Binary black hole simulations for surrogate modeling

Daniel A. Hemberger

Caltech
Walter Burke Institute for Theoretical Physics

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GW150914: BINARY BLACK HOLE MERGER

Figure credit: SXS Lensing

GW150914 followup with the Spectral Einstein Code (SpEC):

- Targeted simulations
  G. Lovelace, Tuesday 4:30pm
- Phenomenological model calibration
- Surrogate model building
  J. Blackman, Wednesday 2:00pm

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- Phenomenological model calibration
- Surrogate model building ← **This talk!**
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Surrogate model

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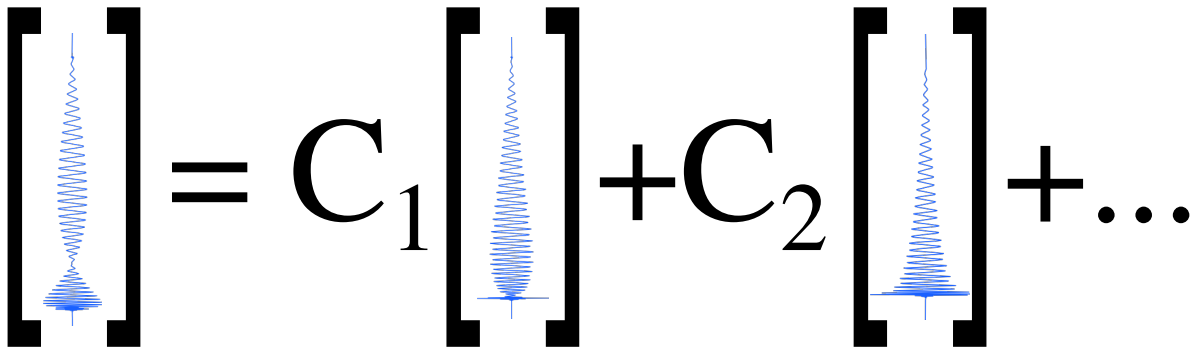
Solution: Perform only the "most distinct" simulations and then interpolate to arbitrary parameters



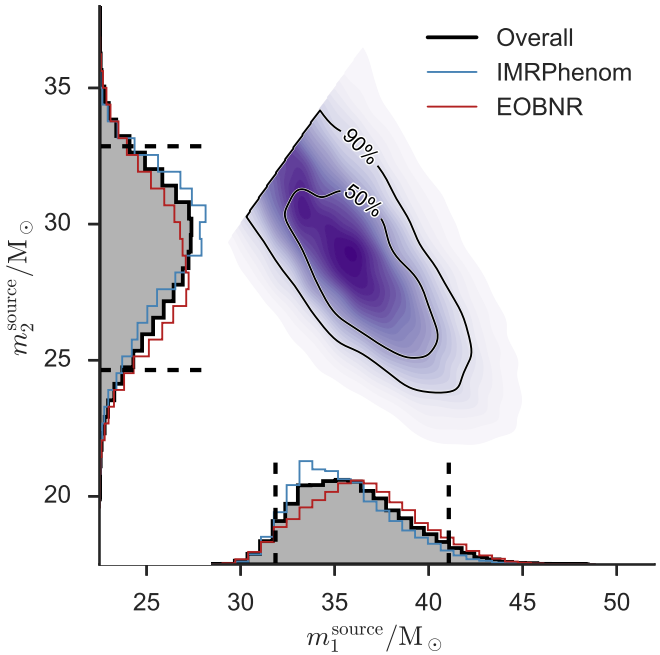
See companion talk (J. Blackman, Wednesday 2pm)

Choosing simulation parameters

How do we choose simulation parameters?

