Title: Quasinormal modes and non-linear behaviour

Speakers: Taillte May

Collection/Series: 50 Years of Horndeski Gravity: Exploring Modified Gravity

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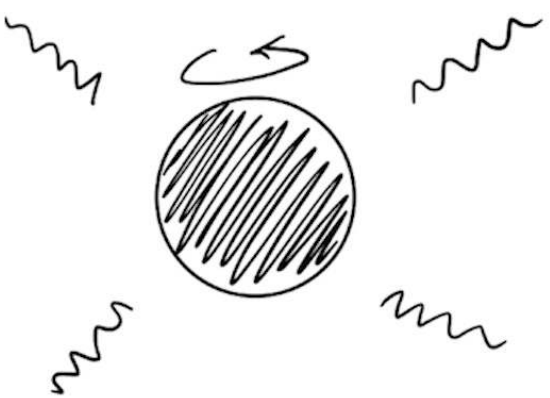
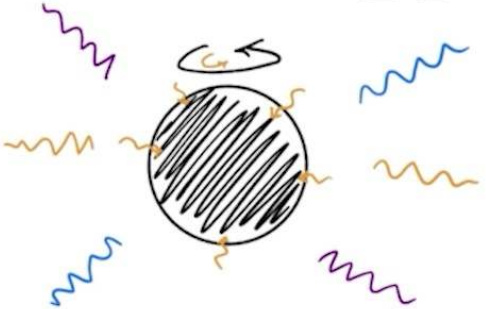
Abstract:

Gravitational waves from black hole binary mergers can tell us a lot about the physics of the system. At the late part of the graviational wave signal, GR predicts the presence of characteristic frequencies (called quasinormal modes) in the signal. Measuring multiple quasinormal modes is a strong consistency test for GR.

Here we probe the regime where a signal can be described entirely by quasinormal modes. We consider a higher order effect, where the remnant black hole is absorbing some radiation and so has a changing mass and spin. We test the contribution of this effect to the signal in a physically relevant scenario. We find evidence that this effect causes other mode excitations as well as a changing frequency contribution.





PERIMETER INSTITUTE

Non-Linear Contributions to Ringdown

Taillte May, Sizheng Ma, Justin Ripley, William East

arXiv:2405.18303

How does this third order effect in ringdown change a linearised mode fit?

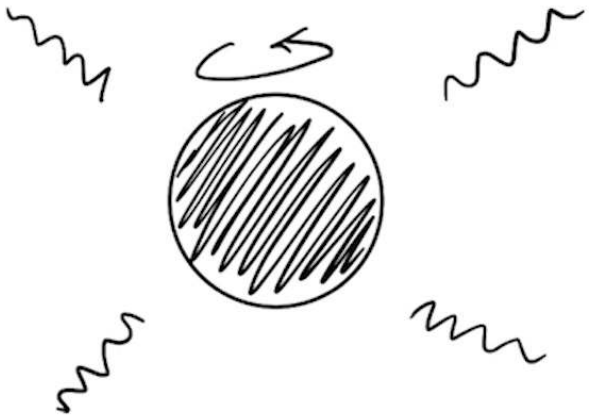
Single linear mode

220 pure

$220 + 220_R + \ldots$

Multiple linear modes
+ more?

Linearised Perturbation – Quasi-Normal-Modes



$$T(M,a,s)\psi^{(1)} = 0$$

$$\mathcal{A} \times e^{im\varphi - i\omega v} R(r)\, S(\vartheta)$$

$$\omega_{\ell mn}$$

[Teukolsky, 1973]

$$\omega_{\ell mn}(a, M) \in \mathbb{C}$$

Measure single complex frequency (e.g. 220)

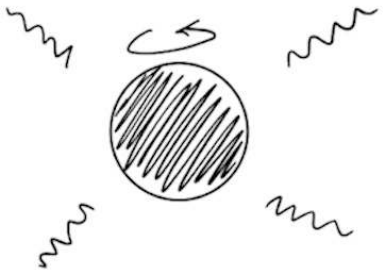
$$\Re\left(\omega_{220}\right) + \Im\left(\omega_{220}\right) \overset{GR}{\rightarrow} M, a \overset{GR}{\rightarrow} \omega_{\ell mn}(a, M)$$

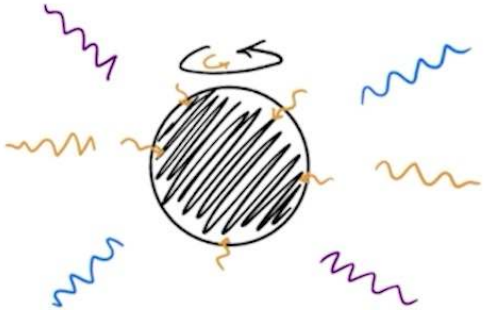
Also measure third frequency component (e.g. real part 221)

$$\Re\left(\omega_{221}\right) \overset{?}{=} \Re\left(\omega_{221}(a, M)\right)$$

[E. Berti et al. 2018, V. Cardoso & P. Pani 2019, O. Dreyer et al. 2003]

