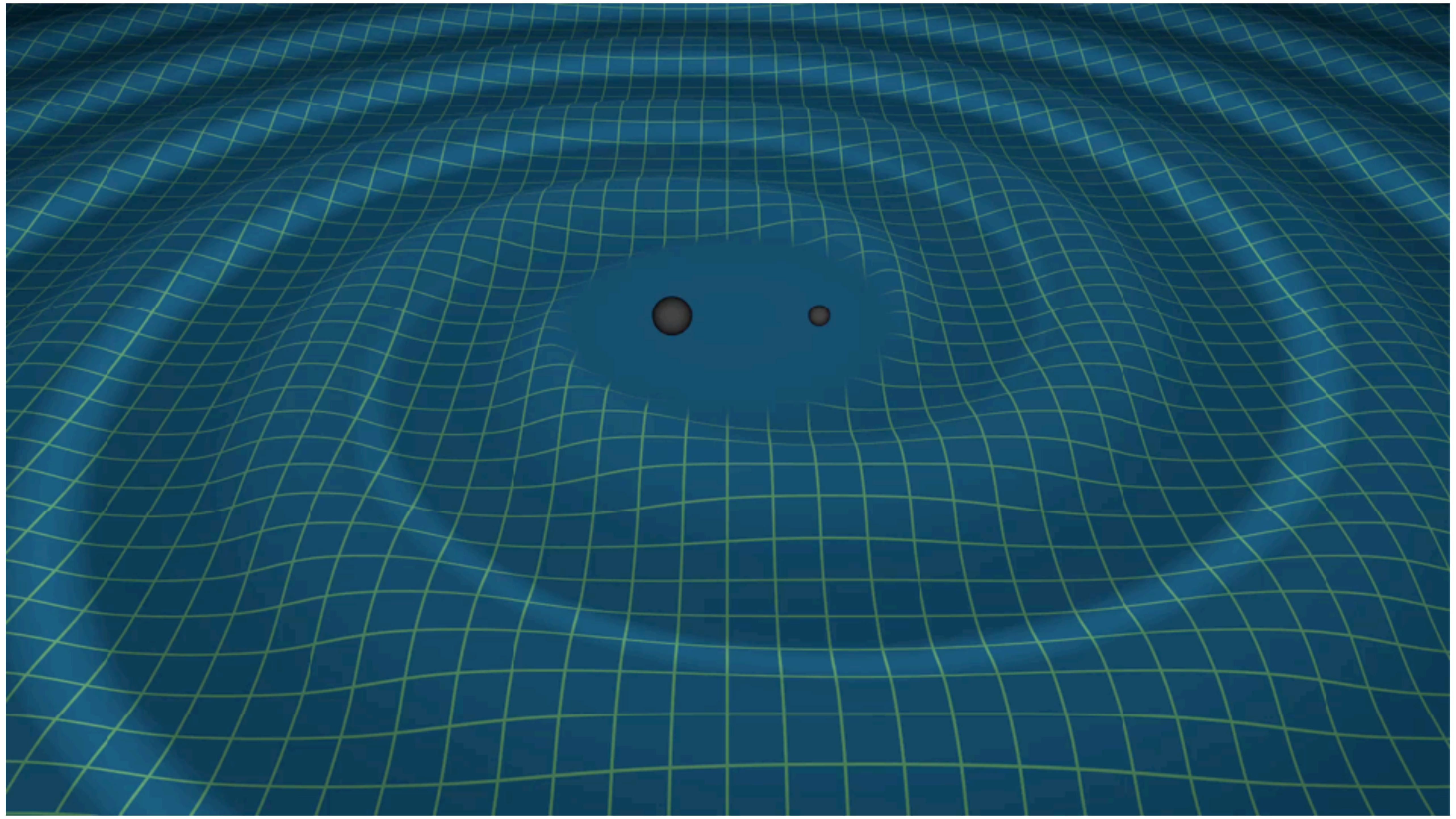
# Astrophysical Lessons from LIGO-Virgo-KAGRA's Black Holes

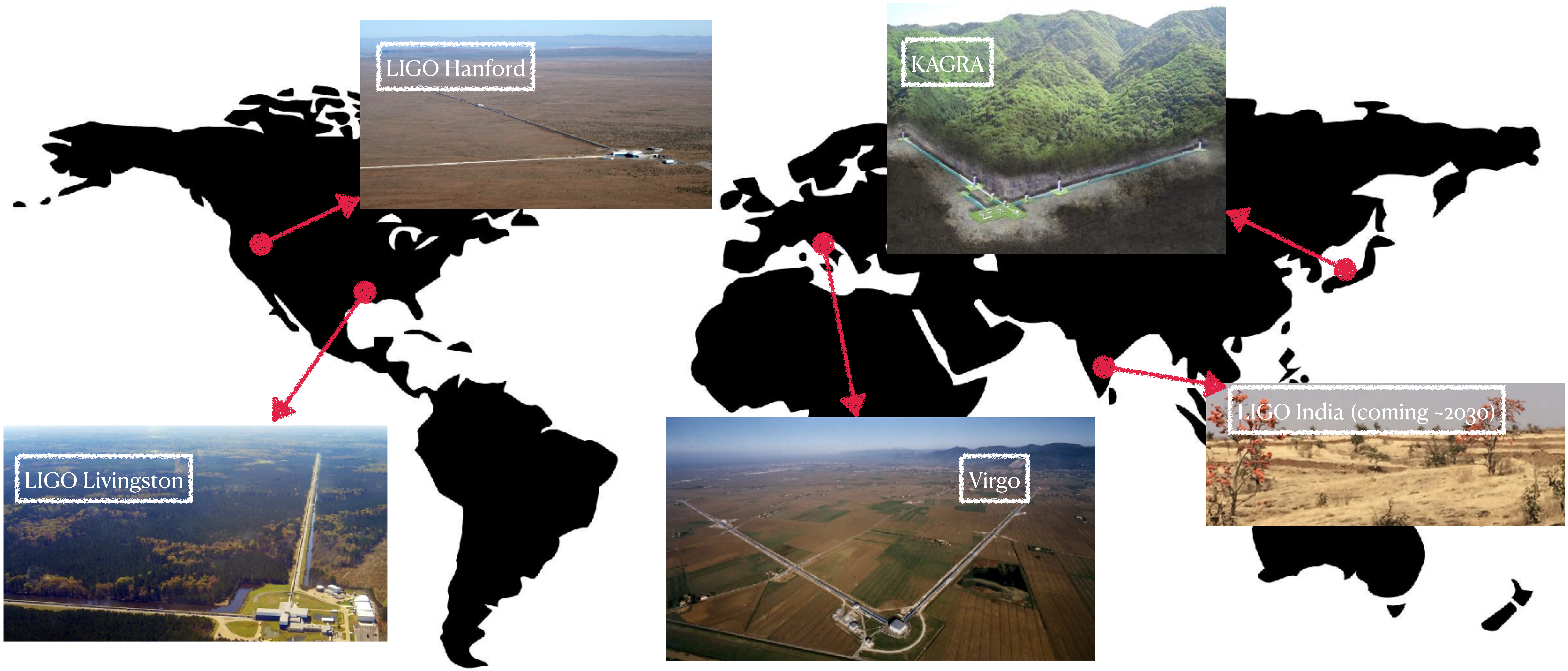



Maya Fishbach (she/her)
fishbach@cita.utoronto.ca

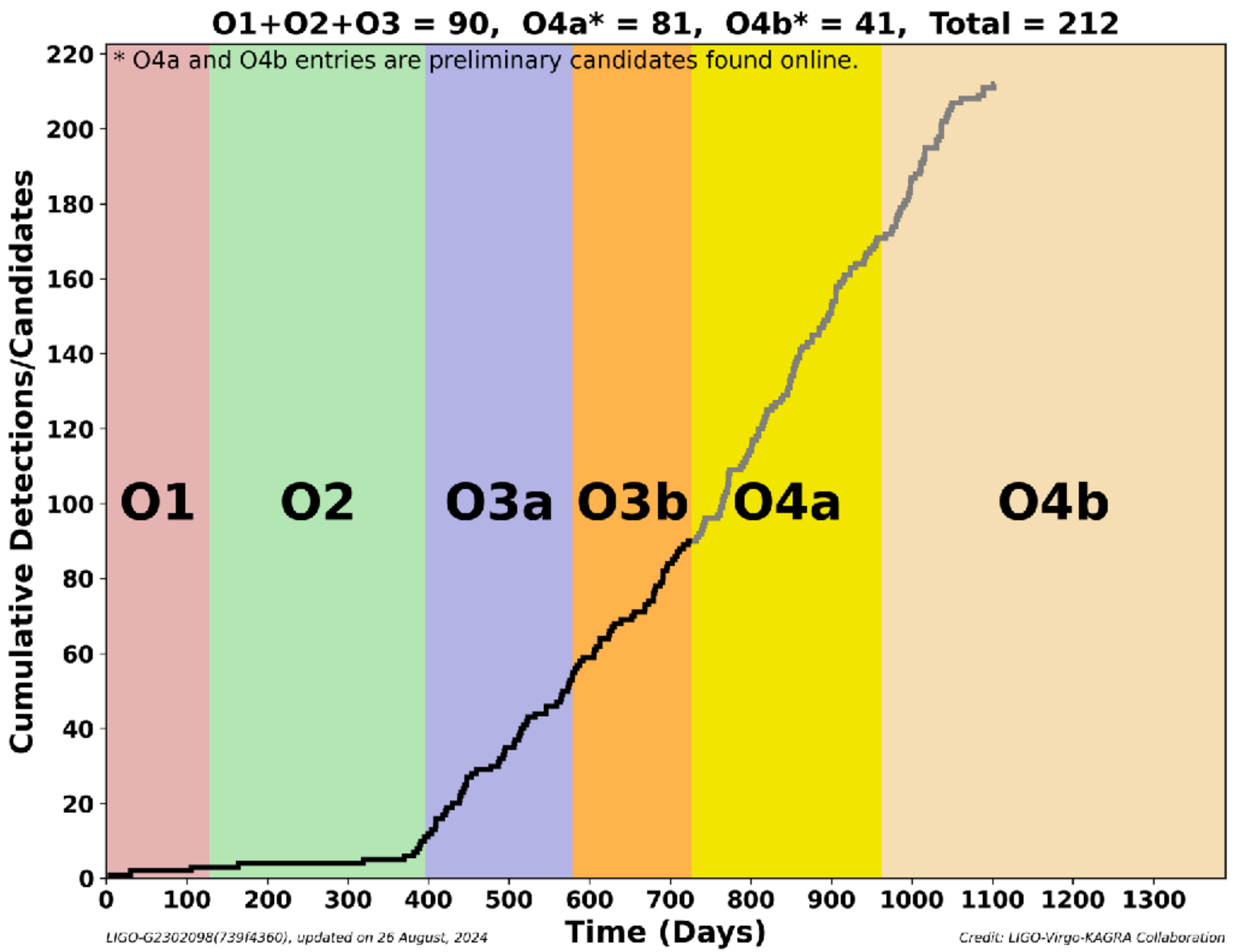

Pollica workshop: Fundamental Physics and Gravitational-Wave Detectors
September 9, 2024


CITA | ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique
UNIVERSITY OF TORONTO

# LIGO-Virgo-KAGRA Detectors



# Over 200 gravitational-wave observations!



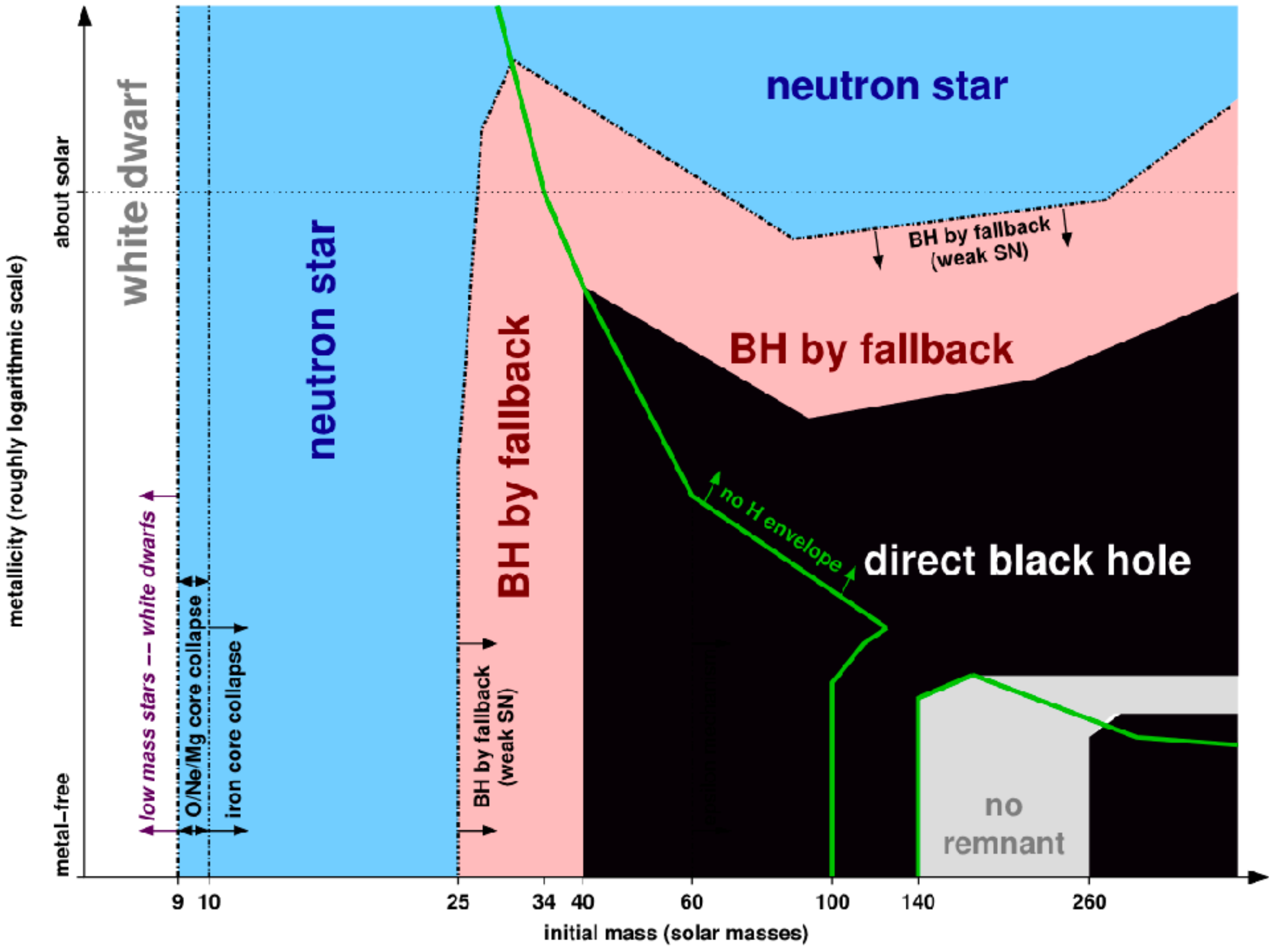
# Masses in the Stellar Graveyard


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

# How are black holes made?

## Compact object remnants of massive stars

Initial metallicity

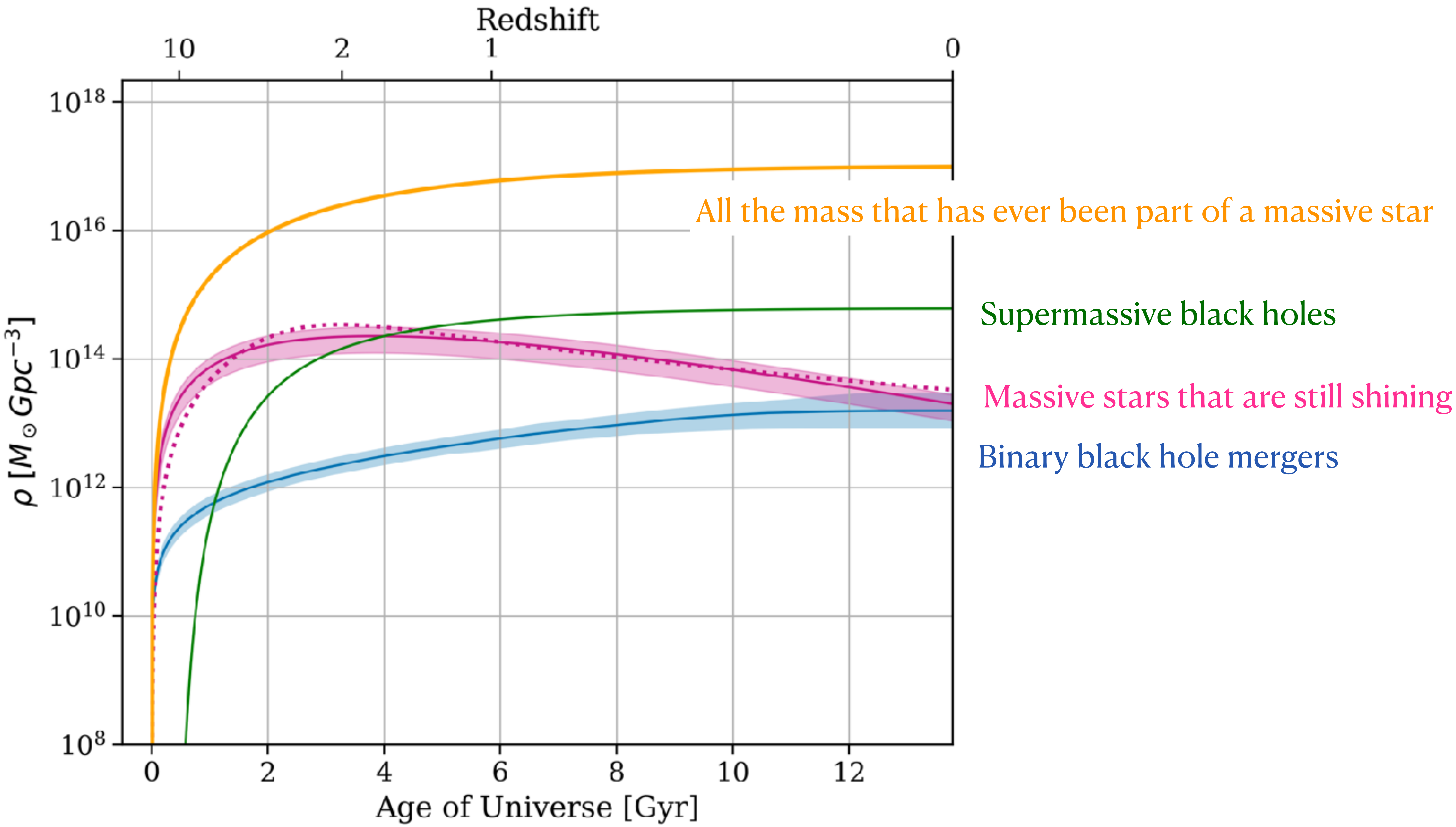



Initial mass of star

Heger, Müller & Mandel (2023)

