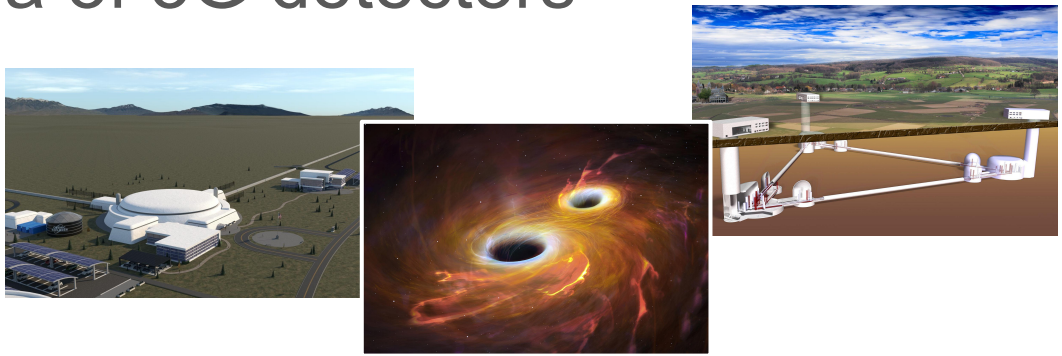
Astrophysical Populations

in the era of 3G detectors



Chairs: Vicky Kalogera, Michela Mapelli

Panel: Martyna Chruslinska, Maya Fishbach, Tassos Fragos, Carl Rodriguez

VIII PAX Meeting, MIT, Boston, August 1 – 3, 2022

1) Number of events with 3G detectors and small-scale features in the populations

What do we really need to disentangle the formation channels of BBHs?

What can we learn from the full 6D spin distribution of BBHs?

Is there a sub-population of black holes with spins < 0.01?

Is there a pair-instability gap? Does it have sharp features?

Can ~10^6 GW events constrain all model parameters of current models?

MASS and SPINS

2) Improved sensitivity at low frequencies and IMBHs

How do IMBH/SMBHs form in the early Universe?

Importance of hierarchical merger scenario?

Is there a distinct population of Pop-III BHs and what are their properties?

IMBHs

3) Extended redshift reach of 3G detectors

How do compact object populations evolve with redshift?

Is the formation efficiency of double compact objects a function of metallicity?

How fast is the early cosmic enrichment?

What is the contribution of faint galaxies to the cosmic star formation?

REDSHIFT

Populations of Merging Compact Objects: Lessons Learned and Open Questions

Maya Fishbach
CIERA/ Northwestern University

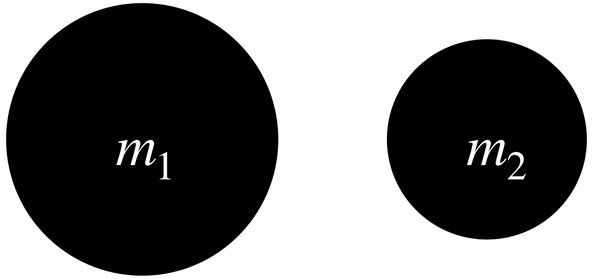
PAX VIII @ MIT
August 2 2022

Northwestern
CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

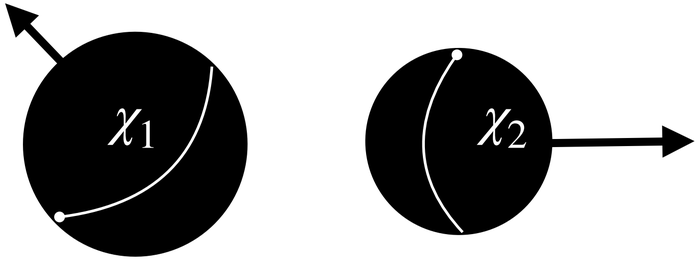
NHFP
NASA Hubble Fellowship Program

Observing Binary Compact Objects

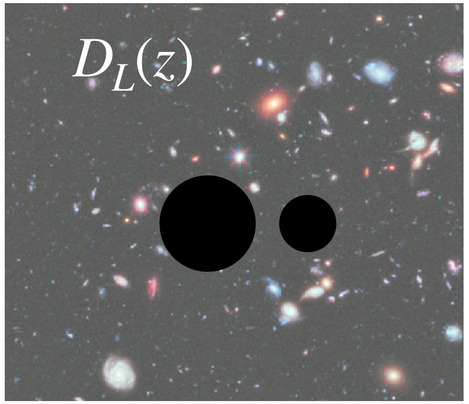
How *big* is each black hole or neutron star?



How fast are they *spinning*? Where are the spin axes pointing?



