Title: Piecing together the formation and evolution of compact objects in binaries

Speakers: Katelyn Breivik

Collection: The 24th Capra meeting on Radiation Reaction in General Relativity

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Abstract: The observation of gravitational waves from 50 pairs of merging black hole and neutron star binaries by the LIGO-Virgo Collaboration offers the first glimpse of the potential to use these populations as tools to study the formation and evolution of compact objects and their stellar progenitors. However, even with dozens of mergers, the dominant formation pathways for merging compact-object binaries remains unconfirmed. Furthermore, even with third generation ground-based detectors, which could potentially discover merging binary black holes across all redshifts out to the epoch of reionization, such mergers only account for a tiny fraction of all black holes formed in the Universe. In this talk I will discuss opportunities to probe the formation environments and scenarios of compact objects using observations from ground- and space-based GW detectors with a particular focus on the complementary source information each detector provides. I will also discuss how GW populations play a role in the larger landscape of observations of compact objects in stellar binaries.

Piecing together the formation properties and environments of compact objects in binaries

Katie Breivik — CCA — Flatiron Institute

24th CAPRA Meeting

My Research Identity

Binary Population Synthesis	Astrometric & radial velocity BH Binaries	Gravitational Wave populations
Open & **accessible** software with easily reproducible results	Black holes w/ companions at intermediate evolutionary phases	Using GW populations as a tool to do astrophysics

Can we constrain the outcomes of binary interactions?

isolated binary stars

cosmic-popsynth.github.io

KB, Coughlin, Zevin + 2020

globular clusters

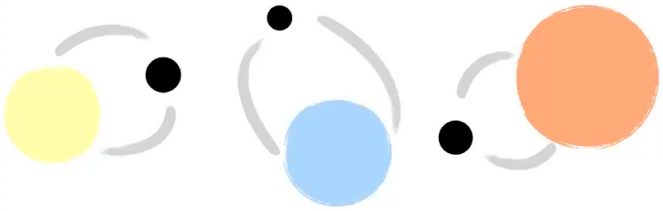
clustermontecarlo.github.io

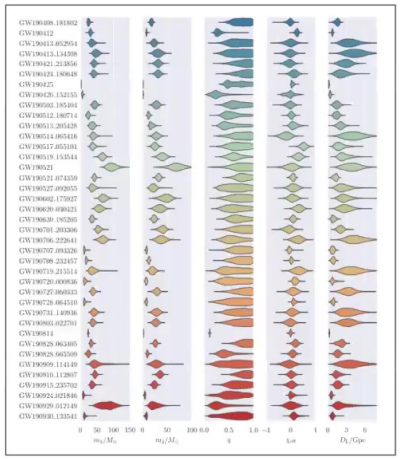
Rodriguez, Coughlin + 2021

Galactic stellar mass BHs orbiting bright stars

SDSS SDSS-V

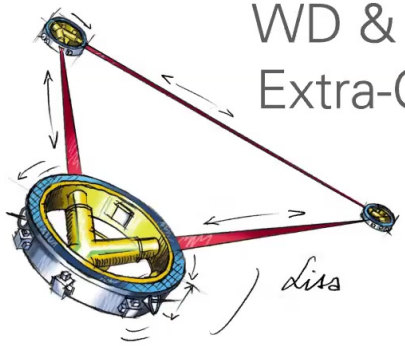
gaia

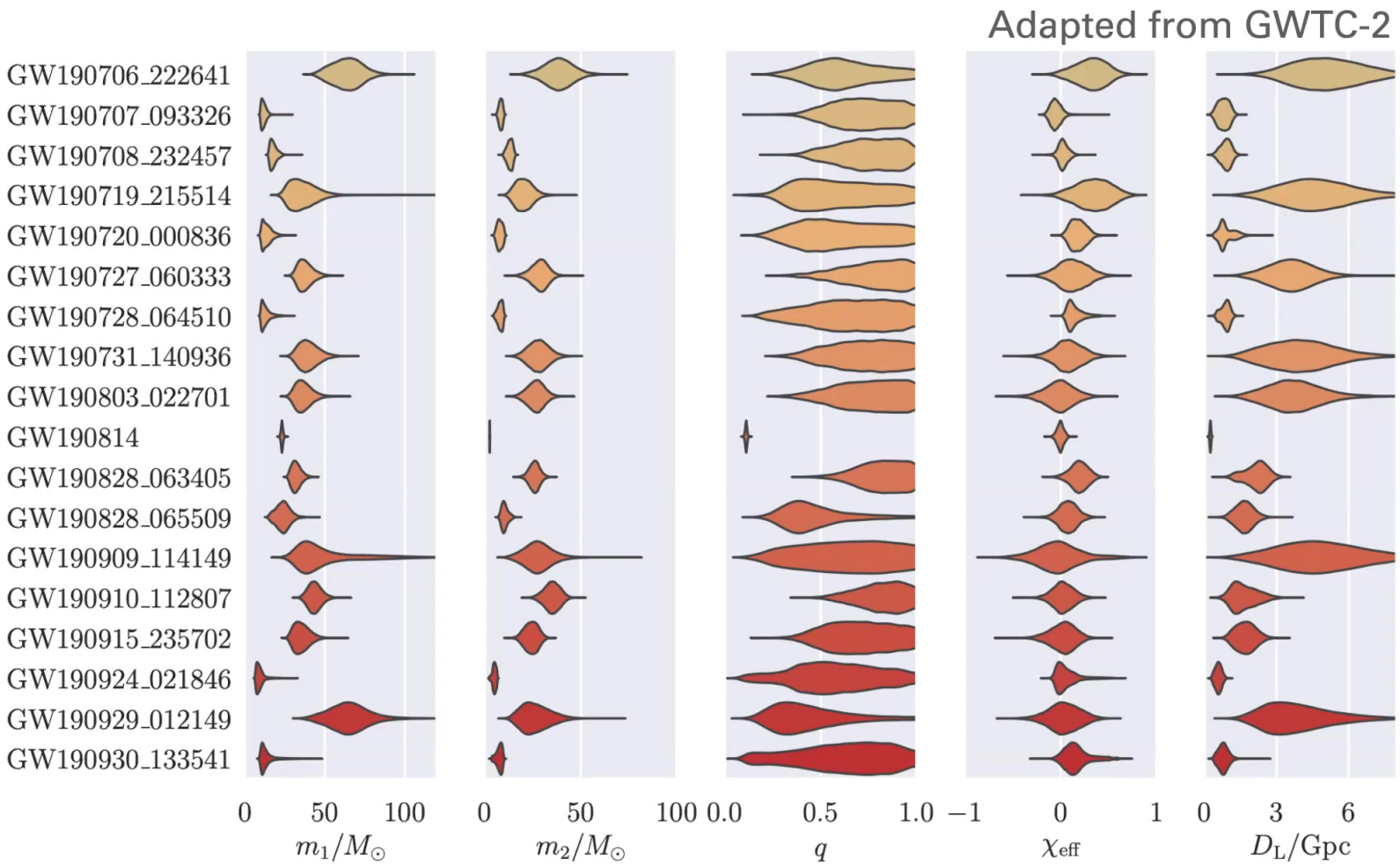




LIGO-Virgo BH & NS mergers

Galactic WD & NS pops Extra-Gx BBHs





We live in the FUTURE — 47 BBH mergers!

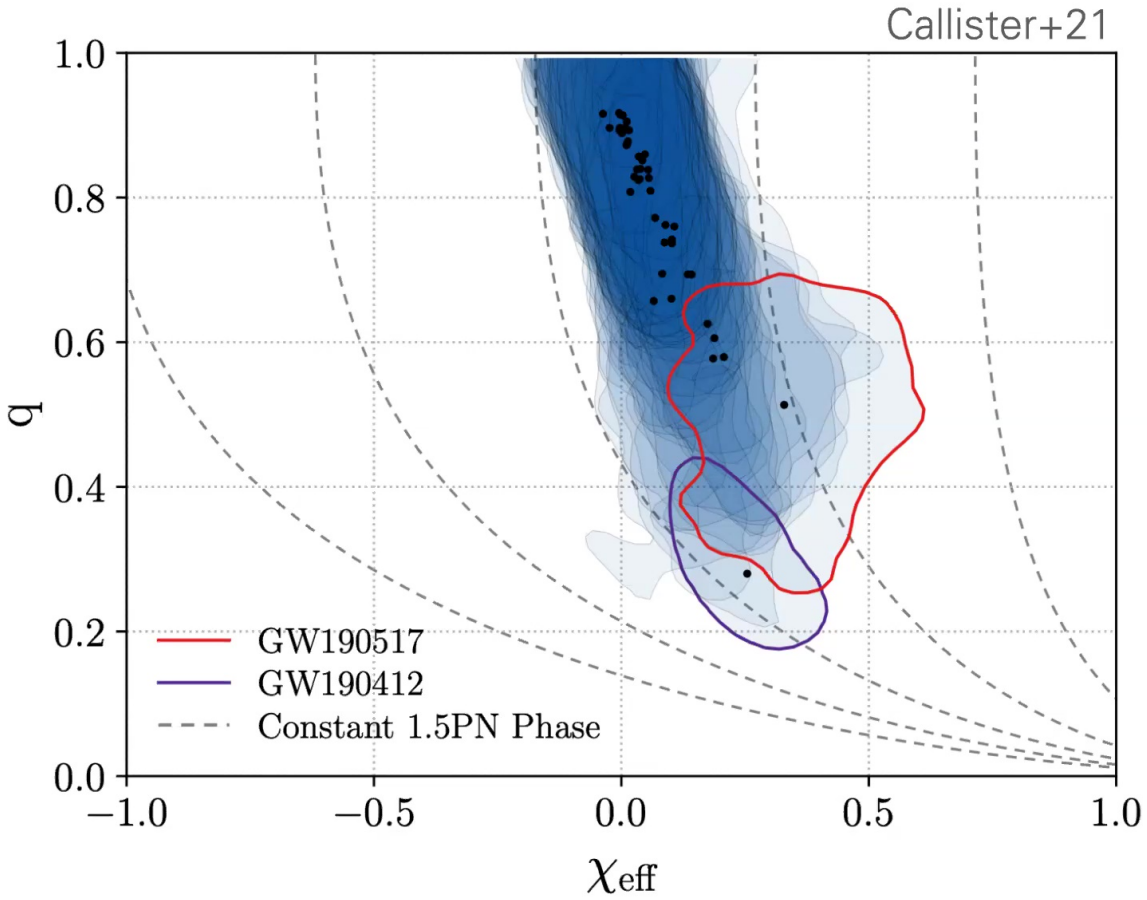
GWTC-2 : 50 mergers total

Black holes with masses >45 $M_\odot$ exist

Spin measurements suggest presence of **multiple** formation channels

arxiv: 2010.14527
2010.14533

Population analyses are showing interesting correlations!



