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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LISA Community Call

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 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

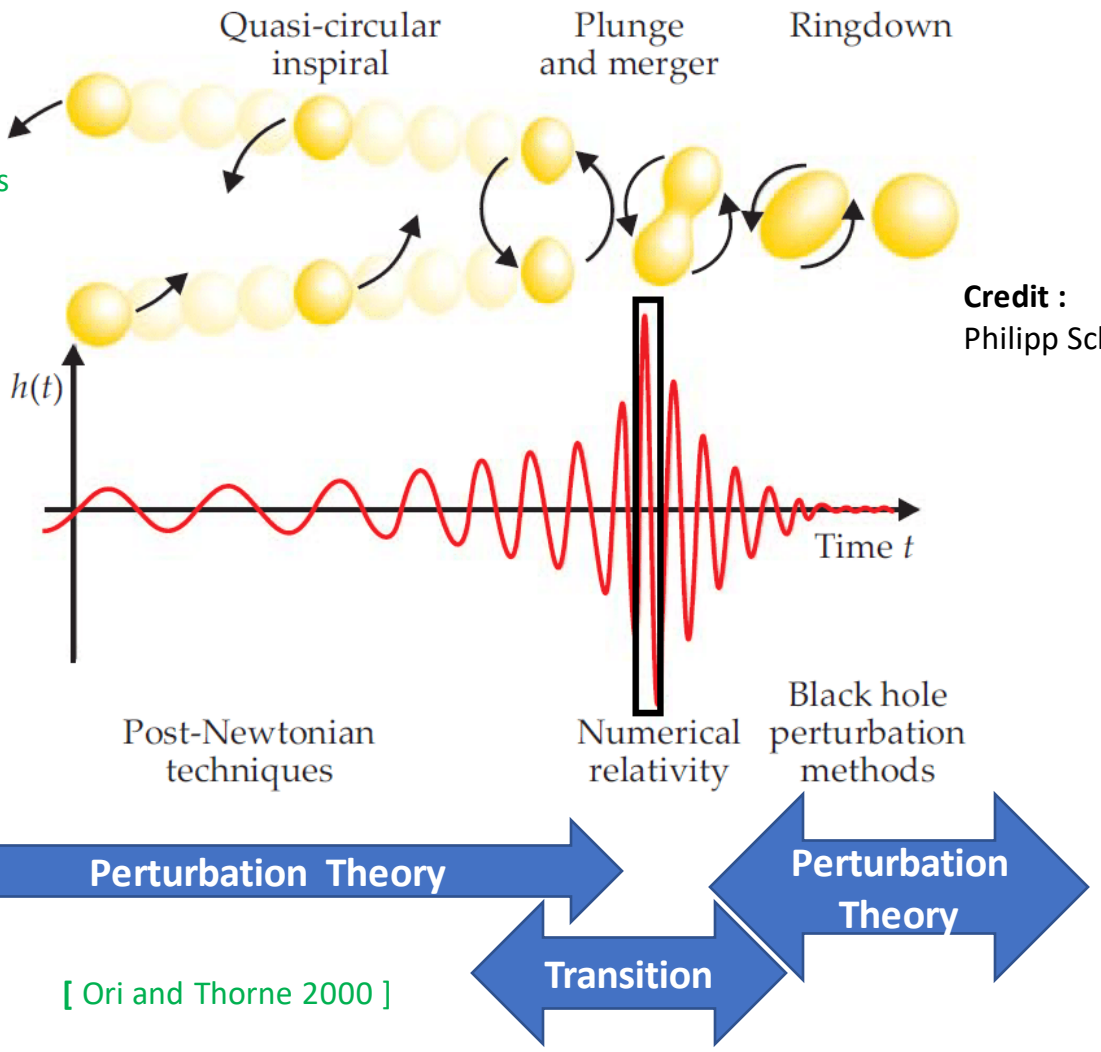
ppBHPT Inspiral-Merger-Ringdown Waveform

[Sundararajan, Khanna, and Hughes 2007]

[Sundararajan, Khanna, Hughes and Drasco 2008]

[Sundararajan, Khanna and Hughes 2010]

