Title: Probing strong gravity with black hole ringdowns

Speakers: Maximiliano Isi

Series: Strong Gravity

Date: May 06, 2021 - 1:00 PM

URL: http://pirsa.org/21050010

Abstract: Gravitational waves provide a unique observational handle on the properties of strong, dynamical gravity. Ringdowns, in particular, cleanly encode information about the structure of black holes, allowing us to test fundamental principles like the no-hair theorem and the area law. In this talk, I will review the status of this effort, including recent observational results and remaining challenges.

probing strong gravity: BH ringdowns

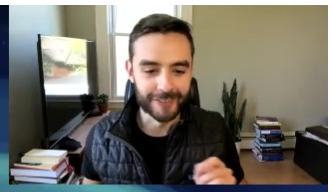
Maximiliano Isi

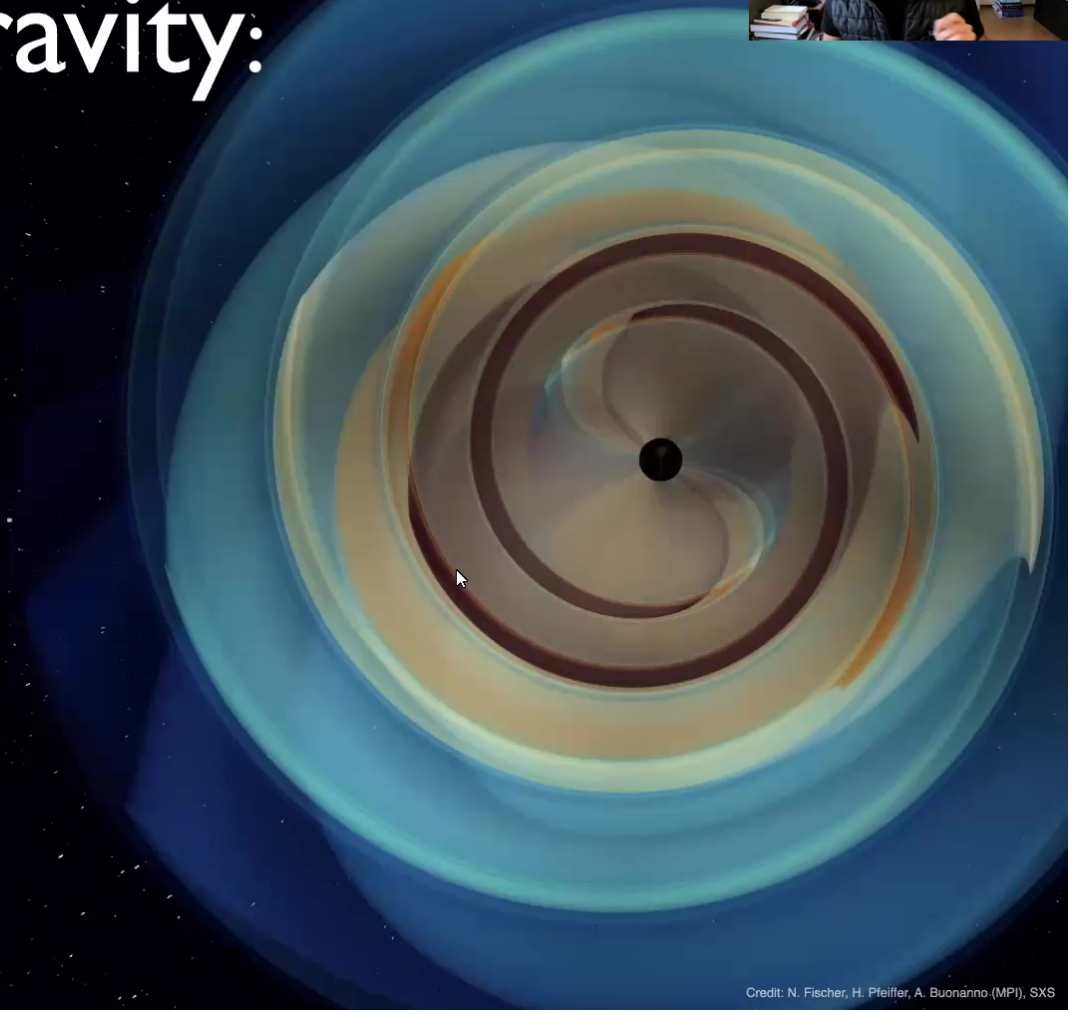
NASA Einstein Fellow @ MIT

based loosely on

[arXiv:1905.00869] [arXiv:2012.04486]
[arXiv:2010.14529] [Isi & Farr, in prep.]

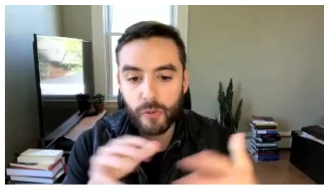
Perimeter Institute – May 6, 2021





Credit: N. Fischer, H. Pfeiffer, A. Buonanno (MPI), SXS

goals



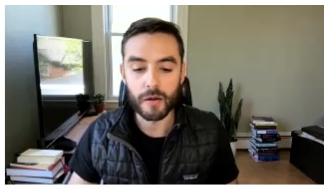
0. argue *ringdowns* are interesting

1. explain data analysis *method*

2. review existing *measurements*

3. dispel some *misconceptions*

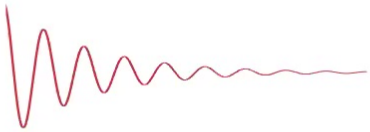
ringdown

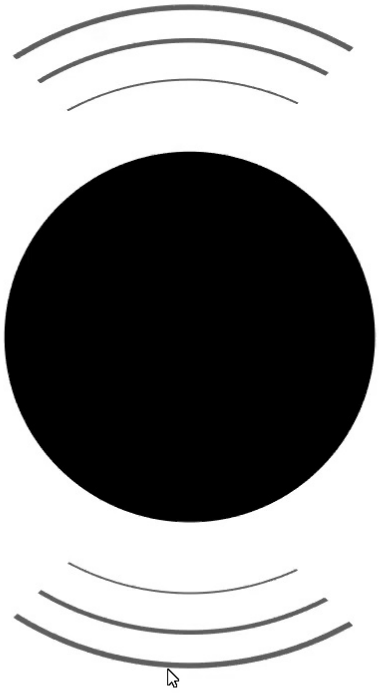


perturbed BH vibrates w/ characteristic frequencies

$$h = \sum_{\ell mn} C_{\ell mn} e^{-i\tilde{\omega}_{\ell mn} t}$$

excitation radiated away as ringdown GWs



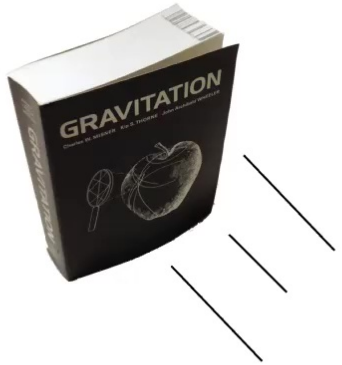


$$\tilde{\omega}_{\ell mn} \equiv \omega_{\ell mn} - i/\tau_{\ell mn}$$

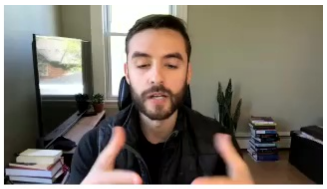
intrinsic geometry

$$C_{\ell mn} \equiv A_{\ell mn} e^{i\phi_{\ell mn}}$$

initial conditions



ringdown



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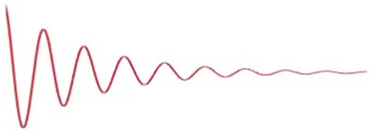

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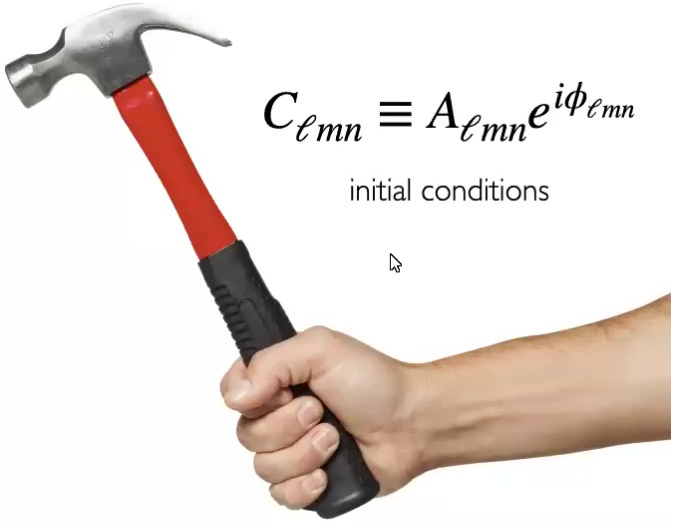
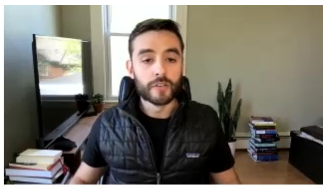


$$C_{\ell mn} \equiv A_{\ell mn} e^{i\phi_{\ell mn}}$$

initial conditions

Kerr black holes



in general relativity, a black hole has only three properties

mass
spin
charge

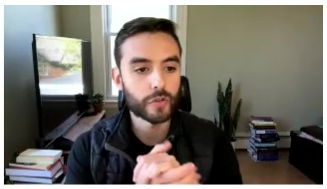
spacetime described by the *Kerr* metric

if not true, not a vanilla BH in GR

should hold for a merger remnant!

Image credit: F. Jimenez Meca, Shutterstock

Kerr black holes



in general relativity, a black hole has only three properties

mass
spin
~~**charge**~~ no charge for *astrophysical* BHs

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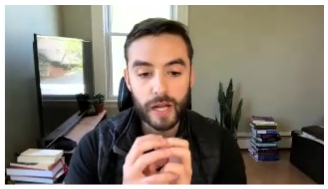
Kerr black holes



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no-hair theorem

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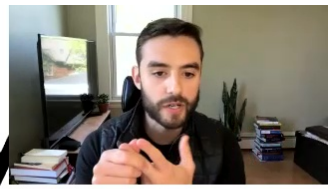
black-hole spectroscopy

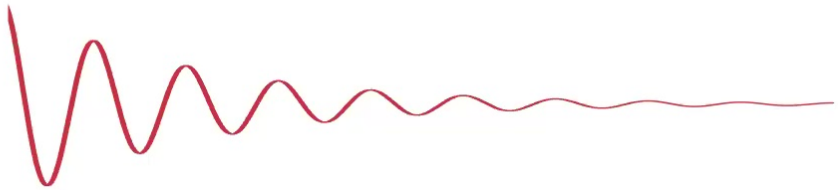


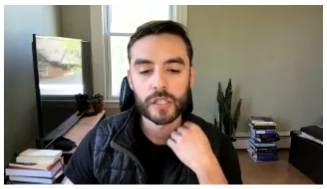
Kerr spectrum depends only on mass and spin

measure BH parameters from GW signal

extract frequency and damping of multiple of modes to check **consistency with Kerr**

$$h = \sum_{\ell mn} C_{\ell mn} e^{-i\tilde{\omega}_{\ell mn} t}$$



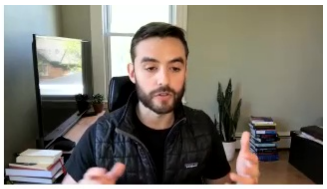


ringdown

$$h \equiv h_+ - i h_\times$$

$$h = \sum_{\ell \geq 2} \sum_{|m| \leq \ell} \sum_{n \geq 0} \left[C_{\ell m n} e^{-i \tilde{\omega}_{\ell m n} t} \, {}_{-2}S_{\ell m}(\tilde{\omega}_{\ell m n}, \chi; \iota, \varphi) \right]$$

ringdown



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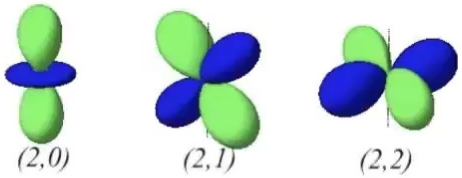
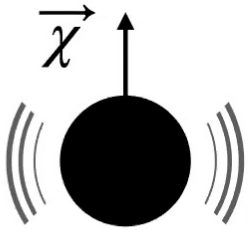


$${}_{-2}S_{\ell m}(\tilde{\omega}_{\ell m n}, \chi; \iota, \varphi) \approx {}_{-2}Y_{\ell m}(\iota, \varphi)$$



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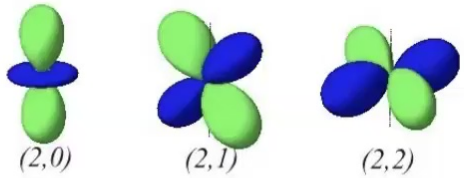
overtone number

$$\tau_{\ell m n} \geq \tau_{\ell m (n+1)}$$



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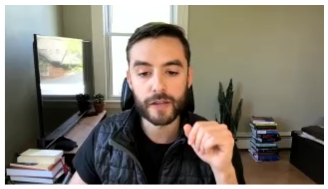
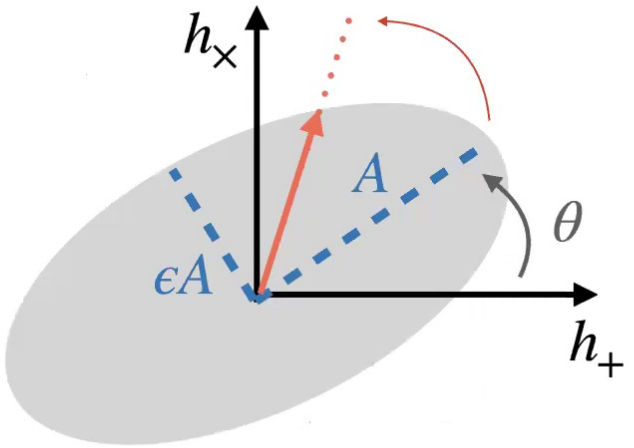
ringdown



$$h \equiv h_+ - i h_\times \quad , \quad j \equiv \{\ell, |m|, n\}$$

$$h = \sum_j \frac{1}{2} A_j e^{-t/\tau_j} \left[(1+\epsilon_j) e^{-i(\omega_j t - \phi_{+j})} + (1-\epsilon_j) e^{i(\omega_j t + \phi_{-j})} \right]$$



α, right ascension; δ, declination

$\theta_j = -(\phi_{+j} + \phi_{-j})/2$, $\phi_{0,j} = (\phi_{+j} - \phi_{-j})/2$

ringdown

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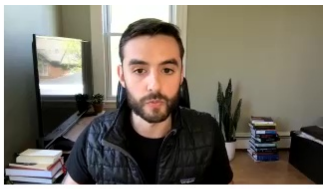
$$\tilde{\omega}_{\ell m n} = - \tilde{\omega}^*_{\ell -m n}$$

ringdown



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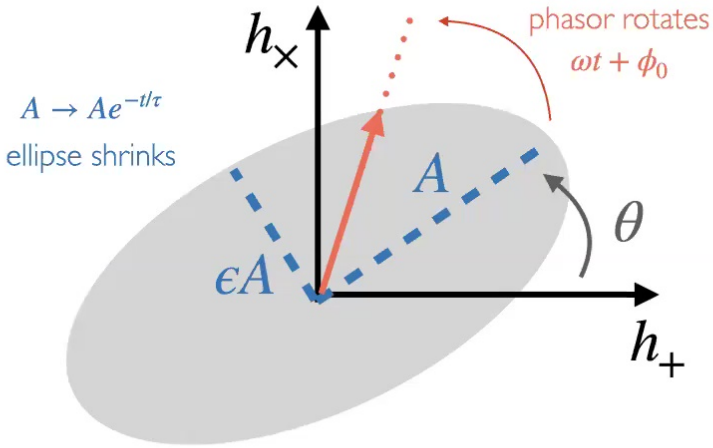
strain at I^{th} detector

$$h_I(t) = F_+^I(\alpha,\delta)\, h_+(t) + F_\times^I(\alpha,\delta)\, h_\times(t)$$



