Surrogate Models of Precessing Binary Black Hole Waveforms from Numerical Relativity Simulations

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Fast and Accurate BBH Waveform Models

Numerical relativity (NR) waveforms:

- Can have very small errors (mismatches of $\sim 10^{-5}$)
- Very computationally expensive

Fast waveform models (EOB, Phenom):

- Have small but much larger errors (mismatches $\lesssim 0.01$)
- Fast enough for parameter estimation ($\sim 10^8$ evaluations)

Why keep improving accuracy?

- Higher SNR events can expose parameter biases
- Statements using many events can reduce the statistical noise
- Tests of GR

Goal: Evaluate many NR waveforms offline, build a fast surrogate model purely from the NR data to be used online

Non-spinning SpEC Surrogate - Summary

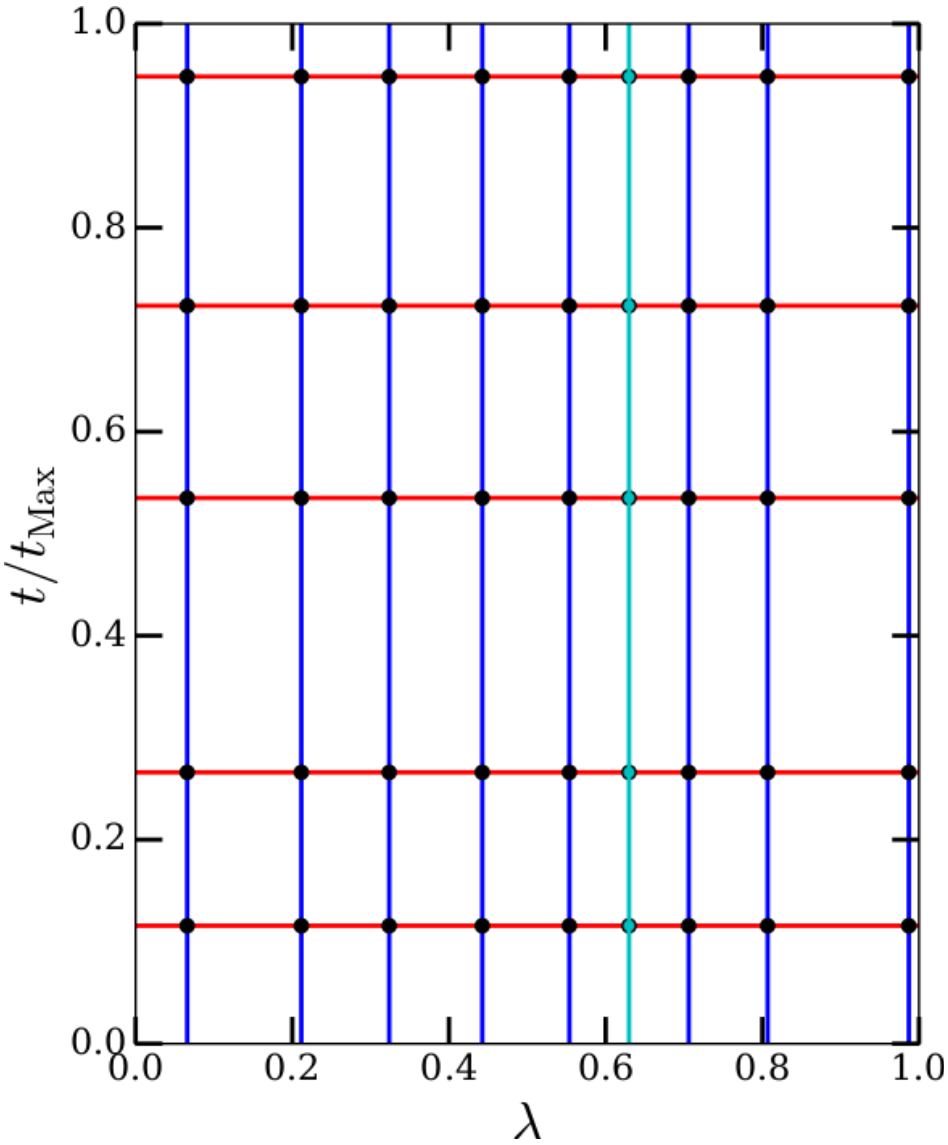
We build a surrogate model for the $1d$ parameter space of non-spinning SpEC BBH waveforms (Blackman et al. 2015)

- Mass ratios $q \leq 10$
- Built from 22 SpEC waveforms
- Includes selected modes with $\ell \leq 8$
- $2750M$ before peak amplitude (~ 15 orbits)
- All modes evaluated in $0.5\,\mathrm{s}$, $\sim 0.01\,\mathrm{s}$ per mode
- Mismatches ≤ 0.001 for $M = 115 M_\odot$ (design sensitivity)
- Available for download at http://www.black-holes.org/surrogates/