BBHs could originate from ***so many*** different channels & environments!!

<u>Dynamical Formation</u>

YSC/GC/NSC
AGN disks
Few body
Triples

<u>Isolated system</u>

Primordial BHs
Pop III binary stars
Standard binary stars
Chemically homogenous

Each formation channel produces different rates & combinations of the GW observables

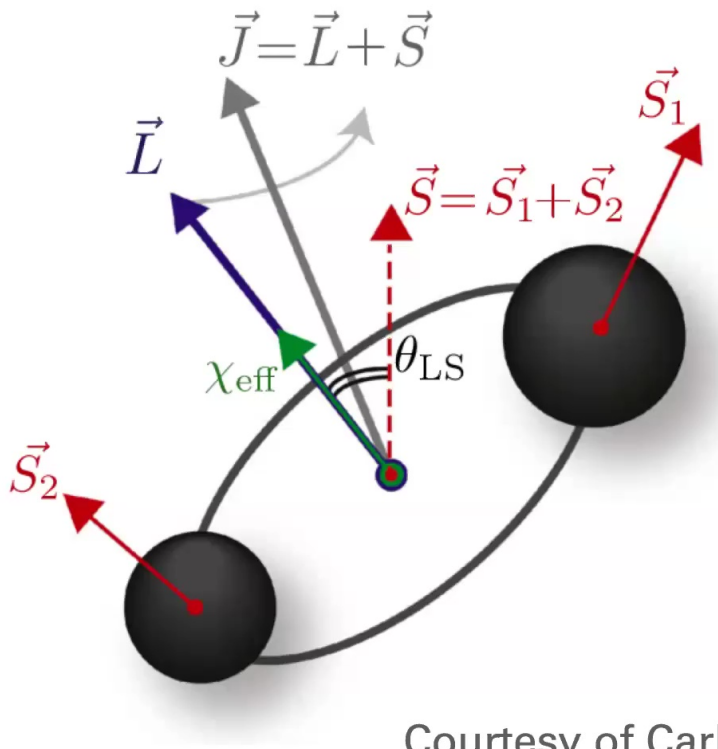
chirp mass = $\dfrac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

mass ratio = m_2/m_1

distance/redshift

eccentricity

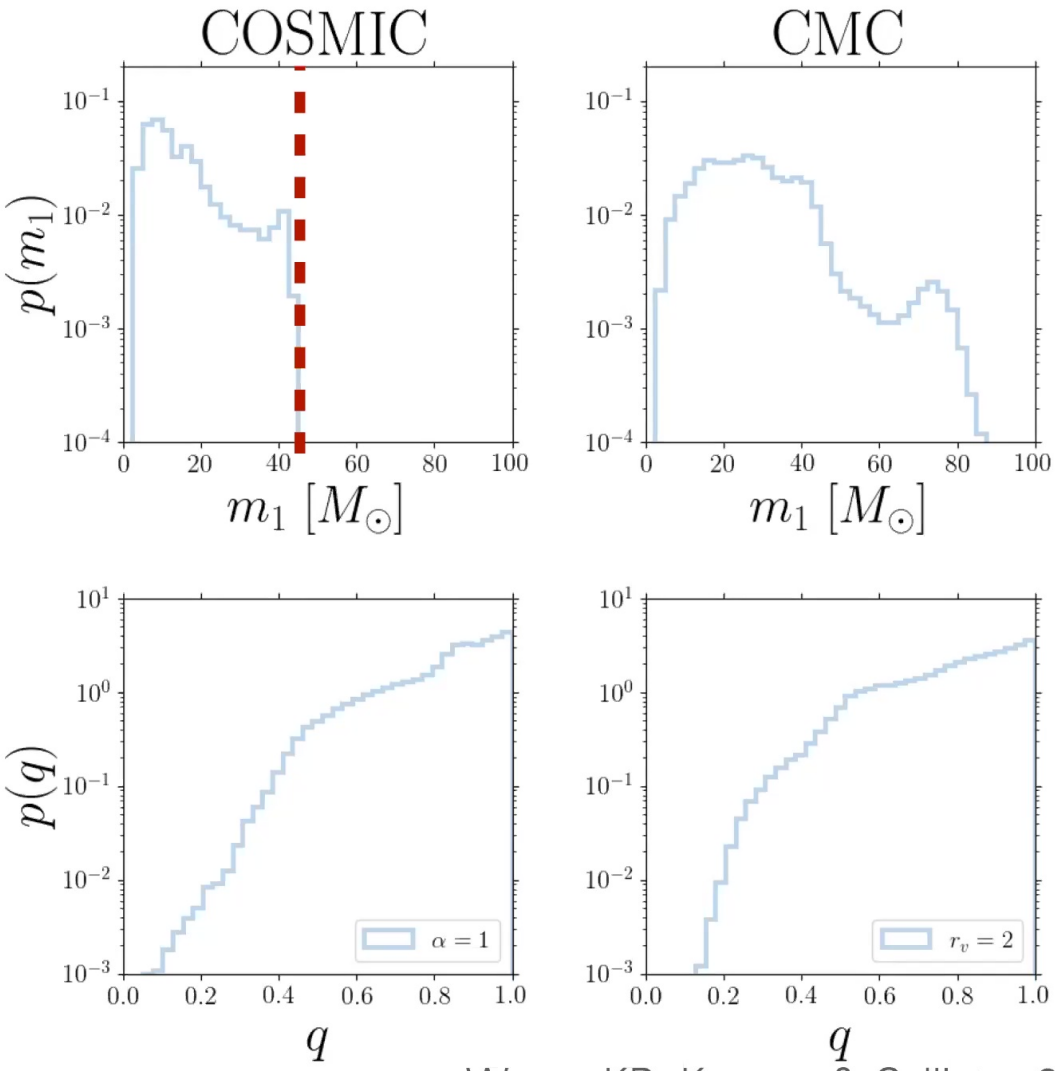
effective spin: $\chi_{\rm eff}$



Courtesy of Carl Rodriguez

Pair instability SN physics only allows isolated binary masses $\lesssim 45\,\mathrm{M}_\odot$

e.g. Farmer+20



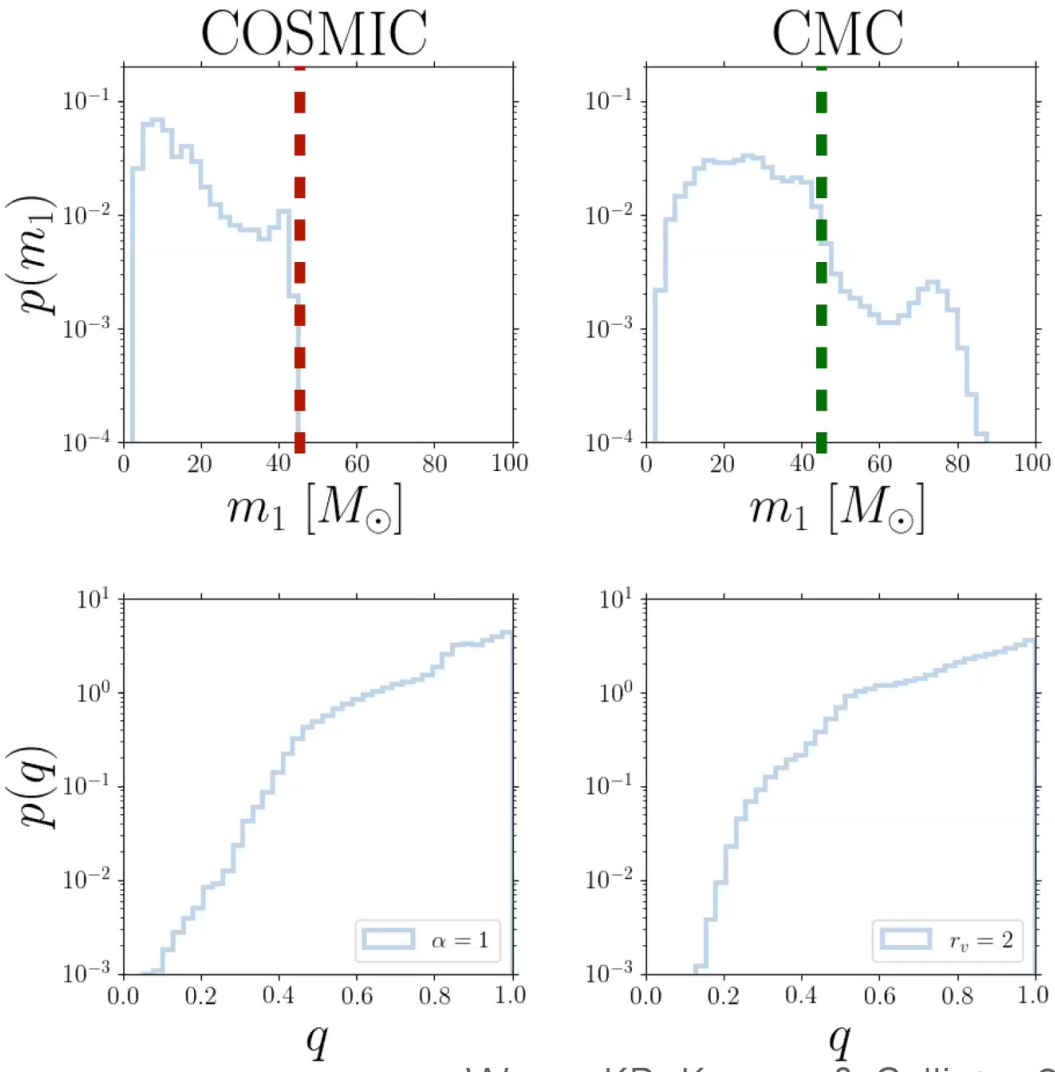
Wong, KB, Kremer & Callister 21

Pair instability SN physics only allows isolated binary masses $\lesssim 45\,\mathrm{M}_\odot$

