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Cosmology and Fundamental Physics from Stellar Mass Binary Black Holes

Will M. Farr

2023-08-23: Current Themes in High Energy Physics, Gravity and Cosmology, NBI

LIGO Orientation

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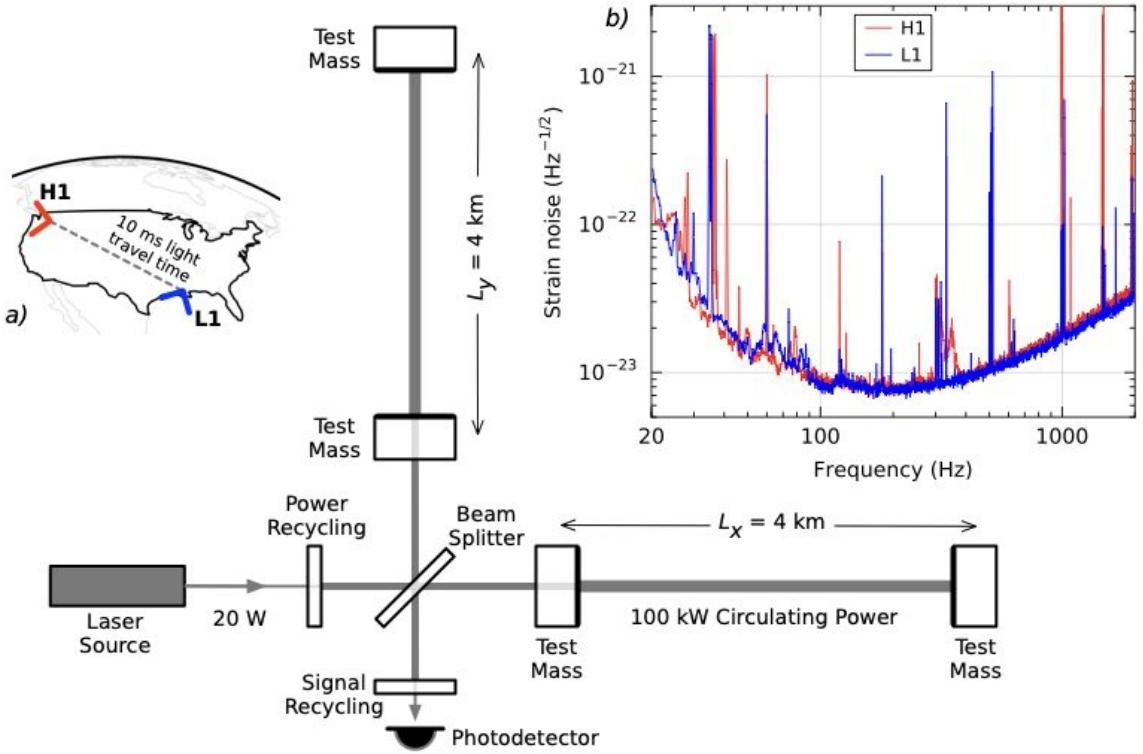
LIGO



[Abbott, et al. (2016)]

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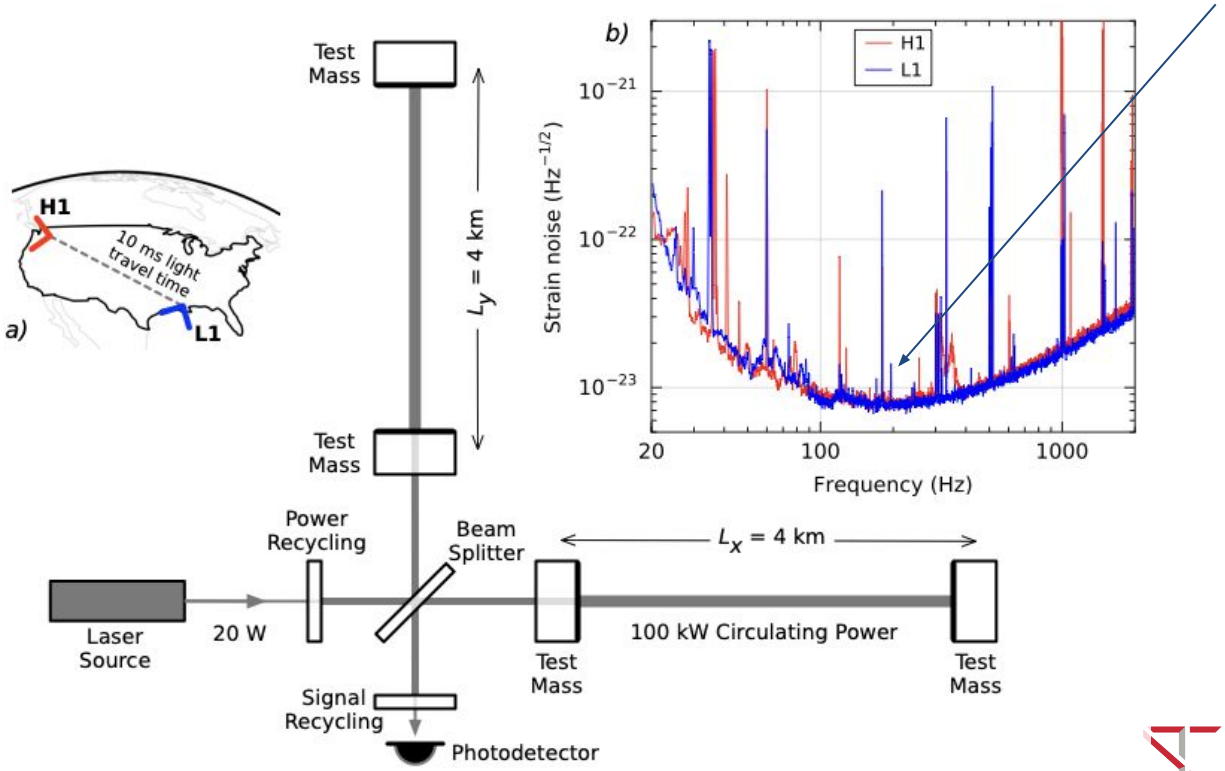
LIGO

$$f_{\rm ISCO} = 200\,{\rm Hz}\,\frac{10M_\odot}{M}$$



Abbott, et al. (2016)

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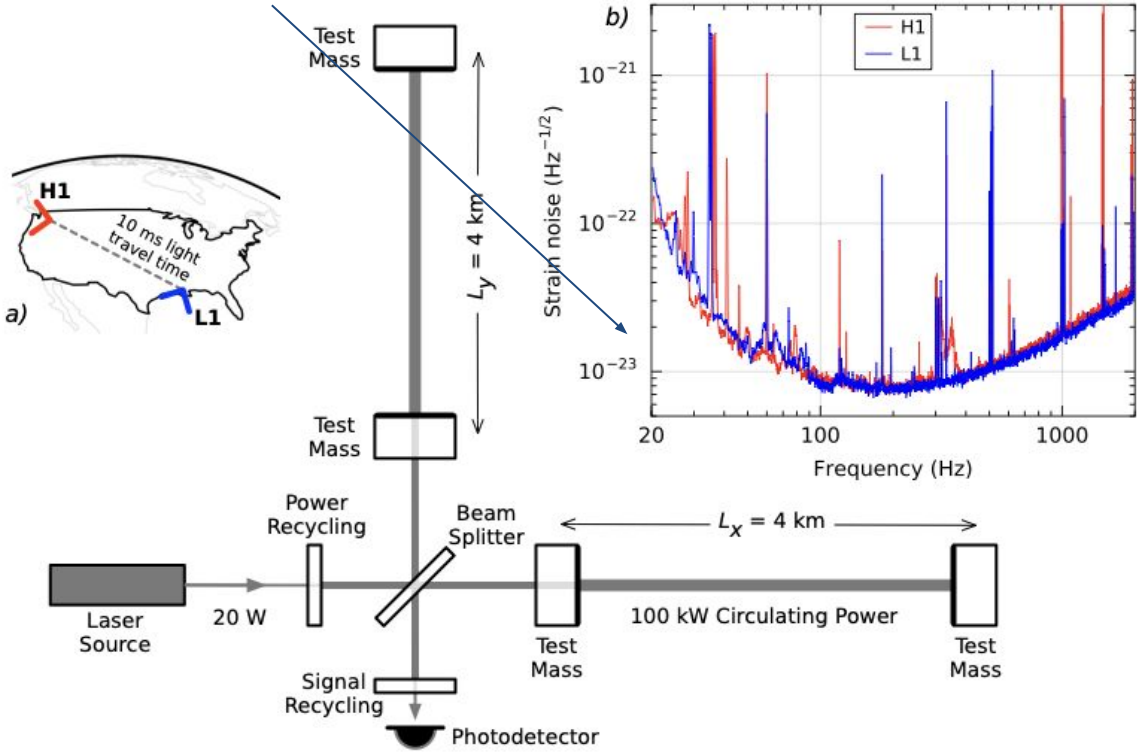
$$h = \mathcal{O}(1) \times \frac{R_{\rm Schw}}{r} \simeq 10^{-23} \frac{M}{10\,M_\odot} \frac{1\,{\rm Gpc}}{r}$$



Abbott, et al. (2016)

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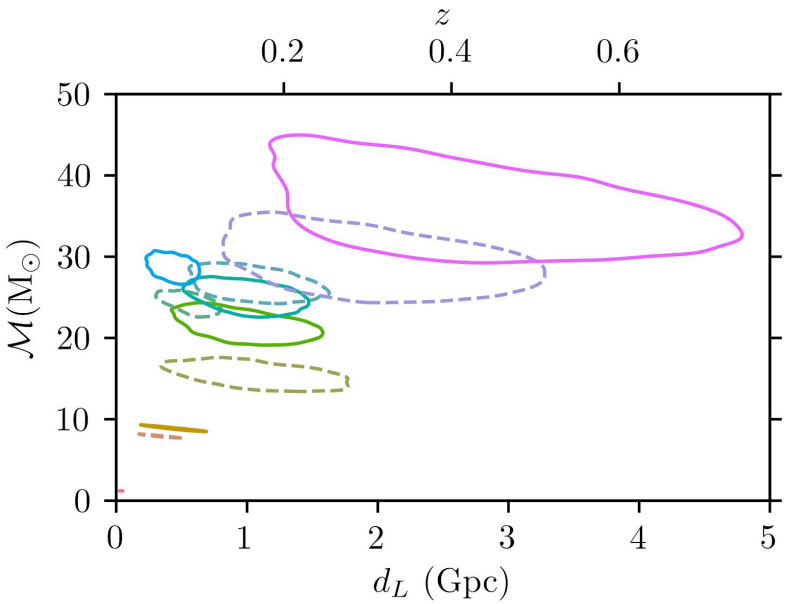
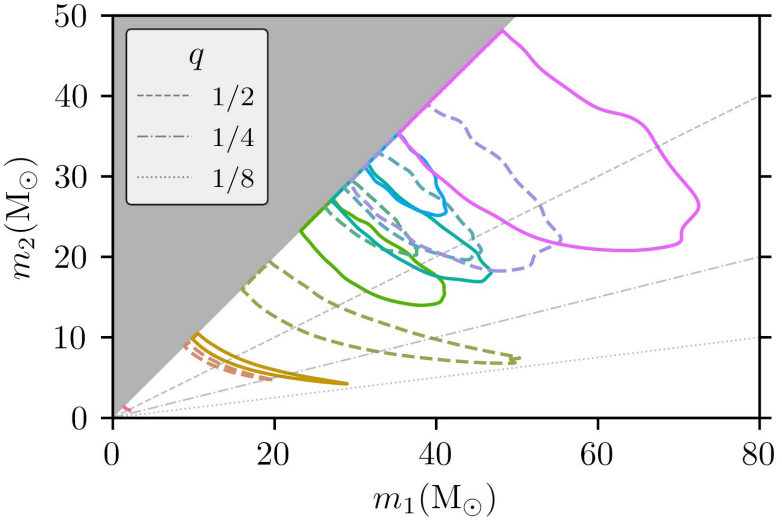
GWTC-1





Abbott, et al. (2019)

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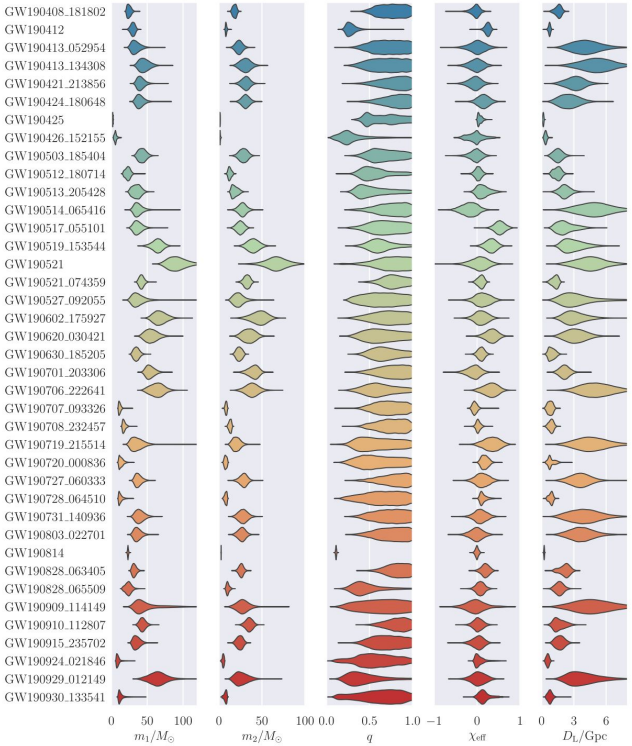
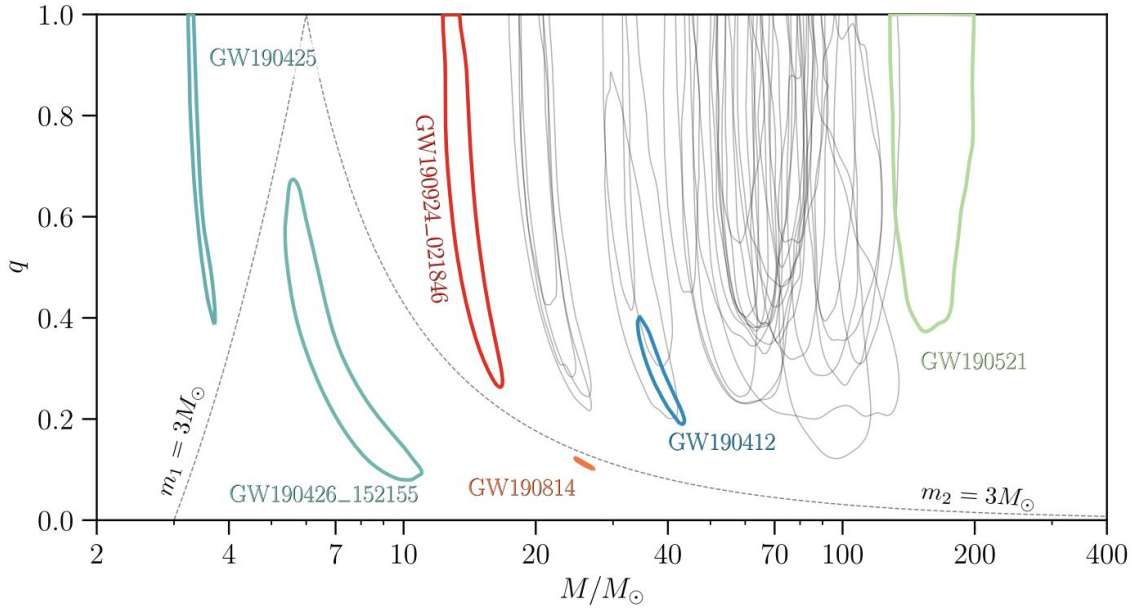
O3a (a == first half, about six months of wall time)





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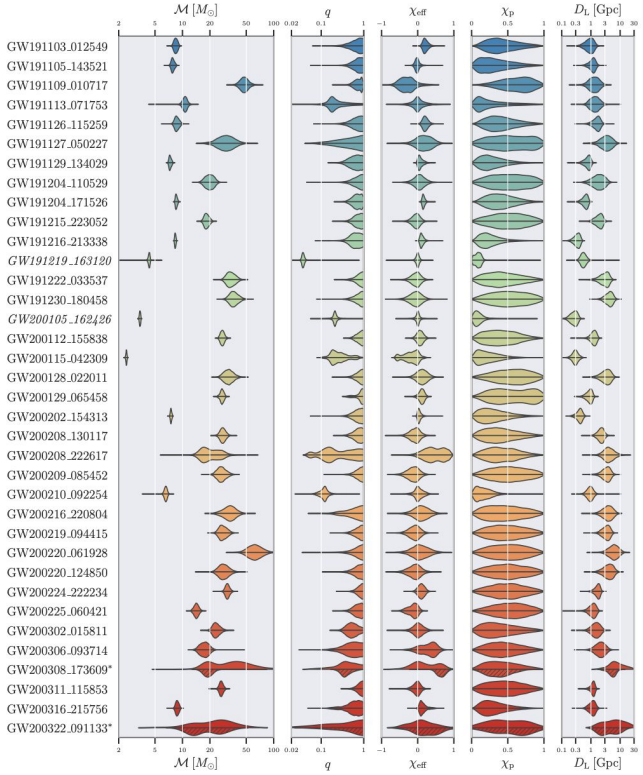
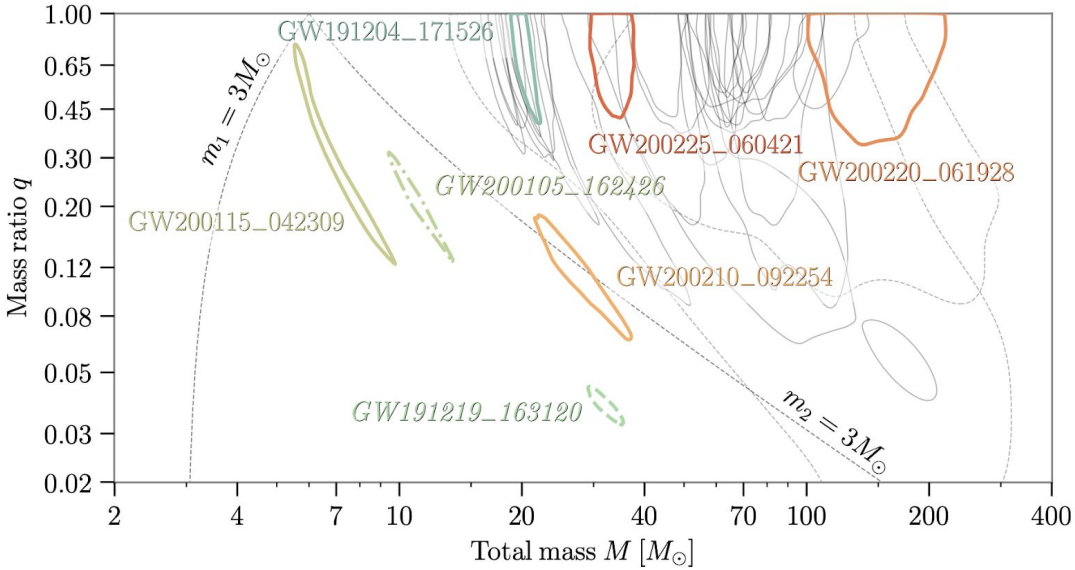
[Abbott, et al. (2020)]

GWTC-3b





[Abbott, et al. (2021)]

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GW Cosmology (-graphy?)

