Title: Minding the Gap: Lessons from LIGO-Virgoâ€™s Biggest Black Holes

Speakers: Maya Fishbach

Series: Strong Gravity

Date: January 28, 2021 - 1:00 PM

URL: http://pirsa.org/21010023

Abstract: Models for black hole formation from stellar evolution predict the existence of a pair-instability supernova mass gap in the range ~50 to ~120 solar masses. The binary black holes of LIGO-Virgo's first two observing runs supported this prediction, showing evidence for a dearth of component black hole masses above 45 solar masses. Meanwhile, among the 30+ new observations from the third observing run, there are several black holes that appear to sit above the 45 solar mass limit. I will discuss how these unexpectedly massive black holes fit into our understanding of the binary black hole population. The data are consistent with several scenarios, including a mass distribution that evolves with redshift and the possibility that the most massive binary black hole, GW190521, straddles the mass gap, containing an intermediate-mass black hole heavier than 120 solar masses.


PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS
Minding the Gap?
Lessons from LIGO/Virgo's
Biggest Black Holes
Maya Fishbach
PI Strong Gravity Seminar
January 28 2021
CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS
NHFP
NASA Hubble Fellowship Program

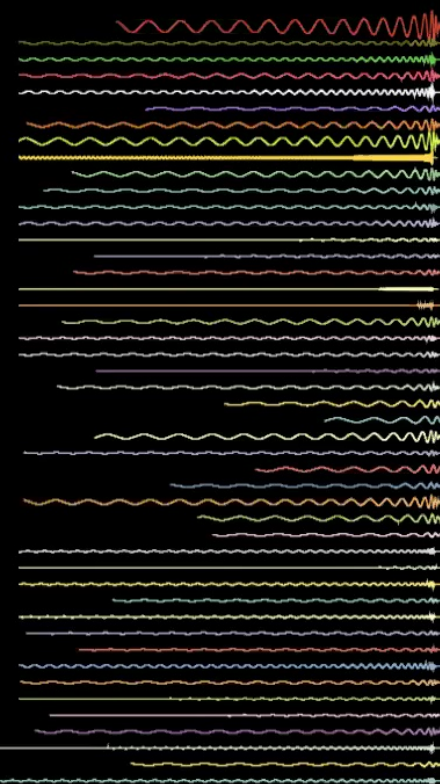
LIGO and Virgo have observed gravitational waves from ~50 mergers

GWTC-2 papers:

Catalog:
dcc.ligo.org/LIGO-P2000061/public
arXiv: 2010.14527

Population paper:
dcc.ligo.org/LIGO-P2000077/public
arXiv: 2010.14533

Tests of GR paper:
dcc.ligo.org/LIGO-P2000091/public
arXiv: 2010.14529



Credit: Chris North & Stuart Lowe,
https://waveview.cardiffgravity.org

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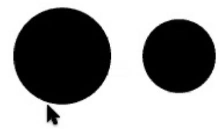
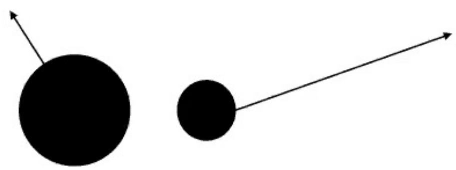
For each binary black hole merger, the gravitational-wave signal encodes:

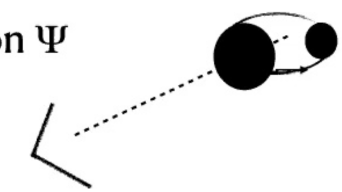
- The masses of the two components $m_1 \geq m_2$



- The component spins a_1, a_2



- Distance d_L, sky position α, δ, inclination ι, polarization Ψ



Measuring these parameters for each event is known as *parameter estimation*

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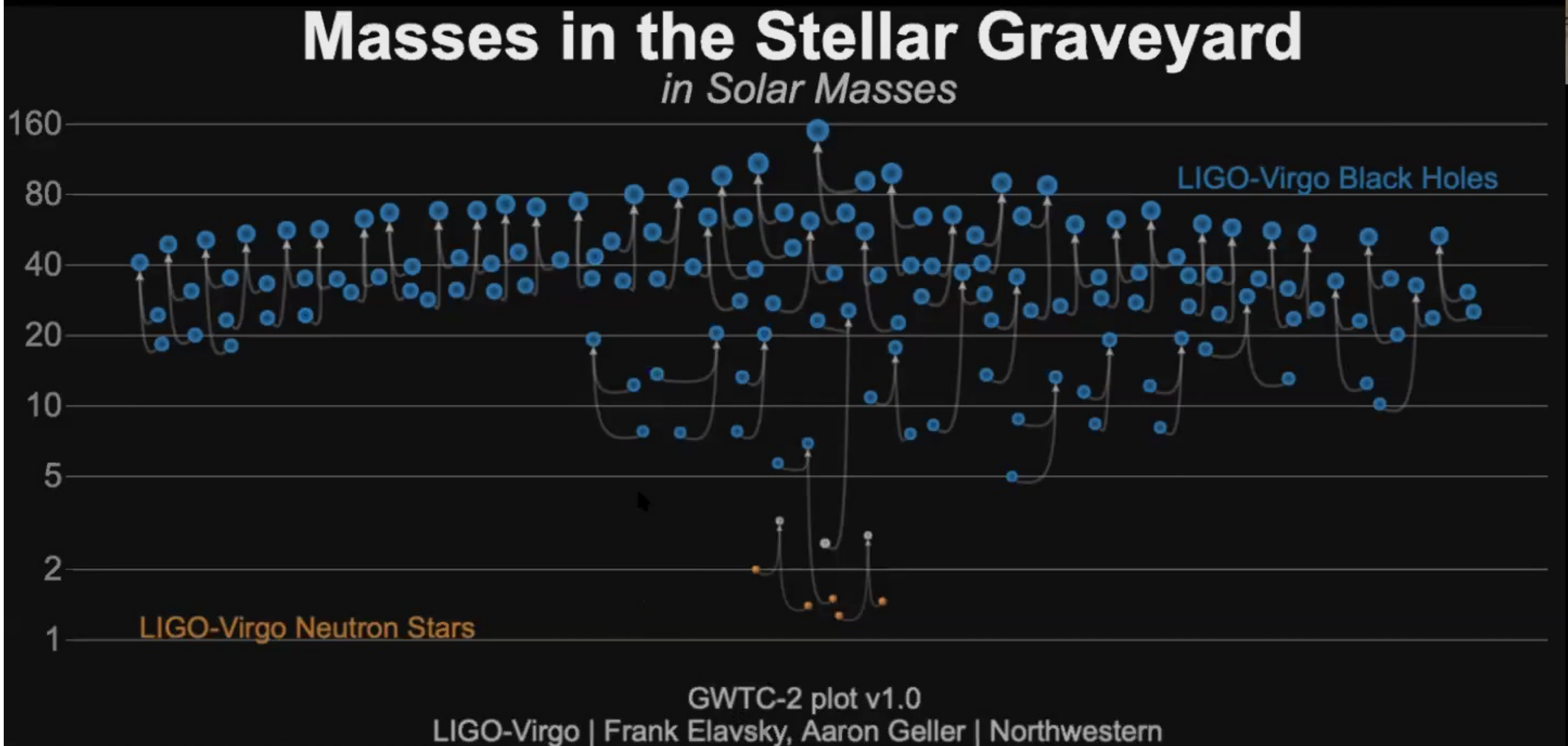
Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

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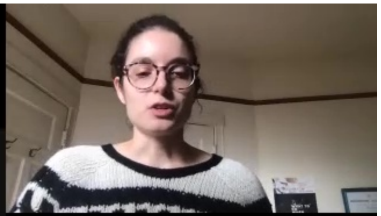

