Predicting Remnant Parameters in Black Hole Binaries

Using Generic Machine Learning Approaches

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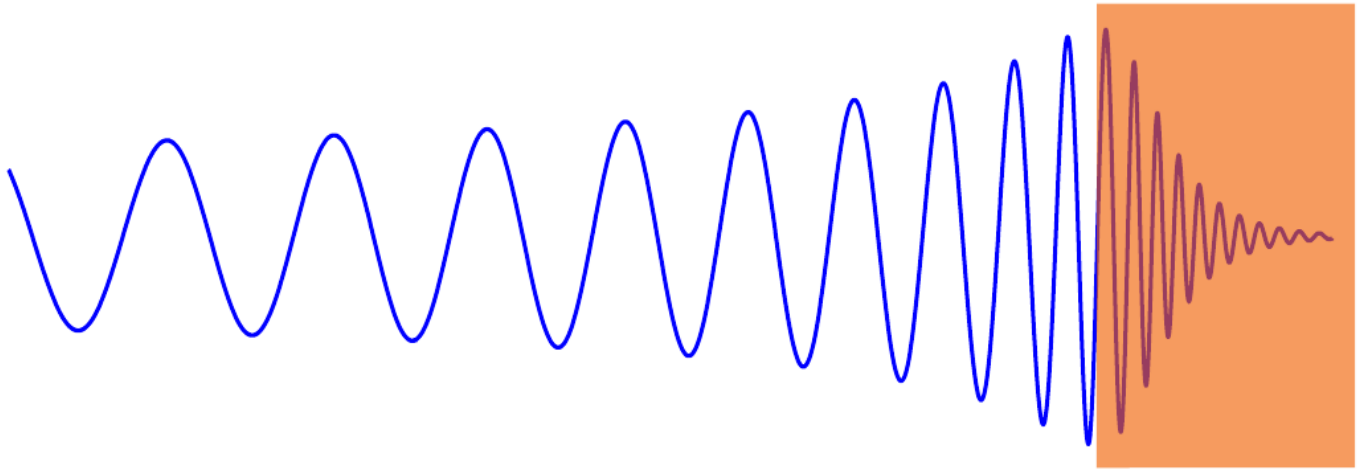
Overview

- Predictions of mass and spin of remnant after binary black hole (BBH) merger
  - Numerical relativity (NR) can do this, but slow
  - Approximate fits: quicker, less computation
- **Goal:** improve fit accuracy
  - more data
  - new techniques
- Compare new fits with previous work
  - Healy and Lousto (2016)
  - Current formulas in LSC Algorithm Library (`LAL`)

Application



- Effective One Body (EOB) formalism
  - Compute waveform during merger and ringdown
  - `LAL` uses mass and spin fits for this

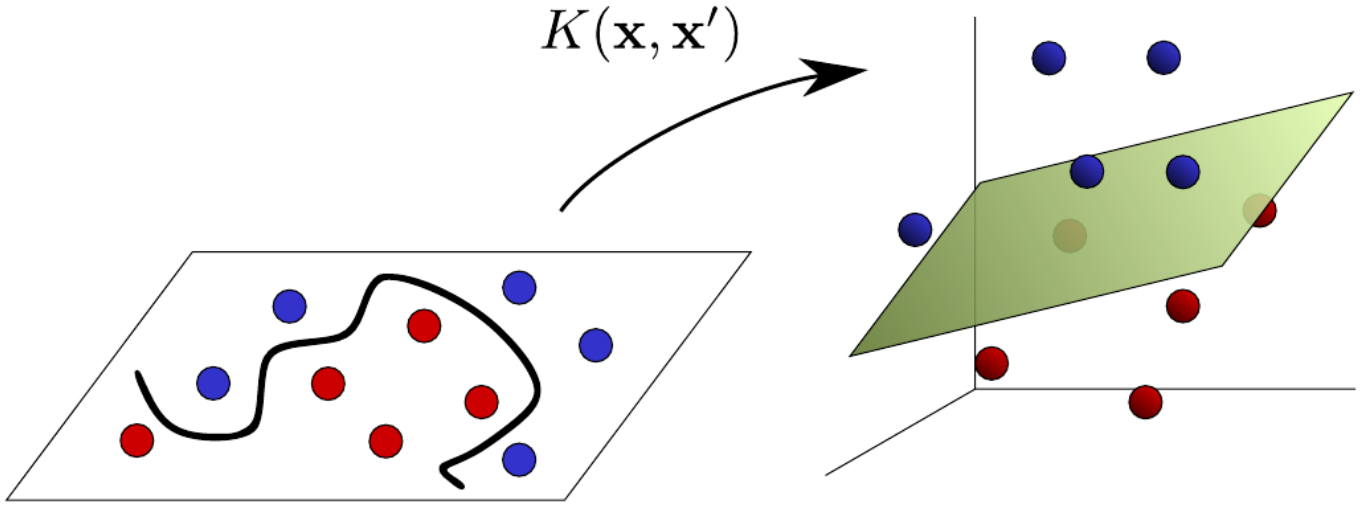
Data and fitting methods

- Data: SXS catalog of BBH simulations
  - Public: ~ 300
  - Not yet public: ~ 1100
- Generic regression techniques

