Title: A multi-mode time-domain surrogate model for gravitational wave signals from comparable to extreme mass-ratio black hole binaries

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Abstract: We present EMRISur1dq1e6, a reduced-order multi-mode time-domain surrogate model of gravitational waveforms for non-spinning black hole binary systems with comparable- to extreme mass-ratio configurations. This surrogate model is trained on waveform data generated by a point-particle black hole perturbation theory (ppBHPT) framework computed from a high-performance Teukolsky equation solver code. In the comparable mass-ratio regime, the gravitational waveforms generated through ppBHPT agree surprisingly well with those from full numerical relativity after scaling of the ppBHPTâ€™s total mass parameter. This model extends the EMRISur1dq1e4 waveform model, which spans 13,500M in duration and includes modes only up to (l,m)=(5,5). EMRISur1dq1e6, on the other hand, covers mass ratios from 3 to 1,00,000, can generate waveforms of duration up to 350,000M, and includes several spherical harmonic modes up to (l,m)=(10,10). The accuracy of training data is further improved by employing an updated plunge model in the ppBHPT framework. EMRISur1dq1e6 surrogate model has been extended to enable data analysis studies in the high-mass ratio regime, including potential intermediate mass-ratio signals from LIGO/Virgo and events of interest to the future observatories such as Einstein Telescope, Voyager and Cosmic Explorer.

A multi-mode time-domain surrogate model for gravitational wave signals from comparable to extreme mass-ratio black hole binaries

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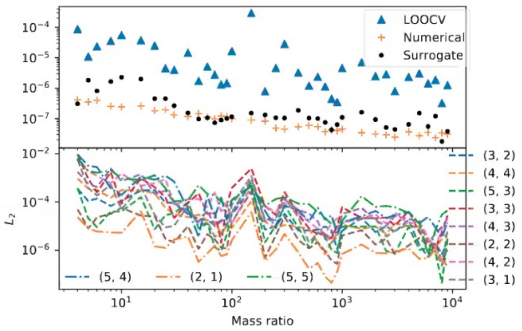
EMRISur1dq1e4

- **Surrogate Model** [Rifat, Field, Khanna & Varma; arXiv.1910.10473]
  - Trained on waveforms from time-domain Teukolsky solver
  - From comparable to extreme mass ratio : $q=[3,10^4]$
  - 13500 M long waveforms
  - Non-spinning
  - Calibrated to NR in the small mass ratio : q=[3,10]
  - Higher Order Modes :

    (2,1),(3,1),(3,2),(3,3),(4,2),(4,3),(4,4),(5,3),(5,4),(5,5)



- **Data Analysis** of Intermediate Mass Ratio Inspirals in AdvLIGO

gw-surrogate

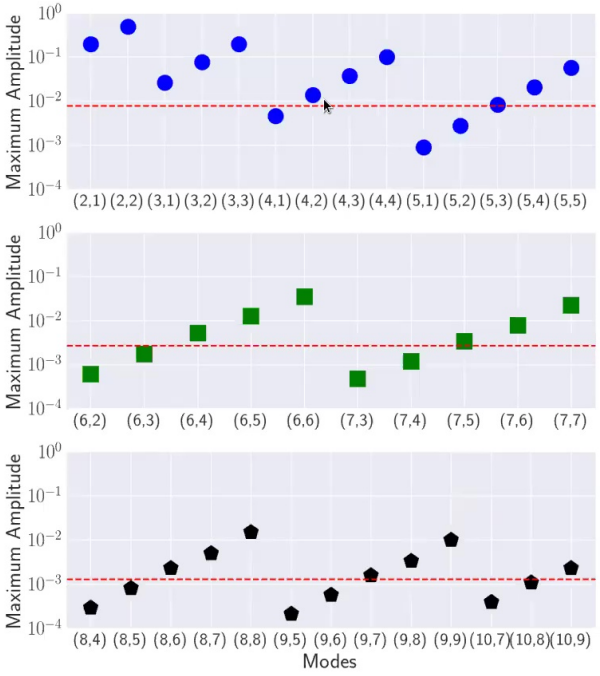
[Field, Islam, Khanna, Rifat, Varma]

Black-hole Perturbation Toolkit

NextGen EMRISurrogate : An Overview

- **Mass Ratio** : q=3 to q=10^6
- **Improved training data** : [Lim, Khanna, Apte & Hughes; arXiv.1901.05902]
  - updated plunge model in the ppBHPT framework
- **More modes** :
  - (2,1),(2,2)
  - (3,1),(3,2),(3,3)
  - (4,2),(4,3),(4,4)
  - (5,3),(5,4),(5,5)
  - (6,4),(6,5),(6,6)
  - (7,5),(7,6),(7,7)
  - (8,6),(8,7),(8,8)
  - (9,7),(9,8),(9,9)
  - (10,8),(10,9)
- **Better match to NR in the small mass ratio regime** :
  - HMs are calibrated too
- **Longer wavefoms** [Relevant for LIGO, Cosmic Explorer, Einstein Telescope]
  -35000M

Which Modes to Choose ?



