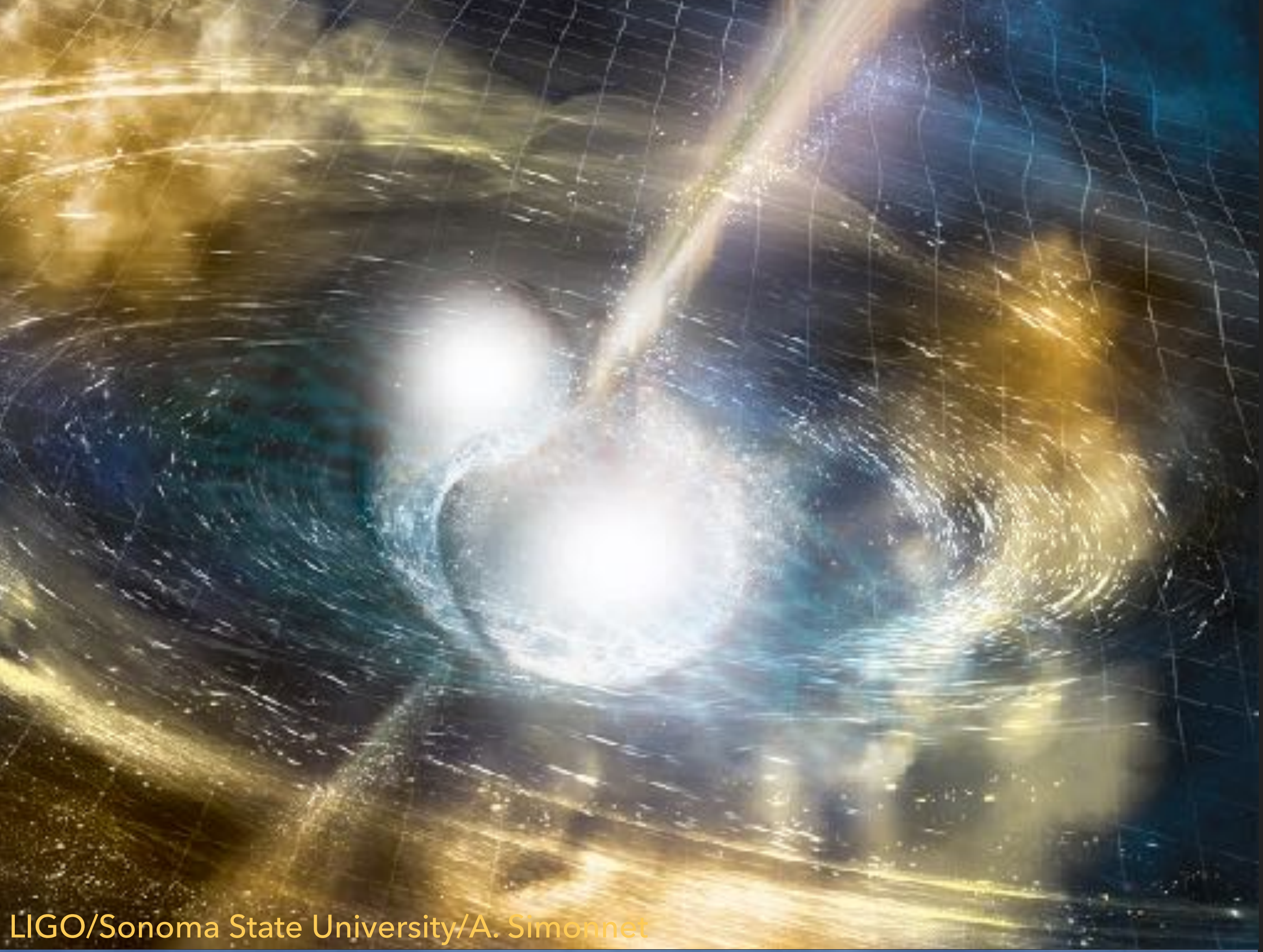

LIGO/Sonoma State University/A. Simonnet

LIGO

Some recent results in gravitational-wave astrophysics

Daniel Holz
University of Chicago

LIGO/Virgo 3rd observing run

- April 1, 2019–March 27, 2020
- ~60 detection alerts
- ~50% more sensitive than in O2!
- O3a catalog: GWTC-2
    - 50 GW events!
- 4 “exceptional” events

GWTC-2

- GWTC-2 paper
  - arXiv:2010.14527
- Testing GR
  - arXiv:2010.14529
- Population properties
  - arXiv:2010.14533

GW190425

- Another binary neutron star event
- Unfortunately, no EM counterpart
- Unusually high mass for neutron stars

The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20 https://doi.org/10.3847/2041-8213/ab75f5
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GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_\odot$

Abstract

On 2019 April 25, the LIGO Livingston detector observed a compact binary coalescence with signal-to-noise ratio 12.9. The Virgo detector was also taking data that did not contribute to detection due to a low signal-to-noise ratio, but were used for subsequent parameter estimation. The 90% credible intervals for the component masses range from 1.12 to 2.52 $M_\odot$ (1.46–1.87 $M_\odot$ if we restrict the dimensionless component spin magnitudes to be smaller than 0.05). These mass parameters are consistent with the individual binary components being neutron stars. However, both the source-frame chirp mass $1.44^{+0.02}_{-0.02}\ M_\odot$ and the total mass $3.4^{+0.3}_{-0.1} M_\odot$ of this system are significantly larger than those of any other known binary neutron star (BNS) system. The possibility that one or both binary components of the system are black holes cannot be ruled out from gravitational-wave data. We discuss possible origins of the system based on its inconsistency with the known Galactic BNS population. Under the assumption that the signal was produced by a BNS coalescence, the local rate of neutron star mergers is updated to 250–2810 $\mathrm{Gpc^{-3}\ yr^{-1}}$.

GW190412

- Binary black hole event
- A big black hole (30 Msun) and a much smaller black hole (8 Msun)
- Clues to how these binary black holes are formed

GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses

We report the observation of gravitational waves from a binary-black-hole coalescence during the first two weeks of LIGO's and Virgo's third observing run. The signal was recorded on April 12, 2019 at 05:30:44 UTC with a network signal-to-noise ratio of 19. The binary is different from observations during the first two observing runs most notably due to its asymmetric masses: a $\sim 30\,M_\odot$ black hole merged with a $\sim 8\,M_\odot$ black hole companion. The more massive black hole rotated with a dimensionless spin magnitude between 0.17 and 0.59 (90% probability). Asymmetric systems are predicted to emit gravitational waves with stronger contributions from higher multipoles, and indeed we find strong evidence for gravitational radiation beyond the leading quadrupolar order in the observed signal. A suite of tests performed on GW190412 indicates consistency with Einstein's general theory of relativity. While the mass ratio of this system differs from all previous detections, we show that it is consistent with the population model of stellar binary black holes inferred from the first two observing runs.

GW190814

- A black hole with a neutron star? Or maybe two black holes?!
- Fascinating either way

The Astrophysical Journal Letters, 896:L44 (20pp), 2020 June 20 https://doi.org/10.3847/2041-8213/ab960f

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GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

Abstract

We report the observation of a compact binary coalescence involving a 22.2–24.3 $M_\odot$ black hole and a compact object with a mass of 2.50–2.67 $M_\odot$ (all measurements quoted at the 90% credible level). The gravitational-wave signal, GW190814, was observed during LIGO's and Virgo's third observing run on 2019 August 14 at 21:10:39 UTC and has a signal-to-noise ratio of 25 in the three-detector network. The source was localized to 18.5 deg^2 at a distance of 241^{+41}_{-45} Mpc; no electromagnetic counterpart has been confirmed to date. The source has the most unequal mass ratio yet measured with gravitational waves, $0.112^{+0.008}_{-0.009}$, and its secondary component is either the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system. The dimensionless spin of the primary black hole is tightly constrained to $\leqslant 0.07$. Tests of general relativity reveal no measurable deviations from the theory, and its prediction of higher-multipole emission is confirmed at high confidence. We estimate a merger rate density of 1–23 Gpc^{-3} yr^{-1} for the new class of binary coalescence sources that GW190814 represents. Astrophysical models predict that binaries with mass ratios similar to this event can form through several channels, but are unlikely to have formed in globular clusters. However, the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models of the formation and mass distribution of compact-object binaries.

GW190521

- Two big black holes creating an intermediate mass black hole
- Both black holes are in the PISN mass gap!

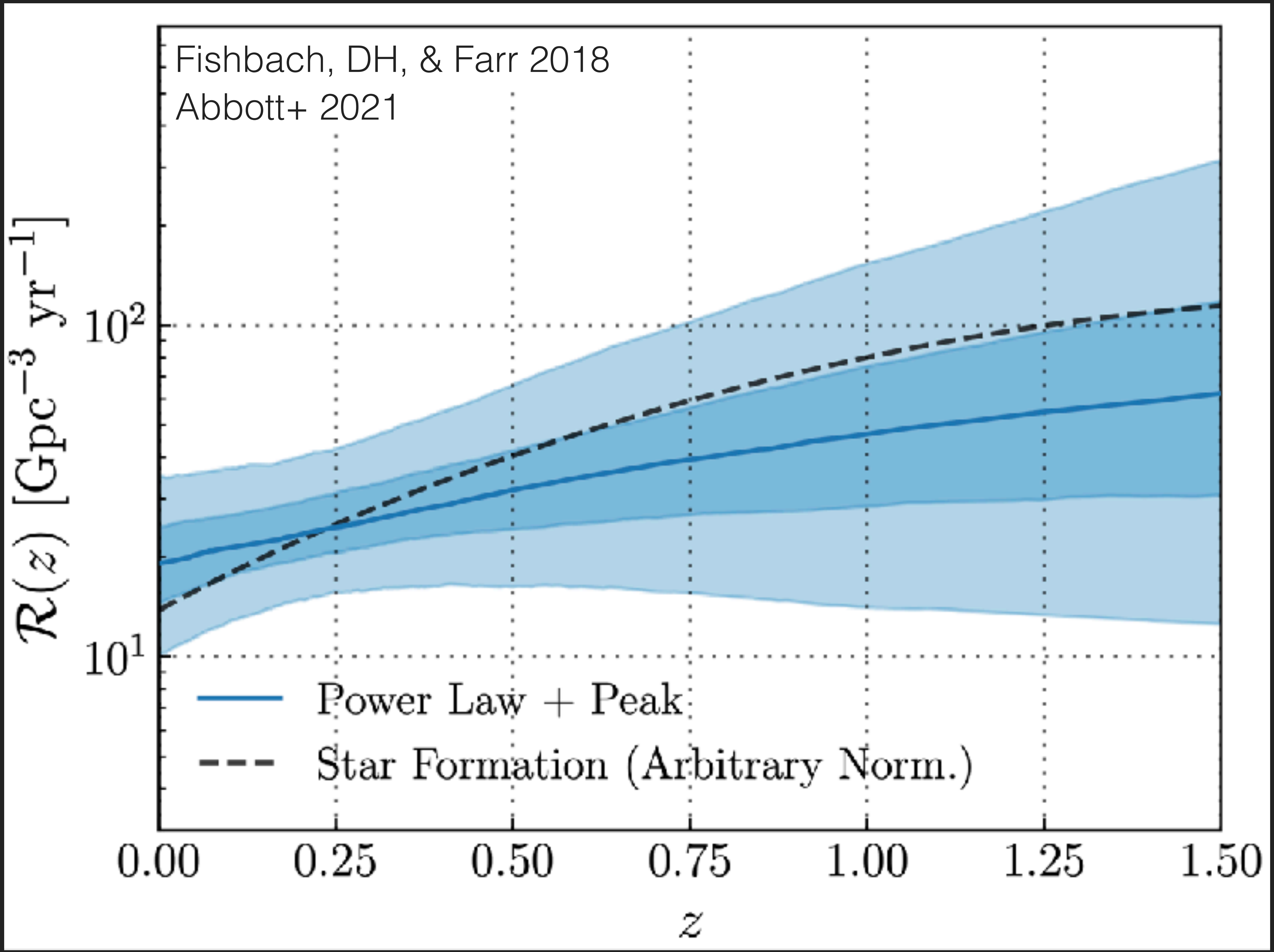
GW190521: A Binary Black Hole Merger with a Total Mass of $150 M_{\odot}$

On May 21, 2019 at 03:02:29 UTC Advanced LIGO and Advanced Virgo observed a short duration gravitational-wave signal, GW190521, with a three-detector network signal-to-noise ratio of 14.7, and an estimated false-alarm rate of 1 in 4900 yr using a search sensitive to generic transients. If GW190521 is from a quasicircular binary inspiral, then the detected signal is consistent with the merger of two black holes with masses of $85^{+21}_{-14} M_{\odot}$ and $66^{+17}_{-18} M_{\odot}$ (90% credible intervals). We infer that the primary black hole mass lies within the gap produced by (pulsational) pair-instability supernova processes, with only a 0.32% probability of being below $65 M_{\odot}$. We calculate the mass of the remnant to be $142^{+28}_{-16} M_{\odot}$, which can be considered an intermediate mass black hole (IMBH). The luminosity distance of the source is $5.3^{+2.4}_{-2.6}$ Gpc, corresponding to a redshift of $0.82^{+0.28}_{-0.34}$. The inferred rate of mergers similar to GW190521 is $0.13^{+0.30}_{-0.11}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.