- Parameters for each simulation chosen by a greedy algorithm using a training space of approximate waveforms
- Parameter bounds informed by:
  1. Estimated parameters of GW150914
  2. Surrogate modeling limitations
  3. Computational limitations

1. Estimated parameters of GW150914



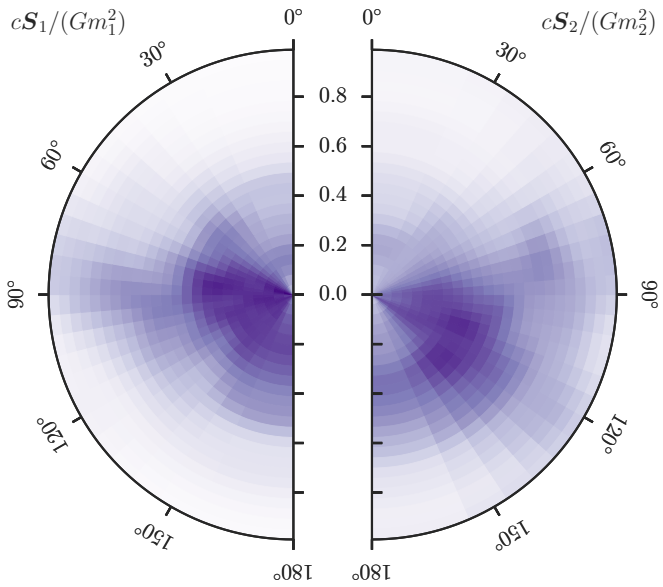
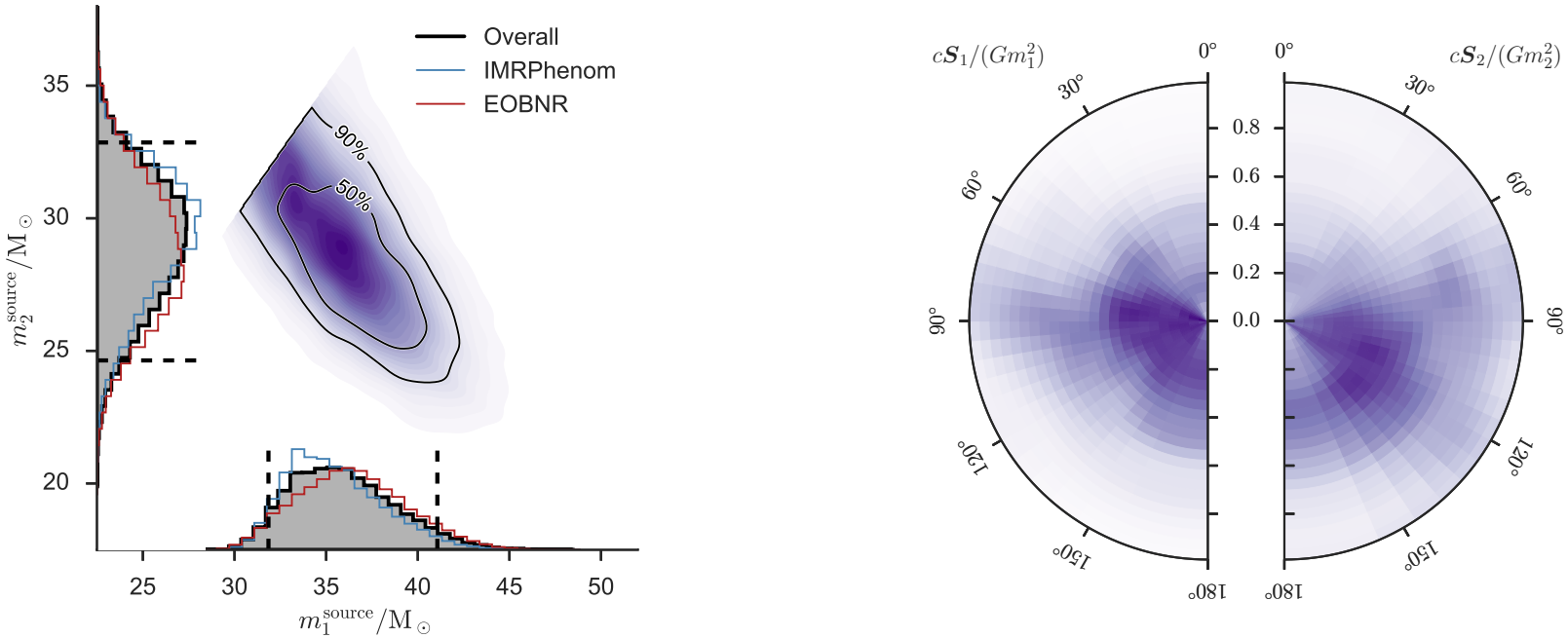