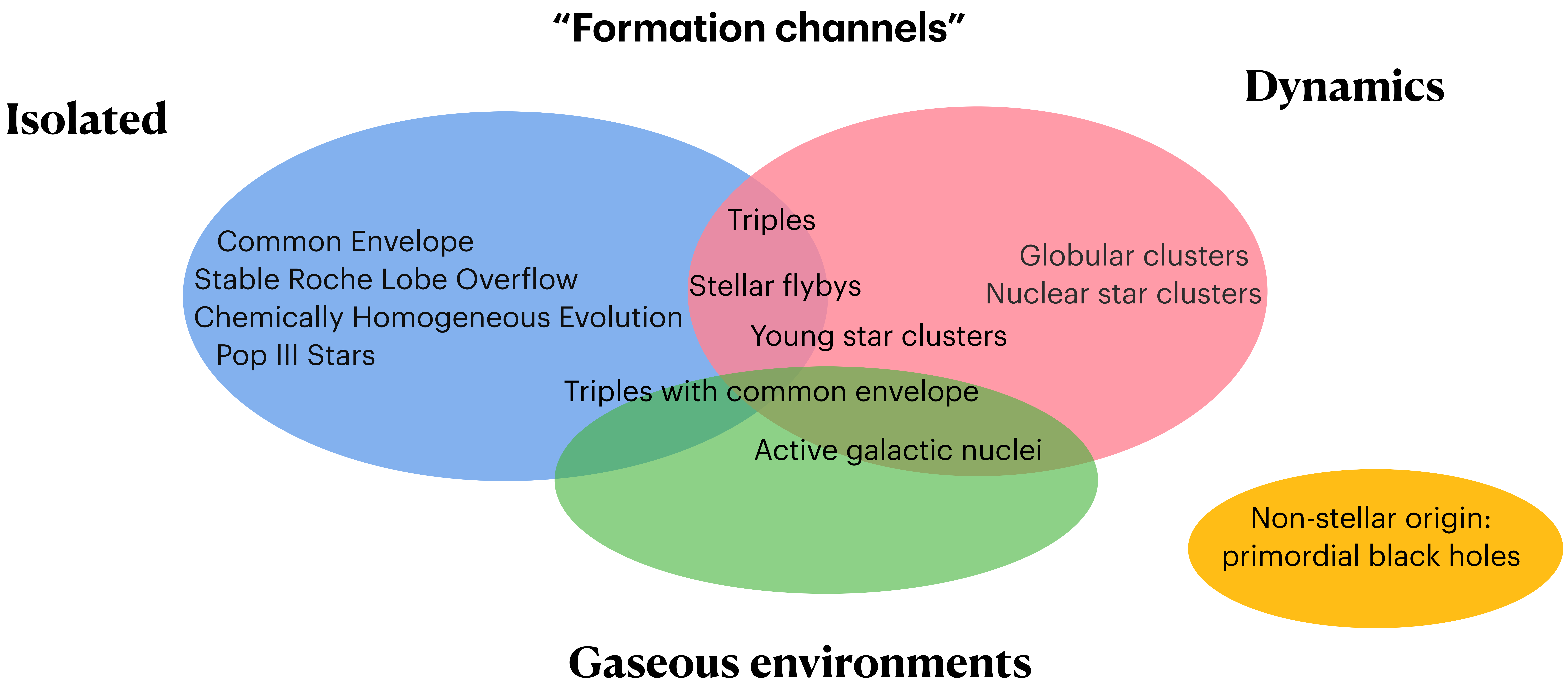
# Only 0.01% of massive stars (by mass) end up in binary black hole mergers

Cumulative mass density




Schiebelbein-Zwack & MF ApJ 970 128 (2024)

# How are *merging binary* black holes made?




Slide adapted from Mike Zevin adapted from Selma de Mink



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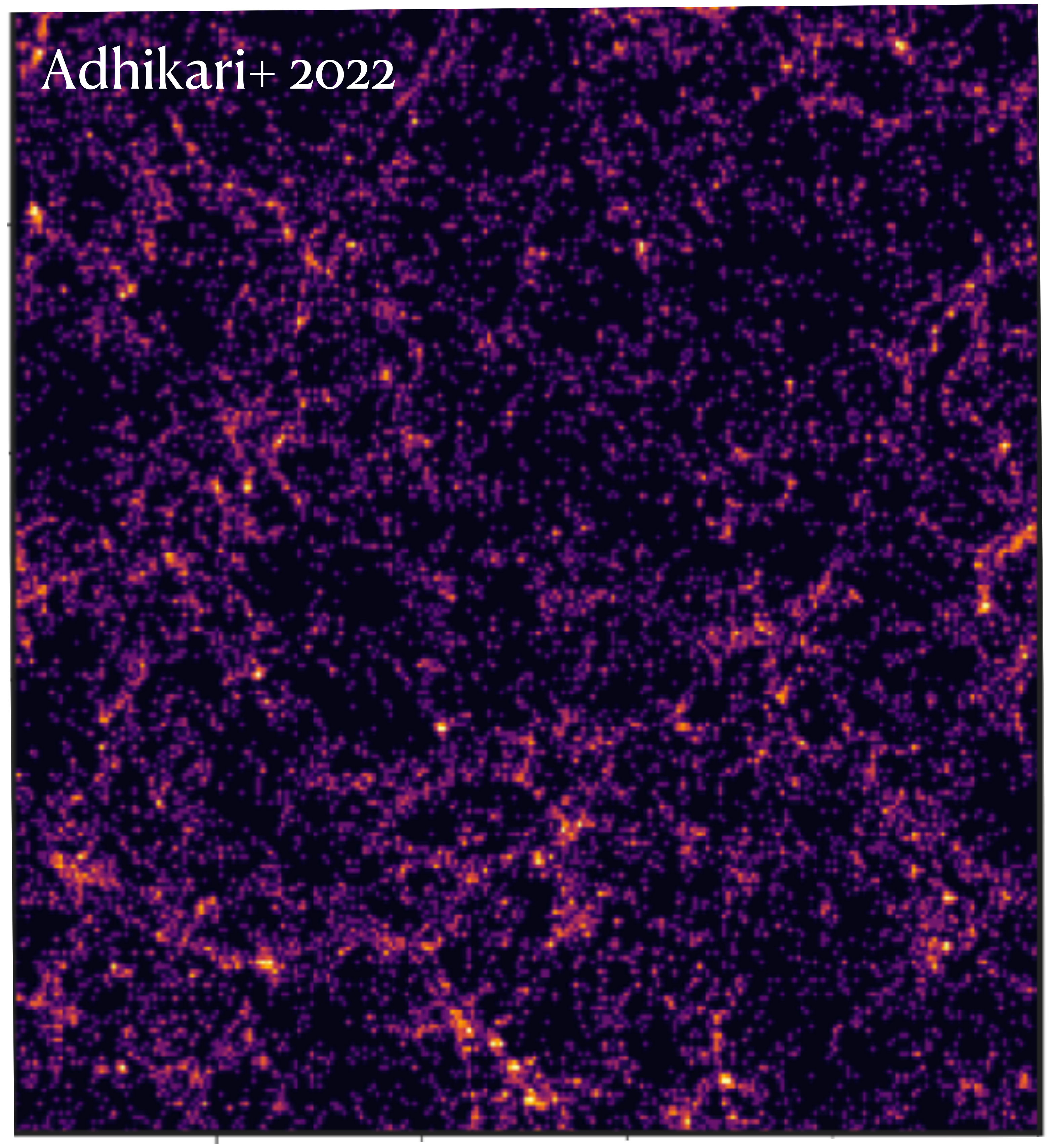
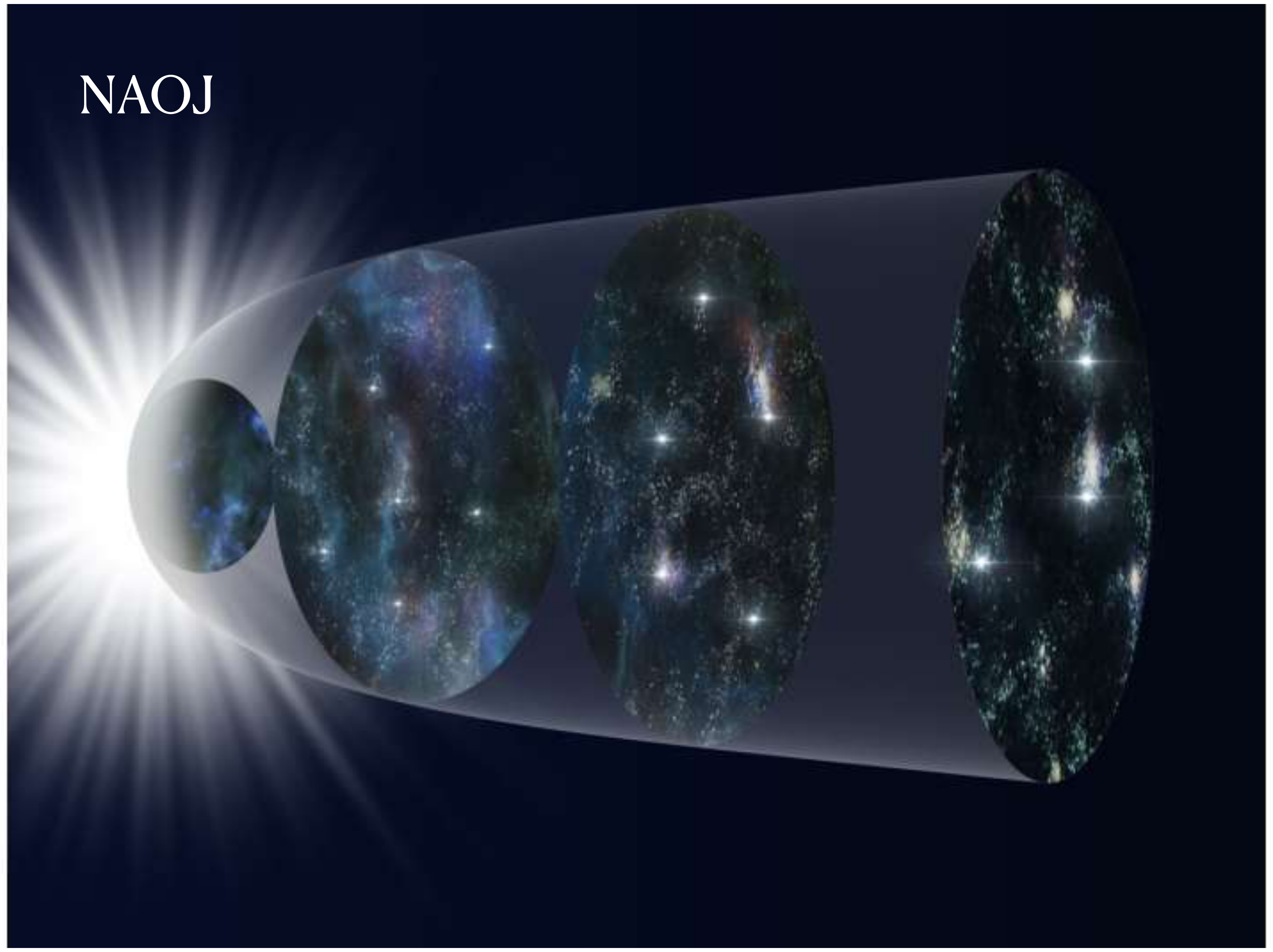
# Where and when do black holes merge?

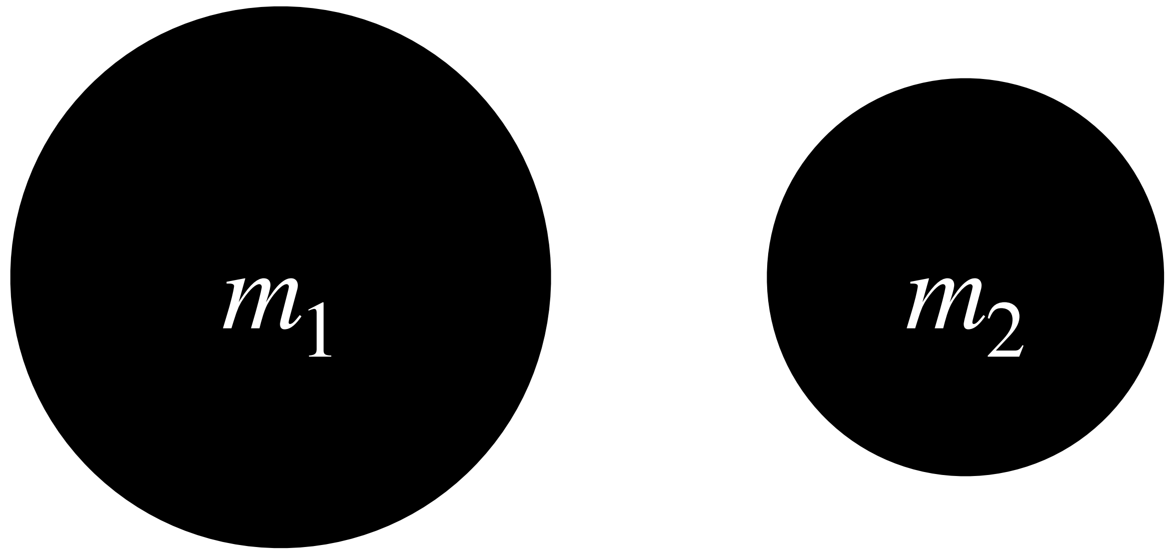
**In the context of large scale structure and the cosmic expansion history**