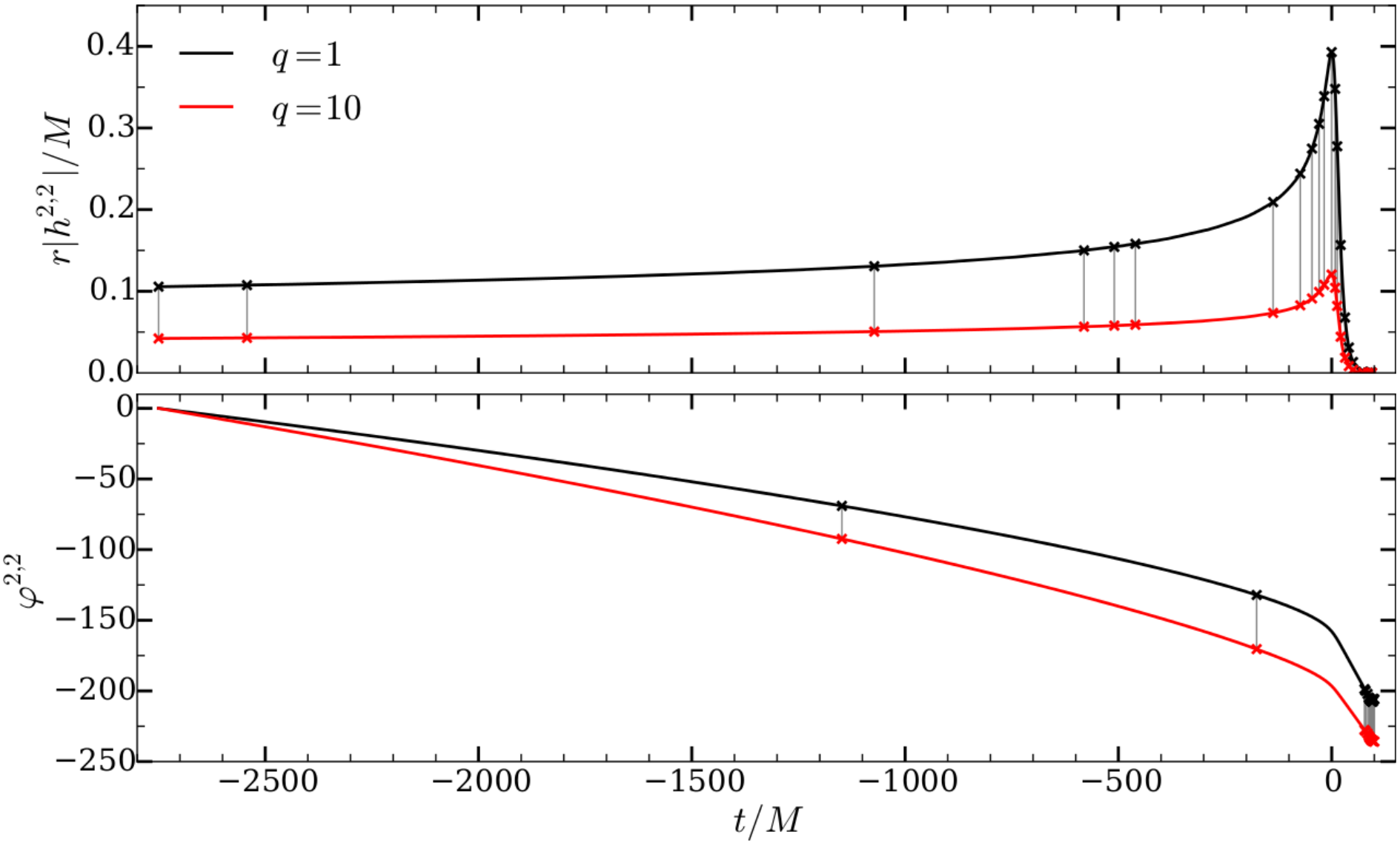
Surrogate Modeling Method

(Field et al. 2014)

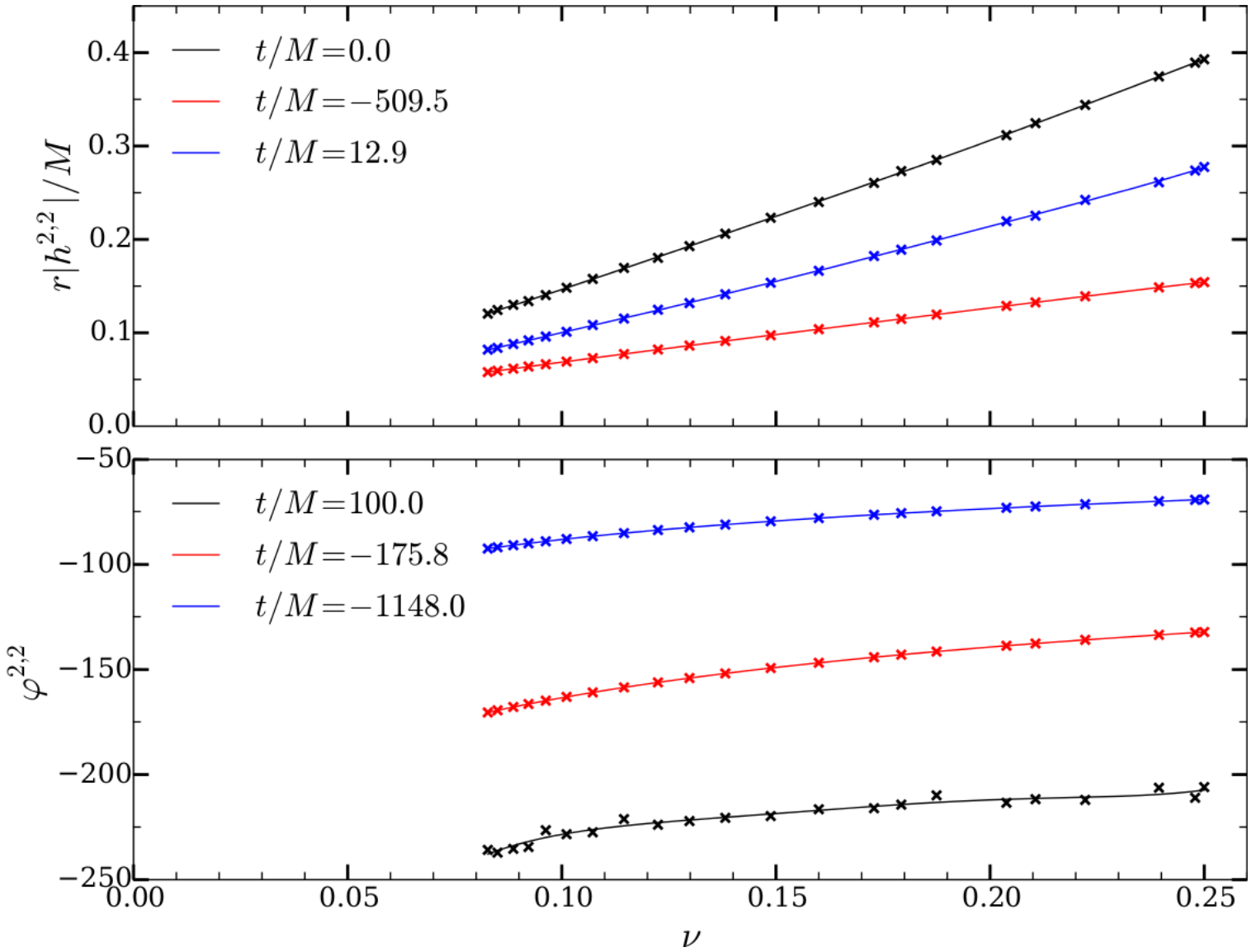
- Have N functions of time (blue lines)
- Compress data using a linear basis of size $m \leq N$
- Find m empirical time nodes (red lines)
- For each time node, fit the known data (black dots) across parameter space
- Evaluate fits at arbitrary parameter(s) λ (cyan dots)
- Use empirical interpolant to determine new data at all times (cyan line)