Parametric vs Non-parametric Fit

- **Parametric** fits optimize function parameters
  - (e.g. $y = A \cos kx + B$)
  - Polynomial expansions (**previous fits**)
- **Non-parametric** fits use training data itself to make predictions
  - Gaussian Process Regression (GPR)
  - Decision Tree Regression

Gaussian Process Regression (GPR)



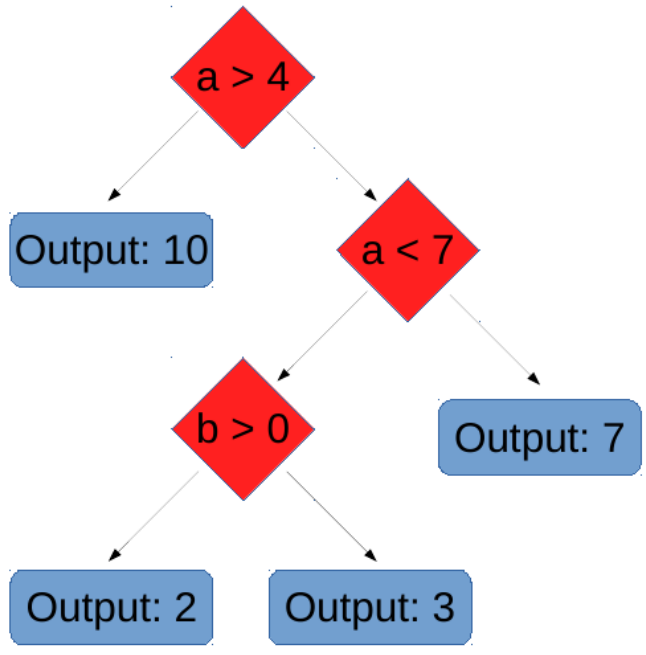
- **Kernel**: nonlinear data transformation
  - RBF kernel

$$K(\mathbf{x}, \mathbf{x}') = \exp\left(-\gamma||\mathbf{x} - \mathbf{x}'||^2\right) \tag{1}$$

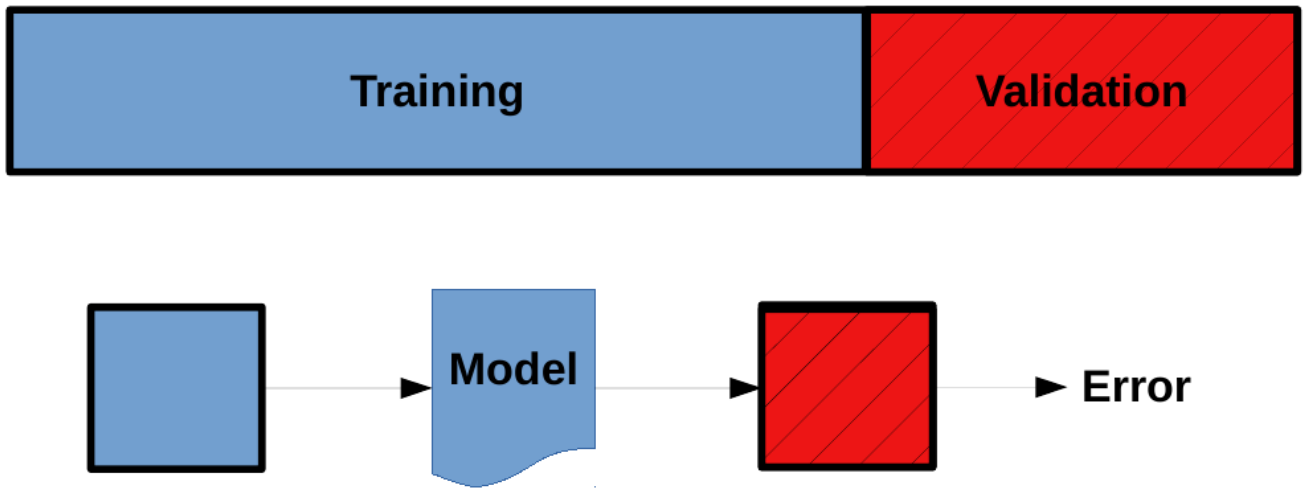
- Training = set kernel hyperparameters (γ)

Decision Tree Regression

- Predictions based on successive **decisions** about input parameters
- Training = construction of **decision tree** from data
- **Ensemble** = combine multiple decision trees