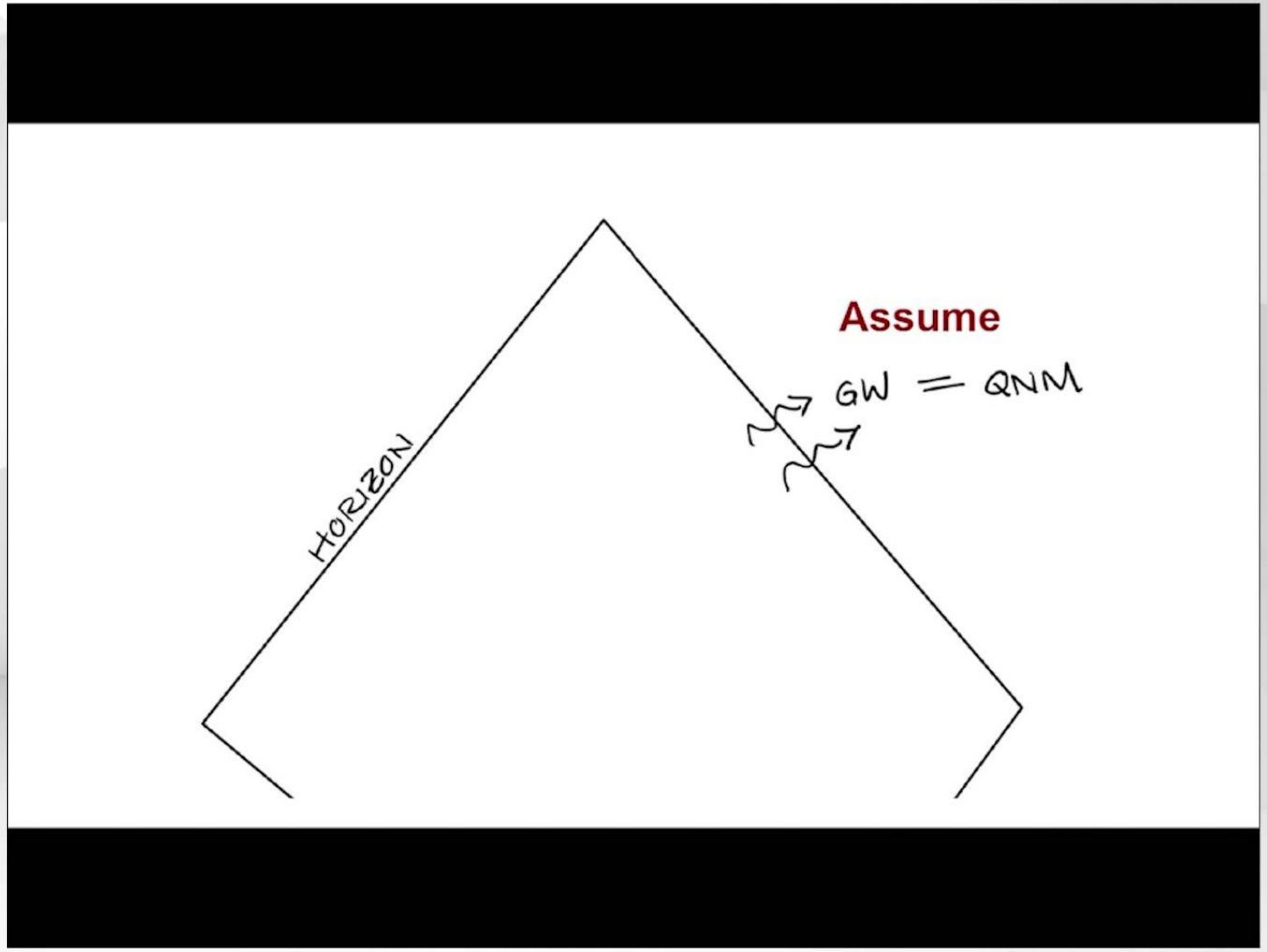
Ringdown
~ Linearised perturbations on Kerr?

