The Journal of Open Source Software

# LEGWORK: A python package for computing the evolution and detectability of stellar-origin gravitational-wave sources with space-based detectors

**Tom Wagg**[1, 2, 3], **Katelyn Breivik**[4], **and Selma E. de Mink**[3, 5, 2]

**1** Department of Astronomy, University of Washington, Seattle, WA, 98195 **2** Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA **3** Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85741 Garching, Germany **4** Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Ave, New York, NY, 10010, USA **5** Anton Pannekoek Institute for Astronomy and GRAPPA, University of Amsterdam, NL-1090 GE Amsterdam, The Netherlands

**DOI:** 10.21105/joss.03998

**Software**

- Review
- Repository
- Archive

**Editor:** Arfon Smith

**Reviewers:**

- @dbkeitel
- @cmbiwer

**Submitted:** 17 November 2021
**Published:** 02 February 2022



## Summary

LEGWORK (LISA Evolution and Gravitational Wave Orbit Kit) is an open-source Python package for making predictions about stellar-origin gravitational wave sources and their detectability in LISA or other space-based gravitational wave detectors. LEGWORK can be used to evolve the orbits of sources due to gravitational wave emission, calculate gravitational wave strains (using post-Newtonian approximations), compute signal-to-noise ratios and visualise the results. It can be applied to a variety of potential sources, including binaries consisting of white dwarfs, neutron stars and black holes. Although we focus on double compact objects, in principle LEGWORK can be used for any system with a user-specified orbital evolution, such as those affected by a third object or gas drag. We optimised the package to make it efficient for use in population studies which can contain tens-of-millions of sources. We hope that LEGWORK will enable and accelerate future studies triggered by the rapidly growing interest in gravitational wave sources. This paper is jointly submitted to ApJ, see Wagg et al. (2021).

## Statement of need

The planned space-based gravitational wave detector LISA (Laser Interferometer Space Antenna, Amaro-Seoane et al. (2017)) will present an entirely new view of gravitational waves by focusing on lower frequencies ($10^{-5} < f/\mathrm{Hz} < 10^{-1}$) than ground-based detectors. This will enable the study of many new source classes including mergers of supermassive black holes (e.g. Begelman et al. (1980); Klein et al. (2016); Bellovary et al. (2019)), extreme mass ratio inspirals (e.g. Berti et al. (2006); Barack & Cutler (2007); Babak et al. (2017); Moore+2017), and cosmological GW backgrounds (e.g. Bartolo et al. (2016); Caprini et al. (2016); Caldwell et al. (2019)). However, this frequency regime is also of interest for the detection of local stellar-mass binaries during their inspiral phase. LISA is expected to detect Galactic stellar-origin binaries containing combinations of white dwarfs, neutron stars, and black holes, ranging from the numerous double white dwarf population, to the rare but loud double black hole population.

The potential to detect stellar-origin sources with LISA has been studied in the past (e.g. Nelemans et al. (2001); Liu (2009); Liu & Zhang (2014); Ruiter et al. (2010); Belczynski et al. (2010); Nissanke et al. (2012)). More recently, the direct detection of gravitational waves with ground-based detectors (Abbott et al., 2016) has led to renewed interest in this topic with many recent papers addressing the issue (e.g. Christian & Loeb (2017); Kremer et al. (2017); Kremer et al. (2018); Korol et al. (2017); Korol et al. (2018); Korol et al. (2019); Korol et al. (2020); Lamberts et al. (2018); Lamberts et al. (2019); Fang et al. (2019); Andrews et al. (2020); Lau et al. (2020); Breivik, Coughlin, et al. (2020); Breivik, Mingarelli, et al. (2020); Roebber et al. (2020); Chen et al. (2020); Sesana et al. (2020); Shao & Li (2021)).

Each of these studies require making estimates of the signal-to-noise ratio of individual binary systems and possibly the slow gravitational wave inspiral that lead to the present-day parameters. So far, most studies made use of custom made codes which have not been made publicly available.

We believe that the large renewed interest in LISA and the stellar-origin sources it may detect will lead to many more studies in the near future that would need similar computations. This leads to a significant amount of redundancy which, at best results in extra work for each individual and at worst leads to an increased chance of introducing mistakes and inconsistencies when translating the necessary expressions to software.