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GW Distances are Easy

$$\frac{c^5}{G} \simeq 3 \times 10^{59}\,\mathrm{erg\,s^{-1}} \simeq 10^6\,\mathrm{SNe}$$

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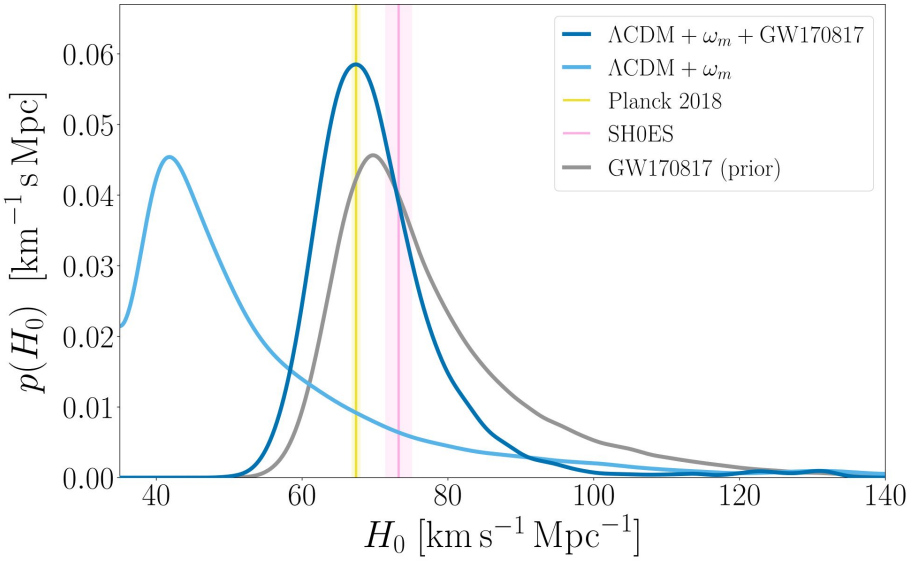
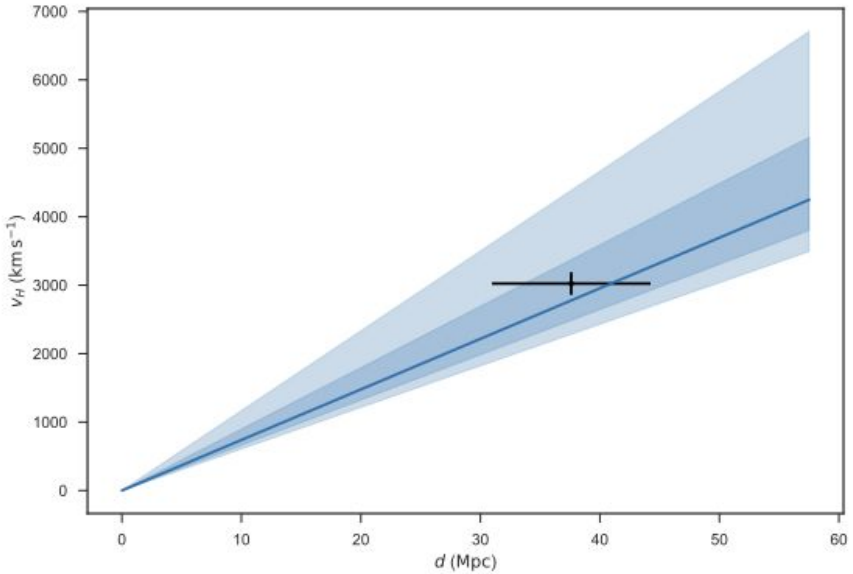
GW Redshifts Are Hard

$$m_{\rm obs} = m\,(1+z)$$

Easy Mode: GW + EM Measurements





[Abbott, et al. (2017)](#)
[Chen, et al. (2020)](#)

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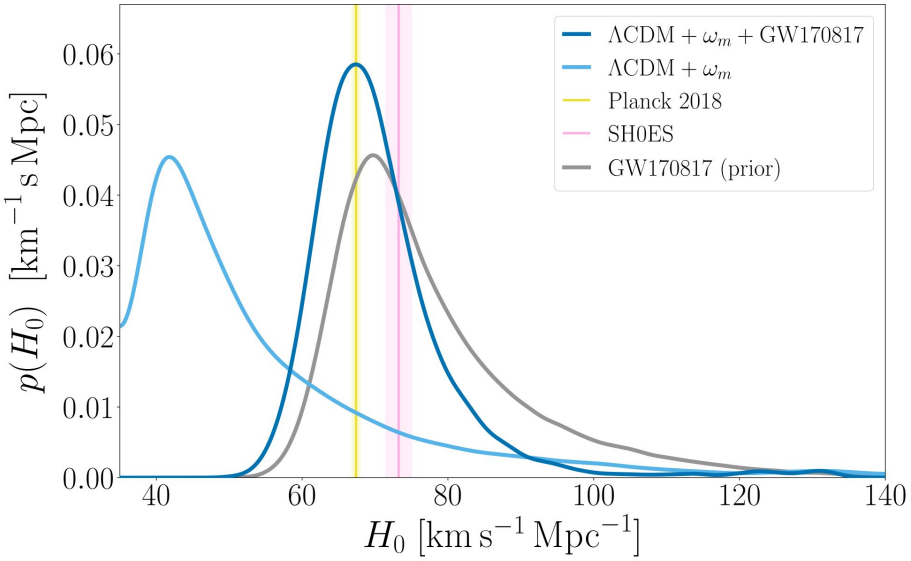
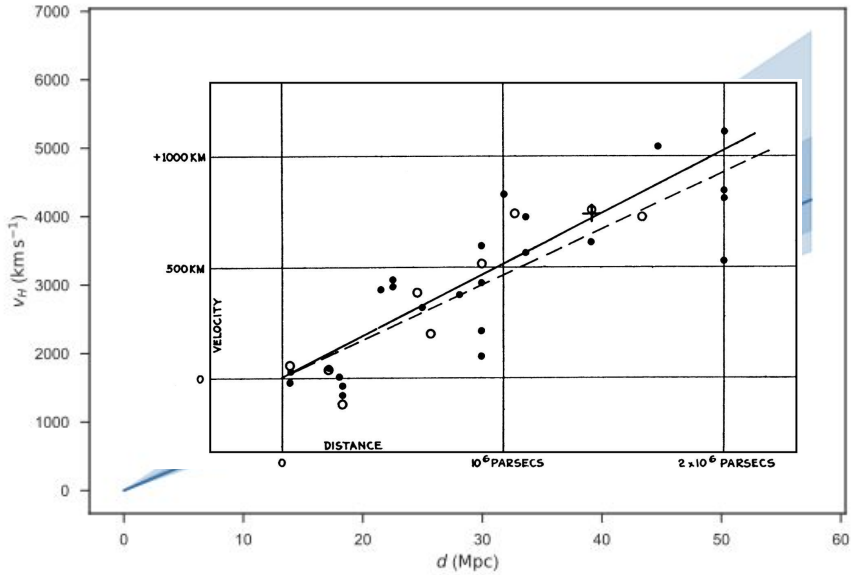
Easy Mode: GW + EM Measurements





[Abbott, et al. (2017)](#)
[Chen, et al. (2020)](#)

[Hubble 1928](#)

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The last time I was at NBI was August 2017; I went home to GW170817… just sayin'.

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Redshifts Without EM Observations

$$m_{\mathrm{obs}} = m\,(1+z)$$

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Redshifts Without EM Observations

If I know this

$$m_{\rm obs} = m(1+z)$$

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Redshifts Without EM Observations

If I know this

$$m_{\rm obs} = m(1+z)$$

Then I can measure this.

[Chernoff & Finn (1993)](#)
[Taylor & Gair (2012)](#)

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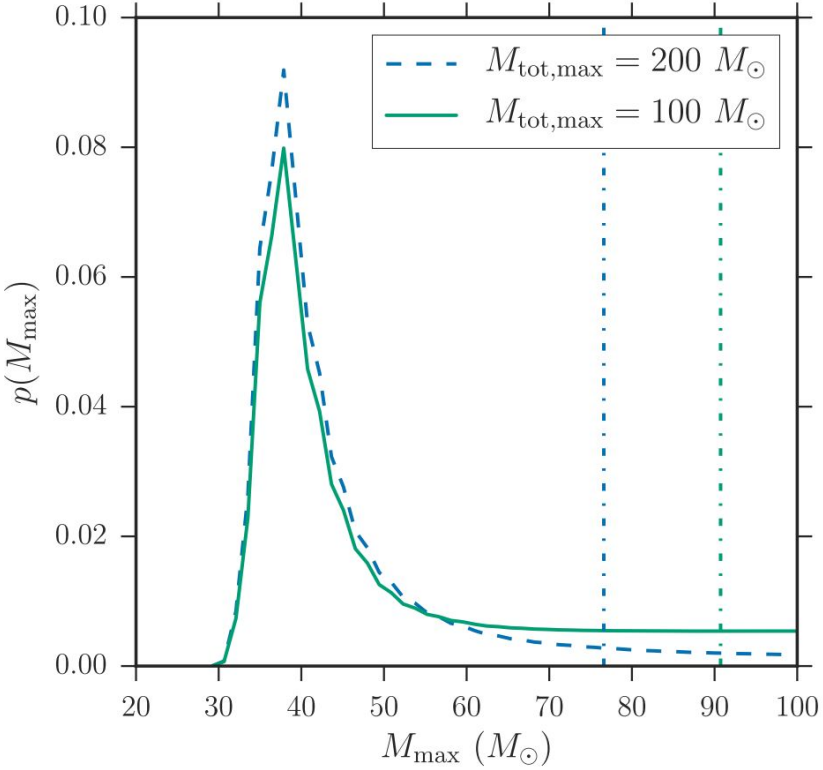
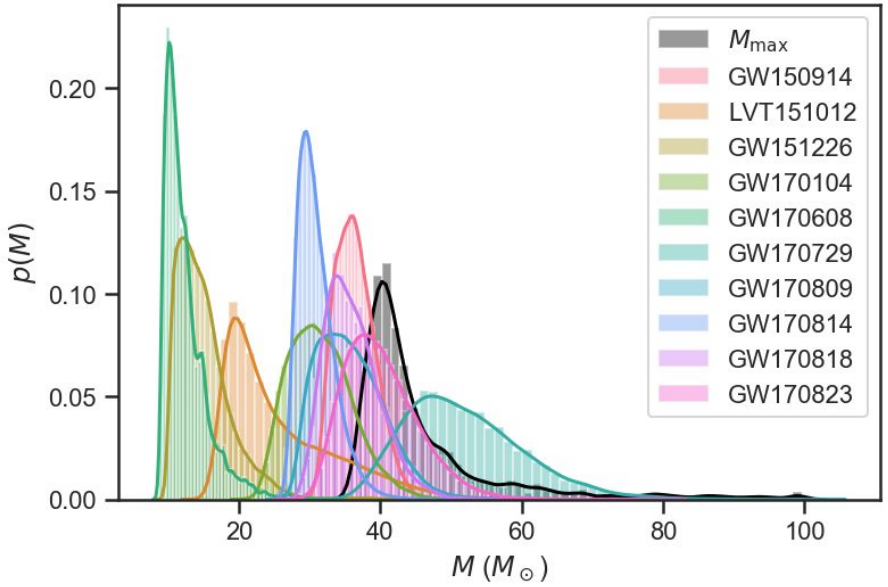
Where are LIGO's Big Black Holes?





[Fishbach & Holz (2017)]

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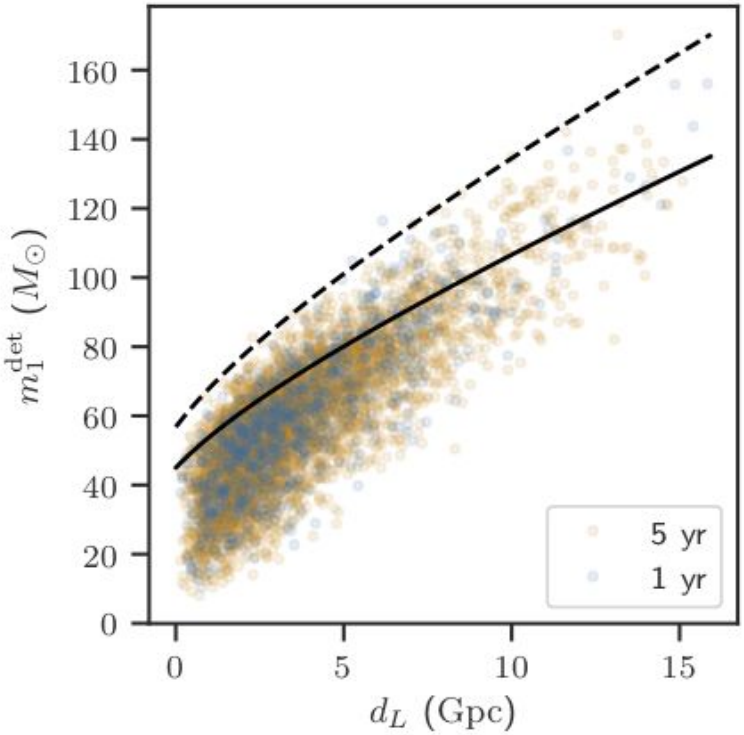
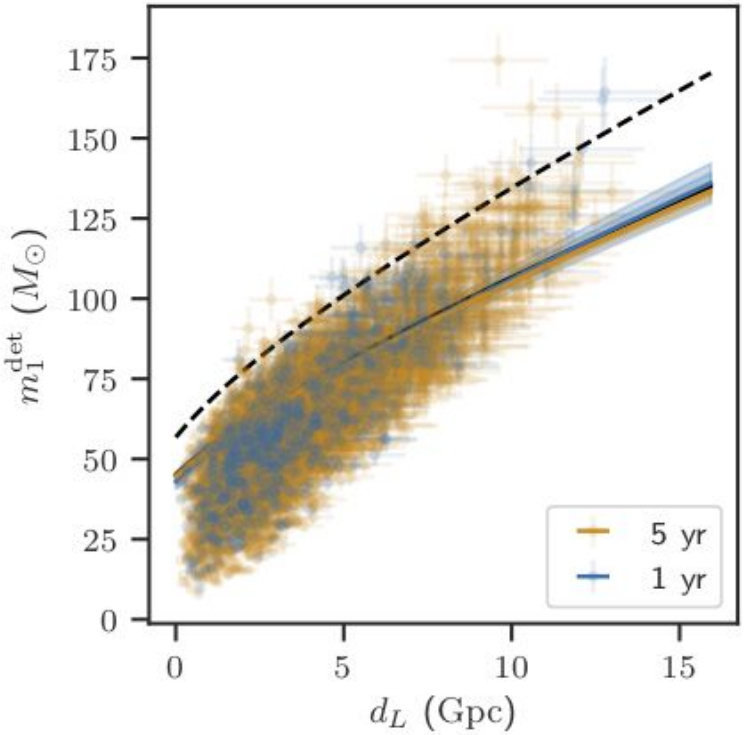
Farr, et al. (2019)





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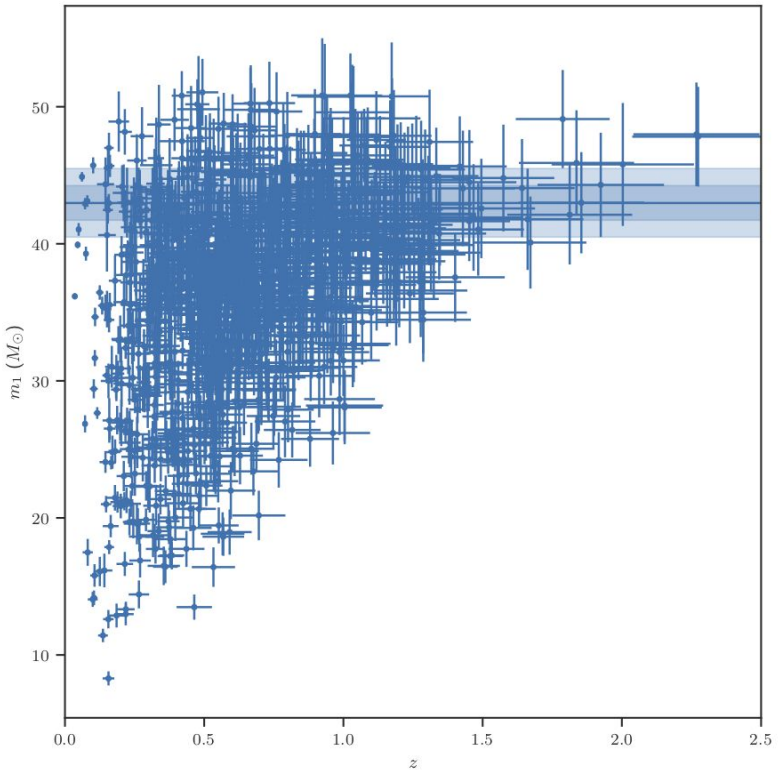
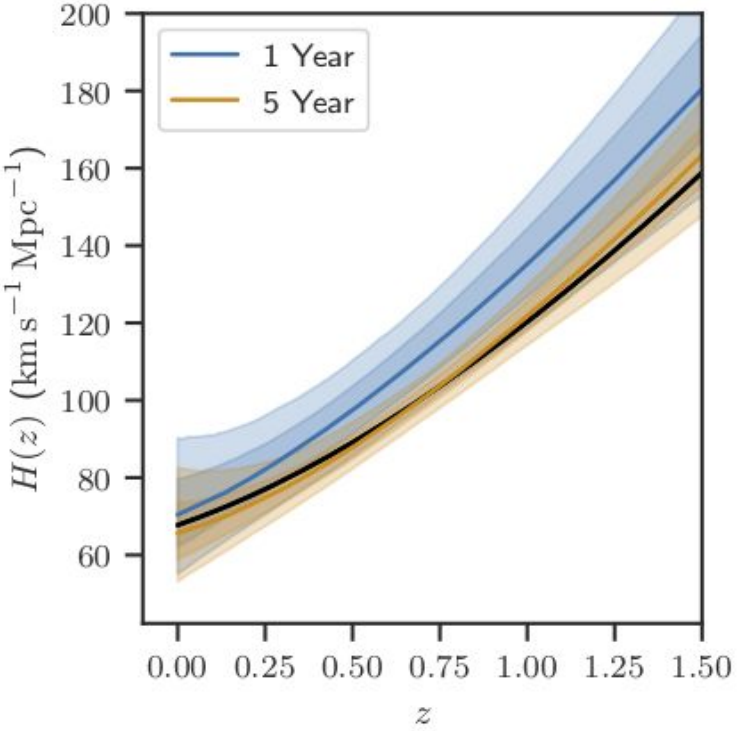
H(z) Measurement





