

LISA AND THE LISA SCIENCE TEAM

ANNA HEFFERNAN
ON BEHALF OF THE LISA SCIENCE TEAM

Classification AMS 2020:

Keywords: LISA, Science Team, gravitational waves, waveforms, compact binaries

1. ABSTRACT

LISA, the Laser Interferometer Space Antenna, due to launch mid-2035, is a large class space mission by the European Space Agency (ESA). In partnership with NASA and ESA-member states, ESA is on track to launch what is expected to be the first space-based gravitational wave detector. By hosting detectors in space, one gains access to a lower frequency band of gravitational wave sources and with them, a plethora of new science. To maximise this scientific gain, ESA and NASA selected 20 scientists for the LISA Science Team, to carry out and/or lead necessary actions on the run up to LISA launch. We give a short overview and update of the LISA mission, some of its science objectives and related waveforms, as well as the work of the LISA Science Team as of December 2025.

2. THE LISA MISSION

LISA will detect gravitational waves (GWs) in the mHz range, complementing current and future ground detectors; the mission and its objectives are fully described in the LISA Redbook [1]. LISA is a constellation of 3 spacecraft (SC) forming an almost equilateral triangle, inclined by 60 degrees to the orbital plane, whose centre of mass trails the Earth's orbit (via 3 slightly inclined orbits around the sun). Lasers, emitting from each SC to the other two, form six null connections and allow tracking of the inter-SC distances. Each connection (two per SC) entails a test mass (TM) within a gravitational reference system (GRS), an interferometric detection system (IDS) that includes an optical bench (OB), a telescope and a laser. The proper distance between TMs (shielded within each SC) is then measured by combining TM to OB and OB to OB interferometry data.

The TM, a 46mm cube of 2kg gold-platinum, and its surrounding hardware is known as the GRS. It is a house of electrodes with capacitive sensing to read the TM position with respect to the housing; this also enables electrostatic shielding of the TM and the use of nano-Newton forces to align the TM for optical measurement. It has a launch-lock device to protect the TM during launch and later release it. A UV illumination system can neutralise the TM from accumulation of static charges, while the vacuum chamber around the TM is maintained via a venting duct to space; the SC also houses gravitational balance masses required to compensate the self-gravity of the SC and instrumentation.

The telescopes both transmit and receive collimated beams between the neighbouring SC and their OBs; separation of the beams is ensured via different polarisations. Each OB consists of 3 interferometers: the inter-satellite interferometer tracks the relative motion (includes angular) between the OBs on each SC, the TM interferometer measures motion

between the OB and the TM (again including angular), and the reference interferometer tracks relative phase fluctuations between the two lasers on board (one in each IDS); this measures differential laser frequency noise, which needs to be subtracted from the data streams. Each laser outputs a power of 2W, yet only a few 100 picowatts are received due to the dispersion of the beams travelling between SC. On reception, the incoming beam is beat against a local oscillator beam (where the dominating shot noise arises).

The telescope, laser and charge management system (minimises residual charge on TMs) are being developed by NASA with all other components being produced by ESA and its member states. We are currently in phase B2; the prime contractor has been selected (OHB), payload preliminary design review is in progress, and payload critical design review will begin shortly. The mission at this phase (implementation) has four structures: the instrument and project team, that is the ESA LISA Project, Performance and Operations Teams with all instrument providers; the science ground segment (SGS) (European Distributed Data Processing Centre, NASA SGS and Science Operations Centre); the LISA Science Team (LST) and its working groups; and the scientific community (including the LISA Consortium) that interacts with both the SGS and the LST. Details of the mission setup are in the Science Management Plan (SMP) [2].

3. LISA SCIENCE

The LISA science objectives are described in the LISA Redbook [1]; we focus on those tied to particular waveform models. In-depth reviews of the modelling and astrophysics can be found in the LISA Waveform and Astrophysics White Papers [3, 4] respectively.