Properties and astrophysical implications of the $150\,M_{\odot}$ binary black hole merger GW190521

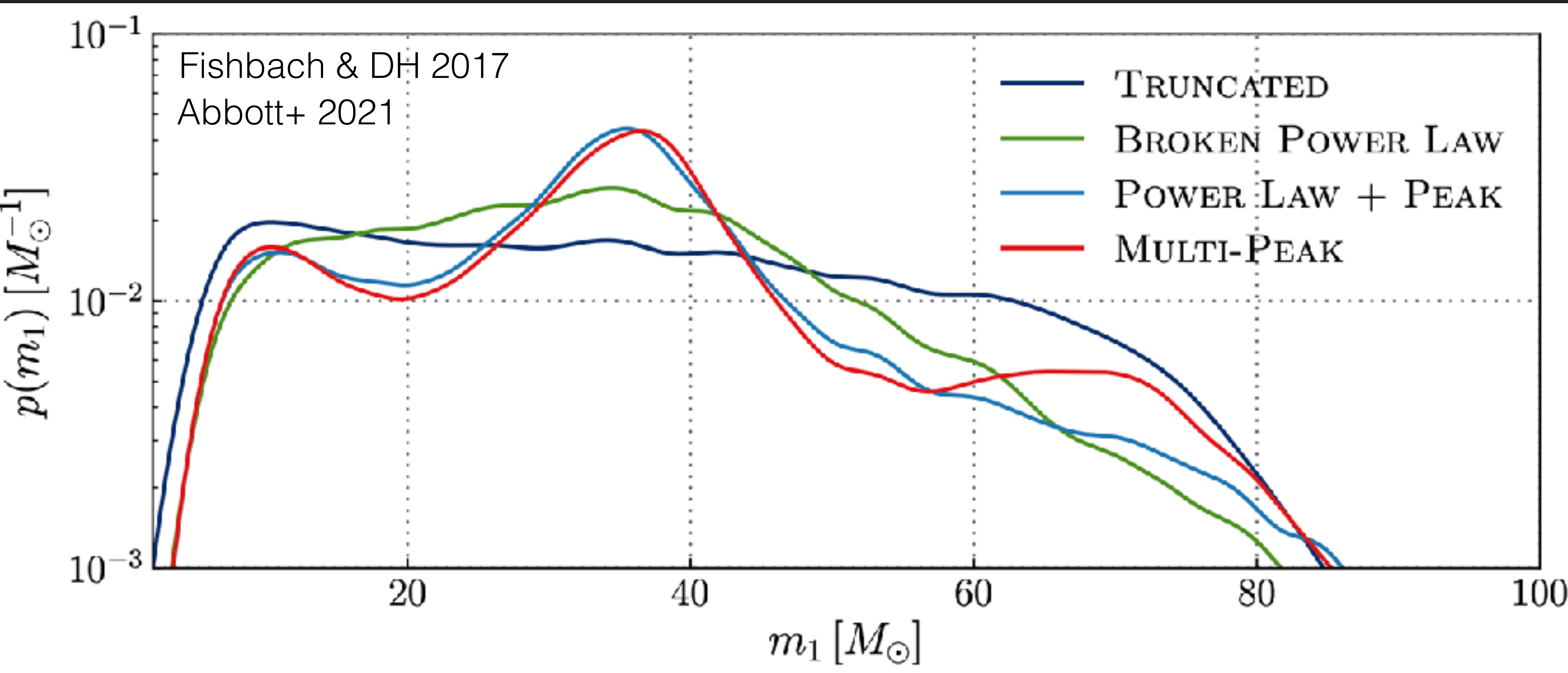
The gravitational-wave signal GW190521 is consistent with a binary black hole merger source at redshift 0.8 with unusually high component masses, $85^{+21}_{-14}\,M_{\odot}$ and $66^{+17}_{-18}\,M_{\odot}$, compared to previously reported events, and shows mild evidence for spin-induced orbital precession. The primary falls in the mass gap predicted by (pulsational) pair-instability supernova theory, while the final mass of the merger ($142^{+28}_{-16}\,M_{\odot}$) classifies it as an intermediate-mass black hole. Under the assumption of a quasi-circular binary black hole coalescence, we detail the physical properties of GW190521's source binary and its post-merger remnant, including component masses and spin vectors. Three different waveform models, as well as direct comparison to numerical solutions of general relativity, yield consistent estimates of these properties. Tests of strong-field general relativity targeting the merger-ringdown stages of the coalescence indicate consistency of the observed signal with theoretical predictions. We estimate the merger rate of similar systems to be $0.13^{+0.30}_{-0.11}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. We discuss the astrophysical implications of GW190521 for stellar collapse, and for the possible formation of black holes in the pair-instability mass gap through various channels: via (multiple) stellar coalescences, or via hierarchical mergers of lower-mass black holes in star clusters or in active galactic nuclei. We find it to be unlikely that

GWTC-2: the rate of BBH mergers evolves?!



- Weak evidence for rate evolution

GWTC-2: there is a dearth of big BBHs



- GWTC-2 confirms that the rate of BBHs with component BBHs above $\sim 45\,M_\odot$ drops precipitously
- This is a plot of **observed** primary black hole masses; the underlying distribution shows an even more pronounced drop

Some results from the last year

- Minding the gap: GW190521 as a straddling binary
  Fishbach & DH 2020 *ApJL*
- Does Matter Matter? Using the Mass Distribution to Distinguish Neutron Stars and Black Holes Fishbach, Essick, & DH 2020 *ApJL*
- Black Hole Coagulation: Modeling Hierarchical Mergers in Black Hole Populations
  Doctor, Wysocki, O'Shaughnessy, DH, & Farr 2020 *ApJ*
- The Origin of inequality: isolated formation of a 30+10$M_\odot$ binary black-hole merger Olejak, Belczynski, DH, Lasota, Bulik, & Miller 2020 *ApJL*
- Nonparametric inference of neutron star composition, equation of state, and maximum mass with GW170817 Essick, Landry, & DH 2020 *PRD*
- Direct Astrophysical Tests of Chiral Effective Field Theory at Supranuclear Densities
  Essick, Tews, Landry, Reddy, & DH 2020 *PRC*
- Counting on Short Gamma-Ray Bursts: Gravitational-Wave Constraints of Jet Geometry Farah, Essick, Doctor, Fishbach, & DH 2020 *ApJ*
- The binary-host connection: astrophysics of gravitational wave binaries from their host galaxy properties
  Adhikari, Fishbach, DH, Wechsler, & Fang 2020 *ApJ*

Some results from the last year

- Shouts and Murmurs: Combining Individual Gravitational-Wave Sources with the Stochastic Background to Measure the History of Binary Black Hole Mergers
  Callister, Fishbach, DH, & Farr 2020 *ApJL*
- Picky Partners: The Pairing of Component Masses in Binary Black Hole Mergers
  Fishbach & DH 2020 *ApJL*
- The Most Massive Binary Black Hole Detections and the Identification of Population Outliers Fishbach, Farr, & DH 2020 *ApJL*
- Jumping the gap: searching for LIGO's biggest black holes
  Ezquiaga & DH 2021 ApJL
- Phase effects from strong gravitational lensing of gravitational waves
  Ezquiaga, DH, Hu, Lagos, & Wald 2021 *PRD*
- One Channel to Rule Them All? Constraining the Origins of Binary Black Holes using Multiple Formation Pathways
  Zevin+ 2021, *ApJ*
- Black Hole Leftovers: The Remnant Population from Binary Black Hole Mergers
  Doctor, Farr, & Holz 2021; arXiv:2103.04001
- When are LIGO/Virgo's Big Black-Hole Mergers?
  Fishbach+ 2021; arXiv:2101.07699

