Title: Binary black hole simulations: from supercomputers to your laptop

Speakers: Vijay Varma

Series: Strong Gravity

Date: November 07, 2019 - 1:00 PM

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Abstract: Simulations that numerically solve Einstein's equations are the only means to accurately predict the outcome of the merger of two black holes. The most important outputs from these simulations are the gravitational waveforms, and the mass and spin of the final black hole formed after the merger. The waveforms are used in extracting astrophysical information from detections, while the final mass and spin are used in testing general relativity. Unfortunately, these simulations are too expensive for direct use in data analysis; each simulation can take a month on a supercomputer. Surrogate modeling is a data-driven approach to modeling, that uses machine learning like techniques to interpolate between hundreds of existing simulations. In this talk, I will discuss some recent developments in surrogate modeling, including a new 7-dimensional model that fully captures the effects of precession; the wobbling of the orbit caused when the black holesâ€™ spin axes arenâ€™t perpendicular to the plane of the orbit. This model reproduces the waveform as well as the final black hole's mass and spin as accurately as the simulations themselves, while taking only a fraction of a second to evaluate on a laptop.

Entanglement and Extended Conformal field theory

Gabriel Wong

Fudan University

Perimeter Institute

Based on ongoing work with Janet Hung and hep-th 1811.10785
with William Donnelly

Binary black hole simulations: from supercomputers to your laptop

Vijay Varma

California Institute of Technology

Perimeter Institute

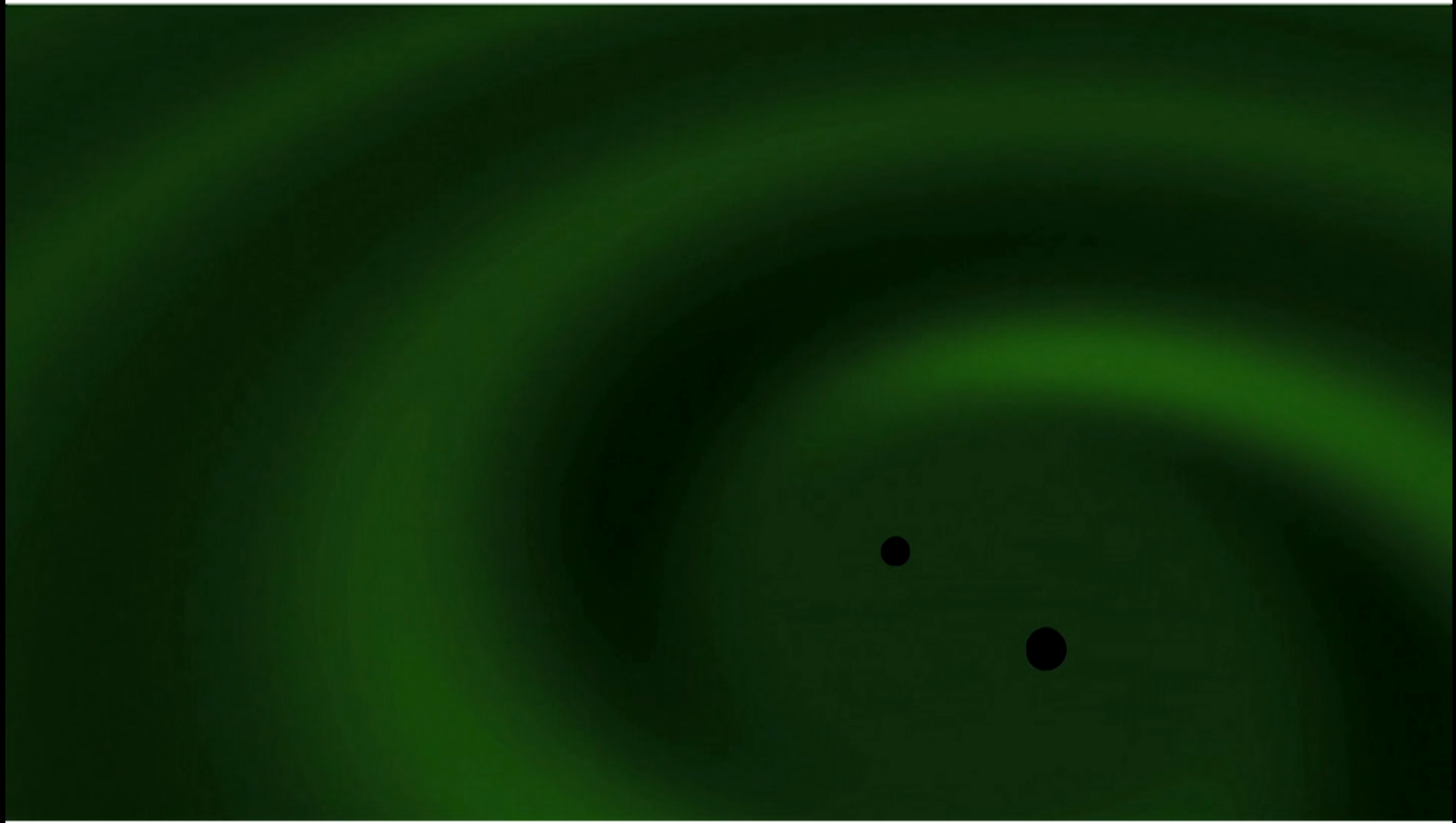
Nov 07, 2019

Background credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

Binary black hole simulations

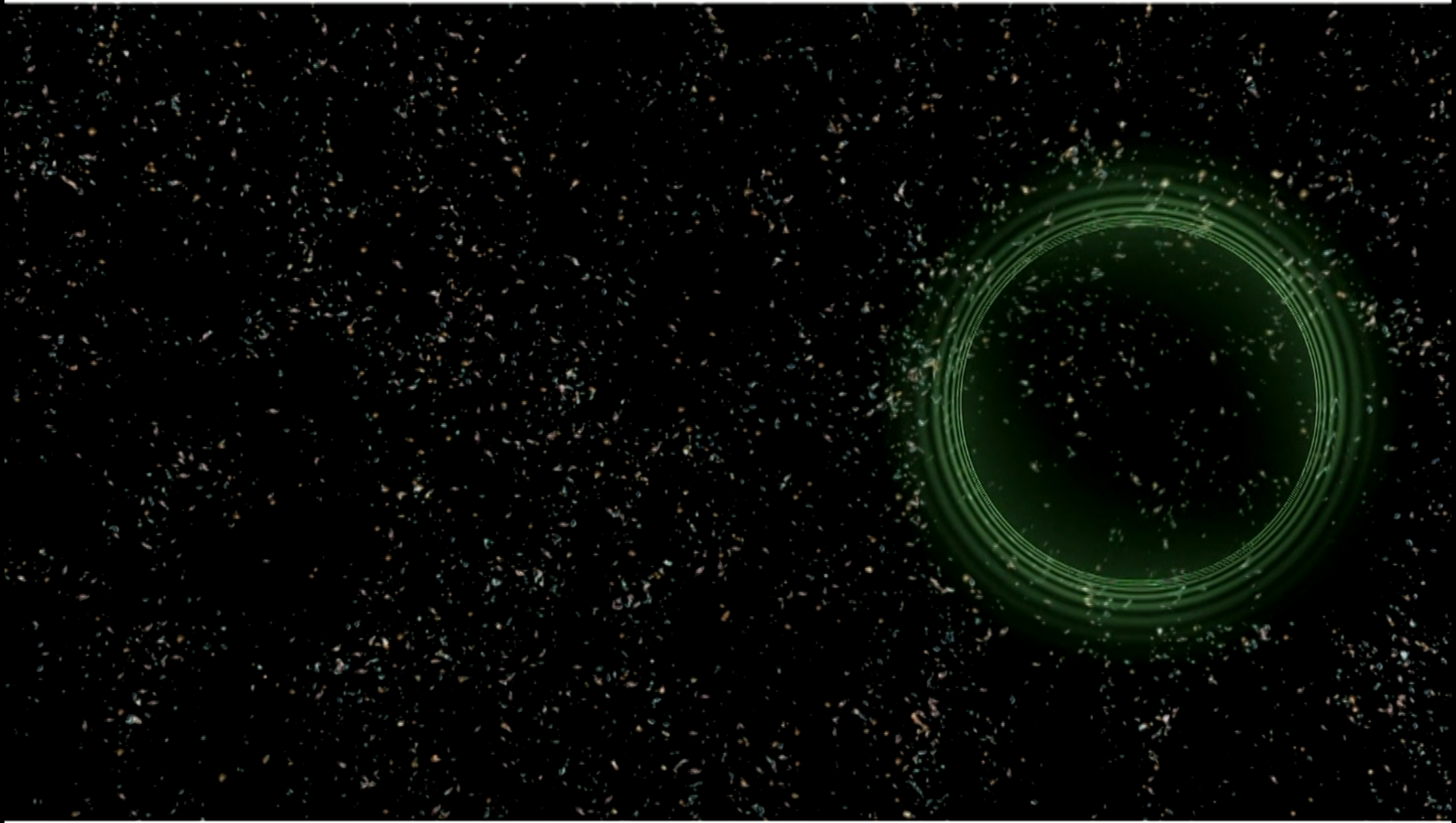
Credit: SXS

Binary black hole simulations



Credit: SXS/LIGO/R.Hurt and T. Pyle

Binary black hole simulations



Credit: SXS/LIGO/R.Hurt and T. Pyle

Binary black hole simulations

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Binary black hole simulations

