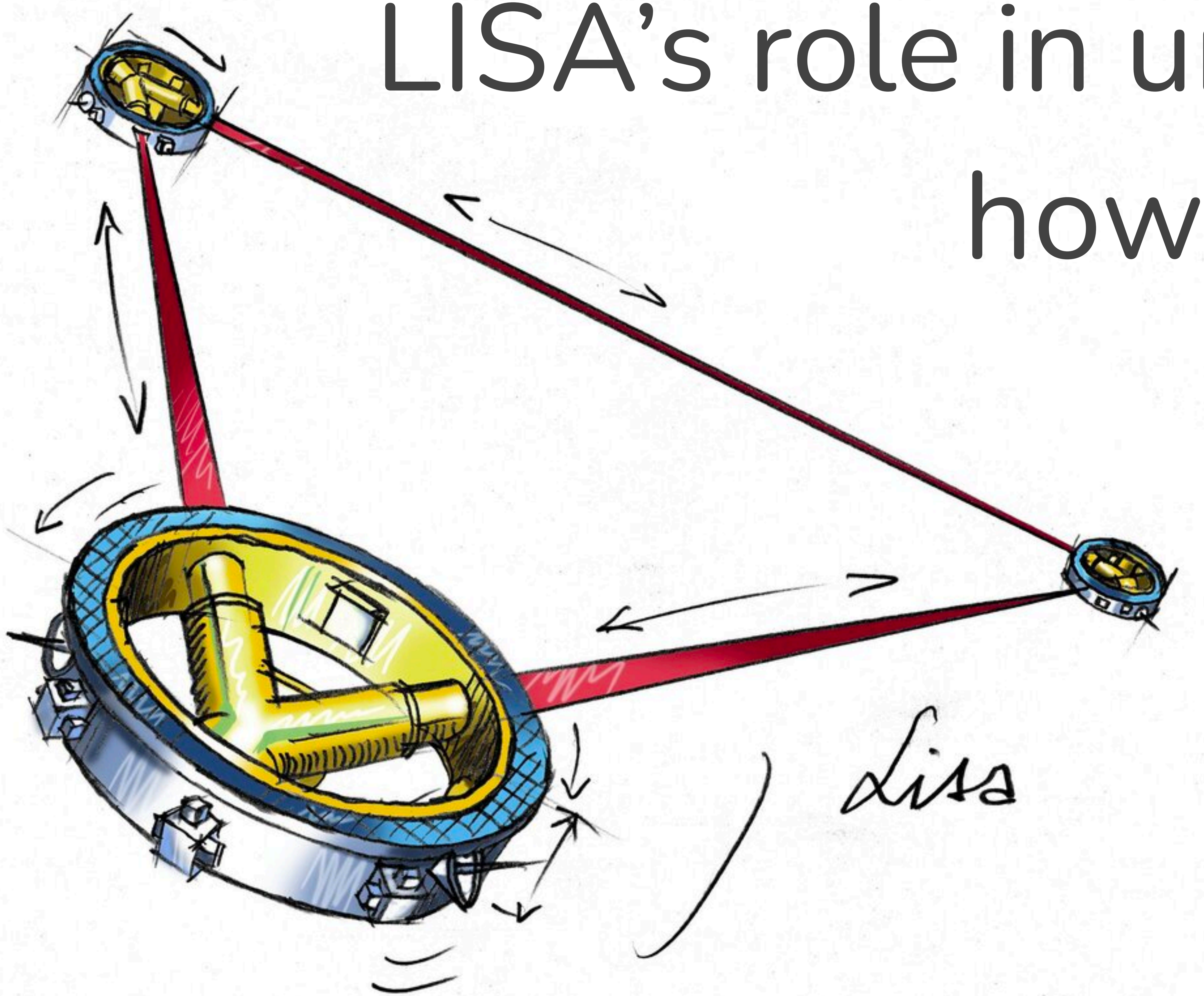
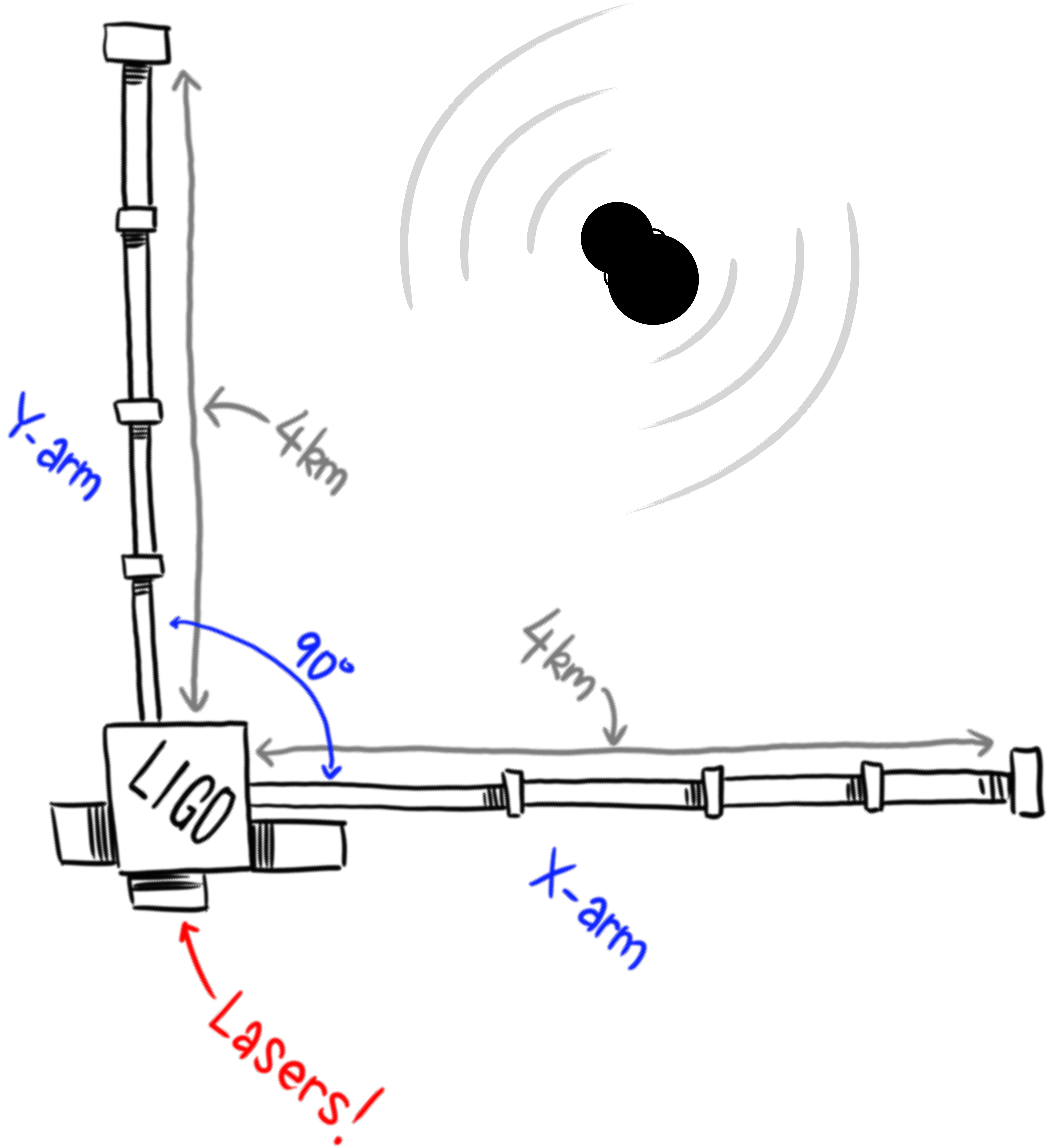


LISA's role in understanding how stellar-mass binary black holes form

Katie Breivik
Carnegie Mellon | McWilliams Center

Ten Years to LISA

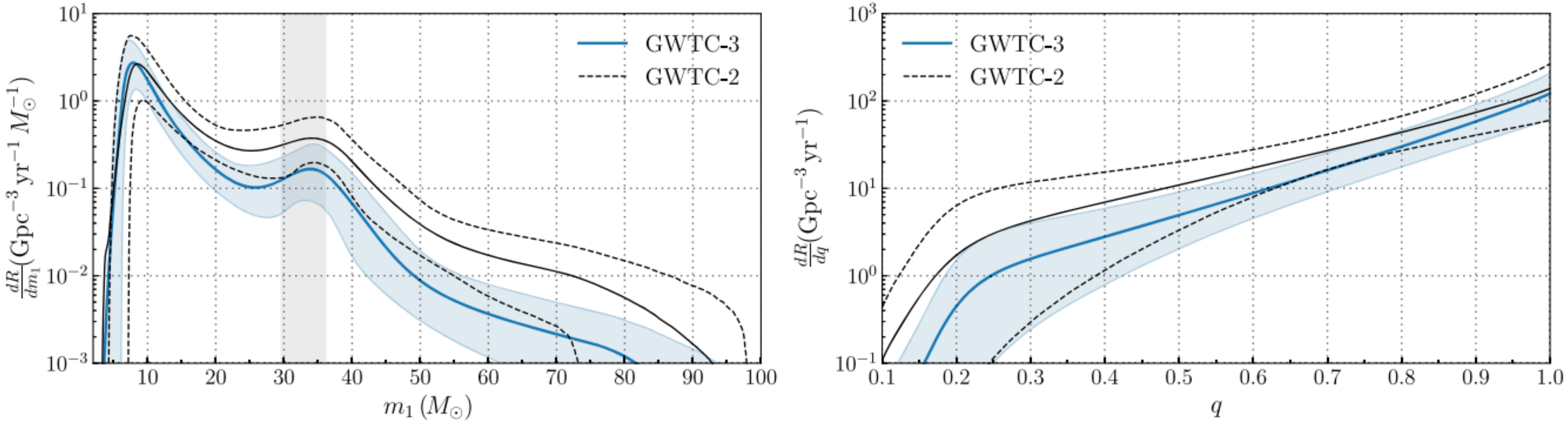


LIGO - Virgo - KAGRA <u>Collaboration</u>

Principle target: pairs of merging neutron stars and black holes

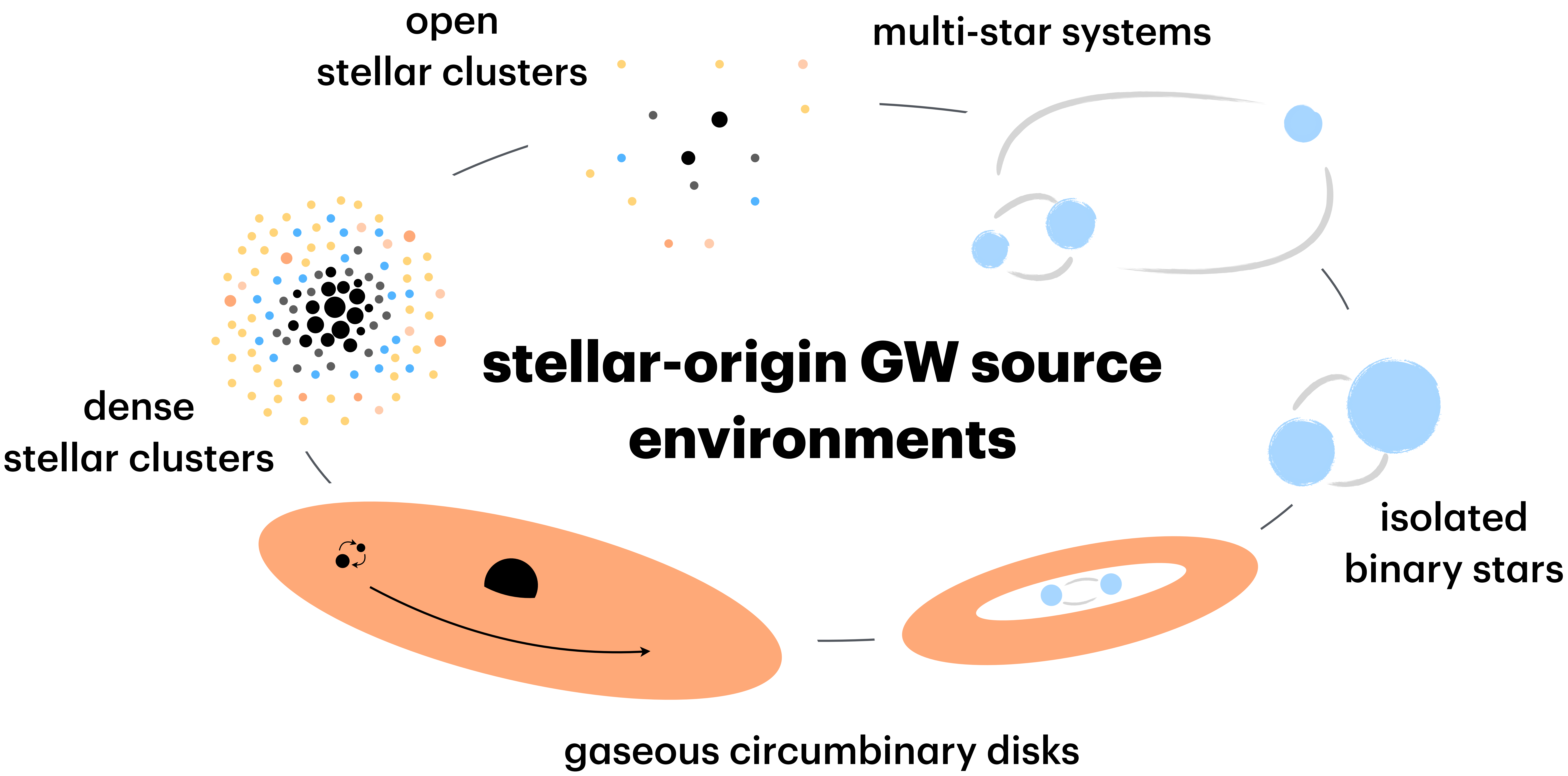
GW150914: first BBH
GW170817: first BNS

GWTC-3 : 90 mergers



Ground-based detectors are measuring the masses of merging binary black holes with increasing precision

GWTC-4 > 200 mergers!

