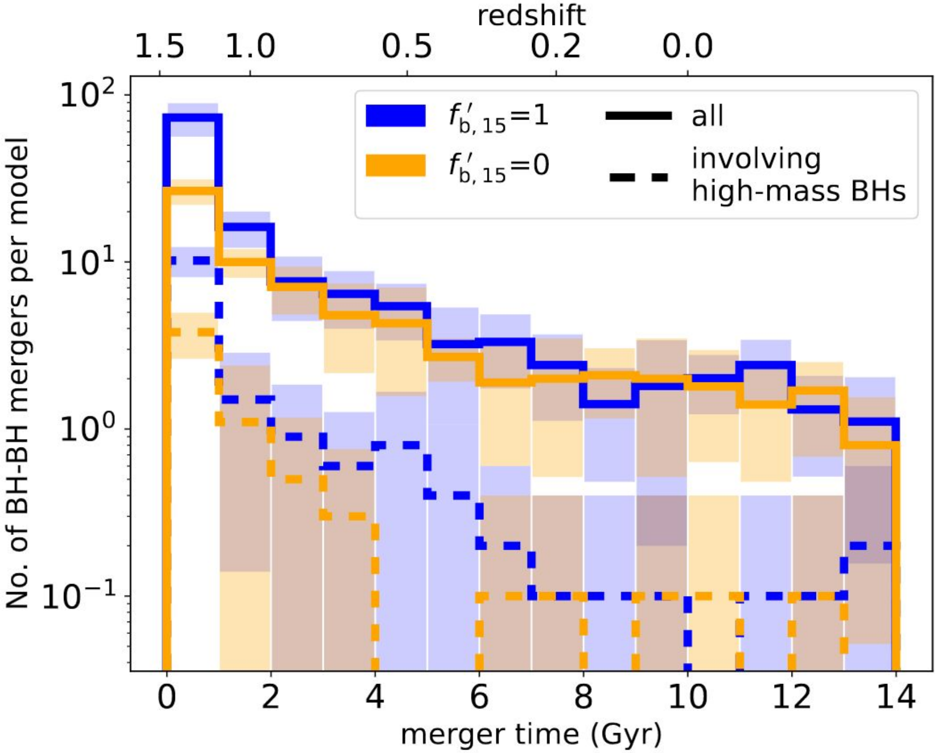


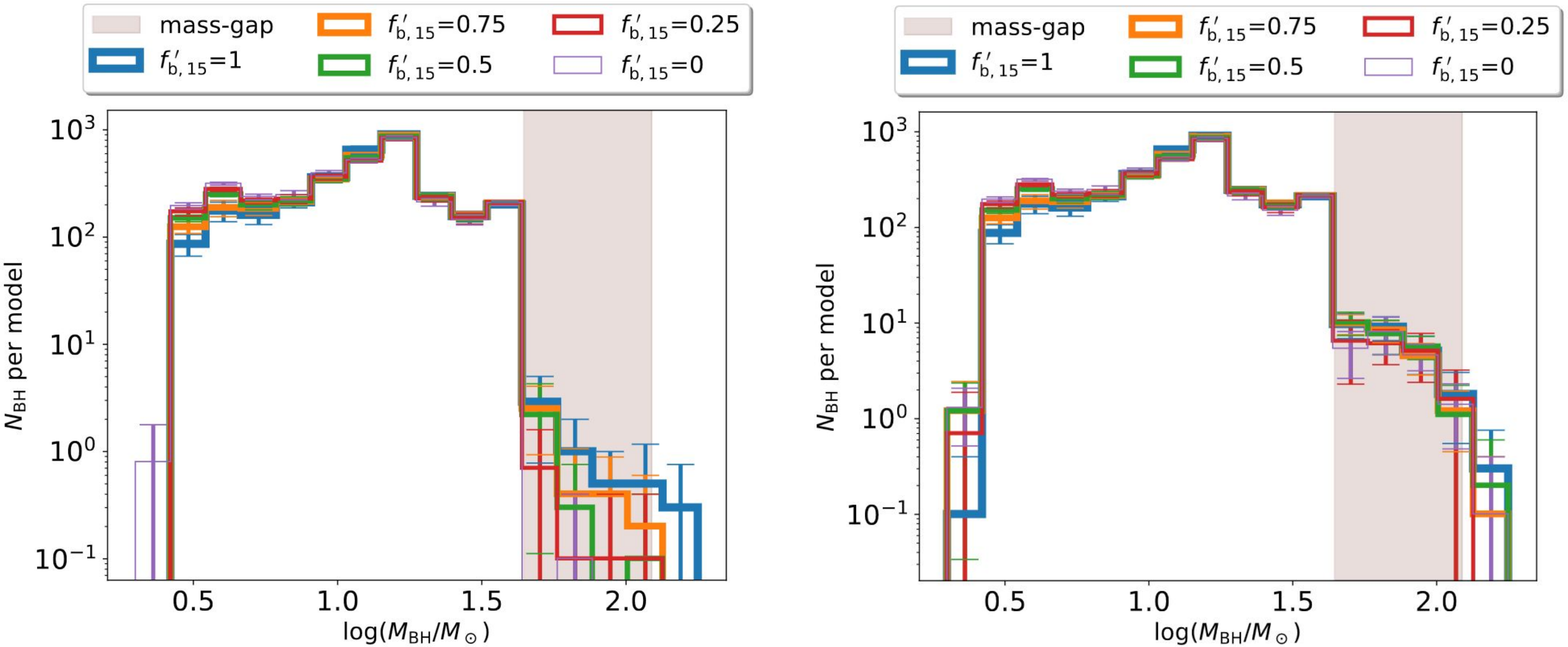
Key Points

- $f'_{b,15}$ affects high-mass BH formation via stellar collapse, both in the number of high-mass BHs as well as the mass of the most massive BH.

