

# Gravitational-wave Observations as Astrophysical Probes

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CAP Congress 2026, Ottawa



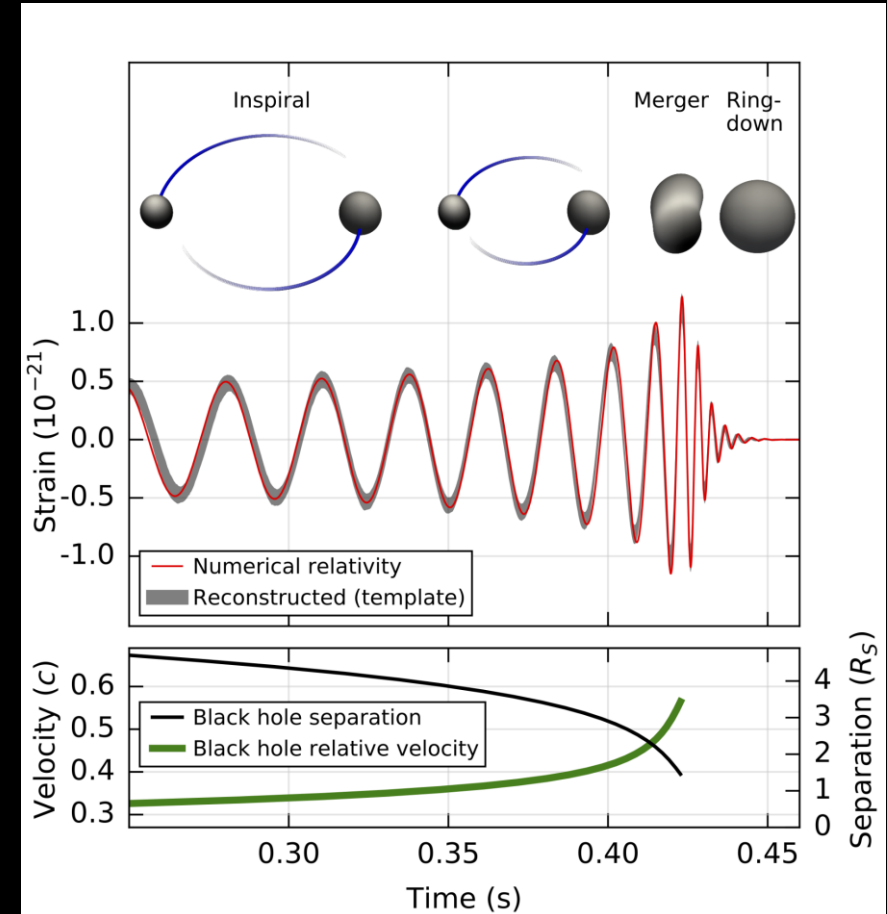
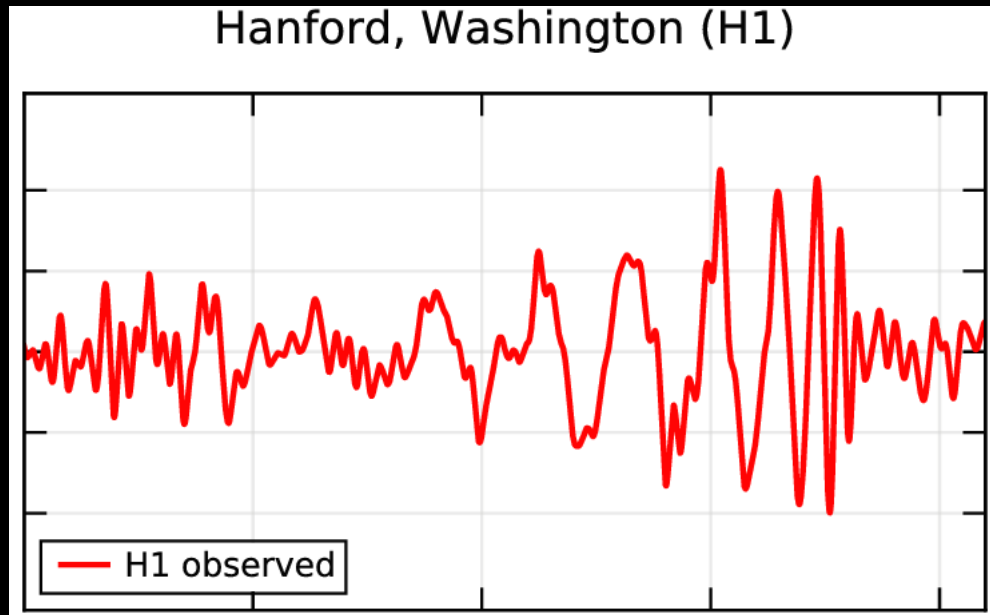
**CITA**  
**ICAT**

Canadian Institute for  
Theoretical Astrophysics

L'institut Canadien  
d'astrophysique théorique

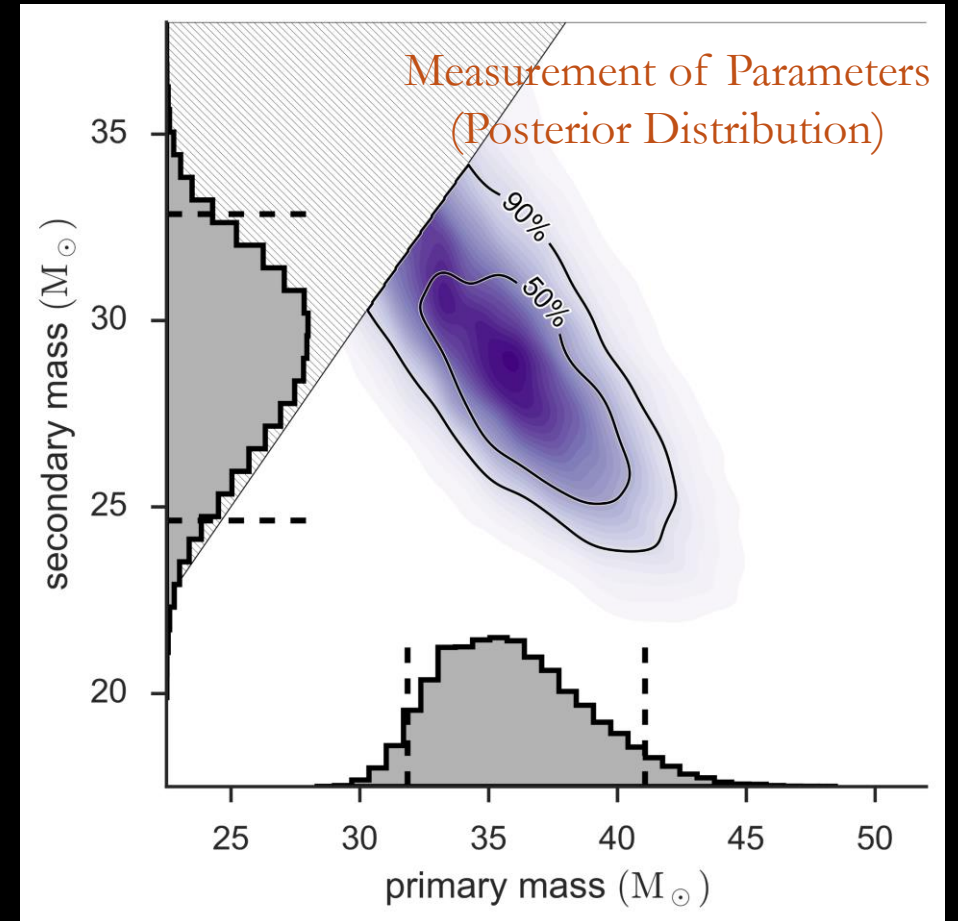
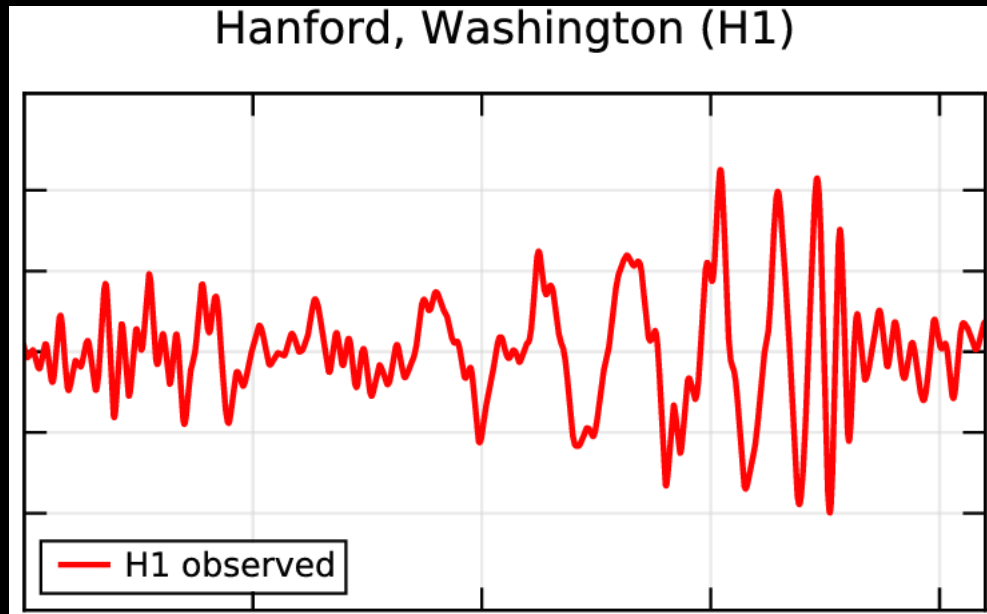
# GW150914: The First Detection

Abbott+ 2016,  
arXiv:1602.03837,  
arXiv:1602.03840



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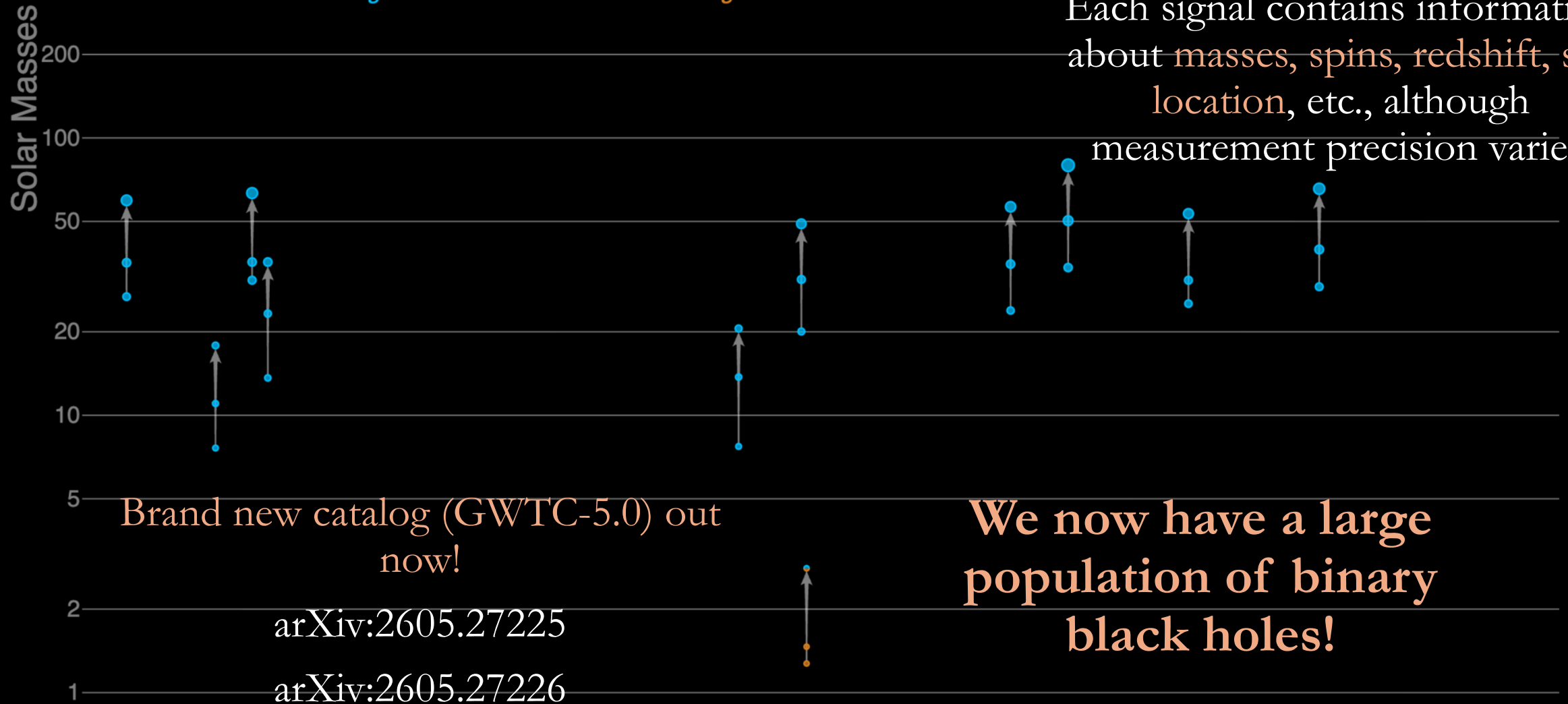