e.g. Farmer+20

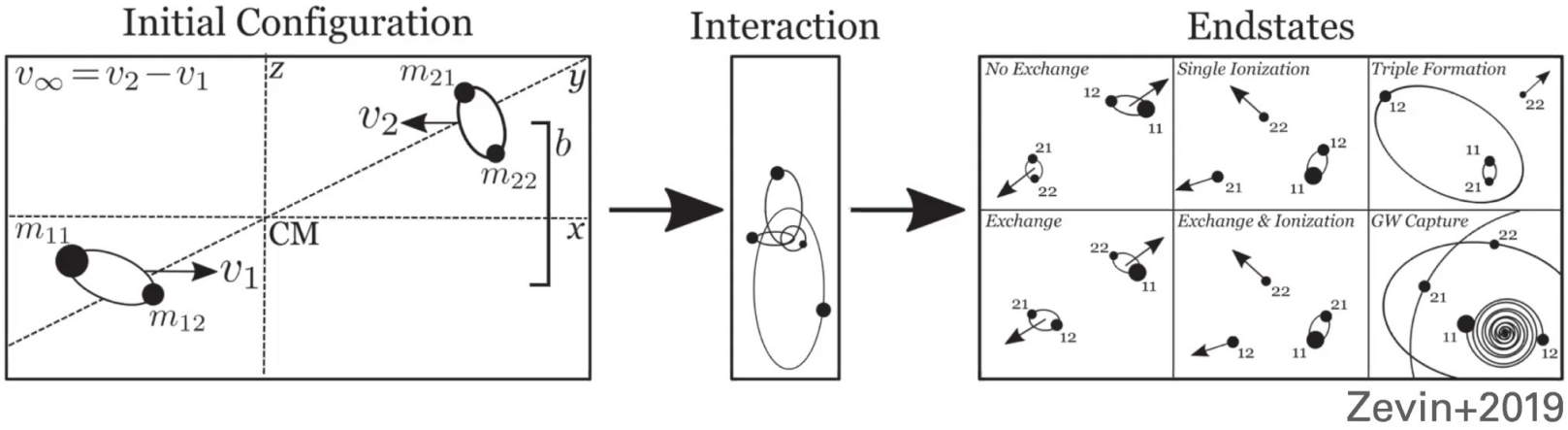
Repeated mergers from dynamical formation are not subjected to this limit

e.g. Kremer+20, Cantiello+21

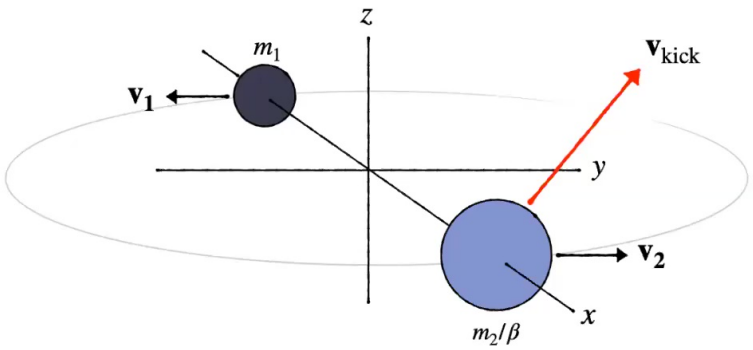


Wong, KB, Kremer & Callister 21

Dynamical interactions inject ecc & randomize spins



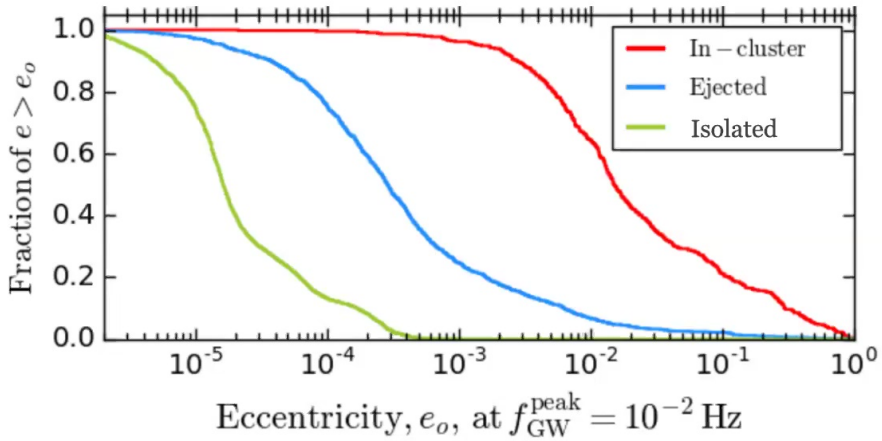
Zevin+2019



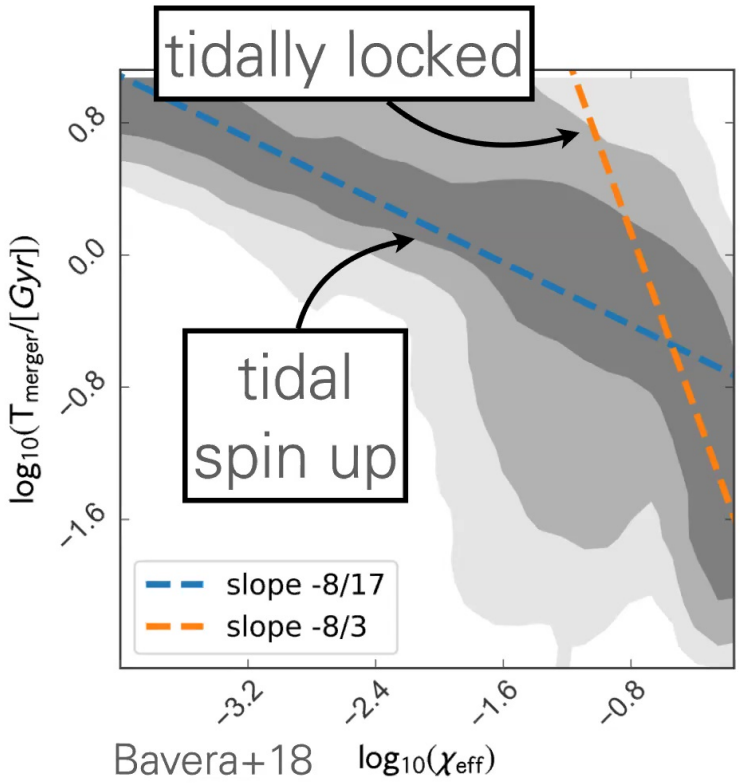
Natal kicks at BH formation can partially misalign spins and inject eccentricity

e.g. Kalogera 1996, Callister+2020

Repeated interactions in dynamical environments produce more eccentric BBHs

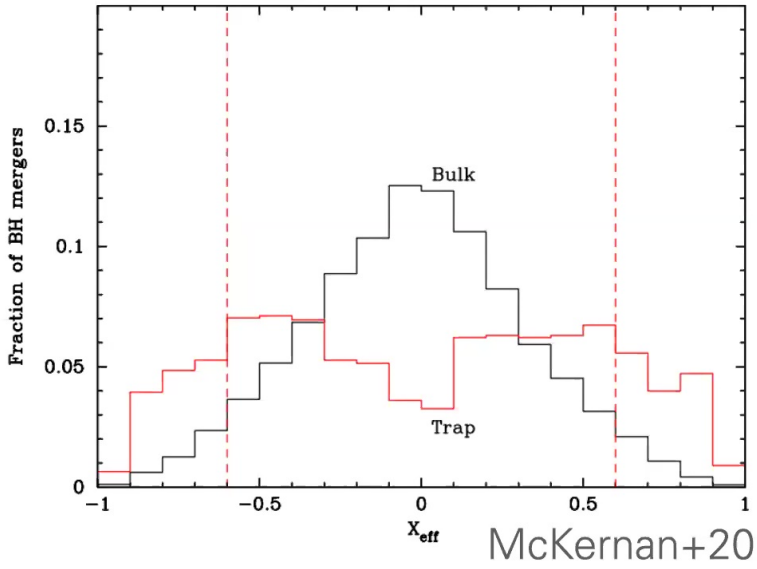


Tides could spin up BBH progenitors



Bavera+18

But so can >2nd generation mergers

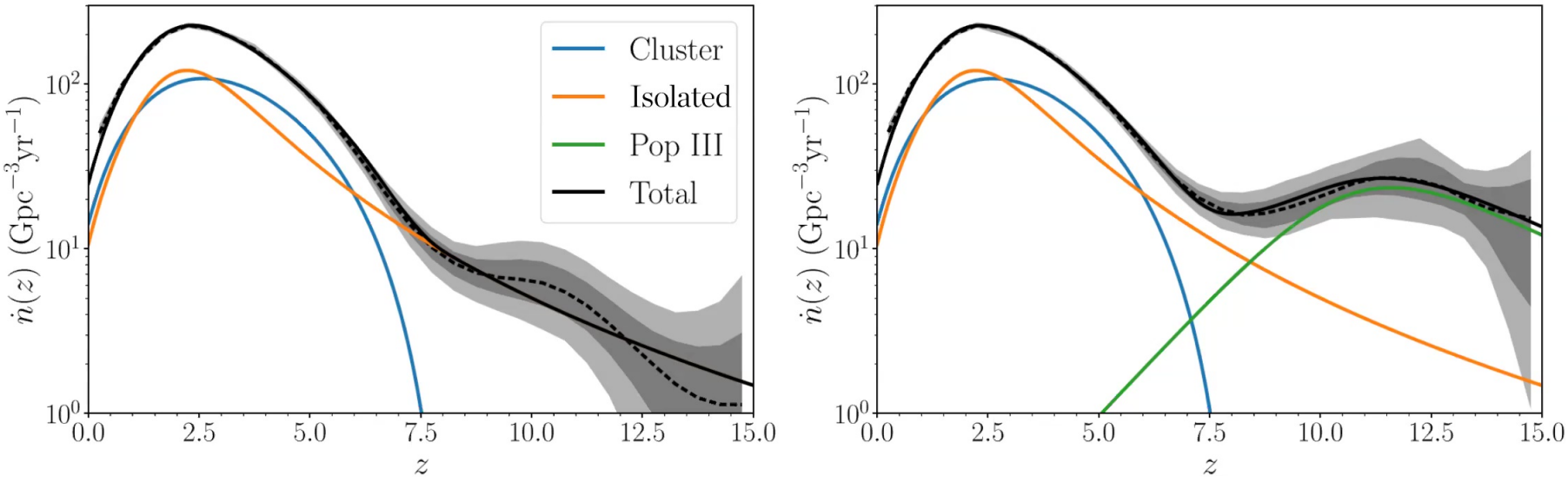


McKernan+20

Migration Trap: repeated mergers

Bulk: 1st gen mergers

Different formation channels should trace different redshift distributions which will be accessible in future LVC data!



