Title: Surrogate model for gravitational wave signals from black hole binaries built on black hole perturbation theory waveforms calibrated to numerical relativity : one model to rule both comparable and extreme mass ratio regime

Speakers: Tousif Islam

Series: Strong Gravity

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Abstract: We present a reduced-order surrogate model of gravitational waveforms from non-spinning binary black hole systems with comparable to large mass-ratio configurations. This surrogate model, BHPTNRSur1dq1e4, is trained on waveform data generated by point-particle black hole perturbation theory (ppBHPT) with mass ratios varying from 2.5 to 10,000. BHPTNRSur1dq1e4 can generate waveforms up to 30,500 m1(where m1 is the mass of the primary black hole), includes several more spherical harmonic modes up to \ell=10, and calibrates both dominant and subdominant modes to numerical relativity (NR) data. In the comparable mass-ratio regime, including mass ratios as low as 2.5, the gravitational waveforms generated through ppBHPT agree surprisingly well with those from NR after this simple calibration step. We argue that this scaling essentially captures higher order self-force corrections in a much simpler way. We also compare our model to recent SXS and RIT NR simulations at mass ratios ranging from 15 to 32, and find the dominant quadrupolar modes agree to better than?10-3. We expect our model to be useful to study intermediate-mass-ratio binary systems in current and future gravitational-wave detectors. Finally, we discuss avenues for improving the model by extending its region of validity.

Zoom link: https://pitp.zoom.us/j/99971588372?pwd=ZVUveUlNeTI1SE5iMzNnVDh0L2xkQT09

Surrogate model for gravitational wave signals from black hole binaries built on black hole perturbation theory waveforms calibrated to numerical relativity:

one model to rule both comparable and extreme mass ratio regime

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Dec 1, 2022
Strong Gravity Seminar
Perimeter Institute

Things I do

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Gravitational Waveform Modelling

- Numerical Relativity Surrogate Models for eccentric binaries
- Perturbation theory based surrogate models from comparable to extreme mass ratio binaries
- Comparison between self-force and perturbation theory waveforms

Test of GR

- Astrophysical and Cosmological tests of beyond GR theories
- Higher modes consistency test for GR
- Applying the test on GW190814

Astrophysics

- Analysis of GW190412
- Mock data analysis of high mass ratio events
- Re-analysis of GWTC-3 with NR surrogates
- Inference of large recoil velocity of remnant black hole from a single GW event

Signal Detection

- Accessing the impact of perturbation theory-based models in high mass ratio searches

Rapid Data Analysis

- Novel algorithm to make data analysis 20 times faster

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Collaborators

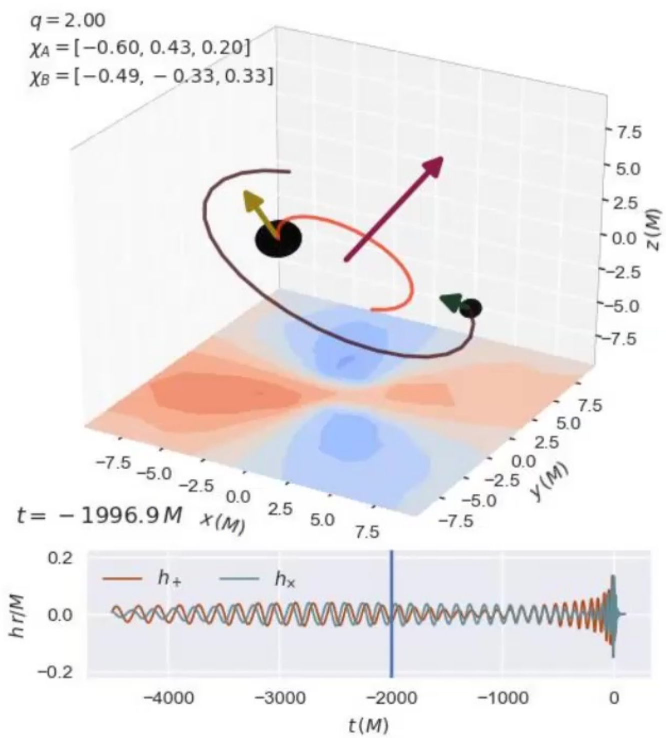
Perturbation Surrogate

Scott Field (UMassD), Scott Hughes (MIT), Gaurav Khanna (URI), Vijay Varma (AEI), Matthew Giesler (Cornell), Mark Scheel (Caltech)
[Islam +, arXiv.2204.01972]

Comparison with Self-force

Barry Wardell (UCD) , Adam Pound (Southampton), Niels Warburton (UCD), Scott Field (UMassD), Gaurav Khanna (URI)
[Islam +, In preparation]

Gravitational Waves from Binary Black Holes



[Courtesy: Vijay Varma]

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Gravitational Waves from Binary Black Holes

Gravitational radiation can be written as a superposition of −2 spin-weighted spherical harmonics

$$
\begin{aligned}
h(t; \mathbf{n}, \boldsymbol{\lambda}) &:= h_+(t; \mathbf{n}, \boldsymbol{\lambda}) - i\, h_\times(t; \mathbf{n}, \boldsymbol{\lambda}) \\
&= \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} Y_{\ell m}^{-2}(\mathbf{n})\, h_{\ell m}(t; \boldsymbol{\lambda}),
\end{aligned}
$$

Described by at-least 17 parameters

- **Intrinsic parameters:**

masses and spin components of the binary, {eccentricity, mean anomaly} (2+6+2)

- **Extrinsic parameters:**

inclination, luminosity distance, right ascension and declination, polarization, phase and merger time (7)

Gravitational Waveform Models

Numerical Relativity (NR) waveforms

Phenomenological Methods

- Post Newtonian Approximations [Blanchet+, Iyer+, Will+, ..]
- Phenomenological waveform Models [Ajith+, London+, Khan+, Hannam+, ..]
- Effective-one-body (EOB) waveform models [Bohe+, Cotesta+, Pan+, Babak+, ..]