***Where* and *when* did they merge?**

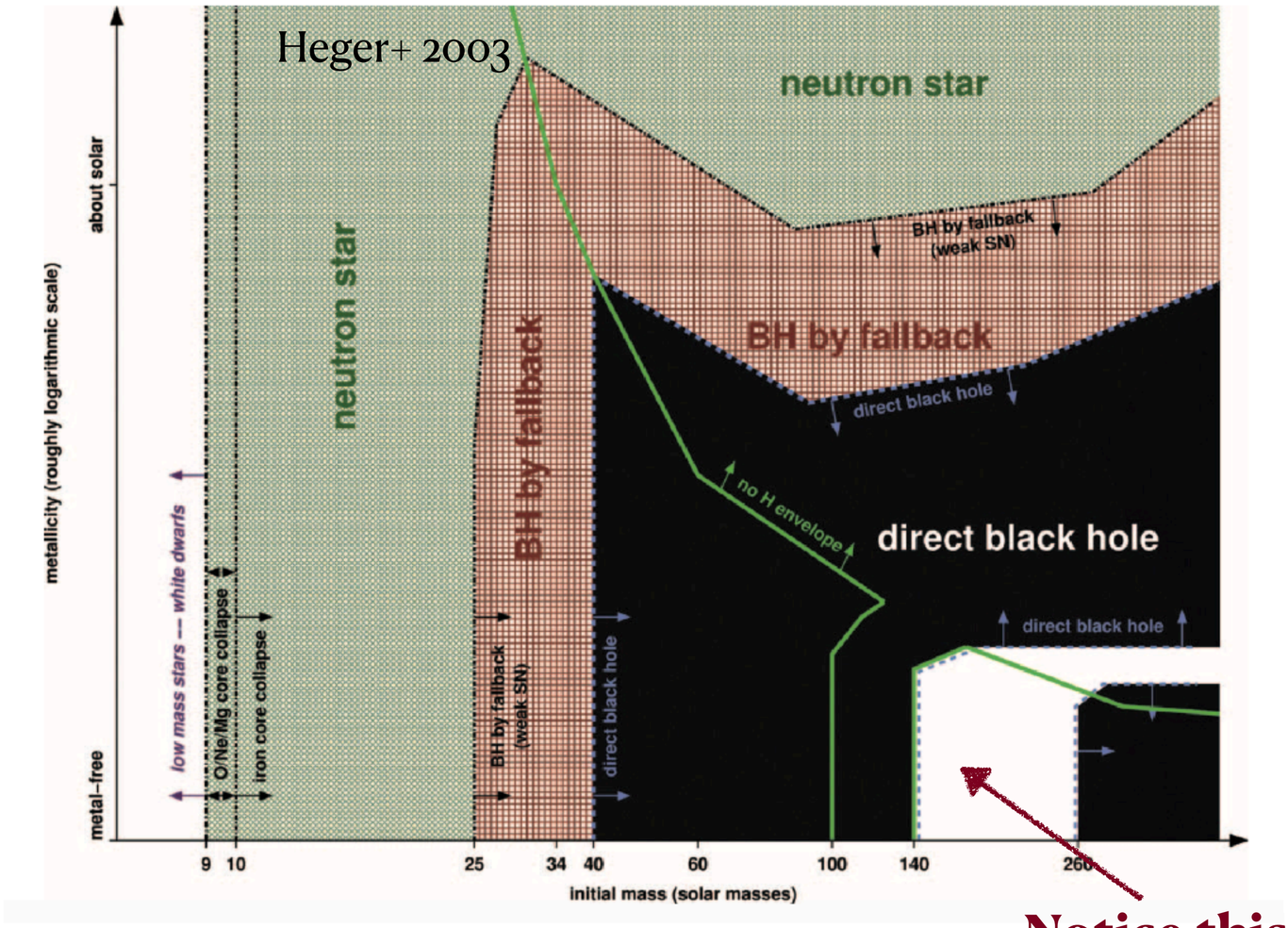


How are these systems made?

How are black holes and neutron stars made?

Compact object remnants of massive stars (or products of a previous merger)

Initial metallicity (abundance of elements heavier than helium)



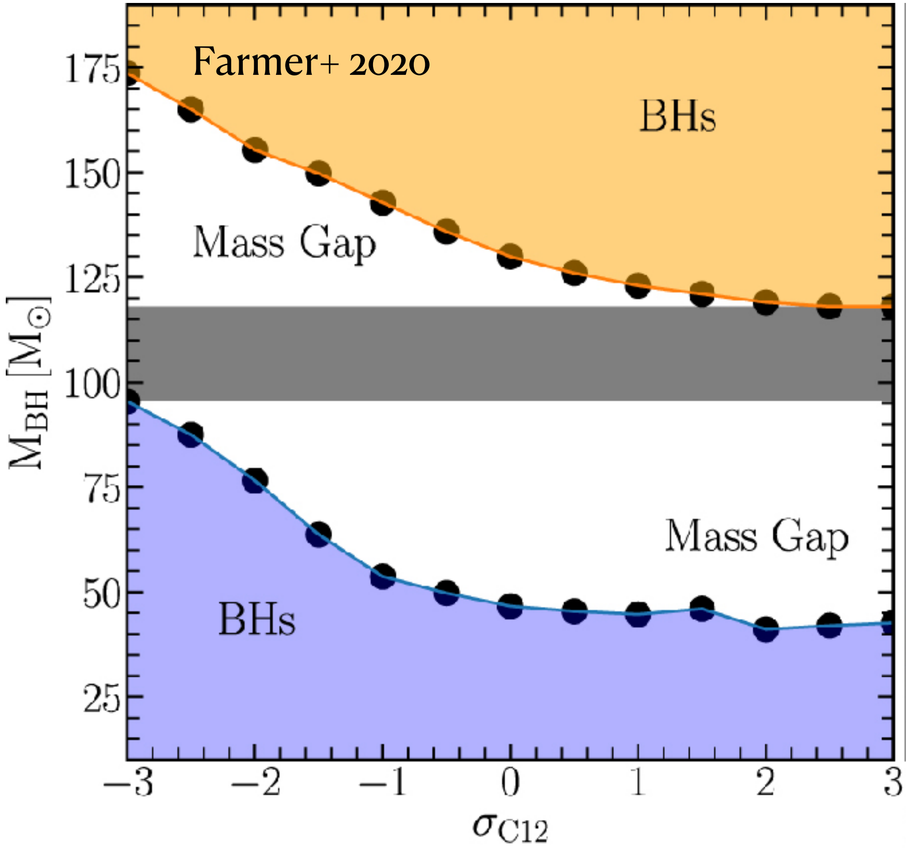
Initial mass of star

Notice this gap!

Note: this diagram is for evolution of *single* stars

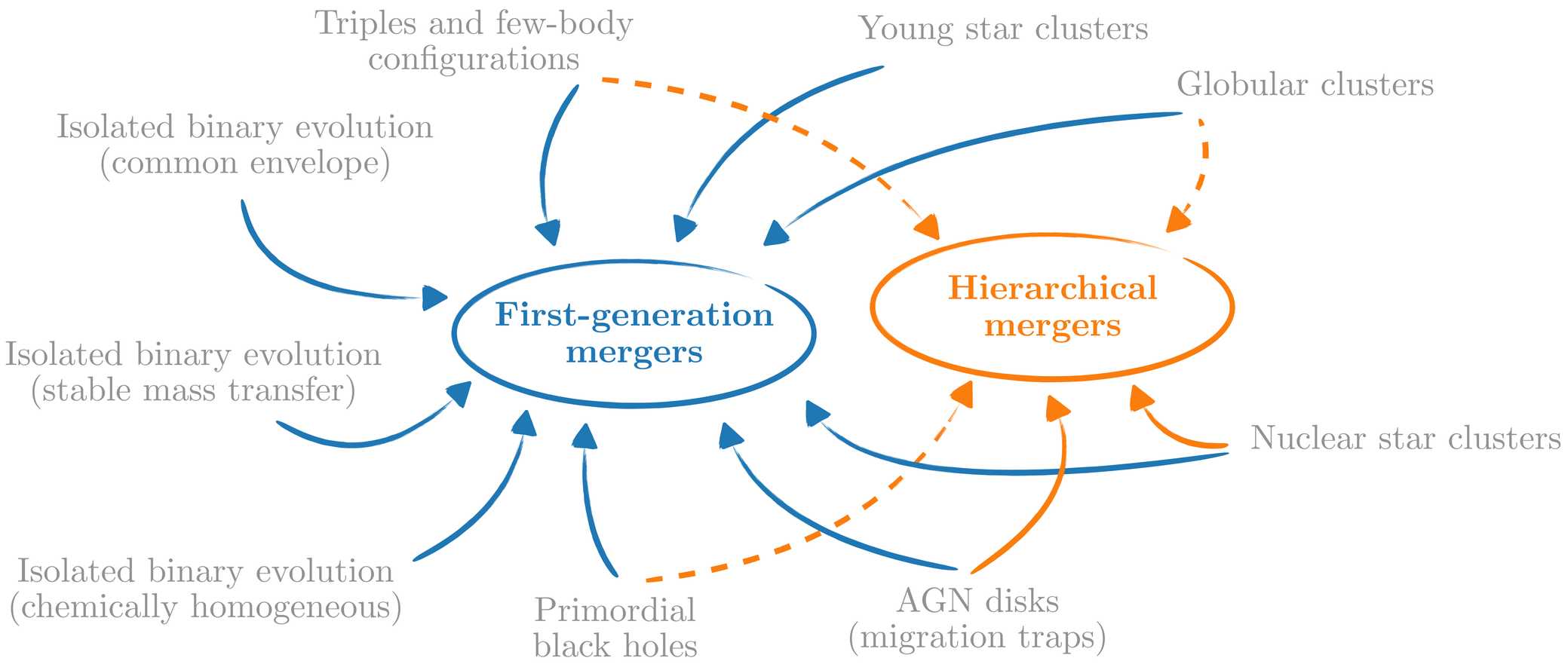
Pair-instability black hole mass gap

- (Pulsational) pair-instability supernovae predict an absence of black holes in the range $\sim 40 - 120\, M_\odot$
- Uncertainties in theorized gap location due to: nuclear reaction rates, stellar structure, accretion, possible beyond-standard model physics
- Black holes that are not formed directly from stars— for example, products of a previous merger — may populate the gap