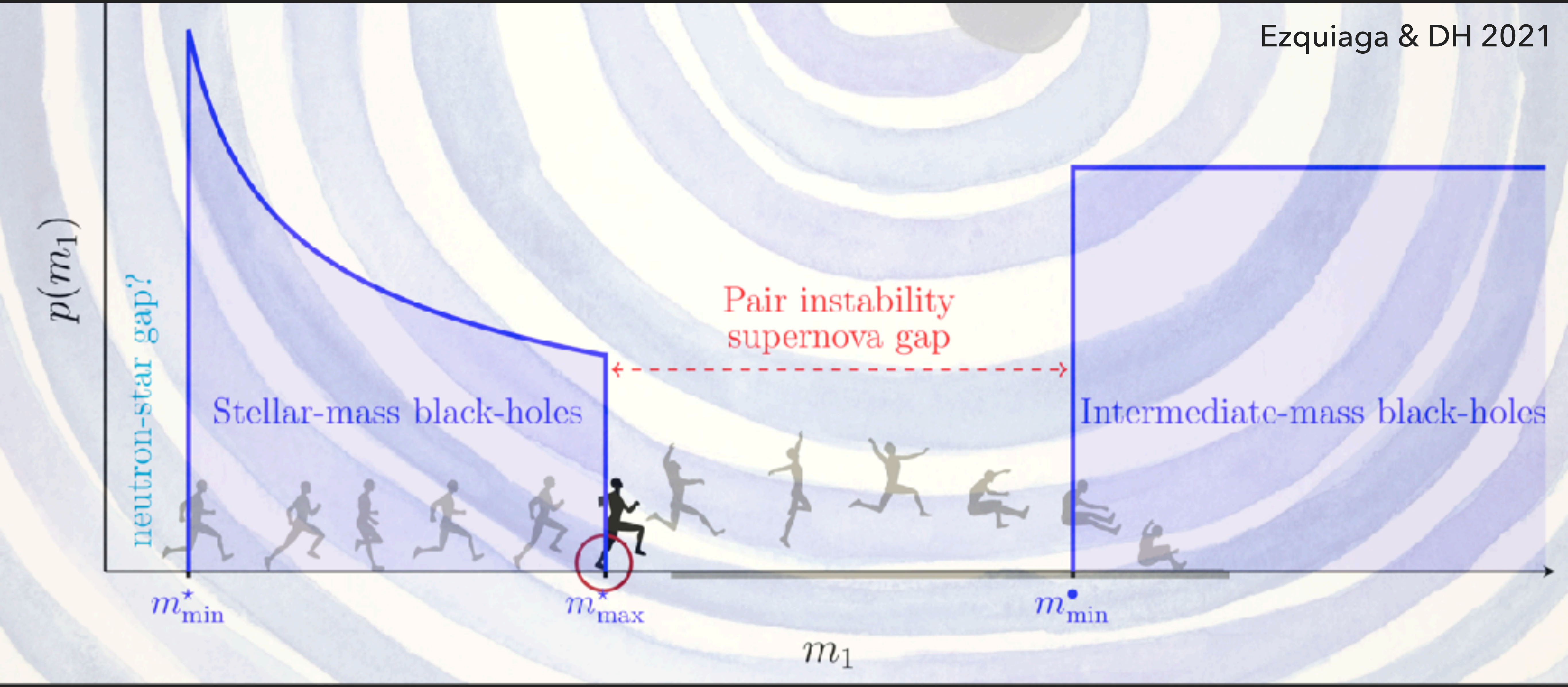
Two black hole gaps

- NSBH gap: in between most massive neutron star and least massive black hole

$$\sim 2.5\,M_\odot < M < \sim 5\,M_\odot$$

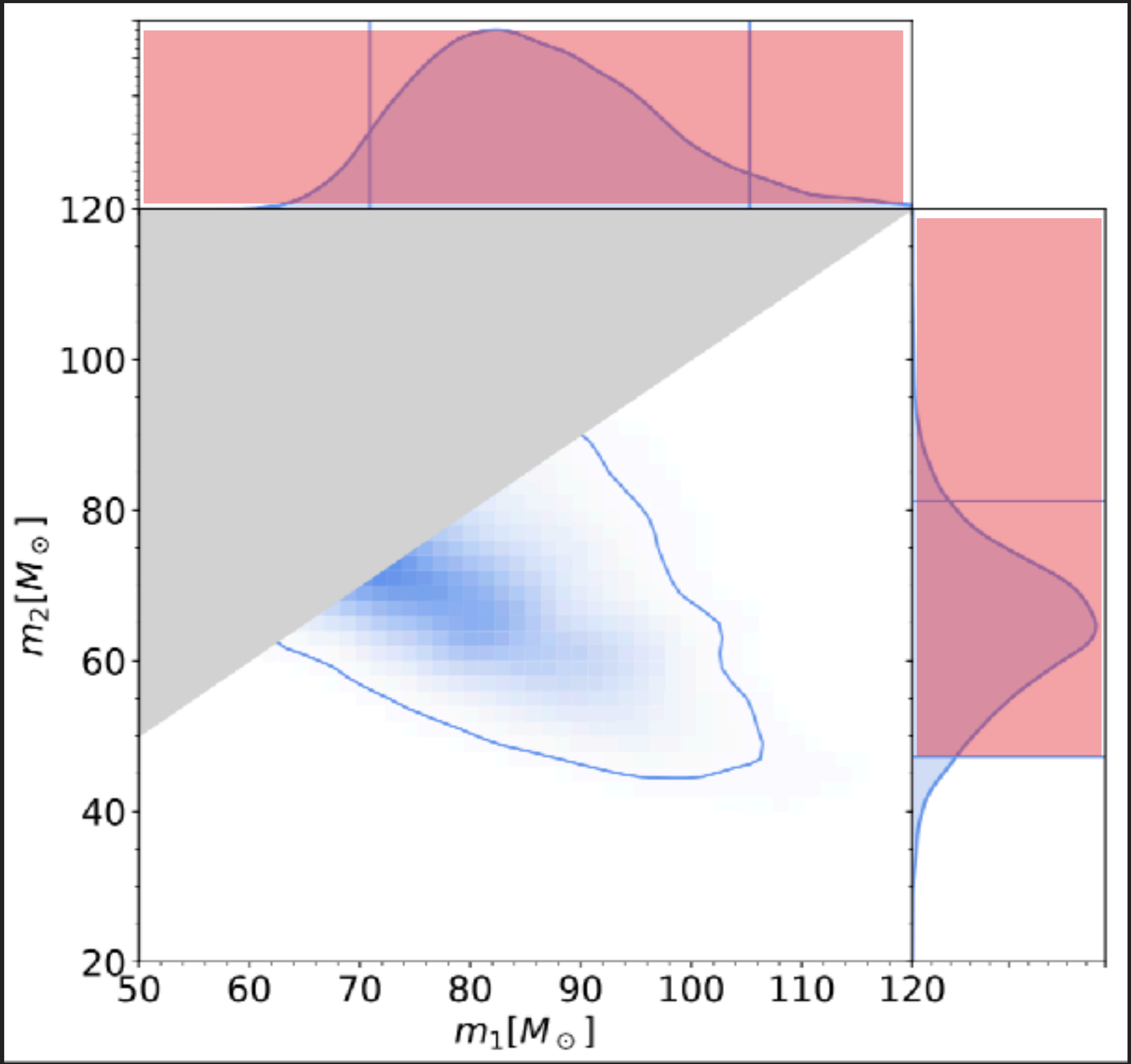
- PISN gap: in between most massive stellar black-hole and least massive IMBH

$$\sim 50\,M_\odot < M < \sim 120\,M_\odot$$



GW190521 is in the PISN mass gap!

- Big black holes (by LIGO/Virgo standards)
- $M_1 = 85^{+20}_{-14}\,M_\odot$, $M_2 = 65^{+17}_{-17}\,M_\odot$, and $M_{\rm total} = 149^{+24}_{-16}\,M_\odot$



Explanation?

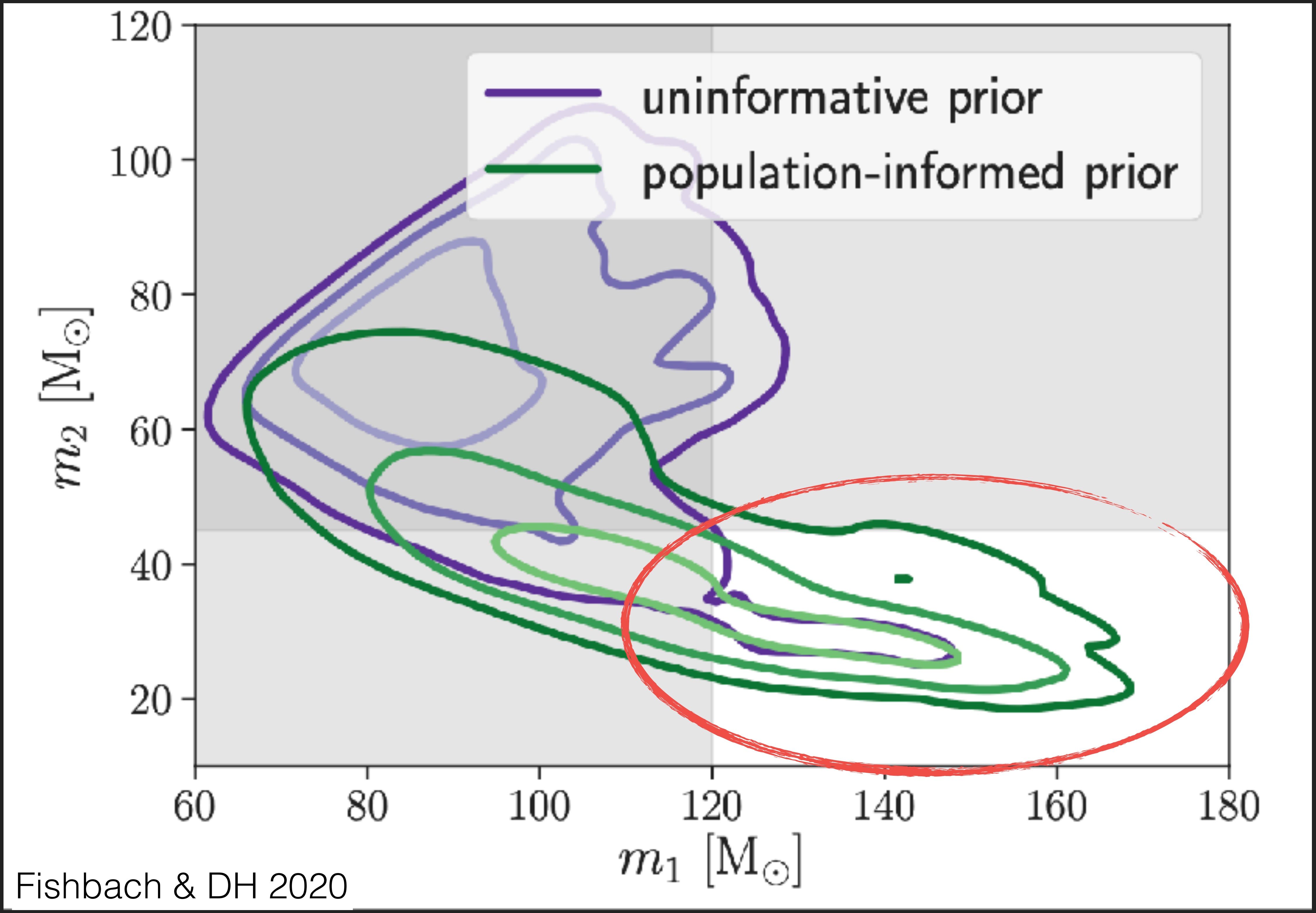
- Pair-instability physics is wrong
- Data/interpretation are wrong
- Alternative scenarios:
    - Hierarchical merger. M_1 is the result of a previous black hole merger
    - Stellar merger. M_1 is the result of a stellar merger generation oversized Hydrogen envelope
    - Source is in an AGN disk (accretion, second generation, etc.)
    - High eccentricity/head-on collision
    - Strong gravitational lensing (sources are at high redshift)
    - Primordial black holes
    - Cosmic strings
    - Core collapse supernova
    - …

Minding the gap!

- Theory says it's very hard to make a black hole in the PISN gap
- Theory says that it's even harder to make two black holes in the PISN gap!
    - Hierarchical formation says rate of double mass gap black holes is $\sim 10^{-6}$ of the full population
- Instead, take as a prior that the smaller black hole is part of the existing LIGO/Virgo BH population
- This pulls m_1 to below the mass gap
- Because total mass is well constrained, this naturally pushes m_2 above the mass gap!

Fishbach & DH 2020

Minding the gap!

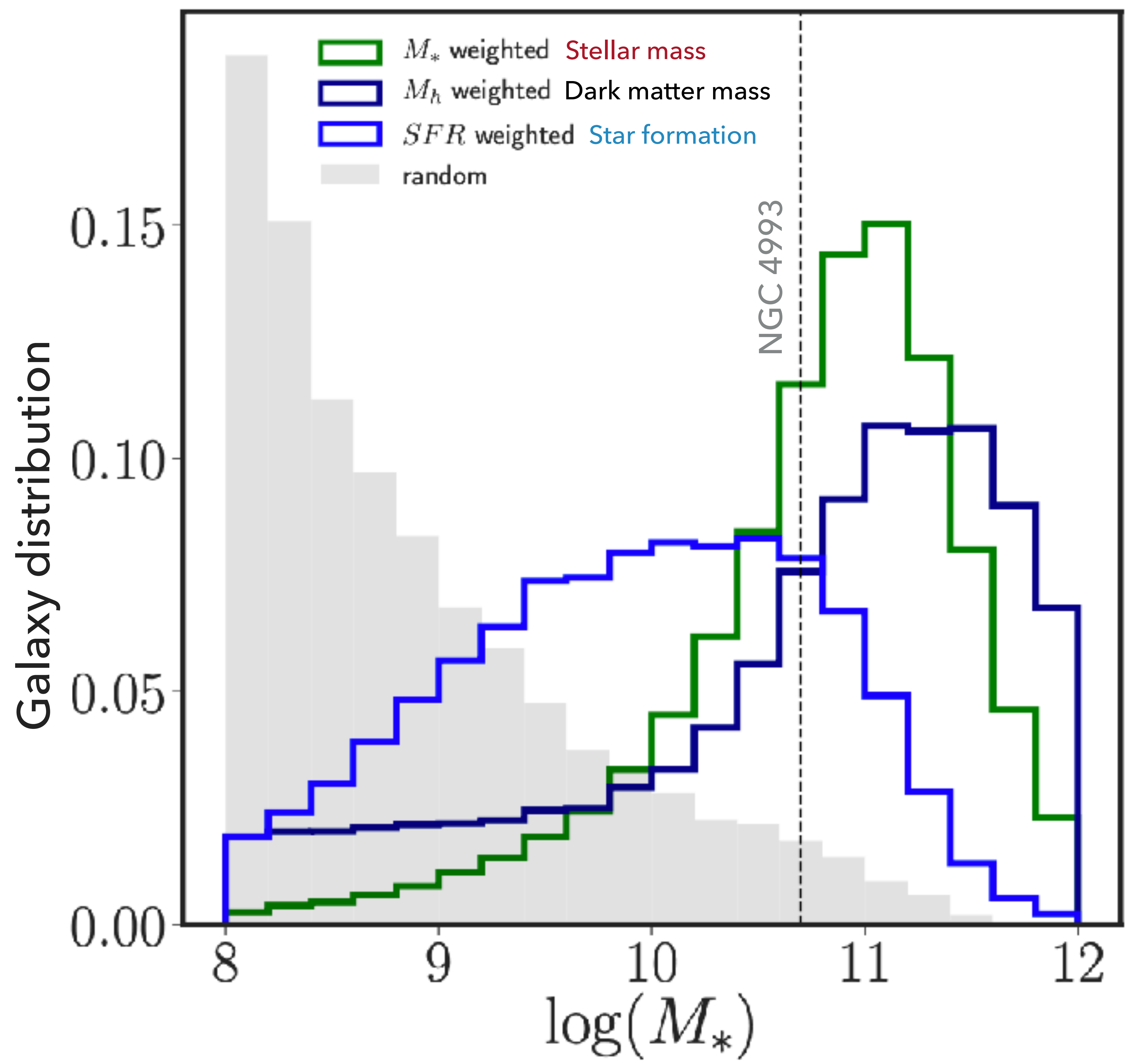


If we assume secondary mass is part of existing population, the primary mass is consistent with being above the gap, and thus fits with PISN theory!

