Merger rate of stellar black hole binaries above the pair-instability mass gap

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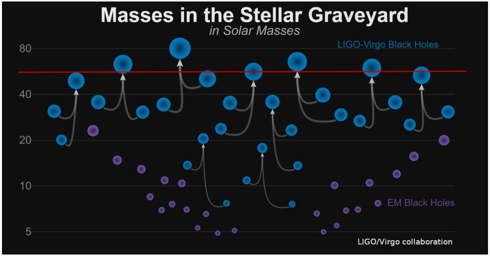
Up so far . . .



LIGO/Virgo detected 10 BHBs merger

$\downarrow$

Merging $\mathrm{M_{BH}} \lesssim 60\,\mathrm{M_\odot}$

$\downarrow$

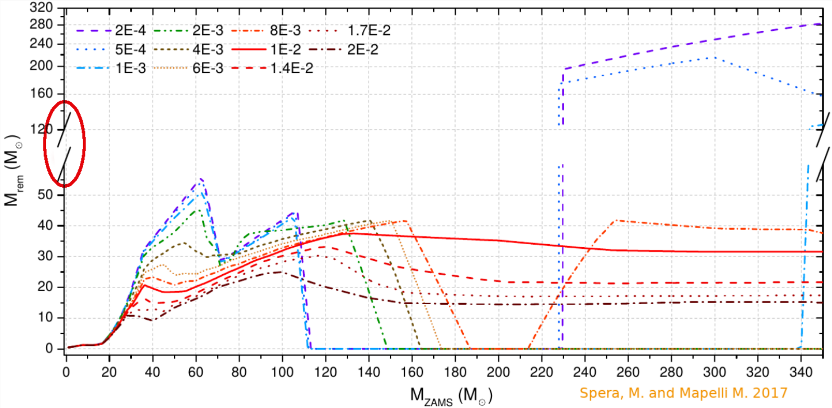
Hint of a mass gap?

How do binary black hole form?

We expect most of these sources to come from isolated binary stars
(Belczynski et al.2016, Mapelli et al.2017)

Population synthesis code (PSC), i.e. Startrack, MOBSE, Compass, outcomes agree with detected distributions
(Belczynski et al.2005, Giacobbo et al.2017, Barrett et al.2017)

What PSC predict for single massive stars?



- Remnant mass correlates with star metallicity
- Pair production prevents formation of BHs in the range $\simeq [60, 120]\,\mathrm{M}_\odot$

Main idea

Question

How can we study BHs above the mass gap?

- Yet undetected population
- Viable seed for MBHB formation and growth

Problem

No PSC can evolve massive binary stars (i.e. $\mathrm{M}_\star > 150\,\mathrm{M}_\odot$)

Large uncertainties on:

- Internal mixing, angular momentum transport
- Common envelope

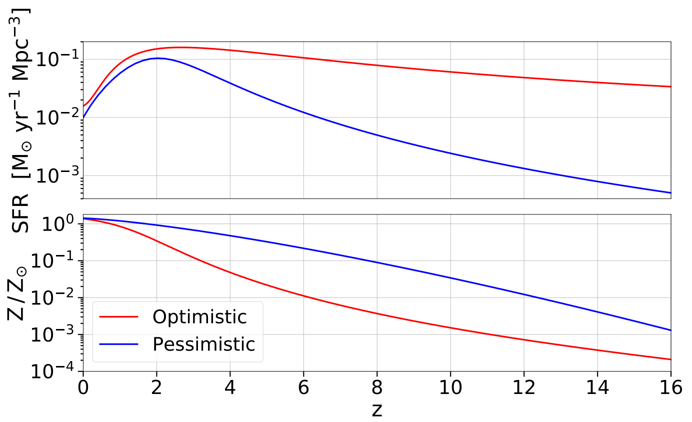
Main idea (AM et al.2019, ApJL, 883, L27)

Evolve single stars up to $\mathrm{M} < 350\mathrm{M}_\odot \rightarrow$ SEVN (Spera, M. and Mapelli, M. 2017)

- Main caveat: Assume stars in binary evolve as single stars
- Model the gap as a sharp cut-off at $[60,\,120]\,\mathrm{M}_\odot$

Ingredients

Star formation rate and metallicity



Stellar initial mass function

$$\xi(\mathrm{M}_\star, \alpha) \propto \mathrm{M}_\star^{-\alpha} \text{ for } \mathrm{M}_\star \in [8,\, 350]\,\mathrm{M}_\odot \text{ and } \alpha = \begin{cases} 2.35 & \boxed{\text{Optimistic}} \\ 2.7 & \boxed{\text{Pessimistic}} \end{cases}$$

