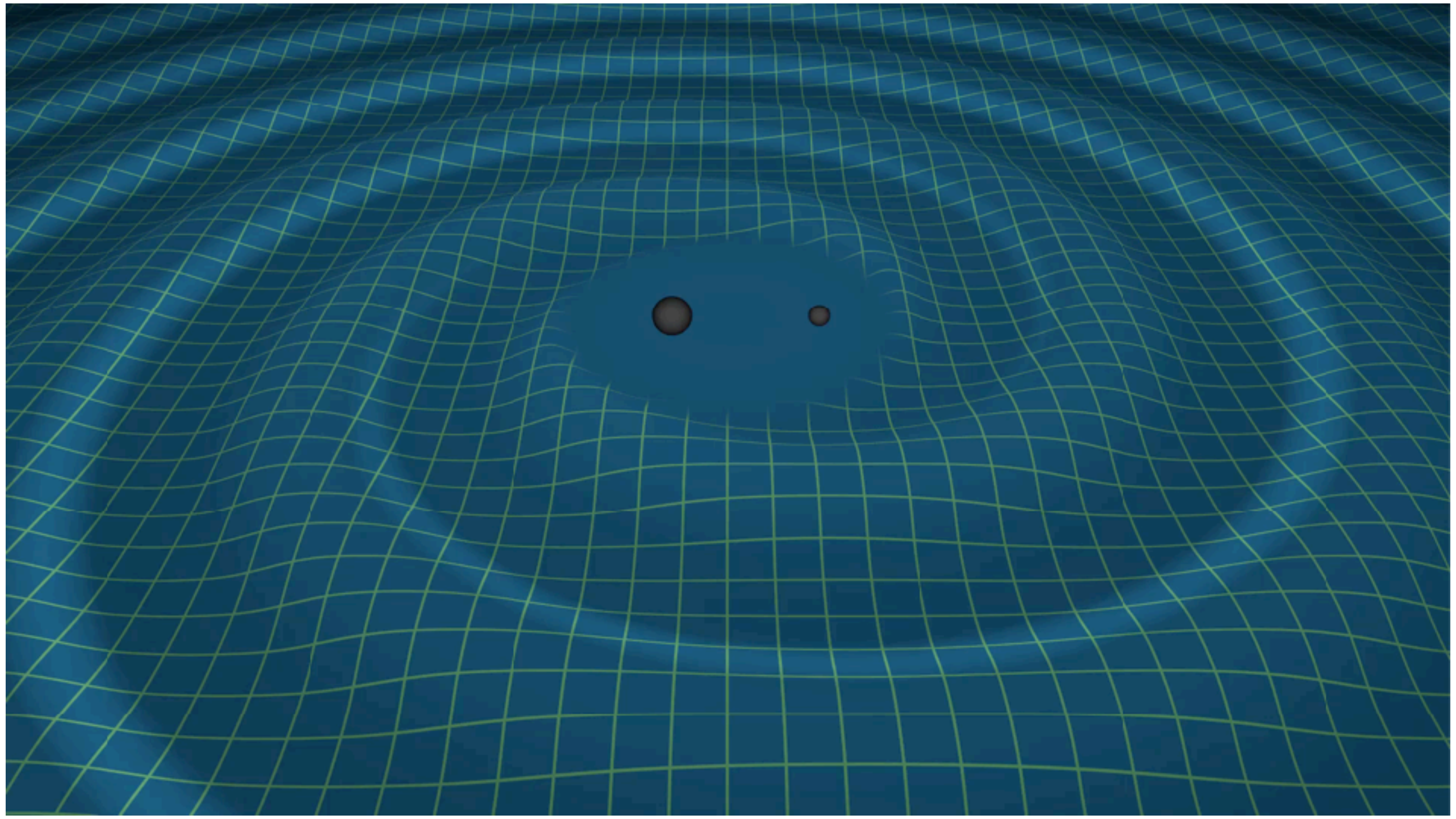
Astrophysical Lessons from LIGO-Virgo-KAGRA's Black Holes



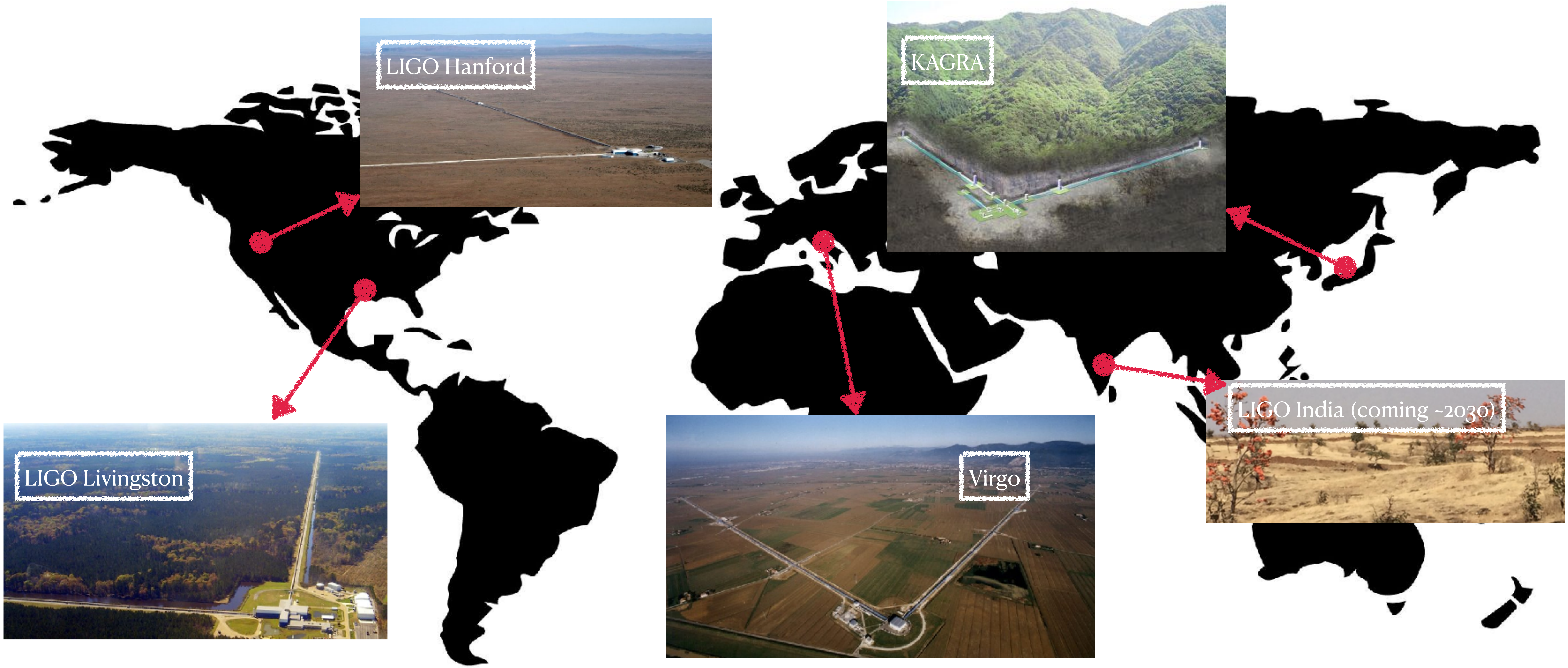
Maya Fishbach (she/her)
fishbach@cita.utoronto.ca

TevPA @University of Chicago
August 29 2024

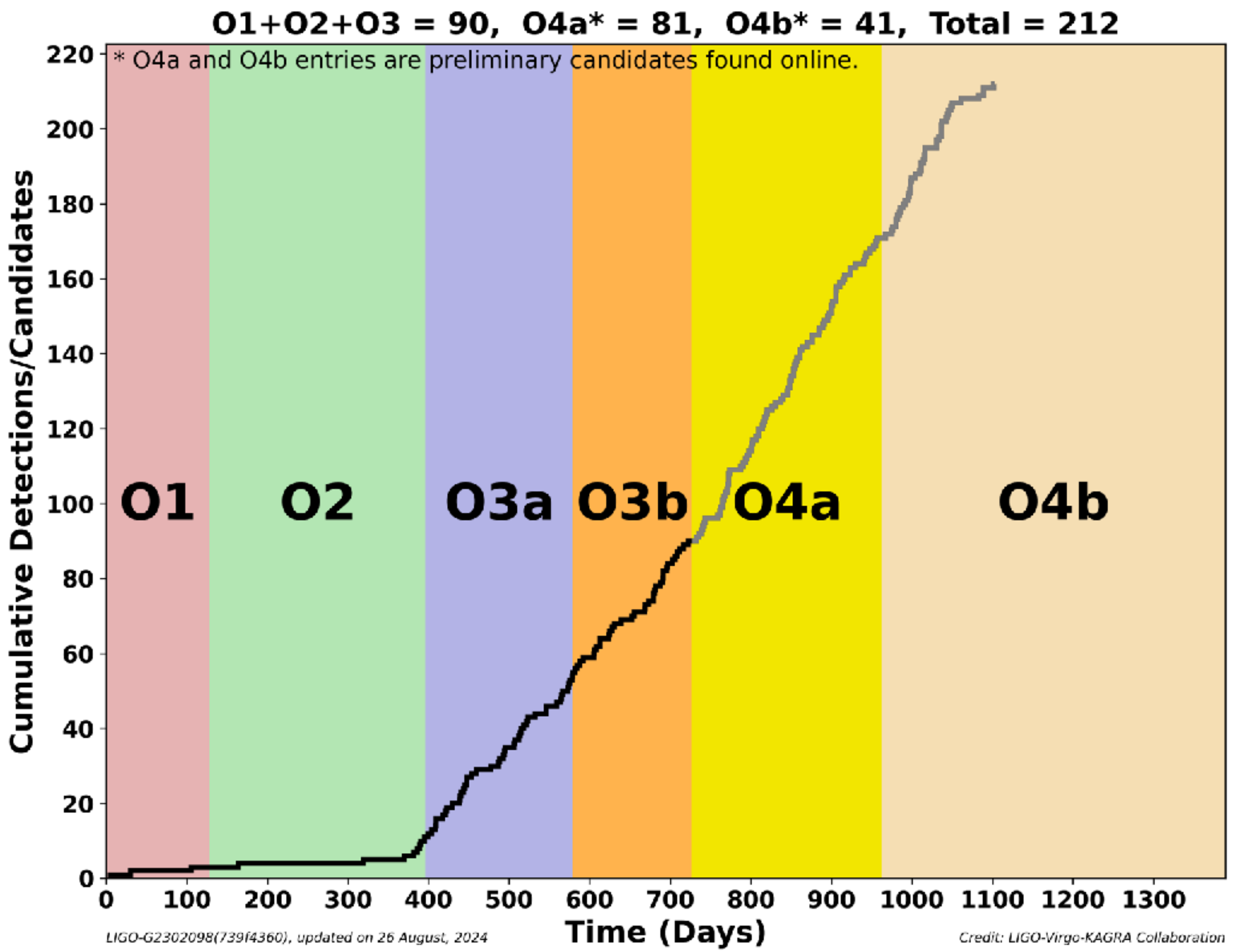
CITA | ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

UNIVERSITY OF TORONTO

LIGO-Virgo-KAGRA Detectors



Over 200 gravitational-wave observations!