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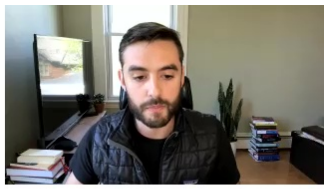
ringdown



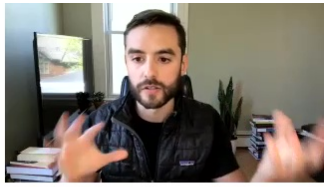
Kerr analysis

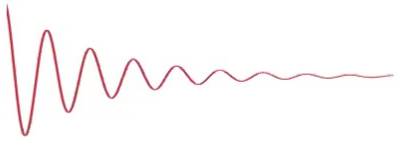
$$\omega_{\ell mn} = \omega^{\rm GR}_{\ell mn}(M,\chi) \quad , \quad \tau_{\ell mn} = \tau^{\rm GR}_{\ell mn}(M,\chi)$$

beyond-Kerr analysis

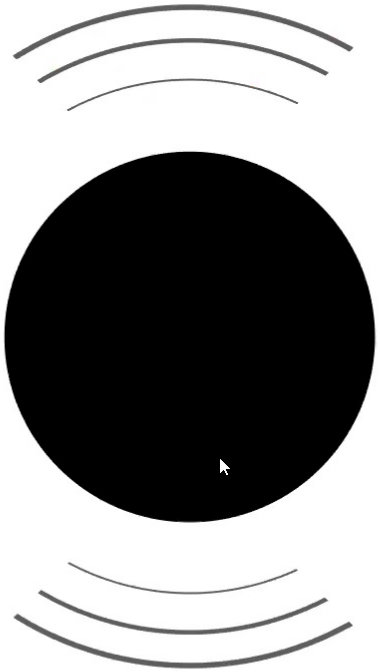
$$\omega_{\ell mn} = \omega^{\rm GR}_{\ell mn}(M,\chi)\left(1+\delta f_{\ell mn}\right) \quad , \quad \tau_{\ell mn} = \tau^{\rm GR}_{\ell mn}(M,\chi)\left(1+\delta \tau_{\ell mn}\right)$$

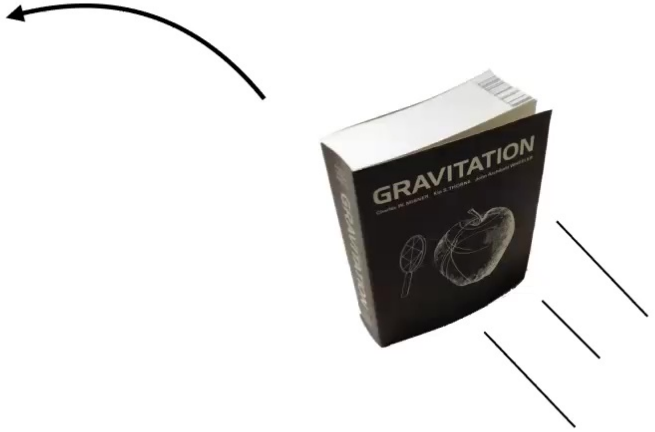
for *all but one* of the modes

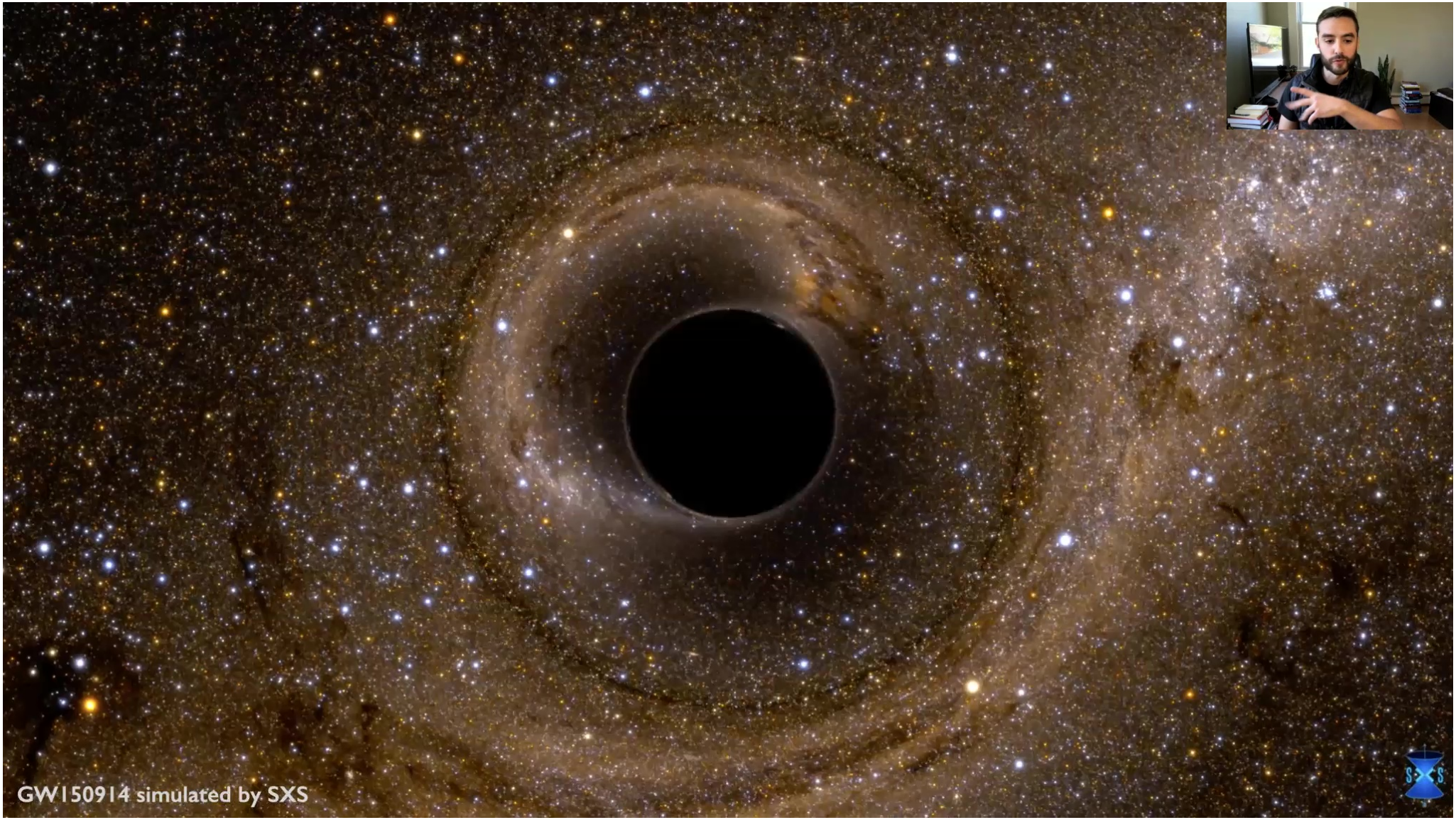


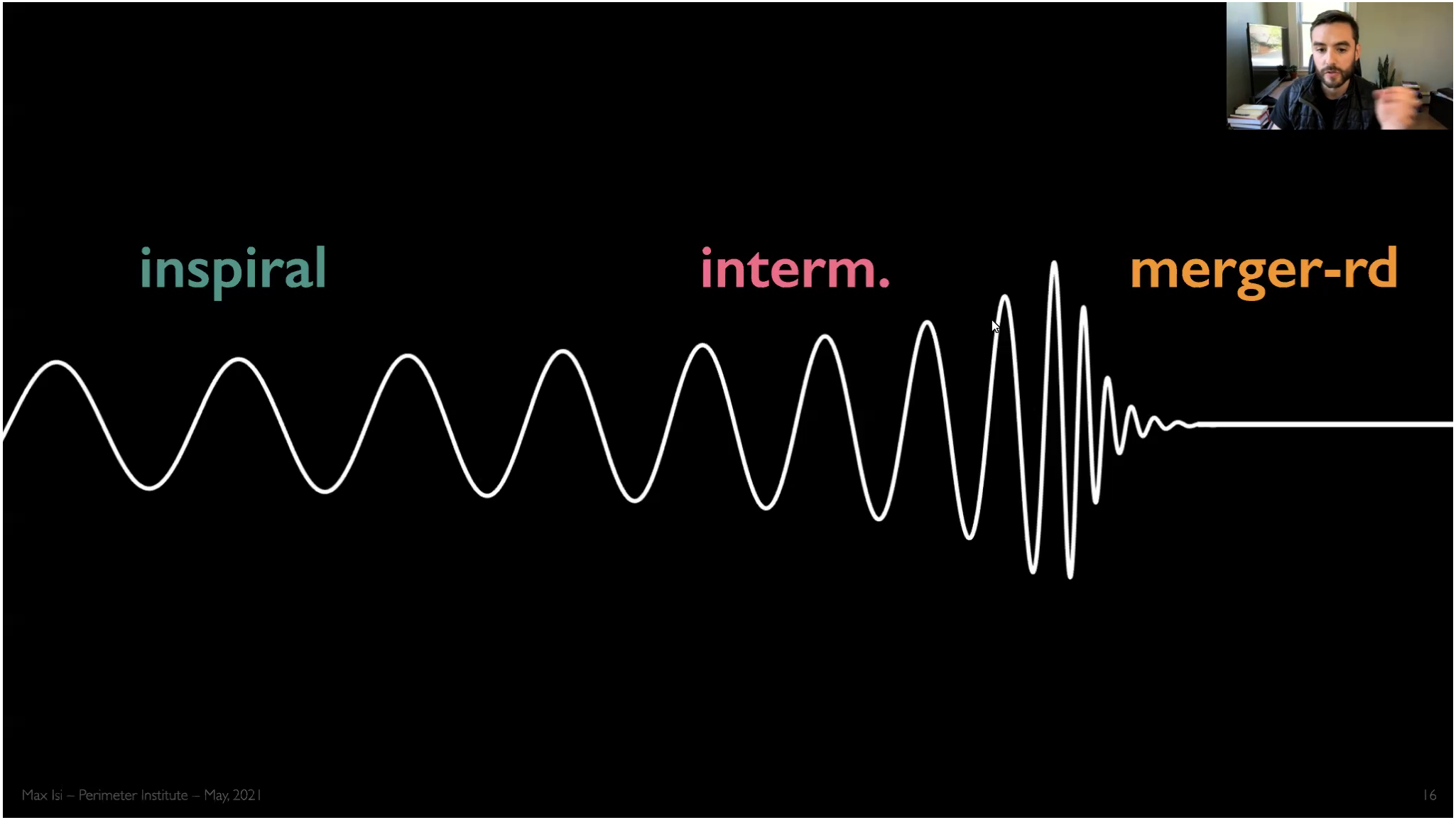


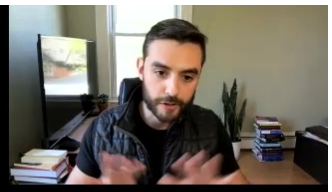
$\{M, \chi, \delta f_{\ell mn}, \delta \tau_{\ell mn}\}$

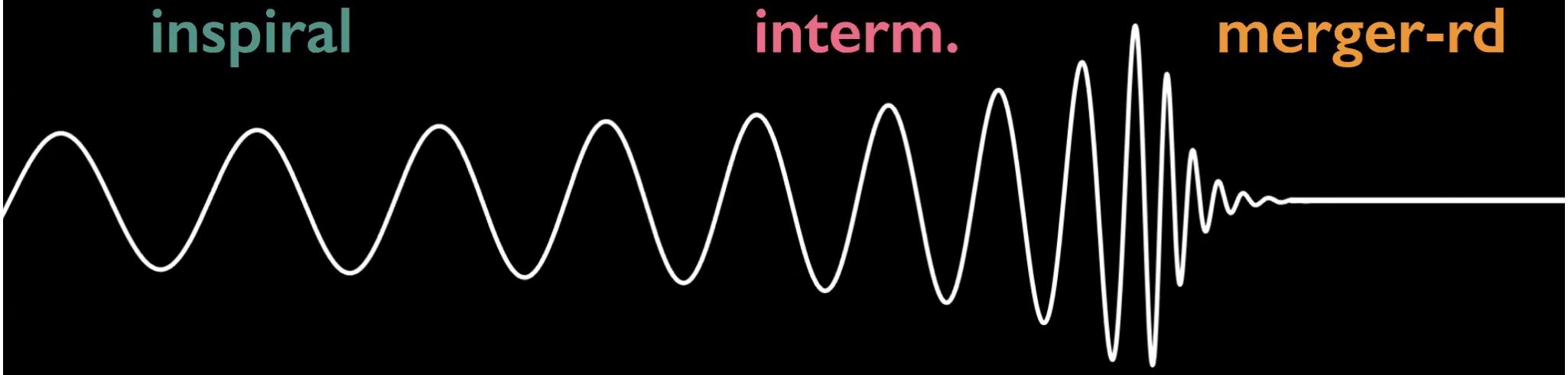




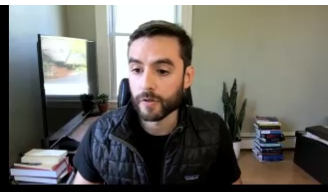

GW150914 simulated by SXS

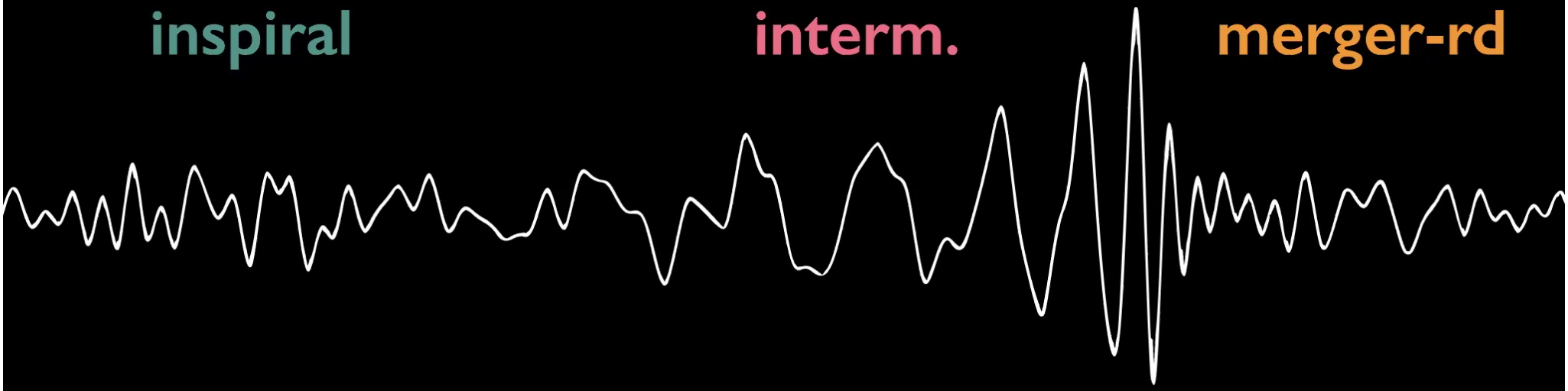

inspiral
interm.
merger-rd





define ringdown *operationally* as superposition of damped sinusoids



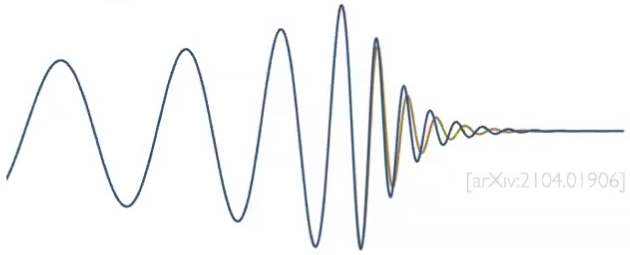


define ringdown *operationally* as superposition of damped sinusoids

strategies

enhanced IMR analysis

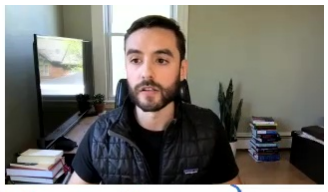
construct IMR model with additional degrees of freedom