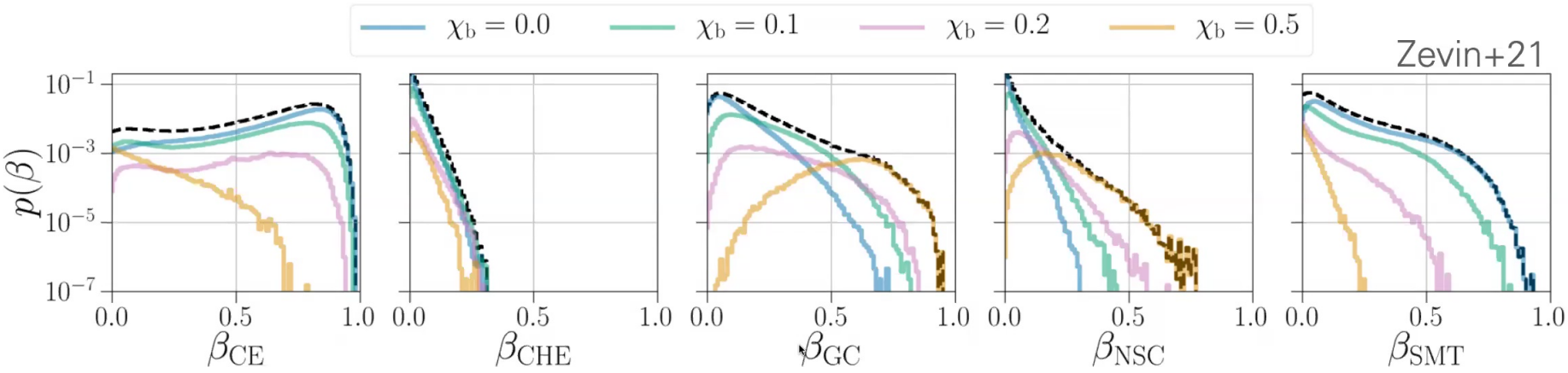
Ng+21

(a) $f_{\rm III} = 0$

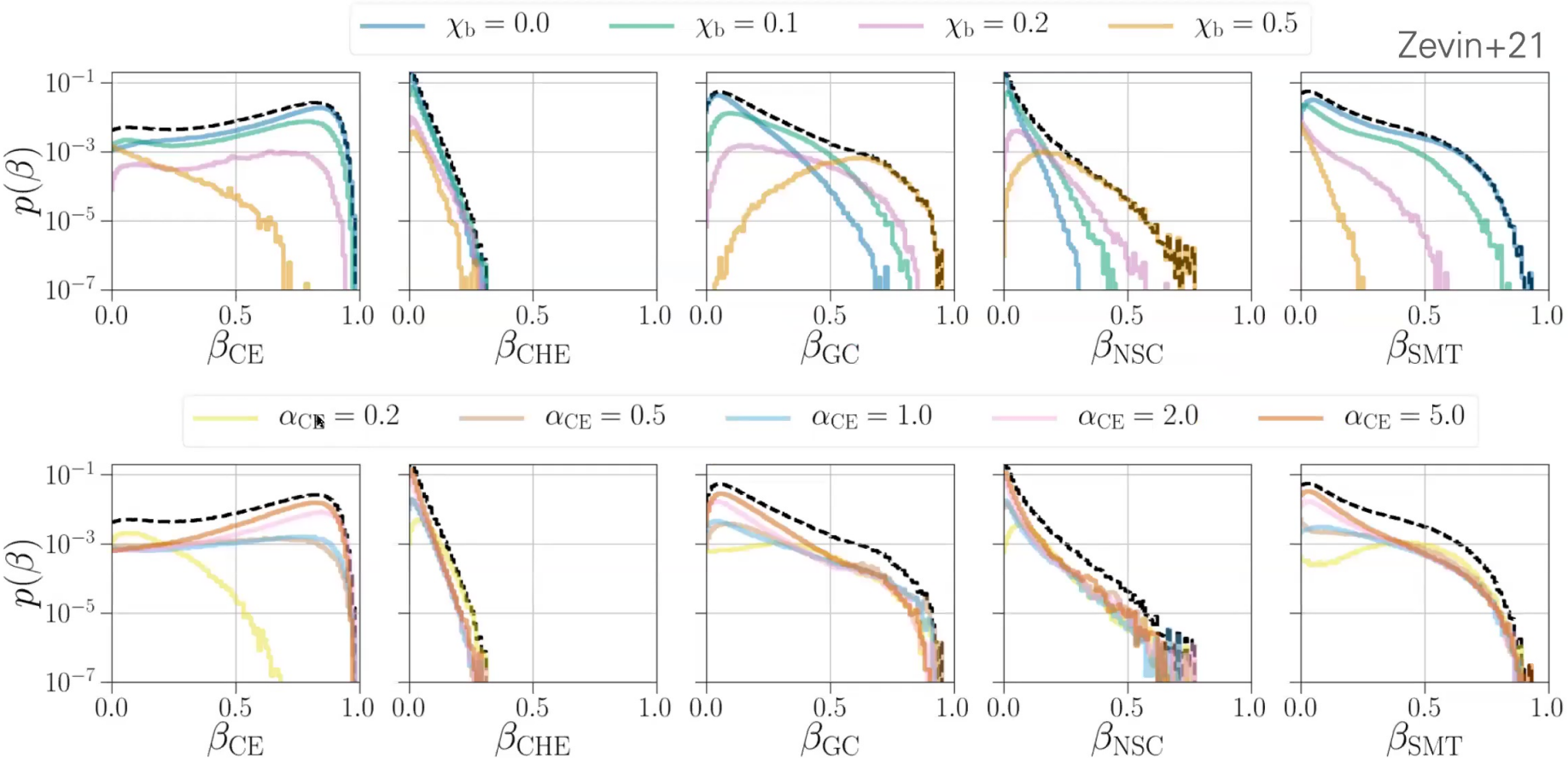
(b) $f_{\rm III} = 0.024$

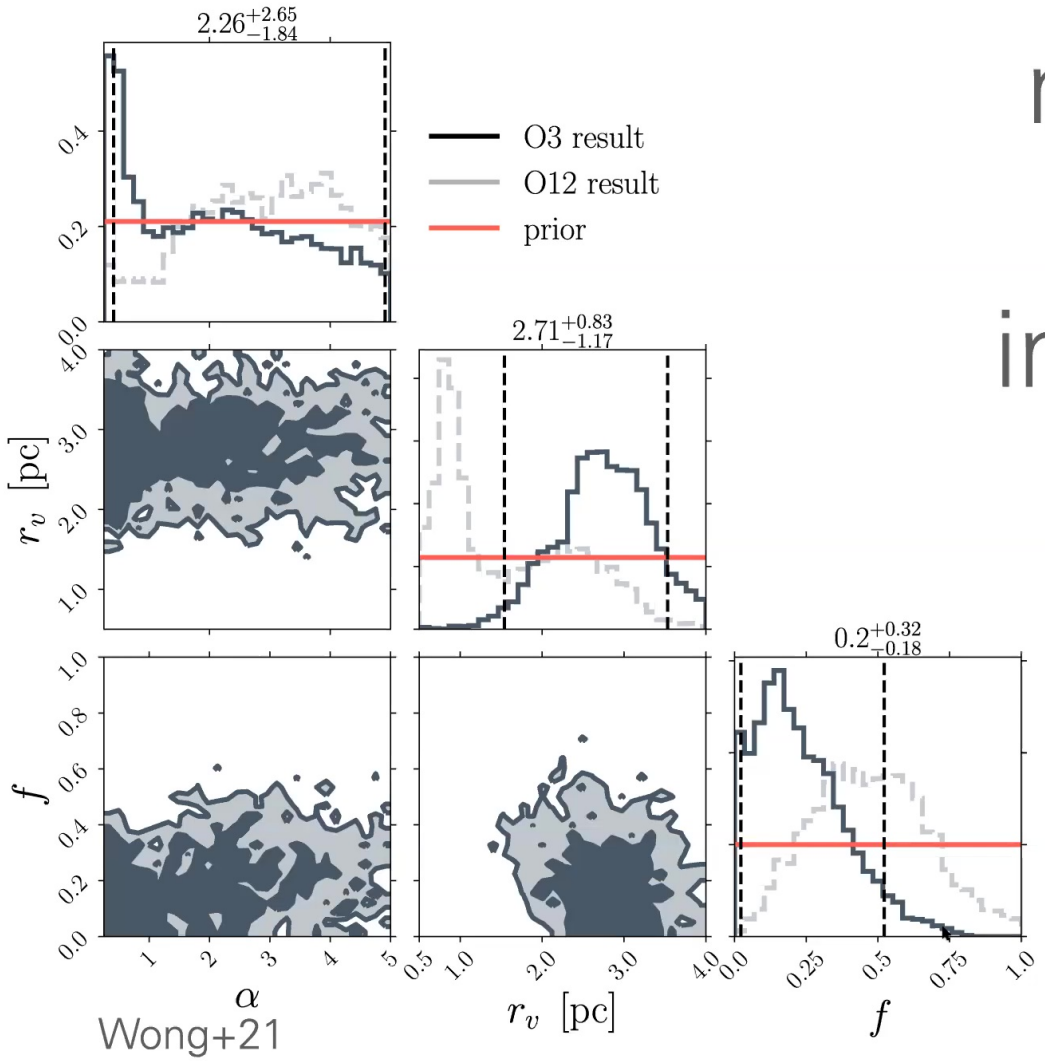
Multi-channel inference is promising!

small dynamical spins ⟶ large dynamical spins



Multi-channel inference is promising!



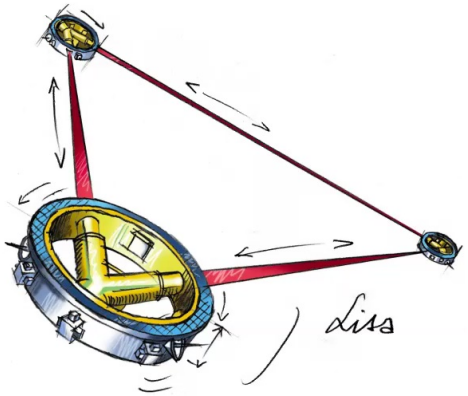


Wong+21

machine learning & hierarchical inference can inform relative channel contribution and model uncertainties!

See also: Taylor+18, Wong+19,20

This is only the beginning!!