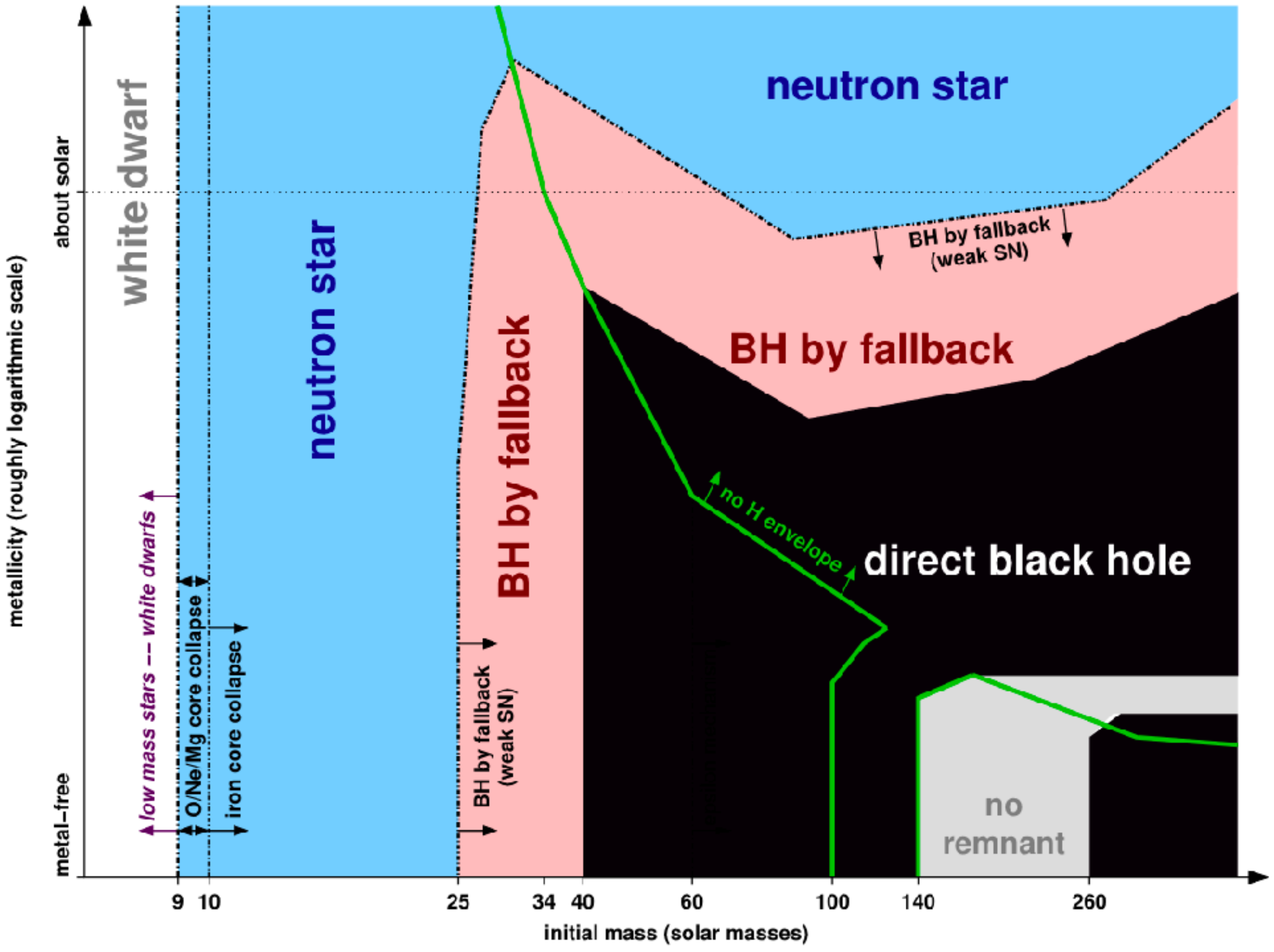
Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

How are black holes made?

Compact object remnants of massive stars

Initial metallicity

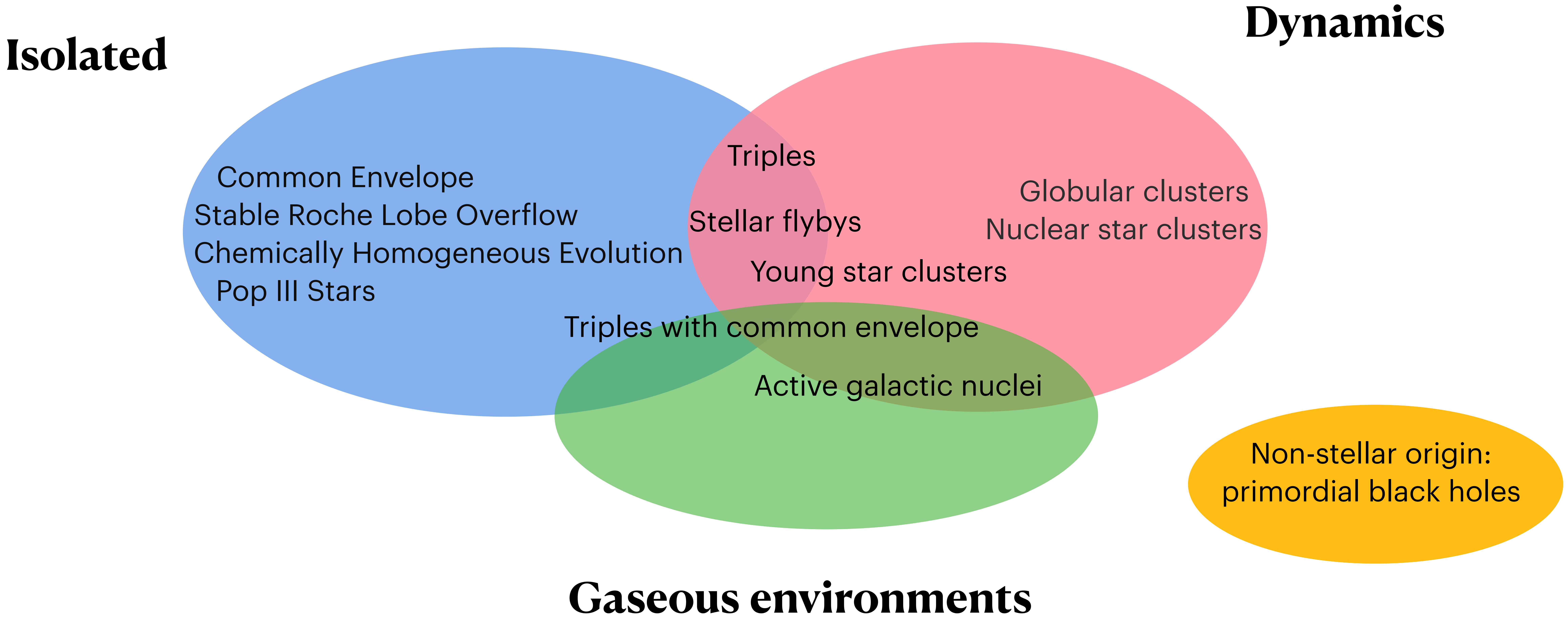


Initial mass of star

Heger, Müller & Mandel (2023)

How are *merging binary* black holes made?

“Formation channels”

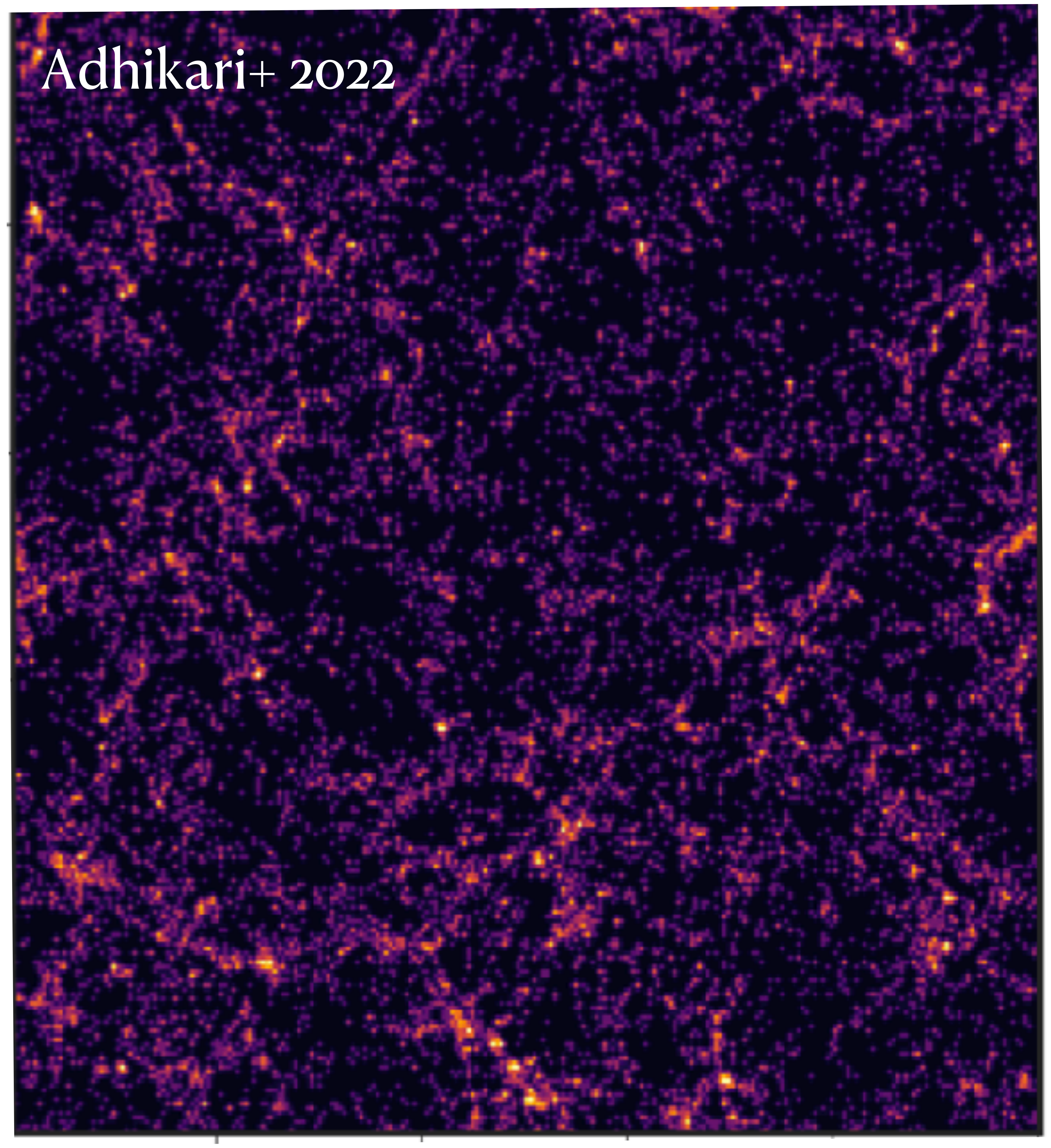


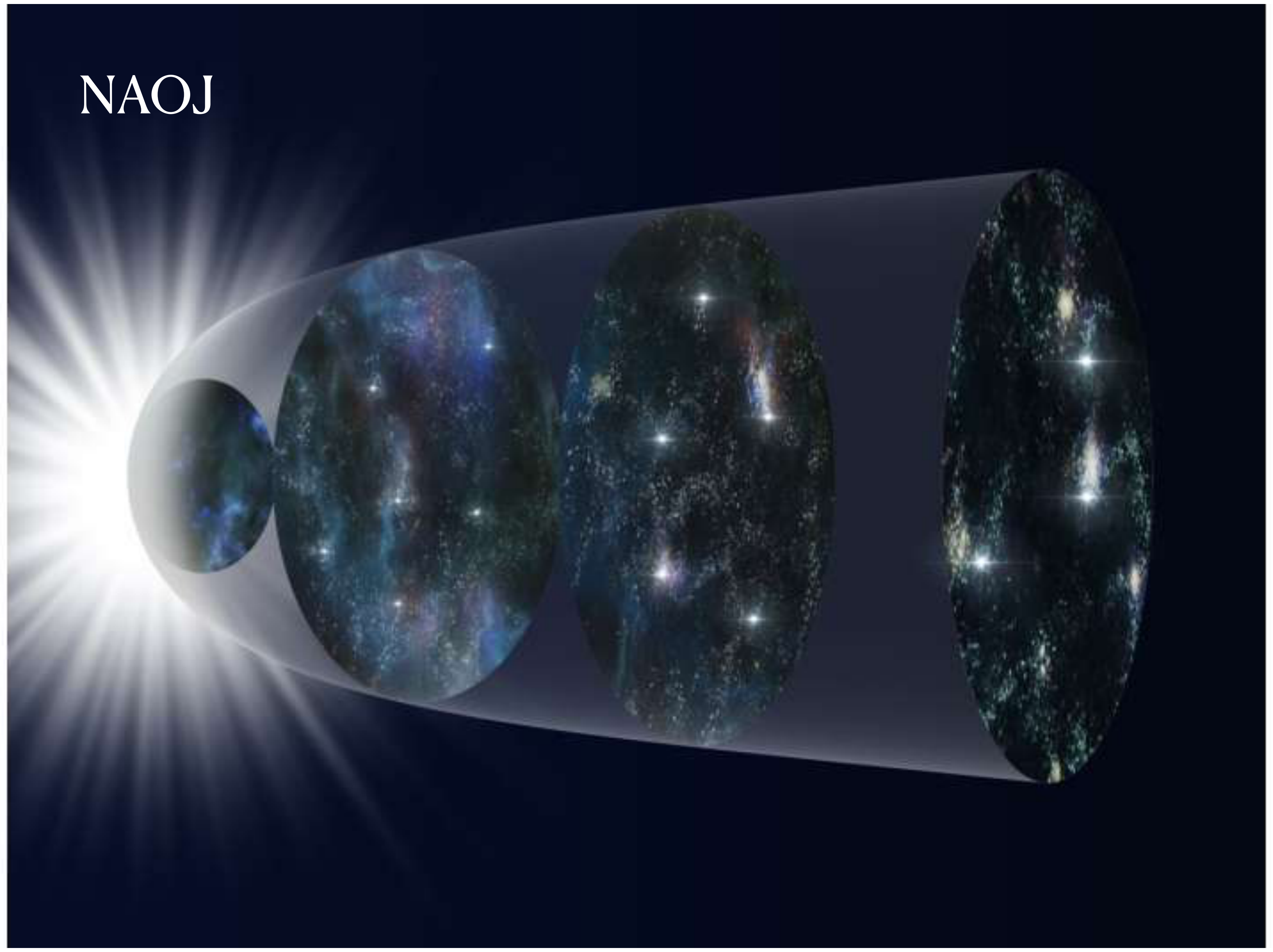
Slide adapted from Mike Zevin adapted from Selma de Mink

6

Where and when do black holes merge?

