

# Binary Black Holes: Sources of nonlinear gravity

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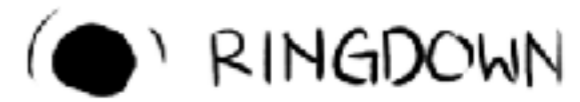


Pandora's Box based on a painting by F.S. Church.

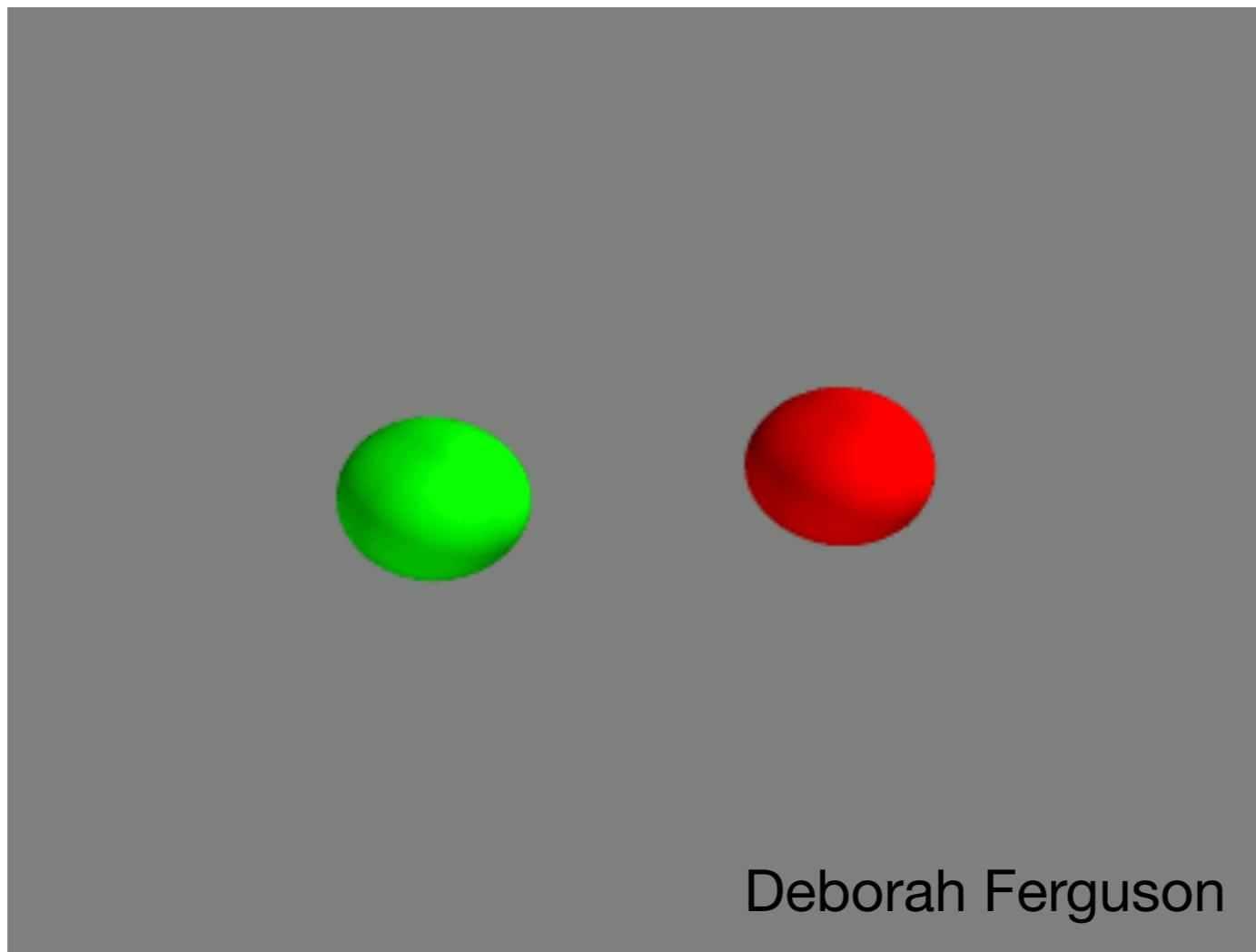
# It's all about the merger



15 parameters