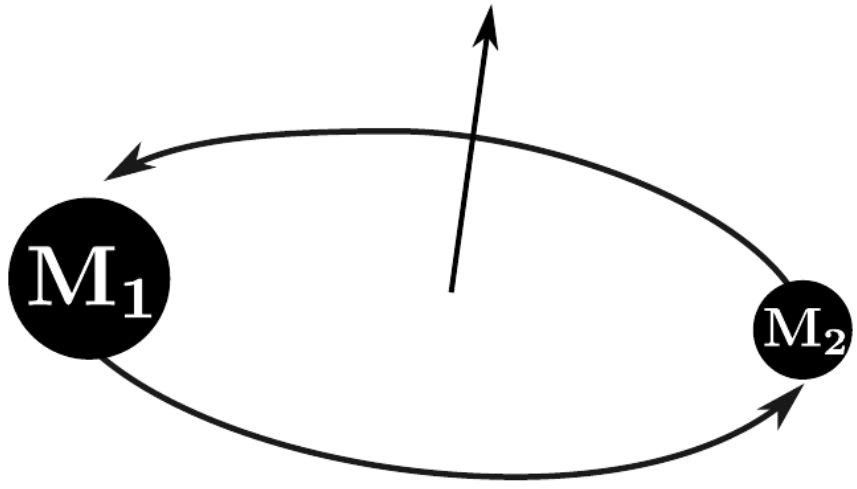


Measuring error



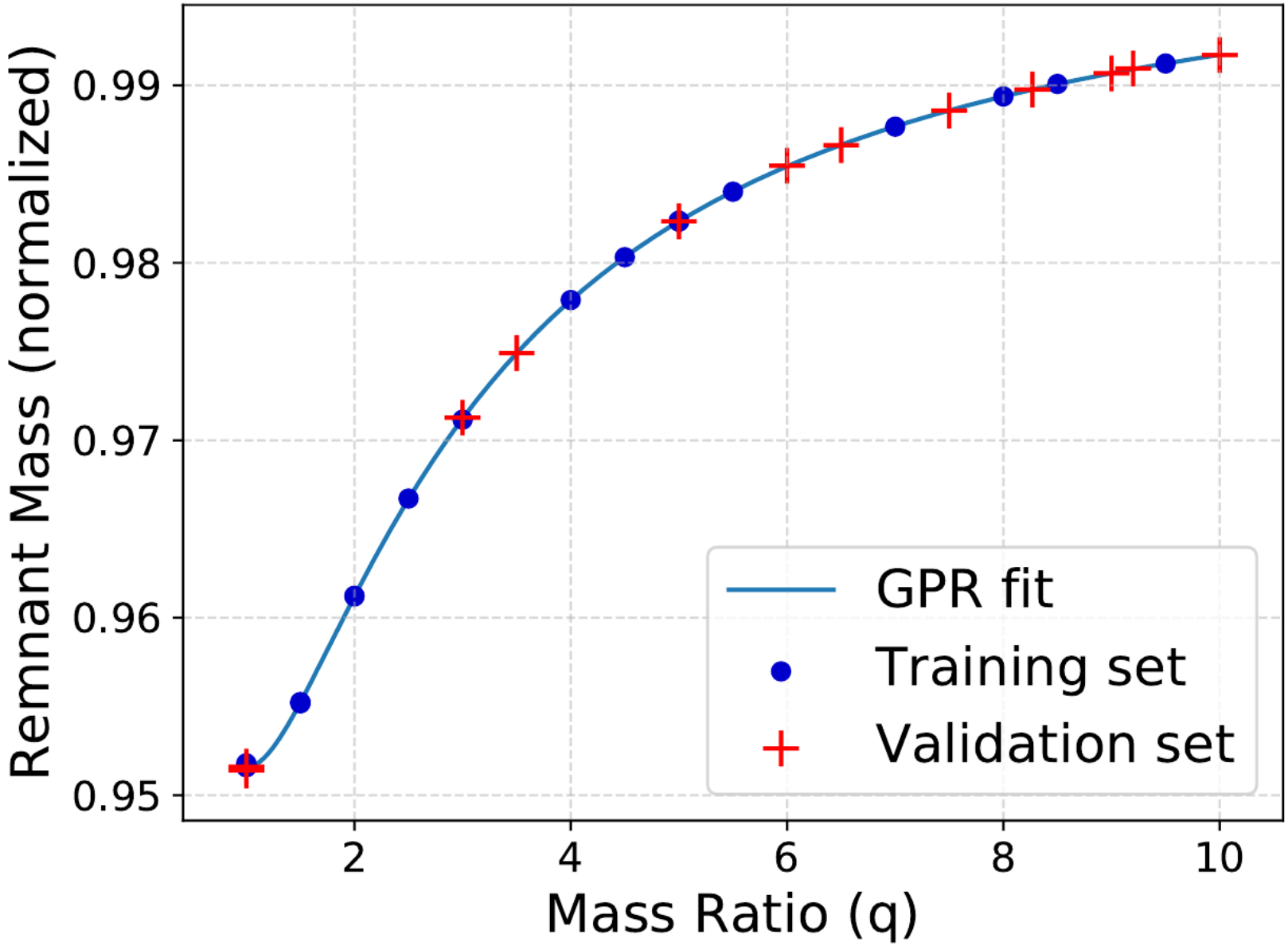
- Training and Validation set partition
  - Designate subset of data not used in training