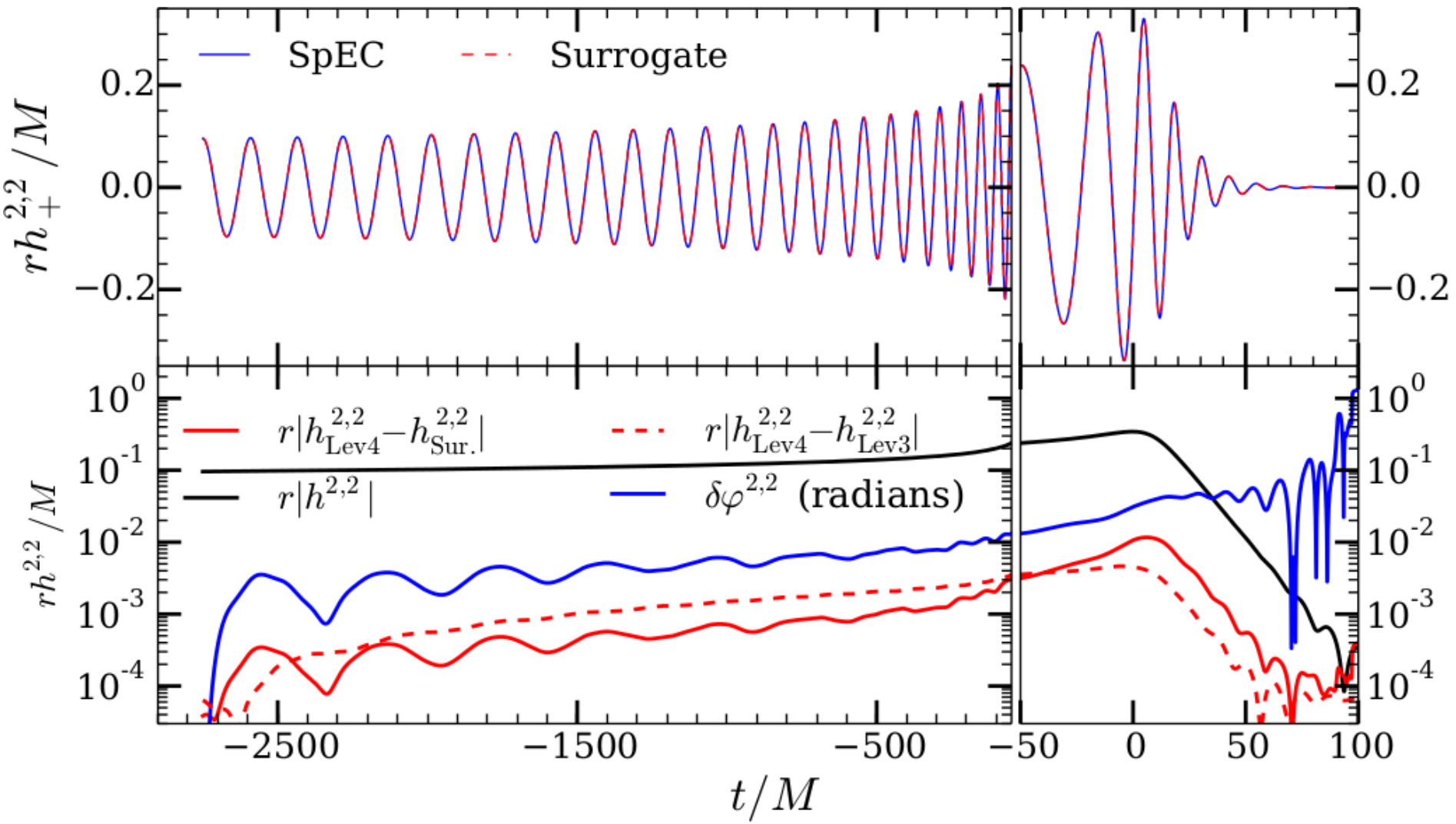
1*d* Non-spinning SpEC Surrogate: Empirical Interpolants