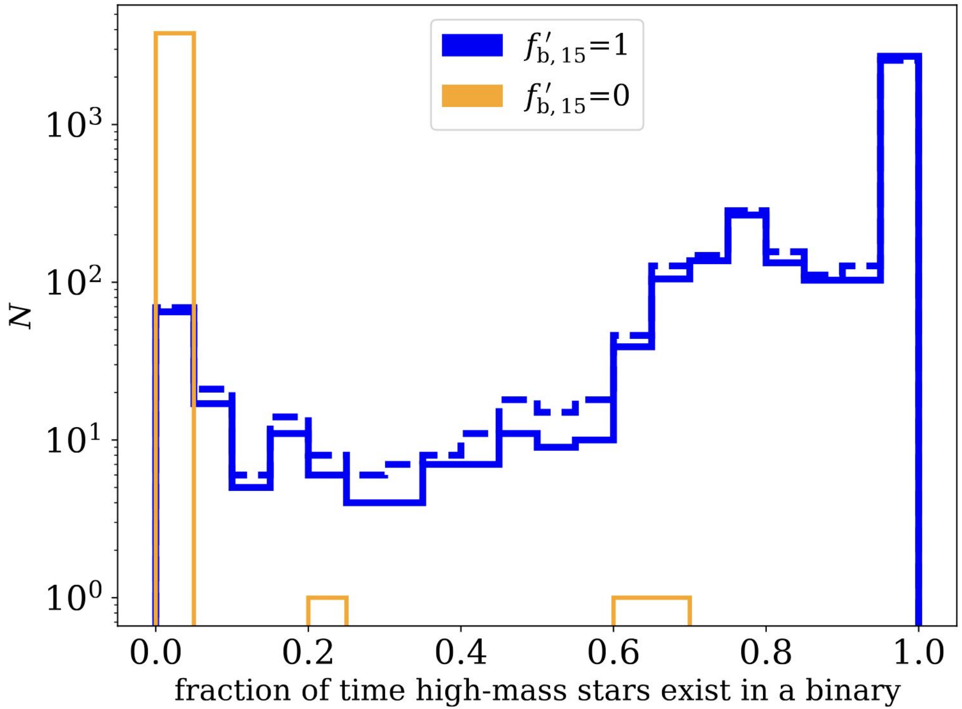
- However, high-mass BH production over a GC lifetime is dominated by the dynamical process of BH-BH mergers, which is not sensitive to $f'_{b,15}$.