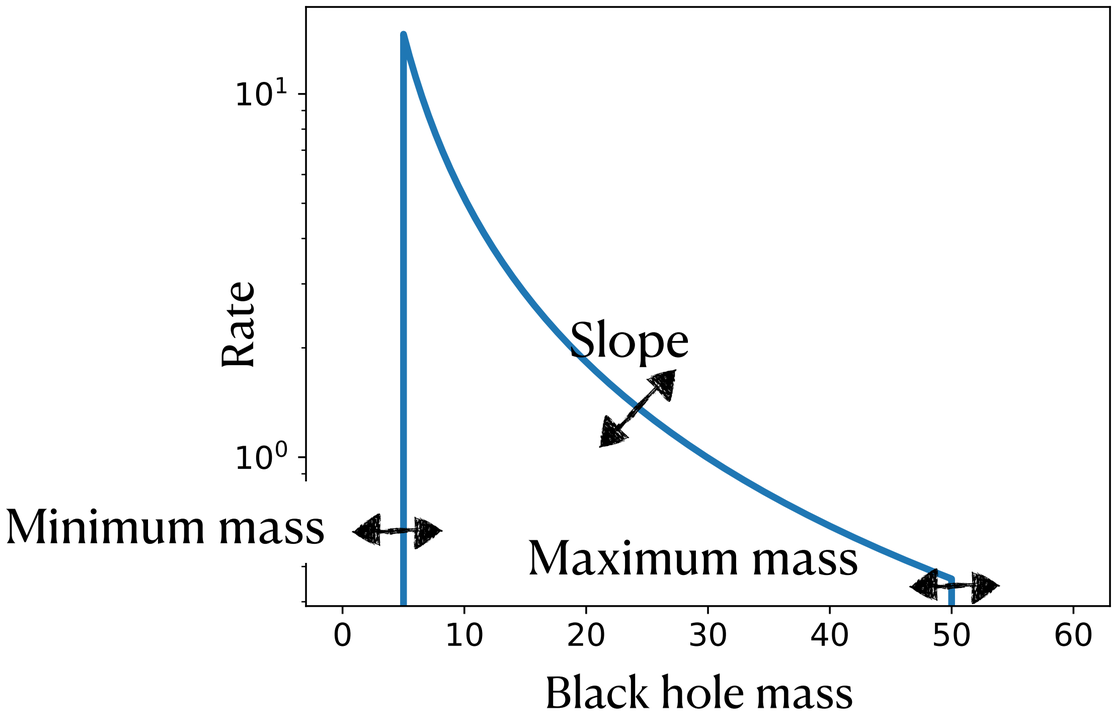
Standard deviations from the median $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

How are *binary* black holes and neutron stars made?



From Single Events to a Population

- Introduce a population model and corresponding **hyper-parameters** that describes the **distributions** of masses, spins, redshifts across multiple events
- Example 1: Fit a **power law** to black hole masses. Hyper-parameters: power-law slope, minimum black hole mass, maximum black hole mass.
- Example 2: Predict black hole population for a suite of **population synthesis simulations**. Hyper-parameters: mass transfer prescriptions, star cluster properties...
- Take into account measurement uncertainty and selection effects



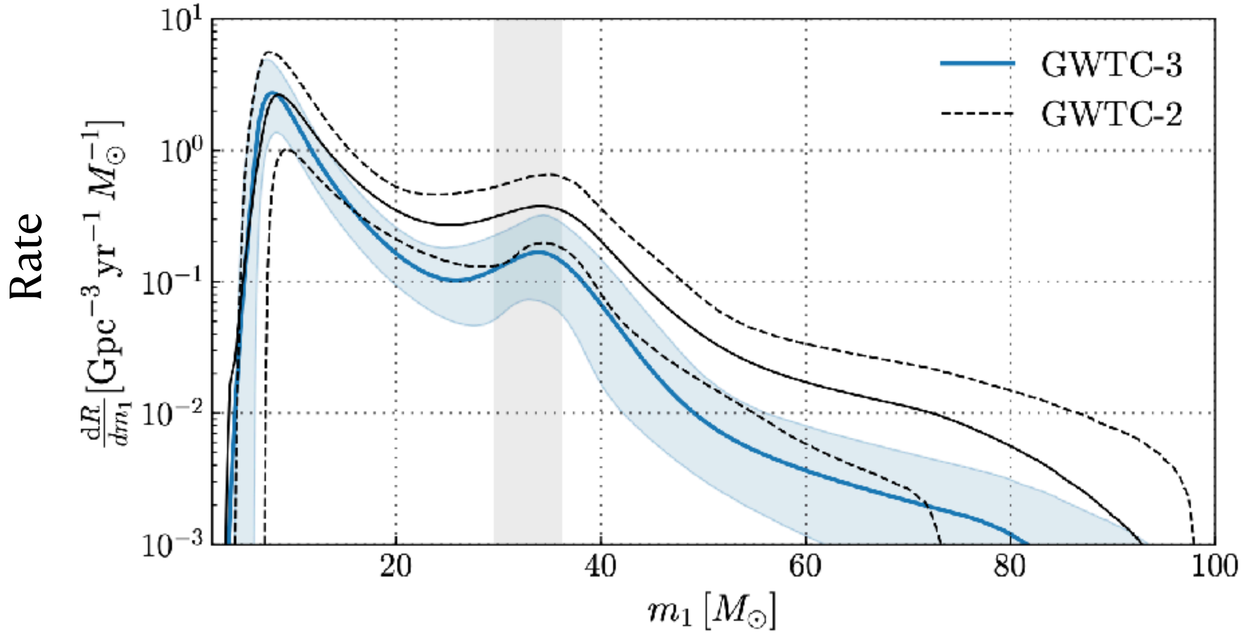
What do we already know about the population of merging black holes and neutron stars? (a small sampling)

There are some, but not many, black holes with masses above 40 solar masses (only ~1% of the population)

Are these big black holes inside the mass gap? (Hierarchical merger products, primordial black holes?)

Is the lower edge of the gap represented by a gradual tapering-off, rather than a sharp cutoff? (Fallback of the hydrogen envelope, accretion, remnants of stellar mergers?)

Does the mass gap start at higher core masses than previously thought? (Different nuclear reaction rates?)