3.1. SO1: Study the formation and evolution of compact binary stars and the structure of the Milky Way Galaxy. This mostly refers to double white dwarfs (DWDs), of which about 10^4 will be individually detectable by LISA; in turn, several hundred of these are expected to have electromagnetic (EM) counterparts enabling multi-messenger studies [5]. Ten's of EM signals have already been identified as DWDs detectable by LISA, the so-called verification binaries [6], which will assist in the scientific verification of the LISA data. It is expected that many more ($\sim 10^7$) DWDs will also emit in the LISA range building a stochastic Galactic foreground. Binaries consisting of either or both neutron stars (NSs) and black holes (BHs) should also be detectable from within our galaxy, however at much lower numbers (tens to hundreds).

In modelling, one only considers the inspiral as these binaries are at large separations and will not merge in the LISA band; thus the post-Newtonian (PN) approximation [7] is employed. In fact, due to weak GW emission at this stage, most signals are expected to be quasi-monochromatic (small frequency drift). A mass-transfer phase can occur in LISA-band DWDs, which determines the binary's fate: either a merger or stable mass transfer that counteracts GW radiation and widens the binary. Tidal effects are also important; their interplay with both mass transfer and GW emission is poorly understood and can affect the binary's final state [8]. For systems with NSs/BHs, close binaries inform us of their initial kick velocity from the individual NS/BH formation during supernova (already seen by EM observations for NSs); high kick velocities will tend to disrupt binaries and this will be observed in their distribution [9]. Indeed, the sheer number of expected detections will not only allow us to make statistical reasoning on all the above but also enables us to map out the Milky Way mass distribution as well as inform merger rates.

3.2. SO2: Trace the origins, growth and merger histories of massive Black Holes across cosmic epochs. Massive BH binaries (MBHBs: masses $\sim 10^6 - 10^9 M_\odot$) , are well outside the scope of ground detectors. LISA will see MBHBs out to arbitrarily large redshift as well as less massive binaries involving intermediate mass BHs (IMBHs: masses $\sim 10^2 - 10^5 M_\odot$). Little is known about IMBHs; only a few on the extremes of their mass range have ever been detected [10, 11, 12], allowing little insight into their origin and evolution spanning these masses. LISA's ability to detect them will spurn a new pool of knowledge. Meanwhile massive BHs (MBHs) have long been confirmed in both the present and early universe by EM observations, including accreting $10^6 M_\odot$ MBHs at redshifts $4 < z < 10$ [13, 14]. LISA's sensitivity to $10^3 - 10^7 M_\odot$ binaries at such redshifts will inform theories on BH growth and their host galaxies across the cosmos, in particular IMBHs at the epoch of MBH formation $z > 10$, which is outside all current telescope's abilities. This in turn will not only unveil insights into their origin, population and growth of mass but information on spin and merging rates. As the signals can stay in the detector from days to weeks (mass dependent), one can alert the global network of EM telescopes to search for multi-messenger signals. This could lead to environmental information on accretion as well as a wealth of complementary data (the only GW-EM multi-messenger to-date, GW170817, led to a groundbreaking number of scientific observations [15]).

In detecting MBHBs, a problem arises: LISA's sensitivity allows jarring SNRs (1000s), exasperating the infamous global fit problem. She will see all sources from all directions simultaneously (modulated by LISA's orbital motion); one must systematically identify and remove signals from the data. SNRs ~ 1000 require waveforms of unparalleled accuracy for removal without remnants poisoning lower-SNR signals. Comparable-mass binary models used by current ground detectors [16] combine PN and numerical relativity (NR), balancing speed, accuracy and parameter space coverage, e.g. effective one body [17, 18], phenomenological [19, 20] and NR surrogates [21]. Neither their current accuracy nor parameter space coverage is good enough for LISA MBHBs [3].

3.3. SO3 Probe the properties and immediate environments of Black Holes in the local Universe using extreme mass-ratio inspirals and intermediate mass-ratio inspirals. Compact objects are predicted to orbit and merge with MBHBs and IMBHs. Stellar-mass BHs ($5 - 10^2 M_\odot$) inspiralling into a MBHB, known as extreme mass-ratio inspirals (EMRIs), are expected to occur in galaxy centres. A stellar-mass BH merging with an IMBH or an IMBH with a MBHB, both called intermediate mass-ratio inspirals (IMRIs), are known as light or heavy respectively; light IMRIs are likely to arise in dense star clusters and dwarf galaxies. EMRIs and IMRIs both generate many GW cycles ($\sim 10^5$) in LISA's band, enabling tight constraints on the primary's spin ($\sim 10^{-5}$) as well as the secondary's eccentricity and inclination, while masses will be measured ($\sim 10^{-2}$). These constitute detections of MBHs and IMBHs accordingly and so will provide insights on the population, parameters and growth mechanisms. Inclination, eccentricity and spin will inform formation channels [22, 23, 24] while the environment (accretion disk [25], multiple bodies [26]) may also imprint on the waveforms.