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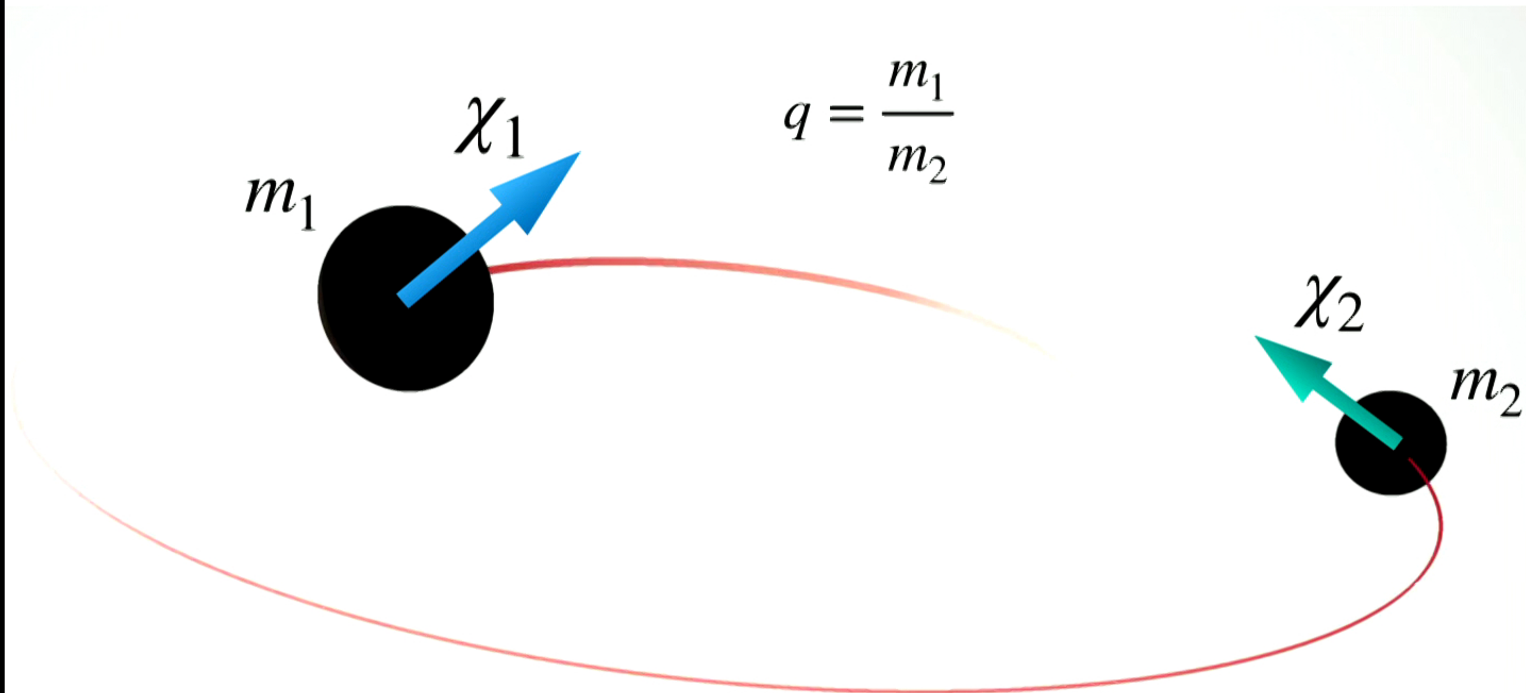
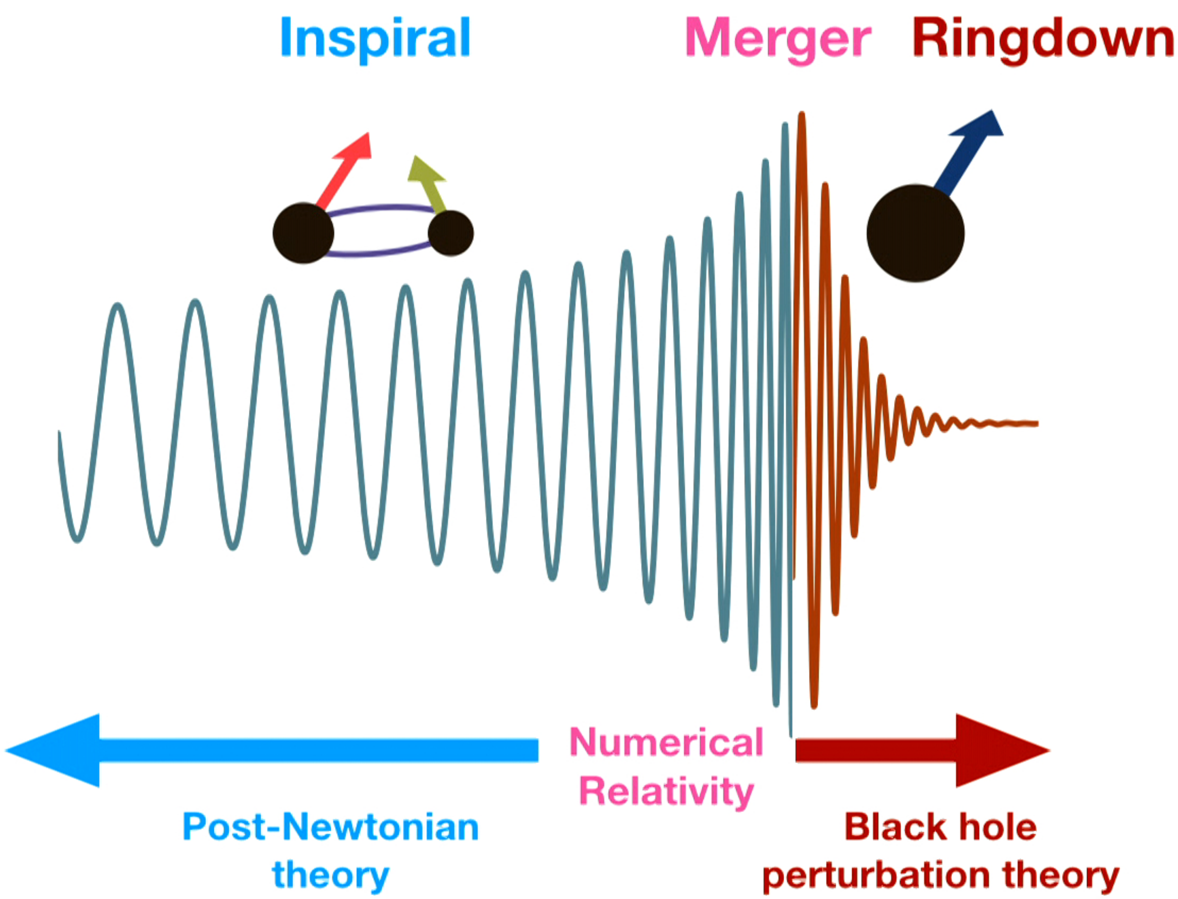
Binary black holes



$$\Lambda = \{q, \chi_{1x}, \chi_{1y}, \chi_{1z}, \chi_{2x}, \chi_{2y}, \chi_{2z}\}$$

Stages of a binary black hole



Numerical Relativity (NR) can be hard!

VOLUME 92, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 28 MAY 2004

Numerical Simulation of Orbiting Black Holes

Bernd Brügmann, Wolfgang Tichy, and Nina Jansen

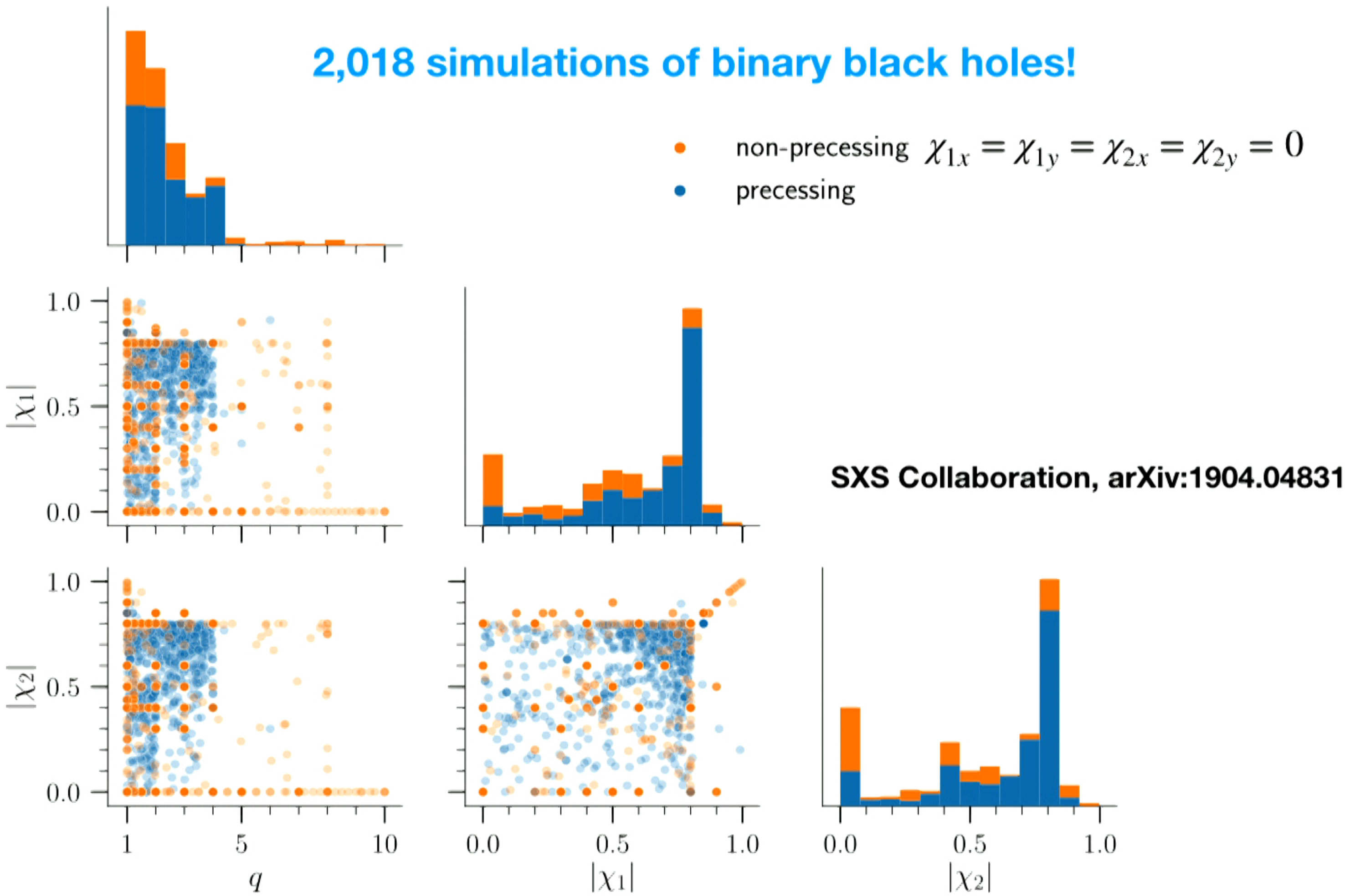
Center for Gravitational Physics and Geometry and Center for Gravitational Wave Physics, Penn State University, University Park, Pennsylvania 16802, USA

(Received 26 December 2003; published 24 May 2004)

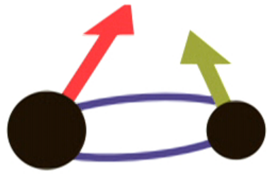
We present numerical simulations of binary black hole systems which for the first time last for about one orbital period for close but still separate black holes as indicated by the absence of a common apparent horizon. An important part of the method is the construction of comoving coordinates, in which both the angular and the radial motion are minimized through a dynamically adjusted shift condition. We use fixed mesh refinement for computational efficiency.

