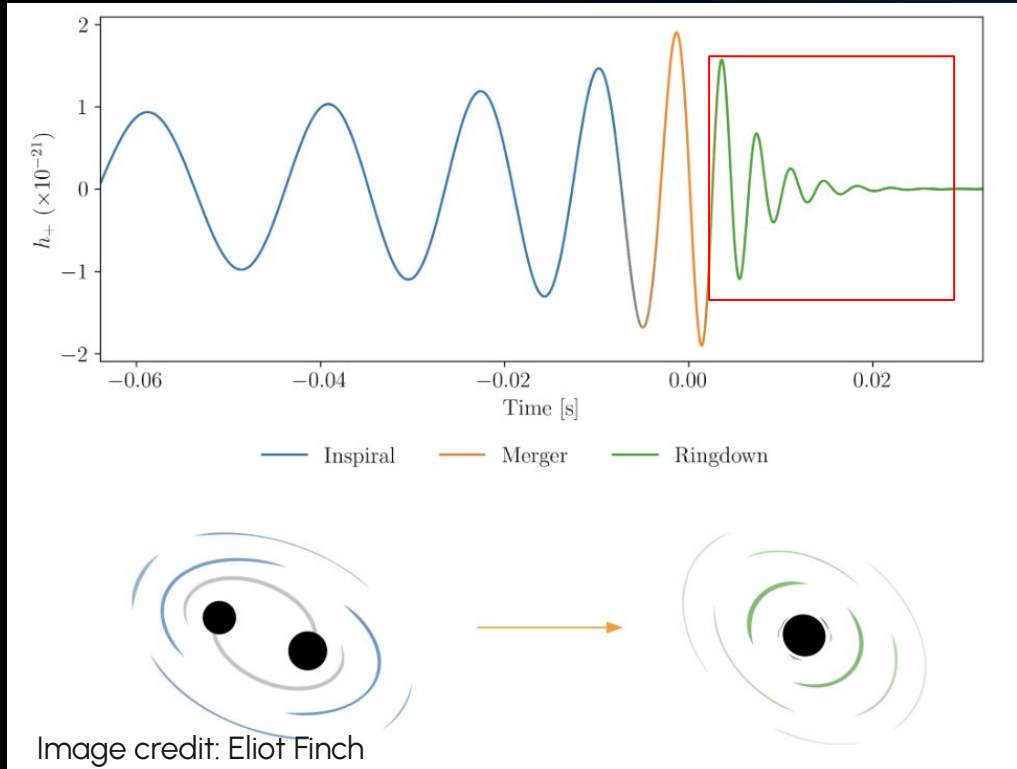# Inferring Inspiral Properties of Binary Black Hole Mergers from the Ringdown

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Mentors: Eliot Finch and Simona Miller

Introduction to Black Hole Ringdown

- Ringdown describes the portion of a gravitational wave signal after the merger

- Perturbed remnant black hole is losing energy and emitting gravitational waves
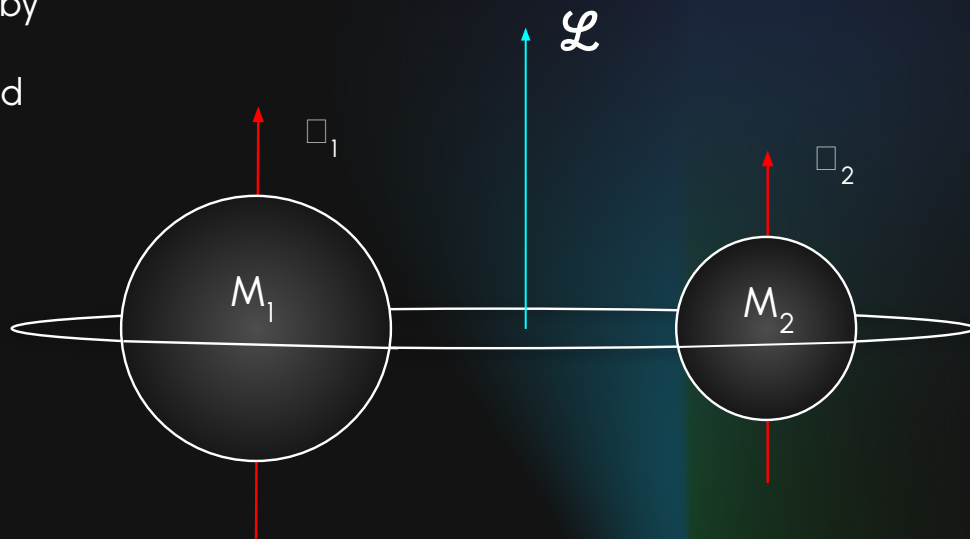
Image credit: Eliot Finch