Primary mass in solar masses

LVK 2021 ApJL 913 L7 (GWTC -2)
LVK arXiv:2111.03634 (GWTC-3)

Effective inspiral spin $\chi_{\rm eff}$

- Effective inspiral spin $\chi_{\rm eff}$ measures the mass-weighted spin along the orbital angular momentum axis

$$\chi_{\rm eff} = \frac{m_1\chi_1 cos\theta_1 + m_2\chi_2 \cos\theta_2}{m1 + m2}$$

- If spins are never tilted by more than 90 degrees, $\chi_{\rm eff} > 0$ always (~field)
- If spin tilts are isotropic, $\chi_{\rm eff}$ symmetric about zero (~dynamics)
- If spin magnitudes are small, $\chi_{\rm eff}$ distribution sharply peaked about zero

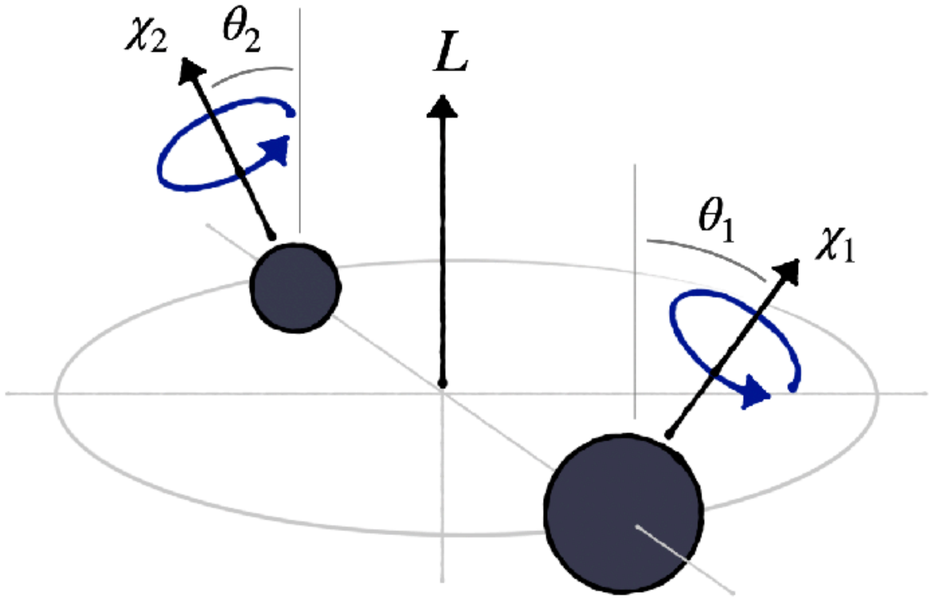
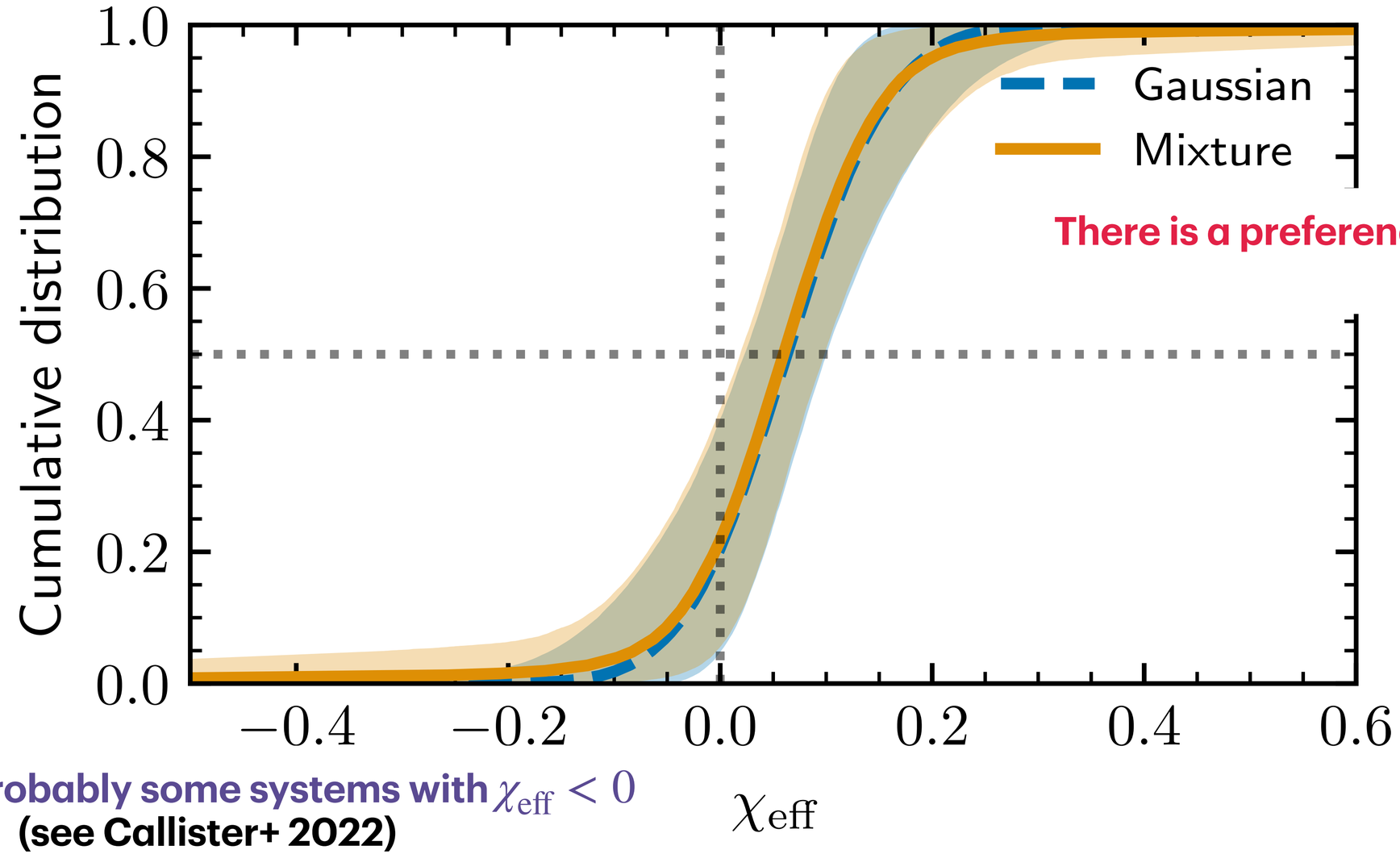