Showed us that massive merging  
black holes exist in the Universe.

# Masses in the Stellar Graveyard

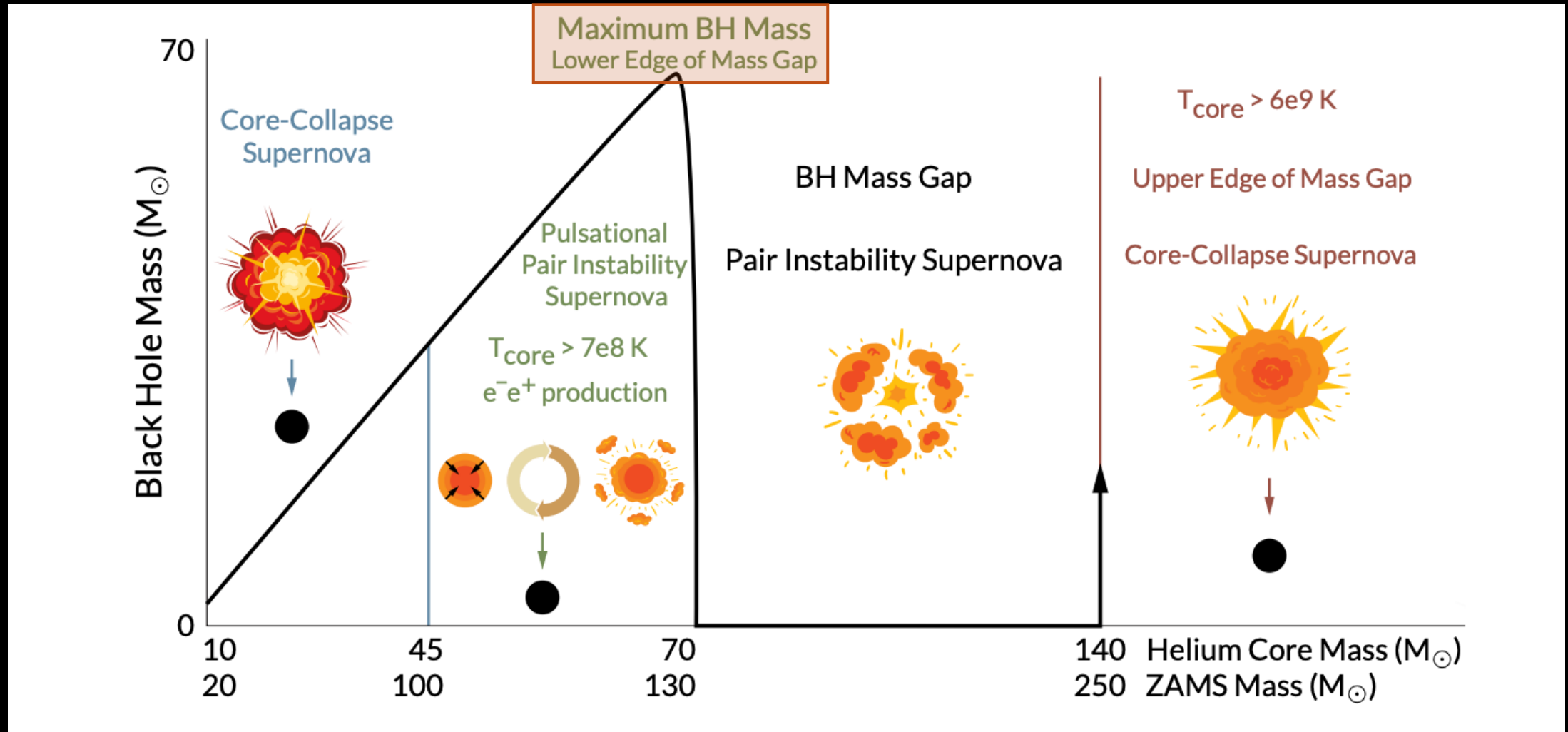
LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars

Each signal contains information about masses, spins, redshift, sky location, etc., although measurement precision varies.



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

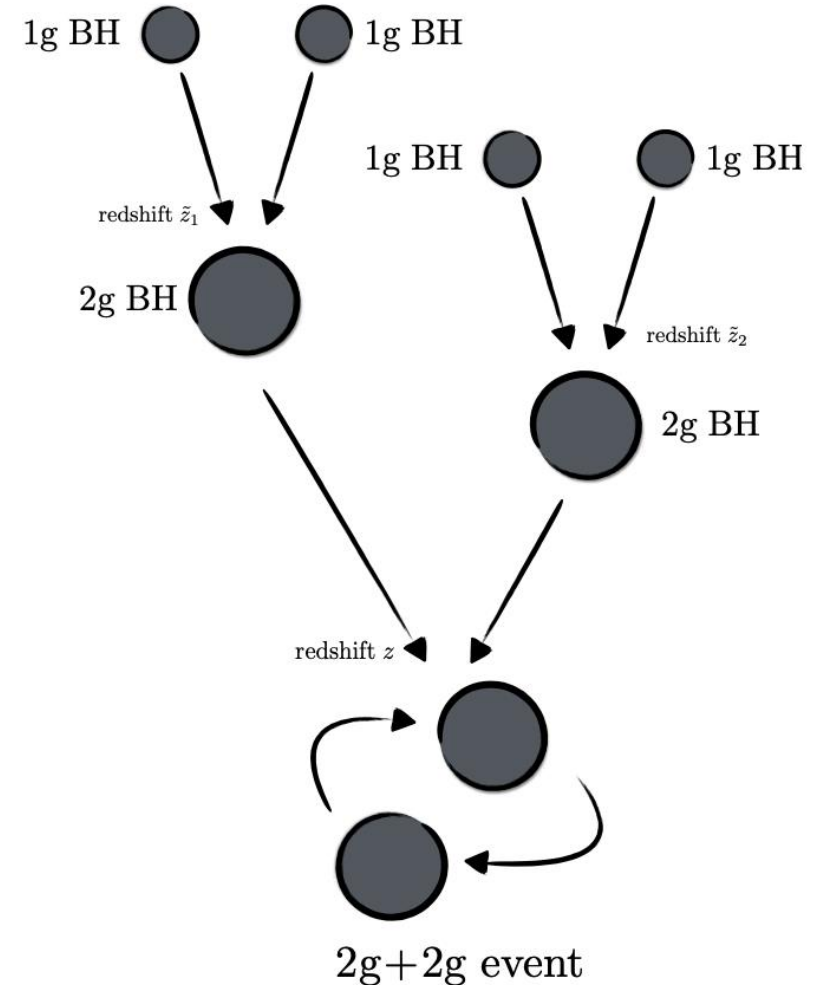
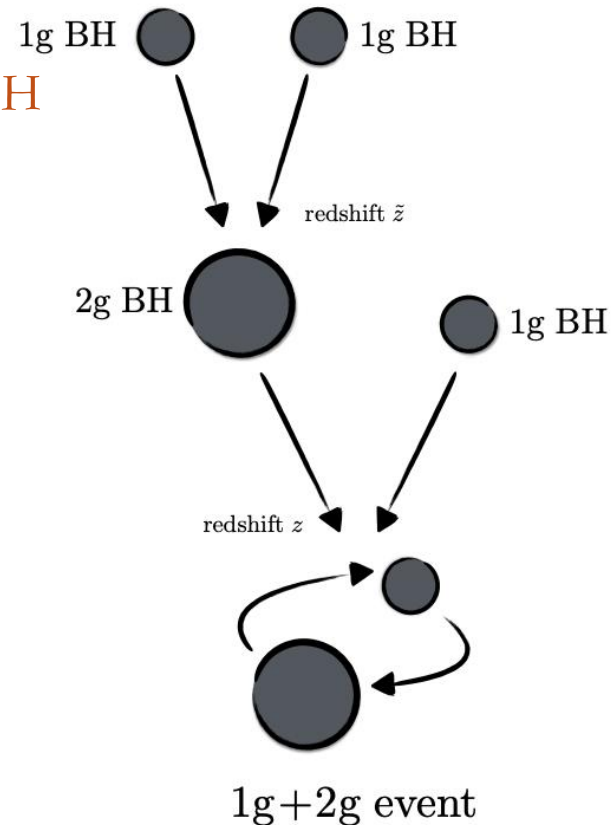
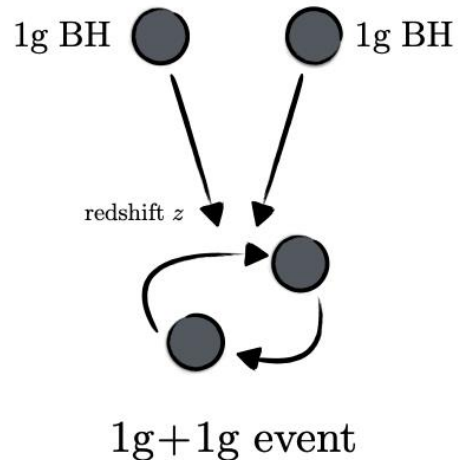
# Population Properties Encode Astrophysics



