

# pygwb: a Python-based library for gravitational-wave background searches

Arianna I. Renzini<sup>1,2¶</sup>, Alba Romero-Rodriguez<sup>3</sup>, Colm Talbot<sup>4</sup>, Max Lalleman<sup>5</sup>, Shivaraj Kandhasamy<sup>6</sup>, Kevin Turbang<sup>3,5</sup>, Sylvia Biscoveanu<sup>4,7</sup>, Katarina Martinovic<sup>8</sup>, Patrick Meyers<sup>9</sup>, Leo Tsukada<sup>10,11</sup>, Kamiel Janssens<sup>5,12</sup>, Derek Davis<sup>1,2</sup>, Andrew Matas<sup>13</sup>, Philip Charlton<sup>14</sup>, Guo-chin Liu<sup>15</sup>, and Irina Dvorkin<sup>16</sup>

<sup>1</sup> LIGO Laboratory, California Institute of Technology, Pasadena, California 91125, USA <sup>2</sup> Department of Physics, California Institute of Technology, Pasadena, California 91125, USA <sup>3</sup> Theoretische Natuurkunde, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium <sup>4</sup> Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139, USA <sup>5</sup> Universiteit Antwerpen, Prinsstraat 13, 2000 Antwerpen, België <sup>6</sup> Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India <sup>7</sup> LIGO Laboratory, Massachusetts Institute of Technology, 185 Albany St, Cambridge, MA 02139, USA <sup>8</sup> Theoretical Particle Physics and Cosmology Group, Physics Department, King's College London, University of London, Strand, London WC2R 2LS, United Kingdom <sup>9</sup> Theoretical Astrophysics Group, California Institute of Technology, Pasadena, CA 91125, USA <sup>10</sup> Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA <sup>11</sup> Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, Pennsylvania 16802, USA <sup>12</sup> Université Côte d'Azur, Observatoire Côte d'Azur, ARTEMIS, Nice, France <sup>13</sup> Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany <sup>14</sup> OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia <sup>15</sup> Department of Physics, Tamkang University, Danshui Dist., New Taipei City 25137, Taiwan <sup>16</sup> Institut d'Astrophysique de Paris, Sorbonne Université & CNRS, UMR 7095, 98 bis bd Arago, F-75014 Paris, France ¶ Corresponding author

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## Introduction

A gravitational-wave background (GWB) is expected from the superposition of all gravitational waves (GWs) too faint to be detected individually, or by the incoherent overlap of a large number of signals in the same band (A. I. Renzini et al., 2022). A GWB is primarily characterized by its spectral emission, usually parameterized by the GW fractional energy density spectrum  $\Omega_{\text{GW}}(f)$ , which is the target for stochastic GW searches (Allen & Romano, 1999),

$$\Omega_{\text{GW}}(f) = \frac{1}{\rho_c} \frac{d\rho_{\text{GW}}(f)}{d\ln f},$$

where  $d\rho_{\text{GW}}$  is the energy density of GWs in the frequency band  $f$  to  $f + df$ , and  $\rho_c$  is the critical energy density of the Universe. Different categories of GW sources may be identified by the unique spectral shape of their background emission; hence, the detection of a GWB will provide invaluable information about the evolution of the Universe and the population of GW sources within it.

## Statement of need

Due to the considerable amount of data to analyze, and the vast panorama of GWB models to test, the detection and characterization of a GWB requires a community effort. Furthermore,

data handling and model building entail a number of different choices, depending on specific analysis purposes. Up until the previous LIGO-Virgo-KAGRA Collaboration (LVK) observing run, O3, the collaboration has relied on an internal MATLAB-based pipeline available at (LVK, 2020) to perform stochastic analyses. This pipeline lacks the ability to perform parameter estimation, as well as modularity and flexibility. This exemplifies the need for an accessible, flexible, and user-friendly open-source codebase for the current and upcoming LVK runs: pygwb. To fully cater to user needs, pygwb is modular and extensively customizable, and is accompanied by exhaustive documentation.

## Method

The GWB spectrum estimation implemented in pygwb is based on the unbiased minimum variance cross-correlation estimator (Romano & Cornish, 2017),

$$\hat{\Omega}_{\text{GW},f} = \frac{\text{Re}[C_{IJ,f}]}{\gamma_{IJ}(f)S_0(f)}.$$

Here,  $C_{IJ,f}$  is the cross-correlation spectral density between two detectors  $I$  and  $J$ ,  $\gamma_{IJ}$  is the overlap reduction function (Allen & Romano, 1999), and  $S_0(f) = \frac{3H_0^2}{10\pi^2} \frac{1}{f^3}$ , where  $H_0$  is the Hubble constant today (Aghanim & others, 2020). The variance of the estimator is given by

$$\sigma_{\text{GW},f}^2 = \frac{1}{2T\Delta f} \frac{P_{I,f}P_{J,f}}{\gamma_{IJ}^2(f)S_0^2(f)},$$

where  $P_{I,f}$  is the power spectral density from detector  $I$  and  $T$  is the duration of data used to produce the above spectral densities. This estimator is optimal and unbiased under the assumption that the signal is Gaussian, isotropic, and continuous. Details on how the estimation is carried out, as well as the implementation of the estimator on large datasets and with many potentially overlapping data segments can be found in our companion methods paper (Arianna I. Renzini et al., 2023).