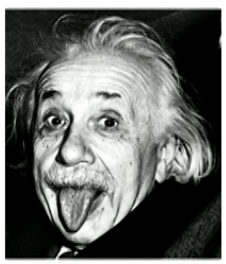
DOI: 10.1103/PhysRevLett.92.211101 PACS numbers: 04.25.Dm, 04.30.Db, 95.30.Sf

NR simulations today



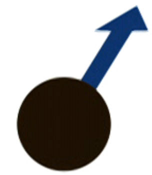
Numerical Relativity

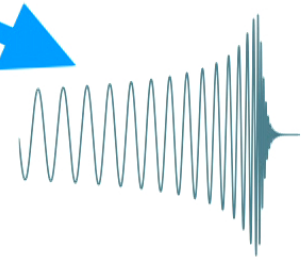




$$G_{ab} = 8\pi T_{ab}$$

Supercomputer





Gravitational waveform → **Infer source properties**

Final BH properties → **Test general relativity**

Phenomenological waveform models

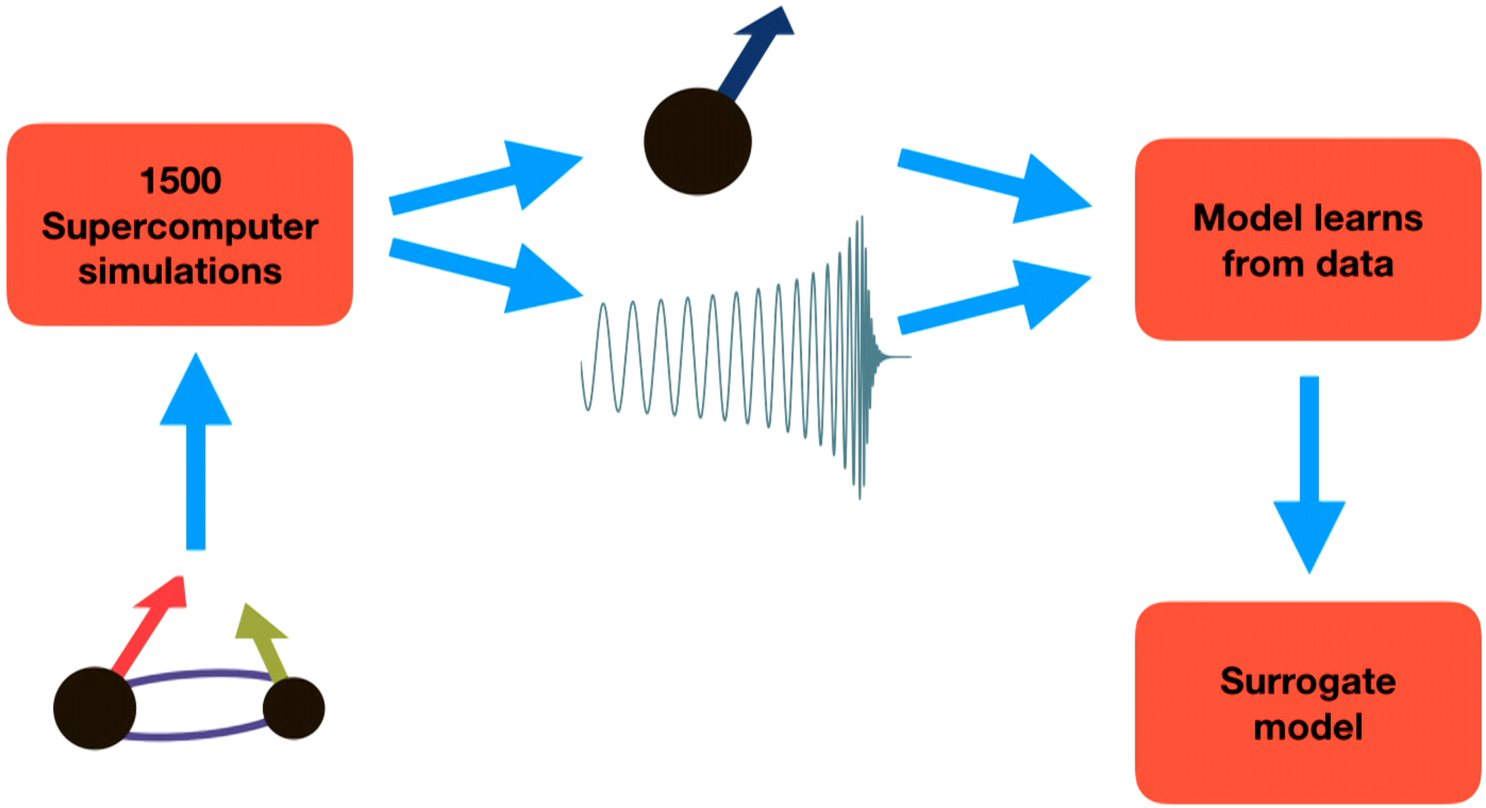
- Two main approaches: IMRPhenom and EOB.
- Come up with ansatz with some free parameters.
- Calibrate to NR to fix free parameters.

$$\phi_{\mathrm{TF2}} = 2\pi f t_c - \varphi_c - \pi/4 + \frac{3}{128\,\eta}(\pi f M)^{-5/3} \sum_{i=0}^{7} \varphi_i(\Xi)(\pi f M)^{i/3}$$

$$\phi_{\mathrm{Ins}} = \phi_{\mathrm{TF2}}(Mf;\Xi) + \frac{1}{\eta}\left(\sigma_0 + \sigma_1 f + \frac{3}{4}\sigma_2 f^{4/3} + \frac{3}{5}\sigma_3 f^{5/3} + \frac{1}{2}\sigma_4 f^2\right)$$