time-domain analysis

truncate data and fit damped sinusoids in time domain

enhanced IMR

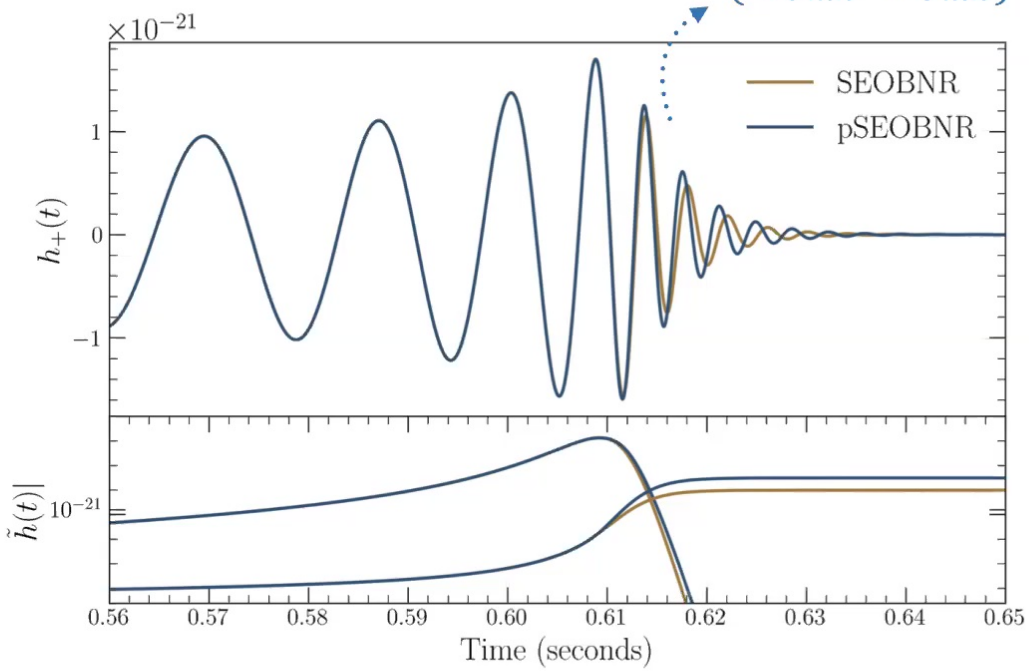


endow waveform with additional **degrees of freedom in ringdown**

Brito+2018 [arXiv:1805.00293]
Ghosh+2021 [arXiv:2104.01906]

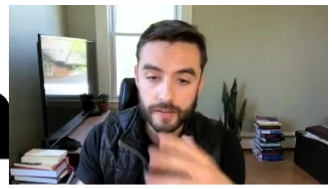
avoid *explicit* choice of ringdown start time in the data

use **regular LVC inference** infrastructure in freq. domain (big plus)



couples ringdown to inspiral

time-domain truncation

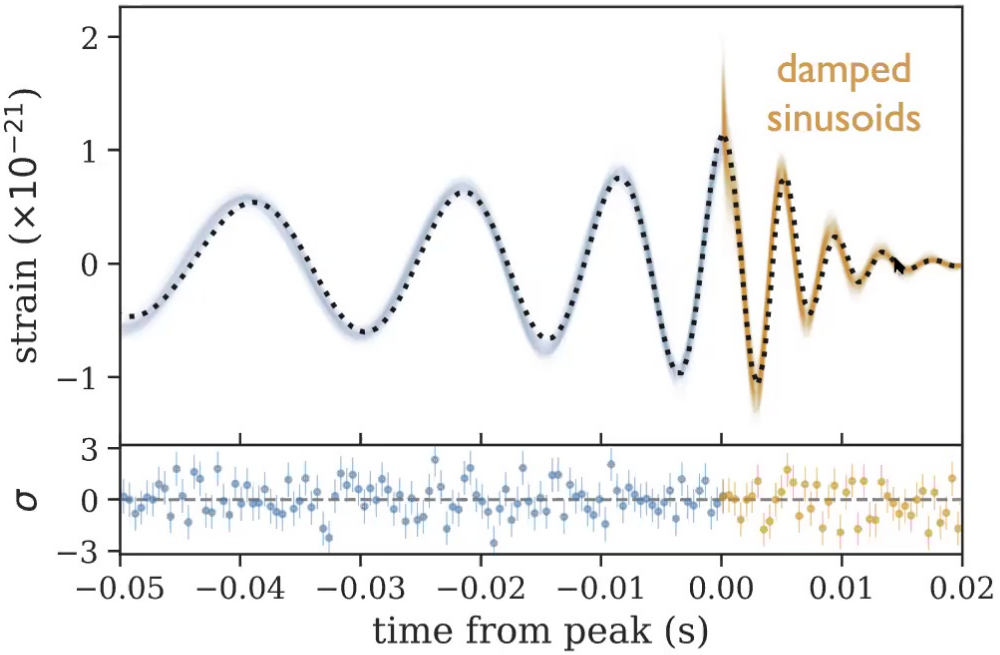


truncate data and fit a number of damped sinusoids

Isi+2019 [arXiv:1905.00869]
Carullo+2018 [arXiv:1805.04760]

assuming data are QNMs + noise from some time on, what are their properties?

technically tricky! cannot use standard LIGO-Virgo approach



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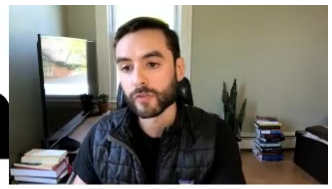

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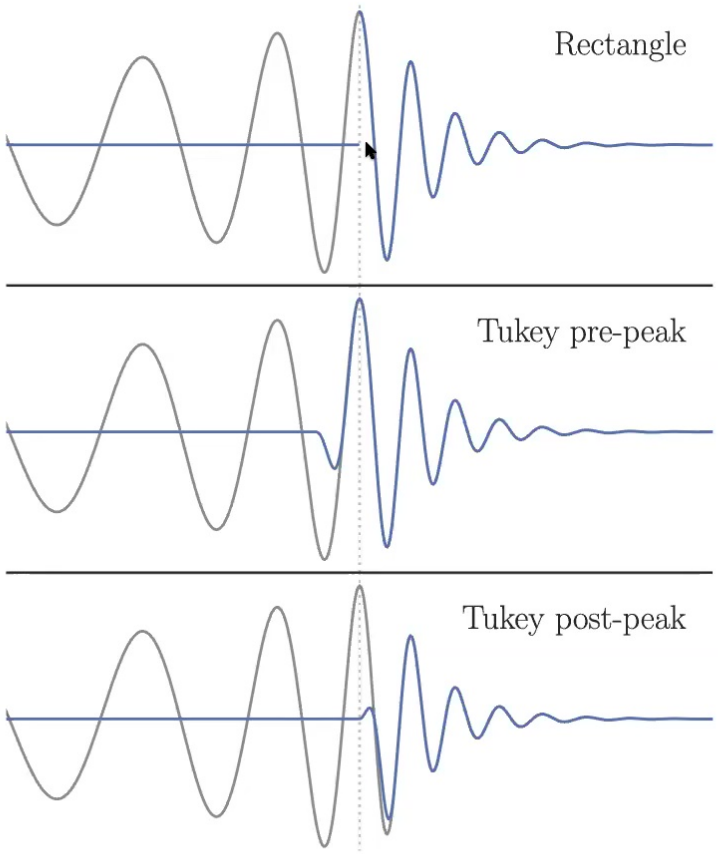

time-domain truncation

truncate data and fit a number of damped sinusoids

Isi+2019 [arXiv:1905.00869]
Carullo+2018 [arXiv:1805.04760]

assuming data are QNMs + noise from some time on, what are their properties?

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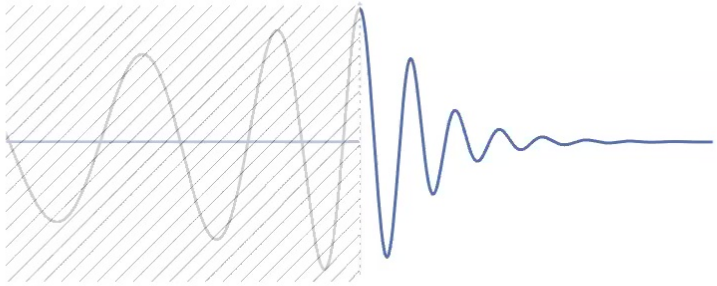
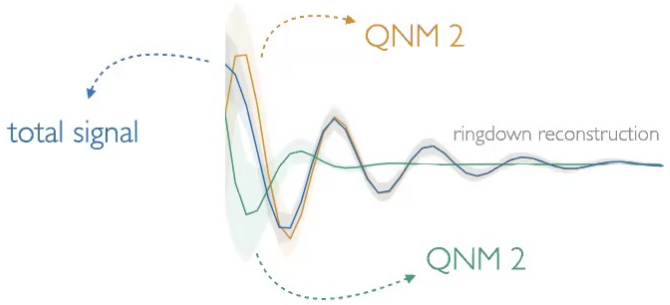
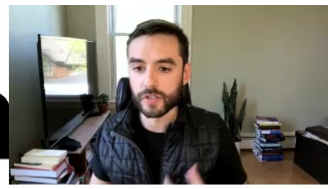


truncate and define likelihood in time domain, using an acyclic covariance matrix



time-domain truncation



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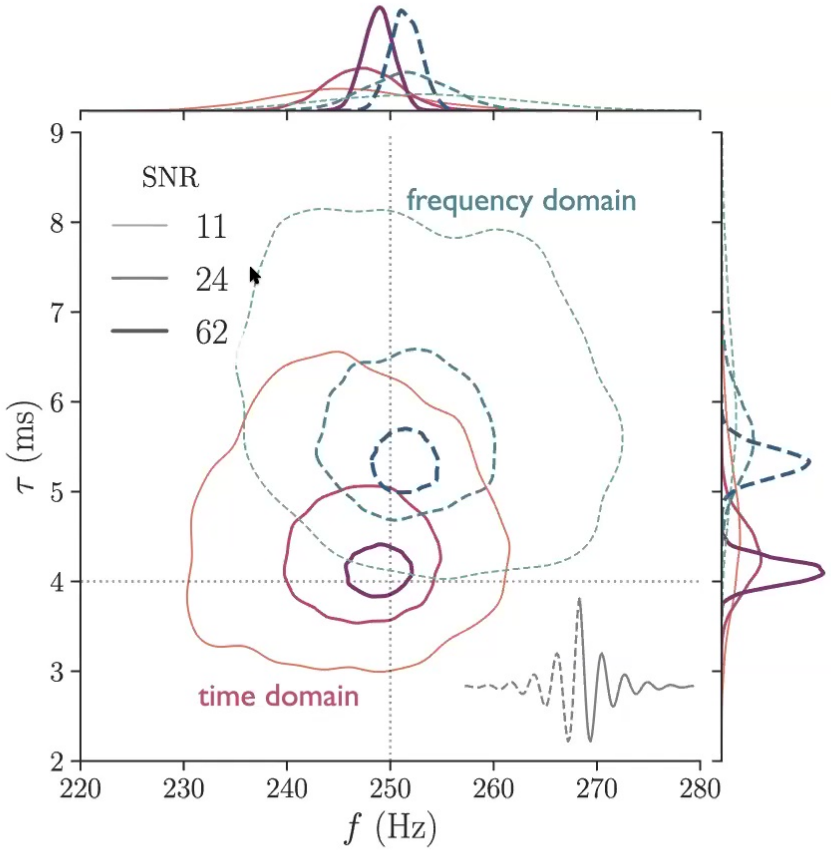
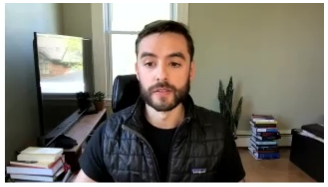
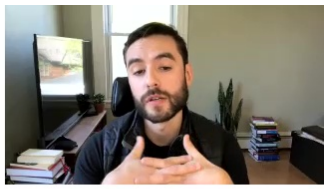




can we actually do this now?

bad news…



according to the *traditional* paradigm:

1. **must look long after peak**
2. **other (angular) modes much weaker**

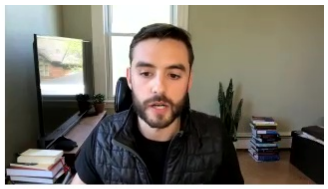
GW150914 as seen by LIGO Hanford*
*whitened and bandpassed [30, 250] Hz

good news!

but ***overtones*** can improve our chances

1. **can look closer to the peak**
2. **don't need other angular modes**

GW150914 as seen by LIGO Hanford*
*whitened and bandpassed [30, 250] Hz



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GW150914 as seen by LIGO Hanford*
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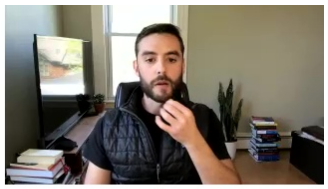
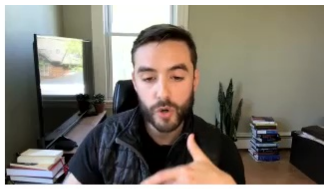
can already do this now

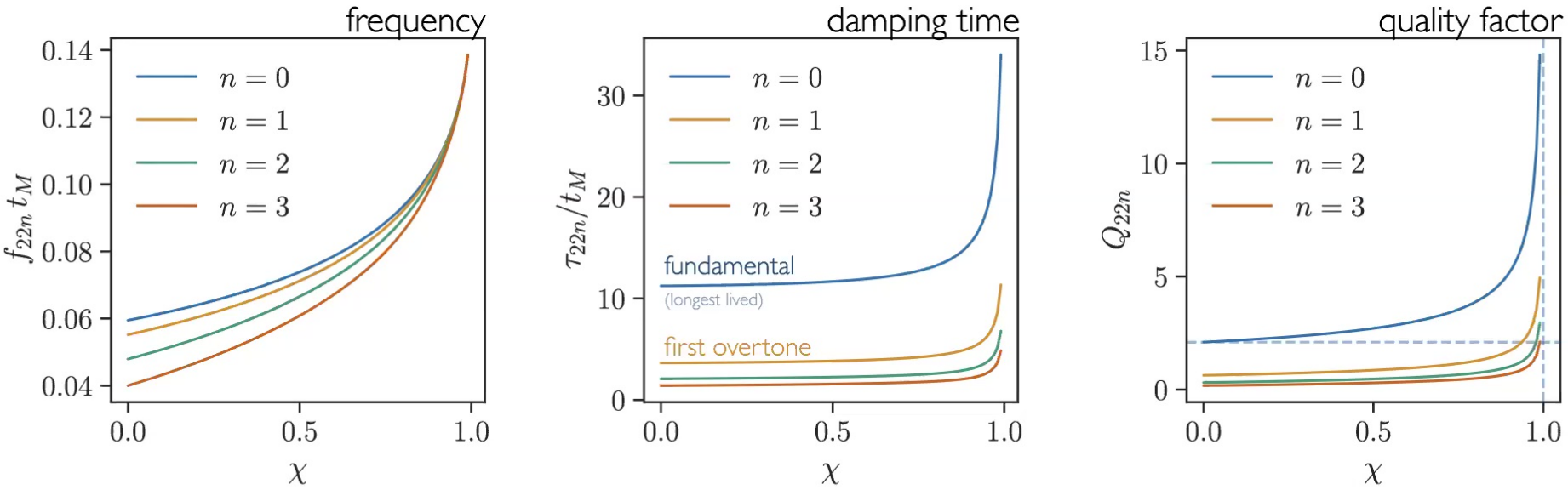


overtones

overtones

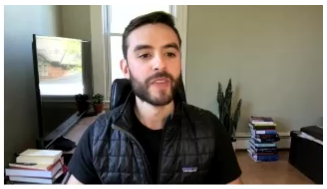


infinite family of tones with a given ℓm



all legitimate solutions to the Teukolsky equation

relevance of overtones



search for overtones in numerical relativity simulations

N=2 t ~ 10M Baibhav et al (PRD 2017) [arXiv:1710.02156]