Figure credit: Thomas Callister

Black hole spin tilts are not random



There is a preference for $\chi_{\rm eff} > 0$

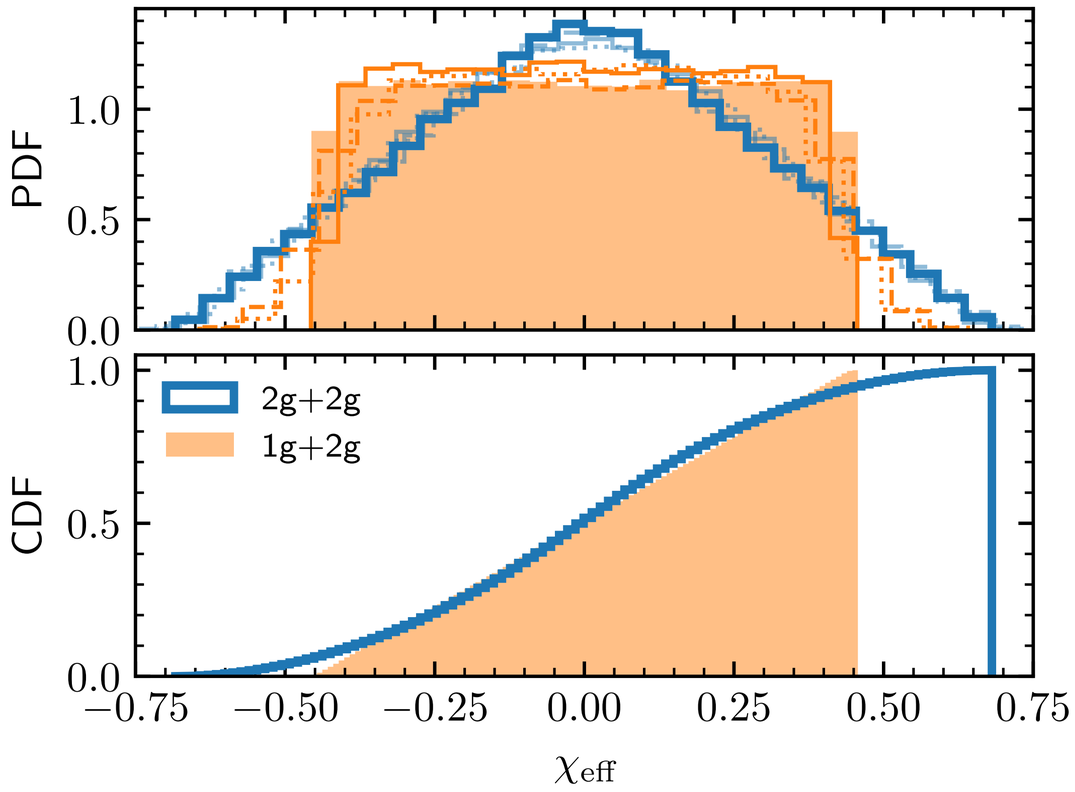
There are probably some systems with $\chi_{\rm eff} < 0$
(see Callister+ 2022)

Black holes in merging binaries tend to be slowly spinning

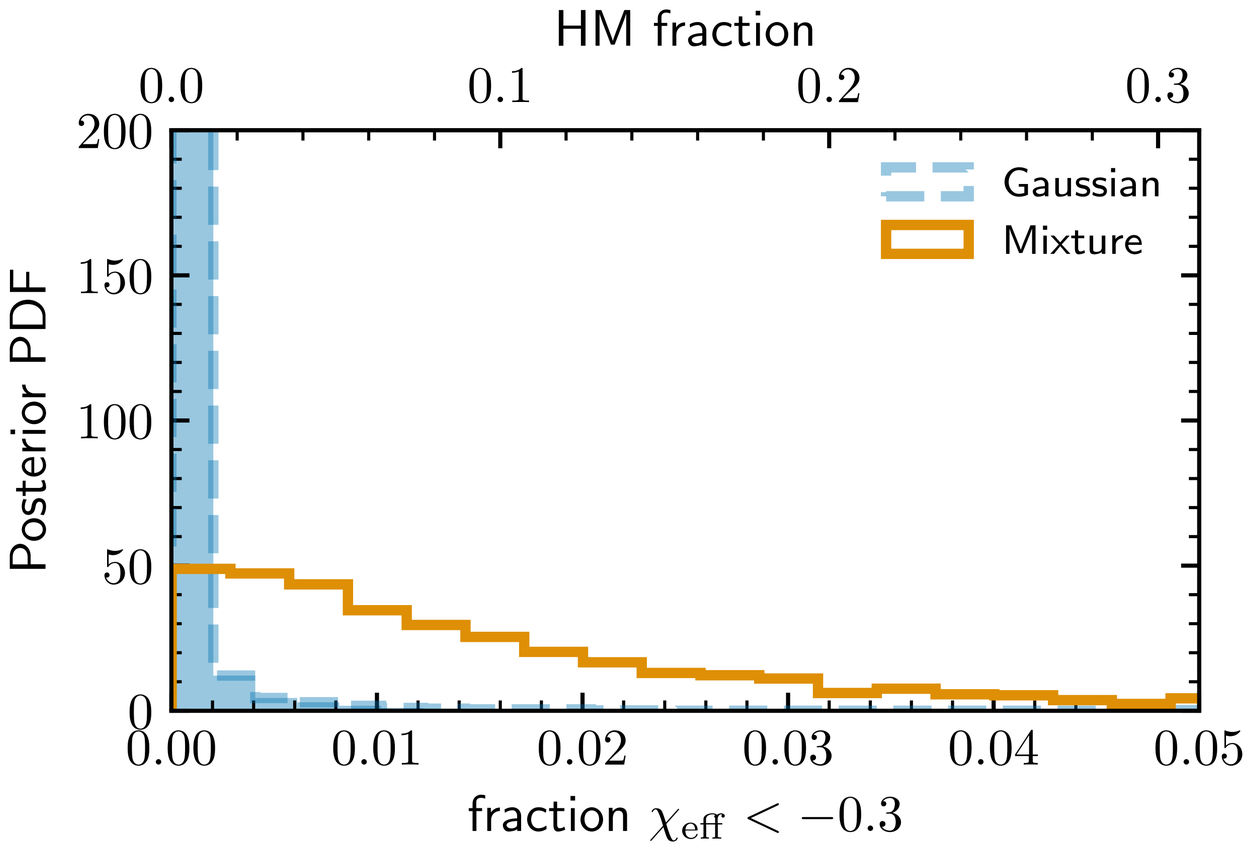
- Is there an **excess of non-spinning** systems? (See Roulet+ 2021, Galaudage+ 2021, Callister+ 2022)
- Why are these black hole spins so much smaller than spins observed in **high-mass X-ray binaries**? (See Gallegos-Garcia+ 2022)
- Absence of large, misaligned spins limits contribution from **hierarchical mergers**

Black holes in merging binaries tend to be slowly spinning

- Absence of large, misaligned spins limits contribution from **hierarchical mergers**