- **More modes** :
  - (2,1),(2,2), (3,1),(3,2),(3,3)
  - (4,2),(4,3),(4,4),(5,3),(5,4),(5,5)
  - (6,4),(6,5),(6,6),(7,5),(7,6),(7,7)
  - (8,6),(8,7),(8,8),(9,7),(9,8),(9,9)
  - (10,8),(10,9)

Mass ratio q=3

Building the Surrogate

4

- **Data Pieces**:

1. Amplitude and Phase of the 22 Mode [Blackman *et al* 2017]
2. Real and Imaginary Part of Higher Modes in the co-orbital frame [Varma *et al* 2018]

Data Compression

- For each data piece, we construct a compact Reduced Basis functions

⇩

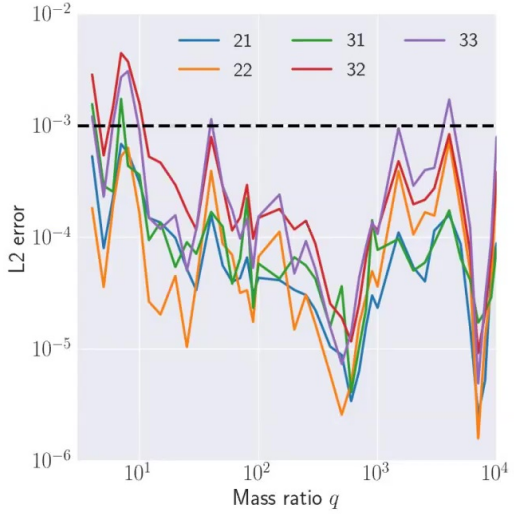
- We then construct a Emperical Interpolant in time using a Greedy Algorithm which picks the most representative time-nodes

⇩

Fitting

- We construct parametric fits of each data piece at each time node across 1d parameter space using Splines / Gaussian Process Regression