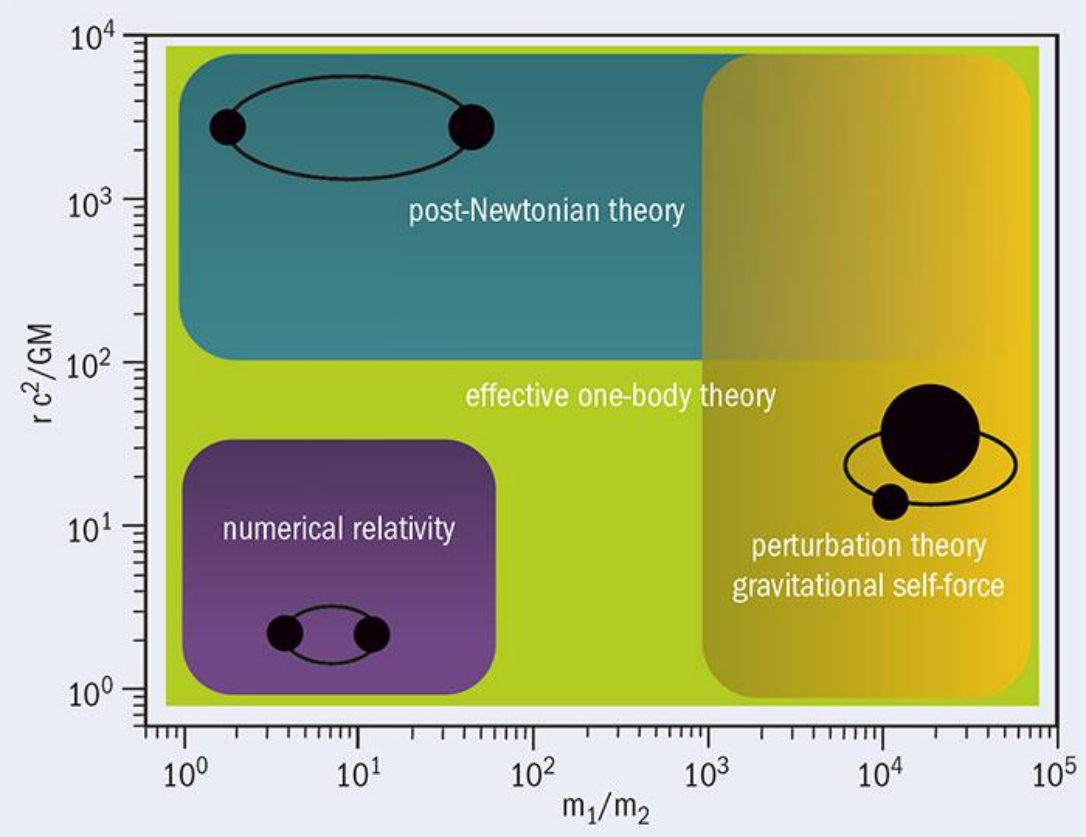
[Zenginoglu and Khanna 2011]



Credit :
Philipp Scharpf

[Ori and Thorne 2000]

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+]

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

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?