LEGWORK is a Python package designed to streamline the process of making predictions of LISA detection rates for stellar-origin binaries such that it is as fast, reliable and simple as possible. This goal makes LEGWORK unique among other implementations of gravitational-wave tools in the literature, which focus on a more broad coverage of the gravitational-wave spectrum and source classes, rather than an optimised approach for certain sources (e.g. Moore et al. (2015); Yi et al. (2021)). With LEGWORK one can evolve the orbits of a binary or a collection of binaries and calculate their strain amplitudes for any range of frequency harmonics. One can compute the sensitivity curve for LISA or other future gravitational wave detectors (e.g. TianQin (Luo et al., 2016), or a user-defined custom instrument) and use it to compute the signal-to-noise ratio of a collection of sources. Furthermore, LEGWORK provides tools to visualise all of the results with easy-to-use plotting functions. Finally, LEGWORK is fully tested to check for consistency in the derivations described in the ApJ paper (Wagg et al., 2021).

Specifically, we implement the expressions by Peters & Mathews (1963) and Peters (1964) for the evolution of binary orbits due to the emission of gravitational waves, equations for the strain amplitudes and signal-to-noise ratios of binaries from various papers (e.g. Flanagan & Hughes (1998); Finn & Thorne (2000); Cornish & Larson (2003); Barack & Cutler (2004); Moore et al. (2015)) and approximations for the LISA and TianQin sensitivity curves given in Robson et al. (2019) and Huang et al. (2020) respectively. This lowest-order post-Newtonian implementation of gravitational radiation does not include the effects of higher-order terms in the post-Newtonian expansion, including spin-orbit coupling or radiation reaction. The strain calculations in LEGWORK also incorporate averages over the detector motion as well as sky position and inclination in order to remain completely analytically solvable. Work which requires the incorporation of a full LISA detector simulation should consider tools like lisacattools or ldasoft (Littenberg et al., 2020). For non-stellar-origin sources, tools like the Gravitational Wave Universe Toolbox are more appropriate (Yi et al., 2021).

The open-source nature of the project means that new users as well as seasoned experts in the field can work together in a collaborative setting to consider new features and enhancements to the package as well as check the implementation. At the same time, with our thorough online documentation, derivations and tutorials, we hope LEGWORK can make this functionality more accessible to the broader scientific community.

# Acknowledgements

We are grateful to Stas Babak, Floor Broekgaarden, Tom Callister, Will Farr, Stephen Justham, Valeria Korol, Mike Lau, Tyson Littenberg, Ilya Mandel, Alberto Sesana, Lieke van Son, the CCA GW group, the BinCosmos group and the COMPAS group for stimulating discussions that influenced and motivated us to complete this project. We thank the BinCosmos group for testing an early version of the package and providing useful feedback. In particular, we thank Lieke van Son for her innovation in inventing the name LEGWORK! TW also thanks Floor Broekgaarden for first suggesting that he investigate LISA and the derivation of the SNR calculation.

This project was funded in part by the National Science Foundation under Grant No. (NSF grant number 2009131), the European Union's Horizon 2020 research and innovation program from the European Research Council (ERC, Grant agreement No. 715063), and by the Netherlands Organization for Scientific Research (NWO) as part of the Vidi research program BinWaves with project number 639.042.728. We further acknowledge the Black Hole Initiative funded by a generous contribution of the John Templeton Foundation and the Gordon and Betty Moore Foundation. The Flatiron Institute is funded by the Simons Foundation.