From stars to BH binaries

Stellar evolution

We evolve single star with SEVN

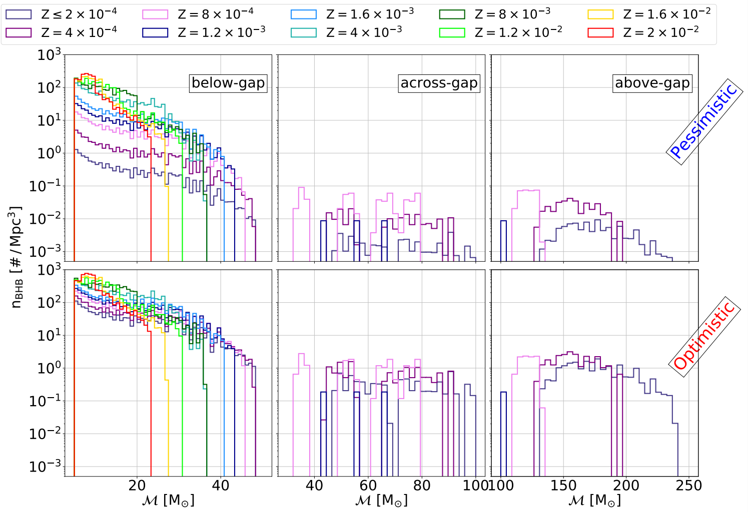
$$0.8 < \mathrm{M}/\mathrm{M}_\odot < 350 \qquad 10^{-2} < \mathrm{Z}/\mathrm{Z}_\odot < 1$$

A couple of more ingredients to get BHBs ...

- Flat mass ratio distribution $q = M_2/M_1 \in [0.1, 1]$ (tested also $q \in [0.5, 1]$)
- Log-flat time delay distribution $p(\tau) \propto \tau^{-1}$ with $\tau \in [50\,\mathrm{Myr}, \mathrm{t_{hubble}}]$

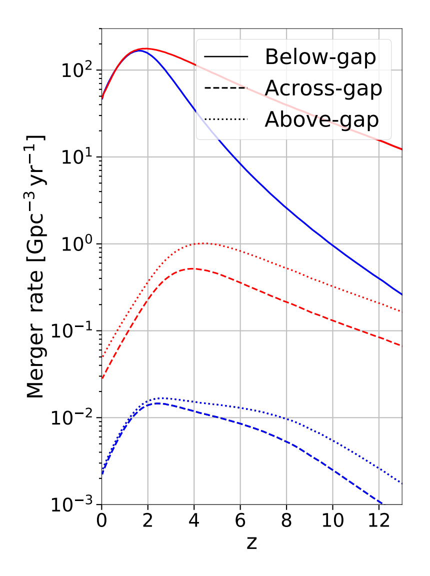
M_{chirp} distribution

Below-gap	Across-gap	Above-gap
$\mathrm{M_1, M_2 < 60\,M_\odot}$	$\mathrm{M_1 > 120\,M_\odot}$ and $\mathrm{M_2 < 60\,M_\odot}$	$\mathrm{M_1, M_2 > 120\,M_\odot}$



Merger rates and detected rates

After normalizing to LIGO/Virgo merger rate . . .



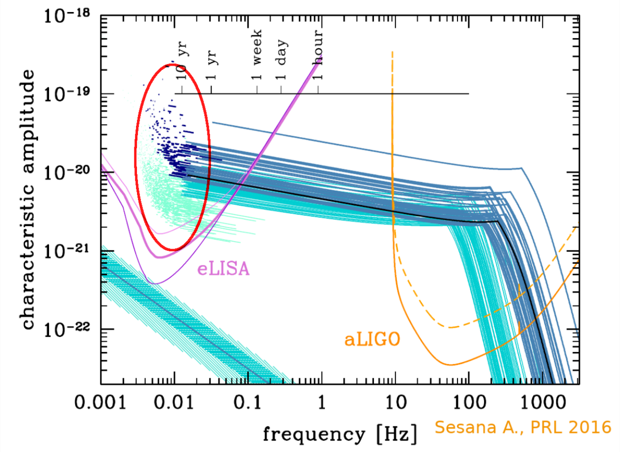
Pessimistic

$[\mathrm{yr}]^{-1}$	LIGO/Virgo design	ET
Across-gap	$\simeq 0.1$	$\simeq 8.1$
Above-gap	$\simeq 0.4$	$\simeq 10.7$

Optimistic

$[\mathrm{yr}]^{-1}$	LIGO/Virgo design	ET
Across-gap	$\simeq 0.9$	$\simeq 213$
Above-gap	$\simeq 6.9$	$\simeq 459$

Moving to low-frequency...

