A new route towards merging massive black holes

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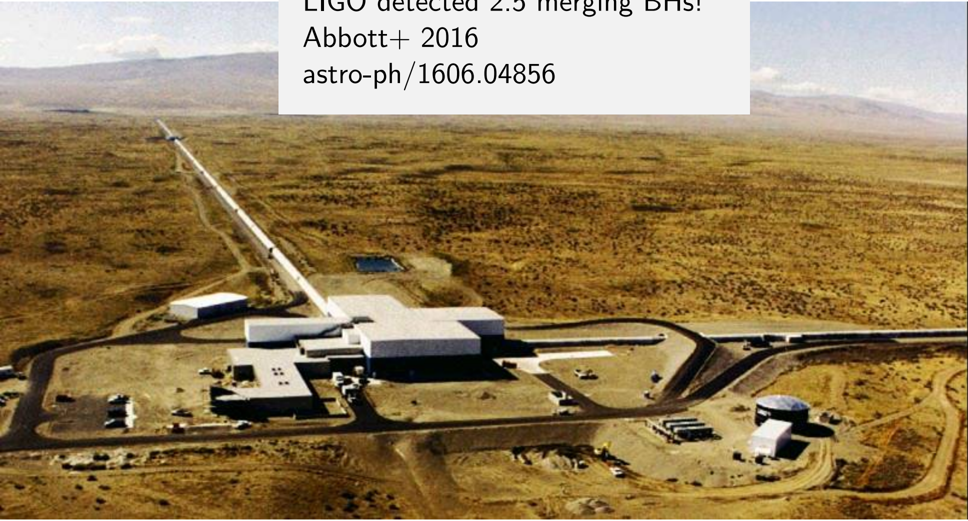
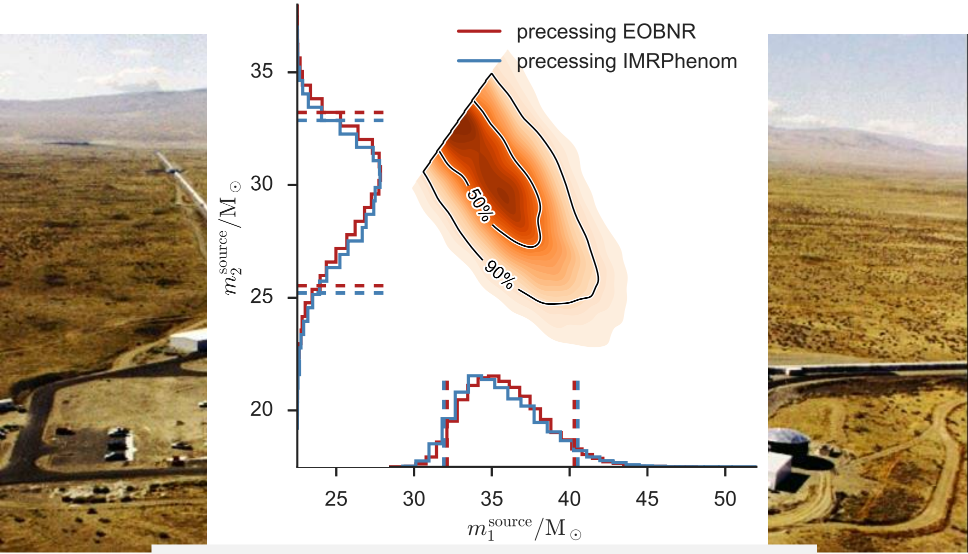
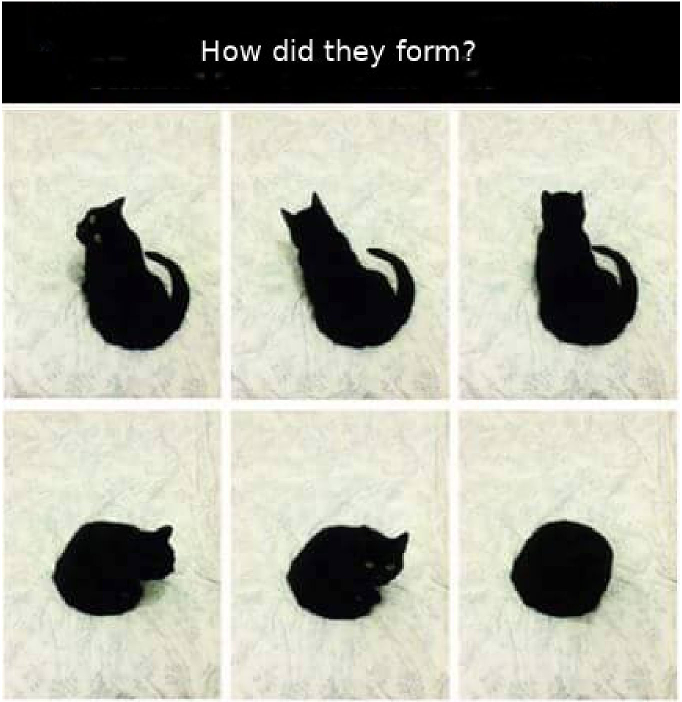
First science run of advanced LIGO detected 2.5 merging BHs!
Abbott+ 2016
astro-ph/1606.04856