1*d* Non-spinning SpEC Surrogate: Fits

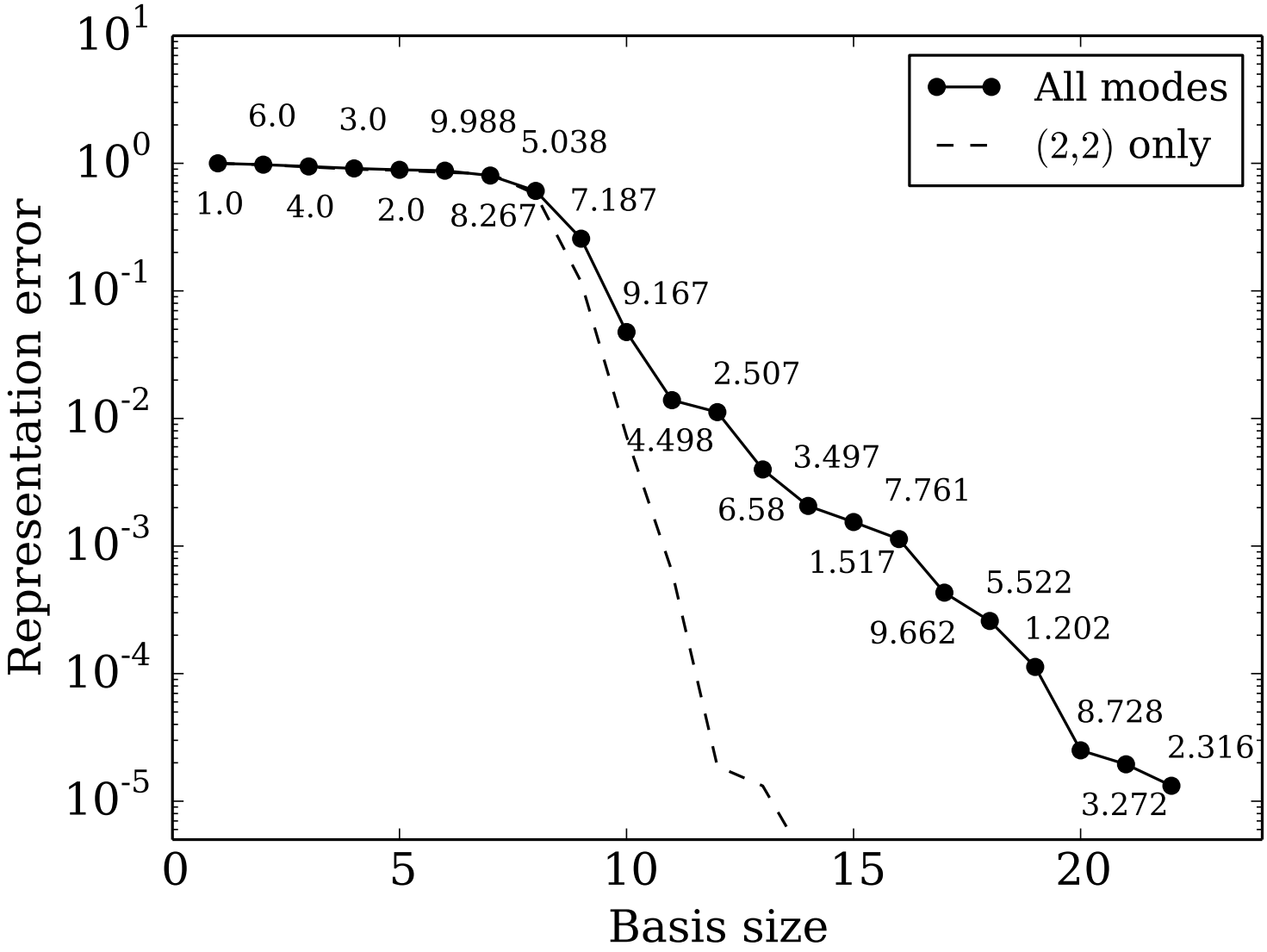


1*d* Non-spinning SpEC Surrogate: Errors



1*d* Non-spinning SpEC Surrogate: Choosing Parameters

Use EOBNRv2 waveforms including higher modes, find greedy parameters

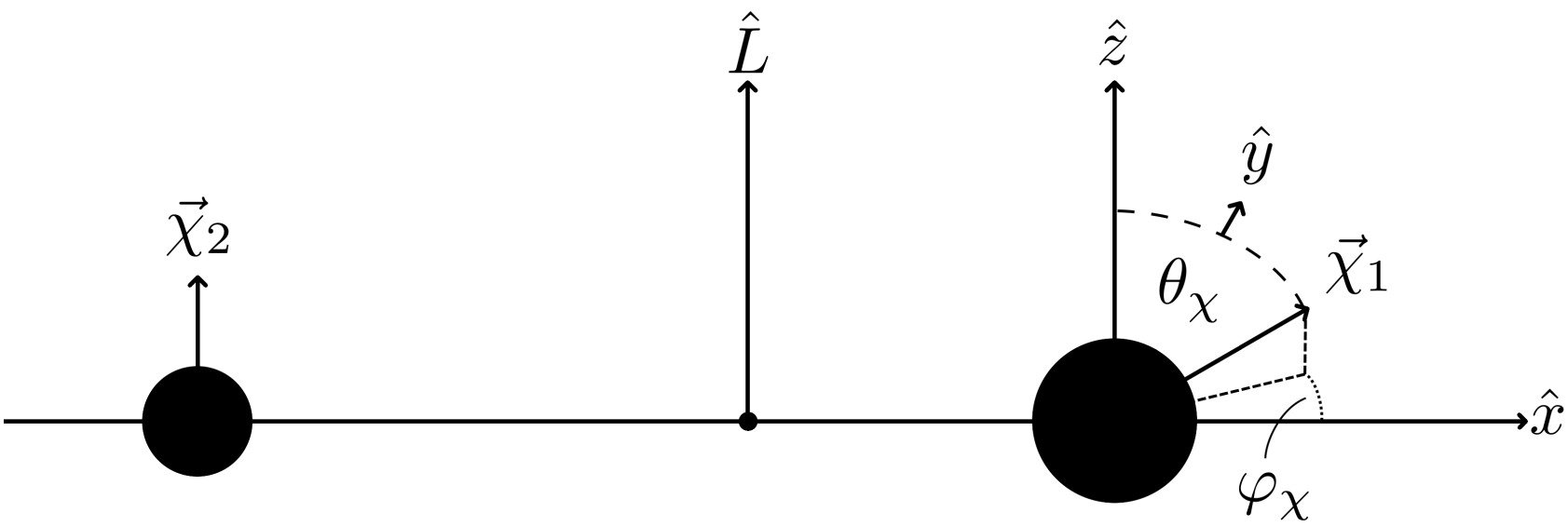


Precessing SpEC Surrogate: Summary

Motivated by GW150914, we build a surrogate model of precessing SpEC waveforms for nearly-equal mass BBH systems