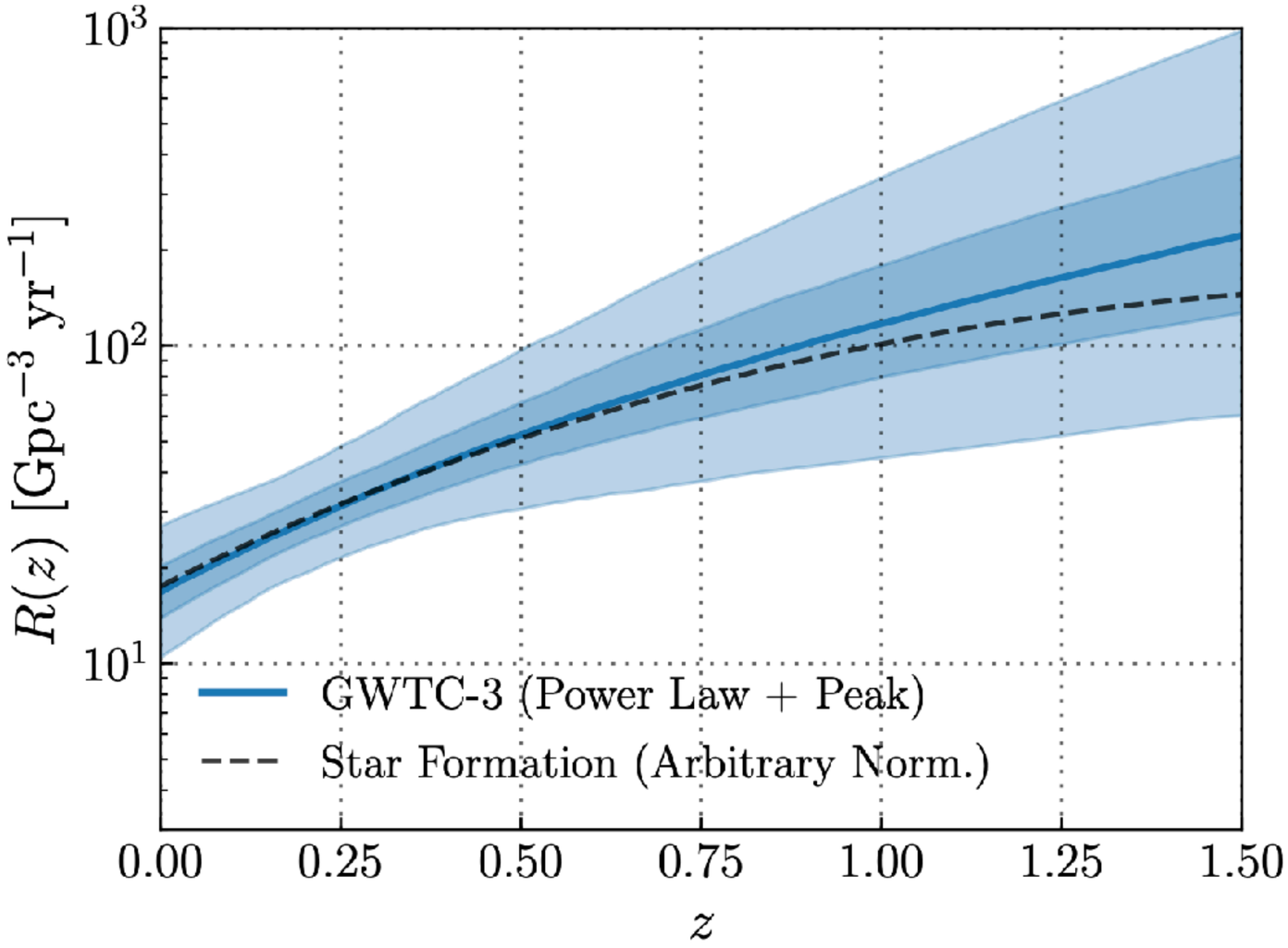


Predicted $\chi_{\rm eff}$ distribution for hierarchical mergers (see also Baibhav+ 2020)



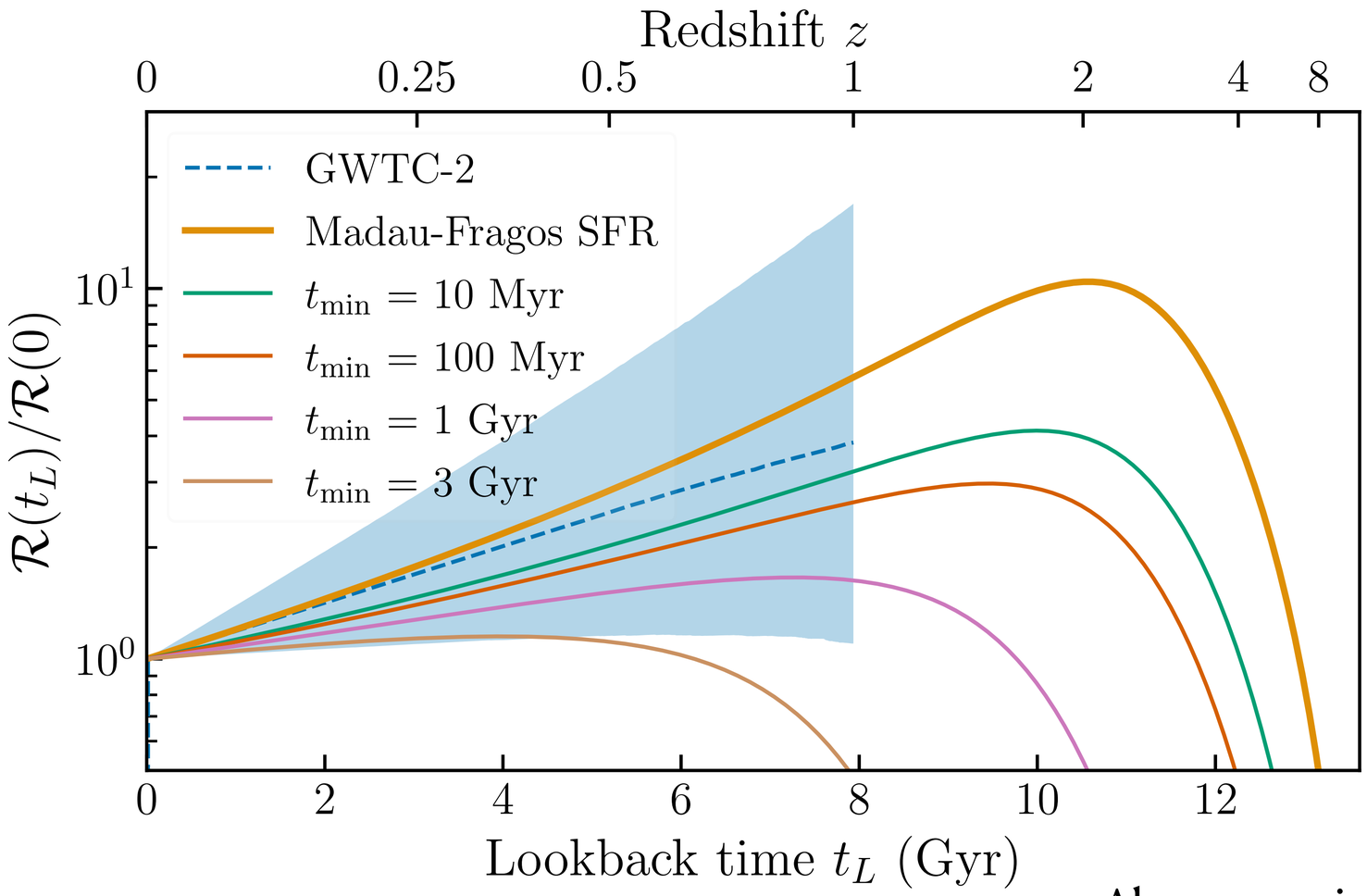
Observed limits on large misaligned spins and corresponding limit in hierarchical merger contribution