# References

Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R. X., Adya, V. B., Affeldt, C., Agathos, M., Agatsuma, K., Aggarwal, N., Aguiar, O. D., Aiello, L., Ain, A., Ajith, P., … LIGO Scientific Collaboration and Virgo Collaboration. (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *116*(6), 061102. https://doi.org/10.1103/PhysRevLett.116.061102

Amaro-Seoane, P., Audley, H., Babak, S., Baker, J., Barausse, E., Bender, P., Berti, E., Binetruy, P., Born, M., Bortoluzzi, D., Camp, J., Caprini, C., Cardoso, V., Colpi, M., Conklin, J., Cornish, N., Cutler, C., Danzmann, K., Dolesi, R., … Zweifel, P. (2017). Laser Interferometer Space Antenna. *arXiv e-Prints*, arXiv:1702.00786. http://arxiv.org/abs/1702.00786

Andrews, J. J., Breivik, K., Pankow, C., D'Orazio, D. J., & Safarzadeh, M. (2020). LISA and the Existence of a Fast-merging Double Neutron Star Formation Channel. *892*(1), L9. https://doi.org/10.3847/2041-8213/ab5b9a

Babak, S., Gair, J., Sesana, A., Barausse, E., Sopuerta, C. F., Berry, C. P. L., Berti, E., Amaro-Seoane, P., Petiteau, A., & Klein, A. (2017). Science with the space-based interferometer LISA. V. Extreme mass-ratio inspirals. *95*(10), 103012. https://doi.org/10.1103/PhysRevD.95.103012

Barack, L., & Cutler, C. (2007). Using LISA extreme-mass-ratio inspiral sources to test off-Kerr deviations in the geometry of massive black holes. *75*(4), 042003. https://doi.org/10.1103/PhysRevD.75.042003

Barack, L., & Cutler, C. (2004). LISA capture sources: Approximate waveforms, signal-to-noise ratios, and parameter estimation accuracy. *69*(8), 082005. https://doi.org/10.1103/PhysRevD.69.082005

Bartolo, N., Caprini, C., Domcke, V., Figueroa, D. G., Garcia-Bellido, J., Chiara Guzzetti, M., Liguori, M., Matarrese, S., Peloso, M., Petiteau, A., Ricciardone, A., Sakellariadou, M., Sorbo, L., & Tasinato, G. (2016). Science with the space-based interferometer LISA. IV: probing inflation with gravitational waves. *2016*(12), 026. https://doi.org/10.1088/1475-7516/2016/12/026

Begelman, M. C., Blandford, R. D., & Rees, M. J. (1980). Massive black hole binaries in active galactic nuclei. *287*(5780), 307–309. https://doi.org/10.1038/287307a0

Belczynski, K., Benacquista, M., & Bulik, T. (2010). Double Compact Objects as Low-frequency Gravitational Wave Sources. *725*(1), 816–823. https://doi.org/10.1088/

0004-637X/725/1/816

Bellovary, J. M., Cleary, C. E., Munshi, F., Tremmel, M., Christensen, C. R., Brooks, A., & Quinn, T. R. (2019). Multimessenger signatures of massive black holes in dwarf galaxies. *482*(3), 2913–2923. https://doi.org/10.1093/mnras/sty2842

Berti, E., Cardoso, V., & Will, C. M. (2006). Gravitational-wave spectroscopy of massive black holes with the space interferometer LISA. *73*(6), 064030. https://doi.org/10.1103/PhysRevD.73.064030

Breivik, K., Coughlin, S., Zevin, M., Rodriguez, C. L., Kremer, K., & al., et. (2020). COSMIC Variance in Binary Population Synthesis. *898*(1), 71. https://doi.org/10.3847/1538-4357/ab9d85

Breivik, K., Mingarelli, C. M. F., & Larson, S. L. (2020). Constraining Galactic Structure with the LISA White Dwarf Foreground. *901*(1), 4. https://doi.org/10.3847/1538-4357/abab99

Caldwell, R. R., Smith, T. L., & Walker, D. G. E. (2019). Using a primordial gravitational wave background to illuminate new physics. *100*(4), 043513. https://doi.org/10.1103/PhysRevD.100.043513

Caprini, C., Hindmarsh, M., Huber, S., Konstandin, T., Kozaczuk, J., Nardini, G., No, J. M., Petiteau, A., Schwaller, P., Servant, G., & Weir, D. J. (2016). Science with the space-based interferometer eLISA. II: gravitational waves from cosmological phase transitions. *2016*(4), 001. https://doi.org/10.1088/1475-7516/2016/04/001

Chen, W.-C., Liu, D.-D., & Wang, B. (2020). Detectability of Ultra-compact X-Ray Binaries as LISA Sources. *900*(1), L8. https://doi.org/10.3847/2041-8213/abae66