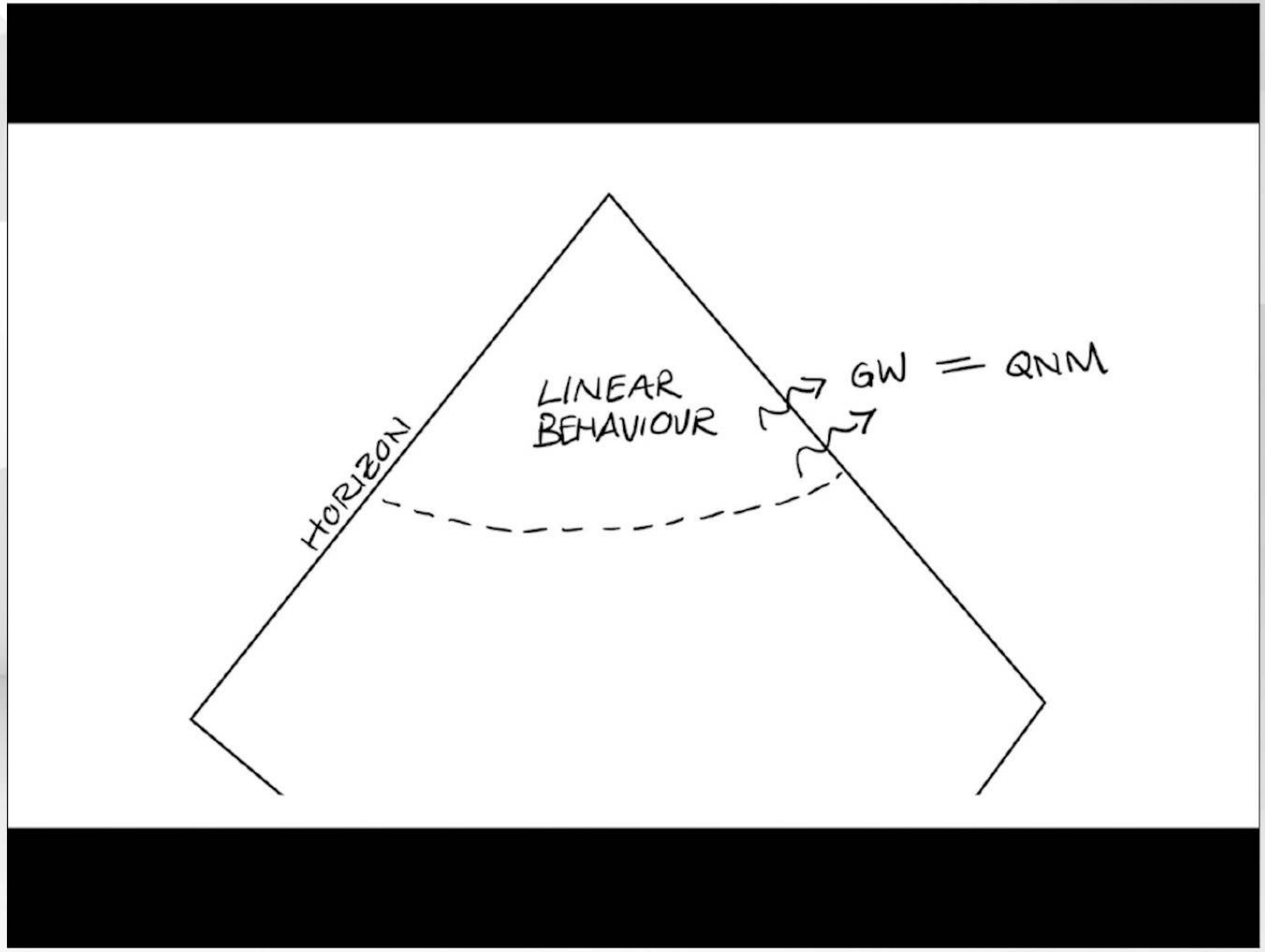




Want to quantify non-linear effects

[M. Cheung et al 2023, K. Mitman et al 2023, S. Ma et al 2022, M. Cheung et al 2024, H. Nakano et al 2007, J. Redondo-Yuste et al. 2023, H. Zhu et al. 2024, S. Ma & H. Yang 2024, B. Bucciotti et al. 2024, P. Bourg et al. 2024, L. Sberna et al. 2022, J. Redondo-Yuste et al. 2024, H. Zhu et al. 2024]


Assume
GW = QNM
HORIZON

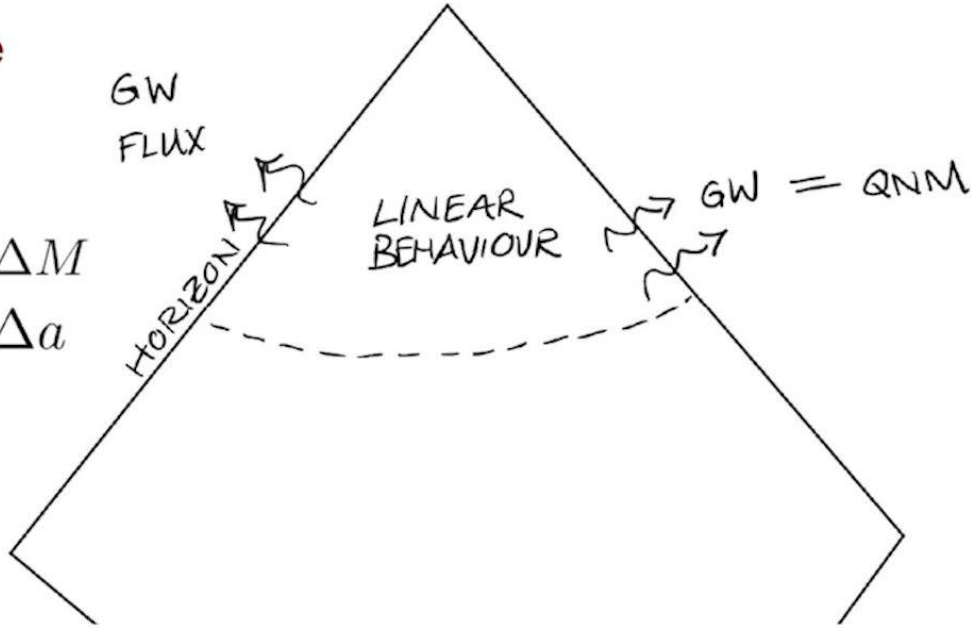

HORIZON
LINEAR BEHAVIOUR
GW = QNM

Can calculate

ΔM

Δa

$\propto \mathcal{A}^2$



[S. Hawking & J. Hartle 1972, S. Teukolsky & W. Press 1974, R. Price & K. Thorne 1986, K. Thorne et al. 1986, E. Poisson 2004, L. Sberna et al. 2021]