Introduction to Black Hole Ringdown

Observed ringdown signal is impacted by

many parameters, including masses and

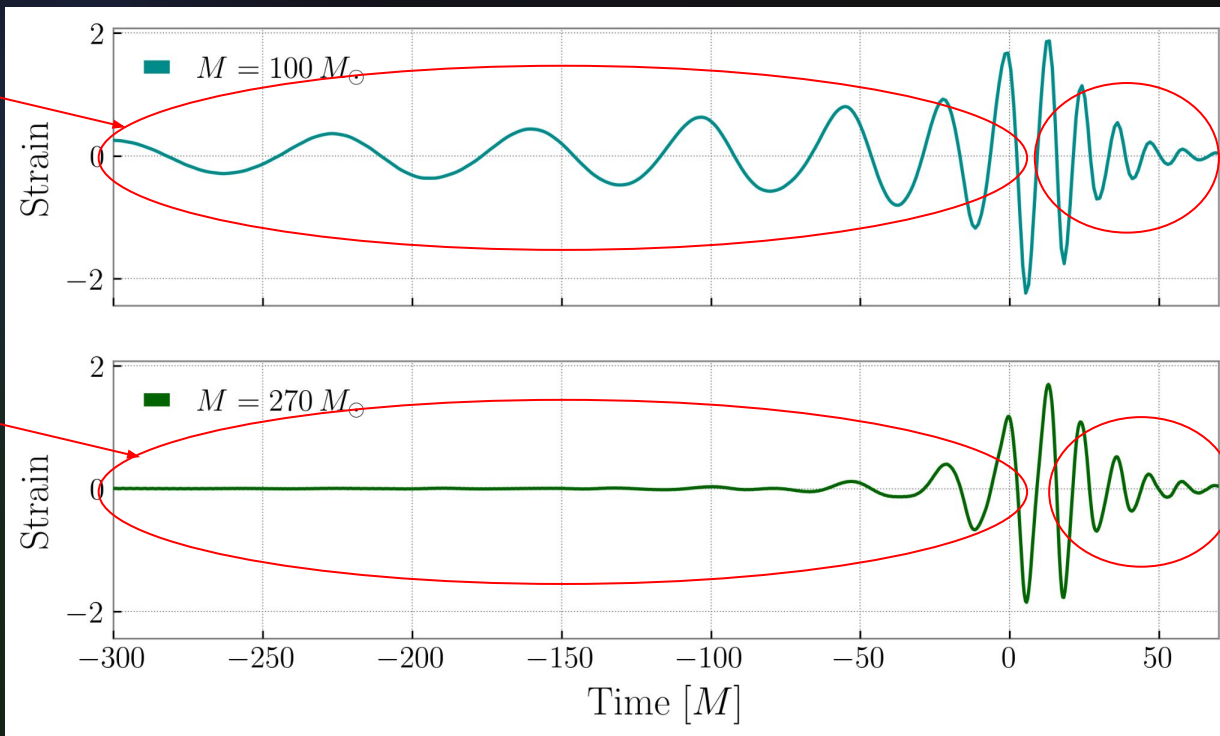spins of progenitor black holes

q: mass ratio, M_1/M_2

χ_1: spin of M_1

χ_2: spin of M_2

How do we know these parameters?

Measure q, $\square_1$, $\square_2$
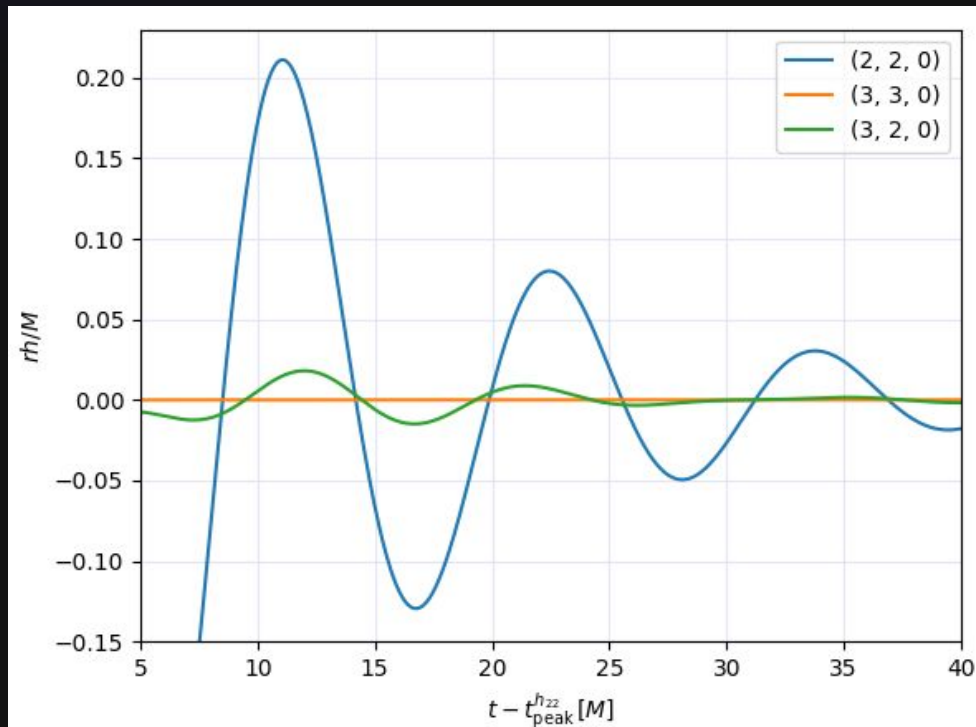
Ringdown determined by q, $\square_1$, $\square_2$

Very little visible inspiral

Can we predict q, $\square_1$, $\square_2$ from ringdown alone?