N=1 t ~ 20M London et al (PRD 2014) [arXiv:1404.3197]

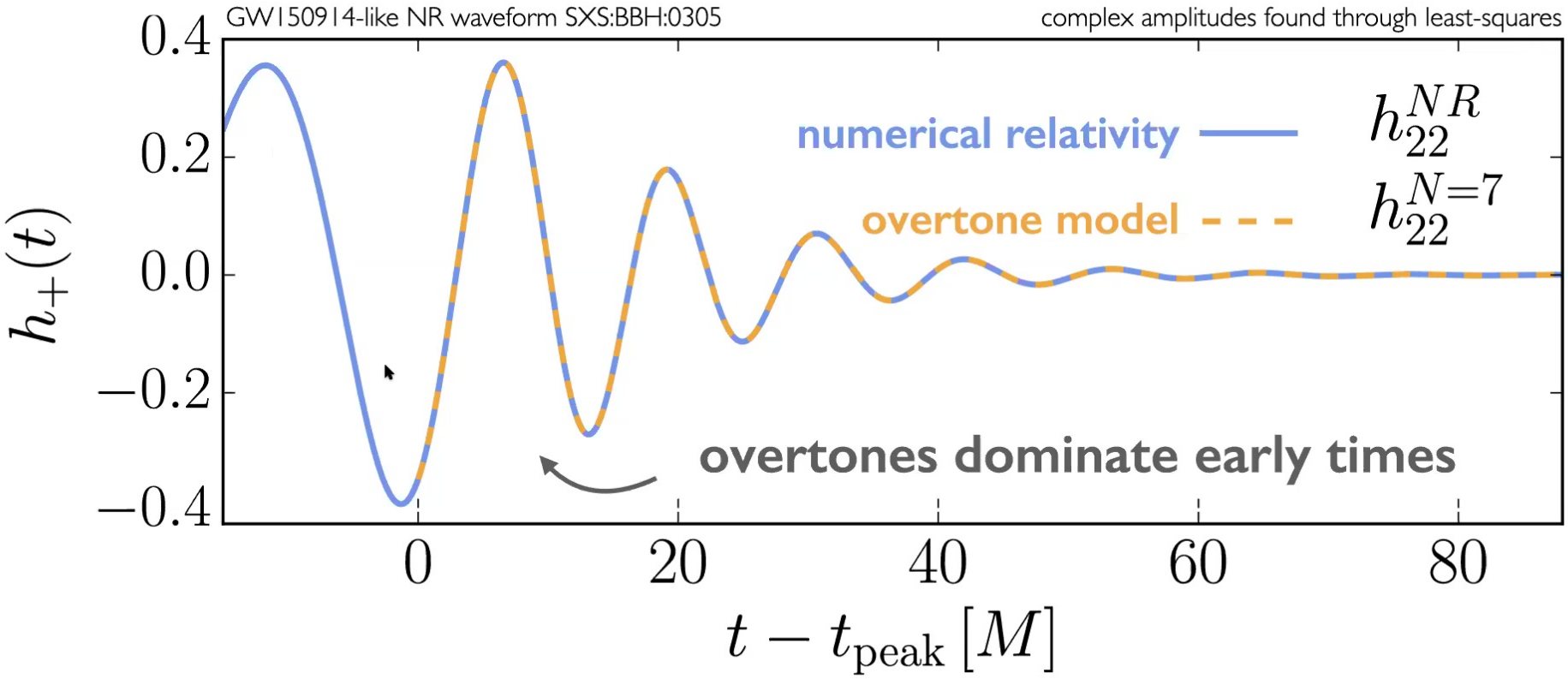
N=3 t < 10M Buonanno et al (PRD 2007) [arXiv:gr-qc/0610122]

Giesler, Isi, Scheel, Teukolsky (PRX 2019) [arXiv:1903.08284]

waveform well-described by QNMs from peak onwards*

*strain of 22 mode for spin-aligned compact binaries using up to 7 overtones

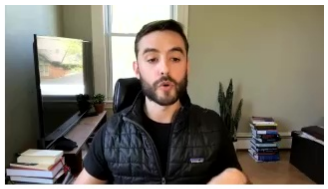
ringdown starts at the peak

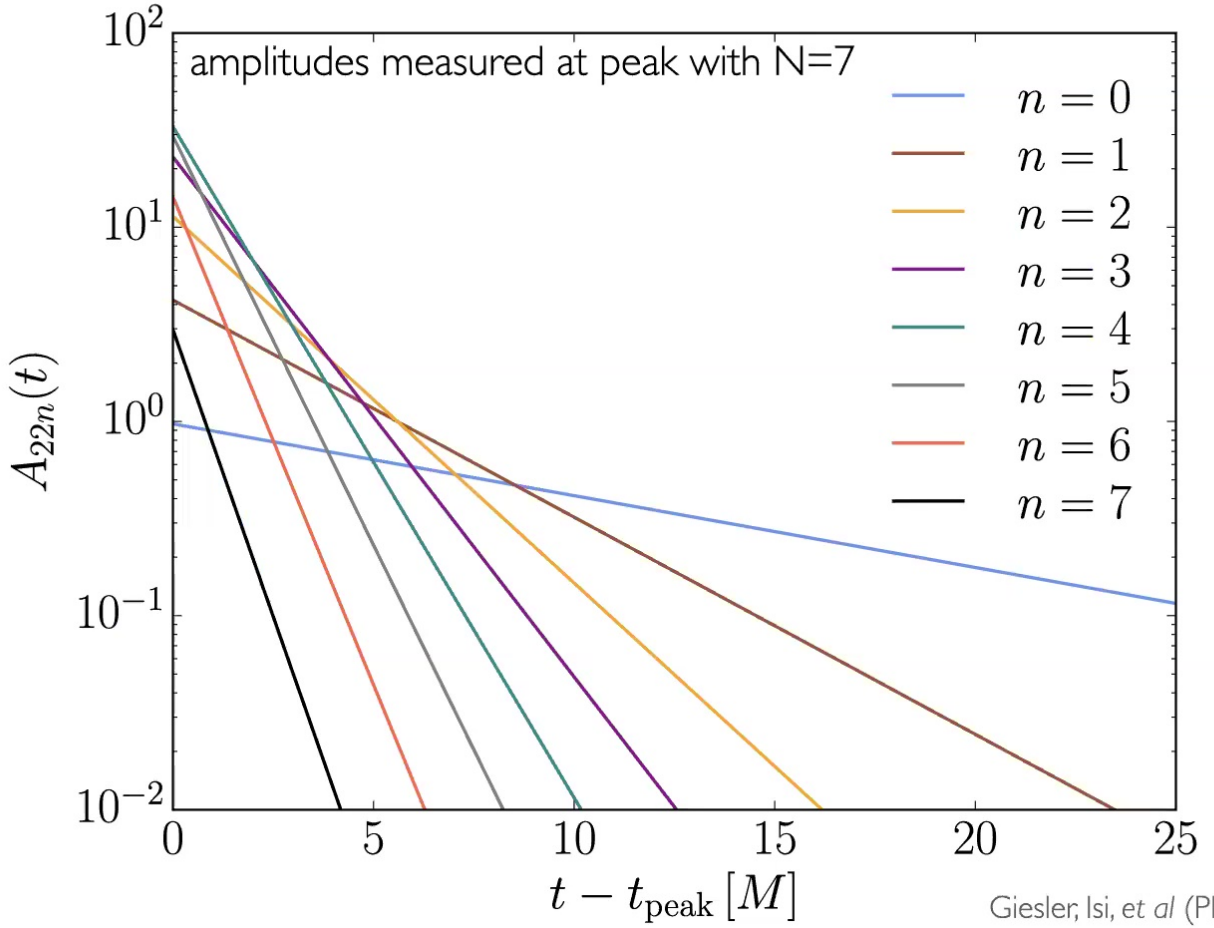


 $1M \sim 0.3\,\mathrm{ms}$ for GW150914

Giesler, Isi, *et al* (PRX 2019) [arXiv:1903.08284]

projected amplitude decay





Giesler, Isi, *et al* (PRX 2019) [arXiv:1903.08284]

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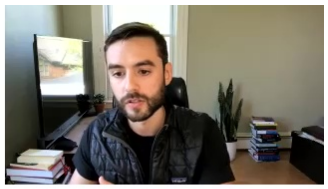

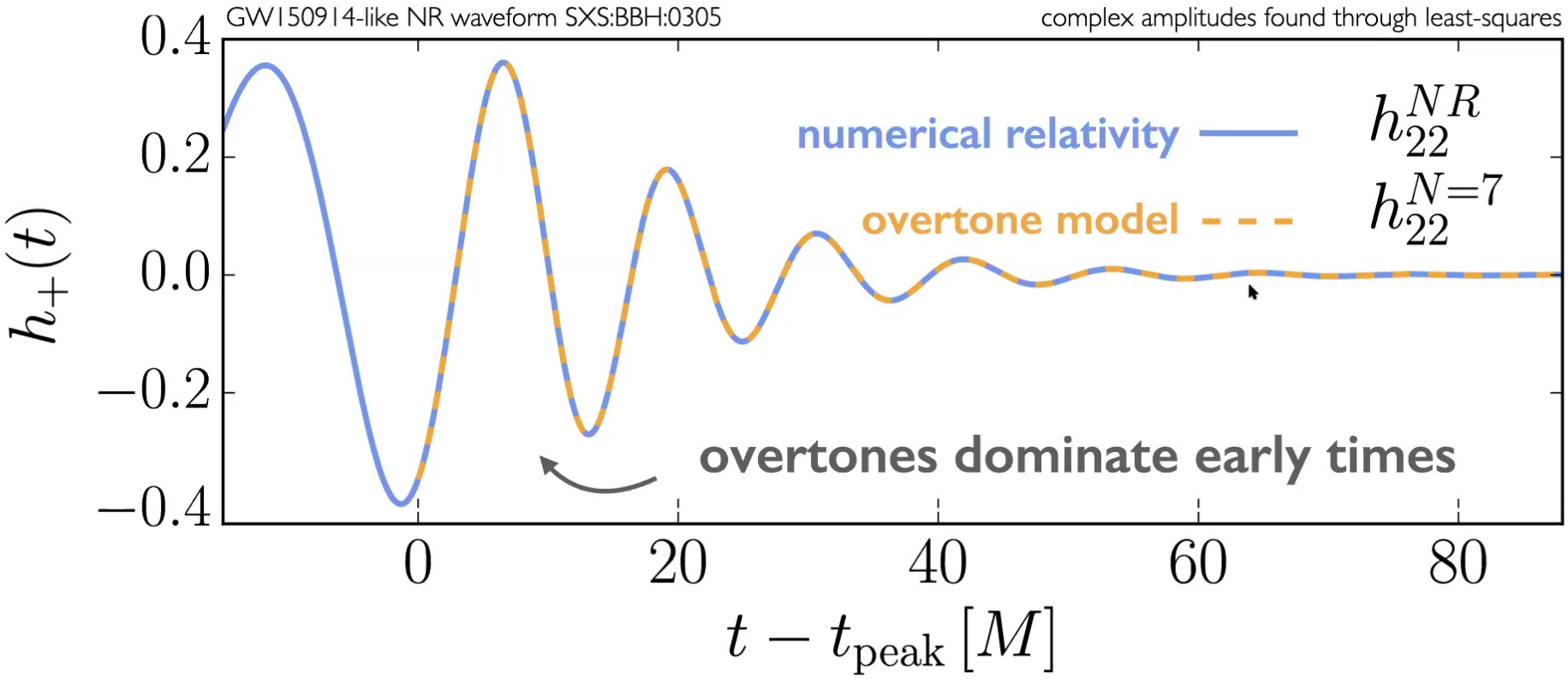

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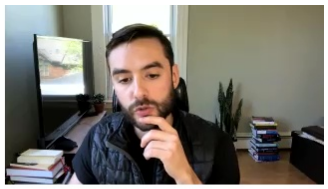