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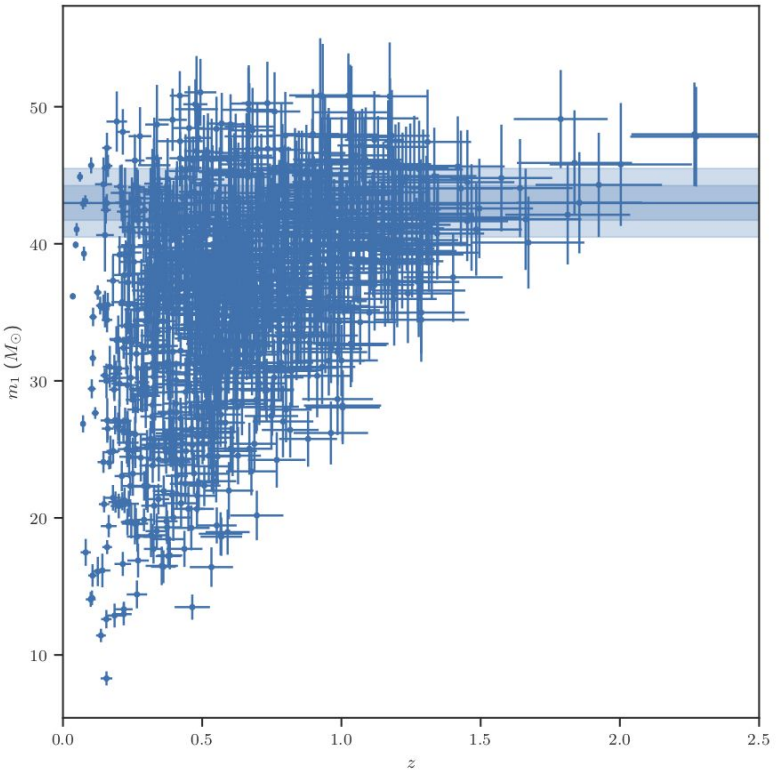
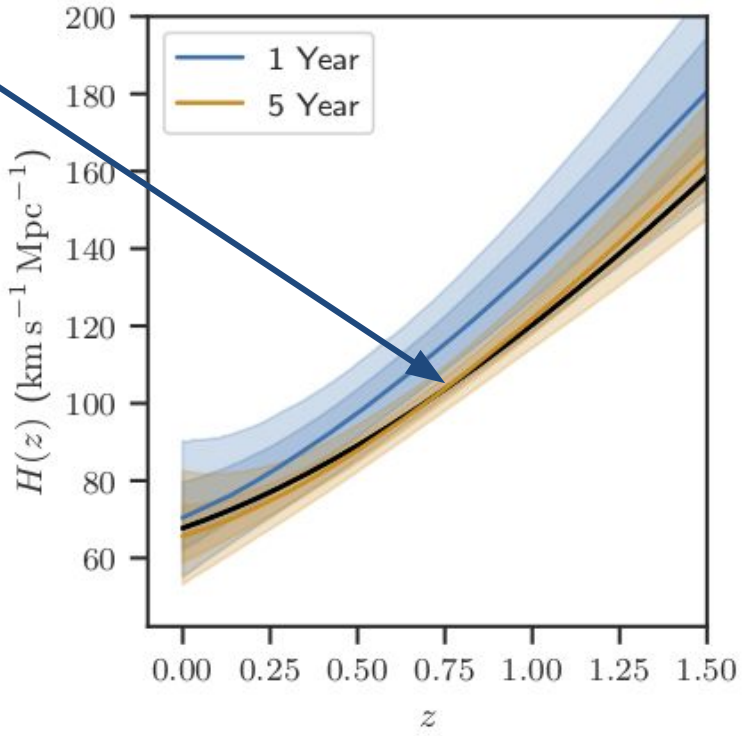
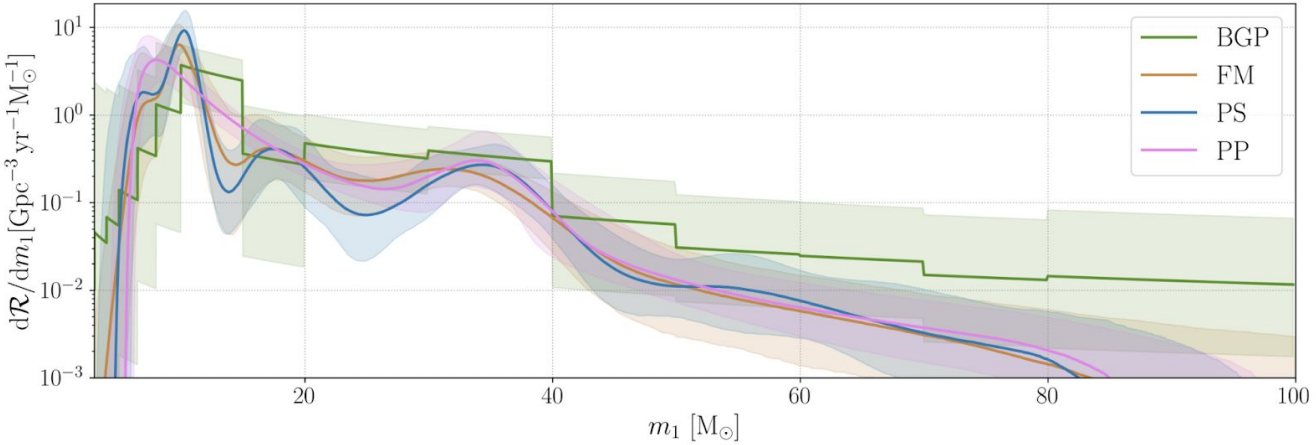
H(z) Measurement

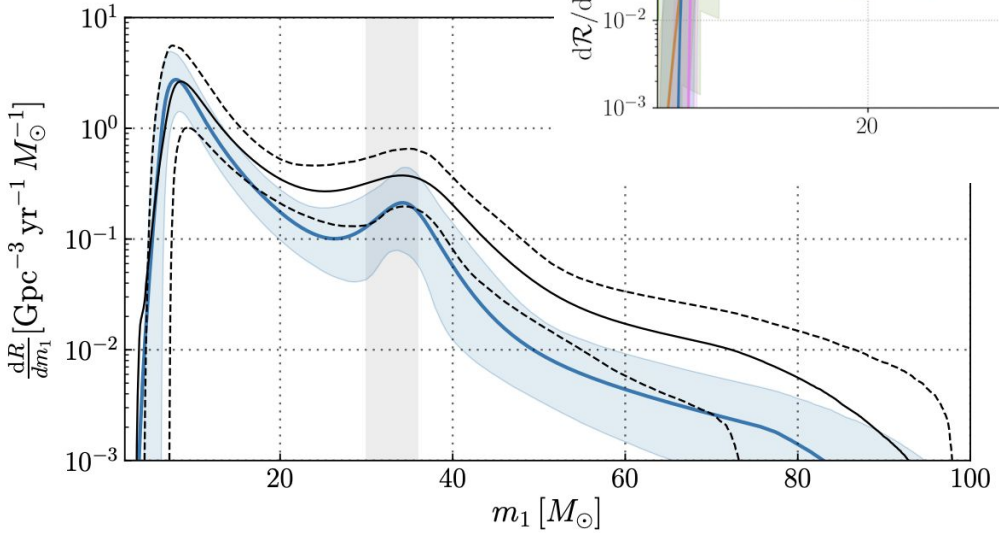
3% at z ~ 0.8 (H0: +/- 2 km/s/Mpc)!





GWTC-3 Populations





[Abbott, et al. (2021)]

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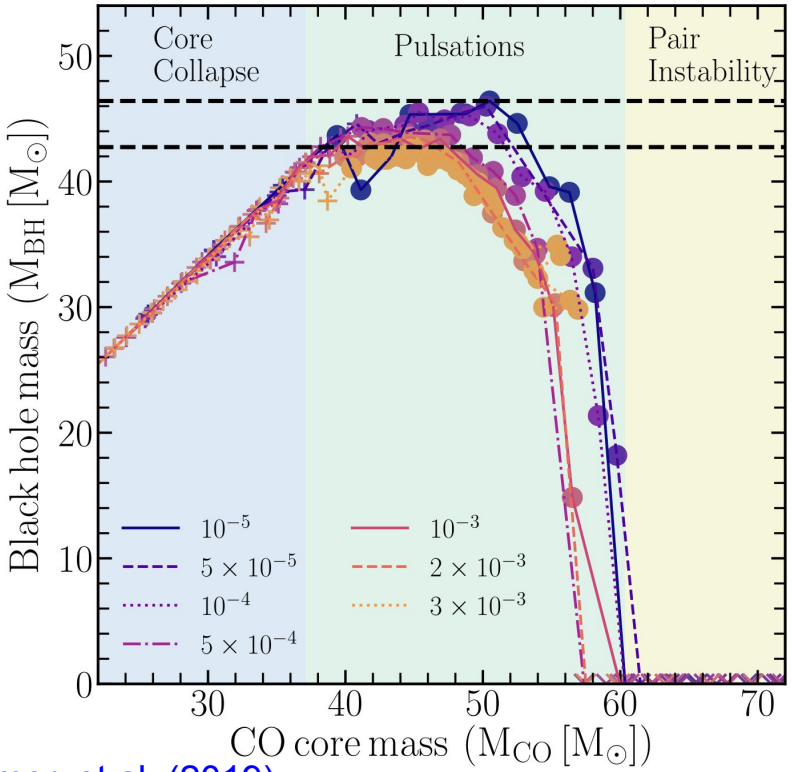
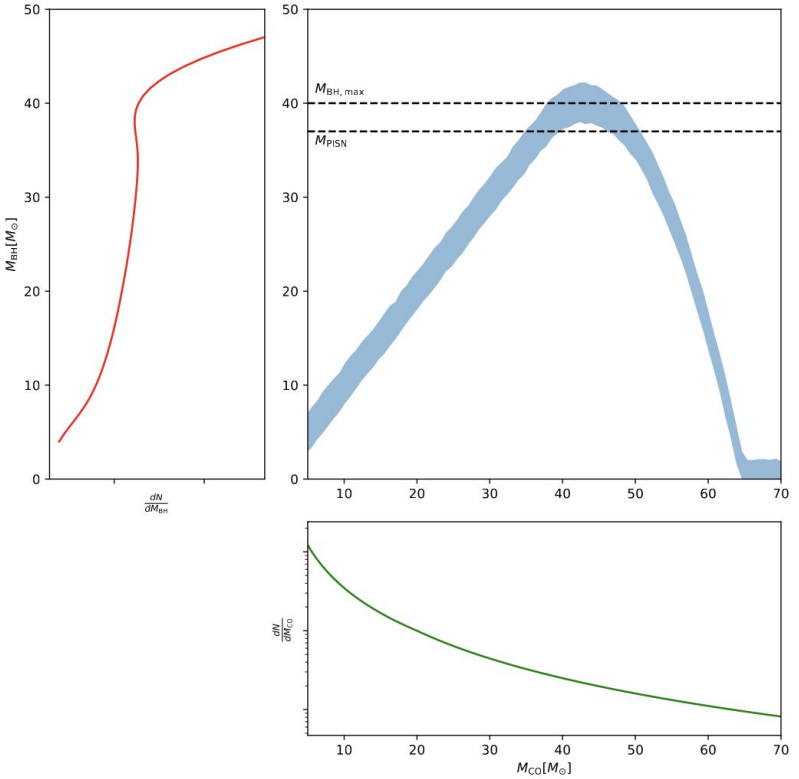
Pair Instability Process

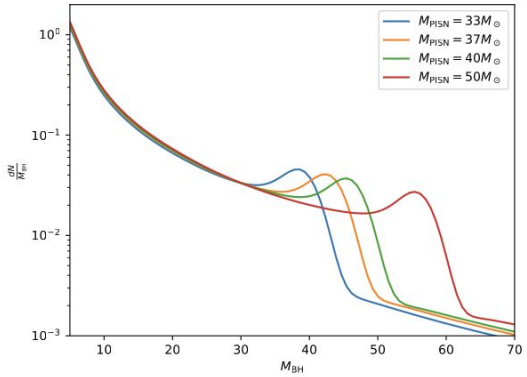


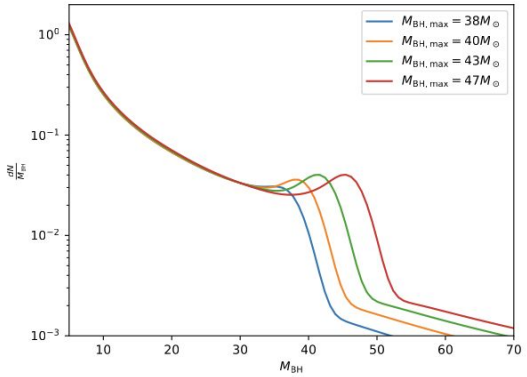
Farmer, et al. (2019)

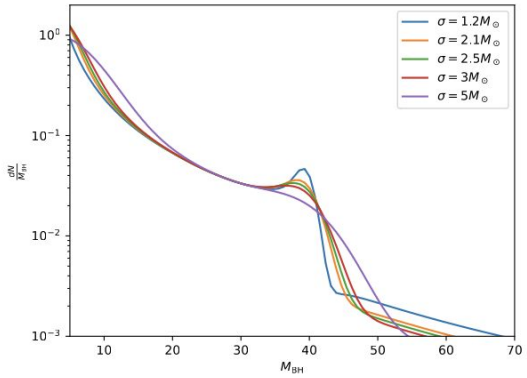
Golomb, Isi & Farr, in prep.; see also Baxter, et al. (2021)

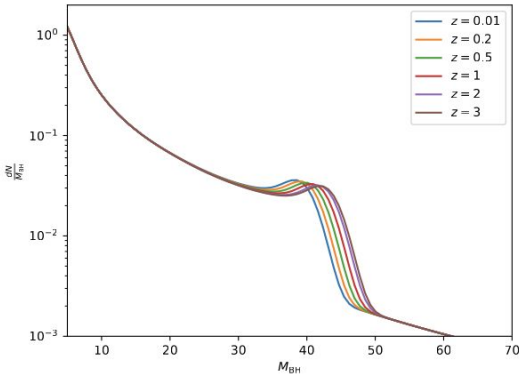


Effect of Structural Parameters









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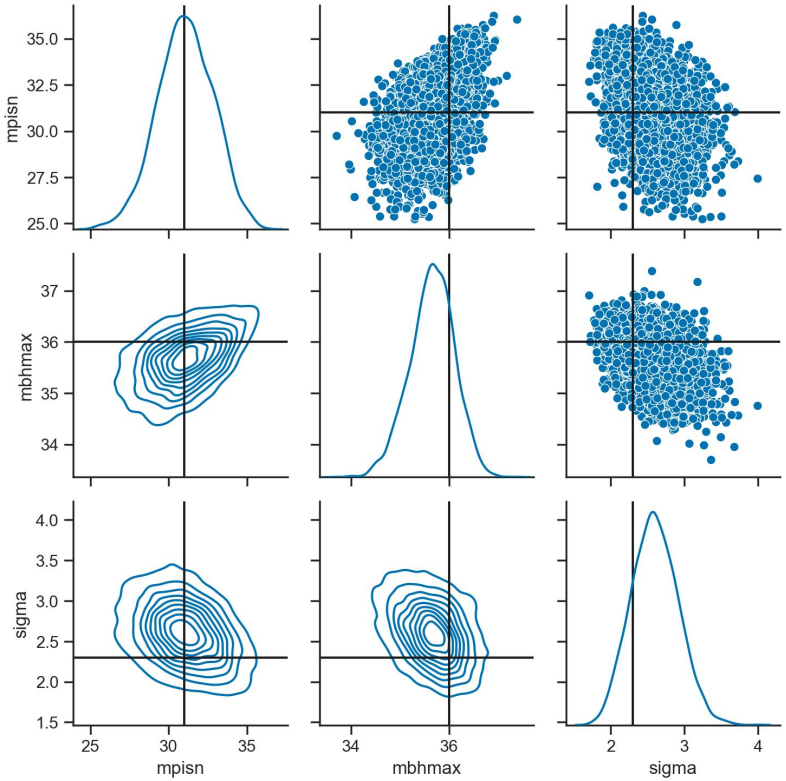
GWTC-3: Constraints on Structural Parameters