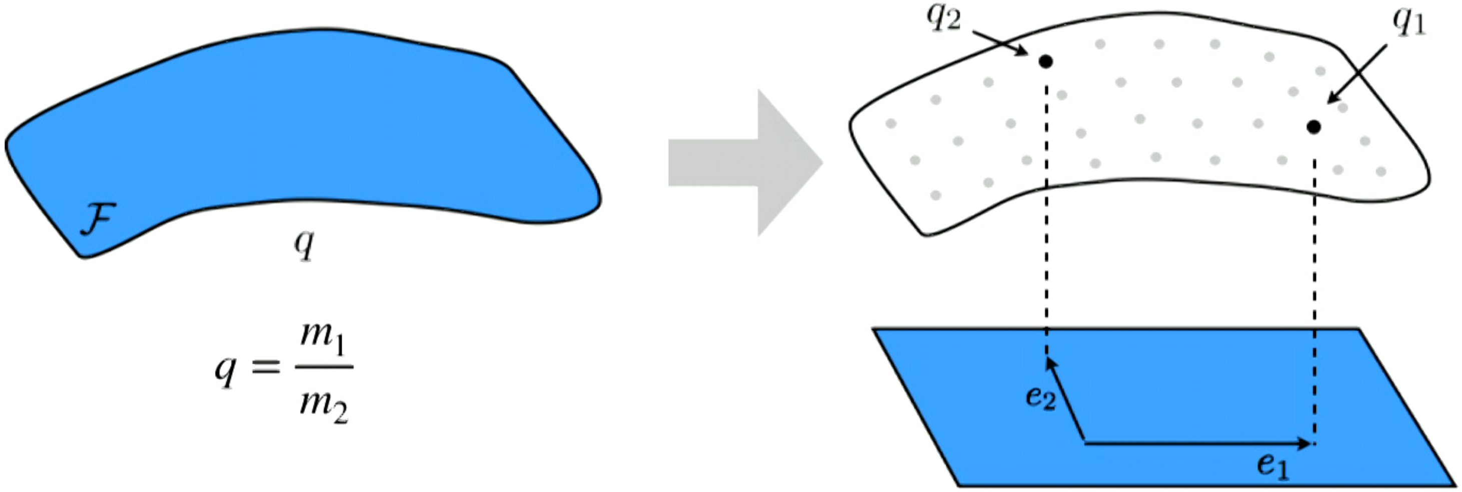
Khan et al, 1508.07253

Surrogate models: A data driven approach



Surrogate modeling: 1d example

Reduced basis

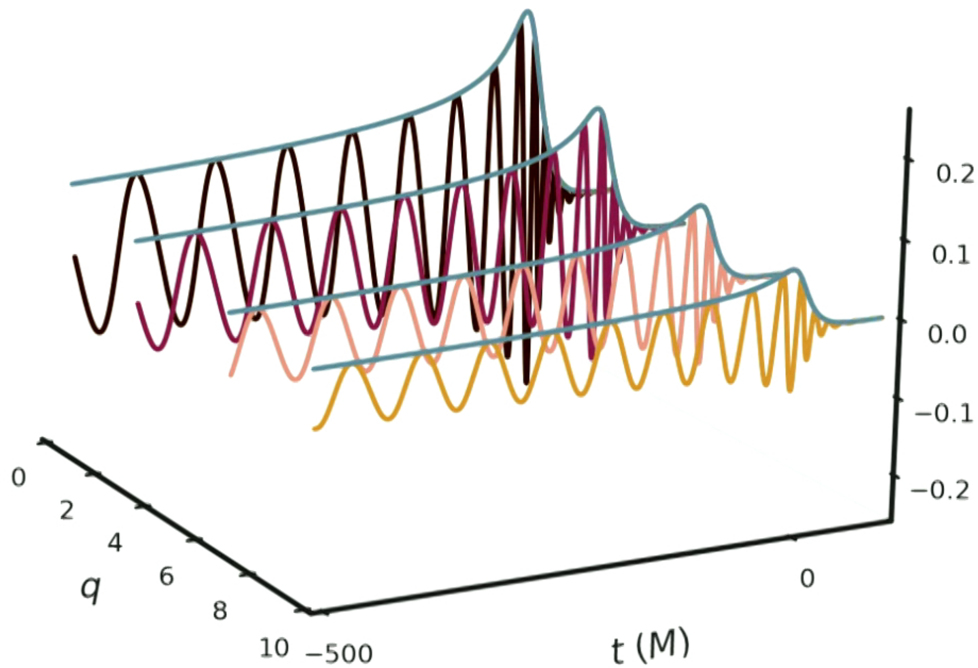


$$q = \frac{m_1}{m_2}$$

$$h(q,t) = \sum_{i=1}^{n} c_i(q)\ e_i(t)$$

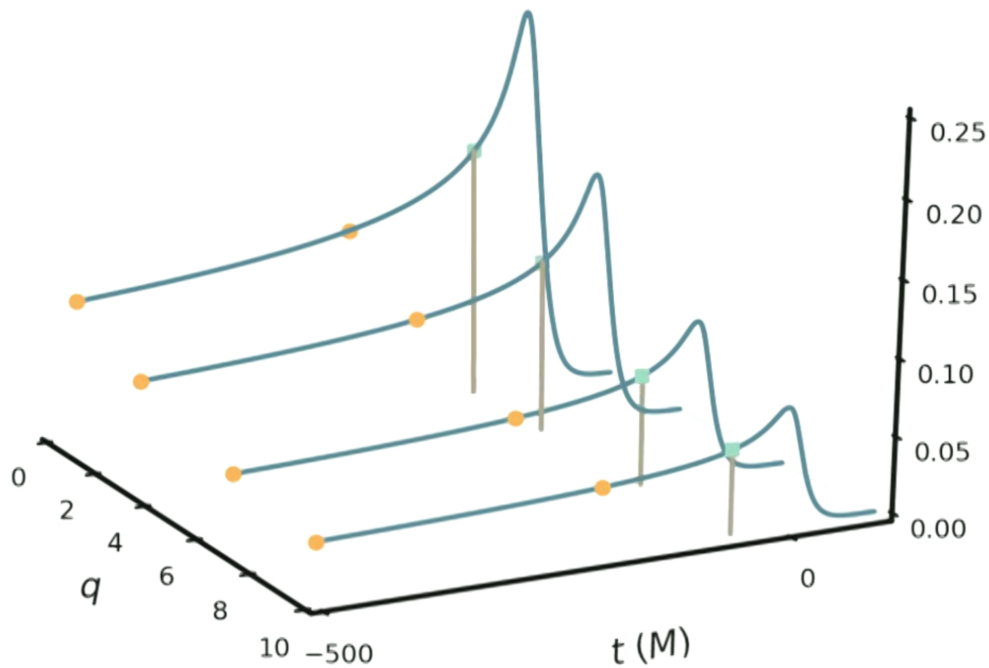
Credit: Chad Galley

Reduced basis



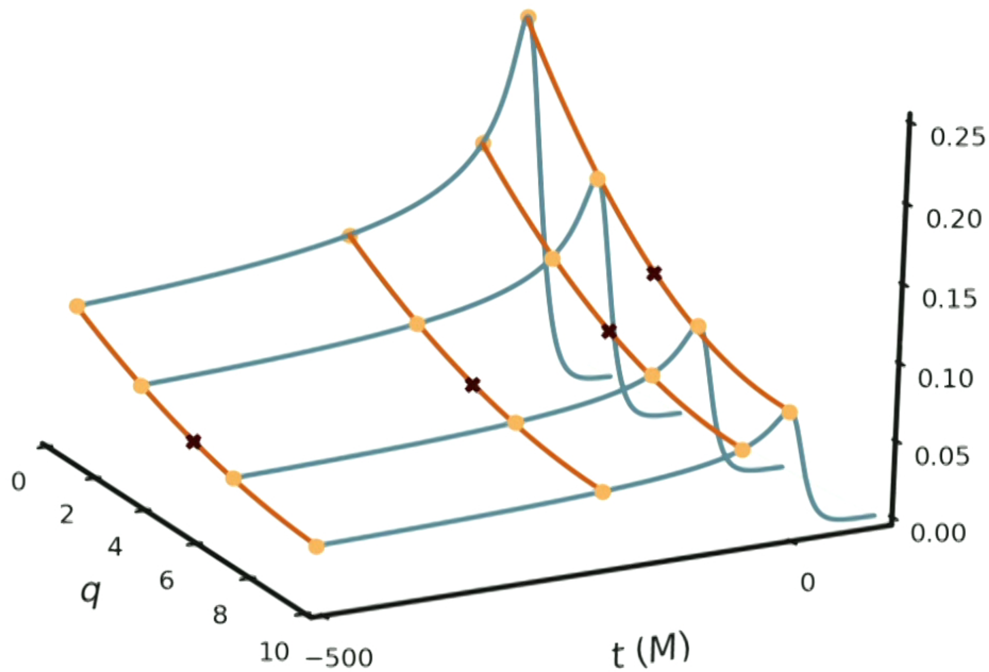
$$h(q,t) = \sum_{i=1}^{n} c_i(q)\ e_i(t)$$

Empirical interpolation



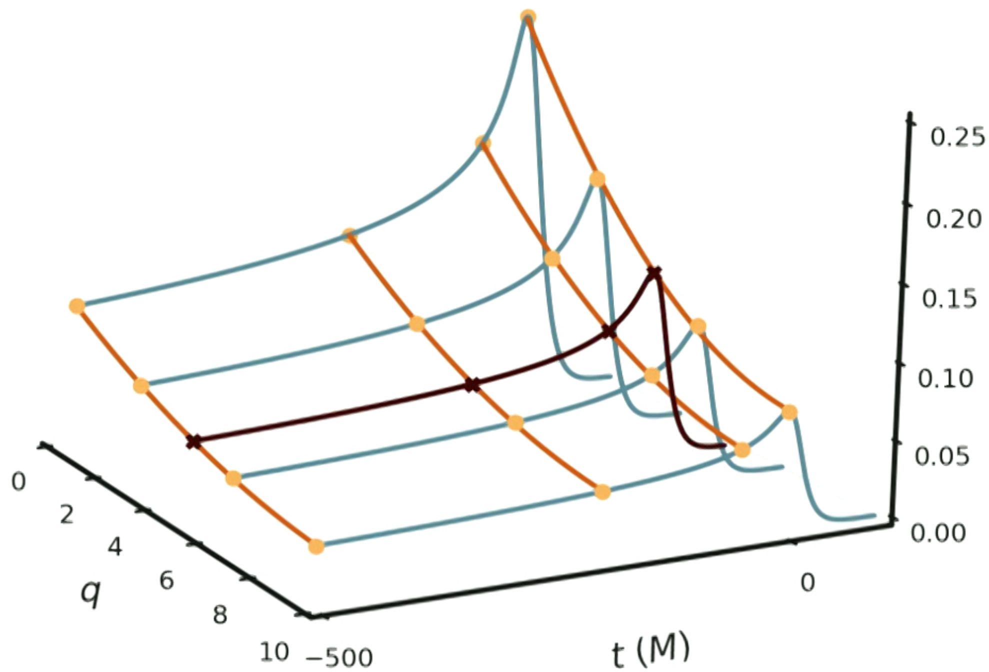
$$A(q,t) = \sum_{i=1}^{n} c_i(q)\, e_i(t) \qquad A(q, t_k) \longleftrightarrow c_i(q)$$

Evaluation



$$A(q, t_k) \longleftrightarrow c_i(q) \qquad A(q,t) = \sum_{i=1}^{n} c_i(q)\; e_i(t)$$

Evaluation

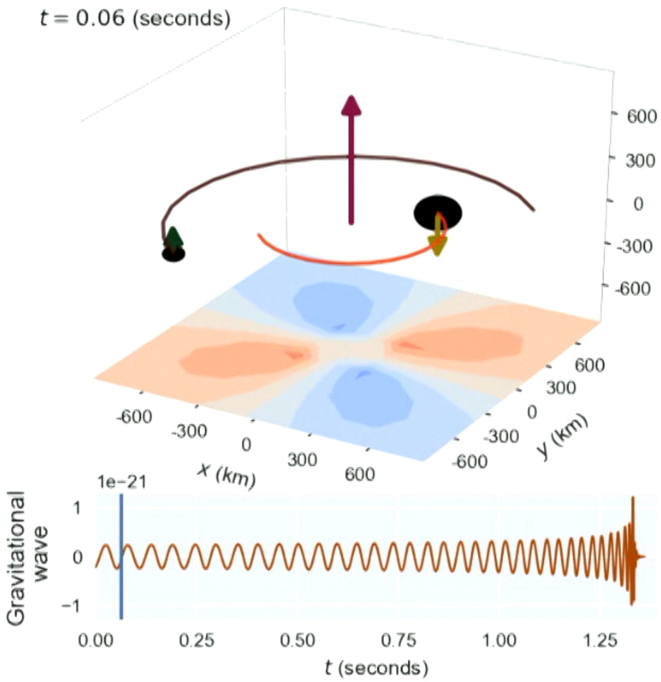


$A(q, t_k)$ ⟷ $c_i(q)$

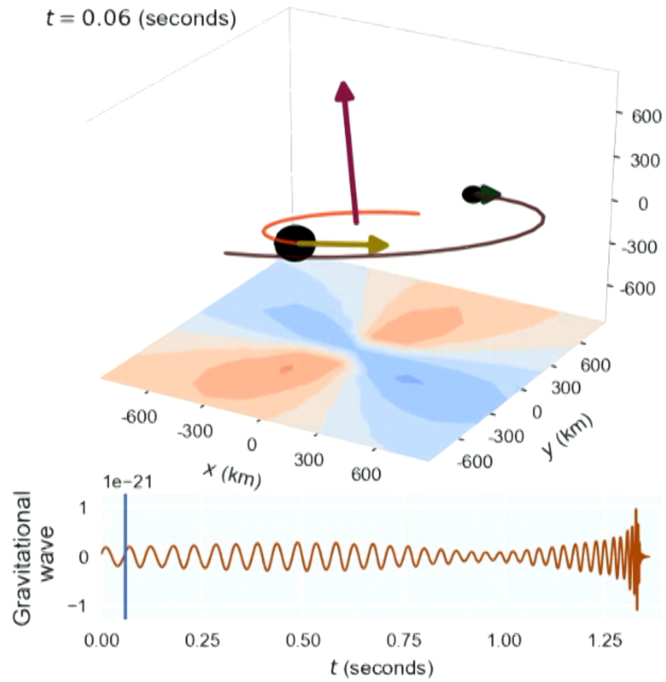
$$A(q,t) = \sum_{i=1}^{n} c_i(q)\; e_i(t)$$