Spinless ($\sim$ 50 simulations)



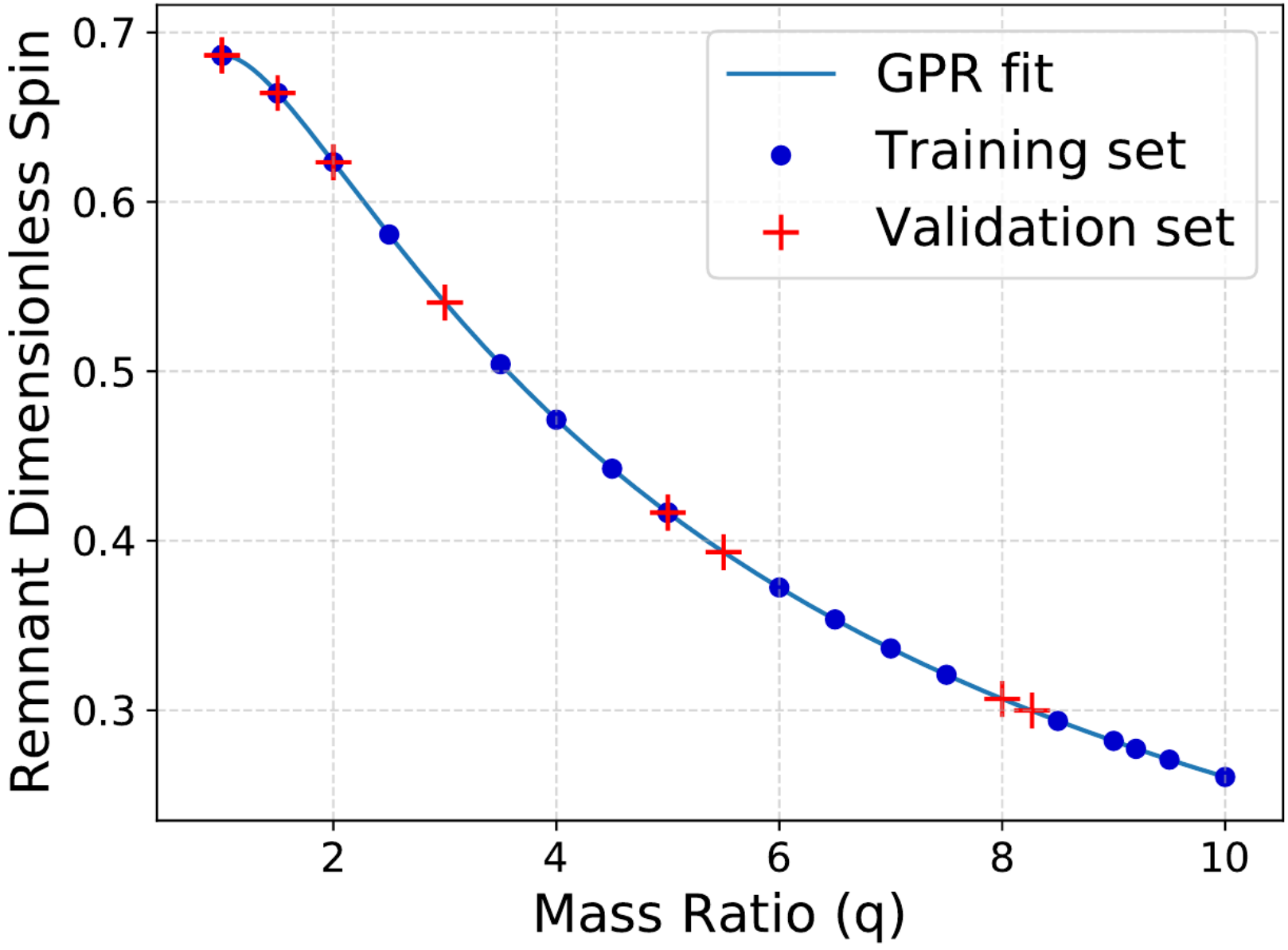
- Only one input parameter (mass ratio $q = \frac{M_1}{M_2}$)
- Fit with GPR