NR Surrogate waveform models [Field+, Blackman+, Varma+, Islam+]

Black Hole Perturbation Theory [Rifat+, Islam+]

Point-Particle Black Hole Perturbation Theory (ppBHPT)

The smaller black hole is modeled as a point-particle with no internal structure.

The framework was originally developed for extreme mass ratio inspirals and/or solving ringdown regime.

First, we compute the trajectory taken by the point-particle.

We use that trajectory to compute the gravitational wave emission by solving Teukolsky equation.

Best Way to generate accurate Waveform for extreme mass ratio binaries

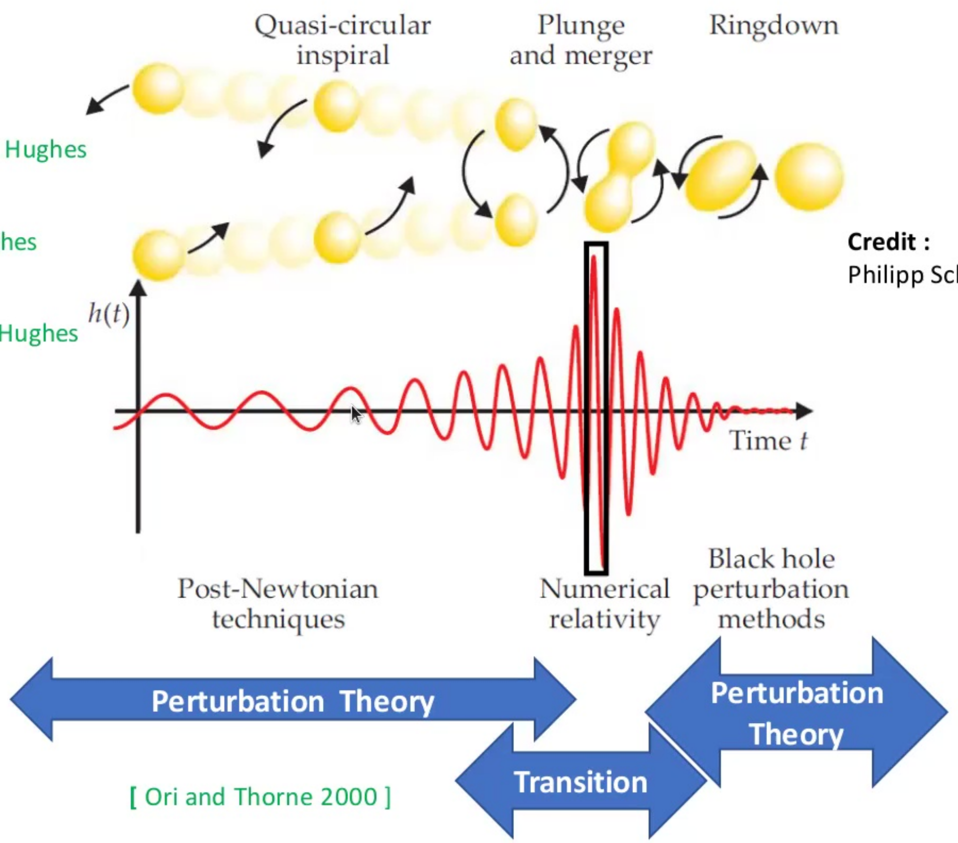
ppBHPT Inspiral-Merger-Ringdown Waveform

[Sundararajan, Khanna, and Hughes 2007]

[Sundararajan, Khanna, Hughes and Drasco 2008]

[Sundararajan, Khanna and Hughes 2010]

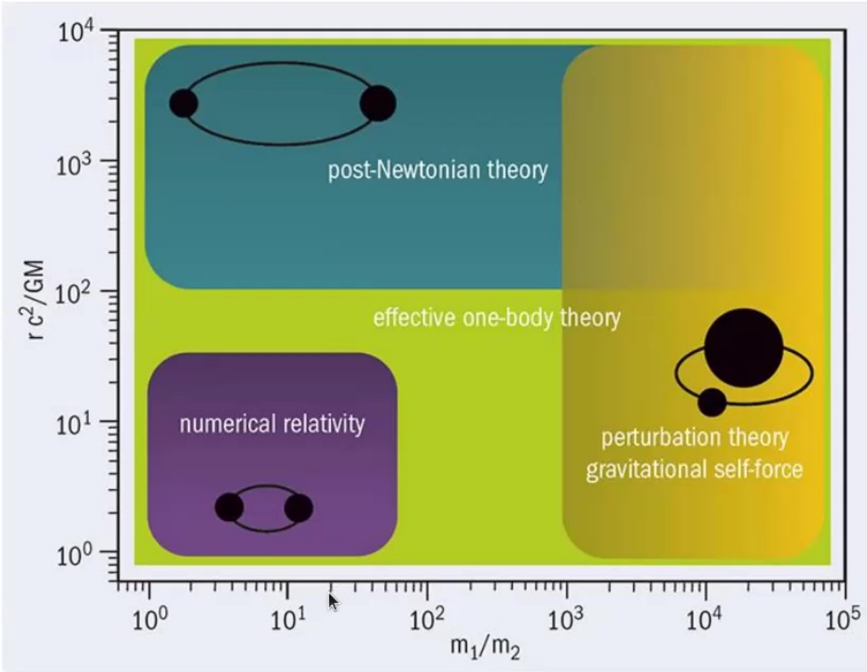
[Zenginoglu and Khanna 2011]



[Ori and Thorne 2000]

Credit : Philipp Scharpf

Where should we trust ppBHPT ?



[Image credit: arXiv:1410.7832]

Why Another Model ?