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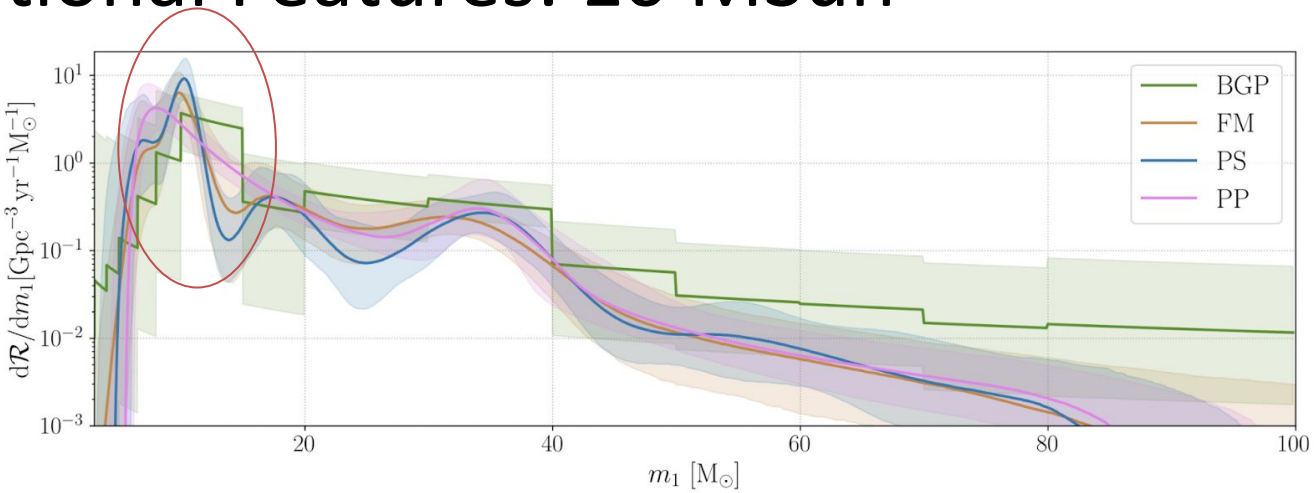
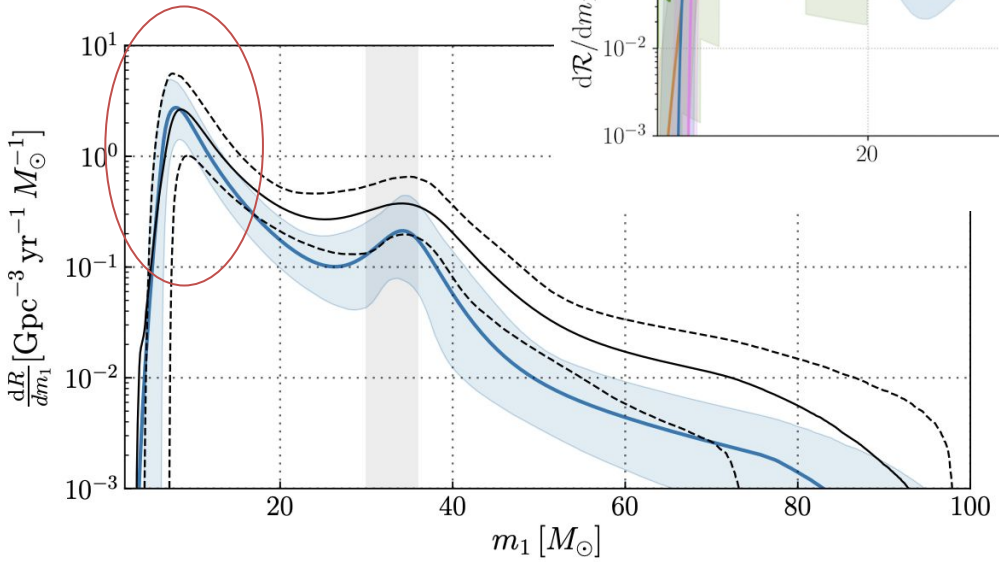
Additional Features: 10 MSun





[Abbott, et al. (2021)]

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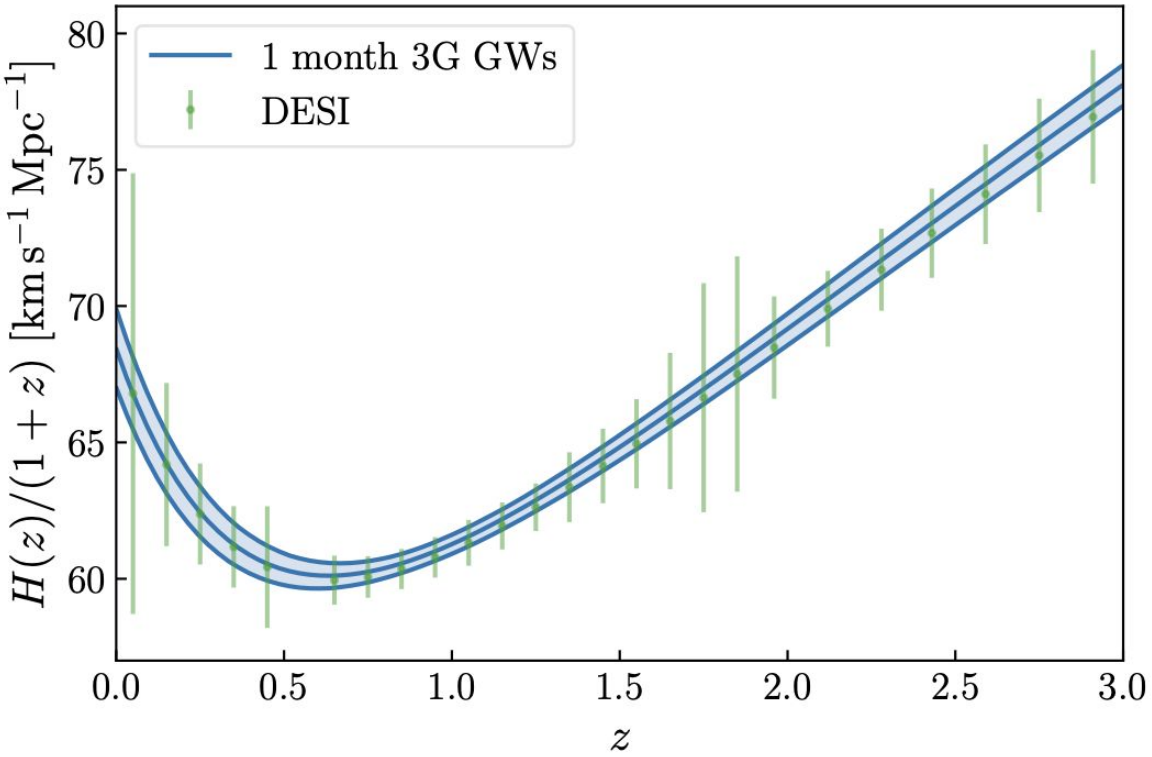
Using Both Features, 3G



Ezquiaga & Holz (2022)

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Ringing Black Holes: Probes of GR in the Strong Field

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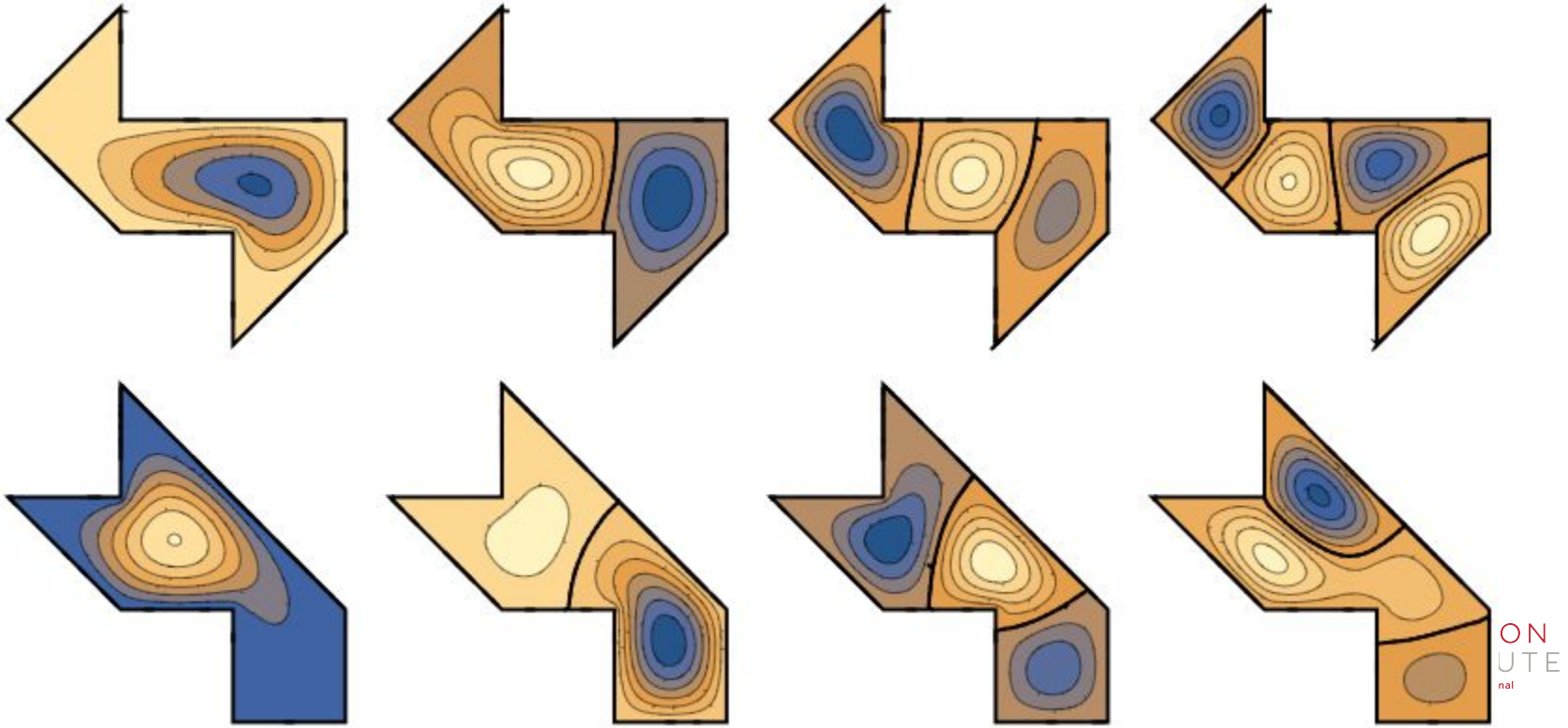
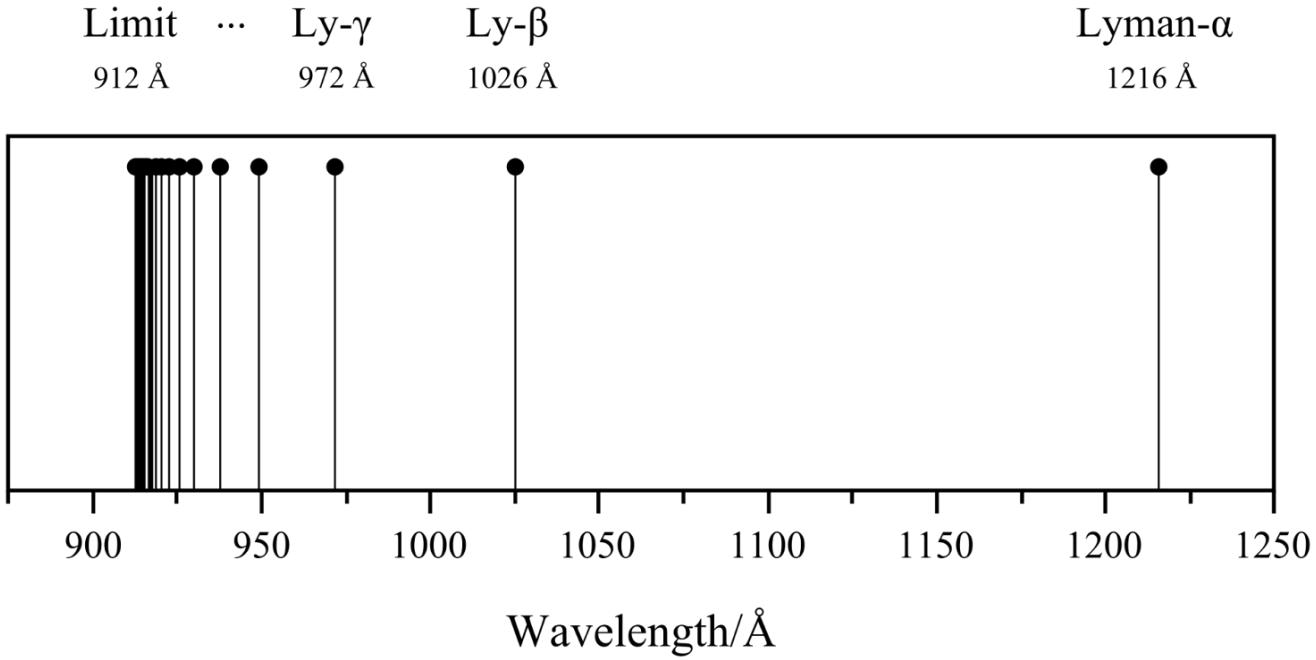
Can you hear the shape of a drum?



We **Can** See the Shape of a Hydrogen Atom



$$\frac{1}{\lambda} = R_H \left(1 - \frac{1}{n^2}\right)$$

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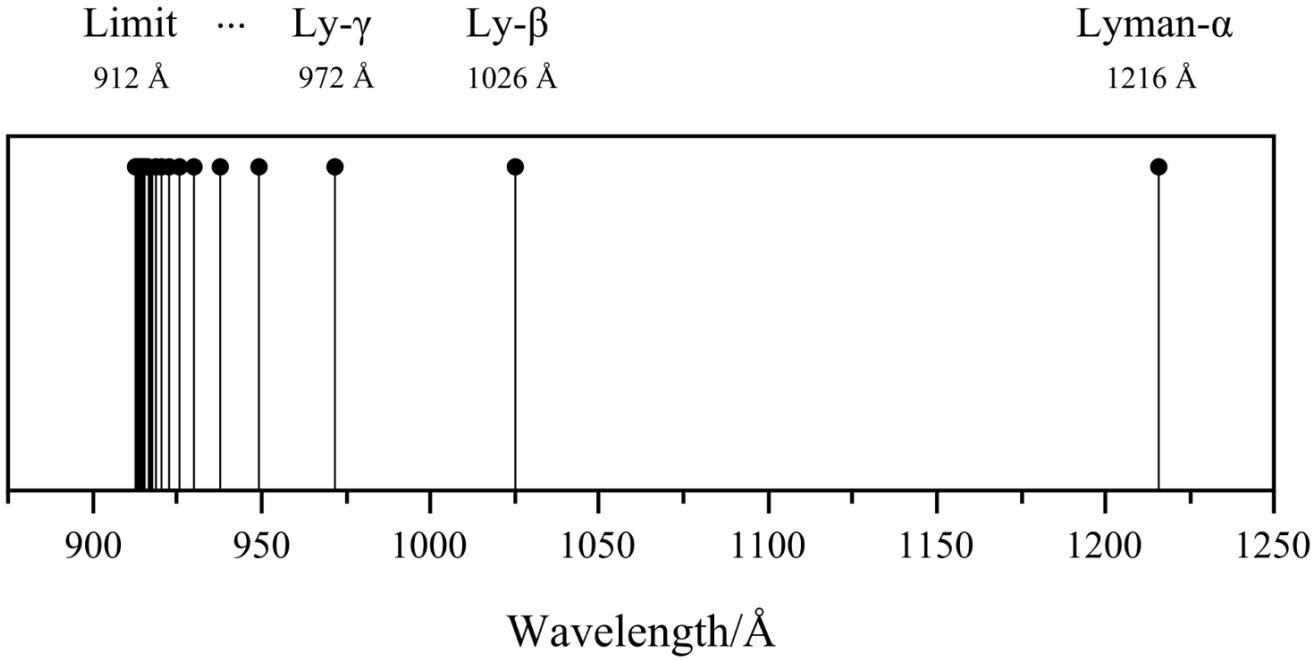
[Wikipedia]

We **Can** See the Shape of a Hydrogen Atom



Structure of H

$$\frac{1}{\lambda} = R_H\left(1 - \frac{1}{n^2}\right)$$

Quantum Mechanics

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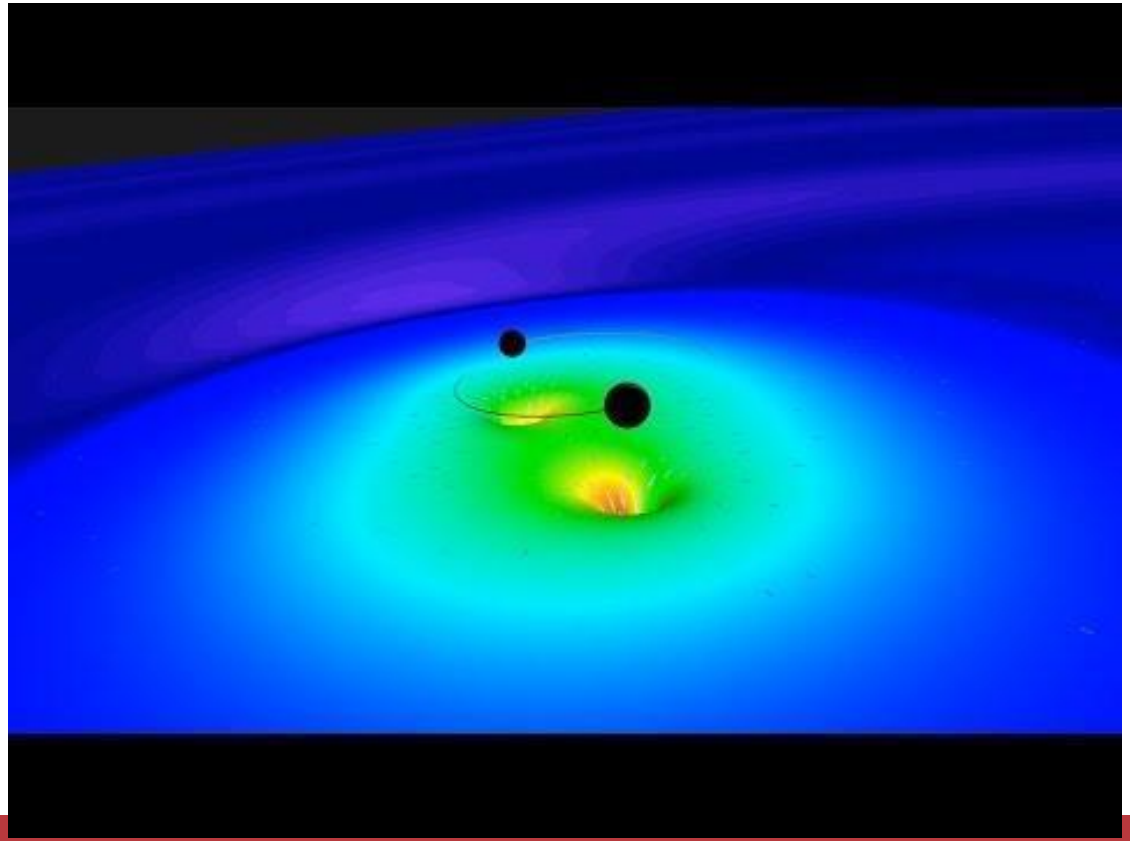
Wikipedia

Black Hole Mergers



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Can We “Hear” the Shape of a Black Hole? Yes!