Our set up

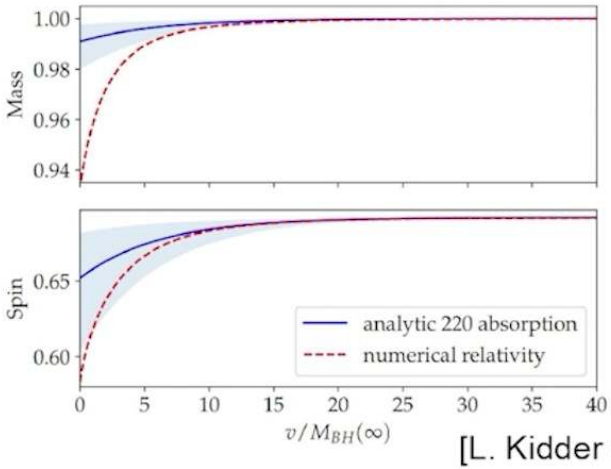
$(\ell mn) = (220)$

Amplitude from NR (equal mass, quasi-circular, remnant spin $a/M = 0.692$)

[Giesler et al. 2019]

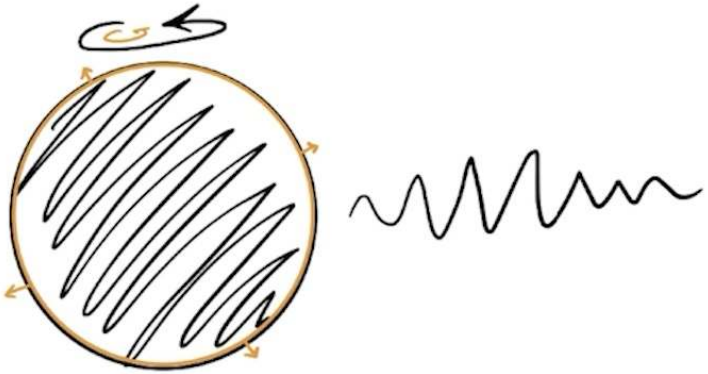
$\Delta M/M = (0.92\%)$

$\Delta a/a = (6.34\%)$



[L. Kidder et al. 2018]