GW150914, Abbott+ 2016 , astro-ph/1606.01210


How did they form?

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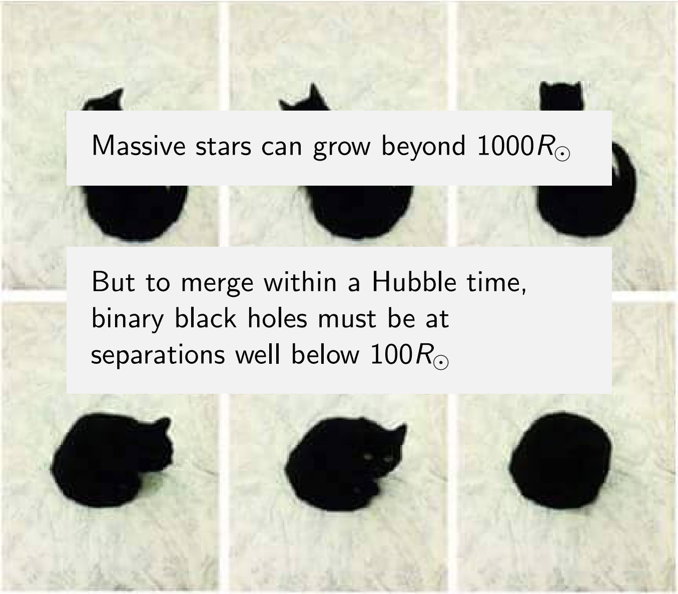
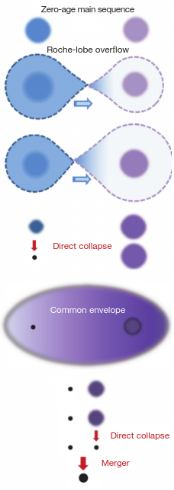
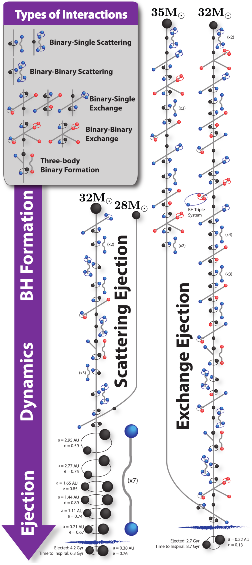


Massive stars can grow beyond $1000 R_\odot$

But to merge within a Hubble time, binary black holes must be at separations well below $100 R_\odot$