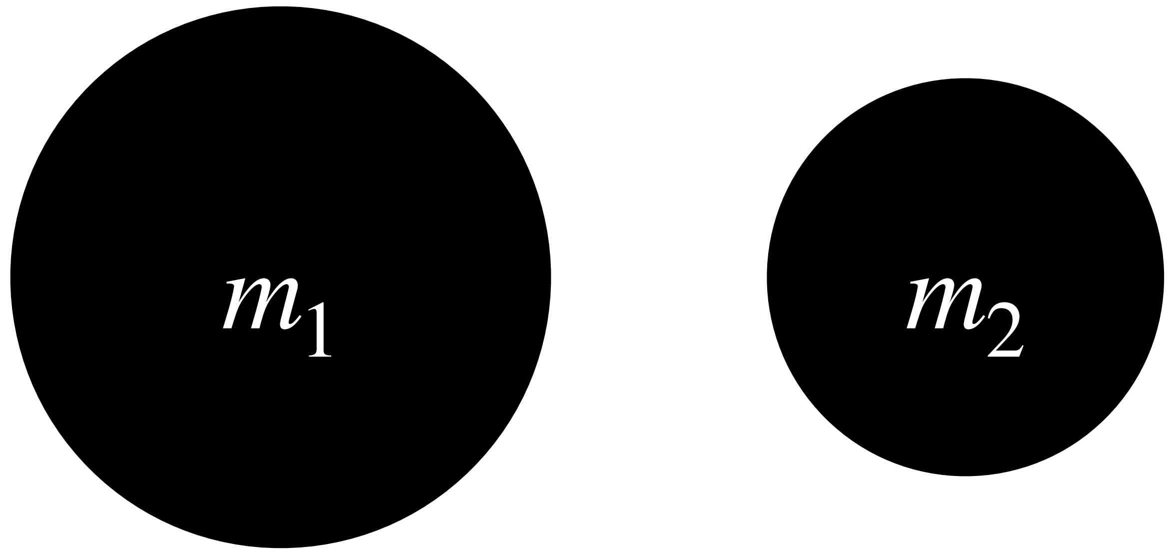
In the context of large scale structure and the cosmic expansion history



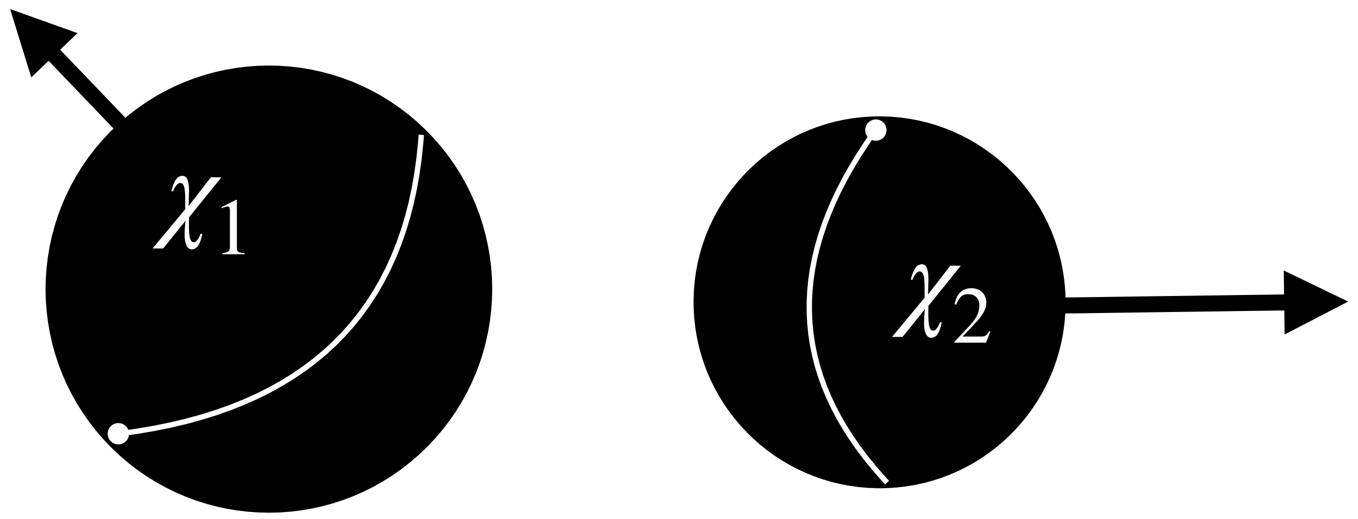


Gravitational waves encode source properties, like...

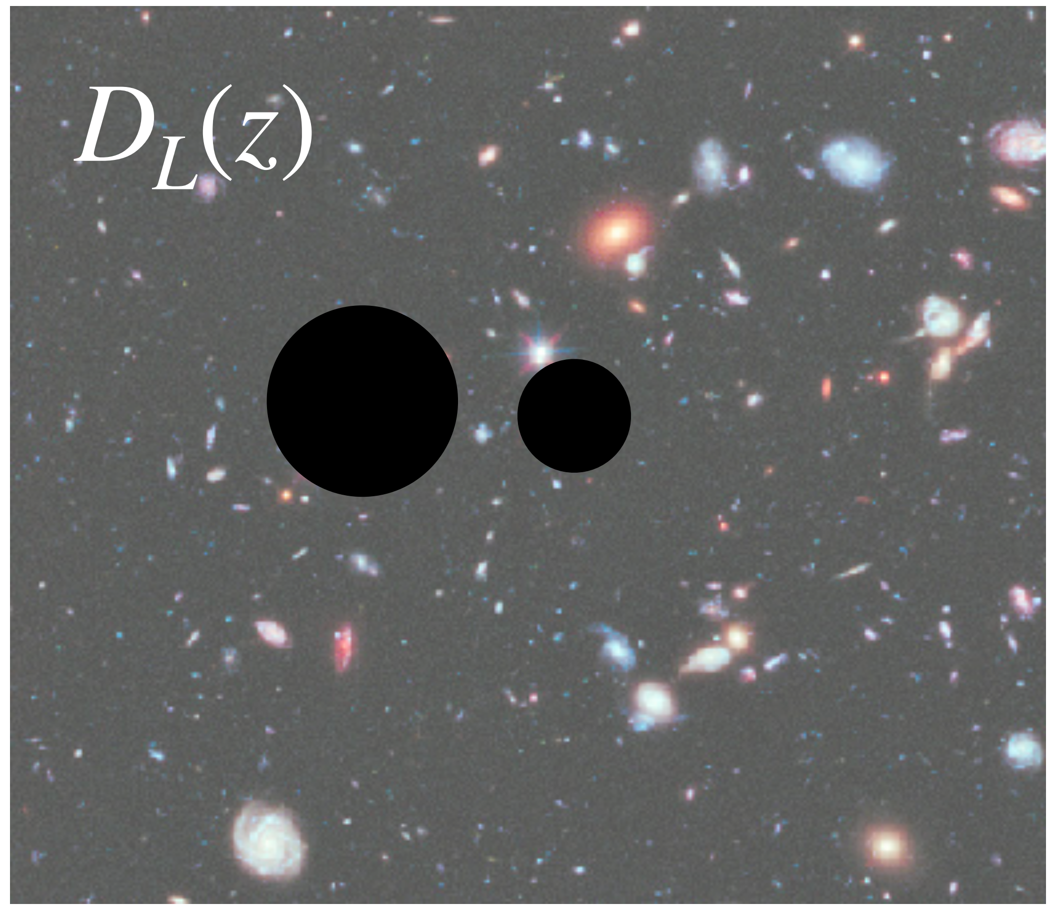
How *big* is each black hole or neutron star?



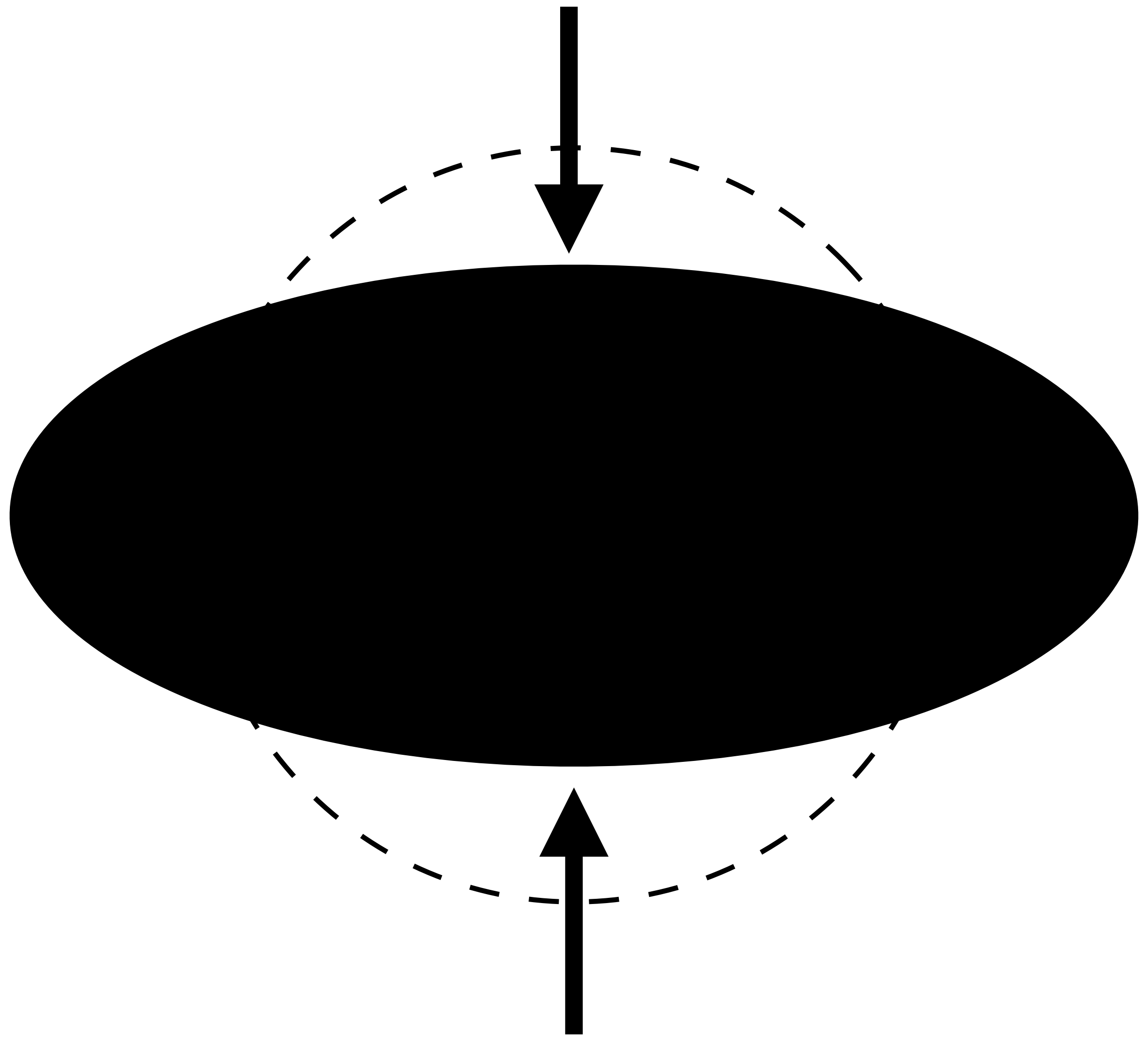
How fast are they *spinning*?