Time evolution in linear code

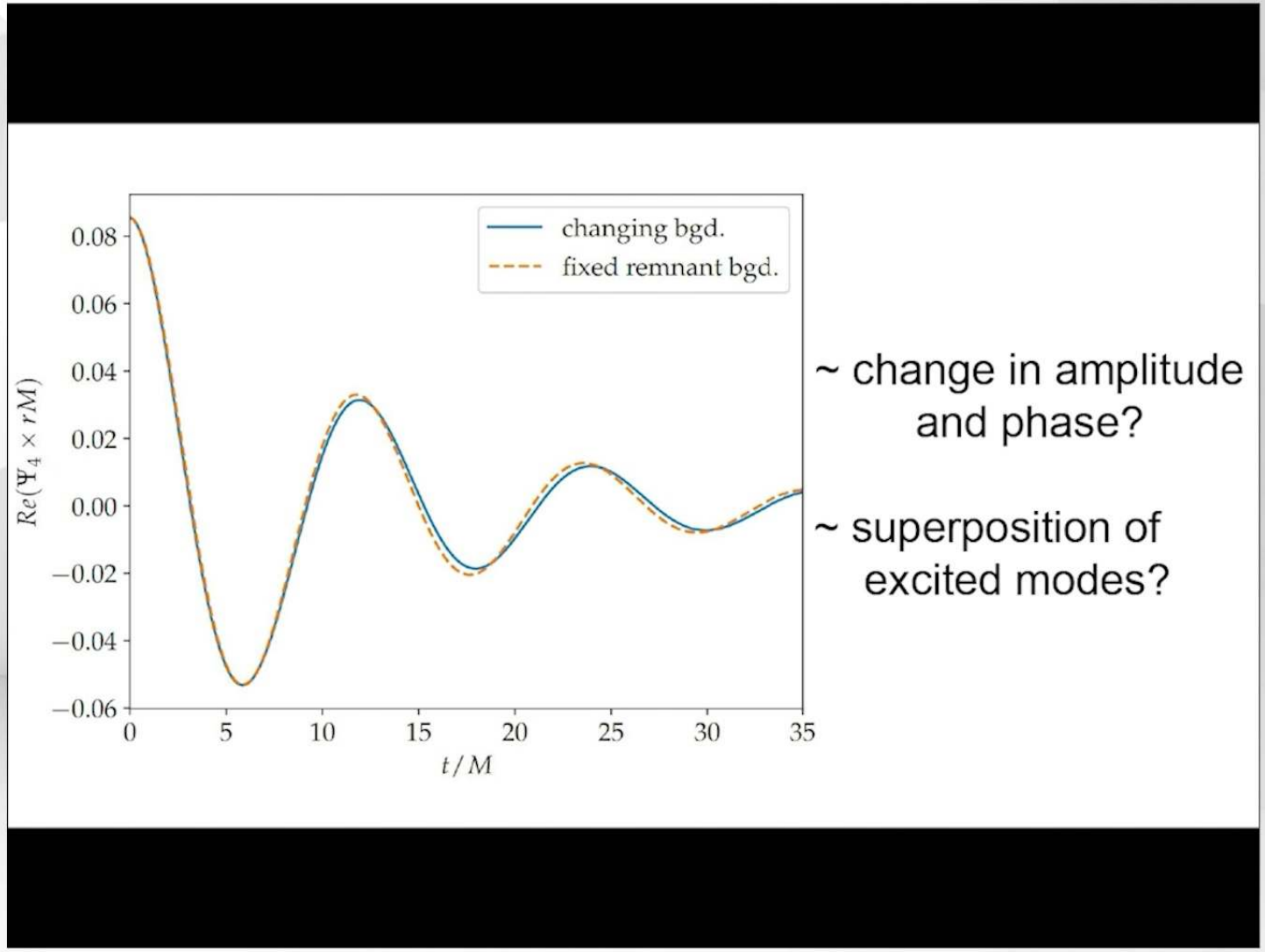


$\omega_{220}(a/M)$

$\mathcal{A}_{(220)}$

$$M_{\rm BH}(t) = M - \Delta M \exp\left[2\Im\omega_{220}t\right],$$
$$a_{\rm BH}(t) = a - \Delta a \exp\left[2\Im\omega_{220}t\right].$$

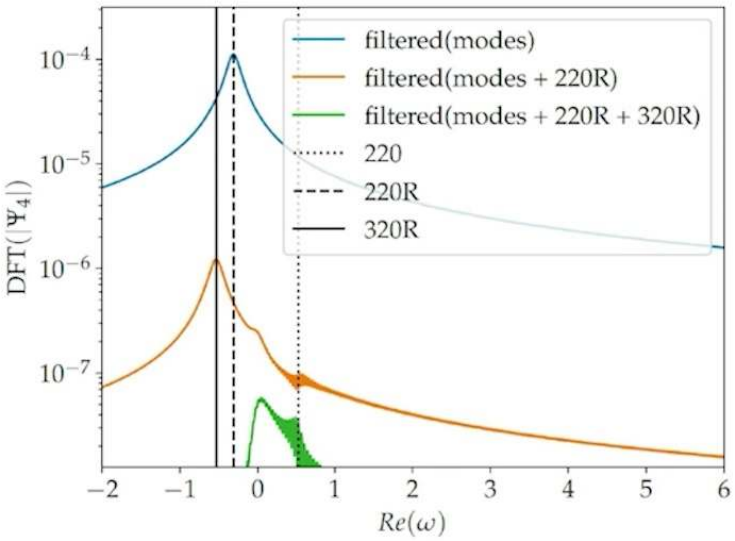
Using methods from
[H. Zhu et al., J. Ripley]

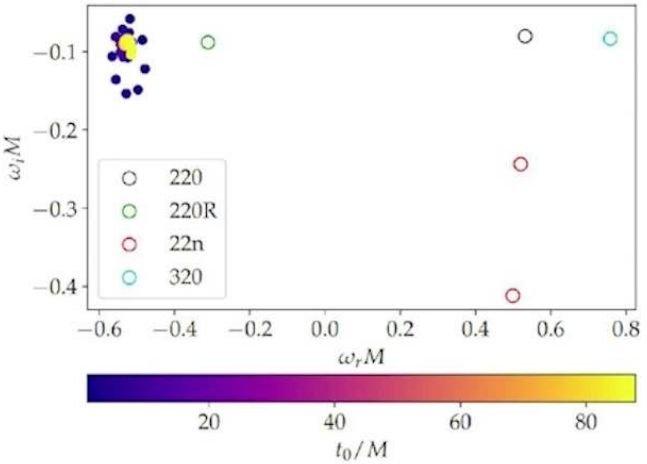


~ change in amplitude and phase?