Figure credit: LVC 2016 (arXiv: 1602.03840)

Parameter estimation with phenomenological models:

- Mass ratio $q \equiv m_1/m_2$ is near unity
- Total mass $M_{\rm tot} \equiv m_1 + m_2$ suggests few orbits
- Component spins $\vec{S}_1$, $\vec{S}_2$ are poorly constrained

1. Estimated parameters of GW150914



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$\Rightarrow$ **Nearly ideal for fast and efficient NR simulations!**

- Not known how to build a (fast) $7d$ surrogate.
- Need $\mathcal{O}(1000)$ simulations for $7d$, but only $\mathcal{O}(300)$ for $4d$.

$$(q, \vec{S}_1, \vec{S}_2)$$

$$\Downarrow$$

$$\phi(\vec{S}_1) = 0$$

$$\vec{S}_2 \parallel \vec{L}$$

$$\Downarrow$$

$$(q, S_1, S_2, \theta_1)$$

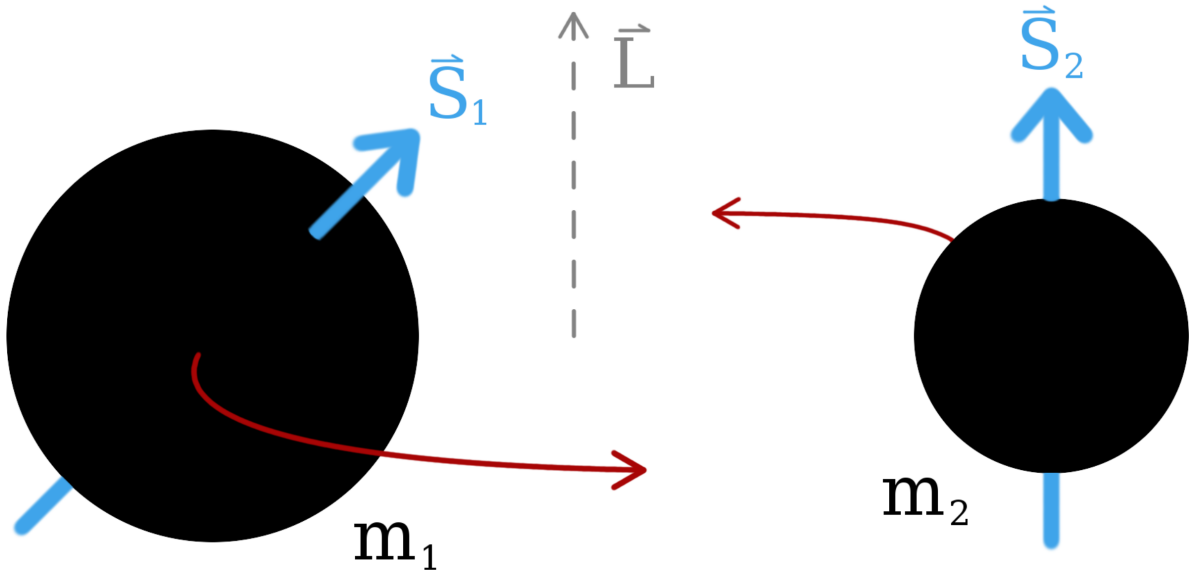
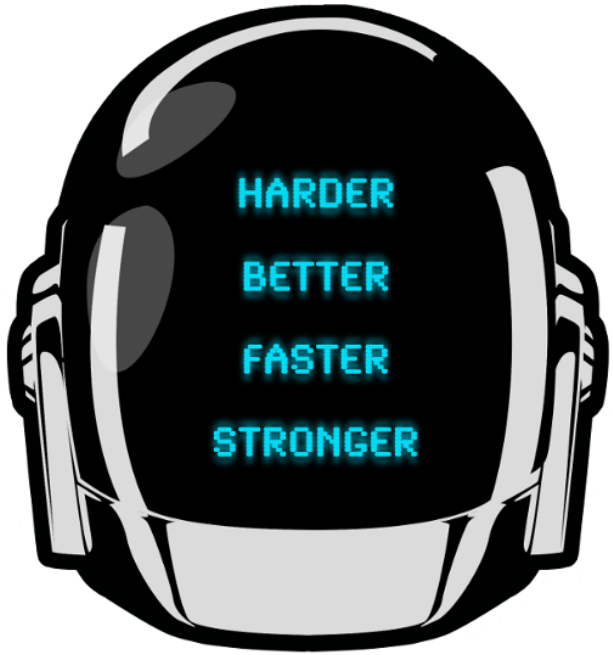