$M = 100 \, M_\odot$

$M = 270 \, M_\odot$

Strain

Strain

Time $[M]$

$-300 \quad -250 \quad -200 \quad -150 \quad -100 \quad -50 \quad 0 \quad 50$

Quasinormal Modes

- Ringdown waveform is a sum of damped sinusoids called quasinormal modes

- Starts at some time after peak strain to avoid nonlinearities in the merger

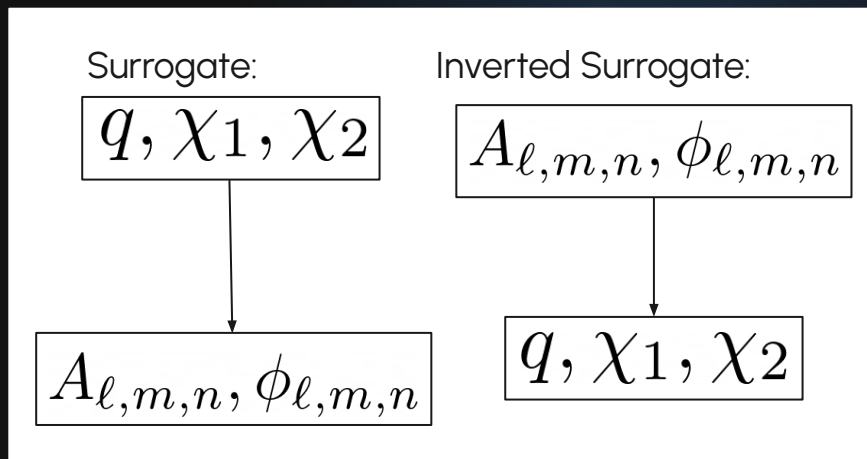$$h \sim A e^{-t/\tau} \cos(2\pi f t - \phi)$$

What is a ringdown surrogate?

There is no analytic way to map between

ringdown and inspiral parameters

A: ringdown strain amplitude

ϕ: phase angle

Surrogate:

$$q, \chi_1, \chi_2$$

$$A_{\ell,m,n}, \phi_{\ell,m,n}$$

Inverted Surrogate:

$$A_{\ell,m,n}, \phi_{\ell,m,n}$$

$$q, \chi_1, \chi_2$$

Inferring Inspiral Properties from Ringdown Signal

1) Create fake inspiral merger ringdown waveform based on q, χ_1, χ_2

2) We fit for amplitudes and phases in ringdown

3) **Use inverted surrogate to infer q, χ_1, χ_2 from amplitudes and phases**

4) Compare inferred parameters to true parameters
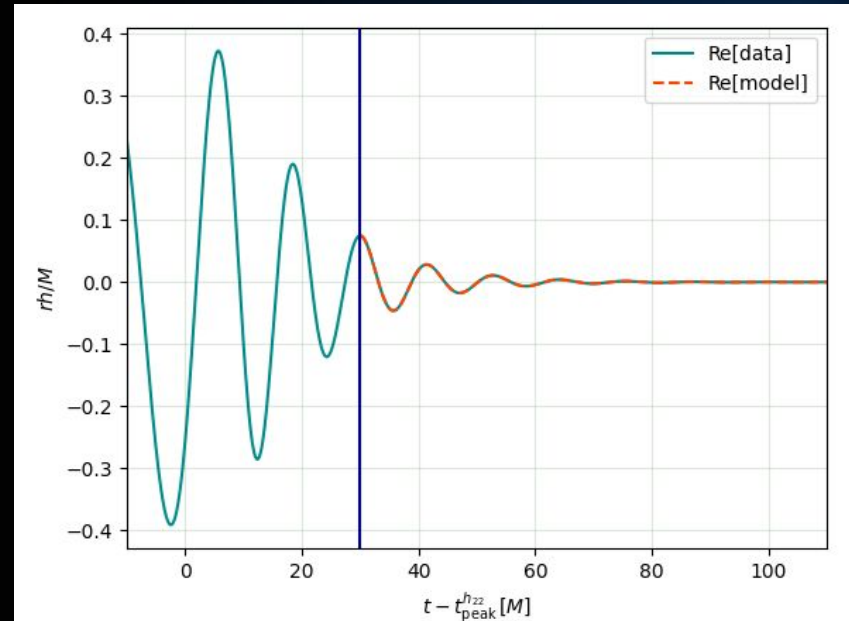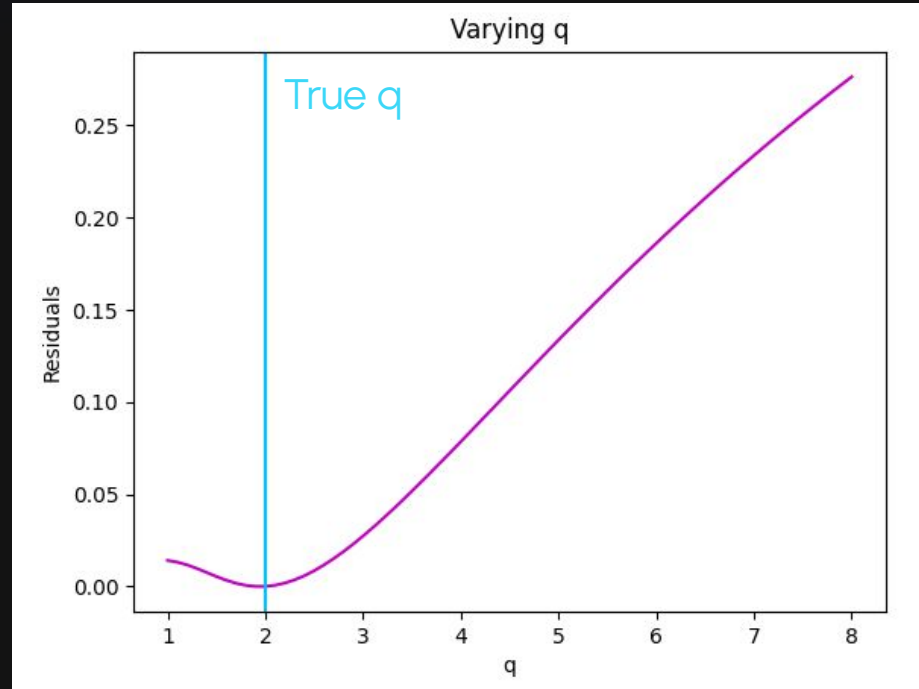
Inverting a Surrogate using Least Squares