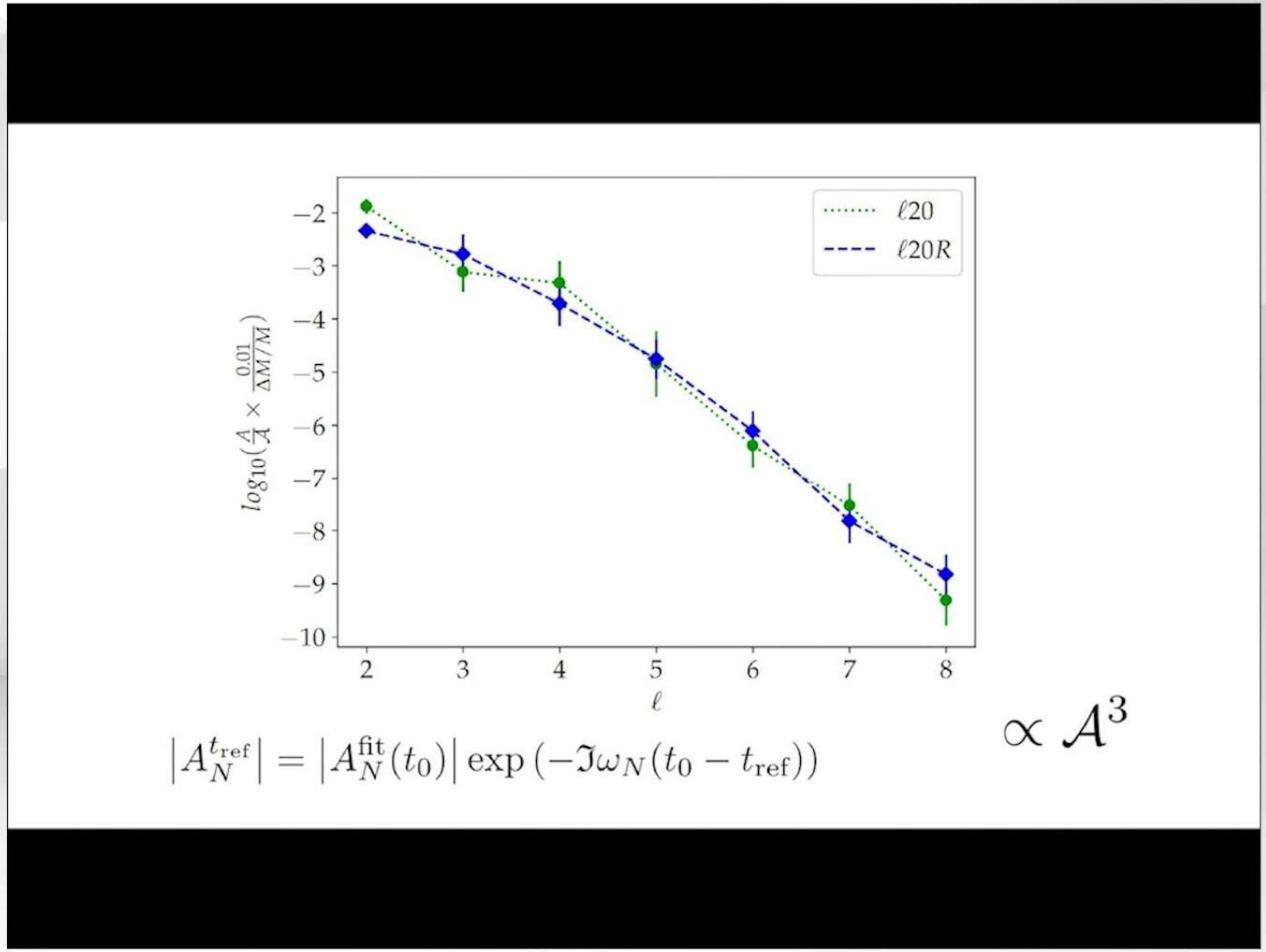
~ superposition of excited modes?

