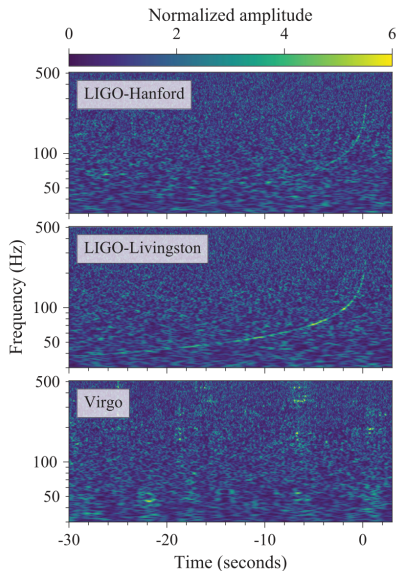


Machine Learning Gravitational Waveforms for Binary Neutron Star mergers

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2021-07-28

GW170817: the first BNS merger detection



Time-frequency representation of the chirping waveform (Abbott et al. 2017).

BNS waveforms are much longer than BBH ones: they only depend on t/M (or fM), where $M = m_1 + m_2$ is the total mass.

GW data analysis

- Signal from detector: $s(t) = h(t) + n(t)$, with noise PSD $S_n(f)$;
- Theoretical waveforms $h_\theta(t)$:
 - Numerical Relativity;
 - Effective One Body;
 - Post-Newtonian;
- Signal searches;
- Parameter estimation and model comparison.

The parameters θ are divided into

- intrinsic ones: masses m_i , spins $\vec{\chi}_i$, tidal deformabilities Λ_i ;
- extrinsic ones: luminosity distance D_L , source inclination ι , sky position (α, δ) , polarization angle ψ , reference time t_0 and phase ϕ_0 .

The Wiener distance

The likelihood used in parameter estimation reads (Maggiore 2007):

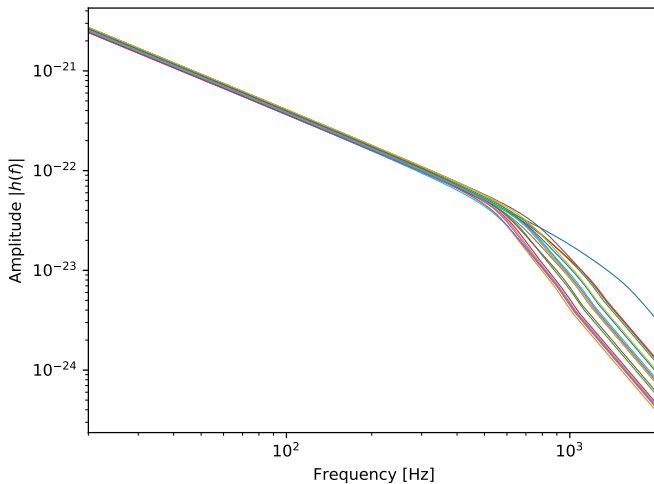
$$\Lambda(s|\theta) \propto \exp\left((h_\theta|s) - \frac{1}{2}(h_\theta|h_\theta)\right), \quad (1)$$

where $(a|b)$ is the Wiener product:

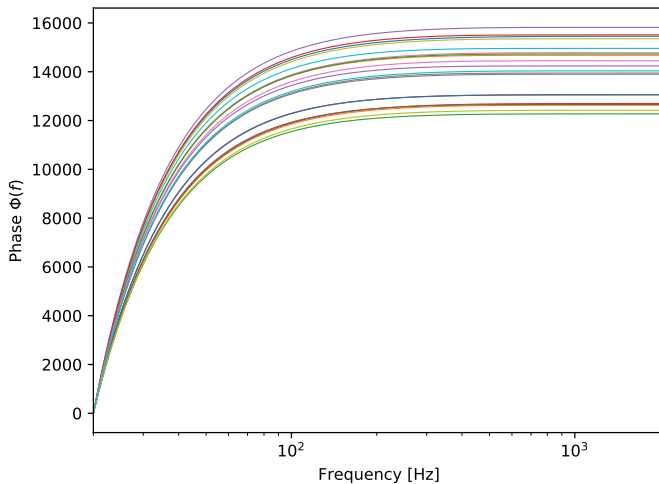
$$(a|b) = 4 \operatorname{Re} \int_0^\infty \frac{\tilde{a}^*(f) \tilde{b}(f)}{S_n(f)} df. \quad (2)$$

We need a fast way to compute accurate theoretical waveforms h_θ in the frequency domain! Typical EOB evaluation times are ~ 100 ms for $f_0 = 20$ Hz, ~ 1 s for $f_0 = 10$ Hz.