- The properties of BH-BH mergers depend on the initial $f'_{b,15}$.

Stellar collapse (< 35 Myr) + BH-BH merger (~ 14 Gyr)

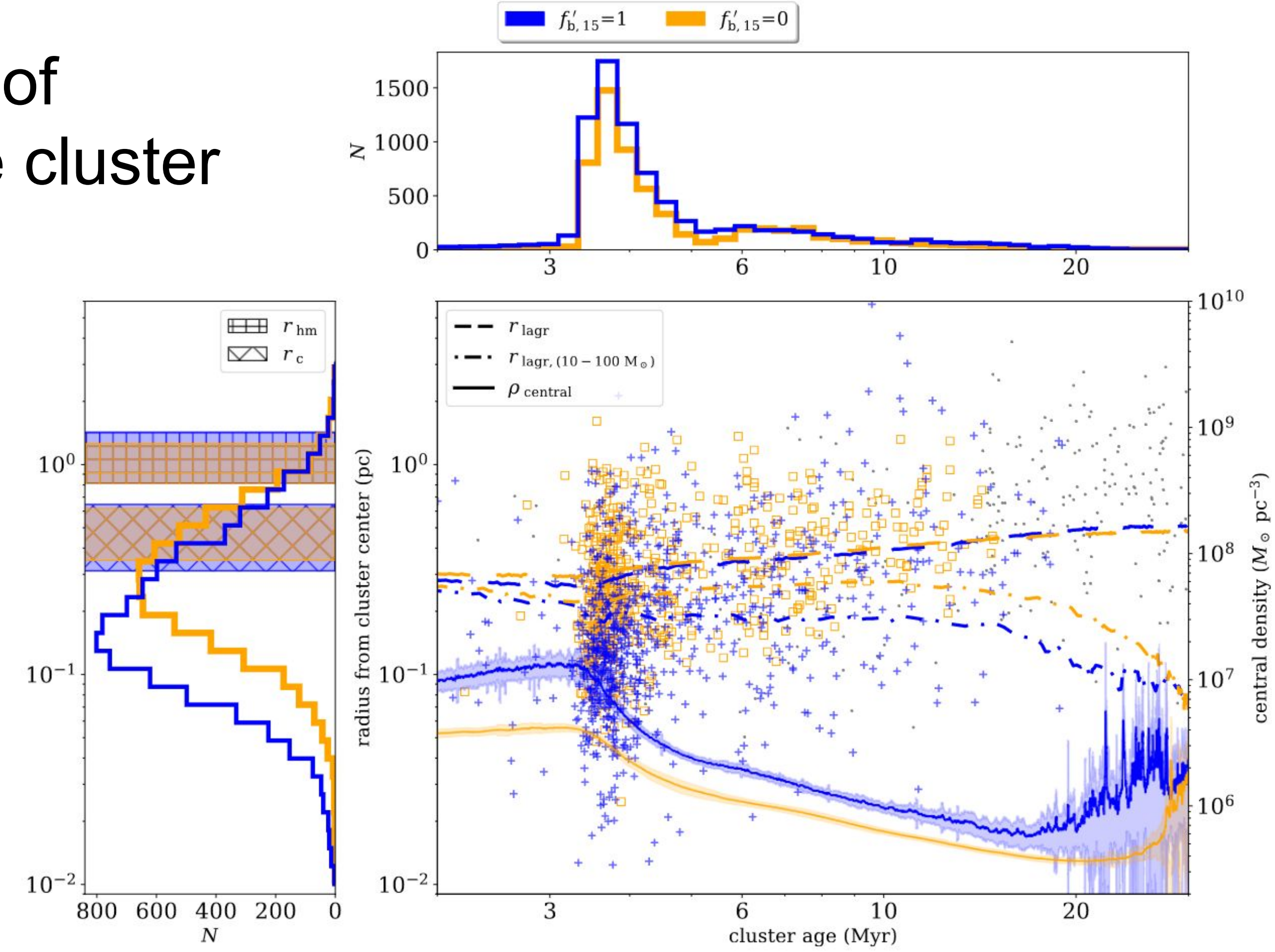


Backup Slides



$f'_{\mathrm{b},15}$=1
$f'_{\mathrm{b},15}$=0
10^3