Black hole merger rate evolves with redshift



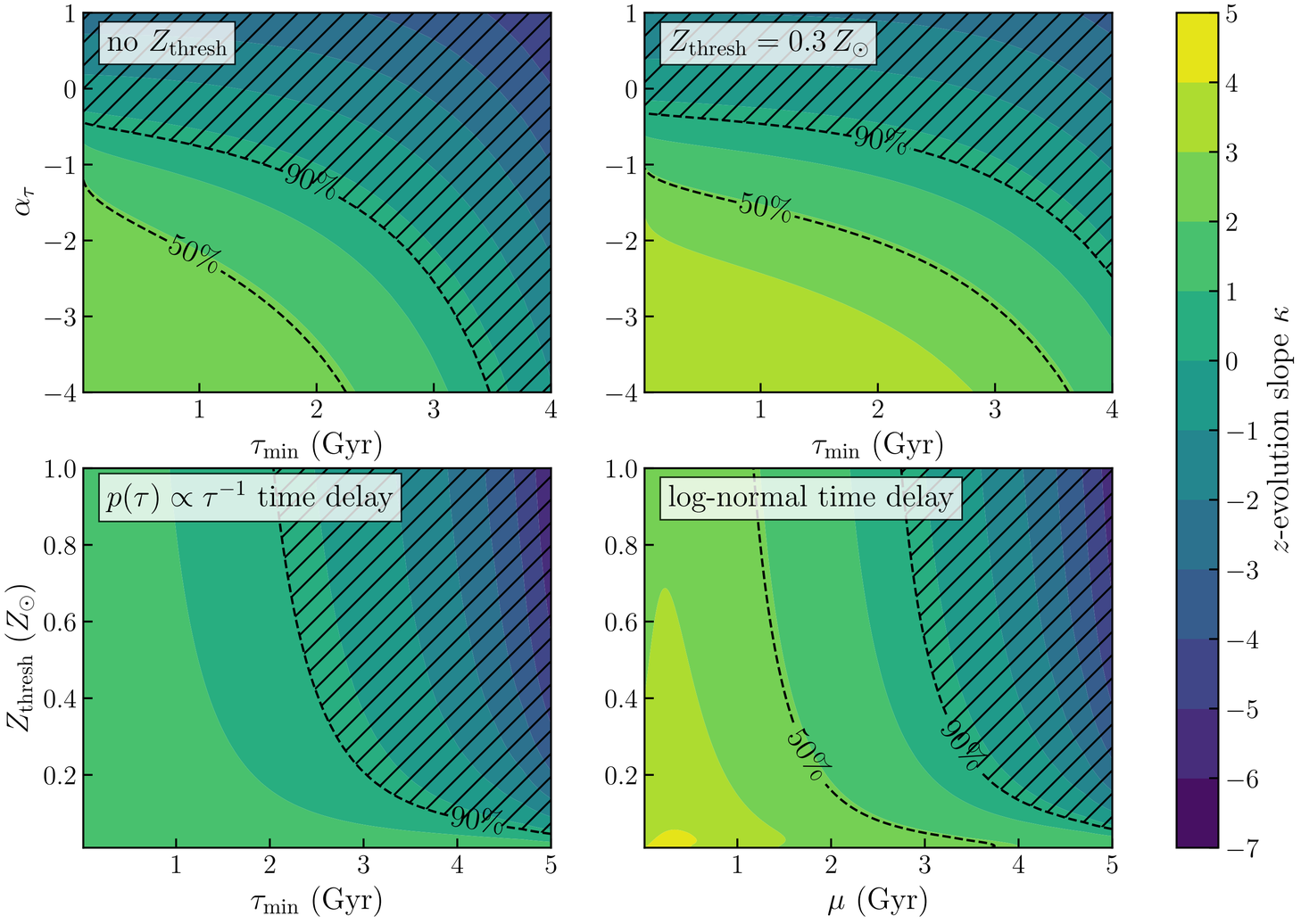
LVK arXiv:2111.03634

Merger rate evolution traces (low-metallicity) star formation rate with delay time



