Title: The Astrophysical Promise of Black Hole Ringdowns

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Collection/Series: Strong Gravity

Subject: Strong Gravity

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Abstract:

The remnant of a binary black hole coalescence is a perturbed black hole, which equilibrates by emitting ringdown gravitational waves. These ringdown waves not only encode information in their frequencies about the spacetime structure of the remnant black hole metric, but also have imprints in their amplitudes of the progenitor black hole binary's properties. In this talk I will highlight recent results in black hole ringdown data analysis and new understanding of astrophysical ringdown amplitudes gleaned from numerical relativity simulations, and will then discuss how ringdown analyses may become a vital tool for making inferences of binary black hole properties - even in situations where the gravitational wave signal from the binary inspiral itself is never directly observed.

The Astrophysical Promise of Black Hole Ringdowns

Harrison Siegel

Perimeter Institute Strong Gravity Seminar, Jan 9th 2025

COLUMBIA UNIVERSITY
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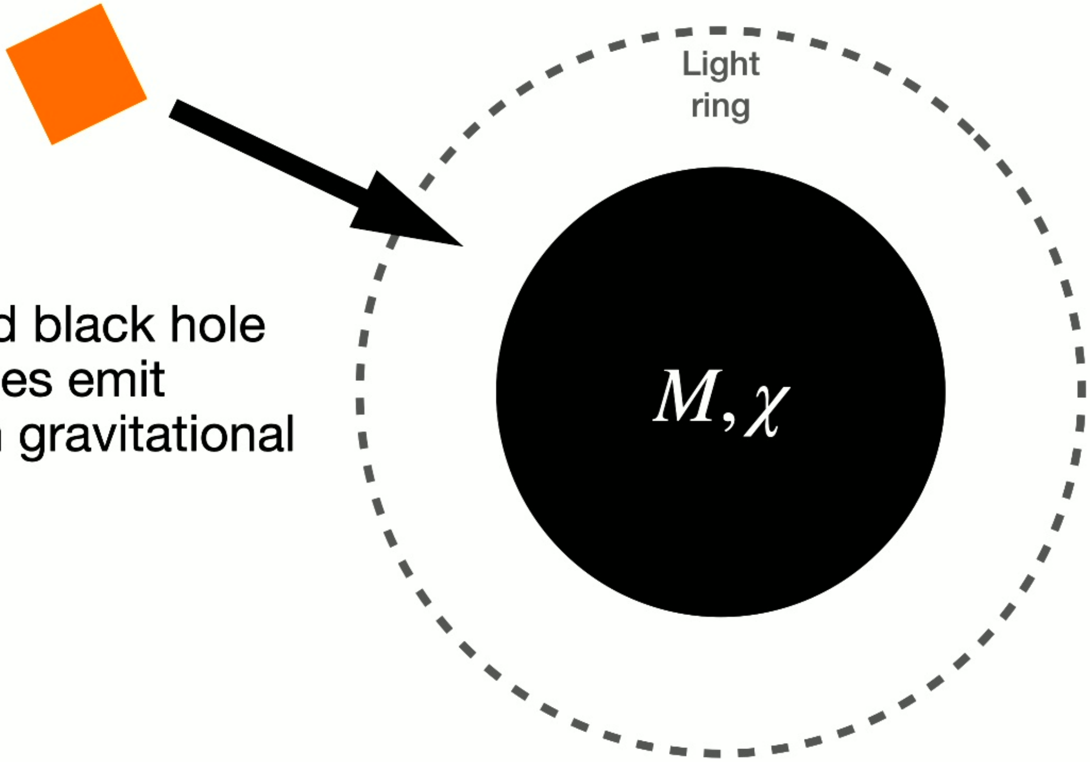
What is black hole ringdown?



Perturbed black hole spacetimes emit ringdown gravitational waves

Ringdown emission has 3 components:

1. Prompt response
2. Quasinormal modes
3. Late-time tails

Quasinormal modes generally dominate astrophysical ringdown

Quasinormal modes (QNMs)

$$h^{\mathrm{QNM}} = \sum_{\boxed{(p,\ell,m,n)\equiv j}} C_j \underbrace{\mathrm{e}^{i\omega_j t-\gamma_j t}}_{\text{Damped sinusoid}} \underbrace{{}_{-2}S_{(\ell,m)}}_{\text{Spin-weighted spheroidal harmonic}}(i\omega_j-\gamma_j,\chi;\iota,\phi)$$

$$C_j = A_j\,\mathrm{e}^{i\phi_j}$$

p: Prograde (+) or retrograde (-)

ℓ, m: Angular indices

n: Overtone index
(n=0 is fundamental mode, n>0 is overtone)

E.g. +220 mode (often *p* is implicitly + and dropped)

Quasinormal modes (QNMs)

$$h^{\mathrm{QNM}} = \sum_{(p,\ell,m,n)\equiv j} \underbrace{C_j\,\mathrm{e}^{i\,[illegible]\,t}}_{\text{Da[illegible] sinusoid}}\;{}_{-2}\underbrace{S_{(\ell,m)}}_{\text{Spin-weighted spheroidal harmonic}}(i\omega_j - \gamma_j, \chi; \iota, \phi)$$

Software Update

Software Update is trying to authenticate user.

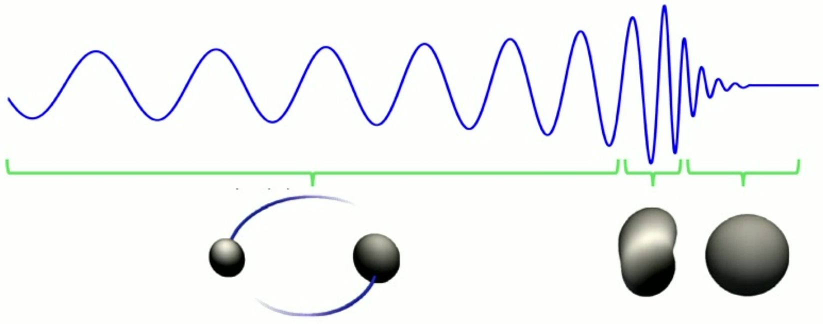
Enter the password for the selected user to allow this.

Richard Fine Man

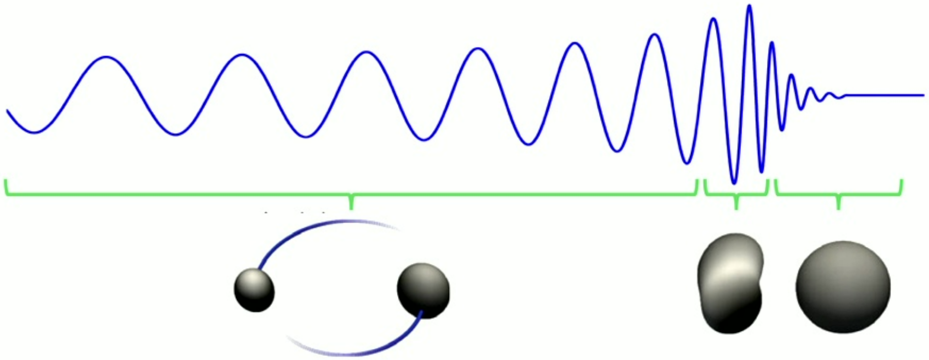
$$C_j = A_j\,\mathrm{e}^{i\phi_j}$$

(ω_j, γ_j) determined by (M, χ) → **Tests of Kerr metric**

C_j determined by initial conditions → **Imprints of binary properties**



Astrophysical QNM amplitudes



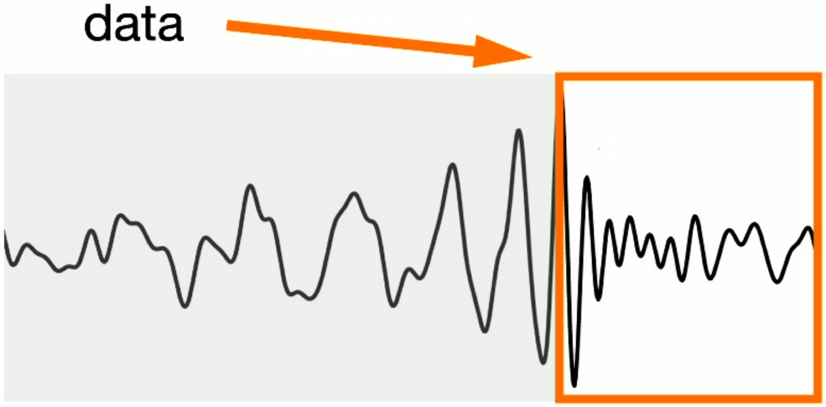
Which QNMs are most excited astrophysically?