Determine for which q, χ_1, χ_2 residual is minimized from least squares

$$C = Ae^{i\phi}$$

$$r_{\mathrm{Re},i} = \mathrm{Re}\left[C_i(q, \chi_1, \chi_2) - C_{i,\mathrm{observed}}\right]$$
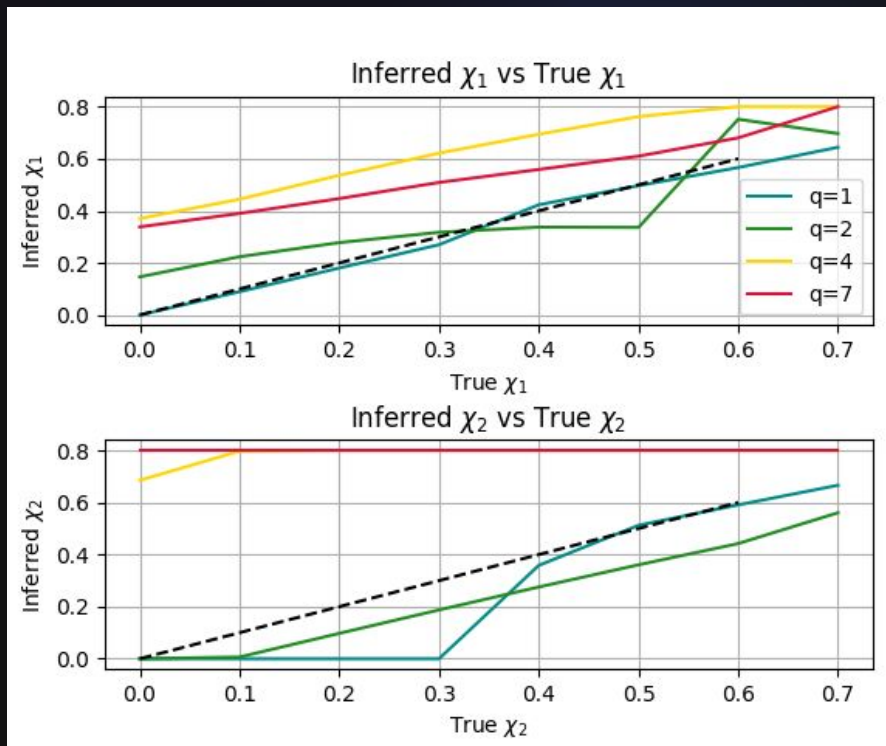
$$r_{\mathrm{Im},i} = \mathrm{Im}\left[C_i(q, \chi_1, \chi_2) - C_{i,\mathrm{observed}}\right]$$

$$\mathrm{residual} = \sum_{i \in \{(\ell,m,n)\}} \left(r_{\mathrm{Re},i}^2 + r_{\mathrm{Im},i}^2\right)$$