Christian, P., & Loeb, A. (2017). LISA detection of binary black holes in the Milky Way galaxy. *469*(1), 930–937. https://doi.org/10.1093/mnras/stx910

Cornish, N. J., & Larson, S. L. (2003). LISA data analysis: Source identification and subtraction. *67*(10), 103001. https://doi.org/10.1103/PhysRevD.67.103001

Fang, X., Thompson, T. A., & Hirata, C. M. (2019). The Population of Eccentric Binary Black Holes: Implications for mHz Gravitational-wave Experiments. *875*(1), 75. https://doi.org/10.3847/1538-4357/ab0e6a

Finn, L. S., & Thorne, K. S. (2000). Gravitational waves from a compact star in a circular, inspiral orbit, in the equatorial plane of a massive, spinning black hole, as observed by LISA. *62*(12), 124021. https://doi.org/10.1103/PhysRevD.62.124021

Flanagan, É. É., & Hughes, S. A. (1998). Measuring gravitational waves from binary black hole coalescences. I. Signal to noise for inspiral, merger, and ringdown. *57*(8), 4535–4565. https://doi.org/10.1103/PhysRevD.57.4535

Huang, S.-J., Hu, Y.-M., Korol, V., Li, P.-C., Liang, Z.-C., & al., et. (2020). Science with the TianQin Observatory: Preliminary results on Galactic double white dwarf binaries. *102*(6), 063021. https://doi.org/10.1103/PhysRevD.102.063021

Klein, A., Barausse, E., Sesana, A., Petiteau, A., Berti, E., & al., et. (2016). Science with the space-based interferometer eLISA: Supermassive black hole binaries. *93*(2), 024003. https://doi.org/10.1103/PhysRevD.93.024003

Korol, V., Koop, O., & Rossi, E. M. (2018). Detectability of Double White Dwarfs in the Local Group with LISA. *866*(2), L20. https://doi.org/10.3847/2041-8213/aae587

Korol, V., Rossi, E. M., & Barausse, E. (2019). A multimessenger study of the Milky Way's stellar disc and bulge with LISA, Gaia, and LSST. *483*(4), 5518–5533. https://doi.org/10.1093/mnras/sty3440

Korol, V., Rossi, E. M., Groot, P. J., Nelemans, G., Toonen, S., & al., et. (2017). Prospects for detection of detached double white dwarf binaries with Gaia, LSST and LISA. *470*(2), 1894–1910. https://doi.org/10.1093/mnras/stx1285

Korol, V., Toonen, S., Klein, A., Belokurov, V., Vincenzo, F., & al., et. (2020). Populations of double white dwarfs in Milky Way satellites and their detectability with LISA. *638*, A153. https://doi.org/10.1051/0004-6361/202037764

Kremer, K., Breivik, K., Larson, S. L., & Kalogera, V. (2017). Accreting Double White Dwarf Binaries: Implications for LISA. *846*(2), 95. https://doi.org/10.3847/1538-4357/aa8557

Kremer, K., Chatterjee, S., Breivik, K., Rodriguez, C. L., Larson, S. L., & al., et. (2018). LISA Sources in Milky Way Globular Clusters. *120*(19), 191103. https://doi.org/10.1103/PhysRevLett.120.191103

Lamberts, A., Blunt, S., Littenberg, T. B., Garrison-Kimmel, S., Kupfer, T., & al., et. (2019). Predicting the LISA white dwarf binary population in the Milky Way with cosmological simulations. *490*(4), 5888–5903. https://doi.org/10.1093/mnras/stz2834

Lamberts, A., Garrison-Kimmel, S., Hopkins, P. F., Quataert, E., Bullock, J. S., & al., et. (2018). Predicting the binary black hole population of the Milky Way with cosmological simulations. *480*(2), 2704–2718. https://doi.org/10.1093/mnras/sty2035

Lau, M. Y. M., Mandel, I., Vigna-Gómez, A., Neijssel, C. J., Stevenson, S., & al., et. (2020). Detecting double neutron stars with LISA. *492*(3), 3061–3072. https://doi.org/10.1093/mnras/staa002