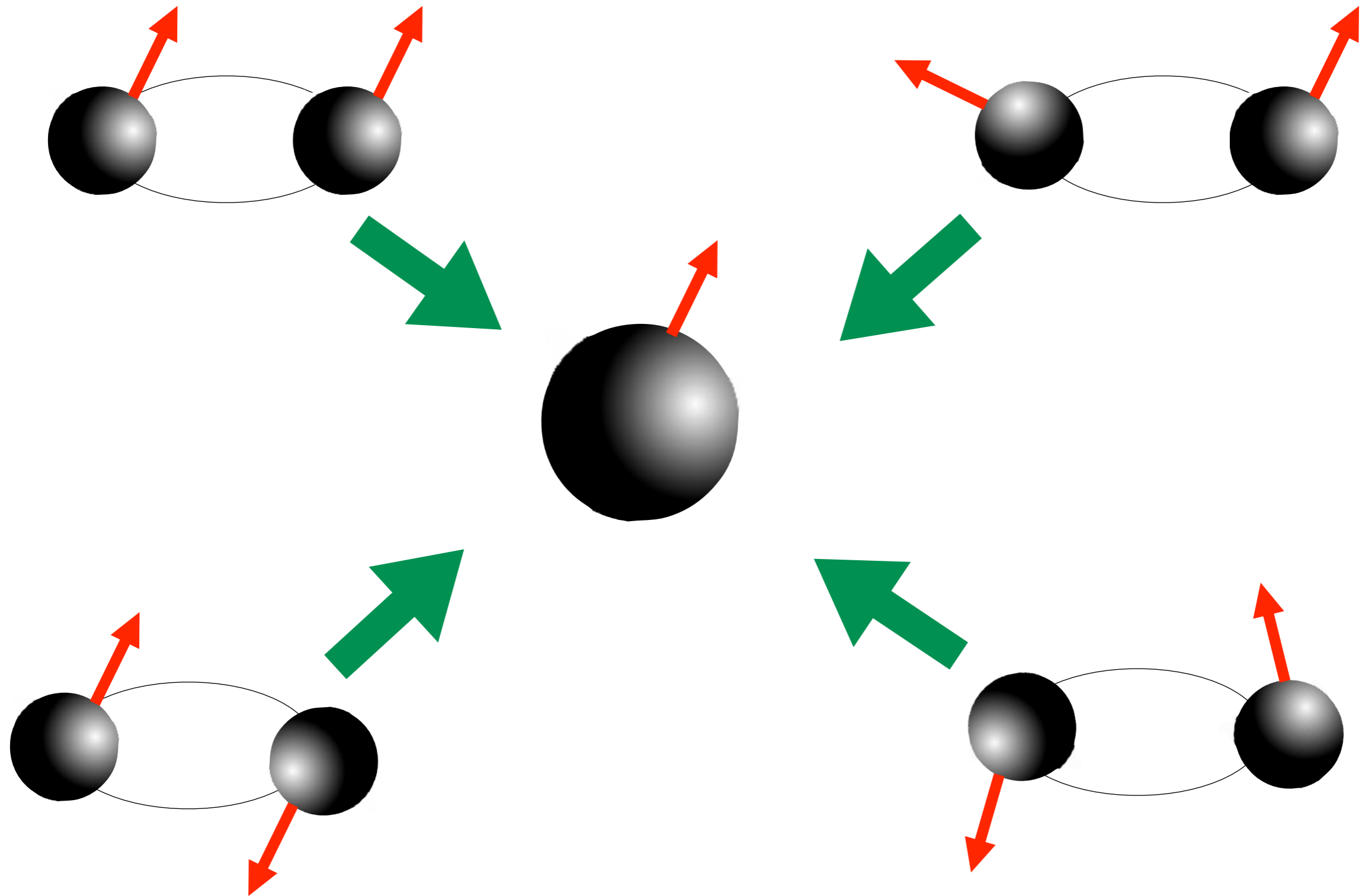


2 parameters

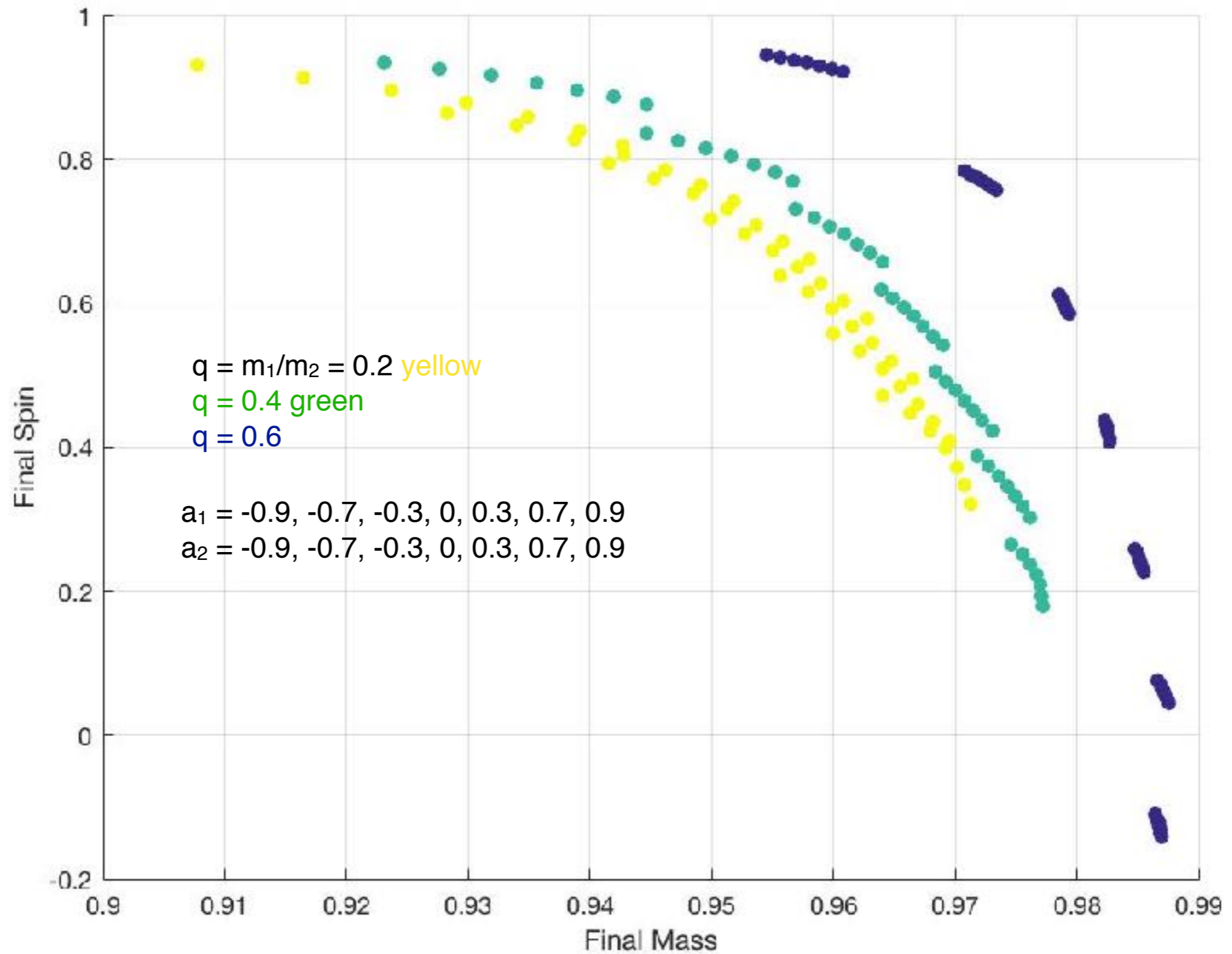


1. NR provides map of excitation of QNMs
2. Provides higher harmonics
3. How the BBH sheds hair

# Multiple Paths to the Remnant BH

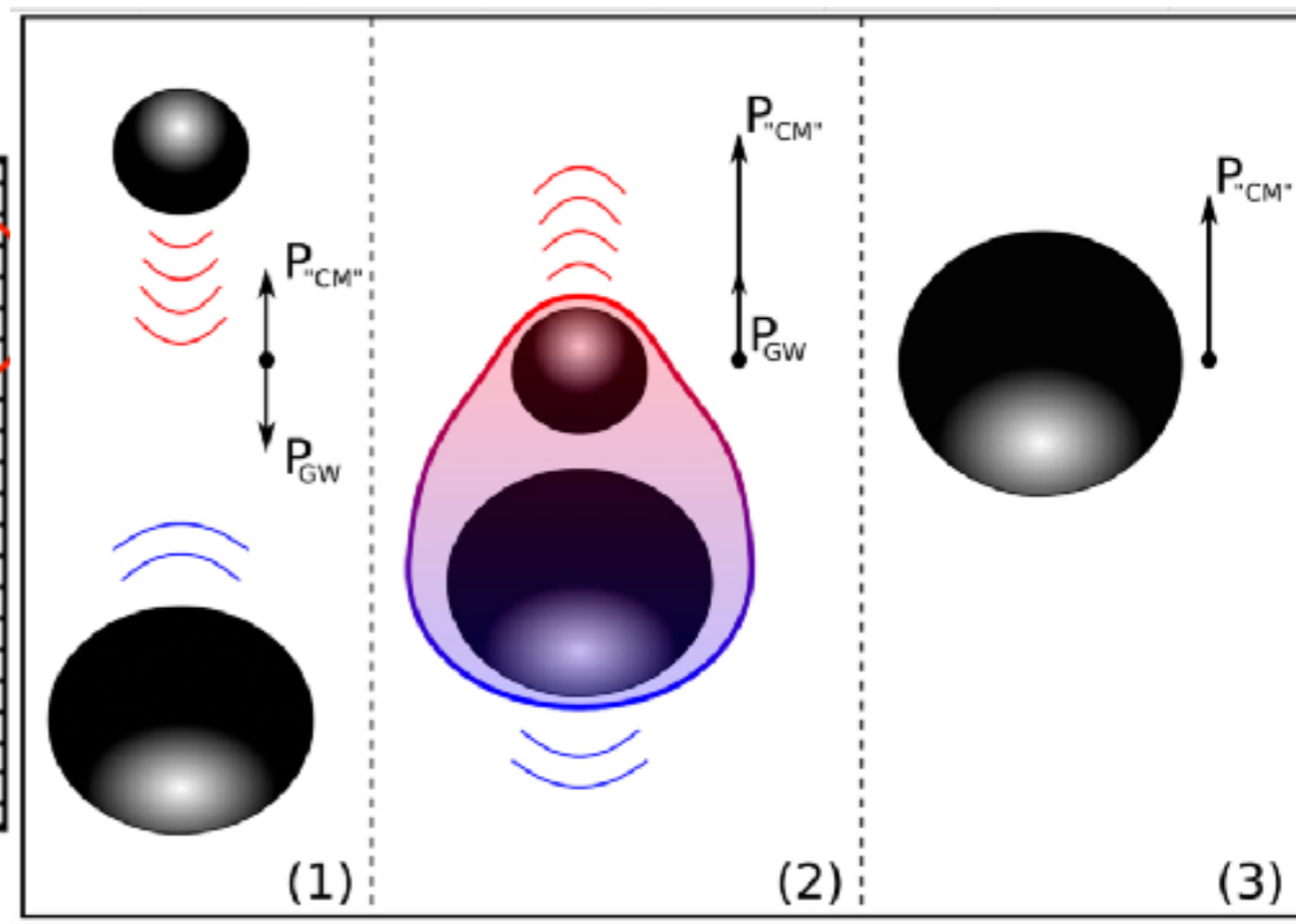
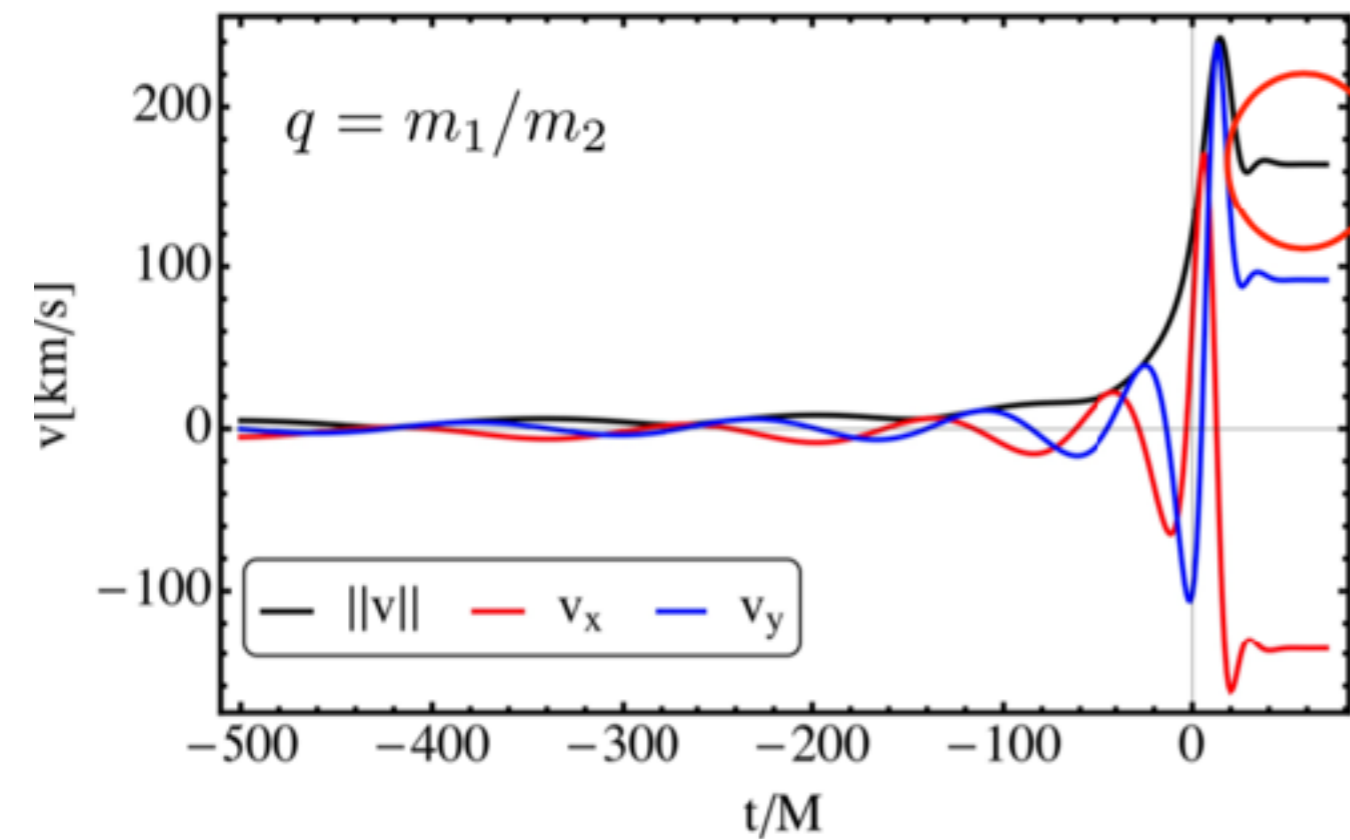