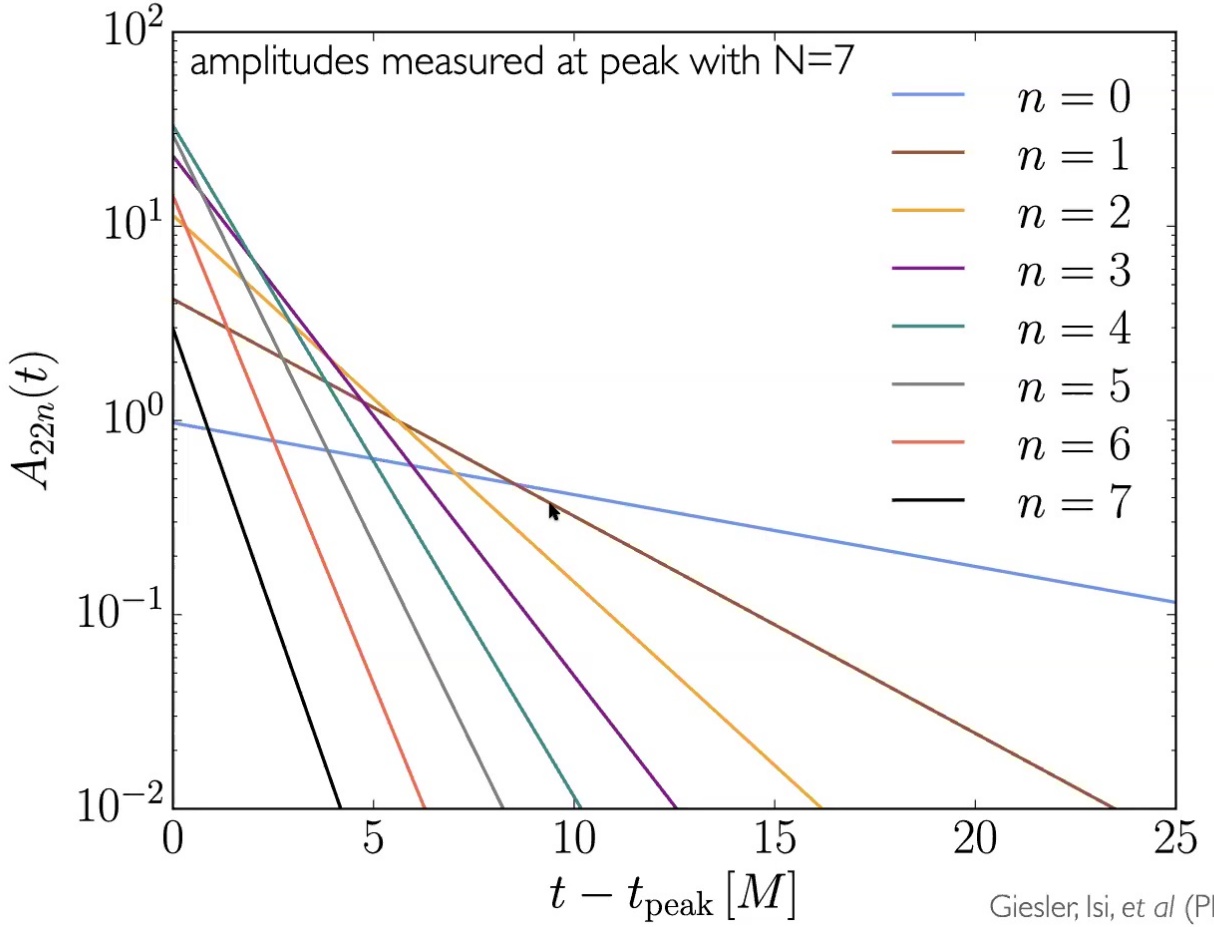

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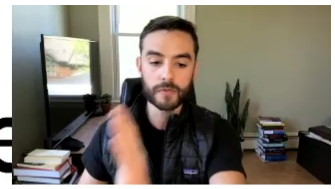
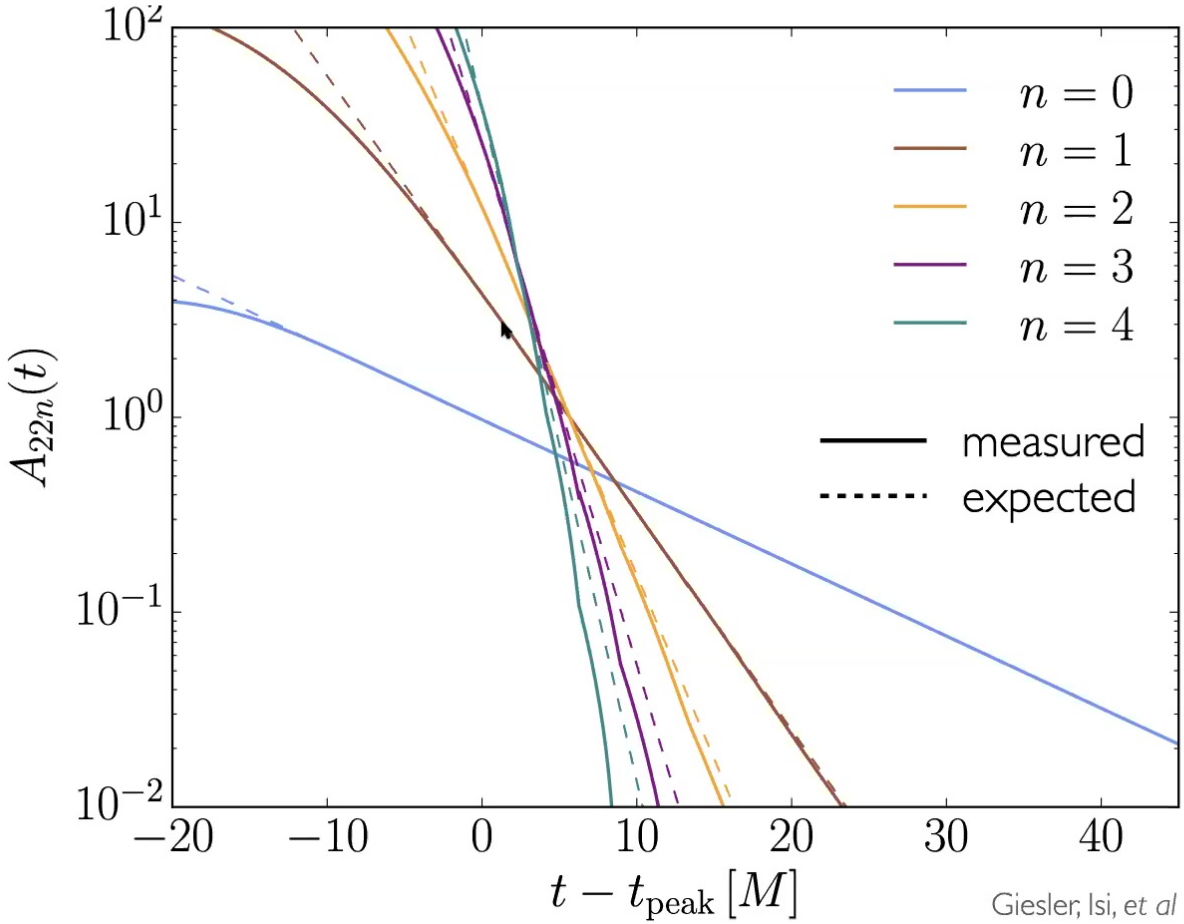
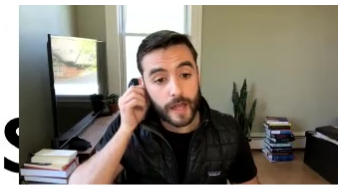
consistent recovery over time



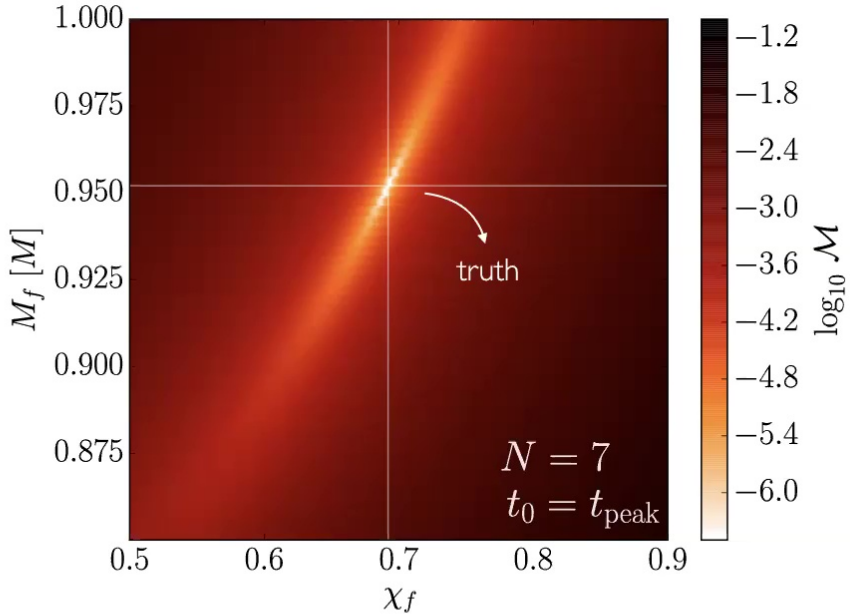


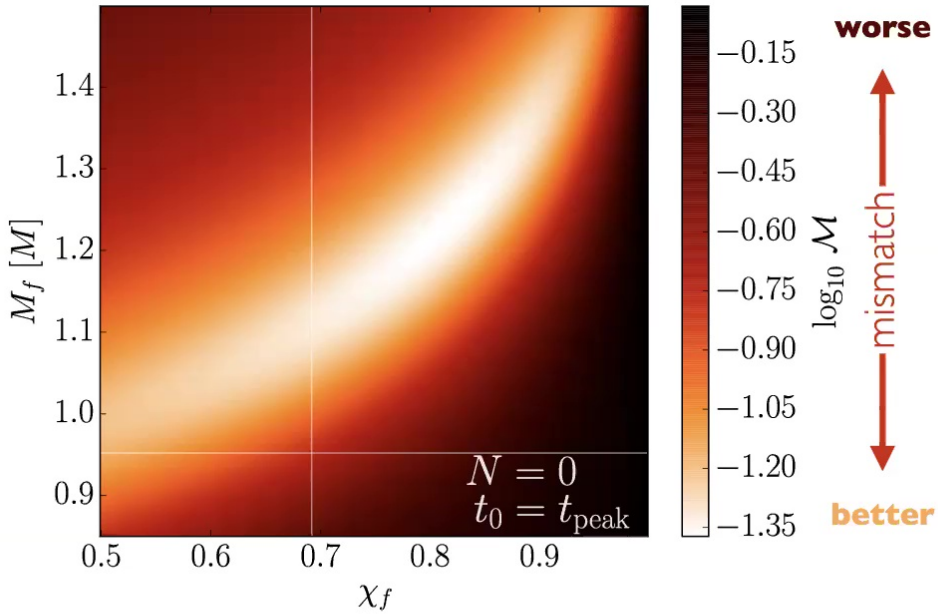
Giesler, Isi, *et al* (PRX 2019) [arXiv:1903.08284]

extracting remnant properties



let BH mass and spin vary in fit, compare to true values





fit with overtones recovers *correct* mass and spin

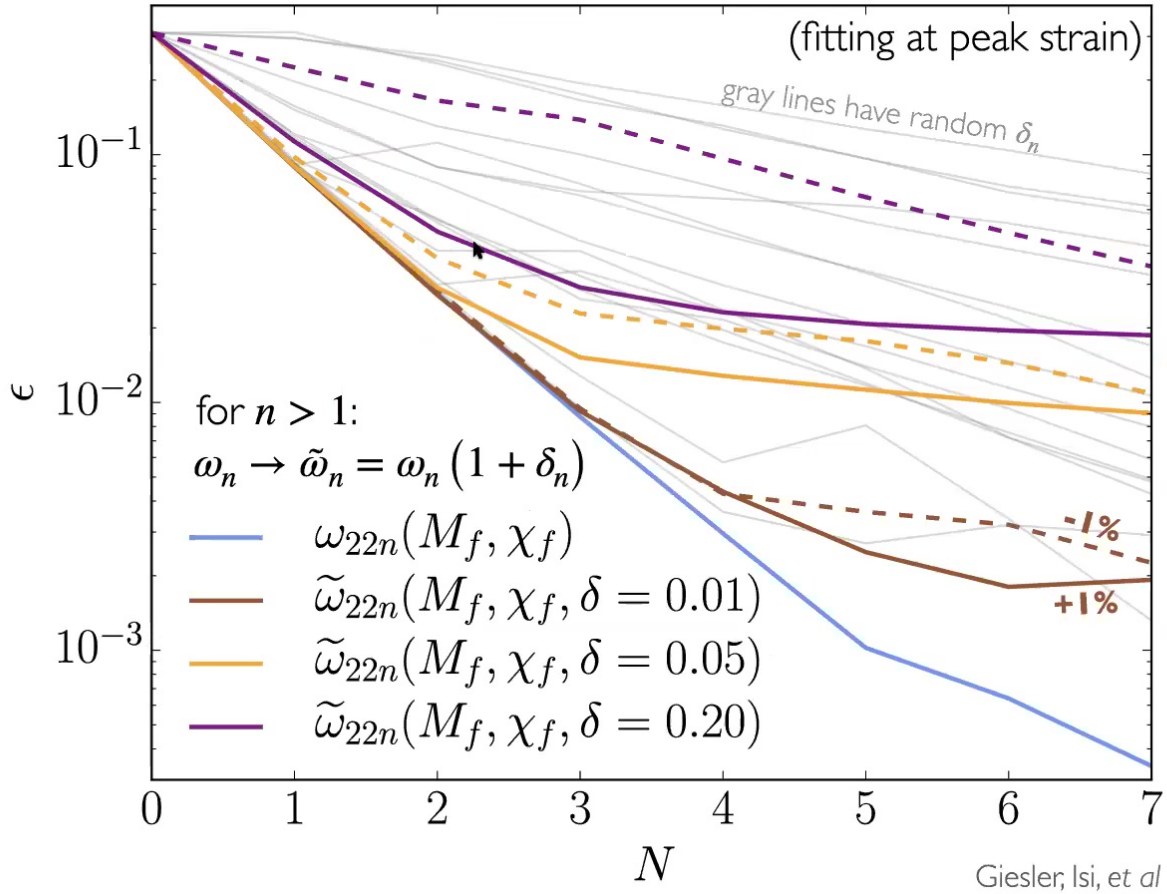
Giesler, Isi, *et al* (PRX 2019) [arXiv:1903.08284]

perturbing the overtones

worse

rms error in recovered mass & spin

better

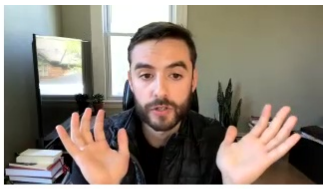


non-GR overtones

GR overtones

Giesler, Isi, *et al* (PRX 2019) [arXiv:1903.08284]

takeaways



spin-aligned NR waveforms are well described by remnant overtone model starting at ~**peak strain**

(looking only at 22 mode)

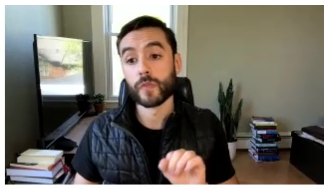
amplitudes are recovered **self-consistently** in time
(for at least $n \leq 4$)

overtones contribute: perturbing their frequencies biases inferred remnant properties

empirical claims!

measurements

GW150914 at the peak

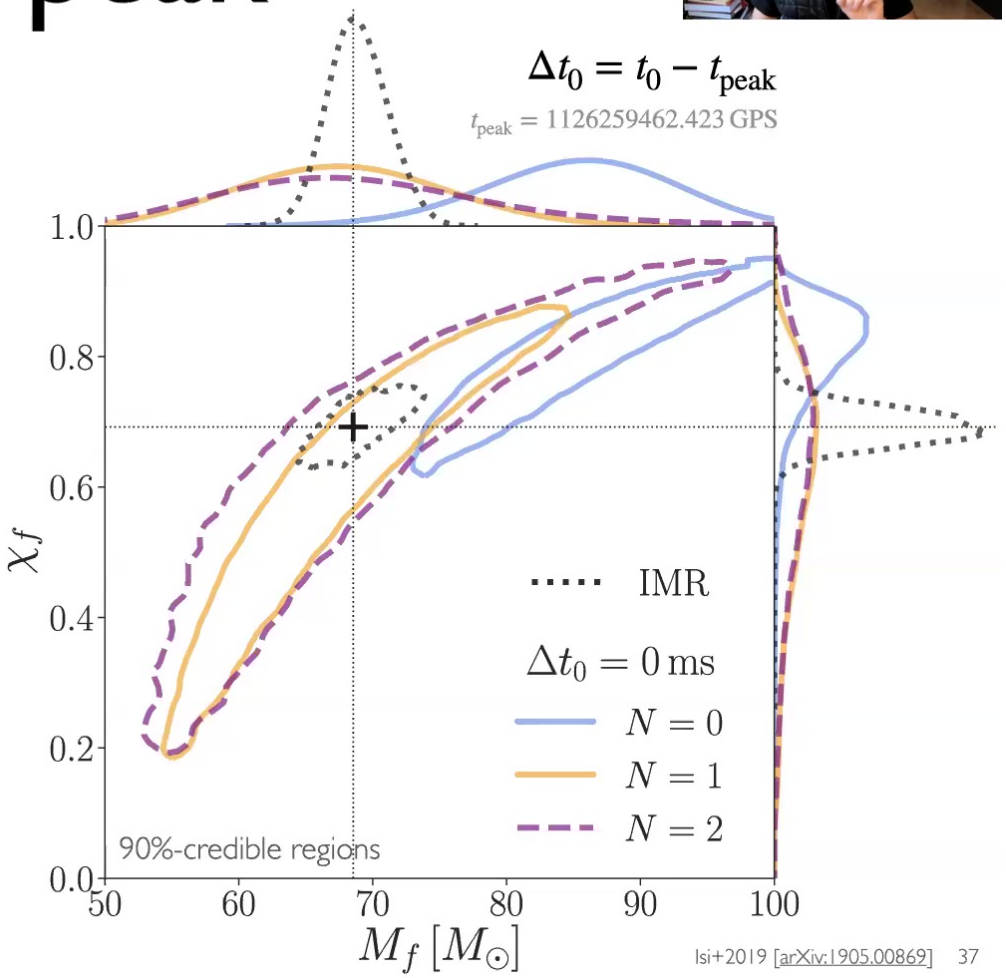


we identify at least **two ringdown modes** in GW150914

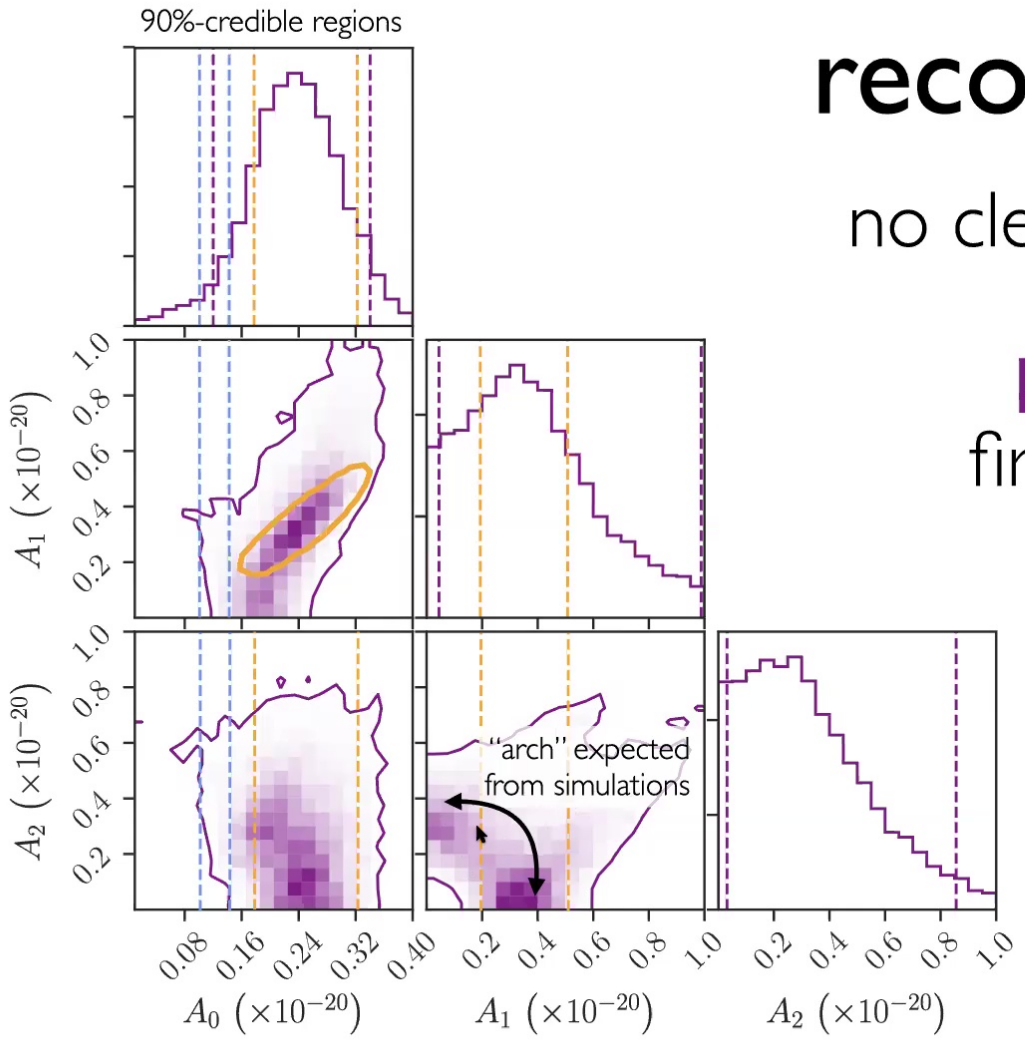
that is the least-damped mode plus **at least one overtone** (N=1)

with N=1, can **measure remnant mass and spin** at the peak

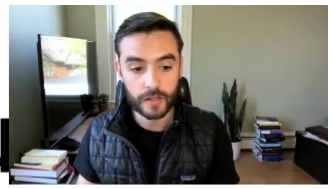
result in agreement with measurement from full waveform