In modelling EMRIs and IMRIs, PN struggles as the binary tightens, while NR slows for differing body sizes. The self-force (SF) program, which perturbs in the mass-ratio, has emerged as the primary modelling approach. The first post-adiabatic SF inspiral-only waveform [27] showed consistency with NR for mass-ratios as low as 10, affirming its

application to IMRIs as well as EMRIs. Current models cover only circular inspirals, with a spinning secondary [28] and small primary spin ($\chi < 0.1$) [29], with promising merger-ringdown developments [30, 31]. Generic (spinning, eccentric, inclined) post-adiabatic SF waveforms are required for parameter estimation of EMRIs and IMRIs [32]; fast (less accurate) adiabatic waveforms for spinning eccentric systems have been developed in the meantime [33] for use in astrophysical studies and for data analysis developments. Combining NR with SF [34] or PN with SF fluxes [35] may also yield generic waveforms.

3.4. SO4 Understand the astrophysics of stellar-mass Black Holes. Over 200 stellar-mass BHs (sBHs) have been detected by the LIGO-Virgo-KAGRA collaboration (LVK) of ground detectors [36], which is expected to reach $\sim 10^4$ by the time LISA flies. These catch binaries merging, when most have circularised; LISA will see sBHs earlier in their inspiral with sensitivity to eccentricity (informs formation channels) and possibly environmental effects. BHs that grew together, from massive stars of a stellar binary collapsing, expect low eccentricity and aligned spins. Binaries formed via dynamical capture will generate a more random distribution of spins in eccentric orbits. LISA may also detect higher-mass sBHs, like GW190521 [37], that sit in the theoretical BH pair-instability mass-gap (a range of masses for which BHs can not form directly from star collapse [38]). BHs in this range form via hierarchical mergers [39] or a combination of mergers and accretion within a disk [40, 41], with each having their own signatures in the waveforms [42], and hence environmental information. In addition LISA may see a sBH that is later detected by ground detectors, allowing a multi-band detection and the ability to send early alerts (months prior to merger), with sky position and expected merger time (down to seconds), to both the EM community (to search for EM counterparts) and the ground detectors (ensure they are live). Multiband detections are notable probes in testing Einstein's relativity [43] and as dark sirens in cosmology [44], the subject of the fifth and sixth science objectives respectively (MBHBs and EMRIs also play large parts in these objectives but this is outside of the scope of this review). In modelling sBHs, due to their comparable mass, one may use the same waveform families and techniques as MBHBs (where generic waveforms are also required).

4. THE LISA SCIENCE TEAM (LST)

The LST, 20 scientists covering several expertise from institutes across Europe and USA, were selected over three calls. As per the SMP [2], the initial 18, announced in July 2024, included 6 from a NASA call, 11 from an ESA call and the LISA Consortium representative, in areas of Astrophysics (Neil Cornish, Erin Kara, Valeriya Korol, Astrid Lamberts, Gijs Nelemans, Elena Maria Rossi, Alberto Sesana, Joey Shapiro Key, Krista Lynne Smith, Alberto Vecchio), Cosmology (Chiara Caprini), Data Analysis (Nikolaos Karnesis, Antoine Petiteau, Stephen Taylor), Instrumentation (Guido Müller, William Joseph Weber) and Waveforms (Anna Heffernan, Deirdre Shoemaker). These were later joined in April 2025 by 2 ESA-selected complementary scientists in Space Weather (Catia Grimani) and Multi-Messenger (Zoltan Haiman), while in October 2025, transfer of the Consortium representative from Gijs Nelemans to Jonathan Gair began. The LST goals [2] are towards maximising the science return of LISA, including communications and access. Occasionally, an urgent matter leads to a taskforce formation; this was the case for LISA input into the European Strategy for Particle Physics, where a team

(including external members) delivered a report within weeks due to a pressing deadline [45]. More defined longterm goals are tackled via working groups (WGs), which can invite external members. There are currently 6 WGs: Alerts, Author List, Communications, Figures of Merit (FoM), L3 Catalog and Science Topical Panels (STPs).