Tuning ppBHPT to NR in small mass ratio regime

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

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

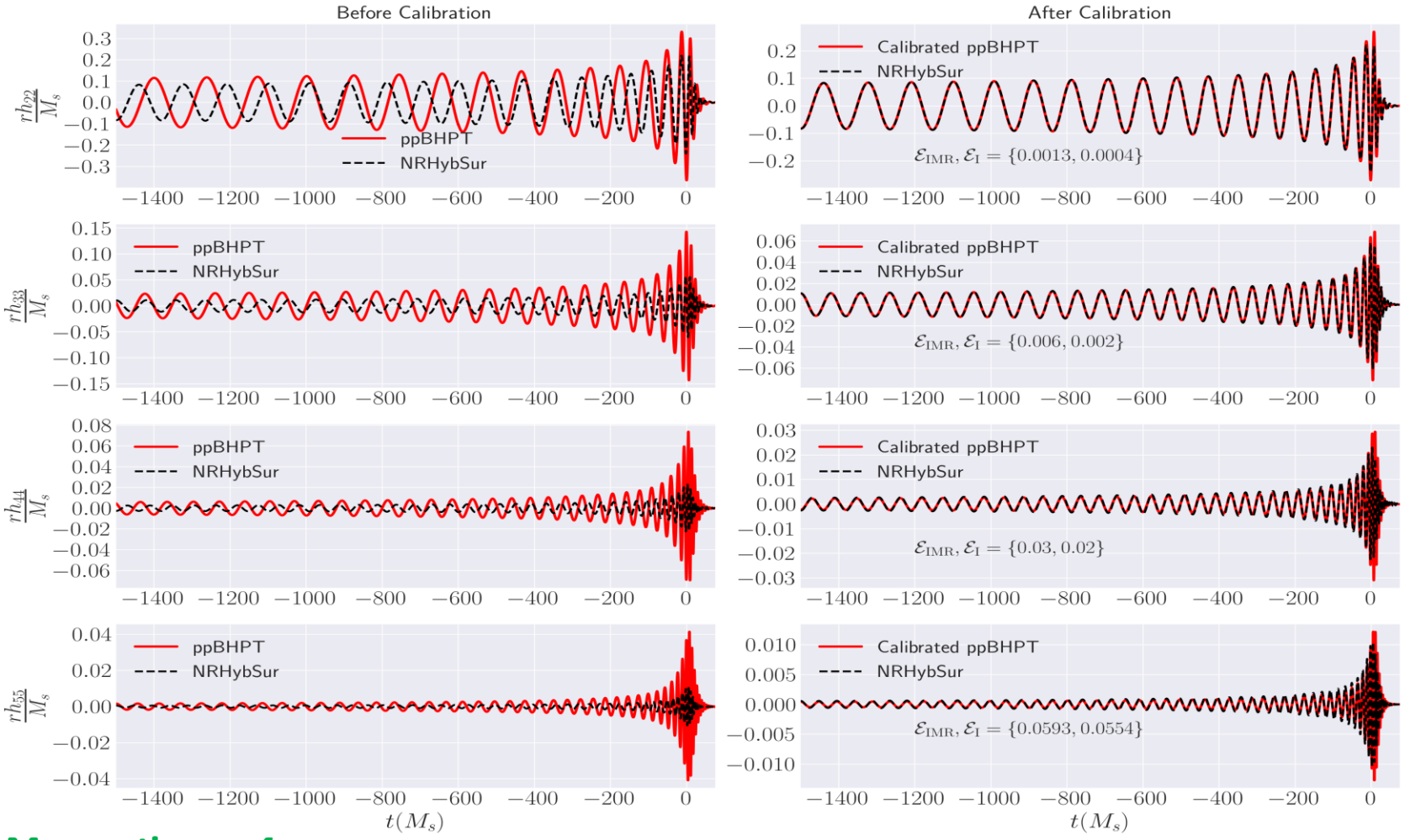
rescaled ppBHPT — **raw ppBHPT**

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

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

Small Mass Ratio Regime :

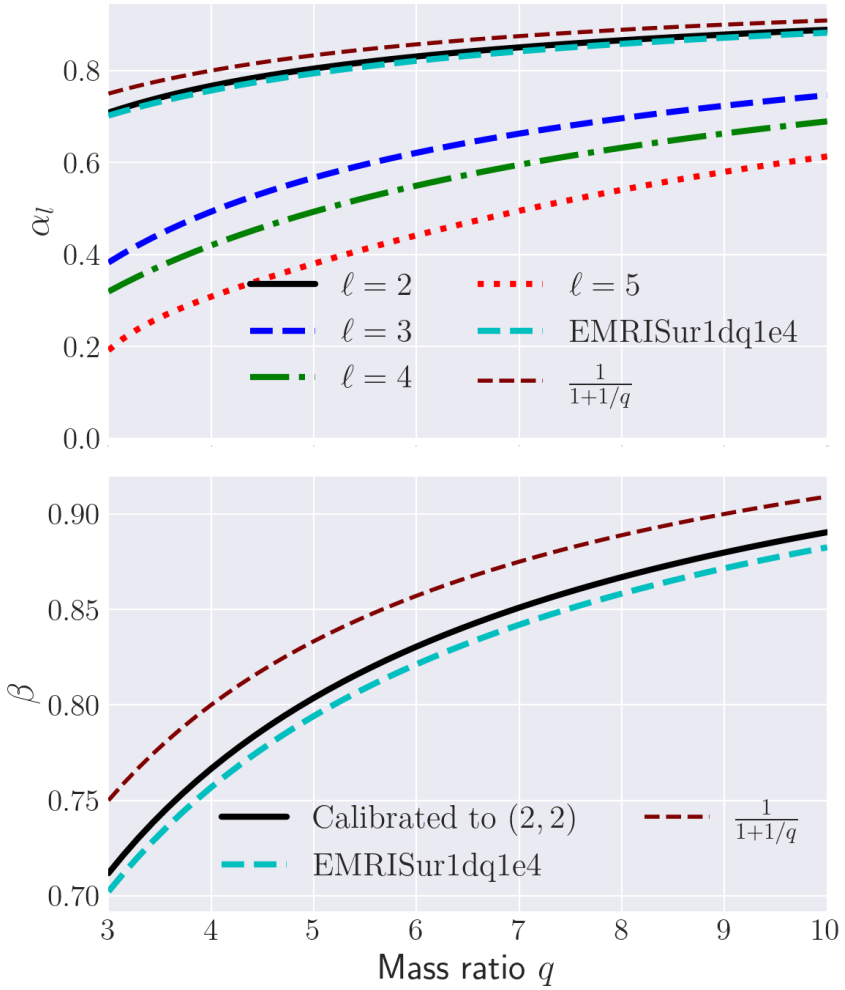
Comparison to NRHybSur3dq8 / example waveforms



Mass ratio : *q=4*

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)