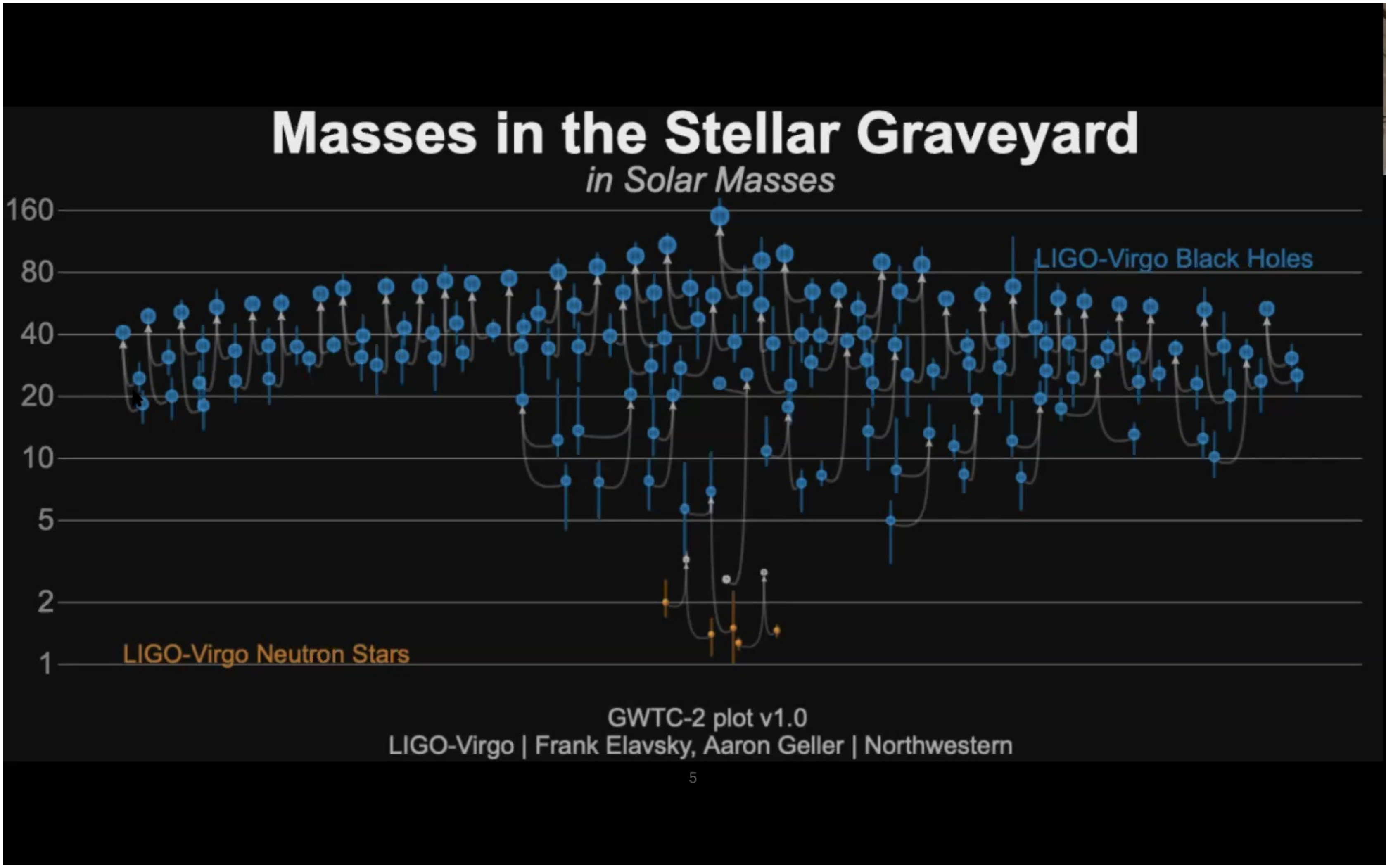

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LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
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Parameter estimation

For individual events, measurement uncertainties are large, and our inferred *posterior* depends on the *prior*

$$p(m_1, m_2 \mid \text{data}) \propto p(\text{data} \mid m_1, m_2) p_0(m_1, m_2)$$

Posterior   Likelihood   Prior

LIGO/Virgo prior: *flat* in (detector-frame) masses

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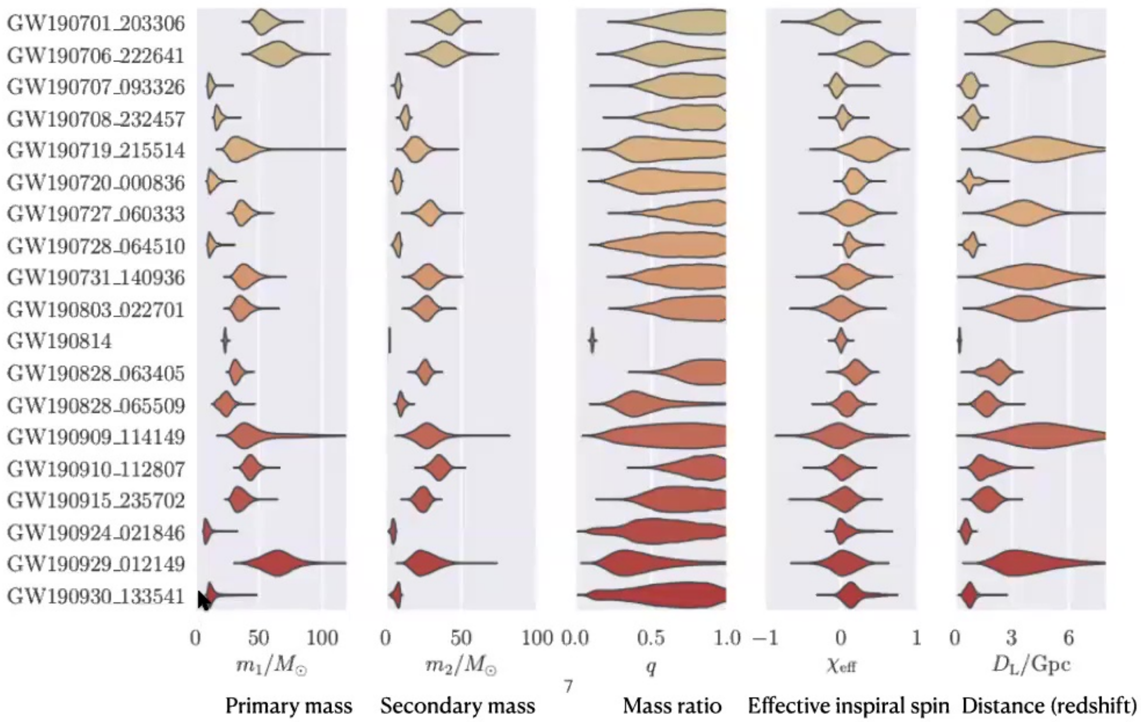
Measurements of individual events' parameters

Subset of events in GWTC-2



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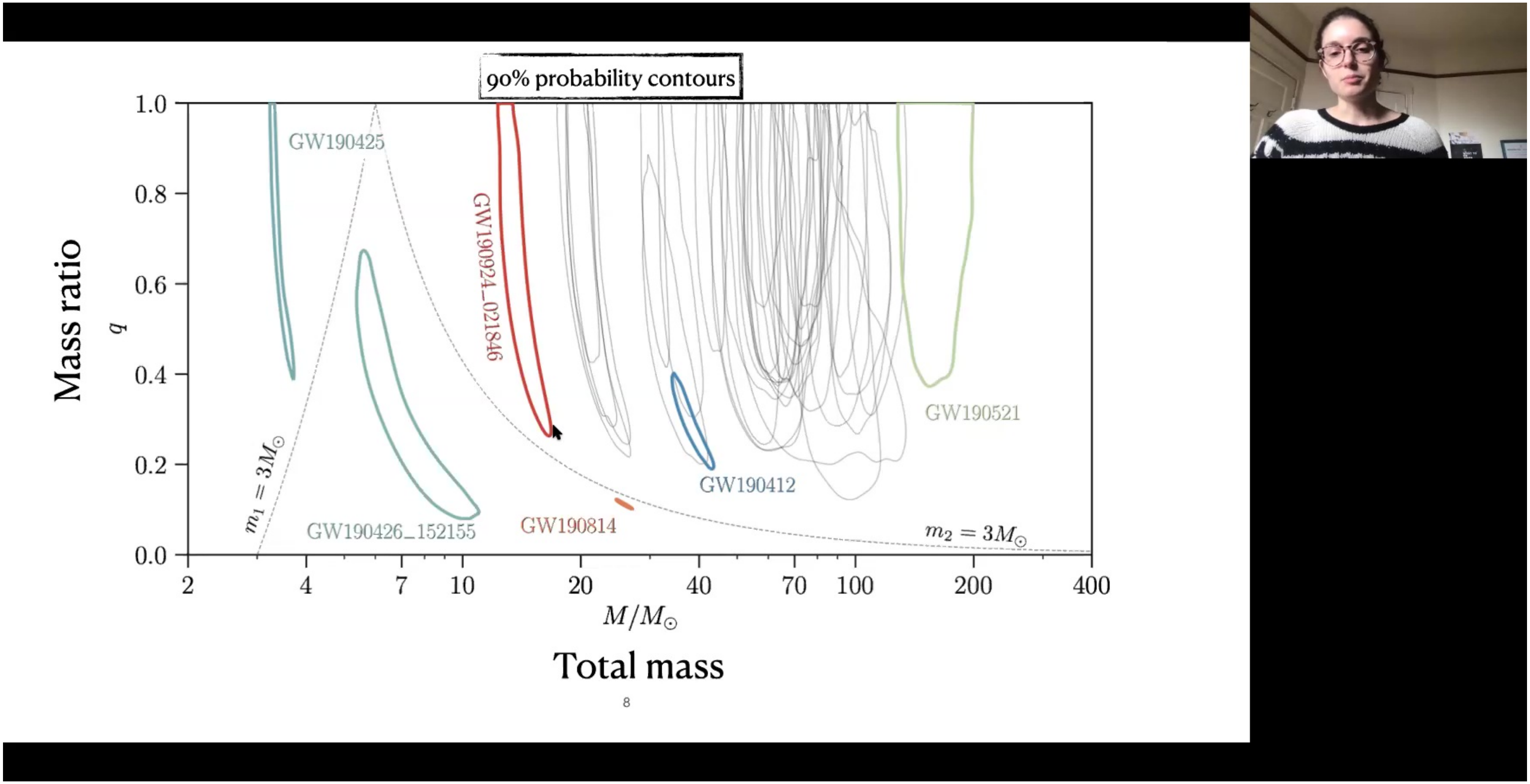

90% probability contours
Mass ratio
q
Total mass
M/M⊙
GW190425
GW190924_021846
GW190426_152155
GW190814
GW190412
GW190521
m1 = 3M⊙
m2 = 3M⊙
1.0
0.8
0.6
0.4
0.2
0.0
2
4
7
10
20
40
70
100
200
400
8

From Single Events to a Population

- Introduce a set of population **hyper-parameters** that describe the **distributions** of masses, spins, redshifts across multiple events
- Example: Fit a power-law model to the mass distribution of black holes, $p(\text{mass} \mid a) \propto \text{mass}^{-a}$
- Take into account **measurement uncertainty** and **selection effects**

Population analysis

Find the "best" prior to use for individual events

$$p(m_1, m_2 \mid \alpha)$$

Population model, common to all systems

Parameter estimation likelihood for event *i*

$$p(\text{data} \mid \alpha) = \prod_i \frac{\int p(\text{data}_i \mid m_1, m_2) \boxed{p(m_1, m_2 \mid \alpha)} \mathrm{d}m_1 \mathrm{d}m_2}{\beta(\alpha)}$$

Likelihood given population hyperparameters

Selection effects: fraction of detectable systems in the population

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Mandel, Farr & Gair arXiv:1809.02063

Astrophysical lessons in the gravitational wave data so far

Masses

- **The black hole mass spectrum *does not* terminate abruptly at 45 solar masses**, but *does* show a feature at ~40 solar masses, which can be represented by a *break* in the power law or a Gaussian *peak*.
- **There is a dearth of low-mass black holes** between 2.6 solar masses and ~6 solar masses.
- **The distribution of mass ratios is broad** in the range ~0.3-1, with a mild preference for equal-mass pairings. (GW190814 is an outlier.)