Spinless: remnant mass plot



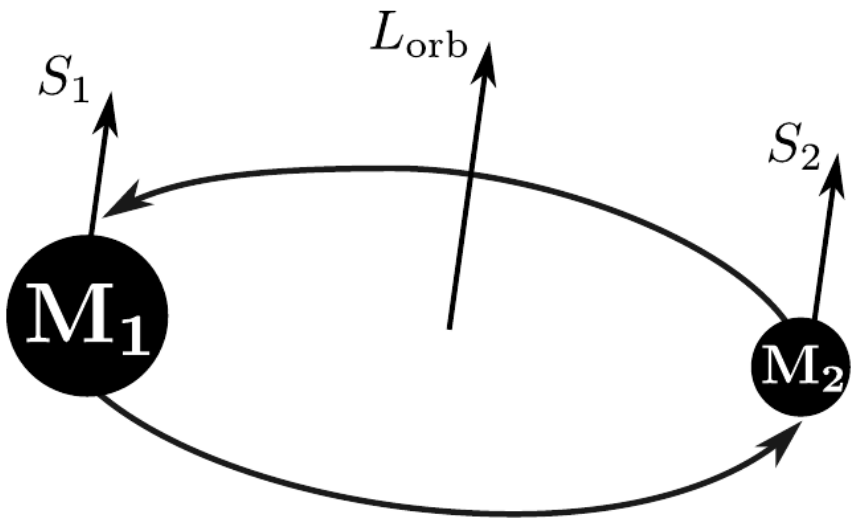
Spinless: remnant mass residuals

Spinless: remnant spin plot



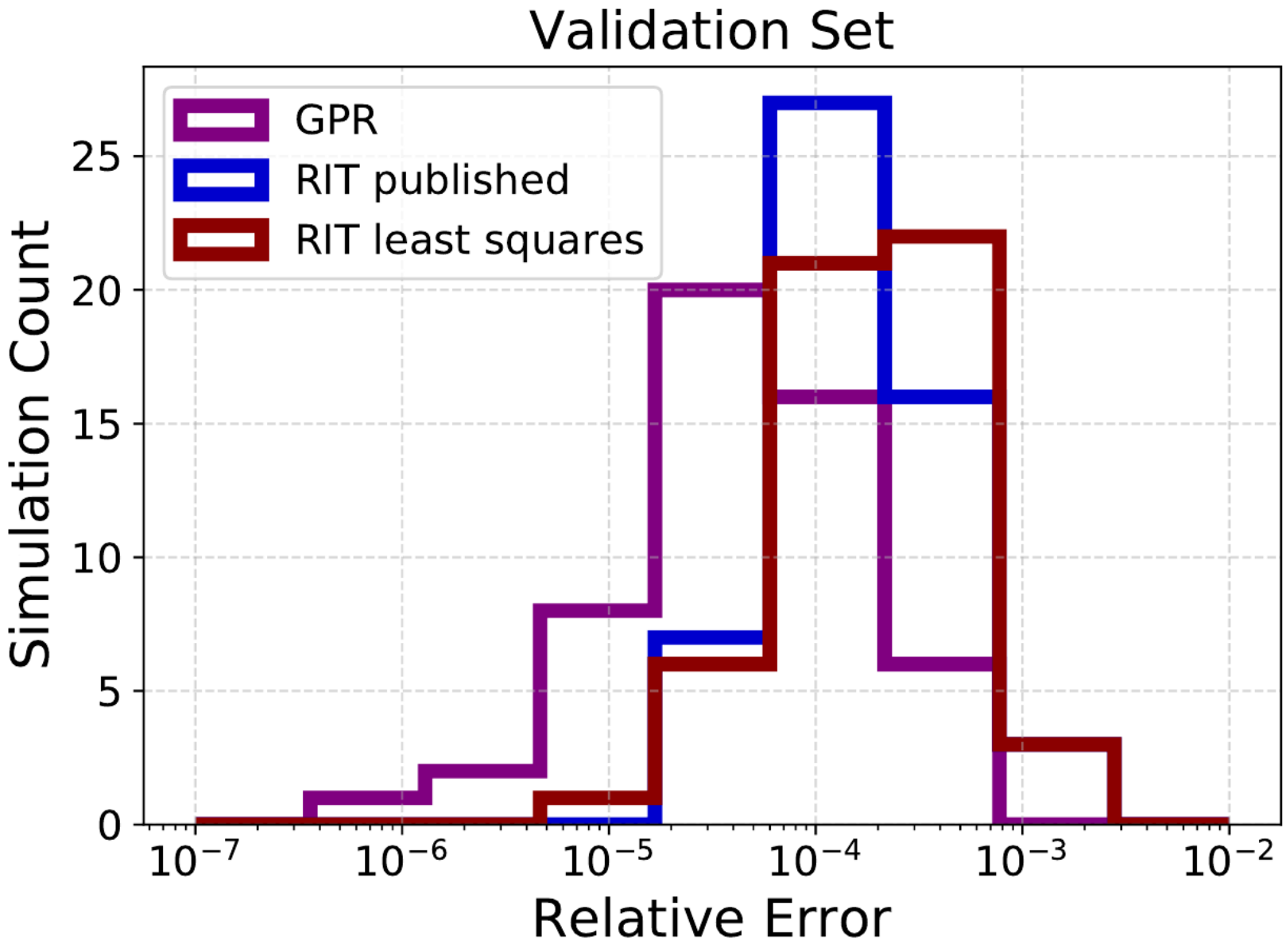
Spinless: remnant spin residuals

Aligned ($\sim$ 200 simulations)

