LISA Science Group Work Packages

N/Ref :	LISA-LCST-SGS-WPD-002
Title	**LISA Science Group Work Packages**
Abstract	LISA Science Group Work Package definition and organisation

	Name	**Date**	**Signature**
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Document Change Record

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Ver.	Date	Author	Description	Pages
0.1	2020/05/26	LSG Core	Initial version	all
0.1	2022/01/20	LSG Core (LISA)	Current Version	

Distribution list

Recipient	Restricted	Not restricted
LSG Core	✗	

Contents

Purpose and Scope

For the Laser Interferometer Space Antenna (LISA) mission [86] ...

Chapter 1

WAV–Waveforms

Work packages in group WAV coordinate and oversee the development of waveform templates for signal analysis. Primary tasks include the definition of waveform accuracy requirements, the development of sufficiently accurate and faithful waveform models, the design and implementation of tools for fast waveform generation, and the development of standard-format interfaces and visualization tools. Different classes of potential sources present distinct modelling challenges and are therefore dealt with under separate WPs.

Accurate waveform models are required as input for search algorithms, and are of vital importance in the interpretation of detected sources, extraction of source parameters, and removal of foreground signals. As an ideal standard, we require that models are sufficiently accurate that "systematic" biases from modelling error are kept subdominant even for the highest-SNR sources expected. This standard has essentially been achieved for some sources but would require much more work for others. Work is also needed in assessing the likelihood and impact of various astrophysical perturbations, and these need to be incorporated in the models if necessary. Finally, it is desirable to design waveform families that incorporate parametrized deviations from GR, or the effect of exotic physics within GR.

	WAV work packages	Priority
WAV.1	Waveform modelling requirements	1
WAV.2.1	EMRI theory development	2
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WAV.2.3	Non-GR and environmental signatures in EMRIs	2
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WAV.7	Cosmic strings and other burst-type sources	3
WAV.8.2	Waveform interface and tools (MBHBs)	1
WAV.8.3	Waveform interface and tools (EMRIs)	1

Structural changes with respect to original Edinburgh document

- Some subpackages promoted to top-level packages, but numbering retained.
- IMRIs (formerly WP 1.5) absorbed in remit of EMRI packages. Need for dedicated IMRI WP to be reviewed routinely.
- Stellar-origin BHBs now a single WP.
- Former WP 1.8.1 (reduced-order models) is now covered under WAV.8.2 and WAV.8.3.

1.1 WAV.1: Waveform modelling requirements

1.1.1 Overview and goals

WAV.1 guides the work of all other WAV packages by identifying the physics input requirements for the waveform modelling effort, and by setting accuracy standards for it. Specific goals:

- Identify the necessary physics that must be included in waveform models for each source category in order to deliver LISA's science requirements.
- Formulate accuracy standards for waveform models, based on the requirement that systematic errors from model inaccuracies or incomplete physics are kept subdominant. Different accuracy standards will apply to different data-analysis tasks (detection, parameter extraction, tests of GR, early alerts for multiband or multimessenger astronomy, etc.)
- Identify modelling priorities for WAV.2–WAV.7 packages.

1.1.2 Deliverables

- White paper containing an initial analysis of modelling requirements (physics input and accuracy). This will draw heavily from work carried out within the Waveforms WG.
- (At regular intervals) technical reports reviewing and updating modelling requirements, modelling priorities and timeline.
- (Foreseeable) Scientific papers on the effect of model systematics

1.1.3 Description of work

The impact of waveform accuracy on systematic biases has been well-studied in the context of ground-based detectors, where systematic end-to-end parameter inference and population inference have been applied. Because of the greater complexity of LISA data analysis (e.g., parameter and population inferences are often inseparable), at present our understanding of waveform accuracy standards rely on less rigorous techniques (e.g., ones based on a Fisher-matrix analysis), which provide only a rough guidance. Building on these legacy studies, the WP will develop more rigorous tools for assessing waveform standards, targeting each of the primary source categories separately.

For EMRIs, the most stringent modelling requirement comes from the mission requirement to be able to test GR with a "golden" EMRI (SNR $>$ 50, spin $>$ 0.9, prograde orbit). In particular, observational requirement OR-5.2 requires the ability to measure the primary mass to at least 1 part in 10^5, the secondary mass to 1 part in 10^4, the primary spin with a relative error of 10^{-4}, and the deviation from the Kerr quadrupole moment with a relative error better than 10^{-3}. Modelling errors, therefore, cannot be allowed to induce biases larger than these thresholds.

Given the large SNR of golden EMRIs, a Fisher matrix approach should give fairly reliable results, although that should be checked and confirmed with a more robust Bayesian analysis. A good indication of the impact of various physical effects can be gained by adding the relevant term to a baseline waveform that qualitatively reproduces the properties of an EMRI waveform. In the past such studies have been done using so called "kludge" waveforms. However, these are known to be unreliable in the last stage of the inspiral before merger, where for example the impact of an anomalous quadrupole moment is largest. It is desirable to replace these kludge waveforms with more accurate ones based on a systematic adiabatic expansion in black-hole perturbation theory. Developing efficient adiabatic EMRI waveforms is therefore the most urgent task for the EMRI packages (WAV.2 and WAV.8.3). Once these are in place, a tool will be created to estimate the parameter bias induced by neglecting various "post-adiabatic" effects in the waveform.

The impact of EMRI waveform modelling errors on detection is strongly dependent on the nature of the search strategy being applied. A coherent template-based search is prohibitively expensive computationally, which necessitates concessions such as the use of semi-coherent methods. From a modelling point of view this relaxes the requirement that EMRI waveforms stay coherent over a full inspiral. As a result, leading-order adiabatic waveforms may be sufficient for detection. This possibility should be explored.

Given the low instantaneous SNR of EMRI waveforms, the effect of modelling errors on the global fit should be minimal, and the corresponding requirements on model accuracy should almost certainly be less stringent than those coming from the requirements of testing GR with golden EMRIs.

For **MBHBs**, modelling considerations are rather different. SNR for these sources can be very high, and waveform accuracy standards must be set commensurably high if model biases are to be kept in check. The high SNR also means that residual fitting errors from model systematics have a much greater impact on the global fit problem. The principal short-term goal is to devise a waveform standard that can be efficiently evaluated and can usefully account for the complex effects of background contamination, to guide waveform development. Recent work has proposed a match-based diagnostic for waveform accuracy, which can be used to assess the impact of waveform systematics in one population of sources on another. We will apply these tools to a range of existing waveform families, astrophysical scenarios and population models, in order to better quantify the various impacts of model systematics. We will advance in steps, initially considering a simple global threshold.

A key long-term goal is the creation of a reliable ecosystem for constant standards (re)assessment. We want to relate waveform accuracy requirements directly to LISA's specific science deliverables, and use end-to-end simulations with production codes to explore the impact of waveform systematics on our science goals. We will direct the development of these tools in WPs WAV.3 and WAV.8.2, and in turn use these tools as they become available.

Most **SOBHBs** observed by LISA will be wide and slowly inspiralling on quasicircular orbits, with weak-gravity effects whose systematics are relatively well understood. It is expected that existing post-Newtonian models are of sufficient accuracy, but this will be reassessed. A small number of SOBHB sources are expected to form in highly relativistic eccentric orbits, complicated both by GR effects and astrophysical perturbations. Model accuracy requirements for these sources will be assessed separately.

IMRIs lie in between SMBHs and EMRIs in a regime that is potentially awkward for the existing modelling methods, which are designed for either. The observational requirement for IMRIs (OR-2.4b) limits itself to the modest ambition of being able to detect IMRIs and measure their components' masses with 10% accuracy at an SNR of 20. The main modelling challenge will be to obtain waveforms that work at all in the relevant mass-ratio range. This can be assessed by studying the overlap between SMBH and EMRI waveforms.

1.1.4 Timeframe and workforce requirements

- Direct the development of efficient adiabatic waveform model for EMRIs. Needed ASAP, requires a community effort, mostly handled by WAV.1.2 and WAV.1.8.3.

- Develop tool for estimating parameter bias on golden EMRIs generated by neglecting a given correction to the equations of motion: 1 FTE-year.

- Catalogue of post-adiabatic effects on EMRIs that need to be included to achieve appropriate accuracy: 1 FTE-year.

- Develop and continuously improve tools to assess parameter and population biases due to residuals from loud SMBHs, and employ with latest SMBH models. Needed ASAP. 1 FTE, indefinitely.
- For loud SMBHs, assess prospects for focused modeling (e.g., direct followup simulations; parameter-dependent accuracy thresholds as motivated by impact of contamination on science return): 0.5 FTEs, indefinitely.
- For eccentric SOBHBs, develop a phenomenologically-parameterized astrophysical model to enable joint inference for (and marginalization over) astrophysical perturbations. Needed on a longer timescale, mostly provided by WAV.6: 1 FTE × 2 years.

1.1.5 Subpackages

WAV.1.1: Modelling requirements for EMRIs & IMRIs
WAV.1.2: Modelling requirements for SMBHs & SOBHBs

1.1.6 Dependencies

WAV.1 work relies on input from the AstroWG (parameters and populations) and WPs WAV.2,4,6 & 8 (tools enabling the exploration of waveform systematics effects). Some of these inputs are critical, but work can be started based on available data and tools. WAV.1 output sets accuracy standards and priorities for all other WPs in the WAV group. A diagrammatic representation of these dependencies is shown at `https://wiki-lisa.in2p3.fr/pmwiki/uploads/LSG/flowchart11.pdf`.

1.1.7 List of projects (ongoing and short term)

- WAV.1.1: Develop tool for assessing impact of modelling error in I/EMRI equations of motion on parameter estimation.
- WAV.1.1: Catalogue post-adiabatic effects on EMRIs that need to be included to achieve appropriate accuracy.
- WAV.1.1: Investigate impact of orbital resonances on waveform modelling requirements.
- WAV.1.1: Review current best astrophysical estimates for plausible I/EMRI parameter ranges (solicit AstroWG input).
- WAV.1.2: Seek feedback on proposed accuracy diagnostic.
- WAV.1.2: Explore utility of proposed accuracy diagnostic for SMBHs and EMRIs.
- WAV.1.2: Identify limiting values of thresholds for accuracy diagnostics.
- WAV.1.2: Solicit feedback on effort level needed to achieve resulting threshold values.
- WAV.1.2: Order-of-magnitude assessment of consequences of not achieving accuracy target goals.

1.2 WAV.2.1: EMRI theory development

1.2.1 Overview and goals

An unknown number of extreme-mass-ratio binary inspirals will be observed, with a long duration and very rich signals of a modest amplitude. The long duration and high complexity of these signals enables extremely high precision measurements and tests of GR, assuming sufficiently accurate waveform templates are at hand. Accurate templates may also be needed for the very identification of many of the sources. Packages WAV.2.* address the significant theoretical and computational challenge of providing sufficiently accurate and physically realistic waveforms for EMRI searches, parameter extraction and science investigations. Within this effort, the objective of package WAV.2.1 is as follows:

- Working within the framework of black-hole perturbation theory, design methods and codes to enable sufficiently accurate calculations of EMRI waveforms within GR, over the entire astrophysically relevant parameter space. The physical model should allow generic spin magnitudes and orientations, and generic orbital inclinations and eccentricities, and it should incorporate all internal-structure attributes of the small object deemed relevant. It should be phase-accurate to within a fraction of a radian over the entire in-band portion of the inspiral.

1.2.2 Deliverables

- A living open-access resource describing the status of the EMRI theory investigations, listing currently running projects, and soliciting work on open problems.

- Method and code (+ publications reporting these) relevant for the formulation of a complete two-timescale model of EMRI evolution, including all necessary physical effects, ready for numerical implementation.

1.2.3 Description of work

WAV.2.1 develops one or more theoretical models of EMRIs with sufficient accuracy for high-precision parameter extraction, excluding non-GR and environmental effects. The models should maintain phase accuracy to much less than 1 radian error for the longest expected signal duration over the full realistic range of system parameters. They should (i) apply for generic bound orbits of a spinning, finite-sized companion around a central Kerr black hole, (ii) be formulated to enable efficient implementation in WAV.2.2, and (iii) be sufficiently modular to allow inclusion of non-GR and environmental effects in WAV.2.3. A detailed work description with a living list of subprojects is available at `https://tinyurl.com/ybsul6vs`

1.2.4 Timeframe and workforce requirements

- *Now – 2 years:* Develop a two-timescale framework for generic, nonresonant orbits of a structureless companion around a Kerr black hole. Fully develop all necessary theoretical inputs for numerical implementation in the special case of equatorial orbits around a Schwarzschild black hole (as a first step). Additional workforce is required for calculations of these theoretical inputs, estimate at 1 FTE × 2 years

- *Now – 3 years:* Incorporate finite-size and transient effects (resonances and the final plunge) into the two-timescale framework. Sufficient workforce is in place, with multiple groups already working on this.

- *Now – 5 years:* Develop a complete two-timescale model, with all necessary theoretical inputs and a practical formulation of the field equations, for generic orbits around a Kerr black hole, including finite-size and transient effects. Significant additional workforce is required, estimated at 2 FTE × 5 years.
- *Later:* Assess utility of the model(s) for implementation and waveform production. Plan to reformulate or refine as needed.

1.2.5 Dependencies

WAV.2.1 depends on WAV.1.1 for an assessment of which physical effects must be included in our models, and the relative science gain from each. The models must also be guided by requirements from WAV.2.2, WAV.2.3, and WAV.8.3 for implementation, inclusion of non-GR and environmental effects, and accelerated waveform production.

The methods developed in WAV.2.1 feed directly into the activities of WAV.2.2 and WAV.2.3. Ultimately this input is critical, but in the shorter term WAV.2.2 and WAV.2.3 can operate relying on approximate or partial methods already available today.

A detailed flow chart for WAV.2.1 dependencies is displayed in `https://wiki-lisa.in2p3.fr/pmwiki/uploads/LSG/flowchart121.pdf`. The Interdependency between the all 3 EMRI packages WAV.2.* is detailed in `https://tinyurl.com/y84qxw6f`.

1.2.6 List of projects (ongoing and short term)

- Complete the development of theoretical inputs for a post-adiabatic model of quasicircular inspirals into a Schwarzschild black hole.
- Derive energy and angular momentum balance laws for more efficient post-adiabatic evolution of equatorial orbits around spinning or nonspinning black holes.
- Derive finite-size effects from first principles and assess their relative impact at post-adiabatic order.

1.3 WAV.2.2: EMRI numerical implementation and waveforms

1.3.1 Overview and goals

WAV.2.2 implements the theoretical frameworks developed in WAV.2.1 and translates them into practical EMRI waveform calculation schemes. The products from this work will be in the form of software that accurately computes EMRI waveforms at the required (1st post-adiabatic) order. These waveform models need not necessarily be fast enough for the data analysis task, but they will provide crucial input to the work of WAV.8.3, which focuses on the development of computationally efficient methods for data processing. The primary objectives of WAV.2.2:

- To produce a physically complete EMRI waveform model valid across the entire relevant portion of the astrophysical parameter space, and accurate enough to enable (in principle) coherent matched filtering over the entire inspiral. To achieve this accuracy, the model must include all corrections through first post-adiabatic order. This includes certain second-order self-force effects, as well as certain internal-structure effects.

- To produce faster EMRI waveform models of lower accuracy standards, as specified by WAV.1.1, for use in data-processing tasks where accuracy must be traded off for speed (first stages of hierarchical searches, alerts for electro-magnetic coincidence searches).

- To provide input to the work of WAV.8.3 on the improvement of Kludge EMRI waveforms.

1.3.2 Deliverables

- A living open-access resource describing the status of the EMRI modelling effort, listing currently running projects, and soliciting work on open problems.

- Method and code (+ publications reporting these) for calculating EMRI waveforms in GR.

- Data catalogues for EMRI waveforms.

Where appropriate, data and software will be made freely available online in a well documented format.

1.3.3 Description of work

This subpackage deals with all computational aspects of EMRI waveform development. A detailed work description with a living list of subprojects is available at `https://tinyurl.com/y9qt4jjh`.

1.3.4 Timeframe and workforce requirements

- *Now – 2 years:* Adiabatic waveform models for generic inspirals into a Kerr black hole. Post-adiabatic waveform model for quasi-circular inspirals into a Schwarzschild black hole. This is a community effort involving many participants; sufficient workforce is currently assigned to these tasks.

- *Now – 3 years:* Incorporate corrections due to a spinning secondary on an eccentric orbit. Continue to develop second-order calculations. Implement the two-timescale evolution scheme for eccentric orbits ready to accept self-force results as they become available. Continue the development of analytic post-Newtonian self-force results. Workforce is sufficient for inclusion of spin. All other tasks require additional workforce, estimated at 1 FTE × 3 years.

- *2 – 4 years:* Incorporate the second-order self-force for an eccentric orbit around a Schwarzschild black hole. Compute the energy and angular momentum fluxes from a spinning secondary moving on a generic orbit about a Kerr black hole. Extra workforce required, estimated at 2 FTE × 3 years.

- *3–5 years:* Incorporate the second-order self-force for a quasi-circular inspiral into a Kerr black hole. Extra workforce required, estimated at 2 FTE × 3 years.

- *5–10 years:* Implement all relevant effects and produce tools for accurate waveform calculations. Extra workforce required, estimated at 2 FTE in each year.

1.3.5 Dependencies

Feeds from WAV.1 for waveform accuracy standards. Feeds heavily from theoretical development in WAV.2.1, especially in regards to second-order calculations. Feeds into WAV.8.3 and the all science interpretation packages that deal with EMRIs. A detailed flow chart for WAV.2.2 dependencies is displayed in `https://wiki-lisa.in2p3.fr/pmwiki/uploads/LSG/flowchart122.pdf`.

1.3.6 List of projects (ongoing and short term)

- Develop software to compute generic adiabatic inspirals into a Kerr black hole.

- Complete the post-adiabatic quasi-circular Schwarzschild waveform model.

1.4 WAV.2.3: Non-GR and environmental signatures in EMRIs

1.4.1 Overview and goals

Typical LISA EMRIs radiate $O(10^5)$ wave cycles in the LISA band. This, combined with the great complexity of the signal, will allow us to perform exquisite tests of gravity and of the geometry around supermassive black holes. The ability to perform these tests crucially depends on our ability to incorporate beyond-GR and environmental effects in the EMRI waveforms. This package deals with all aspects of EMRI waveform development beyond the vacuum GR case. This includes the development of waveforms that can be used to perform tests of GR with golden EMRIs. It also includes the incorporation of possible environmental effects in EMRI waveforms—e.g., the presence of a third body, accretion disks or dark matter environments. The goals, thus, are:

- To devise methods and suitable parametrized waveform families to enable tests of GR and tests of the nature of compact objects with EMRIs, and also enable the description of possible environmental effects like accretion disks, dark matter, or a third perturbing body.

1.4.2 Deliverables

- A living open-access resource describing the status of the EMRI models beyond GR or including environmental effects, listing currently running projects, and soliciting work on open problems.
- Method and code (+ publications reporting these) to enable studies of off-GR and environmental effects in EMRIs.
- Data catalogues for EMRI waveforms beyond GR or including environmental effects.

1.4.3 Subpackages and description of work

A detailed work description with a living list of subprojects is available on https://tinyurl.com/y283dnma.

1.4.4 Timeframe and workforce requirements

- *Now – 1 year:* Conduct a review of results already available on environmental and beyond-GR effects for EMRIs. Using known results assess how systematic model errors and perturbations of astrophysical origin affect the quality of tests of GR with EMRIs: 0.5 FTE-years
- *Now – 2 year:* Work to incorporate known environmental and beyond-GR effects in currently available Kludge and self-force models. Sufficient workforce is in place across several groups
- *Now – 5 year:* Routinely monitor progress on environmental and beyond-GR effects in EMRIs. In parallel keep track of the progress done in building second-order self-force EMRI waveforms in order to coordinate the work needed to incorporate those effects in the most up-to-date self-force waveforms. Develop necessary framework to incorporate non-GR and environmental effects in two time-scale models. Significant workforce is needed, estimated at 3 FTE × 5 years
- *Later:* Routinely Conduct a review of waveform readiness and assess remaining tasks. Workforce required estimated at 0.1 FTE, indefinitely.

1.4.5 Dependencies

The accuracy with which beyond-GR effects and perturbations of astrophysical origin need to be modelled in EMRIs directly depends on the accuracy requirements provided by WAV.1. The development of beyond-GR/non-vacuum EMRI waveforms will be heavily influenced by the progress made in WAV.2.1 and WAV.2.2. The data products of WAV.2.3 will be used by WAV.8.3 to produce efficient waveforms that can be used in data analysis studies. There will be close interaction with WAV.3.3, whose work involves similar expertise. The waveforms developed in WAV.2.3 will input into the science exploitation work of SI.3, SI.6, SI.7 and SI.8. A detailed flow chart for WAV.2.3 dependencies is displayed in `https://wiki-lisa.in2p3.fr/pmwiki/uploads/LSG/flowchart123.pdf`.

1.4.6 List of projects (ongoing and short term)

- Complete the development of theoretical inputs for a post-adiabatic model of quasicircular inspirals into a Schwarzschild black hole.
- Derive energy and angular momentum balance laws for more efficient post-adiabatic evolution of equatorial orbits around spinning or nonspinning black holes.
- Derive finite-size effects from first principles and assess their relative impact at post-adiabatic order.