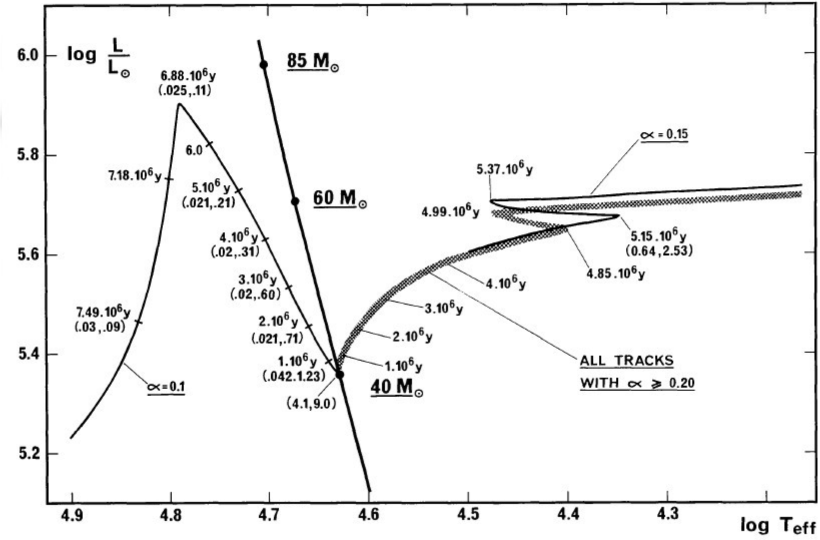


Field, Belczynski et al. (2016)
astro-ph/1602.04531

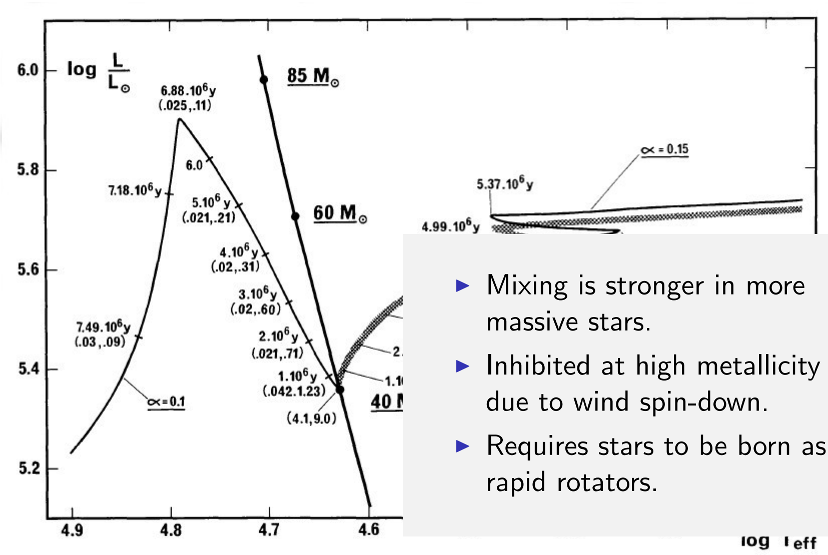


Cluster, Rodriguez et al. (2016)
astro-ph/1604.04254

Chemically homogeneous evolution (Maeder 1987)

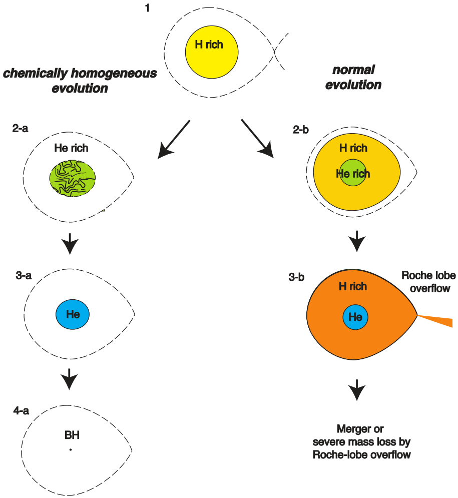


Chemically homogeneous evolution (Maeder 1987)



- Mixing is stronger in more massive stars.
- Inhibited at high metallicity due to wind spin-down.
- Requires stars to be born as rapid rotators.

Tidal locking in close binaries as a source of rapid rotation



Mandel & de Mink 2016

- Possibility of double-BH formation.
- Königsberger et al. 2014: Double He star system in the SMC
  - $M_1 = 66 M_\odot$, $M_2 = 61 M_\odot$
  - $P = 19.3$ days