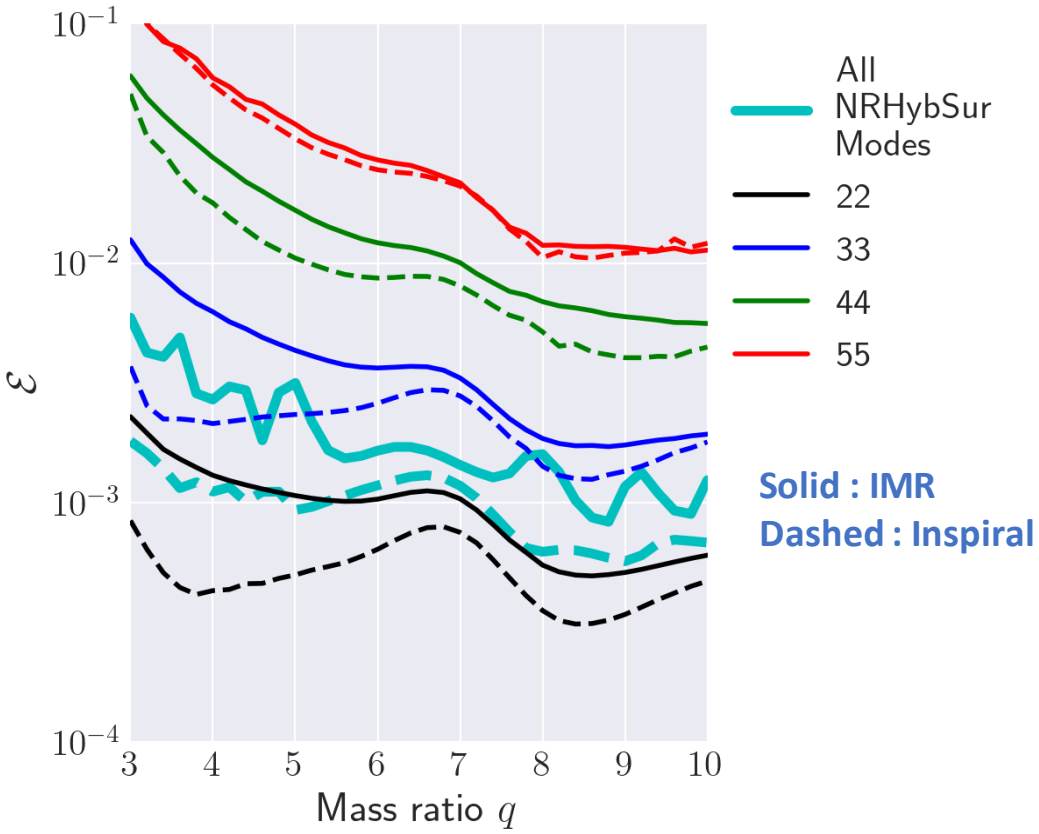
Small Mass Ratio Regime :

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



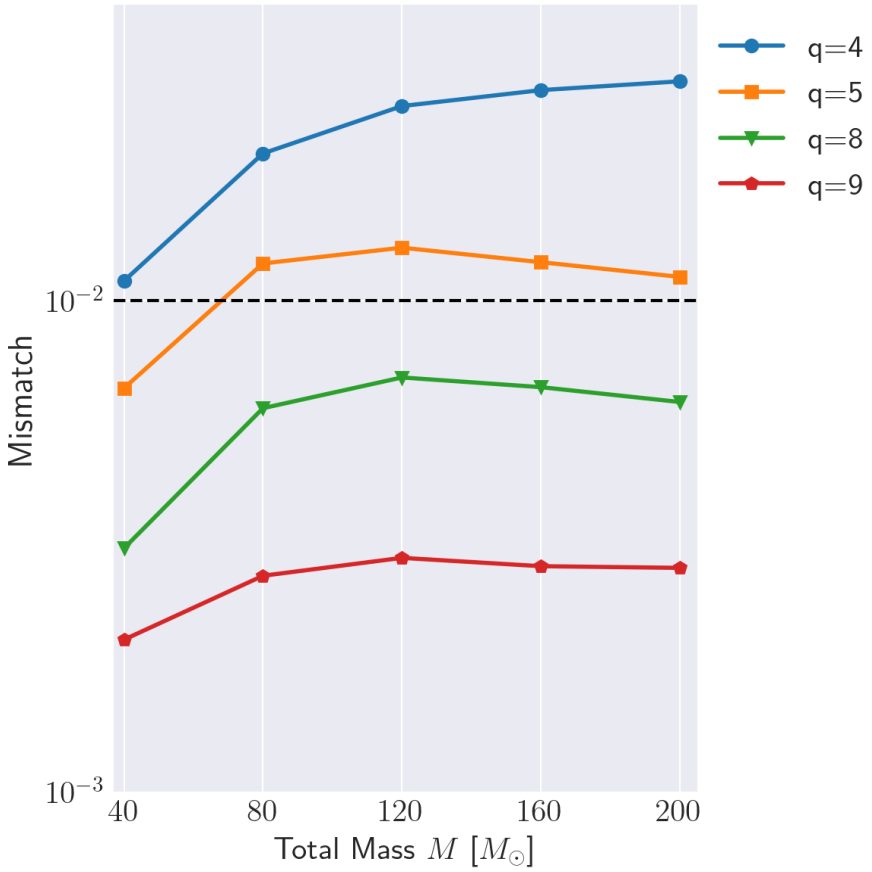
Small Mass Ratio Regime :