1.5 WAV.3.1: Numerical Relativity models of MBHBs in GR

1.5.1 Overview and goals

MBHBs are expected to be the loudest sources of gravitational waves for LISA. These binaries promise to provide the astrophysics and physics communities with rich information about fundamental interactions, parameters of the initial and final black holes, and event rates. The loudness of the signal, meaning high SNR, requires a commensurately high accuracy for the waveforms used to detect and measure their properties. Given that a significant portion of MBHBs will inspiral, merge and ring in band (depending on their total mass), numerical relativity will play a pivotal role in maximizing the science discovery of MBHBs.

Numerical relativity (NR) solves directly the full Einstein equations for the late inspiral of two black holes, their merger and ringdown. The NR community is a robust one, with several public codes and public waveform catalogues available. WAV.3.1 will work with the community and the publicly available products to provide MBHBs waveforms for LISA.

The goal of WAV.3.1 is to provide the full complement of numerical relativity (NR) waveforms that predict, based on the General Theory of Relativity, the gravitational waveforms produced by merging black holes. These waveforms can then be used to construct, improve and validate waveform models, and for other purposes, such as LISA data challenges.

1.5.2 Deliverables

The parameter space of MBHBs is large, and the difficulty to perform numerical simulations differs widely across this space. Therefore, we have divided the NR waveform deliverables between most-likely parameters and all the parameters.

- Determine accuracy of NR waveforms necessary to remove highest SNR signals from data (with WAV.1).
- Survey the currently available public waveforms, accessing their parameter coverage, length and accuracy. Document conventions used by the various catalogs. Highlight additional NR results needed for LISA waveform modeling.
- Create interface code to access the public NR catalogs in a uniform way.
- With the community: ensure availability of NR waveforms that cover most likely LISA source parameters.
- With the community: expand NR parameter space coverage towards numerically challenging configurations, most notably toward high-mass ratio binaries.
- With community: prepare “dream” waveforms, i.e. high accuracy waveforms for binaries in all relevant regions of parameter space.

1.5.3 Description of Work

Numerical Relativity has made rapid progress since the first BHB merger simulations in 2005. Several groups now produce high quality NR waveforms over a wide range of parameters and provide public catalogs of NR waveforms. WAV.3.1 will work with this community to utilize these and future public waveforms catalogs, and to extend them as needed for LISA science purposes.

The first and highest priority is to work with WAV.1 to specify waveform quality standards (accuracy, length, higher-mode content) that can be used to assess suitability of existing NR waveforms. The NR community needs to know this information for LISA waveforms as soon as possible to assess current capabilities and prioritize work moving forward.

Once the standards are understood, we can survey the public catalogs, accessing their parameter coverage, gravitational wave cycle length, and accuracy. This will open the way to work with other packages to determine hot spots in the parameter coverage, such as eccentricity and high-mass ratios.

The next highest priority is to develop interface tools to the public catalogs. These catalogs are not uniform in their metadata nor data format. Rather than creating a standalone LISA NR catalog, we plan to create a suite of software that can read in public waveforms, access them and create usable files for LISA.

The ultimate goal of this package is to provide NR MBHB waveforms for LISA. The goal will be achieved in three levels all in collaboration with the NR community. First is a set of NR waveforms that cover the most likely parameters for MBHBs and the higher harmonics. Second, and the most challenging, is to work towards an extension to higher mass ratios. Third is to provide waveforms for the 'dream' parameters, including high-mass ratio, large eccentricity, and higher harmonics.

1.5.4 Timeframe & workforce requirements

- Waveform quality standards for NR waveforms: 0.5 FTE, 1 year.
- Survey quality of existing public NR catalogs, determine regions with insufficient coverage: 0.5FTE, 1year.
- Tools to access NR catalogs in a uniform way start-up 1 FTE-year, then 0.5 FTEs, indefinitely.
- Compute (or work with community to compute) 'dream' waveforms: 1 FTE, indefinitely, starting year 2 or 3.

1.5.5 Possible subpackages

None currently; to be reviewed.

1.5.6 Dependencies

https://wiki-lisa.in2p3.fr/pmwiki/uploads/LSG/flowchart131.pdf provides a visual map of the dependencies.

- Input from WAV.1, WAV.3.2 on accuracy requirements in terms of accuracy, length, choice and accuracy of higher waveform modes.
- Input from AstroWG on astrophysical expectations of parameters of expected LISA sources.
- Interplay with Wav.2 on the development on intermediate-mass-ratio waveforms.
- Future NR catalogs will likely contain hyperbolic NR simulations, which can be utilized in WAV.7.

1.5.7 List of projects

- Accuracy Assessment: using current NR waveforms, develop assessment metric to measure accuracy. Work with WAV.1 to determine the LISA requirement on NR waveforms. (Now)
- Interface Tools: develop tools to interface with NR public catalogs. (Now)
- NR Survey: Work with NR public catalogs to access current set of parameters and accuracy. This may require the development of tools for interfacing with the catalogs and assessing accuracy first. (As soon as possible)

- Paper: Write a paper presenting the accuracy, tools and survey. Communicate with the broader community where the priorities of LISA need further input from NR and astronomy. (Within a year)
- Data Challenges: Use NR waveforms as injections in data challenges. (Ongoing)
- Eccentric NR Waveforms Meeting: work with the NR groups investing resources in eccentric waveforms. Host a meeting on eccentricity in NR waveforms. This would include PN researchers and waveform modelers.
- High-mass Ratio NR Waveforms Meeting: there are several NR teams working toward this goal that could benefit from a meeting dedicated to moving forward the efforts on this tough topic. Would include EMRI and IMRI researchers and waveform modelers.

1.6 WAV.3.2: Analytical model development for MBHBs

1.6.1 Overview & Goals

Analytical inspiral-merger-ringdown (IMR) waveform models underpin the GW measurements for binary systems. While BHB waveforms are also needed for terrestrial GW detectors, MBHBs pose several unique requirements: (i) MBHBs will be the loudest sources in LISA, making accurate waveforms of utmost importance as modeling inaccuracies could corrupt all measurements. (ii) MBHBs will access a much larger parameter space than BHBs observable by ground-based detectors, with a significant orbital eccentricity, diverse mass ratios, and generically oriented spins. Consequently, the inspiral waveforms of MBHBs will have an extremely rich structure characterized by harmonics of seven different frequencies, with a large number of Fourier modes being important. These interesting features substantially complicate the development of robust models. (iii) LISA's detectors response and bandwidth differs from those of ground-based detectors, which impacts the requirements on length and accuracy of waveforms.

The goal of WAV.3.2 is to provide accurate models of MBHB IMR waveforms for LISA. Further, the models must also be flexible to enable searching for signatures of new physics, and must be computationally efficient for data analysis. Meeting these requirements is a challenging task. It requires including the complexities from many physical effects in models, pushing analytical calculations to higher order, and amalgamating the inputs from various approximation schemes, qualitative physical insights, as well as catalogs of NR simulations. The deeper understanding resulting from these efforts will also have direct consequences for constructing more robust and efficient models in general, for any type of model.

Progress on MBHB waveforms for LISA will also require unifying inputs from the community, where BHB model developments are pursued independently by several groups and focused on LIGO/Virgo sources. WAV.3.2 will concentrate on two major state-of-the-art waveform models for data analysis, the Phenomenological (`IMRPhenom`) and Effective One Body (`EOB`) approaches. Providing waveforms with two different models is of great importance to enable quantifying systematic errors.

The work will proceed along several lines to sequentially include more physics and refine the descriptions. Including eccentricity breaks degeneracies and thus changes the fundamental structure of the models. This will first be studied in the case of aligned spins. Likewise, improved descriptions of the effects of spin precession will first be developed for the simpler case of circular orbits. WAV.3.2 will closely interact with WAV.3.1 on calibrating models against NR. Analytical insights will be important to reduce the number of NR simulations required to produce any type of model within the enormously large parameter space. WAV.3.2 will also closely interact with WAV.8.2 on advancing the computational efficiency, where an improved analytical understanding of different representations of the waveforms will help with constructing fast yet robust approximations.

1.6.2 Deliverables

1. *With WavWG* Survey of existing analytical waveforms, addressing the physics included and parameter coverage, discussing the current approximations and challenges, the extent and accuracy to which the models have been compared to NR and gravitational self-force results, and analytical relativity developments necessary to reach LISA's science potential.

2. *With community*: Waveforms for *eccentric binaries* (aligned spins)
    - convert available analytical information from different perturbative approaches into suitable forms (e.g. coordinates, parameterization) for the IMR models
    - convenient resummations of these inputs, ensure nonsingular circular-orbit limit
    - more detailed analytical modeling of eccentric transitions between inspiral and plunge

  - include merger-ringdown signals to obtain full IMR models, with higher modes
  - perform tests, calibrations, optimization with NR simulation results
  - work with WAV.8.2 to construct fast yet robust approximations to the waveforms

3. *With community*: Further analytical developments to model MBHBs with *precessing spins*
   - push approximations such as multi-scale methods to higher order to avoid singularities plaguing current results, use in the IMR models
   - accurately account for the features of the merger, e.g. symmetry breaking between opposite azimuthal modes
   - test, calibrate, optimize with information from NR
   - work with WAV.8.2 to construct fast yet robust approximations to the waveforms

4. *With community*: Advances in modeling *higher mass ratio* systems
   - include more information from gravitational self-force calculations without introducing pathologies into the models
   - when available use information from new approaches such as amplitudes and effective field theory.

5. *Ultimately*, use the above inputs to develop analytical waveforms for BHBs within GR that include eccentricity and precessing spins, that are accurate over a wide range of mass ratios, and that incorporate all relevant higher modes of the GWs.

6. *Continued further refinements and improvements* as more information from approximation schemes and NR simulations becomes available (more harmonics, larger and more robust parameter space coverage in mass ratio, spins, eccentricity, and improved accuracy).

7. Continued efforts to better understand the map between the time and frequency domain signals and other *analytical, fast approximations* to more efficiently describe features of the waveforms. Develop improved approximations to perform such maps analytically and thus fast and robustly for use in WAV.8.2.

1.6.3 Description of Work

Advances in analytical modeling:

- Several foundational inputs needed for the goals of this WP are already available. Current state-of-the-art waveform models include the effects of generically oriented spins, a few higher modes in the GW signals, and moderately unequal masses. Recent work has included effects of a small eccentricity in these models in cases with aligned spins. LISA waveforms will require going beyond the small-eccentricity approximation, and using more theoretical information to increase the robustness of the models over a larger parameter space. A main aim of the future developments is to maintain flexibility and modularity in the framework, to readily enable incorporating new insights and results and for extensions to tests of GR and BHs. Detailed projects and tasks will differ for the `IMRPhenom` and `EOB` models, hence only the common broad developments are discussed here.

- Inputs for describing generic BHB inspirals are available from post-Newtonian theory, insights into the propagation of GWs, and from gravitational self-force computations. WAV.3.2 will require to explicitly work these out in a suitable format for the `IMRPhenom` and `EOB` frameworks respectively, and developing efficient descriptions for practical use. This will entail a significant effort to restructure the existing models, going beyond the currently available ad-hoc additions of features associated with eccentricity. The models will sequentially increase in complexity and physical realism.

- Additional work will also be required on describing the transition to the plunge, merger, and ringdown waveforms. The initial models will need to be continually refined and updated as new information and inputs become available.

Validating and optimizing the models against NR simulations:

- Progress on WAV.3.2 is largely independent of the timeframe for outputs of WAV.3.1. A number of NR waveforms with eccentricity are already available and can be used for initial comparisons while continuing to improve the theoretical structure of the models.
- Coordination between WAV.3.1 and this WAV.3.2 will also be important for choosing the most useful points in the enormous parameter space to perform NR simulations for calibrating models.

Efficiency for data analysis:

- The implementation, tests, and optimization of waveforms specific for efficient LISA data analysis is the focus of WAV.8.2, with which this WAV.3.2 will closely coordinate.
- In coordination with WAV.8.2., analytical efforts will also be devoted to better understanding and approximating the rich features in the waveforms, as well as aspects related to their use in data analysis such as transforming between time and frequency domains.

1.6.4 Timeframe & Workforce requirements

The time frame for many of the deliverables will vary depending on the community's development of important inputs from theory and NR.

- Deliverable 1 requires about 0.5 FTE, 1 year.
- Deliverables 2–4 will require separate work within the EOB and IMRPhenom frameworks to progressively increase the amount of physics included as well as the accuracy and robustness of the models. The initial effort per each deliverable will require about 2 FTE for 1 year, and continued refinements will require 0.5 FTE per year thereafter.
- Deliverable 5 is the ultimate goal of WAV.3.2 that relies on the deliverables listed above and will require an additional effort of about 2 FTE for 2 years for an initial model.
- Deliverables 6 will require about 1 FTE per year.
- Deliverable 7 is an example of analytical developments needed for robustly improving the efficiency (in contrast to the main goals of accuracy and parameter space coverage for the other deliverables). This is very important as models must be fast to evaluate to be usable for data analysis. This deliverable will require about 0.25 FTE per year, in coordination with WAV.8.2.

1.6.5 Possible subpackages

None currently; to be reviewed.

1.6.6 Dependencies

Input:

- Accuracy requirements from WAV.1.
- NR waveforms from WAV.3.1.

- Efficiency optimizations from WAV.8.
- Insights into parameterisations, resummations, etc, for larger mass-ratios from WAV.2.
- post-Newtonian results from WAV.6.

Output:

- DAFT (data analysis tools), DPE (source identification codes), LDC WG (waveforms for their use).
- WAV.3.1 (feedback on where NR waveforms are most beneficial for continued development).
- WAV.3.3 (base waveforms for non-GR modifications).
- WAV.2 (synergies, insights into parameterisations, resummations, etc, for larger mass-ratios).

`https://wiki-lisa.in2p3.fr/pmwiki/uploads/LSG/flowchart132.pdf` provides a visual map of the dependencies.

1.7 WAV.3.3: Non-GR and environmental signatures in MBHBs

1.7.1 Overview & Goals

One of the fundamental goals of LISA is to test the theory of general relativity (GR) and the nature of supermassive objects. Massive black hole binaries (MBHBs) are the loudest LISA sources and therefore ideal targets for precision tests of GR. The ability to perform these tests will crucially depend on the accuracy within which beyond GR effects can be modelled in the MBHB waveform.

Activities in this WP will involve developing/improving MBHB waveforms that account for beyond-GR effects, both in parametric form and for specific, theoretically-motivated case studies. These waveforms will be the basis for a theoretical interpretation of the signals, so strong synergies with WAV.2.3 and SI. 6-7-8 will be pursued.

The goals of WAV.3.3 are:

- Develop/improve MBHB waveforms that account for beyond-GR effects. This requires the combination of accurate post-Newtonian models beyond GR for the inspiral part with full numerical simulations in modified gravity for the merger and ringdown. Ringdowns can be also studied independently extending black-hole perturbation theory to modified gravity.
- Produce a consistent IMR waveform approximant for (at least) one well-motivated theory of gravity other than GR.
- Develop parametrized, theory-independent, IMR waveforms.
- Provide waveforms to test the nature of supermassive compact objects, and particularly GR's "no-hair" theorem, the Cosmic Censorship Conjecture, and the dynamics and formation of horizons in MBH coalesces.
- Provide waveforms to develop searches for exotic supermassive compact objects, e.g. boson star binaries.
- Provide waveforms to disentangle putative beyond-GR effects from those related to the interaction with matter ("environmental effects").
- Characterize the GW signal from ultralight bosonic fields triggering black-hole superradiant instabilities, both for isolated MBHs and for the post-merger remnant (e.g., merger follow-up searches).
- For all the above, assess the waveform requirements (i.e., accuracy such that systematic error is below the statistical one).

1.7.2 Deliverables

- Parametrized extension of IMR waveforms beyond GR: propagation effects, deviations in the ringdown, deviations in the inspiral part, polarizations.
- Consistent IMR waveform approximant in a well-motivated theory of gravity other than GR. Best candidates: Chern-Simons or Gauss-Bonnet, for which NR simulations are now available.
- Full parametrized MBHB IMR waveforms which incorporate the possibility of exotic near-horizon physics, extreme compact objects other than BHs (e.g., boson stars), and environmental effects (e.g., effect of dark matter environment on the binary).

- Unified modelling of the GW signal from BH superradiant instabilities for searches of ultralight dark matter.

1.7.3 Description of Work

- Theoretical foundations: post-Newtonian and post-Minkowskian calculation in modified gravity and for exotic compact objects. Compute quasinormal modes for BHs in modified gravity and for BH mimickers. Extend current parametrized frameworks for inspiral and ringdown.
- Numerical simulations: explore a few case studies (e.g. Chern-Simons gravity, Gauss-Bonnet gravity, scalar-tensor . theories) in full detail. Understand secular effects that appear to second order in the coupling; simulate binaries in modified gravity beyond effective coupling, e.g. in Gauss-Bonnet gravity.
- Extend current IMR waveform approximants to modified gravity (either parametrically or for case studies).
- Develop unified framework to search for continuous GW signals from superradiant instabilities in case of ultralight dark matter.

1.7.4 Timeframe & Workforce requirements

- Near-term goals (< 2 years):
  - Perform first simulations of BHB mergers in well-motivated theories beyond GR (e.g. Chern-Simons, Gauss-Bonnet) [1.5FTE × 2 years]
  - Develop EOB/Phenom-like IMR waveforms for boson-star coalescence in various models [1 FTE × 2 years]
  - Ringdown tests: general parametrization and specific theories; investigate role of overtones/multiple modes in LISA ringdown tests [1 FTE × 2 years]
  - Outline waveform accuracy requirements for non-GR tests with LISA MBHBs, and carry over such tests developed for ground-based GW detectors [1 FTE × 2 years]
  - Build accurate GW echo templates [1 FTE × 2 years]
  - Develop ringdown tests with mode stacking in LISA [0.5 FTE × 1 years]
  - Outline waveform accuracy requirements for continuous GW searches for axions and ultralight fields with LISA, and carry over such tests developed for ground-based GW detectors [1 FTE × 2 years]
- Medium-term goals (< 5 years):
  - Accurate IMR waveform approximants beyond GR and for exotic compact objects (ECOs), including tidal and spin effects [1 FTE × 5 years]
  - Tests of GR vs. astrophysical and waveform systematics [1 FTE × 2 years]
  - Numerical simulations of BHs with ultralight fields [1.5 FTE × 3 years]
  - Tests of the GW dispersion relation with MBHBs [0.5 FTE × 1 years]
- Long-term goals (> 5 years):
  - Develop first-principles dynamical ECO models; Numerical simulations of ECO mergers [1 FTE × 4 years]
  - Develop full pipeline for parameter estimation in beyond-GR theories and for performing and interpreting tests of the nature of compact objects [1 FTE × 4 years]

1.7.5 Possible subpackages

None currently; to be reviewed.

1.7.6 Dependencies

Input:

- Synergies with WAV.2.3
- WAV.3.1, WAV.3.2: Use of GR results as base for development of beyond GR extensions.

Output:

- SI.6-8 - tests of Fundamental Physics
- DAFT - Data analysis tools
- DPE - Individual and global source identification

1.7.7 List of Projects (ongoing and short term)

- Simulations of BHB mergers in Chern-Simons and Gauss-Bonnet gravity.
- EOB/Phenom-like IMR waveforms for boson-star coalescence in various models.
- Ringdown tests: general parametrization and specific theories; investigate role of overtones/multiple modes in LISA ringdown tests; mode stacking.
- Phenomenology of the BH superradiant instability for LISA sources.

A detailed work description with a living list of subprojects is available on `https://tinyurl.com/y5tyeaex`.

1.8 WAV.4: Galactic binary waveforms

1.8.1 Overview and goals

There should be tens of millions galactic binaries emitting in the frequency band of 0.1–100 mHz. They include interacting AM CVn stars, ultra-compact X-ray binaries, detached double white dwarfs, double neutron stars, white dwarf/neutron star binaries, and likely also black holes with neutron star or white dwarf companions. Among those systems, tens of thousand will be resolvable with LISA. Each will be observable during the entire mission, with a SNR $\propto \sqrt{T_{\text{obs}}}$. The signal will be essentially monochromatic, so that its phase should be well approximated by the Taylor expansion: $\phi(t) = \phi_0 + 2\pi t(f_0 + \dot{f}_0 t/2 + \ddot{f}_0 t^2/6 + ...)$. In some cases $\dot{f}_0$ will be measurable, and for a small number of sources $\ddot{f}_0$ will be measurable, too.

The work of WAV.4 consists mostly in improving the knowledge of the link between the dynamics of the binaries and the values of f_0, $\dot{f}_0$ and $\ddot{f}_0$, in order to inform GB searches and enable the extraction of their astrophysical features—either from the GW signals alone or in combination with electro-magnetic counterparts. Specific goals are to

- enable the triggering of alerts for multimessenger astronomy with accurate localizations;
- enable the extraction or constraining of system parameters when combining GW data with electromagnetic observations; and
- enable the development of fast waveform generation tools required to facilitate analysis of the $\mathcal{O}(10^4)$ observable binaries.

1.8.2 Deliverables

- Code, documentation, and scientific papers reporting numerical and analytical methods for calculating the frequency evolution for the different types of binaries.
- Documents and scientific papers giving parametric phenomenological expressions for $\dot{f}_0$ and $\ddot{f}_0$, including systematic effects that are currently not very well understood.
- A fast waveform generator (method, code and documentation) incorporating all relevant effects.