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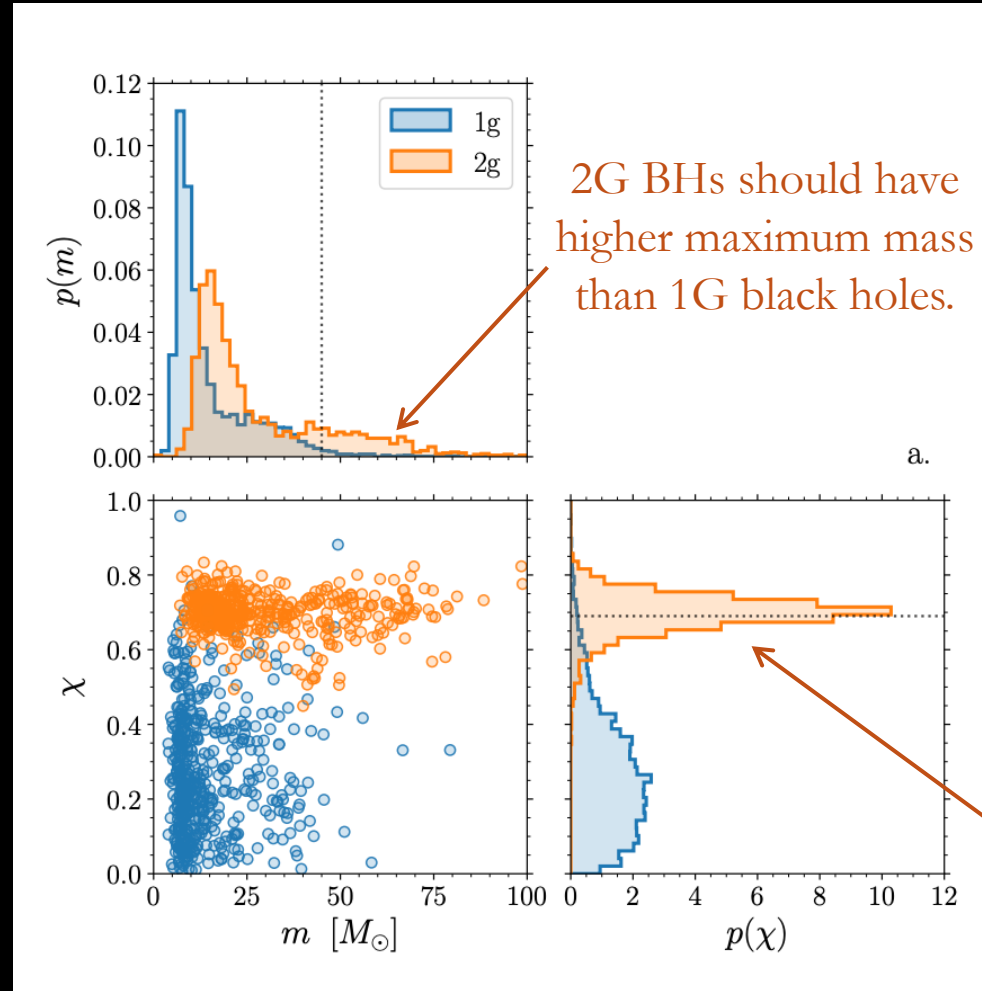
Are our observed BHs made up of smaller BHs?

Natural by-product of BH assembly in dense environments.



# Population Properties Encode Astrophysics

Predictions of 2G BH population.



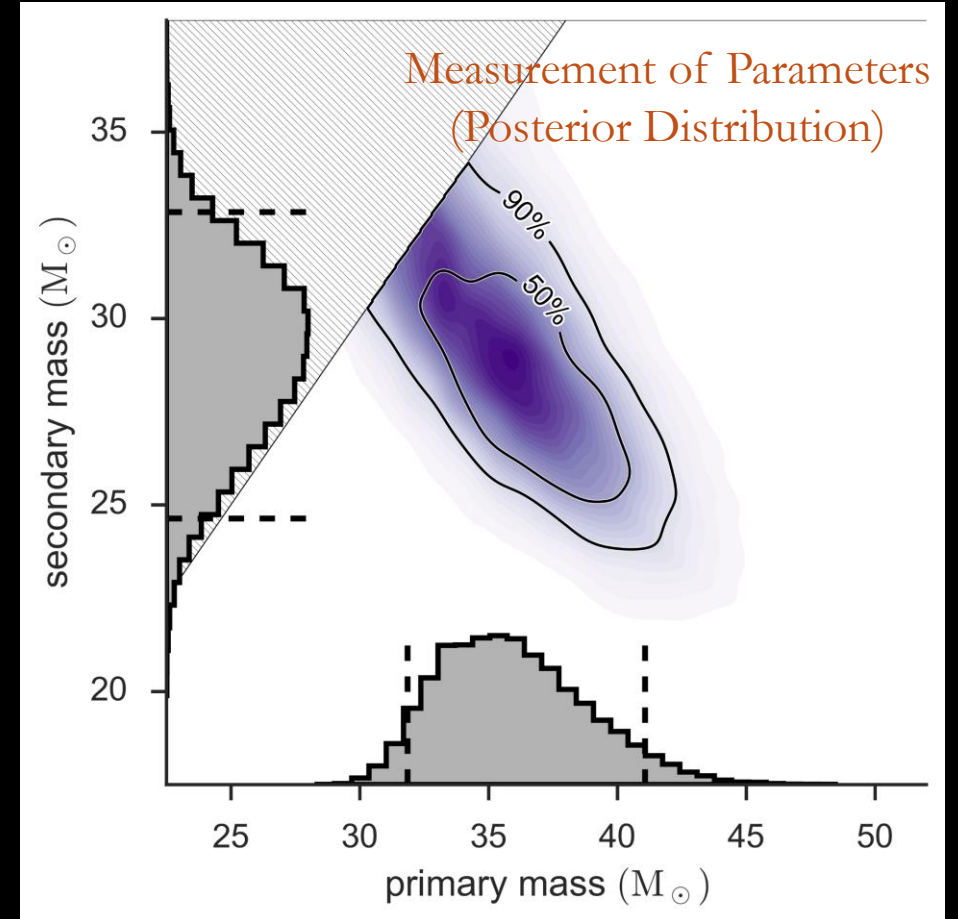
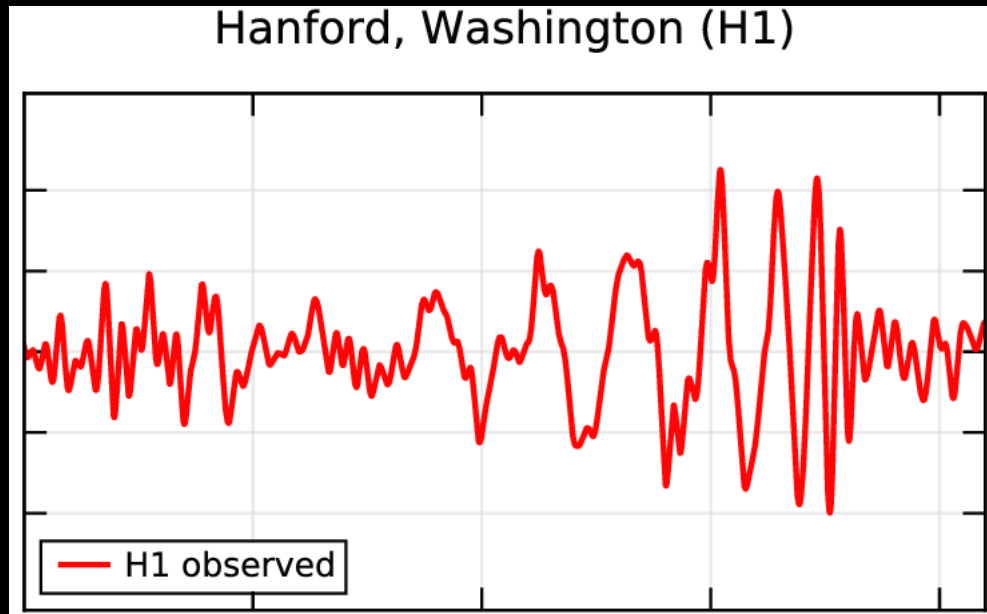
2G BHs should have higher maximum mass than 1G black holes.

Gerosa & Fishbach 2021  
arXiv:2105.03439

2G BHs should have spins concentrated around 0.7.  
Robust prediction of general relativity!

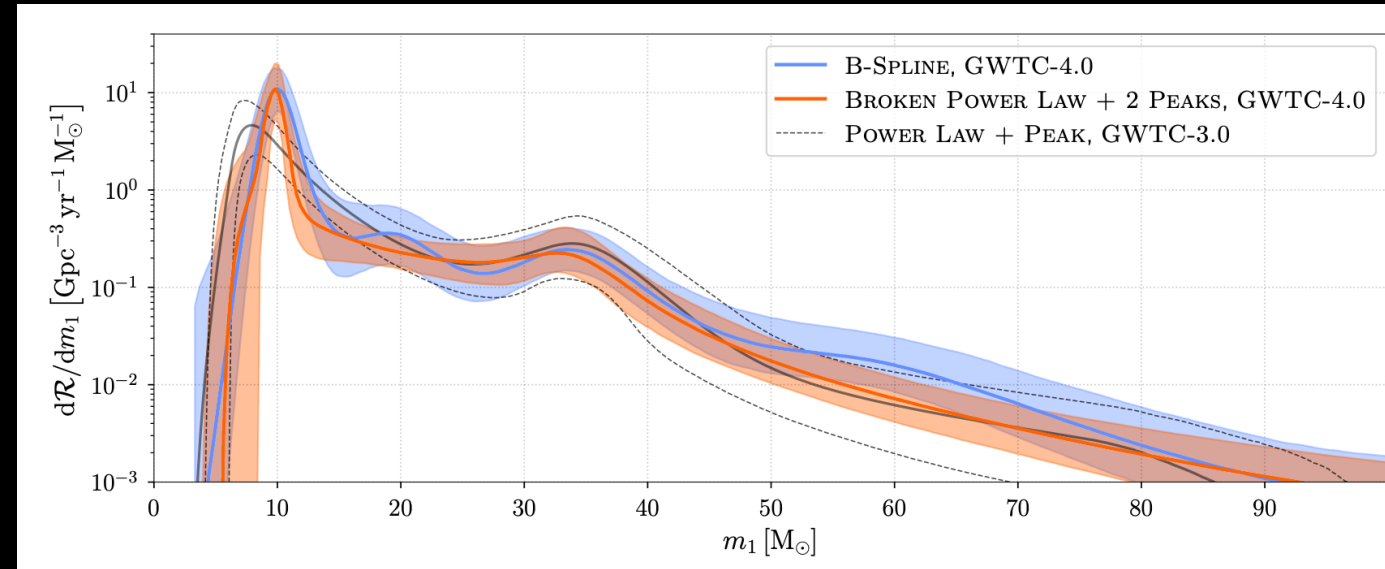
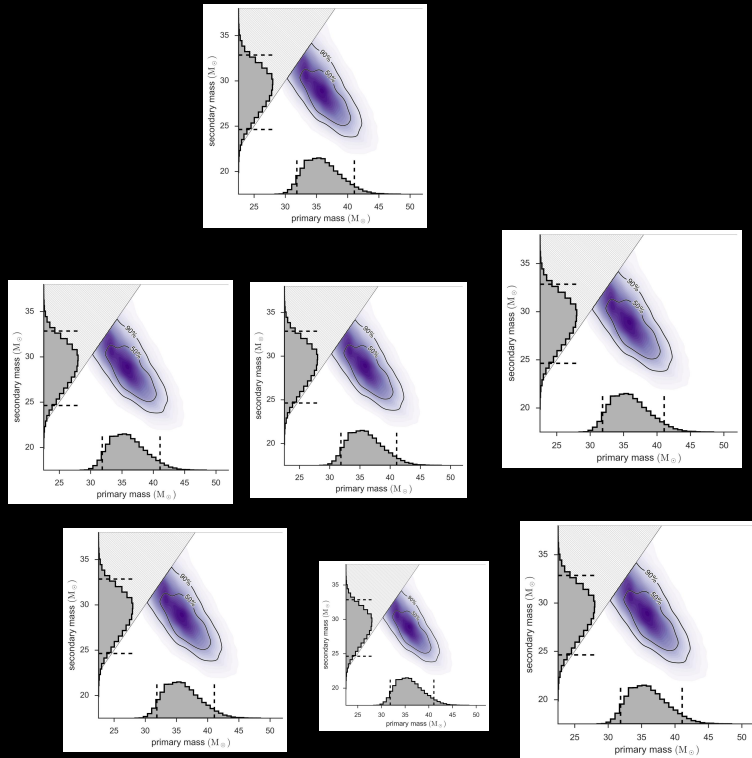
# The Inference Problem