4.1. The Alerts Working Group. Set up at the LST face-to-face in December 2025, this WG is chaired by ZH and VK. The goals are to provide inputs and specifications to the DDPC for developing a pipeline for issuing alerts; design recommendations for SOC on when and how to operate this pipeline and issue alerts; and connect with communities outside LISA to ensure awareness and lead-time needed for triggered EM observations.

4.2. The Author List Working Group. This WG, chaired by NC, JG and GN, aims to create a set of criteria as well as a procedure to populate the heritage and member author lists as described in the SMP [2]. The heritage author lists those who have made a significant contribution to the mission and has no expiration data. The member author list comprises people working on the mission at the time of science operations and has a roll-off period of 2 years. To-date, a survey has been done among the LST members and information has been collected on criteria used by other missions / instruments for authorship. Descriptions of the member and heritage author lists have been formulated and discussed with the full LST. Based on this feedback, the description of the heritage list has been organized under the two categories, *Founders* and *Builders*. Next steps will be to create drafts of the criteria for membership and the selection procedure.

4.3. The Communications Working Group. The Comms WG, chaired by AH and KLS, aims to ensure smooth communications, both internal and external, formally and informally (via mutual members). Internal connects the different WGs, LST members, and project scientists. External refers to interested entities, including the Distributed Data Processing Centre (DDPC members: JG), NASA Science Ground Segment (NSGS: external member Ann Hornschemeier Cardiff of NASA), Lisa Consortium (AH, JG, VK, JSK), Gravitational Wave International Committee (GWIC: JG, AH, JSK) and other such stakeholders. Several lines of external communication have been established: the LST has an official email (LISAScienceTeam@esa.int), moderated by AH and KLS; a FAQ list has been created, which will go live on the ESA LISA website shortly (with other prepared material); close ties to the Consortium communications is set up via shared members VK and JSK; and living slides have been created for use by LST members to minimise repetitive work and unify messaging when presenting on LISA and LST. Internal links are being supported by streamlining interactions between the various WGs in reporting and presenting their progress and deliverables to both other LST members and the scientific community; this includes a response to questions document that ensures consistent messaging about mission timelines, outcomes, authorship, etc.

4.4. The Figures of Merit Working Group. Chaired by AP and AS, with several LST and external members, this WG is concerned with the Figures of Merit (FoM), a set of metrics designed to quantify the mission's ability to meet its science goals, creating a direct link from instrument specs to science objectives. They provide a key tool for the Performance & Operations team, particularly during the development phase when technical or financial constraints may require modifications to the instrument design. The FoM enable such changes to be assessed in terms of their impact on the scientific

return of the mission. They also allow consideration for points of failure during the mission and the scientific consequences. For this reason, ESA has commissioned the LST to define and implement the FoM. The group is currently reviewing the existing set of FoM, both a static [46] and interactive site [47], prepared during earlier stages of the mission definition by the LISA Consortium and streamlining these to a final (LST) version. Ultimately, the WG will deliver a FoM Tool for the Performance & Operations team, understanding how to best achieve this is also being considered by the WG.

4.5. The L3 Catalogue Working Group. This WG, chaired by AL and NK, has been charged with determining the content and format of the Level 3 science catalogue, which is required to include GW candidates with detection confidence, estimated astrophysical parameters, strain time series, and the residual L1 datastream with candidate sources removed. The WG is working on identifying functional priorities and design features for data visualisation to enable preliminary analysis and catalog cross-matching; these will lead into detailed descriptions of tools to be developed for interfacing with the data that will be provided with the data releases. The goal for easy accessibility for all scientists requires considerations of accessibility issues for scientists with no GW speciality.