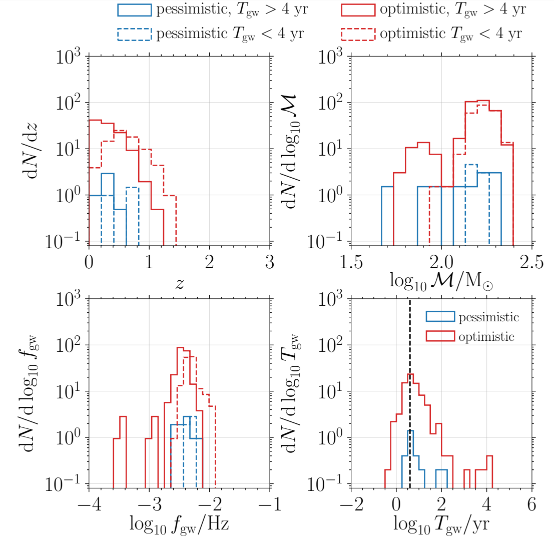


$dN_{\rm source}/df \simeq f^{-11/3} \rightarrow$ more sources at lower frequencies

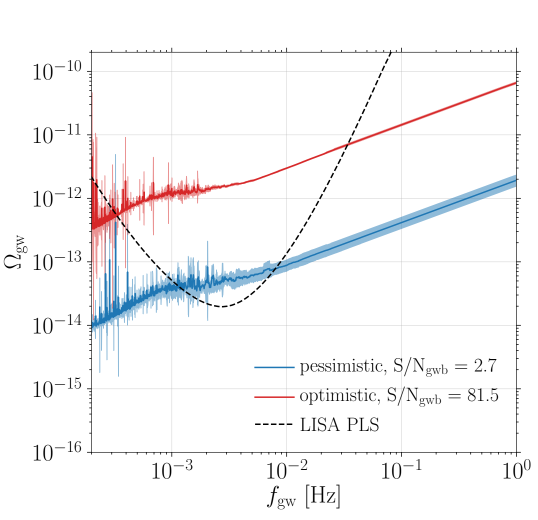
Slow inspiralling sources $\rightarrow$ possible background?

Distributions

Focus only on 'Across-gap' and 'Above-gap' . . .



Background estimates



Comparable to 'below-gap' BHBs and galactic background

Conclusion

Simple approach to describe BHBs above the pair-instability mass gap:

- Reproduce accurate PSC results for 'below-gap' BHBs
- Extendable to different prescriptions and formation scenarios
- Upgradable with new results from PSC or detections
- Soon public available

On the ground...

- LIGO/Virgo at design sensitivity might see a handful of 'above-gap' binaries in the Optimistic scenario
- ET should detect $\simeq 10$ BHBs even in the Pessimistic scenario

From space...

- LISA should detected 'across-gap' and 'above-gap' even in the Pessimistic scenario
- New possible sources of stochastic background

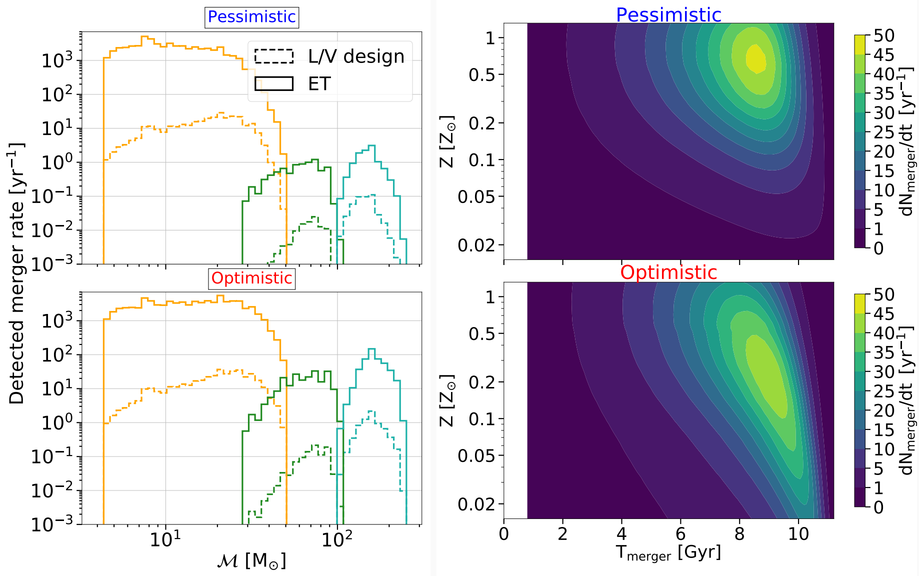
Backup slides

Detection rates	Models							
	Pessimistic		Optimistic		sSFR-mZ		mSFR-sZ	
	‘across’	‘above’	‘across’	‘above’	‘across’	‘above’	‘across’	‘above’
Rate O1/O2 ($\mathrm{S/N} > 8$) [yr^{-1}]	0.001	0.001	0.01	0.03	0.005	0.007	0.003	0.005
Rate LIGO/Virgo design ($\mathrm{S/N} > 12$) [yr^{-1}]	0.1	0.4	0.9	6.9	0.4	1.9	0.3	1.6
Rate ET ($\mathrm{S/N} > 12$) [yr^{-1}]	8.1	10.7	212.8	458.5	61.7	116.3	39.8	68.2