Spins

- Some binary black holes have measurable in-plane spin components, leading to **precession of the orbital plane**.
- Some binary black holes have spins **misaligned by more than 90 degrees**, but the distribution of spin tilts is not perfectly isotropic.
- There are hints, but **no clear evidence that the spin distribution varies with mass**.

Merger rate across cosmic time

- In the local universe, the average **binary black hole merger rate is between 15 and 40 Gpc^{-3} yr^{-1}**
- The binary black hole merger rate **probably evolves with redshift, but slower than the star-formation rate**, increasing by a factor of ~2.5 between $z = 0$ and $z = 1$.

Big Black Holes and the Mass Gap

1. **Where?** First evidence for missing big black holes
2. **What?** Theoretical expectations for pair-instability mass gap and the latest discoveries of big black holes
3. **When?** Evolution of black hole masses across cosmic time
4. **How (and why)?** Astrophysical and cosmological lessons

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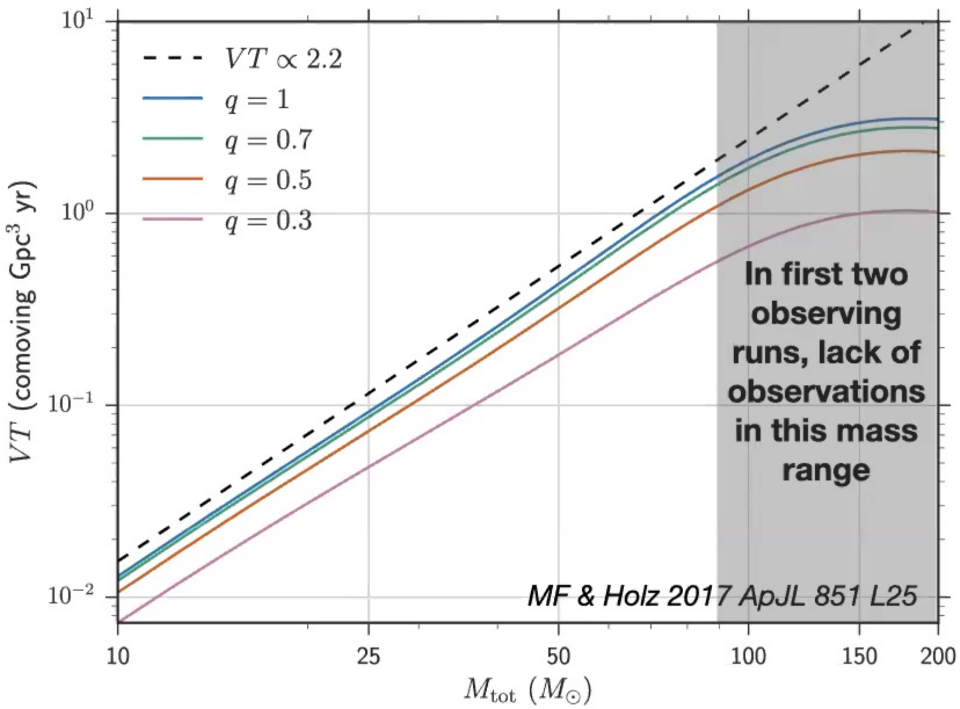
Where are LIGO's Big Black Holes?

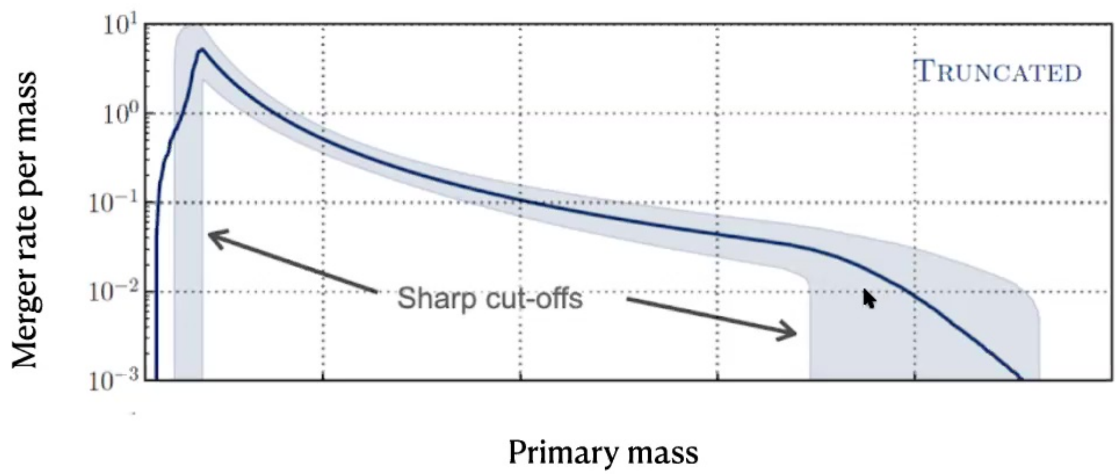
Big black holes are very loud, and yet in the first two observing runs, we did not see any binary black holes with component masses above ~40 solar masses

→ *These systems must be rare in the underlying population.*



With the first 10 binary black holes, we measured the maximum black hole mass to be ~40 solar masses

The black hole masses we observed were consistent with coming from a truncated power law distribution



Abbott+ arXiv:2010.14533

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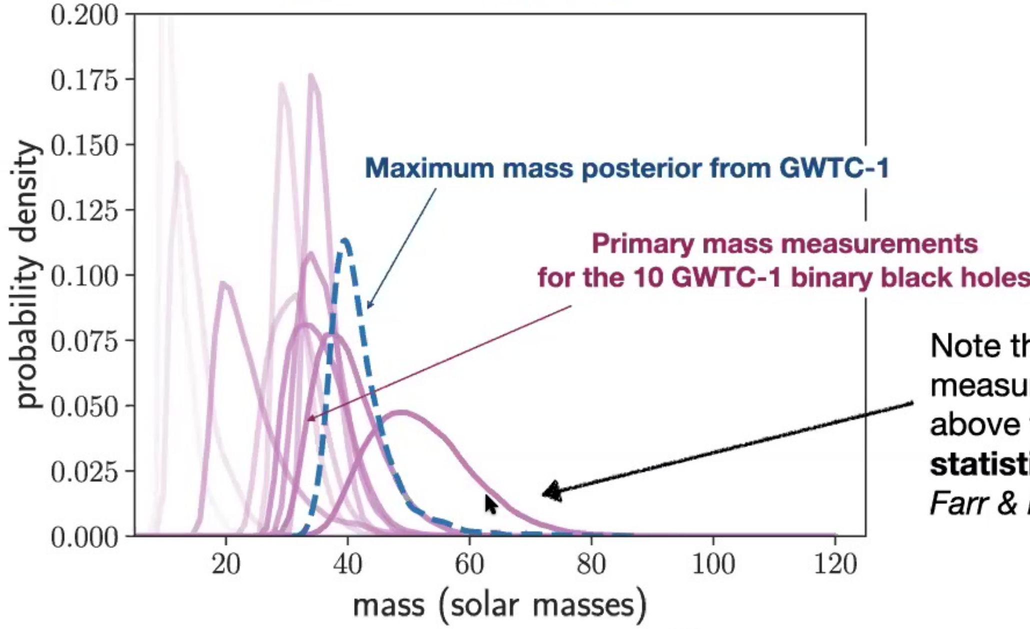
Measurement of the black hole maximum mass from the first 10 events

$$M_{\rm max} = 42.0^{+15.0}_{-5.7}\ M_\odot$$



Note that individual mass measurements may have support above this maximum mass, due to **statistical fluctuations** *(Fishbach, Farr & Holz 2020)*

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What is the black hole mass gap?

- (Pulsational) pair-instability supernovae predict an absence of black holes in the range ~40 - 120 $M_\odot$ (Fowler & Hoyle 1964, Rakavy+ 1967, Bond+ 1984, Heger & Woosley 2002)
- Applies to black holes formed from stellar collapse
- Black holes formed via other channels — for example, from smaller black holes — may populate the gap (e.g. *Are LIGO's Black Holes Made From Smaller Black Holes?* MF, Holz & Farr 2017)

Credit: Gemini Observatory/NSF/AURA/ illustration by Joy Pollard

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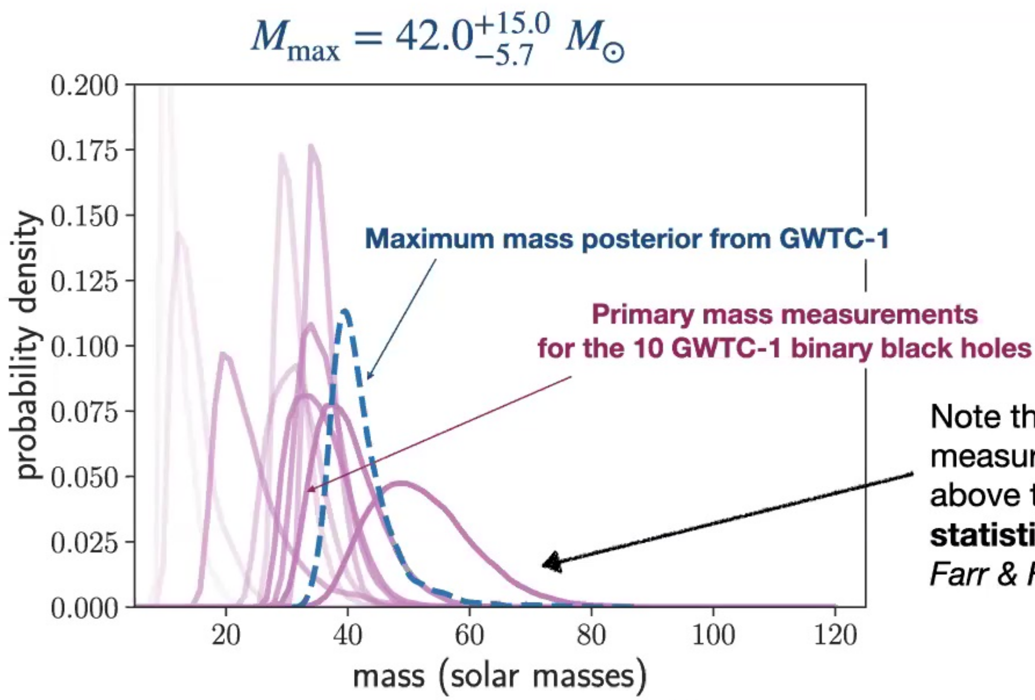

