Characterization of gravitational-wave burst polarizations with the *BayesWave* algorithm

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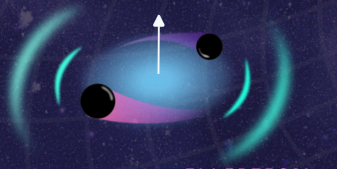
The global gravitational-wave (GW) detector network consists of four interferometers: LIGO Hanford (H) and Livingston (L), Virgo (V) and KAGRA (K); the commissioning of LIGO India is also well underway. The expanding detector network enables more accurate probing of GW polarizations, as each detector measures the combination of polarization states independently. *BayesWave* [1] is a source-agnostic analysis pipeline designed for the joint detection and characterization of GW transients (i.e. bursts) and instrumental glitches. Here, we present a multi-detector analysis on *BayesWave*'s ability to (i) detect and characterize GW burst signals with non-elliptical polarizations and (ii) measure polarization content of GW bursts.

BAYESWAVE MODELS

BayesWave models transient, non-Gaussian features in the data by summing a set of sine-Gaussian wavelets. For coherent GW signals, *BayesWave* offers two types of polarization models: the **elliptical (E) model** and **relaxed (R) model**. Both models assume only tensor polarizations, i.e. the plus (+) and cross (×) modes, consistent with the predictions of general relativity. In **E**, the polarization amplitudes are restricted to $\tilde{h}^{\times} = i\epsilon\tilde{h}^{+}$, where ϵ encodes the degree of elliptical polarization. In **R**, $\tilde{h}^{+}$ and $\tilde{h}^{\times}$ are reconstructed independently, but share the same time-frequency content [2].

DATASET

PHENOMENOLOGICAL BINARY BLACK HOLE (BBH) WAVEFORMS INJECTED INTO SIMULATED GAUSSIAN NOISE FOR HL, HLV AND HLKV



ELLIPTICAL

NON-PRECESSING ($\chi_p = 0$)

NON-ELLIPTICAL

PRECESSING ($\chi_{p,\mathrm{init}} \neq 0$)

CHARACTERIZING POLARZATIONS

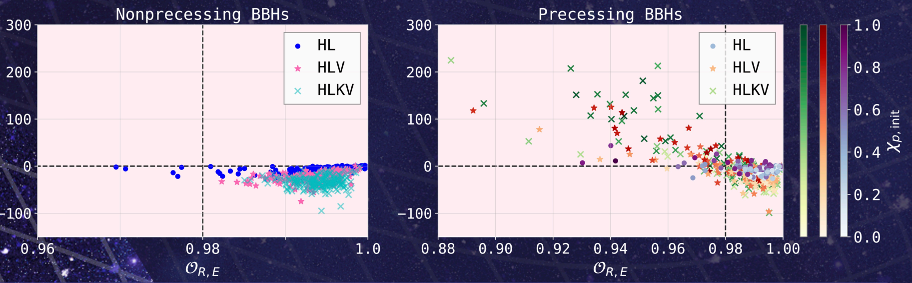


FIG. 1. Log Bayes factor between R and E ($\ln \mathcal{B}_{R,E}$) versus the matched-filter network overlap ($\mathcal{O}_{R,E}$) between R and E reconstructions. $\mathcal{O}_{R,E} = 1$ indicates full agreement between R and E reconstructions and $\mathcal{O}_{R,E} = 0$ indicates no agreement.

Fig. 1 shows $\mathcal{O}_{R,E} > 0.98$ and $\ln \mathcal{B}_{R,E} < 0$ for non-precessing and minimally-precessing signals, i.e. the reconstructions are similar, thus **E** is preferred over **R** for its simplicity. In contrast, for strongly precessing signals, **R** provides more accurate signal characterization than **E**, yielding $\mathcal{O}_{R,E} < 0.98$ and $\ln \mathcal{B}_{R,E} > 0$. As the detector network expands, $\mathcal{O}_{R,E}$ decreases for strongly precessing signals, and $\ln \mathcal{B}_{R,E}$ becomes increasingly positive.

In summary, our results show that $\ln \mathcal{B}_{R,E}$ and $\mathcal{O}_{R,E}$ together can provide indications for nonelliptical polarization, but are insufficient to distinguish between purely elliptical and slightly nonelliptical signals.

MEASURING POLARIZATION CONTENT IN TERMS OF STOKES PARAMETERS

FRACTIONAL POLARIZATIONS

The Stokes parameters (I, Q, U, and V) describe the polarization content of a GW signal. The **total (T)** polarized fraction of the signal is given by:

$$F_{\mathrm{T}}(f) = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}.$$

The fractional **circular (C)** and **linear (L)** polarizations are respectively given by:

$$F_{\mathrm{C}}(f) = \frac{|V|}{I} \quad \text{and} \quad F_{\mathrm{L}}(f) = \frac{\sqrt{Q^2 + U^2}}{I}.$$

MEASUREMENT ACCURACY

Fig. 2 shows that $\mathcal{R}_{\mathrm{RMS}}(F_{\mathcal{P}})$ decreases as the detector network expands, indicating that polarization content is measured more accurately with larger networks, as expected. Fig. 2 also shows that $F_{\mathcal{P}}$ for both non-precessing and precessing BBHs are recovered with comparable accuracy using networks with three or more detectors, i.e. HLV and HLKV. This suggests that the underlying signal morphology does not affect the performance of R in recovering polarization content, when the detector network is sufficiently large.

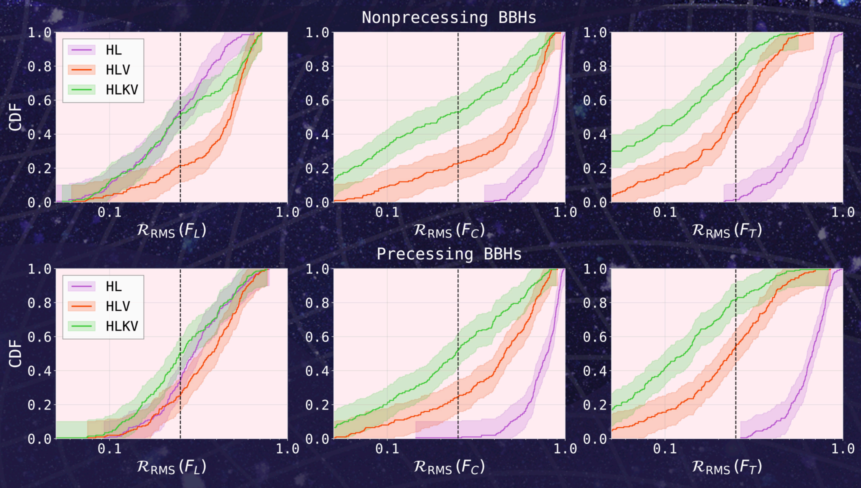


FIG. 2. Accuracy of polarization measurements using the relaxed (R) model. The plots show cumulative distribution functions (CDFs) of root mean square residuals $\mathcal{R}_{\mathrm{RMS}}(F_{\mathcal{P}})$ between the injected and recovered fractional polarization $F_{\mathcal{P}}$, for $\mathcal{P} \in \{\mathrm{L}, \mathrm{C}, \mathrm{T}\}$.

[1] N. Cornish and T. Littenberg, Class. Quantum Grav. 32, 135012 (2015).
[2] N. Cornish et al., Phys. Rev. D 103, 044006 (2021).

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