1.8.3 Description of work

Past studies have devised a frequency-domain model for galactic binaries measured by LISA; obtained understanding of the effect on $\dot{f}_0$ of mass transfer dynamics and tidal effects in accreting circularized white dwarfs binaries; investigated hierarchical systems; and explored the complementarity of GW and electro-magnetic observations.

The immediate workplan is to start with an in-depth review of relevant literature concerning mass transfer dynamics and tidal effects, triplet or quadruplet hierarchical systems, and resonant effects. Input on these will be solicited from the community via the AstroWG. Then, within the first year of work, the goal is to identify all currently missing effects relevant for the determination of f_0, $\dot{f}_0$, $\ddot{f}_0$. These include

- mass transfer (for white dwarf binaries)
- tidal effects and resonances
- eccentricity corrections
- perturbation from outer bodies (for hierarchical systems)

- 1PN corrections (at least for systems involving NSs or BHs)

Within the second and third years of work, the goal is to design reliable orbital models that take all above effects effects into account. As part of this, we will derive and solve the differential equations that govern the evolution of the frequency and other time-dependent system parameters, and produce code that generates the corresponding waveforms. At the same time, again soliciting community input via the AstroWG, we will explore the relevance and importance of any missing physical or astrophysical effects.

In the longer term, the objectives will be to (1) develop a parametric phenomenological waveform model that can be evaluated fast; (2) incorporate any missing physical or astrophysical effects; and (3) interact with the LDC Working Group to assess the quality of parameter extraction and refine the models accordingly

1.8.4 Timeframe and workforce requirements

- *Now – 1 year:* Literature review: taking stock of current knowledge and methods; identification of gaps in the literature. Workforce required estimated at 0.25 FTE years.
- *1 – 3 year:* Design orbital models that take into account all relevant physical effects, and hence produce fully realistic and sufficiently accurate waveforms models. Workforce required estimated at 1 FTE × 3 years.
- *later:* Computational acceleration: parametric phenomenological waveform models for fast evaluation. Continued review of any missing physical or astrophysical effects. Assessment of parameter extraction biases from model systematics: 1 FTE, indefinitely.

1.8.5 Possible subpackages

- WAV.4.1: Astrophysical model
- WAV.4.2: Fast waveform generators

1.8.6 Dependencies

Input:

- AstroWG: inventory of all astrophysical effects that must be accounted for and the likelihood of their realization in a particular GB source; and information on population abundance by GB type.
- WAV.1 (waveform modeling requirements)
- MMA.2 (joint analysis methods/tools for electro-magnetic and GW)
- SI.2 (population studies of GW-only GBs)

Output:

- DPE.5 (tools for detecting un-modeled signals)
- LAP.1 (low latency pipeline on “realistic” data)
- LAP.2 (alert generation)
- LAP.6 (search for un-modeled signals)
- DPE.2 (detection and parameter estimation of GBs)

- CAT (source catalogues)
- MMA.1 (exploration of multi-messenger science with LISA)
- MMA.2 (joint analysis methods/tools for electro-magnetic and GW)
- SI.2 (population studies of GW-only GBs)

1.8.7 List of projects (ongoing and short term)

- Literature review and identification of currently missing effects. Solicit community contribution via the AstroWG.

1.9 WAV.6: Stellar-origin black hole binaries

1.9.1 Overview & Goals

Stellar-mass BH binaries merging in the LIGO/Virgo band may be observable by LISA in their inspiral phase. Merger rates in the LIGO/Virgo band suggest tens/hundreds of such systems may be potentially detectable. However, sufficiently accurate waveforms are necessary to disentangle these sources from the noise, and to correctly estimate their parameters (particularly merger times and sky localization, which are crucial to alert ground-based interferometers, to test GR, and to assess the presence of possible electromagnetic counterparts).

The goals of this WP are to provide accurate and faithful SOBHB waveforms, to enable

- the detection of SOBHBs before merger, and alert ground-based GW detectors in advance;
- the retroactive identification of weak SOBHB inspiral signals in LISA data, based on merger signals detected by ground-based detectors;
- unbiased estimates of source parameters, so as to allow for multi-band astrophysical population analyses, tests of GR (e.g. vacuum dipole radiation) and prompt sky localization for electromagnetic searches.

1.9.2 Deliverables

- Analysis to determine the highest PN orders (in phase and amplitude) needed to provide unbiased parameter estimation for the expected astrophysical population of SOBHB, and provision of faithful GR waveforms.
- Method and code for producing long faithful precessing-spin inspiral-merger-ringdown GR waveforms for cross-band detection and parameter estimation.
- Method and code for producing parametrized waveforms allowing for deviations away from GR and for possible interactions with matter/massive perturbers.

1.9.3 Description of Work

Assessing the waveform model and code needs will depend on collecting existing inputs on the source populations: how many sources can we expect to detect and at which SNR level? What are the mass, spin and eccentricity ranges to cover? Most importantly, what are plausible eccentricity distributions and what is the maximal eccentricity that the waveforms need to cover? Important updates for the population of SOBHB will be given by the O3 run of LIGO/Virgo, while the expected distribution of eccentricities in the LISA band depends on the formation channel of these systems. Reviewing the literature could be done on a short timescale (<1yr).

Preliminaries studies by A. Mangiagli and coauthors have assessed the requirements in the PN order for SOBHB observations in the LISA band. The criterion used is a simplified one, relying on the unfaithfulness to estimate the importance of the waveform systematic error. The authors find a tail of events requiring 3PN waveforms, with the bulk of systems requiring 2PN waveforms. A subsequent extension fo the eccentric case found that, for small initial eccentricities $e \lesssim 0.1$, the 2PN order is required for terms e^2 and the Newtonian order for terms e^6. On the timescale of 1-3 yr, these useful results should be revisited by using Bayesian parameter estimation methods, and extended systems with higher eccentricity.

For the waveforms and instrument response of SOBHB, currently two code bases coexist, one developed by A. Klein and one by S. Marsat (implemented in the LDC code). On a short timescale (<1yr), it would be very useful to cross-check these codes. The first code still lacks the full instrument response while the second code lacks eccentric waveforms. On a longer timescale (1-3yr), those two codes should be integrated together.

We also want our waveforms to ultimately accomodate for modifications of the baseline GR templates, either of astrophysical origin or from modified gravity. A short-term objective (<1yr) will be to collect information about the modifications of GR signals that our codes and future analyses need to be able to cover. On a longer timescale (<5yr), we will need to implement these modifications in existing codes, in a flexible way.

Multiband observations, combining ground-based detectors and LISA, are a promising extension of the LISA science. We need to assess wether accuracy requirements change when considering multiband observations, that will require hybrid waveforms with both PN and NR information. Previous studies and tools could be revisited to include both bands, and extended to Bayesian analyses. This could be done in < 3yr.

1.9.4 Time-frame & workforce requirements

- < 1yr: comparison of existing codes, literature review for the population properties and the GR modifications to consider: 0.5 FTE years.
- 1-3yr: integration of codes with eccentricity with codes with the full instrument response, assessment of waveforms requirements with Bayesian tools, extension to multiband observations: 1 FTE × 2 years.
- 3-5yr:integration of the waveform codes, when ready, in the mission's pipelines: 1 FTE × 2 years.

1.9.5 Possible sub work-packages

None currently; to be reviewed.

1.9.6 Dependencies

Input:

- WAV.1 (accuracy requirements)
- WAV.3.1, WAV.3.2 (late inspiral and merger BHB waveforms)
- AstroWG (population properties of SOBHB)

Output:

- WAV.3.2 (post-Newtonian results)
- DAFT (common data analysis tools)
- CAT (Source catalogs)

1.9.7 List of projects

A list of projects is available at `https://tinyurl.com/lisa-sbhb-waveforms`

1.10 WAV.7: Cosmic strings and other burst-type sources

1.10.1 Overview and goals

A number of sources may be observed where the signal is represented by a short duration burst-type waveform. Examples include cosmic-string cusps or kinks and hyperbolic black-hole encounters. More speculative examples include so-called "Bosenova" collapse events, and oscillaton collisions. Preliminary models for some of these source types (in particular, cosmic-string cusps) have been developed in the past for use in mock LISA data challenges. This work package will fully develop, implement, and routinely review and update waveform models for all relevant burst-type sources.

1.10.2 Deliverables

- Tools to generate waveforms for each modelled burst-type source type.
- Waveform catalogues for burst-type sources.
- Publications reporting these.

1.10.3 Description of work

The work will involve the development of tools to generate waveforms for each burst-like source type. This is a relatively low-priority task, due to the more speculative nature of sources in this category and the relative simplicity of transient searches. The first priority (years 1-2) will be to conduct an initial review of all potential transient sources and their relevance to LISA. Further reviews will be conducted routinely (every 2 years), and additional potential sources will be added to the remit of the work package as they are identified. Specific tasks are as follows.

- **Cosmic-string cusps and kinks**: A generalized theory for both kink and cusp gravitational waveforms is in hand, and waveforms from simulation have been matched to waveforms from a generalized theory. A general code for producing kink and cusp waveforms given the kink or cusp shape and scale parameters is already available. Outstanding tasks:
    - Conduct a thorough literature review to take stock of extant cusp waveform models.
    - Develop the theory of kink waveform models to be on par with those for cusps.
    - Determine which existing simulation codes exist that can produce waveforms relevant to LISA. Adapt those codes the specific LISA data-analysis environment.
- **Other processes involving cosmic strings:** Existing cosmic string waveform models have focused on kinks and cusps, where the signal is well understood. This project will develop similar parametrized models for signals from non-cusp or kink signals from cosmic strings. Also, tools exist to produce waveforms from cosmic string collapse to a black hole [https://arxiv.org/abs/1808.06678], but may need to be adapted to the LISA data-analysis environment.
- **Hyperbolic encounters** of binary systems will produce a transient burst that may be observed by LISA under some circumstances. These sources fall into two primary categories: Extreme-Mass-Ratio hyperbolic encounters, and other hyperbolic encounters. Waveform models for the former are based on black-hole perturbation methods, and for the latter on Numerical-relativity methods. The initial task is to conduct a thorough review of available tools and identify areas where further work is needed.

- Waveforms from **Bosenova**: If bosonic clouds exist around black holes due to superradiant build up, they may undergo episodes of collapse due to self-interactions, so called "bosenova", analogous to those observed for Bose Einstein condensates in condensed matter physics. It has been shown (https://arxiv.org/pdf/1505.00714.pdf) that such bursts would have a potentially detectable amplitude, and began work to look for waveforms in the scalar boson case. This project will monitor continuing efforts in this area.
- Waveforms from **oscillaton collisions**: Black holes formed from collisions of oscillatons can produce distinct gravitational wave signals, which, at high compactness, can be more energetic than equivalent black hole mergers (https://arxiv.org/abs/1910.01950). The distinctness of the gravitational-wave signal allows for tests of the existence of exotic compact objects.

1.10.4 Timeframe and workforce requirements

All tasks are relatively low priority at the moment. Estimated workforce requirements:

- Waveforms from cosmic string cusps and kinks: 1 FTE year
- Waveforms from other cosmic-string phenomena : 1 FTE year
- Waveforms from cosmic string collapse to a black hole: 0.5 FTE years
- Waveforms from Extreme-Mass-Ratio hyperbolic encounters: 1.5 FTE years
- Waveforms from other hyperbolic encounters: 1.5 FTE years
- Waveforms from Bosenova: 1 FTE year
- Waveforms from oscillaton collisions: 1 FTE year

1.10.5 Possible subpackages

1. WAV.7.1 Cosmic Strings
2. WAV.7.2 Hyperbolic Encounters

1.10.6 Dependencies

Input:

- WAV.1 Waveform Accuracy Requirements
- SI.5 Characterisation of Backgrounds
- WAV.2.2 EMRI Waveforms
- WAV.3.1 (Numerical relativity can compute hyperbolic encounters)
- DPE.4 Detection and parameter estimation of EMRIs

Output:

- WAV.8 Waveform interface and tools
- LAP.1 Create low latency pipeline to run on "realistic" data
- DPE.5 Analysis of detected unmodelled events
- DPE.9 Detection of modelled transient sources

These dependencies are described diagrammatically in https://wiki-lisa.in2p3.fr/pmwiki/uploads/LSG/flowchart17.pdf.

1.10.7 List of projects (ongoing and short term)

- Review literature of cosmic-string cusp models; identify required work.
- Develop theory of kink waveform models.
- Review literature of binary hyperbolic encounters; identify required work.

1.11 WAV.8.2: MBHB waveform interface and tools

The purpose of this work package is to lead from the waveform development effort coordinated by WAV.3 to the production of computationally efficient template codes that are integrated into the LISA software environment with well defined interfaces, and are appropriately tested and documented. Two main frameworks exist for constructing computationally efficient waveform models: (1) *Reduced-order models (ROM)*, built either from catalogues of numerical relativity waveforms (often referred to as NR-Surrogate models) or from effective-one-body models, and (2) *Phenomenological waveform models*, based on piecewise closed-form expressions for the amplitude and phase of spherical-harmonic modes. Both approaches rely on catalogues of numerical relativity waveforms, post-Newtonian and effective-one-body results, and qualitative insight into the phenomenology of the waveforms that are modelled. The development of MBHB EOB and phenomenological waveform models across the entire relevant portion of the parameter space, compliant with the accuracy requirements set by WAV.1, is the goal of WAV.3.2.

Fast waveform models have so far only been built for quasi-circular and aligned-spin binaries. For such systems multi-mode frequency domain EOB-ROM and phenomenological models are available, as well as time domain NR-Surrogates. In the precessing, quasi-circular sector, only NR-Surrogates have so far been calibrated against precessing NR waveforms, and only phenomenological frequency domain models provide fast multi-mode precessing waveforms across the whole frequency spectrum.

The goal of this work package is to extend the availability of fast waveform models across the parameter space, in parallel to progress in work package WAV.3.2. The expectation is that the further development of the three main branches (EOB-ROM, Phenomenological, NR-Surrogates) will increase the cross-pollination between these approaches. Beyond the construction of fast model implementation this will also require the development of unified and flexible interfaces, documentation of the models and tests, and the implementation of waveform reviews that take into account practical data analysis applications, as is already common in the LIGO-Virgo collaboration.

1.11.1 Deliverables

1. Implementation of the IMRPhenomX-model in LISA software framework which improves on the currently used IMRPhenomPv2 in evaluation speed, accuracy and availability of higher harmonics. Documentation which also reports testing and optimization with realistic LISA response functions.

2. Extension of deliverable 1 to EOB-ROM and NR-Surrogate models.

3. The construction of new EOB-ROM and NR-surrogate models (based on WAV.3.1+2), including eccentricity effects.

4. Optimization of the models and the LISA response for these models, including hardware acceleration.

5. Guidelines for waveform review procedures, software tools, and the actual reviews.

6. Implementation of practical strategies to accelerate data analysis applications of waveform models, e.g. through acceleration of match calculations in a broader sense (e.g. using reduced order quadrature, multi-banding interpolation or alternative methods), joint tuning of models and parameter estimation pipelines, hierarchical model versions that allow tuning of accuracy versus speed, or entirely new ideas. This will need to be developed jointly with data analysis work packages and focus on waveform aspects.

7. Continuous adaptation of deliverables 1-6 to new waveform models.

1.11.2 Description of work

The first *short-term* priority is to integrate the IMRPhenomX family into the LISA software environment and test evaluation speeds of the LISA response. This will also provide a mechanism for inclusion of further waveform improvements as they become available. Specific tasks include the development of a compatibility package that allows to compile LALSuite waveform models as standalone code with C and Python interfaces; testing and optimization with realistic LISA response functions; and conducting rigorous accuracy evaluations. Work on integrating currently available EOB-ROM and NR-Surrogate models can proceed at least partially in parallel, depending on available resources. A GPU-accelerated version of the non-precessing PhenomHM model is already available, and an extension to the current generation of precessing multi-mode phenomenological models is foreseen for the near future. A key issue at this stage is the provision and documentation of unified waveform interfaces, which are foreseen to be based on recent work on waveform conventions aimed at ground-based detectors, including extensions arising from the more complex LISA detector response.

The construction of efficient waveform models across the plausible MBHB parameter space within the next decade constitutes a formidable challenge and will benefit from a higher level of coordination. An important *mid-term* goal is to develop a more detailed model upgrade plan (in the form of a living document), which highlights opportunities for joint work between groups working on different modelling approaches, and addresses the final challenge to provide robust and computationally efficient generic MBHB waveforms (eccentric and precessing). A realistic development plan depends to some degree on achieving the short-term deliverables (1 and 2), and on recent work to construct the first (and rather new) generation of multi-mode precessing waveform models. In parallel, deliverables 1 and 2 need to be followed up by developing review procedures, and a code base for test codes etc., taking advantage of tools developed for the construction of individual waveform models. Waveform reviews are foreseen to act as a central hub for synergies between different branches of waveform development.

The time scale of constructing new EOB-ROM and NR-Surrogate models will depend on progress in WAV.3.1 and WAV.3.2. Improved insight into waveform phenomenology is needed when extending models to eccentric and eccentric+precessing binaries, in particular to reduce the number of numerical relativity simulations required to explore these higher dimensional parameter regions. The optimization of waveform models and data analysis applications include:

- *Code Optimisation*
  - Accelerated interpolation for multi-banding.
  - Accelerated evaluation of special functions.
  - General code optimisation.
  - GPU implementations.
  - Tuning of multi-banding threshold parameters (tradeoff of accuracy and speed).
- *Development of hierarchical modelling strategies*

  Waveform models do not necessarily have to satisfy accuracy standards that are appropriate for the loudest events across the whole parameter space. Instead, local models may be calibrated for the loudest events, which are more accurate than models with a larger validity range across the parameter space.
- *Tunable parameters in waveform models*

  Optimisation of computational efficiency needs to be applied to data-analysis workflows, not only to waveform evaluation. Tunable parameters in waveforms, which trade between speed and accuracy, can be dynamically adjusted, e.g. accuracy could be relaxed in the burn-in phase of a parameter-estimation simulation, or adjusted as a function of SNR.

The *long-term* goal is summarized by deliverable 6: the continuous adaptation and optimization of models and their integration into the LISA data analysis workflow.

1.11.3 Timeframe and workforce requirements

- Development of a compatibility package for existing waveforms of the LIGO Algorithm Library (LAL), 0.5 FTE-years.
- Testing and optimization with realistic LISA response functions, 0.5 FTE-years.
- Extension to ROMs and NR-Surrogates in the time and frequency domains, 0.5 FTE-years.
- Initial optimization including GPU implementation of current models 1 FTE-year.
- Implementation of first waveform reviews. Will require volunteers from several research groups.
- Development of strategies to accelerate waveforms specifically for data analysis applications (deliverable 6), 0.5 FTE ×2 years, continuous upgrades afterwards.

FTE numbers are estimates of minimal requirements, further community involvement is expected. The timescale of the routine incorporation of new waveform models (deliverables 3 and 7) will depend on the progress in WAV.3.2 and will require a *major effort and commitment from several research groups at least for several years, at least 2 FTE per year.*

1.11.4 Possible subpackages

None currently; to be reviewed.

1.11.5 Dependencies

Input:

- Accuracy requirements from WAV.1,
- NR waveforms from WAV.3.1 and public catalogues,
- Improved analytical waveforms from WAV.3.2, e.g. spinning post-Newtonian eccentric waveforms as a basis for modelling,
- Models for LISA instrument and/or TDI response (LDPG)
- Representation and interface for data analysis algorithms, including tunable parameters (from DAFT).

Output:

- WAV.1 (waveforms for accuracy studies),
- WAV.3.3 (base waveforms for non-GR modifications),
- WAV.3.1 (feedback on where NR waveforms are most beneficial for model calibration),
- WAV.3.2 (feedback on requirements for further analytical developments).
- DAFT
- LLA
- DPE

1.12 WAV.8.3: EMRI Waveform interface and tools

1.12.1 Overview and goals

The ongoing gravitational self-force program will produce EMRI *waveform* models that are highly accurate but computationally intensive, and hence ill suited for direct use in data analysis algorithms. These must be converted into or approximated by *template* models that are i) efficiency-oriented, ii) end-to-end from source parameters to detector response, and iii) extensive in their description of both intrinsic and extrinsic effects. The semi-relativistic “kludges” are existing examples of template models, but are still suboptimal in terms of both speed and accuracy. Computational strategies for comparable-mass binaries, such as the construction of reduced-order-modelling surrogates, cannot be naively applied to the EMRI problem either. This work package addresses the development of efficient template models that are tailored to the unique nature of EMRI signals, as well as the source-specific analysis techniques that will be used to detect and characterise such signals. The main goals can be summarized as follows:

- Interface kludge models with the present data analysis framework through the LDC, placing emphasis on generalisability to future work.
- Identify the optimal strategy or strategies for interfacing template models with new data analysis algorithms, and coordinate development efforts in both areas.
- Construct computationally efficient and fully relativistic template models.

1.12.2 Deliverables

- Fast (sub-sec) and accurate (sub-rad) template models, including some combination of:
  - Integrated treatment of resonances
  - Non-GR and environmental effects
  - Direct generation in some reduced representation
  - Integrated full or approximate TDI response
  - Parallelised implementation for high-performance computing
- Technical documents and/or papers reporting these models.

1.12.3 Description of work, timeframe and workforce requirements

- **Kludge models for LDC and science interpretation.** Implementation and maintenance of kludge models—specifically, the augmented analytic kludge (AAK)—for interim work on generating and analysing LDC data sets, and on science interpretation. Task is largely completed.