Time Domain Errors

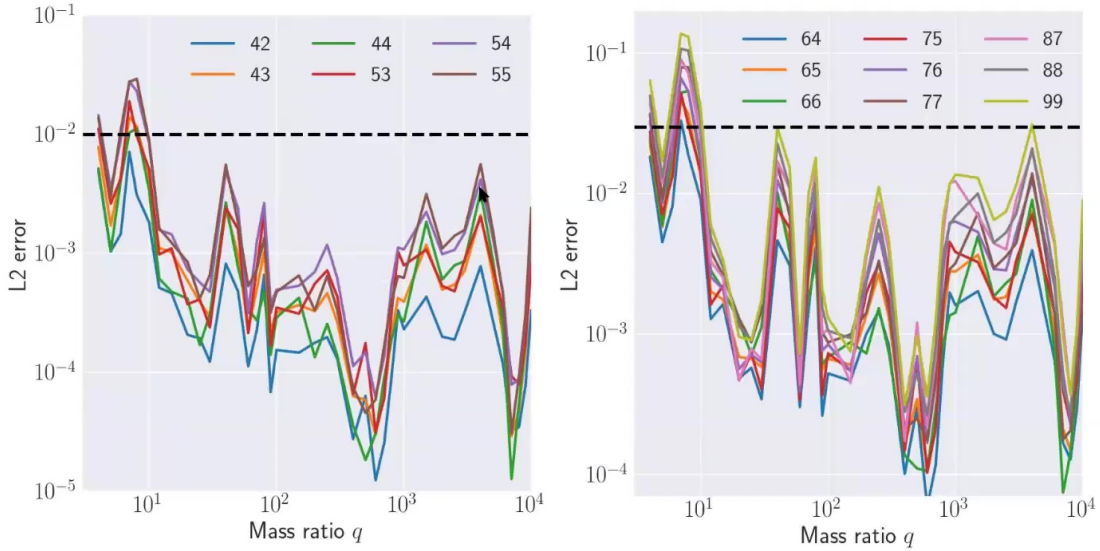


L_2 Errors
between Surrogate and Training Data

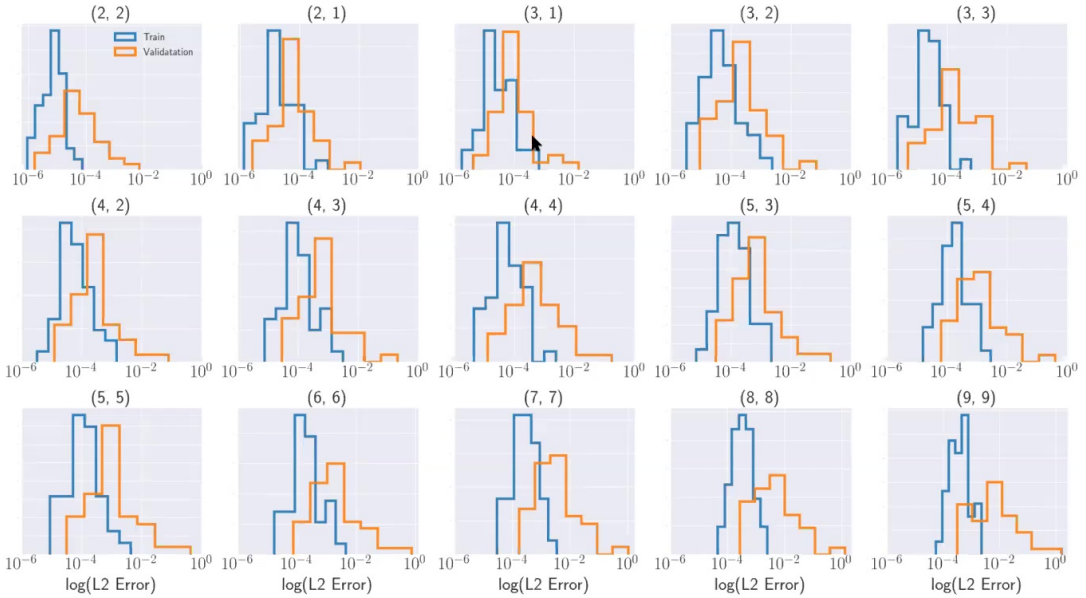
$$\mathcal{E}[h,\tilde{h}] = \frac{1}{2}\frac{\sum_{\ell,m}\int_{t_1}^{t_2}|h_{\ell m}(t)-\tilde{h}_{\ell m}(t)|^2 dt}{\sum_{\ell,m}\int_{t_1}^{t_2}|h_{\ell m}(t)|^2 dt},$$