None of the current NR-Surrogate / EOB / Phenom models are accurate in high mass ratio regime

Intermediate Mass Ratio Binaries : GW190814 (mass ratio q~10)

ppBHPT gives most accurate waveform for higher mass ratio systems; However, it is computationally expensive

"Kludge" Models

[Barack+, Babak+, Gair+, Chua+]

Second Order Self Force

[Wardell+]

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BHPTNRSur1dq1e4 : an overview

Available via → Black-hole Perturbation Toolkit | gw-surrogate

Non-Spinning Binaries : BHPTNRSur1dq1e4

- **Covers comparable to large Mass Ratio** : q=2.5 to q=10^4
- **Trained on ppBHPT waveforms from time-domain Teukolsky Solver** :
  - 0PA waveforms, updated plunge model in the ppBHPT framework
- **Many modes** :
  - 25 modes up to \ell=10
- **Longer waveforms** : **[Relevant for LIGO, Cosmic Explorer, Einstein Telescope]**
  - 35000M
- **Calibrated to NR in the small mass ratio regime** :
  - modes are calibrated up to \ell=5

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Tuning ppBHPT to NR in small mass ratio regime

- Can we build a single model from comparable to large/extreme mass ratio binaries?
- Can we extend perturbation theory framework in small mass ratio regime?
- Do we need to calibrate ppBHPT to NR in the small mass ratio regime ?
- Will the calibration work for all modes?

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Tuning ppBHPT to NR in small mass ratio regime

- **Rescaling ppBHPT waveforms**:
  - up to \ell=5

$$\mathbf{h_{NR}} := h^{\ell,m}_{\mathrm{S},\alpha^\ell,\beta}(t;q) = \alpha^\ell h^{\ell,m}_{\mathrm{S}}(t\beta;q)$$

rescaled ppBHPT

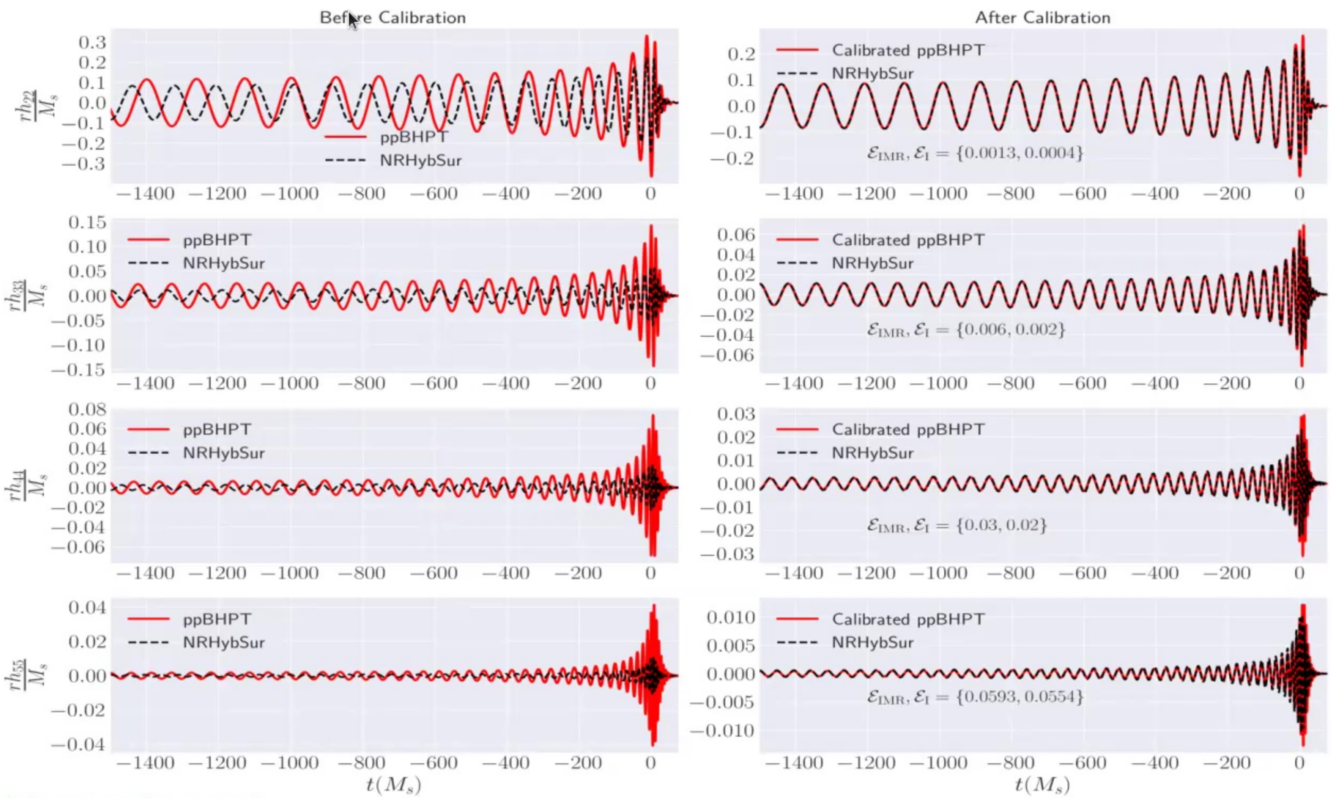
raw ppBHPT

- **Obtain the scaling parameters by optimizing the error between scaled ppBHPT and NR (NRHybSur3dq8)** :

$$\min_{\alpha^\ell,\beta} \frac{\int_{t=-5000M}^{t=115M} \left| h^{\ell,m}_{\mathrm{S},\alpha^\ell,\beta^\ell}(t;q) - h^{\ell,m}_{\mathrm{NRHyb}}(t;q) \right|^2 dt}{\int_{t=-5000M}^{t=115M} \left| h^{\ell,m}_{\mathrm{NRHyb}}(t;q) \right|^2 dt}$$

Small Mass Ratio Regime :

