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gwBOB: A Python Package for Analytical Merger-Ringdown Gravitational Waveforms

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Software

- Review
- Repository
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Summary

gwBOB is an open-source Python package for generating gravitational waveforms for the merger and ringdown portion of black hole binary mergers using the Backwards-One-Body (BOB) model. The BOB model is an analytical, physically-motivated and highly accurate framework that models the merger-ringdown gravitational radiation based on the motion of null geodesics perturbed from the light ring of the remnant black hole (McWilliams, 2019). The model can be configured in various "flavors" based on the choice of initial conditions and the gravitational wave quantity being modeled. `gwBOB` provides a flexible and intuitive interface to generate waveforms from any flavor of BOB, use numerical relativity (NR) data for initial conditions, and validate BOB against NR waveforms. By providing a critical layer of abstraction over the BOB formalism, `gwBOB` greatly simplifies and streamlines the application of BOB for various research problems.

Background

The detection of gravitational waves (GW) has given us a new method to study the universe, separate but complementary to the detection of electromagnetic radiation. The most common sources detected are the inspiral, merger, and ringdown of two black holes. Extracting physical information from these faint signals, such as the masses, spins, and orbital parameters of the binary, requires the development of theoretical models for the gravitational radiation emitted during this process. The modeling process is particularly difficult for the merger portion of the coalescence due to the non-linear nature of Einstein's theory of General Relativity (GR).

While NR simulations produce the most accurate waveforms, the significant computational expense of these simulations makes it impossible to generate enough waveforms to be used in detection pipelines. Instead, researchers must use semi-analytical waveform models, either calibrated to or directly interpolating NR simulations (Blackman et al., 2015; Bohé et al., 2017; Nagar et al., 2018, 2024; Pompili et al., 2023; Varma et al., 2019). The non-linear nature of the merger results in this portion of the waveform being heavily reliant on NR information in all waveform models. As the sensitivity of current and future GW detectors increases, the limited coverage of NR catalogs across a higher dimensional parameter space may become a significant source of systematic error for these models.

The Backwards-One-Body (BOB) model provides an analytical and physically motivated approach to merger-ringdown modeling that is minimally reliant on NR information. As (Kankani & McWilliams, 2025) shows, BOB can model the gravitational wave news, the first time derivative of the gravitational wave strain, to accuracy comparable to state of the art waveform models, all of which are heavily reliant on NR simulations. This package focuses on constructing BOB for the (s = -2, l = 2, m = 2) gravitational wave mode for quasi-circular and non-precessing configurations, but can be used for higher modes and precessing cases as well.

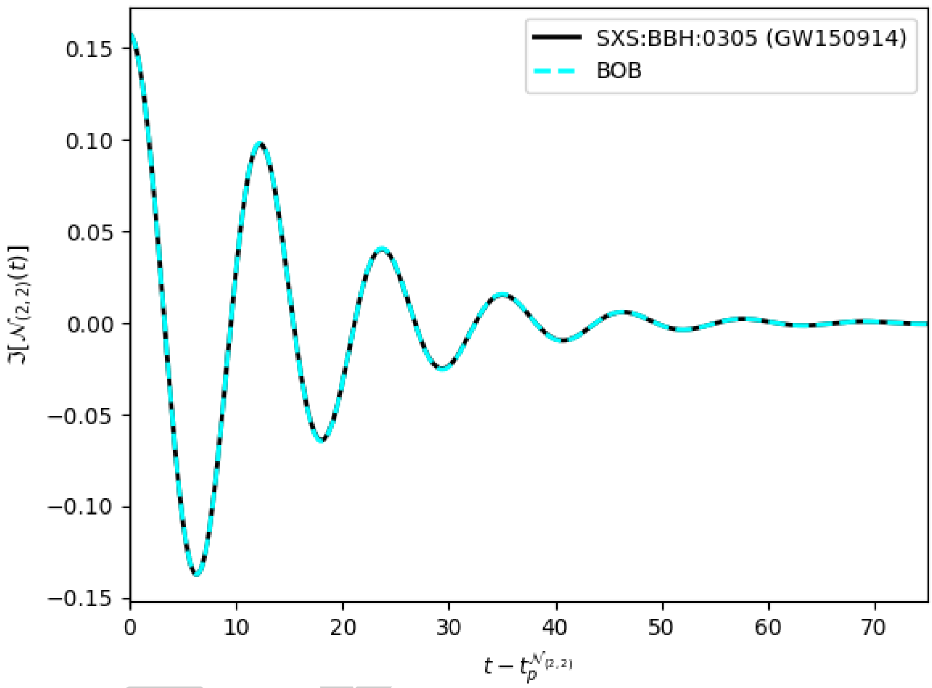

Figure 1: Comparison of BOB and a NR waveform (Boyle et al., 2019) for the imaginary part of the (2, 2) mode of the News for a system with parameters similar to GW150914 (Abbott et al., 2016)