Figure credit: J. Blackman

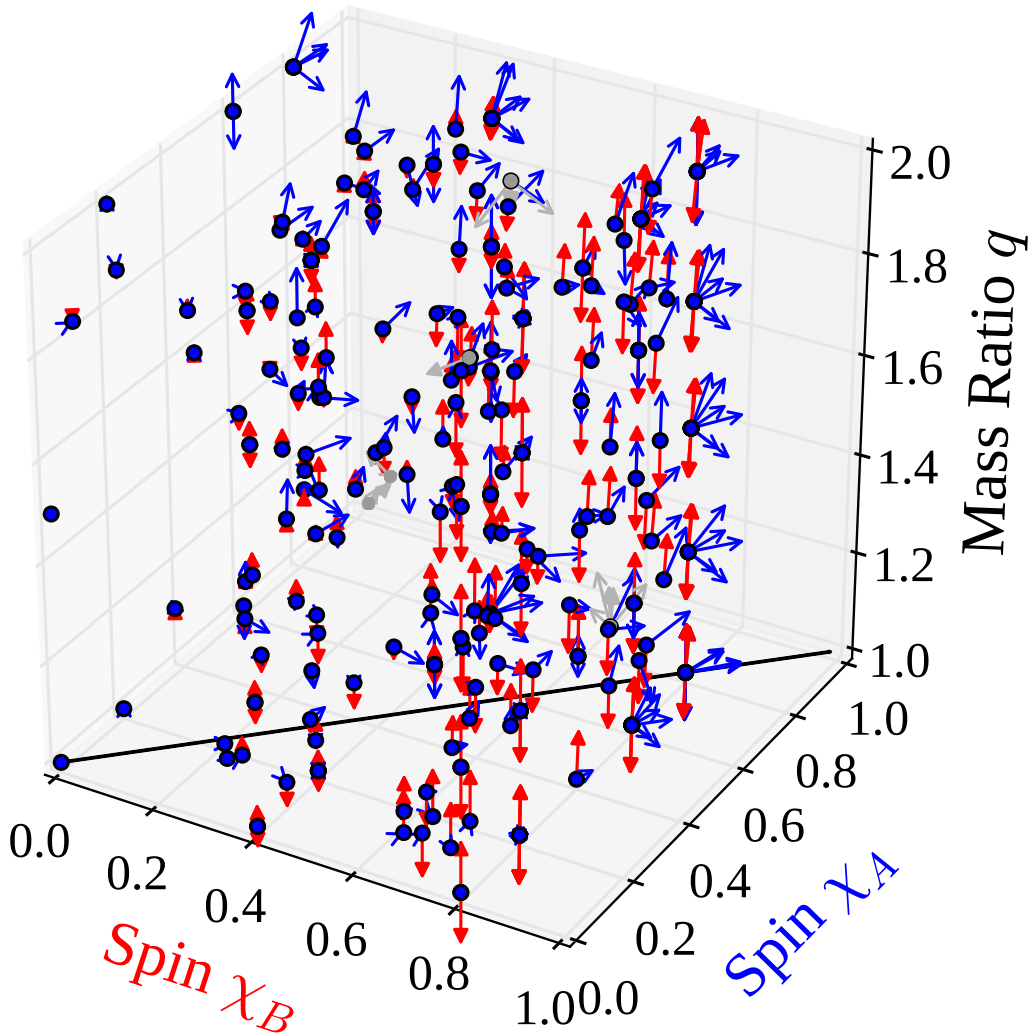
Parameters competing for limited computational resources:

- Higher **numerical resolution**
- Lower **eccentricity**
- Higher **mass ratio and spins**
- Longer **waveforms**
- More **simulations**

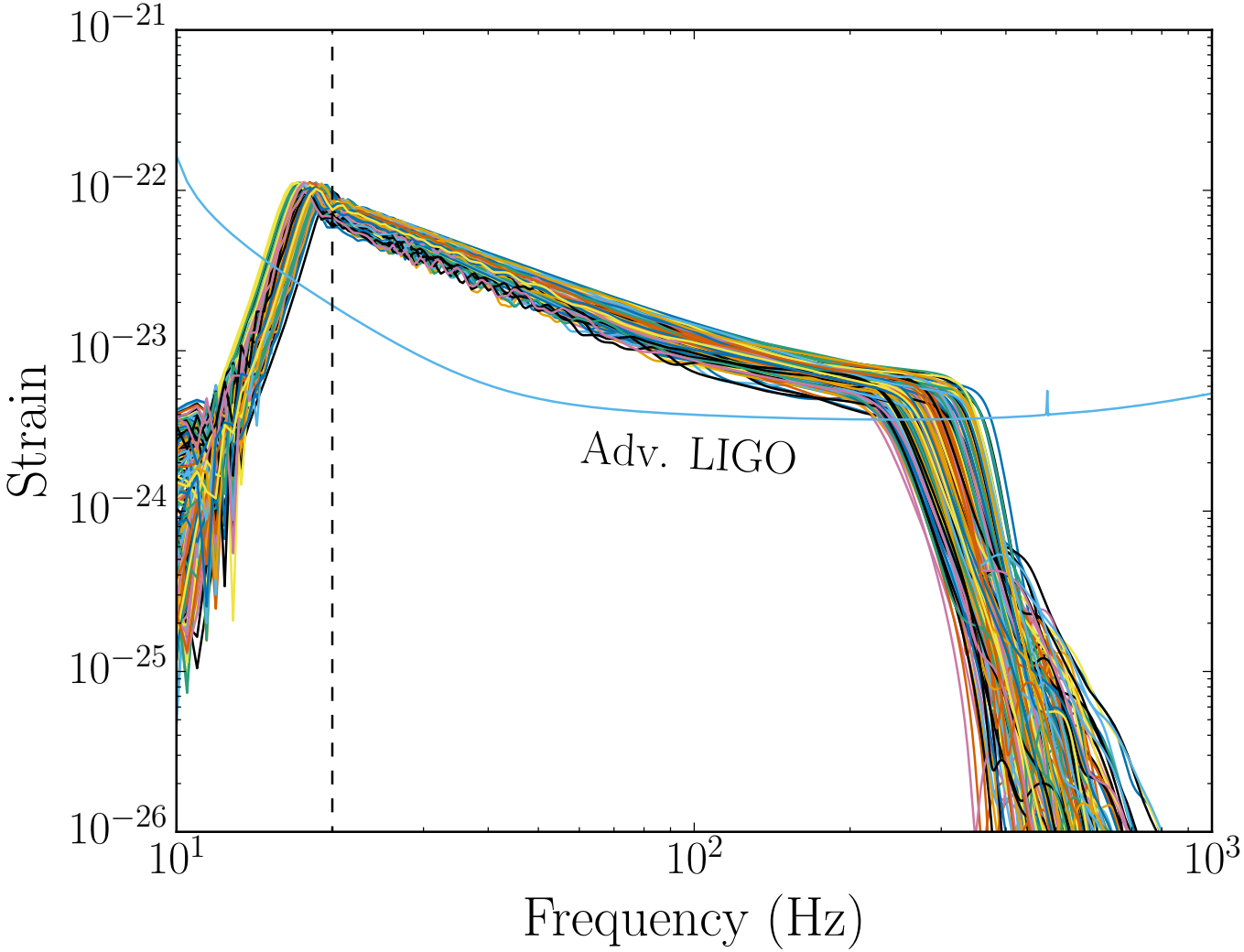


286 simulations
$4d$ parameter space
(9 for model verification)