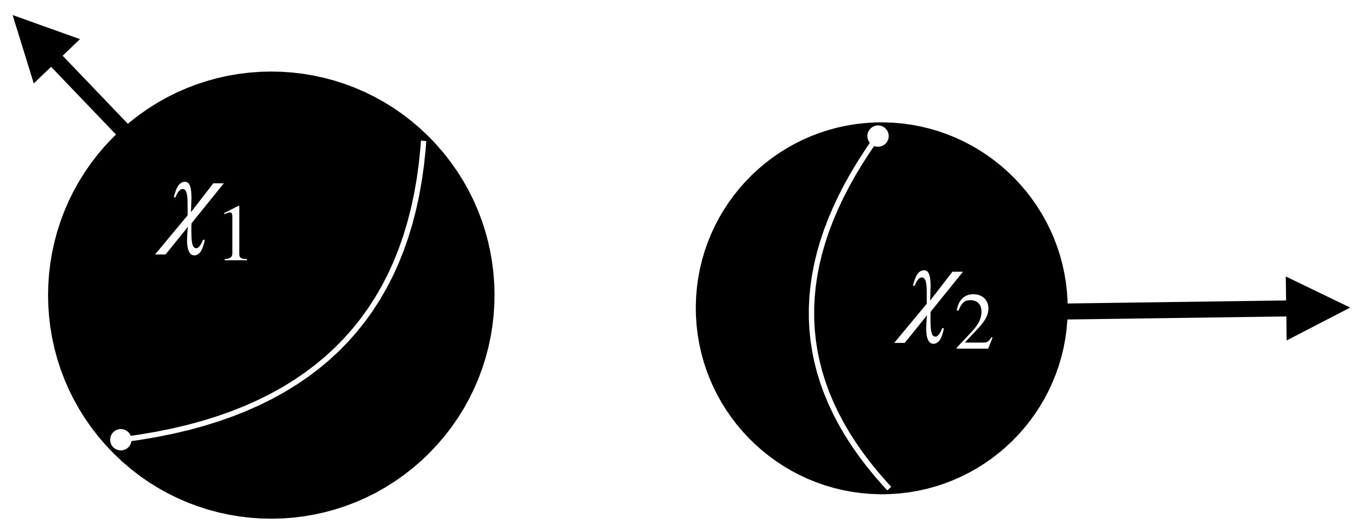



# Gravitational waves encode source properties, like…

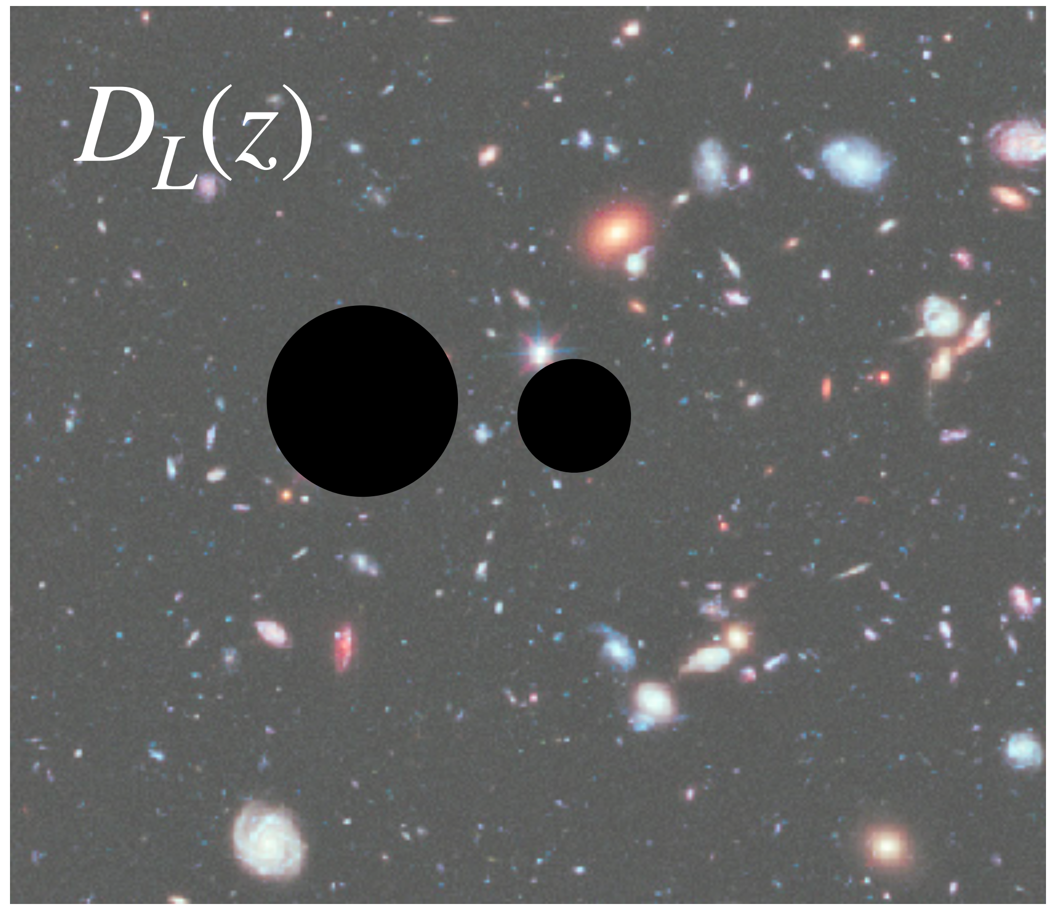
How *big* is each black hole or neutron star?



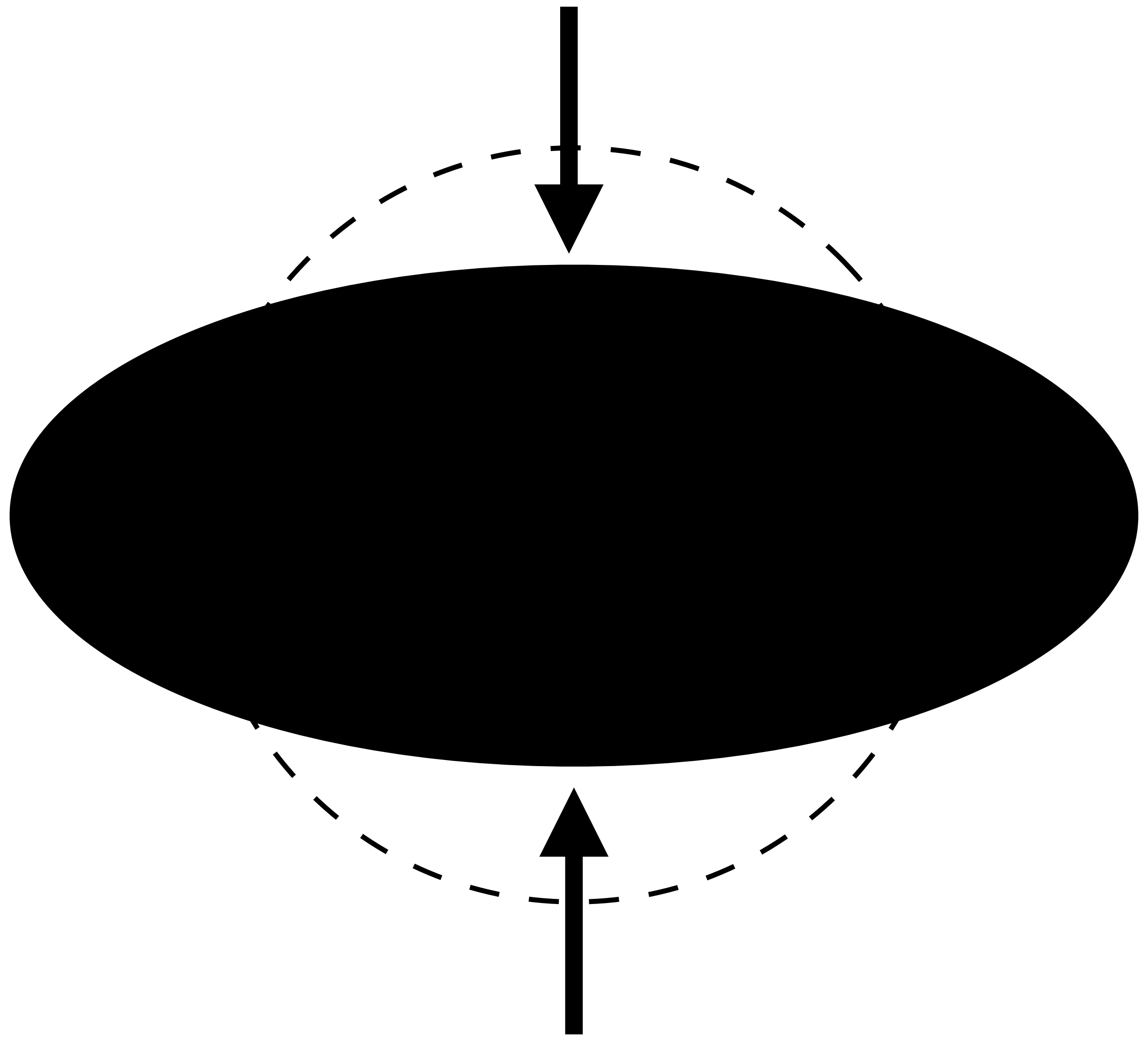

How fast are they *spinning*?




*Where* and *when* did they merge?

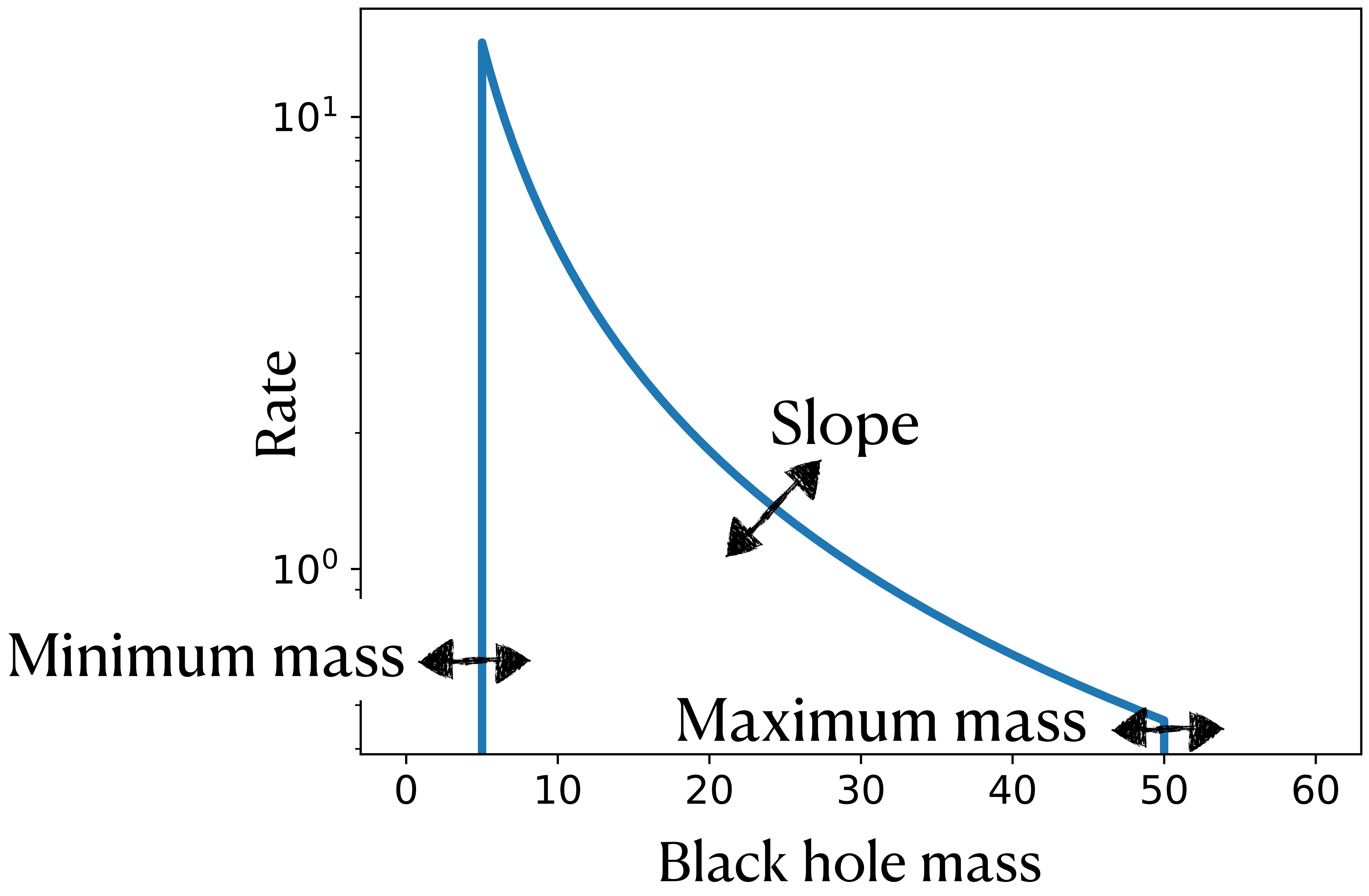



How squishy are neutron stars?



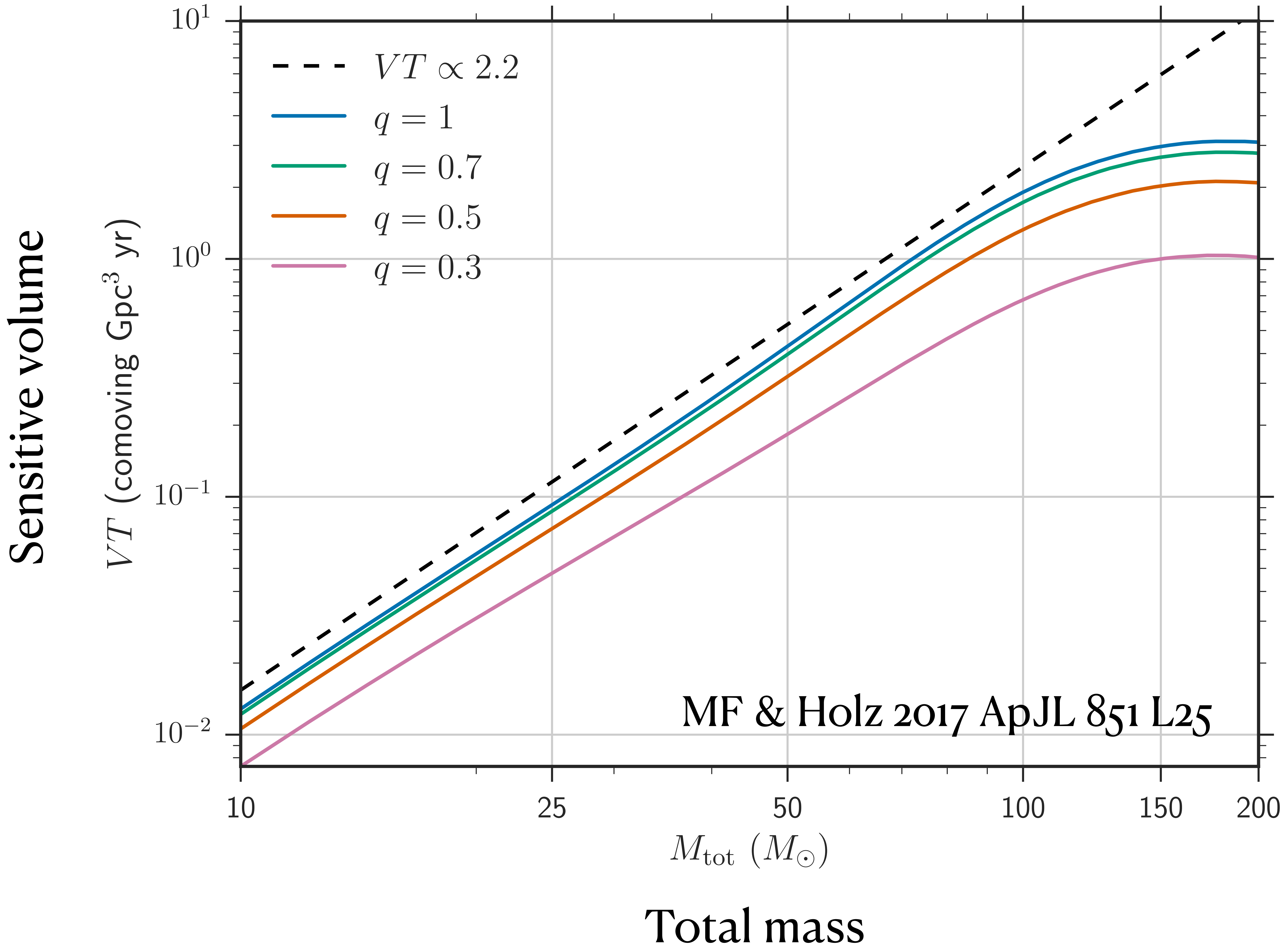
# From Single Events to a Population

- Introduce a population model that describes the **distributions** of masses, spins, redshifts across **multiple events**.
- Example: Fit a power law to black hole masses.
- Take into account **measurement uncertainty** and **selection effects**.
    - Don't just fit the "detected distribution!" (Essick & MF 2024)