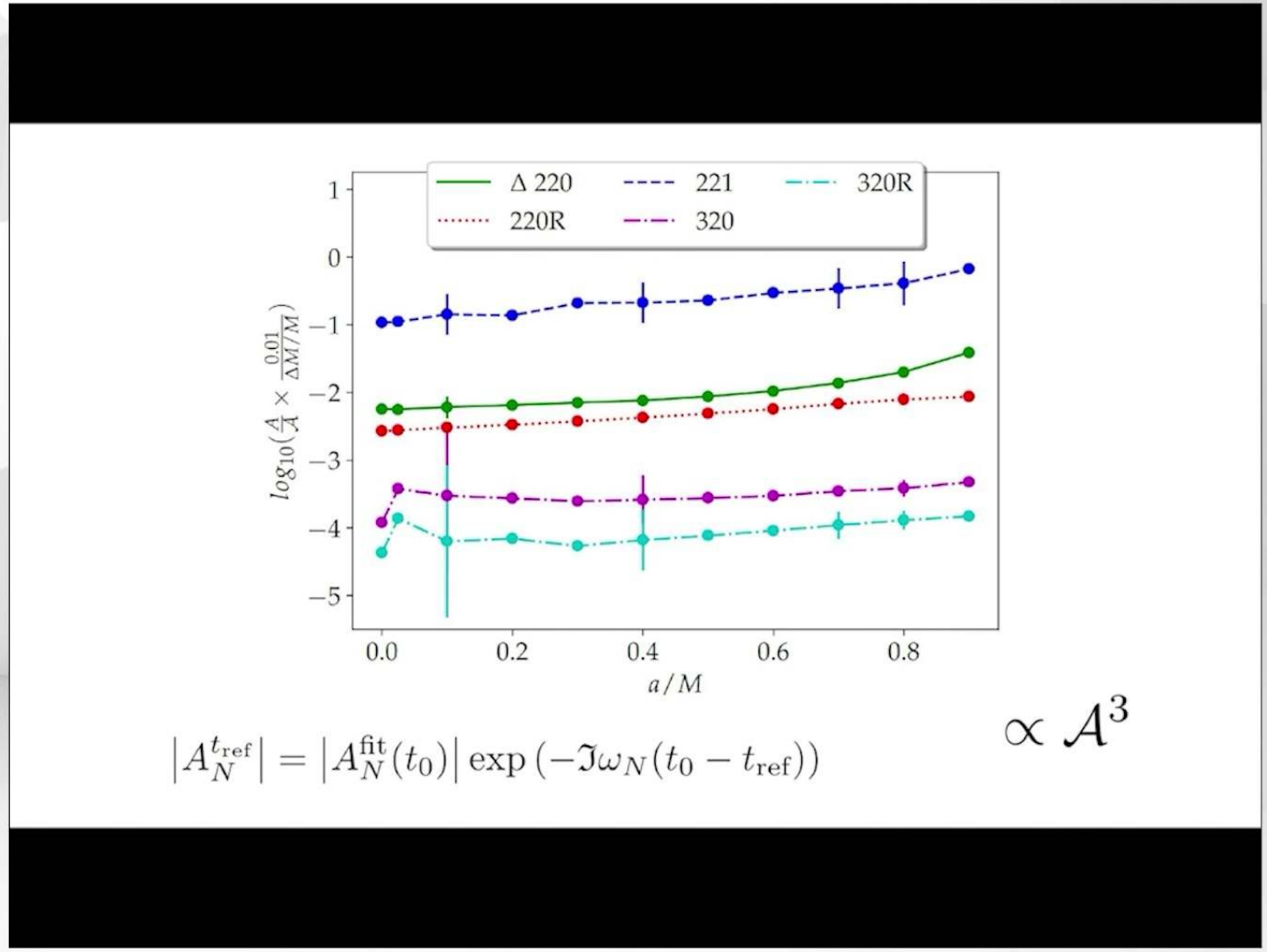
Identifying frequencies



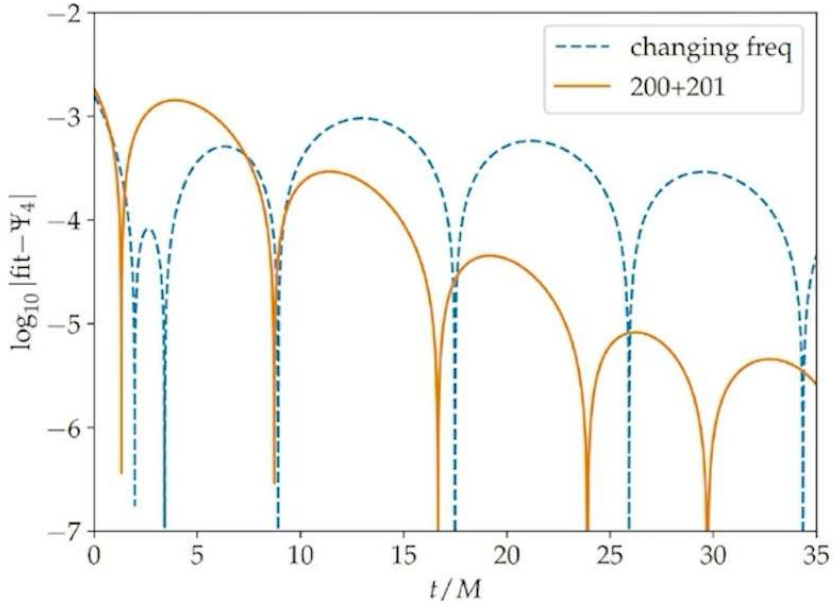


[S. Ma et al. 2022, S. Ma et al. 2023]

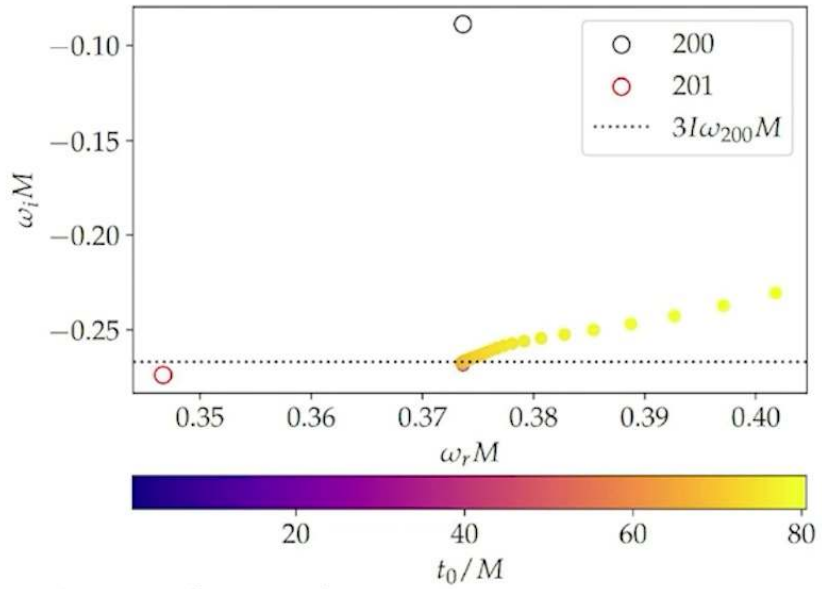

$\ell 20$
$\ell 20R$
$log_{10}(\frac{A}{\mathcal{A}} \times \frac{0.01}{\Delta M/M})$
ℓ
$\left|A_N^{t_{\rm ref}}\right| = \left|A_N^{\rm fit}(t_0)\right| \exp\left(-\Im\omega_N(t_0 - t_{\rm ref})\right)$
$\propto \mathcal{A}^3$