Host galaxy properties

- Binary neutron stars are formed in galaxies
- Observable properties of a galaxy (e.g. stellar mass, star formation rate, metallicity) carry information about its history
- Examine properties of binary host galaxies to learn about how binary neutron stars are formed!
- Binary-host connection (Adhikari, Fishbach, DH, Wechsler, & Fang; arXiv:2001.01025)

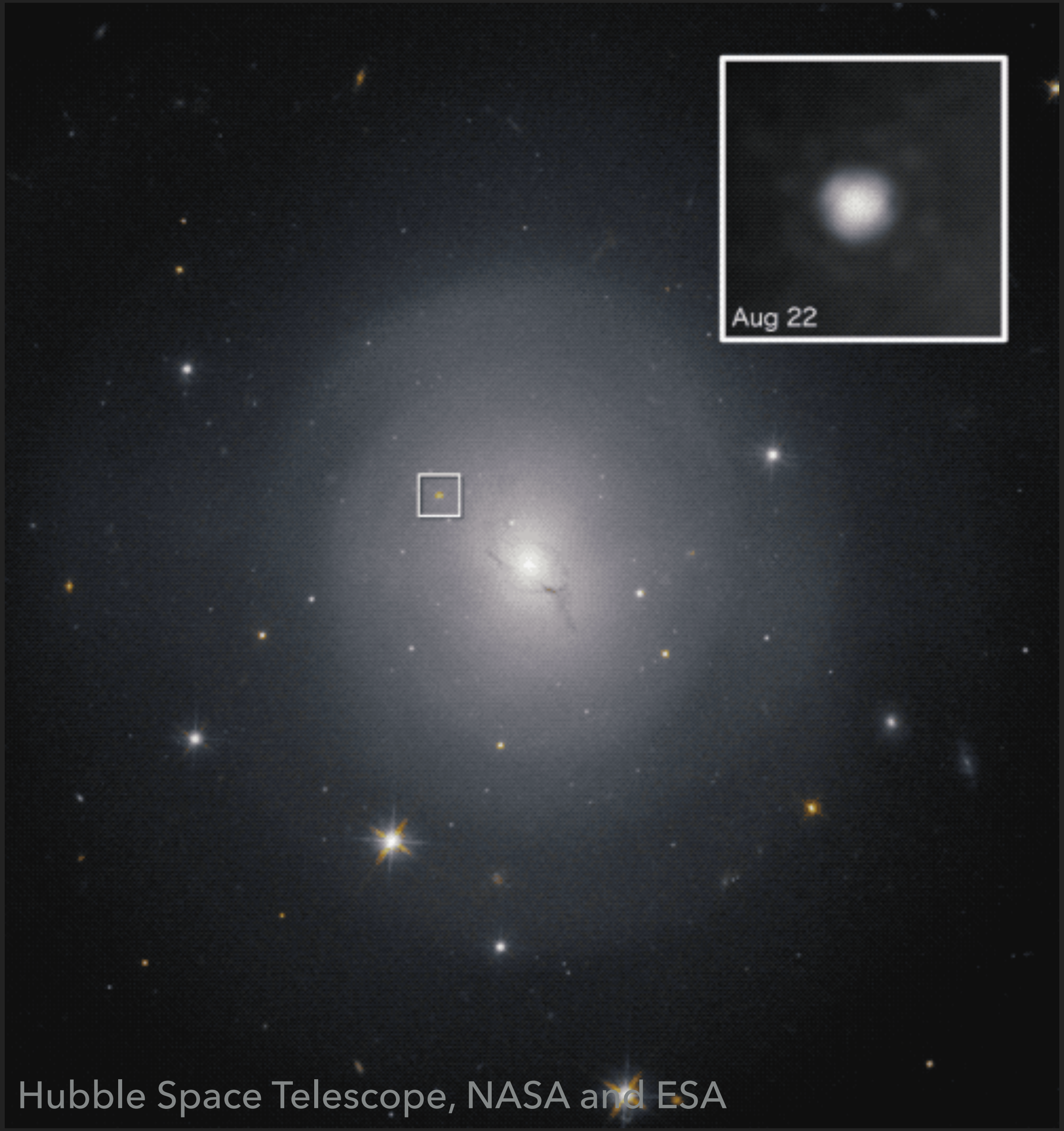
Star formation, stellar mass, or dark matter?!



- Different weightings produce different distributions of host galaxy properties

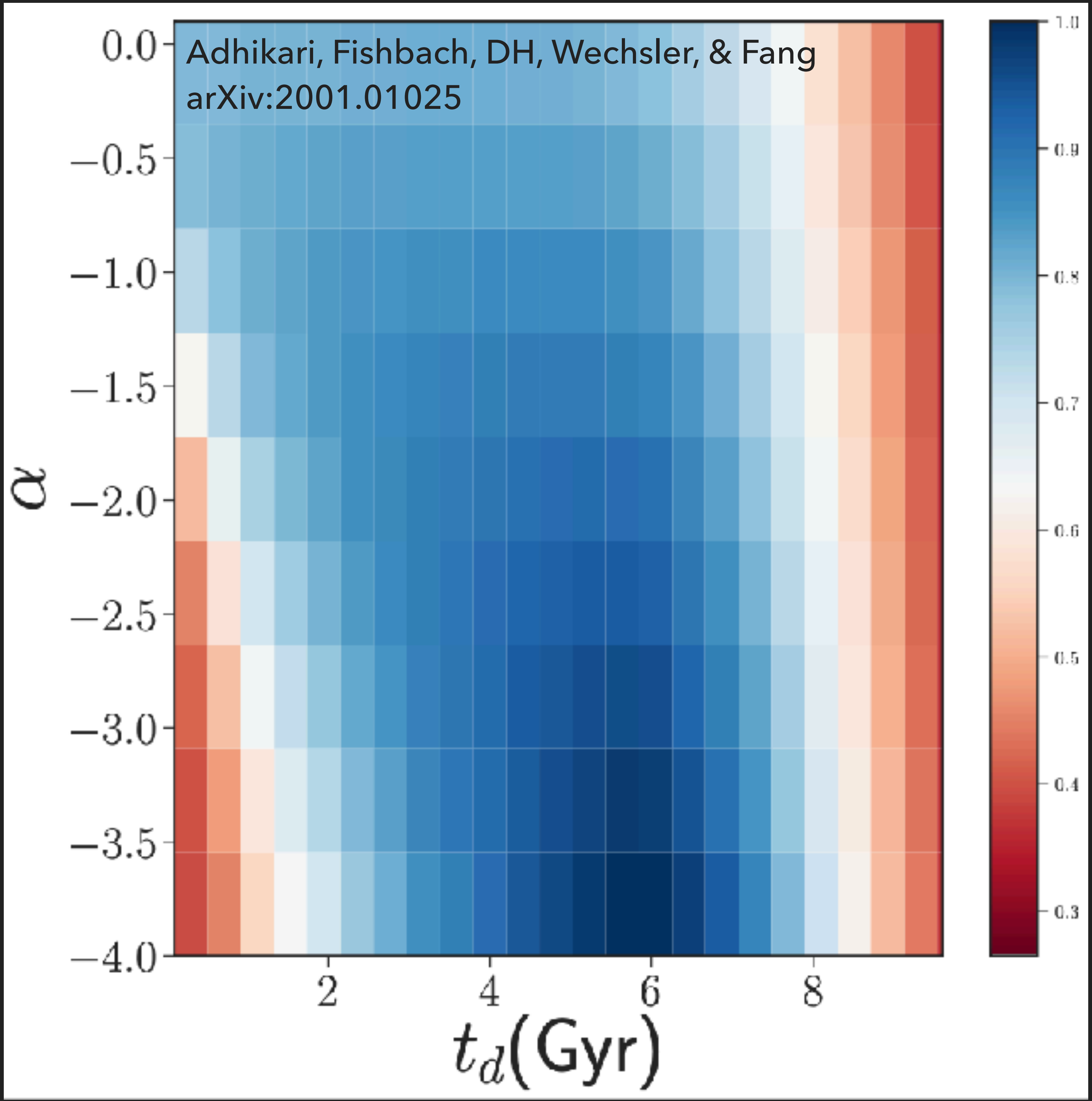
Binary-host connection event #1: GW170817!

- Binary neutron-star merger in gravitational-waves
- Identification of host galaxy: NGC 4993



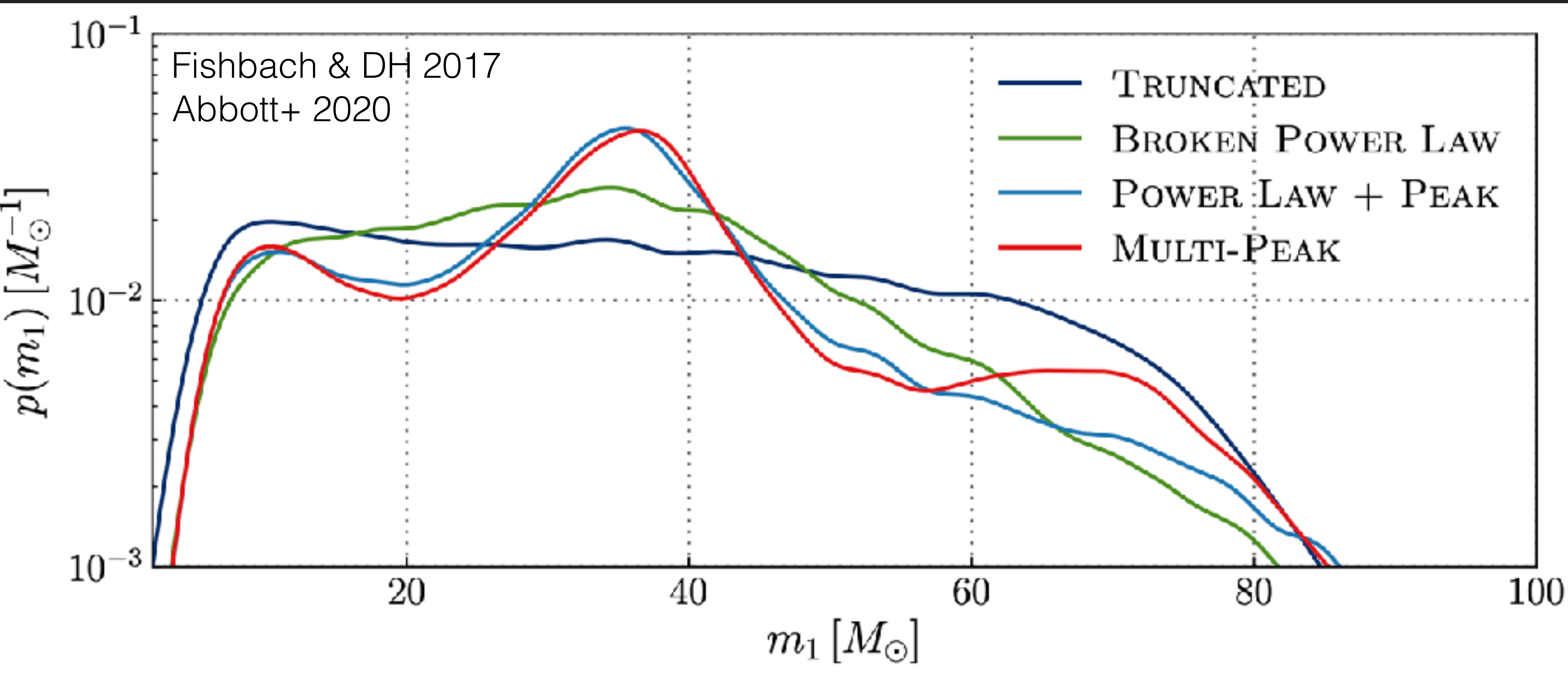
Hubble Space Telescope, NASA and ESA

What do we learn from NGC 4993?