Comparison to NRHybSur3dq8 / example waveforms



Mass ratio : *q=4*

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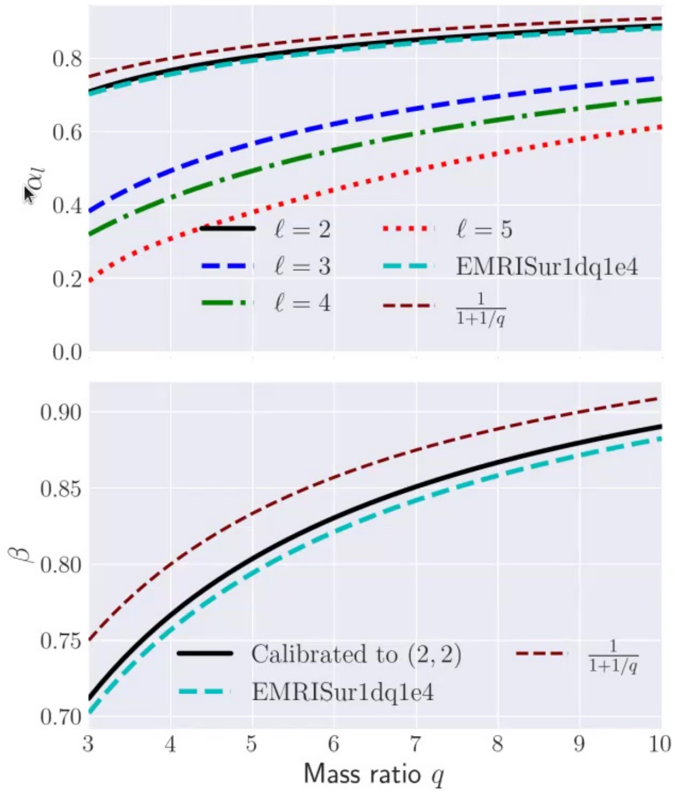
Small Mass Ratio Regime :

Scaling ppBHPT waveforms to match NR



Fourth Order polynomial formula used for the scaling parameters as a function of small mass ratio (1/q)

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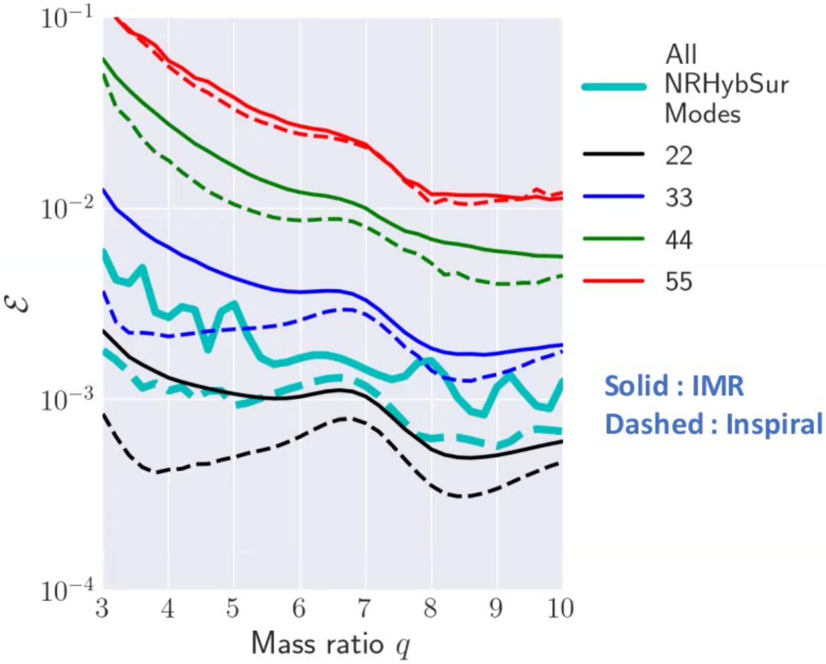
Small Mass Ratio Regime :

Comparison to NRHybSur3dq8 / Time Domain Error

(2,2) mode error ~ 10^{-3}

(3,3) and (4,4) modes error ~ 10^{-2}

Errors drop further when only INSPIRAL waveform is considered



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Small Mass Ratio Regime :

Comparison to NRHybSur3dq8 / Frequency Domain Mismatch

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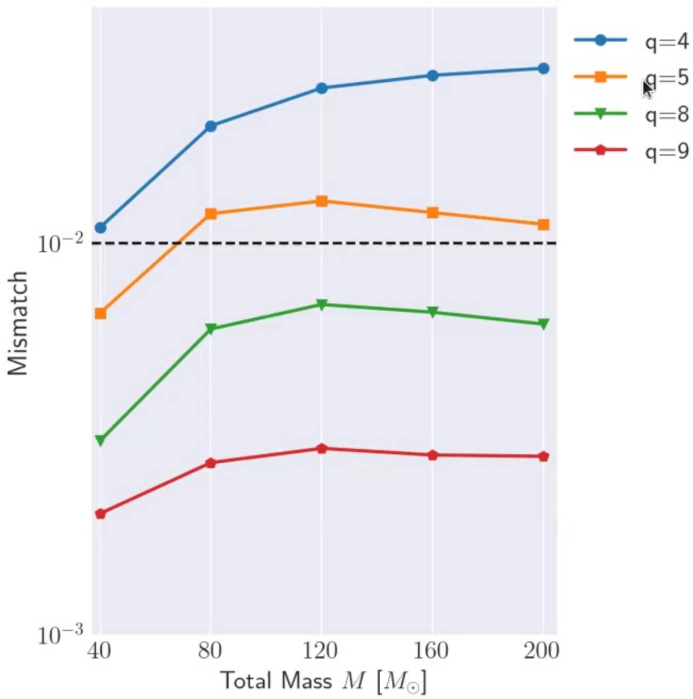
Mismatches are computed assuming advanced LIGO detector