Frequency domain waveforms: amplitude



Frequency domain waveforms: phase



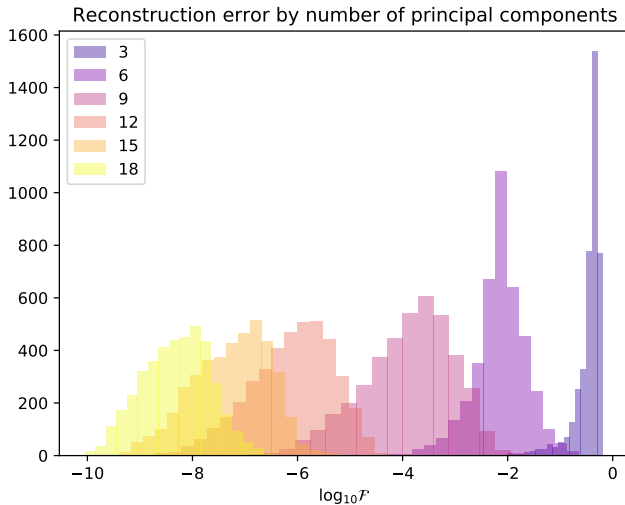
A fast generator of frequency-domain waveforms, currently varying the mass ratio q and the tidal deformabilities Λ_1, Λ_2 .

- A training dataset is generated: residuals of Effective One Body waveforms from the corresponding Post-Newtonian ones;
- dimensionality is reduced through Principal Component Analysis;
- a feed-forward Neural Network learns the map from the parameters to the principal components: $\theta \rightarrow \{\text{PC}_i\}_i$.

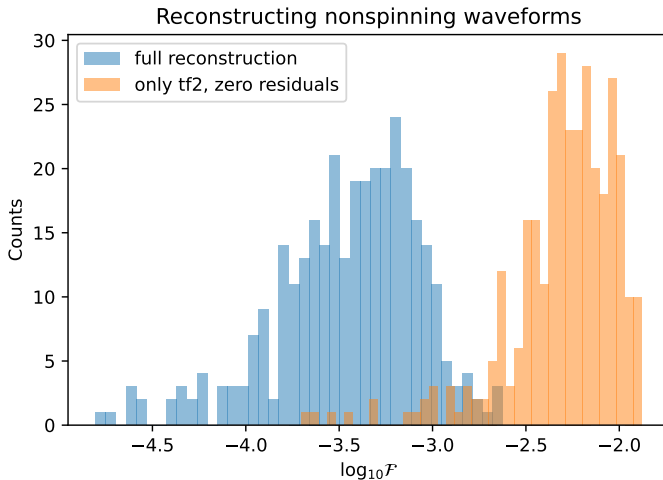
Reconstruction accuracy is evaluated through a distance induced by the Wiener product:

$$\mathcal{F}[a, b] = 1 - \max_{t_0, \phi_0} \frac{(a|b)}{\sqrt{(a|a)(b|b)}}. \quad (3)$$

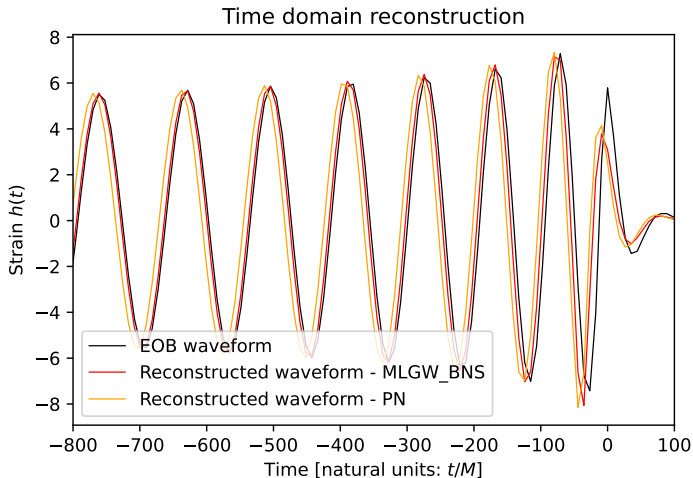
Reconstruction with PCA



Reconstruction with MLGW_BNS: mismatches



Reconstruction with MLGW_BNS: time domain



Technologies

- Python wrapper for `TEOBResumS` for EOB waveform generation;
- python with standard scientific libraries (`numpy`, `scipy`, `matplotlib`) and `pycbc`;
- Neural Network implemented with `scikit-learn`, hyperparameters optimized with `optuna`;
- automated testing with `pytest` and `hypothesis`.

Bibliography



Abbott, B. P. et al. (Oct. 16, 2017). “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral”. In: *Physical Review Letters* 119.16, p. 161101.



Maggiore, Michele (Nov. 24, 2007). *Gravitational Waves: Volume 1: Theory and Experiments*. 1 edition. Oxford: Oxford University Press. 576 pp.