# Distinguish Remnants?

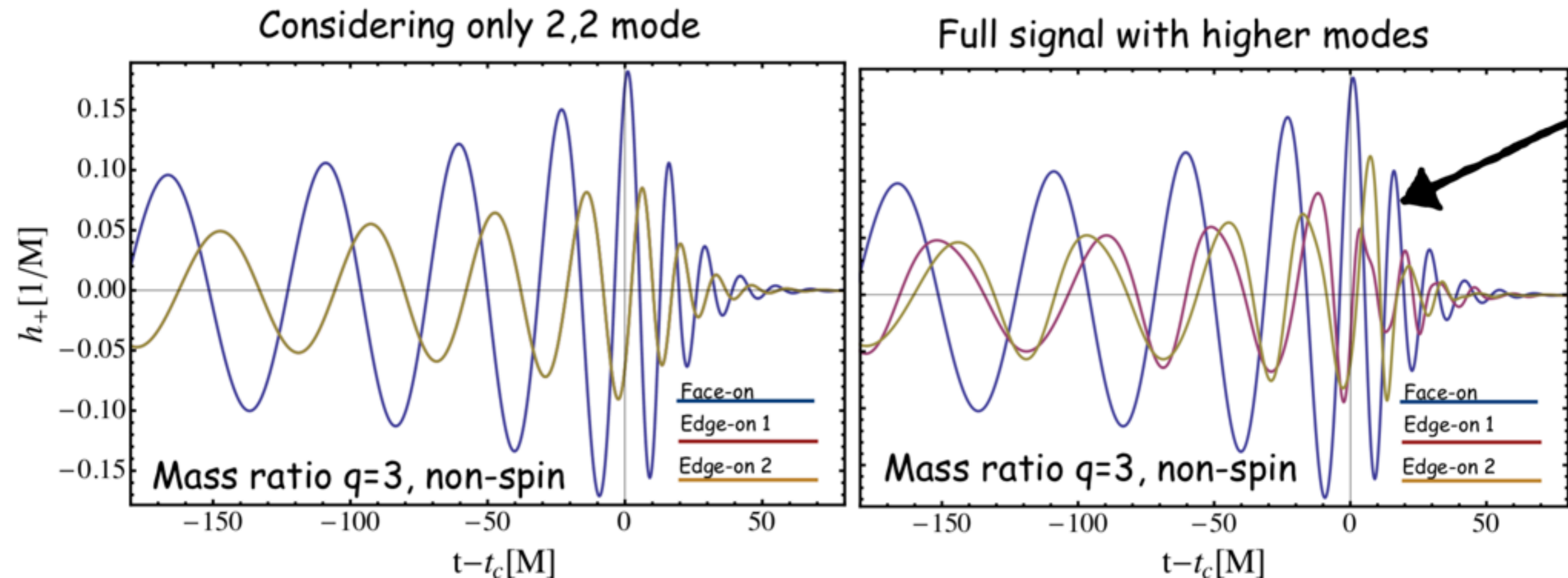


# Except, recoil

The magnitude of the kick is determined by the BH parameters at merger



# The harmonics tell us about recoil and binary orientation

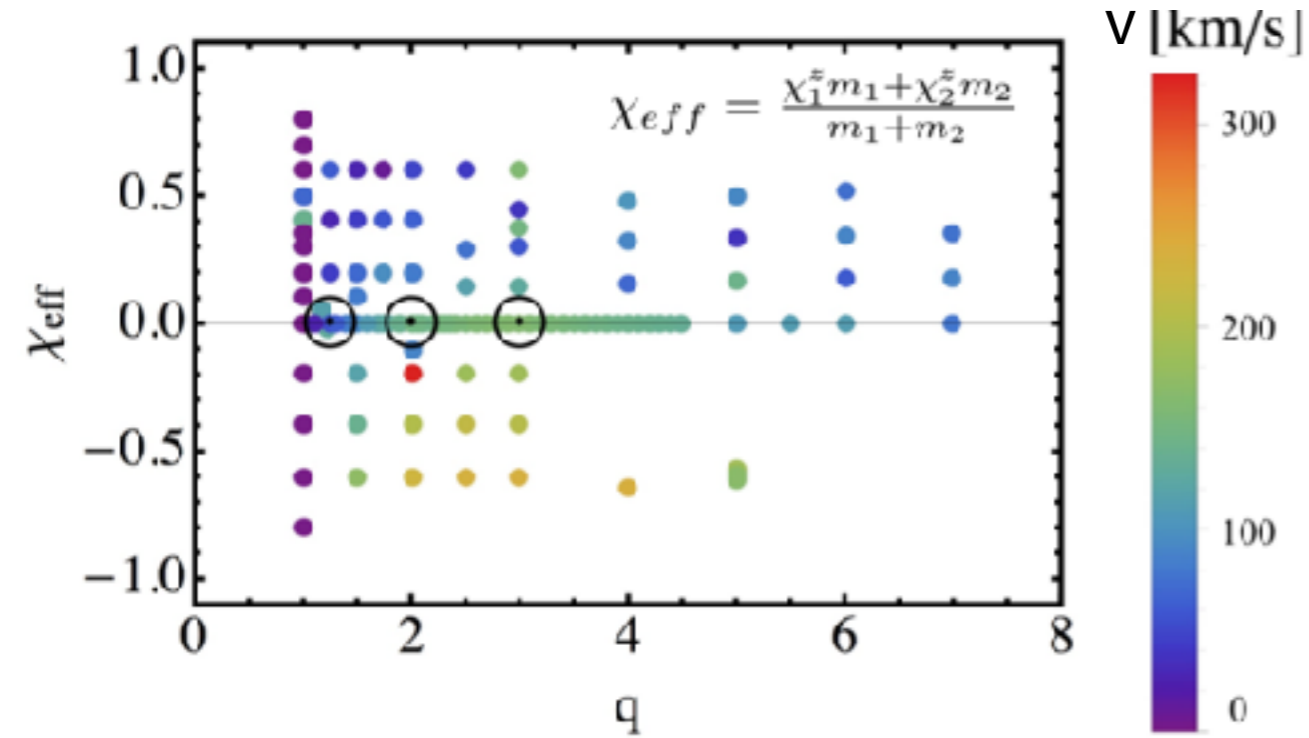


Edge-on 1 BH is moving toward detector  
Edge-on 2 BH is moving away

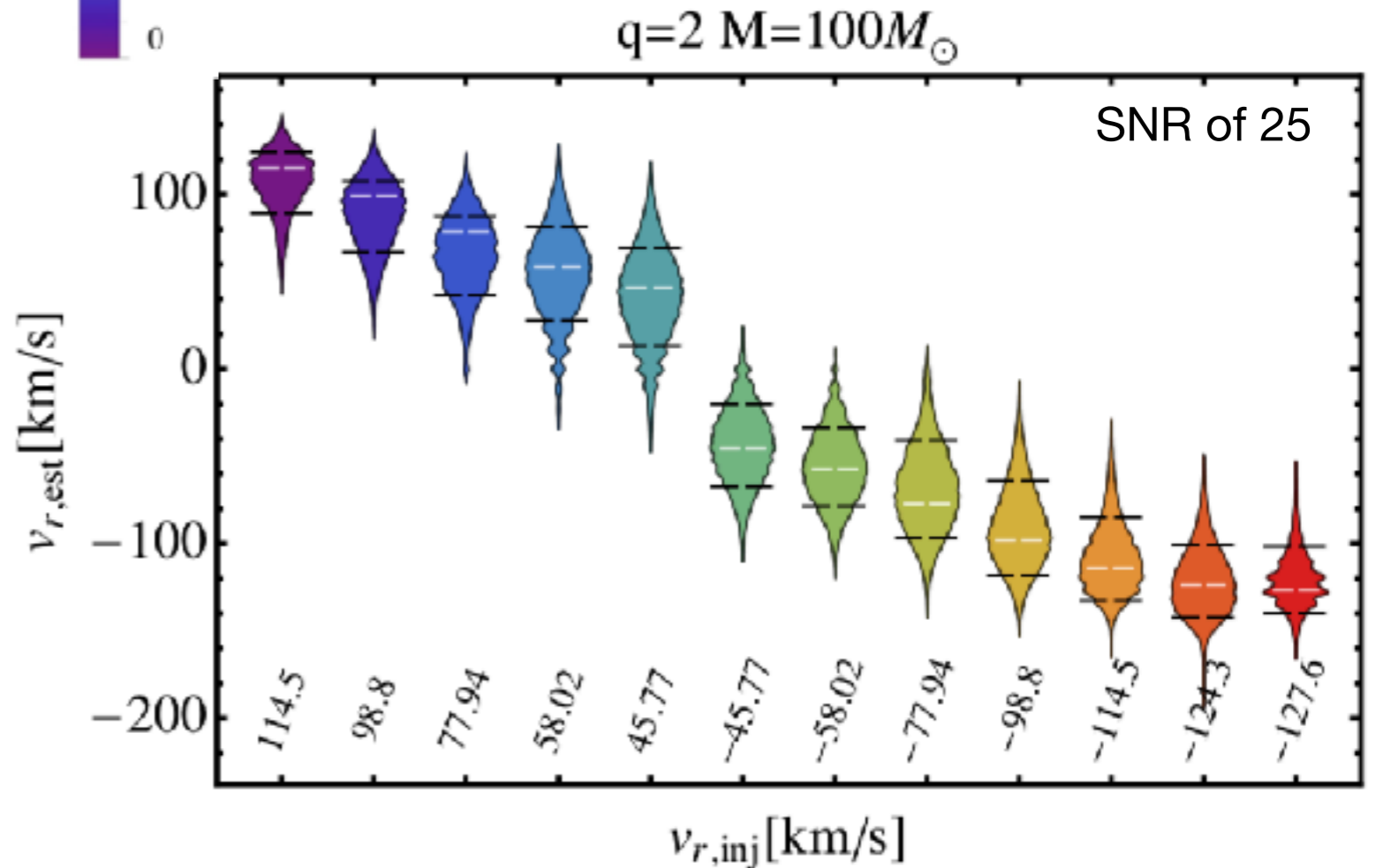
Exploit this difference to measure kicks