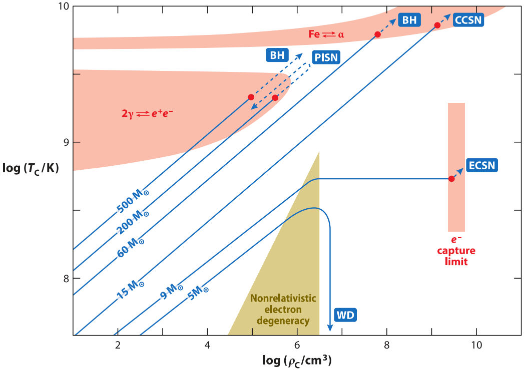
Song+ 2016

de Mink & Mandel 2016

Marchant+ 2016

Pair-instability supernovae, LGRBs

Langer 2012

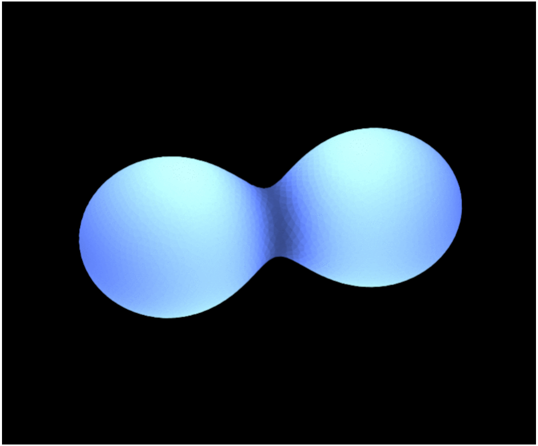


For helium stars, full disruption from explosion for final masses $M \sim 60 - 130 M_{\odot}$. Heger & Woosley 2002

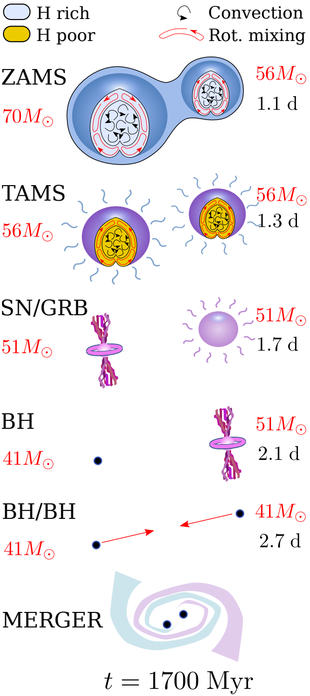
- Additionally, formation of high spin BH+accretion disk can result in LGRBs (Woosley 1993, Yoon & Langer 2005)

Almeida et al. 2015: Massive overcontact binary

$M_1 \simeq M_2 \simeq 30 M_\odot$, $q = M_1/M_2 = 1.008$, $P_{\rm orb} = 1.12\ [\rm d]$

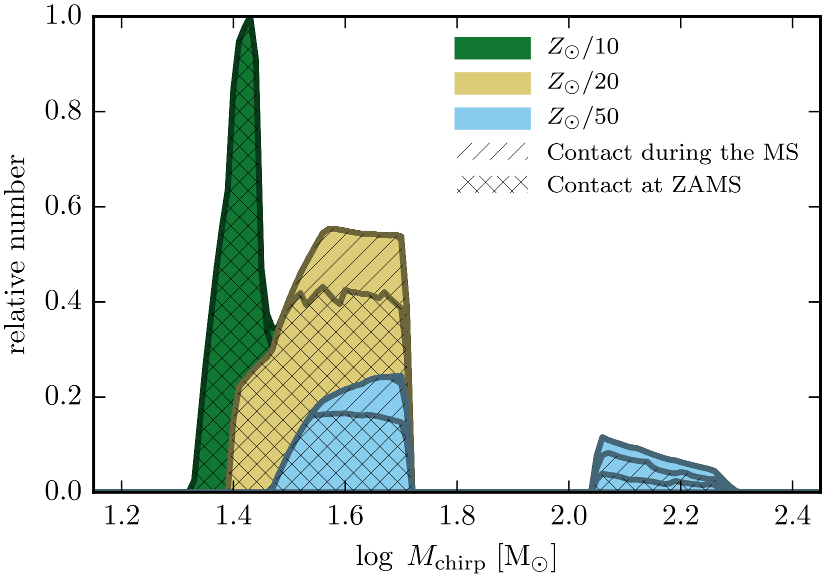


VFTS 352, most massive overcontact binary known.