Model testing in pygwb is performed through Bayesian inference on a select set of parameters, given a parametric GWB model and a likelihood  $p$  of observing the data given the model. Concretely, the above cross-correlation estimator is input data to a Gaussian residual likelihood,

$$p(\hat{\Omega}_{\text{GW},f}^{IJ}|\lambda) \propto \exp \left[ -\frac{1}{2} \sum_{IJ} \sum_f \left( \frac{\hat{\Omega}_{\text{GW},f}^{IJ} - \Omega_{\text{M}}(f|\lambda)}{\hat{\sigma}_{\text{GW},f}^{IJ}} \right)^2 \right],$$

where  $\Omega_{\text{M}}(f|\lambda)$  is the GWB model and  $\lambda$  are its parameters. pygwb currently admits a variety of GWB models, compatible with the Gaussian likelihood above. More information about the parameter estimation and the implemented models can be found in our companion methods paper (Arianna I. Renzini et al., 2023).

## pygwb

pygwb is a Python-based, open-source stochastic GW analysis package specifically tailored to searches for isotropic GWBs with current ground-based interferometers, namely the Laser Interferometer Gravitational-wave Observatory (LIGO), the Virgo observatory, and the KAGRA detector.

The pygwb package is class-based and modular to facilitate the evolution of the code and to increase flexibility of the analysis pipeline. The advantage of the Python language lies in

73 rapid code execution, while maintaining a certain level of user-friendliness, which results in  
 74 a shallow learning curve and will encourage future contributions to the code from the whole  
 75 GW community. A summary of all pygwb modules and its main external dependencies can be  
 76 found in the pygwb schema [Figure 1](#).

77 The package is compatible with GW frame files in a variety of formats, relying on the I/O  
 78 functionality of gwpy ([Macleod et al., 2021](#)). NumPy ([Harris et al., 2020](#)) is heavily used within  
 79 the pygwb code, as well as matplotlib ([Hunter, 2007](#)) for plotting purposes. Some of the  
 80 frequency-related computations rely on functionalities of the scipy ([Virtanen et al., 2020](#))  
 81 package. The astropy ([Collaboration et al., 2022](#)) package is employed for cosmology-related  
 82 computations. The parameter estimation module included in pygwb is based on Bilby ([Ashton  
 83 et al., 2019](#)) and the dynesty ([Speagle, 2020](#)) sampler package.

84 A customizable pipeline script, pygwb\_pipe, is provided with the package and can be run in  
 85 default mode, which reproduces the methodology of the LVK isotropic analysis implemented  
 86 on the most recent observation run ([Abbott et al., 2021](#)). On the other hand, the modularity  
 87 of the package allows users to develop custom pygwb pipelines to fit their needs. A set  
 88 of simple statistical checks can be performed on the data after a pygwb run by using the  
 89 statistical\_checks module. In addition, a parameter estimation script, pygwb\_pe, is also  
 90 included and allows to test a subset of default models with user-defined parameters. pygwb\_pe  
 91 is based on the pygwb parameter estimation module, pe, which allows the user to test both  
 92 predefined and user-defined models and obtain posterior distributions on the parameters of  
 93 interest. Users are encouraged to develop and test their own models within the pe module.  
 94 The pygwb package also contains built-in support for running on HTCondor-supported servers  
 95 using dag files to parallelize the analysis of long stretches of data. Using the dedicated  
 96 pygwb\_combine script, the output can be combined into an overall estimation of the GWB for  
 97 the whole data set.

98 The source code can be found at <https://git.ligo.org/pygwb/pygwb> and <https://github.com/a-renzini/pygwb>, and can be installed from PyPi via `pip install pygwb`. The online  
 99 documentation, tutorials and examples are hosted at [https://pygwb.docs.ligo.org/pygwb/  
 100 index.html](https://pygwb.docs.ligo.org/pygwb/index.html). The package includes a unit test suite which currently covers 80% of the modules.  
 101 pygwb is released under a OSI Approved :: MIT License.

pygwb schema.

Figure 1: pygwb schema.

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