Traditionally, ringdown analyses have assumed:

1. **220 dominant**, all other modes subdominant
2. **overtones** near waveform peak
3. **odd m modes** excited by greater binary **mass ratios** and binary **spin differences**

Time domain ringdown analysis

Fit sum of QNMs to data



* GW150914 Hanford strain; whitened, bandpassed

Different from traditional frequency-domain LIGO analyses

Excise ringdown and define likelihood in time domain - technically tricky

$$\ln \mathscr{L}(\mathbf{d}|\mathbf{s}) = -\frac{1}{2}\sum_{p,q=0}^{N-1}(d_p - s_p)C^{-1}_{pq}(d_q - s_q) + \text{const.}$$

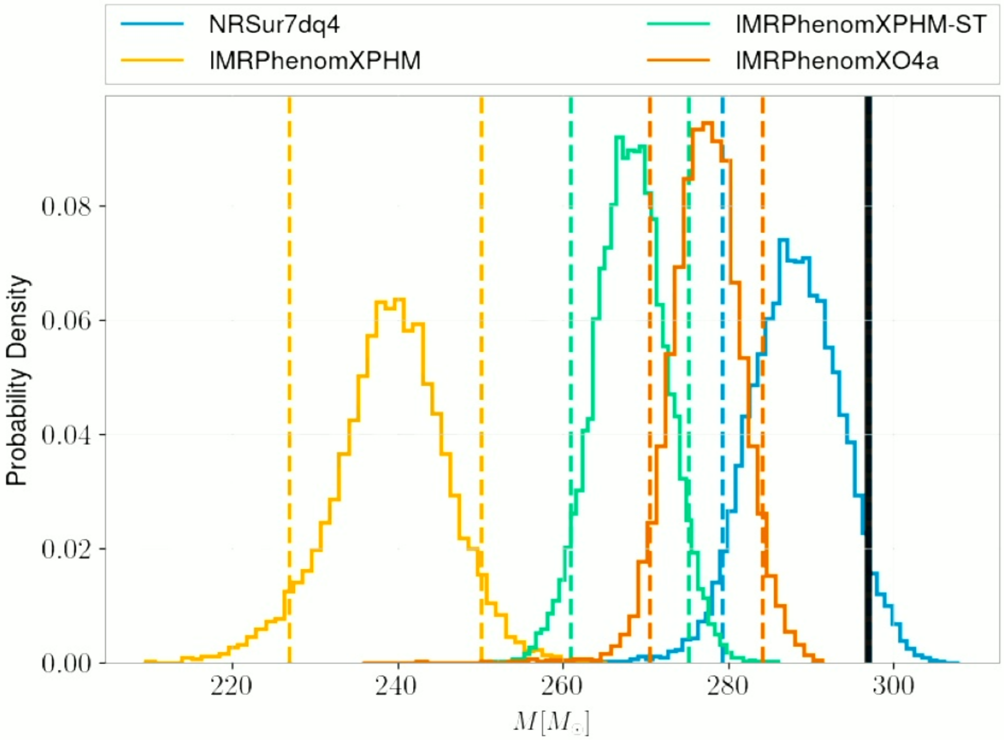
Use acyclic noise covariance matrix C

Signal model s only includes loudest QNMs

To test GR: $\omega_j = \omega_{j_{\mathrm{Kerr}}}\exp(\delta\omega_j),\ \gamma_j = \gamma_{j_{\mathrm{Kerr}}}\exp(\delta\gamma_j)$

See **ringdown** package: https://github.com/maxisi/ringdown

Why not just use IMR waveforms?



Injected: SXS-0623

$q = 0.9$, $\chi_{\mathrm{eff}} = 0.001$, $\chi_p = 0.894$

Figure courtesy of Max Isi, LIGO DCC: G2400889

Heavy precessing systems have large IMR waveform systematics

LVK analyses do not model all dynamics, e.g. eccentricity

Knowledge of astrophysical QNM amplitudes may help to:

1. **Supplement IMR inferences in less well-modeled parameter spaces**

3 takeaways for the rest of talk

1. In ***current LVK data*, **some ringdown signals may be better fit with ***multiple QNMs***

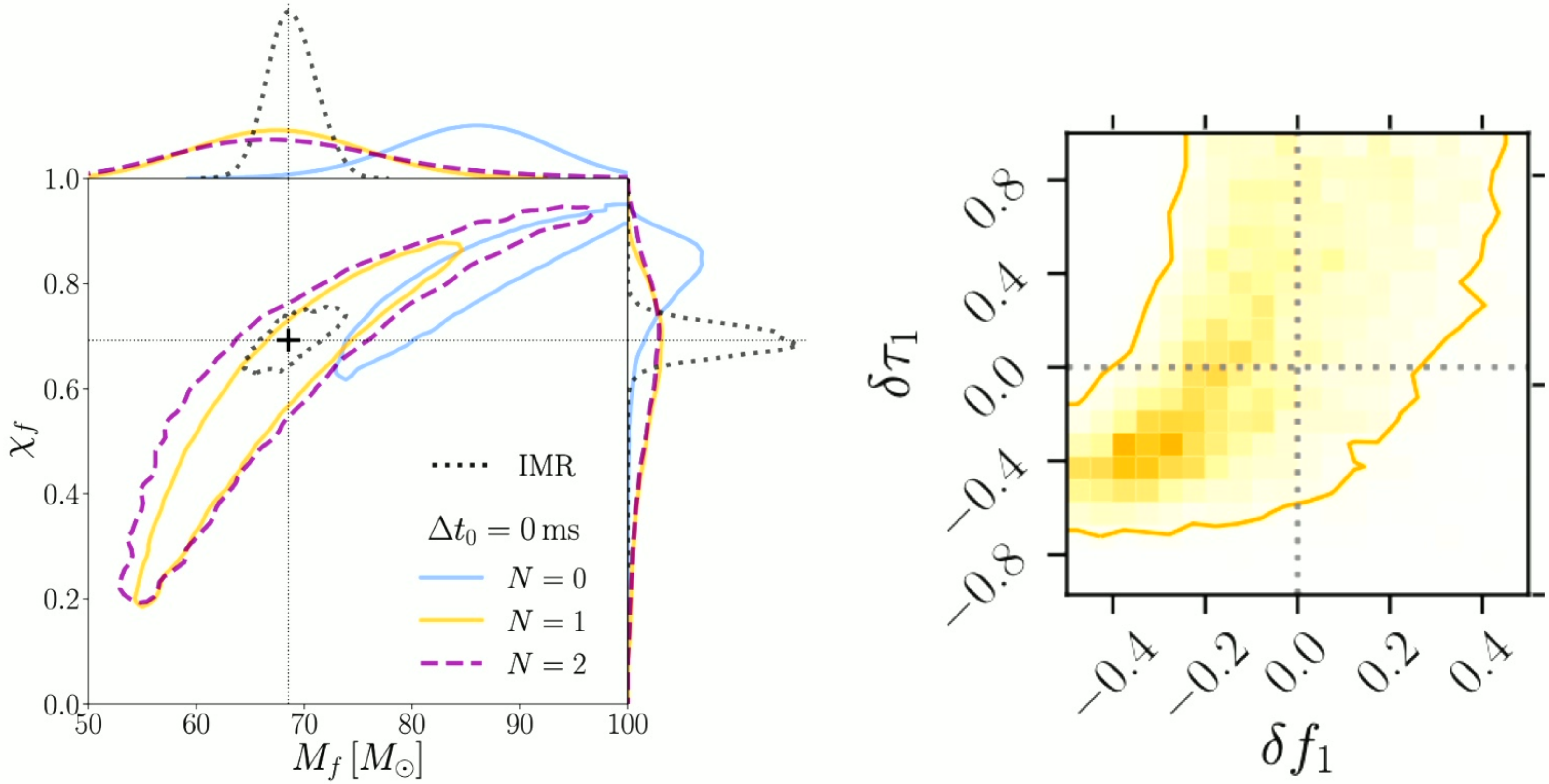
2. Different ***astrophysical systems*** may ***uniquely excite*** different QNMs

3. Using the above, we can not only better ***test GR*** with ringdown but also ***estimate binary parameters***

GW150914 ringdown

GW150914 and overtones

Isi et al. (2019) - we may need to fit **220** and **221** QNMs in GW150914



Isi et al., Phys. Rev. Lett. 123, 111102, (2019)

3 takeaways

1. In ***current LVK data*****,** some ringdown signals may be better fit with ***multiple QNMs***

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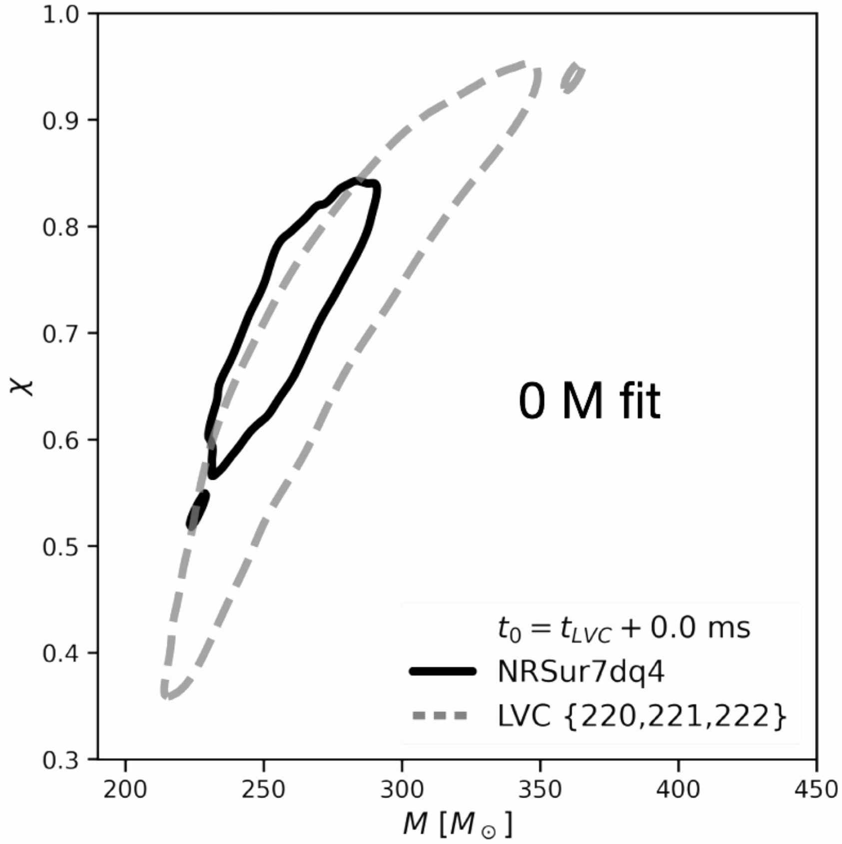
GW190521 ringdown

LVC analysis

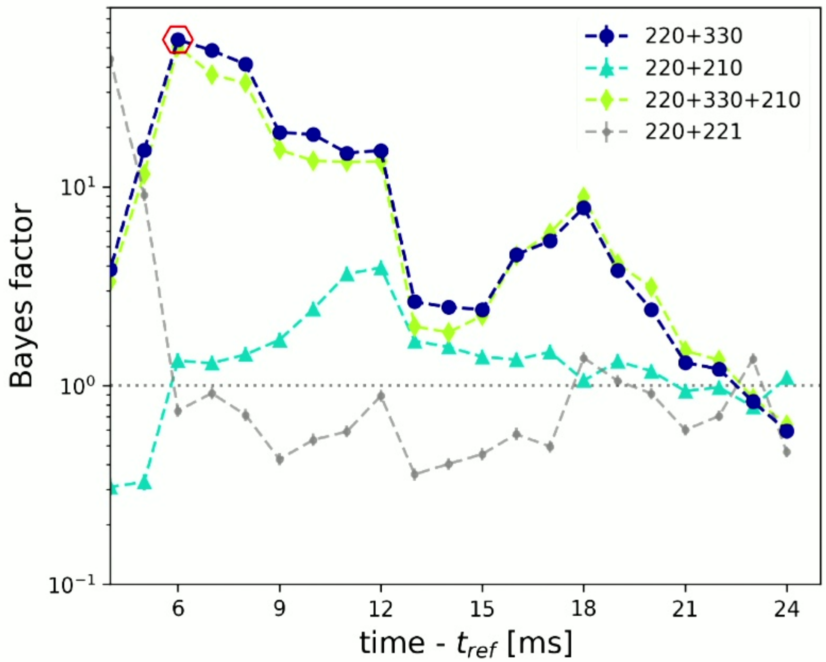
We should try to fit overtones again, right?