Precessing binary black holes

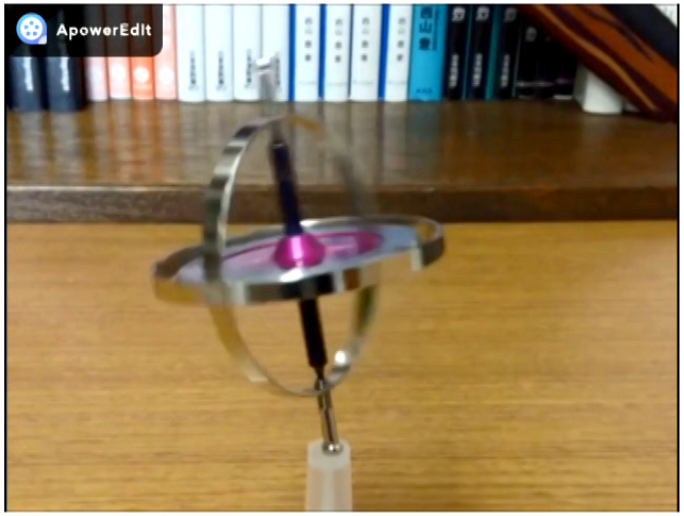
Aligned-spin

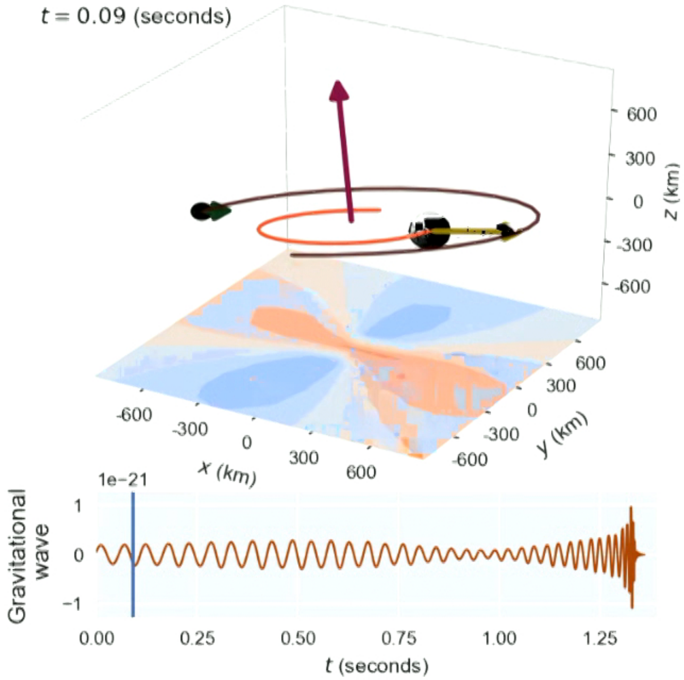


Precessing

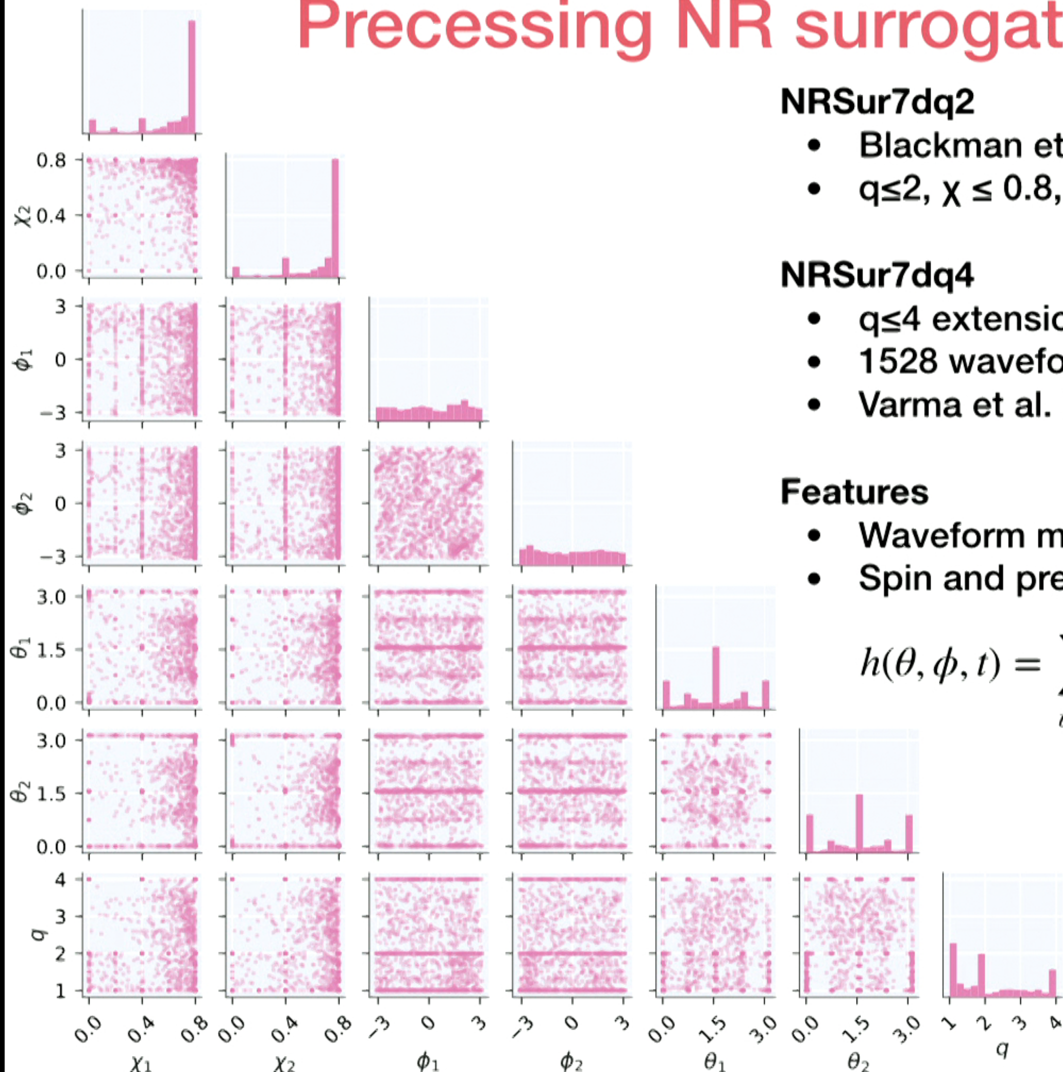


Precessing binary black holes





Precessing NR surrogate model



NRSur7dq2

- Blackman et al. (1705.07089)
- q≤2, χ ≤ 0.8, generically precessing (7d)

NRSur7dq4

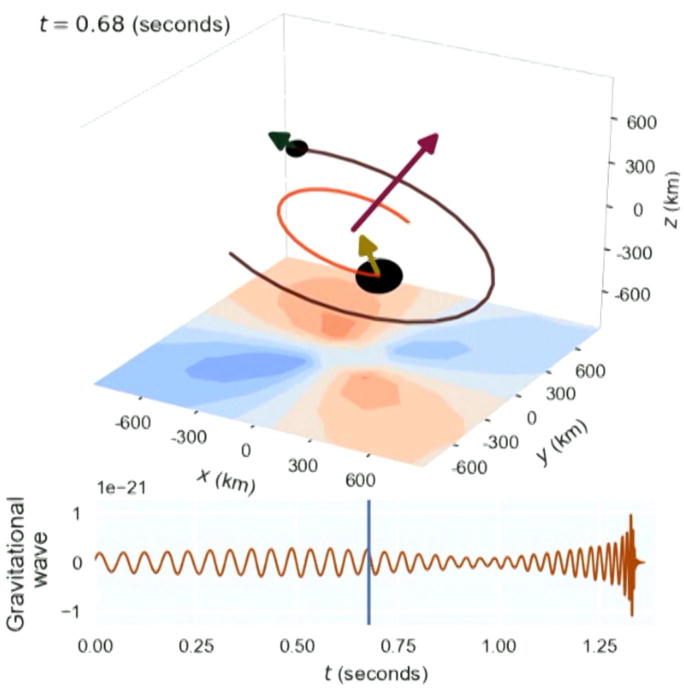
- q≤4 extension of NRSur7dq4
- 1528 waveforms
- Varma et al. (1905.09300)

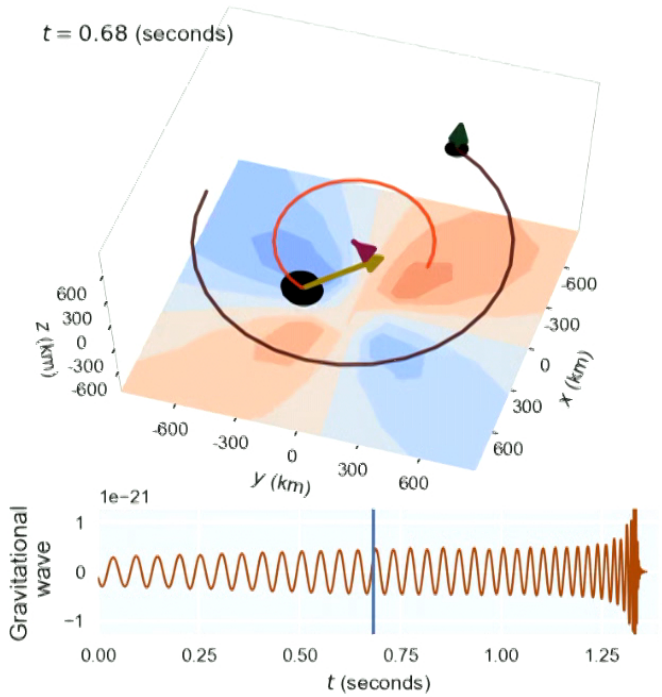
Features

- Waveform modes ℓ≤4, -ℓ≤m≤ℓ
- Spin and precessing frame dynamics

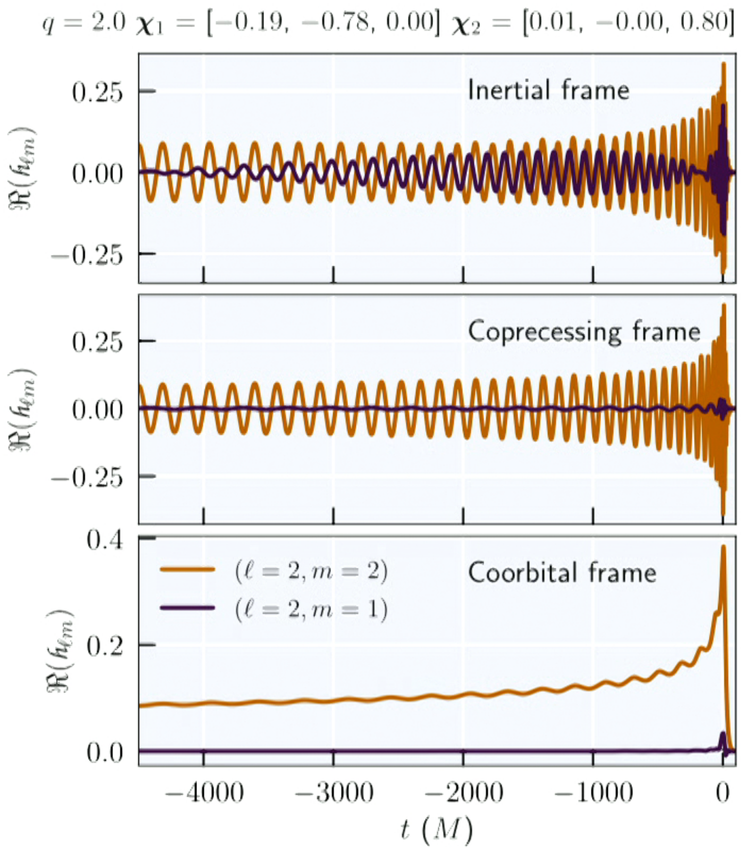
$$h(\theta, \phi, t) = \sum_{\ell,m} {}_{-2}Y_{\ell m}(\theta, \phi)\ h_{\ell m}(t)$$