Where and *when* did they merge?

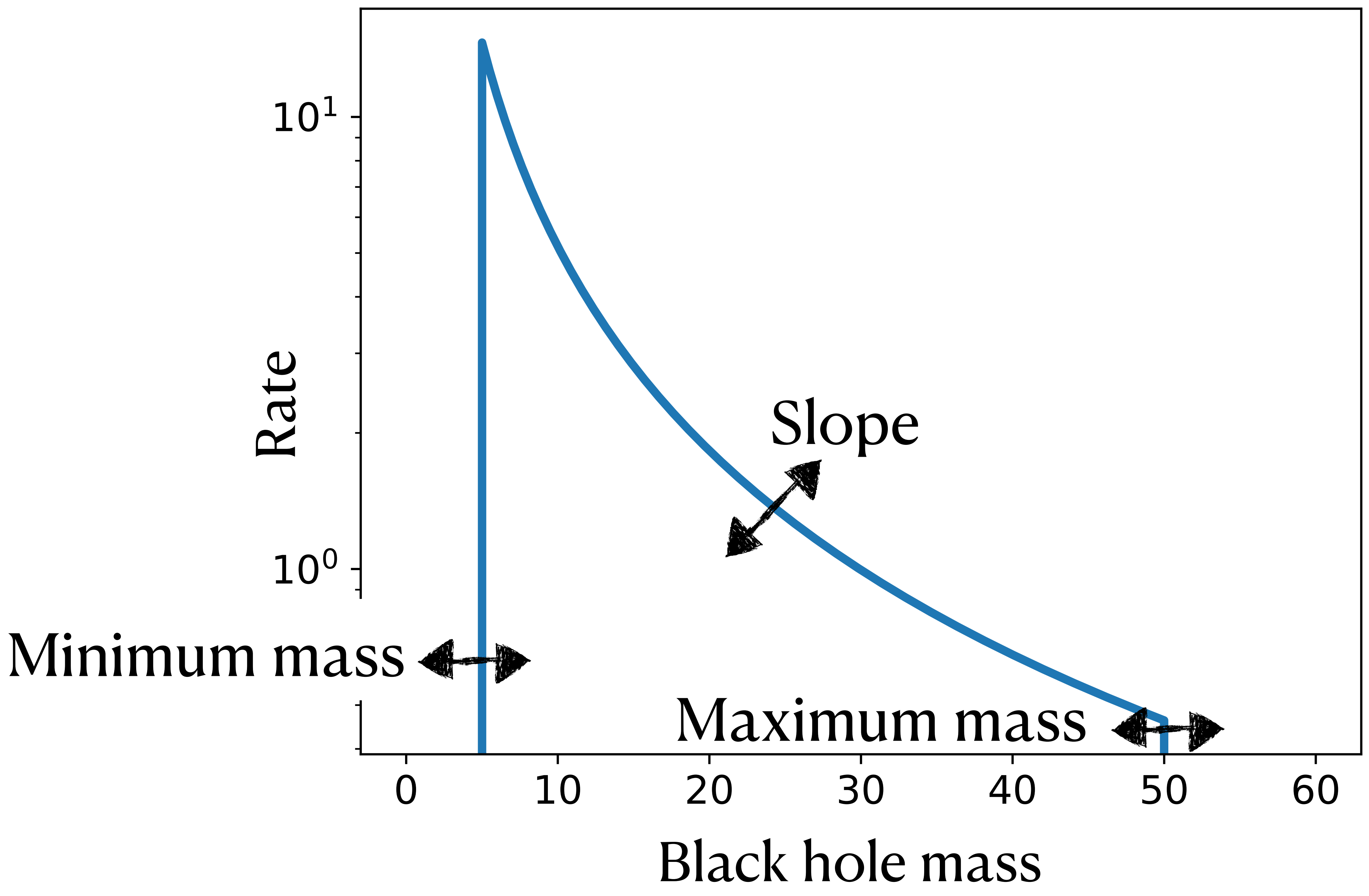


How squishy are neutron stars?



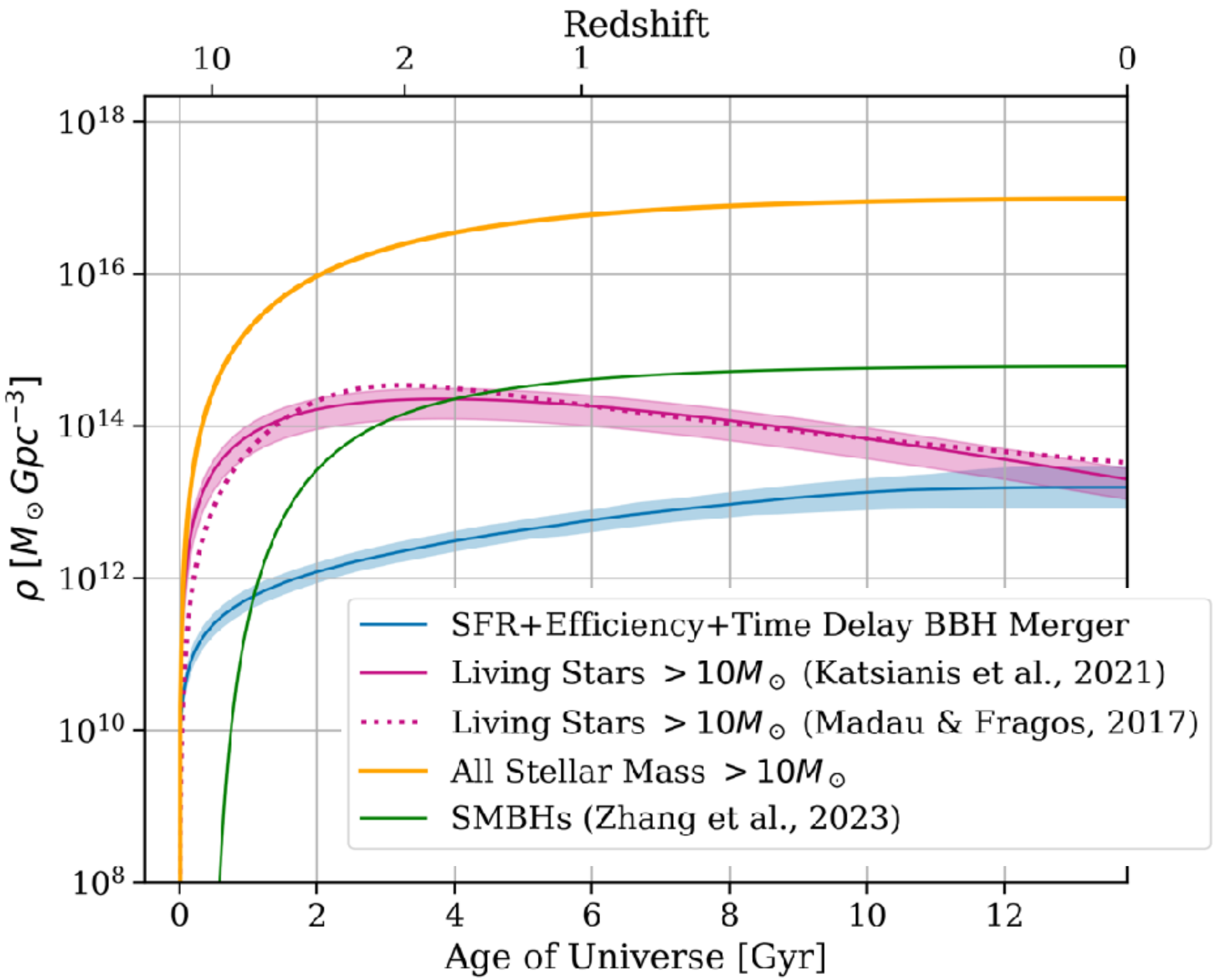
From Single Events to a Population

- 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)



Merging black holes account for only 0.01% of massive stars (by mass), but comparable to the density of massive stars that are still alive

Cumulative mass density



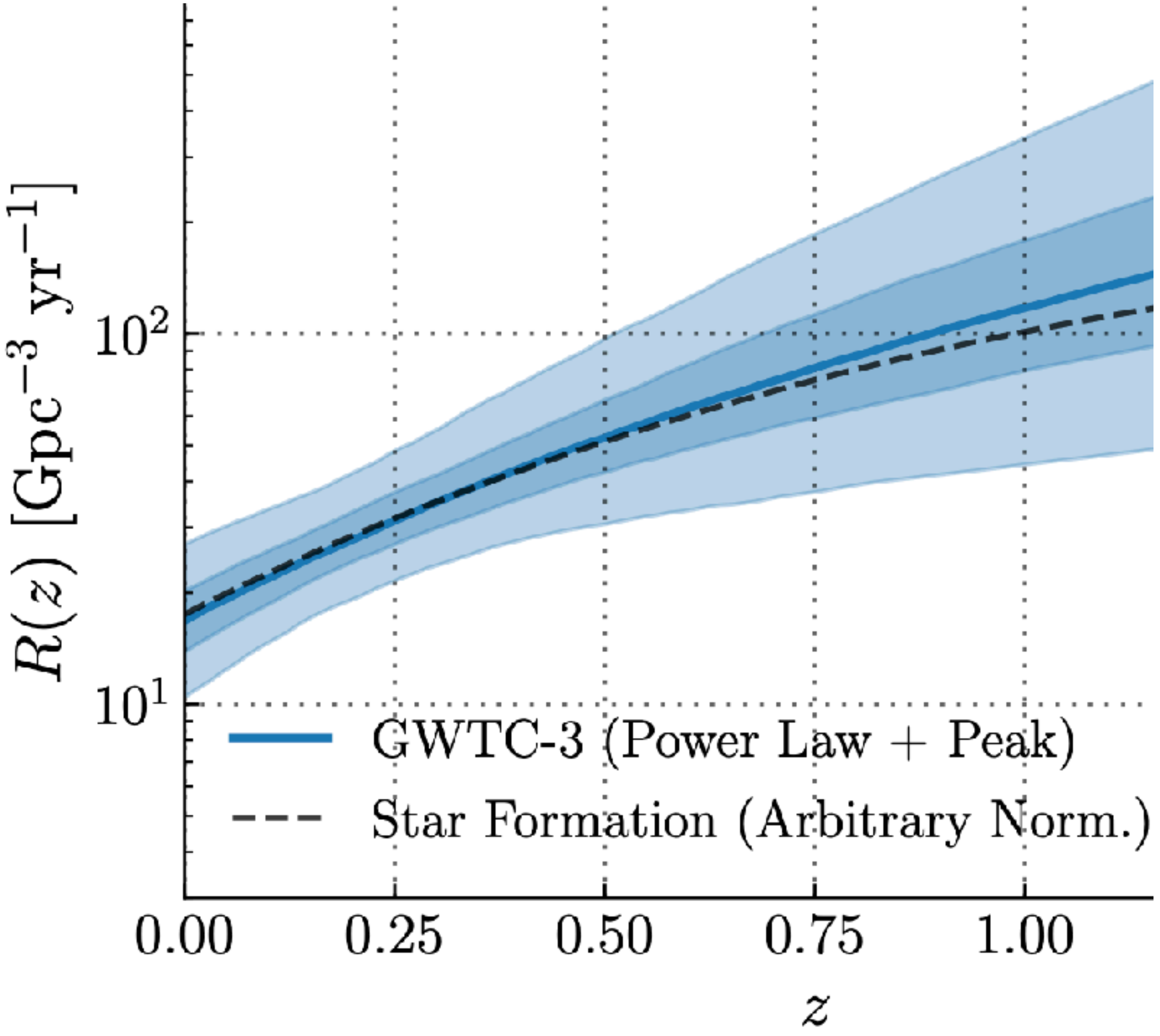
Schiebelbein-Zwack & MF ApJ 970 128 (2024)