Juan Calderon Bustillo, James Clark, Laguna, DS in preparation

# Measuring Kicks



- NR waveforms: injected signal and templates
- Zero noise
- Single advanced LIGO detector at O1

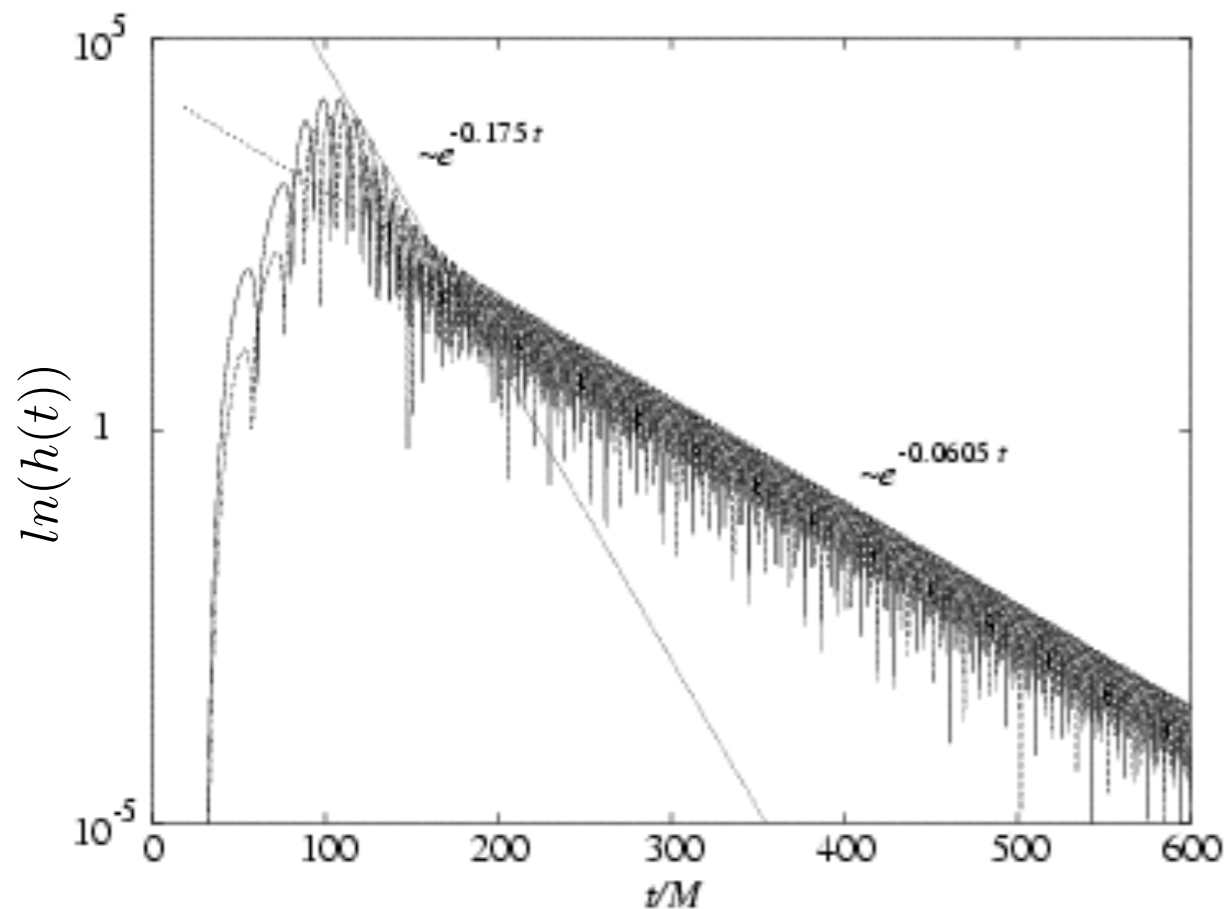
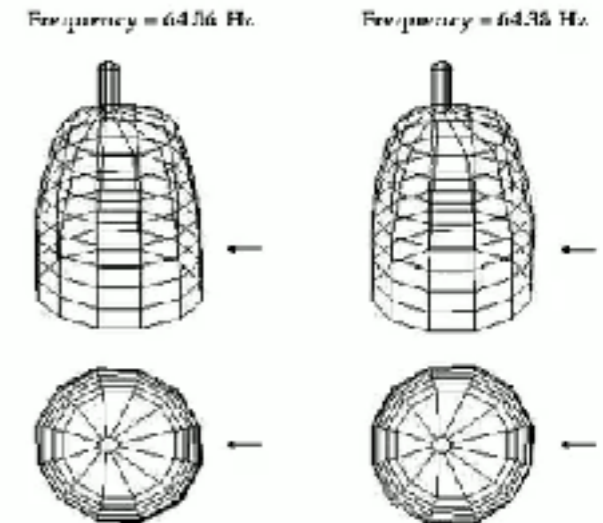


# NR Provides a Map to Ringdown



15 parameters

2 parameters



- Ringdown is completely describable by damped sinusoidal functions.

$$h(t) \propto e^{-t/\tau} \sin(2\pi f t)$$

- The black hole “rings” in tones given by a set of unique complex frequencies called quasi-normal modes.

$$f(M, a) \quad \tau(a)$$

- NR-based formulas predict final mass, spin, recoil & peak Luminosity from initial parameters (Healy et al PRD 2014 & Barausse, et al APJ 2012)

# NR Provides a Map to Ringdown



INSPIRAL



MERGER



RINGDOWN

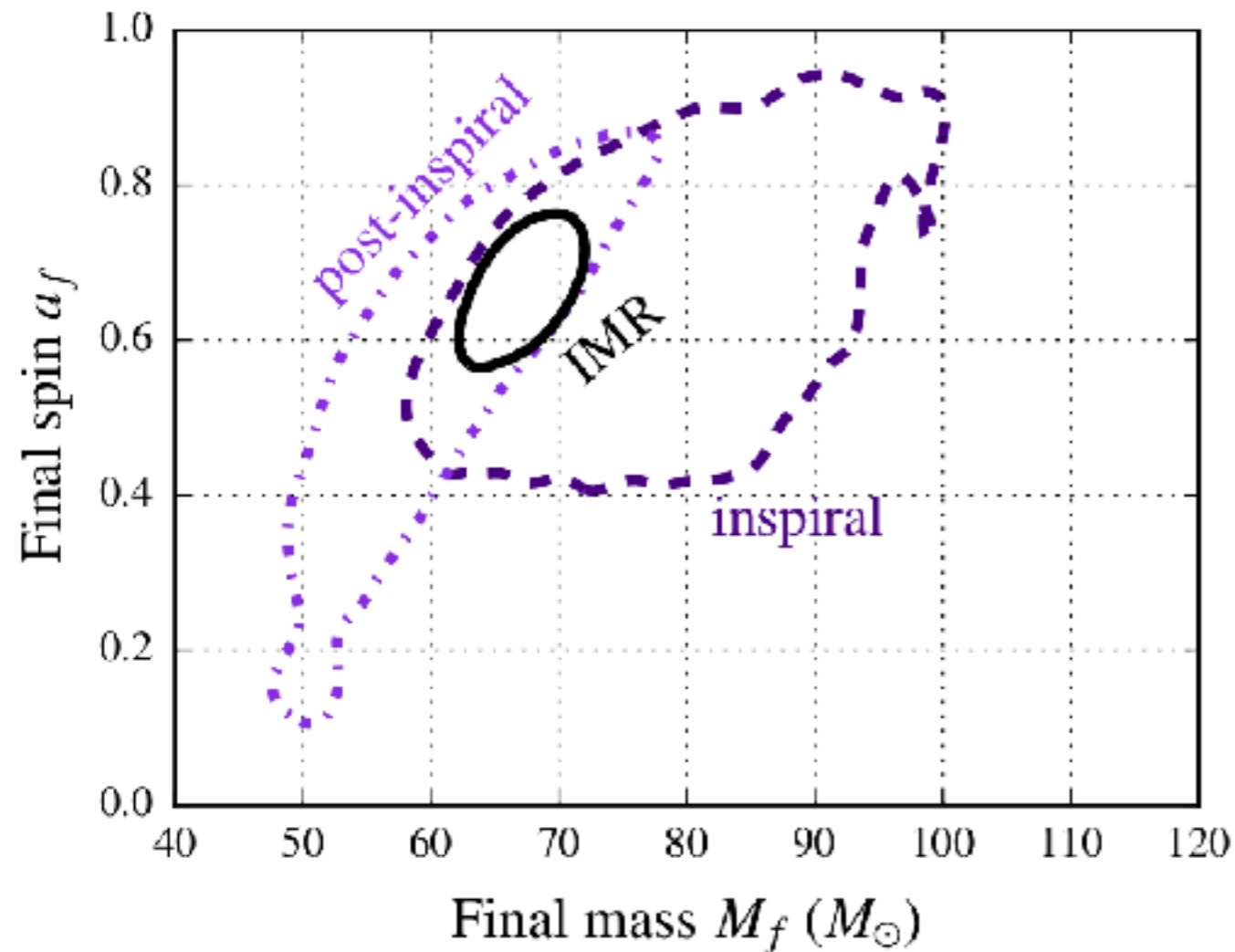
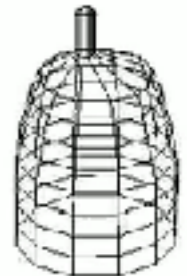
15 parameters

2 parameters

Frequency = 64.56 Hz



Frequency = 64.38 Hz



- Ringdown is completely describable by damped sinusoidal functions.