- $1 \leq q \leq 2$
- $|\chi_{A,B}| \leq 0.8$
- $e \leq 7 \times 10^{-4}$
- $5000M$ ($\sim$20 orbits) + ringdown



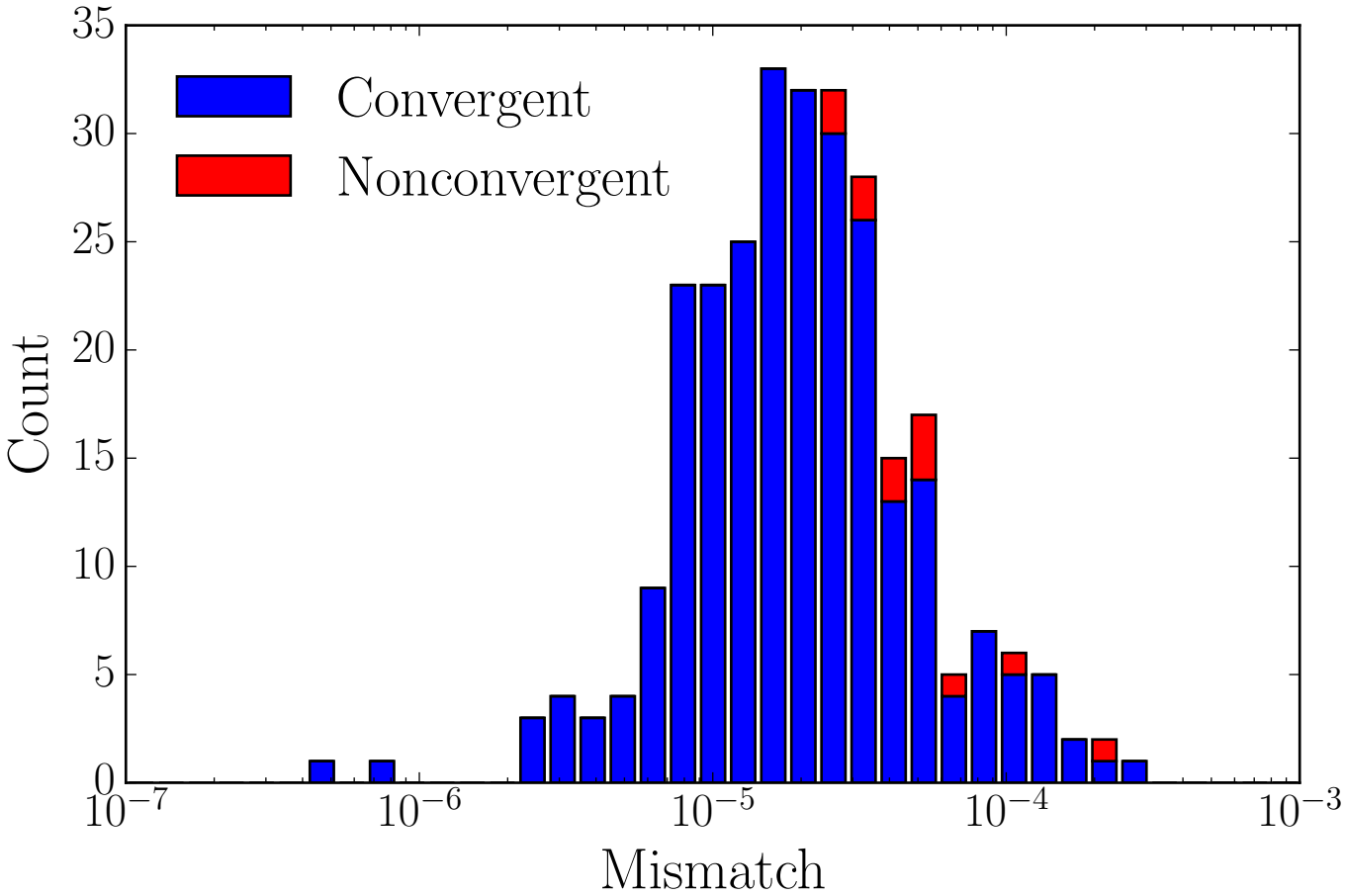
Numerical simulations



NR simulations valid $\gtrsim$ 20 Hz with $M_{\rm tot} = 65 M_\odot$

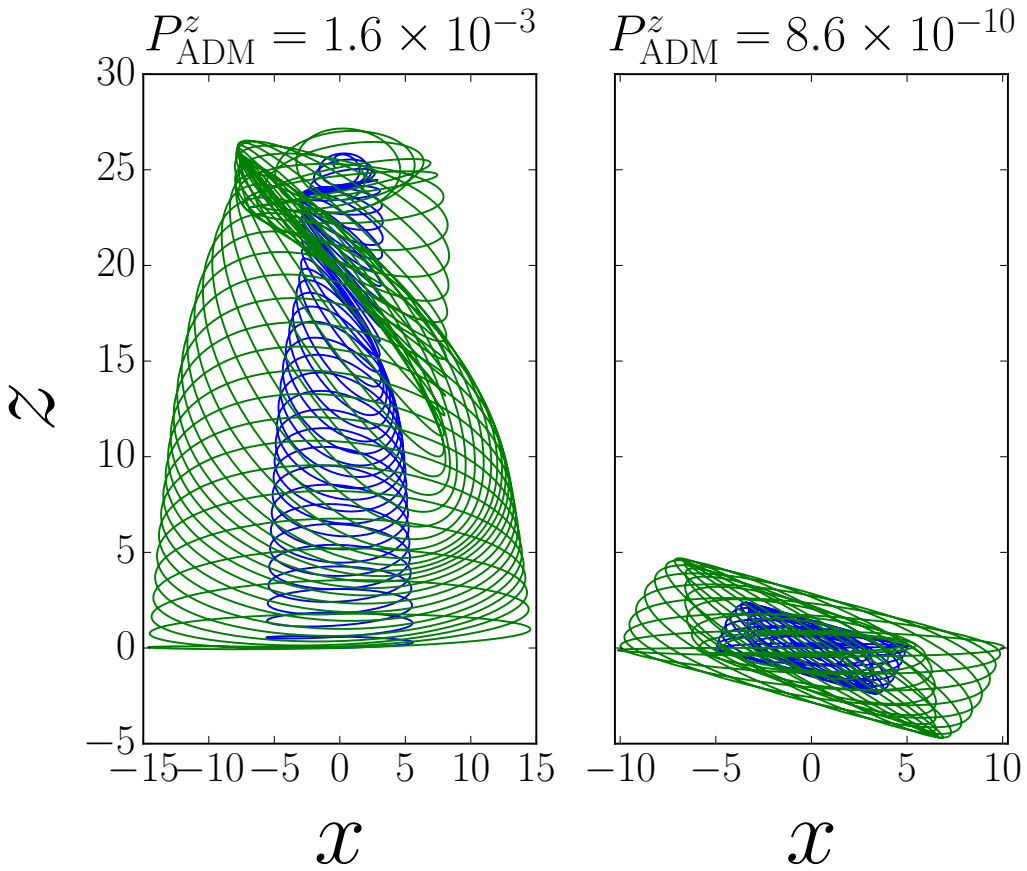
Performed each configuration at three resolutions set by AMR truncation error tolerance e_{AMR}

$$e_{\mathrm{AMR}} \sim 4^{-k}, \quad k = 1, 2, 3$$



Drift of the center of mass:

- Causes undesirable mode mixing in waveforms
- Procedure to clean modes in post-processing not an ideal solution (*cf.* arXiv: 1509.00862)



Conclusions

- Rapidly produced a large number of high-accuracy BBH simulations in the vicinity of GW150914
- Enhancements to SpEC have improved waveform quality
- Simulations were used to construct a surrogate model for fast waveform evaluation
- Will be available at `black-holes.org/waveforms`

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Acknowledgments

Model: J. Blackman, S. Field, C. Galley, P. Schmidt, R. Smith

Simulations: J. Blackman, A. Bohn, N. Demos, A. Garcia, M. Giesler, M. Okounkova, M. Scheel, P. Schmidt, V. Varma