Mismatches decrease as mass ratio increases

For q>=5, mismatches are always below ~0.01



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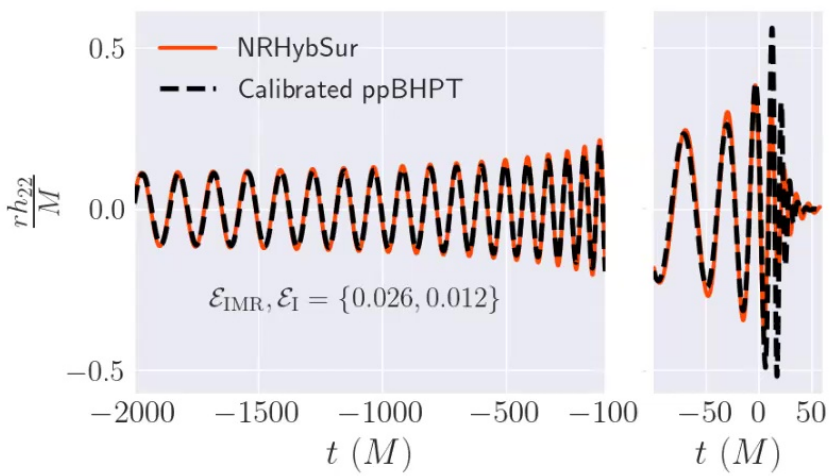
Small Mass Ratio Regime :

How small can we go in mass ratio and still get a good match?



We have been able to obtain reasonable scaling until q=1.2

Surrogate provides an alternative way to generate wfs because ppBHPT code breaks there

Higher modes errors are not as good

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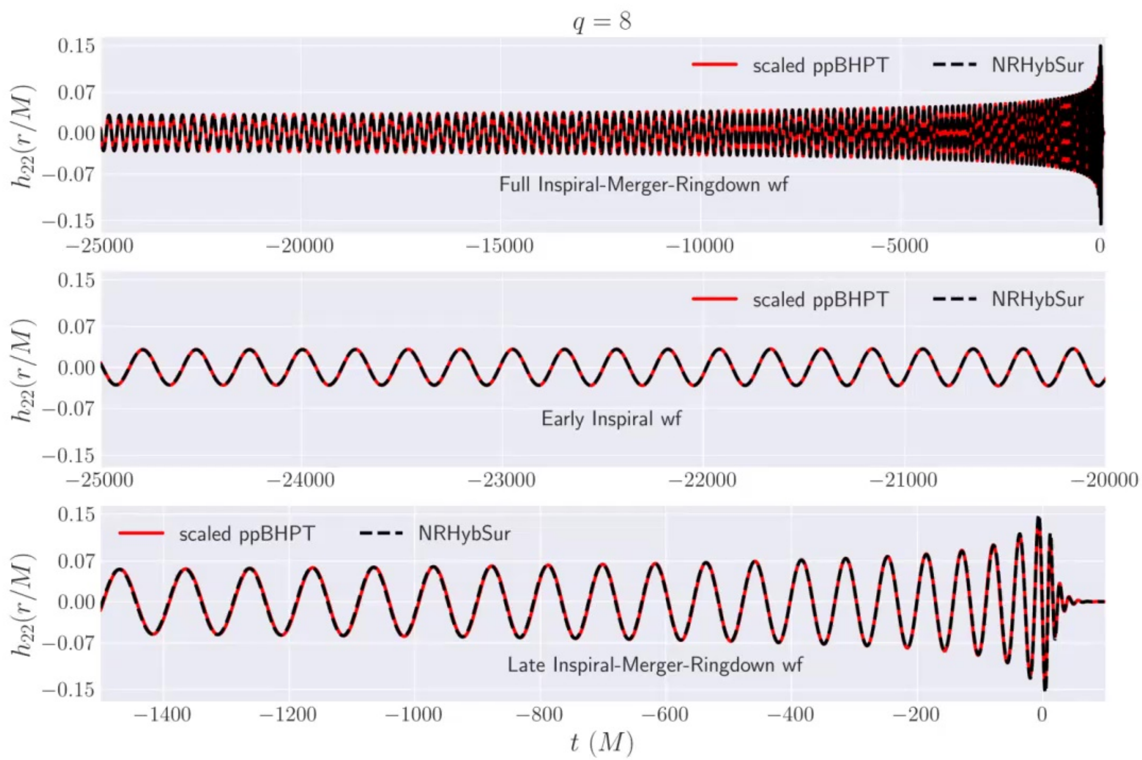
Small Mass Ratio Regime :

[Validation] Testing Scaling over a longer time window



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Small Mass Ratio Regime :