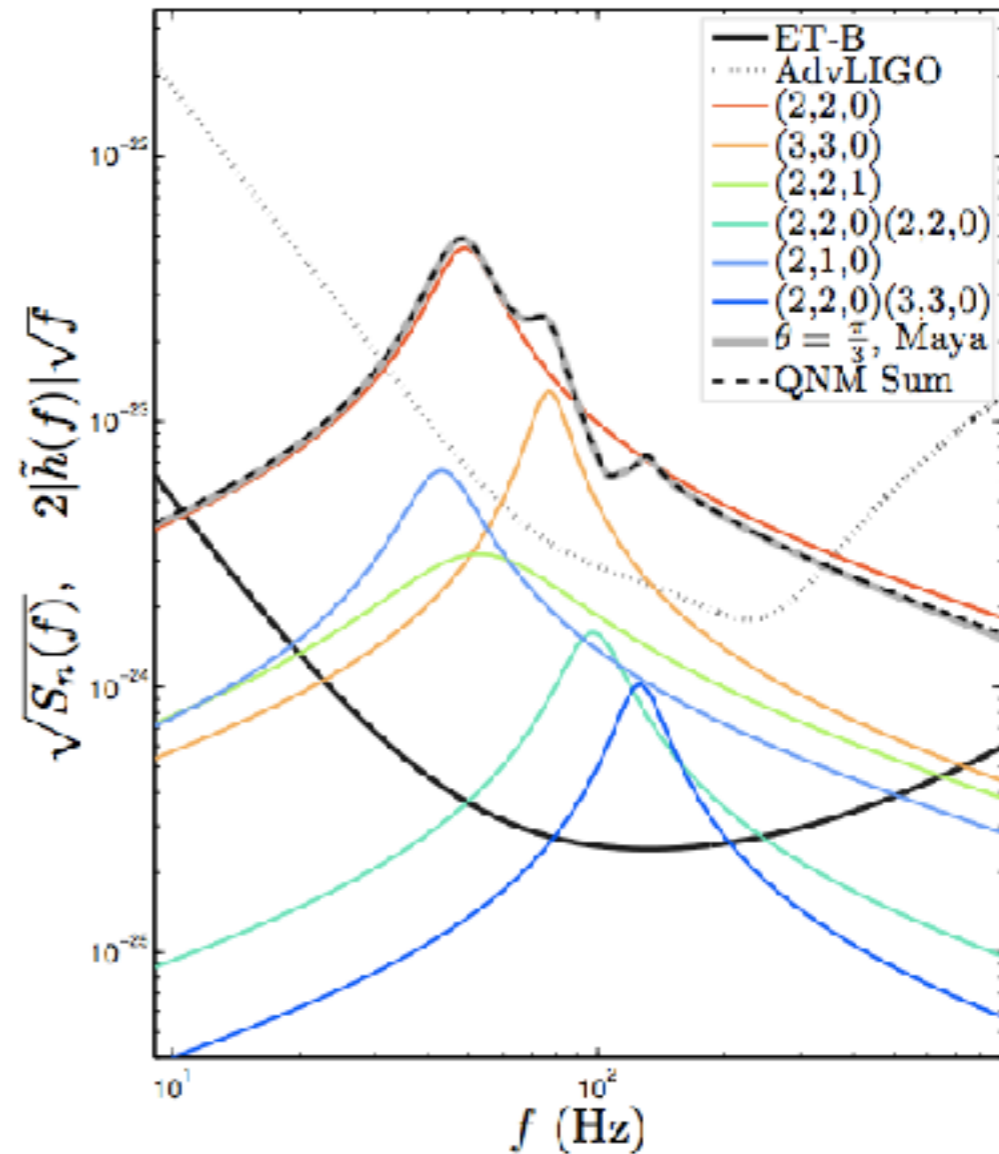
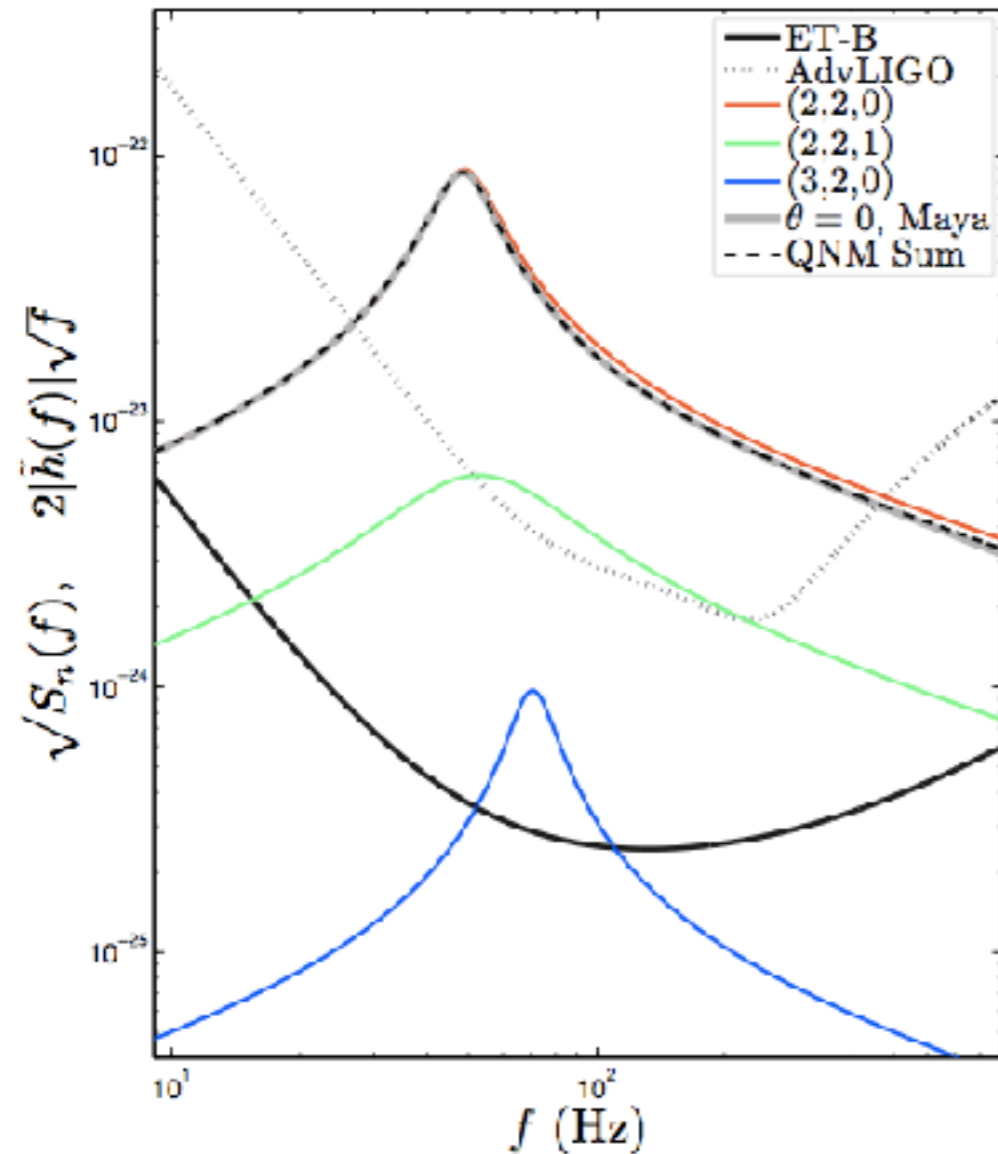
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# Can we measure multiple QNMs?