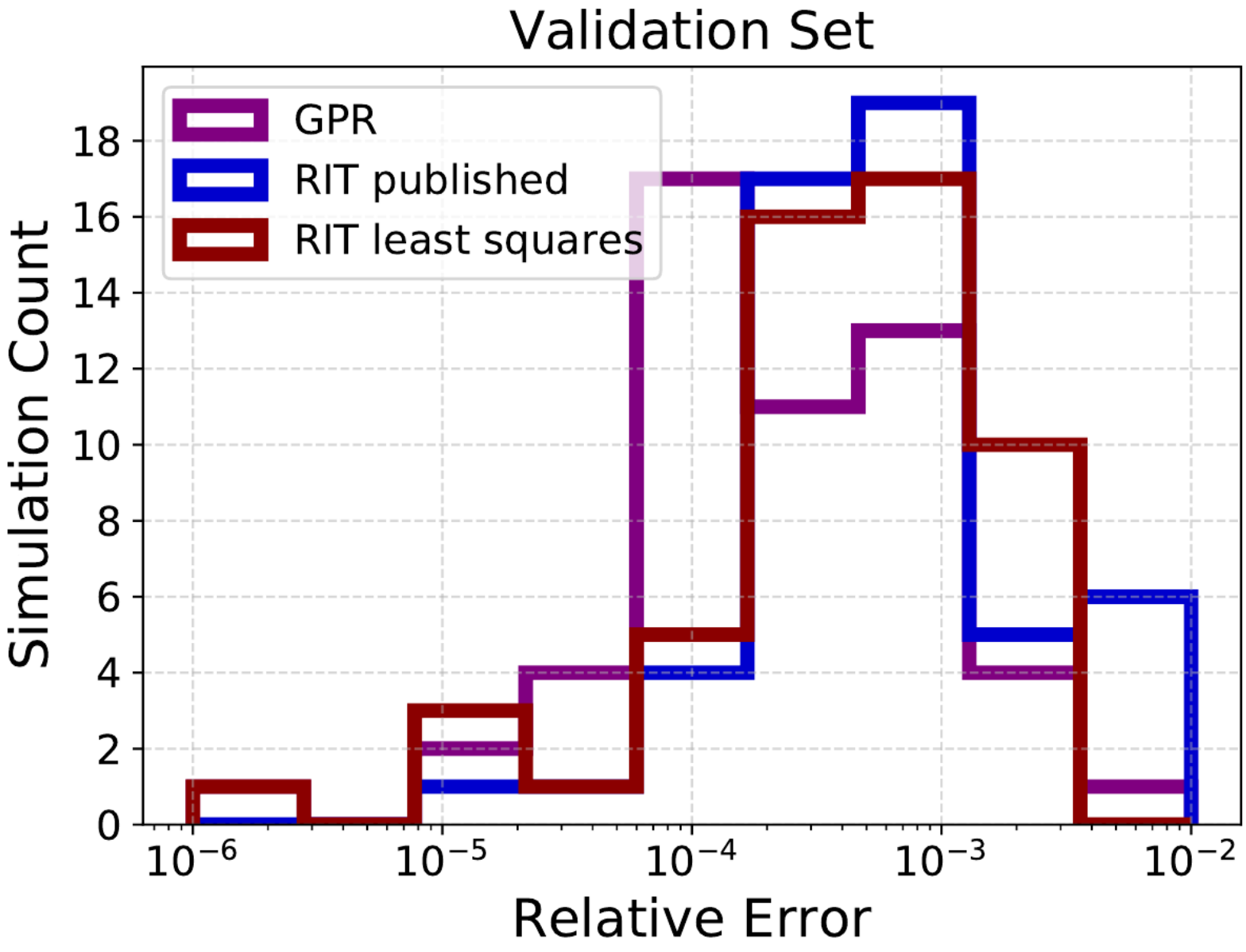


- **Three** input parameters (q, S_1, S_2)
- GPR vs Healy and Lousto (2016) - RIT

