Machine Learning Gravitational Waveforms for Binary Neutron Star mergers

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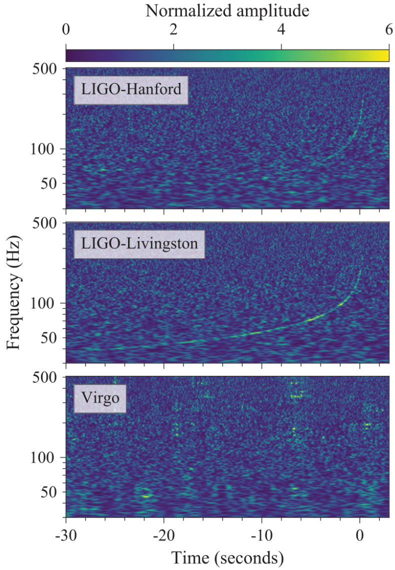
GW170817: the first BNS merger detection



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):

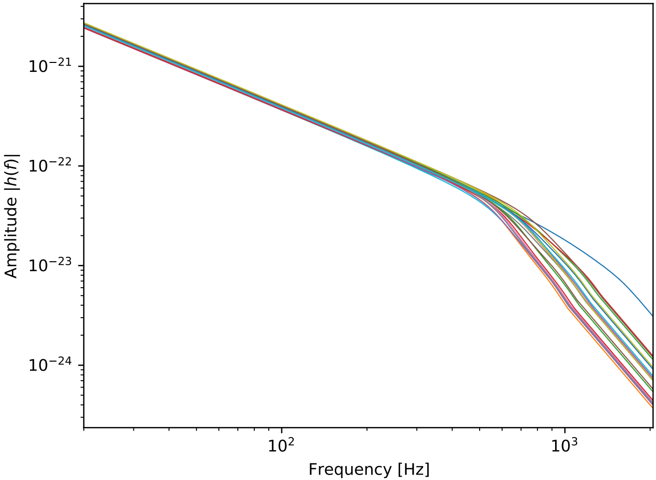
$$\Lambda(s|\theta) \propto \exp\left((h_\theta|s) - \frac{1}{2}(h_\theta|h_\theta) \right) , \tag{1}$$

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

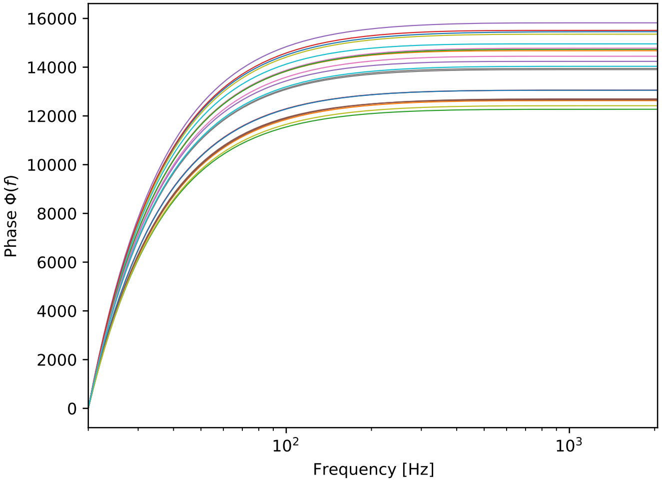
$$(a|b) = 4\,\mathrm{Re} \int_0^\infty \frac{\widetilde{a}^*(f)\widetilde{b}(f)}{S_n(f)} \,\mathrm{d}f \ . \tag{2}$$

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

Frequency domain waveforms: amplitude



Frequency domain waveforms: phase



MLGW_BNS

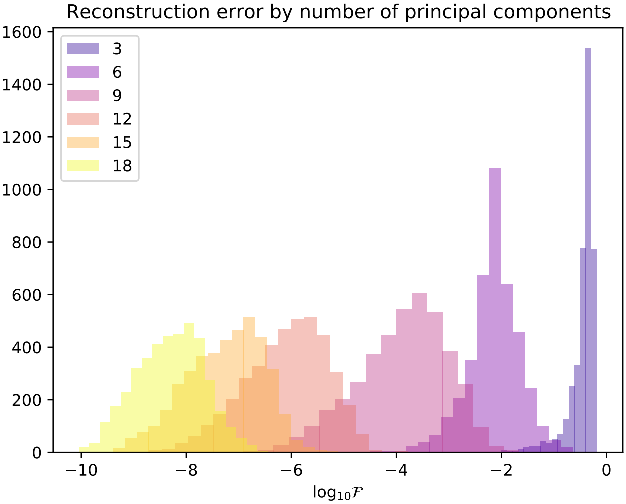
A fast generator of frequency-domain waveforms, currently varying the mass ratio q and the tidal deformabilities Λ_1, Λ_2.

- 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: $\theta \to \{\mathrm{PC}_i\}_i$.

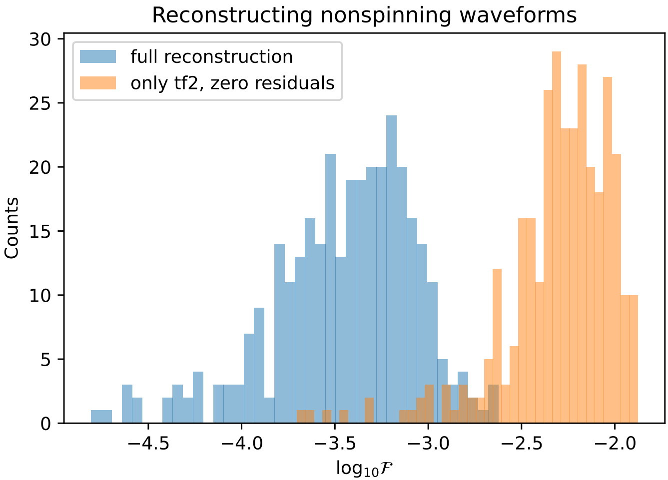
Reconstruction accuracy is evaluated through a distance induced by the Wiener product:

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

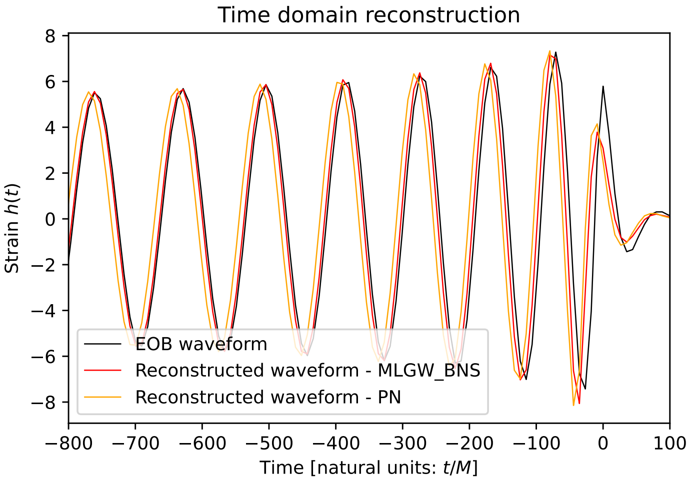
Reconstruction with PCA



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.