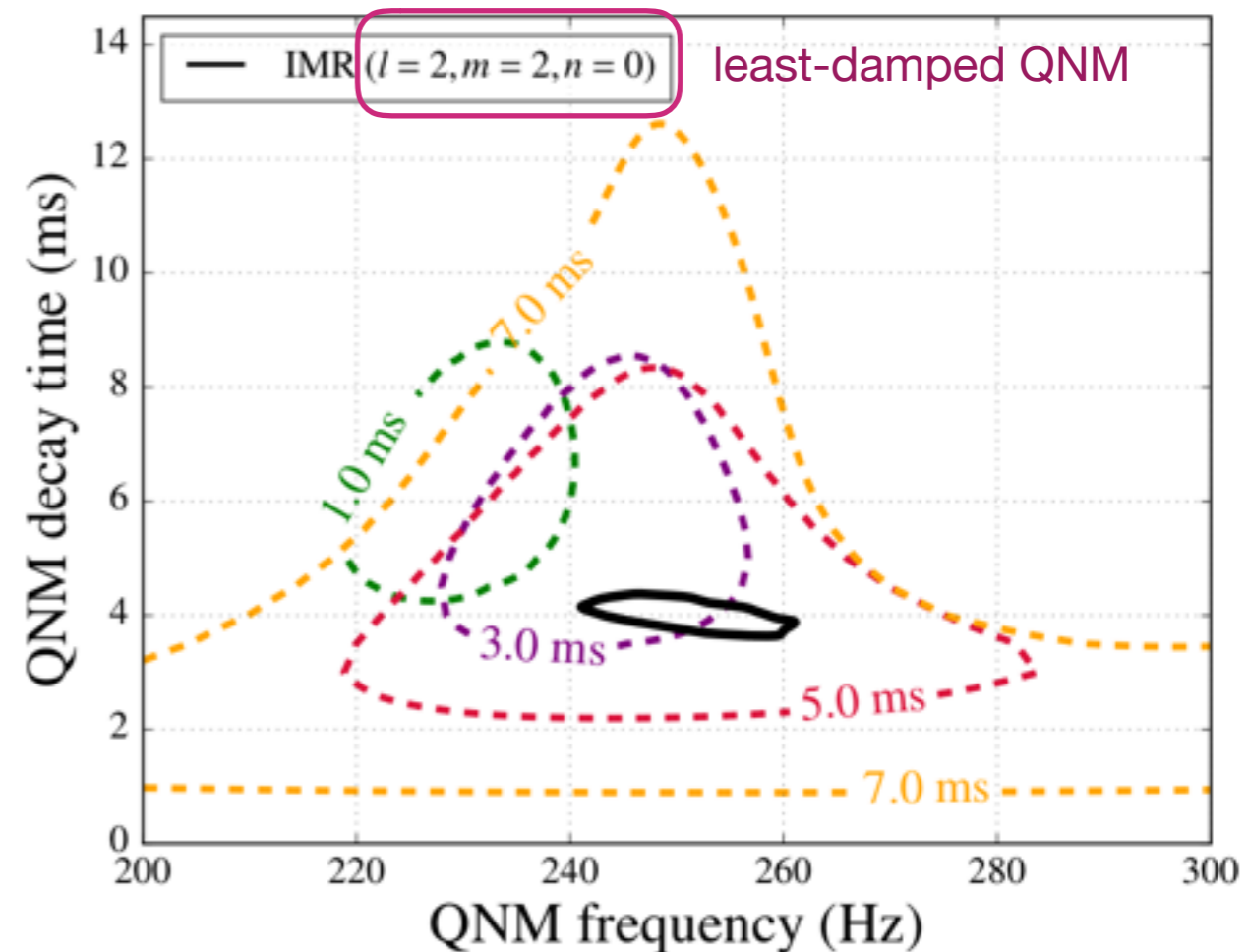
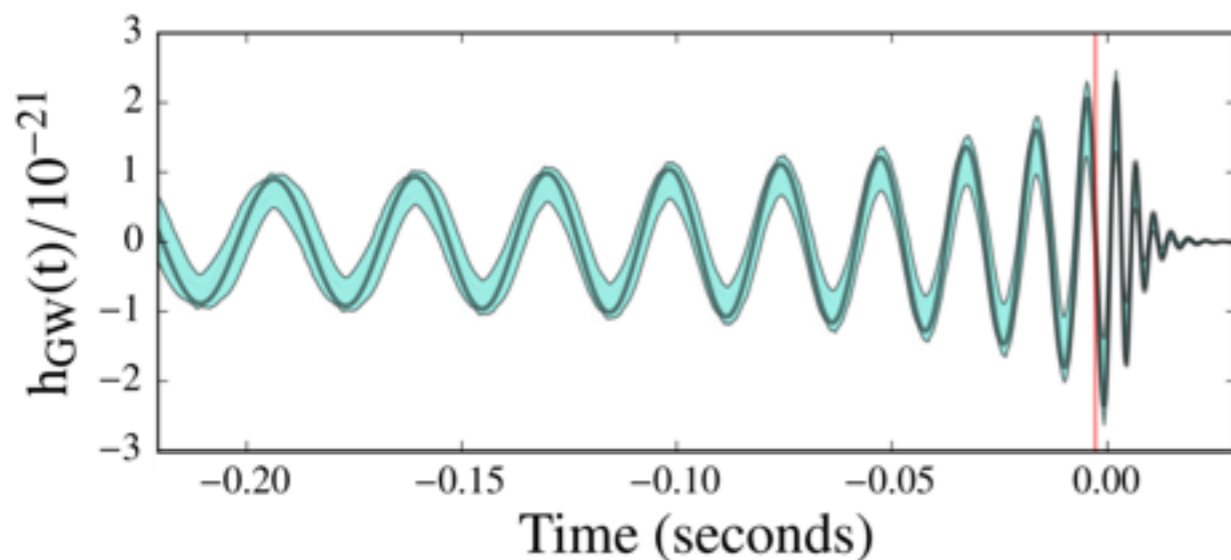


QNM  $q=2$ , 100 Mpc, 350 M  
London et al PRD 2014

Berti et al 2007, Kamaretsos et al 2012, Kelly & Baker 2013  
Detecting: Thrane et al 2017, Yang et al 2017, Bhagwat et al 2016

# Testing consistency of the data with the final m and a

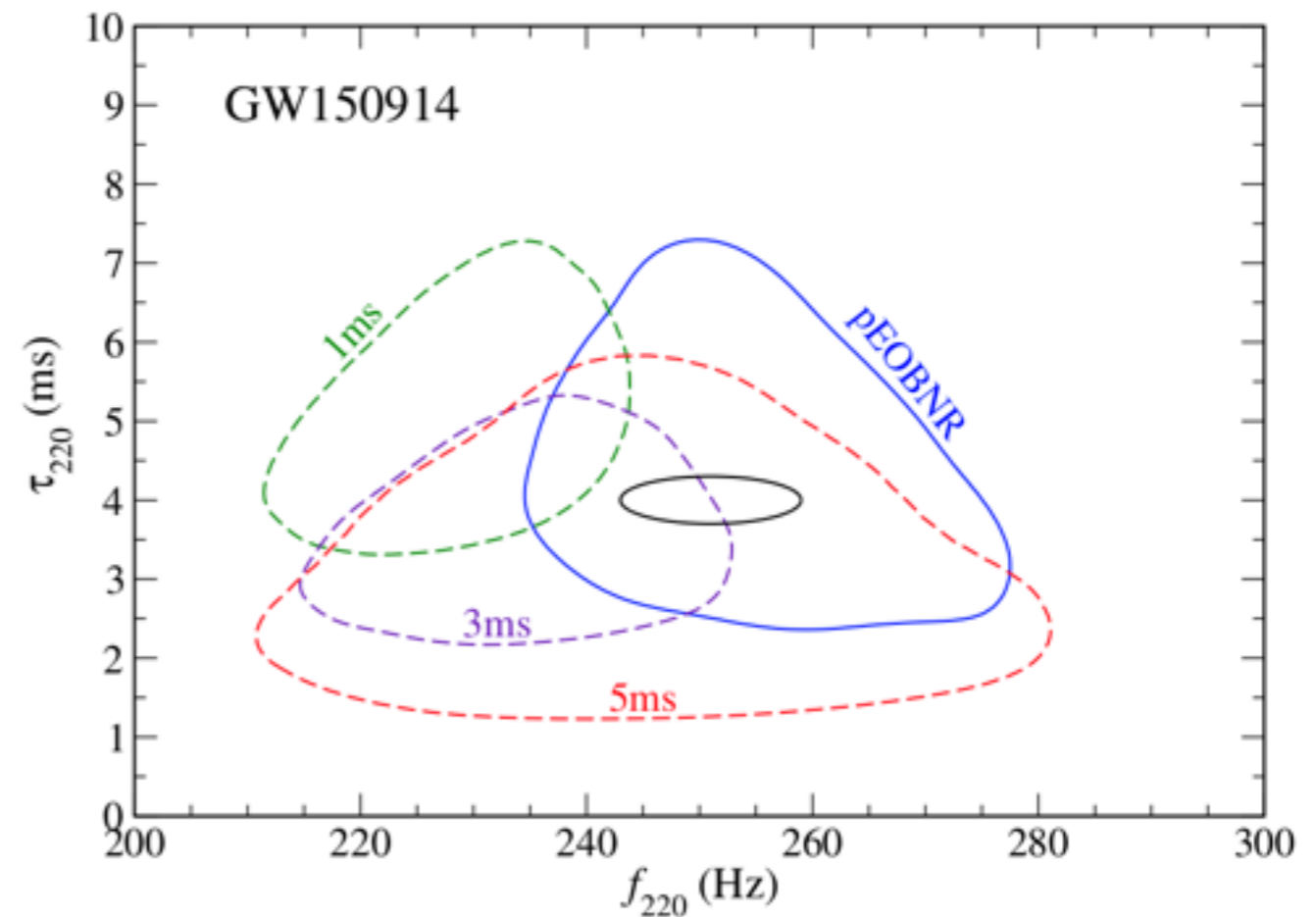
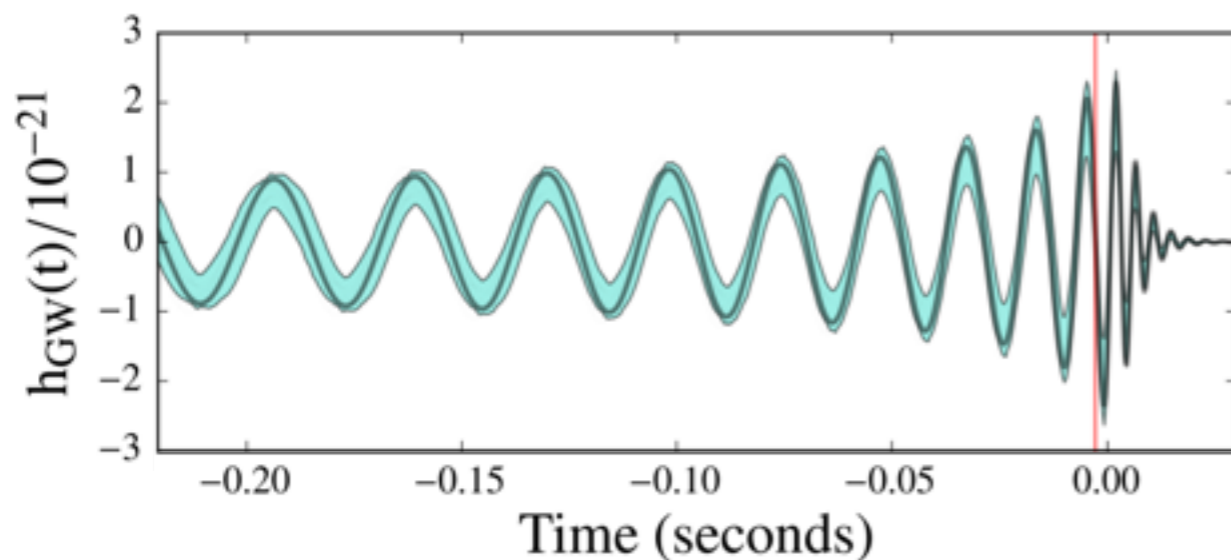
Abbott et al., PRL 116, 221101