Tests with Inverted Surrogate

- Test what regions of [q, χ_1, χ_2] parameter space this fit breaks down

- Fit is much worse with higher mass ratio, especially for χ_2; does not find a good estimate and gets stuck on boundary
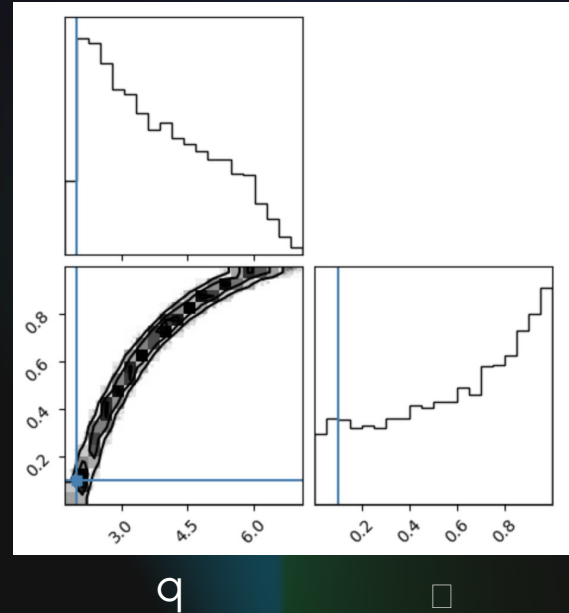
Switching to Sampling

1) Previous method gives point estimate of q, χ_1, χ_2

2) In reality, there can be multiple q, χ_1, χ_2 values that work

3) To explore this, we use sampling and define a likelihood for the inversion

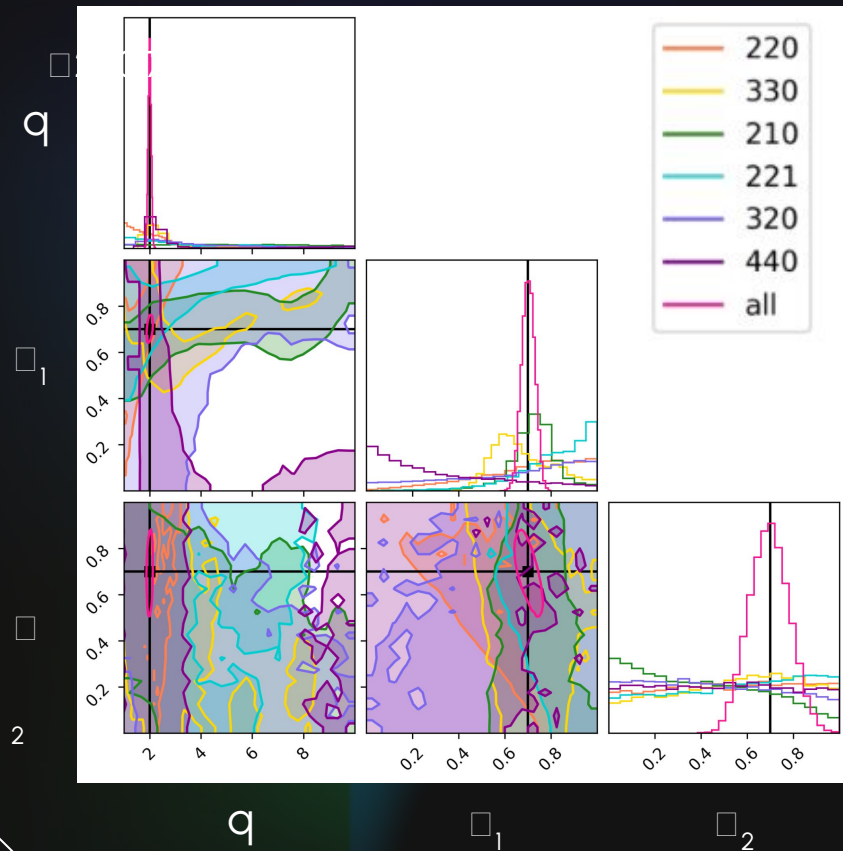4) Now we have a probability distribution for q, χ_1, χ_2

$$log\mathcal{L}_{Re,i}(Re[C_i]|q, \chi_1, \chi_2) \propto -\frac{1}{2}\left(\frac{Re[C_i(q, \chi_1, \chi_2) - C_{i,observed}]}{\sigma}\right)$$

σ is uncertainty in C

Fit for one mode   q=2, ⧠1=0.7,

Fit for two modes   q=2, ⧠1=0.7 ,

Standard Deviation of q for One Mode — Standard Deviation of q for Two Modes

Legend:
- $q = 2$, $\chi_1 = \chi_2 = 0.1$
- $q = 7$, $\chi_1 = \chi_2 = 0.1$
- $q = 2$, $\chi_1 = \chi_2 = 0.7$
- $q = 7$, $\chi_1 = \chi_2 = 0.7$