Δ 220
221
320R
220R
320
1
0
−1
−2
−3
−4
−5
0.0
0.2
0.4
0.6
0.8
a / M
$log_{10}(\frac{A}{\mathcal{A}} \times \frac{0.01}{\Delta M/M})$
$\left|A_N^{t_{\rm ref}}\right| = \left|A_N^{\rm fit}(t_0)\right| \exp\left(-\Im\omega_N(t_0 - t_{\rm ref})\right)$
$\propto \mathcal{A}^3$

Changing frequency contribution

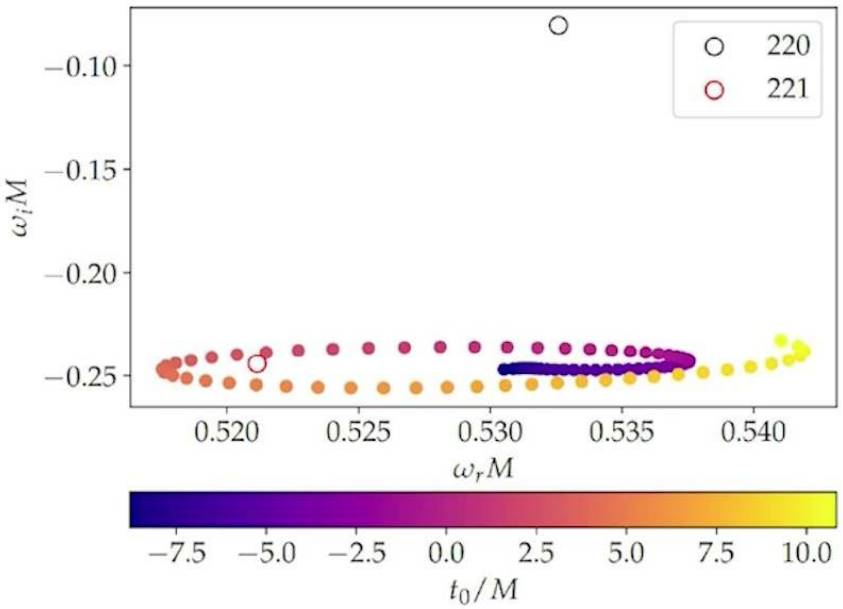


Pure changing frequency after filtering out fundamental mode



$$M_{\rm BH}(t) = M - \Delta M \exp\left[2\Im\omega_{220} t\right]$$

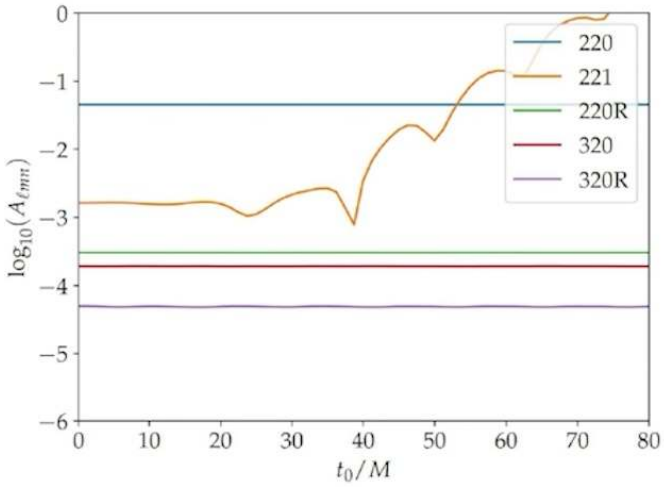
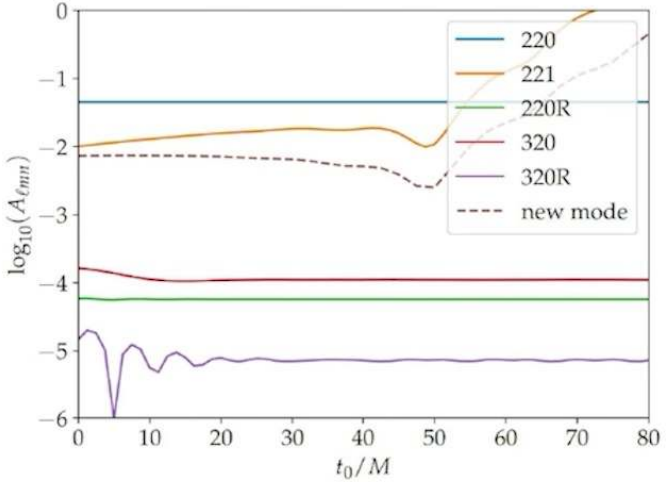
Ambiguity in Overtone – non-mode content



Conclusion

- Want to measure frequencies $\omega_{\ell mn}$, but it's unclear when we should fit these to gravitational wave data.
- A changing background can look like exciting other modes including retrogrades, higher l modes, overtones
- A changing frequency component can be generated by a changing background, and may interfere with overtone fitting.
- This third order effect can be comparable to second order mode doubling

Fixed remnant



Changing background