## Example of selection effects:

# Big black holes are louder than small black holes



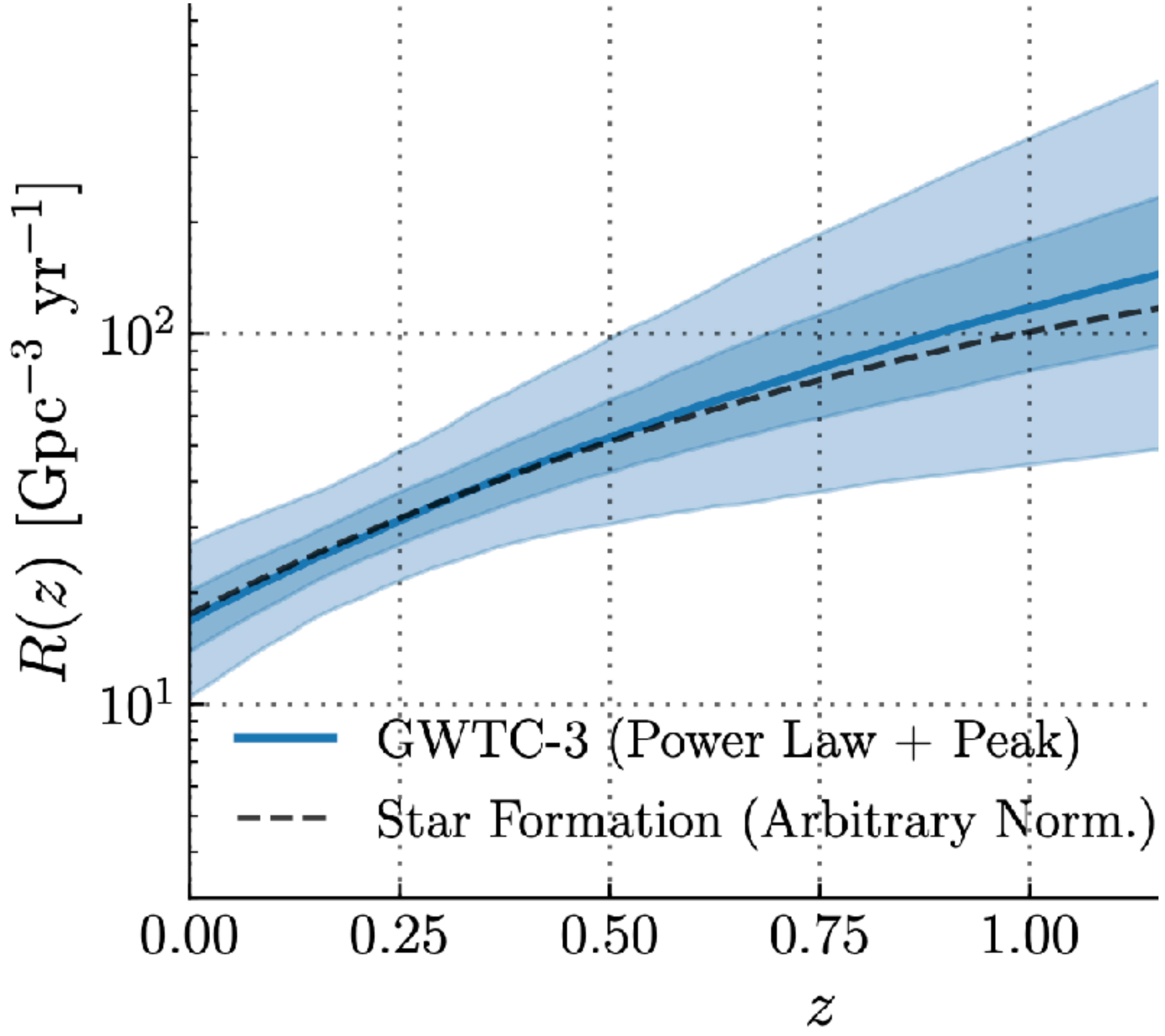
# Learning from (stellar-mass) binary black hole populations

- Black hole merger rate **across cosmic time**
- Most massive black holes and **pair-instability supernovae**
- Implications for **cosmological expansion history**

# Black hole merger rate evolves with redshift*

*assuming fixed Planck '15 cosmological parameters to convert between GW luminosity distance and redshift

Merger rate density

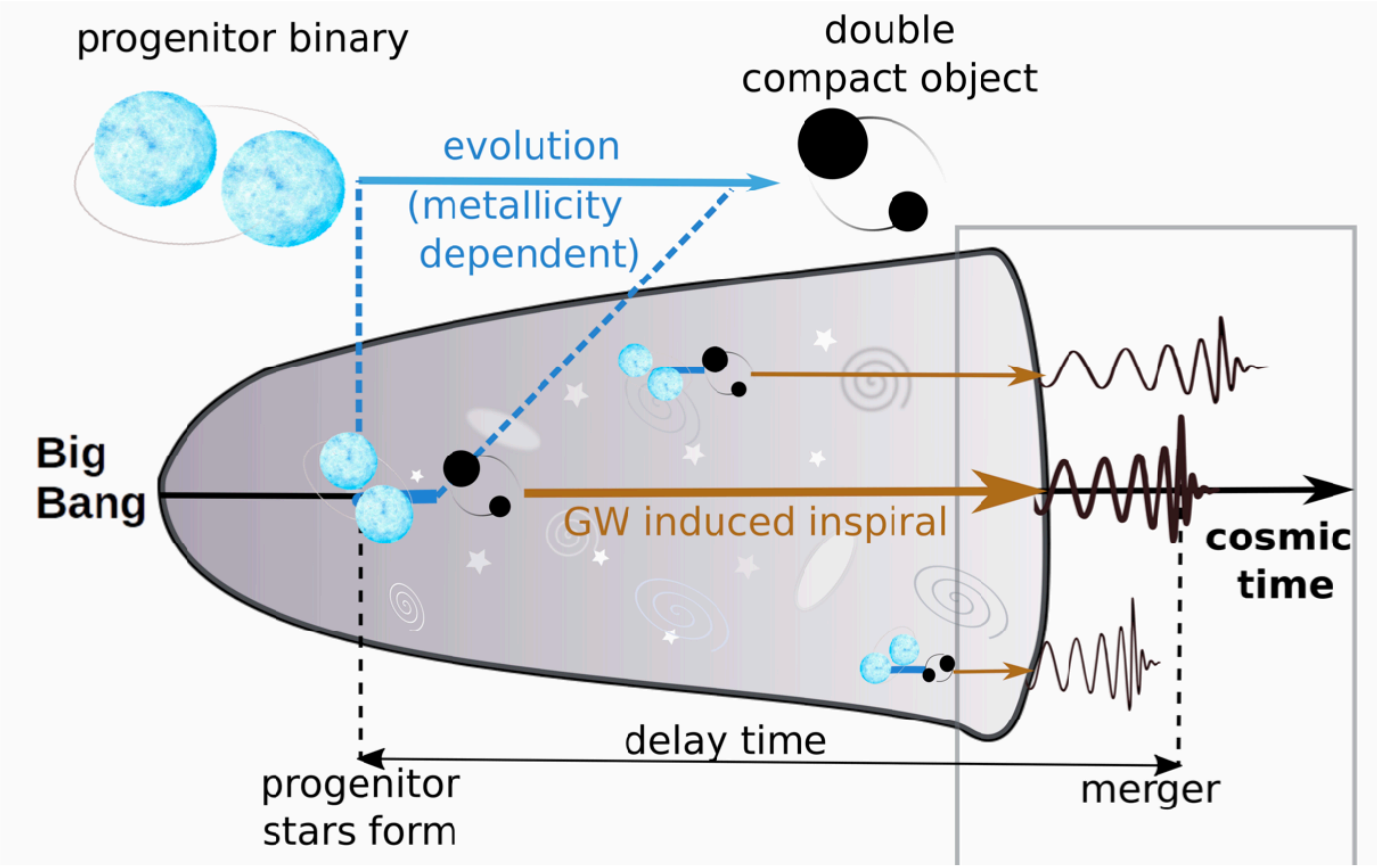



Redshift

LVK PRX 13 011048 (2023)

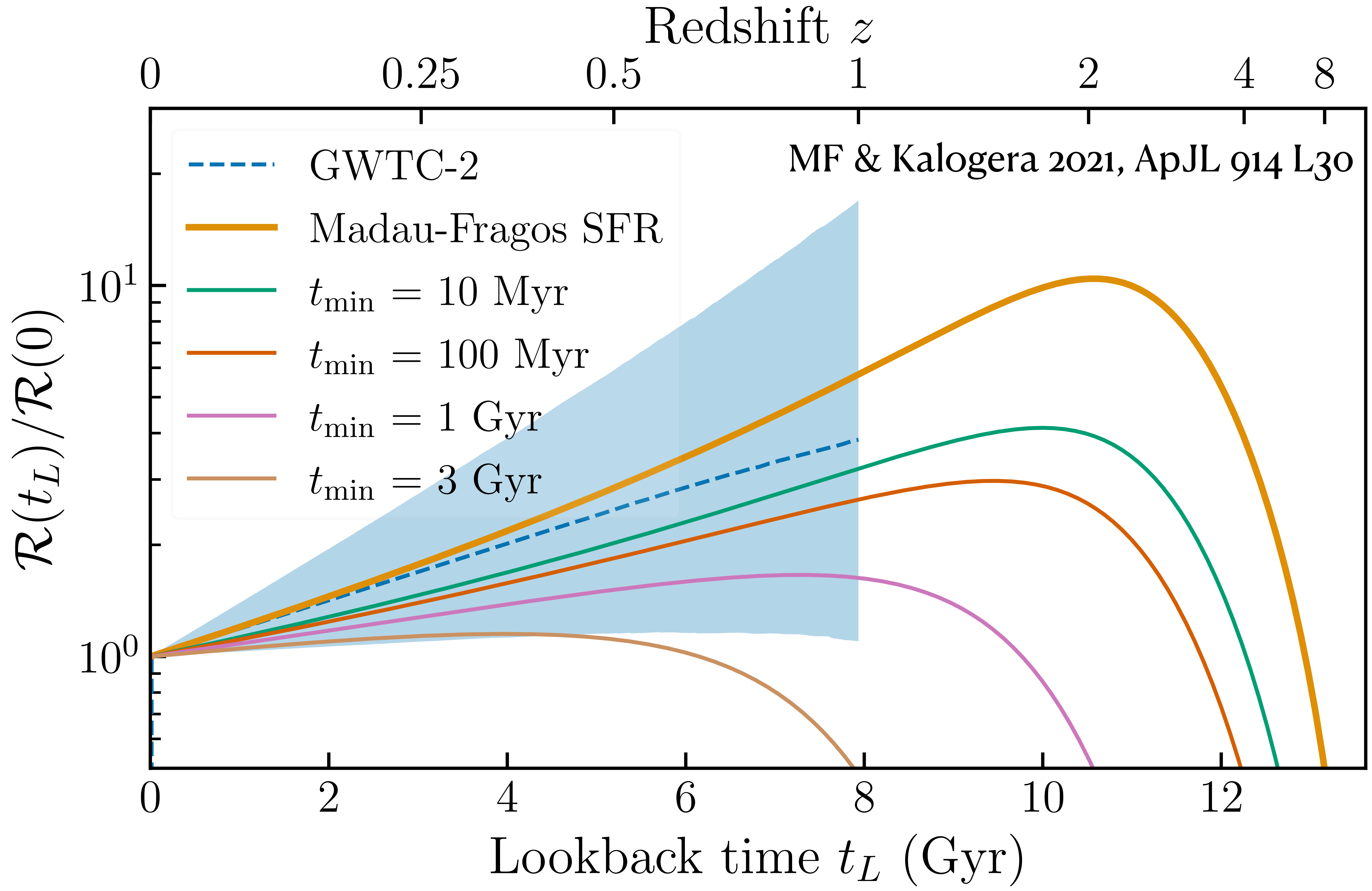
Method based on MF, Farr & Holz 2018 ApJL 863 L41

# Merger rate follows progenitor formation rate + delay time distribution




Chruslinska 2022

# If we know the progenitor formation rate, we can measure the *delay time distribution*

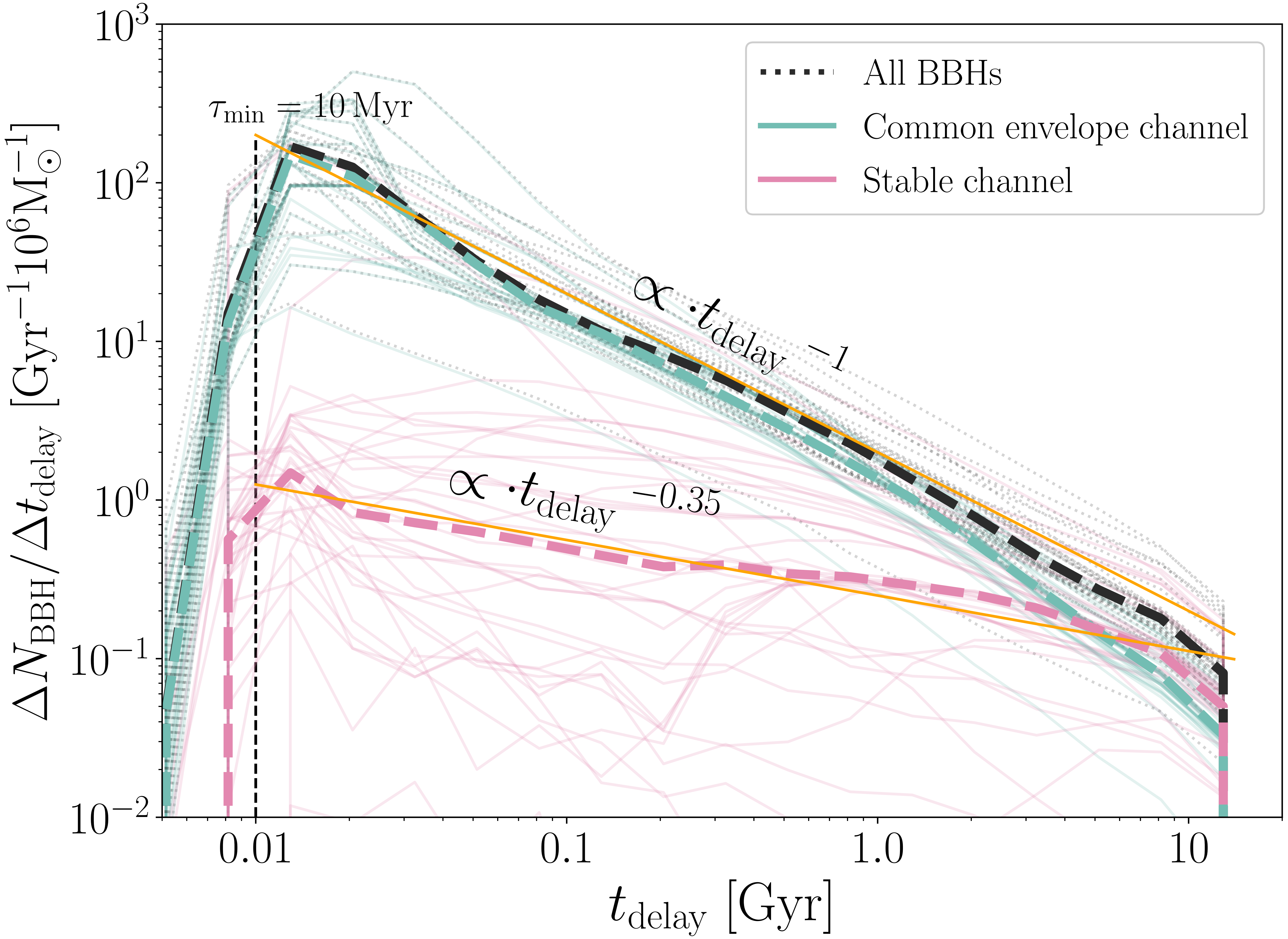



Blue: Inference of the black hole merger rate as a function of cosmic time

Solid lines: Predicted merger rate evolution from different delay time distributions