Multimessenger view of the stellar graveyard

- Merger rate evolution and long **gamma-ray bursts**
- Most massive black holes and **pair-instability supernovae**
- Implications for **cosmological expansion history**

Black hole merger rate evolves with redshift

Merger rate density



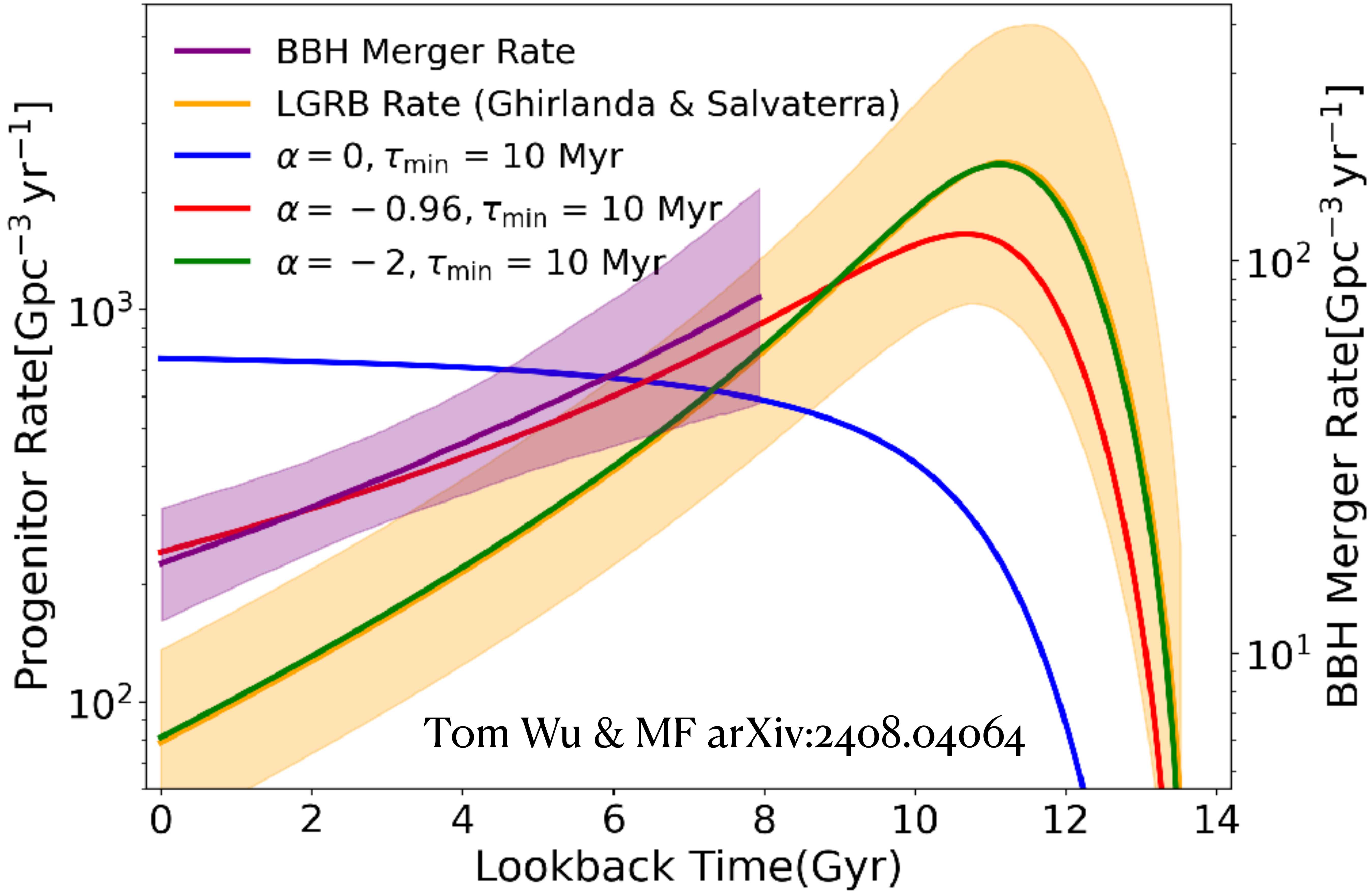
Redshift

LVK PRX 13 011048 (2023)

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

Do long GRBs trace binary black hole formation?

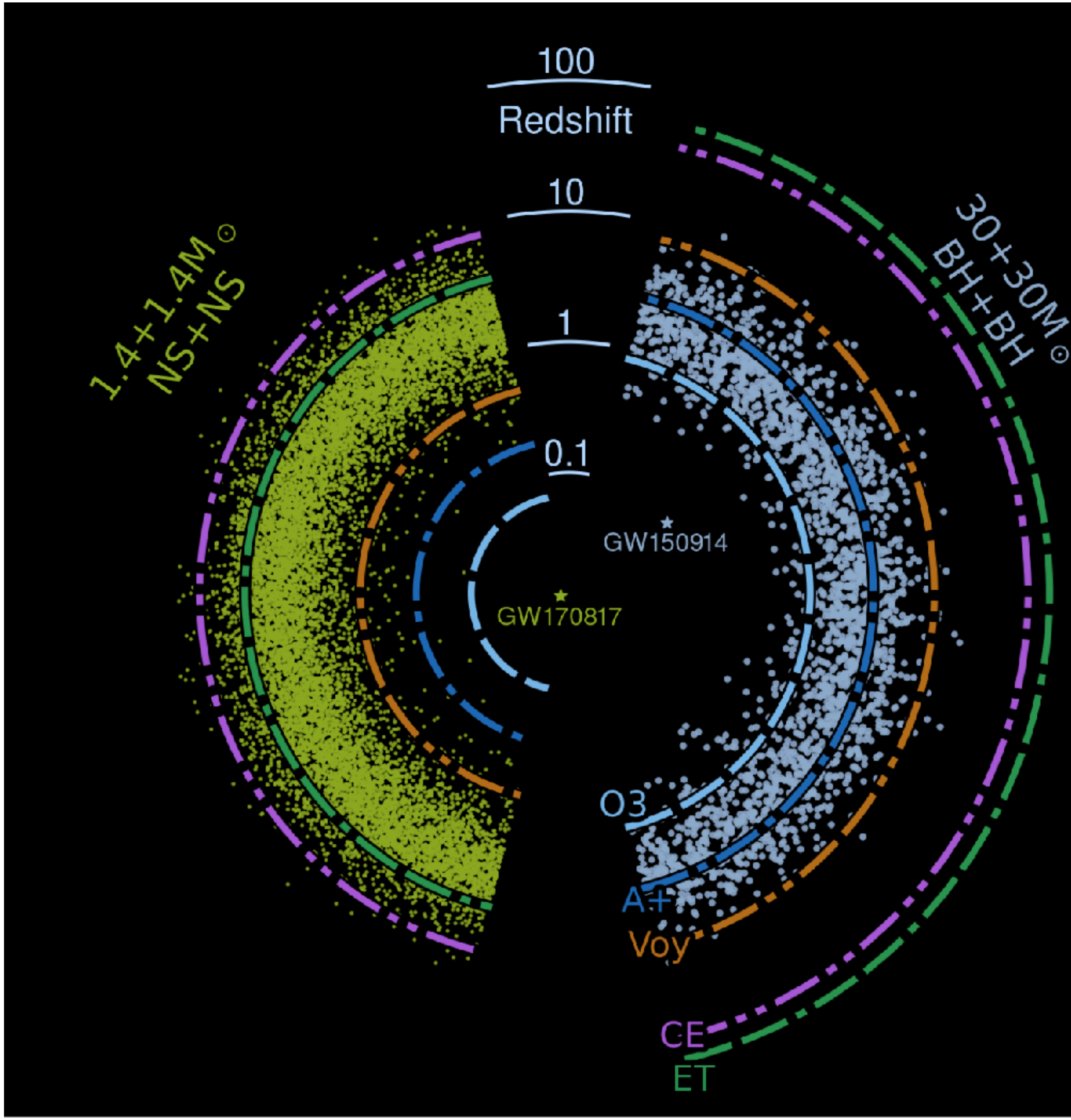
Long GRB Rate with typically-predicted delay time distribution matches shape of binary black hole merger rate (but BBH mergers are ~20 times more rare)



LGRB Rate from Ghirlanda & Salvaterra (2022)
See Bavera, Fragos, Zapartas et al. (2022) for population synthesis predictions

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 $\sim 50 - 130\, M_{\odot}$

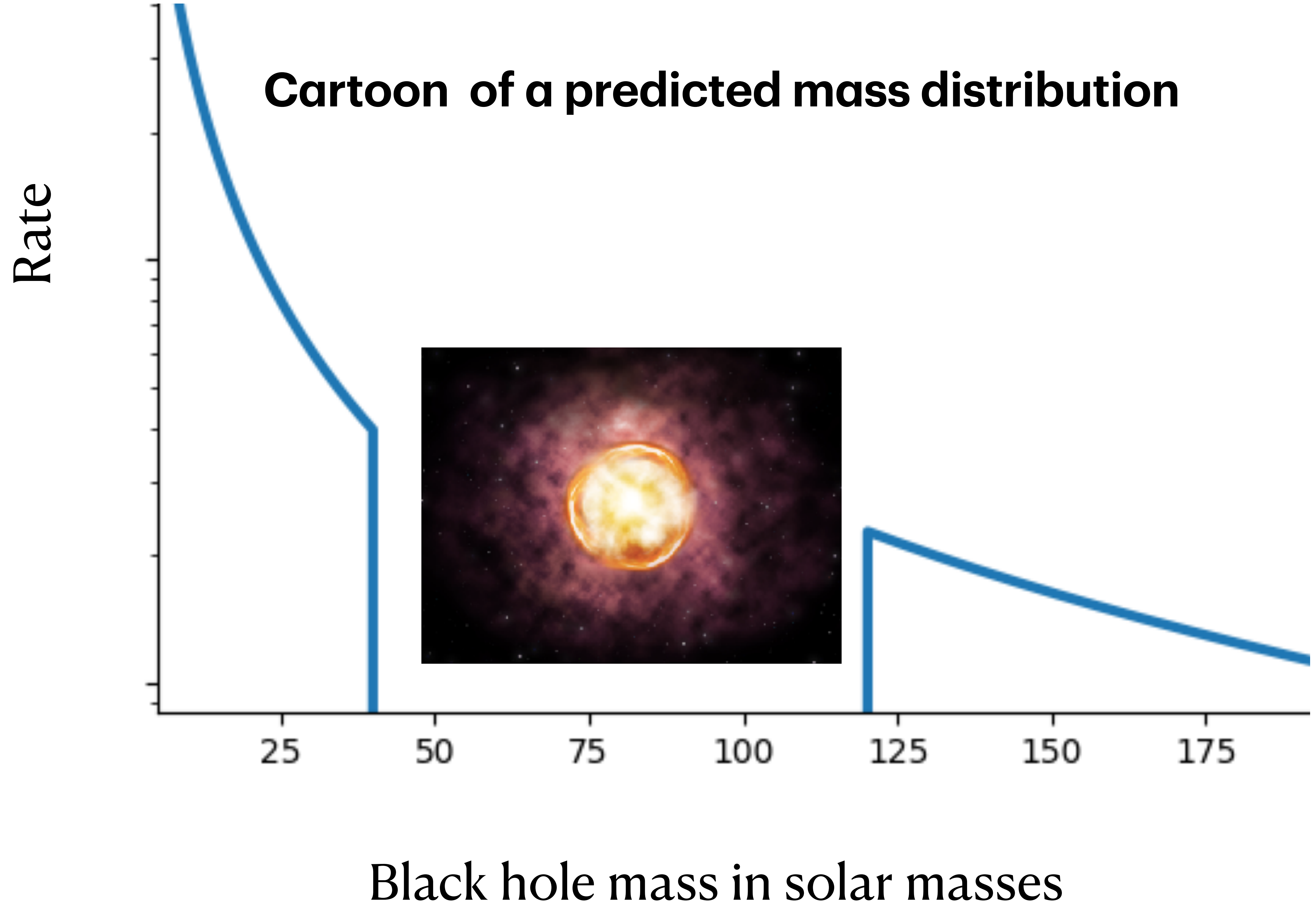
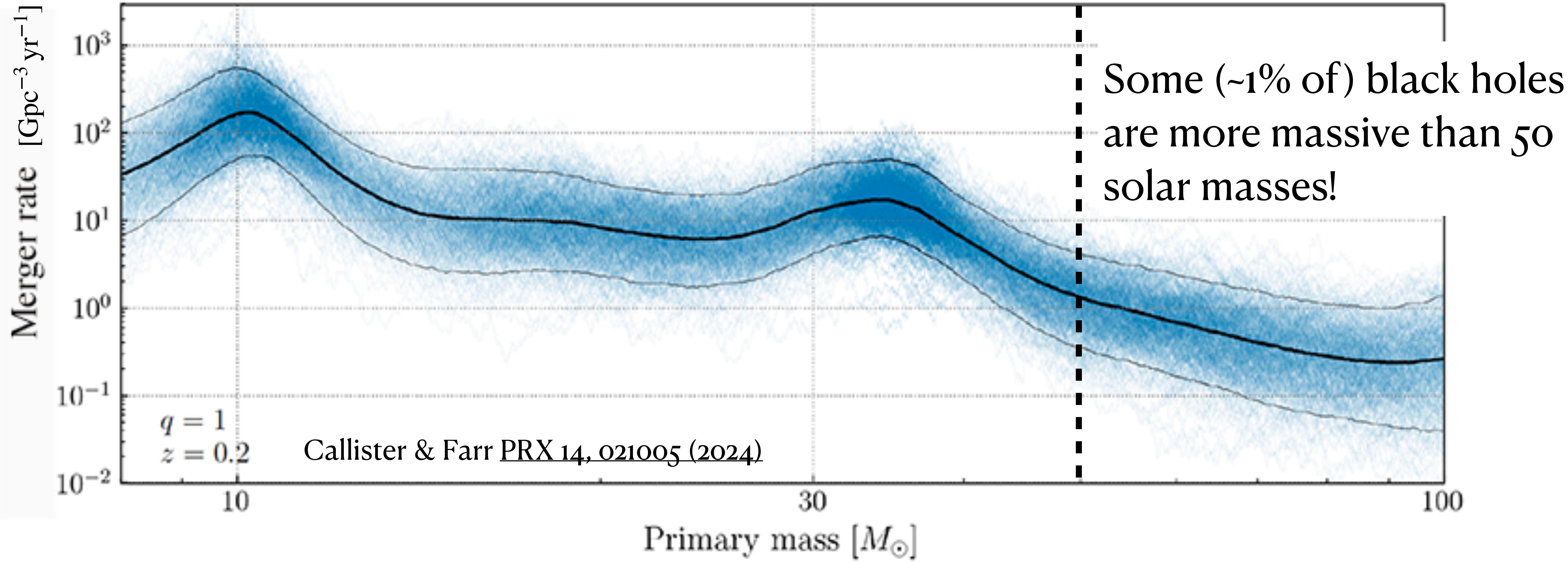