4.6. The Science Topical Panels Working Group. The goal of the Science Topical Panels (STP) WG, chaired by EMR and ST, is to determine the nature of STPs during the Early Release Science Time of the LISA mission, defined as approximately the first 12 months of data collection after a 3-month period of in-orbit commissioning [2]. The STP WG discusses potential panel topics, team composition (including chairs), required expertise, member responsibilities, interaction with the LISA Collaboration and the LISA Consortium, and how all of these issues feed into the solicitation and timeline procedure for topics and members. The goal of the WG is to generate a reduced set of proposed actions that encapsulate different scenarios for broader LST discussion. The STP WG has produced and presented a draft document to the LST that describes several possible procedures which lead to the formation of STPs. Further streamlining of this document, taking into consideration feedback from the LST, is in progress. In addition, an avenue for receiving feedback from the scientific community is being developed.

5. ACKNOWLEDGEMENTS

AH would like to thank her fellow members and project scientists of the LISA science team for their invaluable feedback and illuminating discussions, in particular, Neil Cornish, Jonathan Gair, Zoltan Haiman, Valeriya Korol, Nora Lützgendorf, Guido Müller, Gijs Nelemans, Krista Lynne Smith, Elena Maria Rossi and Joey Shapiro Key. This short review was partially completed while the author was visiting the Institute for Mathematical Sciences, National University of Singapore in 2025. AH is supported by grant PD-034-2023 co-financed by the Govern Balear and the European Social Fund Plus (ESF+) 2021-2027. This work was supported by the Universitat de les Illes Balears (UIB); the Spanish Agencia Estatal de Investigación grants PID2022-138626NB-I00, RED2024-153978-E, RED2024-153735-E, funded by MICIU/AEI/10.13039/501100011033 and the ERDF/EU; and the Comunitat Autònoma de les Illes Balears through the Conselleria d'Educació i Universitats with funds from the European Union - NextGenerationEU/PRTR-C17.I1 (SINCO2022/6719) and from the European Union - European Regional Development Fund (ERDF) (SINCO2022/18146).