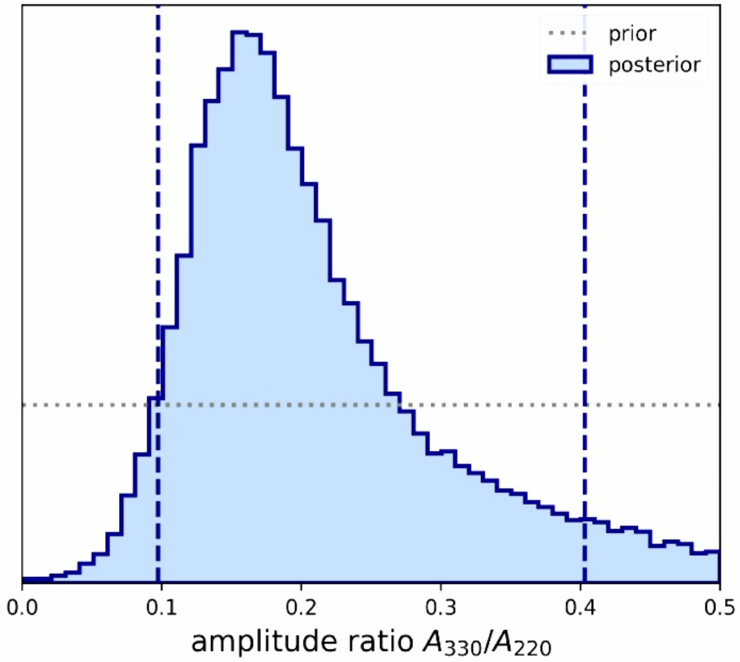


R. Abbott et al 2020 ApJL 900 L13

Capano et al. analysis

Capano et al. claim observation of **330** QNM in GW190521 - not overtones!

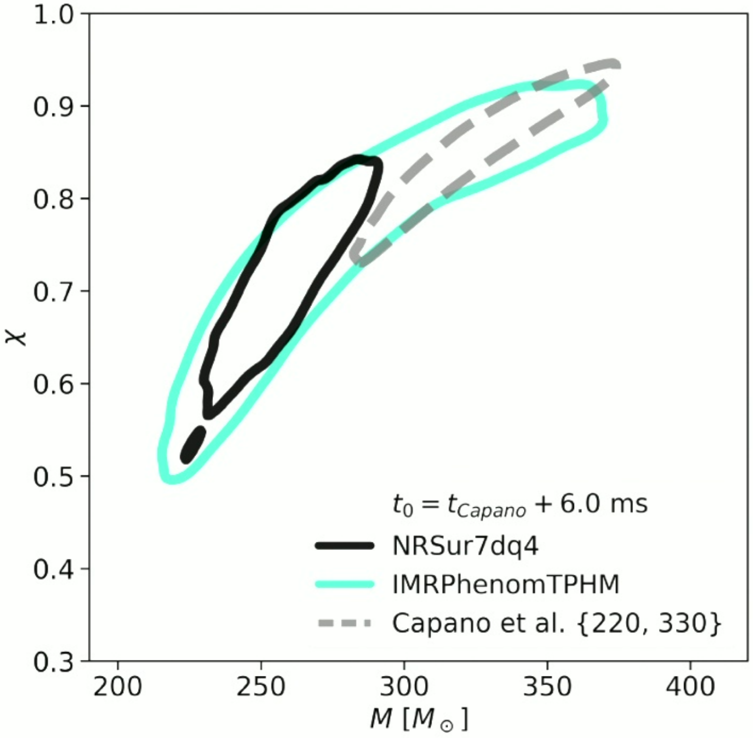


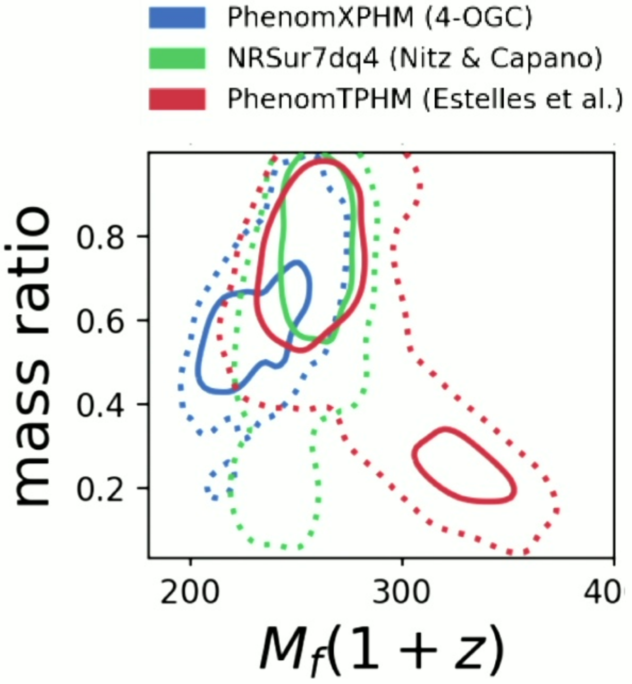


Capano et al., Phys. Rev. Lett. 131, 221402 (2023)

Capano et al. vs IMR

Compared to IMR models for GW190521, *Capano et al.* 330 QNM model needs 1) higher remnant mass and spin, and 2) greater binary mass ratio

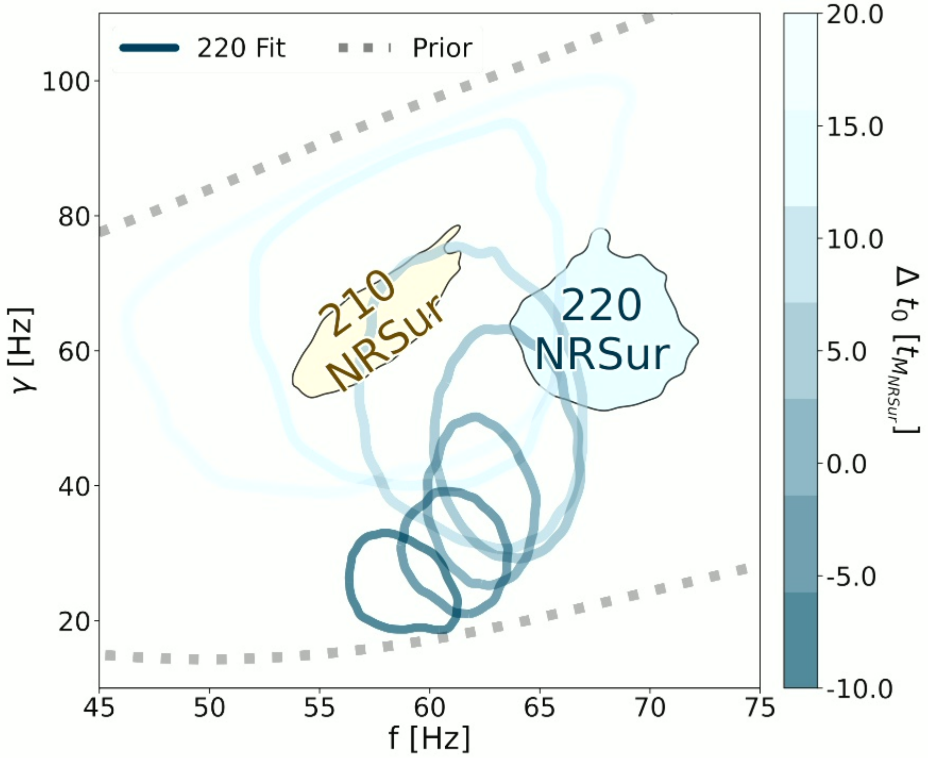




Capano et al., arXiv:2209.00640v3, (2022)