  Specific Deliverables: Standalone C/C++/Python implementation of AAK, including features such as approximate TDI response and native GPU version. Interface to LDC code.

  Timeline: AAK will be maintained until kludges are phased out (over the next few years).

  Estimated workforce requirements: 0.05 FTE, each year

- **Fast framework for fully relativistic waveforms.** Identify and develop computationally efficient methods of generating individual waveform components (self-forced inspiral and phase trajectories, and instantaneous mode amplitudes).

  Specific deliverables:

  - Methods and code for interpolating generic Kerr self-force

  - Methods and code for fast evaluation and summation of Teukolsky mode amplitudes, e.g., neural-network interpolation, high-order PN expansions
  - Implementation of combined framework, possibly with parallelisation

  Timeline:

  - Self-force interpolation: Requires generation of first-order Kerr data; initial investigations and preparatory work could be done over the next 1–2 years.
  - Mode amplitudes: Two methods being developed in parallel, and are potentially complementary. Neural-network interpolation is for Schwarzschild eccentric first, but should be available within next 3 months. 5PN expansions are for generic Kerr (but with limited validity), and should be available within next 3–6 months.
  - Combined framework: Requires all other components to be available; could take 2–5 years.

  Estimated workforce requirements: Self-force interpolation: 0.5 FTE ×2 years; mode amplitudes: 0.5 FTE ×2 years; combined framework: 2 FTE ×4 years.

- **Integrable resonance models.** Develop an efficient modular treatment of transient and tidal resonances. The former is a priority, as it is prerequisite for completion of previous task (fast framework for GR waveforms).

  Specific deliverables:

  - Methods and code for evolving through resonance jumps, including schemes for smooth switching between long- and short-term orbital evolution
  - Methods and code for interpolating over resonance jumps (speculative), assuming negligible loss of accuracy
  - Integration of transient and tidal resonance into above fast waveform framework

  Timeline:

  - Transient resonance models: Requires self-force interpolant, but could rely on toy self-force model first; initial investigations and preparatory work could be done over the next 1–2 years.
  - Tidal resonance models: Lower priority. Investigation of prevalence, impact, and ad hoc approaches to data analysis is underway, and should be completed within next 6–12 months.

  Estimated workforce requirements: Transient resonances: 1 FTE × 2 years; tidal resonances: 0.25 FTE × 4 years

- **Compressed or sparse waveform representations.** Computational cost in EMRI data analysis is dominated not only by waveform generation, but also by operations on the lengthy vectors. This task addresses the direct generation of waveforms in compressed or sparse representations.

  Specific deliverables:

  - Code for generating waveforms directly in compressed (local) representations: ROM surrogates + reduced-order quadratures, ROM with neural networks
  - Methods and code for generating waveforms directly in sparse (global) representations: Frequency domain (traditional), discrete Fourier and/or short-time Fourier transforms (exact), wavelet transforms

  - Compressed or sparse representations of above fast waveform framework

  Timeline: Task has lower priority than waveform generation. Compressed representations are unlikely to scale up to any significant fraction of EMRI parameter space, but could be explored for localized analysis applications over the next 1–2 years. Sparse representations are being investigated, and some results should be available within next 6–12 months.

  Estimated workforce requirements: 0.25 FTE × 4 years

- **Fast TDI response models (EMRI-specific).** Application and possible adaptation of TDI response models to EMRIs, and assessment of their adequacy in terms of both speed and accuracy.

  Specific deliverables:

  - Fast and accurate EMRI-specific TDI response model
  - Integration of TDI response model with above fast waveform framework
  - Assessment of overall template model performance for data analysis

  Timeline: Task has reasonably high priority, since existing LDC implementations of approximate TDI response seem to lack speed and/or accuracy (even in the case of MBH waveforms, with much fewer harmonics). Should ideally be completed within next 6–12 months, but will likely be delayed to 1–2 years due to lack of manpower.

  Estimated workforce requirements: 1.0 FTE × 2 years

1.12.4 Possible subpackages

None currently; to be reviewed.

1.12.5 Summary of Dependencies

- From WAV.1: Accuracy requirements
- From WAV.2.2: Models or data for generic Kerr self-force to second order, and/or for inspiral and phase trajectories to post-1-adiabatic order
- From WAV.2.2: Data for instantaneous mode amplitudes to adiabatic order, assuming this is accurate enough
- From WAV.2.3: Models for non-GR and environmental effects
- From LDPG: Models for LISA instrument and/or TDI response
- From LAP.4: Representation and interface for data analysis algorithms

1.12.6 List of projects (ongoing and short term)

- Completion of kludge models for LDC and science interpretation
- Demonstration of fast waveform framework (with neural-network amplitudes) for eccentric orbits in Schwarzschild
- 5PN amplitudes for generic Kerr inspirals
- Preliminary investigation of tidal resonances
- Preliminary investigation of sparse representations
- Preliminary investigation of fast TDI response models

Chapter 2

DAFT – Data analysis framework and tools

2.1 DATA ANALYSIS FRAMEWORKS AND TOOLS

This section describes a number of work packages and deliverables associated with data analysis tools in general. In particular, an overarching goal of this work package is to form a common framework for testing data analysis methods and prototyping the data analysis pipelines. The main aim is production of level 2 (L2) and level 3 (L3) data sets and partially testing alternative approaches to production of level 1 (L1) data sets. The developed tools will also serve to analyse instrument performance and extract scientific conclusions from LISA data. Wherever possible, we will aim to produce common tools with broad enough interfaces to allow them to be used in multiple contexts, thus minimising duplication and easing maintenance and testing.

2.1.1 Overview and goals

In order to build a consistent and modular data analysis pipeline, all the processing codes have to be implemented in a common framework. This framework should also be the same as the one used for simulation and for preprocessing tasks, given their high level of interaction with the scientific data analysis. The aim of this framework is to ease the interoperability between the various data-processing steps, and ease the execution of the pipeline on arbitrary infrastructure. While its precise functionalities have to be defined in the design phases of the mission along with the DPC, some standard tools can be provided to the community at an early stage to start building a collaborative environment.

We need to identify and build common and key data-analysis algorithms and tools such as Fourier series analysis tools, filtering tools, sampling, optimization and visualization tools. A common reference on those low- or intermediate-level libraries would avoid duplication of efforts to develop them, and ease the comparison of the results obtained by different algorithms at higher level. In order to fulfill its objectives, the library should be modular, easy-to-use, and computationally efficient.

Going one step down: we need to create flexible, efficient, and extensible formats that implement interfaces among data-analysis pipeline elements, and between data-analysis and waveform-generation codes. We need to identify a format to describe astrophysical populations, keeping commonality in the notations and in conventions across various binary systems. We need to leverage future-proof standards (e.g., HDF5, possibly FITS) that have broad adoption, abundant read-write libraries and guarantee of future support. The selected formats should include the provenance and tracking information to ensure provenance of results. A set of tools and methods should also be developed to identify and treat various non-stationary features in the data (gaps, noise fluctuations, lines, glitches).

Last but not least, version control (presumably via git) and documentation are extremely important for the dissemination and consolidation of the tools and methods, and for the usability of the developed framework.

2.1.2 Deliverables

Tools and pipelines that are already available are described below. Here we outline the overall (achieved, on-going, or planned) deliverables, from the top level down:

- A pipeline (prototype) for running data-analysis methods sequentially or in parallel.
- A pipeline to assess the scientific performance of particular LISA configurations.
- Methods (prototypes/proofs of principle) to deal with noise artifacts (gaps, glitches, noise fluctuations).
- A framework to assemble and run pipelines.
- Tools to perform (fast) parameter estimation, to interface with waveform generators, to generate fast TDI responses for various sources, to interface with astrophysical populations of GW sources, to assess GW foregrounds.
- Data containers to store and propagate data products and their processing histories.
- Publicly available git repositories of code examples and documentation.

Work on these pipelines will be organized in six workpackages:

	DAFT work packages	Priority
DAFT.1	Constants (fundamental and LISA-related)	-1
DAFT.2	Data formats and interfaces	0–1
DAFT.3	Data analysis tools	0–1
DAFT.4	Figures of merit for LISA performance	0
DAFT.5	Data-analysis framework prototypes	1–2
DAFT.6	Noise artifact characterization	0–1

These work packages have parallels in the LDPG WPs 1, 2, and 5, so efforts should be harmonized and coordinated.

2.1.3 Description of work

A detailed description of work is given within the description of each project.

2.1.4 Timeframe and workforce requirements

Most of the tasks should be completed before adoption. Given the interdependence of all the aforementioned objectives they share a very high priority—they are "needed now." However, given the limited person-power involved, we will follow an iterative approach. Specifically, we will adapt or build the most urgent tools, and build semi-automated pipelines to deploy them (e.g., as done in assessing low-frequency performance and minimum mission lifetime). We will then update and enhance tools and pipelines working towards an optimal and automated implementation for general use.

Given the urgency of the tasks, the workforce should not be very large at the start and gradually increase. We assess that 5-6 FTE (full time equivalent) would be optimal at the initial stage. The current distribution of the FTE across each project will be given below.

2.1.5 Dependencies

The computational framework will be important for most WPs, since it will ease code development and provide conventions, data formats, and tools. The tools and pipelines will require the following interfaces and inputs:

- A pool of GW models (waveforms) for all sources.
- Astrophysical population models (as probability distribution functions or databases of realizations).
- LISA performance in the format of the noise level (PSD and cross-noise spectral density), as provided by the LISA Performance working group.
- Operational requirements such as mission time, downlink cadence and latency, schedule of maintenance, etc.
- LISA orbit details and parameters.

2.1.5.1 Interaction with LISA Data Challenge

Most code development is currently happening to produce datasets for the LISA Data Challenges. At this stage, code is changing quickly, and it is mostly useful as a playground before further specification leading to implementation by software engineers.

2.1.6 Work packages

2.1.6.1 DAFT.1: Fundamental and LISA-related constants (priority: -1)

We need to adopt a mission-wide set of constants, both fundamental (describing the Universe) and project-related. This project has a very strong overlap with LDPG activities, and it is ongoing, with the involvement of Uwe Lammers, Antoine Petiteau, Maude Le Jeune, Michele Vallisneri and Stas Babak. The current approach is to adopt the database of constants available at ESA and update it on a regular basis as needed.

2.1.6.2 DAFT.2: Data formats and interfaces (priority: 0–1)

2.1.6.2.1 Description: We need to define and implement data models and data formats suitable for the storage and propagation of data (of all levels) and the corresponding metadata. The definition should be very clear for publicly available data products, but could be looser for intermediate analysis files.

The LISA Data Challenges have already employed (or at least considered) several data formats, with data models defined somewhat implicitly. The formats include HDF (to store simulated data and metadata such as configuration, source parameters, code version), JSON (to submit data-challenge entries), FITS (to produce or store sky maps). At a lower level, strain data requires very efficient specialized formats such as the MLDC `FrequencyArray`, or PyCBC's `TimeSeries` and `FrequencySeries`. In addition, tools are in development for to extract, build, store, and publish L3 products such as catalogues.

2.1.6.2.2 Deliverables: We need to issue a recommendation on data models and formats to implement and support within DDPC—of course this will not be the final word on formats, which can be added or dropped later.

We also need to define and develop interfaces to GW waveforms and to astrophysical populations:

- define conventions and develop tools for all types of binaries, as close as possible to those used in the ground-based GW community (this item is already complete within the LDC but can be iterated further);
- define and implement interfaces to the waveform models produced by WAV WG;
- define standards for the application of the LISA response function to waveforms (see corresponding item in DAFT.3);
- define interface and naming conventions for astrophysical populations of GW sources, and develop the corresponding tools. Prototypes exist in the MLDC project;
- develop tools for source catalogues and associated visualizations. The US LISA Study Office has a working group devoted to this activity.

2.1.6.2.3 People involved in this project: Stanislav Babak, Ian Harry, Michele Vallisneri, Antoine Petiteau, Maude Le Jeune, Tyson Littenberg.

2.1.6.3 DAFT.3: Data-analysis tools (priority 0–1)

We need a variety of easy-to-use data-analysis tools for common use cases. Those tools will be used in many different projects, should be made publicly available ASAP (this is very important for the development of the LISA community), and they should be documented with a clear description of their interface.

2.1.6.3.1 Deliverables

- Tools to simulate instrument noise. Prototypes exist in the legacy MLDC project (`https://gitlab.in2p3.fr/stas/MLDC`) and in its LDC evolution (`https://gitlab.in2p3.fr/LISA/LDC`).
- Modules that apply the LISA response function to waveforms; there will be slow and fast methods with various levels of approximation. Working prototypes exist in the MLDC and LDC repositories.
- Tools for computing the analytic noise PSD for various TDI channels (based on LISA noise models), and to evaluate PSD empirically based on data. Both kinds are currently available in the MLDC and LDC repositories.
- GW search tools, both WP-grown or by the LISA community (e.g., with LDC entries), then maintained internally. In addition, searches developed for other GW experiments could be usefully ported to LISA.
- Parameter-estimation tools that produce Fisher-information-matrix estimates and sample Bayesian posteriors (e.g., with MCMC or nested samplers). We have developed some of those tools (see `https://gitlab.in2p3.fr/petiteau/scienceperfs_evalfom`) and also use general-purpose tools that are publicly available (see, e.g., `http://mattpitkin.github.io/samplers-demo/pages/samplers-samplers-everywhere`).
- LISA-specific visualisation tools, or configurations of general-purpose tools (e.g., for corner plots, KDEs, . . .).
- Tutorials. We have several within the LDC, which should be extended, documented, and archived. Tutorials are most useful when they work transparently, hence the need to rely on a standardized environment distributed as a Docker or Singularity image, or available from a DDPC Jupyterhub.

As it is obvious from this list, many tools are already available, but they are scattered across many projects. We need to identify use cases and harmonize the interfaces of those tools, and collect them in a single place so they are available as submodules to various projects.

2.1.6.3.2 People involved in this project: Maude Le Jeune, Sylvain Marsat, Antoine Klein, Alexandre Toubiana, Nikos Karnesis, John Baker, Antoine Petiteau, Stas Babak, Tyson Littenberg, Michele Vallisneri.

2.1.6.4 DAFT.4: LISA performance–figure of merits (priority 0)

During the definition and development of the mission, different configurations will be proposed, which will delve increasingly deeper into the details of the instrument and the pre-processing. For each configuration, a quick evaluation of the science performance will be needed. A pipeline or set of pipelines to achieve this estimation must be developed urgently.

2.1.6.4.1 Objectives

- Quickly estimate the science performance of a given instrument configuration with respect to each observation requirement defined in the Science Requirement Document.
- Refine and update the precision in the evaluation of science performance, integrating in a compact way the output of various studies.
- Emphasize automation, traceability, and reproducibility, given that decision will be taken based on this input.

2.1.6.4.2 Deliverables

- Well defined figures of merit for each science objective.
- A pipeline or a set of pipelines that can provide a "complete" characterization of science performance for a given configuration in a few days or less.
- A metric for assessing the result of the evaluation (e.g., map expected SNRs and uncertainties to colors, with red = failure, orange = risk of losing science, green = ok, blue = high performance, violet = too many sources, need to check data-analysis capabilities!).
- A document complementary to the SRD (and therefore written with the SST) defining the quantities used for assessing science performance, the rationale behind them, and their current implementation.

2.1.6.4.3 Dependencies

- The implementation and evolution of this project depends strongly on the waveform models that are available: for a fixed instrumental configuration, we might have different outcome depending on the sophistication of GW models.
- We also require access to fiducial catalogues of astrophysical sources in form of realizations we can sample from, or of probability distributions (which could be non-informative).
- We need include waveform systematics and astrophysical uncertainties.

The requirement for automation and standardization calls for close collaboration with LDPG.

2.1.6.4.4 People involved in this project: Maude Le Jeune, Sylvain Marsat, Antoine Klein, Alexandre Toubiana, Nikos Karnesis, John Baker, Antoine Petiteau, Stas Babak, Tyson Littenberg, Henri Inchauspe, Alberto Sesana.

2.1.6.5 DAFT.5: Data-analysis framework prototypes (priority 1–2)

We need to investigate, prototype, and make recommendation about the recommended framework that will be used to configure and run data-analysis tools and pipelines. (Nevertheless, Consortium and community members may want to use their own familiar ecosystems, interfacing with LISA tools. That is OK, too.)

2.1.6.5.1 Steps and deliverables: Most of this work will be derived from LDC activities.

- Assemble the tools used in the LISA Data Challenge and identify common parts. Devise a common interface which can be easily retrofit in most of the tools.
- Assess existing frameworks in the GW community (e.g., Bilby, PyCBC, Enterprise, ...): determine if they can be adapted to LISA data analysis, or if we can borrow the best features of each to assemble a LISA-specific framework.
- Develop a prototype framework, light and flexible enough to be run on a single laptop and on a cluster.

2.1.6.5.2 People involved in this project: This work project has almost 100% overlap with LDPG activities, therefore it should share the same set of people who work on the development and implementation of the data analysis pipeline in LDPG. Currently we have the following people: Alberto Vecchio, Ian Harry, Stanislav Babak, Michele Vallisneri, MAude Le Jeune, Antoine Petiteau, Sylvain Marsat, Tyson Littenberg, Neil Cornish.

2.1.6.6 DAFT.6: Noise artifacts (priority 0–1)

2.1.6.6.1 Overview and goals: Previous studies have assessed the impact of design tradeoffs such as arm length, mission duration, orbit, and noise levels on science output. New studies are needed that go beyond the idealized approximation of stationary, Gaussian instrument noise. Sub-projects that will have a large impact on mission configuration and performance may concern:

1. data gaps,
2. stochastic noise non-stationarity,
3. spectral lines,
4. instrumental transients or “glitches”.

This study heavily relies on the experience acquired on the LISA Pathfinder data, which was observed to be prone to these types of artifacts.

2.1.6.6.2 Objectives

- Quantify the impact of data gaps on the science performance.
- Come up with reasonable predictions for the number, duration, and character of unplanned data gaps and disturbances.

- Study the impact of the different scenarios for data gaps due to spacecraft maintenance, and develop an optimal approach to schedule it.

- Develop methods to mitigate the impact of the gaps in the data.

- Assess the impact of non-stationarities and non-Gaussianity of stochastic noise, both instrumental and astrophysical. Develop simulation tools and methods to mitigate impact.

- Assess the impact of spectral lines. After analyzing the nature of the lines (stochastic, deterministic, or both), develop tools to reproduce them synthetically.

- Develop data analysis methods to mitigate the impact of spectral lines.

- Assess the impact of glitches.

- Develop detection algorithms to characterize the statistics and shape of instrumental glitches in LISA Pathfinder.

- Taking LISA Pathfinder glitches as examples, develop tools allowing for the artificial injection of "glitches" in LISA measurement simulations, and assess our ability to mitigate their impact on science performance.

- Develop methods to measure correlations between "glitches" and other instrument channels, which the goal of gaining insight into the nature of glitches.

2.1.6.6.3 Deliverables: For each of the four sub-topics listed in Sec. 2.1.6.6.1, deliverables will include:

- Software tools to generate synthetic artifacts in LISA data based on the best available information to date, and in particular on LISA Pathfinder measurements.

- Software tools to detect of artifacts in measured data.

- Software tools to mitigate the impact of data artifacts and disturbances.

- Extending existing software tools to measure the impact of data disturbances on science, focusing on the precision of GW-source parameter estimation.

- Software tools to study the physical nature of artifacts, by using correlations with other channels, or tracing their propagation in the instrument.

2.1.6.6.4 Description of work: Here we describe the major steps needed to achieve the goals stated in Sec. 2.1.6.6.1. The steps are the same for each data disturbance, regardless of their nature.

1. Analyze the timescale and statistical characteristics of the data artifact, based on the most reliable data currently available (example: LISA Pathfinder measurement, other previous space missions, design information, etc.).

2. Develop a statistical model describing the observed data disturbance. This model should be general enough to account for deviations from the characteristics initially assumed.

3. Implement a time-domain simulator of the data disturbance based on the developed model. Test it by comparing its outputs to available data. Integrate it with a simulator (such as LISANode) which is used for generation of the astrophysical signals in the realistic noise.

4. Assess the impact of data disturbances on science performance prior to mission launch. We will conduct realistic assessments through simulations. We will inject various gravitational-wave sources in two sets of synthetic time series: i) time series affected by disturbances, and ii) time series without any disturbance other than Gaussian stationary noise. We will perform parameter estimation using standard Bayesian techniques and compare the posteriors.

5. Implement a modified likelihood framework accounting for data disturbance designed for data analysis purposes. Apply this adapted framework to the parameter estimation conducted in the previous step, and assess the possible improvement on recovered parameter precision.

6. Implement techniques to detect the artifacts quickly and classify them for the possible future study of their physical nature.

7. Study the impact of the artifacts related to the design choices for the spacecraft architecture. This is especially important for gaps.

8. Write scientific papers and technical notes summarizing results.

2.1.6.6.5 Timeframe and workforce requirements Some preliminary studies were already completed during Phase A, and informed tradeoff choices. This project is time-iterative: we have to revisit the impact of noise artifacts as we advance on the data analysis methods and instrumental study. In this project we also rely on the tools and experience of mitigating similar problems gained in the ground-based GW community and in other projects.

2.1.6.6.6 Dependencies

- Waveform models.
- Tools for assessing instrument/mission design choices and scientific performance tools.
- Very strong inter-dependence with the Low latency pipeline.
- Data analysis tools and methods developed under "idealized" Gaussian noise assumptions.