10^2
10^1
10^0
N
0.0
0.2
0.4
0.6
0.8
1.0
fraction of time high-mass stars exist in a binary

Demographics of collisions in the cluster models



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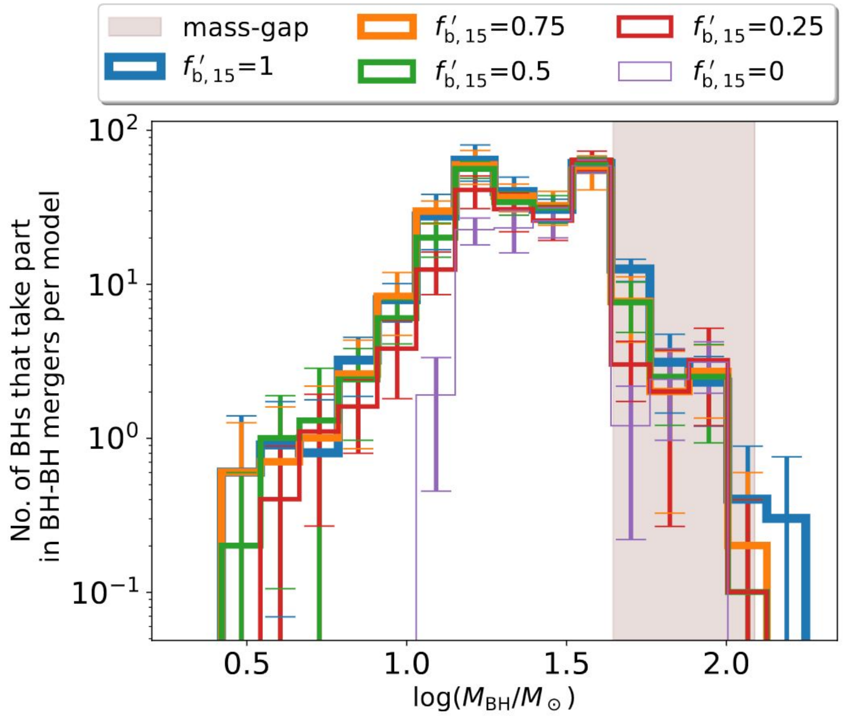