Image credit: Gemini Observatory/NSF/AURA/ illustration by Joy Pollard

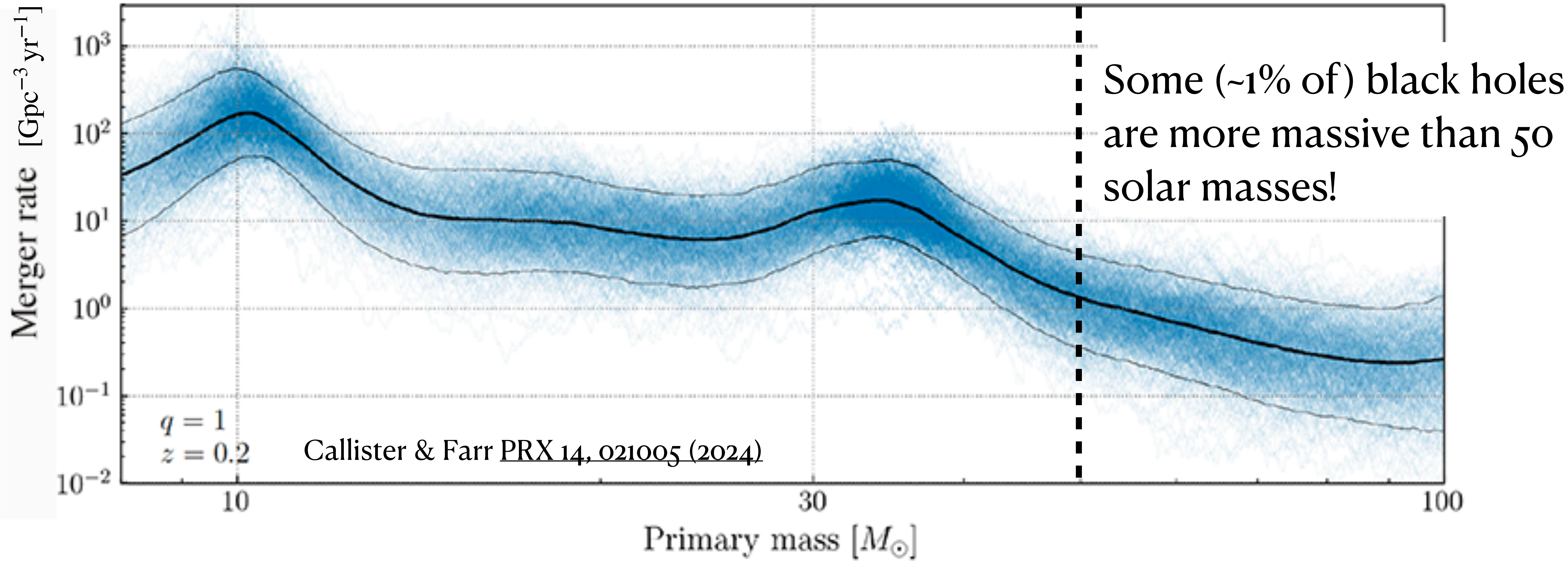
Where is the pair instability mass gap?



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?)

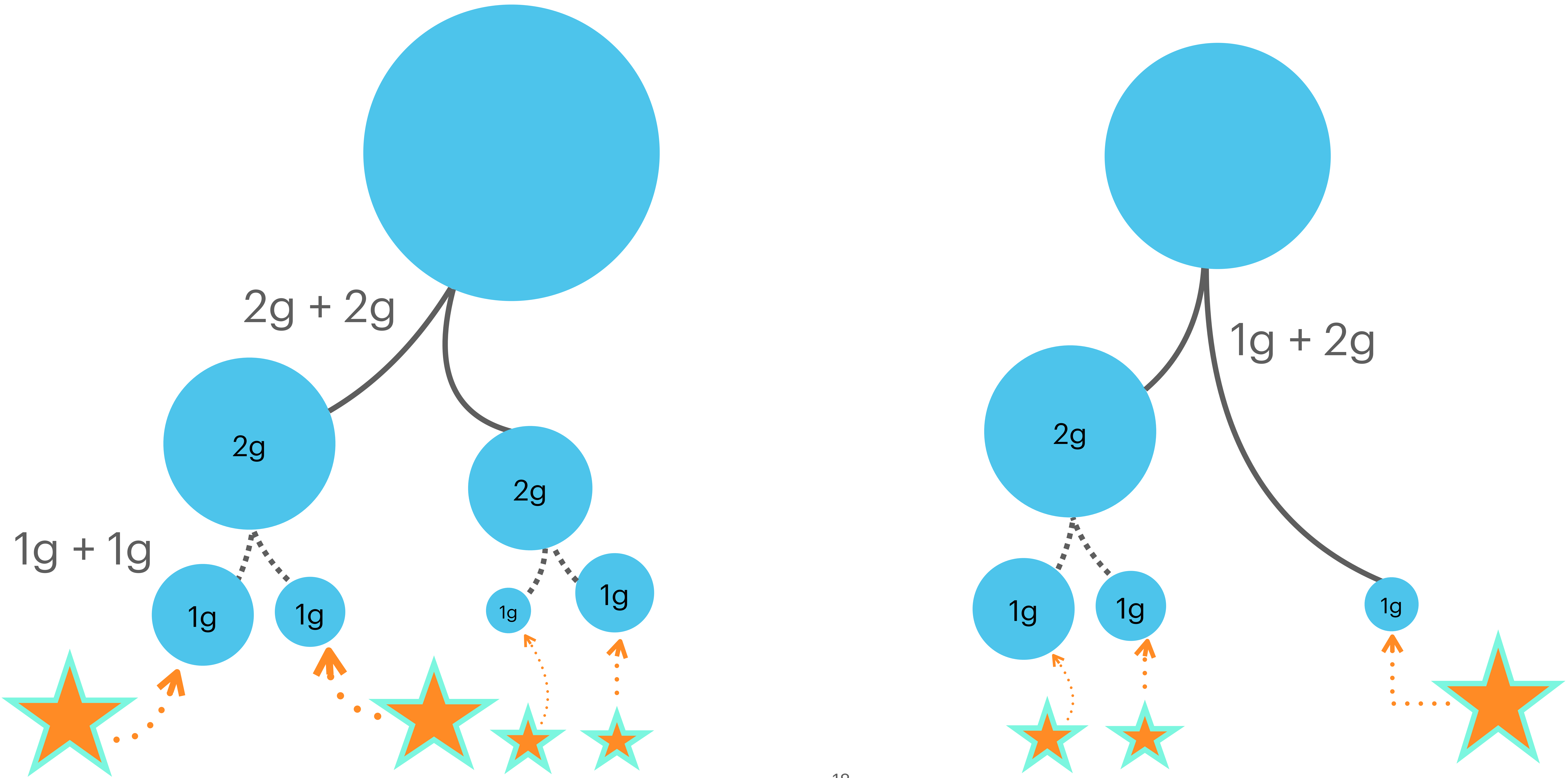
Where is the pair instability mass gap?



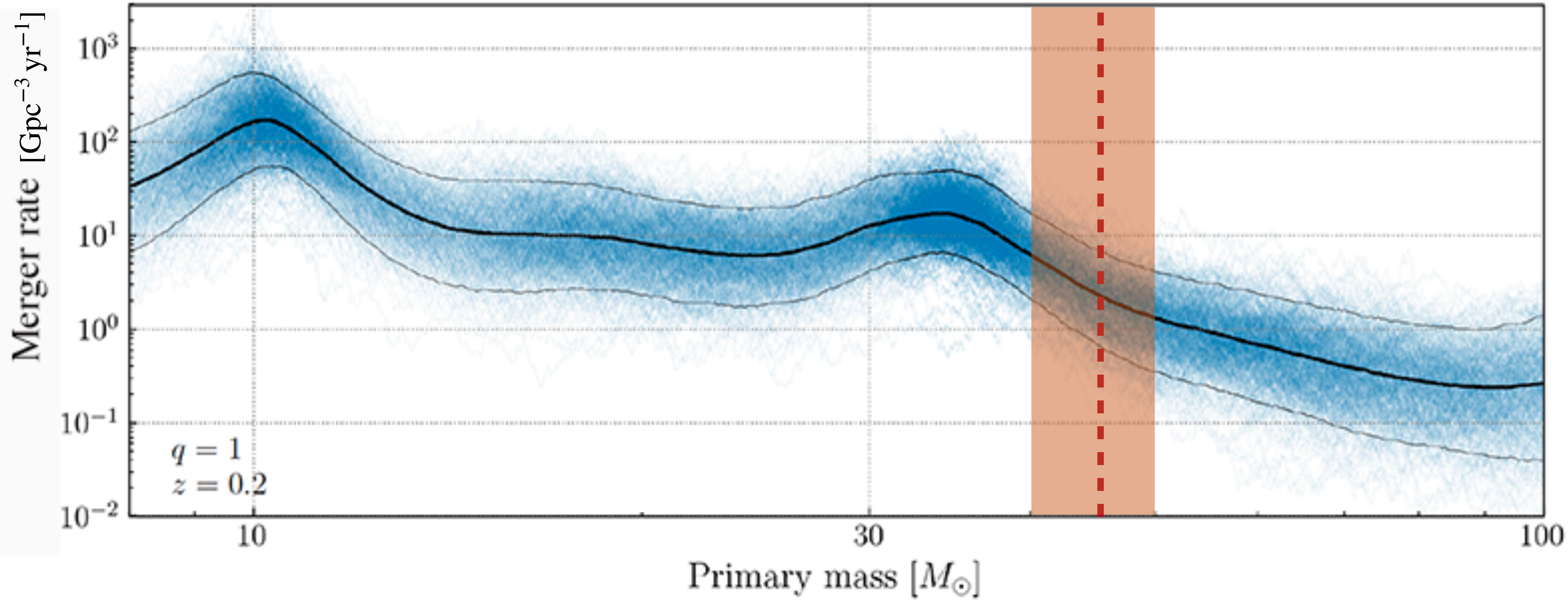
Does the mass gap start at higher masses (adjustment to nuclear reaction rates? New particles in stellar cores?)