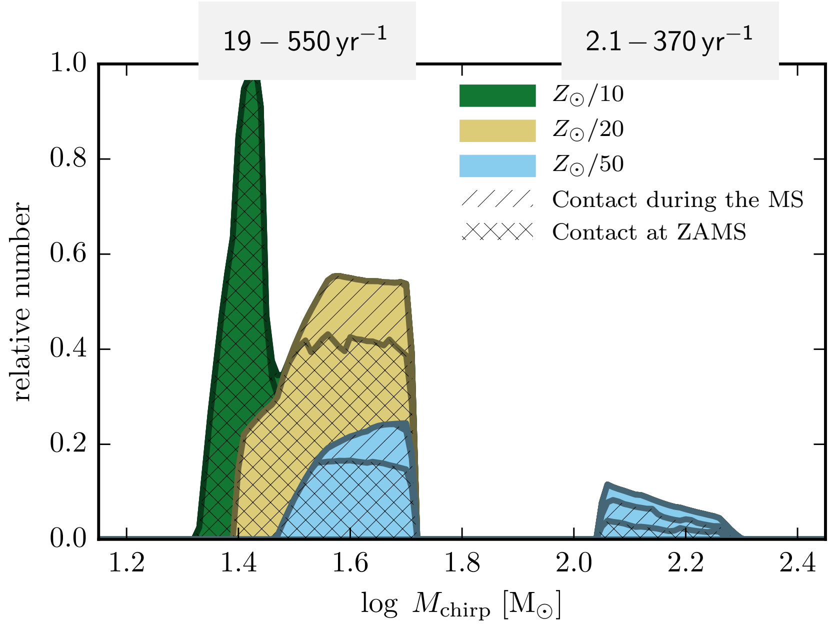


Marchant+ 2016

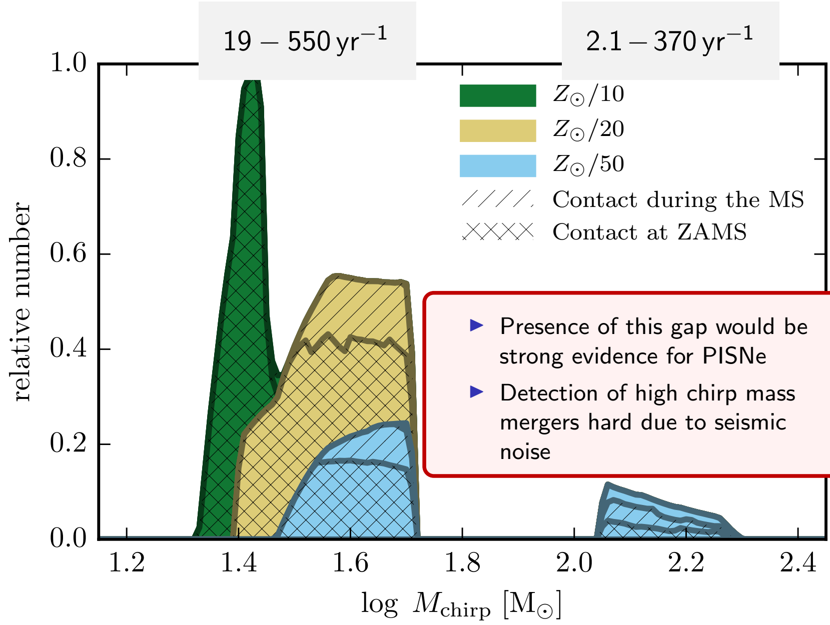
Chirp mass distribution



Chirp mass distribution



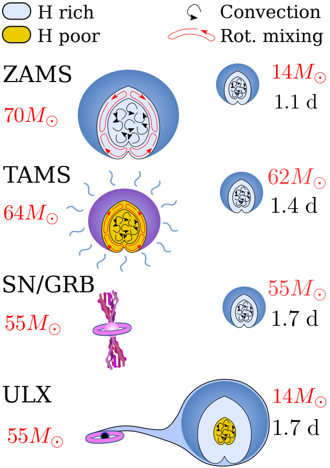
Chirp mass distribution

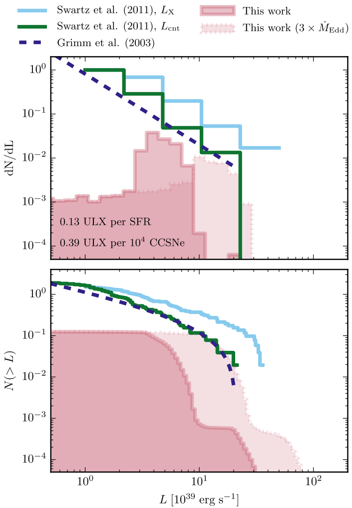


- Presence of this gap would be strong evidence for PISNe
- Detection of high chirp mass mergers hard due to seismic noise