Standard Deviation of χ_1 for One Mode — Standard Deviation of χ_1 for Two Modes

Legend:
- $q = 2, \chi_1 = \chi_2 = 0.1$
- $q = 7, \chi_1 = \chi_2 = 0.1$
- $q = 2, \chi_1 = \chi_2 = 0.7$
- $q = 7, \chi_1 = \chi_2 = 0.7$
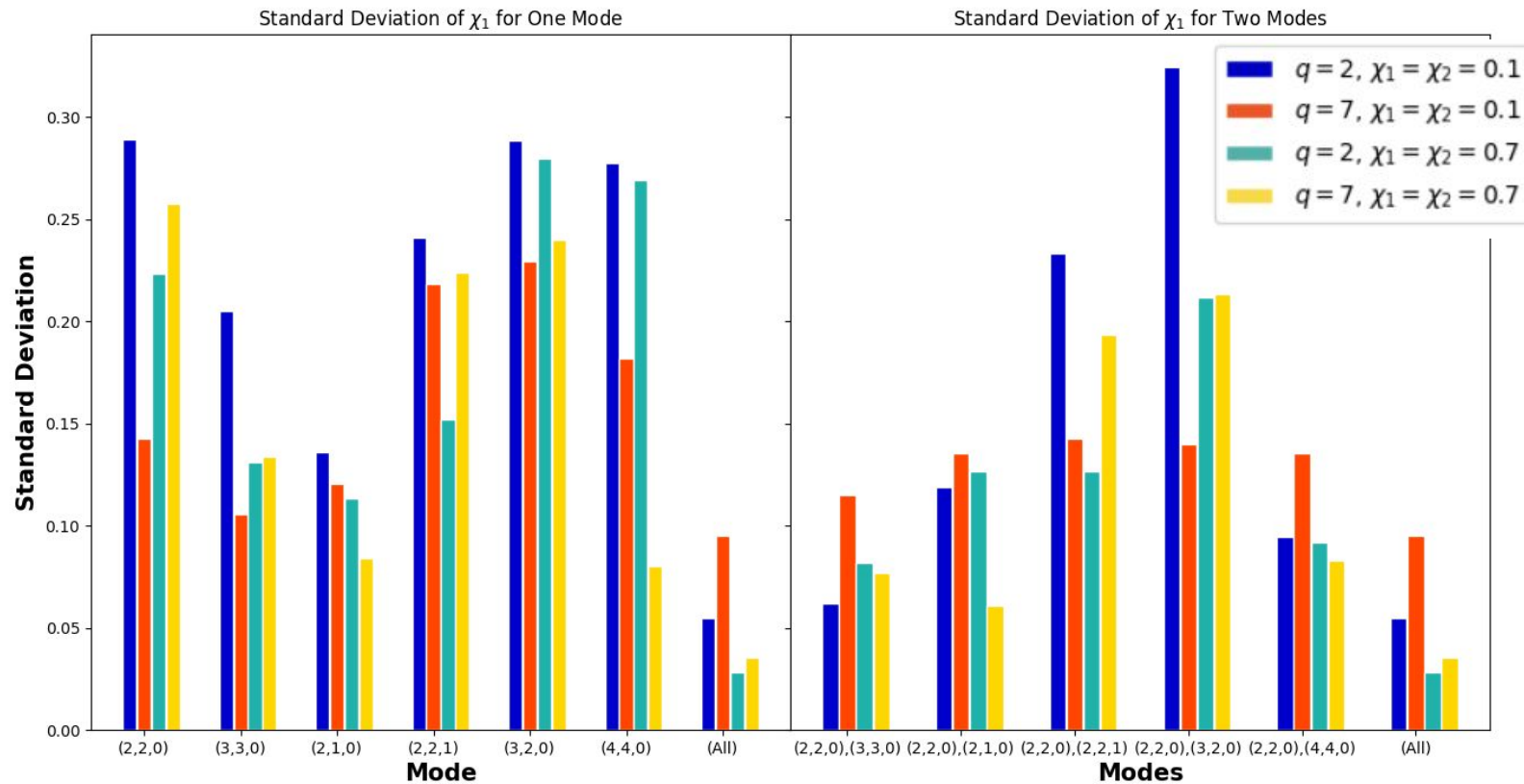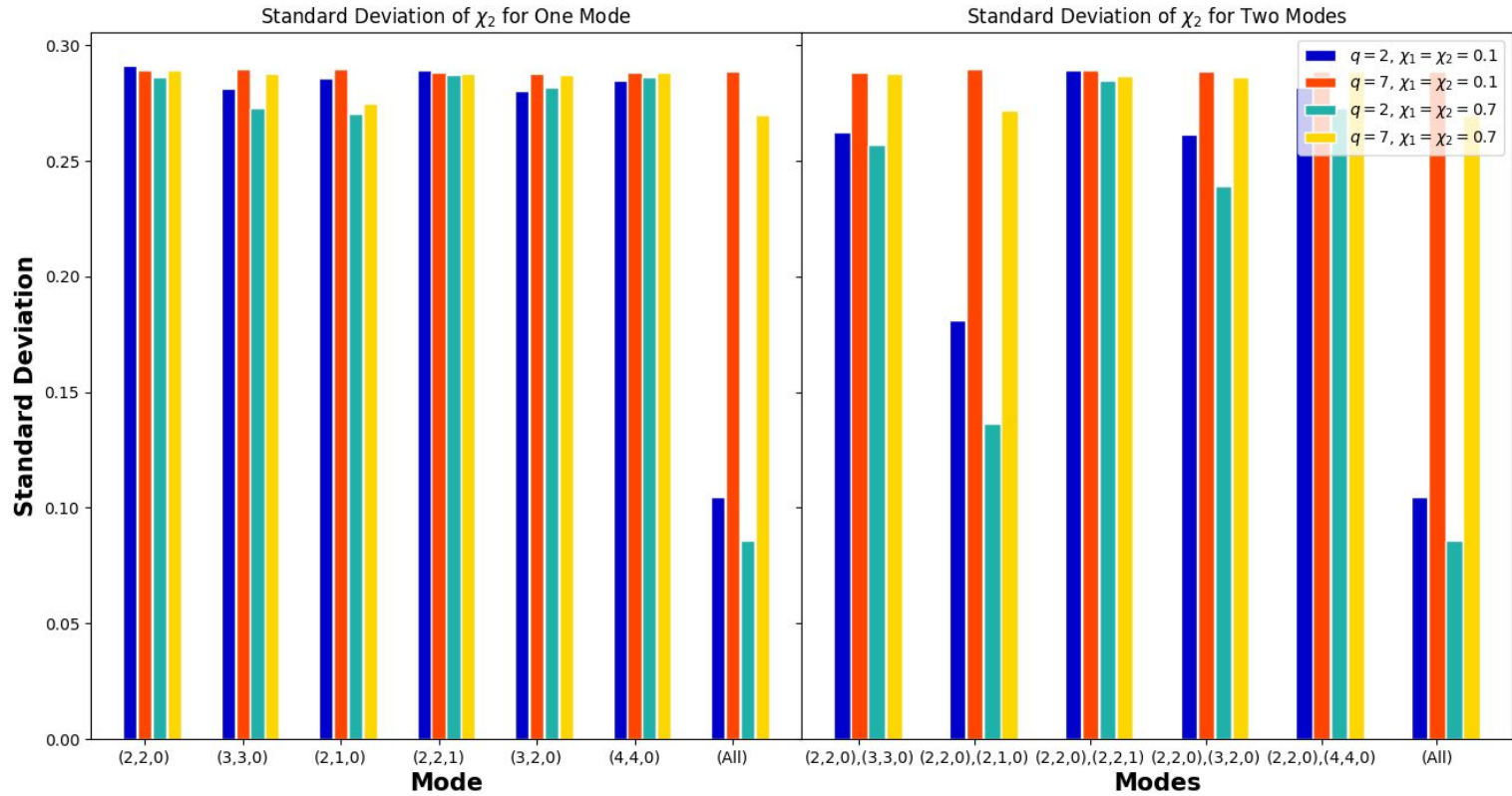
Standard Deviation of χ_2 for One Mode