Reproducing LVC result

First we attempt to reproduce the LVC single-mode analysis for GW190521



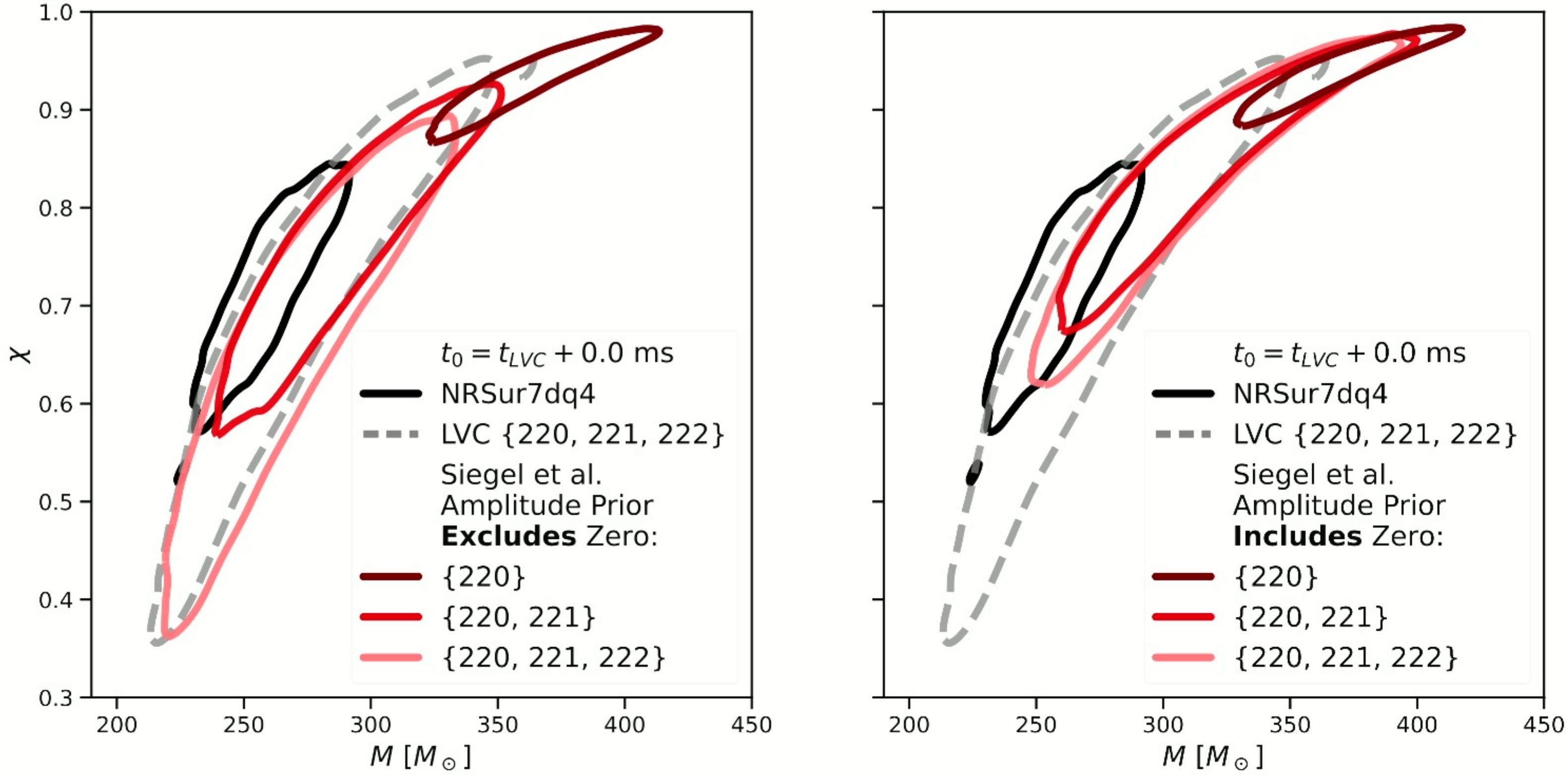
220 alone does not fully agree at any time with IMR

Multiple modes needed?

Siegel et al., Phys. Rev. D 108, 064008, (2023)

Reproducing LVC result

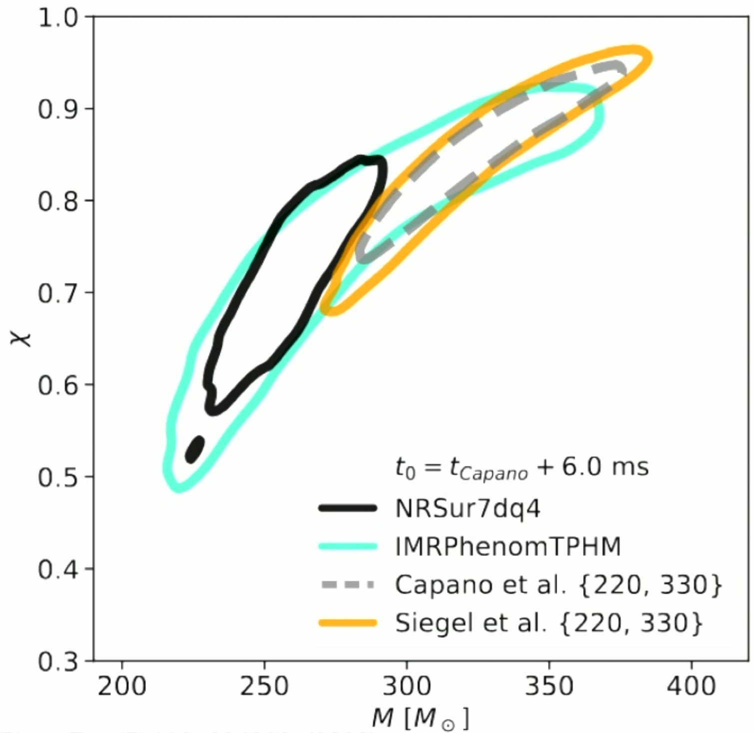
Overtones don't help early time agreement here: dependent on amplitude priors

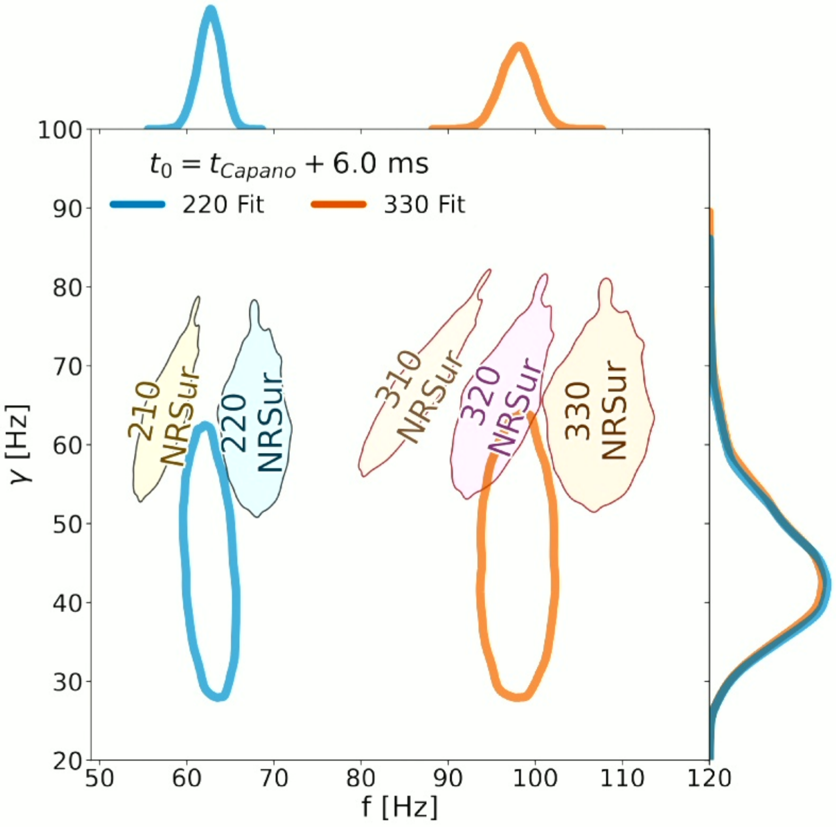


Siegel et al., Phys. Rev. D 108, 064008, (2023)

Reproducing Capano et al. result

We fully reproduce Capano et al. - hints for more NRSur-consistent QNM fits?





Siegel et al., Phys. Rev. D 108, 064008, (2023)

Do any GW190521 QNM fits agree with IMR?

GW190521 remnant is heavy (~ 250 $M_\odot$) → larger IMR model systematics

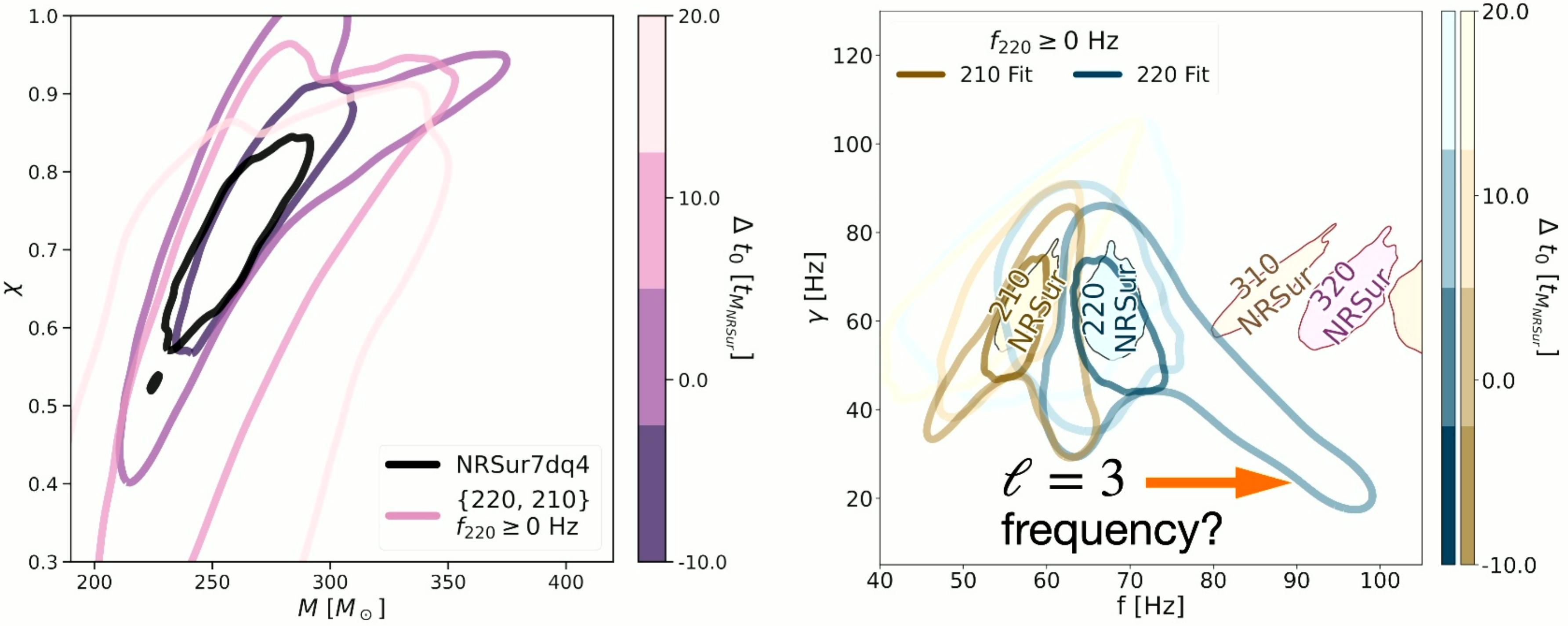
Many alternative explanations for GW190521 have been proposed:

- Eccentric BBH (*Romero-Shaw et al.*, *Gayathri et al.*)
- Dynamically-captured non-spinning BBH (*Gamba et al.*)
- Proca-star head-on collision (*Calderon-Bustillo et al.)*

If the best QNM fits disagree with quasicircular precessing BBH hypothesis, maybe exotic alternatives actually are preferable…

210 + 220 = consistent with IMR!