- NGC 4993 prefers a minimum time delay of ~6 Gyr and a relatively steep slope
- This is because it has a lower than expected star-formation rate for its measured stellar mass

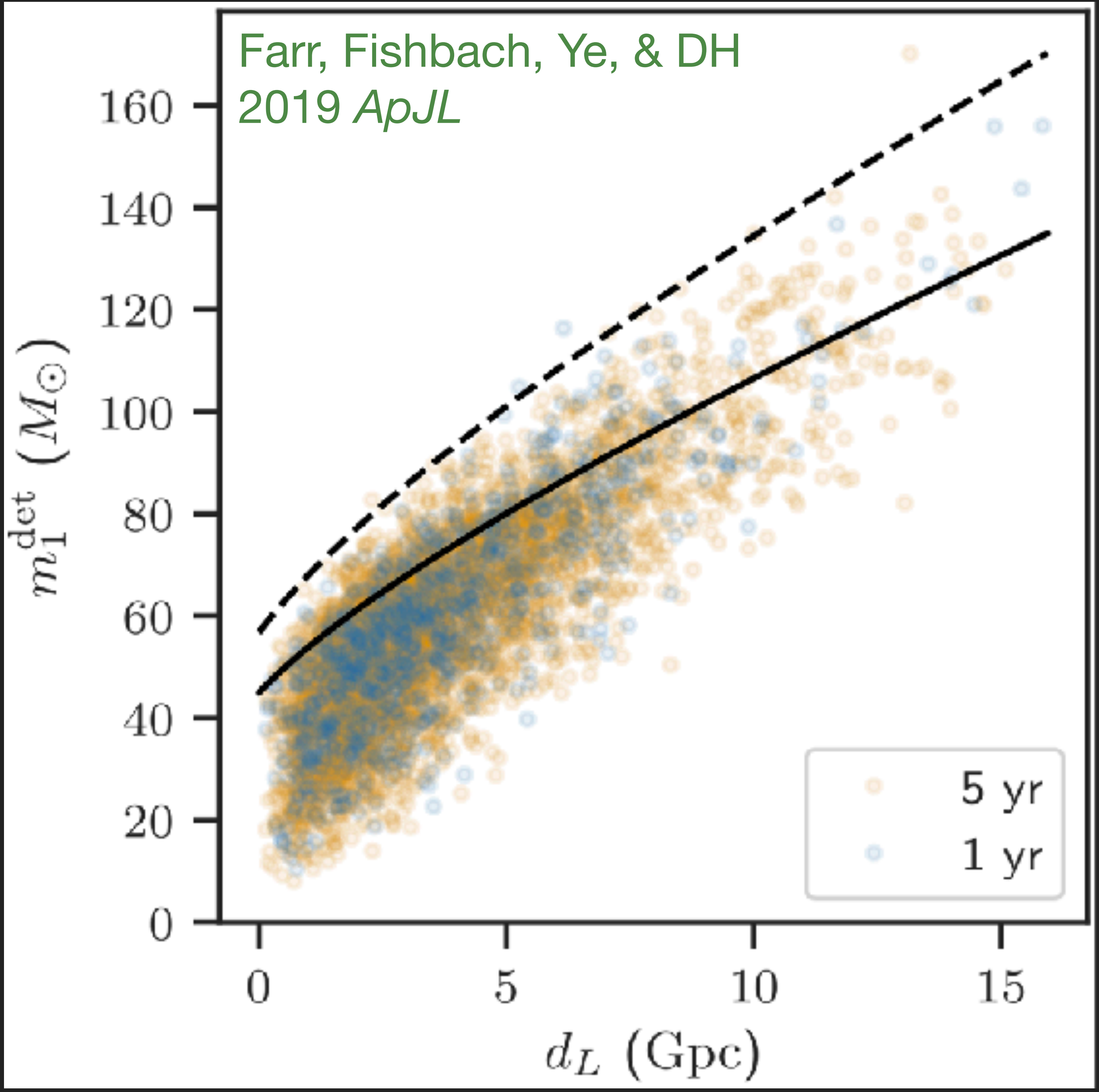
Where are LIGO's big black holes?



- GWTC-2 confirms that there is some sort of feature in the mass distribution of black holes at $\sim 45\, M_\odot$
- This feature redshifts!

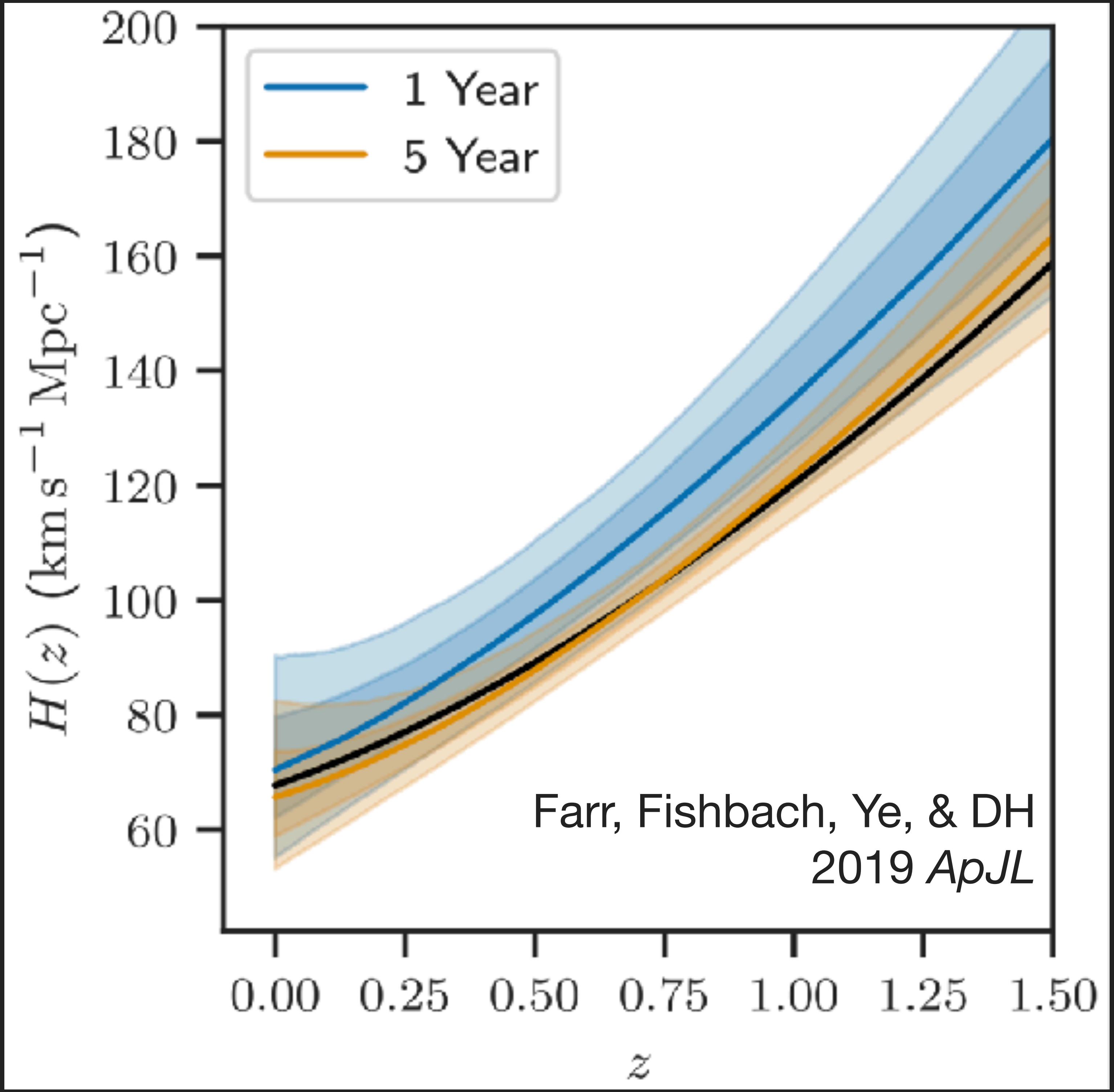
A new method for standard siren cosmology

- LIGO/Virgo is missing big black holes (Fishbach & DH 2017, Abbott+ 2019; 2020)
- Existence of upper mass gap, as expected from pulsational/pair instability supernovae
- The edge of the mass gap imprints an "absorption" feature in the mass distribution of binary black holes
- This feature redshifts, and thus can be used to break the distance-redshift degeneracy!



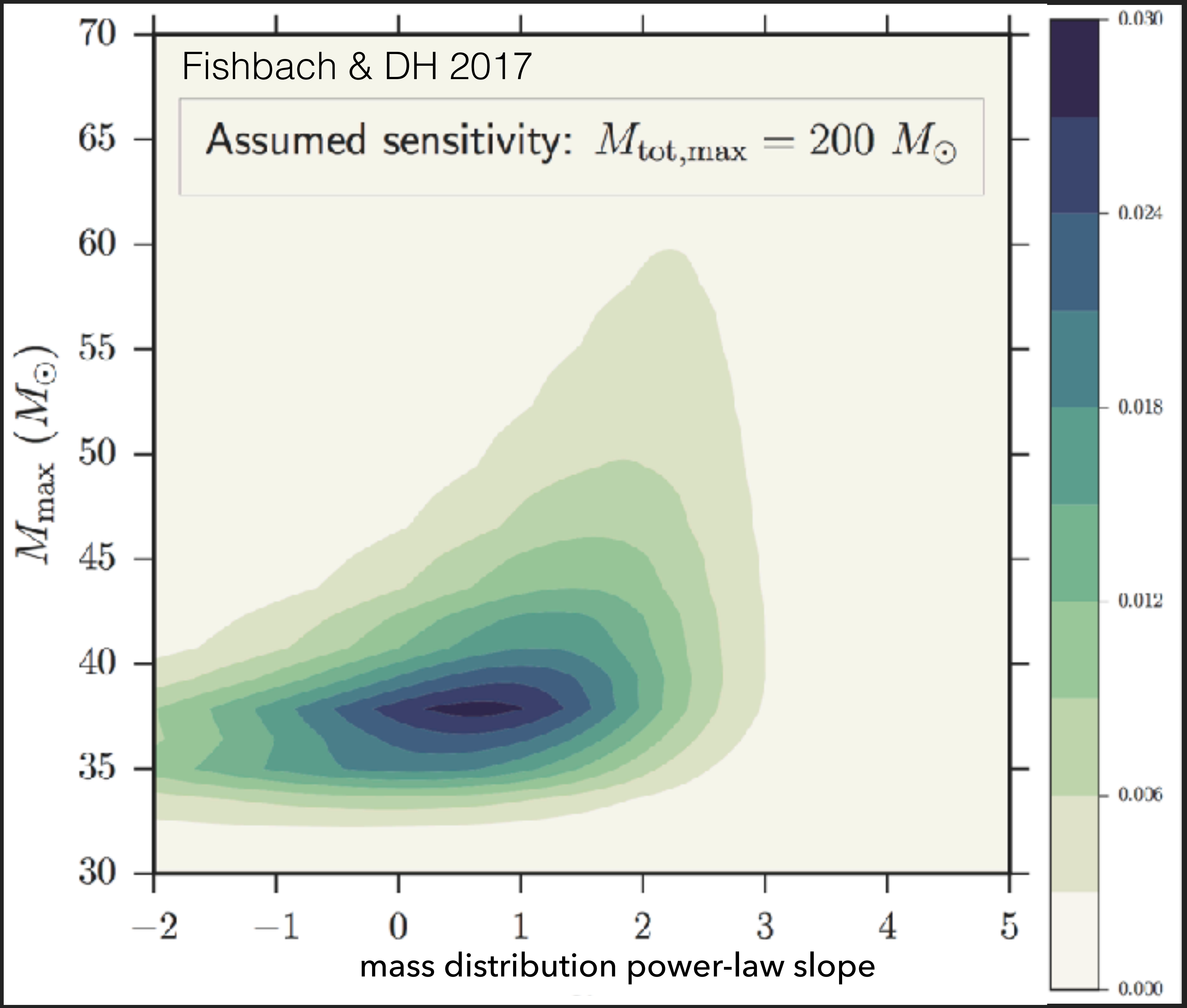
A new method for standard siren cosmology