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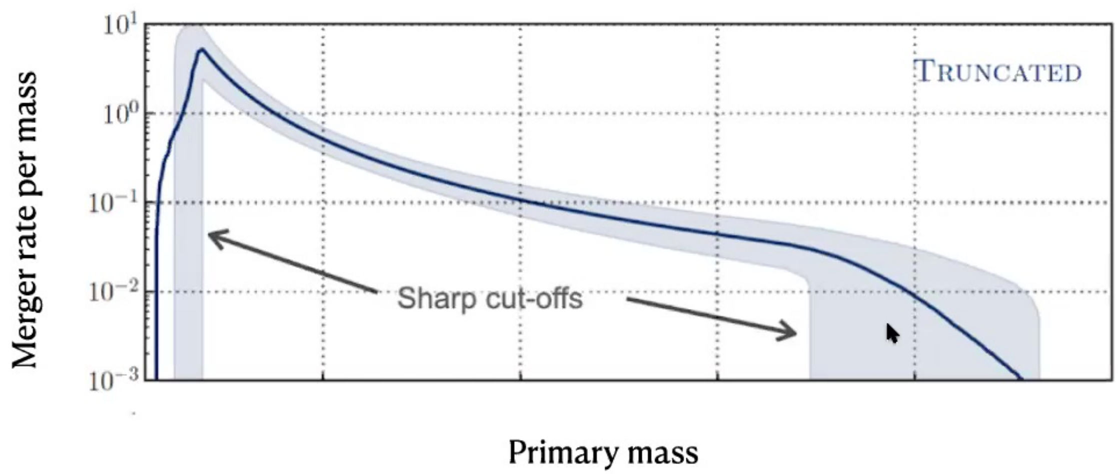

Abbott+ arXiv:2010.14533

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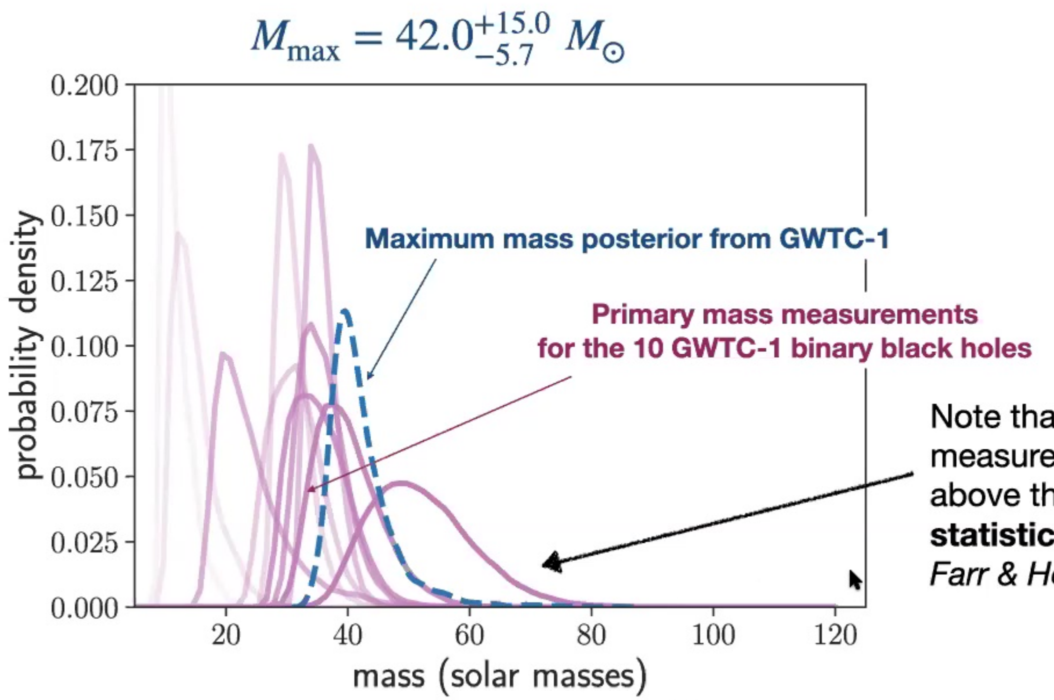

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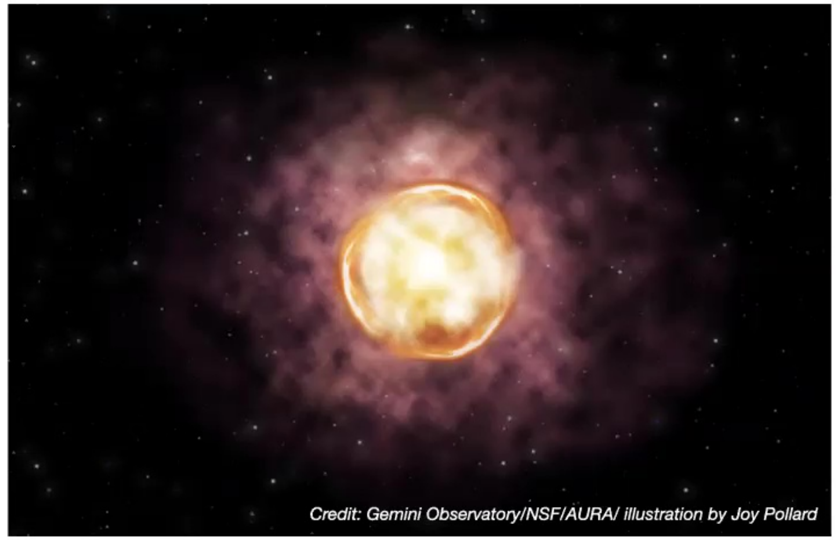

Credit: Gemini Observatory/NSF/AURA/ illustration by Joy Pollard

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What about GW190521?

The New York Times

OUT THERE

These Black Holes Shouldn't Exist, but There They Are

On the far side of the universe, a collision of dark giants sheds light on an invisible process of cosmic growth.


Credit: Carol & Mike Werner/Visuals Unlimited, INC./Science Photo Library

NEWS · 02 SEPTEMBER 2020

'It's mindboggling!': astronomers detect most powerful black-hole collision yet

Gravitational-wave detections suggest merging black holes fell into 'forbidden' range of masses.

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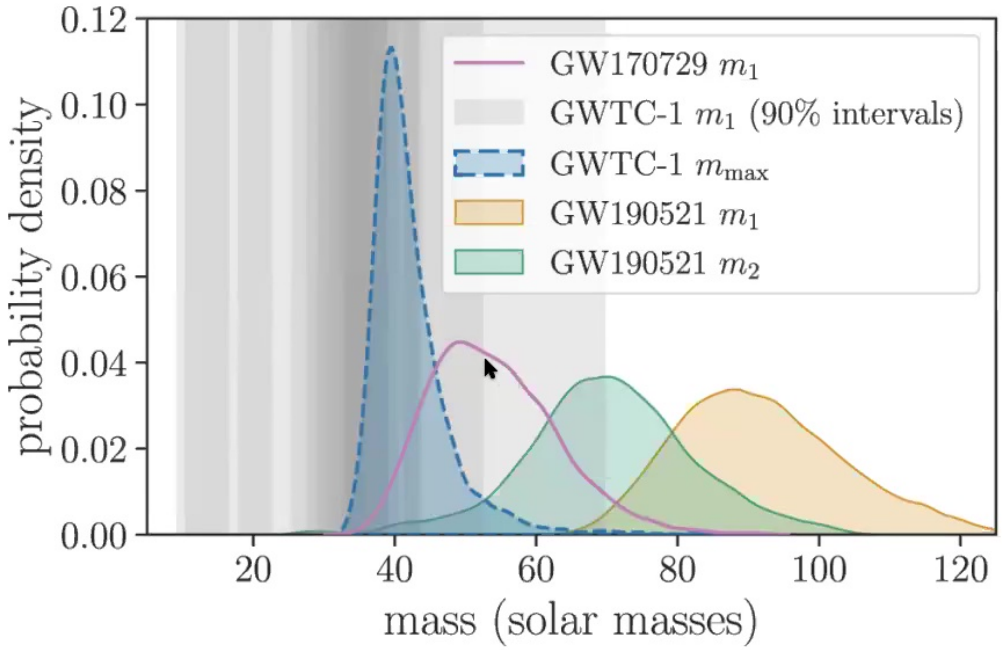
Abbott+ Phys. Rev. Lett. 125, 101102