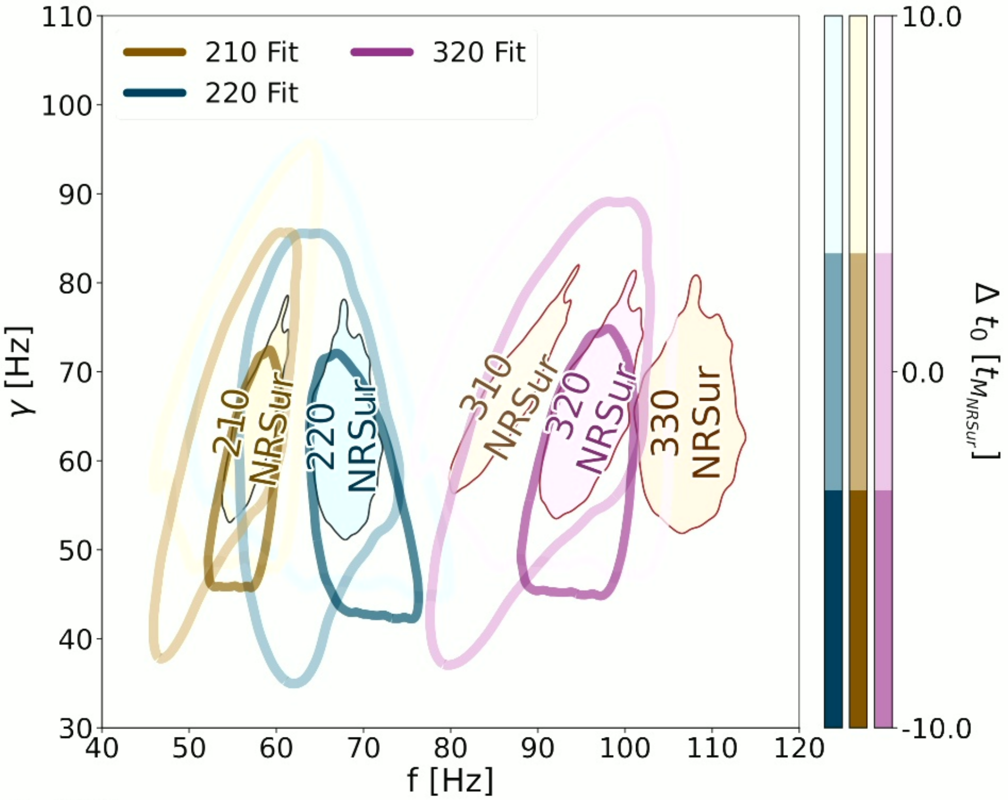
We find that IMR consistency can be achieved, with **220** and **210** QNMs



Siegel et al., Phys. Rev. D 108, 064008, (2023)

210 + 220 + 320 = consistent with IMR!

We find some support for **320** QNM being IMR consistent, not 330

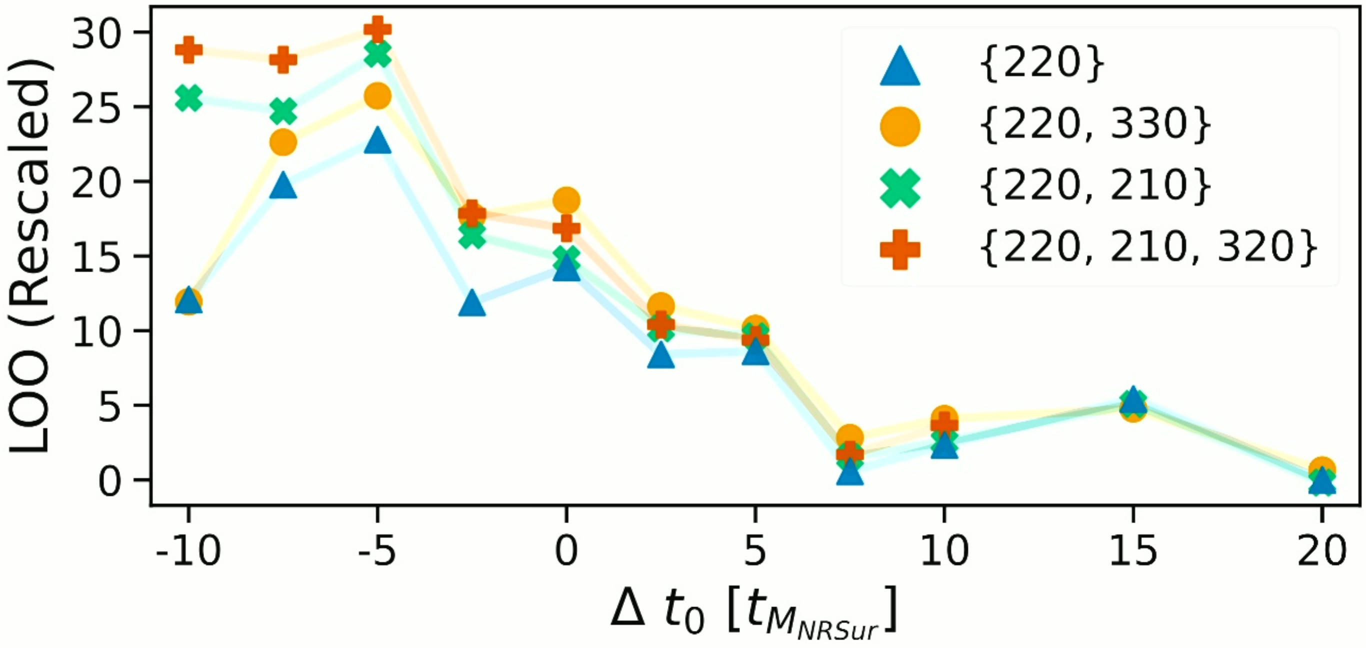


Siegel et al., Phys. Rev. D 108, 064008, (2023)

Goodness of fit

No strong statistical preference for specific QNMs, but **multi-mode fits favored**

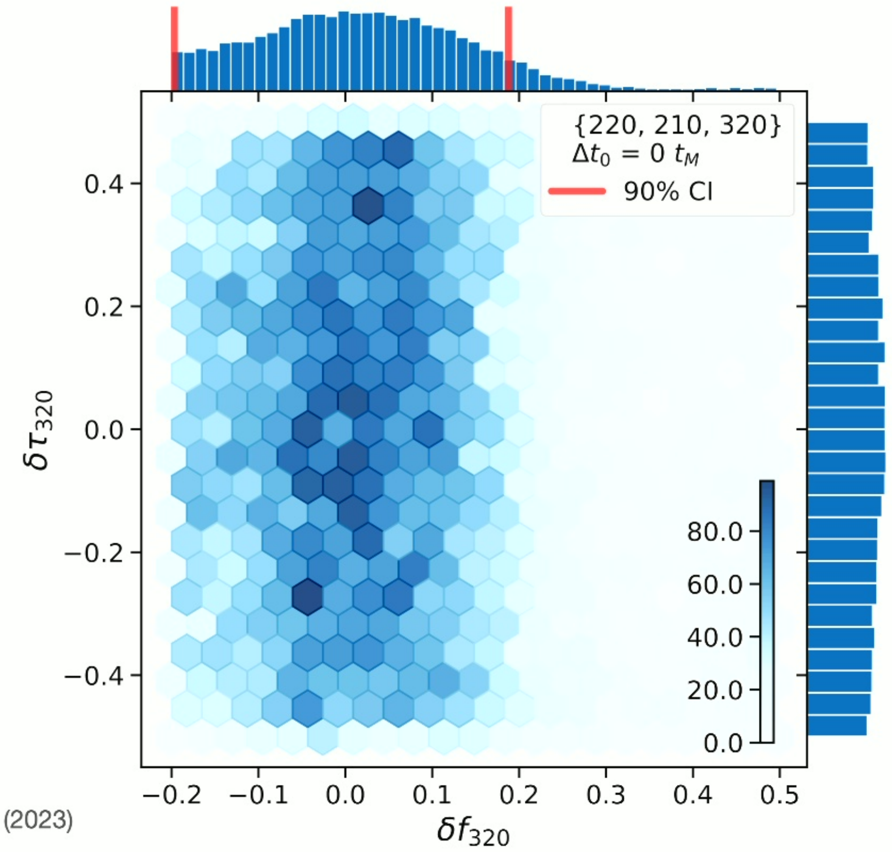
Stronger preferences at early times…



Siegel et al., Phys. Rev. D 108, 064008, (2023)