2.1.6.6.7 On-going work Here we list the tasks which are already under investigation, as well as tasks that will start in the near future:

- Assessment of the distribution of glitch parameters based on the data from LISA Pathfinder.
- Glitch model that can be used in the simulation of the LISA data.
- Study of optimal schedule for the gaps in the data due to the spacecraft maintenance.
- Methods to mitigate the gaps in the data analysis.
- Methods for parameter estimation robust to non-stationarities in the noise.
- Methods to disentangle between the glitches and the astrophysical signals.
- Studies of the physical nature for the glitches which were observed in the LISA Pathfinder data.
- Studies of the propagation of the glitches in the LISA dynamics in order to understand their appearance in the different channels and understanding their origin.

2.1.6.6.8 People involved in this project Natalia Korsakova, Jacob Slutsky, Nikos Karnesis, Eleonora Castelli, Jean-Baptiste Bayle, Matt Edwards, Christine Simpson, Ollie Burke, Lorenzo Sala, Henri Inchauspe, Quentin Baghi.

Chapter 3

LAP – Low-latency analysis pipelines

Certain types of LISA source may be visible to electromagnetic telescopes, which means we need the capability to rapidly identify source candidates in the instrument data so that alerts can be sent out to EM partners for follow-up. In addition, there is good scientific motivation for trying to detect the gravitational wave emission generated during the merger phase of the system. A mechanism must be in place to trigger protected observing periods in advance, to ensure the existence of good quality data for the science analysis. Understanding the performance of the instrument in real time is also important, so that the general quality of data can be checked and any problems on the satellite identified quickly. The tools in this work package are designed to generate and distribute alerts by monitoring the LISA data in real time, as well as monitoring the instantaneous data quality from the instrument.

WP	Description	Priority
LAP.1	Create low latency pipeline to run on “realistic” data	3
LAP.2	Alert generation for EM observatories	3
LAP.3	Trigger generation from GW signals	2
LAP.4	Generation of data quality metrics and flags	2
LAP.5	Source-based observatory diagnostics	2
LAP.6	Search and classification for unmodelled signals	2
LAP.7	Assessment and triggering of protected periods	1

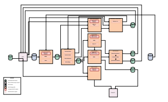

Figure 3.1: Schematic representation of the low latency pipeline.

3.1 Work Package LAP.1: Create low latency pipeline to run on ‘realistic’ data

3.1.1 Overview and goals

The LISA instrument will produce an evolving data set, and the data analysis will likewise need to produce an evolving fit for the many signals in the data. The goal is to build, run and test several different pipelines in order to explore as many options as possible.

The LISA instrument will produce an evolving data set, and the data analysis will likewise need to produce an evolving fit for the many signals in the data. Low latency, ”quick-look” analyses that fold in the latest data are vital for monitoring the instrument performance and generating alerts for possible electromagnetic follow-up of transient signals. The analysis will need to be able to handle gaps and data disturbances, and characterize the instrument noise.

3.1.2 Deliverables

This WP is meant to combine the pipelines for the different astrophysical sources and insure its performance on the realistic non-stationary data in the presence of the noise artefacts.

- Continuous updates on the noise characterisation
- Pipeline for source identification. Initial solution for the global fit
- Refined localization of black hole mergers
- Rapid identification of transient signals

3.1.3 Description of work

This work package is dedicated to combining the components of low latency pipeline into the consistent analysis and ensuring its performance on the realistic data with non-stationary noise and noise artefacts. The analysis will need to be able to handle gaps and data disturbances, and characterize the instrument noise. The general flow of the pipeline will have to follow the preliminary design including, but not restricting to, the following modules: Noise characterization, Source-based Diagnostics, Transient Search, Transient Updates, Targeted Analyses, Data/Detector Characterization etc (see Figure 3.1).

The steps which are needed to achieve this goal will be:

- Combine pipelines for different sources;
- Test the performance of the pipeline on the realistic data in the presence of realistic noise (have to be able to generate realistic noise);
- Test alert generation ;
- Low-latency noise characterisation and diagnostic of the observatory.

3.1.4 Timeframe and human resources requirements

- End of Phase A: requirements document and preliminary versions of pipeline components;
- Mission adoption: working version of the pipeline;
- Closed to the launch of the mission: The pipeline will have to run at SOC.

3.1.5 Possible subpackages

- Noise characterisation in the presence of the signals;
- Updates of the fit;
- Updates on detector characterisation.

3.1.6 Dependencies

- Waveform model (WAVWP)
- Fast waveform generation (WAV1.7)
- Instrument performance monitors and data quality (DAFT.4, DAFTWP.8)
- WP9 ”Noise artifacts” in the Simulation Working group – for the experience and approaches of working with the noise artefacts
- Instrument response modeling (LDPG, Simulation working group)
- timulation working group – for the generation of the realistic noise
- Fast instrument response. *Is there such a group?*

3.1.7 List of projects

- Noise characterisation in the presence of signals;
- Prototype the pipeline.

3.2 Work Package LAP.2: Alert generation for EM observatories

3.2.1 Overview and goals

Rapid alerts are a common part of every space mission, experiment or ground observatory being the central part in a multi-messenger approach to study the Universe. To maximize collaboration with the wider astronomy community new and updated LISA sources must be rapidly and predictably communicated with EM observers. For short-lived transients and in the late stages of MBHB mergers, low-latency source characterization and localization tools to get EM observers on source with minimal delay are of paramount importance.

Moreover, for some of the continuous compact binaries (exceptionally well resolved, verification binaries etc) we will produce catalog at smaller cadence than the usual catalogs.

3.2.2 Deliverables

- Database of potential follow-up experiments and their classification based on the time lapse for their signal to pick up;
- Framework for the alert generation for the EM observatories (i.e. should it be publicly open, should we have contacts with dedicated observatories);
- Procedure to generate alerts;
- Requirements document and software for alert generation for EM observatories.

3.2.3 Description of work

Building on the previous experience, we plan to use the current expertise in order to create and implement a new rapid communication way for LISA.

- Collect all relevant details of the EM experiments, by elaborating a database of experiments capable to detect electromagnetic (from gamma-ray to radio) and also, non-photonic (e.g., cosmic rays, neutrino, etc.) signals that can counterpart the GW detection.

- Providing procedures to generate alerts and distribute them to the observatories;
- In order to provide efficient alerts for the important events we think it is important to develop a phone application based on the state-of-the-art smart technologies that can take alerts from the Cloud.

3.2.4 Timeframe and human resources requirements

- Successful algorithms developed for LIGO/Virgo can be adapted to the LISA case. Prototypes need to be available for time domain LDCs in ~ 1 - 2 yr;
- The agreement with the EM observatories should be done closer to the launch.

3.2.5 Possible subpackages

- Collecting and maintaining the database of relevant EM observatories;
- Tools for alert distribution.

3.2.6 Dependencies

- Significant overlap with Alert Distribution Tools DAFT.2;
- Depends on the product from the LAP.3 which will produce the triggers.

3.2.7 List of projects

- Database of potential follow-up experiments and their classification based on the time lapse for their signal to pick up (subproject underway by RO-LISA);
- Web and phone app for the alert generation;
- Based on the database of potential follow-up experiments provide an assessment study of the optimal technical possibility to set-up web alerts to them. Also test if setting a cloud solution will be the best choice;
- Design of a phone application for alert distribution.

3.3 Work Package LAP.3: Trigger generation from GW signals

3.3.1 Overview and goals

We will need to develop data analysis tools, which can perform fast parameter estimation of the gravitational wave signals. Especially important are sky localisation and time of coalescence for MBHBs.

3.3.2 Deliverables

- Algorithms and implementations for rapid LISA source localization software for short-lived transients;
- Tools for fast parameter estimation;
- Tools for low-latency updates to MBHB source localization in the late stages of the merger;
- Scientific publications describing the method.

3.3.3 Description of work

There will be two limiting cases in this task. One when we detect gravitational wave far from merger and the other one the MBHB is about to merge in less than 2 days.

- Develop the tool for the rapid parameter estimation for the MBHBs, especially concerning the sky localisation;
- Tools for low-latency updates to MBHB source localization in the late stages of the merge;
- Tools for rapid LISA source localization software for short-lived transients. The procedure might be different from the long lived MBHBs.

3.3.4 Timeframe and human resources requirements

- Identification for the requirements on software in SOC (preliminary by the end of phase A, have to stay in contact tell the launch).

3.3.5 Possible subpackages

- Fast waveform database;
- Tools for rapid LISA source localization software for short-lived transients;
- Tools for low-latency updates to MBHB source localization in the late stages of the merger.

3.3.6 Dependencies

- This is the critical deliverable for the multimessenger follow-ups and setting of the protected periods;
- Requires fast waveforms;
- Requires accurate current noise estimates.

3.3.7 List of projects

TBD

3.4 Work Package LAP.4: Generation of data quality metrics and flags

3.4.1 Overview and goals

We have to assess the quality of the data. We expect that there will be intervals when the instrument will be operating at an "ideal" state but some intervals of the instrumental operations which will be still identified as a part of duty cycle, will have not a perfect data quality. For the different levels of data quality we will need to identify data quality flags. Data quality flags will be used to provide an indication as to the quality of the data for specific periods of time, and to explain what are the problems. These fags should be produced immediately when the data is received from the spacecraft.

Through the design, construction, assembly, verification and testing a thorough understanding of the expected performance of the experiment should be achieved.

3.4.2 Deliverables

- Procedure to estimate instrument's noise;
- Catalog of the noise sources (transient and continuous);
- A record of the data quality as a function of time;
- Data quality flags describing the severity of noise problems;
- A daily summary page containing numerous and important data quality indicators;
- Cleaned data.

3.4.3 Description of work

During the operations of LISA it will likely be the case that the experimental performance and noise sources will change with time. As such, the noise budget must be updated frequently (probably daily).

Known noise sources should be cataloged.

The data quality metrics and flags will affect the signal searches. A good coupling must exist between the observed detector data quality and the signal searches. An understanding of the data quality will also be used to understand sources of noise, and to determine if there are methods to eliminate the noise sources. Characterization of the data will also allow for modeling of the noise. This could possibly provide the means for noise subtraction by various methods.

3.4.4 Timeframe and human resources requirements

Methods for data cleaning exist now in the LIGO/Virgo community, and these could be adapted for LISA applications on the same timescale as the development of the new LDC. Many data quality metrics will likely not converge until the completion of the assembly, integration, verification and testing phase of the satellites.

3.4.5 Possible subpackages

- Estimates of noise power spectral densities;
- Glitches in TDI channel and appropriate auxiliary channels: a low latency pipeline to identify correlations.

3.4.6 Dependencies

- Dependency of the ”Noise Artefacts” (WP in Simulation Working Group);
- Tools for detecting glitches and unmodeled signals;
- Tools for modeling instrument performance;
- Tools for assessing instrument/mission design choices;
- Tools for generating and managing data quality indicators.

3.4.7 List of projects

TBD

3.5 Work Package LAP.5: Source-based observatory diagnostics

3.5.1 Overview and goals

General idea is to use verification binaries (VB) as a tool understand the instrument.
The objective is to determine how verification binaries be used to improve upon the TDI ranging that uses pseudo random noise (PRN) modelling, how do the (expected) presence and absence of these binaries in various TDI observables complement the PRN-based TDI ranging and How can VBs be used to validate the calibration of the amplitude and phase of the signals from LISA?

3.5.2 Deliverables

- Pipeline that uses VBs as prior in an optimal estimation method to determine whether adding information from the VBs' signals changes TDI ranging;
- Pipeline for amplitude and phase calibration for a strain and uncertainty of the VB.

3.5.3 Description of work

The residual signal in the null stream (GW free TDI observable) can be to estimate the ranging error. If the error in the ranging due to the SNRs of VBs are smaller compared to the PRN ranging, then we can optimise the PRN.

Given the known parameters from a VB parameter and the LISA orbit and its geometry (and errors arising from those parameters) we have an expected strain with an associated uncertainty. Use this to compare the measured strain and uncertainty when we have the real data to compare against the expected/modelled quantities. The goal is to answer whether some of the strongest VBs can be used to calibrate the amplitude and phase of the signal. The same can be done with newly discovered galactic binaries those which are much brighter than the VBs. Their parameters could be measured relatively quickly and in turn this can be used for calibration validation.

3.5.4 Timeframe and human resources requirements

TBD

3.5.5 Possible subpackages

TBD

3.5.6 Dependencies

- WAV1.4 Provide GB waveforms

3.5.7 List of projects

- As a first study to do is to look at what ranging errors can be derived from VBs alone;
- Then try to combine PRN and VBs;
- Determine if VBs can be used to calibrate the amplitude and phase of the signal.

3.6 Work Package LAP.6: Search and classification for unmodelled signals

3.6.1 Overview and goals

The past research in astrophysics has shown that new unexpected sources are revealed whenever a new detection/observation capability (frequency range, detection medium, etc.) becomes available.

LISA signal may contain, in addition to GW from known and well modelled sources, signals from other potential sources, from signals that last for long time to ones with a very short duration, the so-called GW transients. The sources of short duration of GW transients could be, for example, cosmic string cusps or some new unexpected sources. Therefore, it is very important to have methods to detect gravitational waves from unmodelled sources.

3.6.2 Deliverables

- Technical report – phenomenological models for the unmodelled GW transients and methods to characterize them;
- Scientific paper description of the algorithms that can be used to extract unmodelled GW signals;
- Software implementation of the algorithms to extract unmodelled GW signals, which will run as part of the low-latency pipeline;
- Databases with identified unmodelled GW signals;
- Software tools (will run in LLP) for sky localization of sources of transient signals, when an "surrogate" model can be derived for that type of transient GW signal.

3.6.3 Description of work

There are yet unmodelled astrophysical phenomena expected to emit GW, such as cosmic string cusps and other unpredicted signals.

- If the gravitational energy is emitted over a long time, the signals are harder to detect compared to shorter and louder signals. For shorter transients, it is worth to study the algorithms already used on LIGO/Virgo scientific runs to extract such short transients;
- Developing techniques that can distinguish unmodelled GW signals from instrumental artifacts;
- Developing techniques to characterize unmodelled GW signals;
- Developing the necessary LLP software to extract transients;
- Concurrently using of multiple methods to enhance the unmodelled GW transients detection. (For example, in LIGO/Virgo there are multiple methods: coherent WaveBurst, Spherical Radiometer, STAMP - Zebragard, STAMP - Lonetrack. Each of the above analysis techniques is slightly more sensitive to particular sources, but all of them have sensitiveness on the astrophysical models and also on the ad-hoc models used in characterization of the corresponding pipelines sensitivity.)

3.6.4 Timeframe and human resources requirements

This is largely uncharted territory. Good to explore multiple approaches over the next several years.

Short duration transients are likely the easiest target.

Maybe possible to repurpose LIGO/Virgo burst algorithms in near term.

3.6.5 Possible subpackages

- Methods for transient detection;
- Phenomenological models for unknown transients;
- Methods for parameter estimation of the phenomenological model parameters (such as MCMC, machine learning, etc);
- Methods for the classification of the different physical transients and noise artefacts;
- Transfer functions for all conceivable noise transients (i.e. propagation in LISA Simulators);
- Generic waveform reconstruction techniques (wavelet based, etc)

3.6.6 Dependencies

- DAFT.3
- LAP.1
- LAP.2
- DAFT.6

3.6.7 List of projects

- Study the coherentWaveBurst (cWB) algorithm which has been applied to LIGO / Virgo for using in the case of LISA.

3.7 Work Package LAP.7: Assessment and triggering of protected periods

3.7.1 Overview and goals

The operations of LISA will involve antenna re-pointing, which is required for adjusting the orientation of antennae assembled on the LISA spacecraft in order to maintain the communication link to the Earth.

The goal here is to identify the mechanisms and decisions involved in triggering a protected period on the observatory. We also need to look at the constraints coming from the operations and the instrument itself.

3.7.2 Deliverables

- Technical note, which identifies the loss of science due to the gap in data close to the merger of MBHB;
- Procedure that monitors
  - the schedule of the antenna repointing,
  - triggers of the MBHB events and based on this information defines protected periods within the allowed range;
- Tools to communicate protected periods to SOC/MOC.

3.7.3 Description of work

We have to identify the routine which will combine the information on the scheduled antenna repointing with the triggers of the Coalescence time from the MBHBs and ensure that LISA is operational during the mearger and ringdown.

The repointing times can be adjusted, however, there are limitations within which that can be done. We have to identify how to find the optimal scenatio.

Moreover we need to ensure that routine interruptions are scheduled in such a way as to allow them to be rescheduled to avoid the protected period. This could imply advancing, or delaying of routine maintenance

3.7.4 Timeframe and human resources requirements

The limitations on how much in advance we can trigger the protected periods and what does it imply for the detection, parameter estimation and multimessenger observations have to be identified by the end of Phase A.

Otherwise it is a long term activity but it needs to be integrated in the MOC/SOC development from the beginning.

3.7.5 Possible subpackages

- Understand what is the minimal time when we can trigger rescheduling. Are there possibility to trigger rescheduling later in the emergency case of particularly interesting source.
- Upon detection of a MBHB merger, the decision chain needs to be identified (DPC informs SOC informs MOC, etc).
- Study currently known maintenance activities and look at scheduling those to allow for rescheduling.
- Understand the process of how operationally implement rescheduling.
  What is the impact on MOC/SOC operations?
  Who are the different players involved in the decision making process?
- Is it possible to make an automatic system to schedule protected periods. Implement it.
- How long does a protected period need to be? (how long is the ringdown etc).

3.7.6 Dependencies

- This work package depends on the studies done in the ”Noise artifacts” group (WP9) of the Simulation Working Group.
- *Data products that this WP requires*:
  Estimated Coalescence times

3.7.7 List of projects

Routine to combine predictions for the coalescence time and ringdown length with the schedule restrictions in order to find the optimal adjustment scheme.

Chapter 4

DPE – Source identification codes (Detection and parameter estimation)

NOTE: The format of this section is somewhat different to the others. Work in this work package area is being pushed forward within the LISA Data Challenge group. The work package descriptions below have therefore not been updated since their inception. We encourage prospective members of the consortium who wish to get involved in this area to actively participate in the LDCs and to discuss their contributions with the LDC chairs.

Science with LISA will rely on the identification of as many of the sources present in the data stream as possible, and on understanding any inter-dependencies in the inferred values of the parameters arising from confusion between the signals in the data set. As LISA sources are typically long-lived and present for a significant fraction, if not all, of the mission lifetime, a separate identification of individual sources or source types is not efficient. Instead, we will be attempting to carry out a simultaneous global fit for the parameters of all the sources in the data. This global fit will be continuously updated as additional data is received from the satellites. In practice, the global fit will be supported by additional codes which dig more deeply into the data and are focussed on particular source types. This codes will operate on the most recent best-fit residual from the global fit and will feed back any identified sources to be included in future refinements of the global solution. The WPs described in this section are designed to build this data analysis infrastructure. DPE.1 is designed to build the algorithms and codes that will generate the global fit solution, while the remaining WPs will build the supporting codes identifying different source types, and evaluating instrument data quality.

Table 4.1 summarises the work packages of this group.

4.1 DPE.1 Design of global fit strategies, including definition of output products

Goals/Motivation LISA data analysis presents the unique challenge of numerous overlapping signals. Hierarchical methods based on identification and subtraction of the brightest remaining sources accumulate errors which will bias or prohibit detection of weaker sources. Instead, the main production data analysis pipelines must perform a joint fit to all sources in the data and noise, an algorithmically and computationally challenging task. While different source classes will have dedicated pipelines, the global fit pipeline will provide the interface between the different source pipelines and orchestrate joint updates to all source and noise parameters to prevent the analyses from being harmed by avoidable biases and source confusion. The guiding

WP	Description	Priority
DPE.1	design of global fit strategies, including definition of output products	1
DPE.2	detection and parameter estimation of GBs	1
DPE.3	detection and parameter estimation of MBHBs	1
DPE.4	detection and parameter estimation of EMRIs	1
DPE.5	detection and parameterisation of unmodelled sources	2
DPE.6	detection and parameter estimation of IMRIs	3
DPE.7	detection and characterisation of stochastic backgrounds	1
DPE.8	production of cleaned (of sources) TDI variables	1
DPE.9	detection of modelled transient sources	2
DPE.10	identify data quality indicators and vetoes, and observatory diagnostics	2
DPE.11	develop instrumental "noise" cleaning procedures	2

Table 4.1: Work packages on individual and global source identification codes.

goals are to:

- Develop a joint detection and characterisation pipeline for all sources present in the data.
- Define computationally efficient strategies for incorporating new data and updating the global fit.
- Standardize conventions for how to store information about detections needed to construct the source catalogs.

Outputs

- Top-level pipeline that provides the interfaces between individual source and noise analyses, and coordinates joint updates to all source/noise models.
- Standards for how to report source parameters with uncertainties, and detection confidence, for all astrophysical signals present in the data.

Time-frame

- The global fit pipeline will be developed in step with the LDCs.
- Prototype demonstrations of interfaces between pairs of source-classes in ∼3 yr.
- Prototype demonstrations of global analysis using intermediate versions of individual source pipelines, including production of mock catalogs, in ∼5 yr.
- Final version required L-2y.