Abbott+ 2016,  
arXiv:1602.03837,  
arXiv:1602.03840



# The Inference Problem

Many uncertain measurements from  
different sources



Measurements of population properties [LVK+, arXiv:2508.18083]

# Main Ingredient: Selection Effects

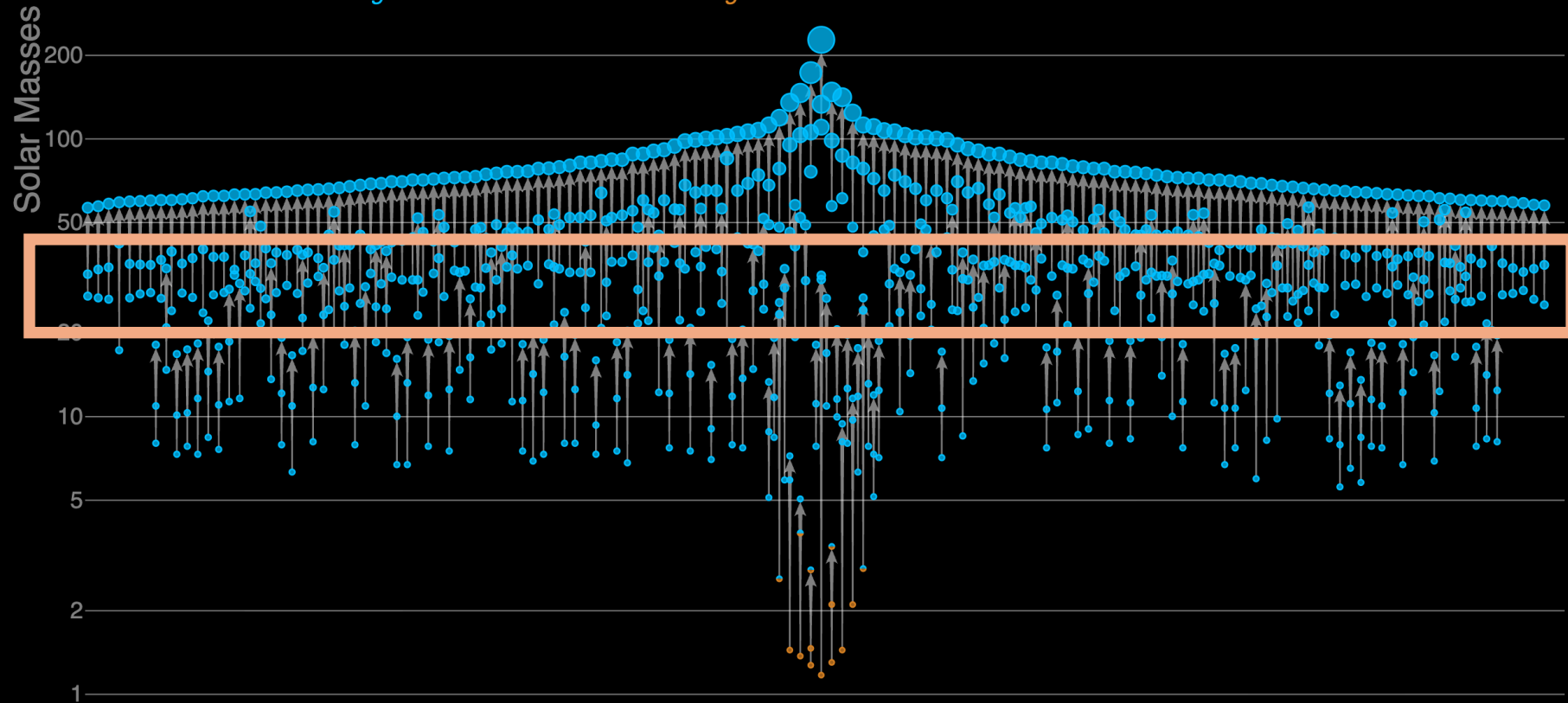
## Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars

$$A_{\text{GW}} \propto \frac{\mathcal{M}^{5/6}}{D_L}$$

Inherently easier to detect massive binaries, and binaries that are close by.

...but we can correct for this!




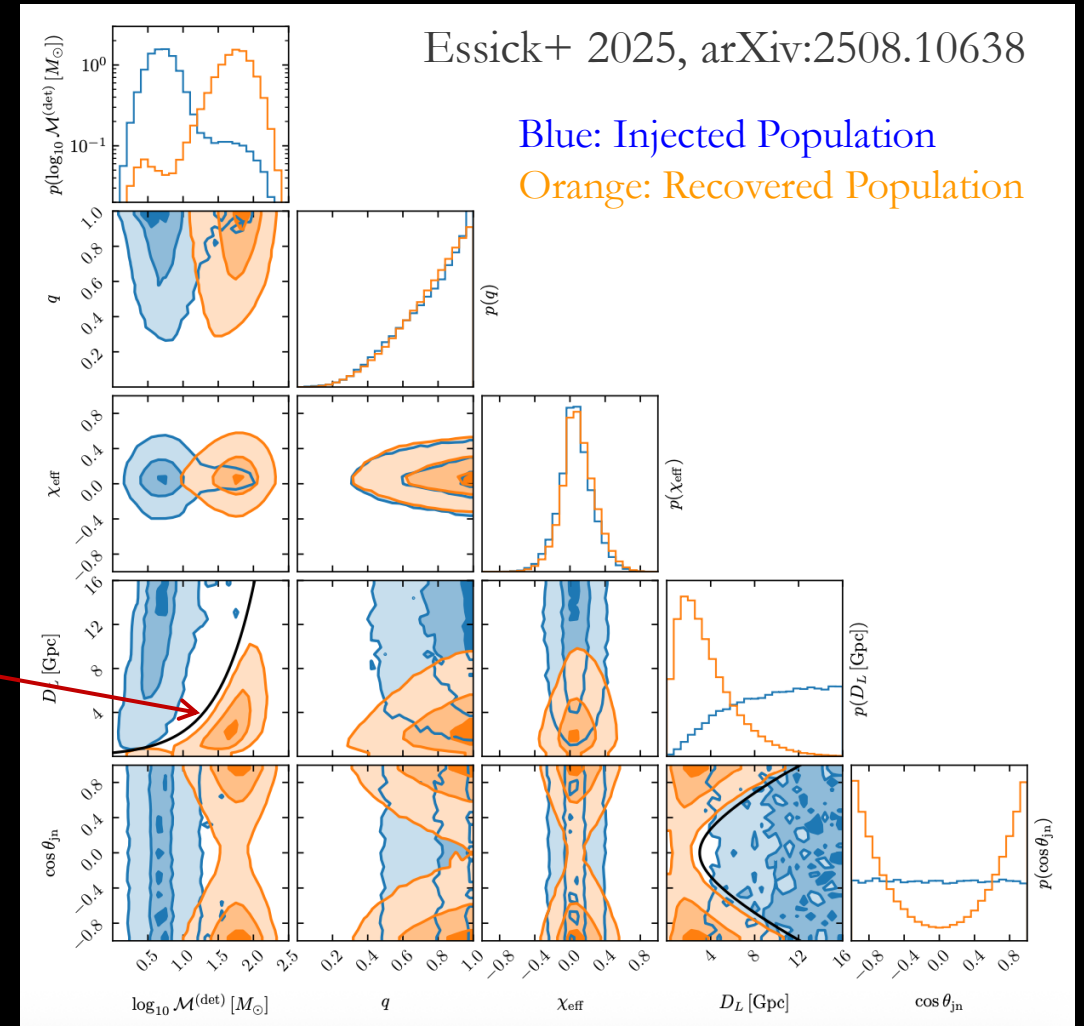
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

# Main Ingredient: Selection Effects

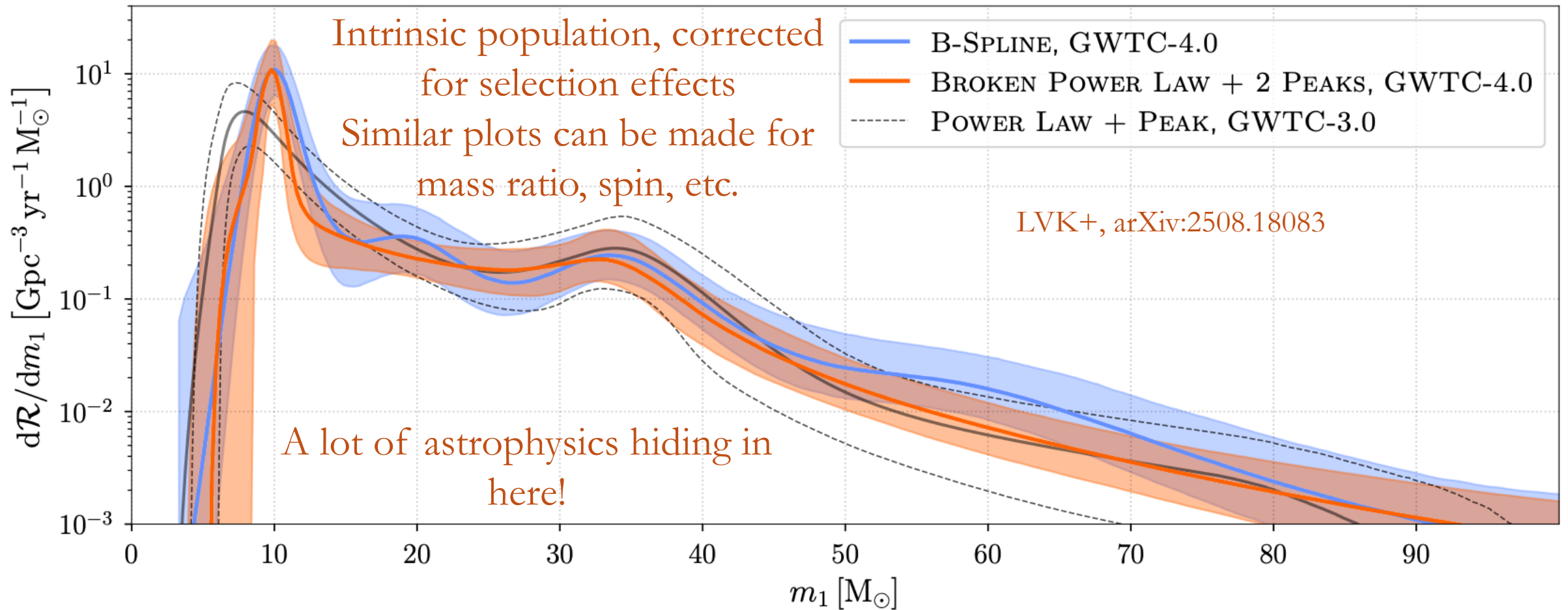
In practice, one also needs to account for search behaviour

Solution: inject millions of fake signals in the data stream and have searches recover them [Essick+ 2025]