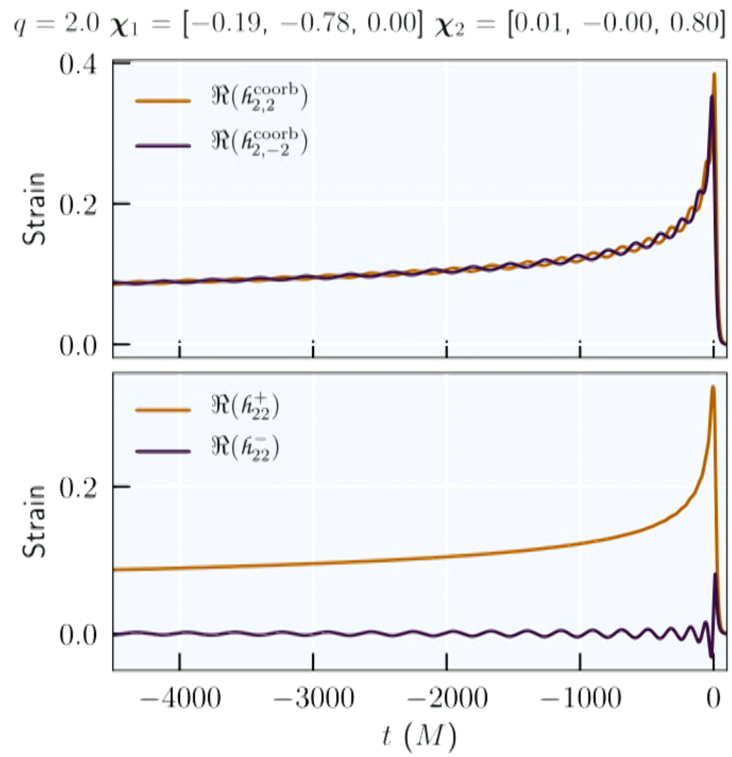
Coprecessing frame



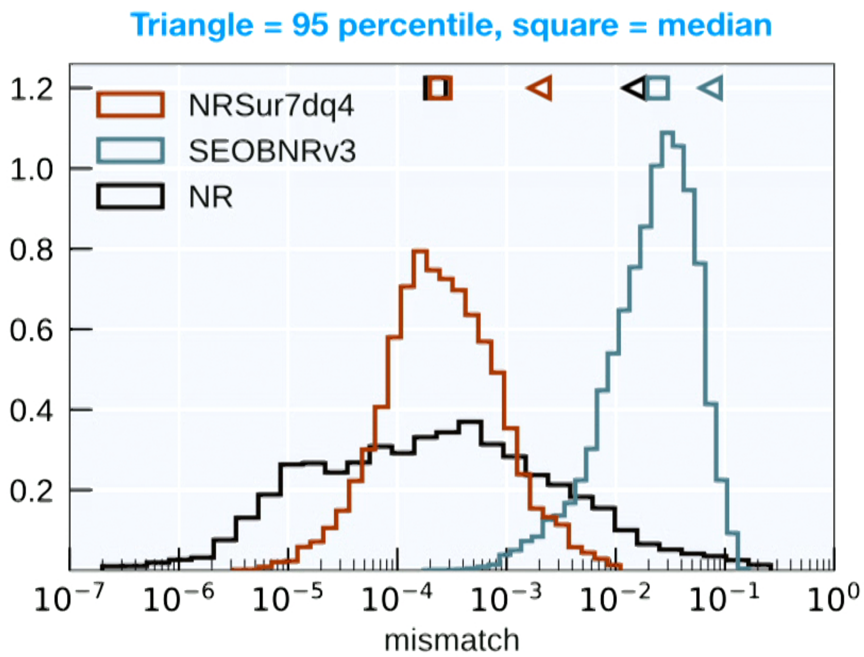


Waveform decomposition





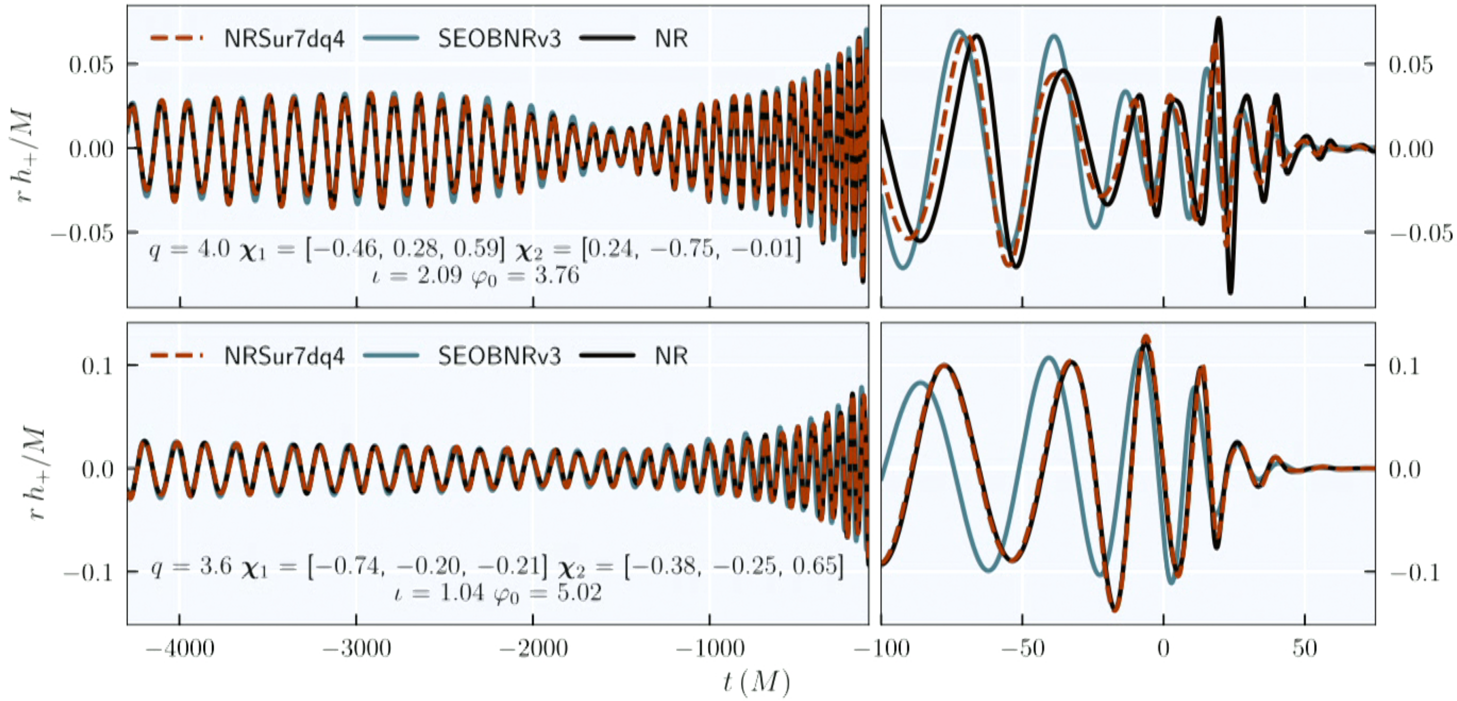
Results



$$\text{Mismatch} = 1 - \frac{\langle h_1, h_2 \rangle}{\sqrt{\langle h_1, h_1 \rangle \langle h_2, h_2 \rangle}}$$

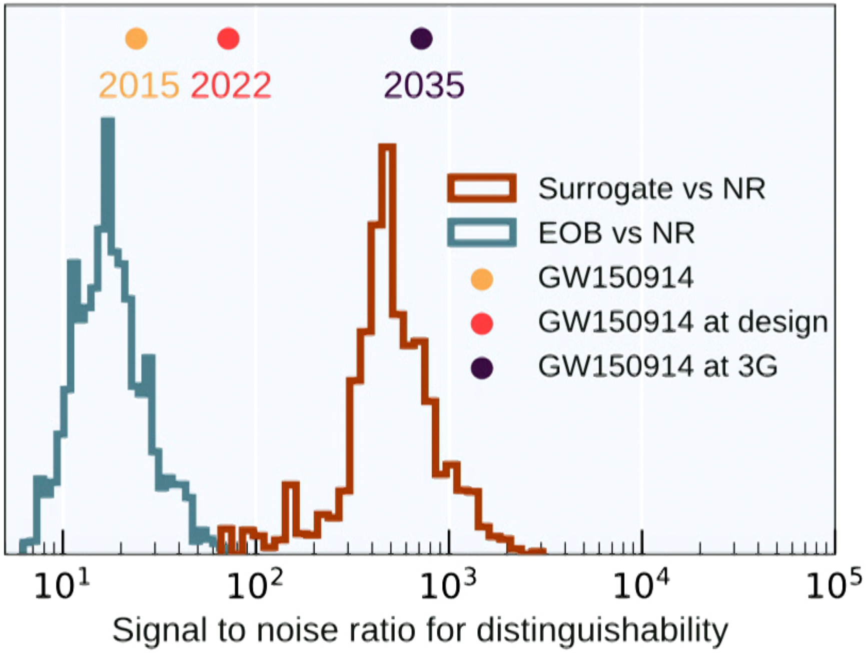
$$\langle h_1, h_2 \rangle = 4\mathcal{R}\left[\int_{f_{min}}^{f_{max}} \frac{\tilde{h}_1(f)\tilde{h}_2^*(f)}{S_n(f)}\, df\right]$$

Worst cases



NRSur7dq4
SEOBNRv3
NR
$r\,h_+/M$
$q = 4.0$ $\chi_1 = [-0.46, 0.28, 0.59]$ $\chi_2 = [0.24, -0.75, -0.01]$
$\iota = 2.09$ $\varphi_0 = 3.76$
$q = 3.6$ $\chi_1 = [-0.74, -0.20, -0.21]$ $\chi_2 = [-0.38, -0.25, 0.65]$
$\iota = 1.04$ $\varphi_0 = 5.02$
$t\,(M)$

Are we ready for precision GW astronomy?

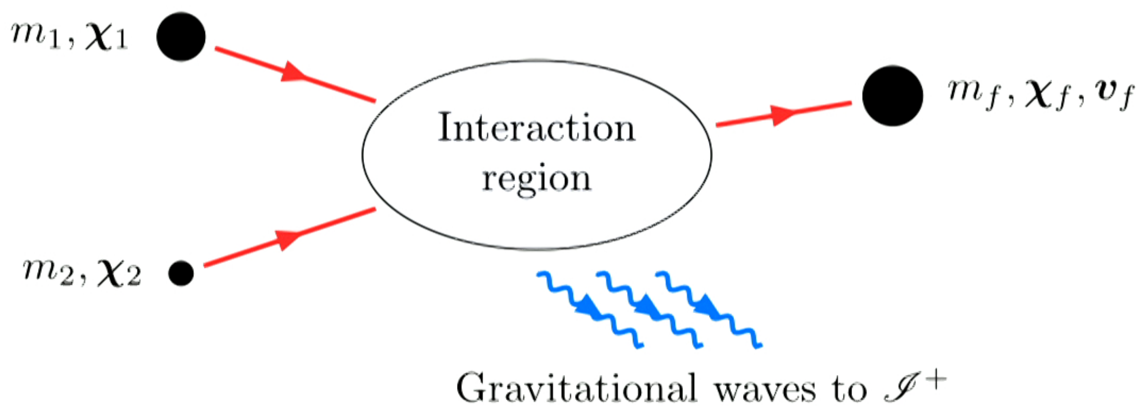


$$\text{Mismatch} \leq \frac{1}{2\rho^2}$$

Flanagan and Hughes, gr-qc/9710129

Upgrading surrogates is easy: just do more accurate NR simulations!

Remnant properties



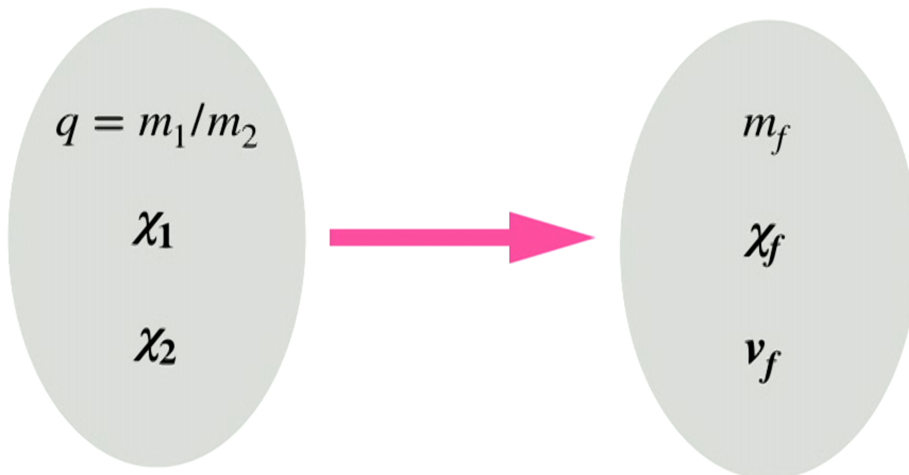
Final mass, m_f ⟷ **Conservation of energy**