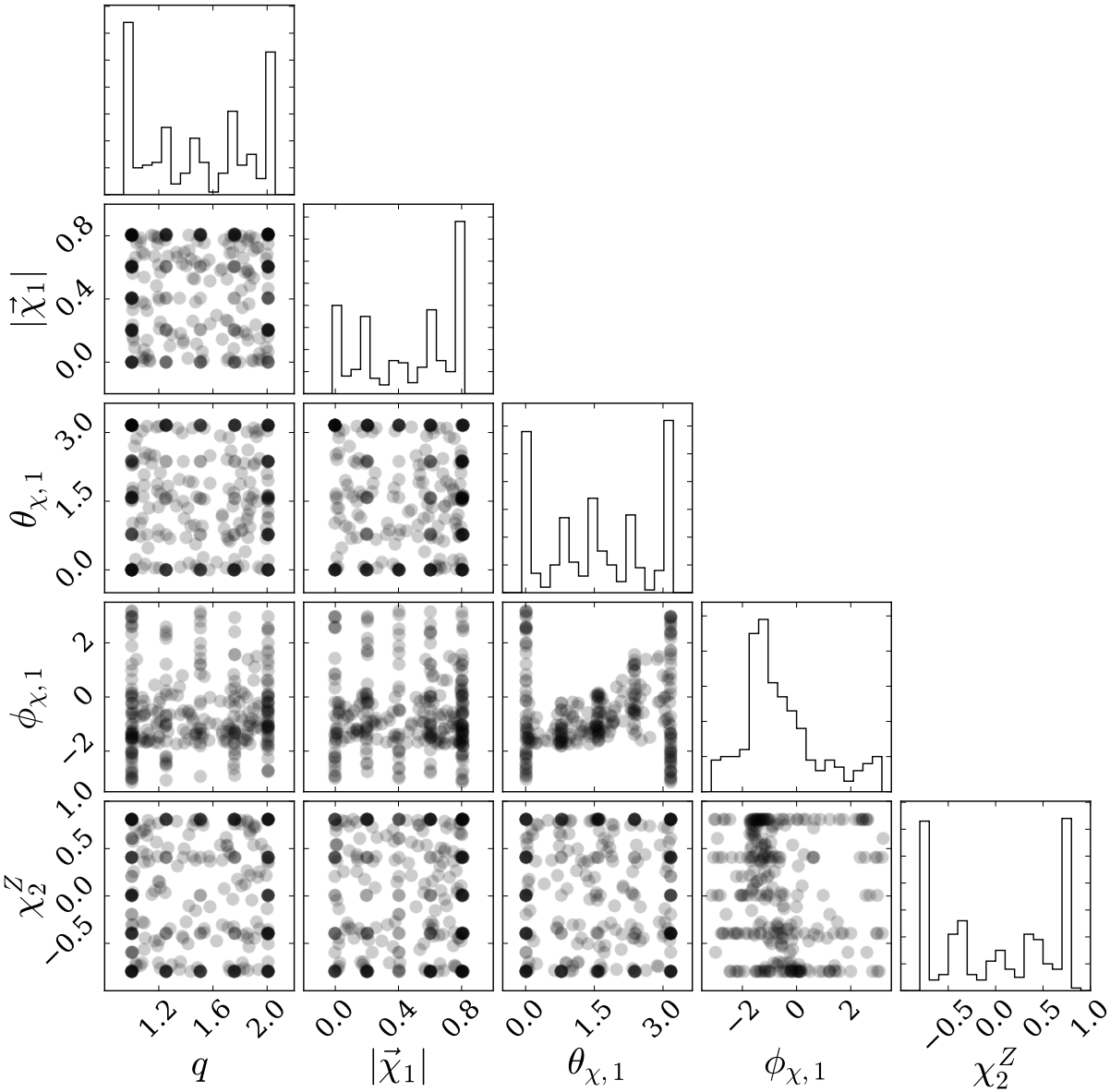
- Smaller black hole spin is initially parallel to $\vec{L}$ (reduces parameter space to $5d$)
- Built from 276 new SpEC simulations (Dan Hemberger's talk)
- Mass ratios $q \leq 2$
- $|\vec{\chi}_i| \leq 0.8$
- Includes $\ell \leq 3$ modes
- $4500M$ before peak amplitude (~ 20 orbits)
- Evaluated in $\sim 1\,\mathrm{s}$
- Typical mismatches of 0.001
- Frequency domain surrogate model built on top - evaluated in $50\,\mathrm{ms}$