Statement of Need

gwBOB provides researchers with a robust and user-friendly Python package, eliminating the need for researchers to build their own custom implementations of BOB. The package allows researchers to easily configure and switch between different flavors of BOB, enabling them to choose the version best suited for their specific research problem. Its interface simplifies initialization by supporting both public NR catalogs (Boyle et al., 2019; Mroue et al., 2013; Scheel et al., 2025) and user provided NR data. Additionally, users can manually specify initial conditions or obtain them directly from NR data. For validation, the package includes built in utilities to streamline comparisons, enabling systematic validation of BOB against both entire NR catalogs and other semi-analytical waveform models. Furthermore, gwBOB includes additional routines for model comparison, such as one for inferring the remnant black hole's final mass and spin by minimizing the mismatch between a BOB waveform and a target waveform. This capability is particularly useful for quantitative comparisons with models constructed from a sum of quasinormal modes. By integrating utilities for initializing, configuring and validating the model, gwBOB provides the first complete open-source framework for incorporating any flavor of BOB into research workflows, dramatically reducing the complexity and time required for researchers to utilize the model.

State of the field

gwBOB is the first publicly available package that allows users to rapidly construct a large variety of BOB flavors and validate them against NR waveforms. As part of the nrpy (Ruchlin et al., 2018) code, a full inspiral-merger-ringdown model, using SEOBNRv5 (Pompili et al., 2023) for the inspiral and a specific flavor of BOB for the merger-ringdown (Mahesh et al., 2025), is available. While this approach focuses on computationally efficiency, and incoporating a specific flavor of BOB into data analysis pipelines, gwBOB is designed on analyzing BOB as a stand-alone merger ringdown waveform, allowing for a construction of a wide variety of flavors and comparisons to NR waveforms.

Software Design

gwBOB is designed to drastically simplify the construction and validation of BOB, abstracting away the complexity of implementing BOB from the end user. Because BOB can be developed in various flavors, and the underlying complexity of the equations can change significantly based on the flavor chosen, the primary design goal was to have the user's code be more reflective of a parameter file, specifying the flavor and comparison to make. To achieve this goal, gwBOB prioritizes research flexibility and ease of use over absolute computational efficiency. When a BOB object is instantiated, several gravitational wave quantities are precomputed and stored. While this increases the initialization time, it drastically simplifies the process of switching between flavors of BOB and comparing to NR waveforms. This design decision is reflective of the most common use case of gwBOB, the generation of various flavors of BOB and comparison against a numerical relativity catalog, which typically consist of a few hundred to thousand waveforms. This stands in contrast to waveform models that are designed for parameter estimation pipelines, where millions of waveforms must be generated and computational efficiency is the utmost priority. gwBOB was intentionally optimized for the former workflow rather than the latter. However, recognizing the diverse applications of BOB, the core equations required to construct BOB are decoupled from the high level user interface. This allows users to easily integrate BOB into their own custom workflows, where performance may be a stronger priority. In particular, we provide NumPy, SymPy and JAX compatible implementations of the BOB equations, allowing users to choose the backend that best suits their own specific research problem (e.g., combining the analytical nature of BOB with the autodifferentiation capabilities of JAX). While gwBOB primarily utilizes the SXS catalog (Boyle et al., 2019; Mroue et al., 2013; Scheel et al., 2025) for NR initial data and waveform comparisons, it also supports user provided NR data allowing for a wide variety of use cases.

Research Impact Statement

This package has been used for the comprehensive analysis of BOB done in (Kankani & McWilliams, 2025). In addition, this package is being actively used by multiple researchers to generate BOB waveforms for various research problems.

Documentation

gwBOB is distributed through PyPI and hosted on GitHub. Documentation is hosted on readthedocs.

AI Usage Disclosure

AI tools including ChatGPT and Gemini were used to assist with code review, documentation, and a limited amount of code generation. These tools were also used to review and suggest edits for this paper. This code was primarily developed by human authors, and all AI outputs were reviewed and approved by the authors.

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