Isi+2019 [arXiv:1905.00869] 37



recovered amplitu



no clear gain from 2nd overtone

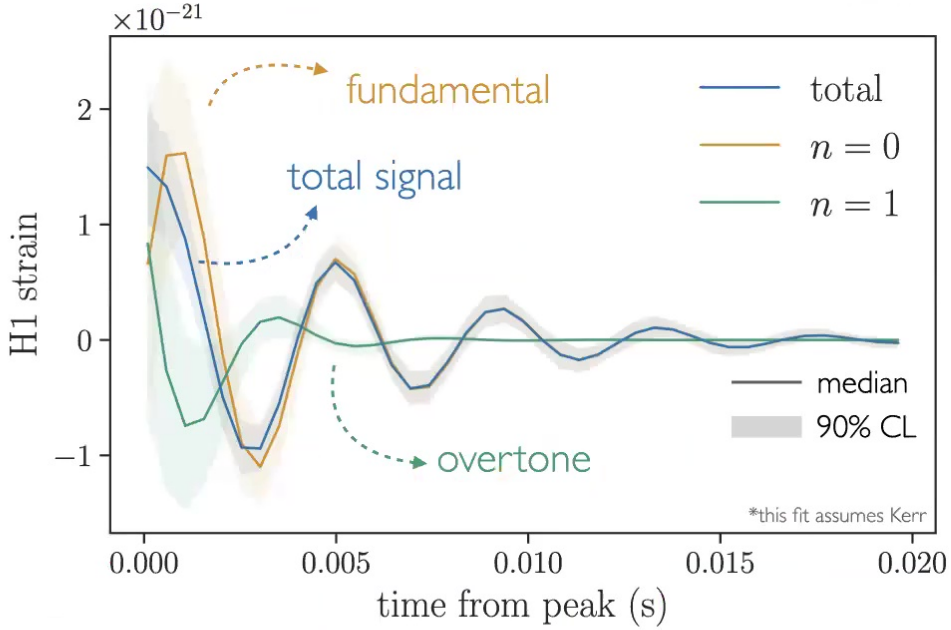
posterior for N=2 favors first overtone, in agreement with **posterior for N=1**

posterior for N=0 misses the mark, as expected at the peak

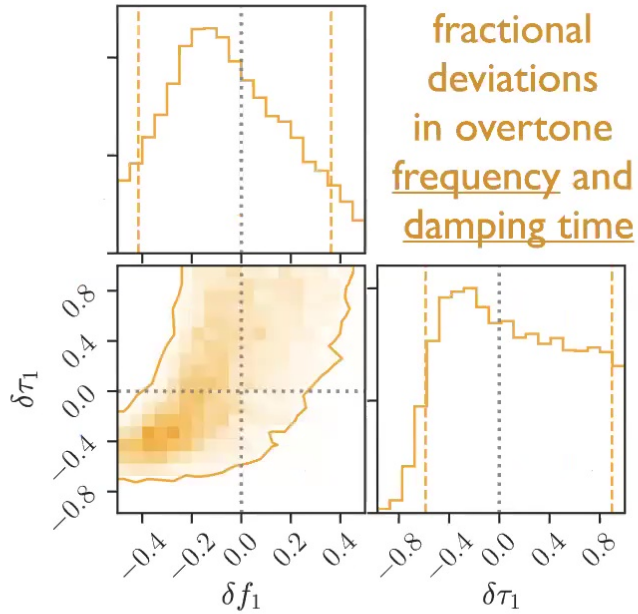
Isi *et al* (PRL 2019) [arXiv:1905.00869]

GW150914

spectroscopic analysis of fundamental + first overtone

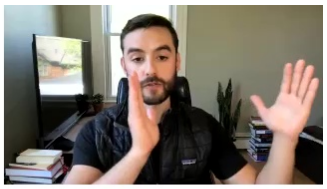


reconstruct fundamental and overtone of 22 mode



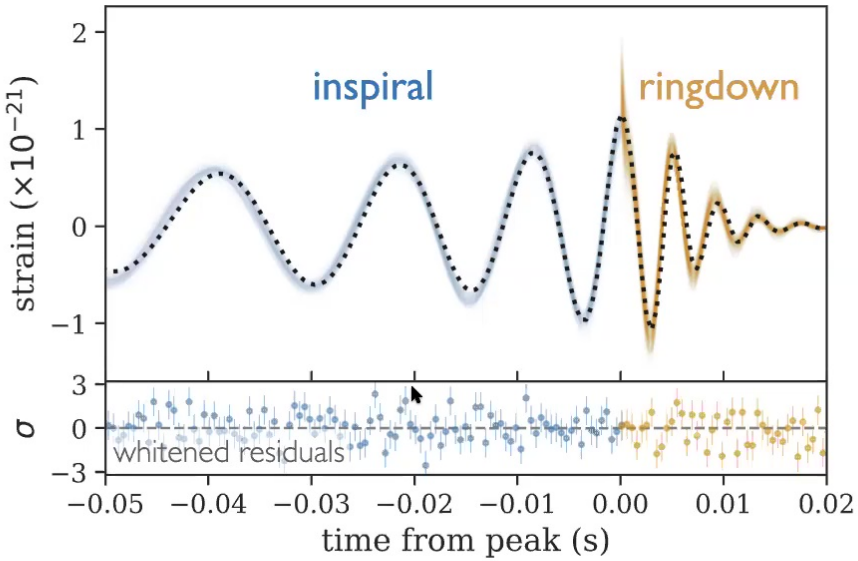
agreement with Kerr ~ 20% at 1σ

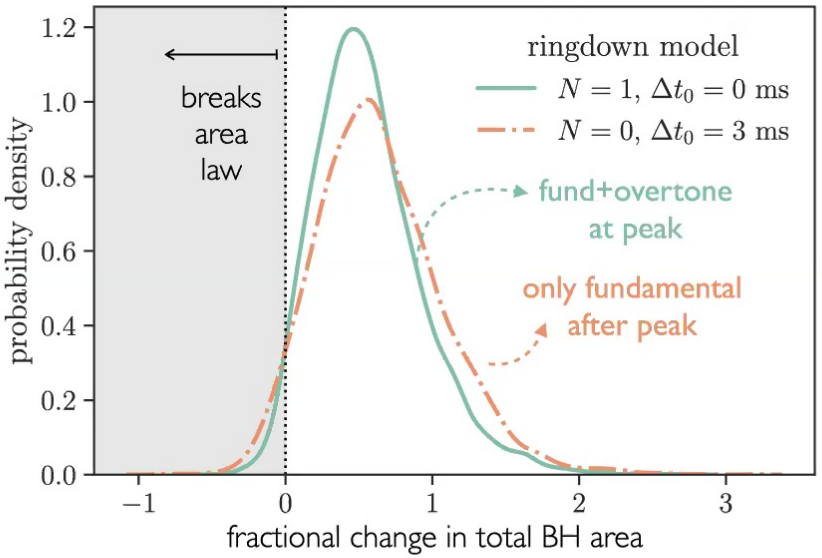
Isi+2019 [arxiv:1905.00869]



GW150914

total BH area must not decrease



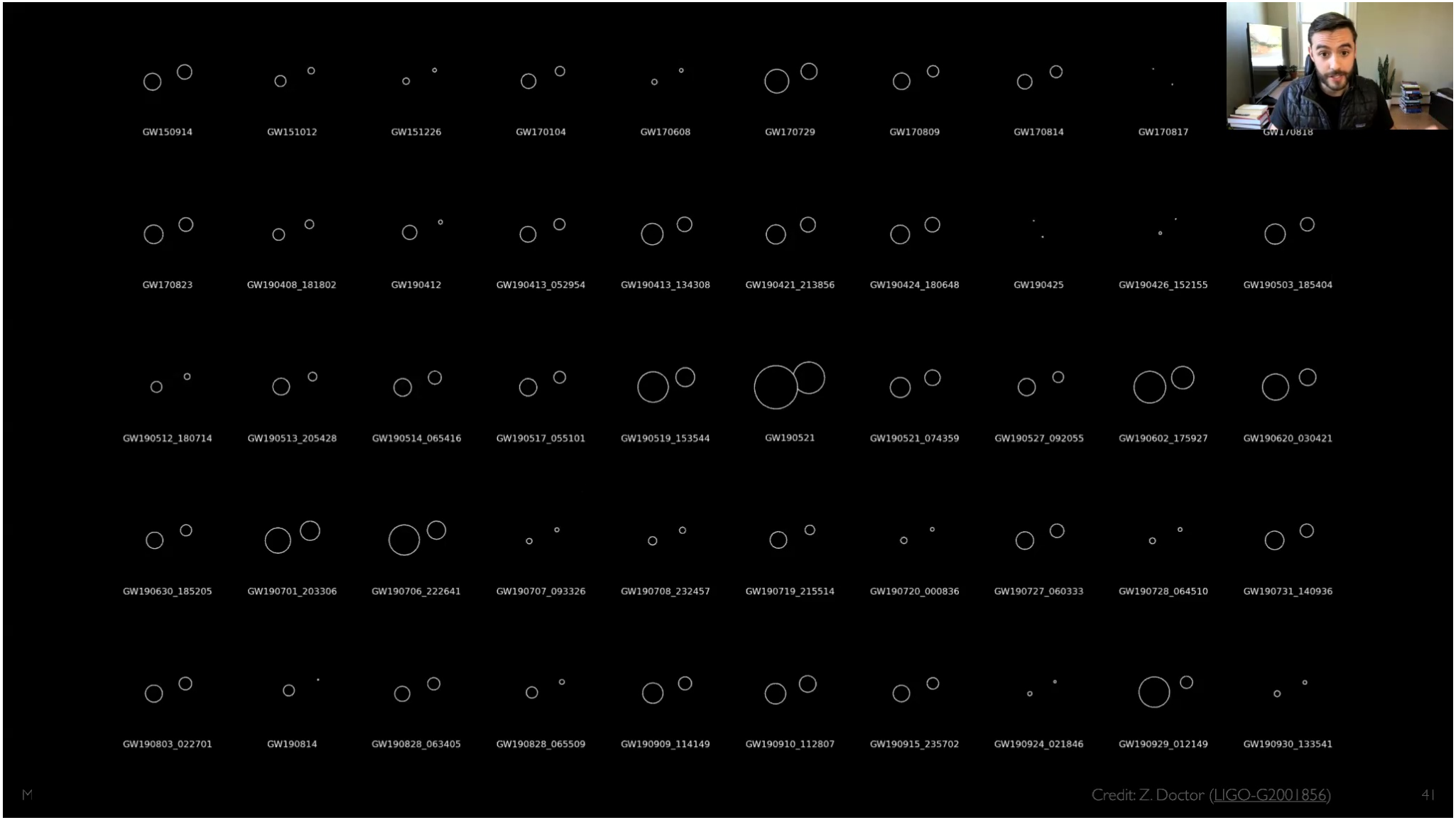


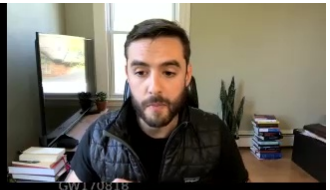
independent ringdown and inspiral measurements

agreement with area law with ~97% credibility

 *the inspiral measurement here was terminated at the peak, but overall conclusions do not change if we cut earlier; feel free to ask!

Isi+2020 [arxiv:2012.04486]


GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170817
GW170818
GW170823
GW190408_181802
GW190412
GW190413_052954
GW190413_134308
GW190421_213856
GW190424_180648
GW190425
GW190426_152155
GW190503_185404
GW190512_180714
GW190513_205428
GW190514_065416
GW190517_055101
GW190519_153544
GW190521
GW190521_074359
GW190527_092055
GW190602_175927
GW190620_030421
GW190630_185205
GW190701_203306
GW190706_222641
GW190707_093326
GW190708_232457
GW190719_215514
GW190720_000836
GW190727_060333
GW190728_064510
GW190731_140936
GW190803_022701
GW190814
GW190828_063405
GW190828_065509
GW190909_114149
GW190910_112807
GW190915_235702
GW190924_021846
GW190929_012149
GW190930_133541
Credit: Z. Doctor (LIGO-G2001856)



GW150914 GW151012 GW151226 GW170104 GW170608 GW170729 GW170809 GW170814 GW170817 GW170818

GW170823 GW190408_181802 GW190412 GW190413_052954 GW190413_134308 GW190421_213856 GW190424_180648 GW190425 GW190426_152155 GW190503_185404

GWTC-2

second LIGO-Virgo transient catalog

Abbott et al (2020) [arXiv:2010.14527]

GW190512_180714 GW190513_205428 GW190514_065416 GW190521_074359 GW190527_092055 GW190602_175927 GW190620_030421

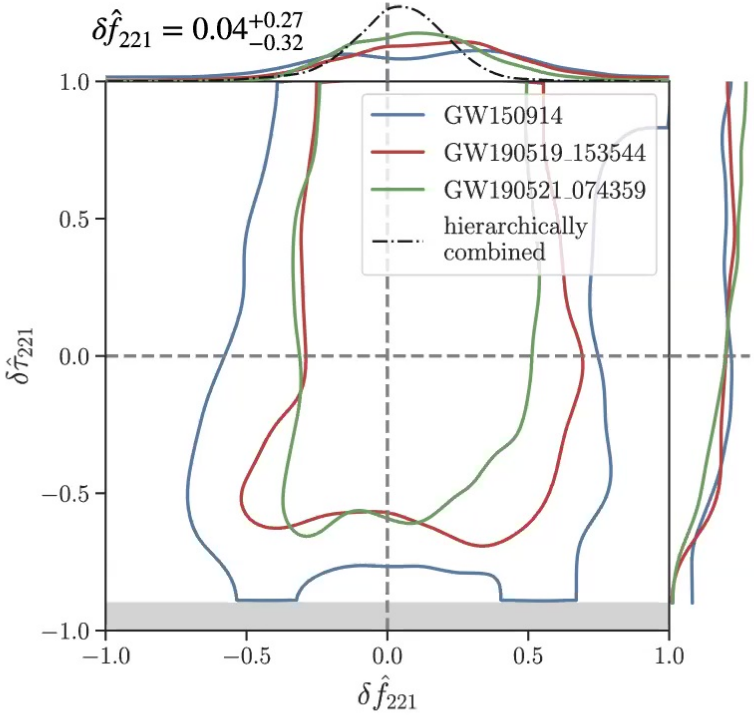
GW190630_185205 GW190701_203306 GW190706_222641 GW190707_093326 GW190708_232457 GW190719_215514 GW190720_000836 GW190727_060333 GW190728_064510 GW190731_140936