REFERENCES

- [1] M. Colpi *et al.* LISA Definition Study Report. arXiv:2402.07571(2024).
- [2] LISA Science Management Plan <https://www.cosmos.esa.int/documents/15452792/15452811/LISA-Science-Management-Plan.pdf/> (2024)
- [3] N. Afshordi *et al.* [LISA Consortium Waveform Working Group], Waveform Modelling for the Laser Interferometer Space Antenna. *Living Rev Rel.*, **28**, 9 (2025), arXiv:2311.01300.
- [4] P. A. Seoane *et al.* [LISA Consortium Astrophysics Working Group], Astrophysics with the Laser Interferometer Space Antenna. *Living Rev. Rel.* **26**, no.1, 2 (2023), arXiv:2203.06016.
- [5] K. Breivik *et al.* Characterizing Accreting Double White Dwarf Binaries with the Laser Interferometer Space Antenna and Gaia,. *Astrophys. J. Lett.* **854**, no.1, L1 (2018), arXiv:1710.08370
- [6] T. Kupfer *et al.* LISA Galactic Binaries with Astrometry from Gaia DR3. *Astrophys. J* **963**, no.2, 100 (2024), arXiv:2302.12719
- [7] L. Blanchet, Post-Newtonian Theory for Gravitational Waves. *Living Rev. Rel.* **17**, 2 (2014), arXiv:1310.1528.
- [8] T. R. Marsh, G. Nelemans and D. Steeghs, Mass transfer between double white dwarfs. *Mon. Not. Roy. Astron. Soc.* **350**, 113 (2004), arXiv:astro-ph/0312577.
- [9] N. Giacobbo and M. Mapelli, The progenitors of compact-object binaries: impact of metallicity, common envelope and natal kicks. *Mon. Not. Roy. Astron. Soc.* **480**, no.2, 2011-2030 (2018), arXiv:1806.00001.
- [10] A. G. Abac *et al.* [LIGO Scientific, VIRGO and KAGRA], GW231123: A Binary Black Hole Merger with Total Mass 190–265 M_⊙. *Astrophys. J. Lett.* **993**, no.1, L25 (2025), arXiv:2507.08219.
- [11] D. Lin *et al.* A luminous X-ray outburst from an intermediate-mass black hole in an off-centre star cluster, *Nature Astron.* **2** (2018) no.8, 656-661 arXiv:1806.05692.
- [12] J. E. Greene, J. Strader, L. C. Ho, Intermediate-Mass Black Holes, *Annu. Rev. Astron. Astrophys.* **58** (2020), 257-312 arXiv:1911.09678.
- [13] R. Maiolino *et al.* JADES - The diverse population of infant black holes at $4 < z < 11$: Merging, tiny, poor, but mighty, *Astron. Astrophys.* **691** (2024), A145 arXiv:2308.01230.
- [14] R. Maiolino *et al.* A small and vigorous black hole in the early Universe, *Nature* **627** (2024) no.8002, 59-63 [erratum: Nature **630** (2024) no.8015, E2] arXiv:2305.12492.
- [15] B. P. Abbott *et al.* Multi-messenger Observations of a Binary Neutron Star Merger, *Astrophys. J. Lett.* **848** (2017) no.2, L12 arXiv:1710.05833.
- [16] A. G. Abac *et al.* [LIGO Scientific, VIRGO and KAGRA], GWTC-4.0: Methods for Identifying and Characterizing Gravitational-wave Transients, arXiv:2508.18081.
- [17] A. Ramos-Buades, A. Buonanno, H. Estellés, M. Khalil, D. P. Mihaylov, S. Ossokine, L. Pompili and M. Shiferaw, Next generation of accurate and efficient multipolar precessing-spin effective-one-body waveforms for binary black holes, *Phys. Rev. D* **108** (2023) no.12, 124037 arXiv:2303.18046.
- [18] S. Akcay *et al.* Effective-one-body multipolar waveform for tidally interacting binary neutron stars up to merger, *Phys. Rev. D* **99** (2019) no.4, 044051 arXiv:1812.02744.
- [19] M. Colleoni *et al.* Fast frequency-domain gravitational waveforms for precessing binaries with a new twist, *Phys. Rev. D* **111** (2025) no.10, 104019 arXiv:2412.16721.
- [20] J. E. Thompson, E. Hamilton, L. London, S. Ghosh, P. Kolitsidou, C. Hoy and M. Hannam, PhenomXO4a: a phenomenological gravitational-wave model for precessing black-hole binaries with higher multipoles and asymmetries, *Phys. Rev. D* **109** (2024) no.6, 063012 arXiv:2312.10025.
- [21] V. Varma *et al.* Surrogate models for precessing binary black hole simulations with unequal masses, *Phys. Rev. Research.* **1** (2019), 033015 arXiv:1905.09300.
- [22] C. Hopman and T. Alexander, The Orbital statistics of stellar inspiral and relaxation near a massive black hole: Characterizing gravitational wave sources, *Astrophys. J.* **629** (2005), 362-372 arXiv:astro-ph/0503672.
- [23] M. Coleman Miller, M. Freitag, D. P. Hamilton and V. M. Lauburg, Binary encounters with supermassive black holes: Zero-eccentricity LISA events, *Astrophys. J. Lett.* **631** (2005), L117-L120 arXiv:astro-ph/0507133.
- [24] M. Volonteri, P. Madau, E. Quataert and M. J. Rees, The Distribution and cosmic evolution of massive black hole spins, *Astrophys. J.* **620** (2005), 69-77 arXiv:astro-ph/0410342.