- Five years of observation of binary black holes with Advanced LIGO/Virgo would constrain $H(z)$at pivot redshift of $z \sim 0.75$ to 2%

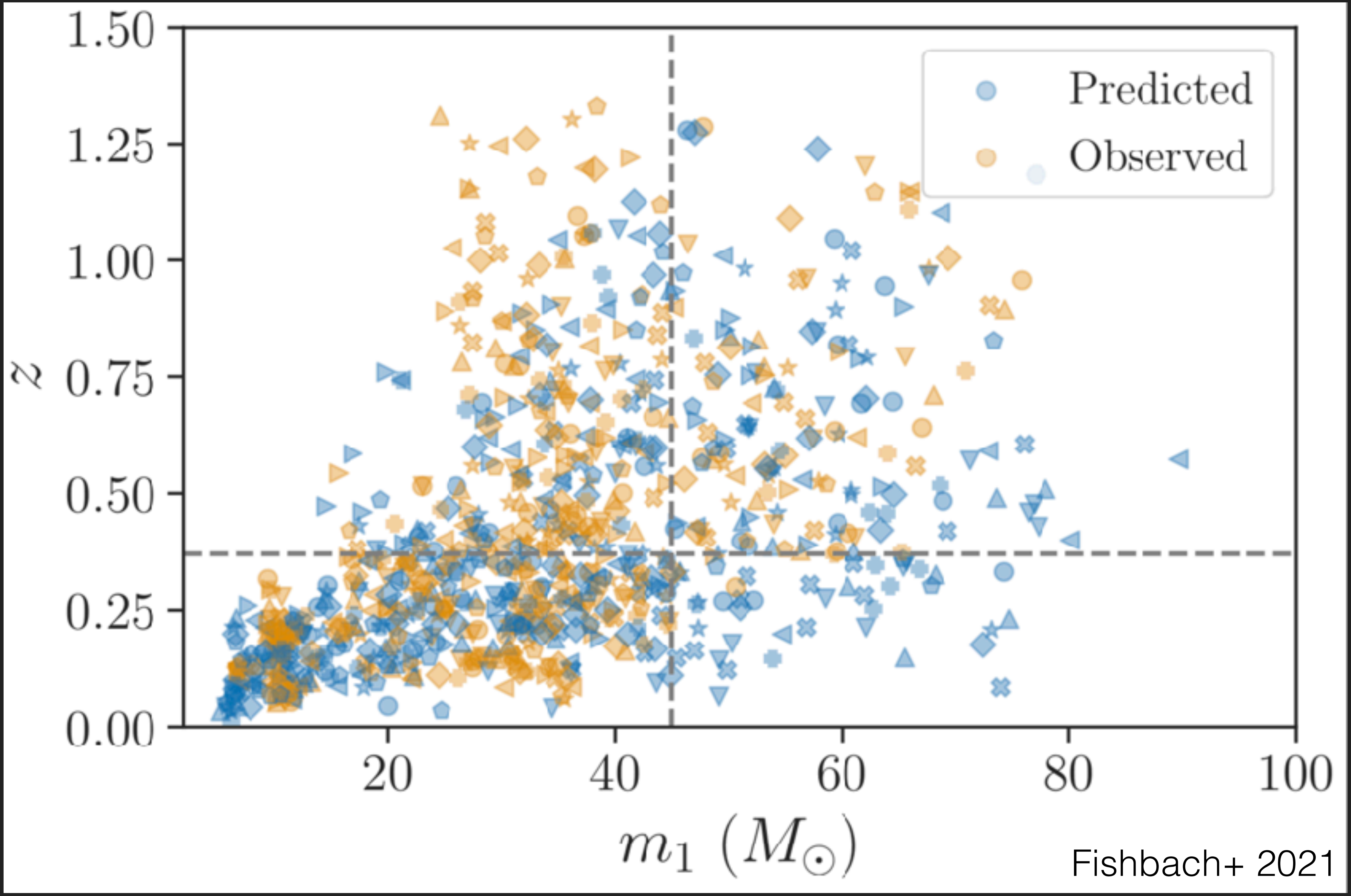


Where are LIGO's big black holes?

- LIGO is sensitive to BHs up to >100 $M_\odot$
- Absence of evidence is evidence of absence
- There exists an upper mass gap (GW190521 notwithstanding)

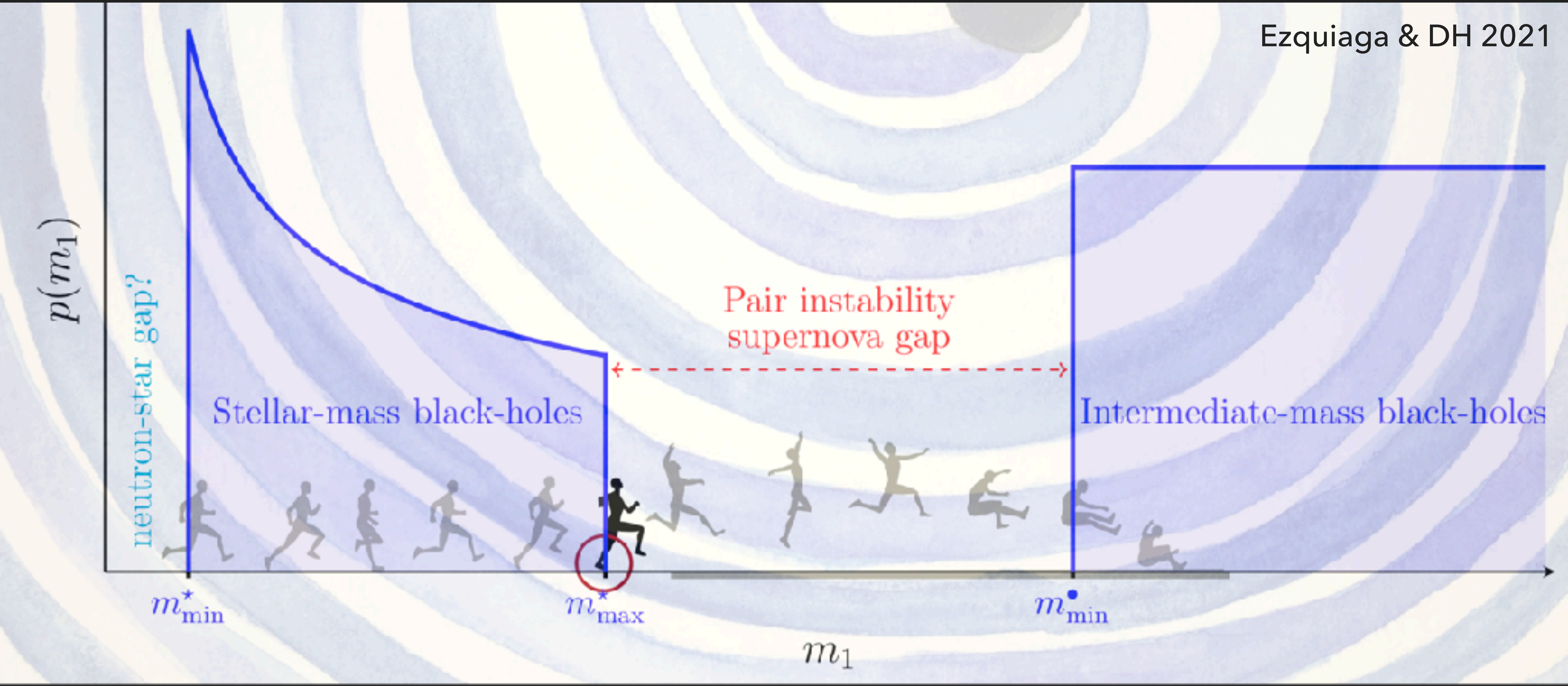


When are LIGO's big black holes?



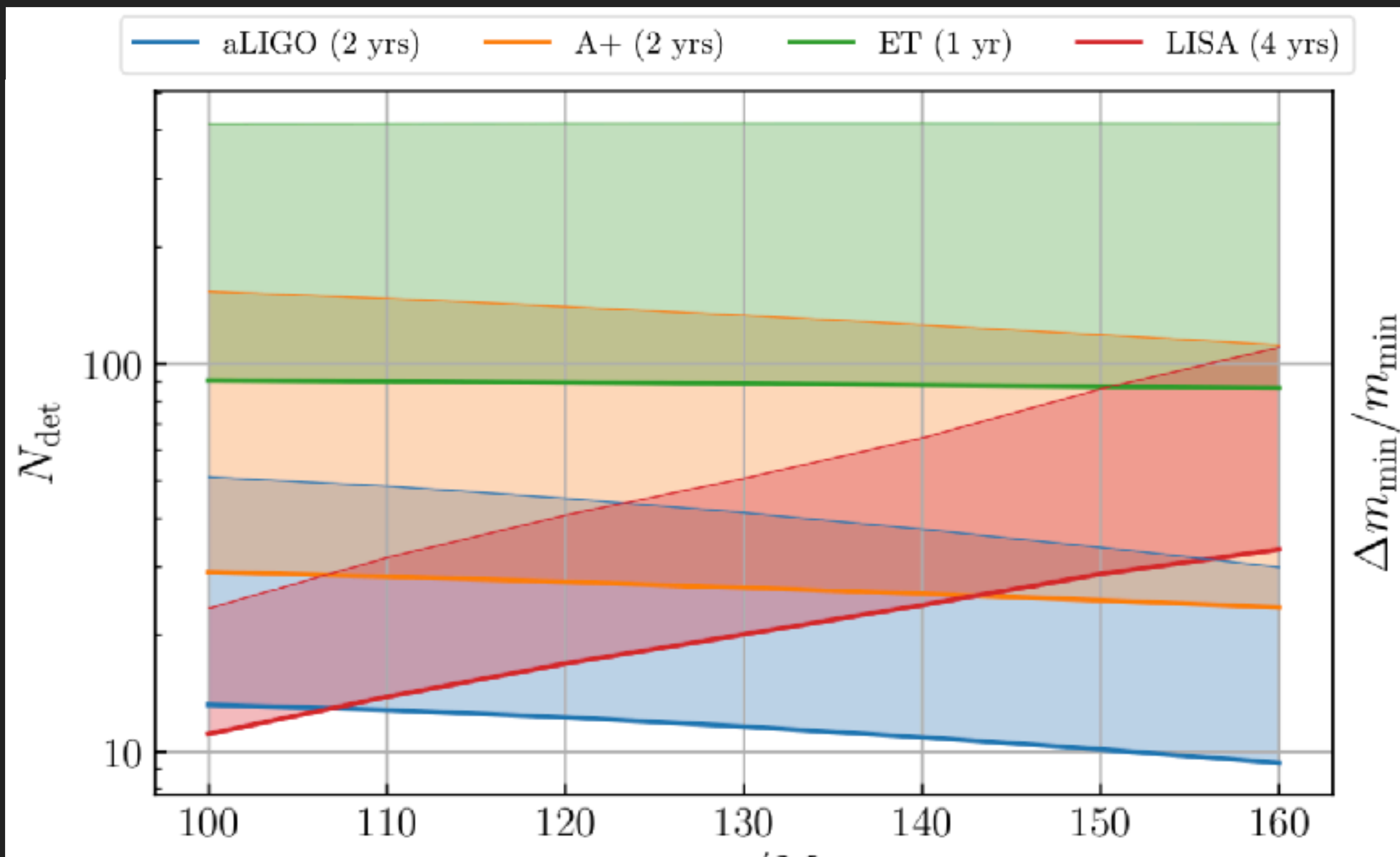
- Weak evidence that the mass distribution of binary black holes evolves with redshift! (blue is a non-evolving truncated model)