Precessing SpEC Surrogate: Parameter Space



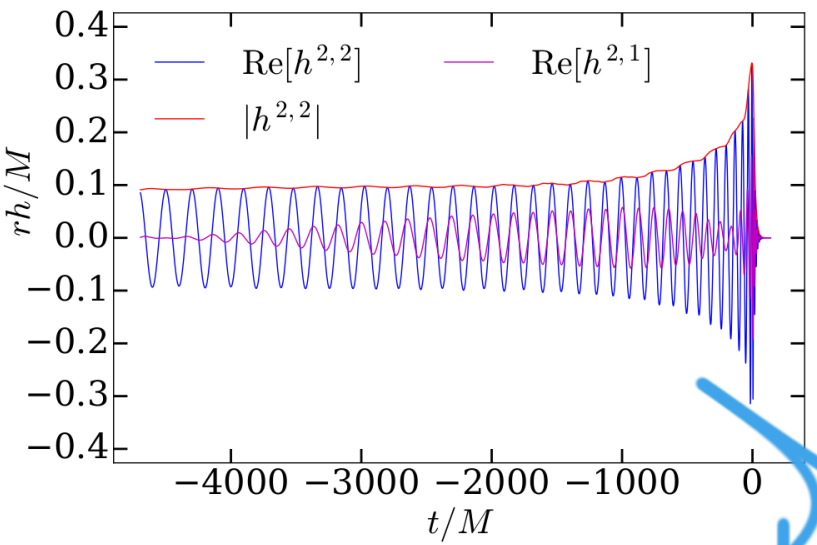
Precessing SpEC Surrogate: Greedy Parameters

- Selected using PN waveforms
- Build full surrogate at each iteration
- Greedy points have $\varphi_\chi = 0$
- NR simulations end up having $\varphi_\chi \neq 0$