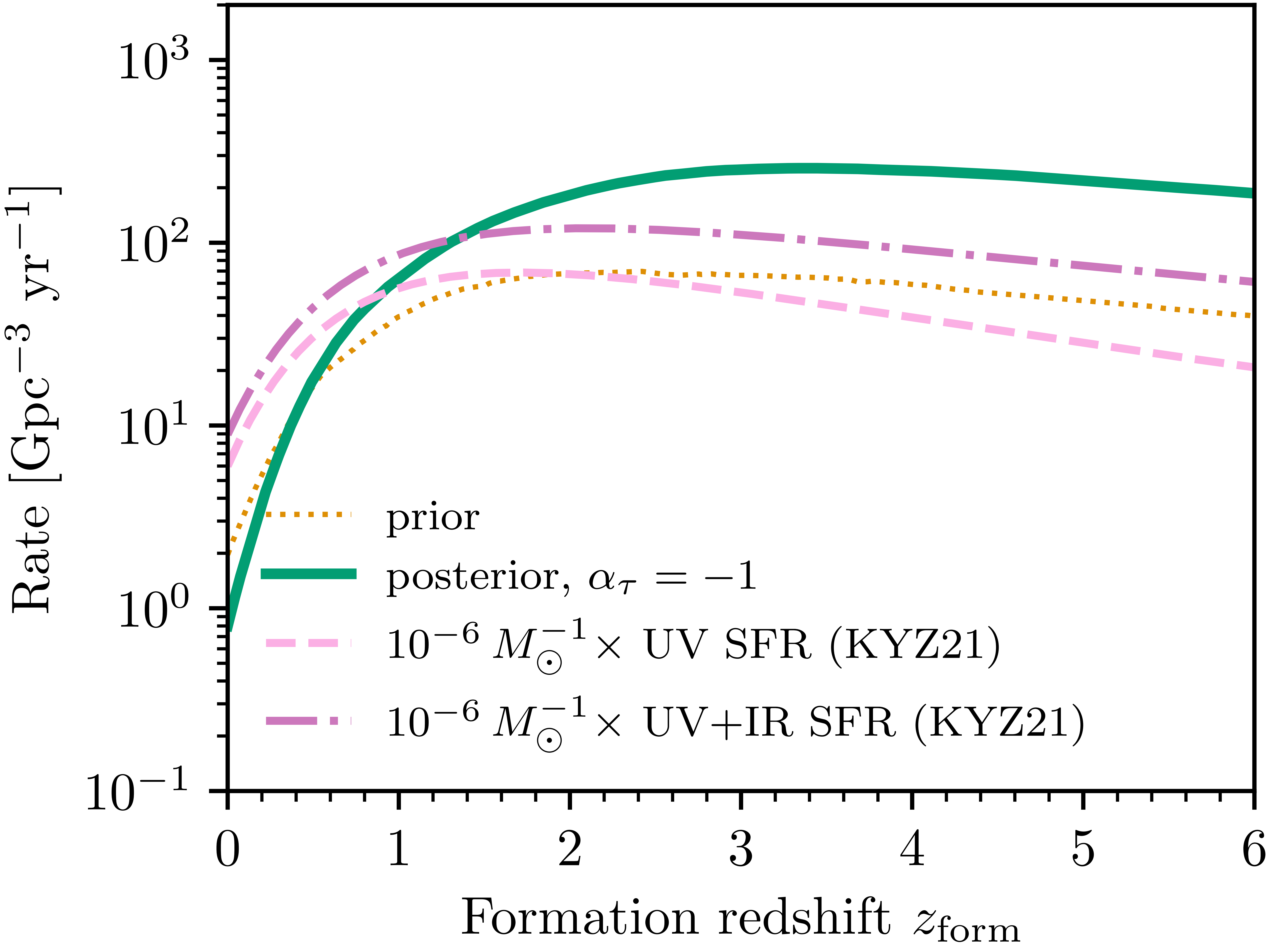
See also Wu & MF (2024) using the long gamma-ray burst rate as the progenitor formation rate

# Delay time distribution informs formation channels




MF & van Son, ApJL 957 L31 (2023)

# Alternatively, if we assume a delay time distribution, we can infer the *progenitor formation rate*

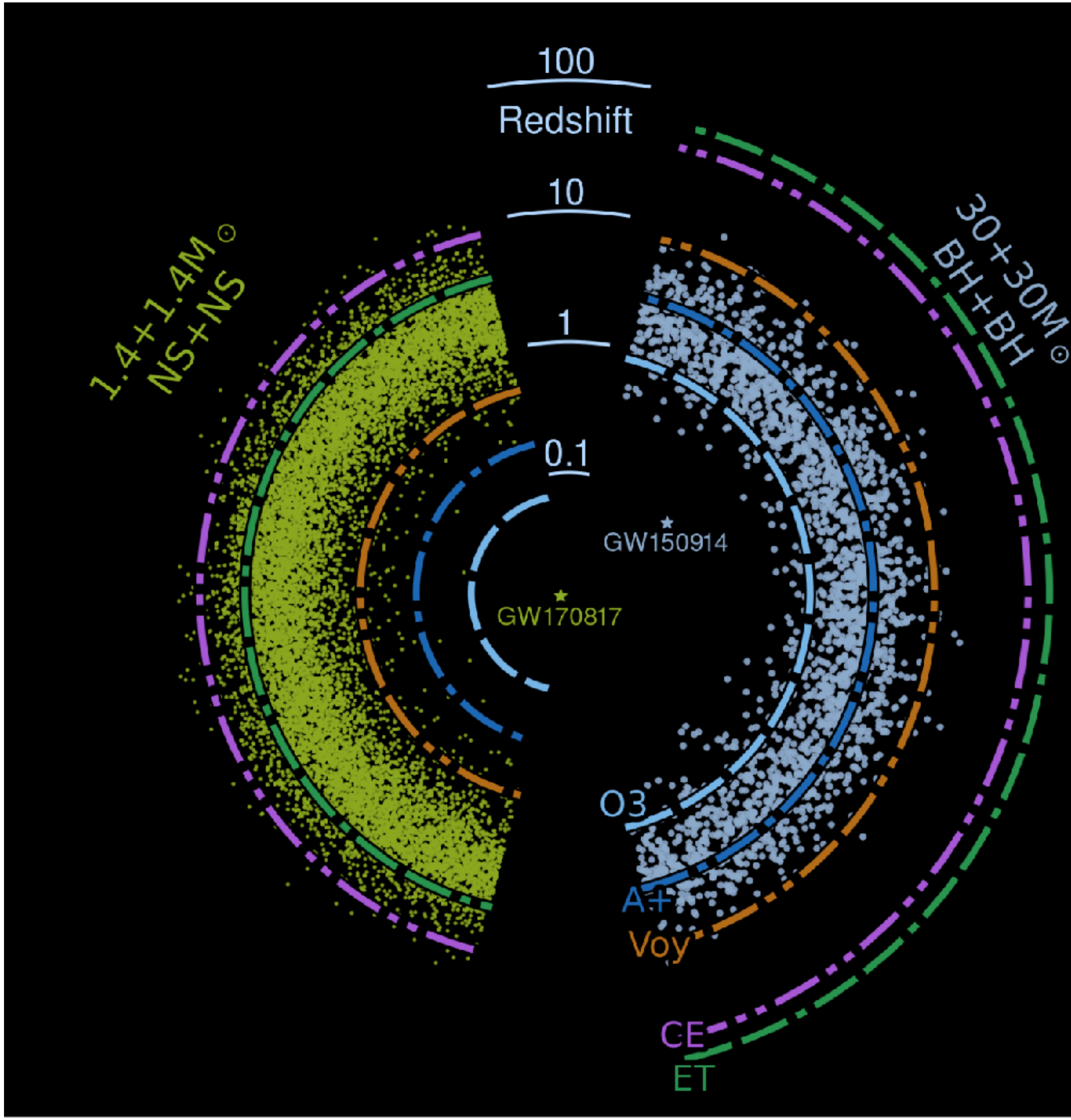



MF & van Son (2023)

# Next generation ground-based gravitational-wave detectors

Mapping the black hole merger rate across *all* of cosmic time, from the very first black holes

Evans et al., Cosmic Explorer Horizon Study, arXiv:2109.09882



# Pair-instability mass gap

For stellar collapse, **(pulsational) pair-instability supernovae** predict an absence of black hole remnants between $\sim 50 - 130\, M_{\odot}$

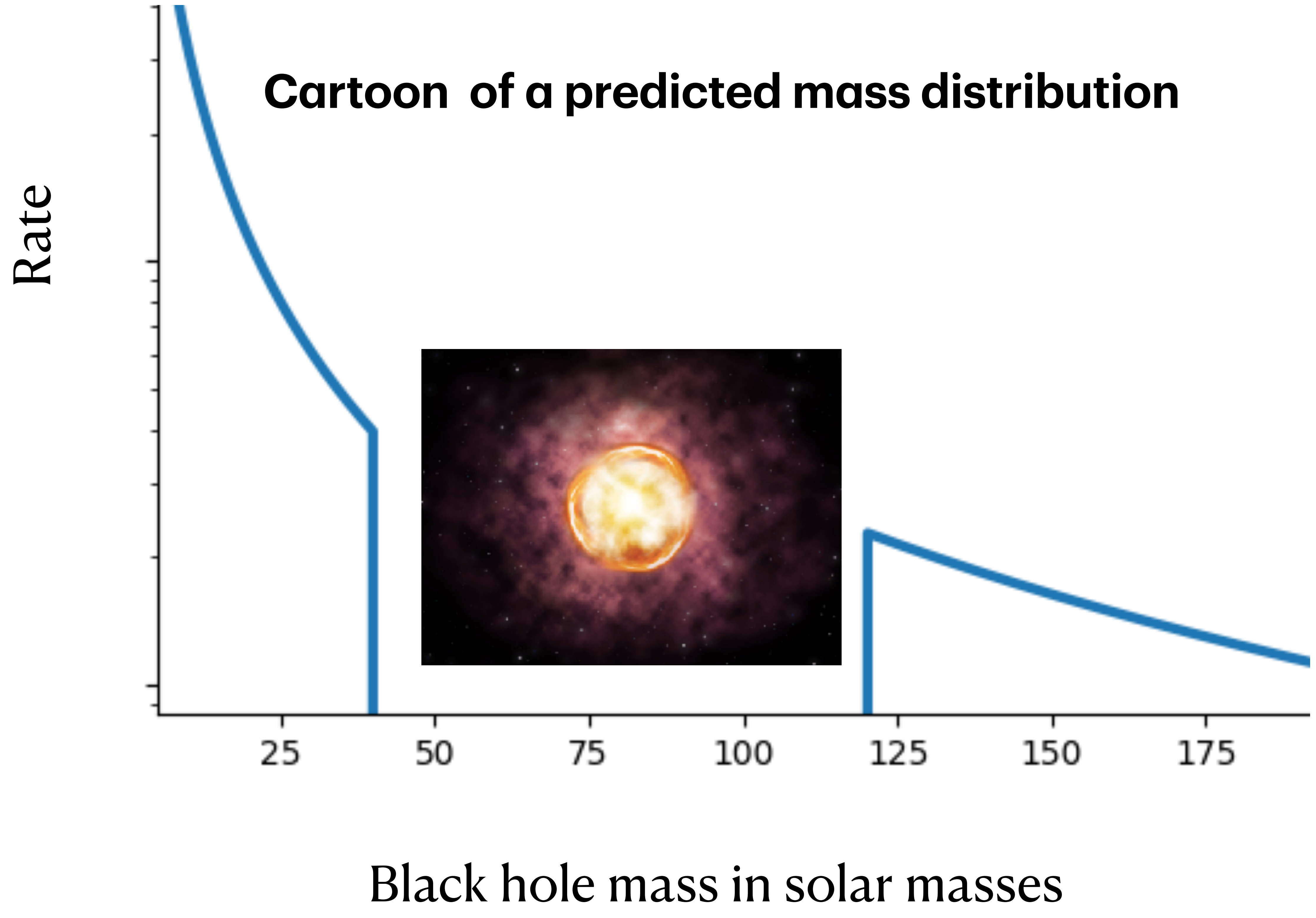
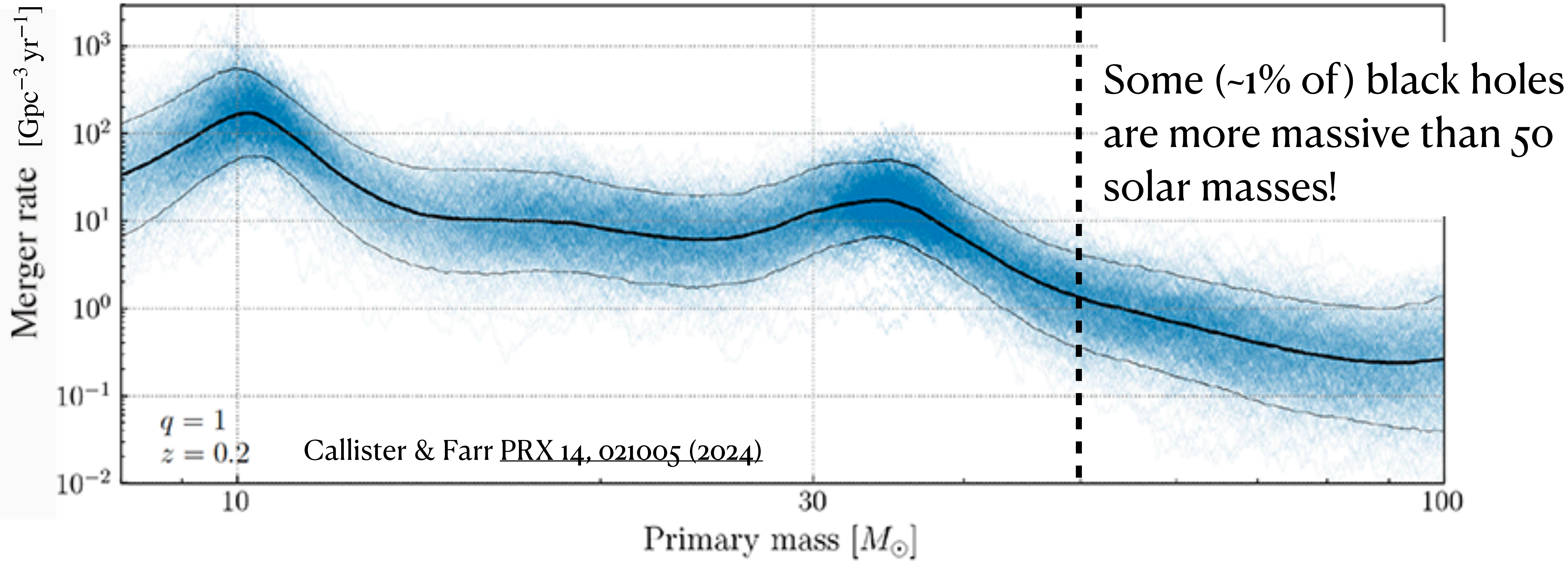



Image credit: Gemini Observatory/NSF/AURA/ illustration by Joy Pollard

# Where is the pair instability mass gap?

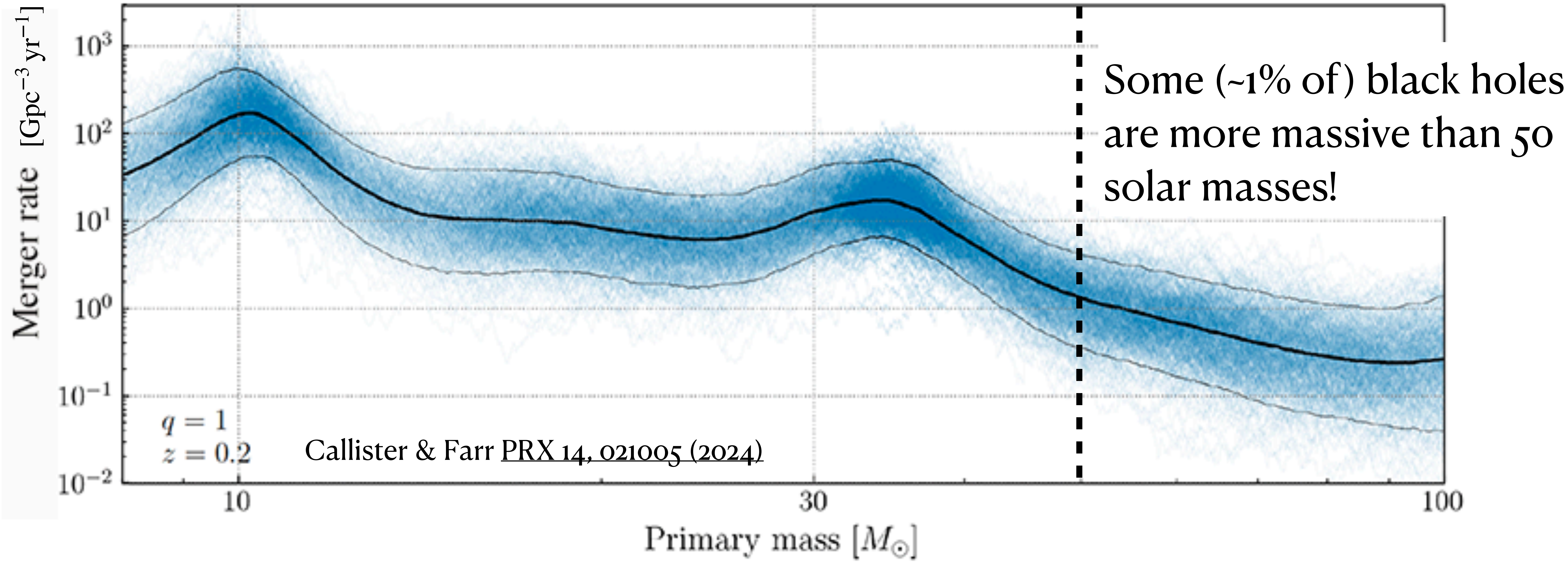



Callister & Farr PRX 14, 021005 (2024)

Does the mass gap start at higher masses (adjustment to nuclear reaction rates? New particles in stellar cores?)

Or do the heaviest black holes have a non-stellar origin? (Merger products of smaller black holes? Primordial black holes?)