Jumping the gap



Jumping the gap

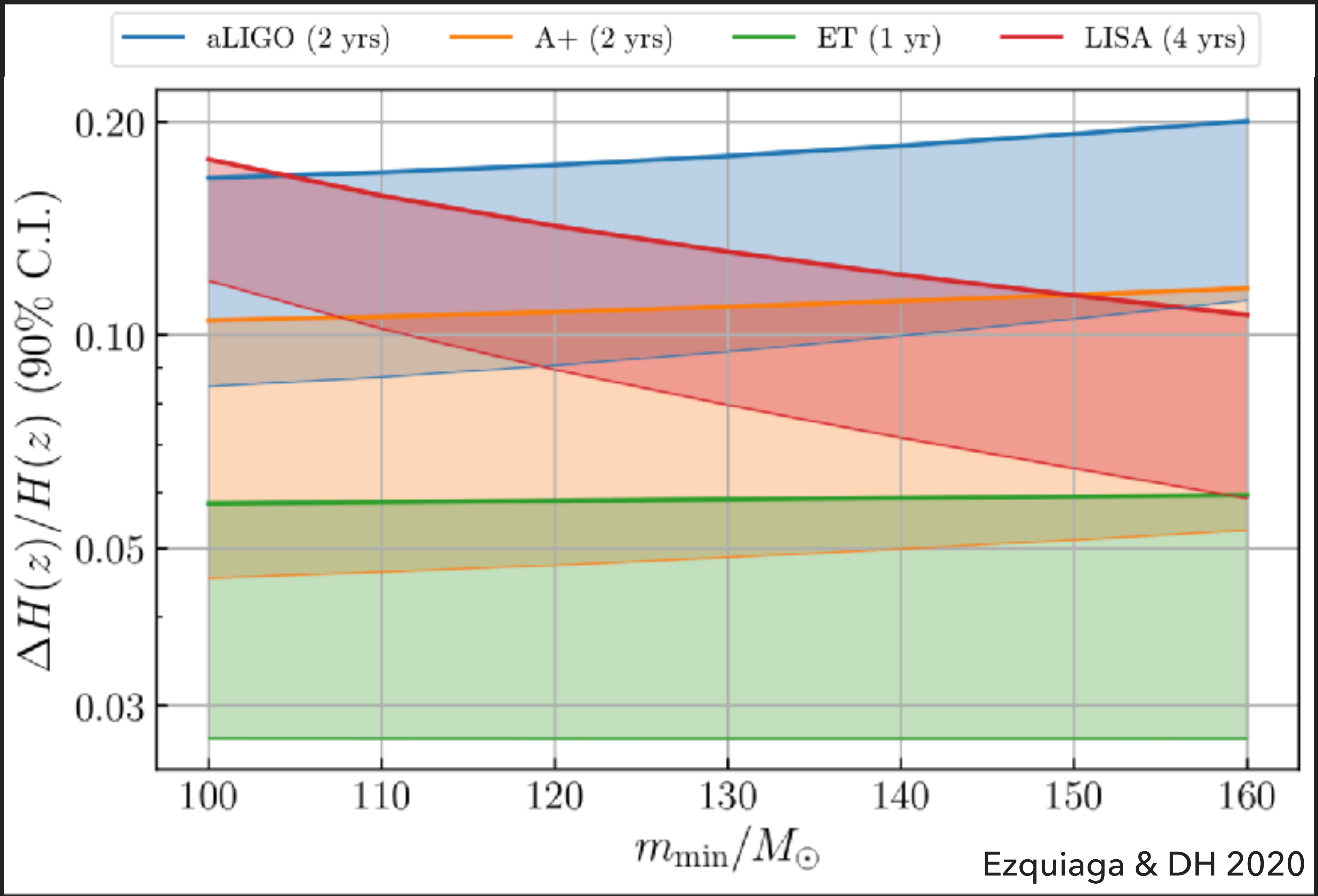
- We expect BHs to exist on the other side of the PISN gap
- These “far side” black holes can be detected by LIGO/Virgo and *LISA*



Ezquiaga & DH 2020

Jumping the gap

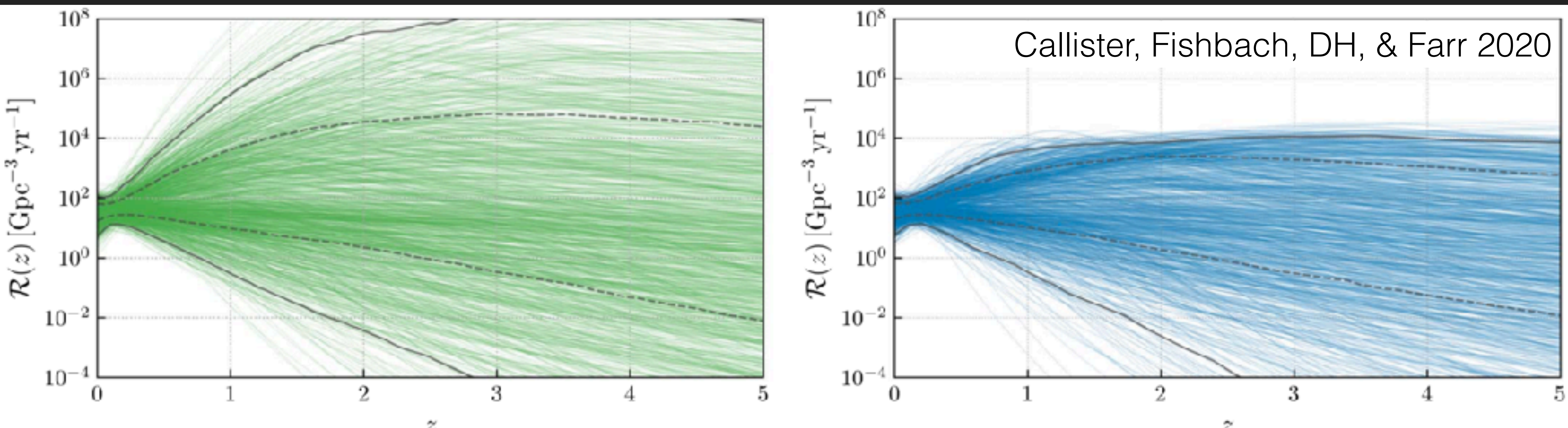
- Some of these binaries can be seen by **both** LIGO/Virgo and *LISA*
- Can do standard siren science with the **upper** edge of the gap



Ezquiaga & DH 2020

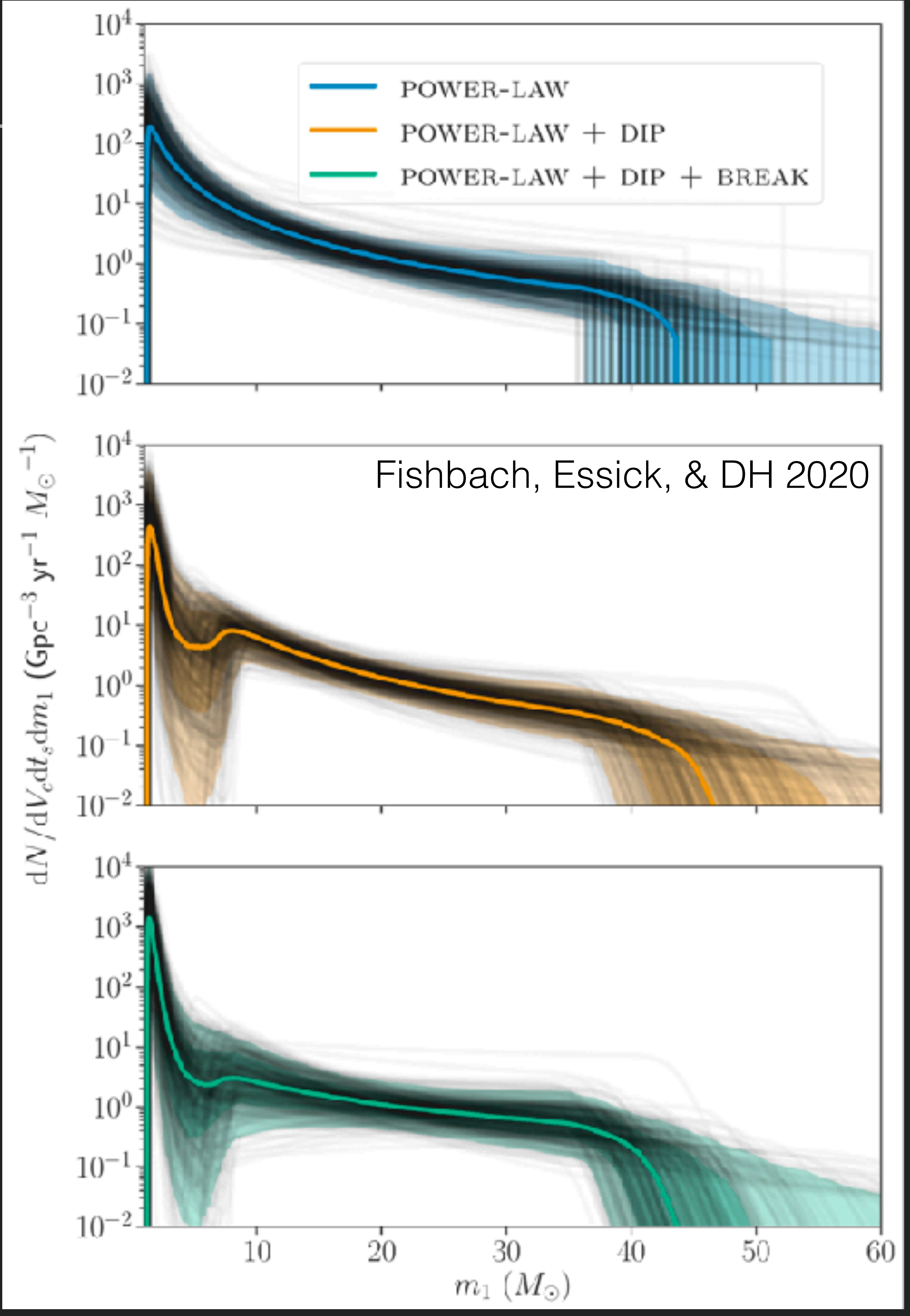
Shouts and murmurs

- Combining GW detections with the **non**-detection of a stochastic background constrains binary formation astrophysics!
- We can already make statements about how the rate of binary mergers evolves with redshift
- In the future, the combination of compact-binary and stochastic measurements will provide strong constraints on the formation mechanisms of binary systems