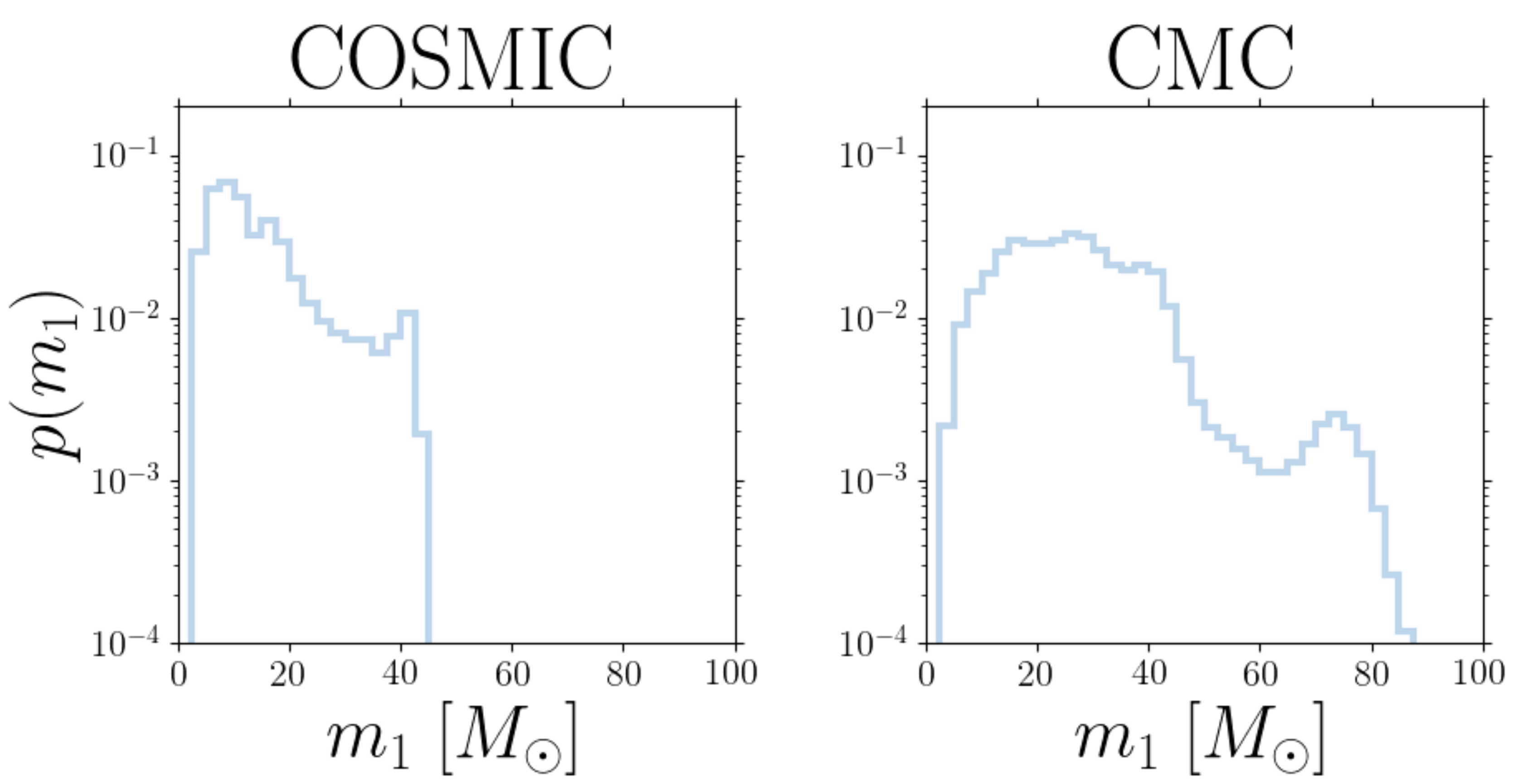


Breivik+2025
arXiv: 2502.03523

Imprints of formation environment from forward modeling

M > 45 $M_\odot$ ⇒ dynamics

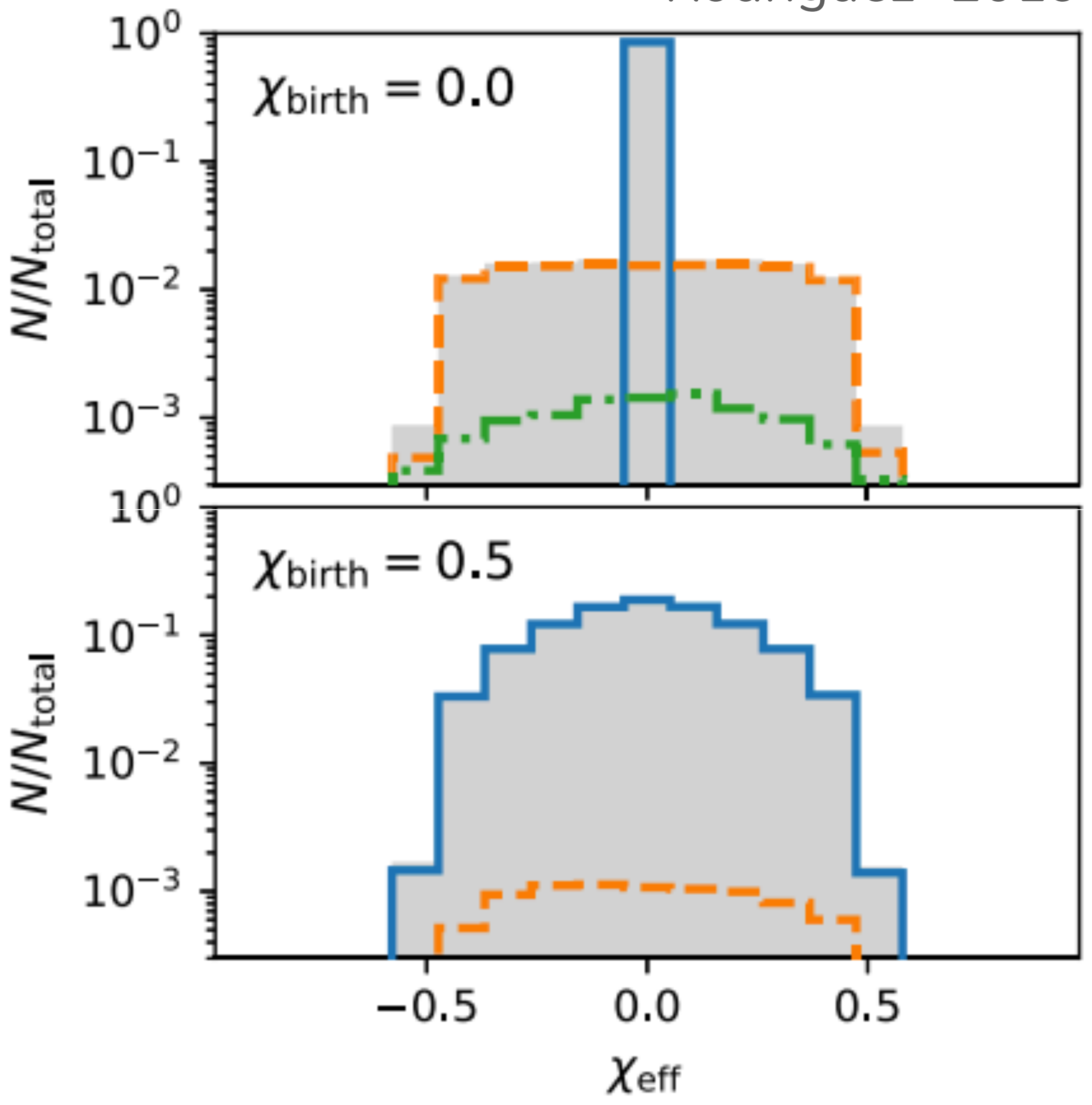
Wong, KB+2019



see also Woosley+17,19, Marchant+19 Farmer+19, Renzo+19, Rodriguez+19, DiCarlo+20,21, Zevin+20