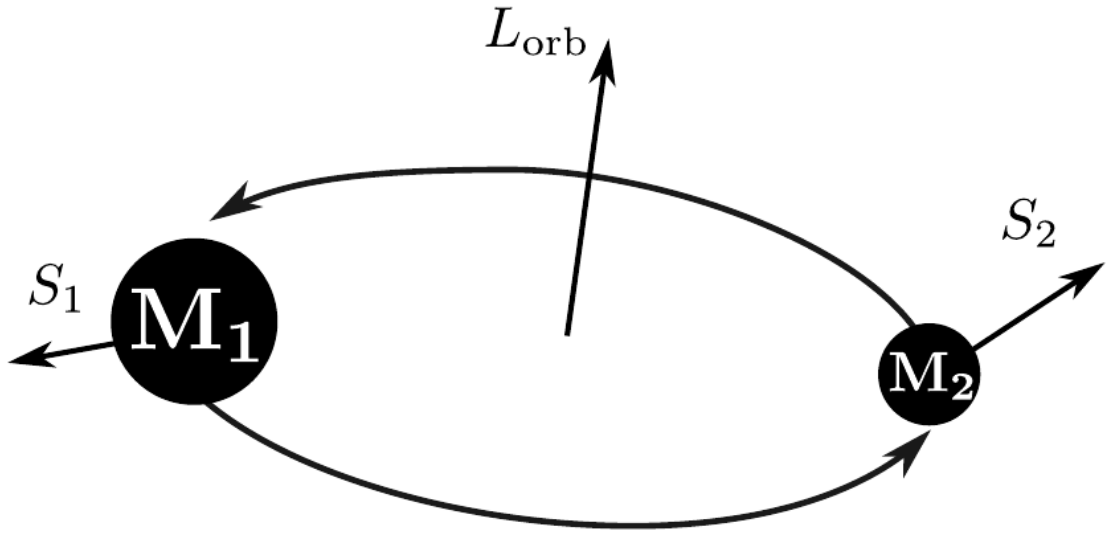
Aligned mass



Aligned spin

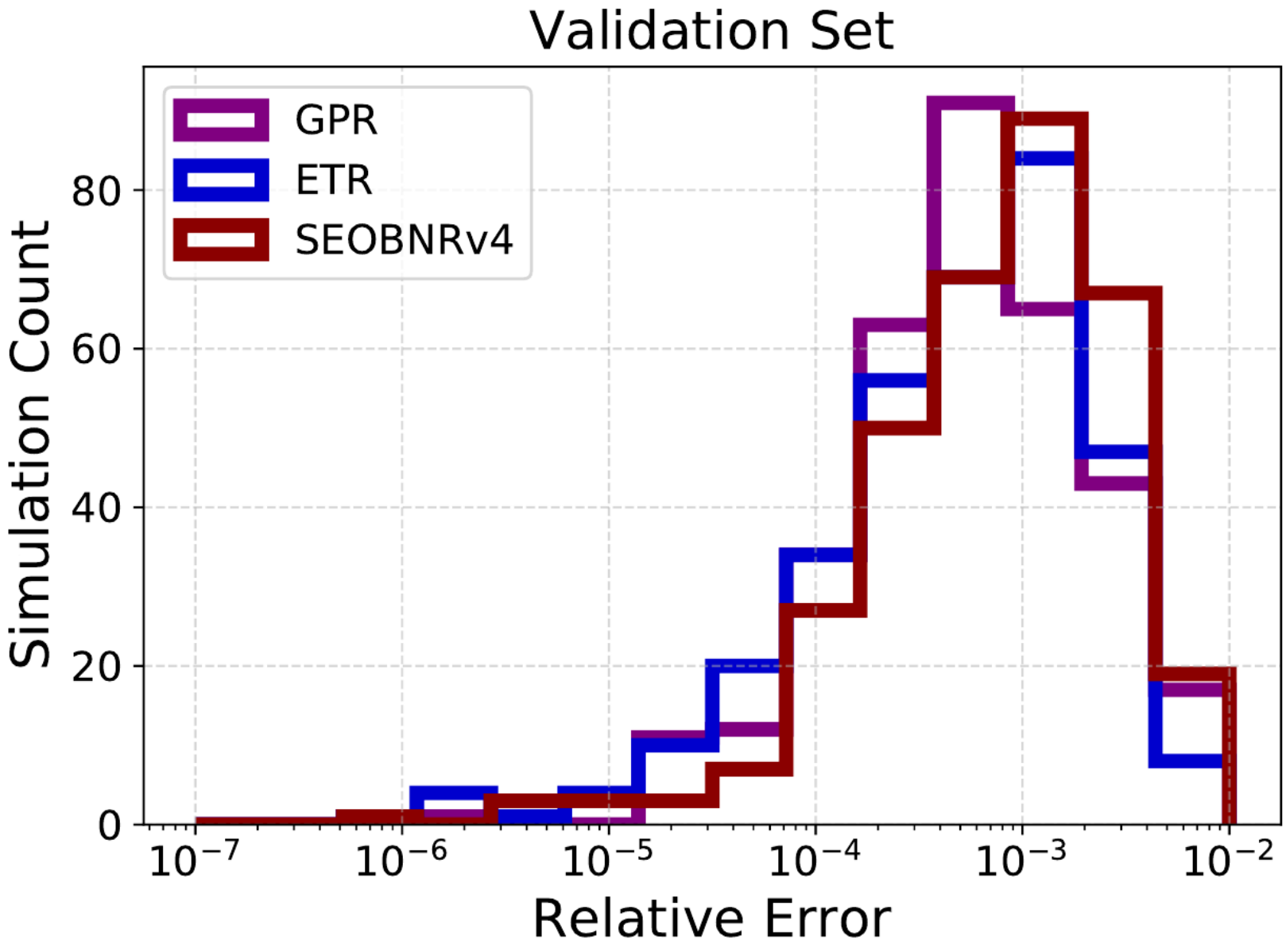


Generic spins ($\sim$ 1400 simulations)