- Vishveshwara (1970): Schwarzschild (quasi) normal modes.
- Press (1971): Numerical calculation.
- Teukolsky (1972, 1973); Press & Teukolsky (1973): Kerr black hole modes (!!)
- Detwiler (1980): Black hole **spectroscopy**.
- And many more besides, up to the present day!

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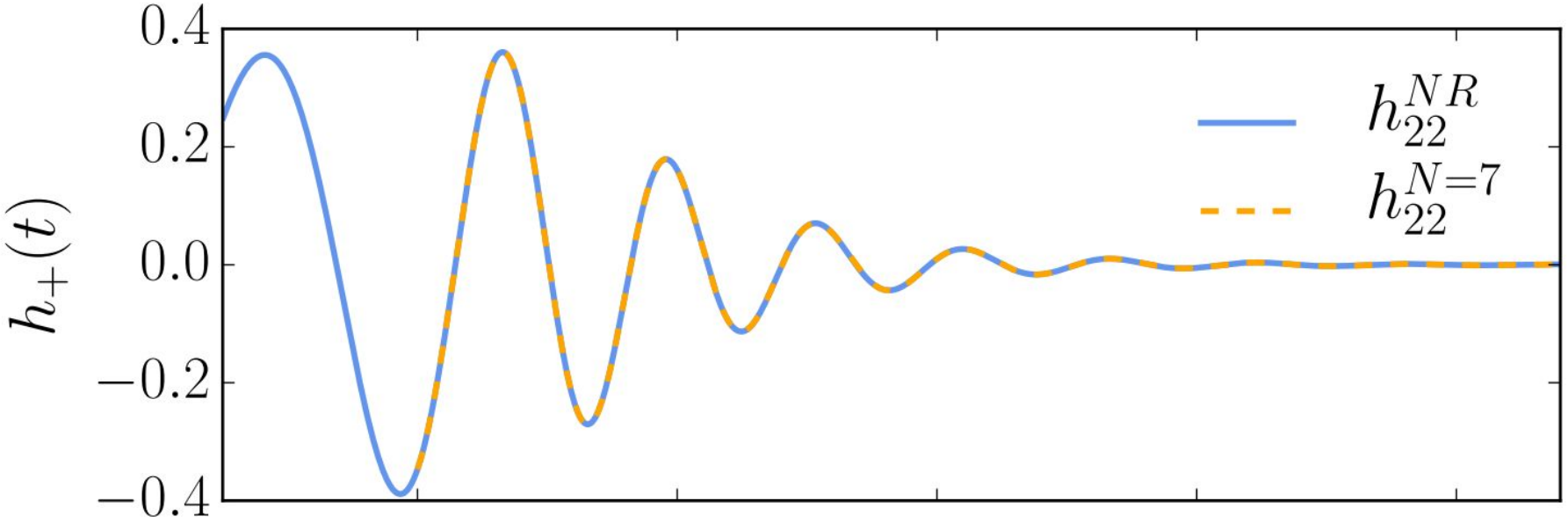
GW150914-Like Calculation



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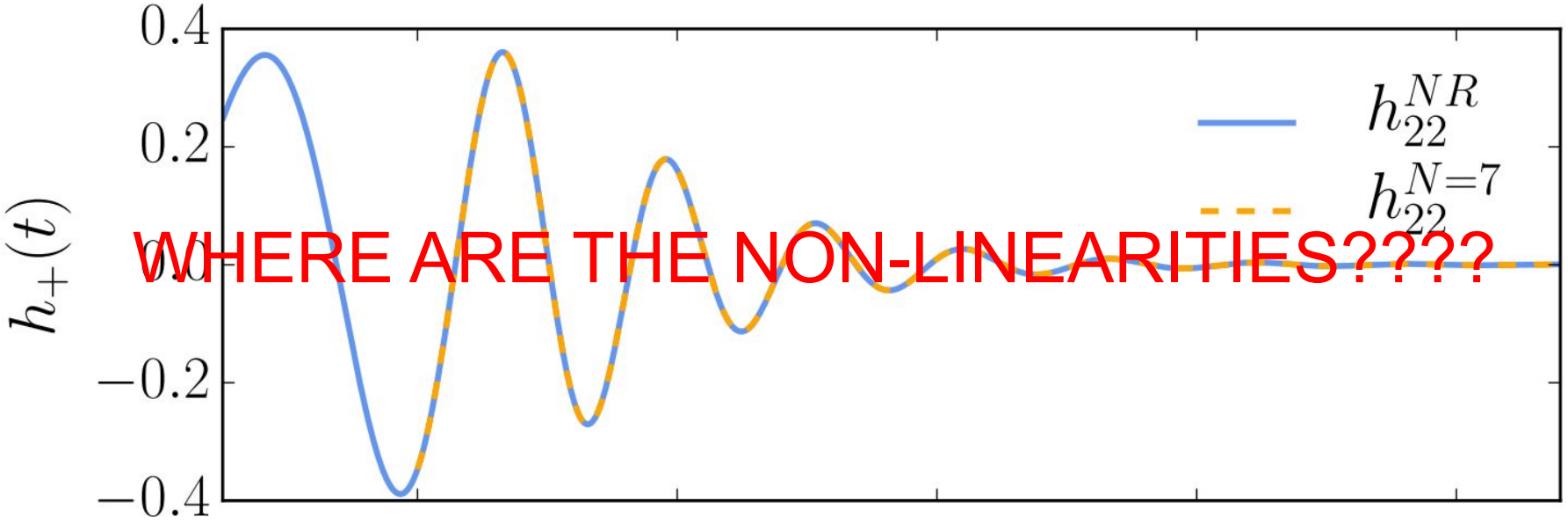
Giesler, et al. (2019)

GW150914-Like Calculation



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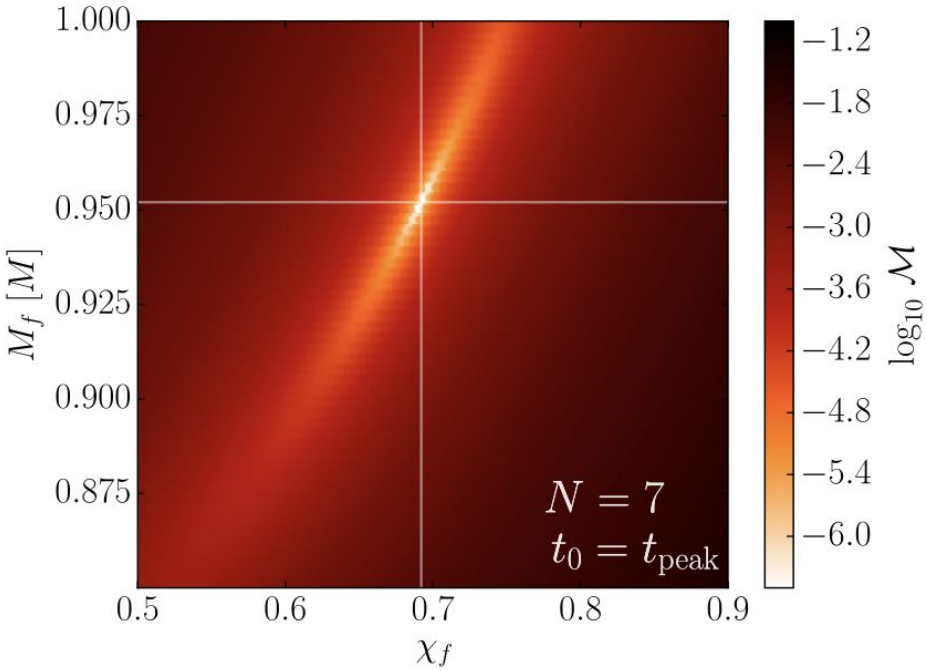
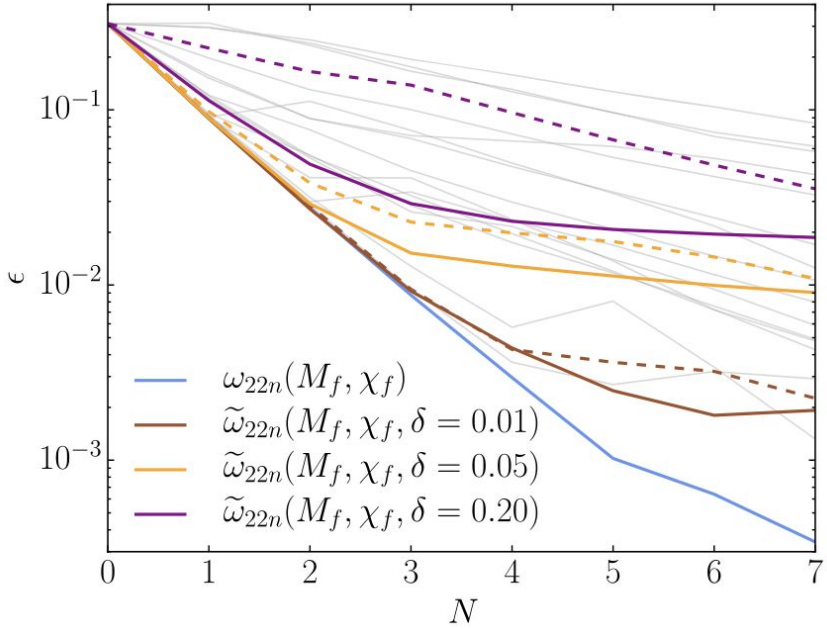
Giesler, et al. (2019)

The Overtones Are Where They “Should Be”





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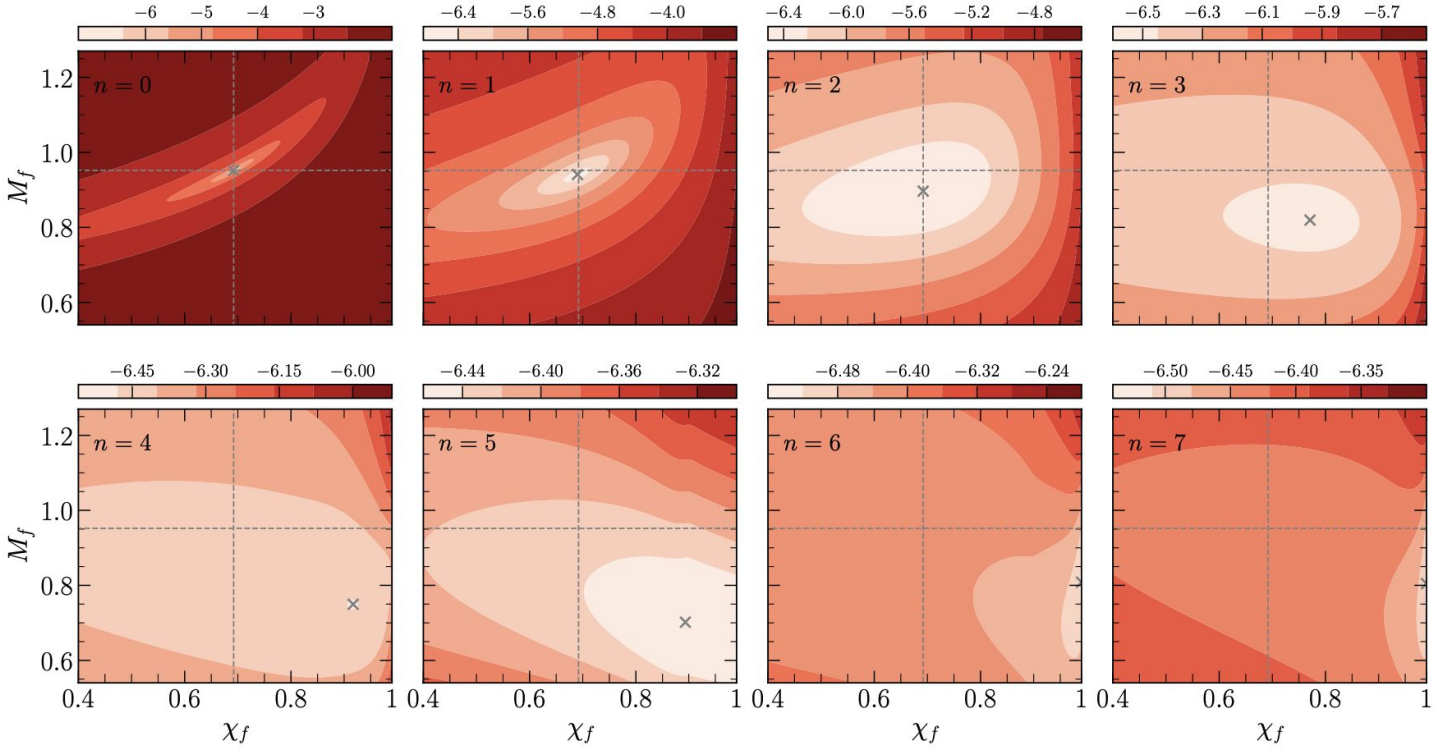
Giesler, et al. (2019)

…More Or Less



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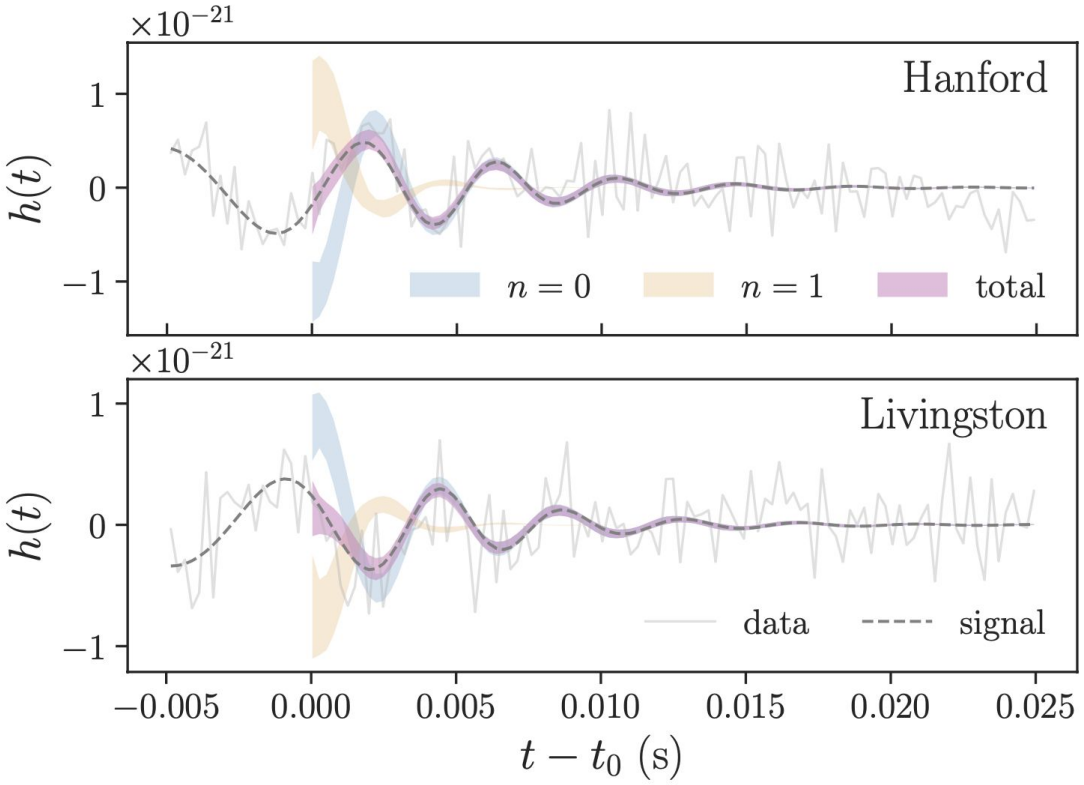
[Baibhav, et al (2023)]

Mock Observation



Isi & Farr (2021)

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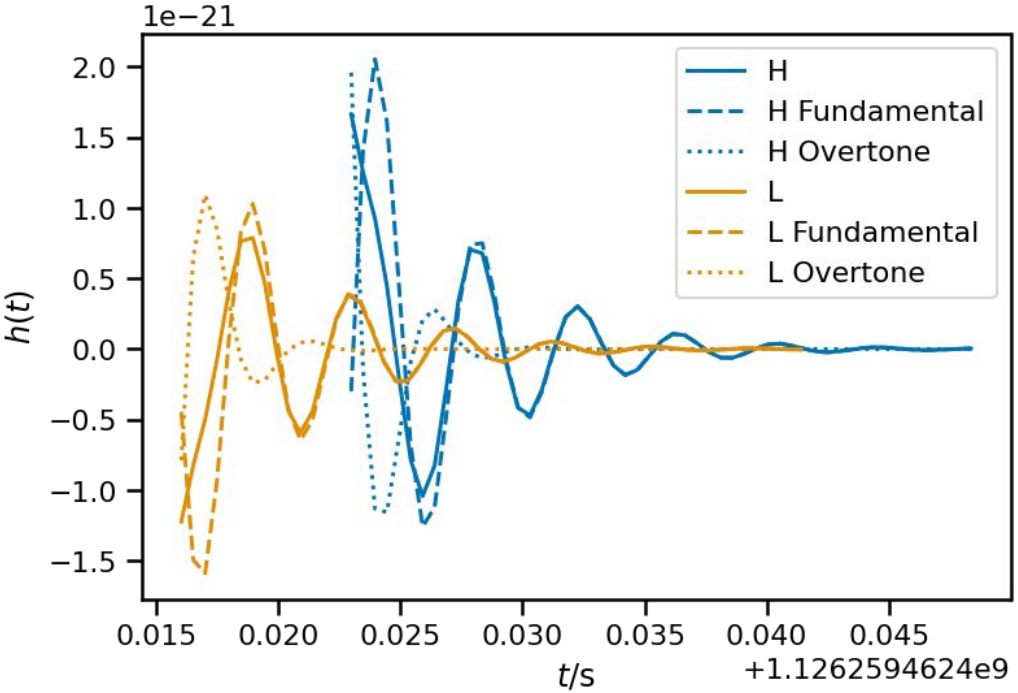
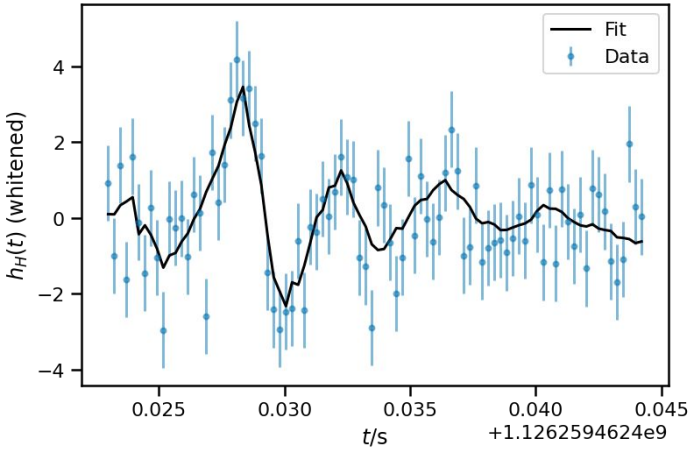
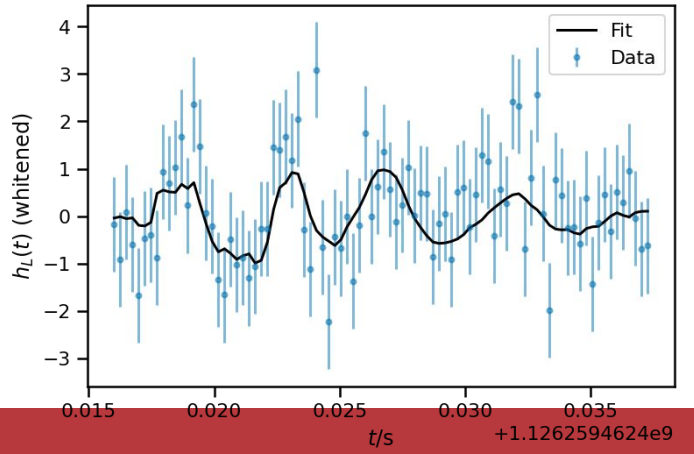
In the Data: GW150914