Isotropic spins ⇒ dynamics

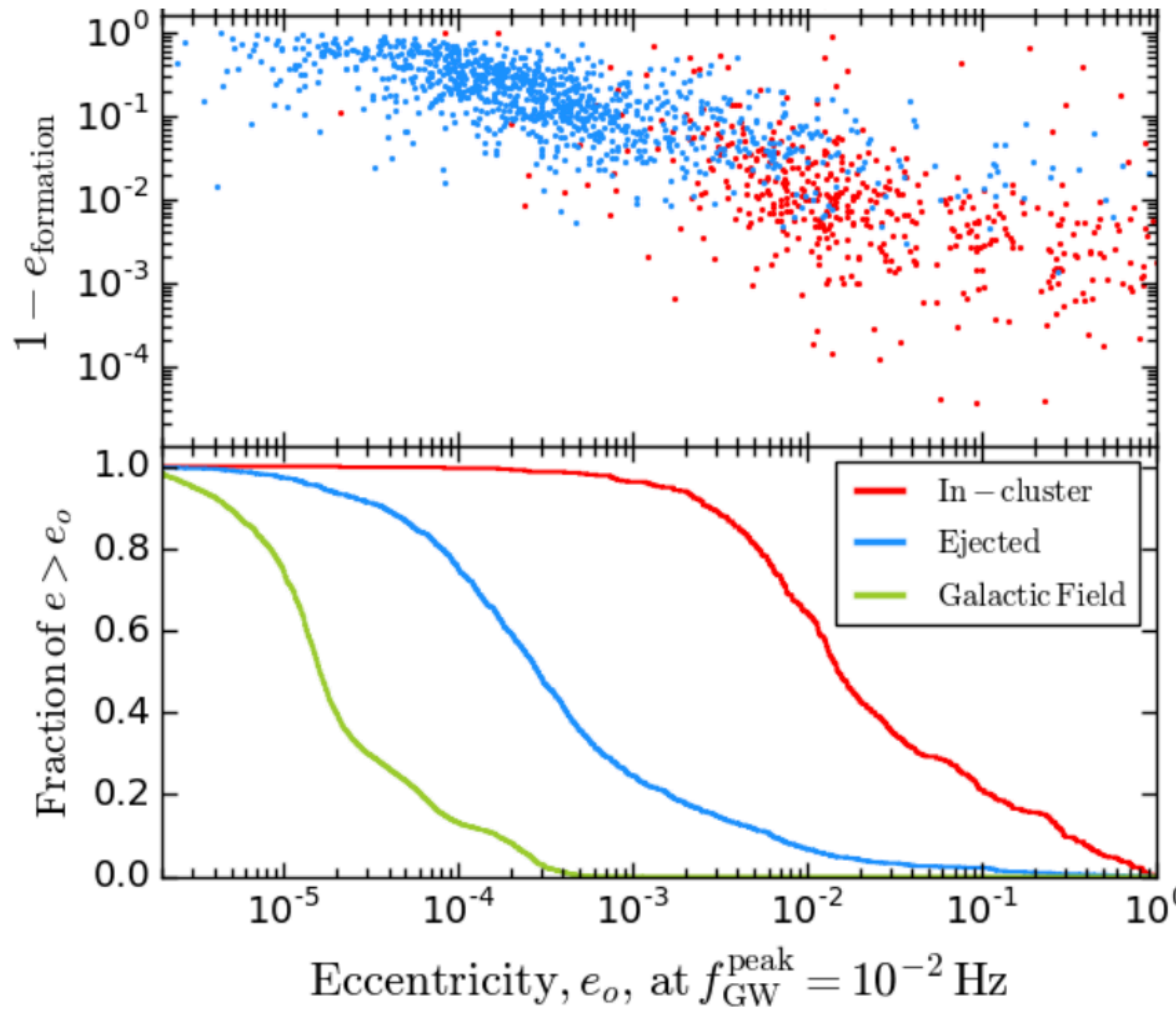
Rodriguez+2019



see also Rodriguez+16, Bavera+20, McKernan+20

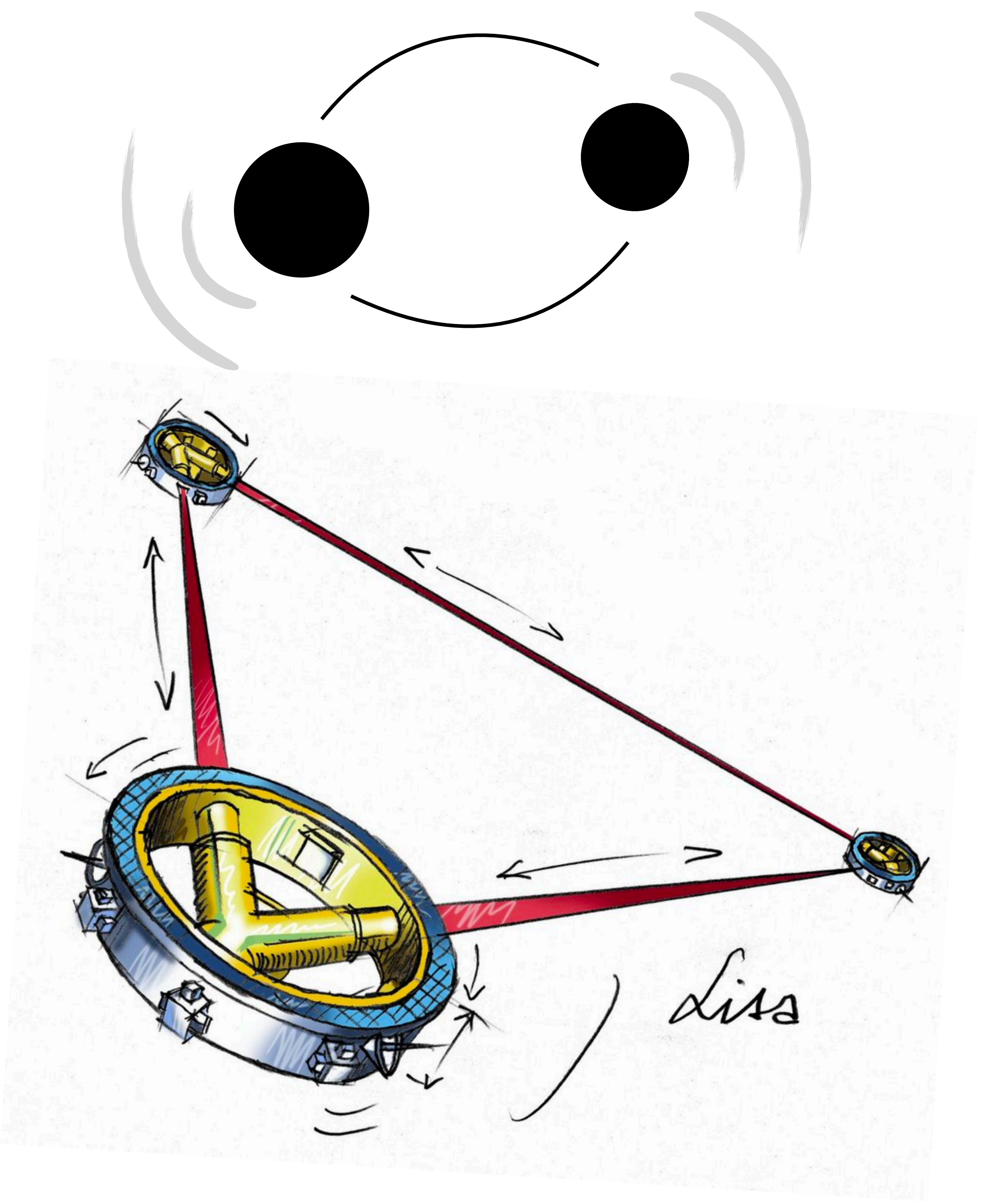
Eccentricity ∝ dynamics

Kremer+2018

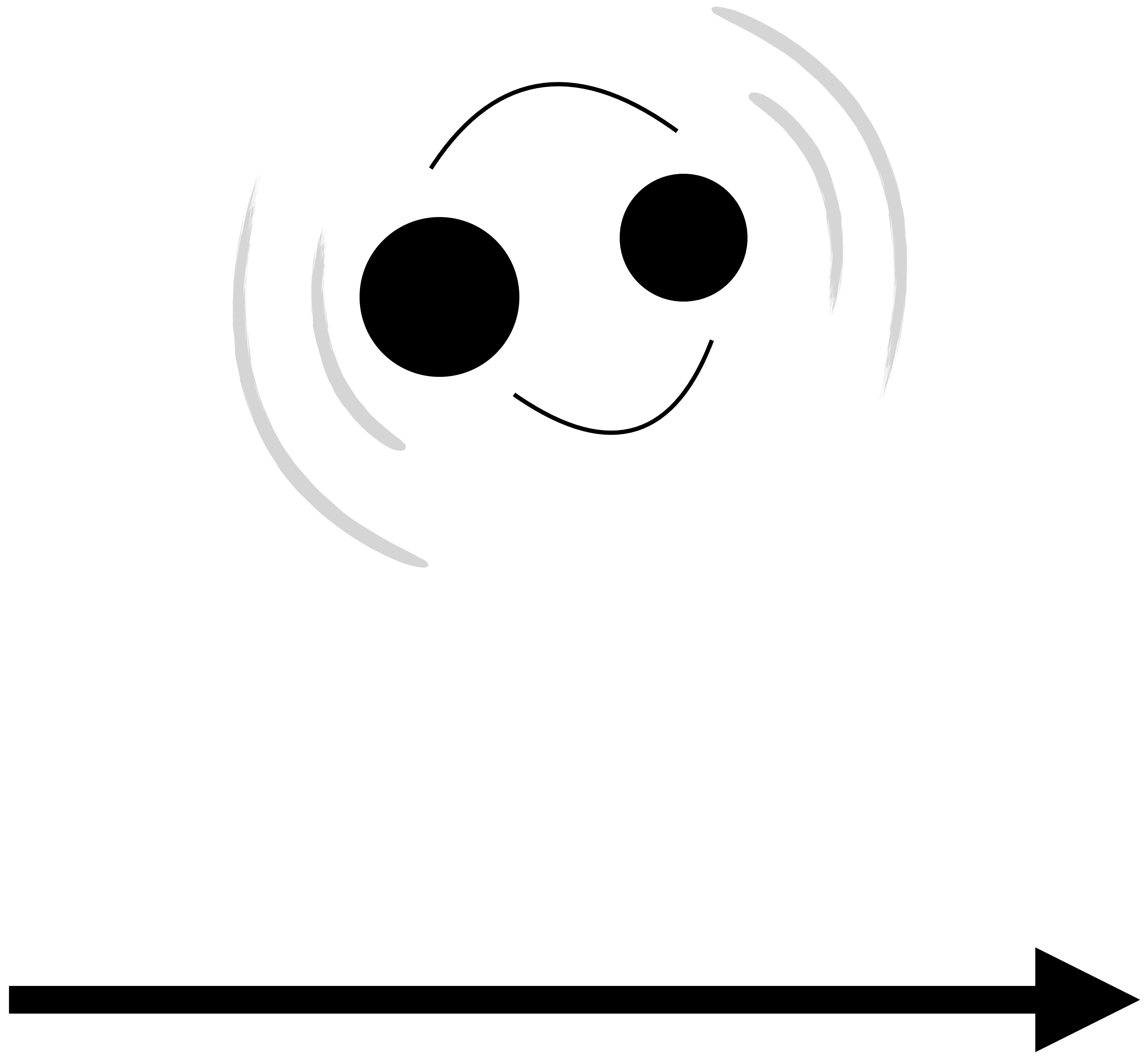


see also KB+16, Nishizawa+16,17, Samsing+17, D'Orazio+18, Rodriguez+18

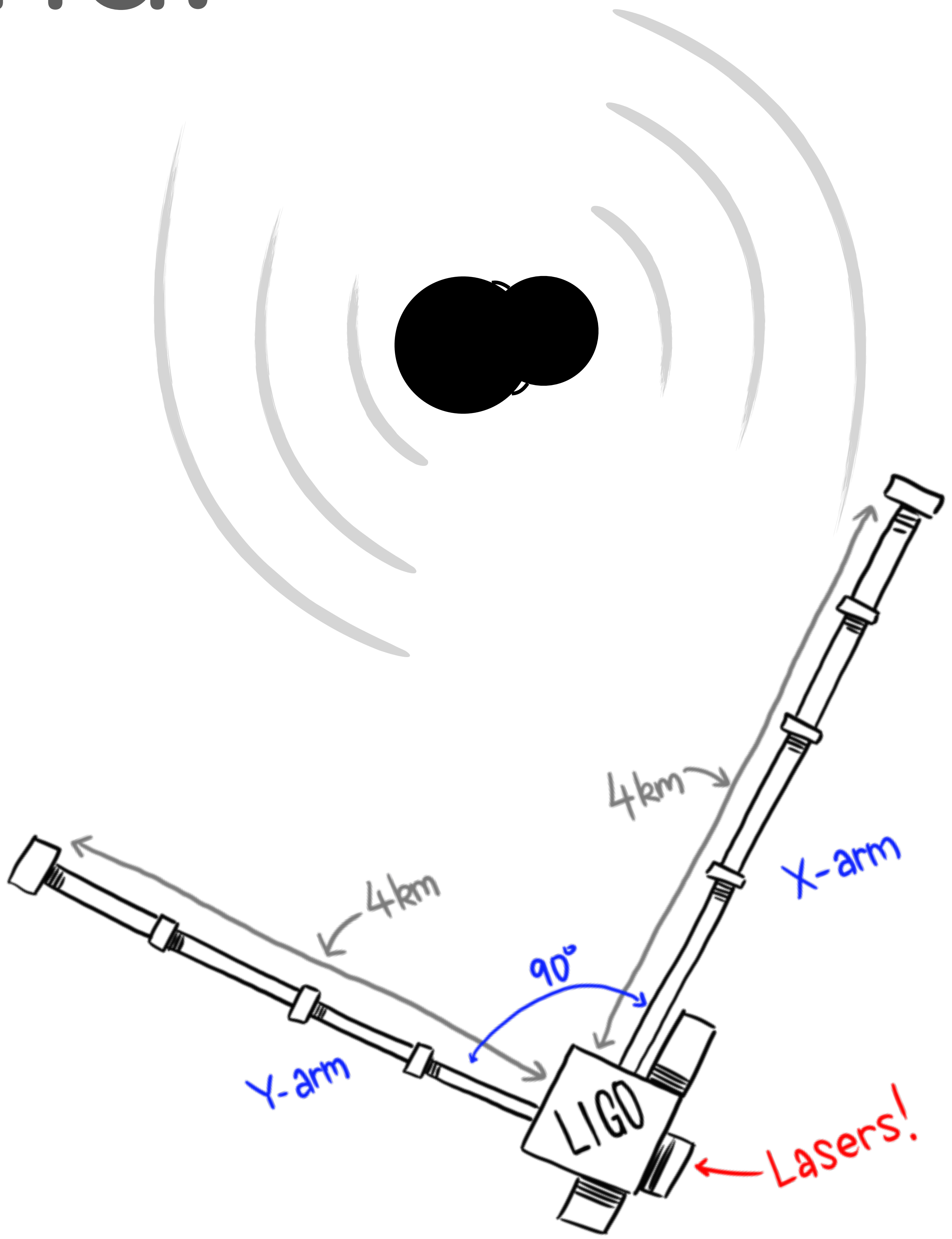
Every GW source that merges passes through the mHz band!