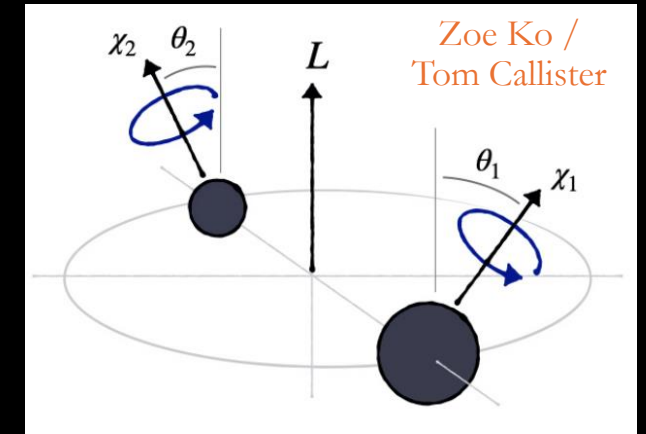
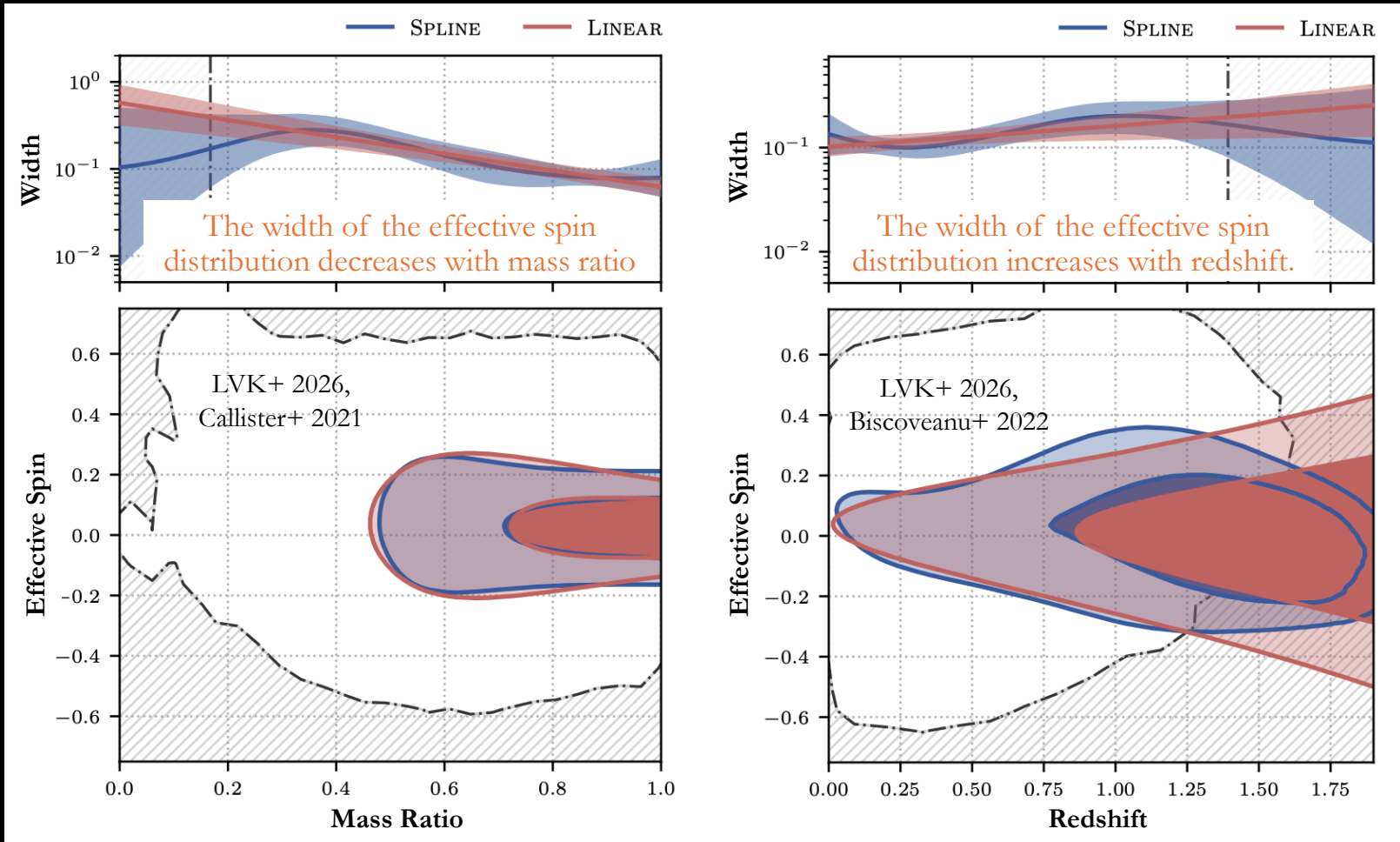
$$A_{\text{GW}} \propto \frac{\mathcal{M}^{5/6}}{D_L}$$




# Primary Mass Distribution of Binary Black Holes



# Observed trends in the GW source population



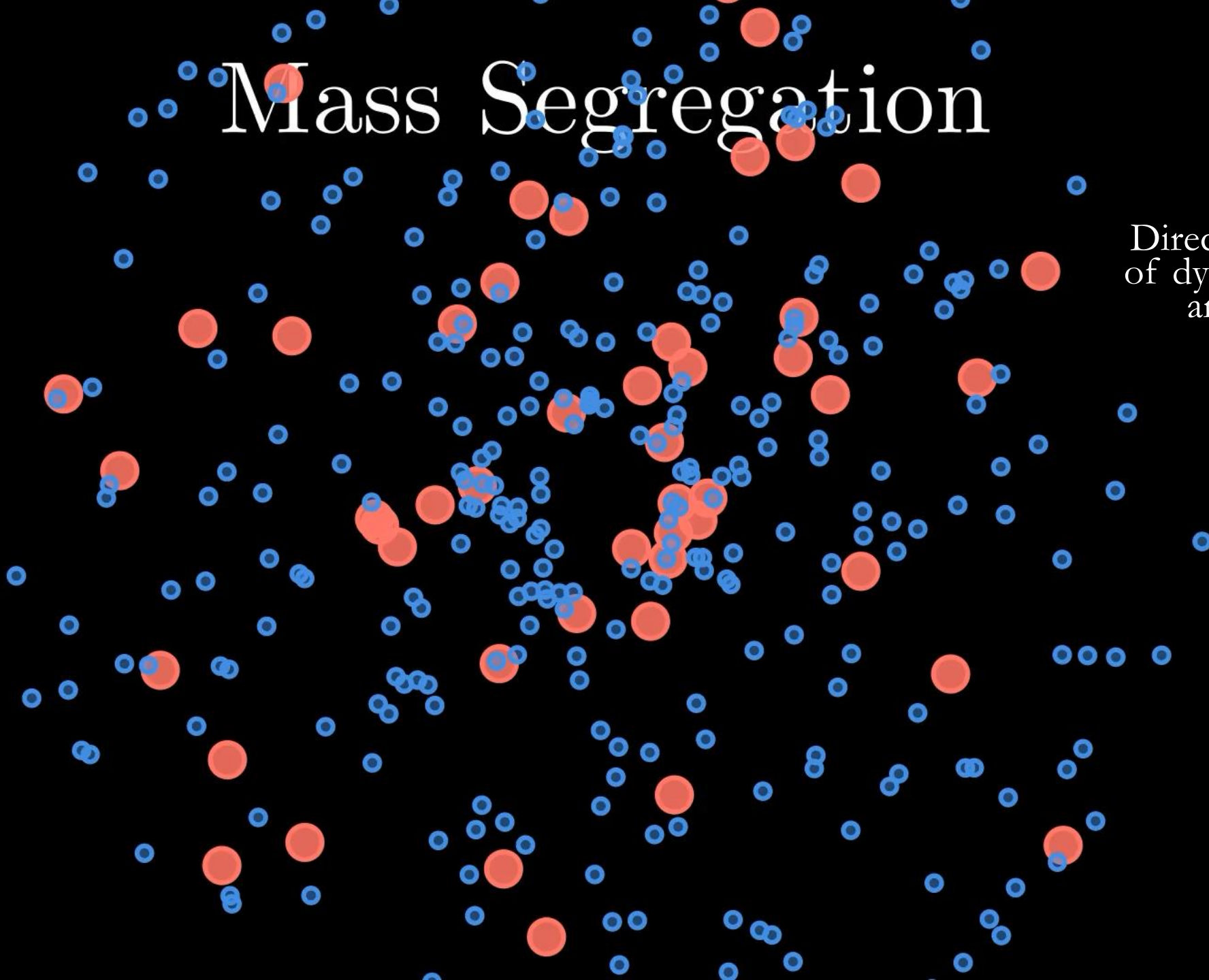
$$\chi_{\text{eff}} = \frac{\chi_1 \cos \theta_1 + q \chi_2 \cos \theta_2}{1 + q} \quad q = \frac{m_2}{m_1}$$

Mass-weighted projection of spins perpendicular to orbital plane; Best measured combination of spins

What astrophysics governs these correlations?

Dense Star Cluster  
 $\sim 10^5 M_{\text{sun}}$ ,  $\sim 1$  pc radius

# Mass Segregation



Direct Consequence  
of dynamical friction  
and the virial  
theorem

# 1G + 1G Black Hole Mergers

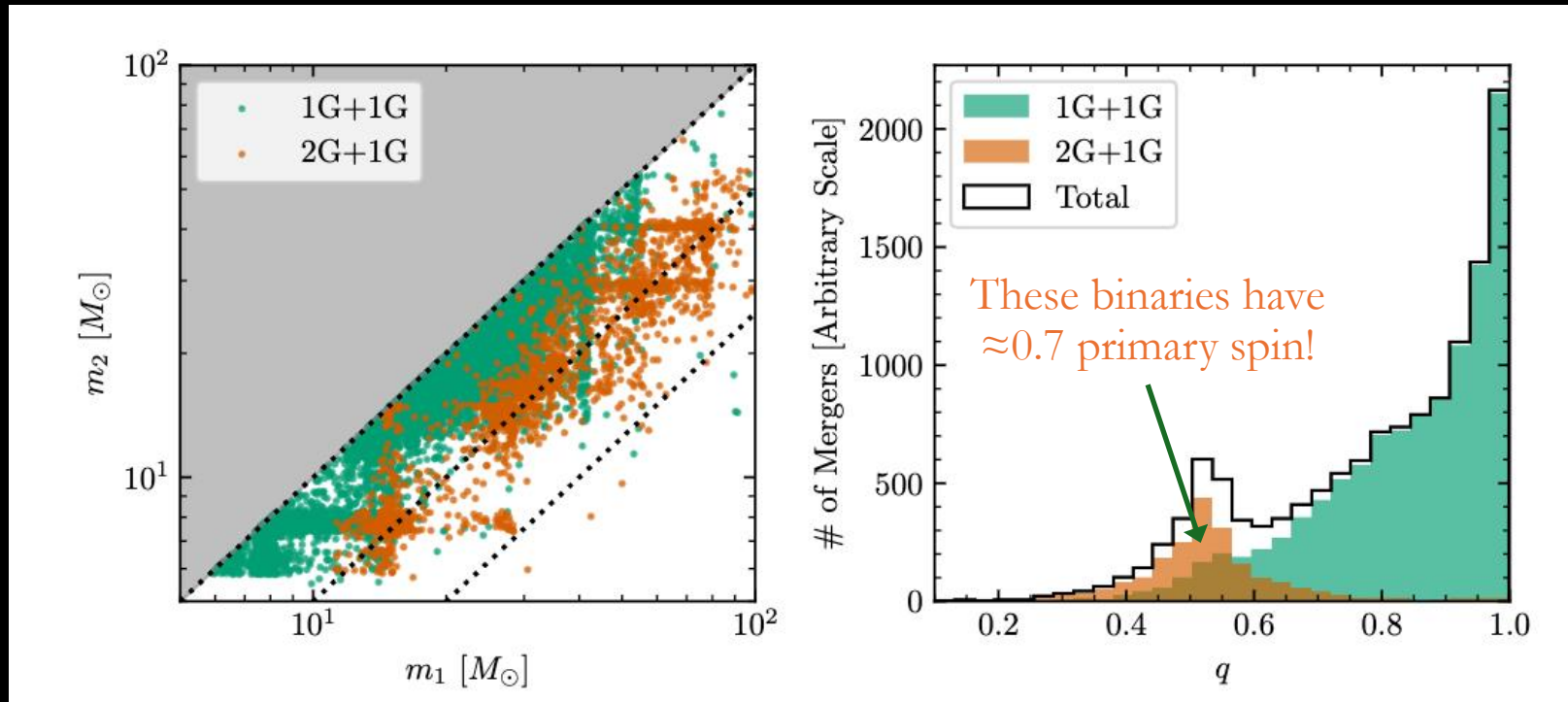
Mass ratio = 1. Remnant has a unique spin value of  $\approx 0.7$