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)?



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)…

frequency

position and orientation

GW strain

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

phase

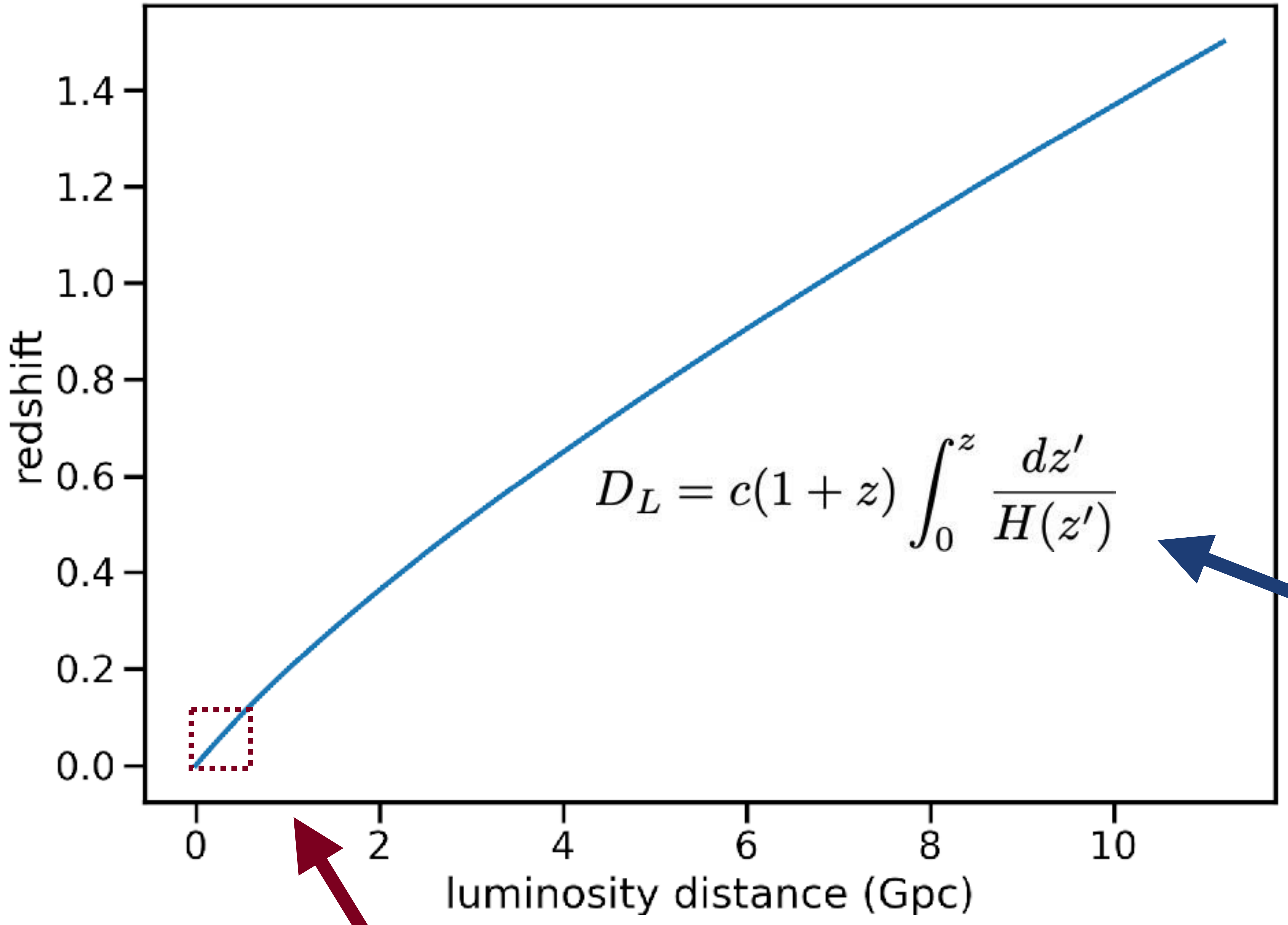
redshifted chirp mass

luminosity distance

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

…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

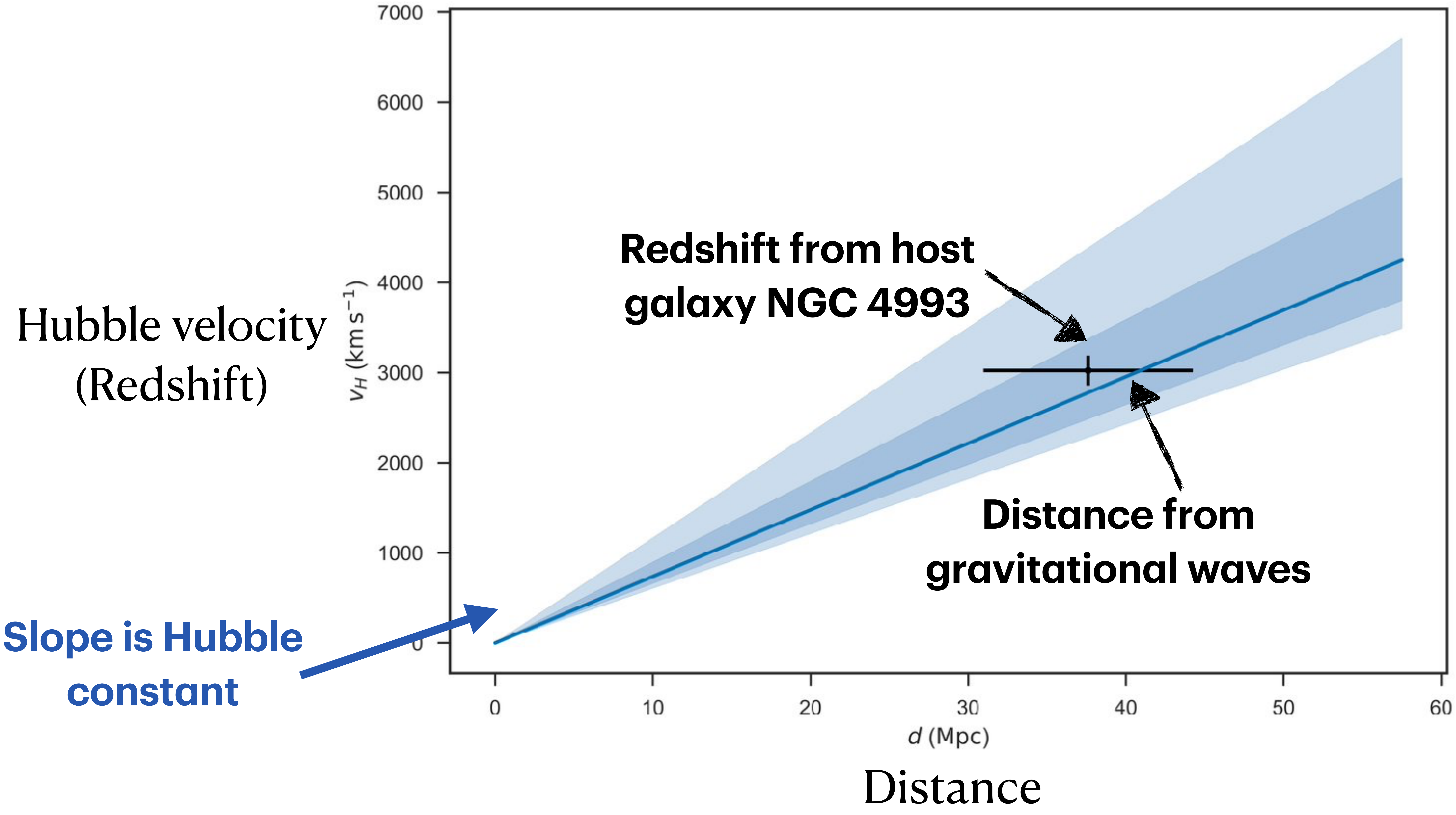
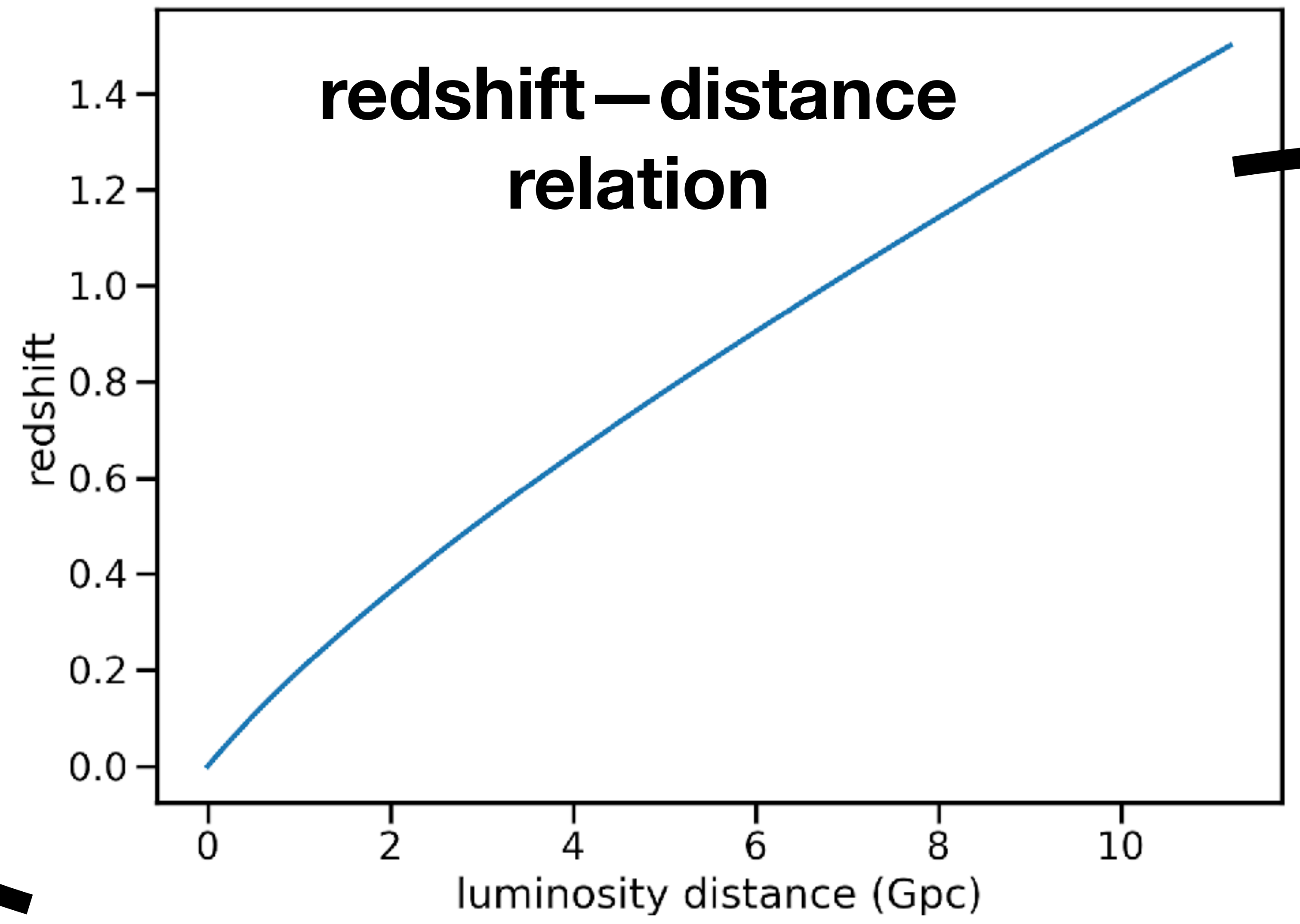
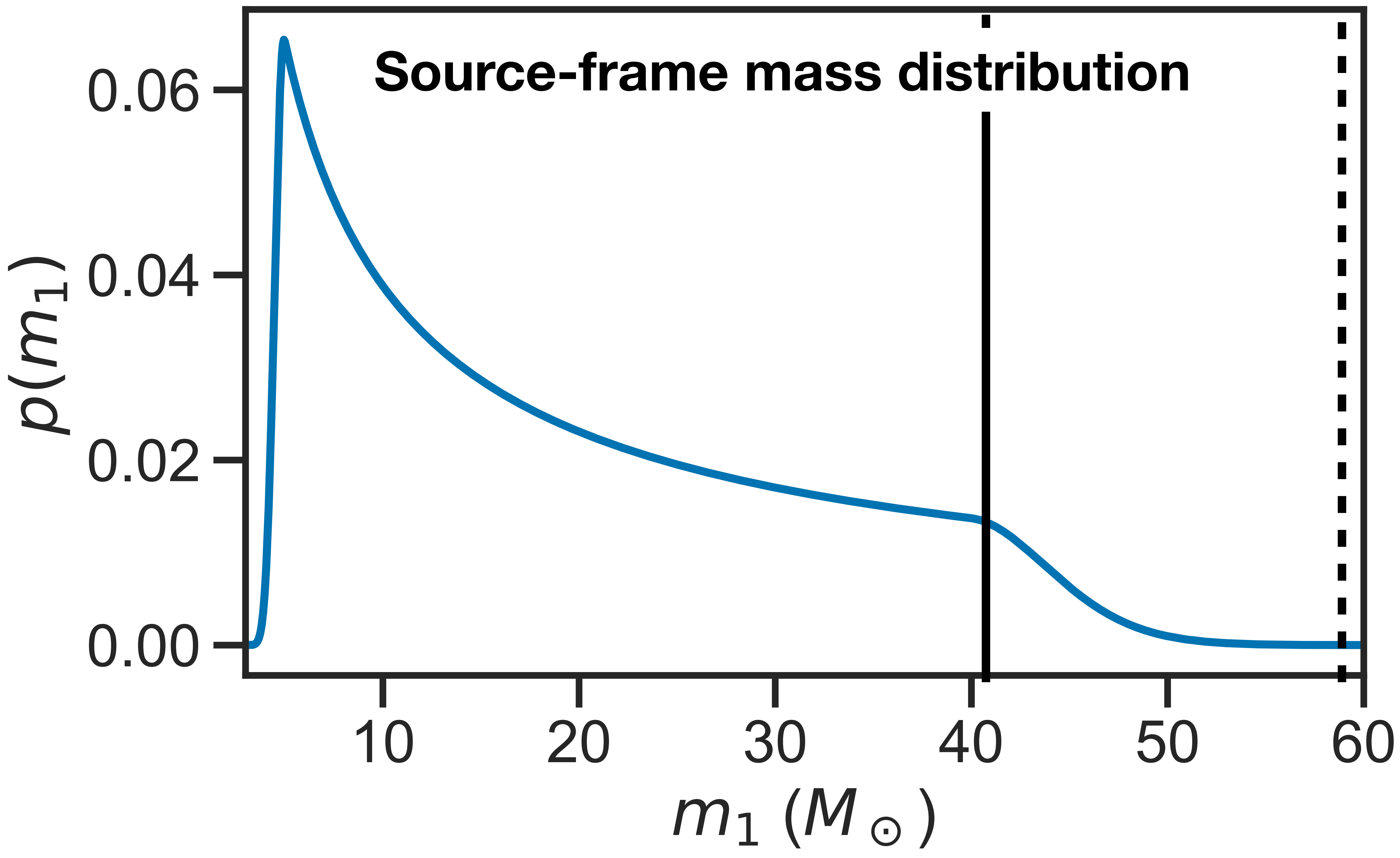