GW190521 in context with the GWTC-1 population



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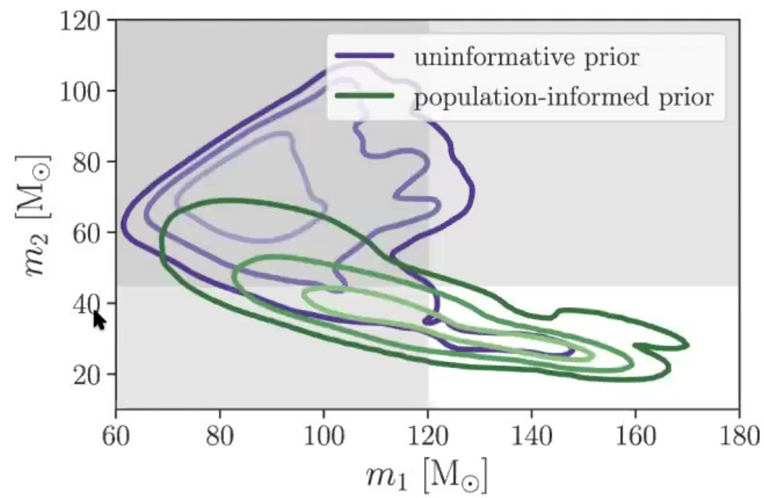
MF & Holz ApJL 904 L26 2020

GW190521 as a "straddling" binary

- Assumption: GW190521 likely contains at least *one* "conventional" black hole
- New prior: the secondary mass of GW190521 belongs to the already-observed black hole population from GWTC-1
- Because the *total mass* is well-constrained — if we assume that the secondary mass is *below the gap*, **the primary mass has a good chance of being *above the gap!***



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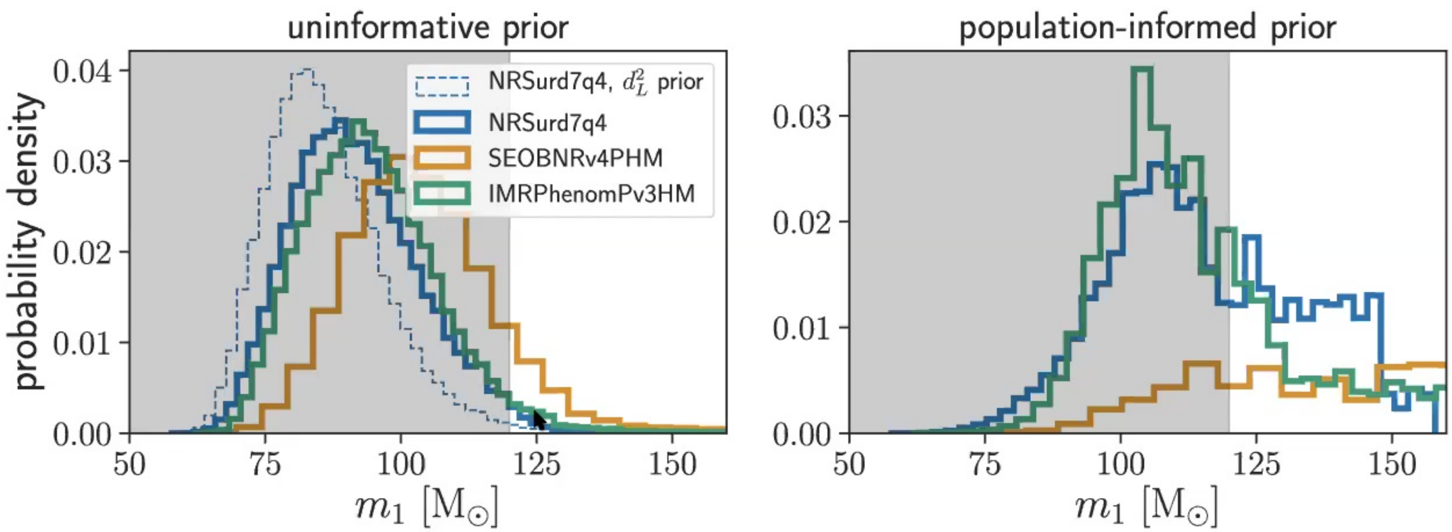
MF & Holz ApJL 904 L26 2020

The primary mass of GW190521 may be above the mass gap



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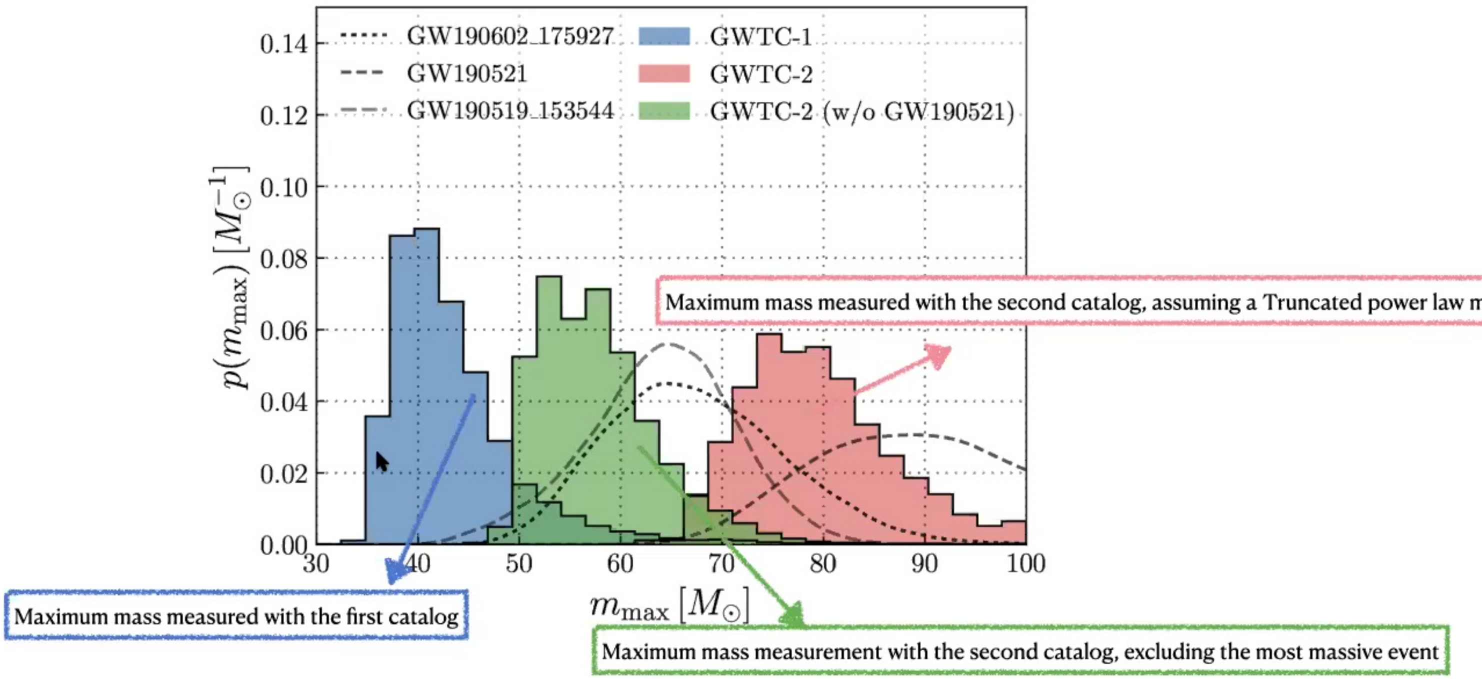
MF & Holz ApJL 904 L26 2020

In addition to GW190521, there are other big black holes in GWTC-2



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Abbott+ arXiv:2010.14533

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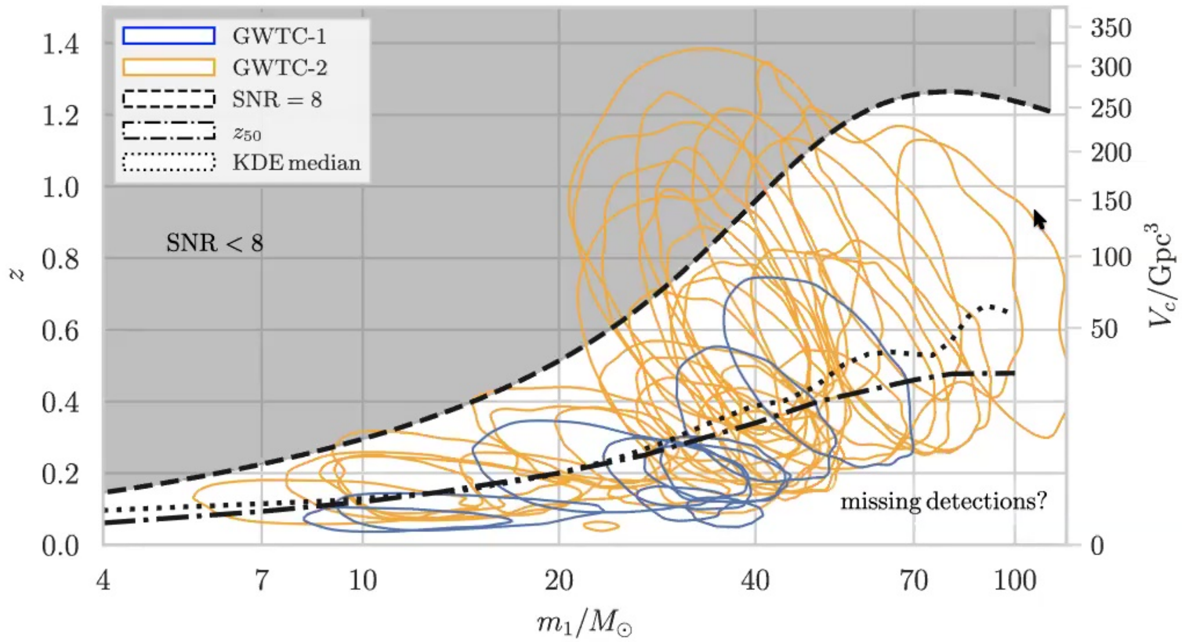
When are LIGO/Virgo's Big Black Hole Mergers?