Comparison to NRHybSur3dq8 / Frequency Domain Mismatch

Mismatches are computed assuming advanced LIGO detector

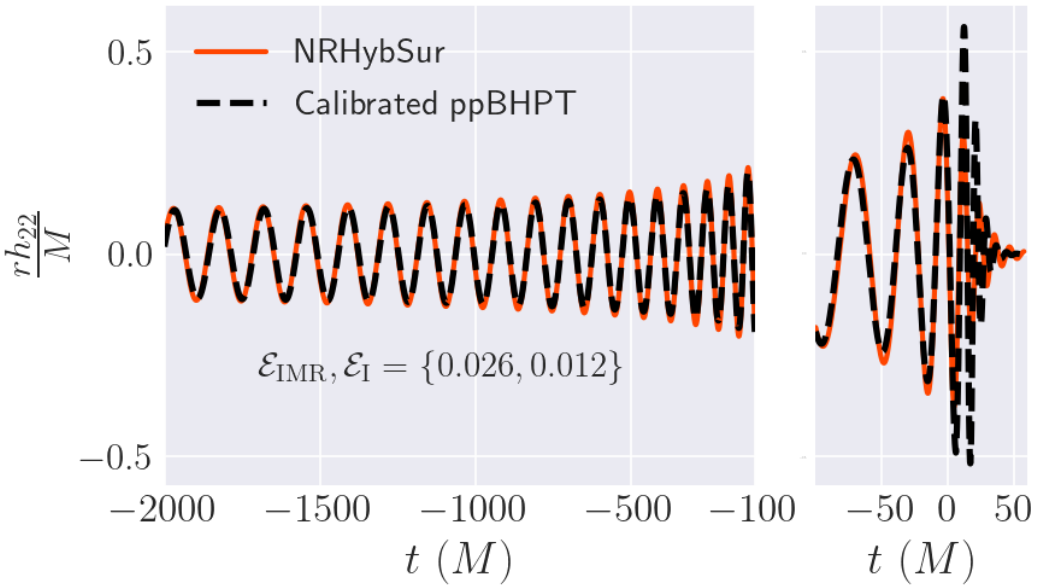
Mismatches decrease as mass ratio increases

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



Small Mass Ratio Regime :

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



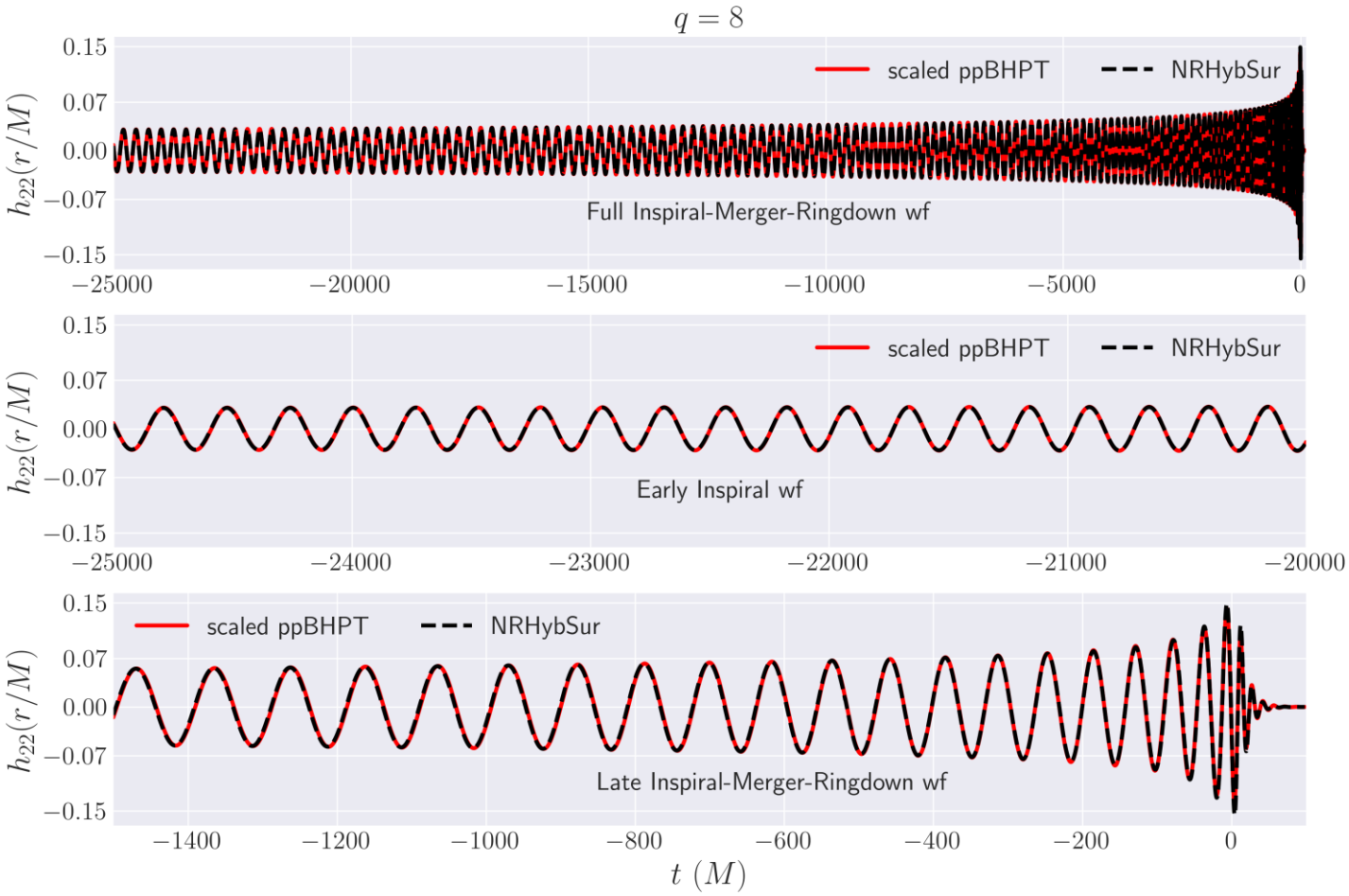
We have been able to obtain reasonable scaling until q=1.2