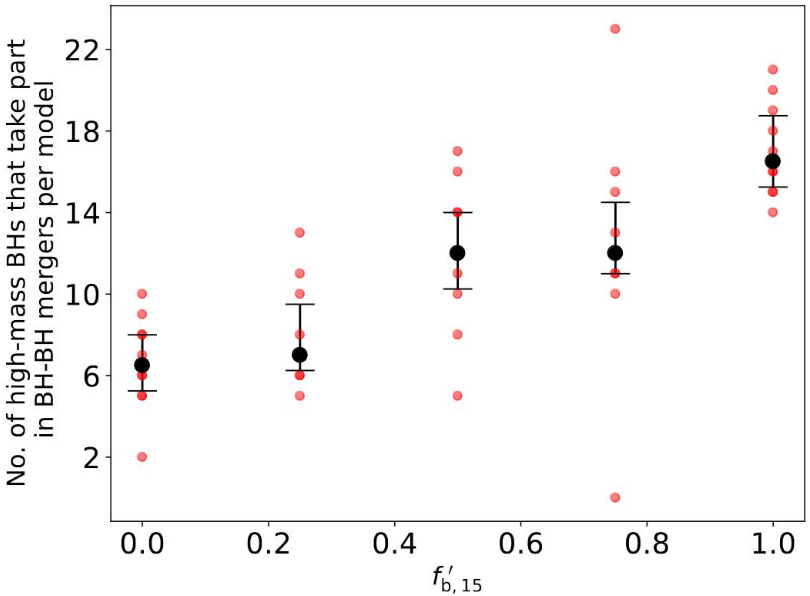

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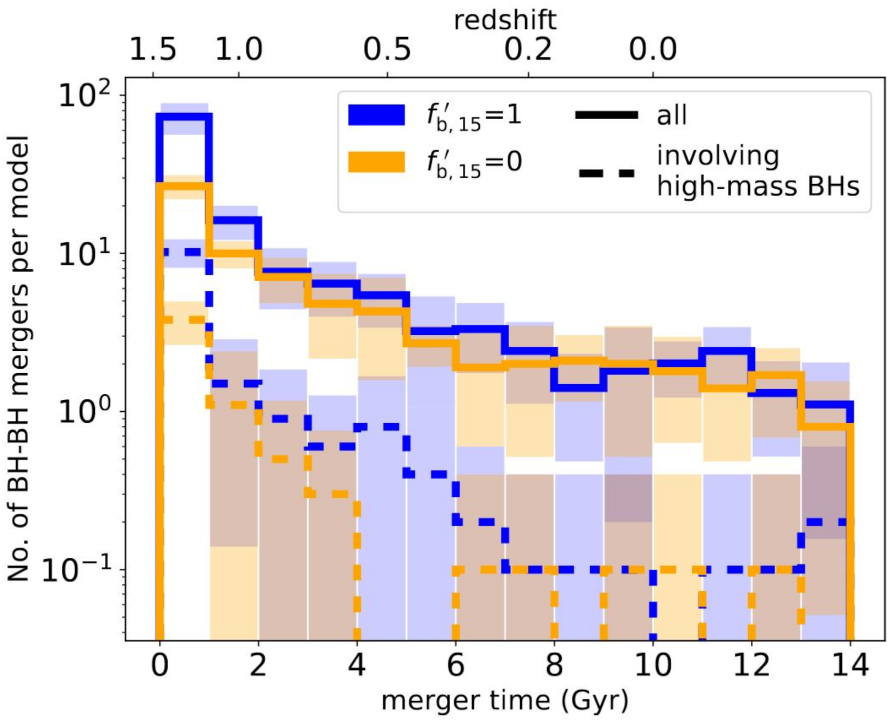