$f_{\mathrm{GW}} \sim 1\,\mathrm{mHz}$



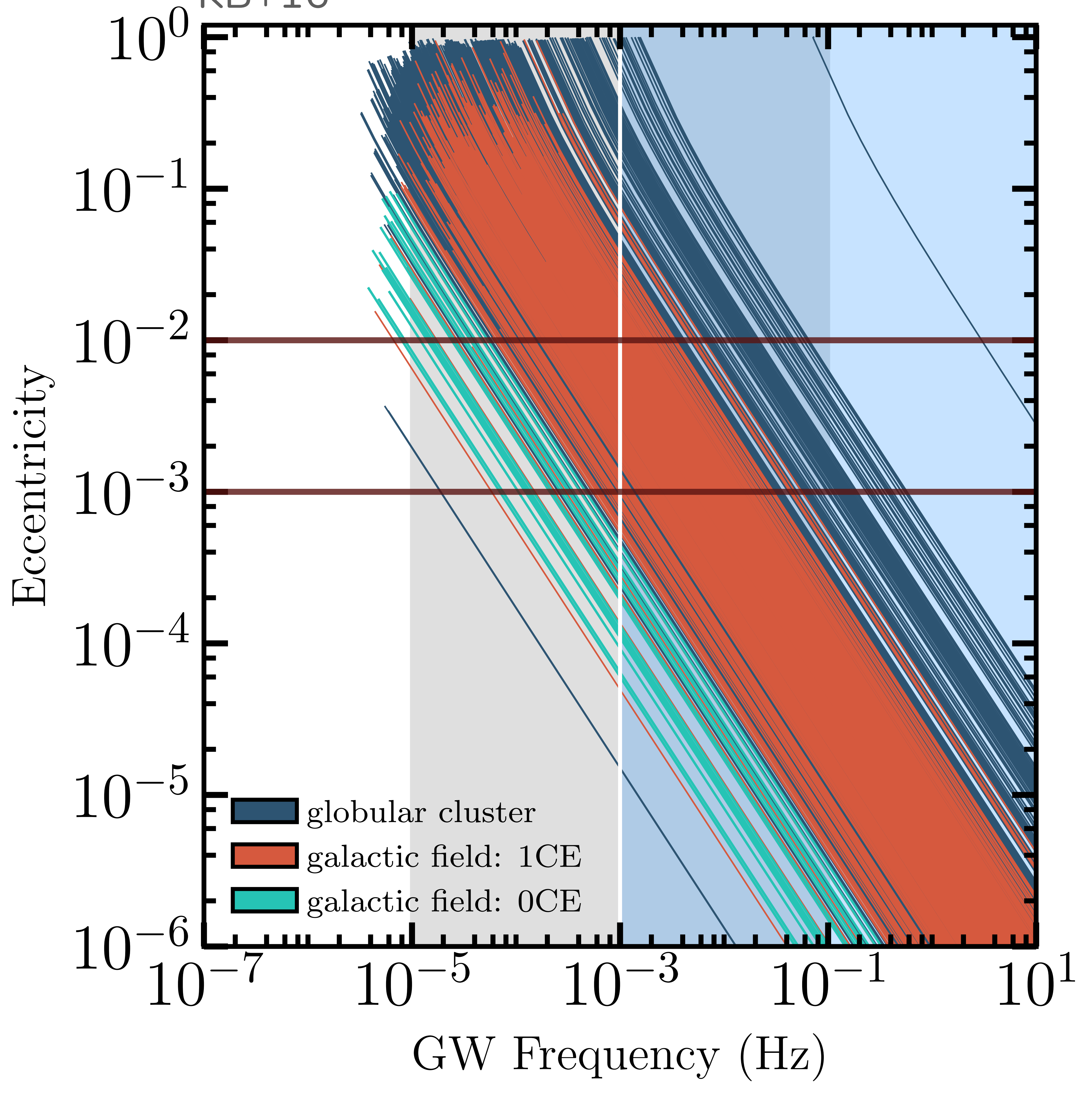
$f_{\mathrm{GW}} \sim 10\,\mathrm{Hz}$



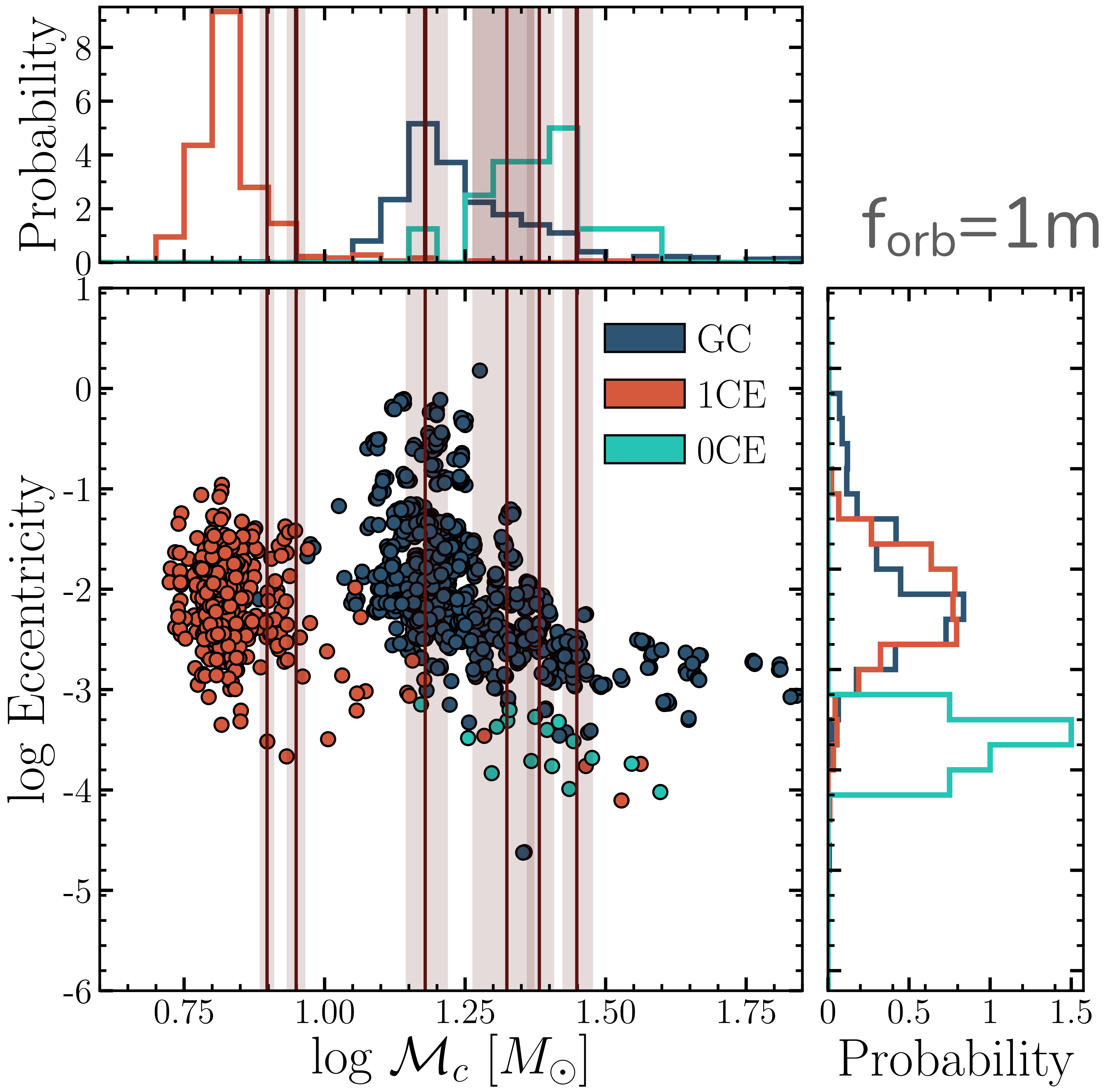
$f_{\mathrm{GW}} \sim 1\,\mathrm{kHz}$

LISA can determine which BBHs are dynamically assembled

KB+16



KB+16

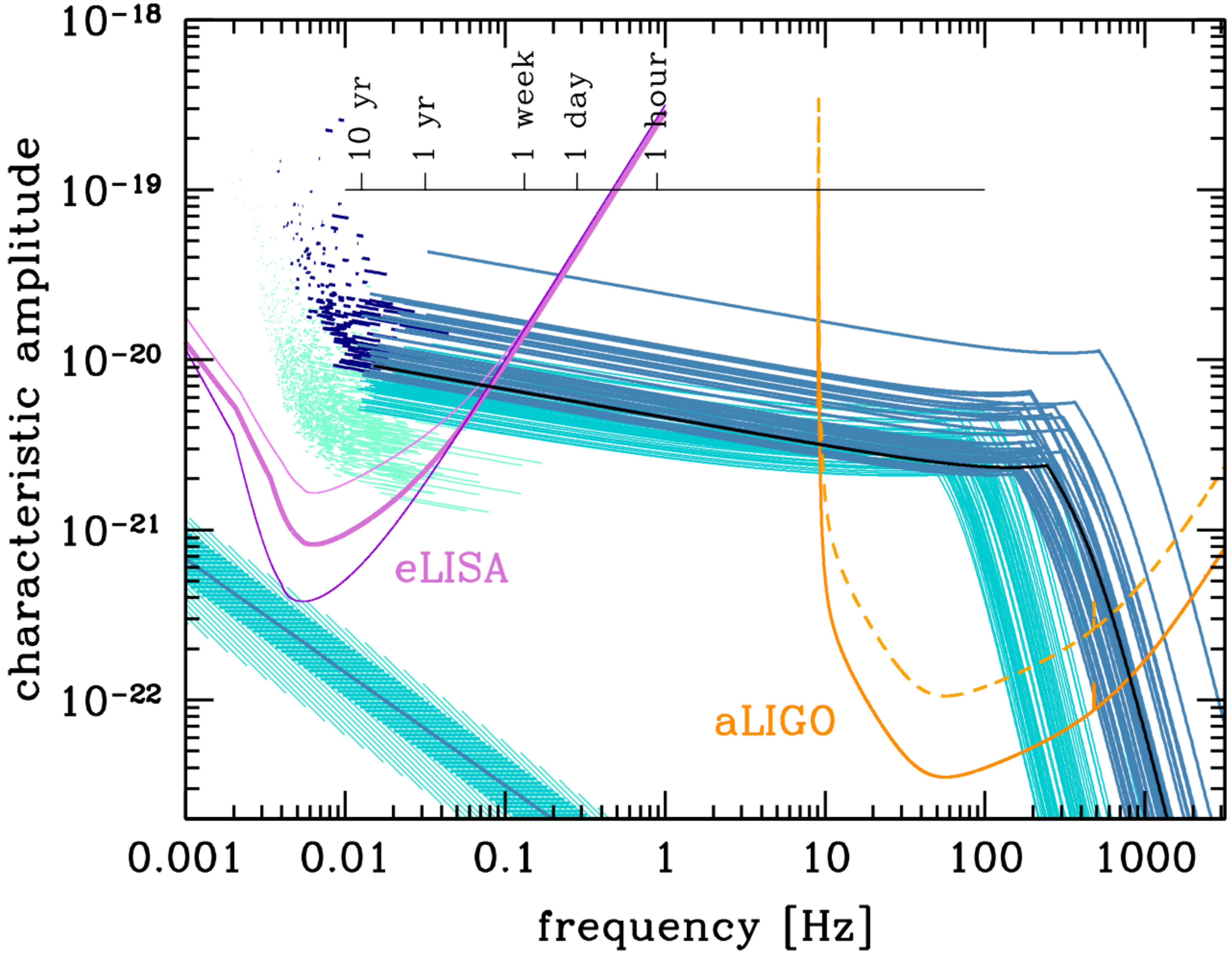


f_{orb}=1mHz

See also: Nishizawa+16,17, D'Orazio+17, Zevin+19

Some BBHs might traverse from LISA to LIGO
on human timescales

Sesana 16



Evolve backward to LISA band based on LIGO rate:

~15-1000 multiband sources

~100-4000 sources resolved

e.g Sesana 16

Forward model from population synthesis:

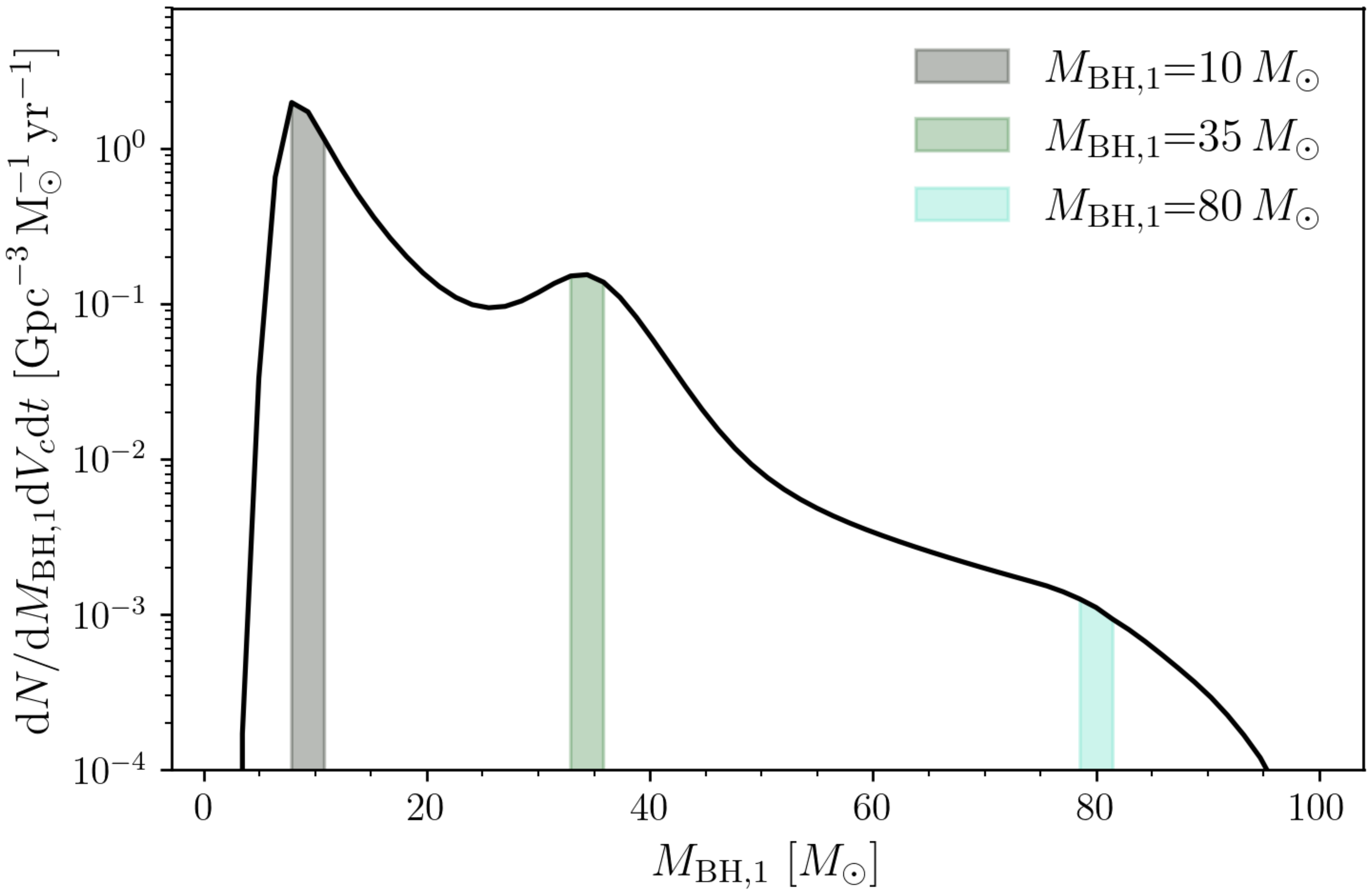
~0-240 sources resolved

e.g. Nelemans+01, Belczynski+10, Nissanke+12, Liu+14, Kremer+18,19, Lamberts+19, Sesana+20, **KB+20**, Shao+21, Wagg+21, Ruiz-Rocha+25

"How many BBHs do we expect based on GWTC-3?"

— a question by Katie Breivik & Will Farr

Assume $e = 0$ and merger rates follow Power Law + Peak



If all BBHs pass through the LISA band the number of BBHs for LISA is

$$\frac{\mathrm{dN_{LISA}}}{\mathrm{d}M_1} = \int \mathrm{d}V_c \int \mathrm{d}f_{\rm orb} \frac{\mathrm{d}N}{\mathrm{d}M_{\rm BH,1}\mathrm{d}t\mathrm{d}V_c} \left\langle \frac{\mathrm{d}t}{\mathrm{d}f_{\rm orb}} \right\rangle$$

where Peters 1964 says:

$$\left\langle \frac{\mathrm{d}f_{\rm orb}}{\mathrm{d}t} \right\rangle = \frac{48}{5\pi} \frac{\left(G\mathscr{M}_c\right)^{5/3}}{c^5} (2\pi f_{\rm orb})^{11/3}$$

$$\frac{\mathrm{dN_{LISA}}}{\mathrm{d}M_1} = \int \mathrm{d}V_c \int \mathrm{d}f_{\mathrm{orb}} \frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{BH,1}}\mathrm{d}t\mathrm{d}V_c} \left\langle \frac{\mathrm{d}t}{\mathrm{d}f_{\mathrm{orb}}} \right\rangle$$

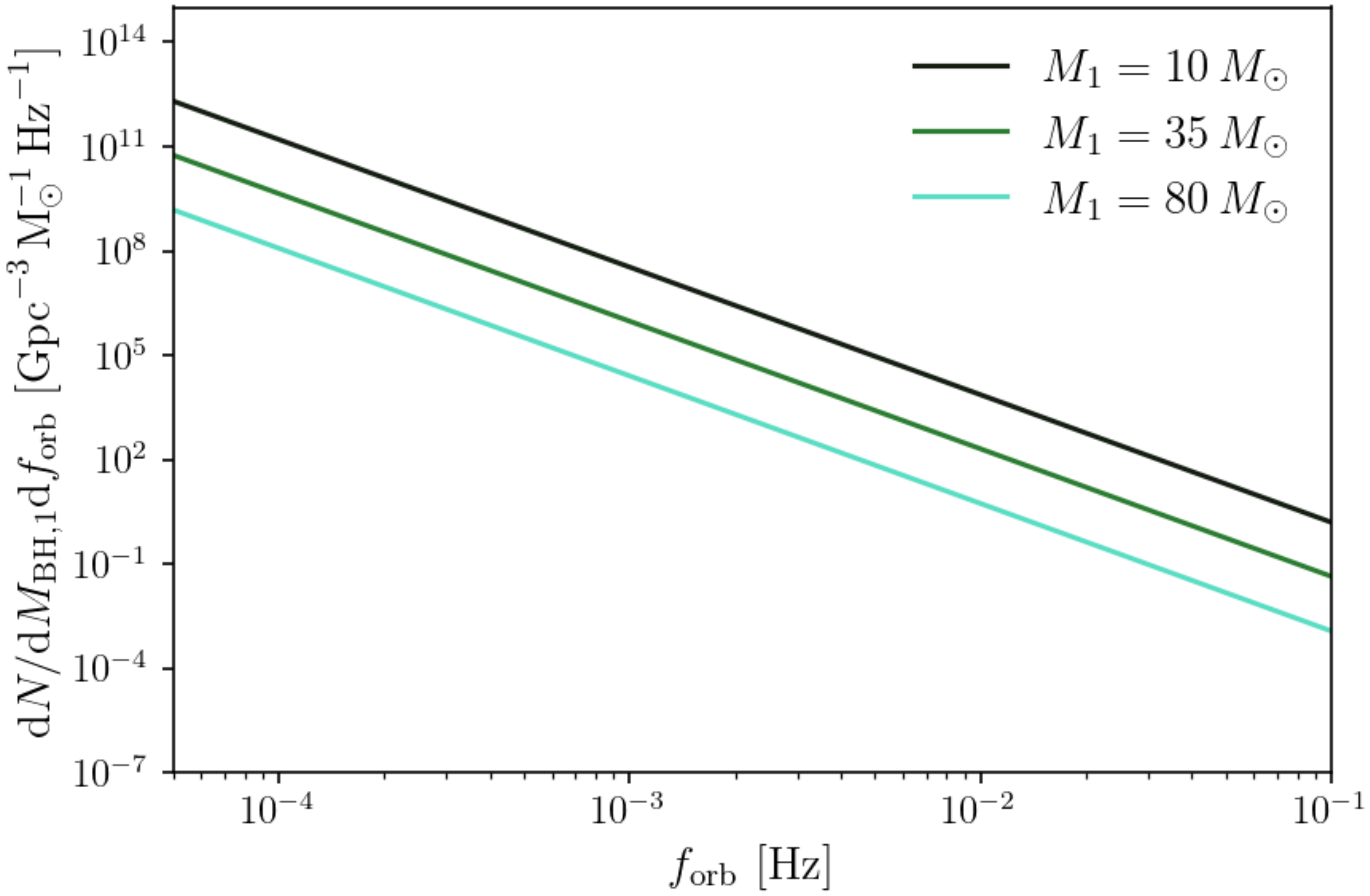
We need to calculate the orbital evolution and horizon distance to determine what LISA will be able to observe

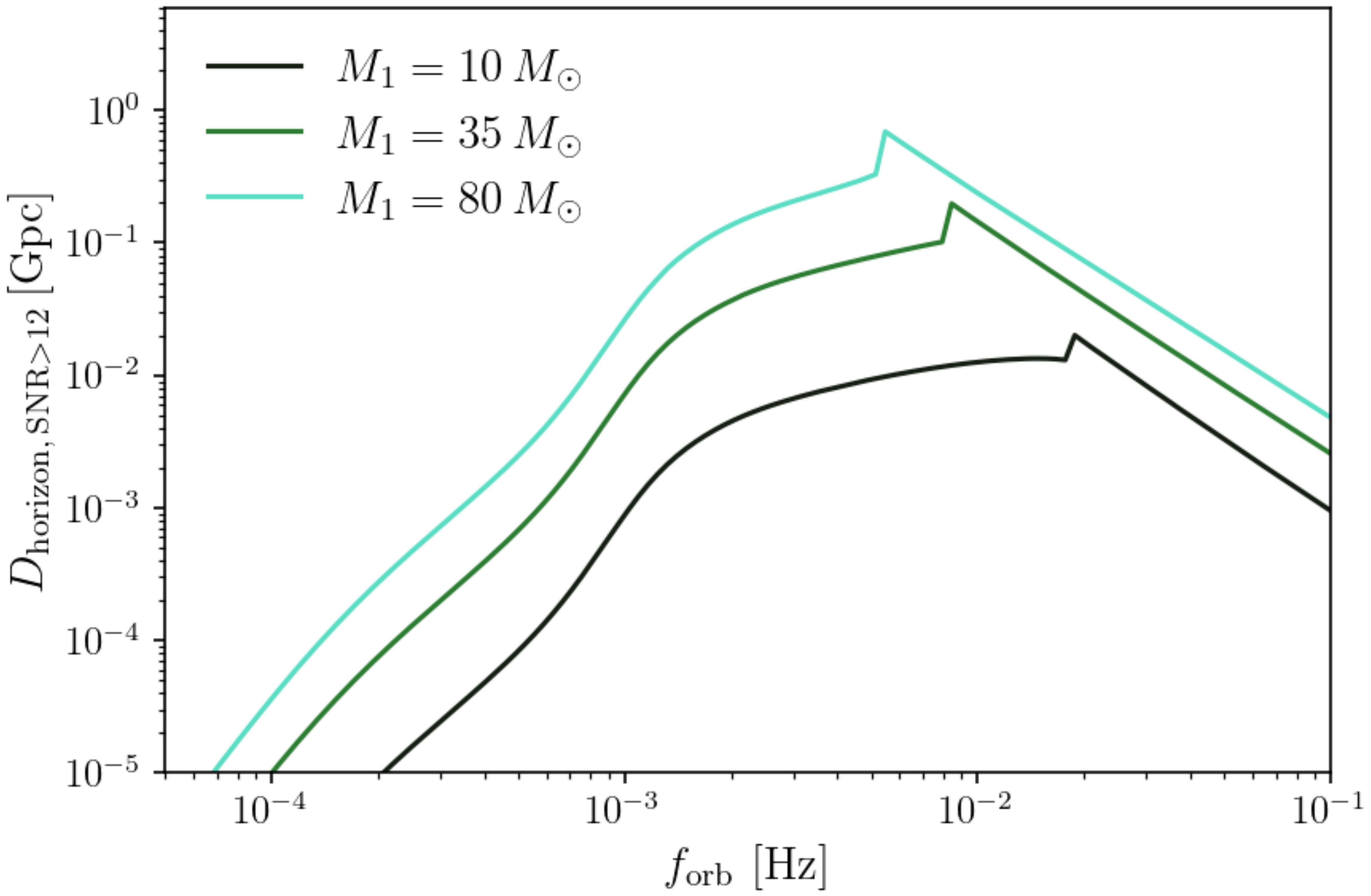
LEGWORK

Wagg,KB+22a,b

Tom Wagg
UW -> CCA

For all your *straightforward but tedious* LISA calculation needs!