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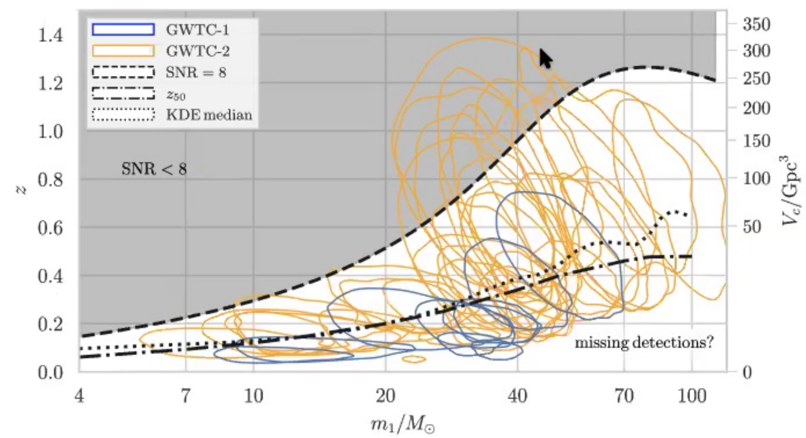
MF, Doctor, Callister, Edelman, Ye, Essick, Farr, Farr & Holz
2021 arXiv: 2101.07699

When are LIGO/Virgo's Big Black Hole Mergers?

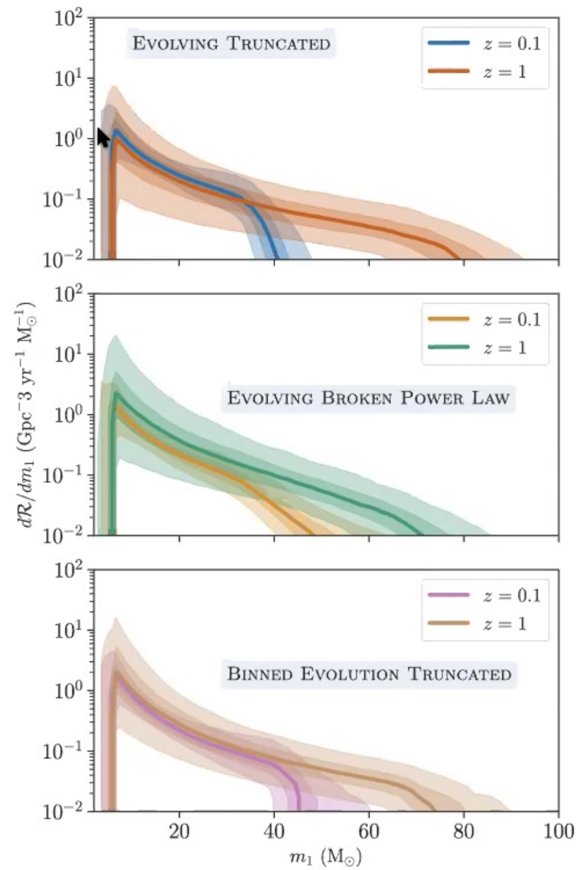
- In the first two observing runs, we were only probing redshifts $z < 0.5$, compared to $z < 1$ in the third observing run.
- The new big black holes of the third observing run are all at higher redshifts.
- Does this indicate that the mass distribution is *different* at high redshifts, or are big black holes rare at all redshifts, and are therefore just easier to find as we probe larger cosmological volumes?



MF, Doctor, Callister, Edelman, Ye, Essick, Farr, Farr & Holz 2021 arXiv: 2101.07699

Evolution of the black hole mass distribution with redshift

- At a fixed redshift, we assume that the mass distribution is described either by a *Truncated power law* or a *Broken power law*
- We allow the parameters of the mass distribution (the maximum black hole mass, the break in the power law) to evolve with redshift
- We infer the model parameters from the data, fitting the merger rate as a function of mass and redshift



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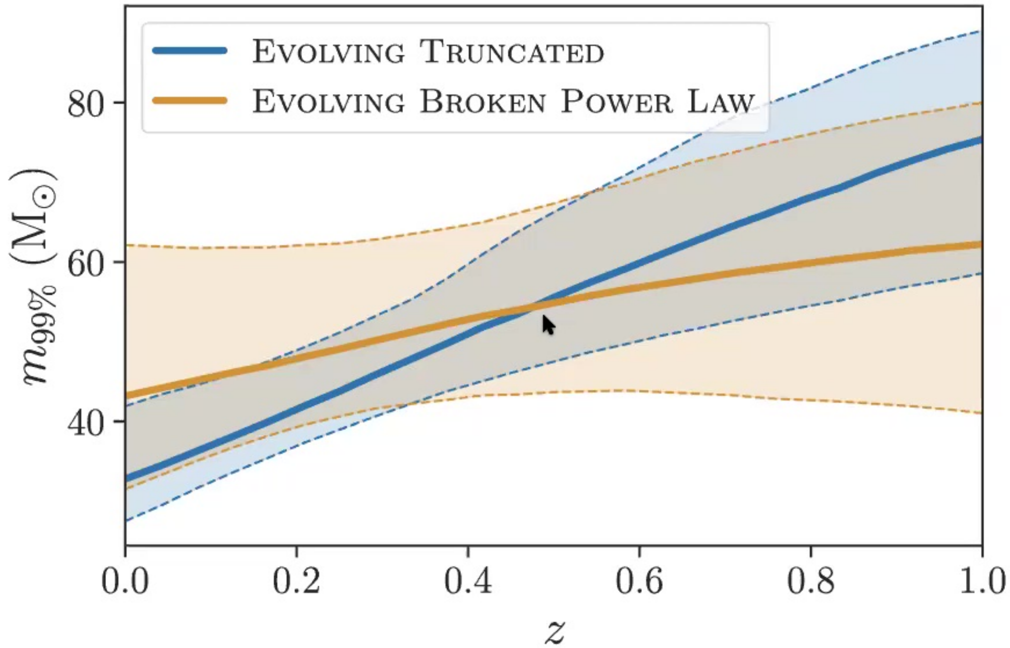
Hints that black holes are bigger at high redshifts



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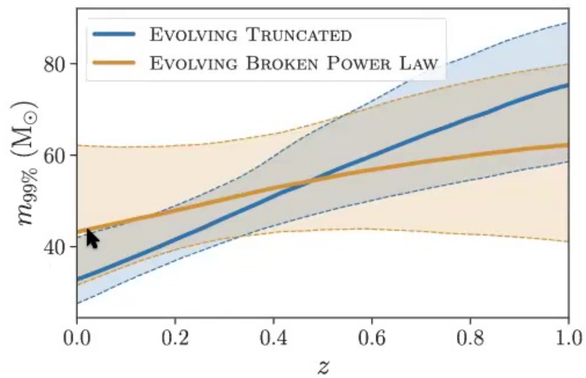
MF, Doctor, Callister, Edelman, Ye, Essick, Farr, Farr & Holz
2021 arXiv: 2101.07699

Hints that black holes are bigger at high redshifts

- If the black hole mass distribution has a *sharp maximum mass cutoff* (which we expect from the pair-instability mass gap), it *must evolve with redshift*.
- If the mass distribution tapers off more gradually at high masses (e.g. a *break* in the power law), the data are consistent with no mass evolution.



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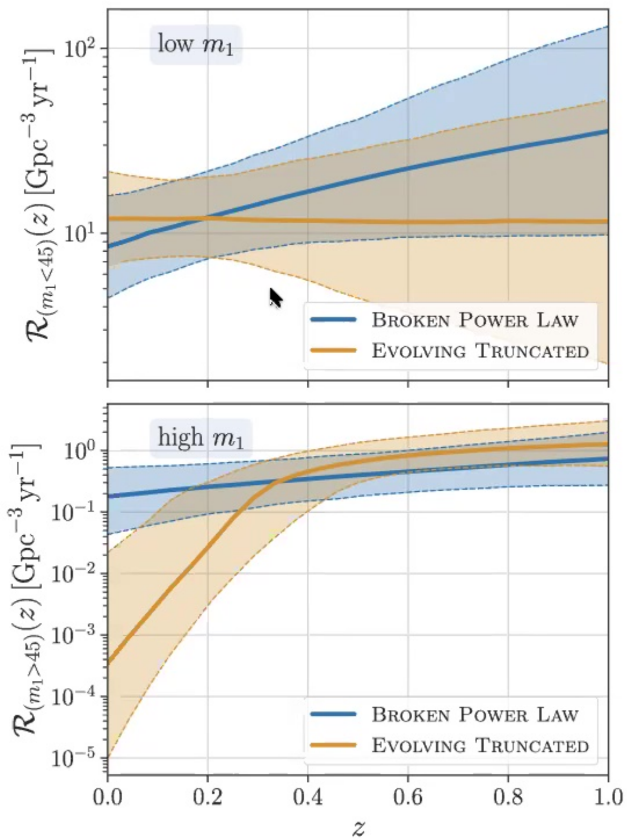
MF, Doctor, Callister, Edelman, Ye, Essick, Farr, Farr & Holz 2021 arXiv: 2101.07699

The merger rate across cosmic time

- If the mass distribution does not evolve with redshift, the overall merger rate, at all masses, evolves.
- Alternatively, it is possible that with increasing redshift, only the biggest black holes merge at an increasing rate



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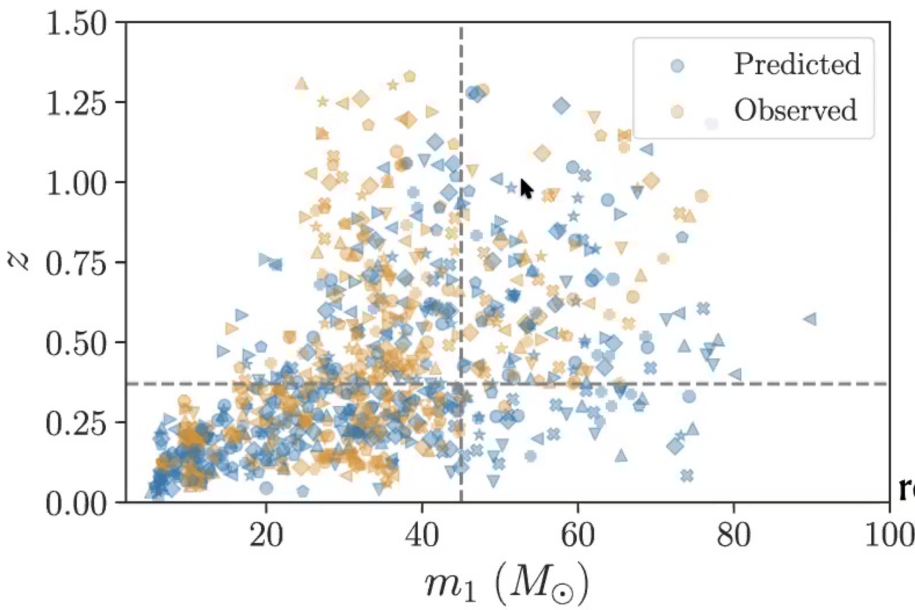
Distinguishing between an evolving sharp cutoff and a non-evolving break



How many detections did we observe at high masses, low redshifts, compared to what the model predicts?