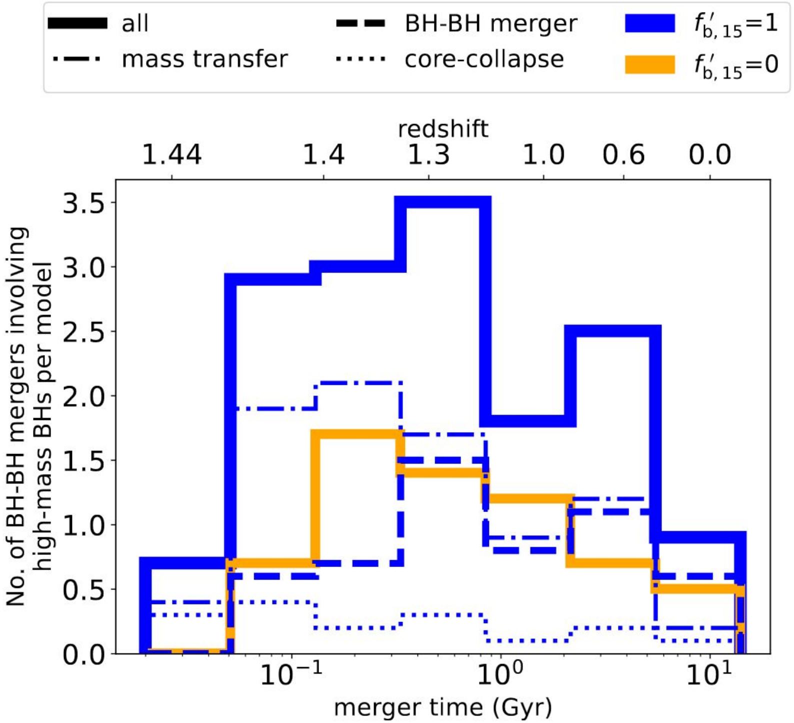

$f'_{\mathrm{b},15}$	$f_{\mathrm{b},15}$	N_{BH}		$N_{\mathrm{BH,high}}$		$M_{\mathrm{BH,max}}$	
		core-collapse	BH-BH merger	core-collapse	BH-BH merger	core-collapse	BH-BH merger
1	1	3164^{+22}_{-52}	$47.5^{+15.2}_{-5}$	$4^{+1.75}_{-1}$	$21.5^{+1.5}_{-3.5}$	$119.5^{+20.7}_{-41.4}$	$112.3^{+11.8}_{-7.8}$
0.75	0.63	3105^{+110}_{-63}	$50.5^{+13.2}_{-5.2}$	$3^{+1.5}_{-0.75}$	$20.5^{+2}_{-1.25}$	$88^{+7.9}_{-30}$	$117.3^{+8.3}_{-19.3}$
0.5	0.36	3133^{+77}_{-21}	$49^{+7.2}_{-7.8}$	$1.5^{+0.5}_{-0.5}$	$21.5^{+3.75}_{-4.25}$	$54.4^{+10.3}_{-3.9}$	$112.8^{+2.5}_{-10.2}$
0.25	0.16	3169^{+88}_{-47}	$36.5^{+4.2}_{-3.2}$	1^{+0}_{-1}	$18^{+2}_{-1.75}$	$51.9^{+7.4}_{-8.3}$	$116.5^{+1.6}_{-18.2}$
0	0	3294^{+106}_{-51}	$30.5^{+2.5}_{-4}$	0^{+0}_{-0}	20^{+3}_{-5}	$43.5^{+0.1}_{-0.1}$	$113.9^{+1.6}_{-3.5}$

$f'_{b,15}$	Full cluster life						
	All		High-mass		High-mass BBH formation channel		
	In-cluster	Ejected	In-cluster	Ejected	Core-collapse	BBH merger	Mass transfer
1	48^{+15}_{-6}	72^{+12}_{-3}	5^{+1}_{-1}	10^{+2}_{-0}	16	53	84
0.75	54^{+10}_{-6}	70^{+6}_{-3}	3^{+1}_{-1}	8^{+2}_{-2}	15	46	52
0.5	49^{+7}_{-7}	64^{+3}_{-5}	4^{+1}_{-2}	7^{+1}_{-1}	11	44	55
0.25	34^{+7}_{-1}	54^{+4}_{-0}	2^{+2}_{-1}	4^{+2}_{-1}	5	51	14
0	30^{+3}_{-4}	40^{+5}_{-3}	2^{+1}_{-1}	4^{+1}_{-1}	0	62	0
	$0 < z < 1$						
1	10^{+2}_{-2}	26^{+4}_{-3}	0^{+0}_{-0}	3^{+1}_{-1}	4	16	15
0.75	12^{+1}_{-4}	26^{+4}_{-3}	0^{+0}_{-0}	2^{+2}_{-1}	3	15	7
0.5	12^{+2}_{-6}	24^{+2}_{-2}	0^{+0}_{-0}	2^{+1}_{-1}	2	14	7
0.25	8^{+3}_{-4}	22^{+1}_{-2}	0^{+0}_{-0}	2^{+1}_{-1}	0	17	4
0	10^{+5}_{-2}	20^{+3}_{-3}	0^{+1}_{-0}	1^{+0}_{-0}	0	14	0