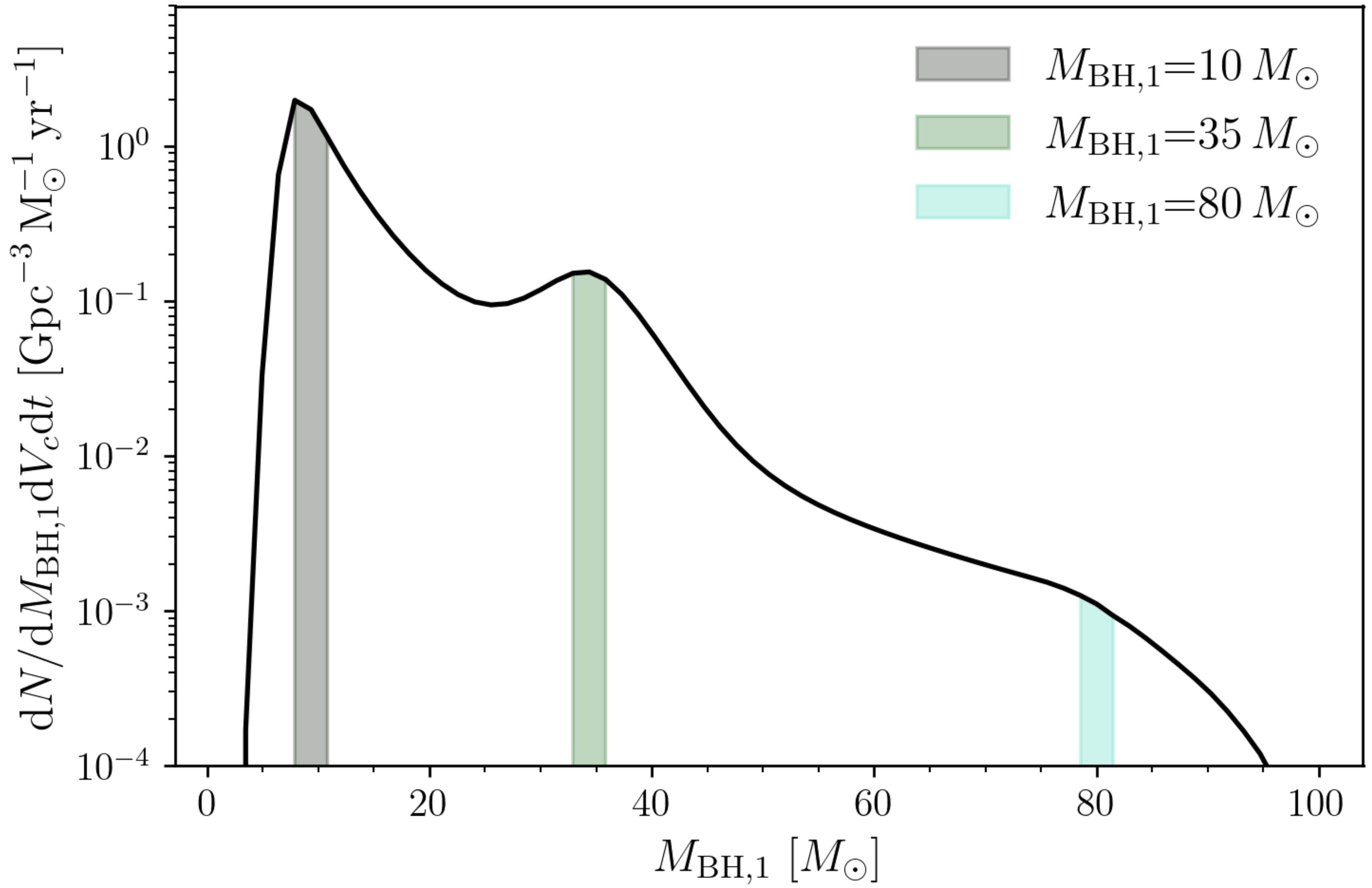


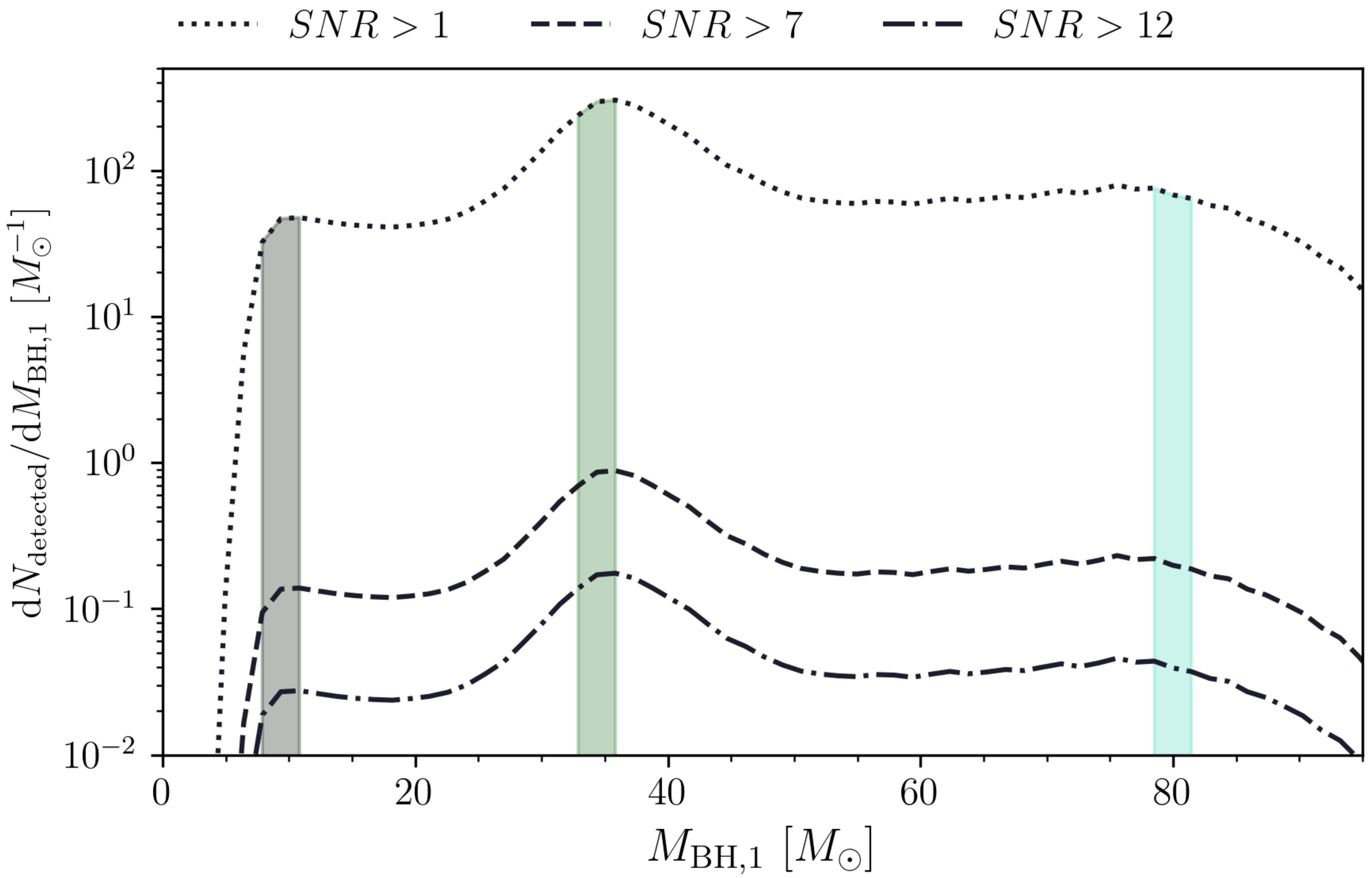
The orbital evolution is easy since we just have a power law:

$$\left\langle \frac{\mathrm{d}f_{\mathrm{orb}}}{\mathrm{d}t} \right\rangle = \frac{48}{5\pi}\frac{(G\mathcal{M}_c)^{5/3}}{c^5}(2\pi f_{\mathrm{orb}})^{11/3}$$

The horizon distance peaks where the time to chirp out of the LISA band equals the observation duration (8 yrs here)

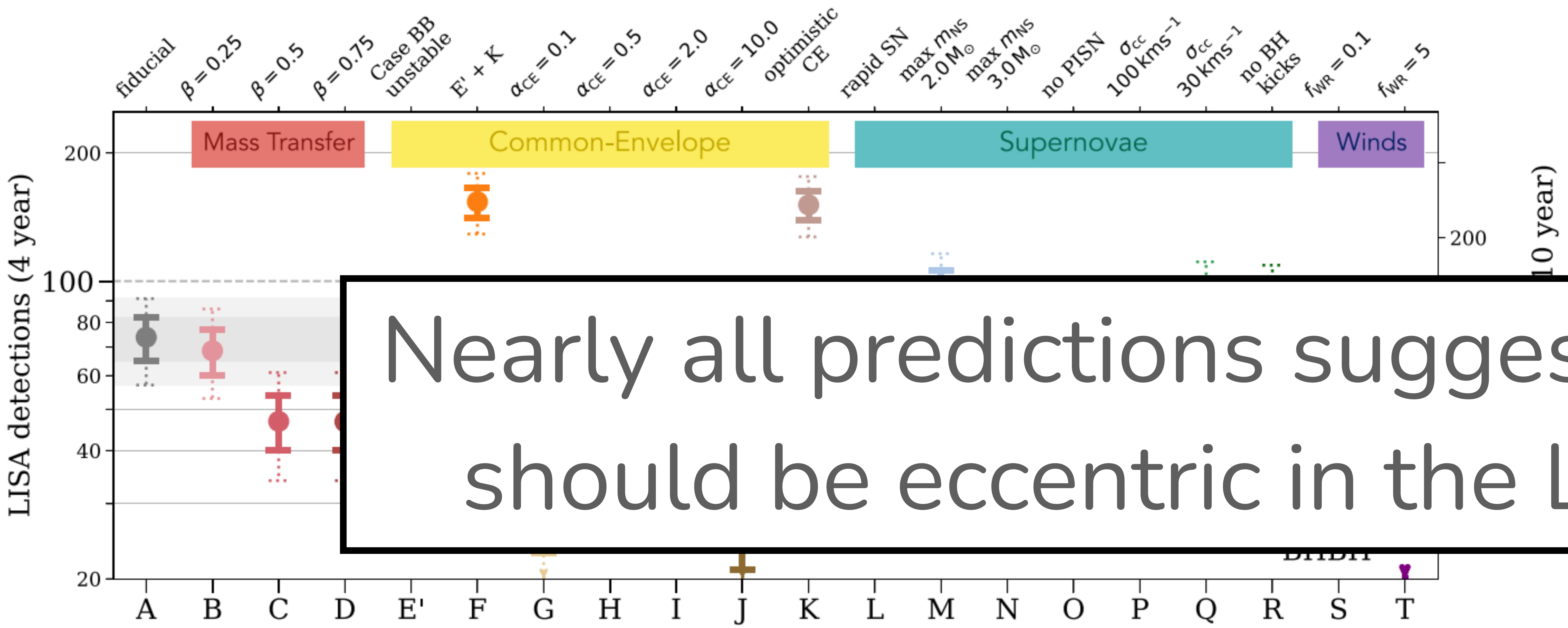
If all BBHs are circular: LISA is most likely to observe BBHs in ground-based 35 $M_\odot$ peak



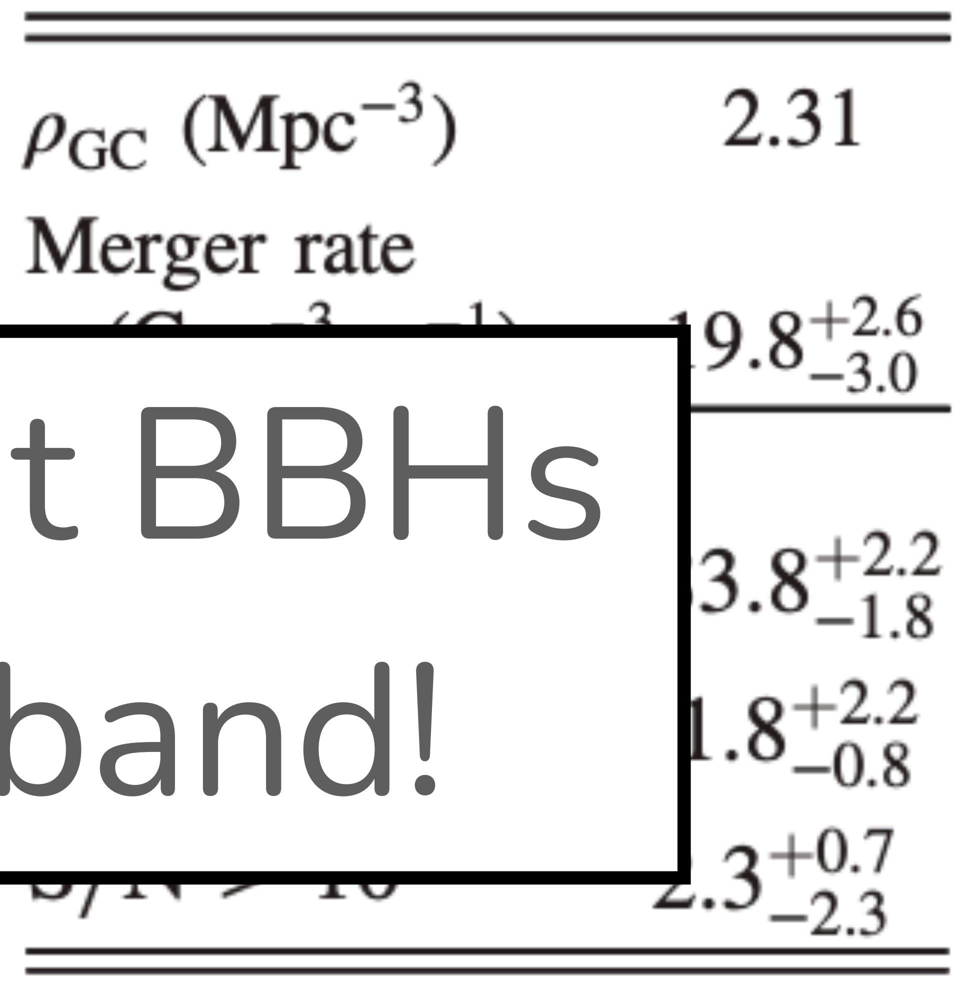


$N_{\mathrm{SNR}>1} = 7530$ $N_{\mathrm{SNR}>7} = 22$ $N_{\mathrm{SNR}>12} = 4$

$N_{\mathrm{SNR}>1} = 7530$ $\quad N_{\mathrm{SNR}>7} = 22$ $\quad N_{\mathrm{SNR}>12} = 4$



Wagg+2022



Kremer+2019

Nearly all predictions suggest that BBHs should be eccentric in the LISA band!