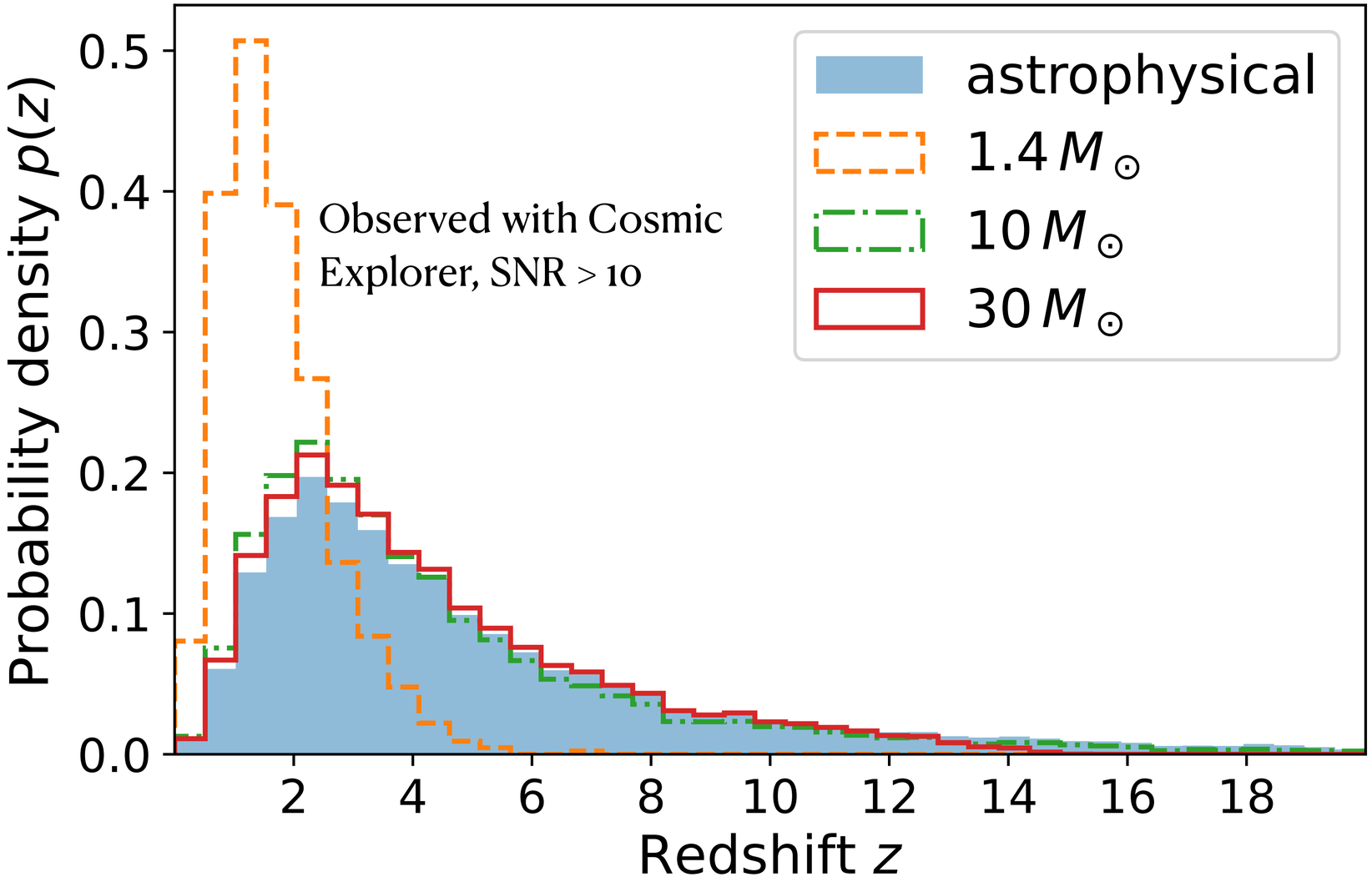
Also see review by Chruslinska 2022

We can start to infer the low-metallicity star-formation rate and time-delay distribution, but lots of degeneracies.

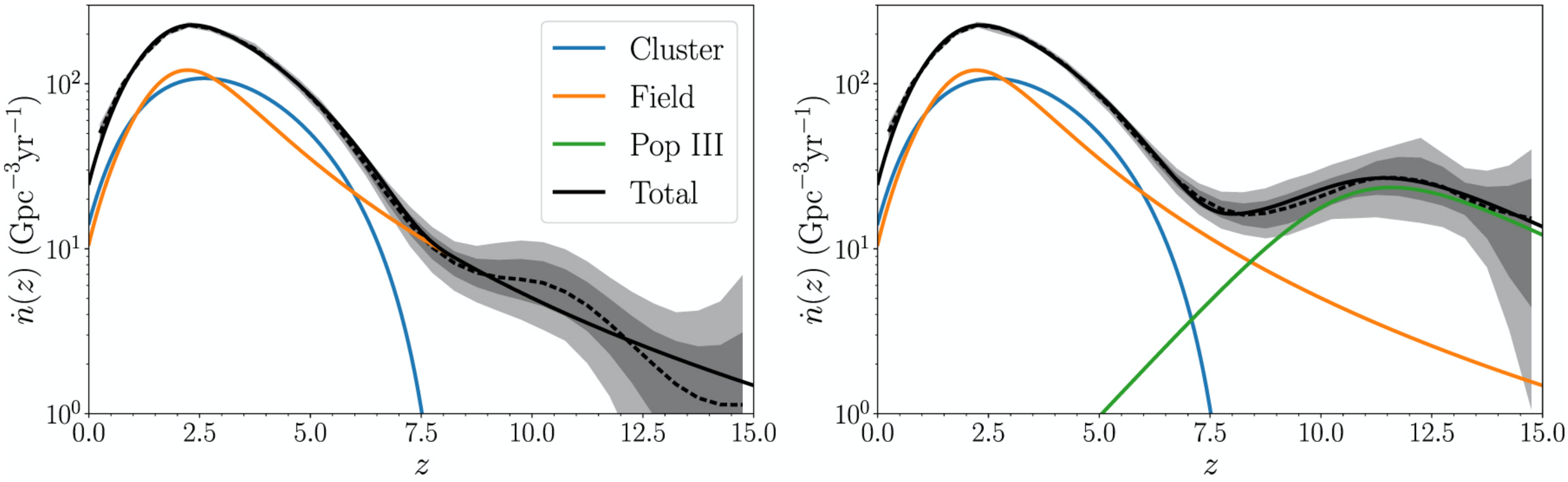


What can we still learn about the population of merging black holes and neutron stars? (a smaller sampling)

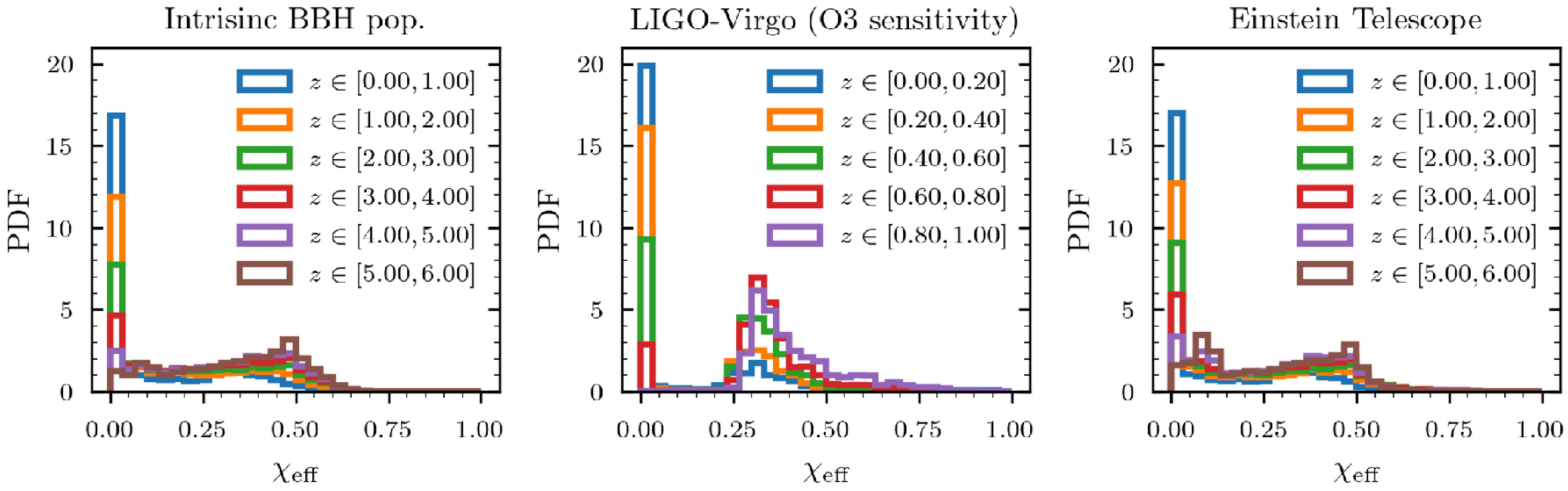
The high-redshift gravitational-wave Universe



Measure the merger rate across cosmic time, out to the very first mergers



Measure evolution in the spin distribution (and disentangle it from evolution in the mass distribution)



Populations of Merging Compact Objects

(Some) Lessons learned

- Black hole mergers produce black holes with masses > 100 solar masses
- There are features in the black hole mass distribution beyond a power law! Possibly related to supernova explosion mechanism?
- Black hole spin distribution supports a mix of formation channels
- The black hole merger rate increases with increasing redshift out to z ~ 1, with a slope that looks like the (total) star-formation rate

(Some) Open questions

- What are the most massive black holes produced by stellar collapse? How about hierarchical mergers?
- Are there sharp features in the mass and/or spin distribution?
- When did the first black holes merge in cosmic history?
- What does the high-redshift compact binary population look like?