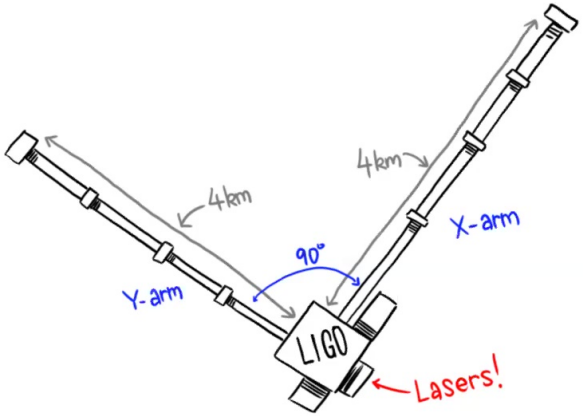


LISA
launch 2035ish
bucket: 1-6 mHz

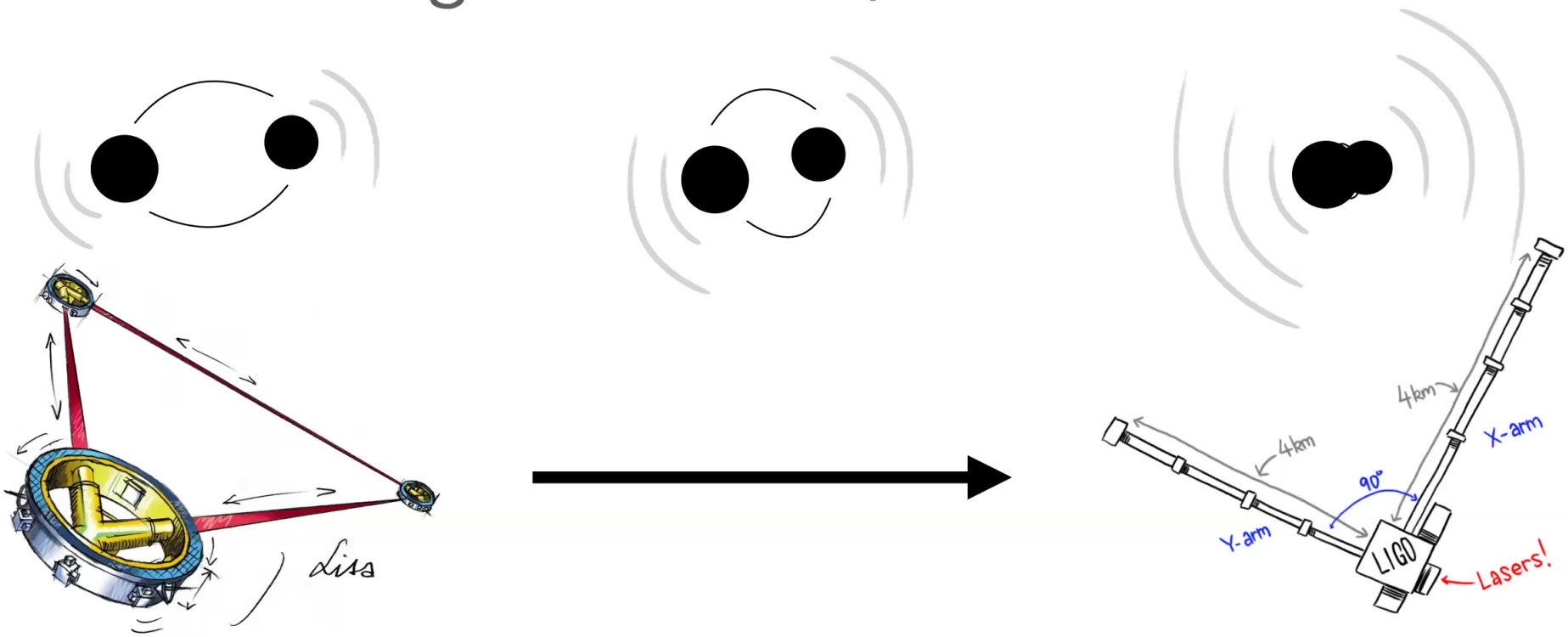
TianQin
launch 2030s
bucket: 10-100 mHz

Advanced LVK
2024ish
bucket: 60-200 Hz

3rd Generation
mid/late 2030s
bucket: 10-200 Hz

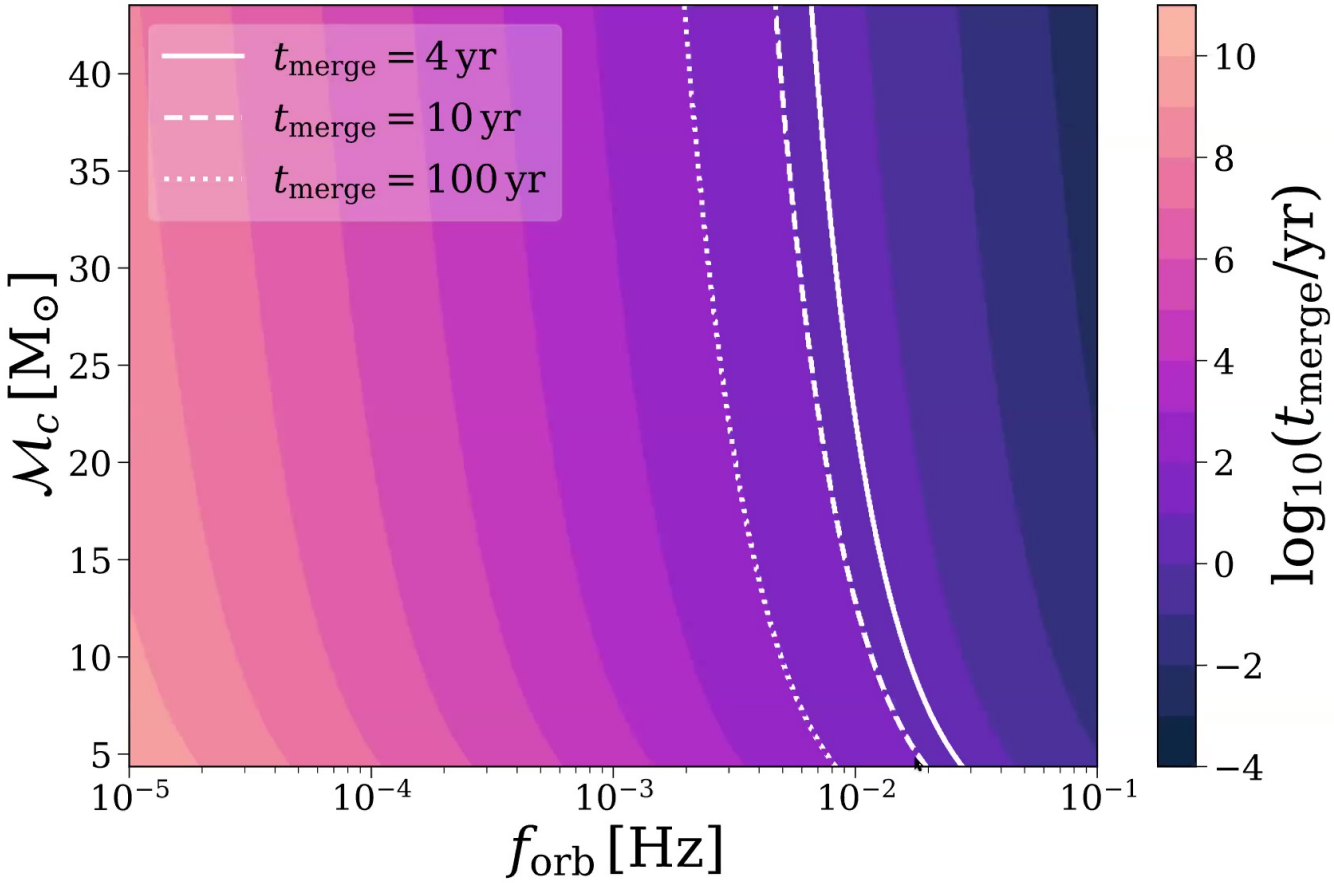


Every GW source that merges passes through the mHz/dHz band!



$f_{GW} \sim 1\,\mathrm{mHz}$ $f_{GW} \sim 10\,\mathrm{Hz}$ $f_{GW} \sim 1\,\mathrm{kHz}$

mHz BBHs are evolving slowly



Ground/space based observatories provide **complementary** probes of BBHs

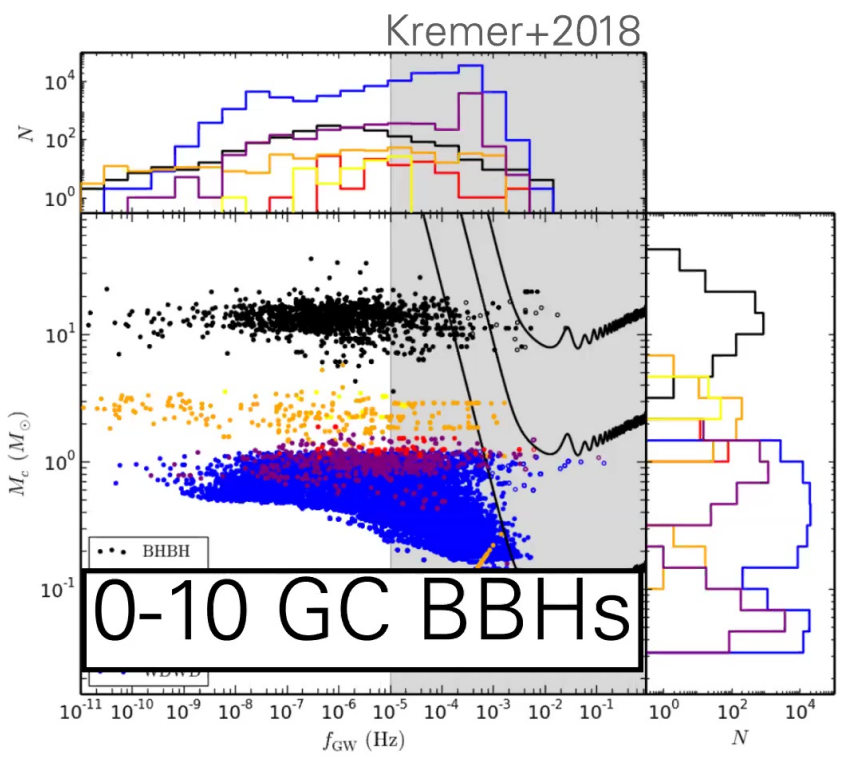
chirp mass
eccentricity
spin?
'close by'