- Given the IMR waveform, test against a series of “GR” predictions (damped sinusoids)
- Consistent with an Einstein BH
- Not proof of an event horizon, alternate states ....

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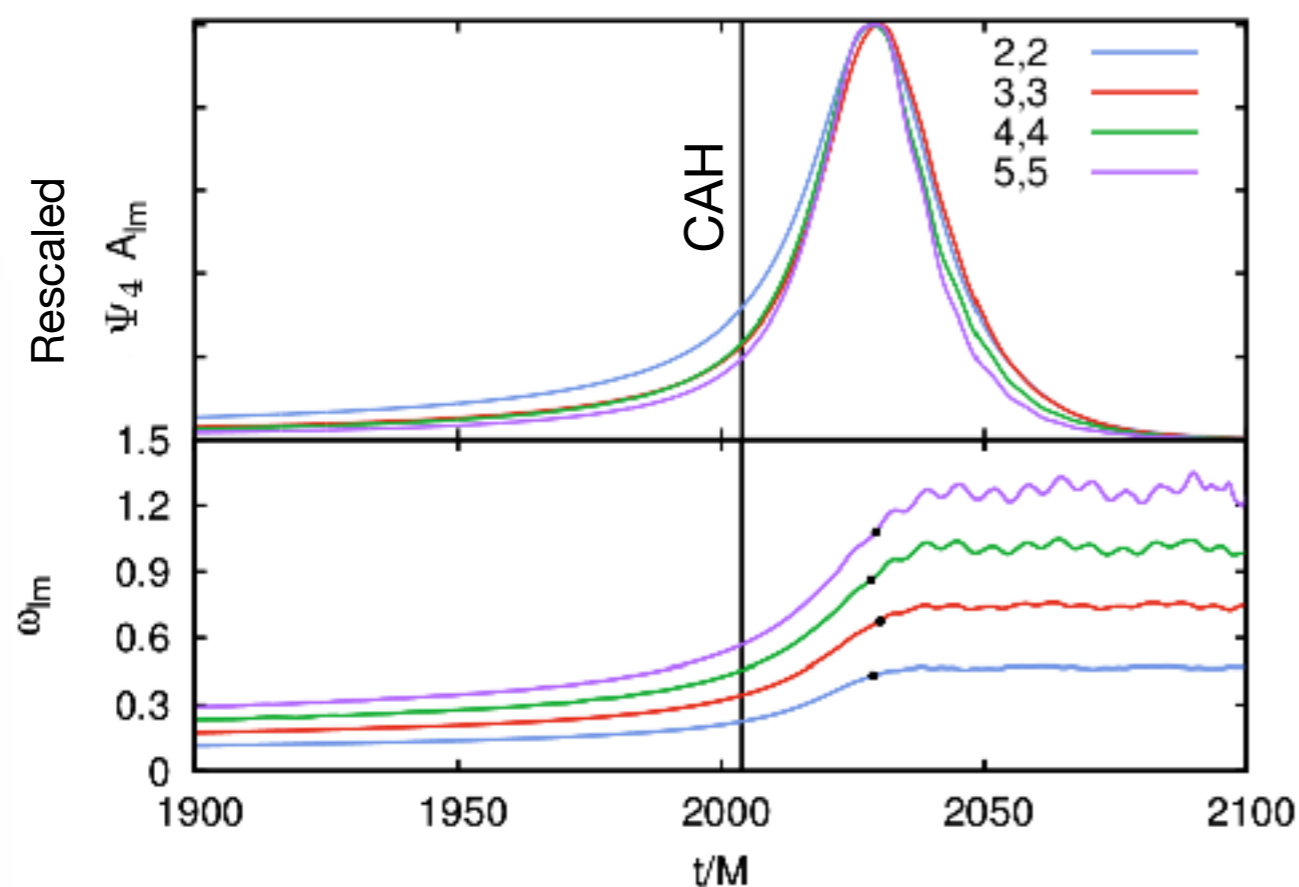


Brito, Buonanno, Raymond arXiv:1805.00293

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# Alternatives to ringdown?

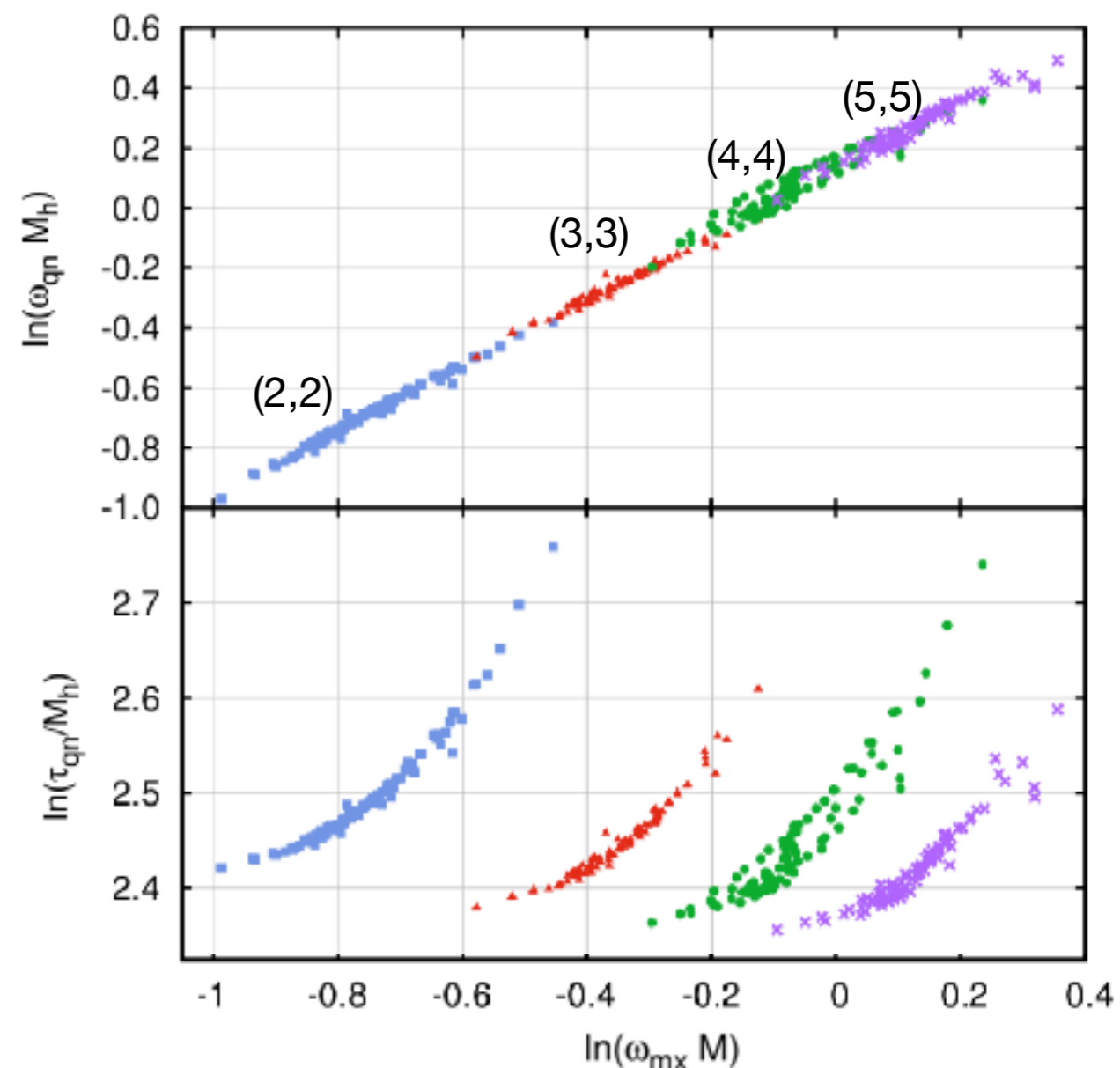
Correlation between frequency at peak amplitude and final mass and spin (Healy, Laguna, DS CQG 2014)