# 2G + 1G Black Hole Mergers

Mass Ratio = 0.5;  $\chi_1 \approx 0.7$

# Theoretical Expectation: Population Synthesis

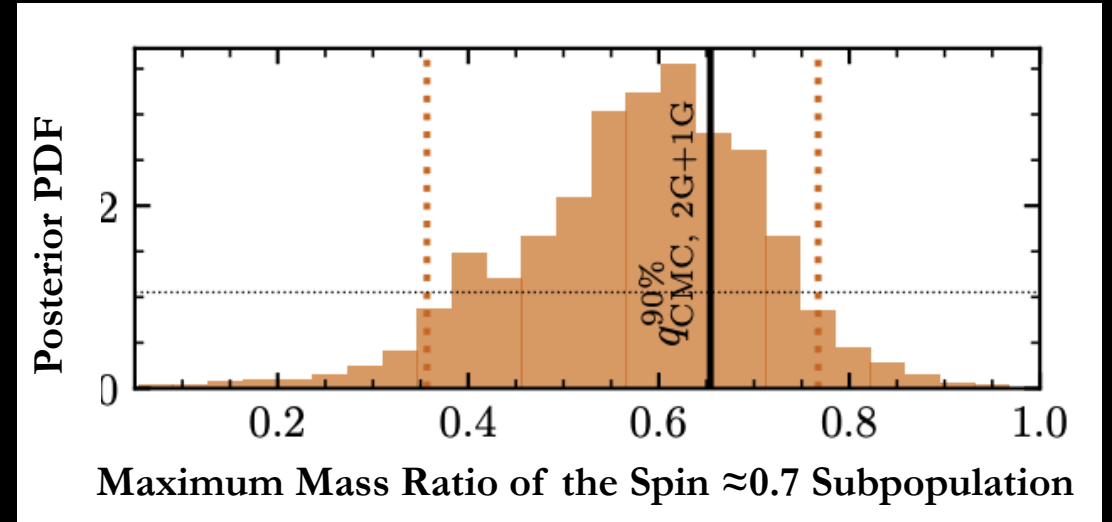
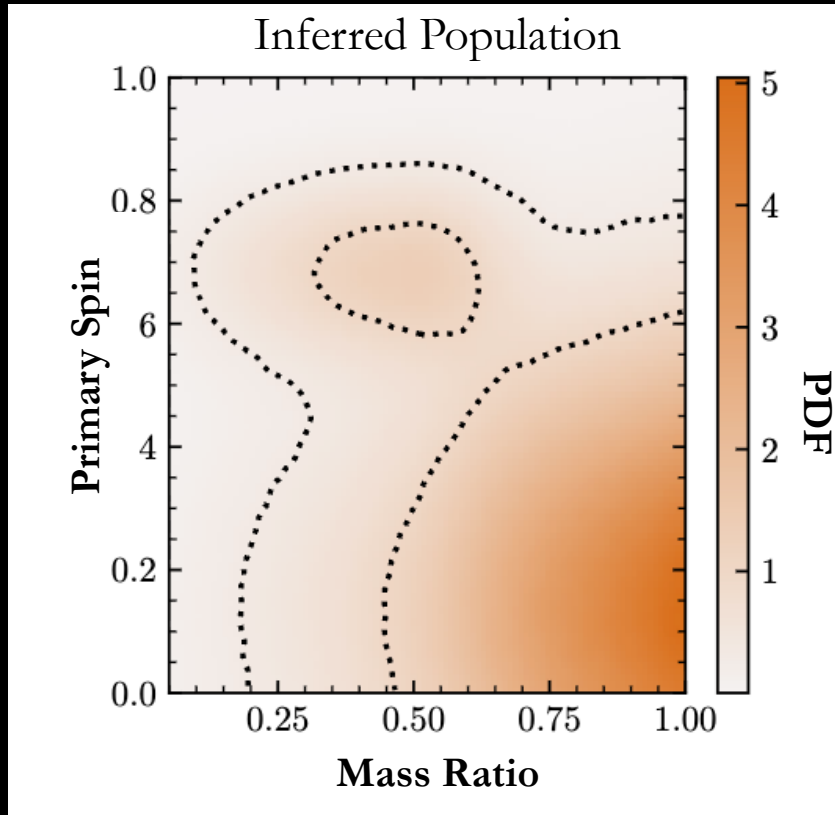
Vijaykumar, Farah,  
Fishbach 2026, ApJL  
arXiv:2601.03457



Adapted from the **Cluster Monte Carlo simulations** [Kremer+ 2021] of dense star clusters. Depending on cluster mass and density, 2G+1G mergers can make up 5-30% of all mergers in dense star clusters.

# Which mass ratios in the GW data have spin $\approx 0.7$ ?

Vijaykumar, Farah,  
Fishbach 2026, ApJL  
arXiv:2601.03457

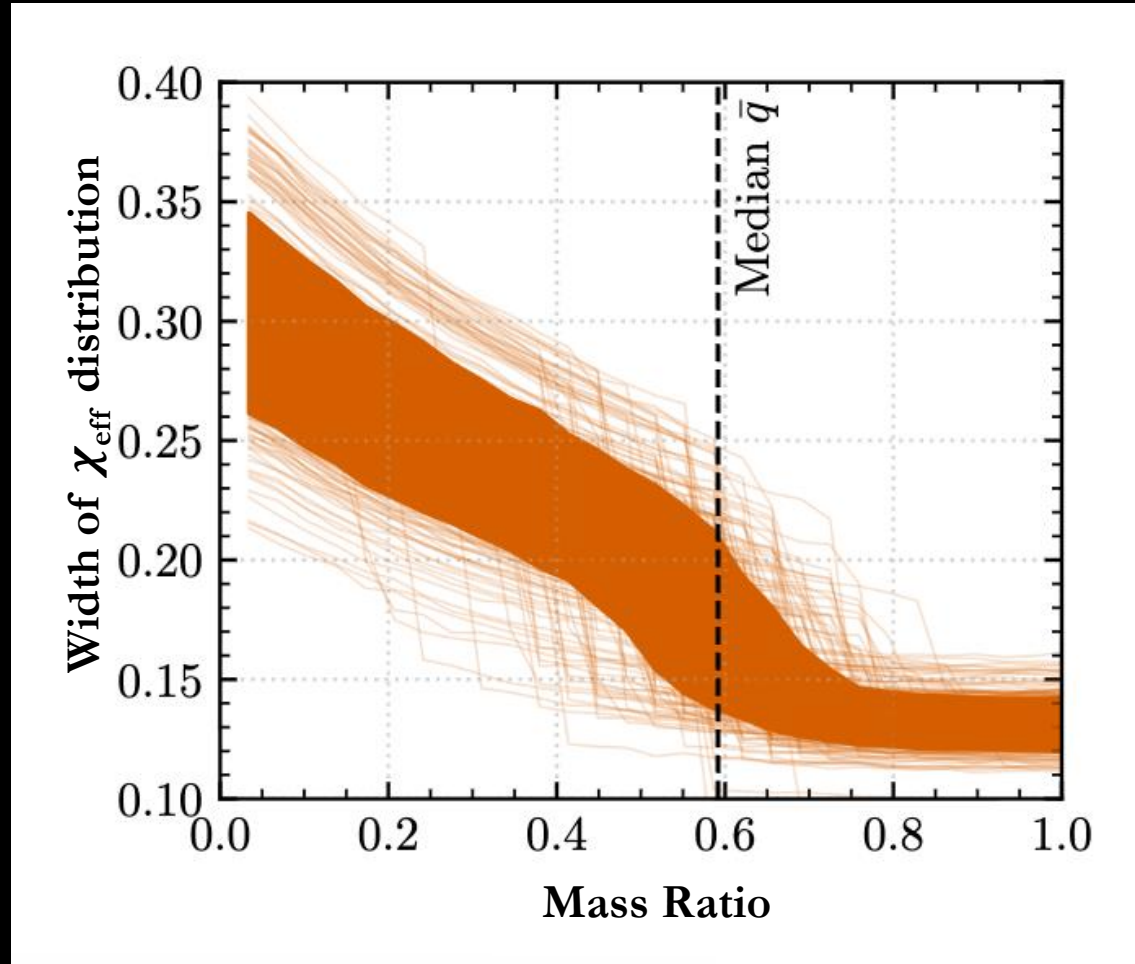


There is a subpopulation in the data that lies at spin  $\approx 0.7$  and **unequal mass ratio**! Makes up about  $\sim 5$ -  
 $15\%$  of the total population.

Taken with the rest of the population, **primary spin and mass ratio appear anti-correlated**.