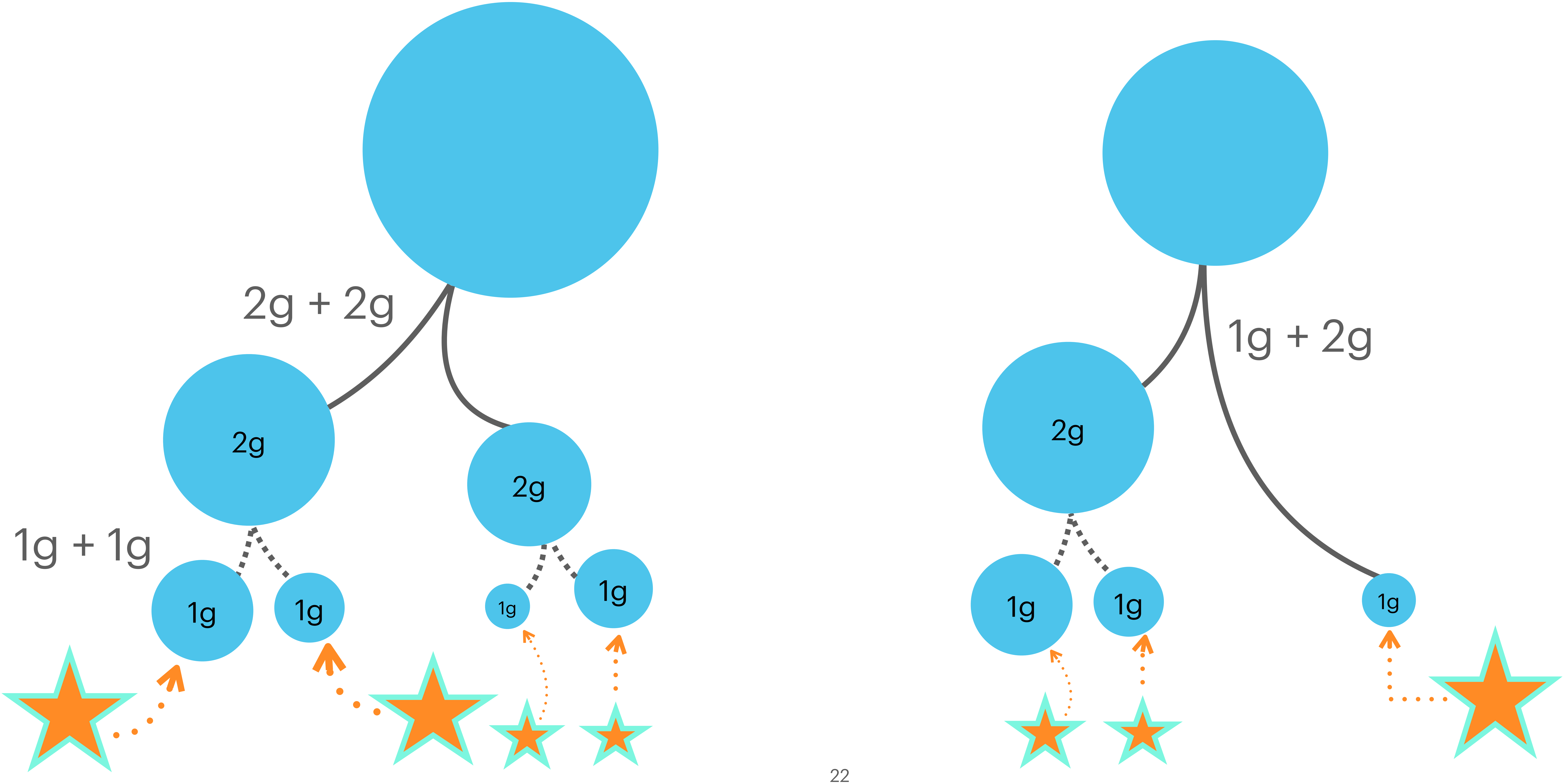
# Where is the pair instability mass gap?




Does the mass gap start at higher masses (adjustment to nuclear reaction rates? New particles in stellar cores?)

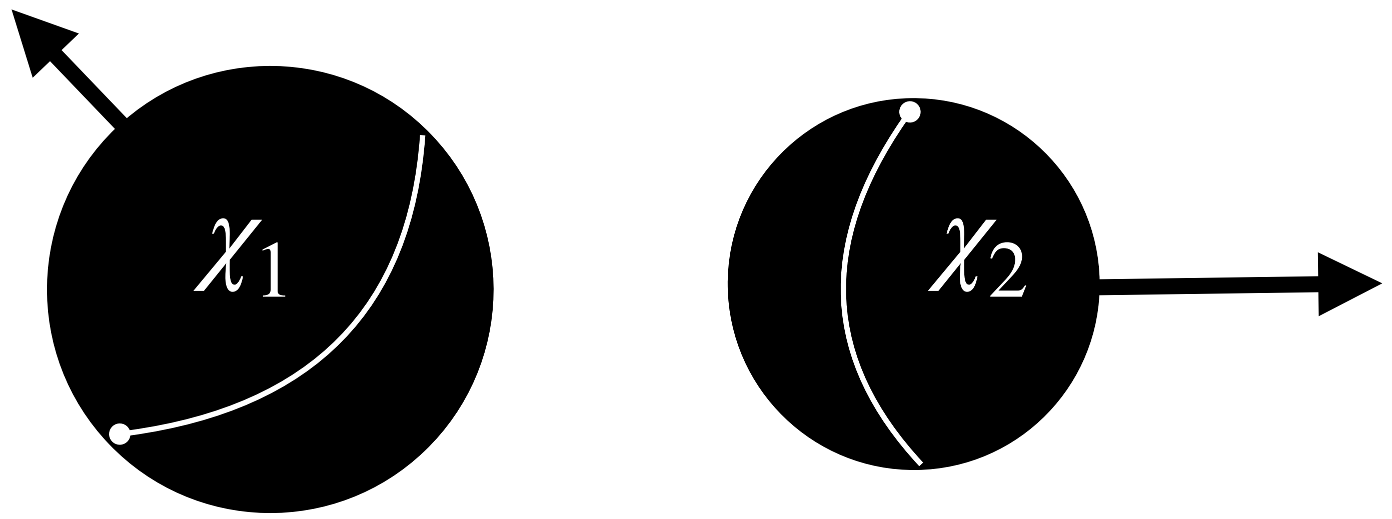
Or do the heaviest black holes have a non-stellar origin? (**Merger products of smaller black holes?** Primordial black holes?)

# Could the biggest black holes be made out of smaller black holes (rather than stellar collapse)?

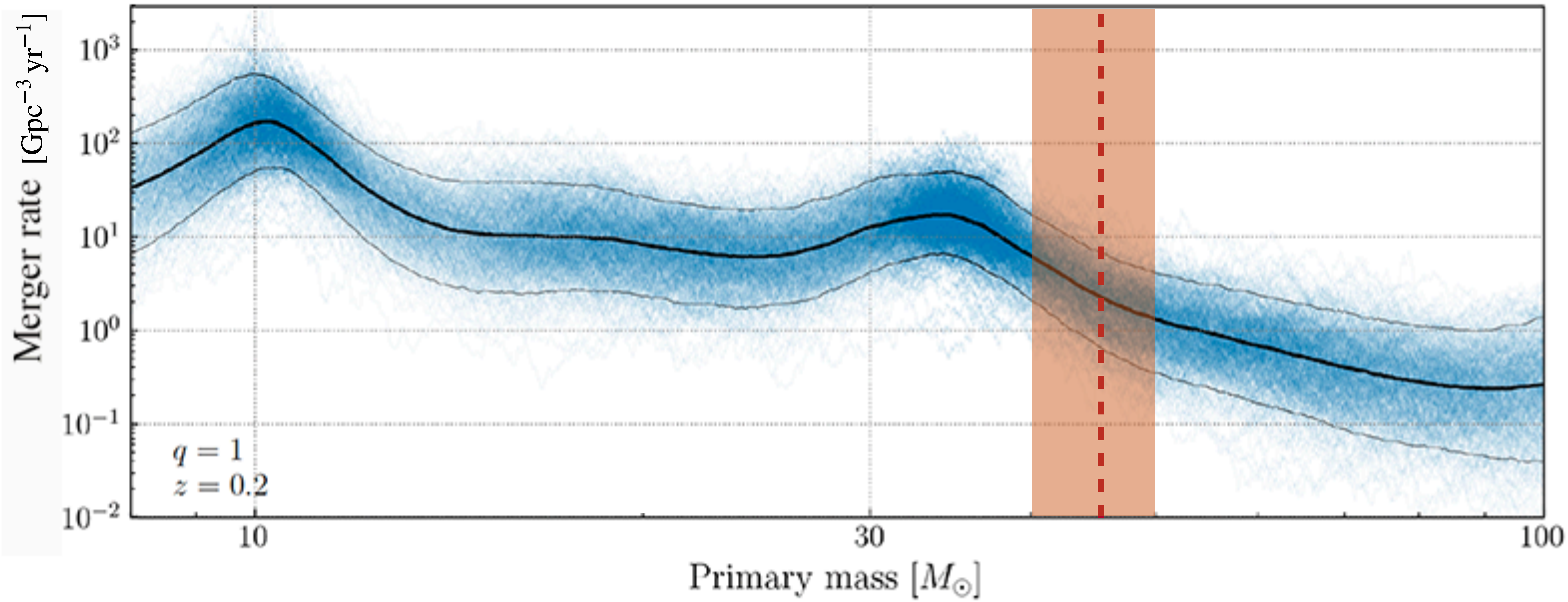


# Using spin to distinguish hierarchical mergers

- 2g black holes tend to spin at dimensionless spin magnitude ~0.7 (e.g., MF, Farr & Holz 2017)
- Hierarchical mergers are dynamically assembled, so spin tilts are randomly oriented
- Fixed fraction of hierarchical mergers will have large, misaligned spins



# Black holes above ~45 solar masses are spinning more rapidly, suggesting they are made from smaller black holes




Lower edge of pair-instability mass gap?

Antonini, Romero-Shaw & Callister arXiv:2406.19044
Ongoing investigations by Adith Praveen & MF *in prep*

# Standard Siren Cosmology

Binary coalescences provide a direct measurement of the luminosity distance (Schutz 1986)…

$$h(t) = \frac{\mathcal{M}_z^{5/3} f(t)^{2/3}}{D_L} F(\text{angles}) \cos(\Phi(t))$$

GW strain

frequency

position and orientation

redshifted chirp mass

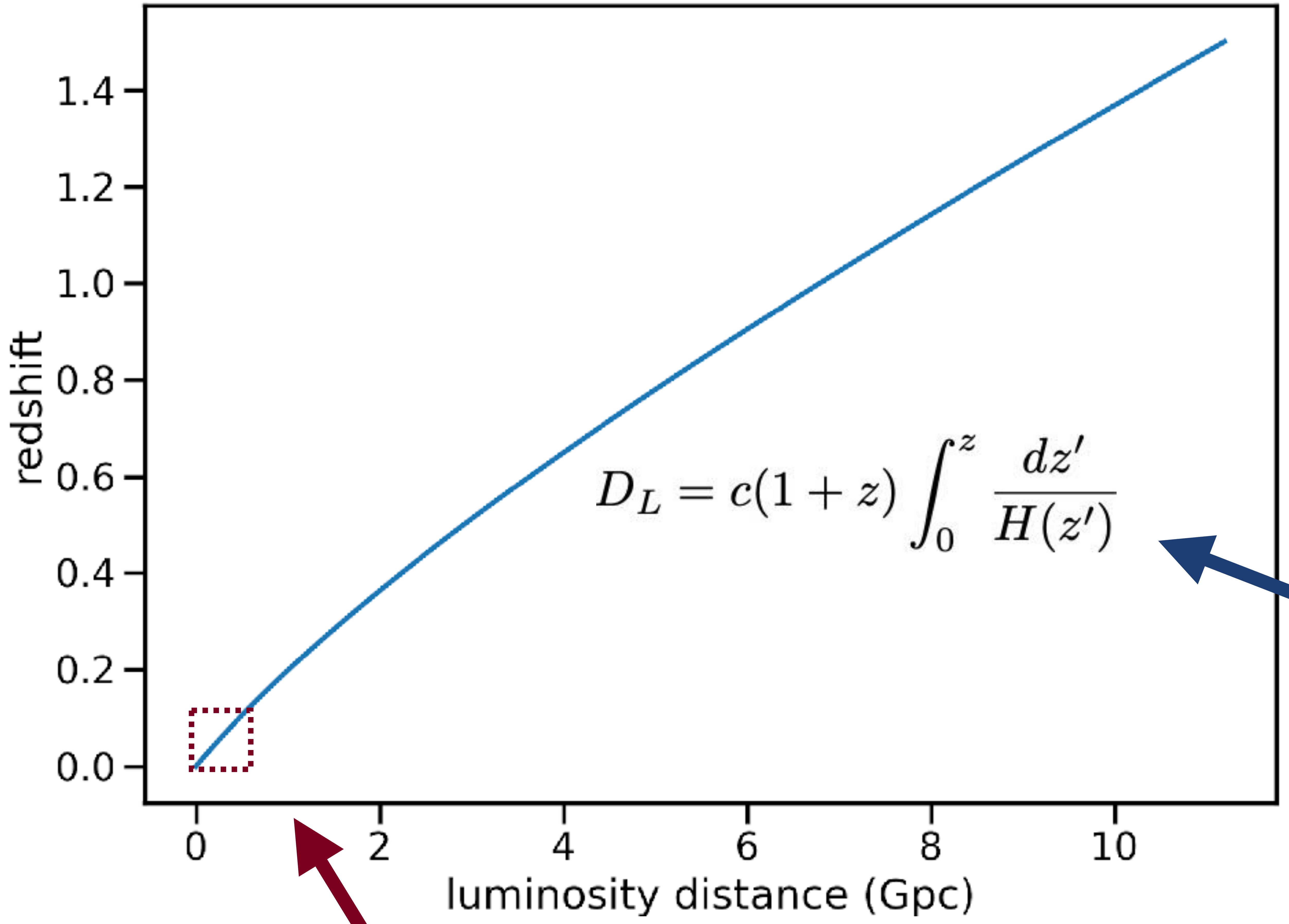
luminosity distance

phase

$$\mathcal{M}_z = \left( \frac{5}{96} \pi^{-8/3} \left( f(t) \right)^{-11/3} \dot{f}(t) \right)^{3/5}$$

…but the redshift is degenerate with the mass

# Goal: measure the redshift—distance relation



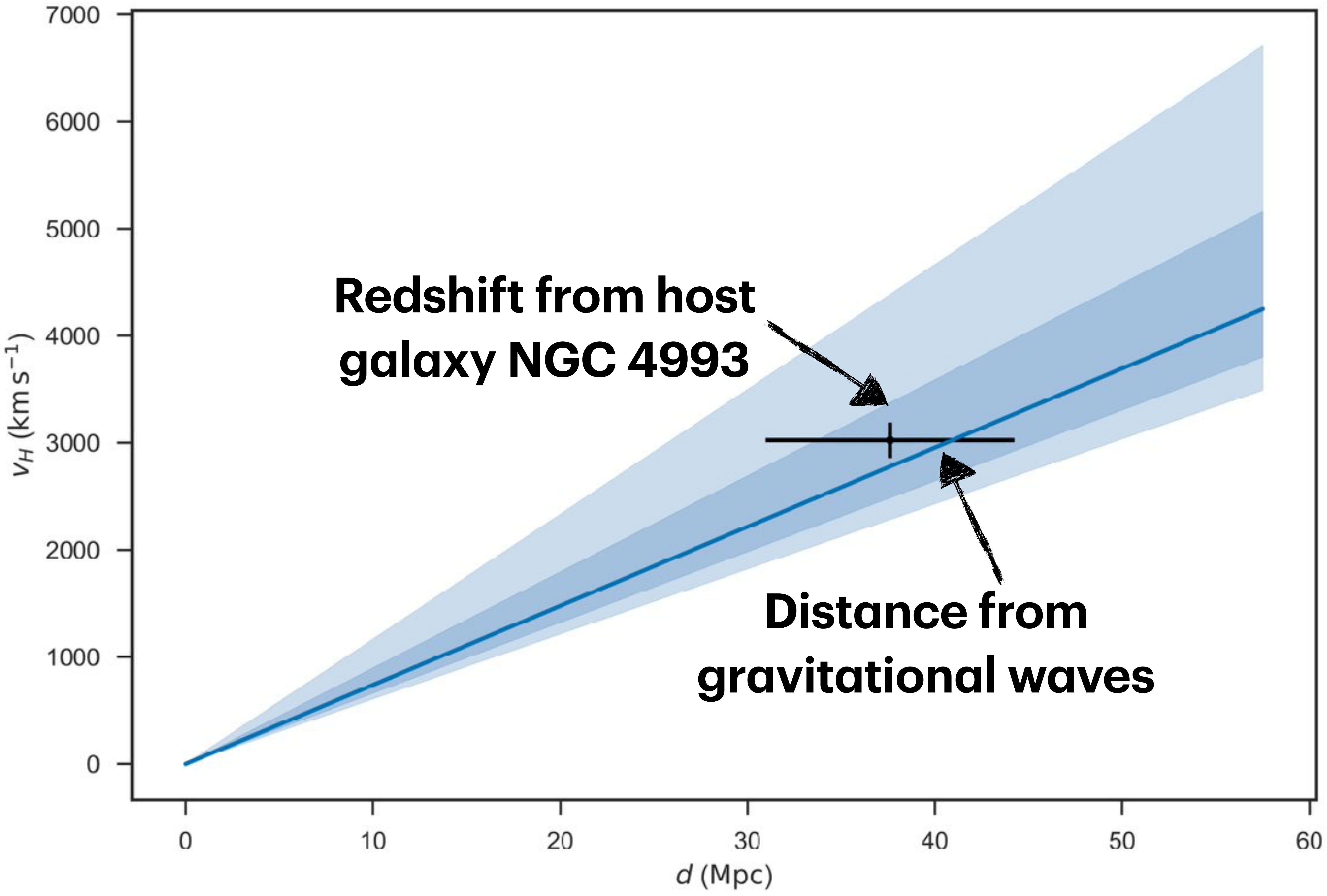

**And thereby infer cosmological parameters**

Depends on constituents of the Universe: matter density, dark energy density, dark energy equation of state