Code: SpEC, GWFrames (SXS Collaboration)

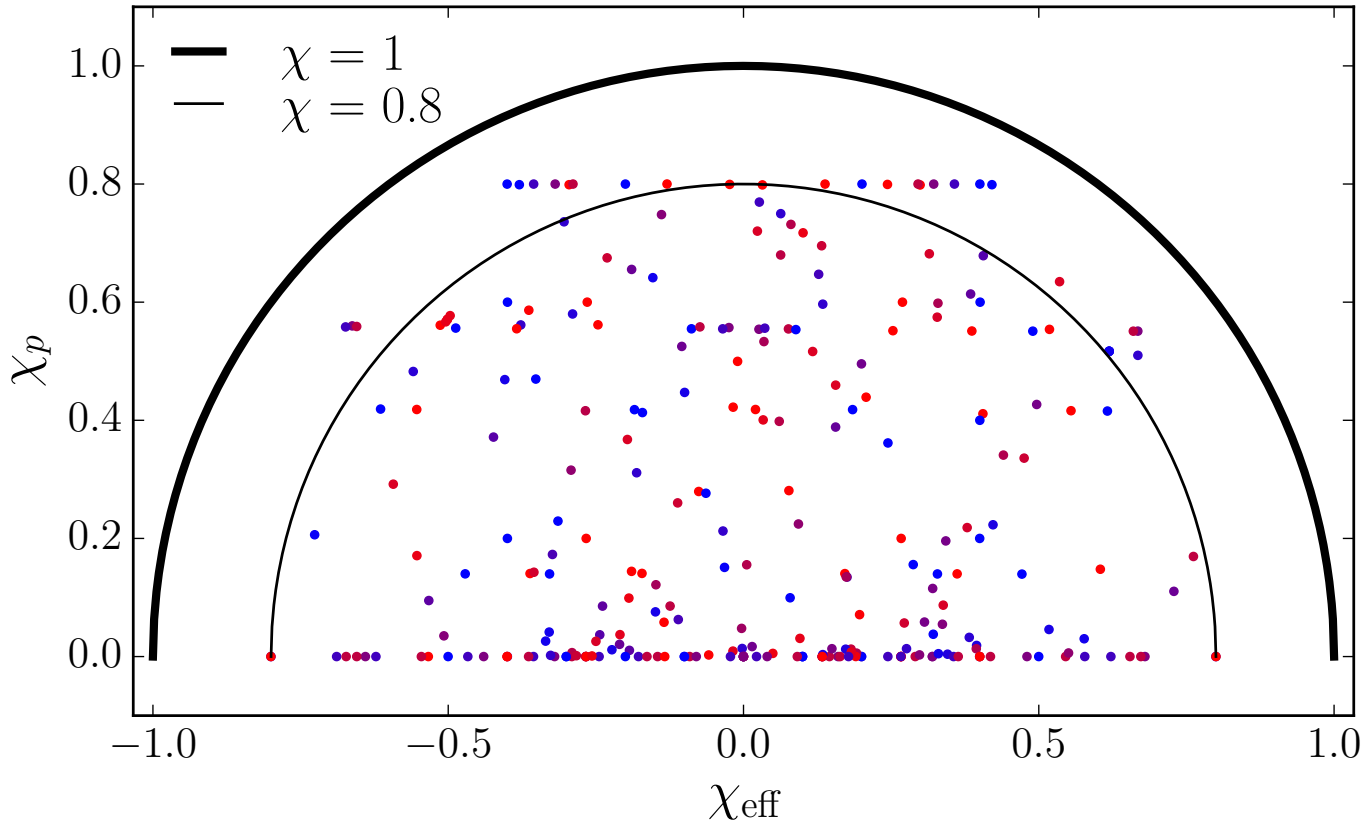
Simulating eXtreme Spacetimes

Black holes, neutron stars, and beyond...

Supplemental Figures

Coverage of the phenomenological spin parameter space
(*cf.* arXiv: 1408.1810)

$$\vec{S}_1 \mapsto \vec{S}_{\rm eff} + \vec{S}_p$$
$$\vec{S}_2 \mapsto 0$$



Phenomenological mapping