Possible sub work-packages

- Prototype algorithms of pair-wise fits to identify incompatibility between single-source pipelines early in their development, and evaluate degree of covariance/confusion between different source types.
- Development of parameterized realistic noise model to incorporate into global fit pipeline.

Dependencies

- Data analysis tools DAFT.5, DAFT.2
- Instrument response modelling (TDI) DAFT.3
- Individual source identification codes DPE.2-DPE.7 and dependencies therein
- Source catalogs CAT.1

4.2 DPE.2 Detection and parameter estimation of GBs

Goals/Motivation

- Develop one or more pipelines for joint identification and characterisation of all resolvable GB signals.
- Develop one or more pipelines for detailed analysis of single GBs (could be a use-case of the full search pipeline).
- Pipeline(s) must interface with global fit pipeline, operate on raw data or latest residuals from the global fit, and return a list of the GB's source parameters, uncertainties, and detection confidence.

Outputs

- Pipeline for GB detection and characterization of full galaxy which will interface with global fit pipeline.
- Pipeline for detailed study of isolated GBs.

Time-frame

- Pipeline(s) will evolve with LDCs, prototype algorithms demonstrated within a year.
- Mature algorithms adapted to realistic data scenarios in ∼5 yr.
- Final version required L-2y.

Possible sub work-packages

- GB contribution to global fit pipeline
- Dedicated single-source GB pipeline for detailed analysis (including all relativistic and astrophysical effects).

Dependencies

- Waveform modeling WAV1.4 and fast waveform generation WAV1.8
- Data analysis tools DAFT.5, DAFT.2
- Instrument response modelling (TDI) DAFT.3

4.3 DPE.3 Detection and parameter estimation of MBHBs

Goals/Motivation

- GIven the degeneracies on the parameters observed in old-days MLDC we need to develop more than one pipeline for identification and characterization of MBHB signals
- The pipelines should be split and/or coupled with GB detection/characterization
- The pipeline should be a part of the global fit either right away or be inserted into the global fit with preliminary estimation of source parameters with the low latency.
- The pipeline should be flexible enough to utilize different/evolving models for MBHB signal and be robust to possible systematics in the signal modelling (marginalization over uncertainties).
- Pipeline delivers catalogue of source (both over and sub-threshold) with associated uncertainties (both in numbers and parameters)

Outputs

- Several stand-alone pipelines running in parallel for cross-checking, or a single pipeline utilizing several methods.
- Pipeline incorporated in the global fit analysis, interacting with other pipelines (or being a part of one global pipeline).

Time-frame

- Pipeline will be developed within LDC, the first version should be available within a year.
- Robust pipeline which is able to recover datectable (loud enough) MBHB in presence of other major sources and non-stationary noise $\sim$ 5y
- Final version L-2y

Possible sub work-packages

- Stand-alone pipeline(s) for detecting MBHB (see above)
- MBHB detection as apart of a global fit with/without input form the stand-alone pipeline

Dependencies

- Overlap with LAP.1, DPE.1
- Depends on WAV1.2, WAV1.8, DAFT.5, DAFT.2, LAP.3, LAP.4, CAT.1, CAT.2

4.4 DPE.4 Detection and parameter estimation of EMRIs

Goals/Motivation

- Develop one or more pipelines for identification and characterisation of EMRI signals.
- Pipeline should interface with global fit pipeline. It will operate on the latest residuals from the global fit and return a list of identified EMRI sources for subsequent incorporation in and refinement by the global fit.

- Pipeline should be able to use the best available EMRI model at the current time, but also be robust to waveform modelling uncertainties, e.g., by including marginalisation over waveform model uncertainties.
- Pipeline outputs are catalogues of source parameters and uncertainties.

Outputs

- A pipeline for EMRI identification and characterisation.

Time-frame

- Preliminary pipelines for EMRI characterisation were developed during the MLDCs. Existing pipelines have not been shown to be robust to modelling uncertainties or source confusion.
- Improved and robust pipelines need to be developed on a ∼ 5y timescale and verified within the MDCs.
- Final versions required L-2y.

Possible sub work-packages Sub work-packages would be built around different approaches to EMRI data analysis.

- Stack-slide EMRI search pipeline. Exhaustive EMRI search using templated search for short (∼ 2 wk) sections of EMRI signals, later combined incoherently.
- Stochastic EMRI search pipeline. EMRI search based on tuned MCMC algorithm, as used in the MLDCs.
- Semi-coherent EMRI search. First identify individual EMRI waveform harmonics using phenomenological templates, then combine to identify sources and increase significance.

Dependencies

- EMRI waveform modelling (WAV1.2). Search will use best available templates, or approximations tuned to match these.
- Common data analysis framework and tools (DAFT.5, DAFT.3, DAFT.2).
- Fast waveform generation tools (WAV1.7). The EMRI search will rely on fast but accurate approximations to EMRI waveforms.
- Instrument response modelling (DAFT.3) and data quality indicators (LAP.3, LAP.4).
- Global fit strategy (DPE.1). EMRI search will operate on cleaned data provided by global fit pipeline and return EMRI catalogues for incorporation in global fit.
- Catalogue structure and interfaces (CAT.1, CAT.2). The output from the EMRI search pipeline must include the data products required for cataloguing.

4.5 DPE.5 Detection and parameterisation of unmodelled sources

Goals/Motivation The 2010 *New Worlds New Horizons* Decadal survey remarked that "It would be unprecedented in the history of astronomy if the gravitational radiation window does not reveal new, enigmatic sources." To be in a position to make such discoveries we need techniques that can detected unanticipated and unmodelled signals. The task is complicated by the fact that LISA is one instrument, so the coherent network analysis techniques used to search for unmodelled signals in the LIGO/Virgo data are not immediately applicable. The signal-insensitive Sagnac channel, and differences in the transfer functions for signals and noise will key to any detection strategy.

- Develop techniques that can distinguish unmodelled signals from instrumental artifacts
- Develop techniques to characterize unmodeled signals

Outputs

- One for more analysis tools for extracting unmodelled signals
- Tools to characterize unmodelled signals (frequency content, time evolution, duration *etc*)

Time-frame

- This is largely uncharted territory. Good to explore multiple approaches over the next several years
- Short duration transients are likely the easiest target. May be able to repurpose LIGO/Virgo burst algorithms in near term

Possible sub work-packages

- Transfer functions for all conceivable noise transients
- Generic waveform reconstruction techniques, possibly wavelet based

Dependencies

- LISA Instrument Simulator (DAFT.3)
- TDI models for noise transients (DAFT.3)
- TDI models for generic signals (DAFT.3)

4.6 DPE.6 Detection and parameter estimation of IMRIs

Goals/Motivation

- A black hole of intermediate mass ($M \sim 10^2$–$10^4 M_\odot$) (IMBH) inspiraling into a massive black hole will appear as an IMRI in LISA. The existence of IMBHs is uncertain, but detection of one or more IMBHs would be highly significant.
- We separate IMRIs from EMRIs because waveform models are more uncertain for mass ratios in the IMRI range, $\sim 10^{-4}$–10^{-2}. Handling waveform uncertainties will be crucial in this search.
- This pipeline will interface with the global fit pipeline in a similar way to the EMRI pipeline (DPE.4).

Outputs

- A pipeline for detection and characterisation of IMRIs.

Time-frame

- Due to the speculative nature of these sources, this is not a priority work package. After development of searches for MBHBs (DPE.3) and EMRIs (DPE.4), the efficiency of those searches for detecting IMRIs should be assessed.
- Further tuning and optimisation of an IMRI search will continue during mission development and tested within the LDCs.
- Final version required L-2y.

Possible sub work-packages Sub work-packages would be built around different pipelines, as in the EMRI case, e.g.,

- Stack-slide IMRI search.
- Stochastic IMRI search.
- Semi-coherent/time-frequency IMRI search.

Dependencies

- IMRI waveform modelling (WAV1.5). Search will use best available templates, or approximations tuned to match these.
- Common data analysis framework and tools (DAFT.5, DAFT.3, DAFT.2).
- Fast waveform generation tools (WAV1.8).
- Instrument response modelling (DAFT.3) and data quality indicators (LAP.3, LAP.4).
- Global fit strategy (DPE.1). IMRI search will operate on cleaned data provided by global fit pipeline and return IMRI catalogues for incorporation in global fit.
- MBHB and EMRI searches (DPE.3, DPE.4). IMRI search will most likely be derived from searches for other source types.
- Catalogue structure and interfaces (CAT.1, CAT.2). The output from the IMRI search pipeline must include the data products required for cataloguing.

4.7 DPE.7 Detection and characterisation of stochastic backgrounds

LISA data are expected to contain several contributions from stochastic foregrounds/backgrounds – of astrophysical and/or cosmological origin – including (i) the foreground from WD-WD binaries at mHz frequencies, (ii) a possible foreground from EMRIs in the same frequency range, (iii) a foreground from stellar-mass black holes at $\sim$ 0.01 Hz, (iv) a foreground from neutron stars in the frequency range of the stellar-mass black holes, and (v) a background from processes in the early Universe whose level is unknown.

Goals/Motivation

- To detect and characterise stochastic signals present in LISA data.
- To characterise the properties of the stochastic signals present in the data (the signals may not be Gaussian and/or stationary and/or isotropic)

Outputs

- Pipeline(s) for the detection and characterisation of stochastic gravitational-wave signal(s).
- Given the nature of the problem, and the lack of an existing end-to-end approach that deals with conditions that are remotely realistic, it is highly desirable that multiple approaches and pipelines are developed early on to explore performances and trade-offs.
- The pipeline ability to identify and characterise the signals will depend on the TDI outputs and links available in the configuration, and will need to work under the different conditions (level of stationarity/Gaussianity of the noise, data drop-outs and corruption) and configurations. Depending on which links are available, the ability to recover stochastic background could be totally compromise. An important output of this WP in the early phase of development is to identify the minimal instrumental conditions/configuration for the recovery of a stochastic signal.

Time-frame

- A preliminary pipeline was developed during the MLDCs. However the operation conditions were highly idealised (Gaussian and stationary instrumental noise, primarily full 6 links available in the LISA instrument).
- Final version required L-2yr.

Possible sub work-packages

- Gaussian/stationary background signal vs more generic backgrounds
- Isotropic background
- Anisotropic background
- Physical characterisation of multi-component background/foreground based on de-fault (TBD) models
- A possible additional hierarchy of the WPs is to have workpackages for the ”full-configuration” (6 links) and as for each of them sub-workpackages that deal with ”reduced-configurations” (less than 6 links)

Dependencies

- This workpackage depends on pretty much everything else, as it deals with the analysis of ”what is left” after all the individual sources have been resolved. (add numbers)
- The workpackage depends on all the data-characterisation workpackages (add numbers)
- It depends on all the WPs that deal with identification of resolvable sources, global fit, cleaned data, TDI reconstruction (I will need to add numbers later)

4.8 DPE.8 Production of cleaned (of sources) TDI variables

Goals/Motivation While the global fit is a necessity for the final catalog of sources, detailed analyses of individual sources will not want to be burdened by the full set of global-fit parameters. Examples where the analysis would want to focus on a single source include investigations of relativistic and astrophysical effects beyond the standard waveform models, or low-latency updates of merging SMBH parameters to be communicated with EM observing partners.

- Provide robust global-fit subtraction tools including error budgets from source parameter uncertainties.
- Provide up-to-date cleaned TDI variables which can quickly be modified to focus on single sources for low-latency parameter updates.
- Provide clean residuals for instrument and noise characterization work.

Outputs

- Tools to produce residuals from the global fit with uncertainties.
- Tools to add back individual sources of interest for detailed/updated analysis.
- Error-budget from waveform subtraction for the cleaned TDI variables.

Time-frame

- These are straightforward tools they depend on waveform, search pipeline, and catalog development. Can be demonstrated in early LDCs.
- Final version L-2yr.

Possible sub work-packages

- Develop algorithms for incorporating uncertainties from signal subtraction into analyses of residual data.
- Develop tools to interface with catalog and add back sources to TDI variables for further analysis/updates to parameters.

Dependencies

- Waveform models WAV1.1-WAV1.8
- Data analysis tools DAFT.5-DAFT.2
- Instrument response modelling DAFT.3
- Individual and global source identification codes DPE.1-DPE.6
- Source catalogues CAT.1,CAT.2,CAT.5

4.9 DPE.9 Detection of modelled transient sources

Goals/Motivation

- Develop a pipeline for identifying short-duration modelled transient sources in the LISA data stream.
- Known potential transients are cosmic strong cusps and extreme-mass-ratio bursts.
- Pipeline must be as robust as possible to instrumental artefacts and hardware failures.

Outputs

- A pipeline for identifying, characterising and cataloguing modelled transient sources in the LISA data.

Time-frame

- This is a lower priority than other modelled source types due to the uncertain event rate.
- This search will be more sensitive to instrumental artefacts. Assessing robustness will rely on the development of the tools for characterising and simulating instrumental noise, so this must happen first.
- Preliminary pipelines needed on a $\sim$ 5yr timescale, to be verified in LDCs. Searches for cosmic strings were demonstrated in the MLDCs, but without contamination from instrumental artefacts.
- Final pipelines required L-2y.

Possible sub work-packages

- Pipeline for identifying extreme-mass-ratio burst signals.
- Pipeline for identifying cosmological burst sources. NB this is likely not to be a separate work package, but just the previous pipeline with a different waveform model.

Dependencies

- Waveform modelling (WAV1.7).
- Common data analysis framework and tools (DAFT.5, DAFT.3, DAFT.2).
- Instrument response modelling (DAFT.3) and data quality indicators (LAP.3, LAP.4).
- Search for unmodelled transients (LAP.5). The search for unmodelled transients will be sensitive to modelled transients so the development of these two packages is linked. The pipelines could run completely independently or the unmodelled transient search could trigger the modelled search, with the modelled search also being used to find quieter signals.
- Global fit strategy (DPE.1).This search will most likely operate on cleaned data provided by global fit pipeline and return lists of identified transients for incorporation in global fit. It could also be part of the global fit pipeline.
- Catalogue structure and interfaces (CAT.1, CAT.2). The output from the search pipeline must include the data products required for cataloguing.

4.10 DPE.10 Identify data quality indicators and vetoes, and observatory diagnostics

Observatory diagnostic allows to identify segments of bad data that can negatively affect the detection and analysis of GW signals. When segments of poor data quality are identified a data quality warning should be released, eventually veto flags should be issued in order to exclude the given segments from the analysis of GW signals. Data quality warnings and vetoes should be issued if the origin of the data quality degradation can be clearly identified.

Goals/Motivation

- Spurious signals (e.g. glitches, micro meteoroids impacts) can be mistaken for transient GW signals.
- Total or partial loss of data can occur because of downlink failure, sub-system failure, SC to SC link failure.
- Anomalies or malfunctioning in a subsystem can generate extra noise at the output of the instrument.
- Any anomaly in the data can affect the ability of reconstructing TDI variables.
- Data anomalies could impair the ability of extracting GW signals.

Outputs

- Identification of the indicators of the healthy status of the instrument.
- Identification of possible sources of instrument anomalies affecting the quality of the data.
- A set of pipelines monitoring the healthy status of the instrument.
- A set of pipelines generating data quality indicators.
- A set of pipelines generating veto flags.

Time-frame

- Investigation of data quality indicators should start within 1 year time frame.
- Pipelines development should start within 1 year. Pipelines should be tested in the framework of the LDCs.
- Fully functional preliminary pipelines are needed in 5 years.
- Final version of the pipelines are required at L-2y.

Possible sub work-packages

- Monitoring the healthy status of the optical metrology system. Analysis of the impact on science, data quality indicators and veto flags generation.
- Monitoring the healthy status of the GRS. Analysis of the impact on science, data quality indicators and veto flags generation.
- Analysis of the environmental monitors (radiation monitors, magnetometers, thermometers), impact on science, data quality indicators and veto flags generation.
- Detection of spurious signals (e.g. glitches, micro meteoroids), cross-correlation analysis of all available channels and their signature in TDI.
- Impact of instrument maintenance (e.g. TM discharge, telescope repointing, mode change) and instrument calibration (e.g. signal injections) on data quality.
- Vetoes generation as a consequence of instrument anomalies (e.g. total or partial loss of data, sub-system fault).

Dependencies

- Common data analysis framework and tools (DAFT.3, DAFT.2, DAFT.6).
- Instrument response modelling (DAFT.3)
- Generation of data quality metrics and flags (LAP.3)

4.11 DPE.11 Develop instrumental 'noise' cleaning procedures

Goals/Motivation

- Achieving the optimal observatory performance will likely involve the removal of noise through post-processing.
- This will first rely on the identification of noise couplings from some auxiliary channels to the TDI outputs.
- for each identified noise contribution
  - the transfer function needs to be parameterised and identified, studied and monitored.
  - the source noise measurement needs to be monitored and maintained as part of the routine data set.
- for any such coupling mechanism, 'safety' to GW signal needs to be assessed. This could be achieved by searching for the presense of high-SNR signals in those channels, or by performing dedicated hardware injections. Look at what has been done in LIGO in this regard.
- for such couplings, the correct point in the signal processing chain to do the subtraction needs to be identified. For example, it could be done before TDI, or as part of the TDI application, or post TDI.
- some of these couplings will require dedicated experiments to measure appropriate parameters. Examples of this are calibration of the coupling of laser power fluctuations as a force noise on the test masses. Another would be the subtraction of SC jitter through tilt-to-length couplings.

Outputs

- List of expected couplings and noise subtractions based on the experience from LPF.
- List of 'new' couplings which were not studied in LPF.
- Designs of required calibration experiments to be performed in operations.
- Identification of analysis tools.

Time-frame

- This work should be looked at reasonably early, during Phase A, from the point of view of ensuring that, for the 'known' couplings:
  - the required auxilliary signals are made available
  - the required experiments can be performed from a hardware point of view
- in the longer term, simulations and hardware development may reveal new couplings which will need to be studied.

Possible sub work-packages

- Correlations and couplings of TTL through TDI (part of Simulation WG work)
- Correlations and coupling of RIN through TDI (part of Simulation WG work)
- Adaptation of LPF calibration experiments to LISA situation

Dependencies

- there is a link with the data analysis tools
- there is a strong link with the work plan of the Simulation WG

Chapter 5

CAT – Catalogs

5.1 Catalogs

5.1.1 Overview and goals

The LISA catalogues are the top-level science product of the mission, together with high-profile publications and data releases accompanying discoveries and surveys. Even those will be supported by the catalogues, either through specialised products, or targeted "views". Thus, the catalogues will be the primary interface between the LISA mission (and by extension the science team and the core user group contributing to searches) and the broader astronomical community, which will use the catalogues to derive and test, e.g., MBH and Galactic-binary population models. The catalogues will also support EM counterpart alerts. Because of the global-fit nature of the LISA science solution, the catalogues will also be a crucial object internally within the LISA data system and science analysis. The internally facing catalogues are updated continuously by data-analysis pipelines to report new detections and revise parameter estimates, and it is accessed by the pipelines to perform partial waveform subtractions from the dataset.

The goals of this WP are:

- To develop a flexible interface between the global posteriors produced by the various data analysis pipelines and the end users. The latter should be allowed to select specific source(s) or source class(es) and to marginalize over unwanted source parameters
- Interface and combine the gravitational wave catalogs with the electromagnetic counterpart catalogs that will be provided by partner telescope

5.1.2 Description of work

The starting point will be the distribution(s) of the global posteriors produced by the various data analysis pipelines. Ideally, each pipeline should produce a file with the global (tabulated) posterior probabilities in bins of $\sum_i N_s^i \times N_p^i$ parameters, where N_s^i is the (best estimate for the) number of detected sources, N_p^i is the number of parameters per sources, and the index i denotes different classes of sources (MBHBs, EMRIs, SOBHBs, GBs, etc). In practice N_p^i may differ among different classes of sources. Indeed, while typically it will be ~ 15 (i.e. the parameters will be the masses, the spins, the sky position, the distance, the source inclination, the initial phase, the merger time and the polarisation angle), for some classes of sources some parameters may be dropped (e.g. the spins), while for others additional parameters might be added (e.g. eccentricity for MBHBs, environmental effects for EMRIs, deviations from GR in certain pipelines etc). Each choice of the number of parameters N_p^i will produce a different posterior distribution and thus a different catalogue. These choices will have to be made on the basis of theoretical (WAVWP, SIWP) and data analysis (DAFTWP) considerations. Moreover, the global posteriors should be provided with and without the priors on z (and thus on d_L) and sky position coming from EM observations (MMAWP).

Therefore, the starting point will be a set of global posteriors produced by different pipelines (using different samplers, waveforms, parameters, priors). CATWP will then consist of designing a flexible and fast interface allowing users to query this huge global posterior file(s). The users should be able to select what variables they want to keep and what variables they want to marginalise on. Marginalisation will be achieved by summing over lines or rows of the initial global posterior file. Users should also be allowed to select a specific class of sources (i.e. marginalise over all other source classes), or even focus on a single source. They should also be allowed to obtain just a list of detections with best estimates for the source parameters as well as (if required) errors bars or covariance matrices. On top of this, for each source in the catalogues, SNRs and false alarm rates conveying the significance of the detection should be provided separately.

This approach hinging on "scaling down" a huge posterior file according to the individual user's needs seems preferable over inquiring about the preferred format of the catalogue with different community/individuals. It is in fact clear that there will be as many preferred formats as communities or even individual scientists, and that these preferences will evolve with time. More importantly, any catalogue format will be obtainable with the above "top-down" procedure, which only requires *(i)* a fast way to "jump" to a given row/line of the global posterior file and sum over it; *(ii)* a fast way to find the best estimates for a given parameters and the corresponding variance and covariances (this being required to produce lists of detections with error bars and/or covariance matrices).