Local slope is the *Hubble constant*

# GW170817: A standard siren with an electromagnetic counterpart

Hubble velocity
(Related to redshift)




Distance

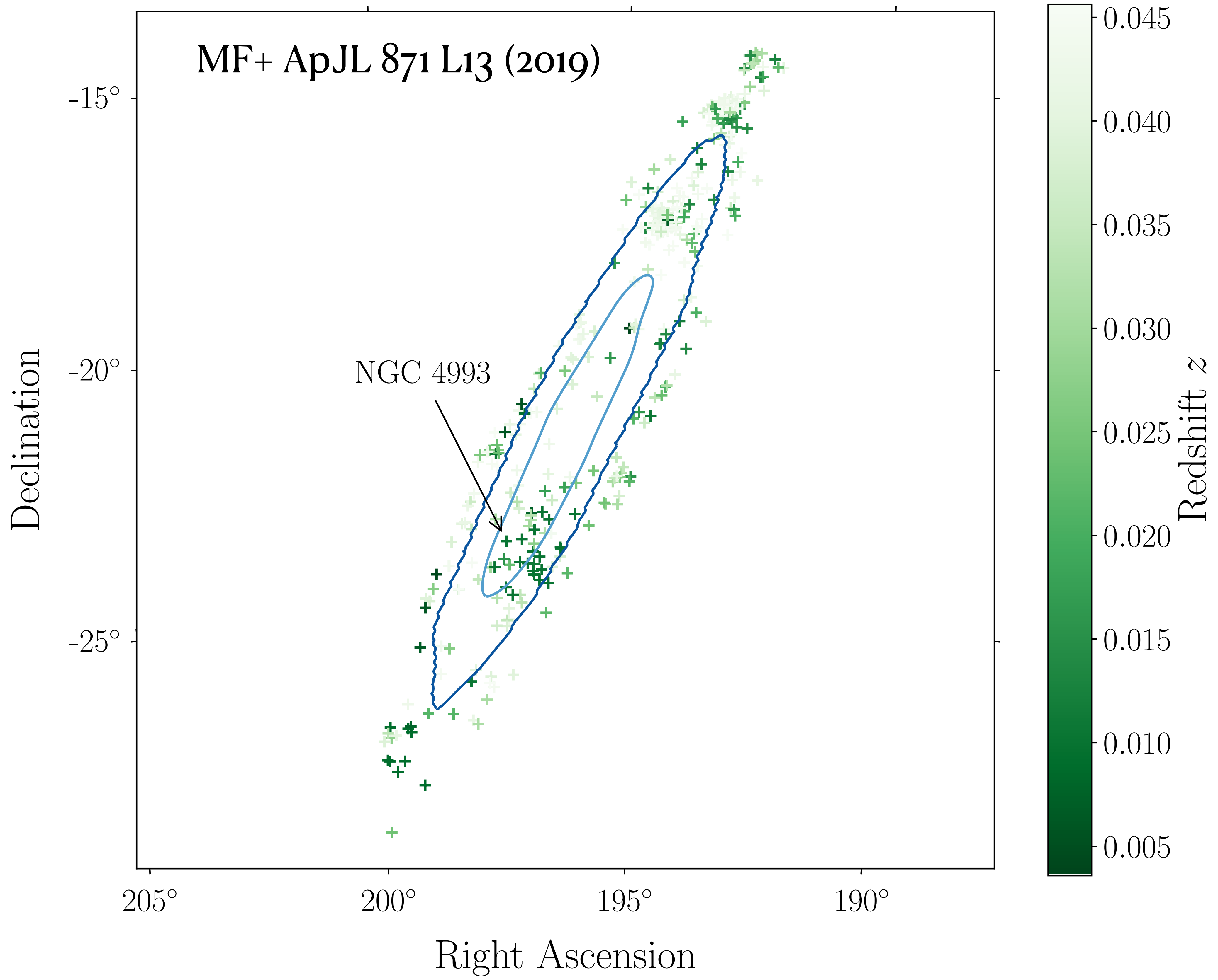


Figure Credit: Will Farr/ LIGO Scientific Collaboration

# Standard sirens with galaxy catalogs

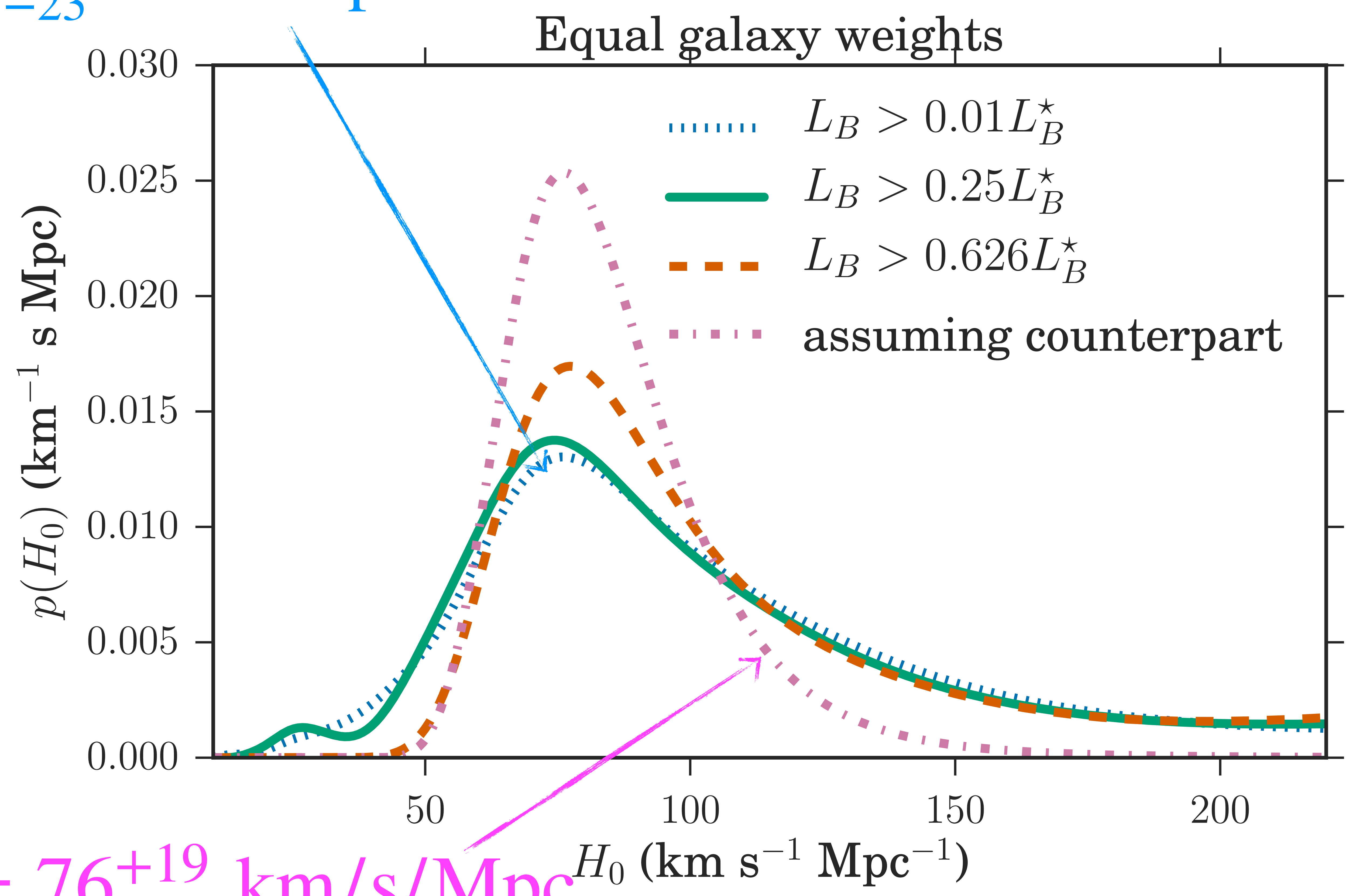
## What if we didn't know GW170817's host galaxy?

- From GW data, 90% sky localization of 16 sq. deg
- Consider all ~400 galaxies in GW localization volume
- Most of the galaxies belong to a single group, containing NGC 4993



# (Exceptionally) informative Hubble constant measurement

$H_0 = 76^{+48}_{-23}$ km/s/Mpc



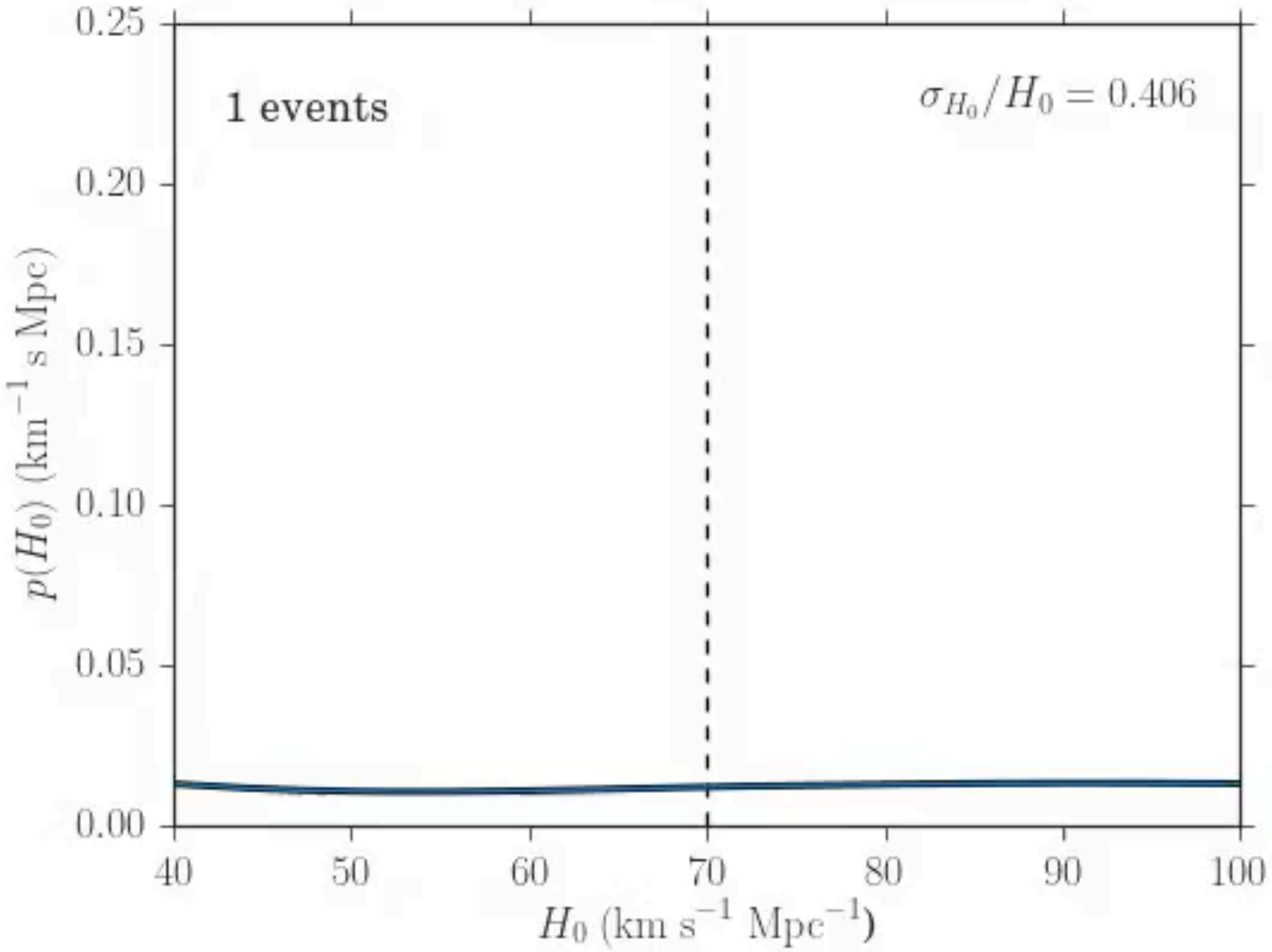

$H_0 = 76^{+19}_{-13}$ km/s/Mpc

MF+ ApJL 871 L13 (2019)

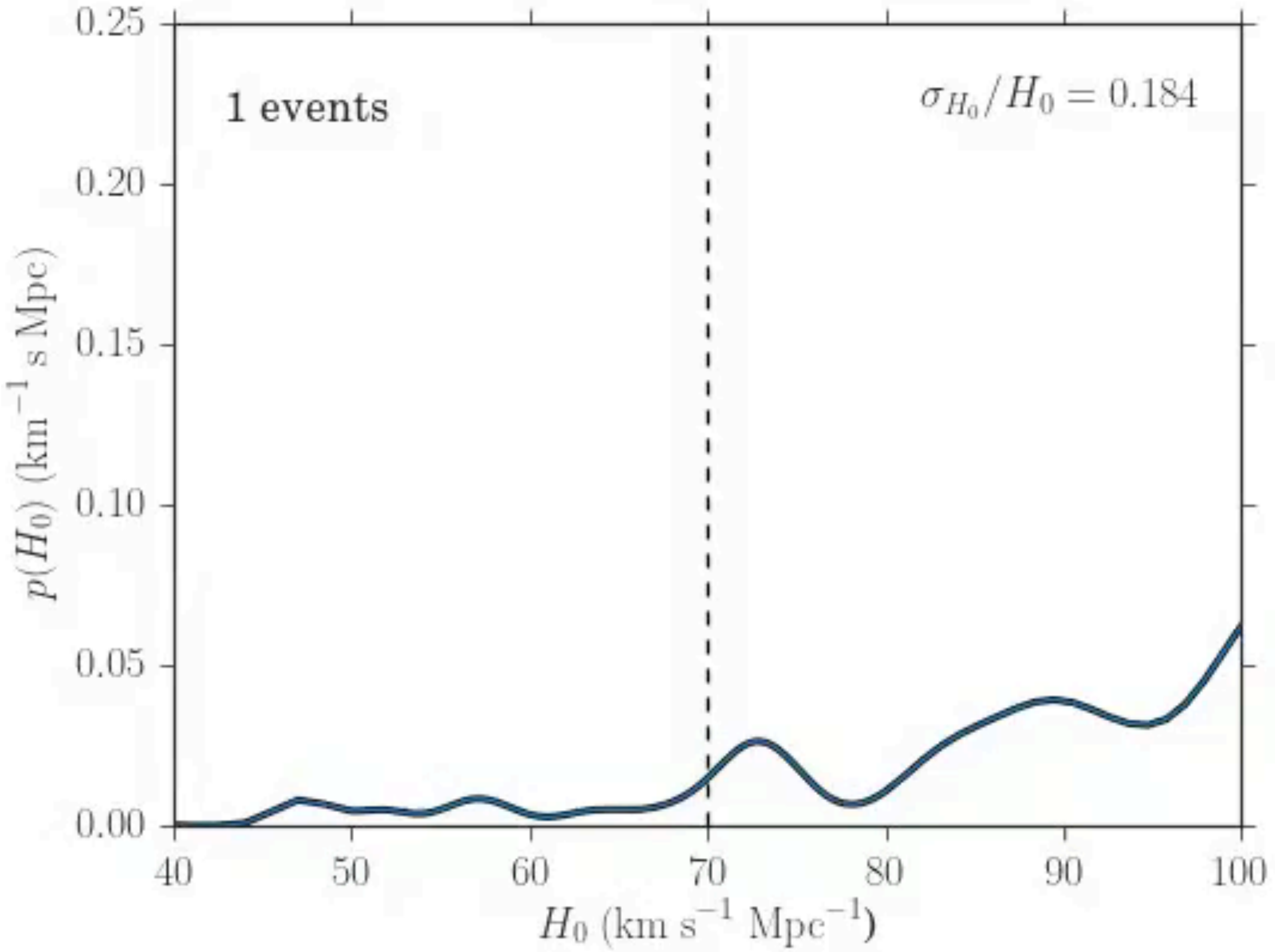
# Comparing the galaxy catalog to the counterpart method