Final spin, χ_f ⟷ **Conservation of angular momentum**

Final velocity, v_f ⟷ **Conservation of linear momentum**

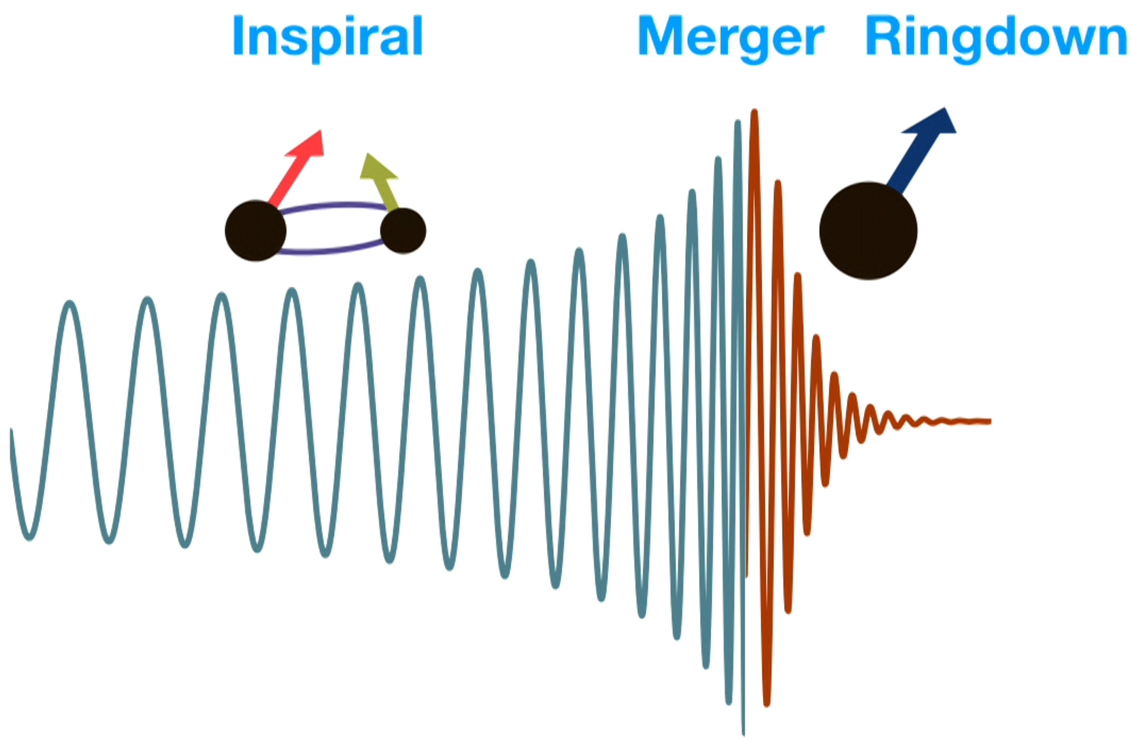
Remnant surrogate model

Goal: Map component BHs to remnant

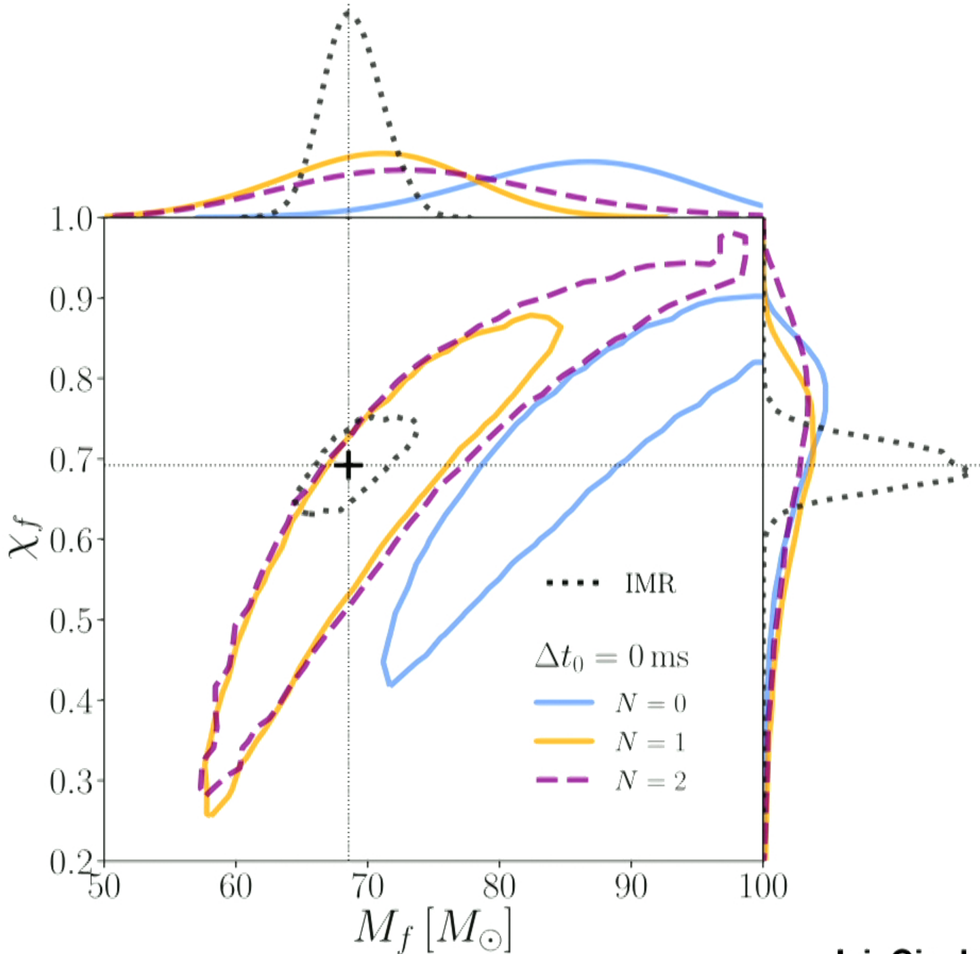


Skip the messy strong-field regime!

Stages of a binary black hole



Remnant properties use case



Isi, Giesler et al., 1905.00869

Phenomenological fits

$$\frac{M_{\rm rem}}{m} = (4\eta)^2 \Big\{ M_0 + K_1 \tilde{S}_\parallel + K_{2a}\,\tilde{\Delta}_\parallel \delta m + K_{2b}\,\tilde{S}_\parallel^2 + K_{2c}\,\tilde{\Delta}_\parallel^2 + K_{2d}\,\delta m^2 + K_{3a}\,\tilde{\Delta}_\parallel \tilde{S}_\parallel \delta m + K_{3b}\,\tilde{S}_\parallel \tilde{\Delta}_\parallel^2 + K_{3c}\,\tilde{S}_\parallel^3 + K_{3d}\,\tilde{S}_\parallel \delta m^2 + K_{4a}\,\tilde{\Delta}_\parallel \tilde{S}_\parallel^2 \delta m + K_{4b}\,\tilde{\Delta}_\parallel^3 \delta m + K_{4c}\,\tilde{\Delta}_\parallel^4 + K_{4d}\,\tilde{S}_\parallel^4 + K_{4e}\,\tilde{\Delta}_\parallel^2 \tilde{S}_\parallel^2 + K_{4f}\,\delta m^4 + K_{4g}\,\tilde{\Delta}_\parallel \delta m^3 + K_{4h}\,\tilde{\Delta}_\parallel^2 \delta m^2 + K_{4i}\,\tilde{S}_\parallel^2 \delta m^2 \Big\} + \Big[1 + \eta(\tilde{E}_{\rm ISCO} + 11)\Big]\,\delta m^6, \quad (1)$$

Healy and Lousto, 1610.09713

What can we do better?

Fitting method

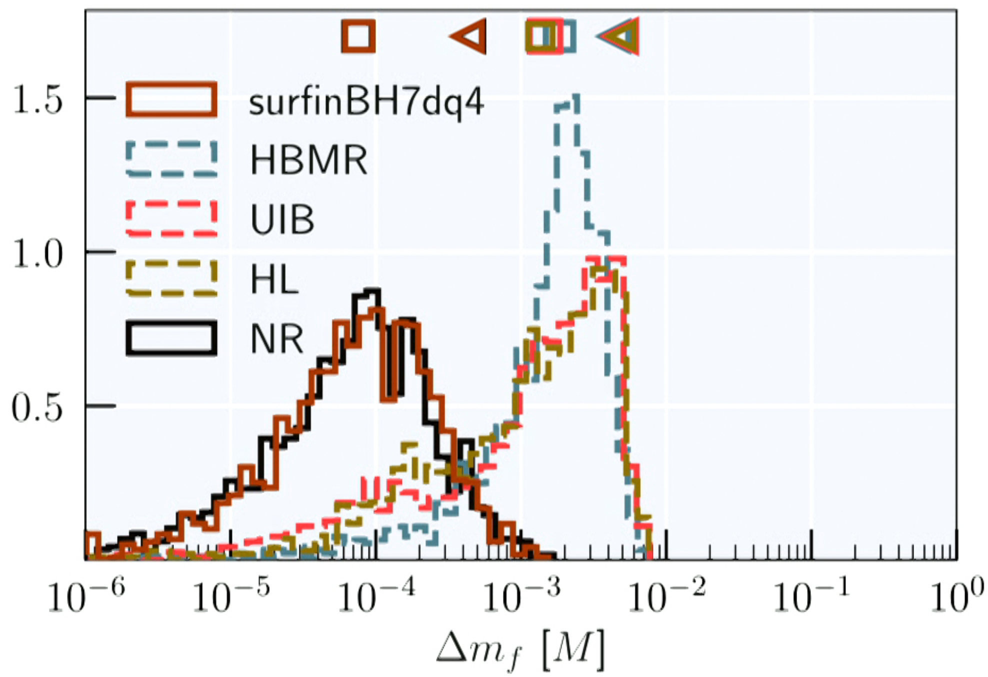
- Gaussian Process Regression (GPR).
- No need to assume phenomenology, let the data speak for itself!

Training with precessing NR

- Directly train model against generically precessing NR simulations.
- Reproduce NR as accurately as NR itself!

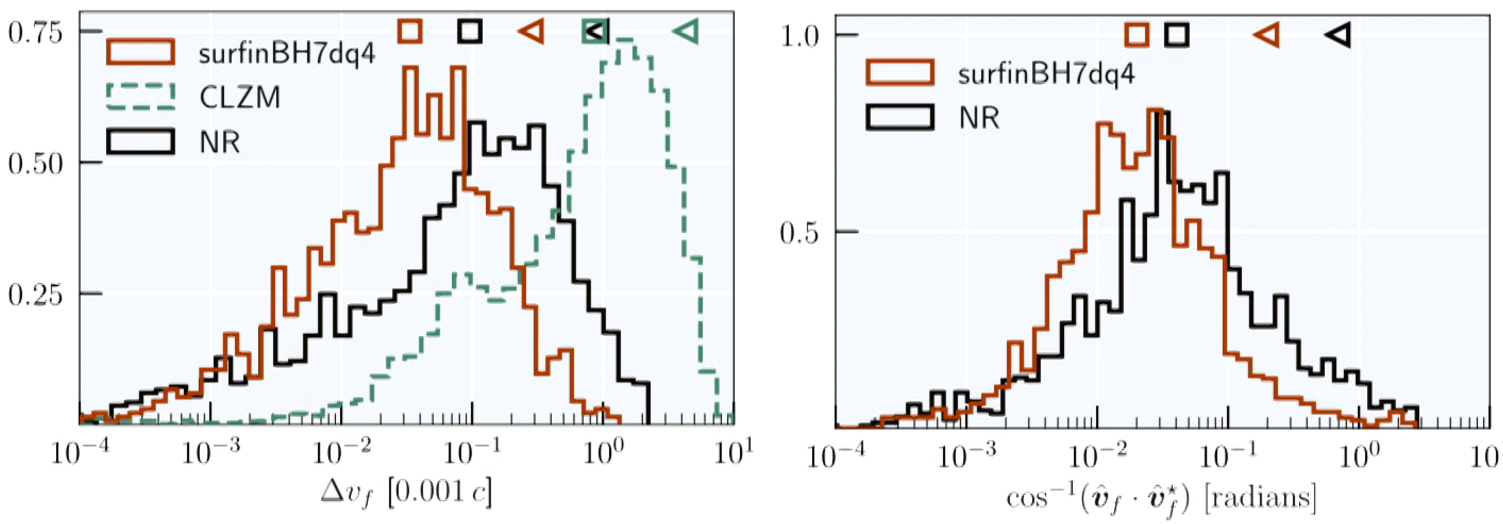
Varma et al., 1809.09125

Precessing remnant model: final mass



- HBMR = Hofmann, Barausse, and Rezzolla (1605.01938)
  + Barausse, Morozova, and Rezzolla (1206.3803)
- HL = Healy and Lousto (1610.09713)
- UIB = Jimenez-Forteza, et al. (1611.00332)
- CLZM = Campanelli, Lousto, Zlochower, and Merritt (1605.01067)