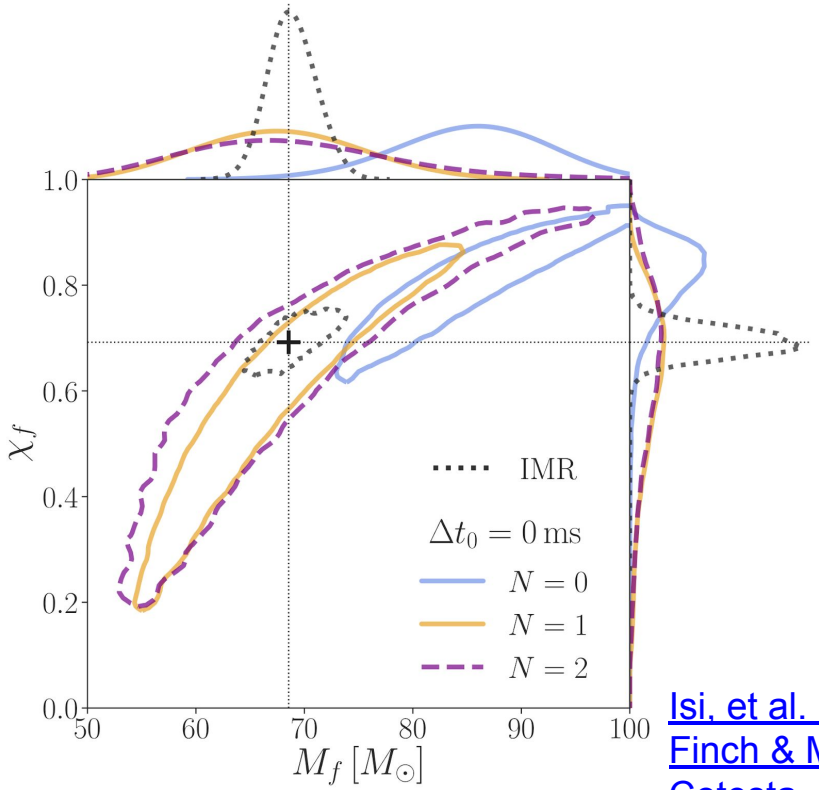


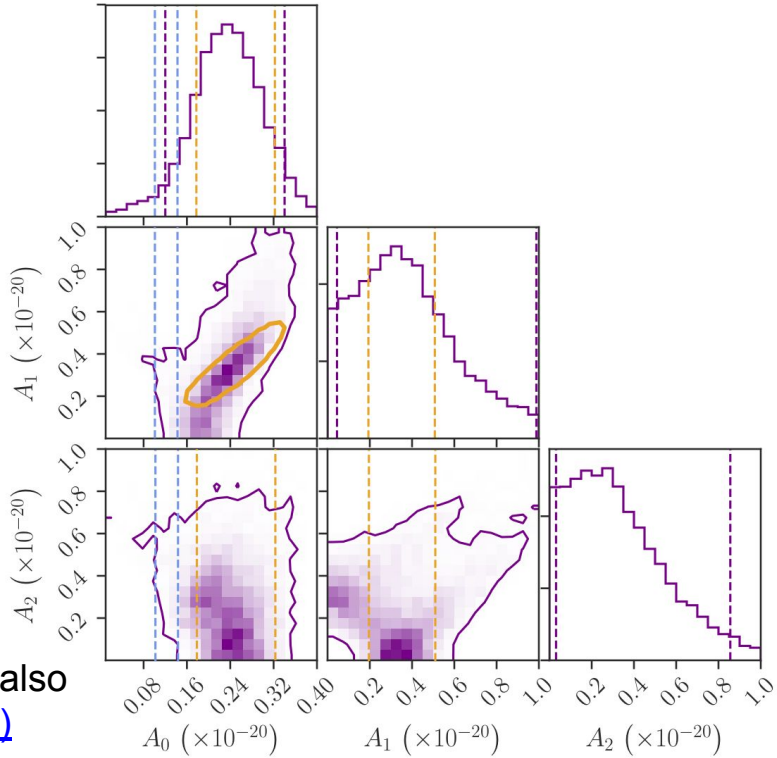




Isi, et al. (2019)

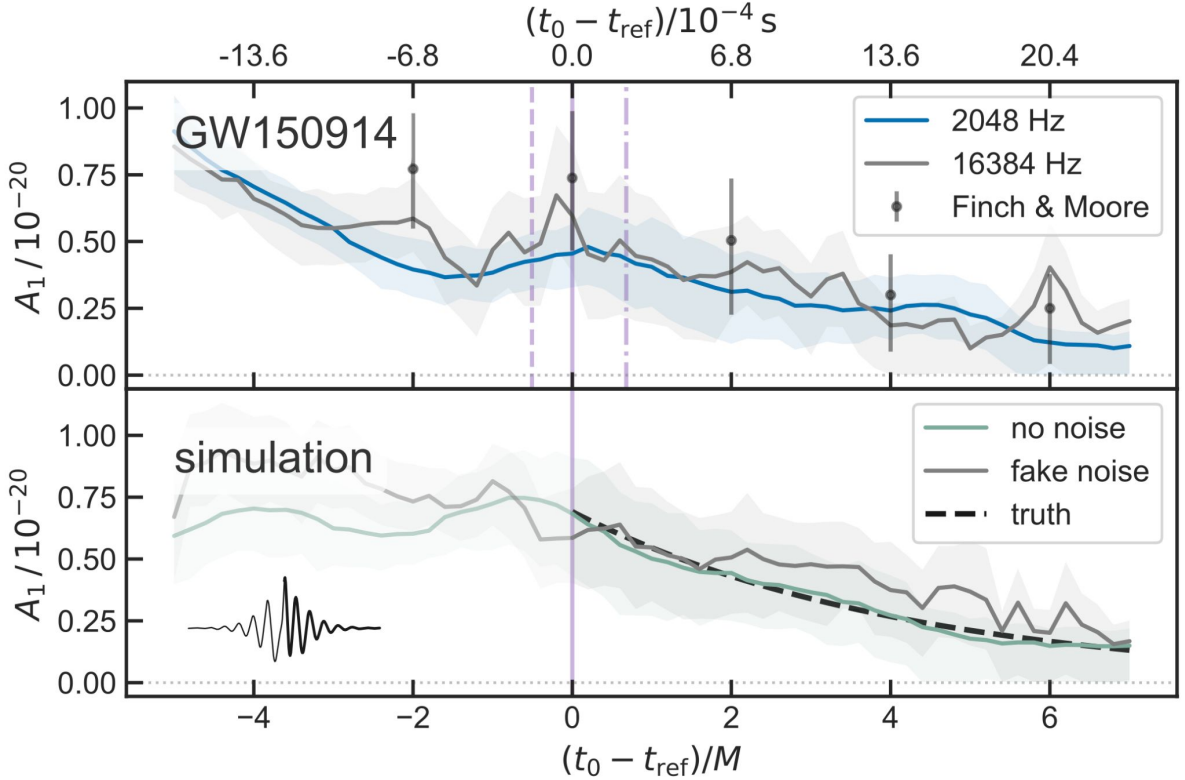
Multiple Modes in GW150914





Isi, et al. (2019); see also
Finch & Moore (2022)
Cotesta, et al (2022)

Multiple Modes in GW150914



Isi, et al. (2019); see also
Finch & Moore (2022)
Cotesta, et al (2022)

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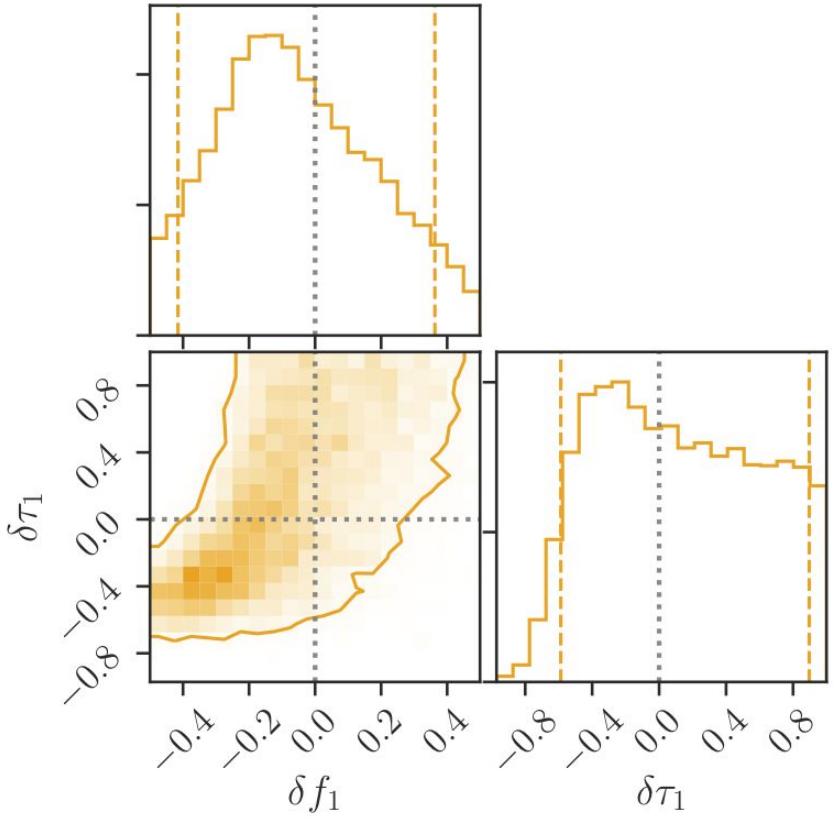
Testing General Relativity



Isi, et al. (2019)

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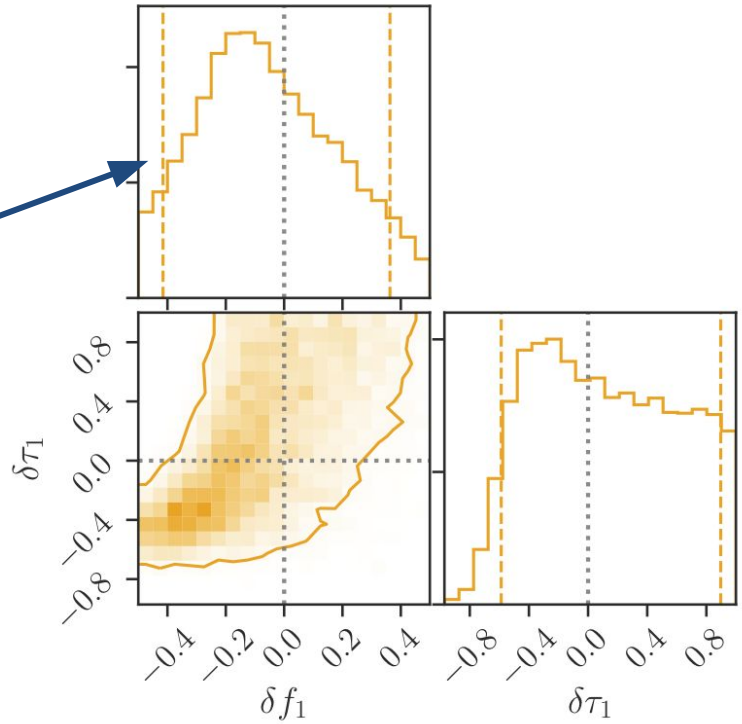
Testing General Relativity

GR to +/- 20%



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Isi, et al. (2019)

GW190521 (A—nearly—ringdown only event)

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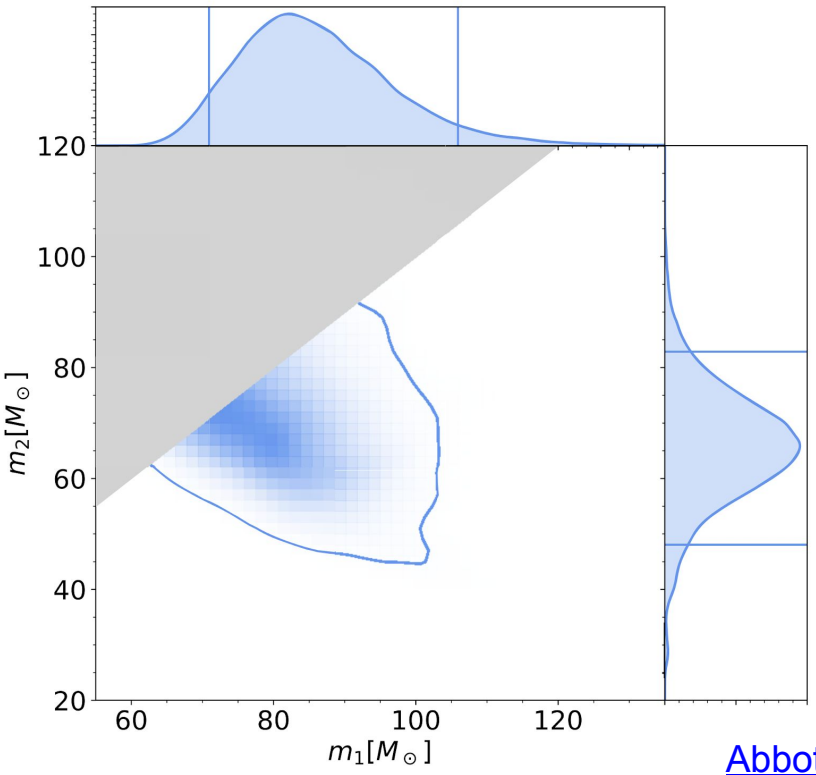
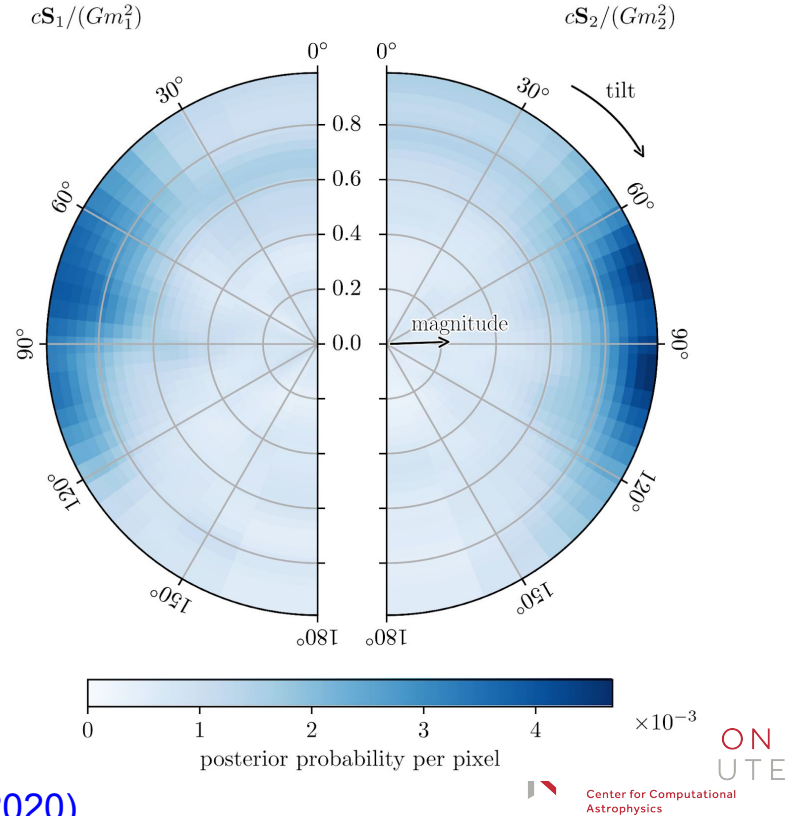
GW190521: A Massive, Precessing BBH





[Abbott, et al. (2020)]