TGR

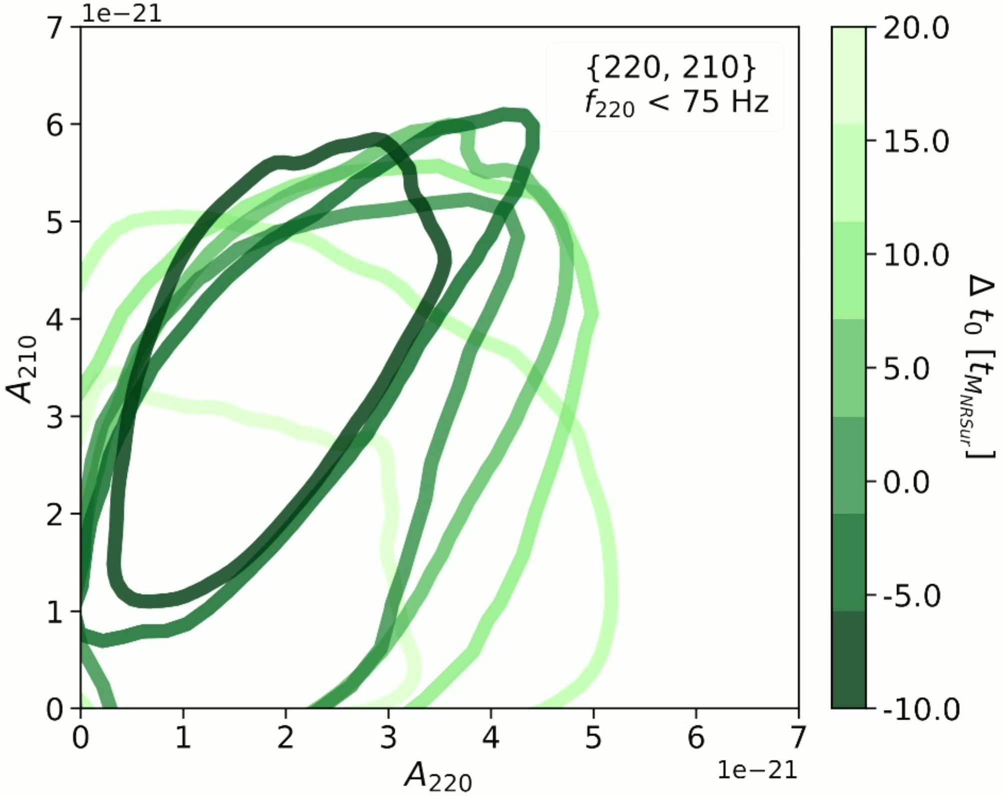
Tests of GR with 210 + 220 + 320 confirm Kerr frequencies at 10-20% level



Siegel et al., Phys. Rev. D 108, 064008, (2023)

Loud 210?

210 amplitude is unexpectedly large…



Siegel et al., Phys. Rev. D 108, 064008, (2023)

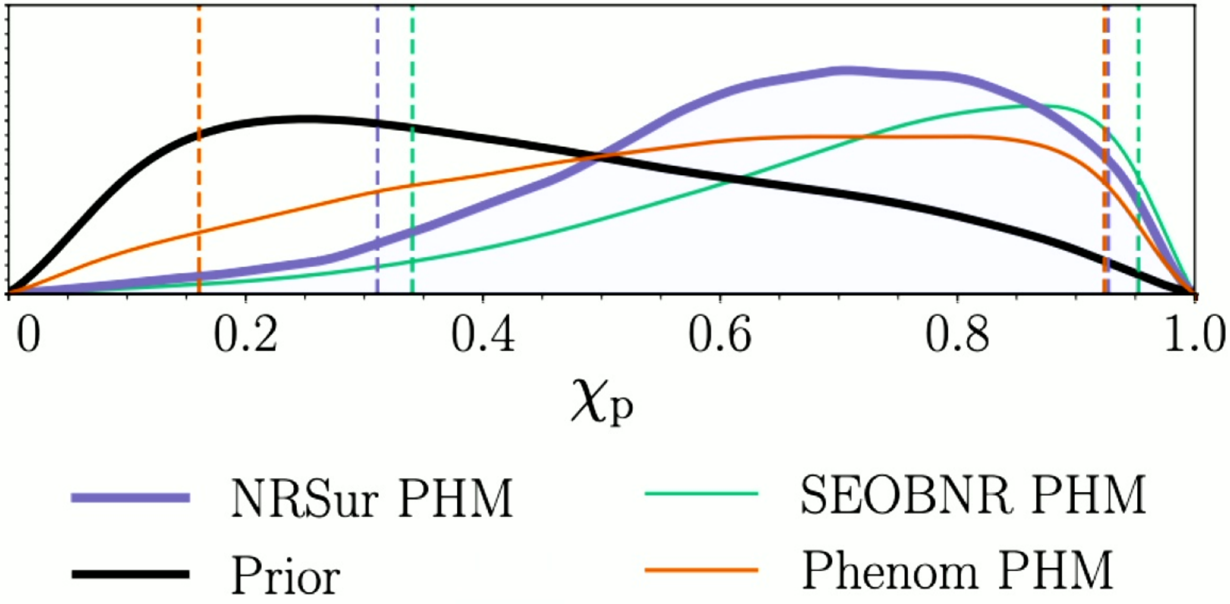
Loud 210?

Mass ratio of IMR is close to 1…

R. Abbott et al 2020 ApJL 900 L13

Loud 210?

Mass ratio of IMR is close to 1… but could precession excite large A_{210}?



R. Abbott et al 2020 ApJL 900 L13

3 takeaways

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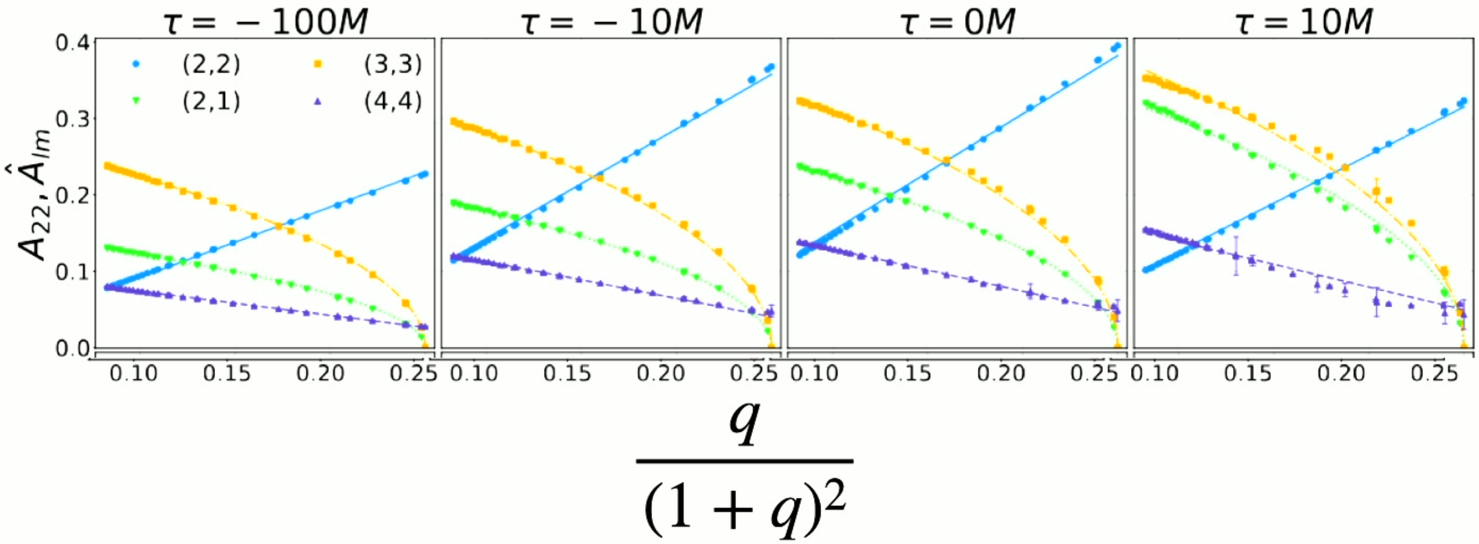
Precession and ringdown

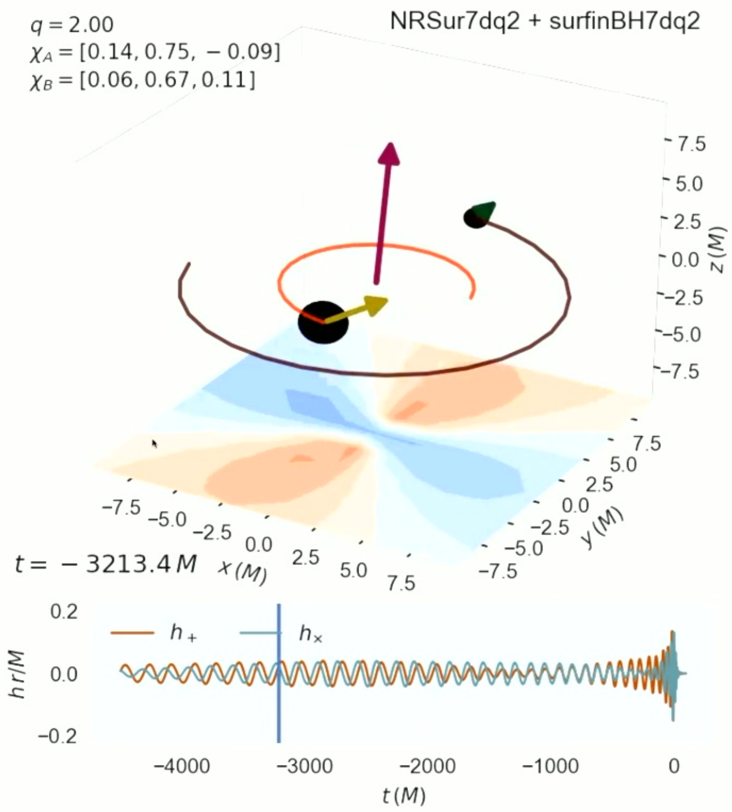
Mapping binary properties to QNM amplitudes

Hints of a direct and simple mapping between pre- and post-merger emission (for dominant ringdown emission of non-spinning and spin-aligned systems)