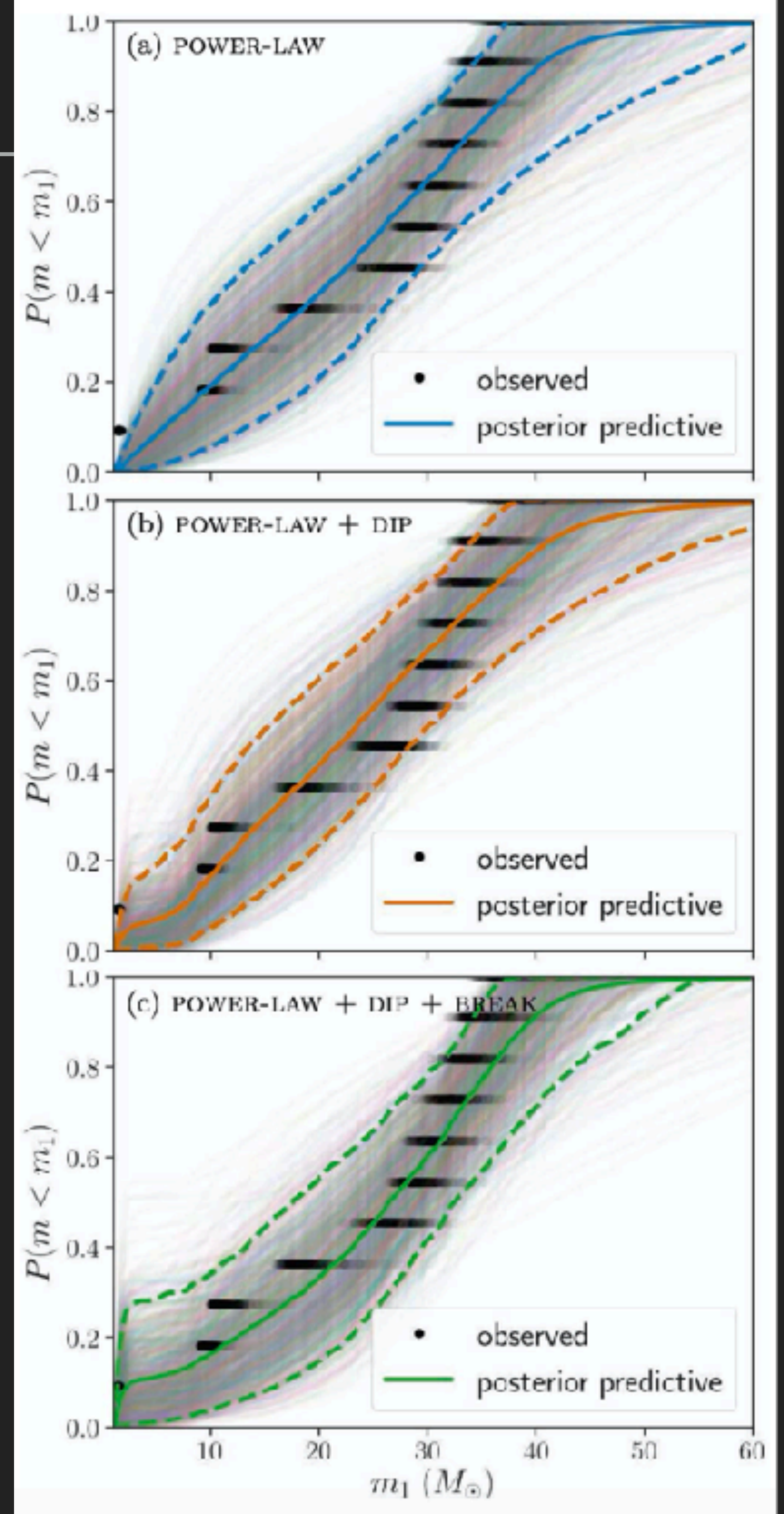
Does matter matter?

- In O1+O2, we detected 1 event with $m_1 < 2\,M_\odot$, 10 events with $m_1 > 5\,M_\odot$, and nothing in between
- Does the mass distribution of detections indicate the presence of a NS-BH mass gap?
- Can we infer, from GW data alone, that there exists a population of $m_1 < 2\,M_\odot$ objects which are different from the binary black hole population?



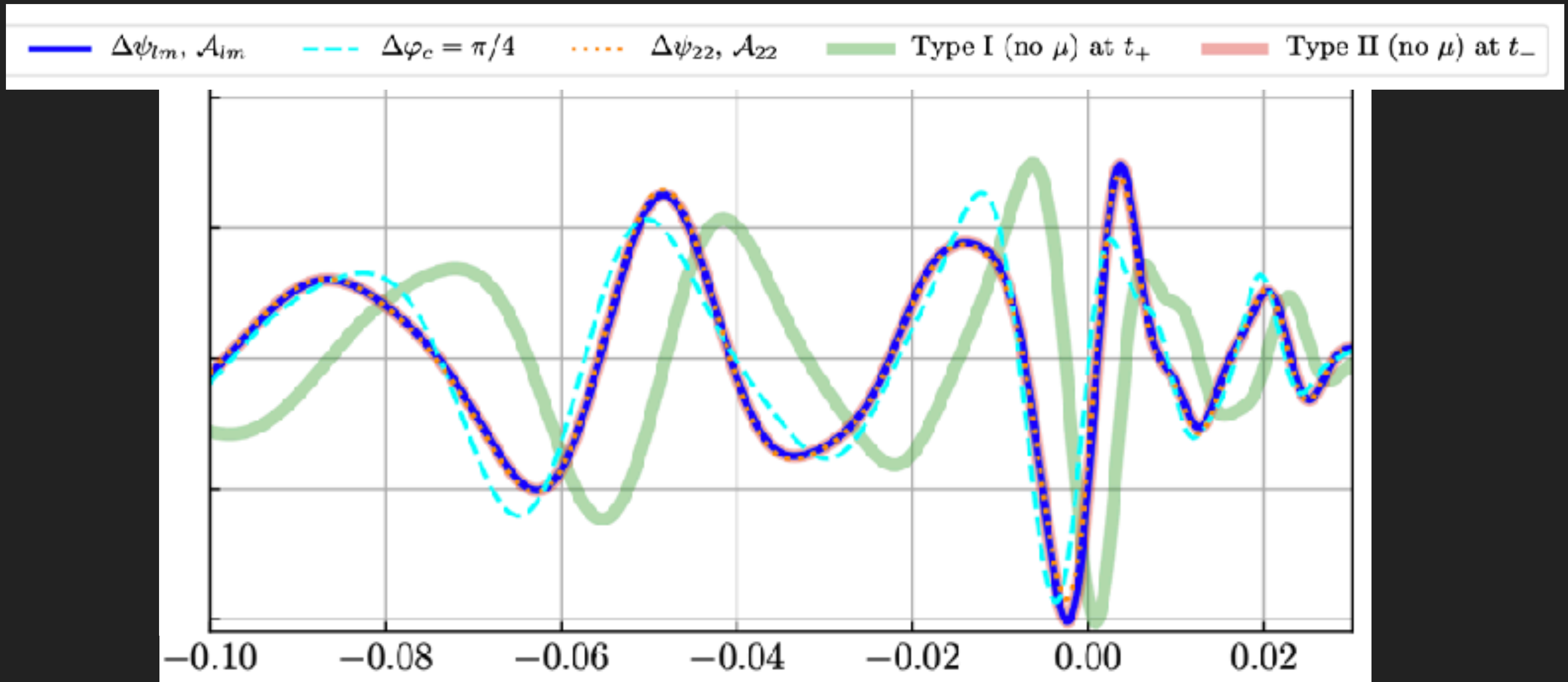
Does matter matter?

- The O1+O2 data prefers mass distributions with a mass gap between NS and BHs, even without looking for matter effects in the waveforms
- Formalism for determining classes of events



Gravitational lensing of gravitational waves

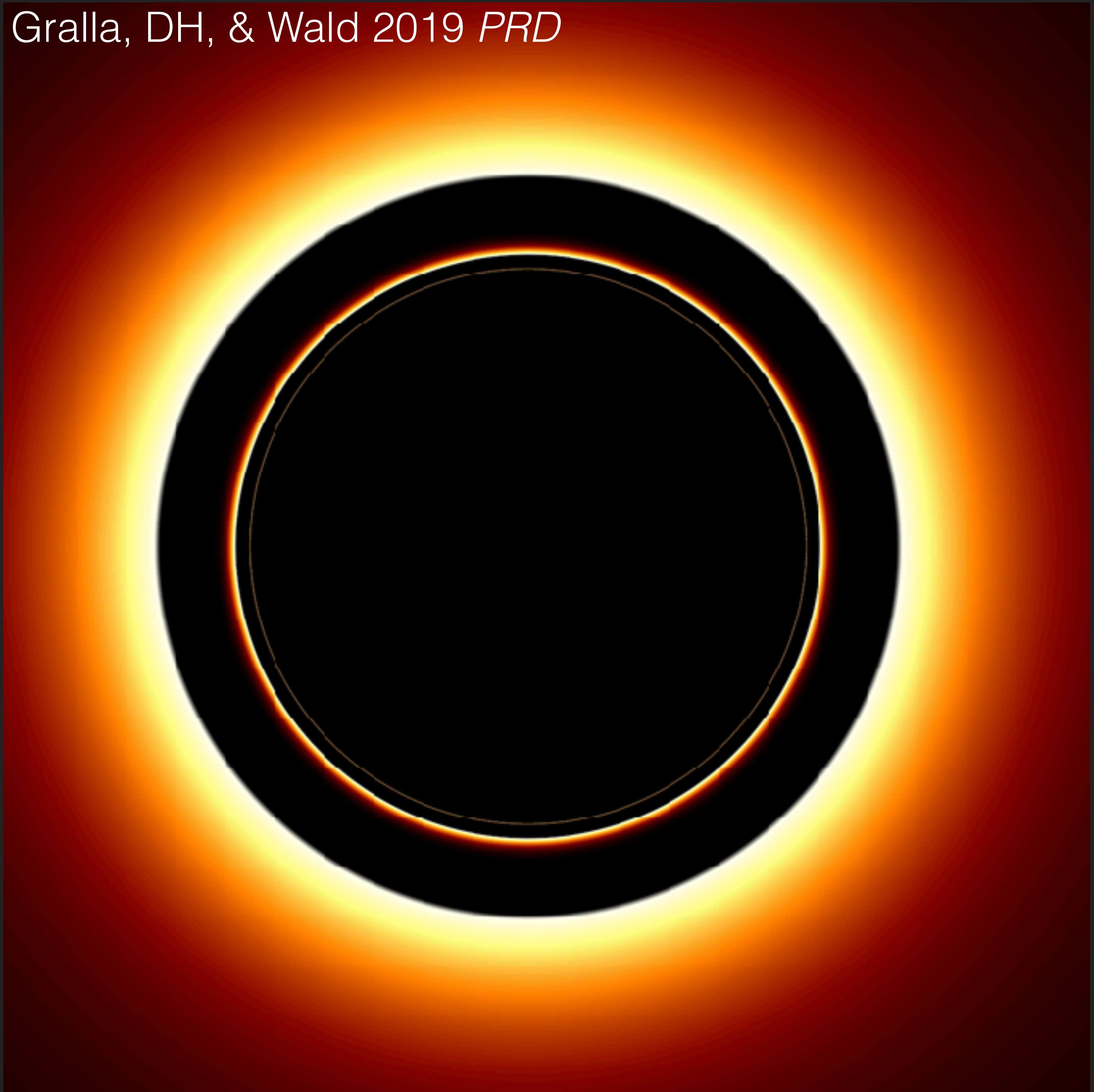
- In the future, some GW sources will be multiply imaged by strong lensing
- When gravitational waves pass through a caustic, the phase of the waves rotates
- Some strongly-lensed gravitational-wave waveforms are inconsistent with gravitational-wave templates!



Ezquiaga+ 2021

Black hole shadows and photon rings

- EHT has produced an amazing image
- They are not seeing the shadow of a black hole, nor are they seeing photon rings (photons circling around the BH many times)
- They are seeing interesting properties of the accretion disk around the ISCO



The future is loud and bright

- The era of gravitational-wave astronomy has arrived!
- LIGO, Virgo, and KAGRA are expected to turn back on at design sensitivity in ~2 years: "As of November 2020, the O4 observing run is projected not to begin before June 2022, due to both key procurement delays and COVID-related delays."
- The future should bring incredible statistics, additional spectacular events, and hopefully some interesting surprises as well!