Backup slides

Detection rates	Models							
	Pessimistic		Optimistic		sSFR-mZ		mSFR-sZ	
	'across'	'above'	'across'	'above'	'across'	'above'	'across'	'above'
Detected events in 4 yr								
LISA events ($\mathrm{S/N} > 8$)	0.2	1.3	2.9	42.5	0.6	12.9	0.3	8.6
LISA events ($\mathrm{S/N} > 8$ & $T_{\mathrm{gw}} < 4\,\mathrm{yr}$)	< 0.1	0.8	0.5	19.3	< 0.1	5.8	< 0.1	4.6
LIGO/Virgo multiband events ($\mathrm{S/N} > 12$)	< 0.1	0.5	0.4	8.8	< 0.1	2.9	< 0.1	1.9
ET multiband events ($\mathrm{S/N} > 12$)	< 0.1	0.8	0.5	19.3	< 0.1	5.8	< 0.1	4.6
$\mathrm{S/N}_{\mathrm{gwb}}$ background in LISA	2.7		81.5		18.9		14.8	
Detected events in 10 yr								
LISA events ($\mathrm{S/N} > 8$)	0.6	6.2	6.2	152.1	1.9	33.0	1.7	27.0
LISA events ($\mathrm{S/N} > 8$ & $T_{\mathrm{gw}} < 10\,\mathrm{yr}$)	0.1	3.6	1.5	102.6	0.3	22.1	0.6	18.2
LIGO/Virgo multiband events ($\mathrm{S/N} > 12$)	1	1.6	1.2	34.7	0.2	8.6	0.5	5.6
ET multiband events ($\mathrm{S/N} > 12$)	0.1	3.6	1.5	102.6	0.3	22.1	0.6	18.2
$\mathrm{S/N}_{\mathrm{gwb}}$ background in LISA	3.7		117.8		26.9		21.4	

Backup slides



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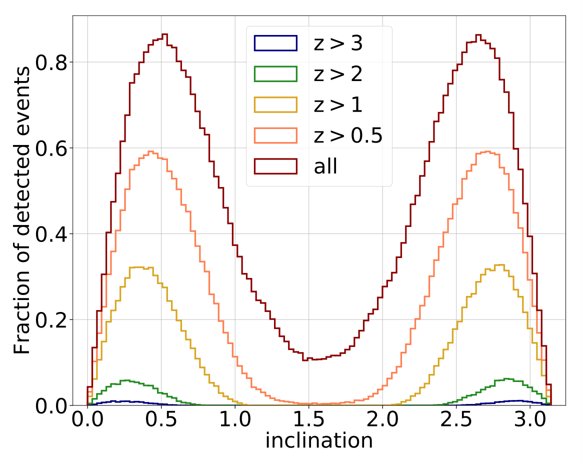
For the Optimistic model and 'Above-gap' sub-population



Possible EM signature from BH-BH merger?

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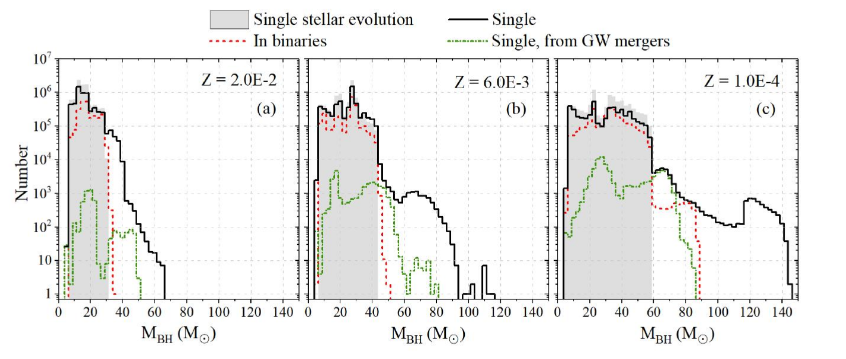
BHs mass distribution comparison (Spera, M. et al.2018)



Backup slides

BHs mass-ratio distribution comparison (Spera, M. et al.2018)