**For binary neutron stars, convergence is ~7 times slower with galaxy catalog compared to unique host. For black holes, convergence is even slower because localization volumes are bigger.**

Statistical




Counterpart

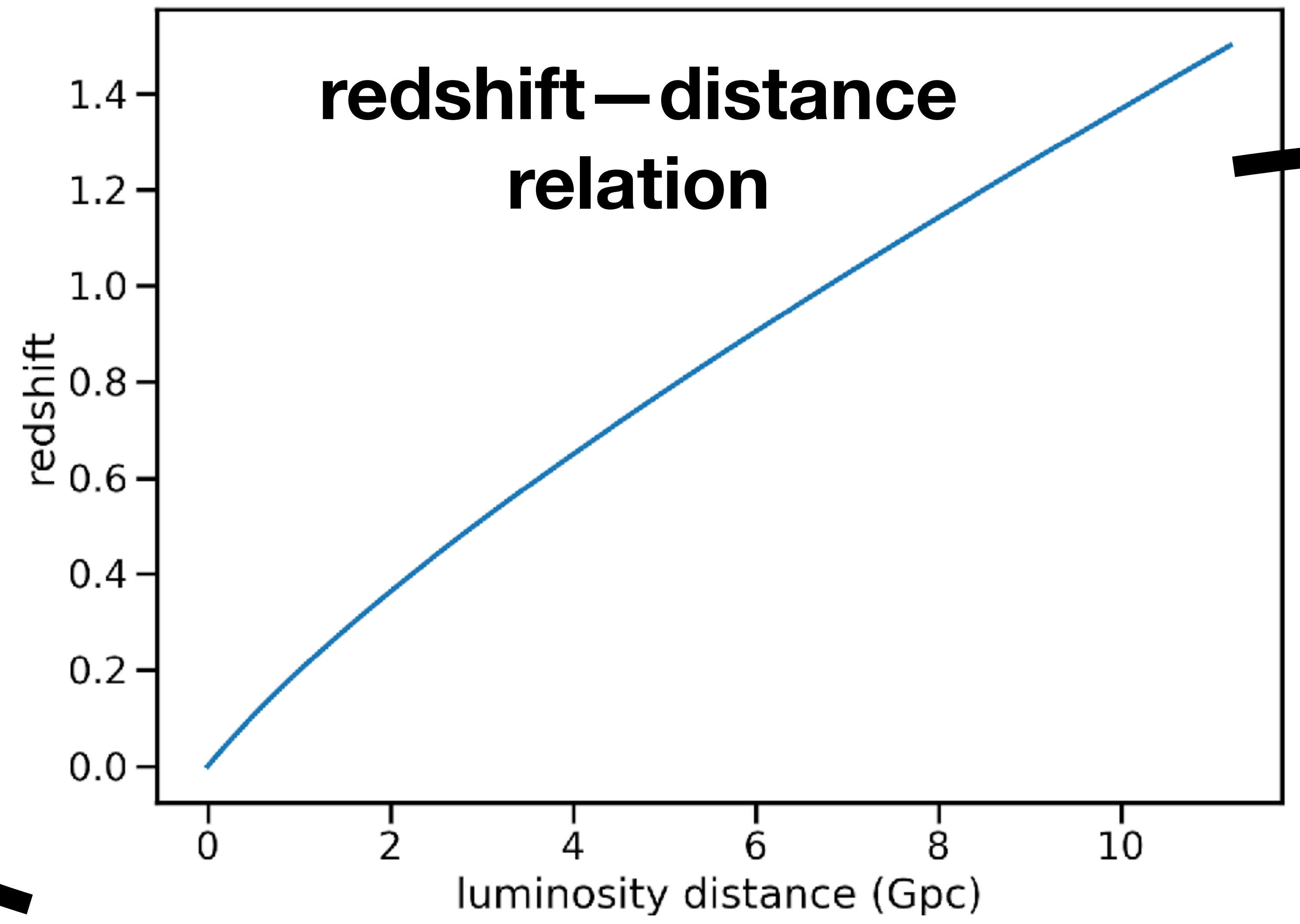


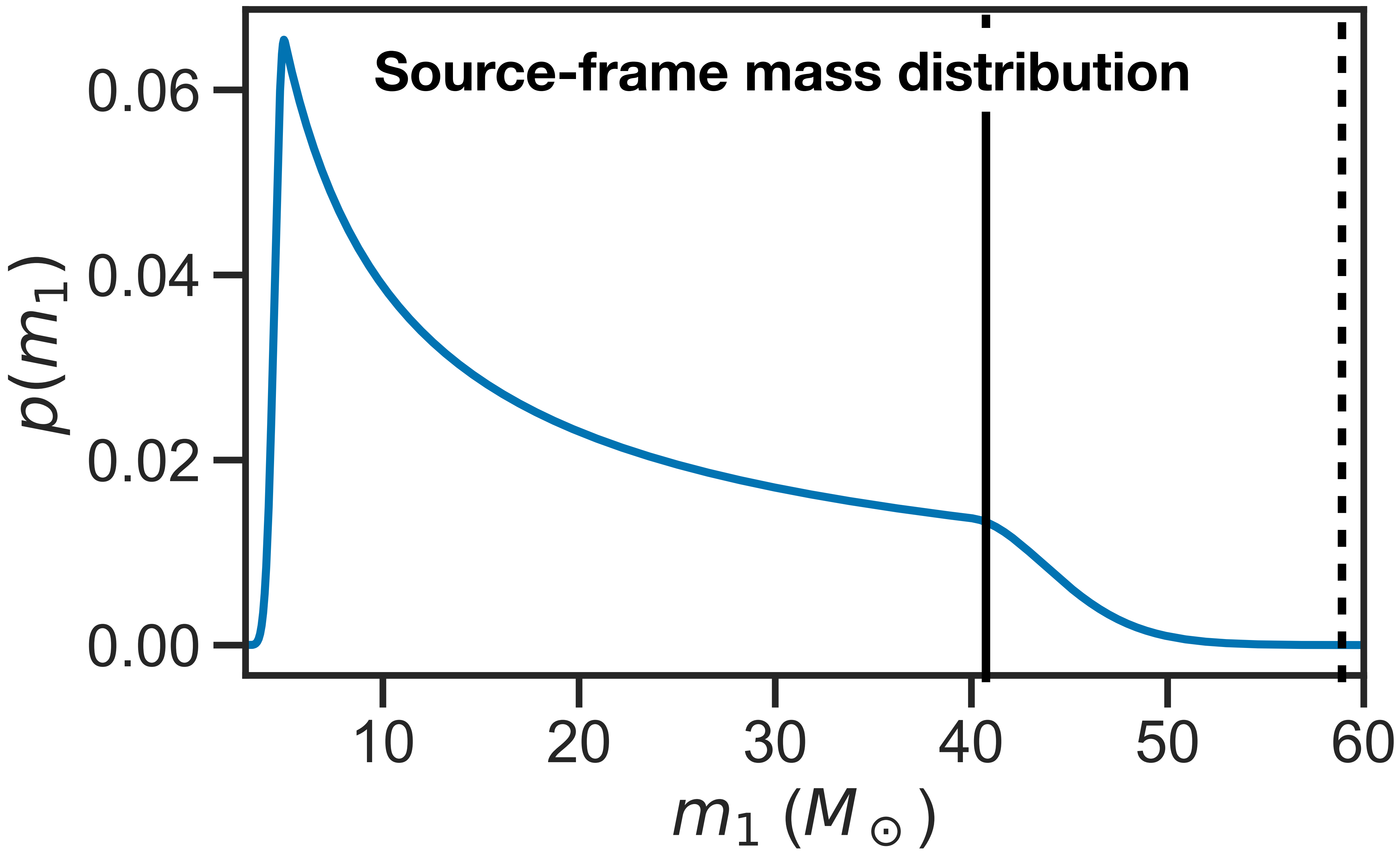

Combined measurement with N events converges as ~40%/√N compared to ~15%/√N for sources with a counterpart

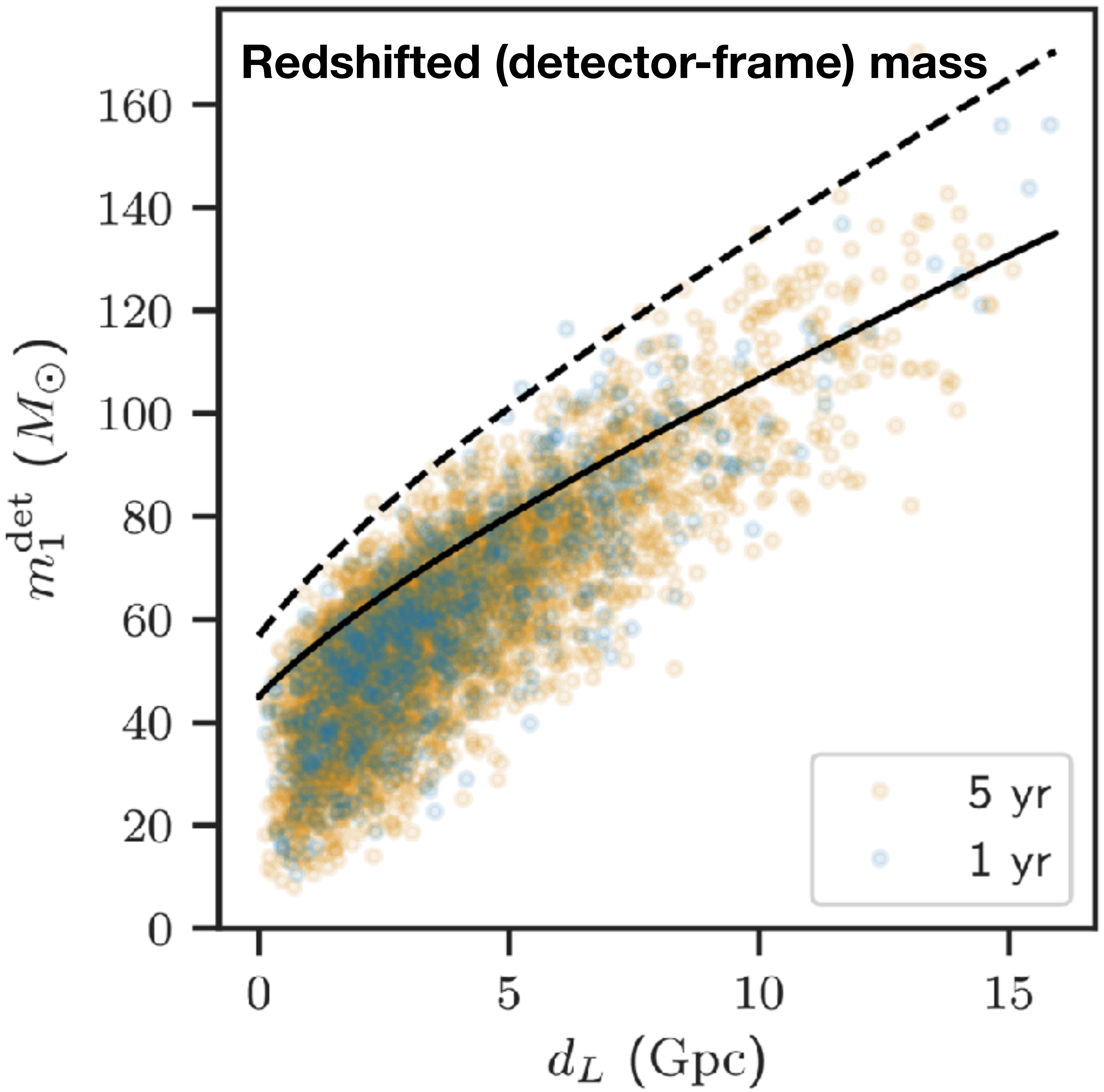
Chen, MF & Holz Nature 562 545 (2018)
MF+ ApJL 871 L13 (2019)

# Spectral Sirens:

Simultaneously infer source population and redshift—distance relation

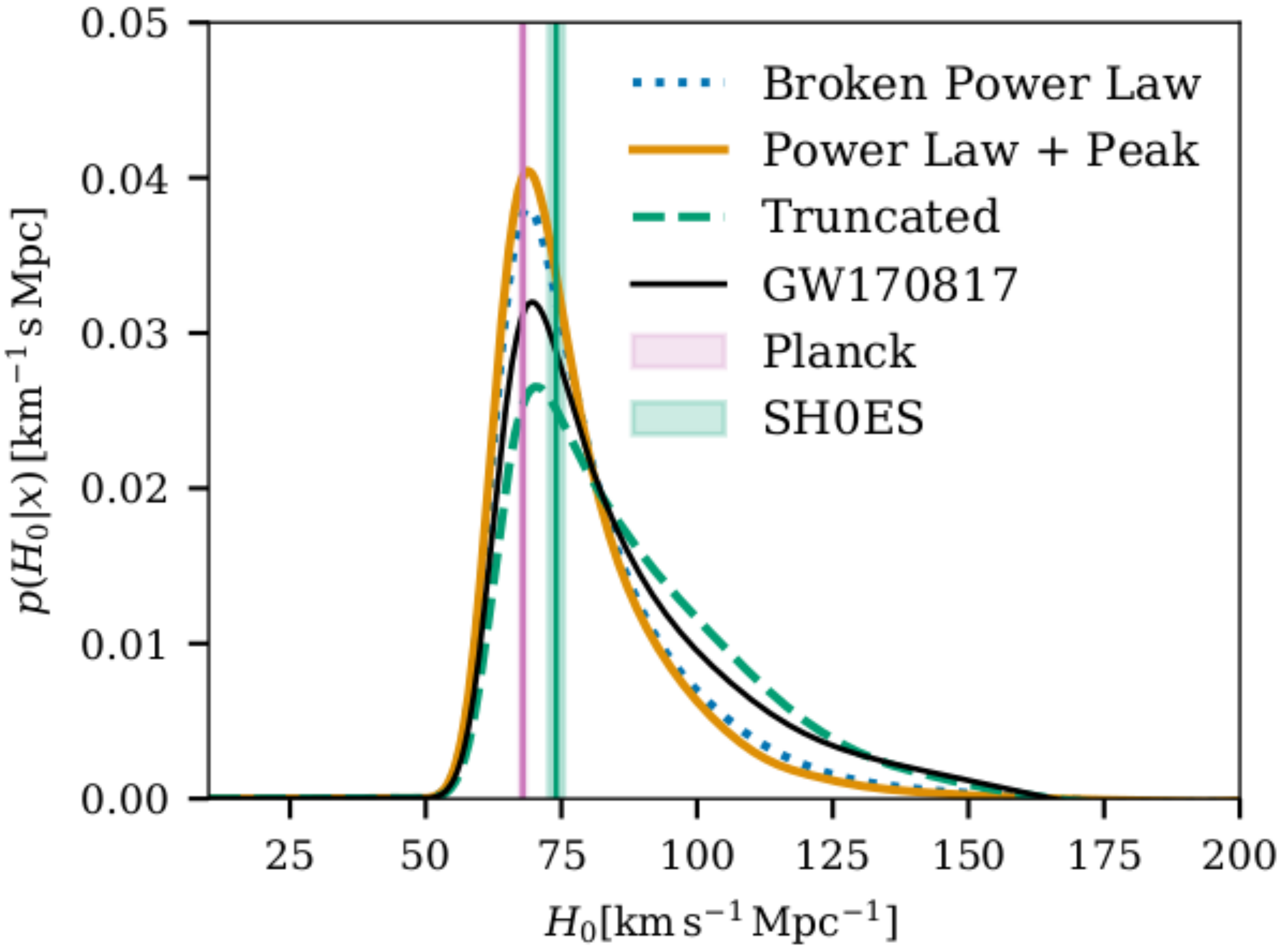



Farr, MF, Ye & Holz ApJL 883 L42 (2019)

# Application of spectral siren cosmology to latest gravitational-wave catalog




LVK ApJ 949 76 (2023)

# Learning from LIGO-Virgo-KAGRA black hole populations

- Black hole mergers across **cosmic history**
  - Redshift evolution of the merger rate informs progenitor formation (galaxy evolution) and delay time distribution (formation channels)
  - Cross-correlate with other transients, like gamma-ray bursts, fast radio bursts, etc.
- Most massive black holes and **pair-instability supernovae**
  - Do black hole spins imply that the lower edge of the pair-instability mass gap is at ~45 solar masses?
  - What are the implications for nuclear physics and beyond standard model physics?
  - Does this match the observed rate of pulsational/ pair-instability SNe?
- Measuring the **cosmic expansion history**
  - Use pair-instability and other features in the mass distribution to simultaneously infer redshifts and distances
  - Gravitational-wave standard sirens are also uniquely sensitive to dark energy theories and gravitational lensing