Littenberg, T. B., Cornish, N. J., Lackeos, K., & Robson, T. (2020). Global analysis of the gravitational wave signal from Galactic binaries. *101*(12), 123021. https://doi.org/10.1103/PhysRevD.101.123021

Liu, J. (2009). Gravitational wave radiation from close double white dwarfs in the Galaxy. *400*(4), 1850–1858. https://doi.org/10.1111/j.1365-2966.2009.15574.x

Liu, J., & Zhang, Y. (2014). Gravitational-wave radiation from double compact objects with eLISA in the Galaxy. *126*(937), 211. https://doi.org/10.1086/675721

Luo, J., Chen, L.-S., Duan, H.-Z., Gong, Y.-G., Hu, S., Ji, J., Liu, Q., Mei, J., Milyukov, V., Sazhin, M., Shao, C.-G., Toth, V. T., Tu, H.-B., Wang, Y., Wang, Y., Yeh, H.-C., Zhan, M.-S., Zhang, Y., Zharov, V., & Zhou, Z.-B. (2016). TianQin: a space-borne gravitational wave detector. *Classical and Quantum Gravity*, *33*(3), 035010. https://doi.org/10.1088/0264-9381/33/3/035010

Moore, C. J., Cole, R. H., & Berry, C. P. L. (2015). Gravitational-wave sensitivity curves. *Classical and Quantum Gravity*, *32*(1), 015014. https://doi.org/10.1088/0264-9381/32/1/015014

Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. (2001). The gravitational wave signal from the Galactic disk population of binaries containing two compact objects. *375*, 890–898. https://doi.org/10.1051/0004-6361:20010683

Nissanke, S., Vallisneri, M., Nelemans, G., & Prince, T. A. (2012). Gravitational-wave Emission from Compact Galactic Binaries. *758*(2), 131. https://doi.org/10.1088/0004-637X/758/2/131

Peters, P. C. (1964). Gravitational Radiation and the Motion of Two Point Masses. *Physical Review*, *136*(4B), 1224–1232. https://doi.org/10.1103/PhysRev.136.B1224

Peters, P. C., & Mathews, J. (1963). Gravitational Radiation from Point Masses in a Keplerian Orbit. *Physical Review*, *131*(1), 435–440. https://doi.org/10.1103/PhysRev.131.435

Robson, T., Cornish, N. J., & Liu, C. (2019). The construction and use of LISA sensitivity curves. *Classical and Quantum Gravity*, *36*(10), 105011. https://doi.org/10.1088/1361-6382/ab1101

Roebber, E., Buscicchio, R., Vecchio, A., Moore, C. J., Klein, A., & al., et. (2020). Milky Way Satellites Shining Bright in Gravitational Waves. *894*(2), L15. https://doi.org/10.3847/2041-8213/ab8ac9

Ruiter, A. J., Belczynski, K., Benacquista, M., Larson, S. L., & Williams, G. (2010). The LISA Gravitational Wave Foreground: A Study of Double White Dwarfs. *717*(2), 1006–1021. https://doi.org/10.1088/0004-637X/717/2/1006

Sesana, A., Lamberts, A., & Petiteau, A. (2020). Finding binary black holes in the Milky Way with LISA. *494*(1), L75–L80. https://doi.org/10.1093/mnrasl/slaa039

Shao, Y., & Li, X.-D. (2021). Population Synthesis of Black Hole Binaries with Compact Star Companions. *920*(2), 81. https://doi.org/10.3847/1538-4357/ac173e

Wagg, T., Breivik, K., & de Mink, S. E. (2021). LEGWORK: A python package for computing the evolution and detectability of stellar-origin gravitational-wave sources with space-based detectors. *arXiv e-Prints*, arXiv:2111.08717. http://arxiv.org/abs/2111.08717

Yi, S.-X., Nelemans, G., Brinkerink, C., Kostrzewa-Rutkowska, Z., Timmer, S. T., Stoppa, F., Rossi, E. M., & Portegies Zwart, S. F. (2021). The Gravitational Wave Universe Toolbox: A software package to simulate observation of the Gravitational Wave Universe with different detectors. *arXiv e-Prints*, arXiv:2106.13662. http://arxiv.org/abs/2106.13662