Precessing model: final kick

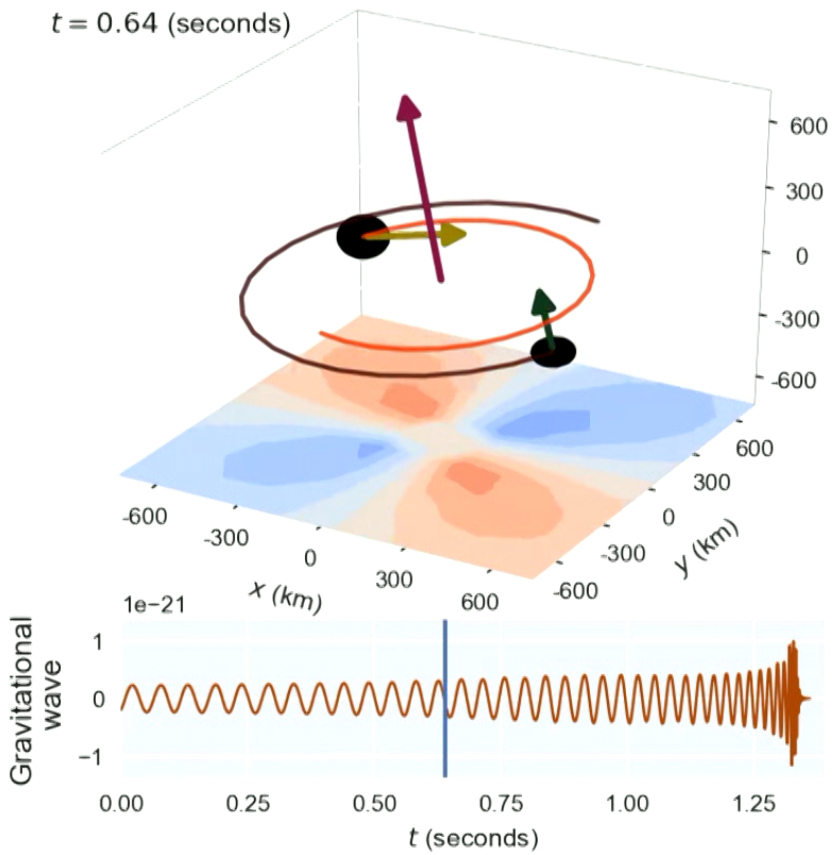


Fit accuracy requirements

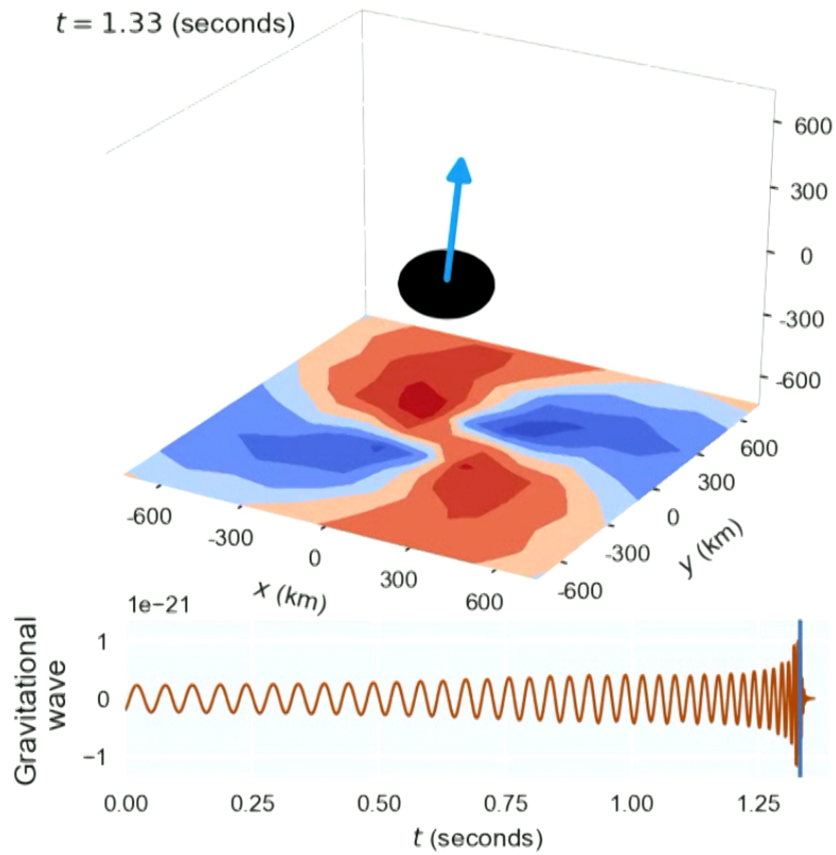
	Δm_f	$\Delta\chi_f$	Validity
GW150914 [1]	$0.1M$	0.1	
At design $(3\times\rho)$	$3.3\times10^{-2}M$	3.3×10^{-2}	
Current fits (95 percentile)	$5\times10^{-3}M$	2×10^{-2}	$5\times\rho_{GW150914}$
Our fits (95 percentile)	$5\times10^{-4}M$	2×10^{-3}	$50\times\rho_{GW150914}$

[1] Abbot et al, 1606.04856

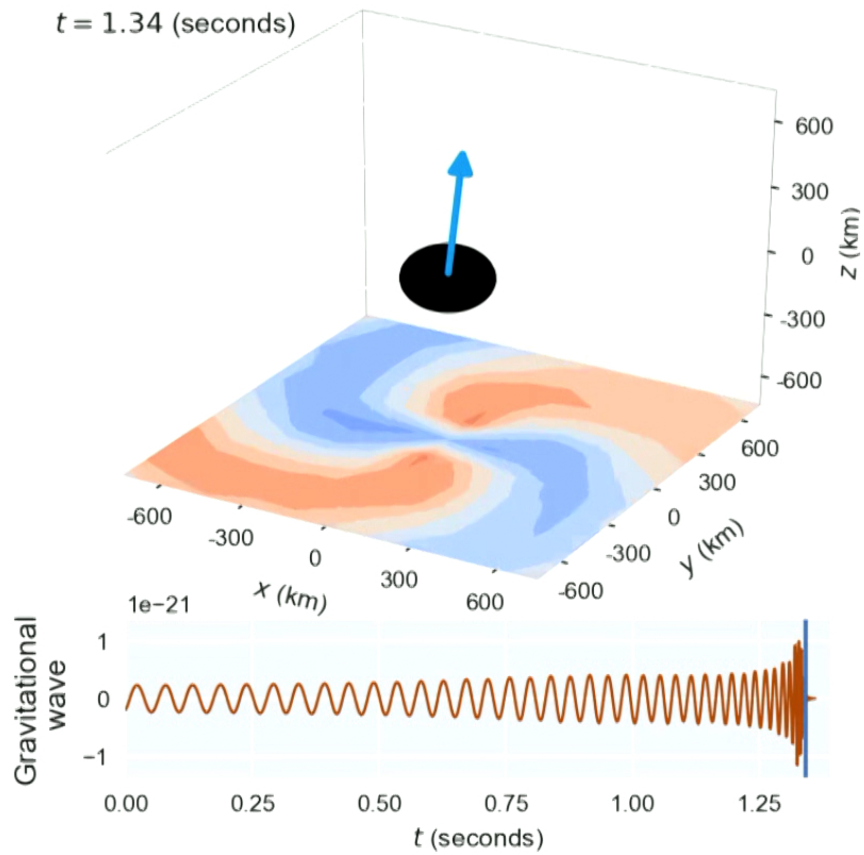
Putting it all together: the super kick



Putting it all together: the super kick

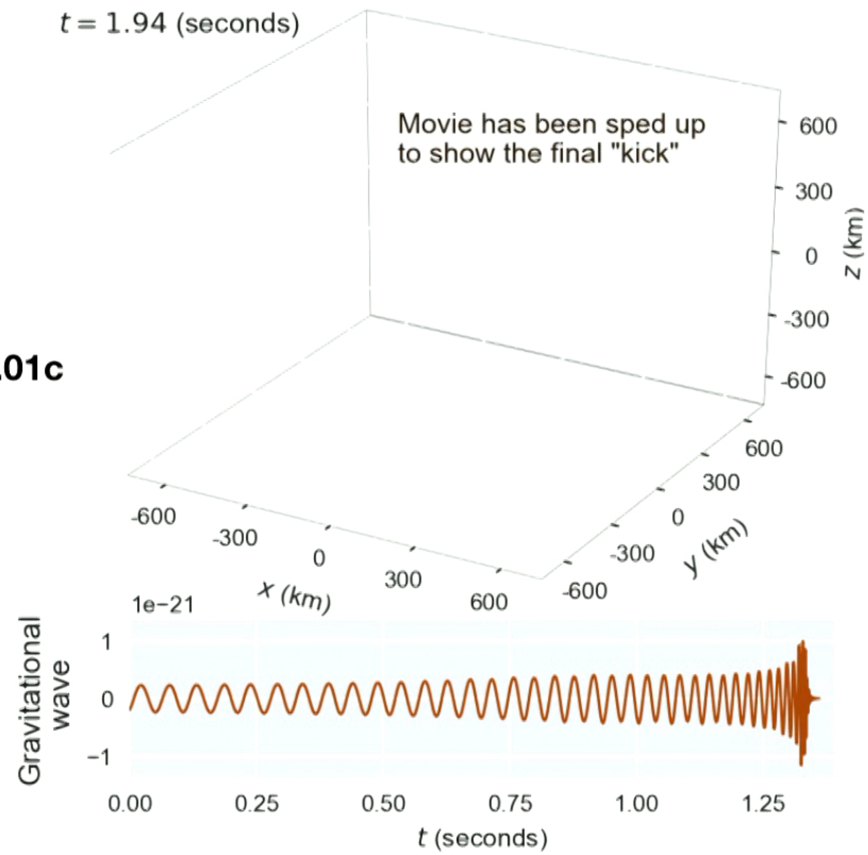


Putting it all together: the super kick



Putting it all together: the super kick

Final velocity = 0.01c



Summary

- Numerical relativity simulations are accurate but very expensive
- Surrogate models cheaply reproduce the accuracy of simulations
- Surrogate models for waveform and final BH from precessing BBH
- More accurate than existing models by an order of magnitude

Surrogate models take:

Binary black hole simulations from supercomputers to your laptop!

Thank you!

movies at vijayvarma392.github.io/binaryBHexp