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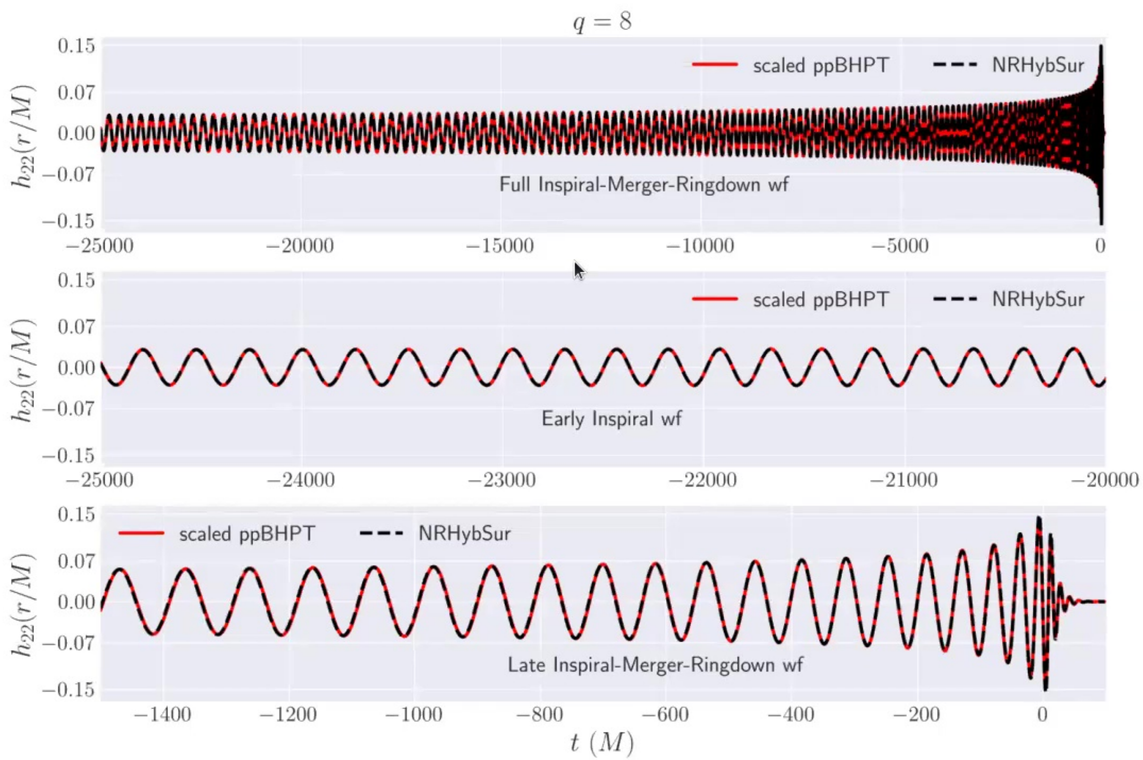

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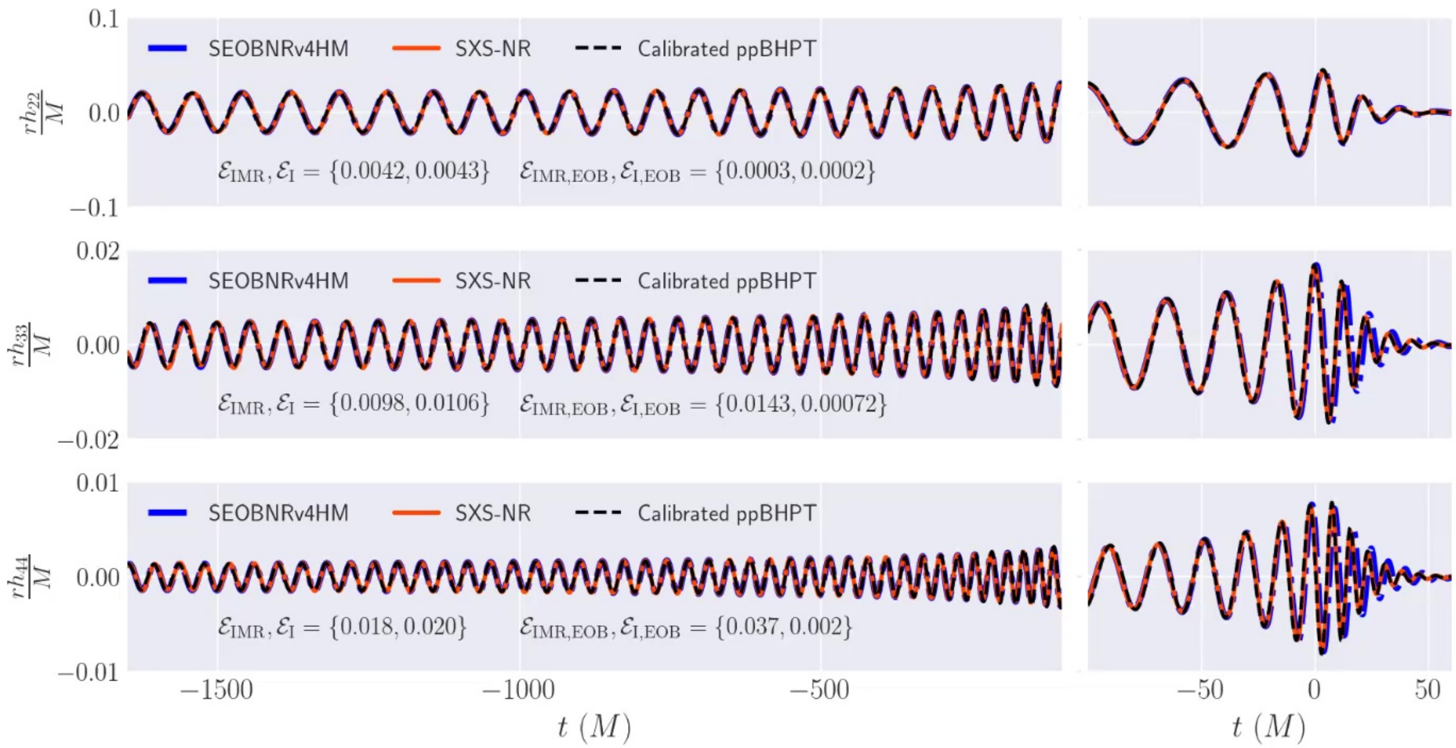
Testing Scaling in Intermediate Mass Ratio Regime :

[Validation] Comparison to SXS NR at q=30

NR Simulation : Matthew Giesler, Mark Scheel *et al*



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Explaining Alpha-Beta Scaling:

Comparison to Higher Order Self-force Calculation

$$h_{NR} := h^{\ell,m}_{\mathrm{S},\alpha^\ell,\beta}(t;q) = \alpha^\ell h^{\ell,m}_{\mathrm{S}}(t\beta;q)$$

rescaled ppBHPT

raw ppBHPT

Second Order Self-force Calculation

$$h_{NR} := h_{0PA} + h_{1PA}$$

raw ppBHPT

[Wardell, Pound, Warburton et al, 2021]