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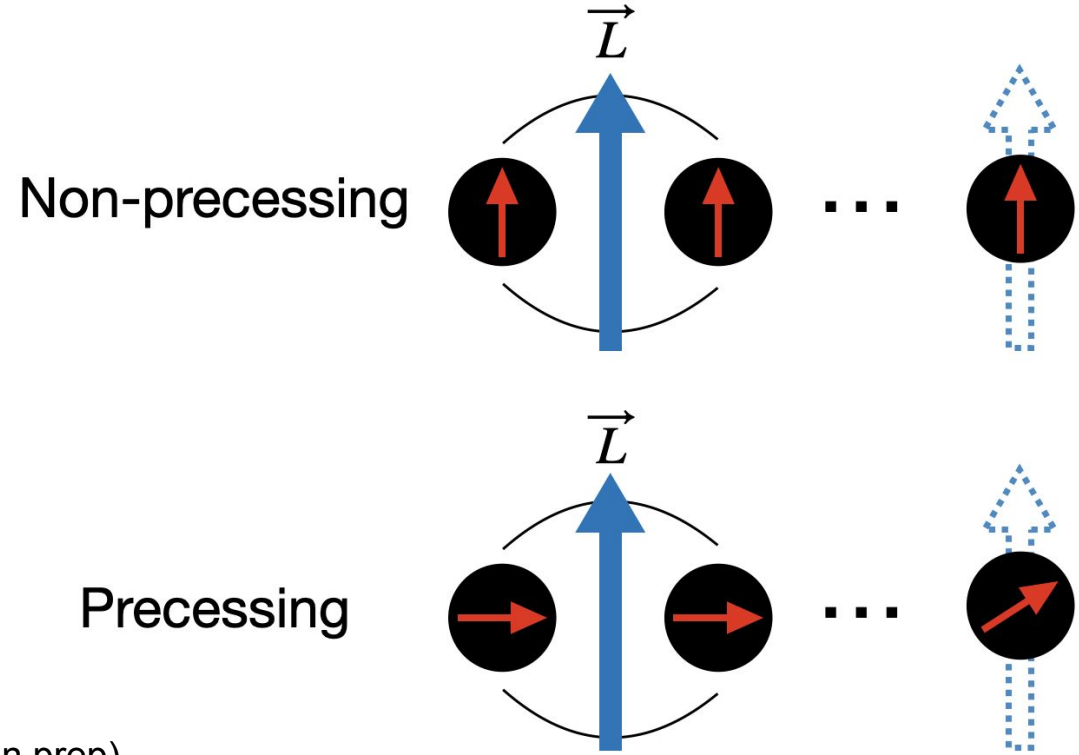
Precession and Ringdown



Zhu, Siegel, Isi & Farr (in prep)

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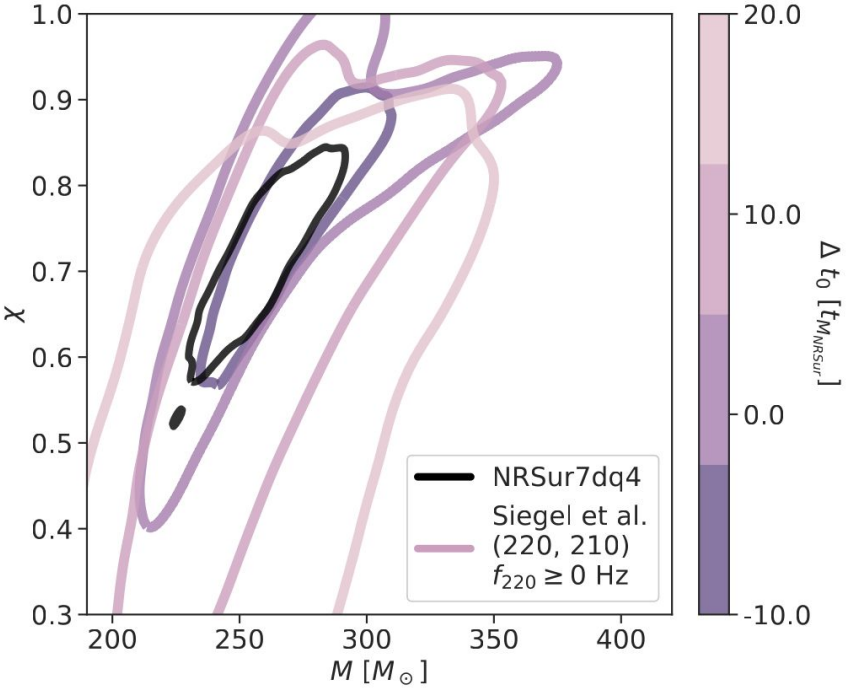
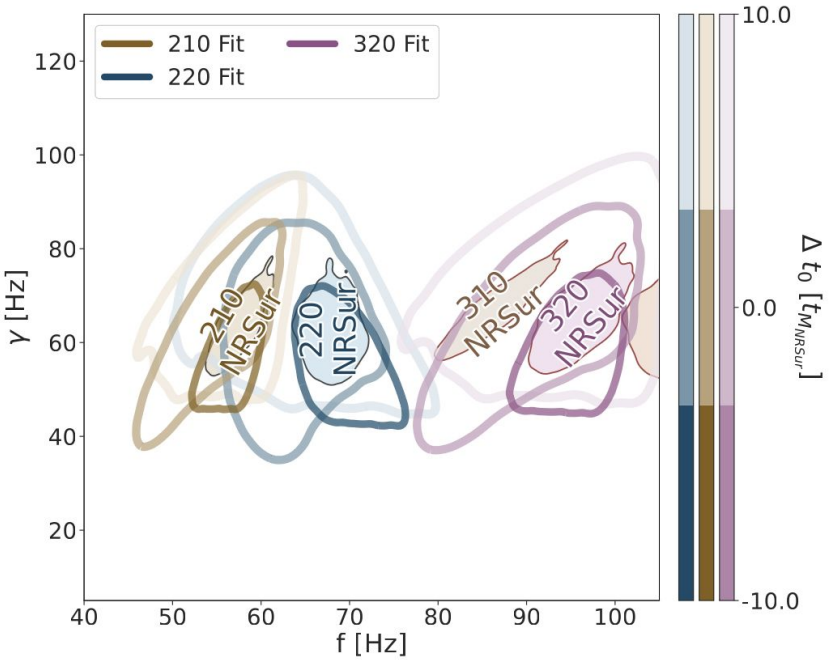
GW190521 Kerr Mass and Spin





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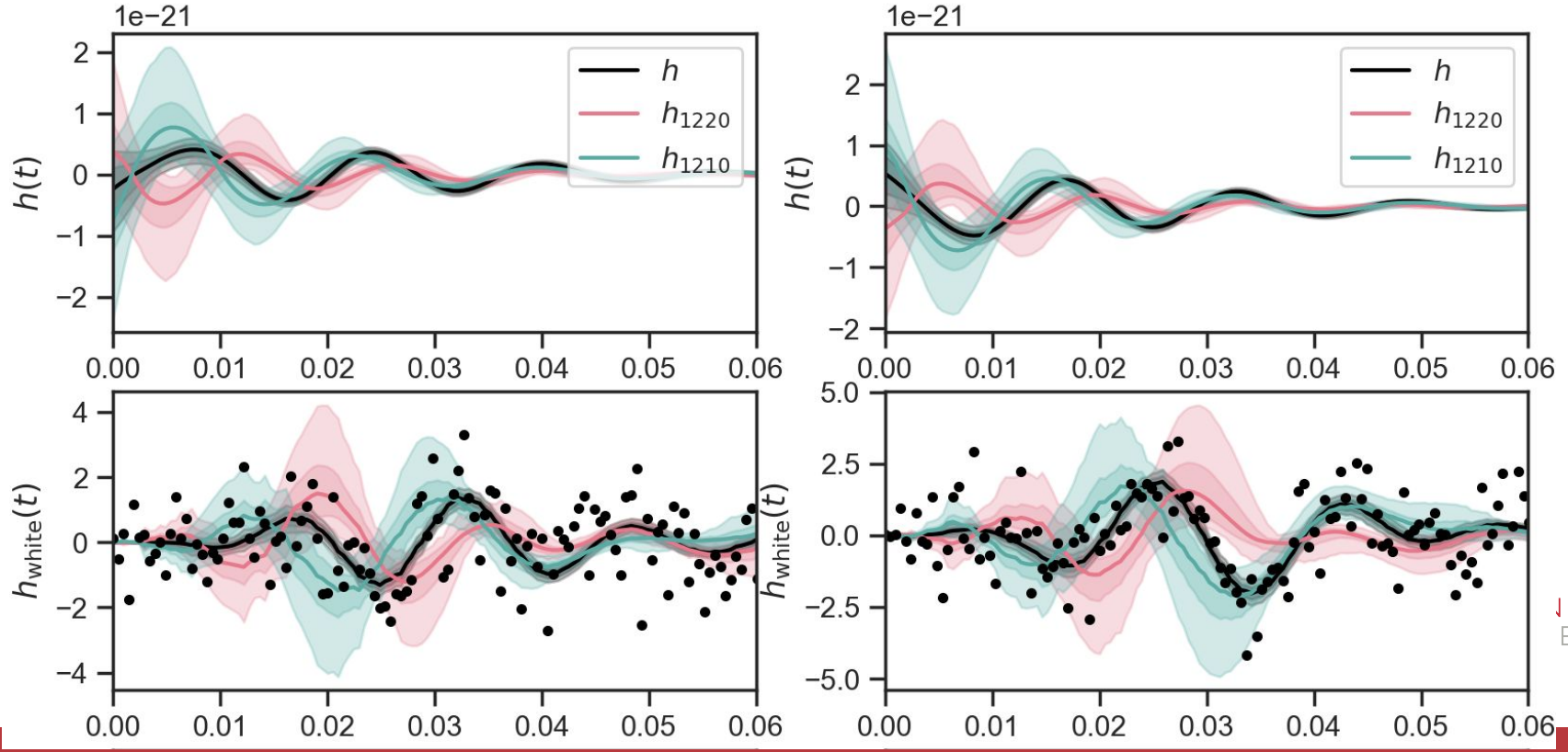
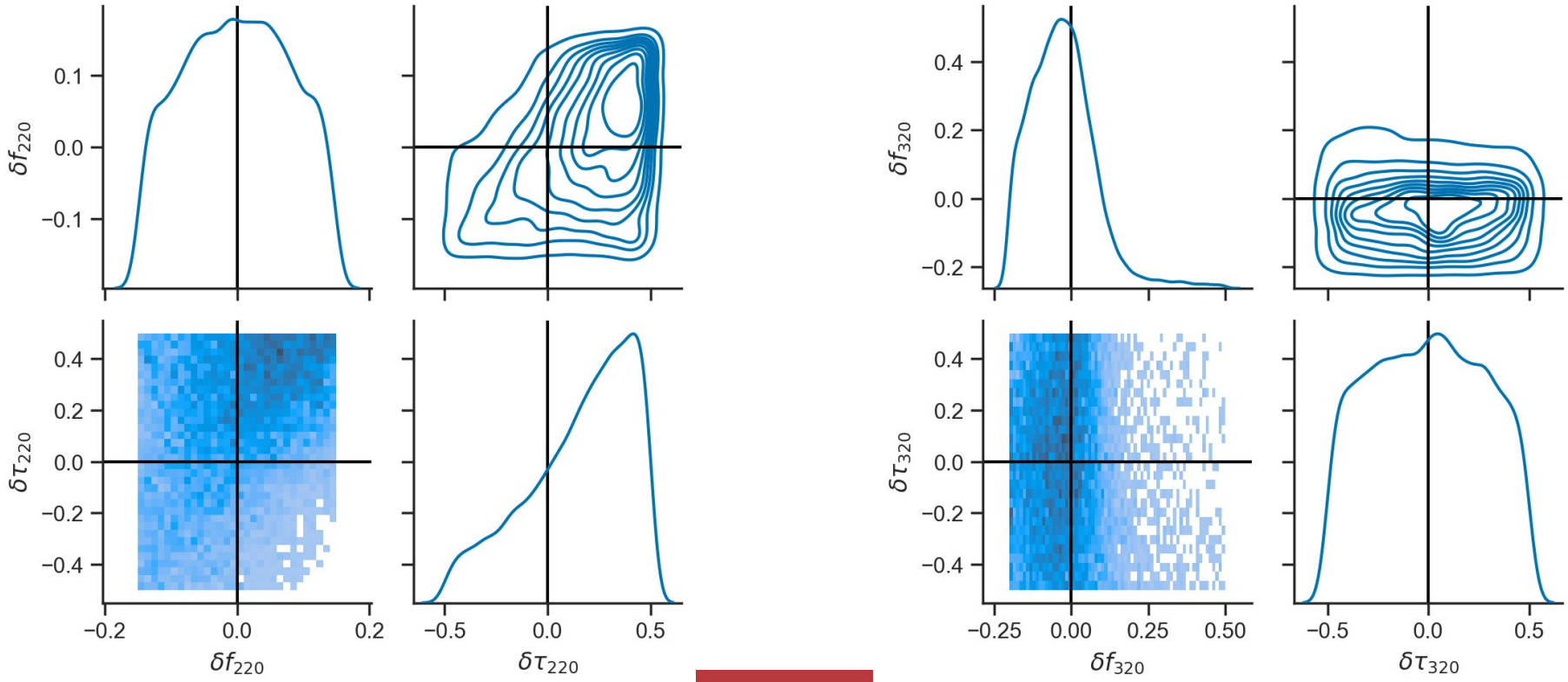
Siegel, et al. (2023) (see also Capano, et al. (2021))

Waveforms

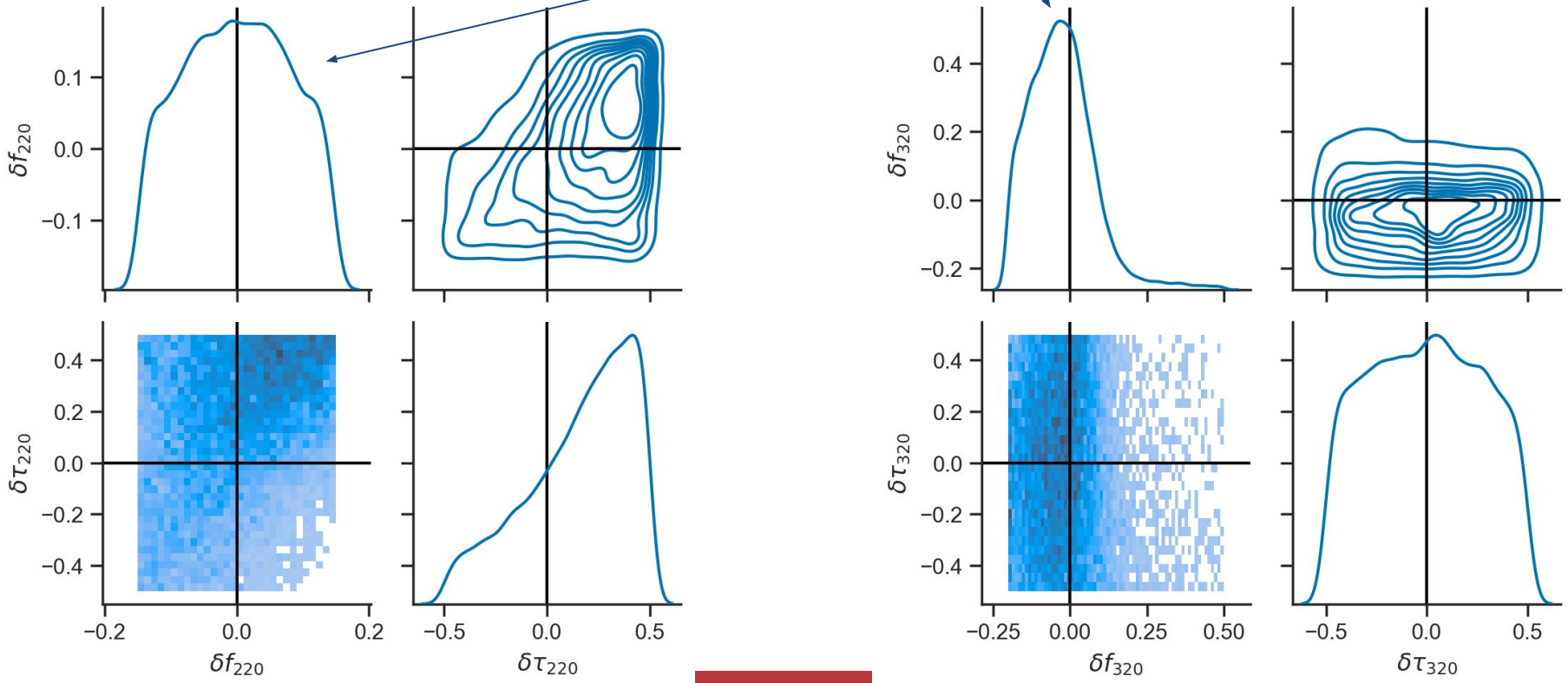


GW190521 Test of GR



GW190521 Test of GR

GR to +/- 20%



Where We Are With Ringdowns

Wikipedia

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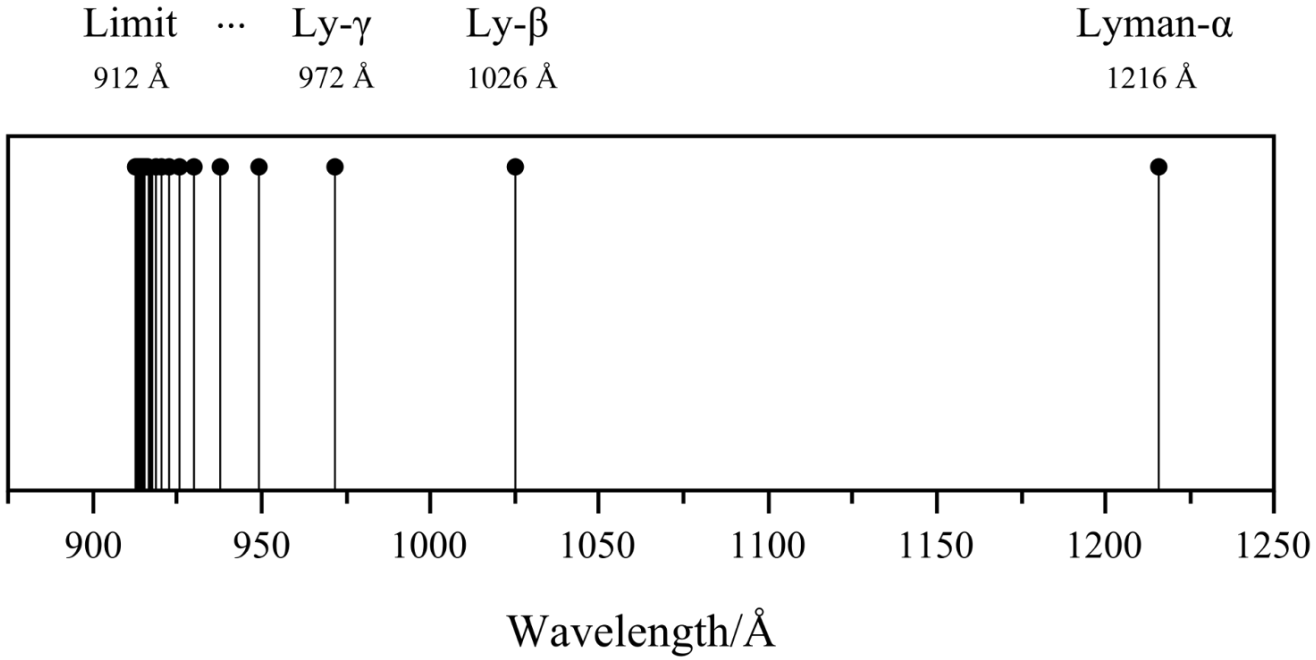
Where We Will Be One Day….