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MF, Doctor, Callister, Edelman, Ye, Essick, Farr, Farr & Holz 2021 arXiv: 2101.07699

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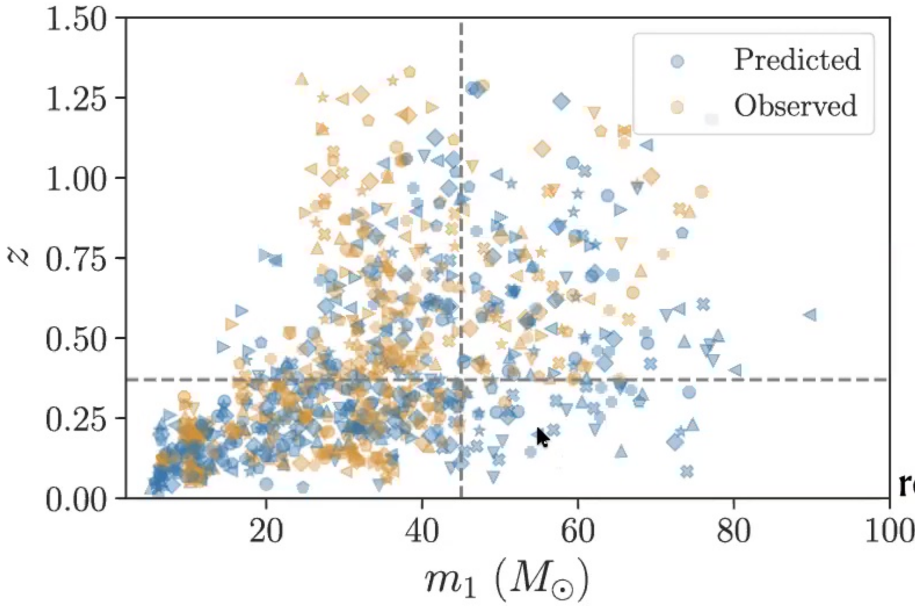

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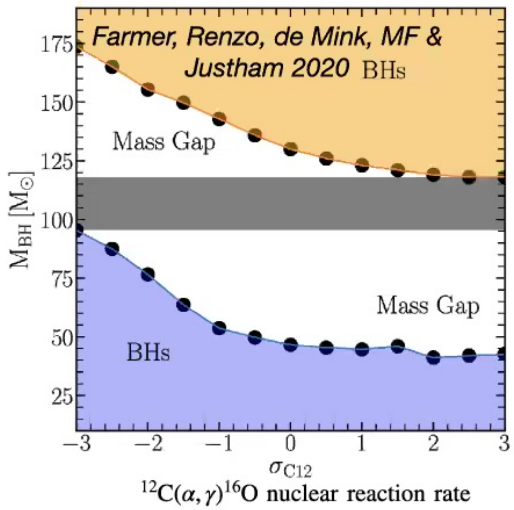
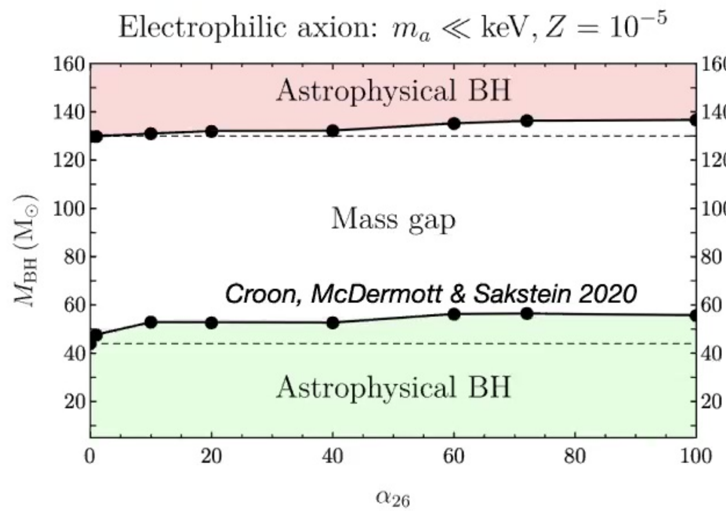
Measuring the location of the pair-instability gap can help us resolve uncertain physics

Uncertain nuclear physics



(standard deviations from the measured median)

Possible beyond-standard model physics



Electron-axion coupling

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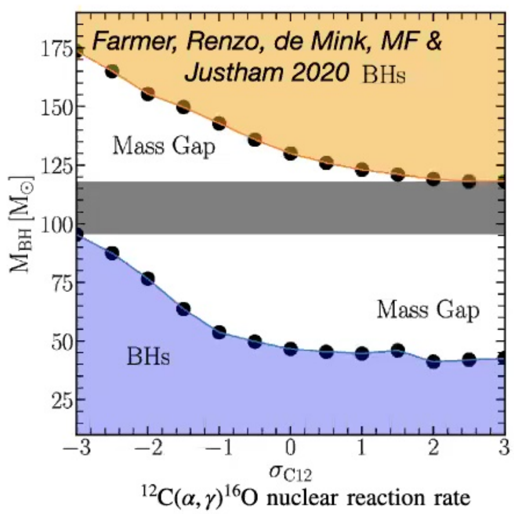

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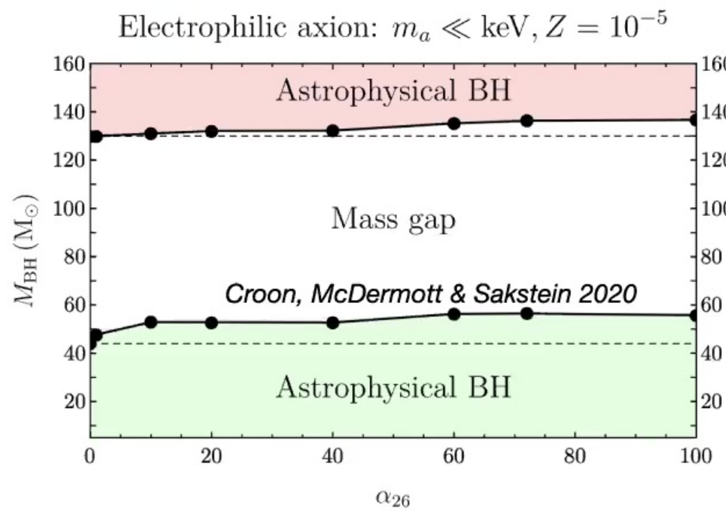

Electron-axion coupling

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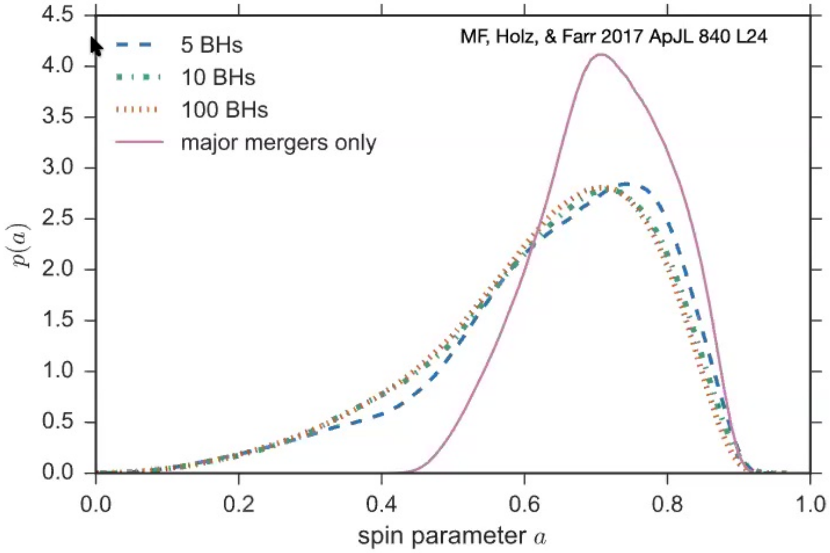
Evidence for multiple formation channels?

- Are the big black holes we observe formed differently from the low-mass black holes?
- In addition to their redshift evolution, we can learn from the spin distribution: both the magnitude and the orientation

Expected spin magnitude distribution for BHs formed from previous mergers



See recent analysis by Kimball+ 2020 arXiv:2011.05332

The pair-instability feature as a cosmological probe

Standard Sirens: 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; redshifted chirp mass; frequency; position and orientation; luminosity distance; phase

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

...and the redshifted masses.