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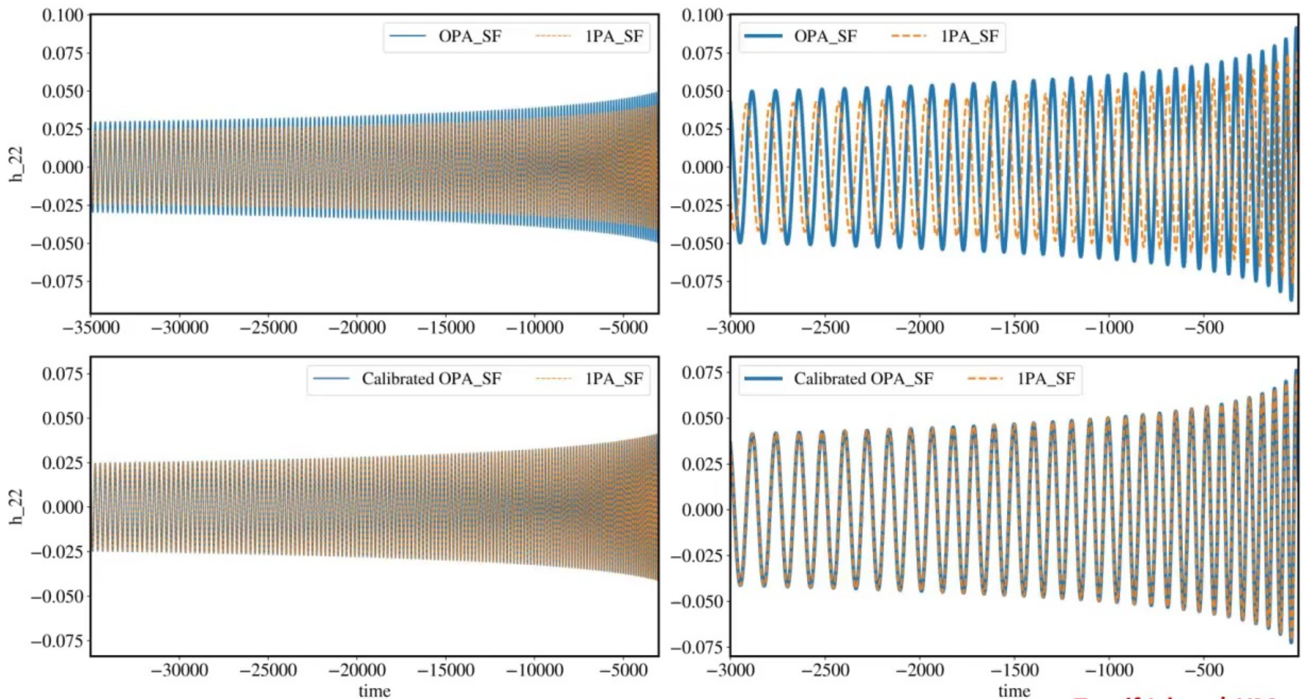
Explaining Alpha-Beta Scaling:

Comparison to Higher Order Self-force Calculation

1PA self-force waveform can be obtained using 0PA self-force waveform using an alpha-beta rescaling !!



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rescaled ppBHPT

raw ppBHPT

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[Wardell, Pound, Warburton et al, 2021]

Explaining Alpha-Beta Scaling:

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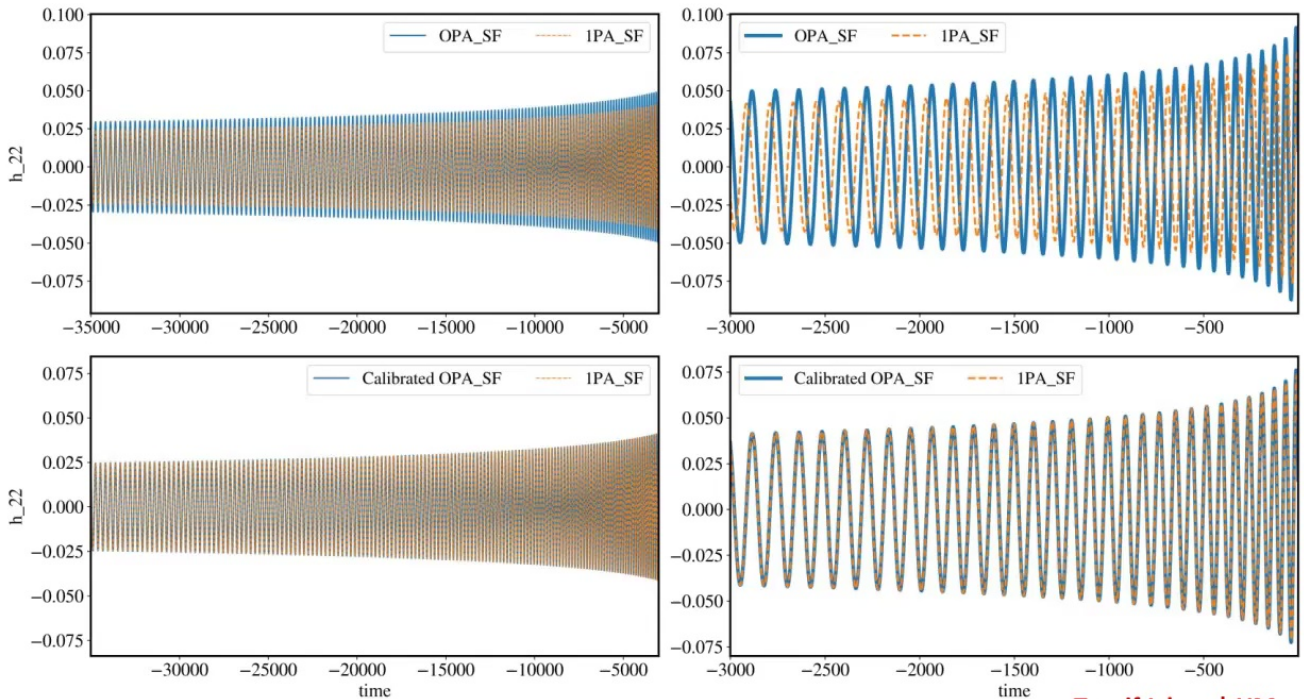