Population synthesis predictions can be ~roughly~ correct, but there are a lot of uncertainties!

See also: Nelemans+01, Belczynski+10, Nissanke+12, Liu+14, Kremer+18, Lamberts+20, Sesana+20, KB+20, Shao+21, **Ruiz-Rocha+25 <— see Krystal's talk later!!**

$$\frac{\mathrm{d}N_{\mathrm{LISA}}}{\mathrm{d}M_1} = \int \mathrm{d}V_c \int \mathrm{d}f_{\mathrm{orb}} \frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{BH},1}\mathrm{d}t\mathrm{d}V_c} \left\langle \frac{\mathrm{d}t}{\mathrm{d}f_{\mathrm{orb}}} \right\rangle \quad \text{: circular}$$

$$\downarrow$$

$$\frac{\mathrm{d}N_{\mathrm{LISA}}}{\mathrm{d}M_1} = \int \mathrm{d}V_c(e, f_{\mathrm{orb}}) \int \mathrm{d}f_{\mathrm{orb}} \frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{BH},1}\mathrm{d}t\mathrm{d}V_c} \left\langle \frac{\mathrm{d}t(e, f_{\mathrm{orb}})}{\mathrm{d}f_{\mathrm{orb}}} \right\rangle \quad \text{: eccentric}$$

$$\left\langle \frac{da}{de} \right\rangle = \frac{12}{19} \frac{a}{e} \frac{[1+(73/24)e^2+(37/96)e^4]}{(1-e^2)[1+(121/304)e^2]}$$

The integration of this equation is tedious but straightforward. We find $a(e)$ to be

$$a(e) = \frac{c_0 e^{12/19}}{(1-e^2)} \left[1 + \frac{121}{304} e^2 \right]^{870/2299}, \qquad (5.11)$$

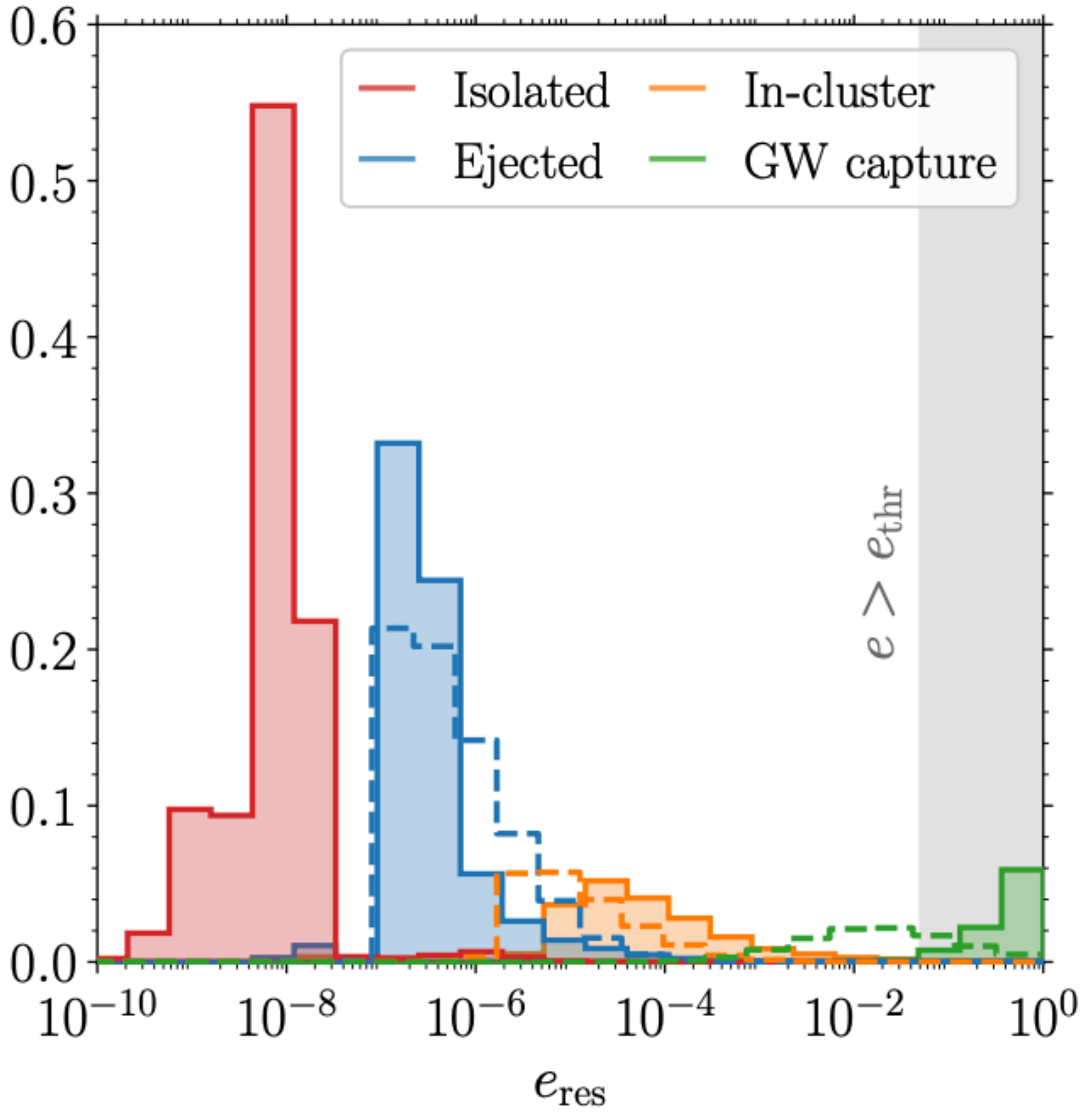
where c_0 is determined by the initial condition $a = a_0$ when $e = e_0$.

I was made for this 🥹

LEGWORK

At f=10 Hz, e is almost always too small to measure for ground-based detectors

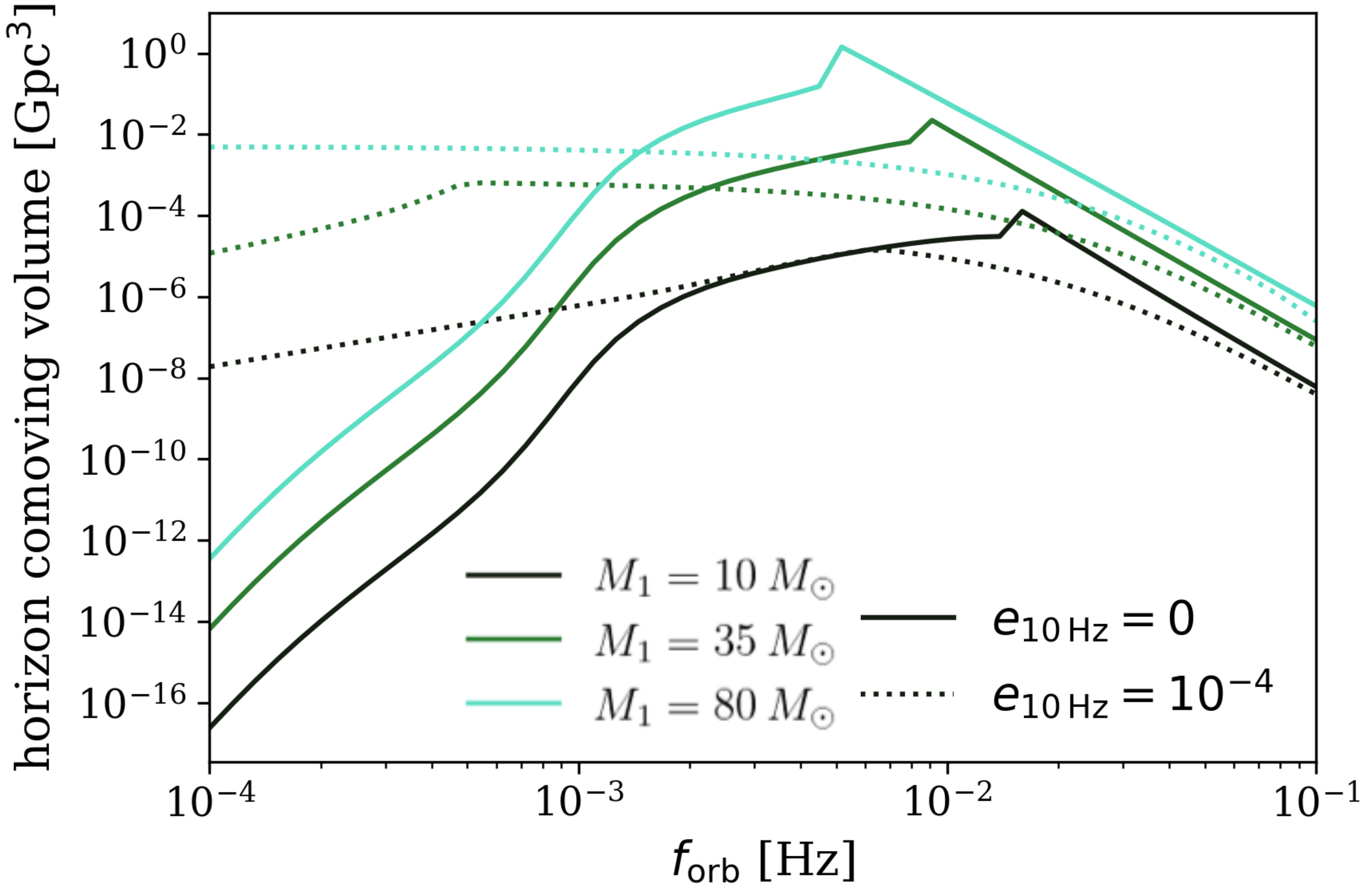
What about LISA?