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

Higher modes errors are not as good

Small Mass Ratio Regime :

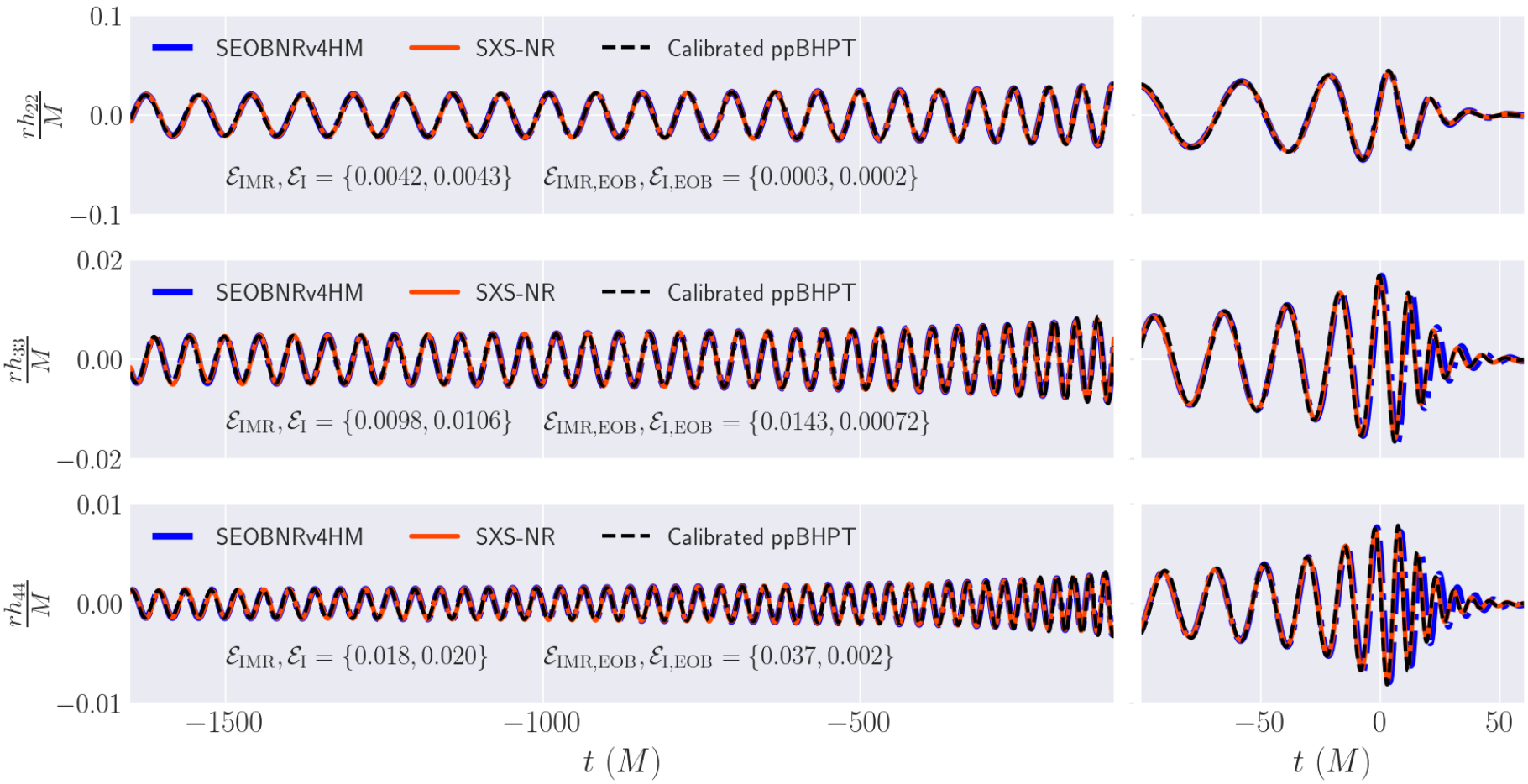
[Validation] Testing Scaling over a longer time window



Testing Scaling in Intermediate Mass Ratio Regime :