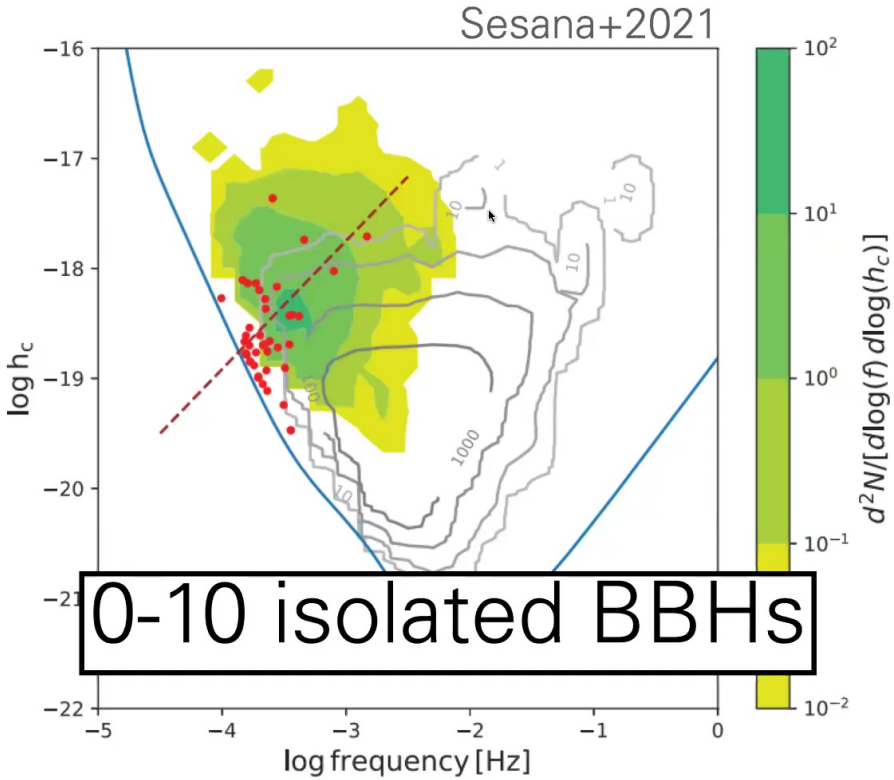
see recent work by Buschiccio+ Arxiv: 2106.05259

chirp mass
mass ratio
spin
'far away'

$f_{\rm GW} \sim 1\,{\rm mHz}$ → $f_{\rm GW} \sim 1\,{\rm kHz}$

Forward modeling prefers BBHs with f_{GW}<1 mHz because they evolve ~10^4 times slower at 0.1 mHz than at 10 mHz

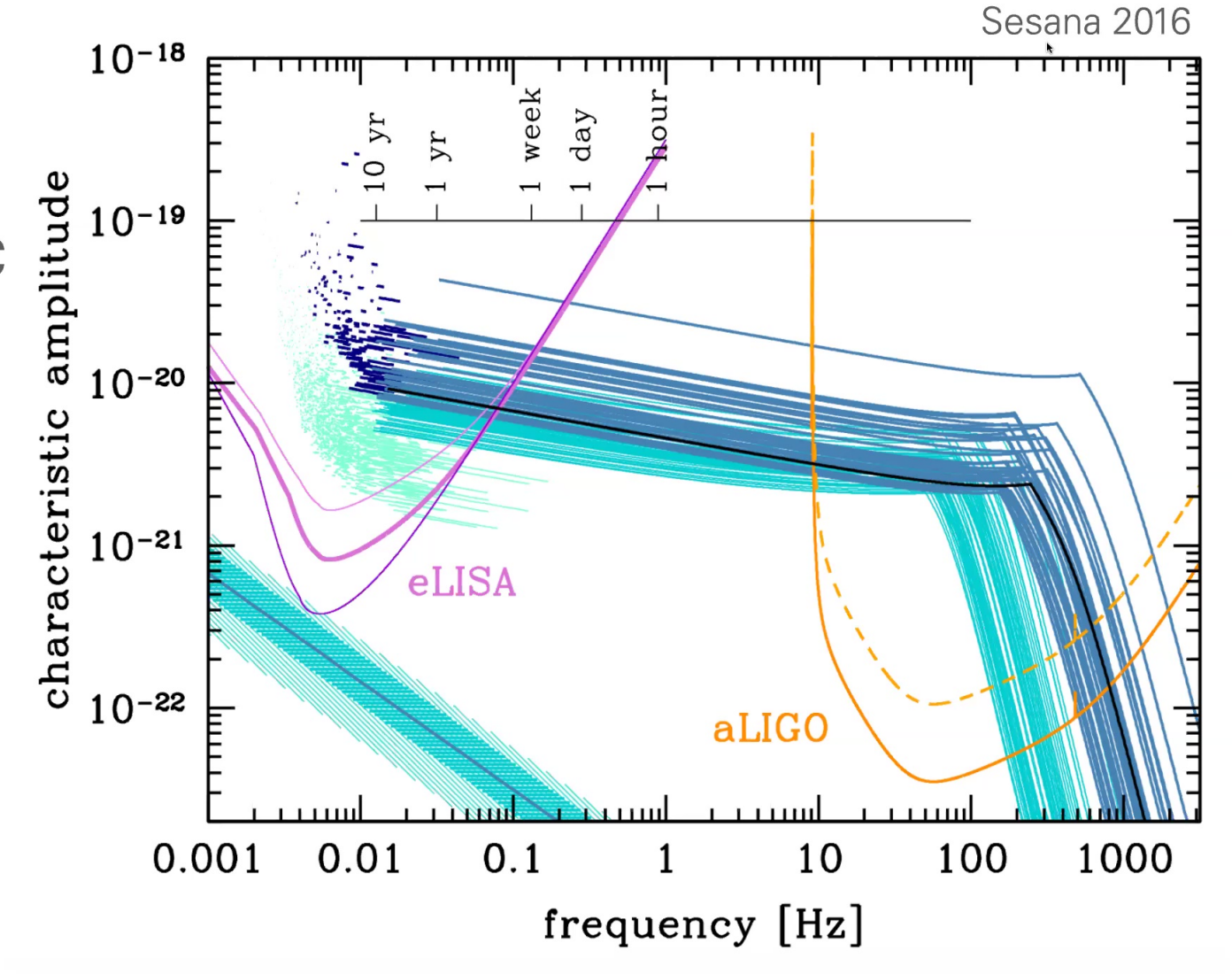




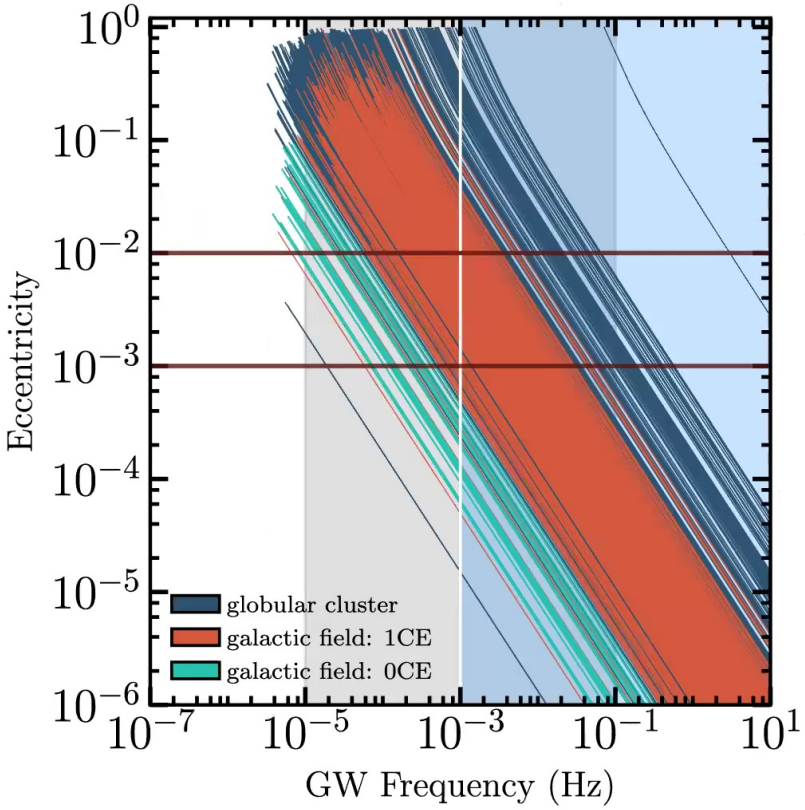
Backward modeling is more optimistic

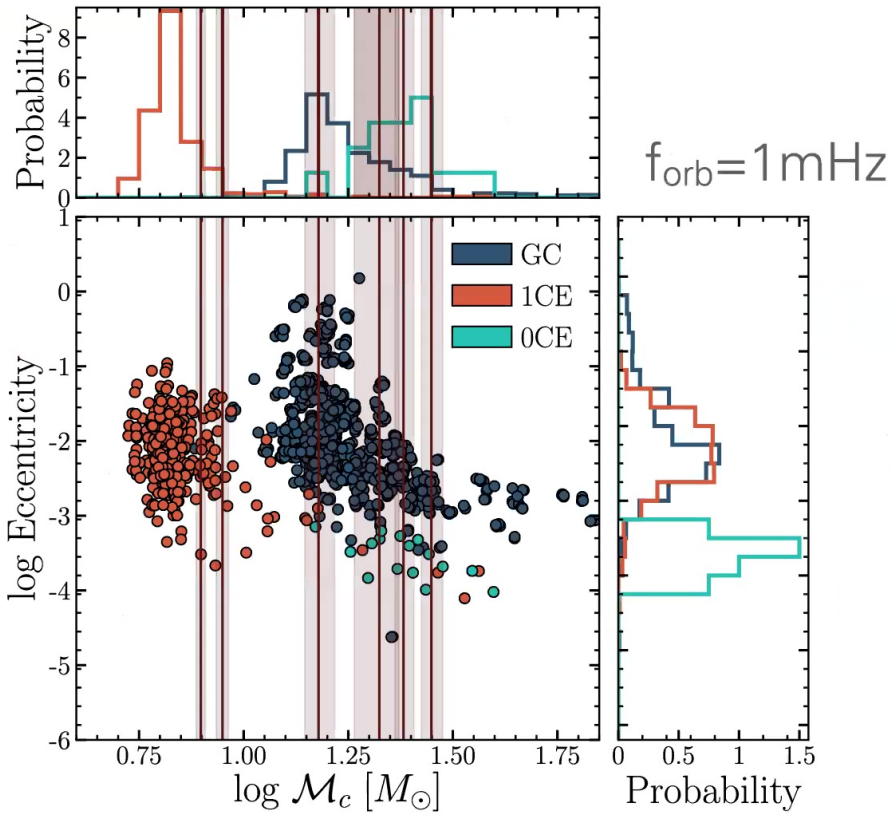
~100-3000 LISA BBHs

~20-700 multiband BBHs



Two dimensional parameter comparisons could be **very** informative!