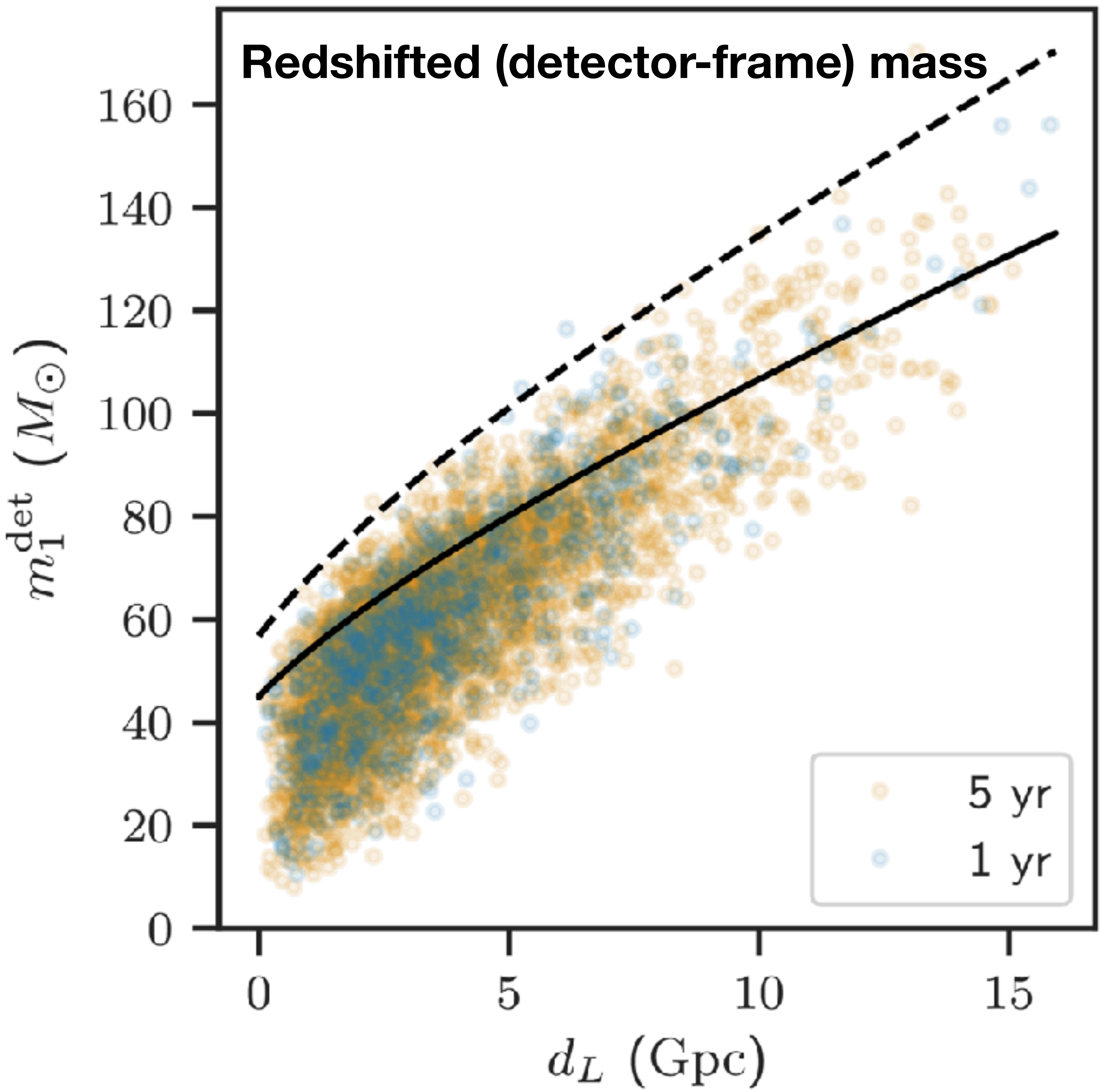
Figure Credit: Will Farr/ LIGO Scientific Collaboration

Spectral Sirens:

Simultaneously infer source population and redshift—distance relation

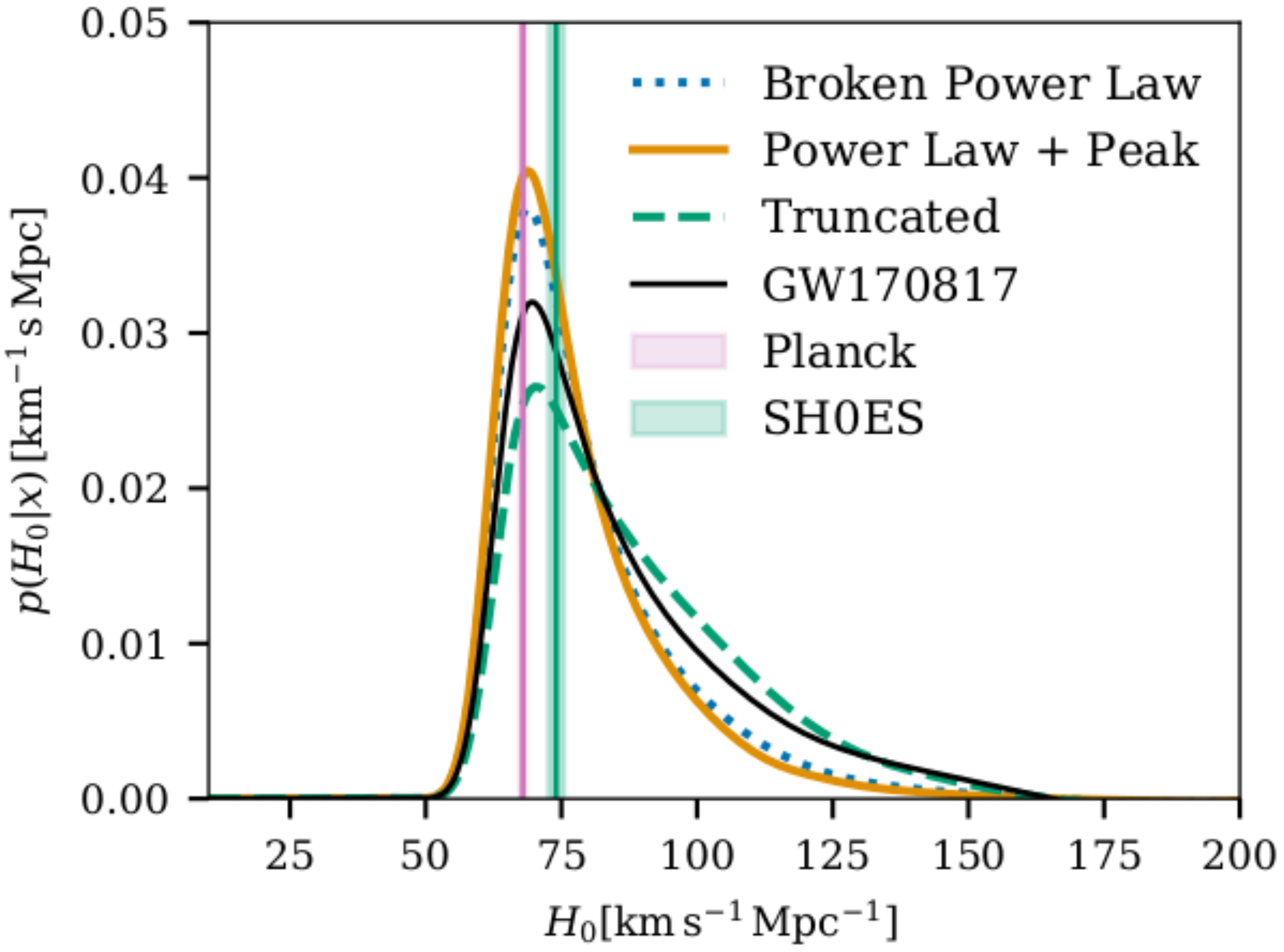






Farr, MF, Ye & Holz ApJL 883 L42 (2019)

Application of spectral siren cosmology to latest gravitational-wave catalog



LVK ApJ 949 76 (2023)

Multimessenger view of the stellar graveyard

- Redshift evolution of black hole merger rate and long **gamma-ray bursts**
  - Long gamma-ray bursts may trace progenitor rate of binary black hole mergers, with flat-in-log delay time distribution
  - Do long gamma-ray bursts produce spinning black holes? (How do black holes get their spins?)
- 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 particle 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