[Validation] Comparison to SXS NR at q=30

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



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

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

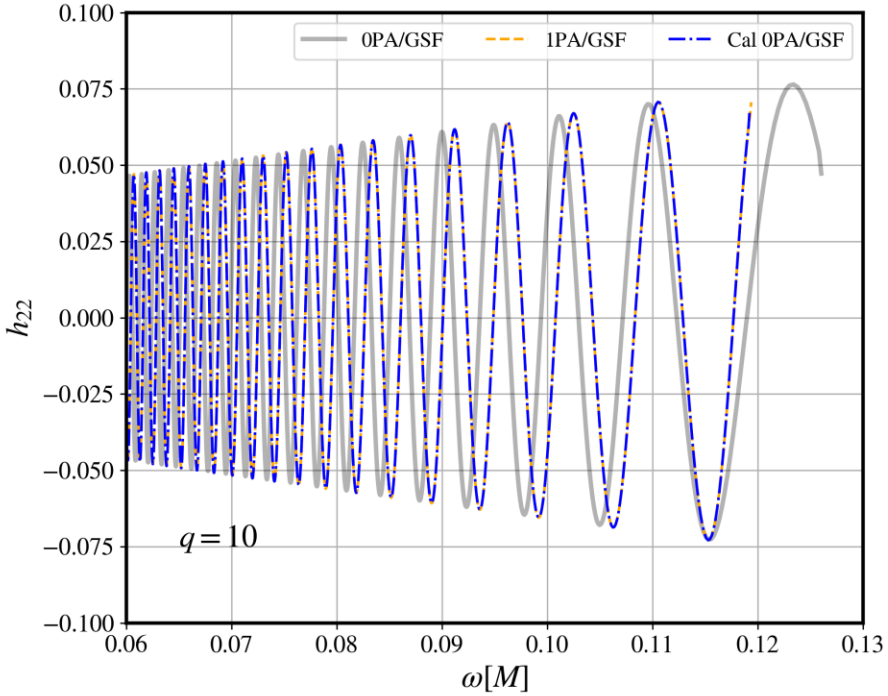
raw ppBHPT

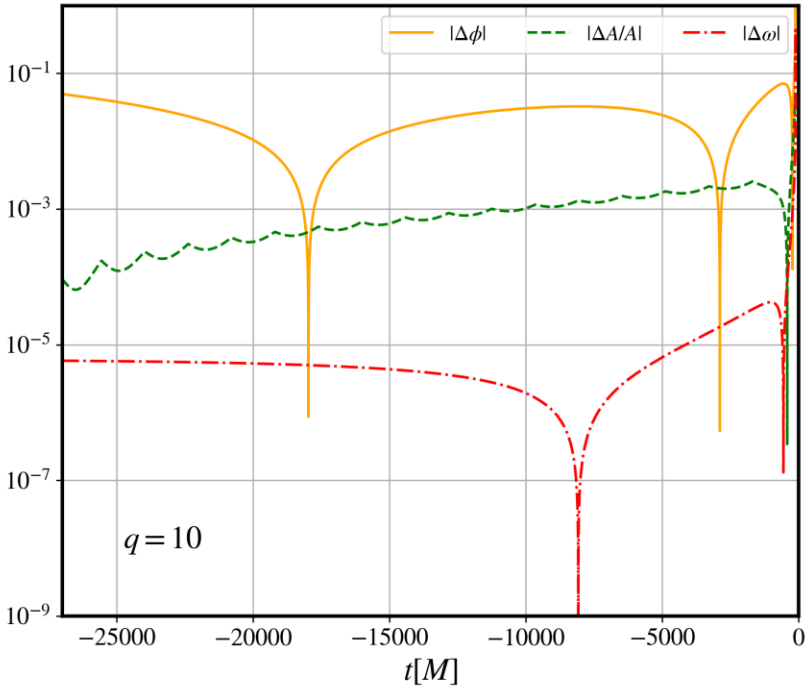
[Wardell, Pound, Warburton et al, 2021]

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 !!





Explaining Alpha-Beta Scaling:

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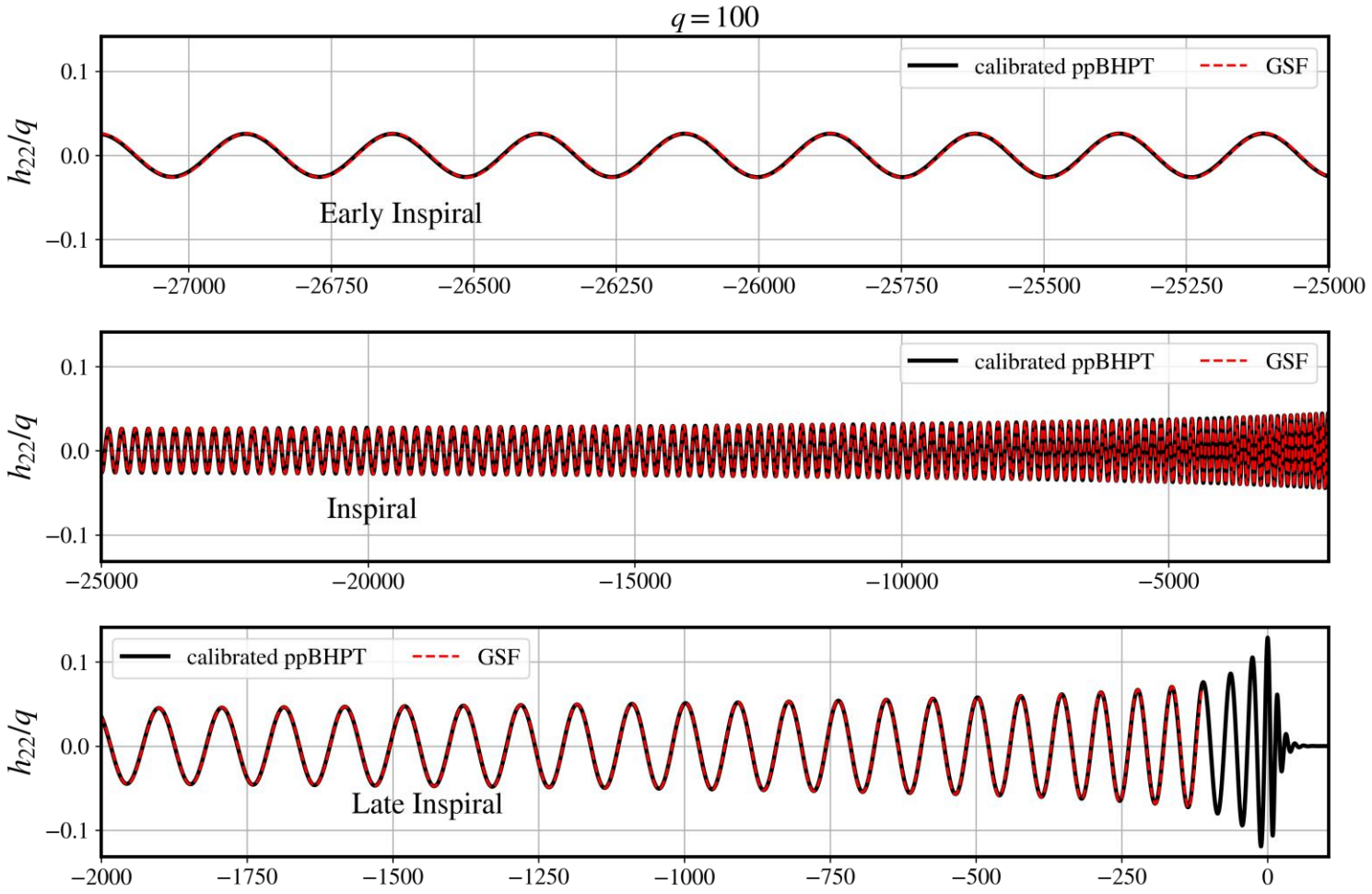


What's Next in BHPTNRSur?

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]

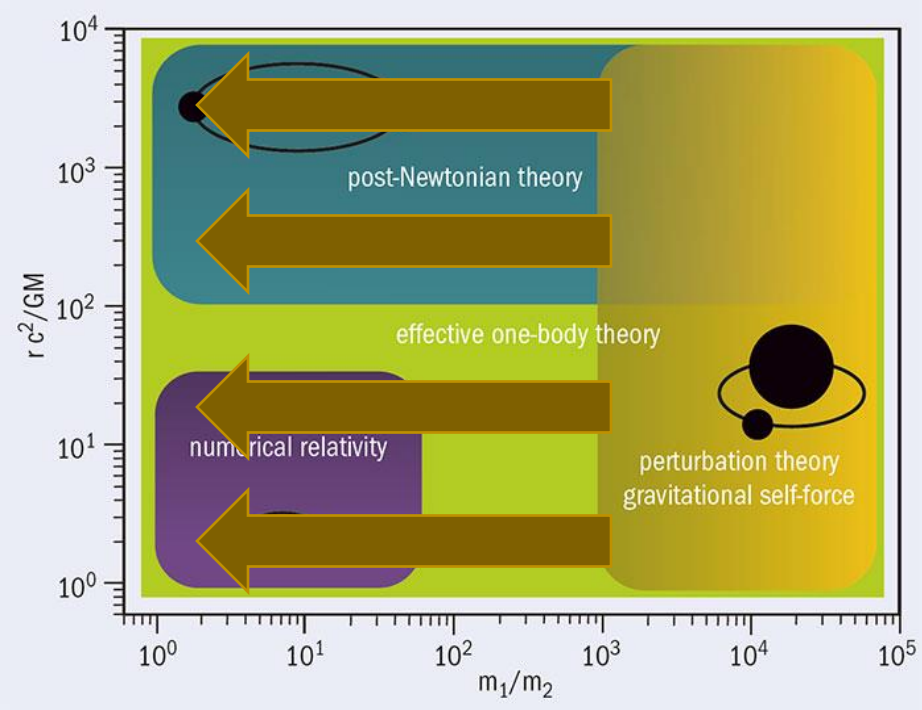
Ritesh Bacchar, *Tousif Islam*, Scott Field, Gaurav Khanna

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