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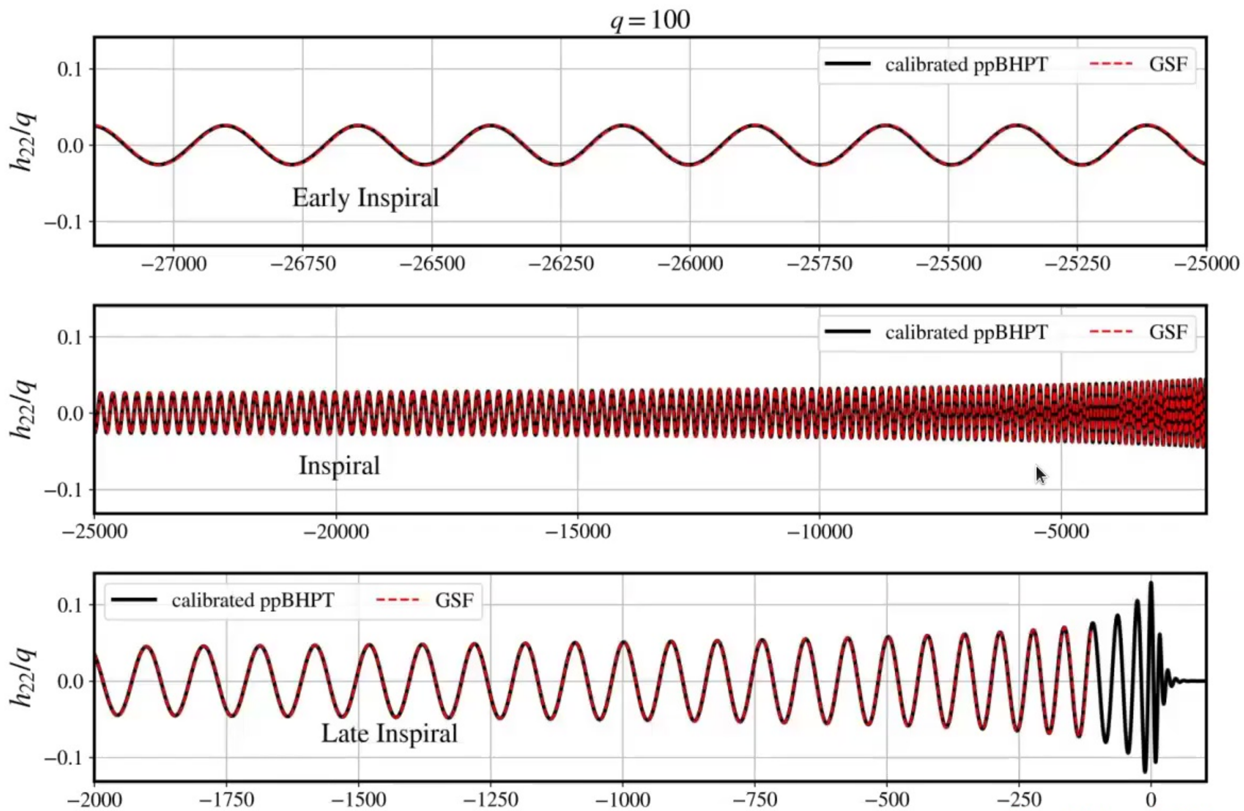

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What's Next in BHPTNRSur?

Aligned spinning Model [3<=q<=10000; -0.6<=a<=0.6]

Katie Rink, Kevin González-Quesada, Scott Field, *Tousif Islam*, Gaurav Khanna, Vijay Varma

Eccentric Model [3<=q<=100; 0.0<=ecc<=0.2]

Tousif Islam, Scott Field , Gaurav Khanna, Niels Warburton

Precessing Spin Model [3<=q<=10000; slightly misaligned system]

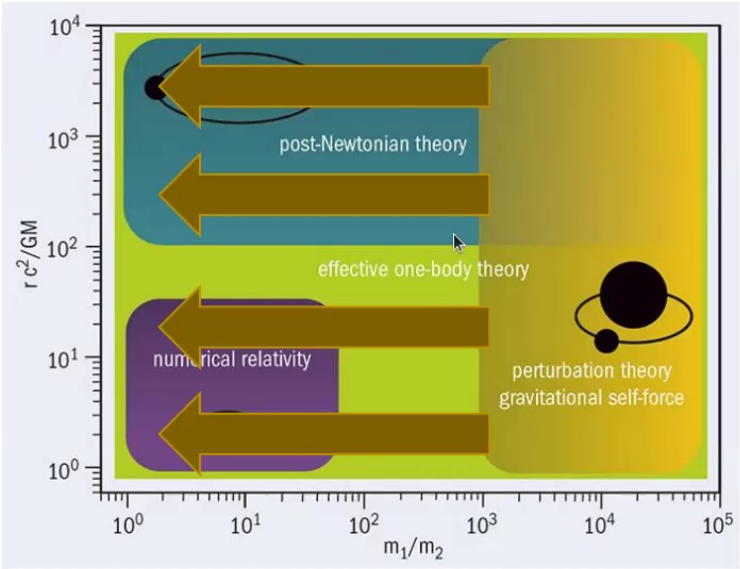
Ritesh Bacchar, *Tousif Islam*, Scott Field, Gaurav Khanna

```
git clone https://github.com/BlackHolePerturbationToolkit/BHPTNRSurrogate.git
```

```
pip install gwsurrogate
```

Summary

ppBHPT waveform model from comparable to extreme mass ratios including higher order modes (1.2<=q<=10,000)



Thank You

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