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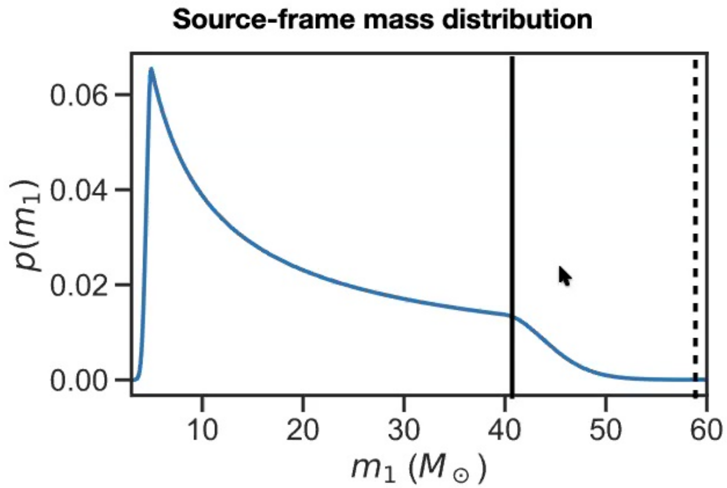
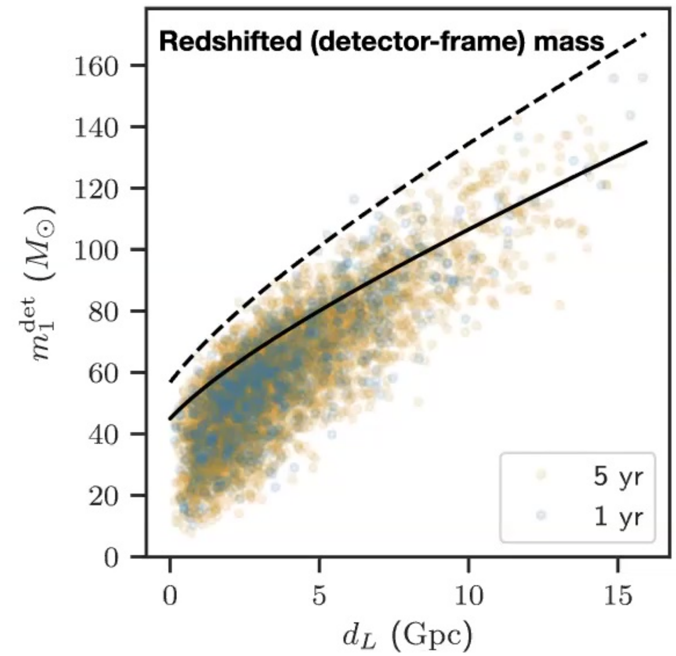
If we assume that the source-frame mass scale *does not evolve*, we can measure redshift from the pair-instability feature





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

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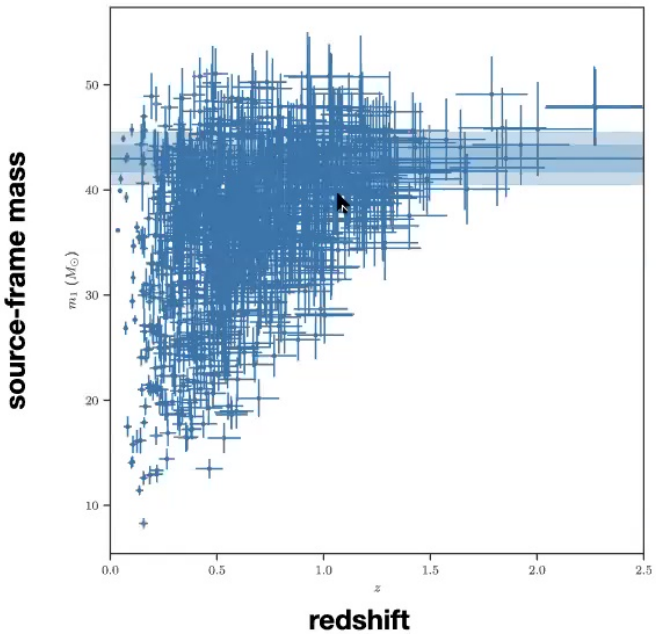
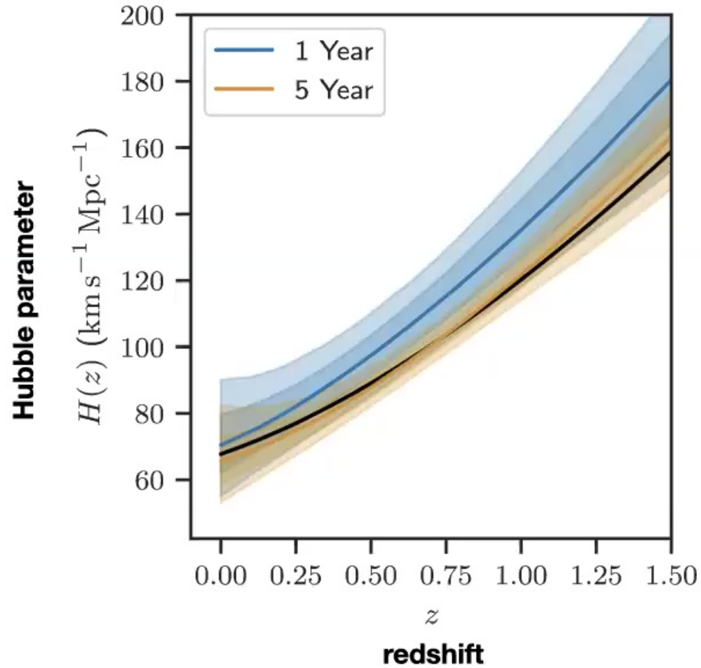
We will be able to simultaneously measure the source-frame mass distribution and the redshift-distance relation





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

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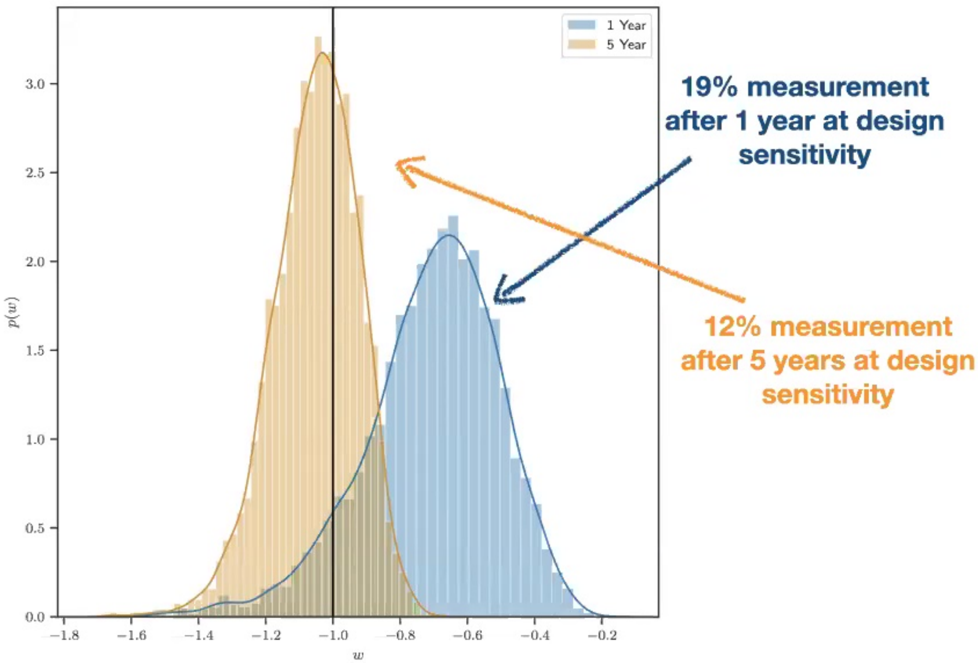
Combining this with a 1% local measurement of Ho and the $\Omega_m h^2$ measurement from the CMB, we will be able to constrain the dark energy equation of state



Dark energy equation of state *w* in wCDM model

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

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Lessons from LIGO/Virgo's Biggest Black Holes

1. **Where?** LIGO/Virgo's first two observing runs revealed a dearth of binary black holes with component masses above ~40 solar masses
2. **What?** The dearth of big black holes was consistent with the theoretically-predicted pair-instability mass gap. However, the third observing run revealed a population of big black holes above the previously-inferred maximum mass cutoff. Perhaps we have even observed a black hole on the far side of the mass gap.
3. **When?** One possibility is that these big black holes only merge at high redshifts, perhaps because of metallicity evolution or the presence of another formation channel that contaminates the mass gap.
4. **How (and why)?** The rate of big black hole mergers across cosmic time provides clues to how they formed. Regardless of whether it is a sharp cutoff, there is clearly a feature in the black hole mass distribution at ~40 solar masses. Connecting this to the physics of supernova explosions will allow us to constrain uncertain nuclear and particle physics, as well as measure cosmological parameters.

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Astrophysical lessons in the gravitational wave data so far

Masses

- **The black hole mass spectrum *does not* terminate abruptly at 45 solar masses**, but *does* show a feature at ~40 solar masses, which can be represented by a *break* in the power law or a Gaussian *peak*.
- **There is a dearth of low-mass black holes** between 2.6 solar masses and ~6 solar masses.
- **The distribution of mass ratios is broad** in the range ~0.3-1, with a mild preference for equal-mass pairings. (GW190814 is an outlier.)

Spins

- Some binary black holes have measurable in-plane spin components, leading to **precession of the orbital plane**.
- Some binary black holes have spins **misaligned by more than 90 degrees**, but the distribution of spin tilts is not perfectly isotropic.
- There are hints, but **no clear evidence that the spin distribution varies with mass**.

Merger rate across cosmic time

- In the local universe, the average **binary black hole merger rate is between 15 and 40 Gpc^{-3} yr^{-1}**
- The binary black hole merger rate **probably evolves with redshift, but slower than the star-formation rate**, increasing by a factor of ~2.5 between $z = 0$ and $z = 1$.

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