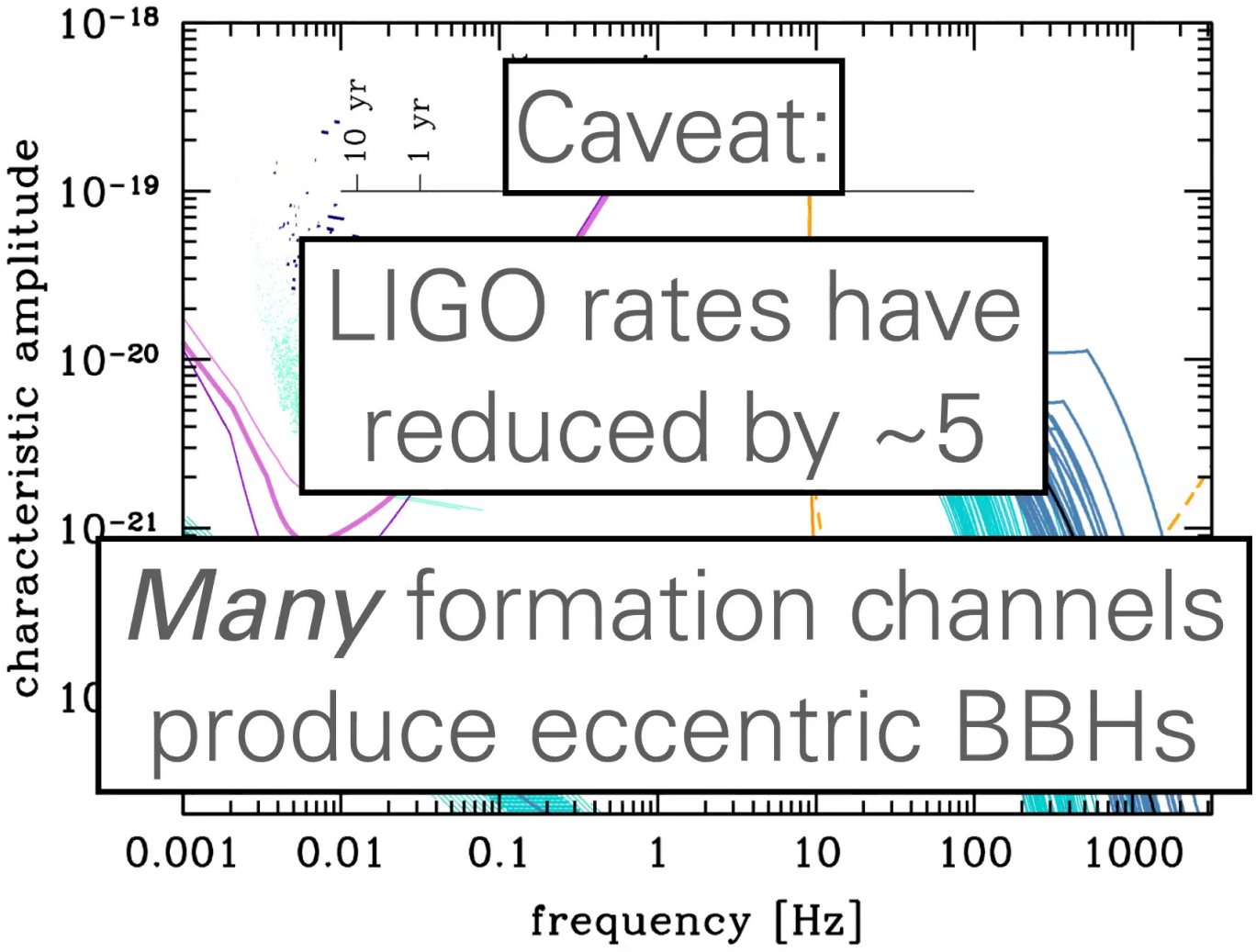
KB, Rodriguez + 2016, Nishizawa+2016,2017

Backward modeling is more optimistic

~20-600 LISA BBHs

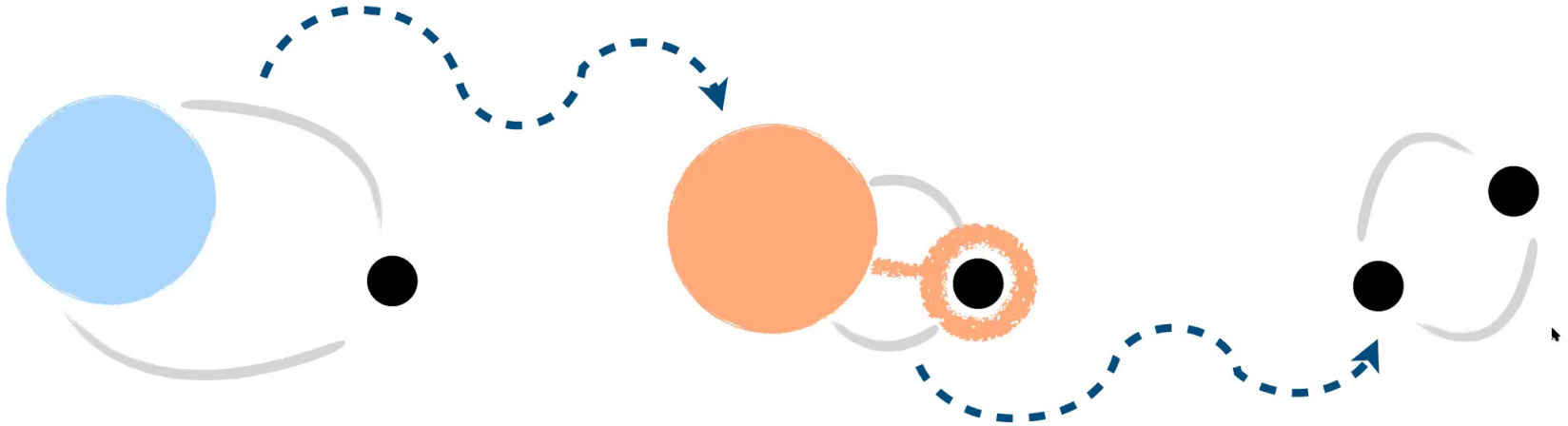
~4-140 multiband BBHs

Sesana 2016

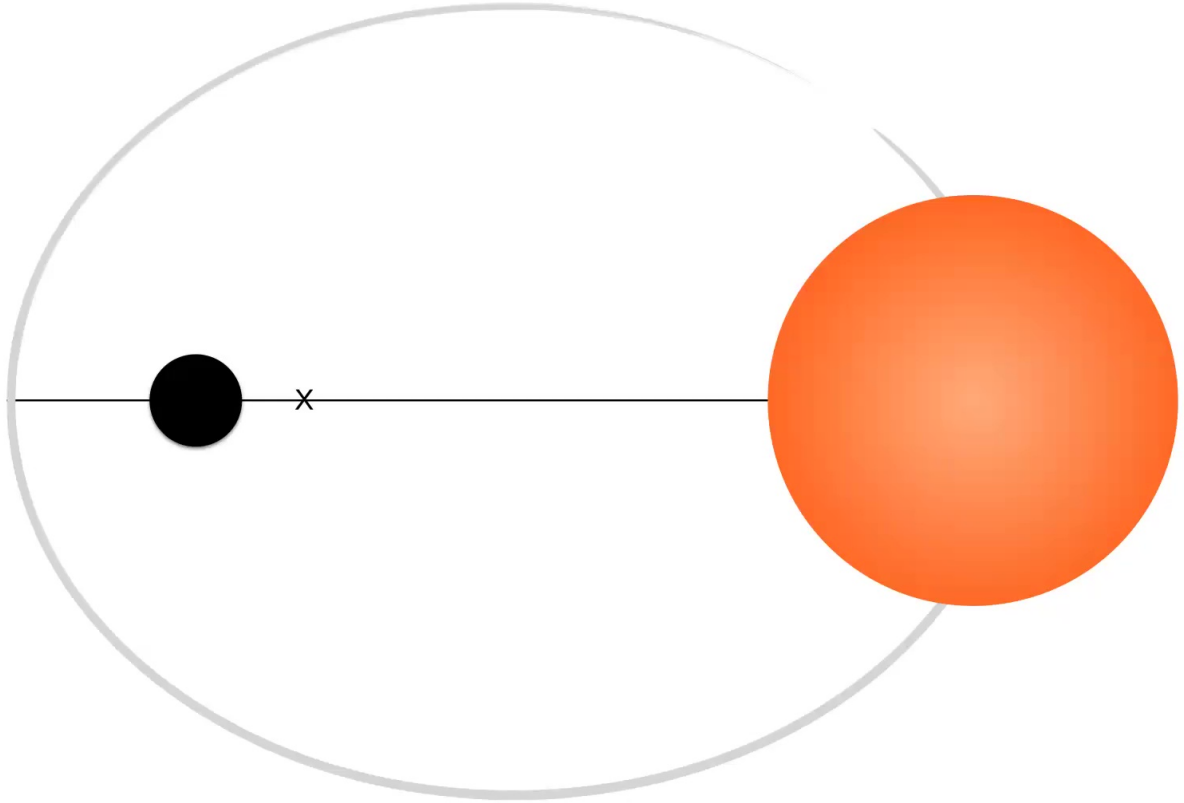


The biggest challenge in using GW populations to study binary evolution is determining which GW sources actually come from binary stars