Formation of ULXs

Marchant+, in preparation

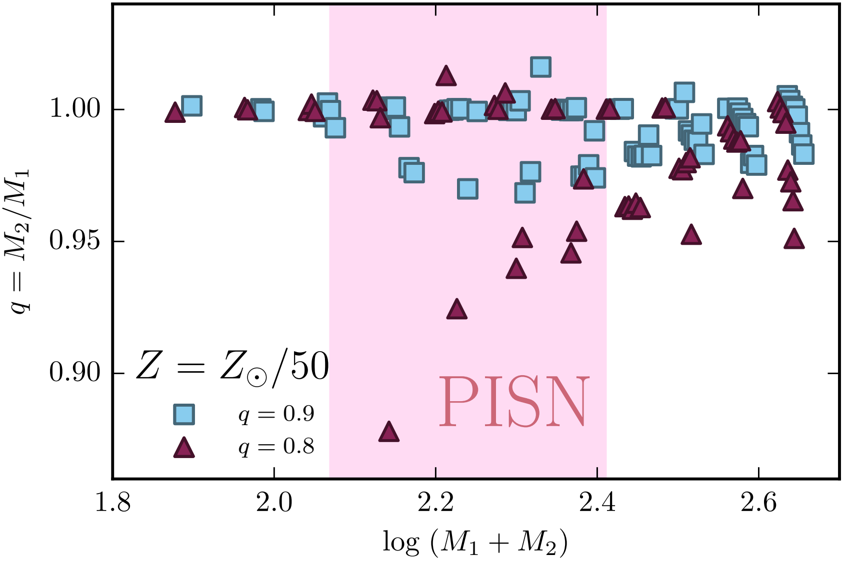




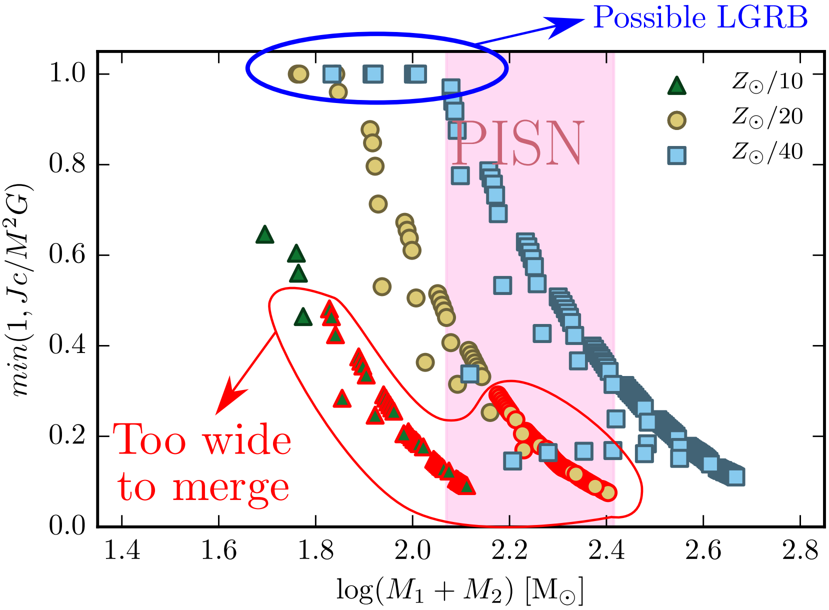
Conclusions

- Chemically homogeneous evolution in very massive binaries provides a common channel for LGRBs, PISNe, ULXs and merging double BHs.
- Consistent with the masses measured for GW150914, but low observed spin could be an issue.
- Detection of a gap in measured chirp masses of merging BHs could provide strong evidence por PISNe (and also on PPISNe).
- At low metallicity, BHs with high spin could be produced resulting in LGRBs through the collapsar model.
- Synchronization of the binary components can result in both stars ending their lives within a timescale of a few 100 yrs.
- Future observations by aLIGO and other facilities will provide strong constraints on this model. If seismic noise remains too high to detect $M_{\mathrm{chirp}} > 100 M_{\odot}$, might need to wait for eLISA, ET.