$$\ln(\hat{\omega}_{\text{qn}}) = f_1 + f_2 \ln(\hat{\omega}_{\text{mx}})$$

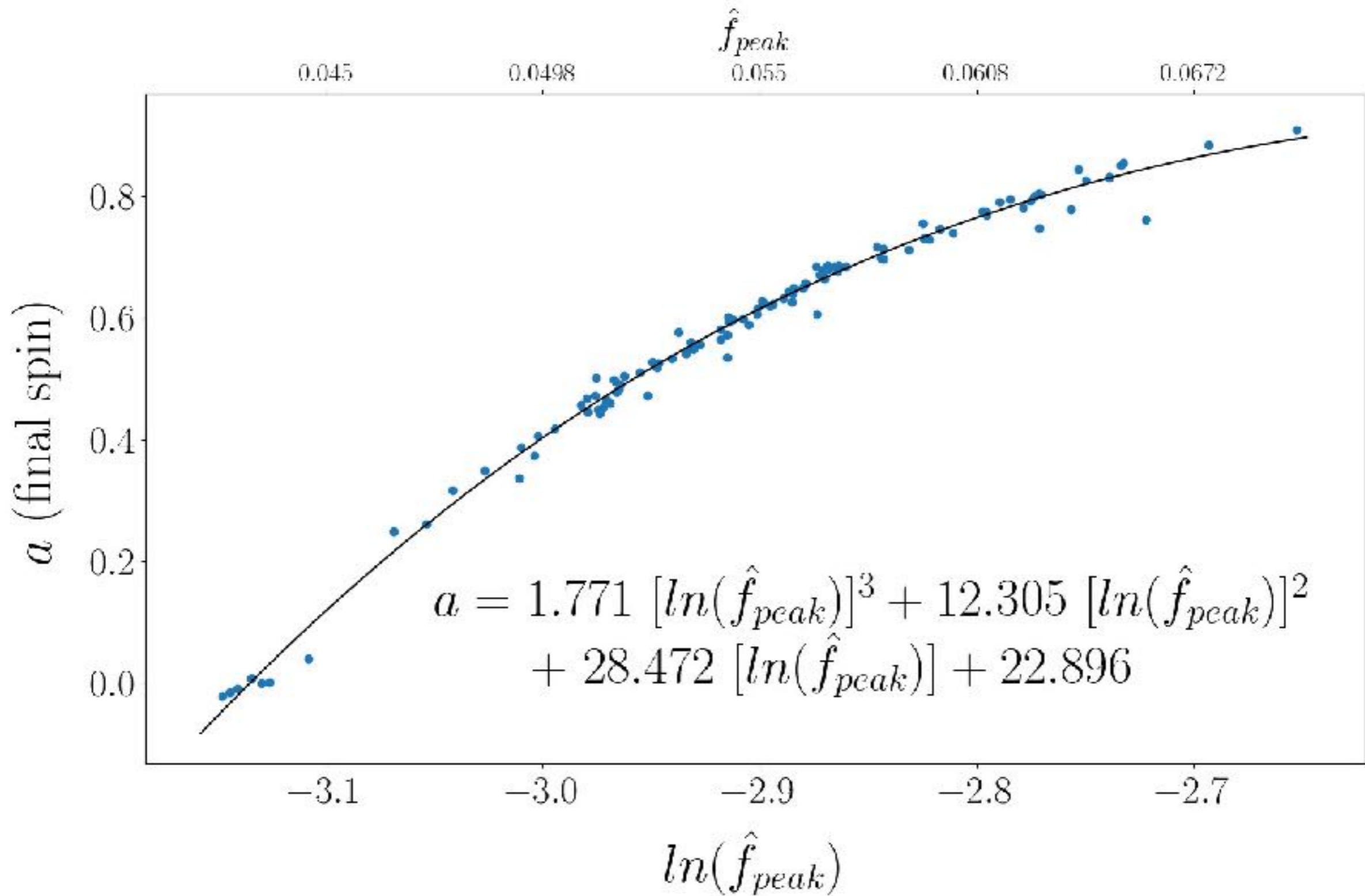
$$\ln(\hat{\tau}_{\text{qn}}) = g_1 + g_2 \ln(\hat{\omega}_{\text{mx}}) + g_3 [\ln(\hat{\omega}_{\text{mx}})]^2$$

$$\ln(Q) = h_1 + h_2 \ln(\hat{\omega}_{\text{mx}}) + h_3 [\ln(\hat{\omega}_{\text{mx}})]^2$$



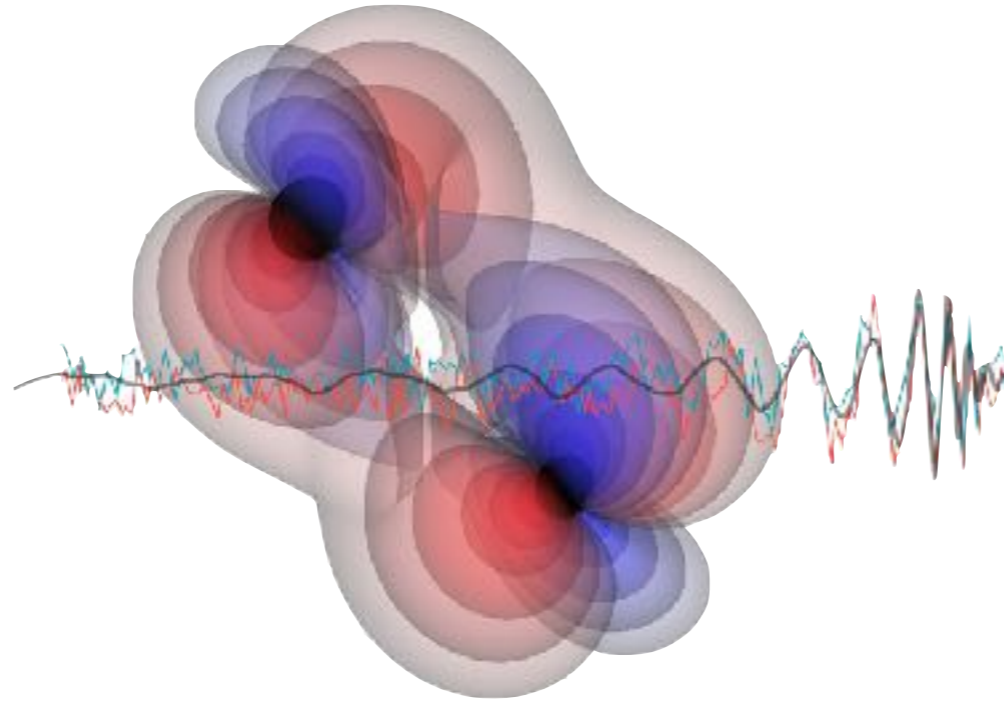
$$\hat{\omega}_{\text{qn}} \equiv \omega_{\text{qn}} M_h; \quad \hat{\tau}_{\text{qn}} \equiv \tau_{\text{qn}}/M_h \quad \hat{\omega}_{\text{mx}} \equiv \omega_{\text{mx}} M$$

# Now with strain



Deborah Ferguson, in preparation

# Challenges Ahead



- Just begun to explore strong gravity in the universe
- Beginning to see higher harmonics get their moment to shine
- Increase in work on ringdown and what it can teach us about gravity
- All this only gets more interesting as the detectors get better
- Exciting times ahead

$$\ln(\hat{\omega}_{\text{qn}}) = f_1 + f_2 \ln(\hat{\omega}_{\text{mx}})$$

$$\ln(\hat{\tau}_{\text{qn}}) = g_1 + g_2 \ln(\hat{\omega}_{\text{mx}}) + g_3 [\ln(\hat{\omega}_{\text{mx}})]^2$$

$$\ln(Q) = h_1 + h_2 \ln(\hat{\omega}_{\text{mx}}) + h_3 [\ln(\hat{\omega}_{\text{mx}})]^2$$

$$\hat{\omega}_{\text{qn}} \equiv \omega_{\text{qn}} M_{\text{h}}; \quad \hat{\tau}_{\text{qn}} \equiv \tau_{\text{qn}} / M_{\text{h}}$$

$$\hat{\omega}_{\text{mx}} \equiv \omega_{\text{mx}} M$$

Mode	22	33	44	55
$f_1$	0.1364	0.0926	0.1414	0.1454
$f_2$	1.0985	0.9965	1.0304	1.0164
$g_1$	3.5564	2.7419	2.4850	2.3677
$g_2$	2.3279	1.2249	0.7520	0.2835
$g_3$	1.2044	1.0502	1.1775	0.8340
$h_1$	2.8479	2.1287	1.9369	1.8130
$h_2$	3.0018	2.1433	1.7487	1.4528
$h_3$	0.9130	0.9370	0.7258	0.2841