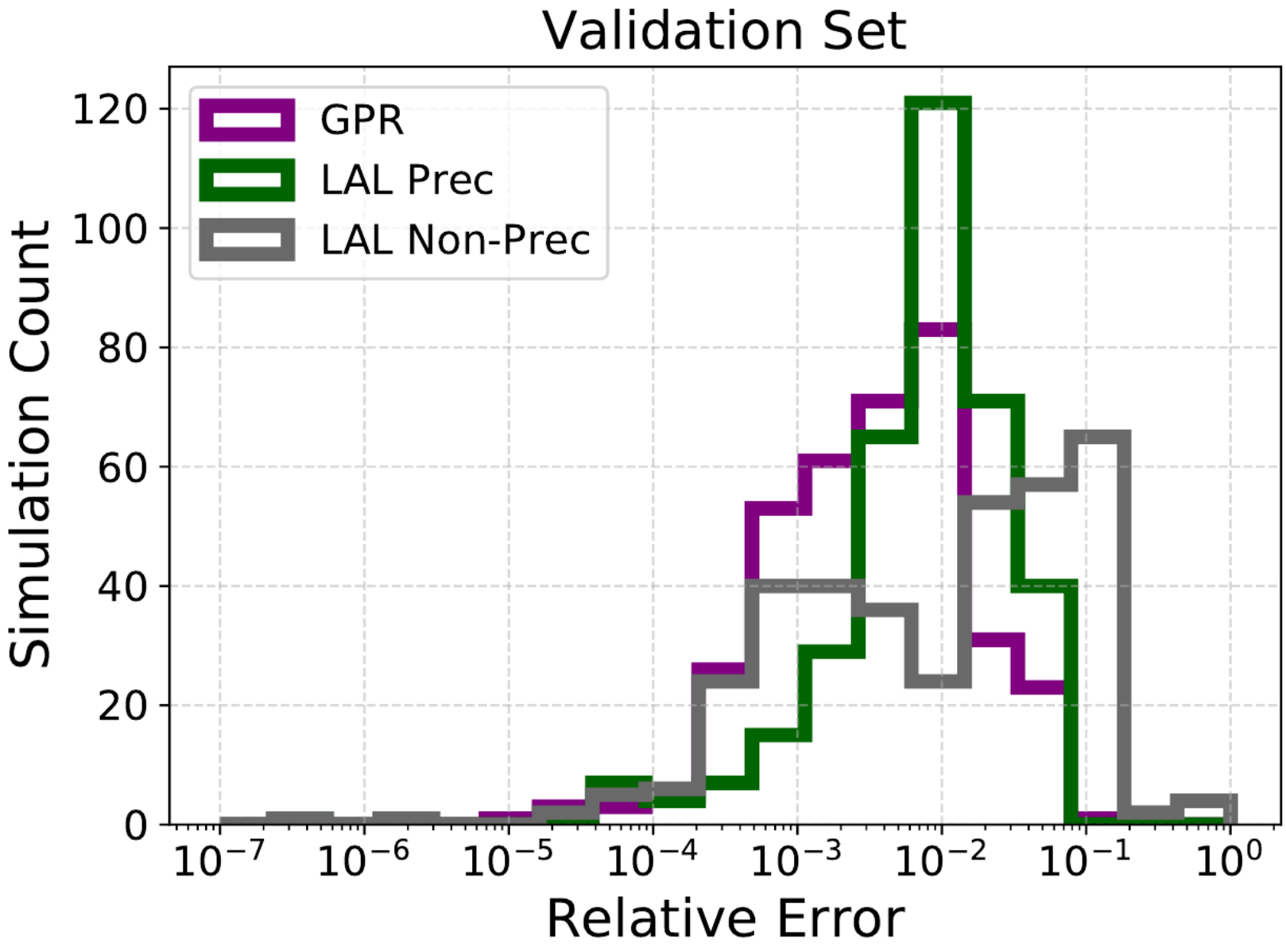


- **7 dimensional** input space
- Comparing:
  - GPR
  - Extremely Randomized Trees (ensemble)
  - EOB fits implemented in LAL

Remnant mass



Remnant spin magnitude



Summary

- Remnant parameter predictions needed
- Can predict with NR simulations
  - Accurate, but slow and computationally intensive
  - LIGO data analysis requires approximate fits
- Non-parametric methods can improve accuracy

Acknowledgments