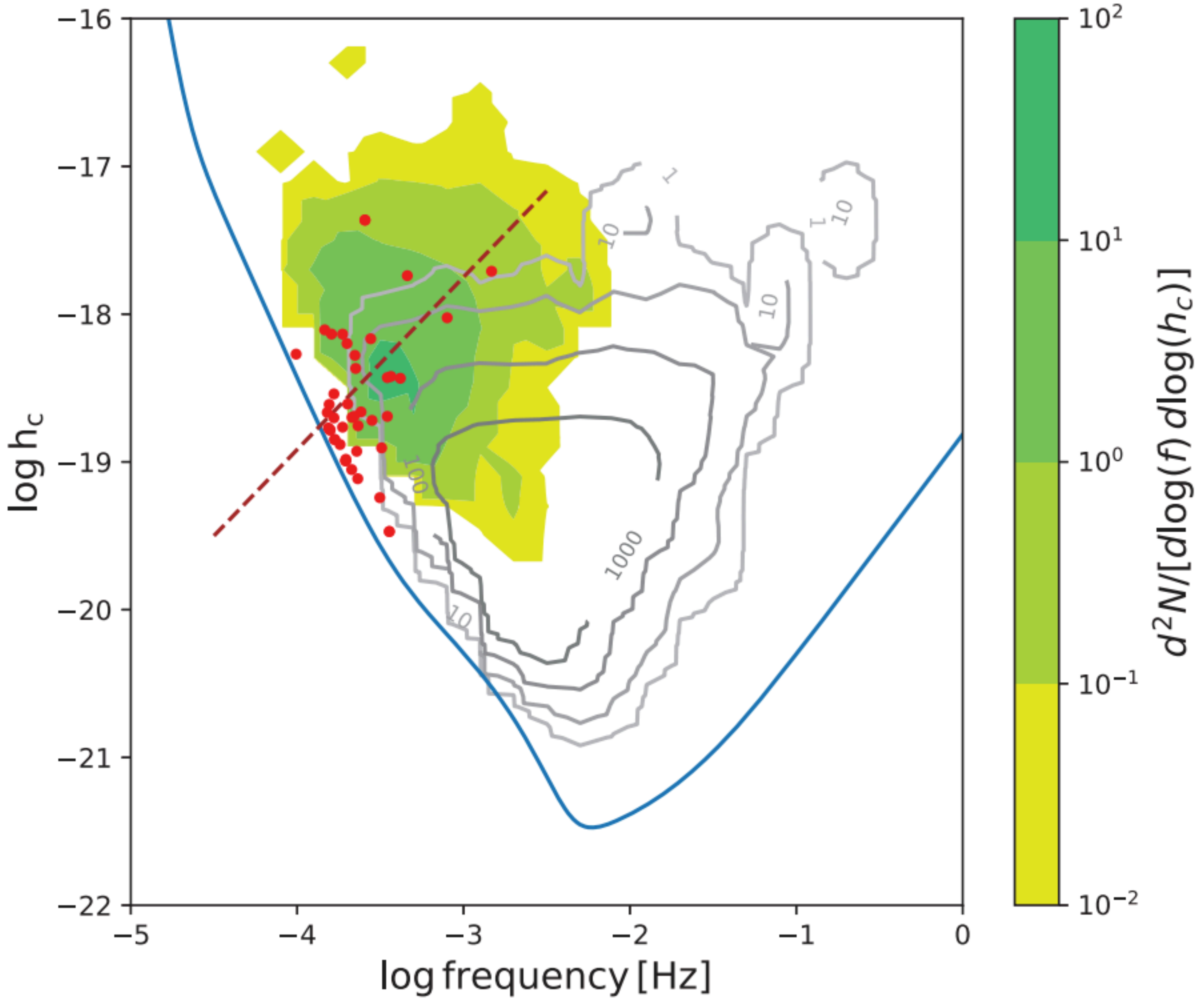
Fumagalli+2024

eccentricity reduces horizon at high f and increases horizon at low f

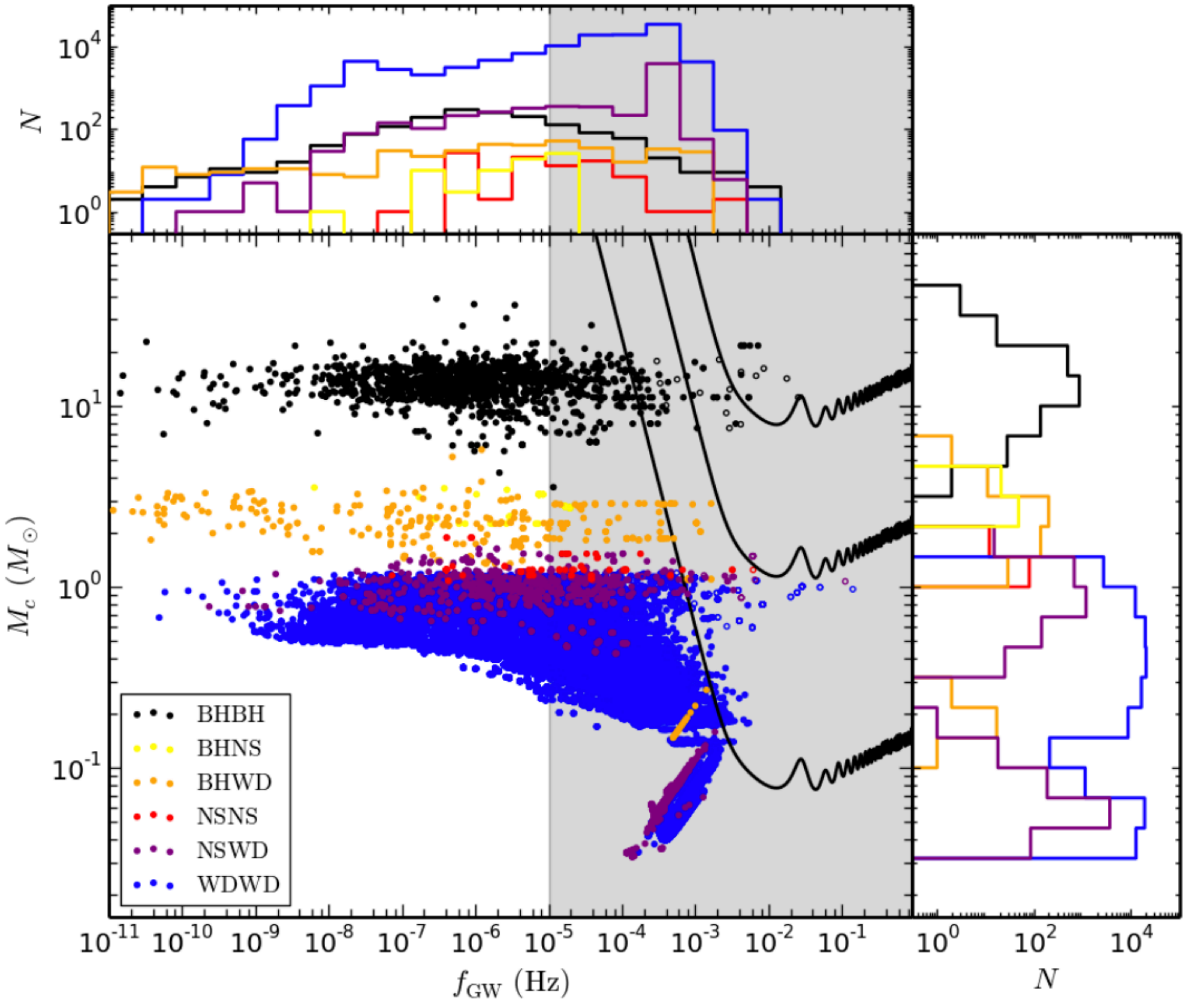
—> more eccentric sources at low f



At these low frequencies, the chirps aren't measurable — this makes them tough to confirm as BBHs 👎🏻