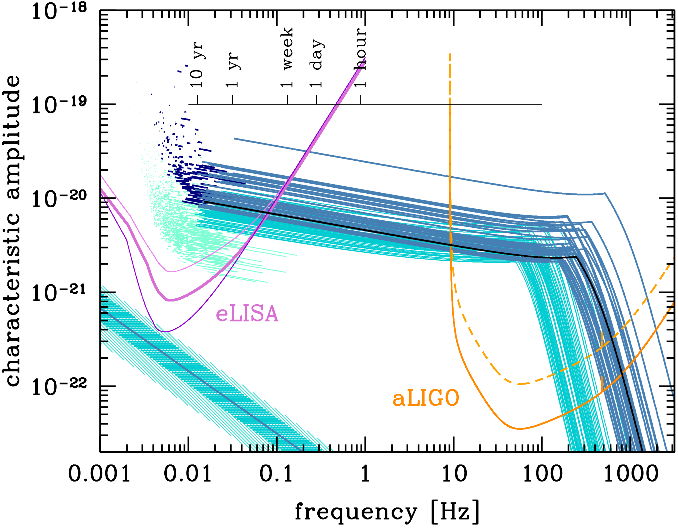
Mass ratios



Final BH spins and LGRBs



Sesana 2016



10 yr
1 yr
1 week
1 day
1 hour
eLISA
aLIGO
characteristic amplitude
frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
0.001
0.01
0.1
1
10
100
1000

Back-of-the-envelope rate estimates

$$R_{MWEG} = R_{SNe} \times f_{\rm binary} \times f_P \times f_q \times f_{\rm IMF} \times f_Z$$

- $R_{SNe} \sim 10^{-2}\ yr^{-1}$
- $f_{\rm binary} \sim 1/3$
- $f_P \sim 0.05$
- $f_q \sim 0.2$
- $f_{\rm IMF} \sim 0.05 - 0.01$ (above and below PISN gap)
- $f_Z \sim 0.1$

$$R_{MWEG} \sim 2 \times 10^{-7}\ [{\rm yr}^{-1}]; 3 \times 10^{-8}\ [{\rm yr}^{-1}]$$

aLIGO detection rates

Abadie et al. 2010:

$$N_{\rm gal} = \frac{4}{3}\,\pi\,\left(\frac{d_{\rm horizon}(M_{\rm chirp})}{\rm Mpc}\right)^3\,(2.26)^{-3}\,(0.0116)$$

- $d_{\rm horizon}(M_{\rm chirp})$: distance limit for detection ($\propto M_{chirp}^{15/6}$).
- $(2.26)^{-3}$: averaging due to relative inclinations and sky positions.
- $0.0116\ {\rm Mpc}^{-3}$: Extrapolated density of MWEGs (Kopparapu et al. 2008)

For a massive BH-BH merger with $M_{\rm BH} = 60\ M_\odot$ (or $130\ M_\odot$), we get $d_{\rm horizon} \simeq 10\ {\rm Gpc}$ (or $d_{\rm horizon} \simeq 19\ {\rm Gpc}$)

aLIGO detection rates

Z	$Z_\odot/50$	$Z_\odot/20$	$Z_\odot/10$	$Z_\odot/4$
dBH/SN $<$ PISN (10^{-3})	0.67	1.3	0.34	0
dBH/SN $>$ PISN (10^{-3})	0.27	0	0	0
LIGO rate [yr^{-1}] $<$ PISN	3539	5151	501	0
LIGO rate [yr^{-1}] $>$ PISN	5431	0	0	0

Table: Fraction of systems per SN that result in double BHs that would merge in less than $13.8\,\mathrm{Gyr}$ (upper 2 rows), and aLIGO detection rates (lower 2 rows), assuming that all galaxies have the corresponding metallicity, both above and below the PISN gap.

Rate Estimates: $19 - 550\,\mathrm{yr}^{-1}$ for BH-BH mergers below the PISN gap and of $2.1 - 370\,\mathrm{yr}^{-1}$ above the PISN gap.

Königsberger et al. 2014, HD5980

Table 6
Orbital Solutions for *Stars A* and *B*

Element	N v 4944 RVs		System A+B
	Star A	Star B	
$M \sin^3 i$ ($M_\odot$)	61 (10)	66 (10)	127 (14)
$a \sin i$ ($R_\odot$)	78 (3)	73 (3)	151 (4)
K (km s^{-1})	214 (6)	200 (6)	...
e	...	...	0.27 (0.02)
ω_{per} (deg)	...	...	134 (4)
V_0 (km s^{-1})	...	...	131 (3)
P_{calc} (days)	...	...	19.2656 (0.0009)

Table 7
Orbital Solution for *Star C*

Element	Current Analysis	Schweickhardt (2000)
P_C (days)	96.56 (0.01)	96.5
T_{peri} (HJD)	2451183.40 (0.22)	2451183.3
e	0.815 (0.020)	0.82
ω (deg)	252 (3.3)	248
K (km s^{-1})	81 (4)	76

$$P_C / P_{A+B} = 5.0089$$