Suitable visualisation tools should also be provided to plot the chosen posteriors. Interfacing with ESA's virtual observatory (ESA Sky) seems also desirable. Ancillary tools allowing the users to visualise the residuals of the data when certain or all sources are subtracted may also be useful to some users, but those should probably be provided by DPEWP.

Clearly, the LISA catalogue should implement some form of journaling and version control to account for the differences between subsequent data releases.

5.1.3 Approximate timetable for one or more initial projects

An ideal playground to test these ideas is the LDC. Global posterior files may be handed over to CATWP members (if any!) to build the aforementioned "catalogue generator". The tool may then be handed over to e.g. the Astrophysics, Cosmology and Fundamental Physics WGs, who may try to perform the analyses that they would like to apply to the real data (e.g. astrophysical model inference). This would be an ideal way to engage the community and it would "educate" it about what will be feasible with the real data. Nevertheless, the catalogue generator that will we will produce will very likely be obsolete by the mission's launch.

5.1.4 Dependencies

- DPEWP: global posterior files; the latter will depend on source description in file formats (DAFTWP);

- MMAWP: EM measurements of z and sky position, to be used as prior by the Bayesian parameter estimation of DPEWP;

- WAVWP & SIWP: choice of the parameters to include in the Bayesian parameter estimation of DPEWP.

5.1.5 Work packages

5.1.5.1 CAT.1 Definition and design of catalogue(s) and interface with global fit solutions

5.1.5.1.1 Objectives

- Design LISA catalogue as a database that supports several modes of use and different queries, ranging from the internal global fit to the needs of astronomers.
- Develop tools and methods to incorporate as much information as possible about source-parameter uncertainties (e.g., as Monte Carlo sample files) and about correlations between sources.
- Allow catalogue to be accessed efficiently for the purpose of reconstructing the data likelihood (or a partially marginalized/extremized likelihood) as a function of source parameters.
- Allow catalogue to be accessed efficiently for the purpose of building partially regressed data products (e.g., dataset minus best-fit detected SMBHs and loud Galactic binaries).
- Design catalogue in tandem with the LISA data-archive interface.
- Catalogue (or a catalogue extension) may allow also ingestion and access of data about EM counterpart searches and observations.

5.1.5.1.2 Deliverables

- Catalogue design whitepaper.
- Catalogue specification document.
- Catalogue implementation as database (several versions support increasing functionality).
- Libraries and code examples to access and update catalogue (see also CAT.3).
- Simulated source lists and records to populate prototypes.

5.1.5.1.3 Timeframe

- Simple prototype by third (?) LDC.
- Initial design by beginning of Phase A.
- Full design and prototype by end of Phase A.
- Mature design by end of Phase B.

5.1.5.1.4 Possible subpackages

- Single-source catalog entries.
- Multi-source interface and management of correlations.
- Multimessenger catalog.

5.1.5.1.5 Dependencies

- Catalogue will be updated or queried by many pipelines and tools across all WPs.
- Catalogue will depend on source description in file formats (DAFT.2), and may be partially implemented through those.

5.1.5.2 CAT.2 Tools for interfacing, visualisation, storage, searching, etc.

5.1.5.2.1 Objectives

- This WP amounts to implementing the basic functionality of the LISA data archive for internal and external query.
- The WP will provide software interface specification and implementation for pipelines to obtain/update entries from/to catalogue.
- The WP will provide tools, examples, and tutorials for GW and EM astronomers to query catalog, produce meaningful visualization of entries under various aggregations, etc.

5.1.5.2.2 Deliverables

- Use-case/design document.
- Web/database service providing access to catalogue database (and multiple versions thereof).
- Web interface for human access, allowing complex/graphical queries.
- Visualization plugins for web interface and/or external applications.
- Scripting tools for automated access by pipelines.
- Simulated catalogues for testing.

5.1.5.2.3 Timeframe Follows CAT.1 since it implements it operationally.

- Simple prototype by third (?) LDC.
- Initial design by beginning of Phase A.
- Full design and prototype by end of Phase A.
- Mature design by end of Phase B.

5.1.5.2.4 Possible subpackages

- Server.
- Web interface.
- Visualization tools.
- Scripting access tools.

5.1.5.2.5 Dependencies

- Catalog design CAT.1.
- Data exchange formats DAFT.2.
- Data-analysis framework prototypes DAFT.5.

5.1.5.3 CAT.3 Protocols for catalogue evolution, QA, and change tracking

5.1.5.3.1 Objectives

- New source entries will appear and will be updated as the dataset is collected, and as increasingly sophisticated analysis pipelines are applied to sources. The catalogue should fully support these insertions and updates.
- The catalogue should be capable of maintaining concurrent (and possibly discrepant) accounts of the same source, or even different number of sources.
- Accordingly, we should define an index of "catalogue record quality" and maintain fully accessible provenance information in order to support catalogue queries.
- Thus, the LISA catalogue should implement a sophisticated form of journaling and version control.

5.1.5.3.2 Deliverables

- Use-case/design document.
- Implementation in database schemas and housekeeping code.
- "diff" and "log" tools (text-based and graphical) for catalogue entries and queries.
- Testing suite for QA.
- Simulated catalogues and catalogue updates for testing.

5.1.5.3.3 Timeframe

- Mature design by end of Phase B.

5.1.5.3.4 Dependencies

- CAT.1 and CAT.2

5.1.5.4 CAT.4 Management of catalogue release, dissemination, etc.

5.1.5.4.1 Objectives

- As much as the catalogue will be a living object, continuously updated throughout the mission and beyond, the needs of coherence and reproducibility suggest that the outward-looking catalogue should be made available to the astronomical community in regular incremental releases.
- Catalogue releases should always accompany new data products (e.g., TDI files), and will need to be properly "synchronized."
- We need to develop a plan for the releases, looking at examples from other missions and observatories, and gathering input from the astronomical and GW community.
- We need to develop requirements and quality controls for what is included in a release, as well as timelines and responsibilities to produce and approve them. Again, look for high-profile examples (e.g., SDSS).

5.1.5.4.2 Deliverables

- Use-case/design document.
- Plans for accompanying publications, talks, etc.
- Web interface.
- Simulated releases (including very complete ones for “final” mock data challenges).

5.1.5.4.3 Timeframe

- Mid phase B.

5.1.5.4.4 Dependencies

- CAT.1, CAT.2, and CAT.3.

5.1.5.5 CAT.5 Cataloguing of unmodelled sources

5.1.5.5.1 Objectives

- GW sources detected without direct reference to a physical waveform model require appropriate representation in the catalog, which will be married closely to the analysis that produced the detection: for instance, the catalog entry may represent a posterior distribution of wavelet coefficients.
- The catalog may consist directly of a posterior distribution of reconstructed waveforms.

5.1.5.5.2 Deliverables

- Schemas and specification document.
- Software tools.
- Simulated example entries.

5.1.5.5.3 Timeframe

- End of phase A.

5.1.5.5.4 Dependencies

- CAT.1, CAT.2, CAT.3, and most SI work packages.

Chapter 6

MMA – Multi-messenger astronomy

Introduction

It has been recognised that combining gravitational wave (GW) data from LISA with other messengers (including both photons and particles) can deliver science not accessible to either observable alone. Therefore, to maximize the scientific return of the LISA mission, the synergy between LISA and these other forms of messengers is of paramount importance. The high science gain of a synergistic use of GW detectors covering a broad frequency range, combining LISA with both lower-frequency (e.g. pulsar timing) and higher-frequency (e.g. ground-based detector) GW observations, has likewise been recognised.

The overall goal of the The Multi-Messenger Astronomy (MMA) Work Packages (WPs) is to create the tools and infrastructures that will allow us to realize the full scientific potential of multi-messenger and multiband data.

Table 7.1 summarizes the multi-messenger astronomy work packages.

WP	Description	Priority
WPMMA.1	Exploration of MMA Science with LISA	1
WPMMA.2	Joint MMA Analyses	2/3
WPMMA.3	Preparations needed for LISA to make use of external data	2/3
WPMMA.4	Communications, logistics and procedures	2/3

Table 6.1: Multi-messenger Astronomy Work Packages.

6.1 WPMMA.1: Exploration of multi-messenger and multi-band science with LISA

Overview: This work package is to develop an understanding of the science potential for LISA in the context of multi-messenger astronomy, the broader astronomy and astrophysics community, as well as the gravitational wave community beyond LISA. It is expected that some of this work overlaps with areas of the Science Investigation Work Package, but with two differences. First we focus here more narrowly on the areas of interplay with astronomy and astroparticle communities outside LISA. Second, the scope here extends beyond the high-level key science investigations, and includes lower-level preparation to assure that LISA data products and tools are prepared and released to facilitate such additional science.
Goals: The overarching goal of this work package is to collect and organise prospective multi-messenger science opportunities [28] to guide the more specific preparatory work in the other MMA work packages and for the purposes of the Consortium more broadly.
Subpackages: See two subpackages below.

6.1.1 Multiband and multimessenger science opportunities with LISA

6.1.1.1 Overview and Goals

The goal of this work package is to enumerate the extra science derivable only from combinations of LISA + external data that is not accessible to either type of data alone.

The resulting enumerated list will consist of science questions that can be addressed by each type of LISA source listed below, combined with various types of external data.

We expect this list to range from well-established and relatively well-developed ideas (such as probing cosmology with standard sirens) to novel, less understood, or more speculative examples (such as probing speed differences of photons and gravitons or understanding the formation of massive black holes in the collapse of supermassive stars).

We expect this list to evolve over time, and a goal is to create and maintain an evolving depository. The catalog will enumerate promising multi-messenger and multi-band sources & science opportunities, with brief descriptions of each type of source and the science that can be addressed with them through multi-messenger data. A mechanism will be implemented to keep this list up to date.

A possible venue for the above is a review article in Living Reviews of Relativity.

6.1.1.2 Deliverables

We envision an authoritative document, listing science questions that can be addressed by each type of LISA source, combined with various types of external data. We expect to organize this document around each type of source:

- Massive black hole (MBH) binary mergers
- Stellar-mass compact object binaries & mergers
- EMRIs/IMRIs
- Stochastic background

For each source category, the document will include

- The list of science questions that can be addressed by LISA + external data, with detailed explanations of what progress can be made by combining LISA with other datasets that can not be achieved, or could only be done significantly less well, with either data alone.

- The external dataset(s) necessary, including identifying the relevant instruments and surveys (both existing and planned) that can provide these data, along with an assessment of their status, and whether these external data will be expected to be available automatically or further work is required to secure them. A related responsibility is to keep track of known practical issues/subtleties in the use of external data, and which teams in external collaborations are best suited to advise on these.

- The theoretical predictions necessary for EM and/or particle counterparts for LISA sources, and an assessment of the status of these predictions, identifying key areas where theory tools are missing or underdeveloped. This includes the development of numerical simulations necessary to accurately predict the signals in the EM and GW sectors.

- Identifying the possible practical hurdles in performing multi-messenger and multi-band studies, and developing techniques to overcome these. These include issues involving the preparation of theoretical models and simulations, as well as in the use of future observational data.

- An overall assessment of the level of readiness to exploit MMA science opportunities, and a clear summary of the key missing steps.

6.1.1.3 Description of work

Producing the above document will require a team effort, with expertise spanning the science with the different types of sources, the relevant astronomical data across all bands, from radio to gamma-rays, as well as theoretical expertise.

6.1.1.4 Timeframe and workforce requirement

We envision each of the four source-categories to correspond to a chapter in this document, and led by a single team member, drawing on the expertise of multiple team members. For example, an expert in X-ray astronomy will contribute to all four chapters, when called on by the lead assigned to each chapter. We expect assembling the writing team of approximately 10 individuals to take 1-2 months, and the document will then take 6 months to produce.

6.1.1.5 Possible subpackages

Each of the four chapters of the document can be thought of as its own sub-package.

6.1.1.6 Dependencies

The subpackages here will have overlap with many other WPs in this document, as well as with:

- The Science Investigation WPSI.1.3 (massive BHs); WPSI.2.1,.2.2,.2.3 (stellar-mass compact objects); WPSI.3 (EMRIs,IMRIs,XMRIs, etc..); WPSI.4 (Standard Sirens);

- DAFT WP;

- The Athena-LISA synergy document;

- White paper by the Astrophysics Working Group;

- White paper by the Fundamental Physics and Cosmology Working groups.

6.1.1.7 List of projects

As defined above.

6.1.2 Astronomical signatures of LISA sources

6.1.2.1 Overview and Goals

The goal of this subpackage is to establish an authoritative but evolving collection of state-of-the-art reference models for multimessenger studies.

The most basic example of this is a list of reference models for the luminosity, spectral energy distribution, and lightcurves of potential EM and particle counterparts. Another is the expected population and demography of each type of LISA source.

It is acknowledged that such predictions are uncertain, and the depository will contain information on these uncertainties.

This resource will be necessary for instrument builders and observers to estimate instrumental capabilities for LISA counterpart searches and for interpreting any counterpart that has been identified.

The same reference models will provide challenges to the theory community to further explore their predictions. Likewise counterpart signal models, together with rate models provide a challenge to the broader observing community to understand the prevalence of signals which may be mistaken for LISA counterparts.

6.1.2.2 Deliverables

The deliverable will be a series of formal publications summarizing the state-of-the-art in model predictions for each of the four types of LISA sources. These publications can begin to be developed as internal documents, but should eventually appear as regular journal publications, such as a comprehensive New Astronomy Review article. Model predictions will include signatures of individual sources, as a function of their parameters, as well as predictions for the population, with event rates and demographic information. The models will provide standard assumptions for signatures and rates for the use of researchers with other expertise both within the Consortium and in the broader community. The document will also clarify outstanding questions or limitations in the models ripe for further study. Periodically, as knowledge improves, new additions to the standards will be written.

Another related deliverable will be a public website, together with a series of underlying formal publications, providing information about the standards, with references and any codes or data sets needed for practical use of the standard models, allowing any researcher to compute predicted signals for their own purposes. A LISA team member must be assigned a coordinating role to create this website, and to solicit contributions from the authors of the codes and the model-builders, as well as to ensure periodic updates to this website, so that it remains up-to-date.

6.1.2.3 Description of work

Building an authoritative assemblage of reference models and an associated repository will require significant team effort, combining expertise from theorists, simulation experts, and population model builders, for each of the different source types.

First steps will include the identification of which processes and/or populations should be represented in the first generation of reference models, and the design of a process defining the reference models which allows appropriate community input and review (e.g. to address disagreements and uncertainties in theoretical predictions). The trade-offs between complexity, functionality to observers, and precision of these reference models are yet to be developed, and will be made in consultation with experts and stakeholders and will include a degree of community participation. A supporting website will then be created with an interface that is easy to use, and is easy to keep up-to-date. An important step here will be to identify to required resources (e.g. hosting a website, storage, IT support, etc.).

As a minimum, the first version of the repository will provide information about the teams' objectives and references to existing models in the literature.

Significant expert curatorial work will be needed to define reference models which balance the goals of representing the state-of-the-art understanding, while making the information easily usable by external researchers. For example, rather than merely citing papers on the expected spectrum of a particular type of source in a particular wave band, the website will contain simulated data in tabular form, including python codes to generate models, etc.

Finally, new calculations may need to be performed to obtain key missing predictions, or making key predictions more reliable. While much of this activity happens in regular journal papers, the community members in charge of this repository can highlight and facilitate this needed theoretical work.

6.1.2.4 Timeframe and workforce requirement

We expect the initial version of the repository to take 2-3 years to create, and will require a team of 5-6 individuals. Computing resources will need to be identified, and a management structure will then have to be created to keep the repository up-to-date.

6.1.2.5 Possible subpackages

Possible subpackages are

- Design and create repository website, both content and format-wise.
- Each of the four different source types can be thought of as its own sub-package.
- Signatures of individual sources vs. population models can be thought of as different sub-packages.

6.1.2.6 Dependencies

The subpackages here will have overlap with many other WPs in this document. Additionally, mock source catalogs are being developed in other internal LISA efforts. In particular, synergies with the WP,WG below are expected:

- The Science Investigation WPSI.1.3 (massive BHs); WPSI.2.1,.2.2,.2.3 (stellar-mass compact objects); WPSI.3 (EMRIs,IMRIs,XMRIs, etc..); WPSI.4 (Standard Sirens);
- LISA Data Challenge WG.

6.1.2.7 List of projects

As defined above.

6.2 WPMMA.2: Joint multi-messenger and multi-band analyses

Overview: While the first work package above enumerates the science opportunities and the expected nature of multi-messenger sources, specific tools will be required to fully realize the multi-messenger, multi-band science potential.

Goals: The objective of this work package is to create these numerical tools to exploit the full scientific potential of the LISA GW events by adding EM/particle/multi-band GW information. These tools should be built so that they can be potentially used by all Consortium members and by scientists outside the Consortium.

Subpackages: See three subpackages below.

6.2.1 Mock Data Challenges

6.2.1.1 Overview and Goals

Mock data challenges on LISA multimessenger science will be an important preparatory step to build multi-messenger tools. We expect to work with LDC (LISA Data Challenge) and external partners outside LISA to design and conduct mock data challenges in both directions.

One example is to provide a mock LISA data catalog to astronomers and to GW scientists focused on ground-based detectors and pulsar timing arrays, so that they can begin developing expectations for how to apply LISA data for their own purposes.

An example in the reverse direction is to provide an EM catalog or EM archive to scientists focused on LISA, so that they can assess how LISA analysis or inferences may be impacted (for example, the confidence level of a detection).

The main goals are to engage interested scientists, stimulate development of tools and methods, and to provide a platform for demonstrating capability, before LISA is launched.

6.2.1.2 Deliverables

The deliverables will be mock data challenges, organized and executed in both directions. We envision that all participants in the data challenge will also participate in distilling the results and lessons from the challenge, and writing up the conclusions in a journal paper. We also envision that the data challenges can periodically recur, with several future editions (similar to, e.g., the GREAT data challenges in the context of gravitational lensing).

6.2.1.3 Description of work

The first type of mock data challenge will involve several steps.

- Design the precise parameters and format of the data challenge
- Create mock LISA data catalog(s) with different types of sources at various levels of significance and with a range of parameters. These choices will be guided by astrophysical population models.
- Identify target individuals and groups outside LISA, as well as venues to advertise the activity
- Assemble list of invitees and issue invitations to participate
- Collect submissions, analyze differences, present results and draw conclusions

The second type of mock data challenge will be similar, except mock EM source catalogs will be created, and the target audience for the challenge will be LISA scientists.

6.2.1.4 Timeframe and workforce requirement

We envision this activity can take 1-2 years, and involve 6-8 team members (with 1-2 team members leading the effort for each source type). In future editions of data challenges, the effort would be reduced, using previous editions as templates, so we expect only 6 months to a year will be required.

6.2.1.5 Possible subpackages

Each mock challenge (for each distinct source type) can be thought of as a sub-package.

6.2.1.6 Dependencies

The subpackages here will have overlap with many other WPs in this document. Additionally, the mock data challenges will overlap with the DAFT WP and LDCWG.

6.2.1.7 List of projects

As defined above.

6.2.2 Electromagnetic and particle data analysis

6.2.2.1 Overview and Goals

This work package is for developing methods for joint analysis of LISA data plus EM or particle data. This includes several different types of analyses, such as (i) searches for EM and particle counterparts based on LISA source properties, (ii) usage of existing EM and particle catalogs, (iii) EM/particle inputs to real-time LISA signal search, (iv) follow-up prioritization schemes.

Our goals include creating a joint LISA+EM/particle analysis methods document, and developing plans for pipelines (and eventually the actual pipelines themselves) for joint LISA+EM/particle data analysis and for high-level astrophysical inference.

6.2.2.2 Deliverables

A joint LISA+EM/particle analysis methods document. This document will consider all four types of analyses above, and discuss, in depth, the related practical issues and required tools. Examples here include: given source properties measured by LISA for a MBH binary, including localization info, what is required to search existing EM source catalogs? What are the best catalogs to use? Where to find the tools to perform the search? What are the best observational strategies for follow-up with the EM telescopes?

Joint LISA+EM/particle data analysis pipelines, to jointly analyse GW data and information from tentative or expected counterparts, in fully consistent statistical frameworks. In practice, this will likely entail four separate pipelines for the four types of analyses mentioned above; and possibly further distinct pipelines for different types of GW sources.

Developing a high-level astrophysical inference pipeline. An example here includes: theoretical predictions for a source population will depend on assumed parameters (say, accretion duty cycles of MBHs). Such parameters can be inferred and constrained by jointly analyzing LISA and EM data.

Developing joint analysis pipelines for non-transient EM signals, such as the properties of sources in galaxy catalogs or intensity mapping data, with the GW sources detectable from LISA. Development of independent data analysis pipelines for different types of GW sources will be required.

6.2.2.3 Description of work

Writing the joint EM/particle analysis methods document will require experts well versed in astronomical databases and tools, as well as in statistical analyses and inferences.

6.2.2.4 Timeframe and workforce requirement

We expect the writing task for the joint EM/particle analysis methods document can be accomplished by a small group of 5-6 members and take 3-6 months. Creating the data analysis and inference pipelines are significantly longer-term tasks, which we expect to take several years.