# This May Explain the $q - \chi_{\text{eff}}$ Correlation!

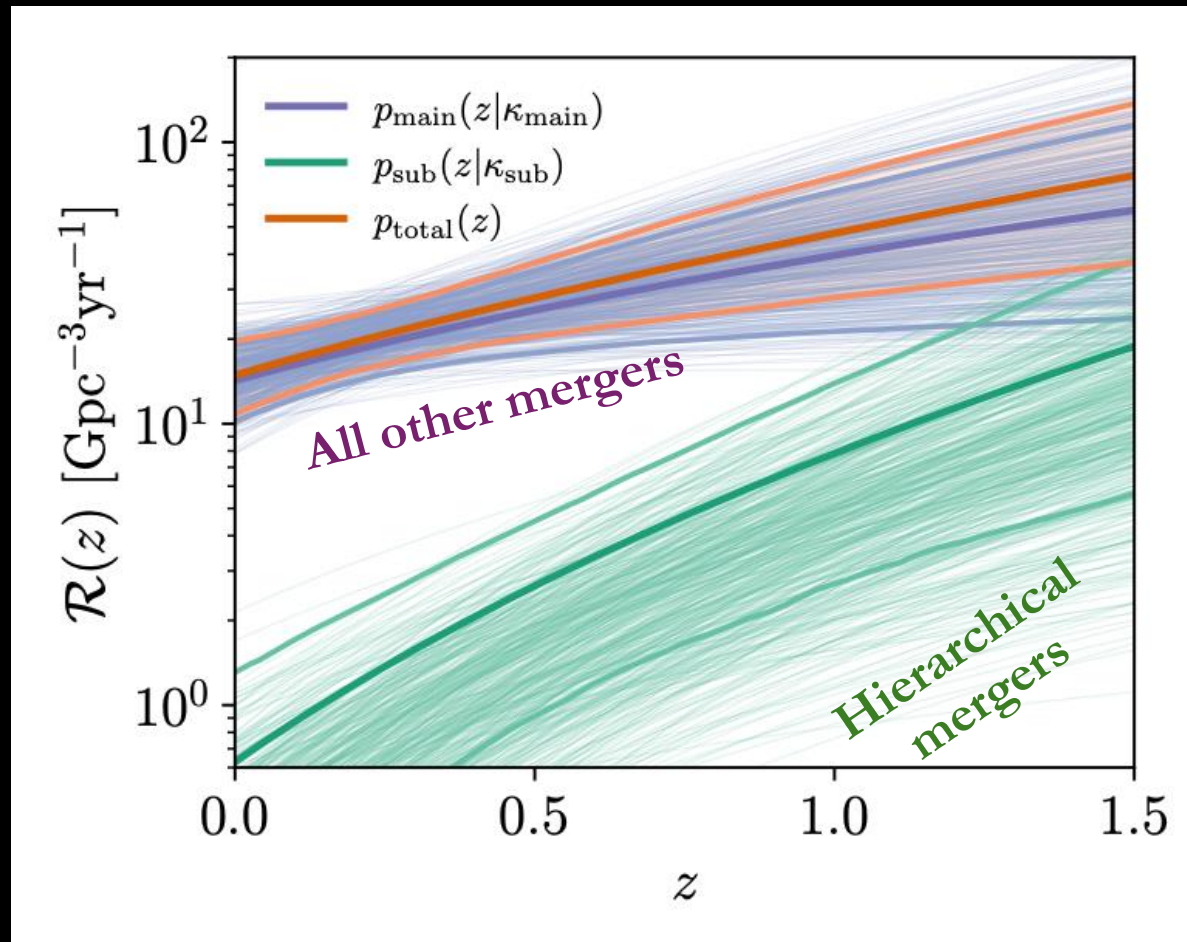
Vijaykumar, Farah,  
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Anti-correlation between  
primary spin magnitude  
and mass ratio  $\rightarrow$   
Anti-correlation between  
width of  $\chi_{\text{eff}}$  distribution  
and mass ratio.

# How does the merger rate of spin $\approx 0.7$ objects evolve with redshift?

Farah, Vijaykumar,  
Fishbach 2026, ApJL  
arXiv:2601.03456

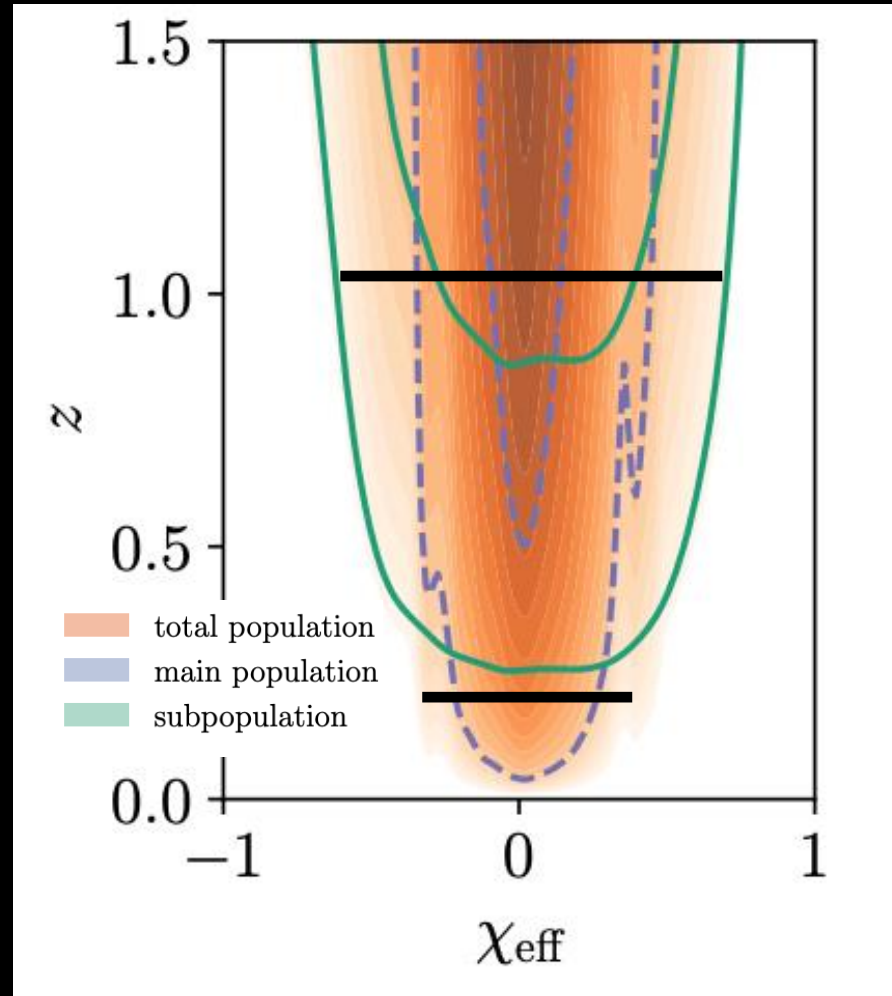


The hierarchical merger rate, while lower than the rate of all other mergers, increases faster with redshift.

That is, hierarchical mergers preferentially lie at higher redshift.

# This May Explain the *redshift* - $\chi_{\text{eff}}$ Correlation!

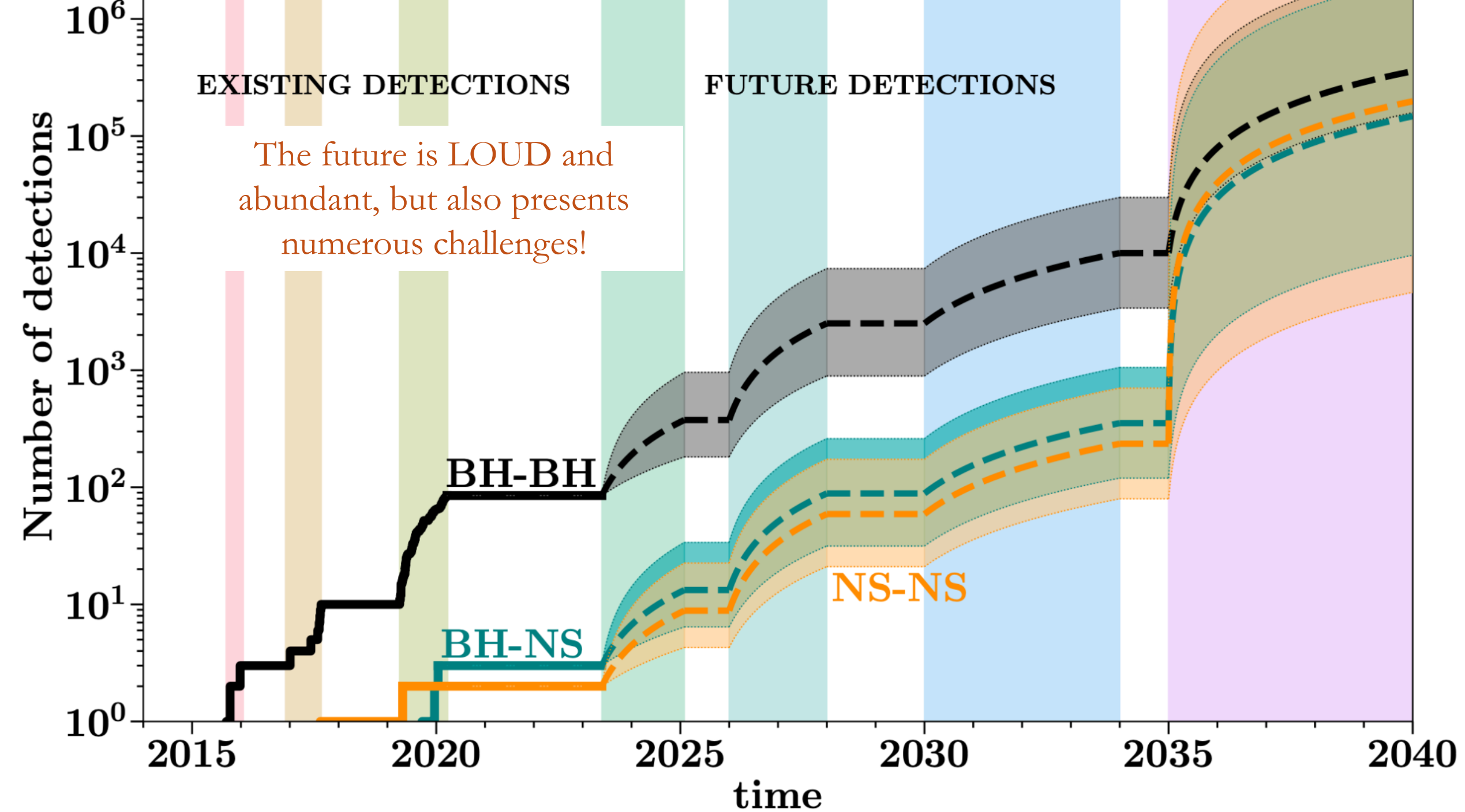
Farah, Vijaykumar,  
Fishbach 2026, ApJL  
arXiv:2601.03456



More hierarchical mergers  
at high redshift  $\rightarrow$   
Larger  $\chi_{\text{eff}}$  distribution  
width at high redshift.

# Takeaways

- Population-level analyses provide information about the formation and evolution of binary black holes.
- There is evidence for a subpopulation of hierarchical mergers in gravitational-wave data
- Compared to the rest of the population, this subpopulation prefers:
  - Mass ratios away from 1
  - Larger redshifts
- This subpopulation may explain the observed population-level trends between effective spin, mass ratio, and redshift.



# Thanks for Listening!

## Any Questions?

Get in Touch!