Borhanian *et al.*, Class.Quant.Grav. 37 (2020) 6, *065006*

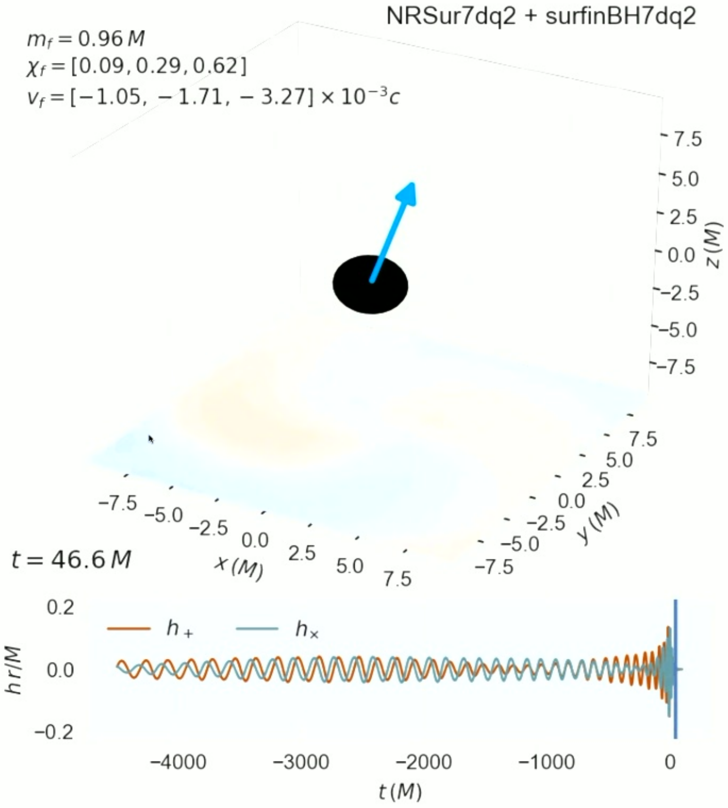
Precession and the co-orbital inspiral frame



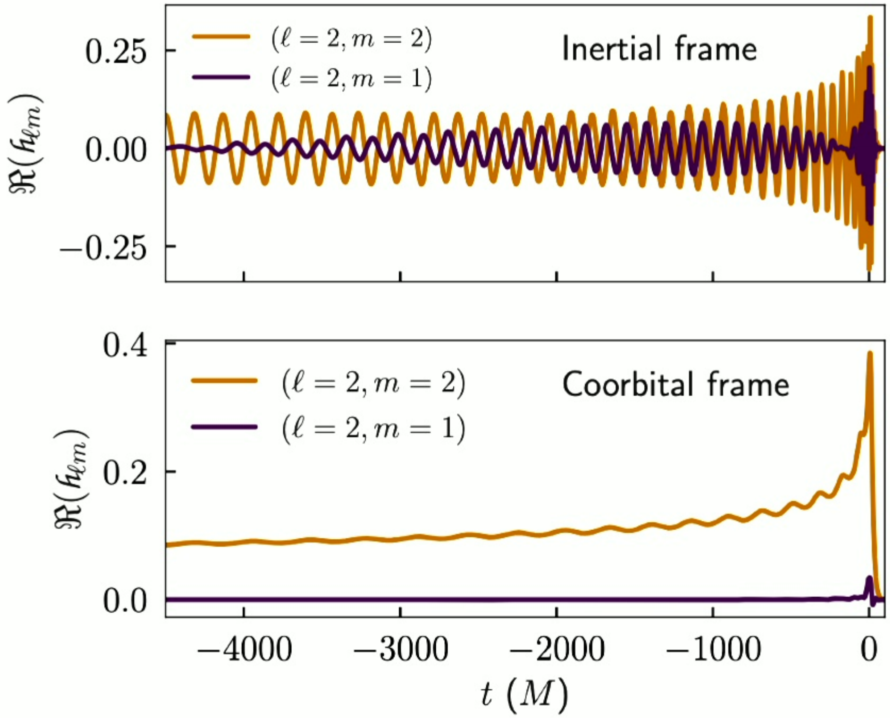
Varma et al., CQG 36 (2019) 9, 095007

Varma et al., PRR 1 (2019) 033015

Precession and the co-orbital inspiral frame



Varma et al., CQG 36 (2019) 9, 095007

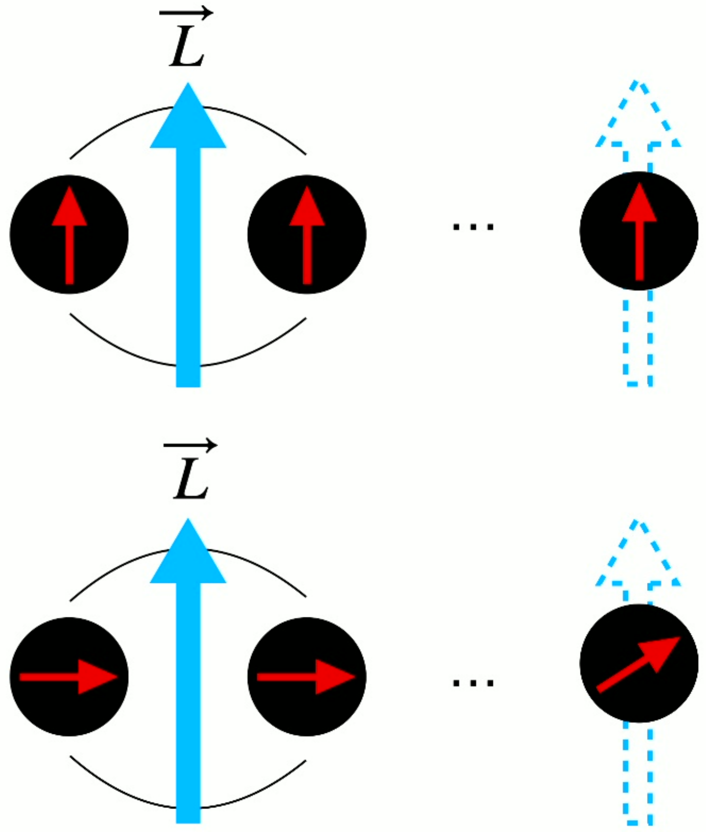


Varma et al., PRR 1 (2019) 033015

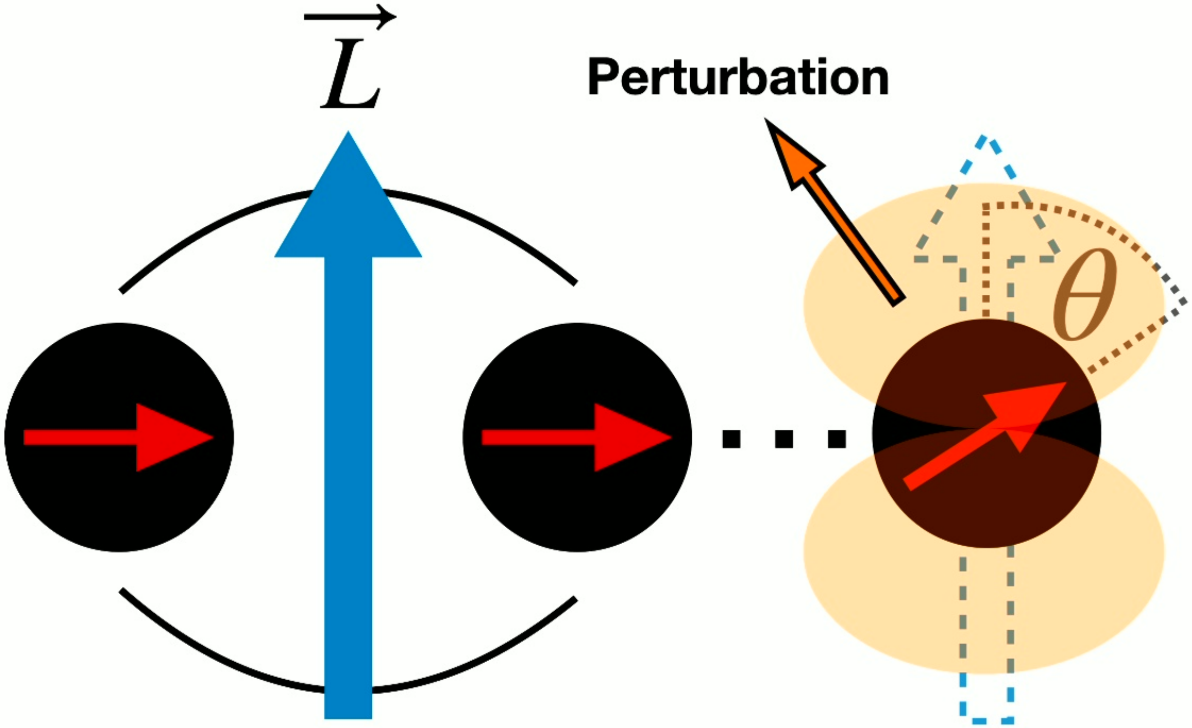
Precessing binaries, remnant orientations