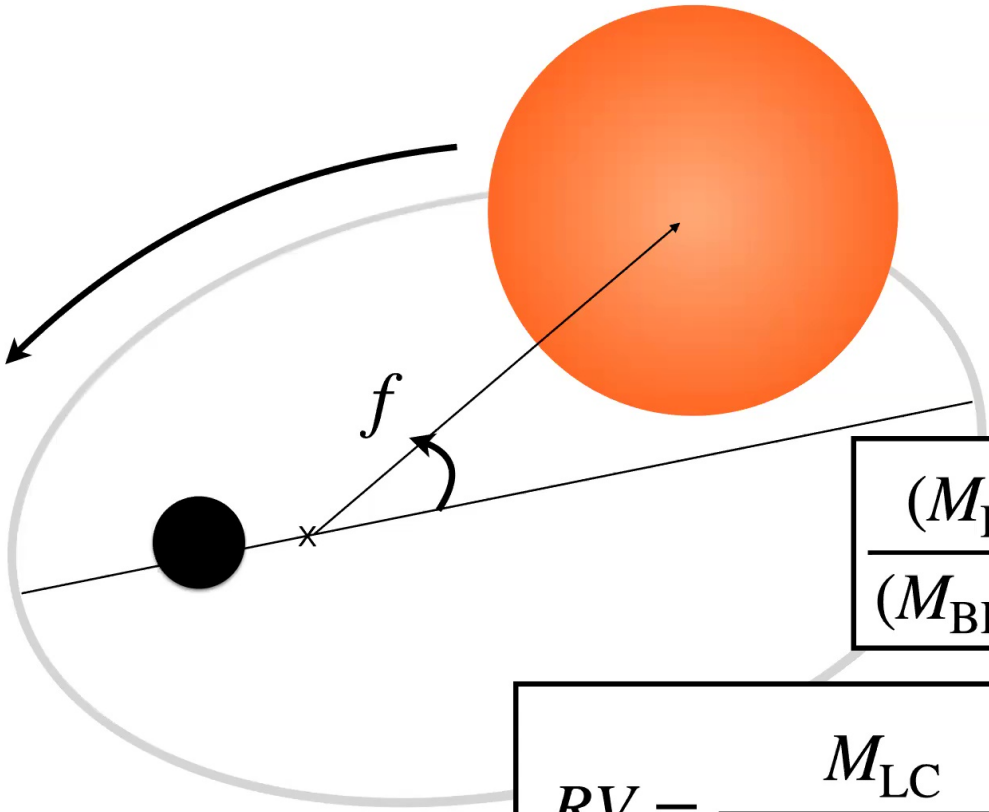
Binary evolution models that produce BBH mergers also produce intermediate phases of evolution



Detached black hole binaries



Radial-velocity black hole binaries

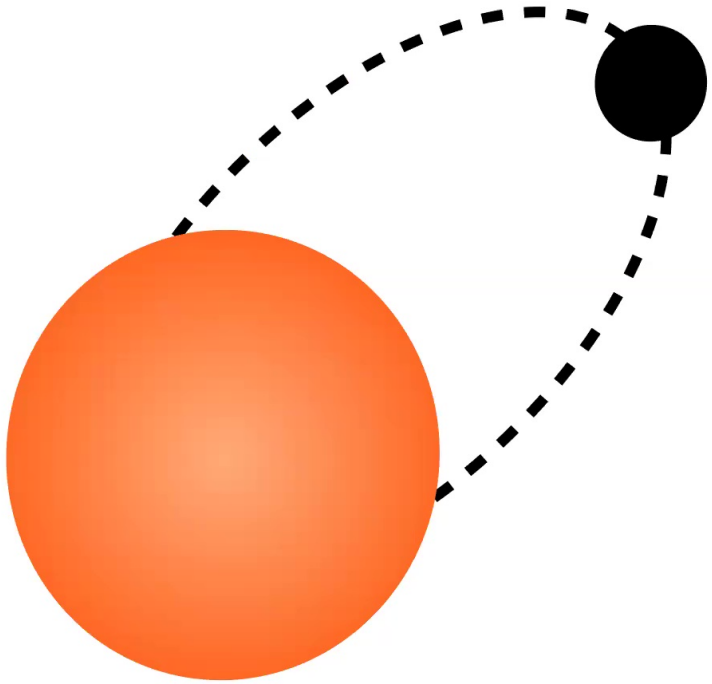


e.g. Andrews, KB+2019

$$\frac{(M_{\rm BH}\sin I)^3}{(M_{\rm BH}+M_{\rm LC})^2} = \frac{K^3}{G}\left(\frac{P_{\rm orb}}{2\pi}\right)(1-e^2)^{3/2}$$

$$RV = \frac{M_{\rm LC}}{M_{\rm BH}+M_{\rm LC}}\frac{2\pi}{P_{\rm orb}}\frac{a}{1-e^2}\left(\cos f \sin I + e\sin I\right)$$

Tidally locked low mass BH candidate + red giant companion



2M0521

$$M_{\rm BH} = 3.3^{+2.8}_{-0.7}\,{\rm M}_\odot$$

$$M_{\rm LC} = 3.2^{+1.0}_{-1.0}\,{\rm M}_\odot$$

$$P_{\rm orb} = 83.2\,{\rm day}$$

$$e = 0, \quad \sin(i) = 0.97$$

V723 Mon

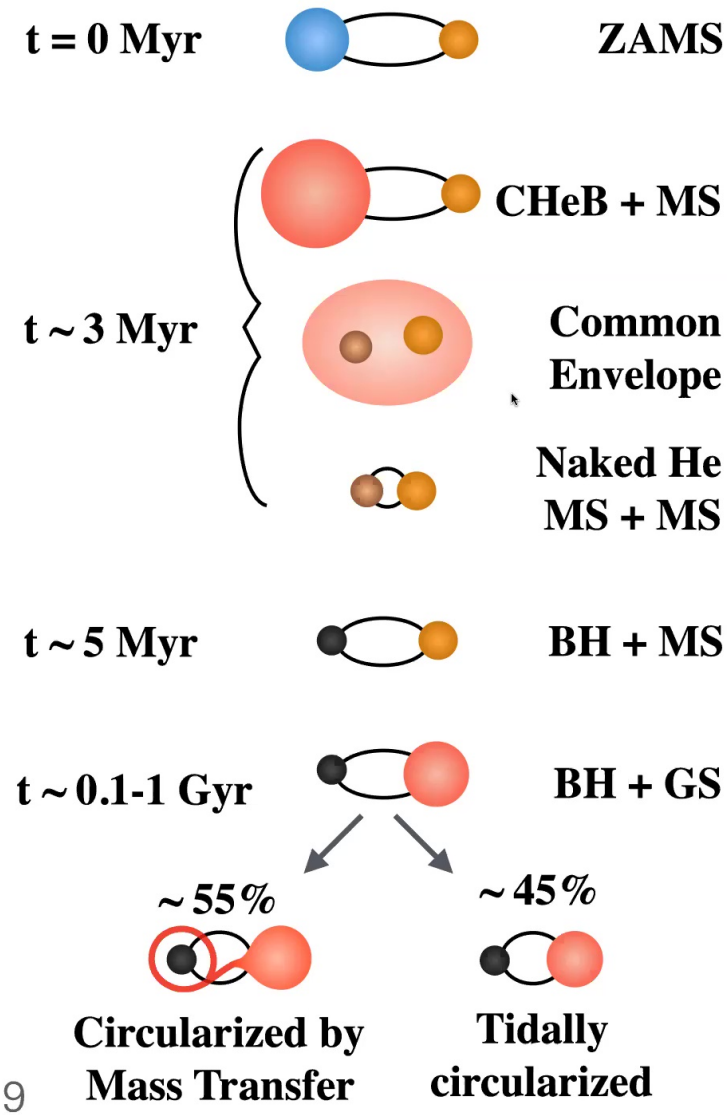
$$M_{\rm BH} = 2.9^{+0.1}_{-0.1}\,{\rm M}_\odot$$

$$M_{\rm LC} = 0.85^{+0.1}_{-0.1}\,{\rm M}_\odot$$

$$P_{\rm orb} = 60\,{\rm day}$$

$$e = 0, \quad \sin(i) = 0.99$$

Thompson+2019, Jayasinghe+2021

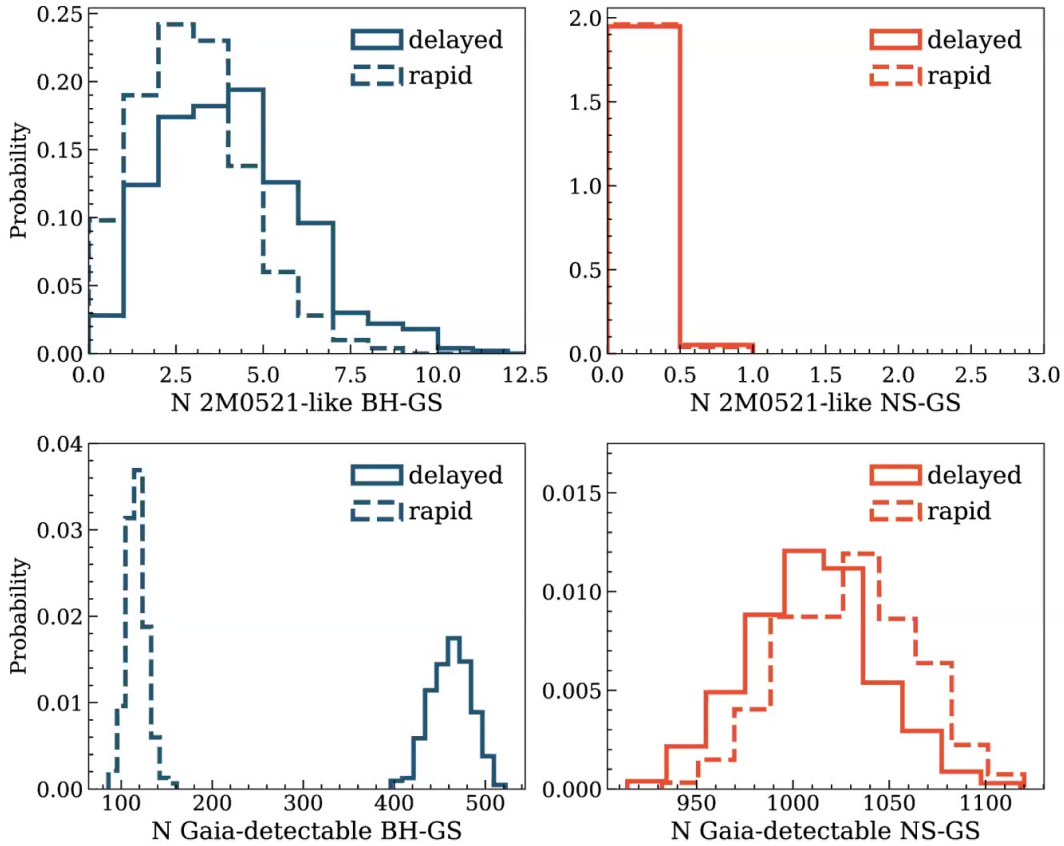


KB+2019

All non-interacting BH - low mass GS with circular orbits and $P_{\rm orb} < 5\,{\rm yr}$ are the result of common envelope

A potential new class of post common envelope binaries

The presence of 2M0521 and V723 Mon implies a larger, ***yet undiscovered***, population



KB+2019

APOGEE

$$1450\,\mathrm{K} < T_{\mathrm{eff,peak}} < 3000\,\mathrm{K}$$

$$H < 15$$

Gaia

$$3000\,\mathrm{K} < T_{\mathrm{eff,peak}} < 8300\,\mathrm{K}$$

$$G < 20$$

Constraints across orbit sizes and messengers will provide the best understanding of how BHs form in binary systems