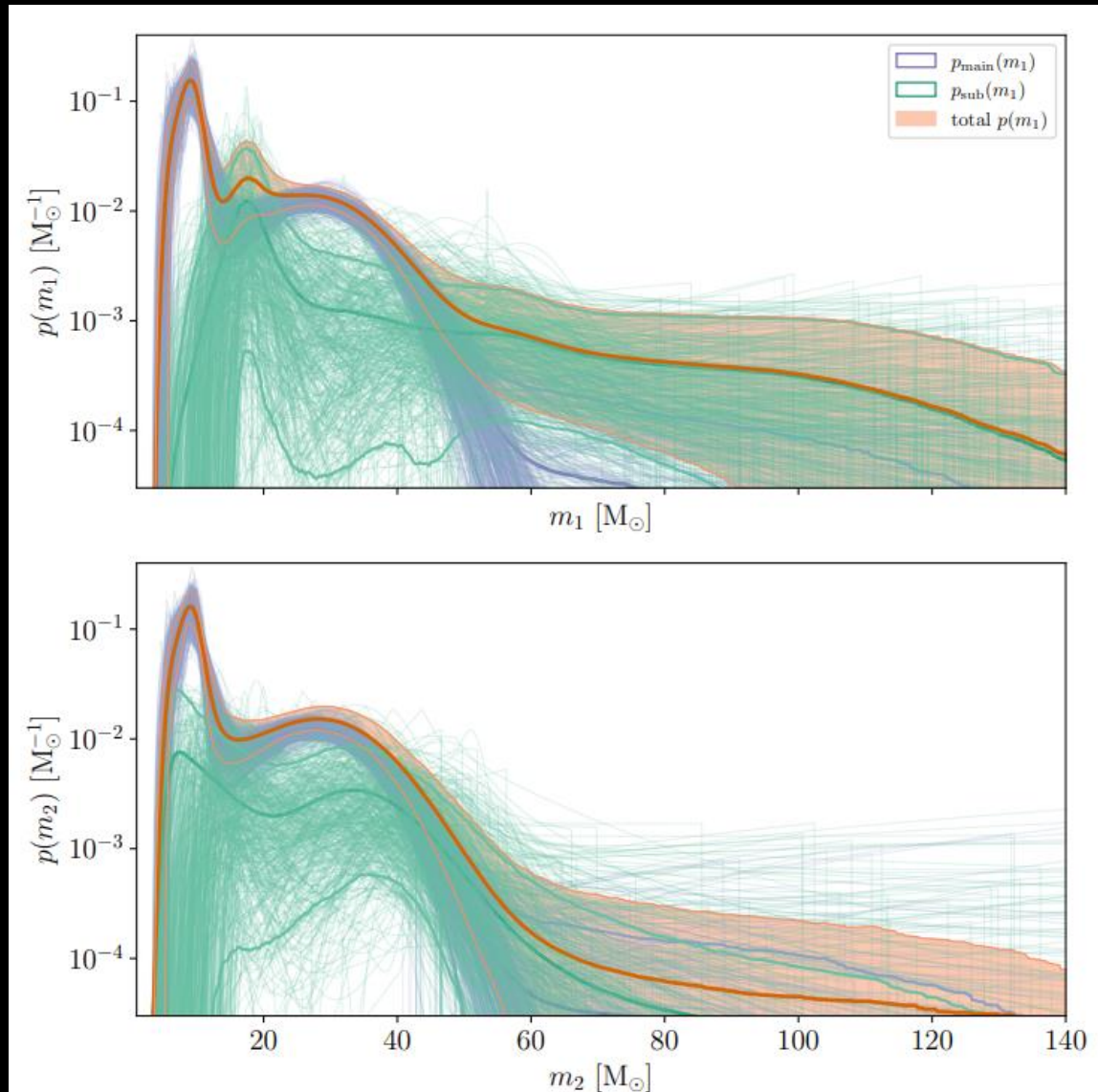
Website: [adivijaykumar.github.io](https://adivijaykumar.github.io)

Email: [aditya@utoronto.ca](mailto:aditya@utoronto.ca)

# Extra Slides

# The mass distribution of hierarchical mergers

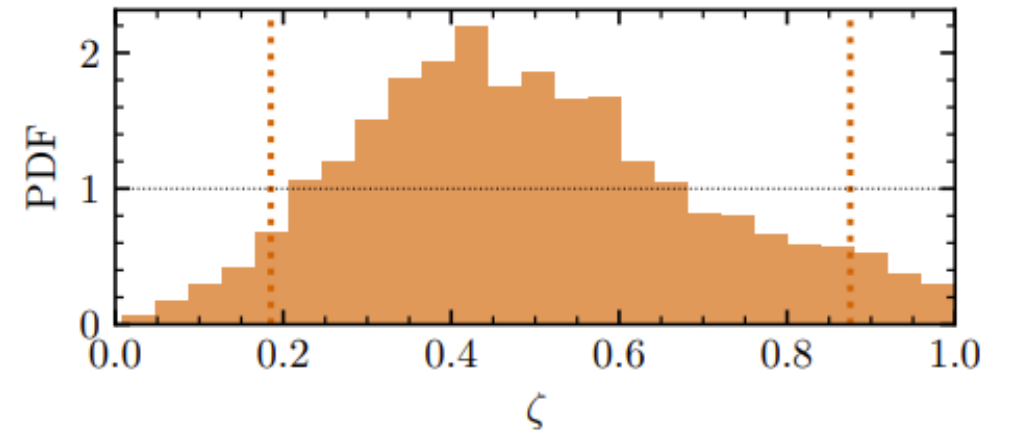
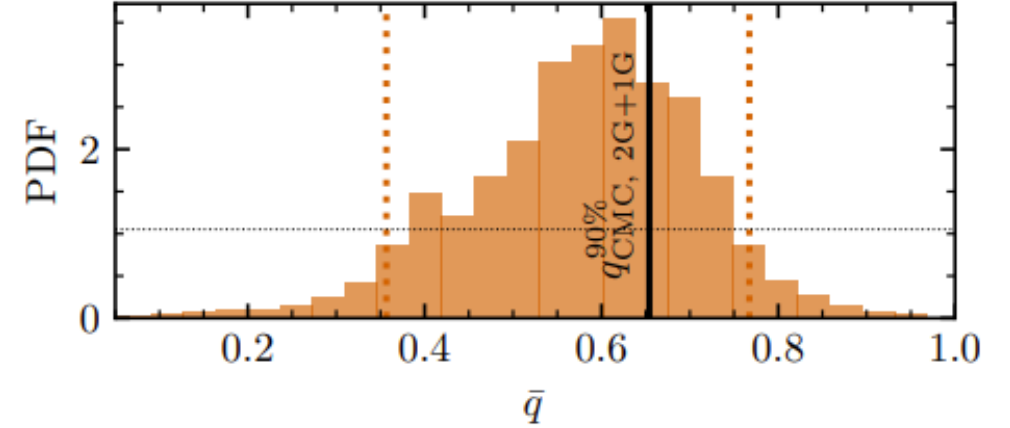
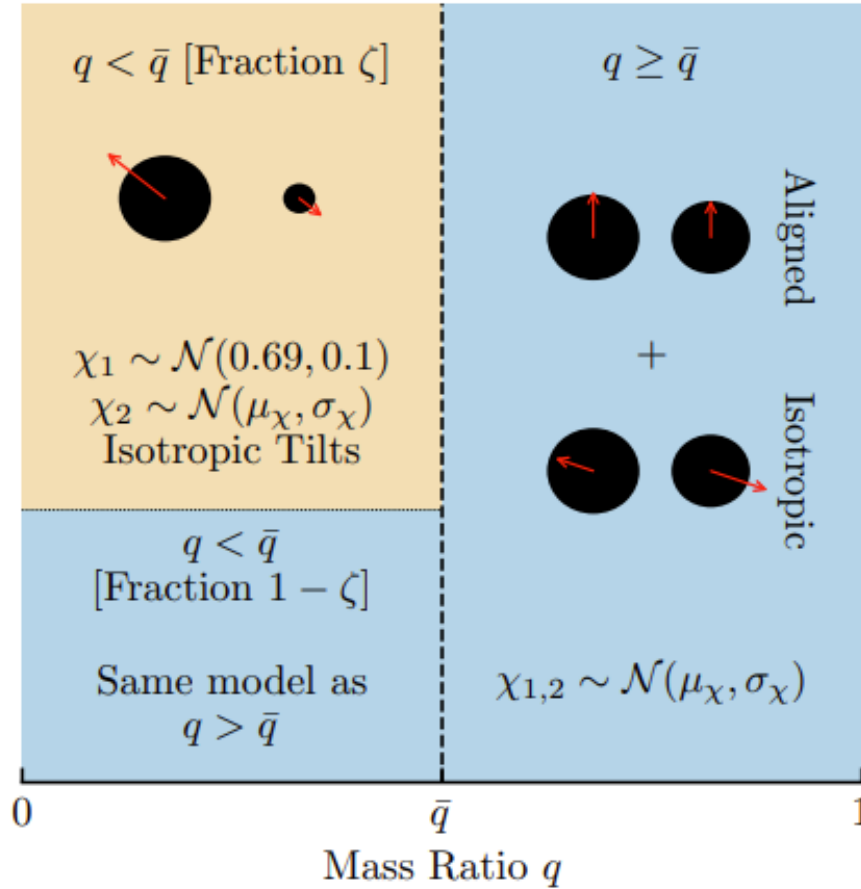
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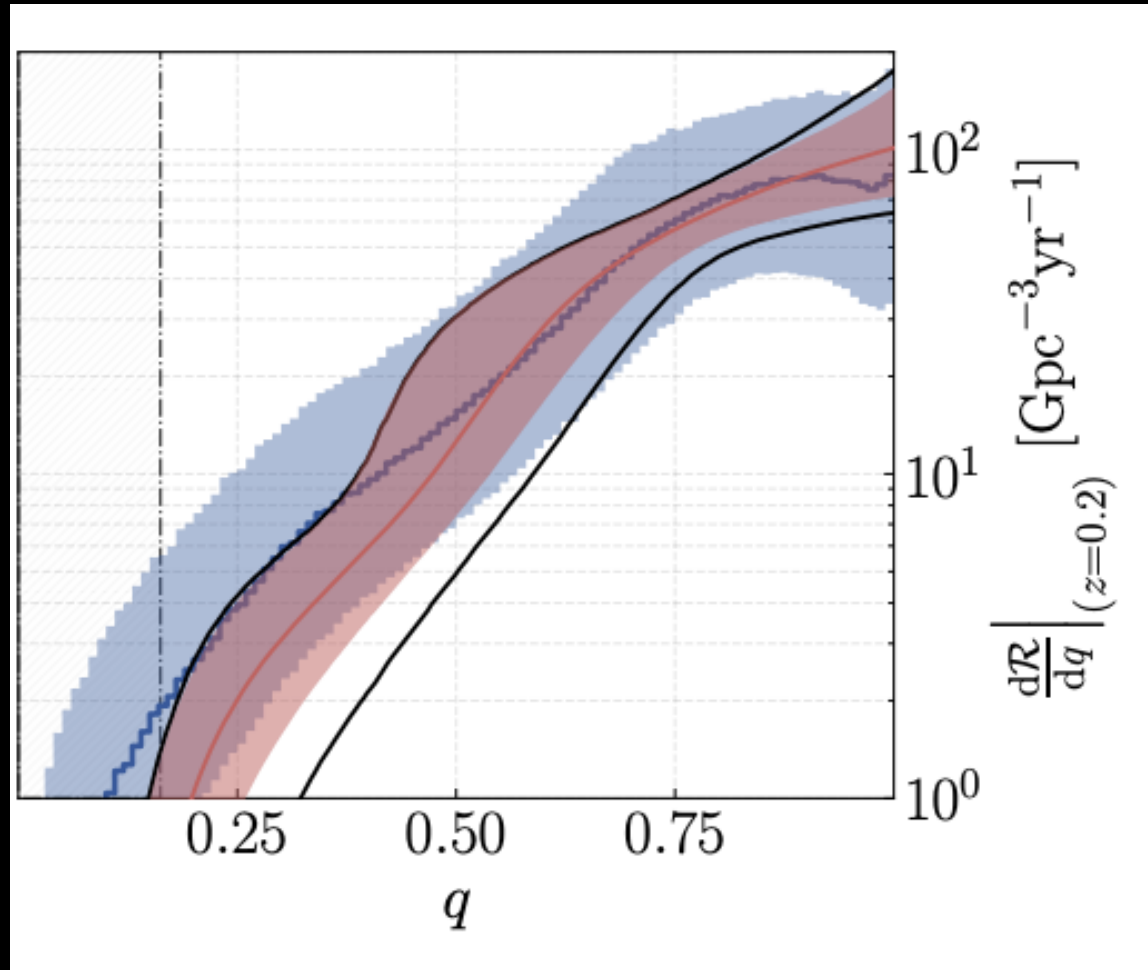
The hierarchical merger subpopulation extends to higher primary masses, and peaks at roughly twice the mass.

# Model

Vijaykumar, Farah,  
Fishbach 2026, ApJL  
arXiv:2601.03457



# Model



# GWTC-5.0 Population Results