GW190803_022701 GW190814 GW190828_063405 GW190828_065509 GW190909_114149 GW190910_112807 GW190915_235702 GW190924_021846 GW190929_012149 GW190930_133541

Credit: Z. Doctor (LIGO-G2001856)

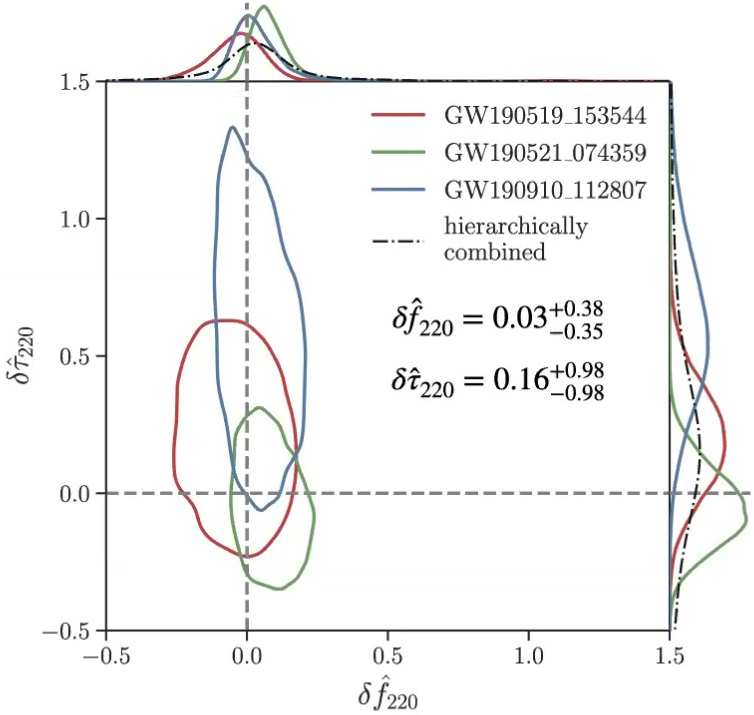
GWTC-2 ringdowns

damped sinusoids



Carullo+2018 [arxiv:1805.04760], Isi+2019 [arxiv:1905.00869]

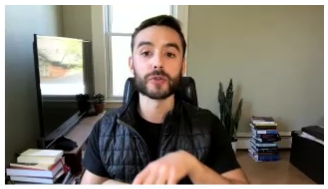
enhanced IMR model



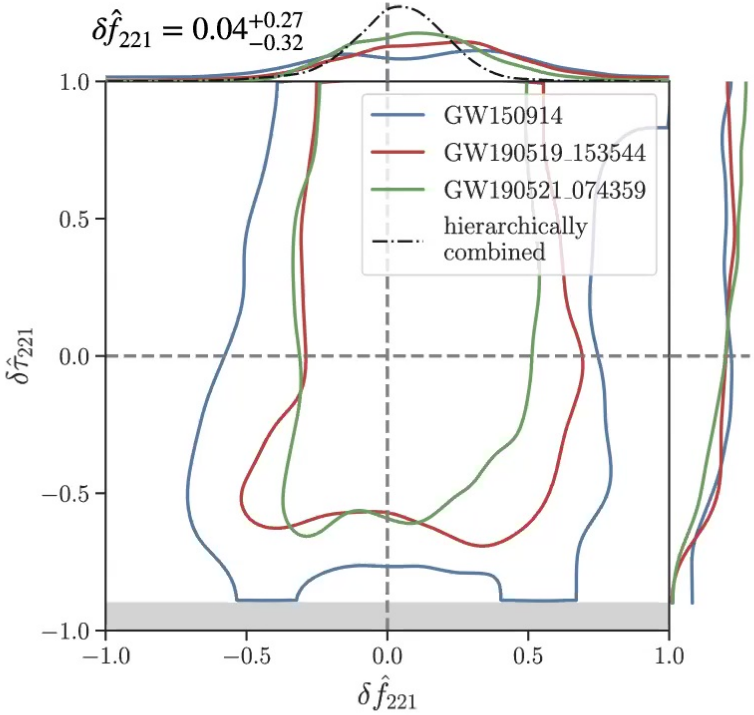
Brito+2018 [arxiv:1805.00293], **UPDATED RESULTS** Ghosh+2021 [arxiv:2104.01906]

Abbott+2020 [arxiv:2010.14529]

GWTC-2 ringdowns

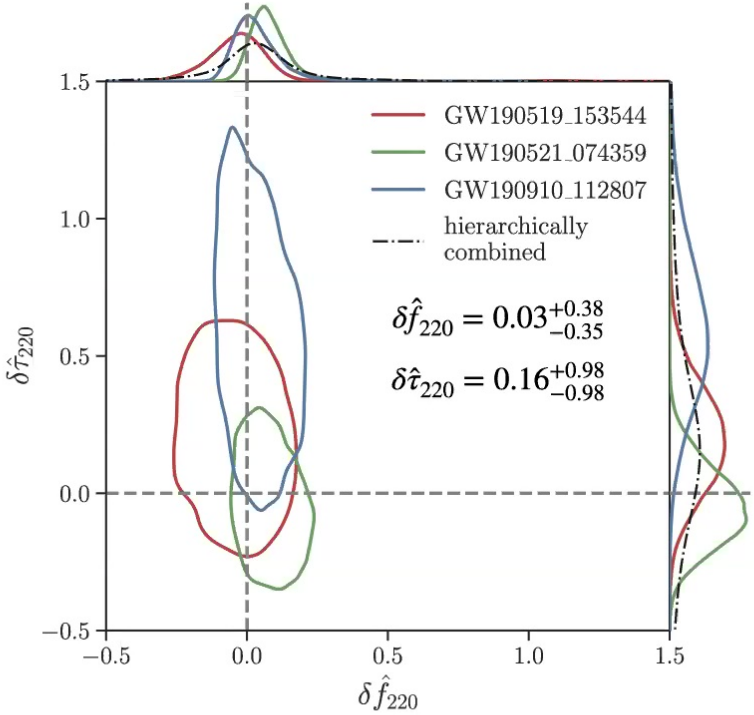


damped sinusoids



Carullo+2018 [arxiv:1805.04760], Isi+2019 [arxiv:1905.00869]

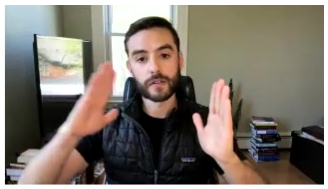
enhanced IMR model



Brito+2018 [arxiv:1805.00293], **UPDATED RESULTS** Ghosh+2021 [arxiv:2104.01906]

→ Abbott+2020 [arxiv:2010.14529]

common questions



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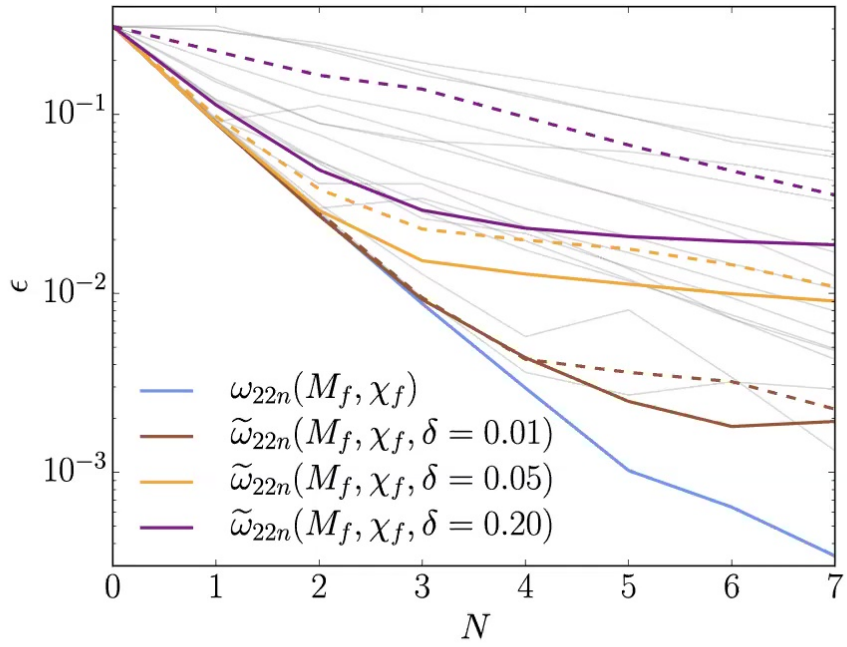

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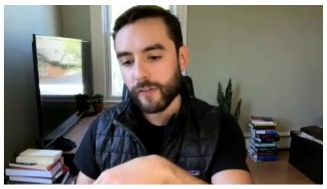

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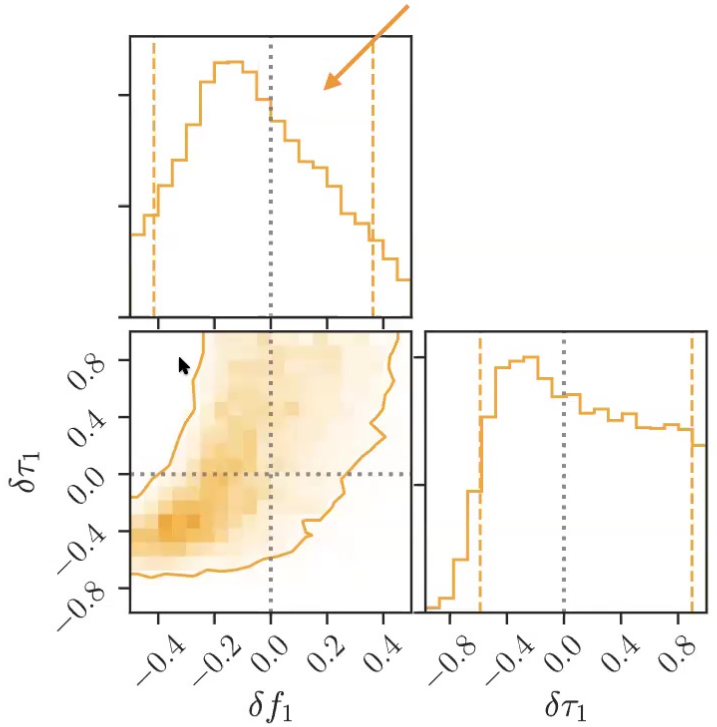

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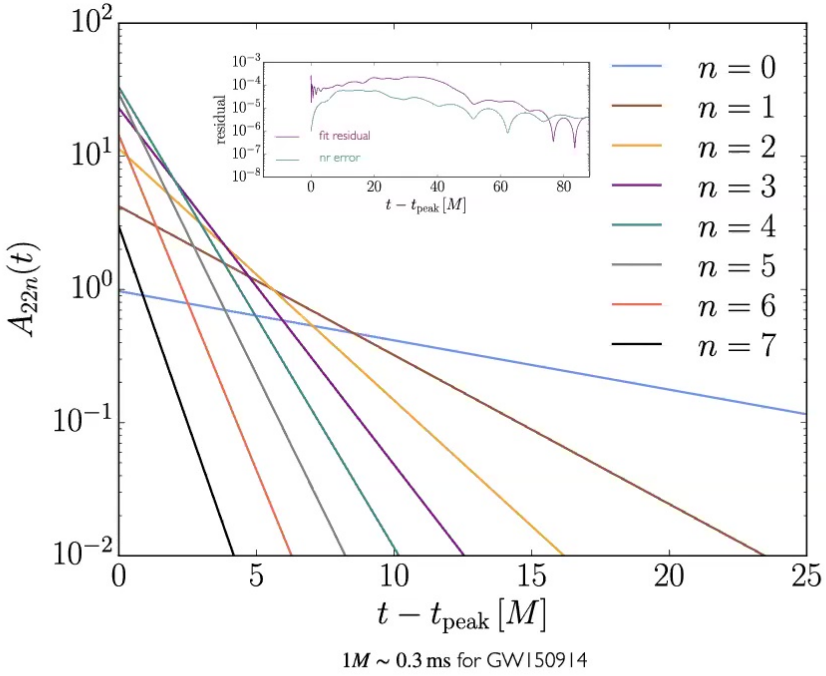

$1M \sim 0.3\,\mathrm{ms}$ for GW150914

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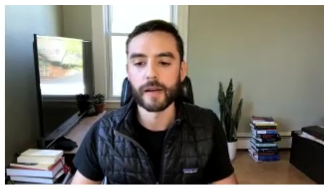

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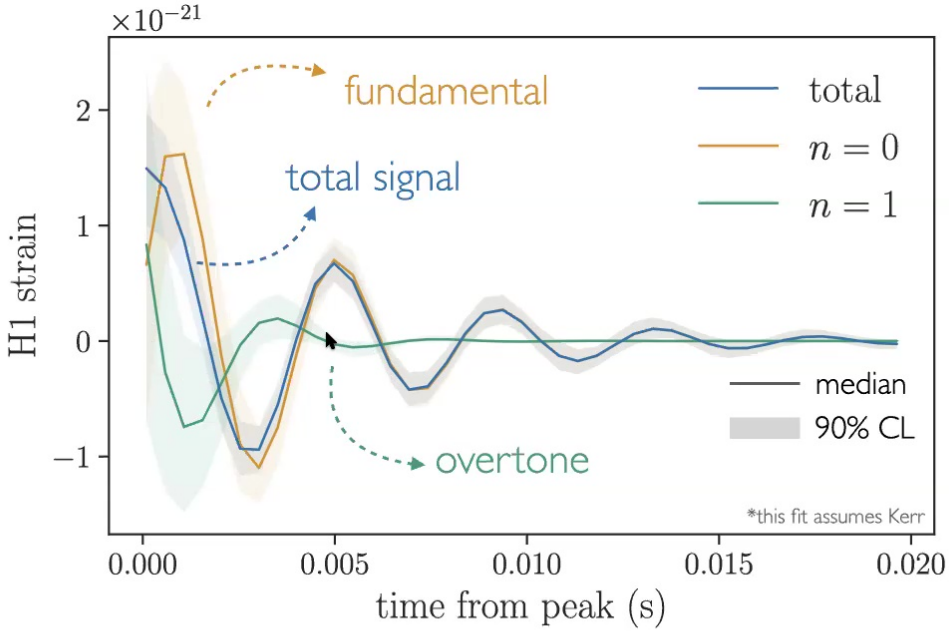
lower OTs **clearly not δ-functions** with our time resolution



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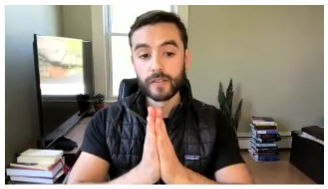

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based on the **misconception** that resolving modes requires