Structure of H

$$\frac{1}{\lambda} = R_H\left(1 - \frac{1}{n^2}\right)$$

Quantum Mechanics

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Wikipedia

GWs: A Cornucopia of Cosmological Tests

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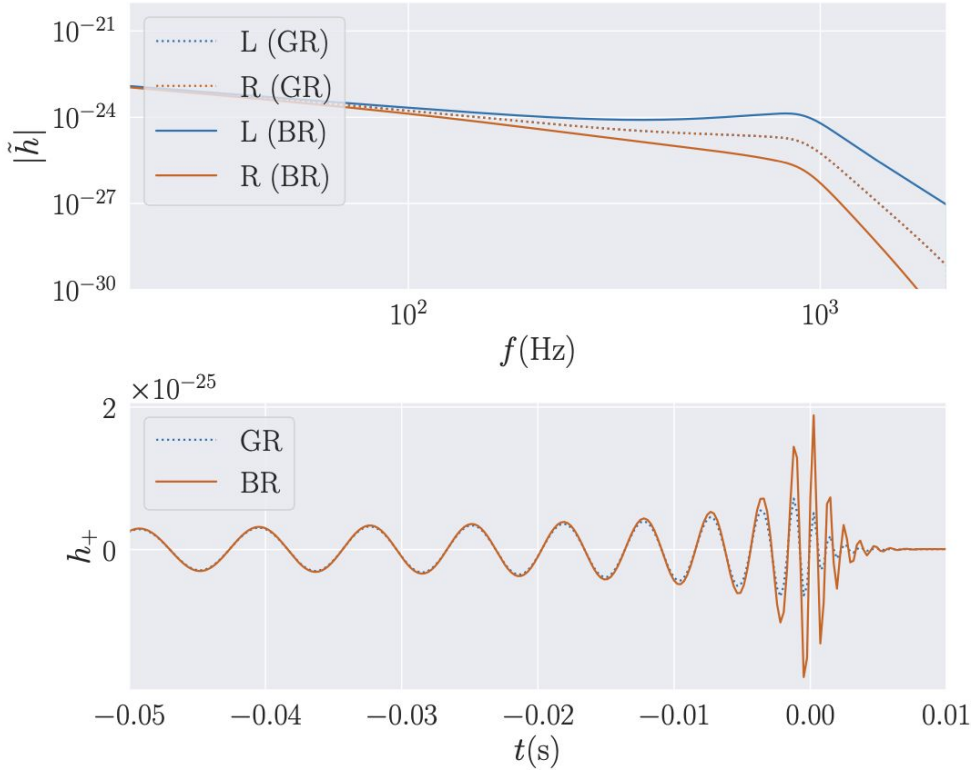
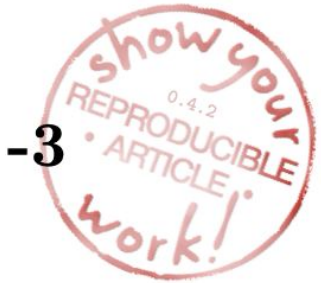
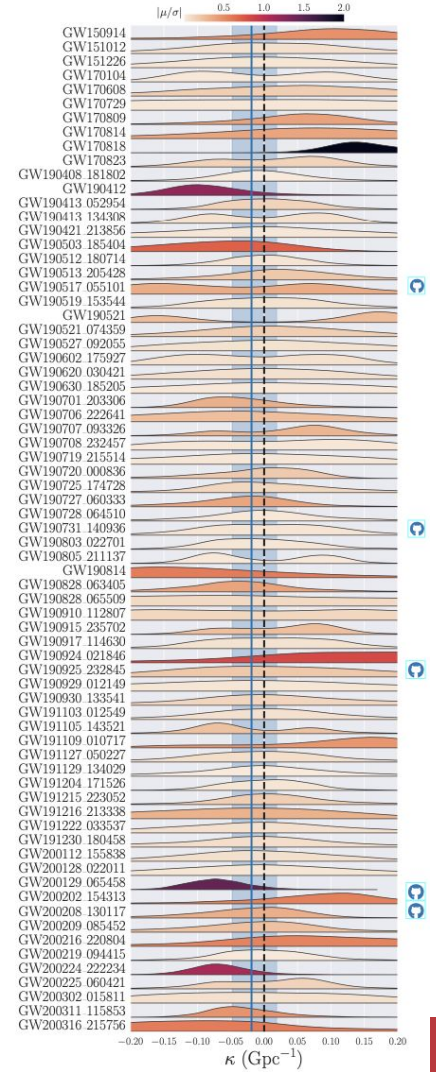
Birefringence

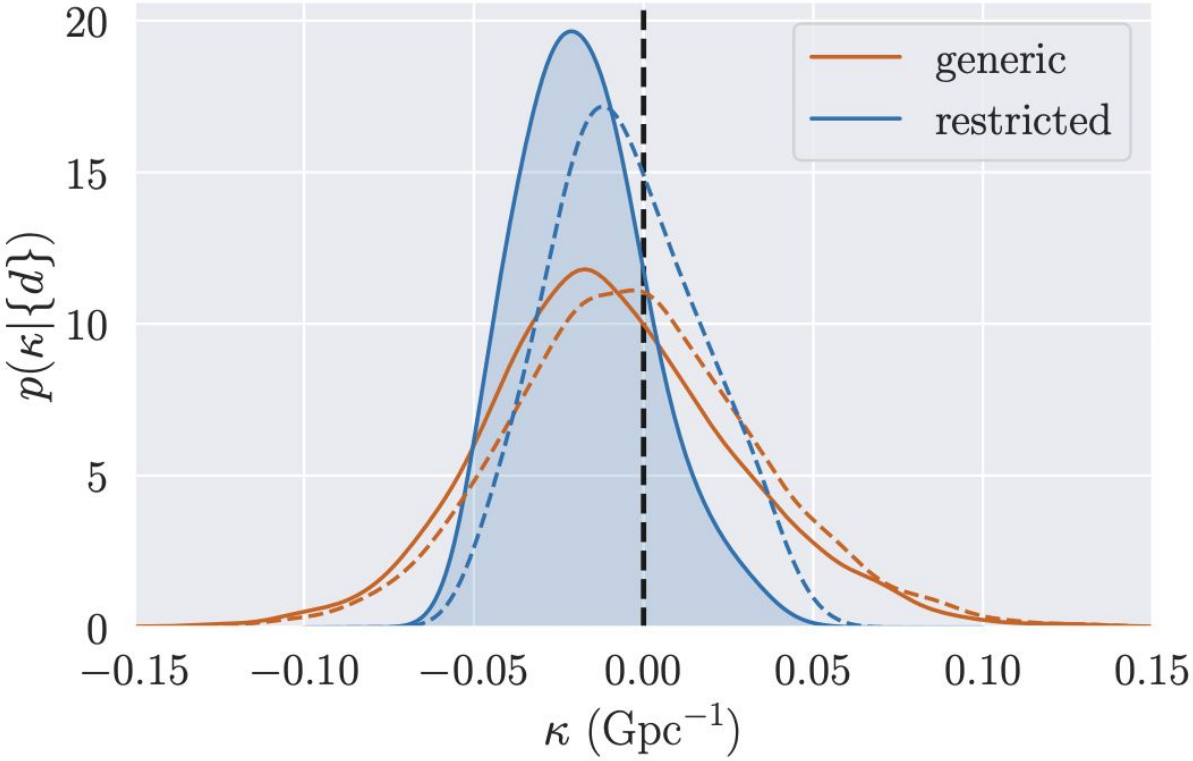






Ng, et al. (2023)

Birefringence: < 5% attenuation per Gpc



Ng, et al. (2023)

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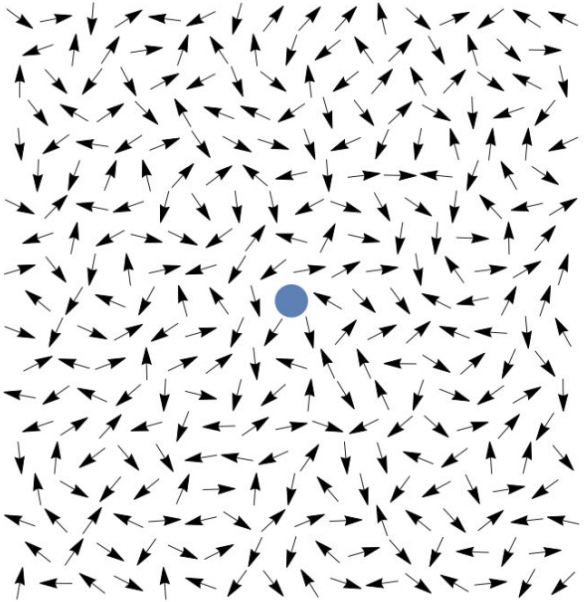
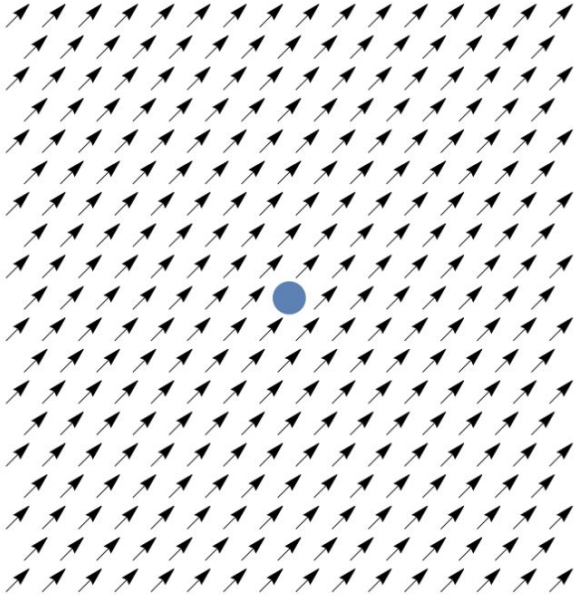
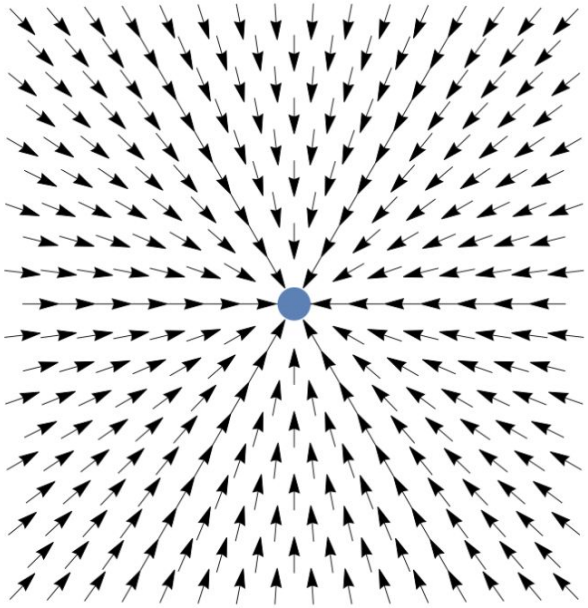
Isotropy: Hard For Stars (even NS); Easy for BH







Isi, Farr, & Varma (2023)

Vitale, Biscoveanu, & Talbot (2022)

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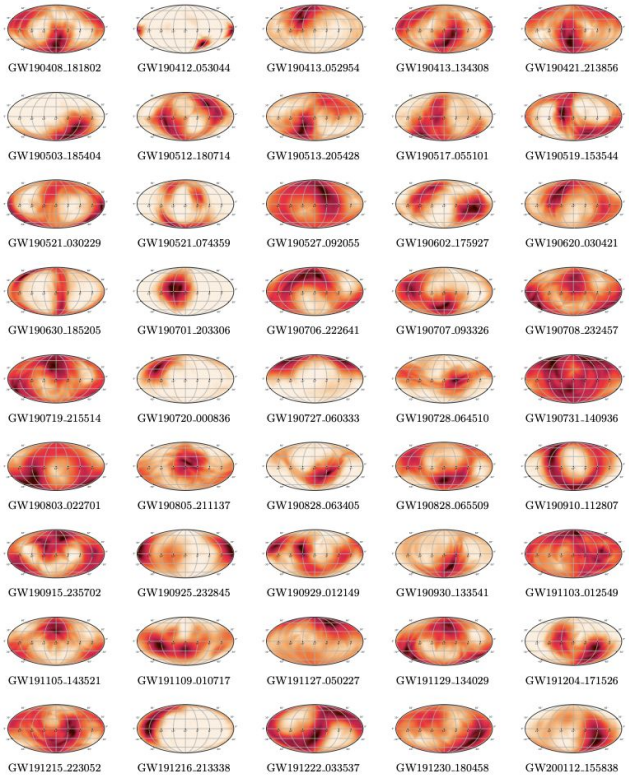
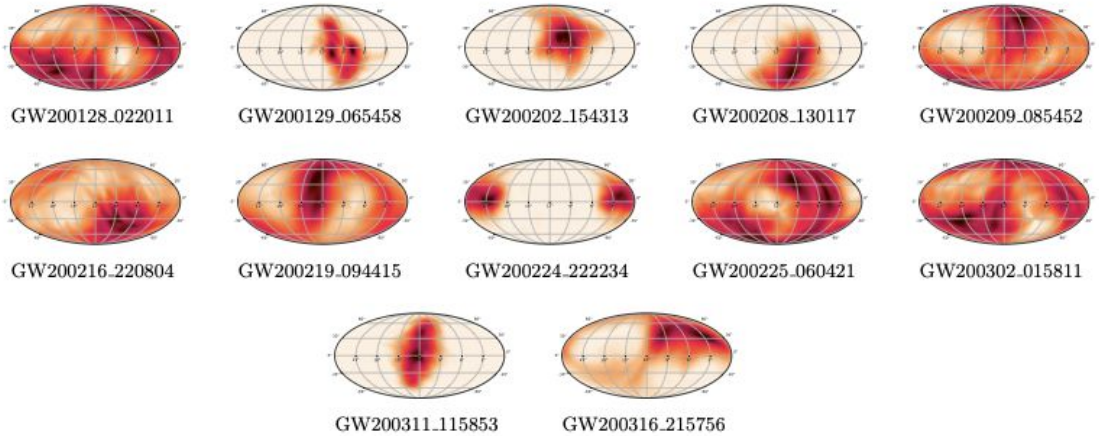
Orbital Orientations of GWTC-3…





[Isi, Farr, & Varma (2023)]

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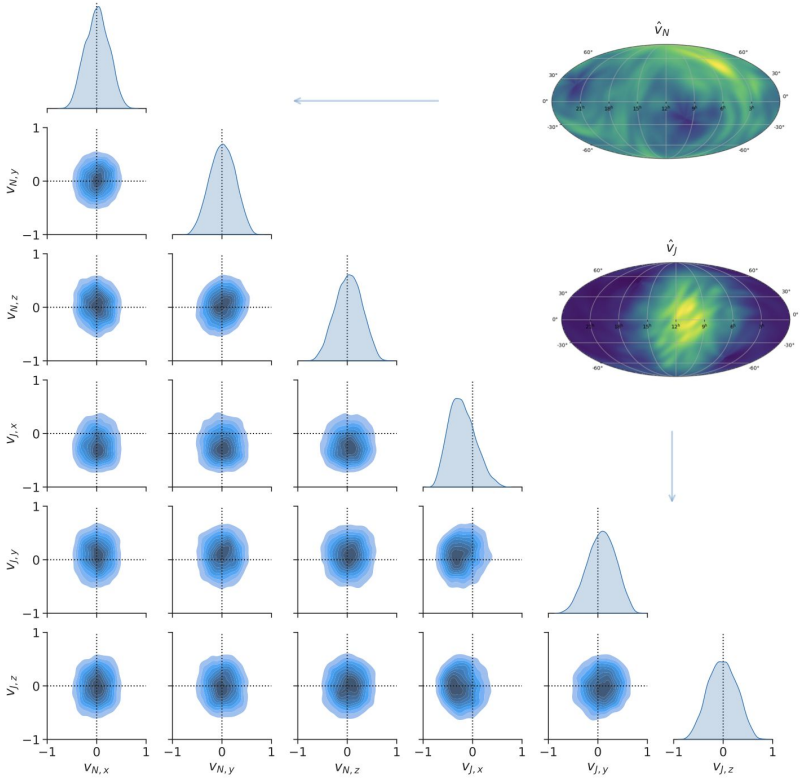
…are Isotropic (no Surprise!)



[Isi, Farr, & Varma (2023)]

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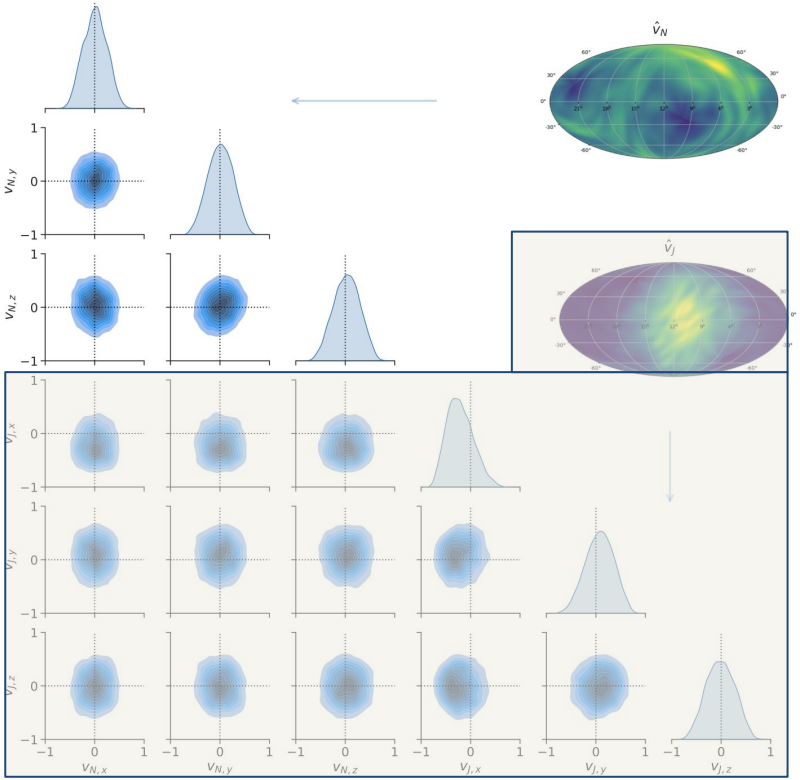

Essick, et al. (2023)

Isi, Farr, & Varma (2023)

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