Standard Deviation of χ_2 for Two Modes
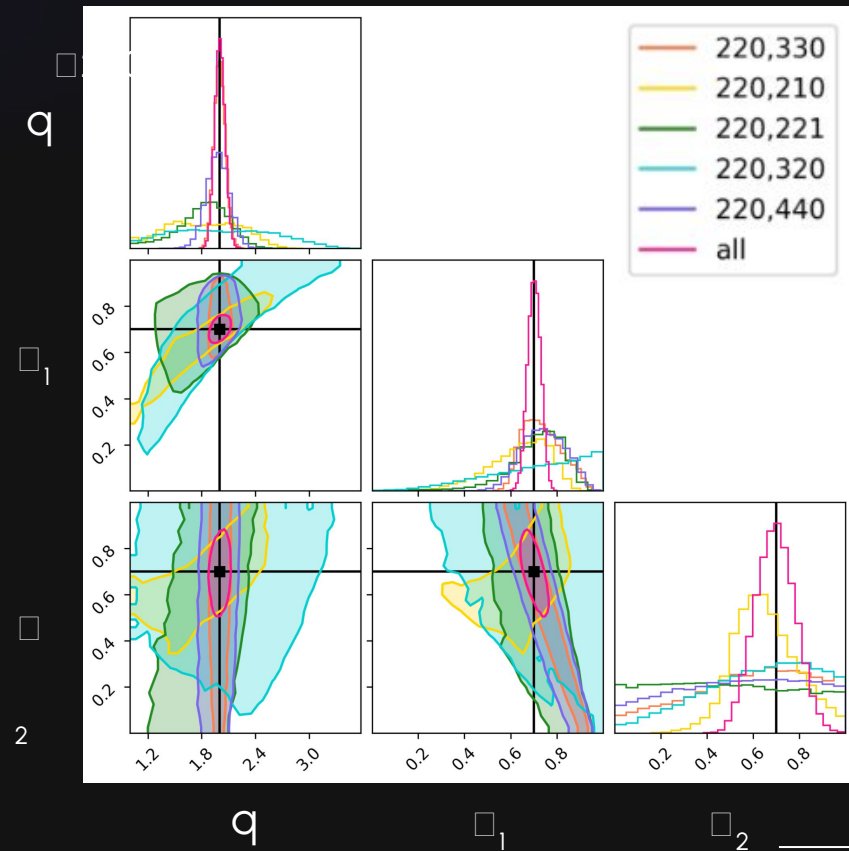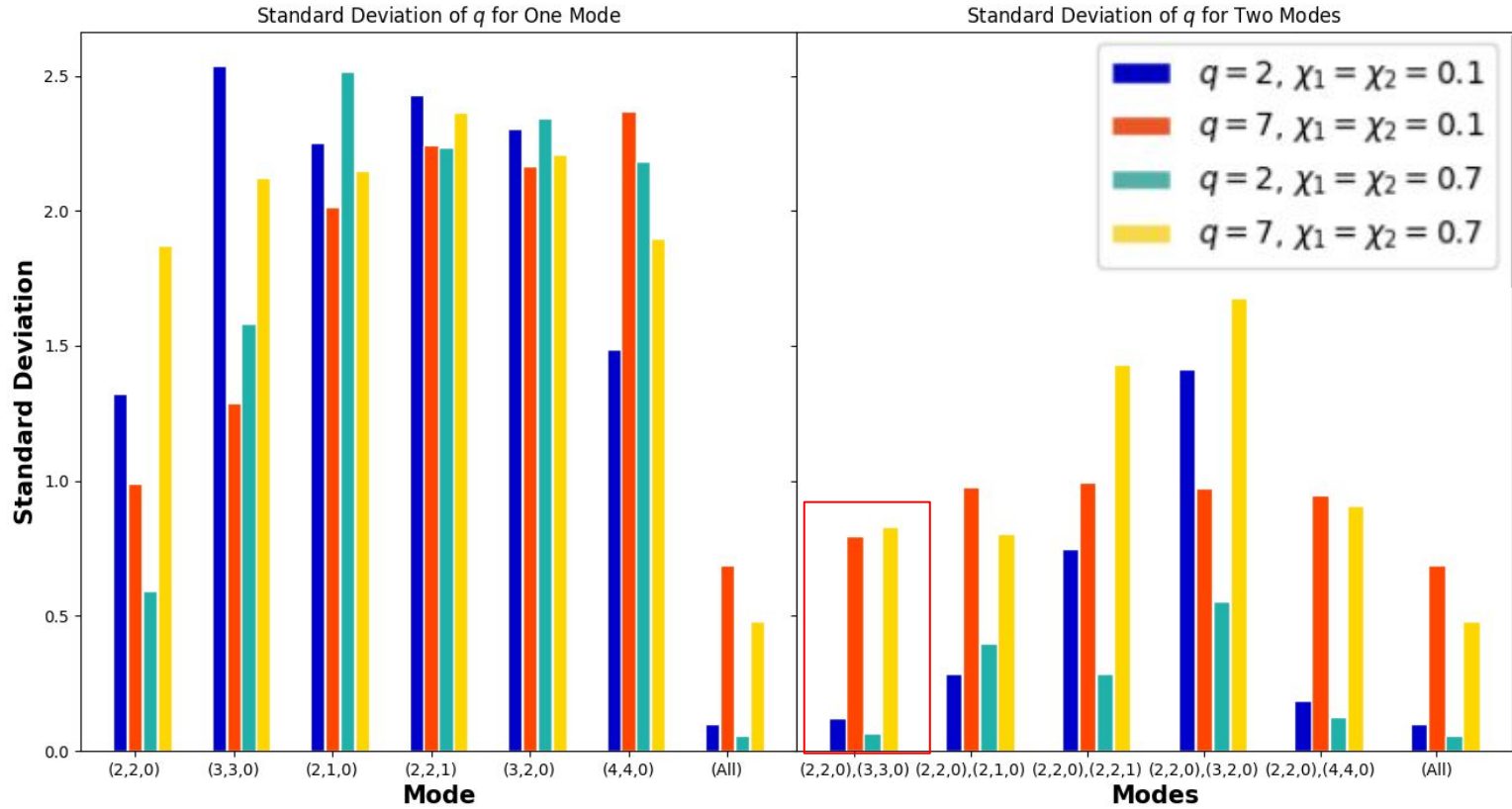
Conclusions

- It is possible to infer inspiral parameters from the ringdown alone

- We have inverted a ringdown surrogate to return q, χ_1, χ_2 when given {A_{lmn}, ϕ_{lmn}}

- (2,2,0) and (3,3,0) combination gives best constraints on q and χ_1 in the cases we've considered, but (2,2,0) and (2,1,0) gives good constraints on spin in some cases

Future Work

- Vary noise to determine at what SNR χ_2 can be constrained

- Further explore using residual from strain instead of amplitudes

- Repeat similar analysis for precessing systems

Acknowledgements

Mentors: Eliot Finch and Simona Miller

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Surrogates and Models Used

- qnmfits applied to NRHybSur3dq8 for "observed" data

- Jaxqualin, surfinBH, qnmpredictor used for "model" data

Surrogate/Model	Code Base	Description
–	qnmfits	Fit QNMs with least squares
–	Jaxqualin	QNM amplitude fits based on polynomials
NRSur3dq8_RD	surfinBH	QNM amplitude fits based on Gaussian processes
NRHybSur3dq8	gwsurrogate	IMR waveform surrogate
q8_3dAl	qnmpredictor	QNM amplitude fits based on Gaussian processes

Tests with Least Squares Inversion