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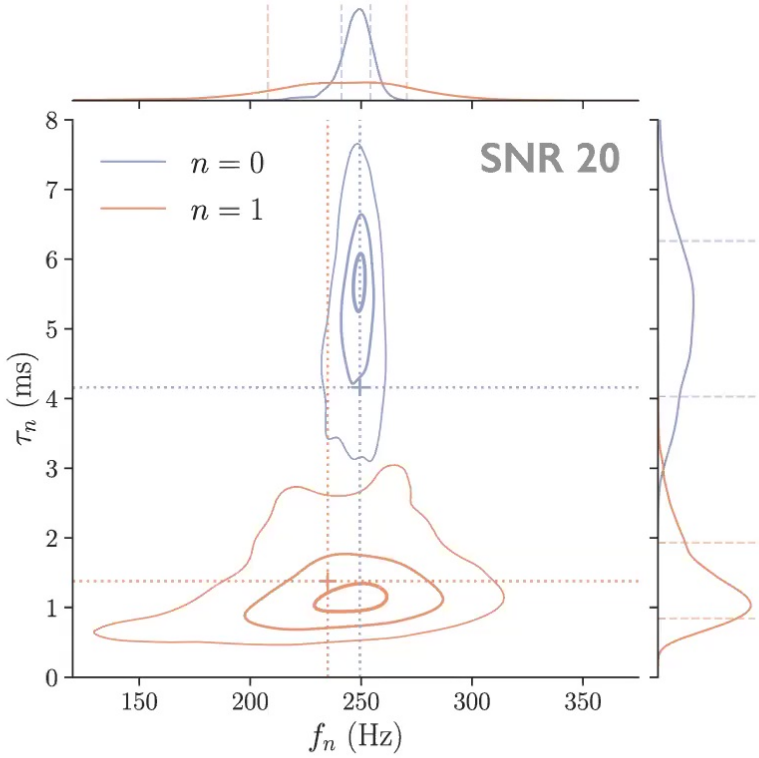

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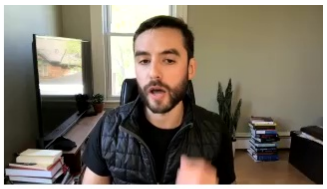

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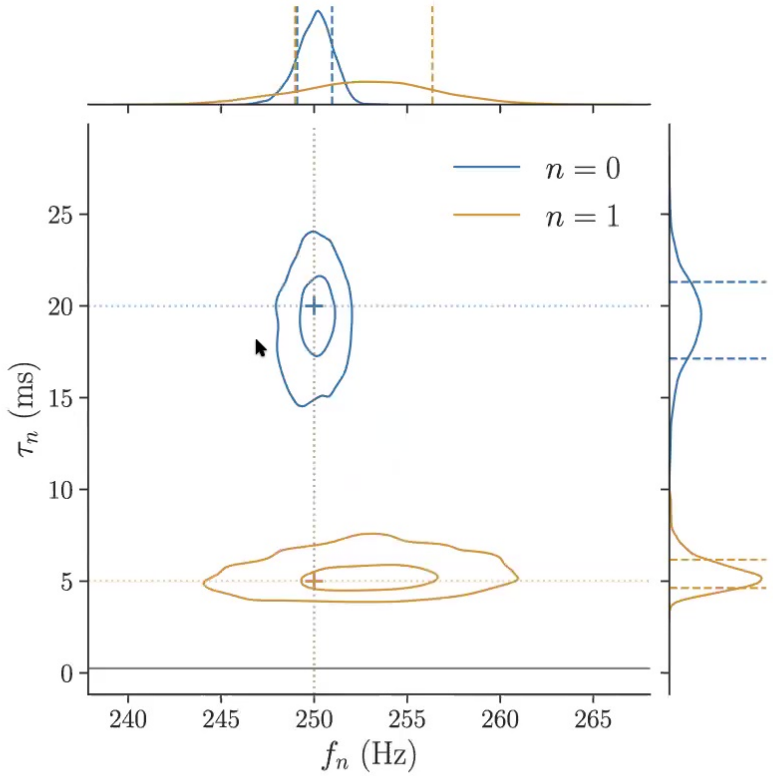

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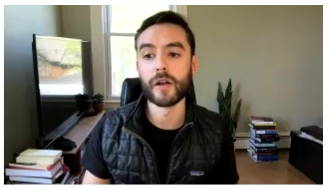

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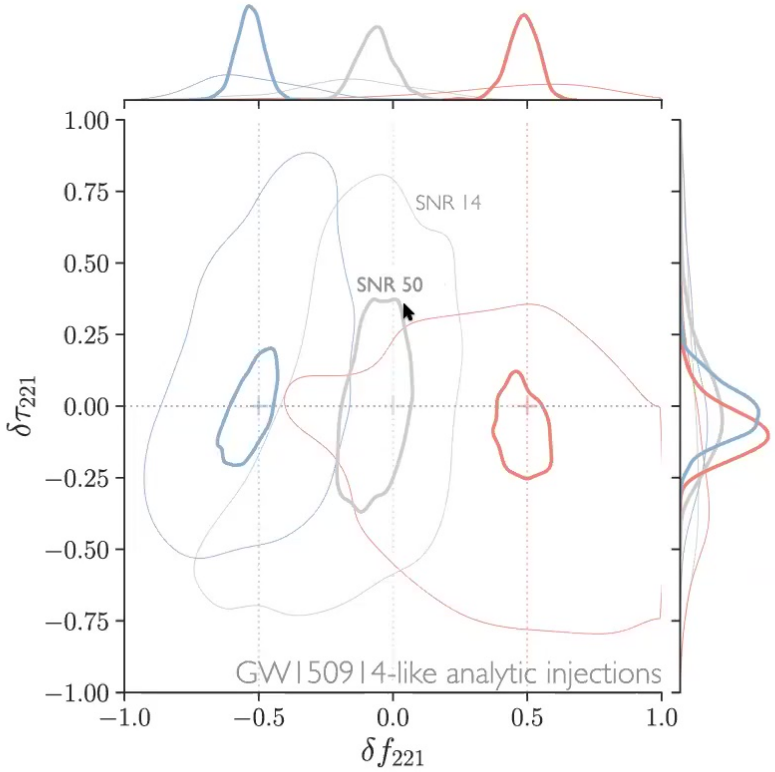

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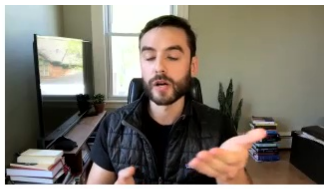

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separating modes in the f-τ plane doesn't imply we measure a **fractional deviation** well

precision in τ_1 ≠ precision in $\delta\tau_1$

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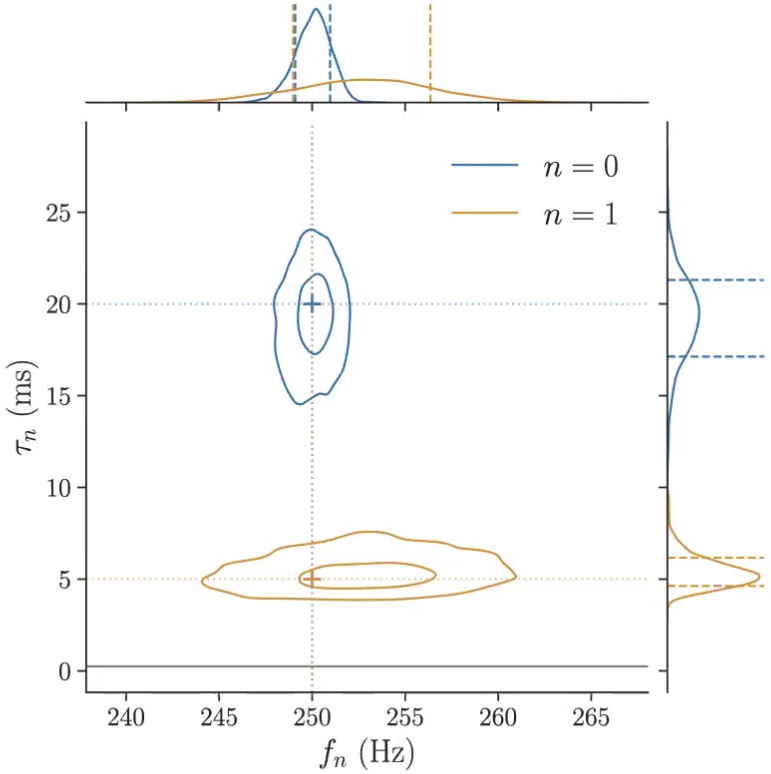
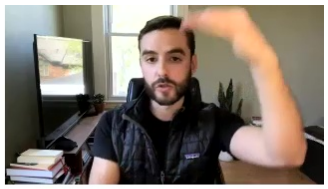


Isi & Farr (in prep.) 51

common questions



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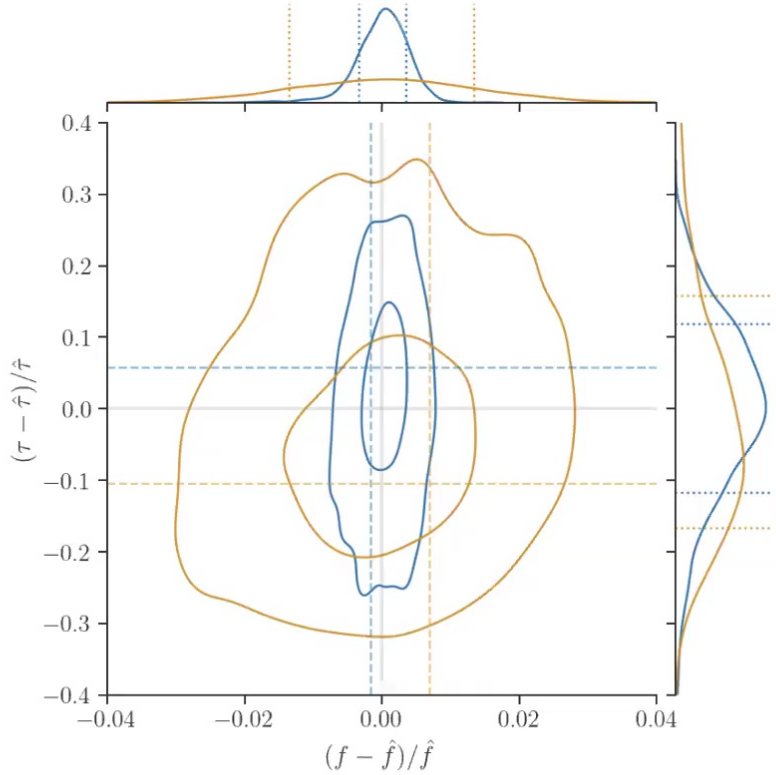

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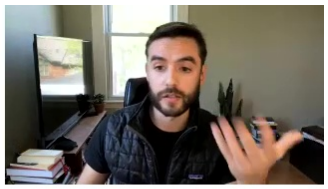

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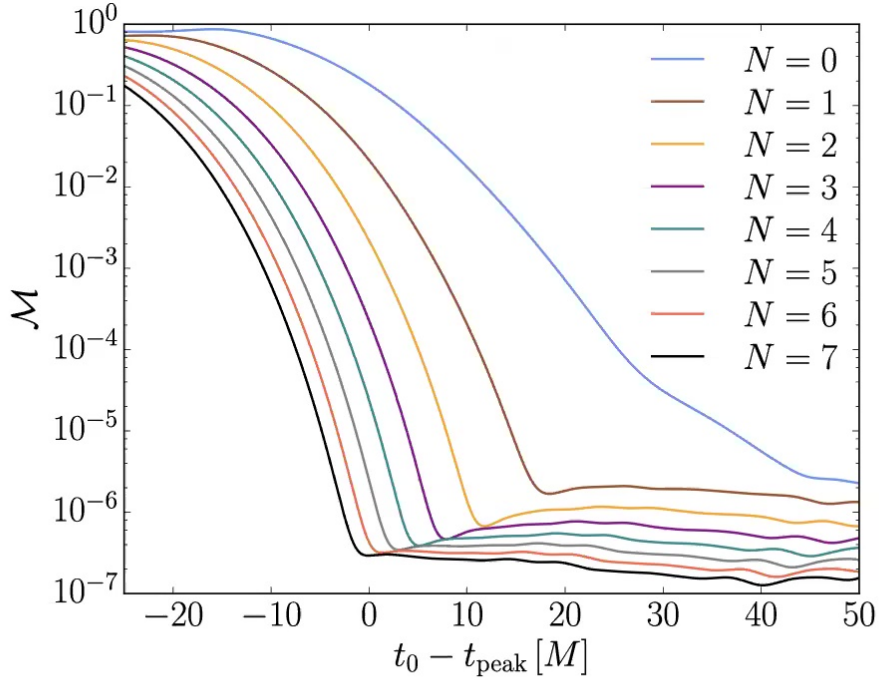

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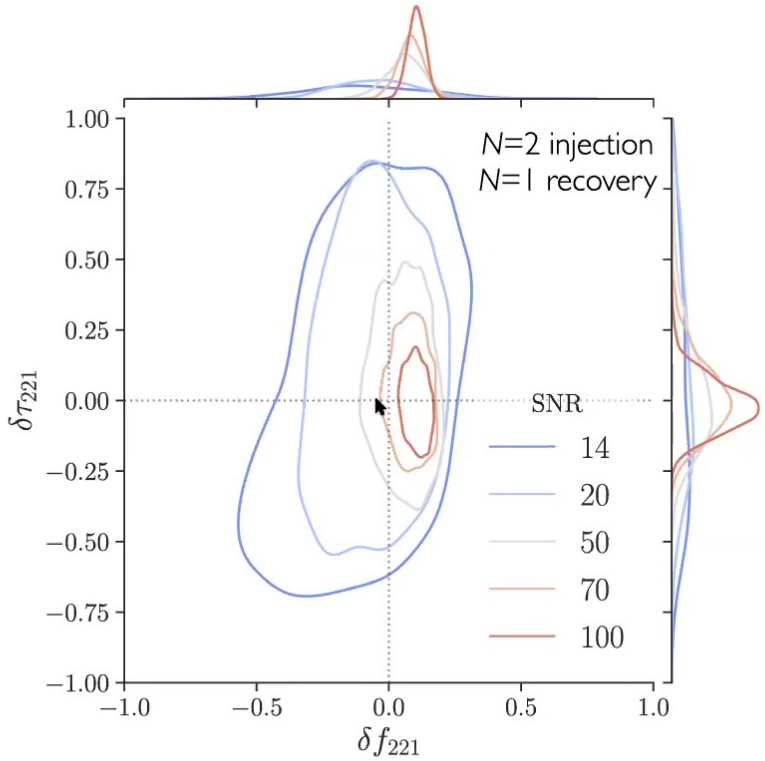
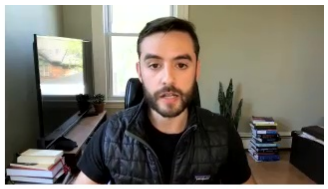


GW150914-like analytic injections Isi & Farr (in prep.)



conclusion

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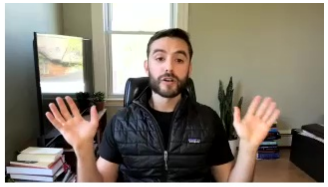
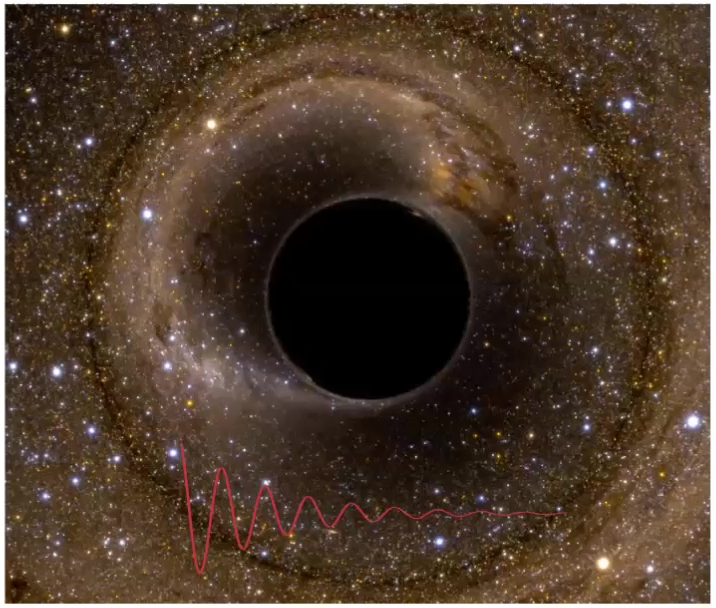


black hole spectroscopy can give us a particularly clean way to learn about strong gravity

recent insights and measurements have **revitalized** this program

many **open questions** and opportunities for **innovation**



exciting time!

this material was based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.