Non-precessing

Precessing



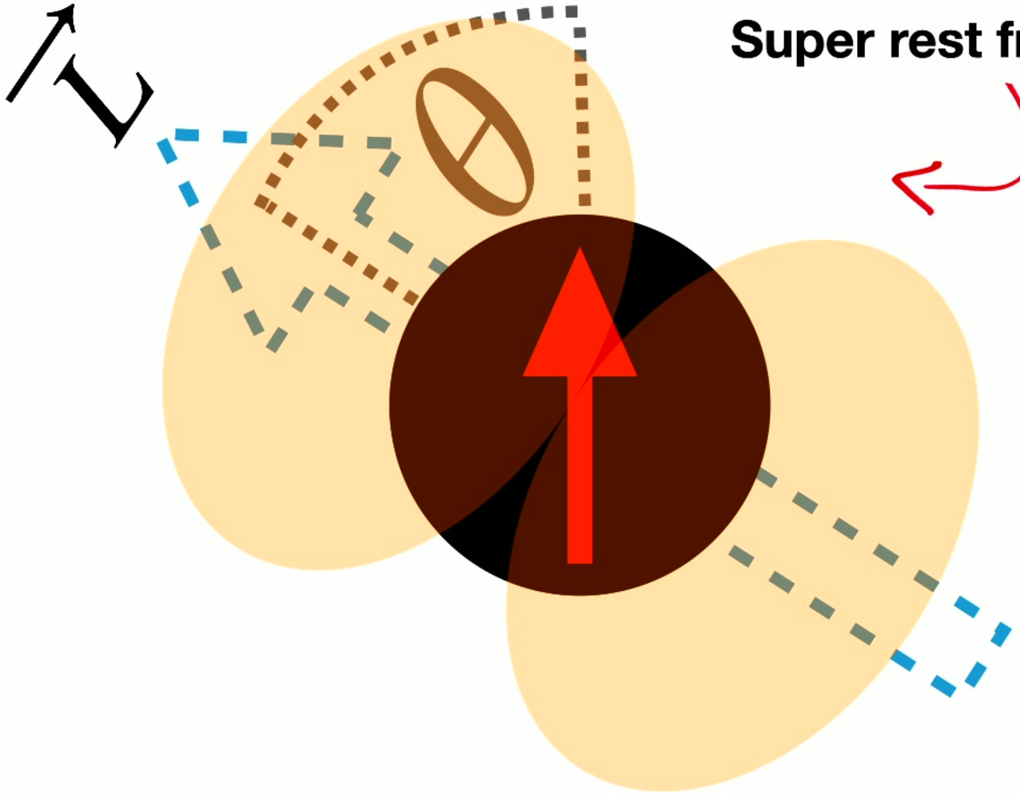
Precession and ringdown



Assume perturbation of remnant is mostly $(\ell, m) = (2,2)$ *in inspiral co-orbital frame*

Zhu, Siegel, Mitman, et al. [arXiv:2312.08588], (2023)

Precession and ringdown



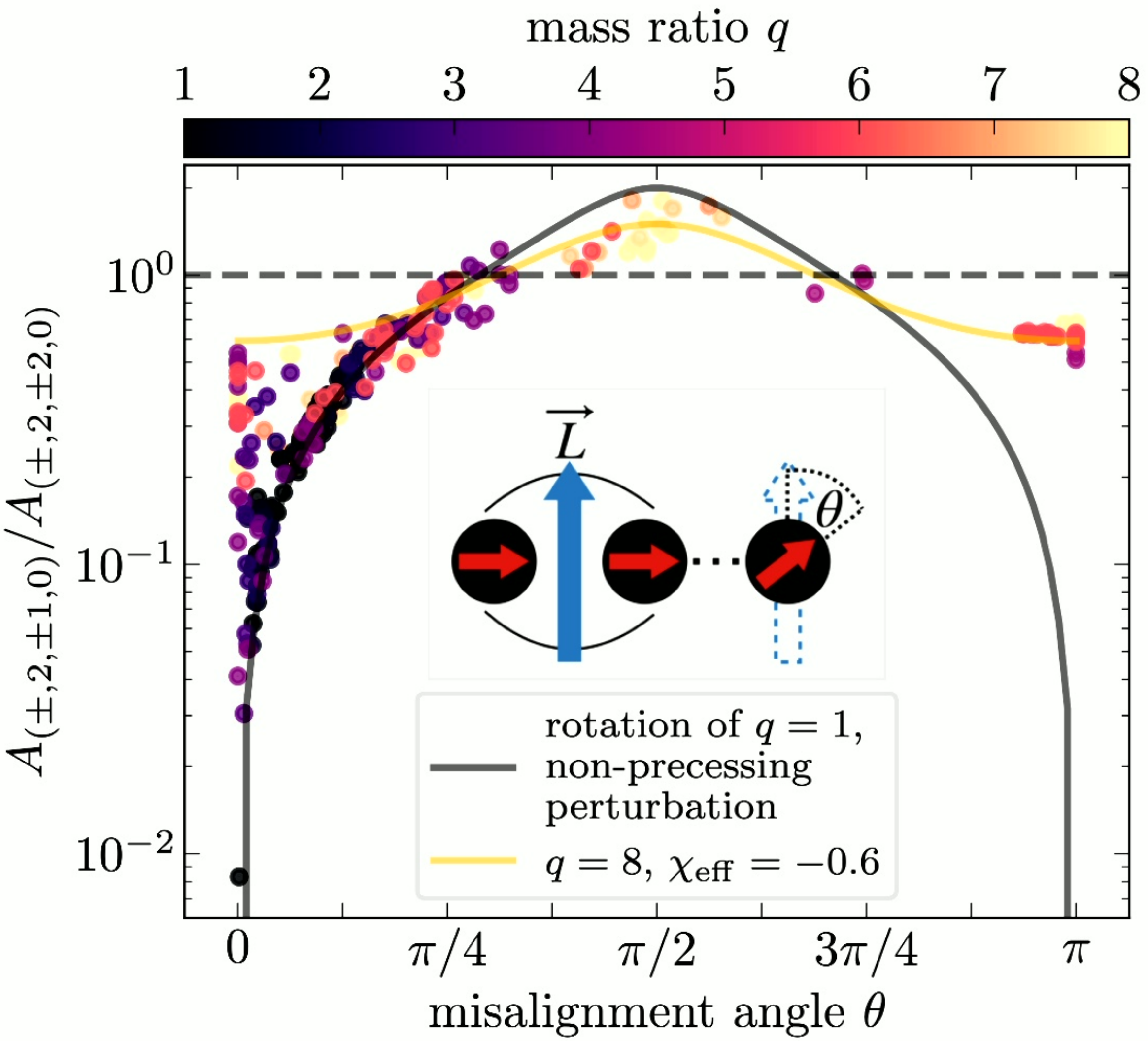
Super rest frame

Perturbation is rotated w.r.t. remnant spin

Perturbation's angular content mixes into:

1. $\ell \neq m$
2. **retrograde**

Zhu, Siegel, Mitman, et al. [arXiv:2312.08588], (2023)



NR simulations

(ℓ,m) = (2,±2) prograde QNMs ***not always dominant***

$\ell\neq m$ and retrograde ℓ=2 QNMs can be dominant

Zhu, Siegel, Mitman, et al. [arXiv:2312.08588], (2023)

3 takeaways

1. In ***current LVK data*,** some ringdown signals may be better fit with ***multiple QNMs***
2. Different ***astrophysical systems*** may ***uniquely excite*** different QNMs
3. Using the above, we can not only better ***test GR*** with ringdown but also ***estimate binary parameters***

The future (in my opinion)

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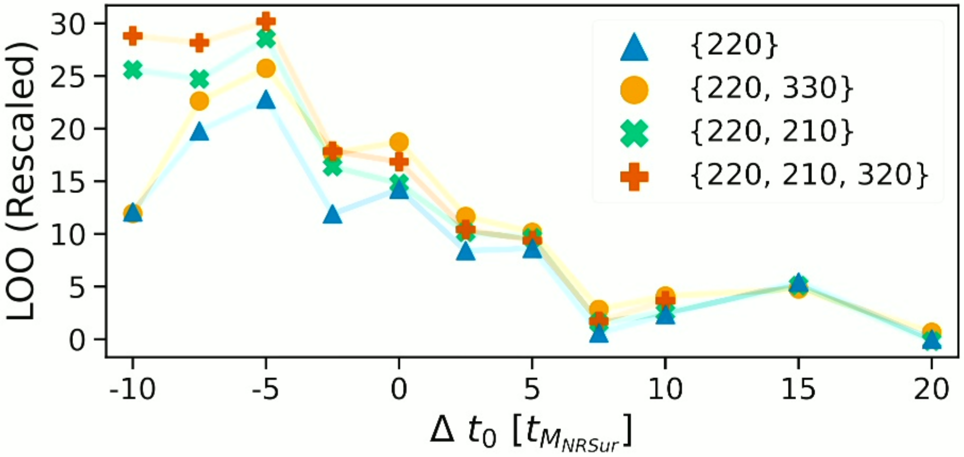
The future of LVK data analysis:

Physically motivated QNM amplitude and phase priors to:

1) break degeneracies in posteriors

2) better measure binary parameters

NR surrogate QNM models promising



Siegel et al., Phys. Rev. D 108, 064008, (2023)

The future (in my opinion)

The future of ringdown modeling:

Understanding overtone excitations, e.g. do overtone amplitudes always follow the excitation factors in astrophysical systems?

$$C_{lmn} = E_{lmn} T_{lmn}$$

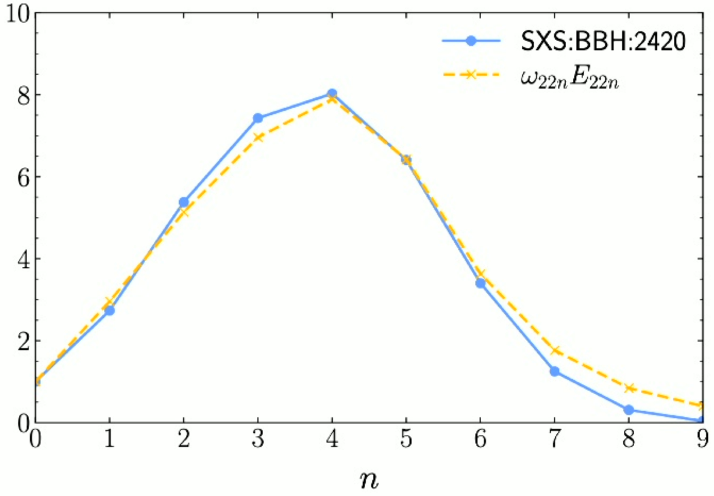


FIG. 12. The $(2, 2, n)$ NR amplitudes as measured in the moderate-spin case of SXS:BBH:2420 and the excitation factors $\omega_{22n} E_{22n}$ for $\chi = 0.75$. The excitation factors are computed using $t_0 = 2.5$ and both curves are normalized such that $C_{220} = \omega_{220} E_{220} = 1$.

Giesler et al., [arxiv:2411.11269], (2024)

Thanks for listening!
Happy to take questions

Harrison Siegel

Perimeter Institute Strong Gravity Seminar, Jan 9th 2025

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