- [25] F. Duque, L. Sberna, A. Spiers and R. Vicente, Extreme-mass-ratio inspirals in relativistic accretion discs, arXiv:2510.02433.
- [26] Z. Pan, H. Yang, L. Bernard and B. Bonga, Resonant dynamics of extreme mass-ratio inspirals in a perturbed Kerr spacetime, *Phys. Rev. D* **108** (2023) no.10, 104026 arXiv:2306.06576.
- [27] B. Wardell *et al.* Gravitational Waveforms for Compact Binaries from Second-Order Self-Force Theory, *Phys. Rev. Lett.* **130** (2023) no.24, 241402 arXiv:2112.12265.
- [28] J. Matheus, A. Pound and B. Wardell, Self-force calculations with a spinning secondary, *Phys. Rev. D* **105** (2022) no.8, 084031 arXiv:2112.13069.
- [29] J. Matheus, B. Wardell, A. Pound and N. Warburton, Post-adiabatic self-force waveforms: slowly spinning primary and precessing secondary, arXiv:2510.16113.
- [30] L. Küchler, G. Compère and A. Pound, Self-force framework for merger-ringdown waveforms, arXiv:2506.02189.
- [31] L. Honet, L. Küchler, A. Pound and G. Compère, Transition-to-plunge self-force waveforms with a spinning primary, arXiv:2510.13958.
- [32] O. Burke *et al.* Assessing the importance of first postadiabatic terms for small-mass-ratio binaries, *Phys. Rev. D* **109** (2024) no.12, 124048 arXiv:2310.08927.
- [33] C. E. A. Chapman-Bird *et al.* Efficient waveforms for asymmetric-mass eccentric equatorial inspirals into rapidly spinning black holes, *Phys. Rev. D* **112** (2025) no.10, 104023 arXiv:2506.09470.
- [34] N. A. Wittek, L. Barack, H. P. Pfeiffer, A. Pound, N. Deppe, L. E. Kidder, A. Macedo, K. C. Nelli, W. Throwe and N. L. Vu, Relieving Scale Disparity in Binary Black Hole Simulations, *Phys. Rev. Lett.* **134** (2025) no.25, 251402 arXiv:2410.22290.
- [35] L. Honet *et al.* Spin-aligned inspiral waveforms from self-force and post-Newtonian theory, arXiv:2510.16112.
- [36] A. G. Abac *et al.* [LIGO Scientific, VIRGO and KAGRA], GWTC-4.0: Population Properties of Merging Compact Binaries, arXiv:2508.18083.
- [37] R. Abbott *et al.* [LIGO Scientific and Virgo], GW190521: A Binary Black Hole Merger with a Total Mass of $150M_{\odot}$, *Phys. Rev. Lett.* **125** (2020) no.10, 101102 arXiv:2009.01075.
- [38] S. E. Woosley and A. Heger, The Pair-Instability Mass Gap for Black Holes, *Astrophys. J. Lett.* **912** (2021) no.2, L31 arXiv:2103.07933.
- [39] D. Gerosa and M. Fishbach, Hierarchical mergers of stellar-mass black holes and their gravitational-wave signatures, *Nature Astron.* **5** (2021) no.8, 749-760 arXiv:2105.03439.
- [40] H. Tagawa, B. Kocsis, Z. Haiman, I. Bartos, K. Omukai and J. Samsing, Mass-gap Mergers in Active Galactic Nuclei, *Astrophys. J.* **908** (2021) no.2, 194 arXiv:2012.00011.
- [41] I. Bartos and Z. Haiman, Accretion is All You Need: Black Hole Spin Alignment in Merger GW231123 Indicates Accretion Pathway, *Astrophys. J. Lett.* **996** (2026) no.2, L44 arXiv:2508.08558.
- [42] K. Inayoshi, N. Tamanini, C. Caprini and Z. Haiman, Probing stellar binary black hole formation in galactic nuclei via the imprint of their center of mass acceleration on their gravitational wave signal, *Phys. Rev. D* **96** (2017) no.6, 063014 arXiv:1702.06529
- [43] T. Baker, E. Barausse, A. Chen, C. de Rham, M. Pieroni and G. Tasinato, Testing gravitational wave propagation with multiband detections, *JCAP* **03** (2023), 044 arXiv:2209.14398
- [44] N. Muttoni, A. Mangiagli, A. Sesana, D. Laghi, W. Del Pozzo, D. Izquierdo-Villalba and M. Rosati, Multiband gravitational wave cosmology with stellar origin black hole binaries, *Phys. Rev. D* **105** (2022) no.4, 043509 arXiv:2109.13934
- [45] C. Caprini *et al.* [LISA Science Team], Science of the LISA mission: A Summary for the European Strategy for Particle Physics, arXiv:2507.05130 (2025)
- [46] LISA Consortium Figures of Merit (Static), https://wiki-lisa.in2p3.fr/fom-sites/dc_82_fmin_1e-4/site/ (2024)
- [47] LISA Consortium Figures of Merit (Interactive), <https://lisa-science-explorer.in2p3.fr/> (2024)

DEPARTAMENT DE FÍSICA, UNIVERSITAT DE LES ILLES BALEARS, IAC3 – IEEC, CRTA. VALDEMOSSA KM 7.5, E-07122 PALMA, SPAIN

Email address: anna.heffernan@uib.eu