Leave-One-Out-Cross-Validation Study

Time Domain Errors

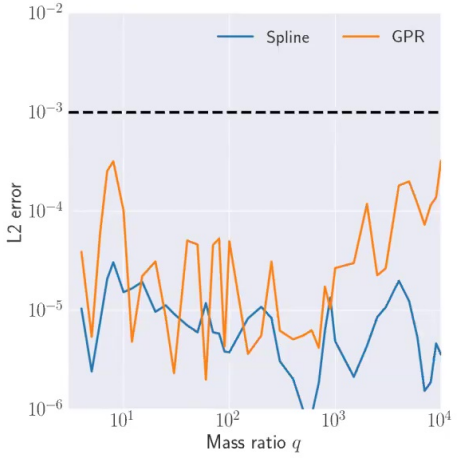


Time Domain Errors

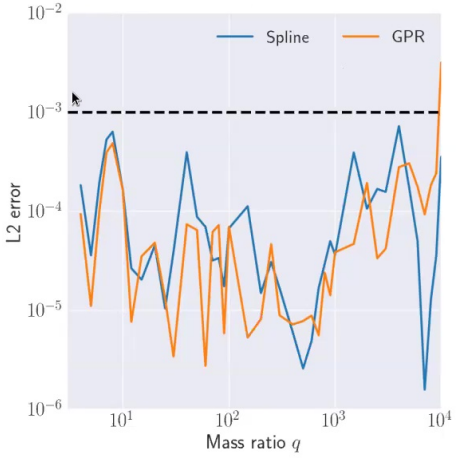


Time Domain Errors

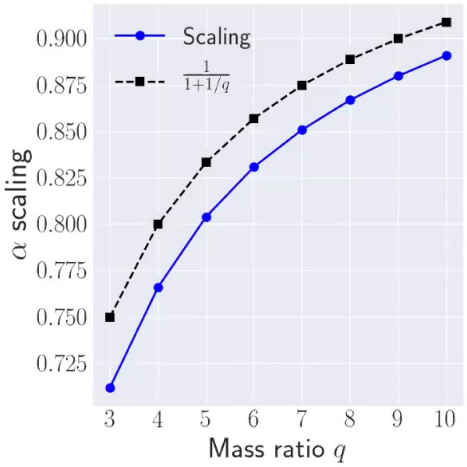
Training



Validation



Small Mass Ratio Regime : Comparison to NRHybSur3dq8

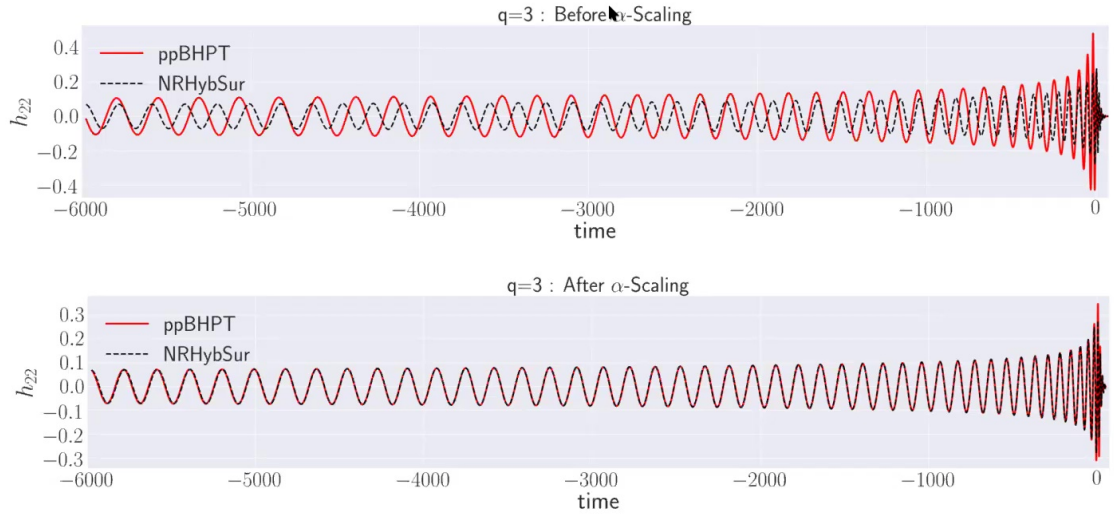


Mass Scaling

$$h^{\ell,m}_{\mathrm{s},\alpha}(t;q) = \alpha h^{\ell,m}_{\mathrm{s}}(t\alpha;q)$$

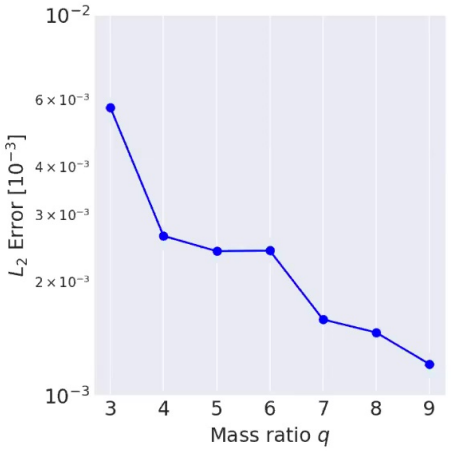
A third order polynomial in symmetric mass ratio

Small Mass Ratio Regime : Comparison to NRHybSur3dq8

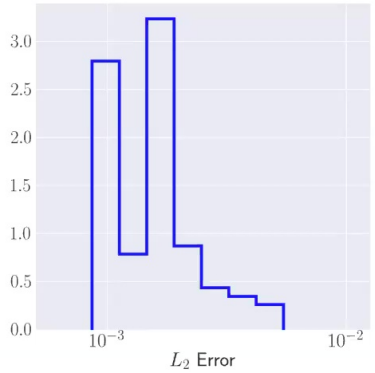


Small Mass Ratio Regime : Comparison to NRHybSur3dq8

22 Mode Errors



22 Mode error histogram



Conclusion

The Model will eventually be extended up to $q=10^6$

We will model modes up to l=10

We show that ppBHPT waveforms can be matched to NR with a simple mass scaling

Our model will help data analsyis in both comparable to intermediate mass ratios in the context of current detectors

Thank You