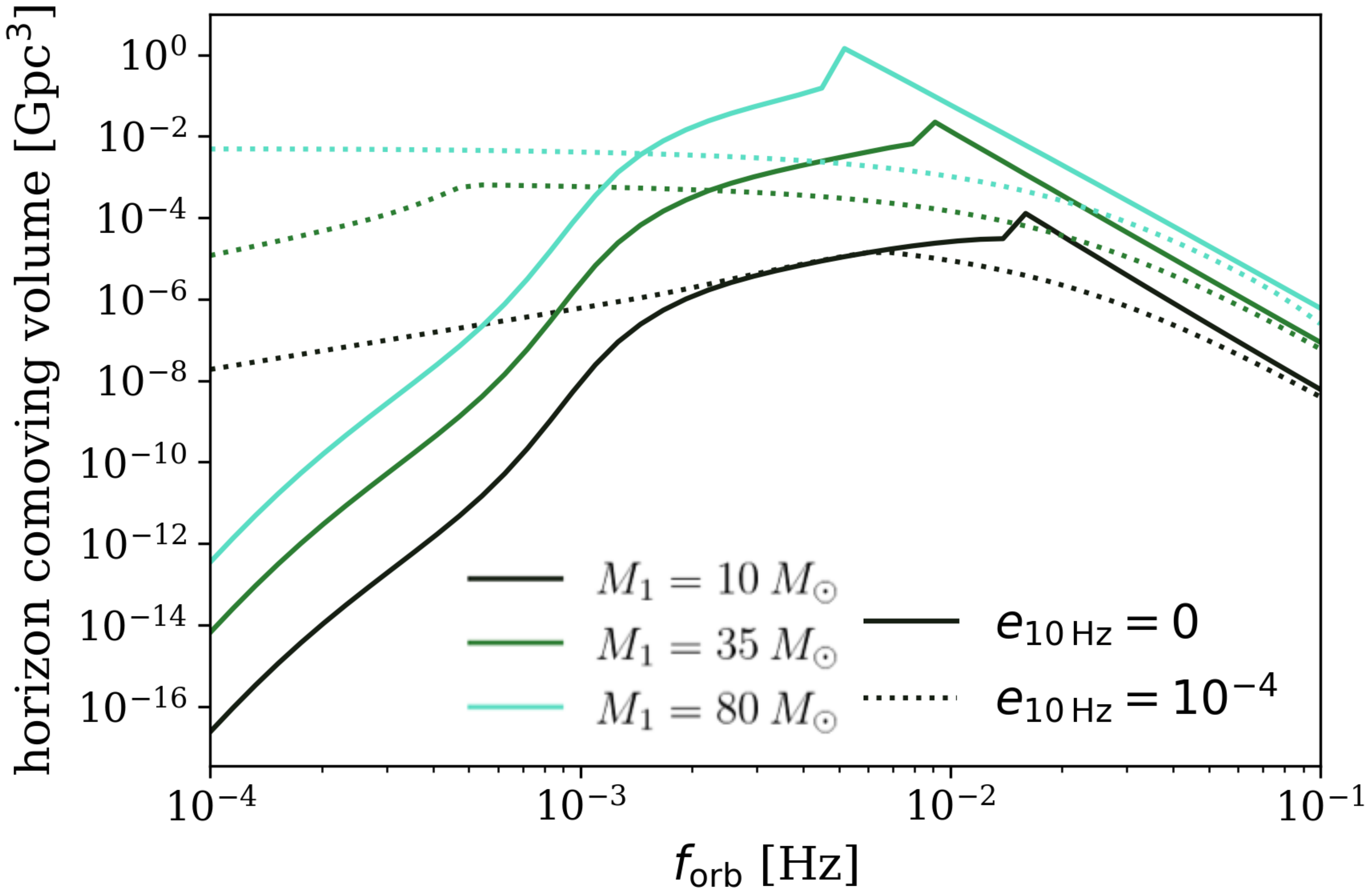
Sesana+2020; Lamberts+2019



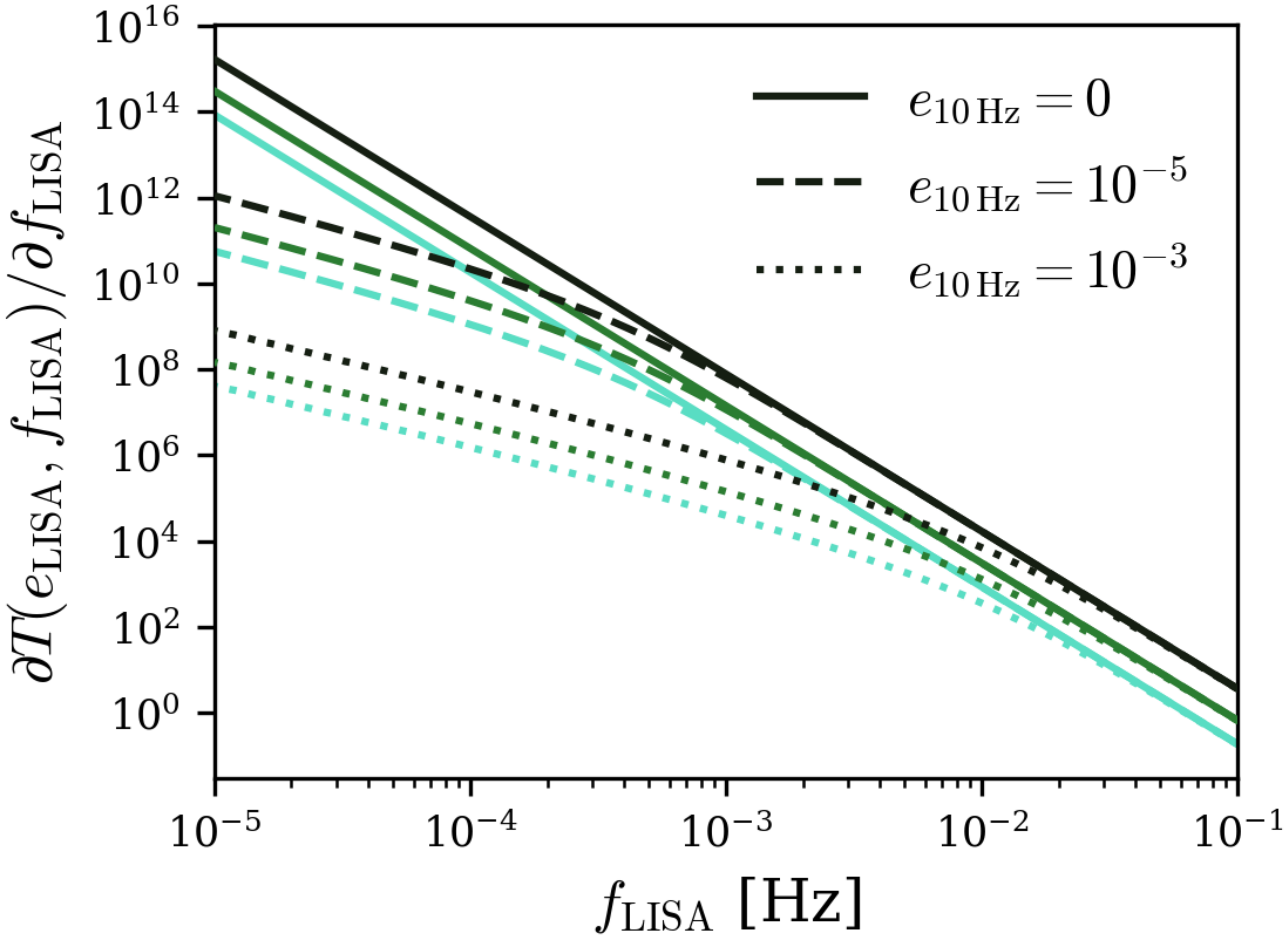
Kremer+2018

This reduces horizon at high f and increases horizon at low f

—> more eccentric sources at low f

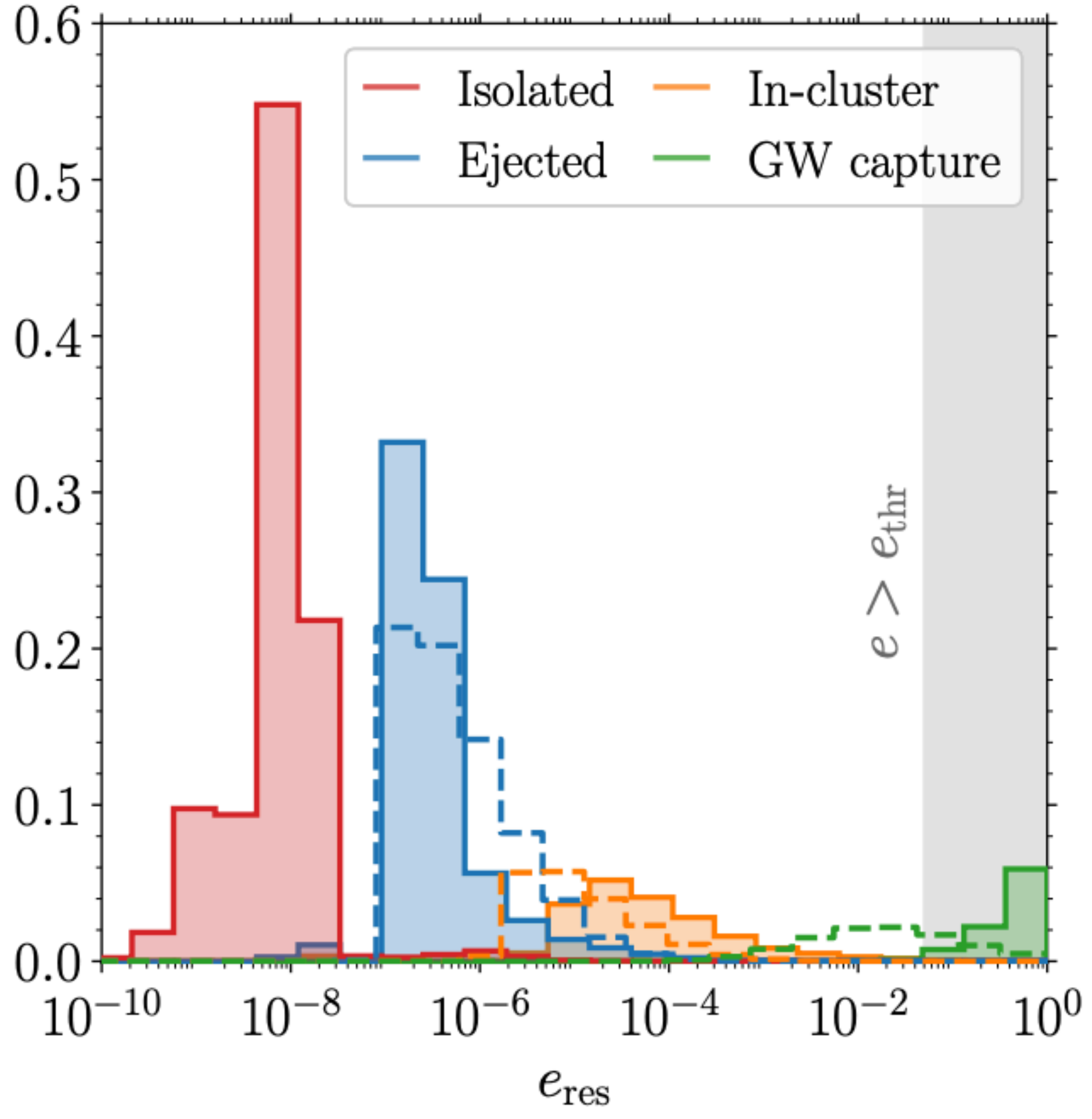


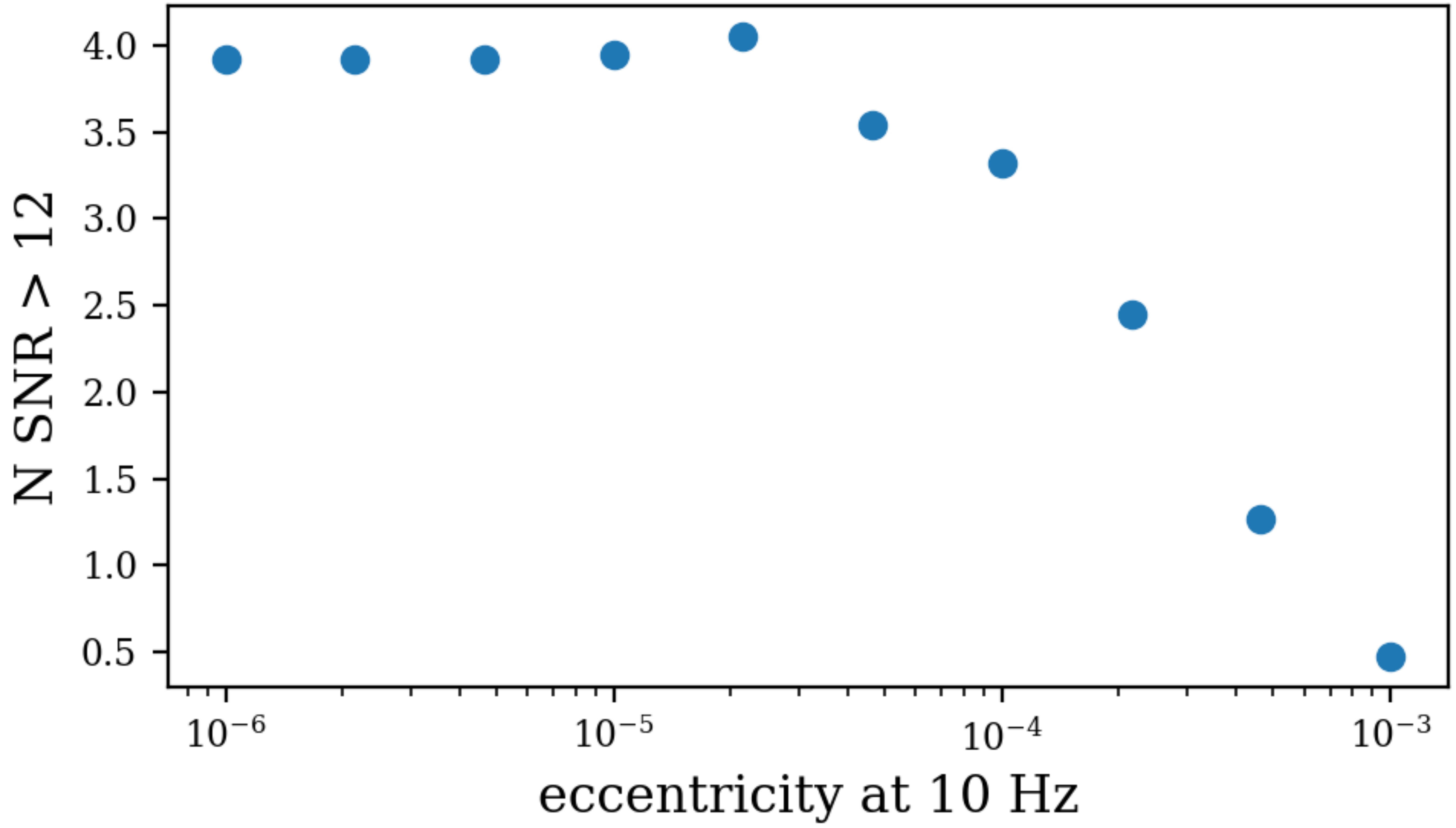
Eccentricity also leads to faster orbital evolution so sources spend less time in the LISA band



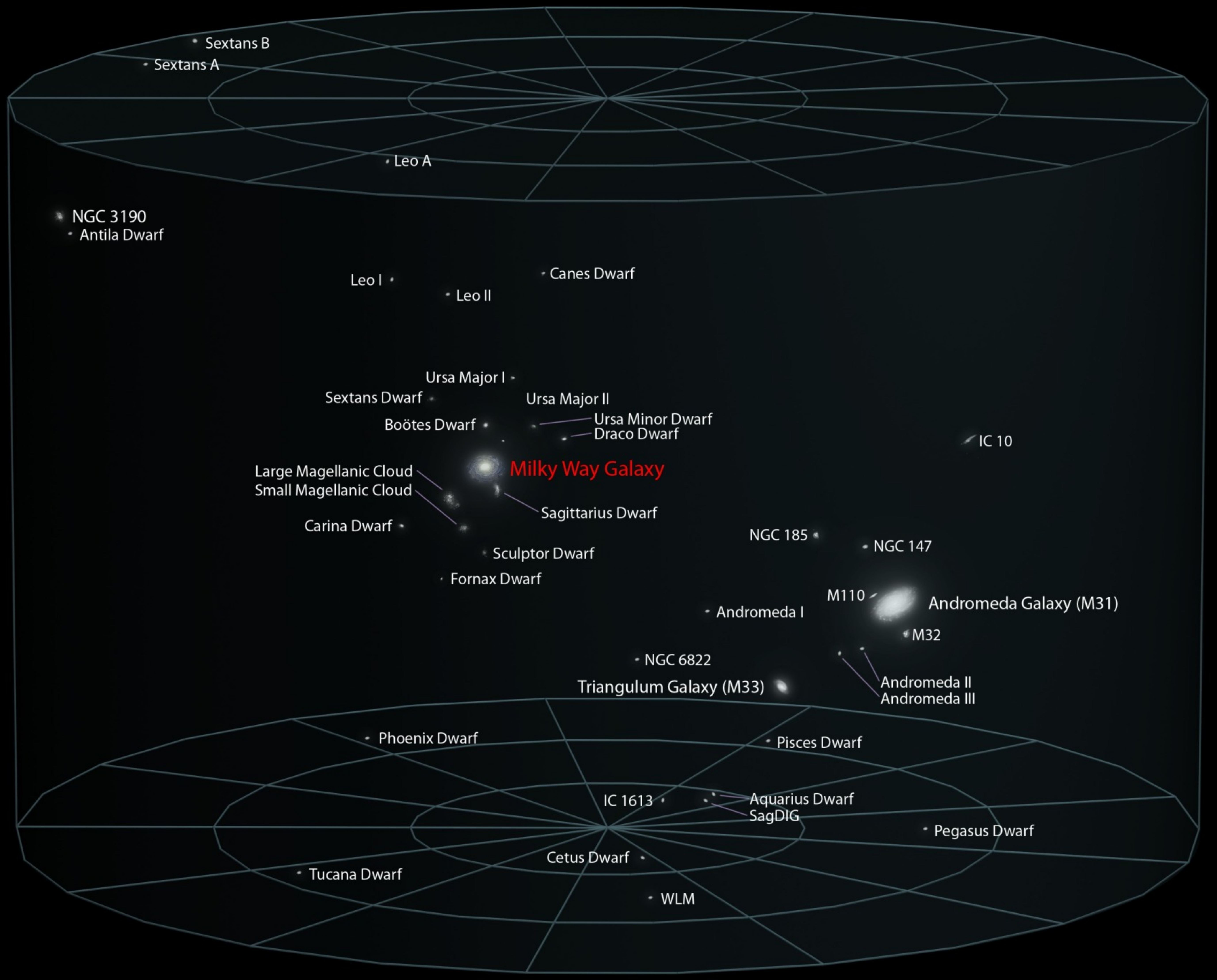
If all ground-based sources are very eccentric*: LISA may not discover *any BBHs*.

*GW capture





Local Galactic Group



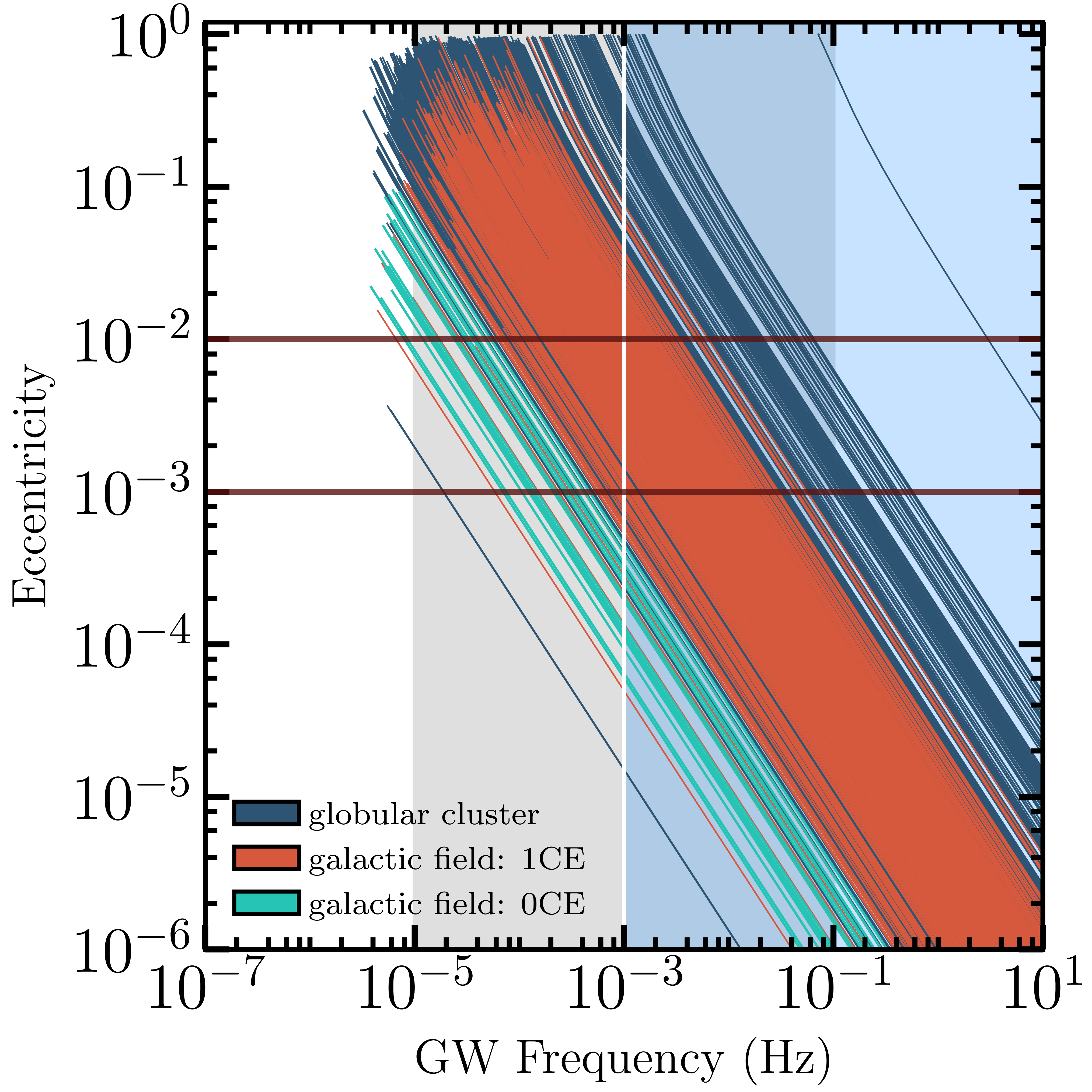
Caveats:

$$\frac{\mathrm{dN_{LISA}}}{\mathrm{d}M_1} = \int \mathrm{d}V_c \int \mathrm{d}f_{\mathrm{orb}} \frac{\mathrm{d}N}{\mathrm{d}M_{\mathrm{BH},1}\mathrm{d}t\mathrm{d}V_c} \left\langle \frac{\mathrm{d}t}{\mathrm{d}f_{\mathrm{orb}}} \right\rangle$$

This calculation assumes a uniform volumetric merger rate

The local group is *clumpy* and may account for the higher numbers predicted by population synthesis at lower frequencies

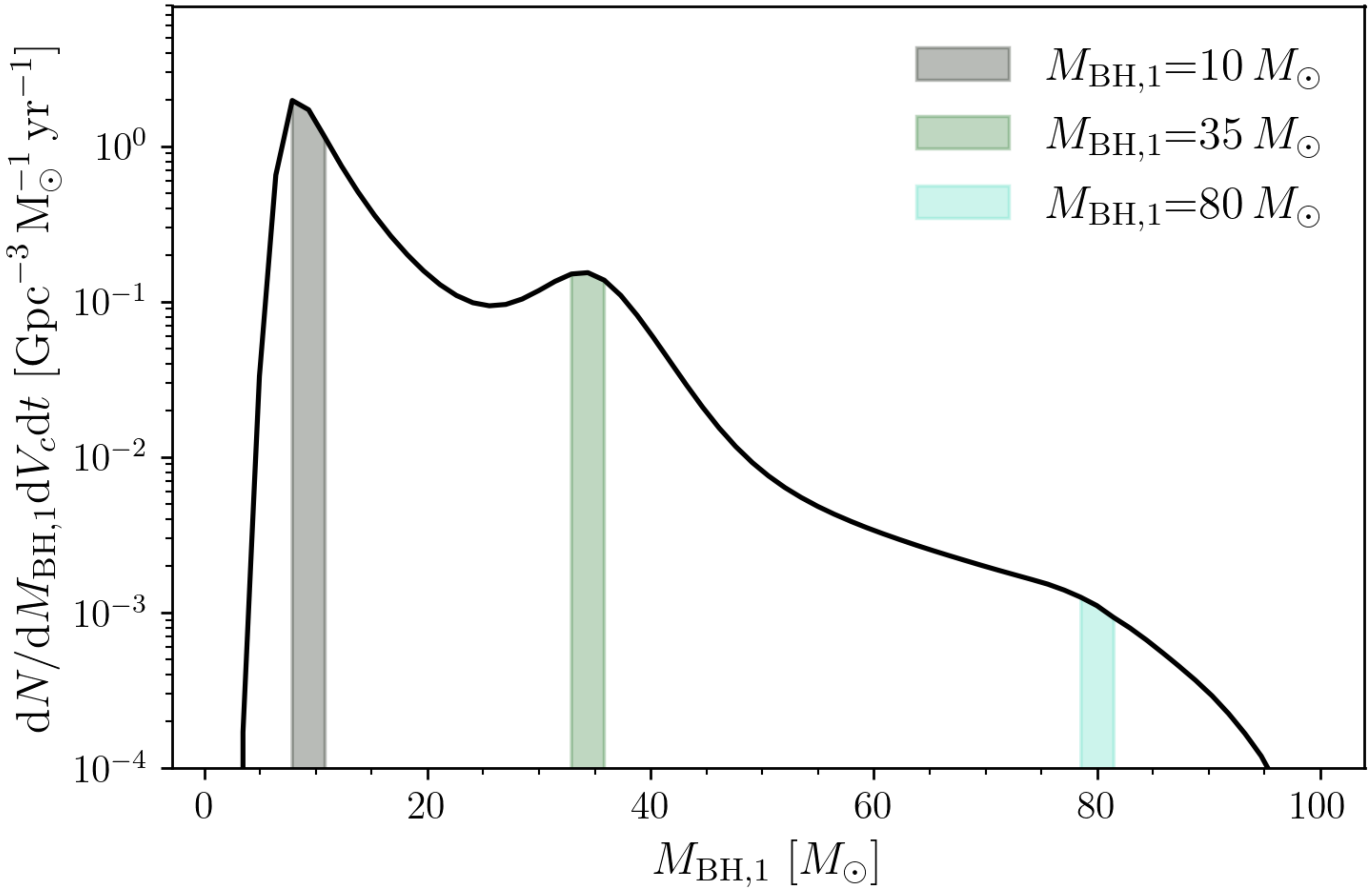
Caveats:



Calculation assumes that BBHs form with frequencies f <10^{-4} Hz and assumes orbit-averaged SNR calculation

Dynamical channels really might be forming BBHs at higher frequencies

Caveats:



Calculation relies on parametric modeling (Power Law + Peak) which is almost certainly not 100% accurate

Should be updated once we have better/updated BBH mass distribution measurements

Summary

1. The number of multi band BBHs that LISA may observe is likely low (10s) — lower if the population is dominated by eccentric BBHs

1. Even if LISA observes ***zero*** *(0)* BBHs, looking for them will place constraints on the fraction of the population that retains residual eccentricity from their formation environment.

2. Data-driven predictions provide a necessary complement to population synthesis predictions

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