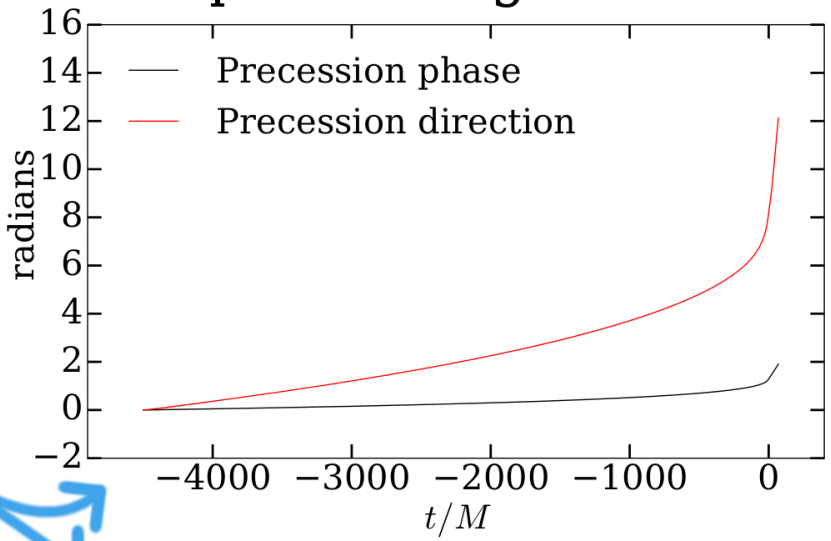


Precessing SpEC Surrogate: Waveform Decomposition

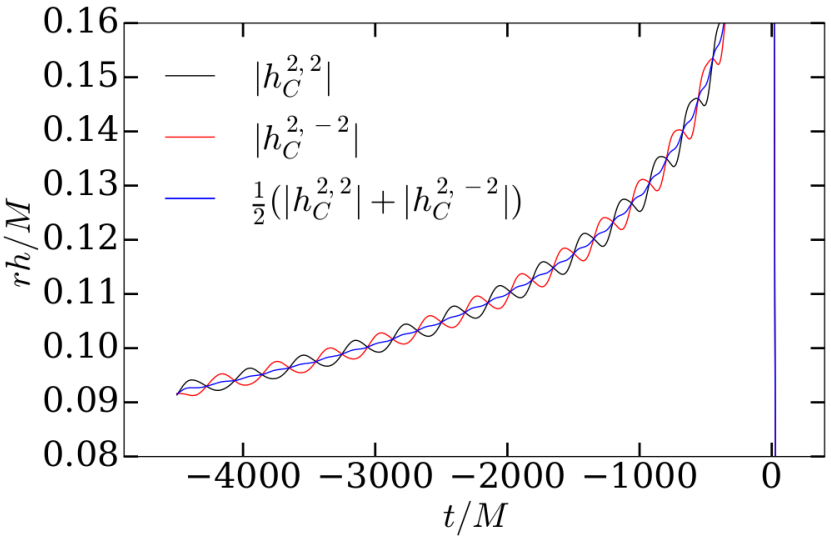
Inertial Frame Waveform



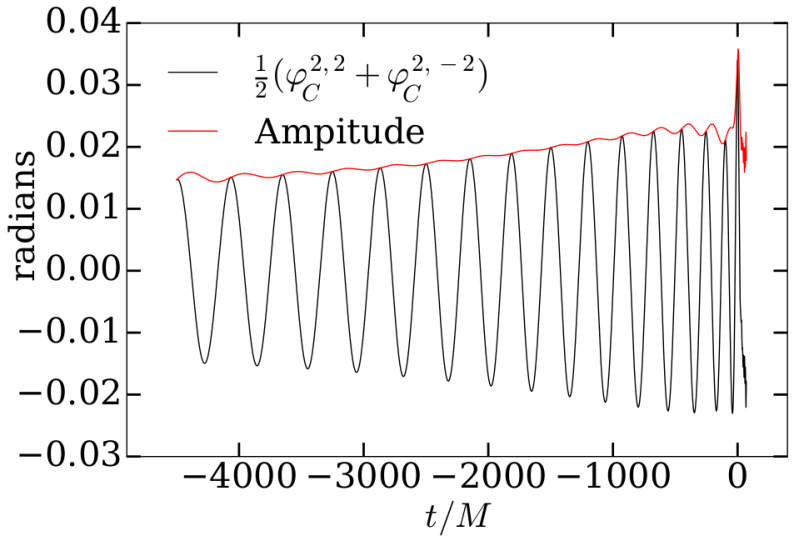
Coprecessing Frame



(L,±m) secular amp/phase

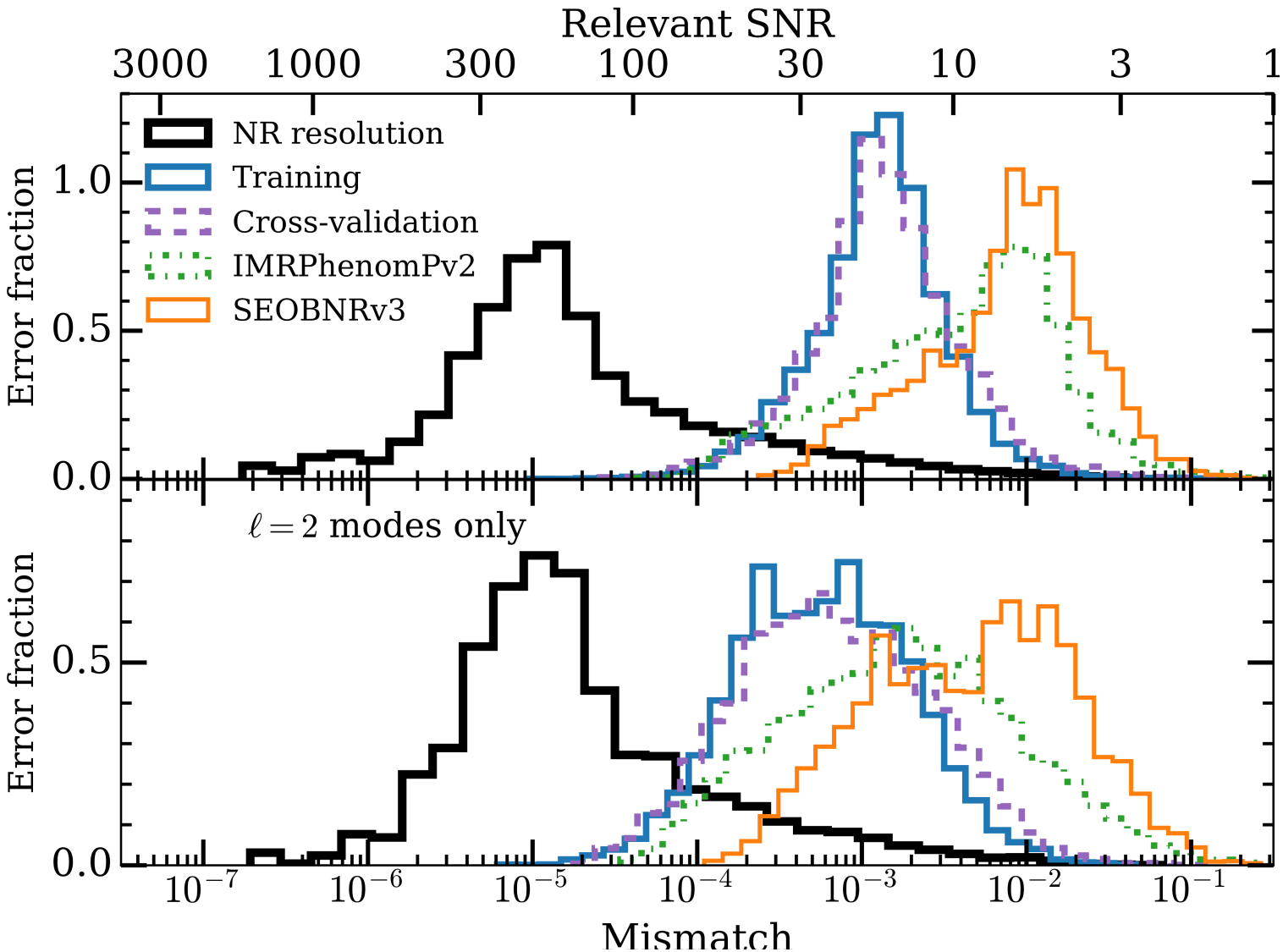


(L,±m) nutating amp/phase



Precessing SpEC Surrogate: Mismatches

Random extrinsic parameters, single detector, flat PSD

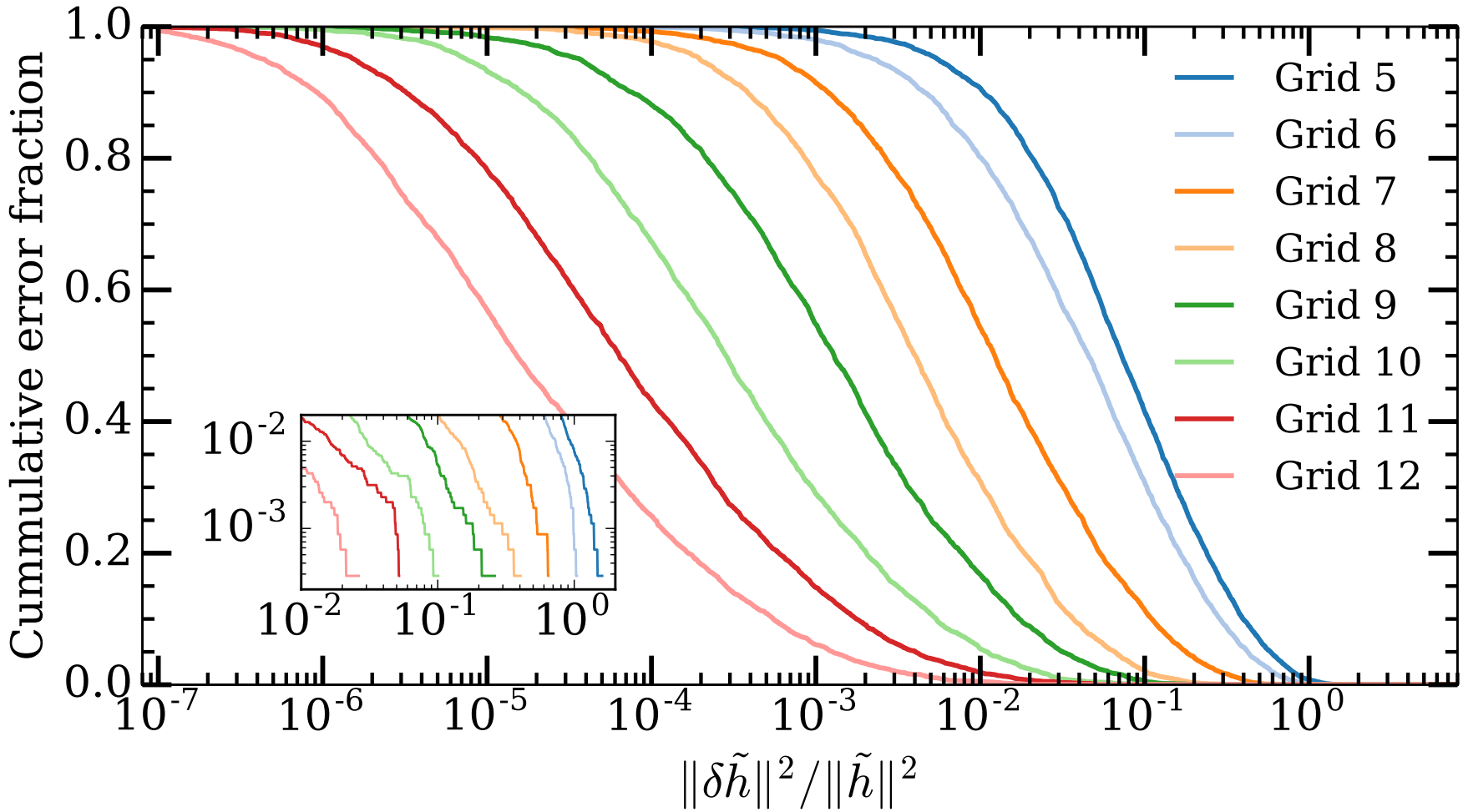


Precessing SpEC Surrogate: Frequency Domain

We build a surrogate model for the Fourier transform of the (tapered) output of the time domain precessing surrogate model
Similar method to SEOBNRv2_ROM (Prrer 2016):

- Evaluate time domain model on a grid of points in parameter space
- Taper the waveform modes
- Perform a FFT to obtain the frequency domain waveform modes
- For each mode, build a reduced basis and empirical interpolant
- Use $5d$ cubic tensor-spline interpolation to interpolate empirical nodes over the parameter space
- Compute errors using parameters off the grid
- Increase grid size until errors are sufficiently small
- Can be evaluated in $50\,\mathrm{ms}$

Precessing SpEC Surrogate: Frequency Domain



Summary and future work

$1d$ non-spinning SpEC surrogate model:

- $q \leq 10$
- Comparable accuracy to SpEC waveforms used to train the model

$5d$ precessing SpEC surrogate model:

- Suitable parameter range for GW150914 parameter estimation
- Errors are significantly larger than SpEC waveform errors
- More accurate than other waveform models within its range of validity

Next steps:

- Parameter estimation on GW150914 data with precessing surrogate
- Build a fully precessing $7d$ model (many new simulations required)
- Hybridize the output of surrogate models with PN or EOB
- Go to higher mass ratios (for the precessing case)