6.2.2.5 Possible subpackages

The work can be naturally divided by source type as well as by EM band.

6.2.2.6 Dependencies

The pipelines will heavily depend on the sub-WAV1.2 in this document, and will overlap with the proposed data challenges in sub-DAFT.5.

6.2.2.7 List of projects

As defined above.

6.2.3 Multi-band gravitational wave analyses

6.2.3.1 Overview and Goals

This work package mirrors the previous one, but is for developing methods for joint analysis LISA data plus data from ground-based GW interferometers and/or PTAs, or other emerging GW detections methods.

The detections of stellar-mass compact object mergers by LIGO [1] and Virgo [9] provided a new class of sources potentially observable across different GW bands [5], from mHz (LISA) to Hz-kHz (LIGO-Virgo). LISA will observe these objects relatively early in their inspiral (weeks or even years prior to merger), providing complementary information to ground based observations, for example by measuring eccentricity and possibly environmental influences and spins, possibly shedding light on their origin and allowing precision tests of General Relativity. Merger times and sky locations will also be known in advance.

Possible multi-band detections of a stochastic GW background by LISA, PTAs and earth-based gravitational-wave detectors are also crucial for disentangling the origin of the signal (astrophysical and/or cosmological) and for imposing constraints on early universe and fundamental physics scenarios (such as the presence of phase transitions leading to cosmic strings, or the nature of the inflationary model)

With the coming upgrades to LIGO and Virgo, the completion of KAGRA [22] and LIGO-India [99], the planned construction of third-generation gravitational-wave detectors, the Einstein Telescope [145] and the Cosmic Explorer [2], and the potential addition of “mid-band” detectors such as DECIGO [102], AGIS [81], and AION [25], our frequency coverage will be broadened, and our ability to probe the stellar mass and intermediate mass black hole populations will improve by orders of magnitude by the time LISA is launched.

Individual MBH binaries are not expected to be detected by both LISA and PTAs, as LISA is sensitive to the mergers of $M_{\rm BH} \sim 10^{5-7}\,{\rm M}_\odot$ BHs while the PTAs are sensitive to more massive BHs with $M_{\rm BH} \sim 10^{8-9}\,{\rm M}_\odot$ BHs. The two GW frequency ranges probe complementary BH mass ranges, which are nevertheless part of the same underlying population of MBHs, necessitating tools to facilitate their joint interpretation.

Finally, ground-based detections can facilitate a targeted search in the LISA archival data stream for sub-threshold events.

6.2.3.2 Deliverables

A document will summarize the analysis tools required to jointly interpret multi-band GW data. For example, what steps are involved in fitting a stochastic GWB, predicted in a particular class of models, to LISA + PTA data? Likewise, in fitting parameters for single sources detected by both LISA and ground-based detectors. How to best perform a targeted search in the LISA data and to assess the fidelity of sub-threshold events?

A mock data catalog of multi-frequency sources will be created to facilitate preparatory analysis and pipeline development.

A data analysis pipeline for joint LISA and ground-based detections. This pipeline will have several features:

- Refinement of jointly fit source parameters
- Search LISA data for sub-threshold events, given information for a ground-based event
- Astrophysical interpretation: fit population models in different formation channels for stellar-mass binaries, and different seeding/accretion prescriptions for MBH binaries, to jointly fit and disentangle these channels.
- Fundamental physics interpretation: search for deviations from GR.

The pipelines can be applied to mock data catalogs, and result in several technical journal papers in advance of LISA's launch.

Another necessary tool will be a LISA data archive, containing the time-ordered data, parameter estimations, etc. which can be used by the network of ground-based GW detectors (such as LIGO, Virgo, KAGRA, LIGO-India, the Einstein Telescope, and Cosmic Explorer) and PTAs after the LISA mission.

6.2.3.3 Description of work

The joint multiband analysis document is envisioned to be a comprehensive overview, summarizing key points, and exisiting literature.

On the other hand, development of the pipelines will involve significant code development, and experts from all relevant bands, as well as input from theorists with expertise in modified gravity theories.

6.2.3.4 Timeframe and workforce requirement

Creating the joint analysis document will require at least three experts, in the PTA, LISA, and ground-based detector bands, as well as experts in modified gravity and astrophysical modeling, and will take 6-9 months.

Creating the pipeline will be a major undertaking, and will involve significant code development, as well as participation by astrophysics model builders and experts in modified gravity theories, and will likely taking several years.

6.2.3.5 Possible subpackages

The joint analysis document is a separate sub-package. The pipeline can be broken down into four distinct sub-packages, one for each of the four different source types as indicated above.

6.2.3.6 Dependencies

The pipeline development will have overlap with the LDC WG, and it will overlap with the mock data challenge proposed in DAFT.5. Additionally, inferences about deviations from GR, and their interpretation, will overlap with the Fundamental Physics Working Group's activities and WPSI.7.

6.2.3.7 List of projects

As defined above.

6.3 WPMMA.3: Preparations needed for LISA to make use of external data

Overview: This work package is to enable the use of information coming into the Consortium effort which is generated by other astronomers with outside resources.

The clearest example for this may be the use of "verification binaries": galactic binaries (mostly double white dwarfs) that are strong sources of GWs and are known and understood before LISA's launch. These have long been recognized as part of LISA's science program. However, more information about galactic binaries will be available for multimessenger applications beyond the verification objective. Furthermore, this external knowledge will grow over time through LISA operations, in particular from follow-up of systems detected by LISA.

Similarly, information from any definitive massive black hole merger counterpart events (e.g. in the X-rays by Athena) can be fed back into the analysis to better constrain these observations.

In general, we can divide this effort into two stages requiring different combinations of expertise and resources. The first stage involves *gathering* information from external sources through archival studies and observing campaigns. The second stage involves following the information through to its impact on Consortium objectives, encoding the information in a form needed for Consortium processing and addressing the consequent impacts and requirements.

Broadly, we anticipate applications of external data in 1) specific areas of Key Science Investigation, 2) the generation of "best-informed" GW inference products, and 3) the production of auxiliary data products to support community science application of LISA data.

Goals: We anticipate two main goals for this class of data. First, to provide input for external 'priors' to use in generating 'best informed' LISA posteriors and other inference data products. Priors are expected to play an especially large role in low-S/N detections by LISA and to break parameter degeneracies (for example, if an EM counterparts pins down the redshift and sky location). Second, to provide input for 'verification' observations where clear GW observations can be predicted before launch and may be applied in commissioning processes to verify that the instrument and analysis are functioning as expected.

Subpackages: See four subpackages below.

6.3.1 Gathering astrophysical information on galactic binaries

6.3.1.1 Overview and Goals

Tight Galactic white dwarf binaries can be guaranteed GW sources for LISA. This population of persistent GW sources can be observationally characterized prior to LISA's launch. This data set is important for both instrument calibration and science exploitation.

The goal of this subpackage is to collect and organize astronomical data on galactic binaries which can be applied in LISA development activities, and eventually in LISA operations. The more specific goal is to create and maintain an evolving catalog of verification binaries, with their pertinent information and references, collected on a dedicated website.

6.3.1.2 Deliverables

An easy-to-update website containing an evolving catalog of all known verification binaries, with their pertinent information and references, including expected S/N for LISA. The website will likely be published in document form at some stage.

6.3.1.3 Description of work

Designing and creating the website will involve searching through the literature, and finding and collating the relevant information and references for each source. Additionally, the expected GW properties of each source needs to be elucidated.

6.3.1.4 Timeframe and workforce requirement

We expect this activity can be accomplished in 1-2 months by 1 or 2 dedicated team members. It will however be important to keep the list of known VBs up-to-date. While the actual work involved would be less significant, a dedicated coordinator must be tasked with this.

6.3.1.5 Possible subpackages

N/A.

6.3.1.6 Dependencies

There is overlap with activities in the DAFT WP and the WPSI.2.

6.3.1.7 List of projects

As defined above.

6.3.2 Processing astrophysical data on galactic binaries for LISA

6.3.2.1 Overview and Goals

After observational data has been collected from external sources, more work is needed to prepare that data for explicit application in LISA data processing. Developing and applying these processes involves less interaction with other astronomers but more direct interaction with data analysis and sometimes instrumentalists within the Consortium. Preparing best-informed data products likely requires representing the external observations in the form of statistical prior models on gravitational wave system parameters. Preparing data for verification tests and for assessing the quality of available data for these tests may require working with the LISA Instrument Group.

Specific goals of this work package are:

- Identify the specific calibration goals and external input format
- Assess the number of VBs needed to meet the calibration goals
- Identify observational strategies to acquire the necessary VB sample prior to LISA's launch
- Ensure that the above sample is gathered and fully analyzed, collaborating with observers outside LISA as needed

6.3.2.2 Deliverables

The main deliverable here is the identification of a clear procedure, going from the catalog of VBs to their use in LISA's data analysis. The procedure should be implemented and performed on mock LISA data.

Additionally, a list of necessary new VBs, fully analyzed, are a deliverable.

6.3.2.3 Description of work

6.3.2.4 Timeframe and workforce requirement

Identifying the specific calibration goals and external input format will require working with the LISA Instrument Group and the Data Analysis working group.

Gathering and analyzing new VBs will likely require collaborating with observers outside LISA.

6.3.2.5 Possible subpackages

Identifying the specific calibration goals and strategies, and gathering and analyzing new VBs are two natural sub-WPs.

6.3.2.6 Dependencies

There is overlap with activities in the LDC WG, DAFT and WPSI.2.

6.3.2.7 List of projects

As defined above.

6.3.3 EM/particle/multi-band data on massive binaries for LISA

6.3.3.1 Overview and Goals

Massive BH binaries are subjects of intense searches across the EM spectrum, from radio, optical/IR, UV, and X-ray observations, as well as in particle detector data and by PTAs. There exist several dozen compact MBH candidates. It is expected that the nature and our understanding of these candidates can impact LISA operations. For example, prioritizing prompt LISA alerts might depend on the expected properties of 'afterglow' signals, which can be informed by these external observations.

The goal of this subpackage is to explore the potential impact of external data on MBH binaries on LISA, and to prepare for its application in LISA science investigations.

At this point, it is not yet clear what specific information about the MBHB population will be available and applicable in the delivery of LISA science products, but two classes of information seem likely to be important.

The first is any information about the MBH and galaxy populations and associations which might be needed in the search for electromagnetic counterparts to LISA observations of MBHBs. These counterparts are extremely important to many of LISA's potential key science investigations, and in the broader application of LISA data in community science. A similar historical example was the identification of galaxy catalogs by LIGO for use in identifying counterparts. What information will we need in hand, and in what form, in order to conduct LISA science, how do we collect it and share it appropriately?

A second mode to consider is the real-time collection of specific counterpart information associated with LISA mergers. If an association is made, how is that identification formalized, and what kind of additional information should be collected for LISA science applications? How quickly is this information needed for optimum science returns? How can this information be applied in further constraining formal "best-informed" GW inferences, and what other preparation is needed for LISA applications? As an example, how do we collect and formalize information about photometric and or spectral redshift measurements for application in standard siren cosmology studies?

6.3.3.2 Deliverables

The first deliverable is an assessment of whether and how external data on MBH binaries may impact LISA science investigations and the associated science ground segment (SGS) planning.

6.3.3.3 Description of work

In the absence of an individual "VB" in the MBH regime, this work package is hypothetical in nature. It will involve thinking through various scenarios and then *planning* the procedures and resources required to perform (or at least support) the realisation of those science opportunities.

For example, how might EM counterpart information be collected and processed in real time. How would both real-time and precursory information (populations, backgrounds?) be formally fed into LISA analysis, and how might real-time information impact analysis or operations. For example, should latency/scheduling be impacted if there is a unique quasar in LISA's sky location determined for an ongoing merger? Which specific LISA key science projects (e.g. cosmology with standard sirens) rely on external observations, and what data collection, data processing, and other preparations are needed to support those objectives?

6.3.3.4 Timeframe and workforce requirement

This work package is somewhat open-ended, but we envision it could involve 2-3 team members, with expertise in EM facilities and upcoming EM missions, modelling EM signals and populations of mergers involving MBHs, as well as consultation with the LDC WG and DAFT WP.

6.3.3.5 Possible subpackages

As defined above.

6.3.3.6 Dependencies

There is possible overlap with activities by the Astrophysics Working Group, and with WPSI.1, and other MMA sub-WPs.

6.3.3.7 List of projects

As defined above.

6.3.4 Other sources of astrophysical information

6.3.4.1 Overview and Goals

Other types of external information, such as population constraints (for all LISA source types), may need to be brought into the LISA analysis. Such information might be flowing into the project either before launch or in real-time operations. This may include, for example, characterizing ambient false alarm rates for potential EM counterparts and real-time EM localization of counterpart candidates, or making an assessment of the rates and populations of GW sources using EM observations (e.g. information on the prevalence and expected properties of massive BH seed formation from the collapse of supermassive stars, available from instruments such as Lynx, Athena, or JWST). For example, EM observations can be useful in distinguishing between the initial seeds. Such measurements from the EM observations can be used as a prior for the analysis of LISA data. Likewise, it is possible that some detected LISA EMRI sources may be associated with tidal disruption events.

Information from other classes of GW observations may also be applied for 'best-informed' analyses. In general, relatively little attention has been given to preparing this kind of information for LISA so this subpackage lumps together all other classes of incoming information (and is expected to expand over time).

6.3.4.2 Deliverables

The first deliverable is an assessment (roughly during phase A) of other areas beyond galactic binaries and MBHBs where externally collected data may be useful or essential in executing LISA's science program.

6.3.4.3 Description of work

Consult with documents and teams from the Astro WG, the Science Investigation WP team and members of the MMA team to identify potential inputs for LISA, including information constraining populations and rates for EMRIs, stellar-origin BHs (SOBHs) and other sources, as well as potential information from associated coincident observations (e.g. from ground-based observations of SOBHs).

6.3.4.4 Timeframe and workforce requirement

The initial workload is modest (0.1-0.5FTE for phase A). Subsequent work will depend on the results of the initial survey.

6.3.4.5 Possible subpackages

If some areas emerge which deserve specific focus and significant investment, these may be spun off in an additional (parallel) subpackage.

6.3.4.6 Dependencies

There is overlap with the other sub-packages in this section as well as with the DAFT WP.

6.3.4.7 List of projects

As defined above.

6.4 WPMMA.4: Communications, logistics and procedures

Overview: This work package explicitly focuses on interfacing with other astronomy and astrophysics communities, including GW communities focused on ground-based interferometers and PTAs.
Goals: The goals are to provide liaison with those communities, prepare arrangements for any data sharing efforts or joint operations, understanding needs for external communities for data release content and policies and associated tools, and related market development for LISA products.
Subpackages: See two subpackages below.

6.4.1 Data sharing

6.4.1.1 Overview and Goals

This subpackage focuses on sharing data with external communities. This might include sharing alerts and circulars, source catalogs, as well as tools (software, processing tools, likelihoods). Goals include developing the requirements and planning for all of the above, as well as developing the necessary specific external user interfaces.

More specific goals are:

- Identify the minimum set of data from the LISA analysis pipeline that must be commmunicated to enable prompt follow-up of LISA sources by EM instruments
- Determine content, efficient formats, and timing of data sharing more generally, i.e. for alerts and circulars, source catalogs
- Enumerate publicly shared tools (software, processing tools, full posteriors) and eventually develop these tools.

- Determine avenues, forums, and policies for such data sharing that maximize science return and efficiency, while respecting confidentiality.

6.4.1.2 Deliverables

A document presenting an in-depth analysis of the benefits and trade-offs of various data sharing approaches, assessing likely scenarios for responses of the astronomy community to different levels of data sharing.

A document deliberating and presenting detailed plans for the development of publicly shared tools.

6.4.1.3 Description of work

The main work here will consist of two parts. The first is to consider the impact of various data-release approaches and technicalities on the astronomy communities across all wavelength bands.

The second is to consider in more detail the actual tools required to implement data sharing, as well as software that should be shared with the data.

6.4.1.4 Timeframe and workforce requirement

We envision this work package as one of the key activities of the MMA team, which will employ a large fraction of the team, and will likely rely on recruiting experts from outside LISA (including broad community assessments via polls), and that this will be an on-going activity for several years, with continuous refinements of plans.

6.4.1.5 Possible subpackages

Data sharing policies and tool developments would naturally constitute two related, but separate sub-packages.

6.4.1.6 Dependencies

There is overlap with the DAFT and CAT WPs' activities.

6.4.1.7 List of projects

As defined above.

6.4.2 Develop and plan interfaces with target communities outside LISA

Beyond understanding the data sharing requirement, it will be necessary to develop the necessary specific external user interfaces. Additionally, specific MOUs and/or more informal liaisons will need to be developed and established. The goal of this subpackage is to identify MOU target communities and instruments and to establish the necessary formal and informal liaisons.

6.4.2.1 Deliverables

The deliverables of this work package are

- A list of target partners for possible MOUs, and preliminary language and content for these MOUs with each partner.

- Concrete descriptions of specific external user interfaces to be developed, and plans for these developments.

6.4.2.2 Description of work

The work will consist of several steps, including

- Identifying possible partners with whom it is feasible and scientifically beneficial to stipulate agreements with.
- Establishing preliminary agreements regarding information sharing and publication policies with a broad range of groups involved in EM counterpart searches and ground-based GW detectors.
- Devising a specific protocol for sending triggers to our partners, and interacting with those testing such protocols for refinement.

6.4.2.3 Timeframe and workforce requirement

The first steps of this effort can be performed by a small group of 5-6 dedicated team members, internally to the LISA MMA team. Once the targets for MOUs have been identified, a larger effort will be required to engage in discussions with staff at each target facility or project.

We envision the first part can be accomplished in 3-6 months, while the actual drafting of MOUs and the design and construction of data-sharing interfaces will take several years.

6.4.2.4 Possible subpackages

The efforts in this workpackage may be naturally divided into sub-packages involving different astronomical communities (i.e. optical, radio, X-ray).

6.4.2.5 Dependencies

This work package has overlap with many other sub-packages in this document, and high-level policies will have to be developed in consultation with the LSG and other LISA leadership.

6.4.2.6 List of projects

As defined above.

Chapter 7

SI – Science investigation

Introduction

The Science Investigation (SI) Work Packages (WPs) summarize and ensure the delivery of the main scientific goals of the mission, building upon the tools provided by the WPs of the previous groups and the associated pipelines. LISA has a formidable scientific potential, reaching far into the domains of astrophysics, cosmology and fundamental physics. It is therefore natural to group the mission goals according to those three categories.

On the astrophysics front, the LISA observatory has as prime objective to shed light into the processes of formation of the first seed BHs, formed in primeval halos, and upon which the MBHs, ubiquitous in todays galaxies, have grown. LISA will let us peer deep into the young Universe, when the first dark matter halos collapse and the first stars are forming, providing exquisite information on the mass spectrum of the earliest MBHs. LISA will also explore the hierarchical build up of MBHs by detecting the loud signal of coalescing MBHs of $\sim 10^6\, M_\odot$ across all cosmic ages to probe their concordant evolution with galaxies. GW information will likely be associated to electromagnetic counterparts in radio or optical/X-ray, which will help us to connect the realm of strong gravity to the physics of accretion and possibly jet formation. Exploiting the full LISA potential will require the building of astrophysically motivated interpretation pipelines to tell apart competing models for the evolution of these sources, as detailed in WPSI.1. At the opposite end of the compact object (CO) mass scale, LISA will detect a vast number of Galactic and extra-galactic binaries and it will probe the galactic population of white dwarfs, neutron stars and stellar origin BHs in binaries in a unique way, providing the first census of close binaries and shedding light into the processes of star formation and evolution in (interacting) binaries. LISA will also explore the Universe beyond our Milky Way Galaxy. WPSI.2 is dedicated to the exploitation of those sources, from the study of CO progenitors and their formation channel, to the exploration of the Galaxy's geometry and structure. Finally, the combination of massive and stellar objects is likely to produce a large number of extreme and intermediate mass ratio inspirals (EMRIs/IMRIS) of various nature. From an astrophysical standpoint, those are particularly valuable to understand the dynamics of dense nuclei and provide a census of quiescent MBHs at the low end of the mass function, where EM observations are scarce. Those are the goals detailed in WPSI.3.

LISA is also a unique cosmological probe. First of all, the coalescing binaries observed by LISA can be thought of as standard sirens, so we can estimate cosmological parameters (via GW-only observations combined in a statistical fashion, or via GW+EM observations) out to progressively higher redshift through the observation of SOBHs, EMRIs and MBHs. Assessing the potential of LISA as a cosmological probe and constructing dedicated pipelines is the subject of WPSI.4. Second, LISA has the potential of detecting SGWBs of astrophysical and/or cosmological origin, as detailed in WPSI.5. The detection (or lack thereof) of a stochastic background allows us to impose constraints on astrophysical population models, high-energy physics and, outstandingly, the very early Universe. GWs can, in fact, pierce through the "last scattering" surface generating the CMB and reveal SGWBs of primordial origin, possibly due to first-order phase transitions at the electroweak scale and beyond, topological defects, PBHs, and more.

Finally, LISA is a unique fundamental physics experiment. As detailed in WPSI.6, LISA may reveal the presence of dark matter (DM) through the study of a large population of signals from binary BHs, whose mass and spin distributions may have been affected by interactions with DM; detect minute dephasings in the waveforms from individual sources due to environmental DM effects (such as drag or accretion); and distinguish between BHs and hypothetical self-gravitating DM structures, like boson stars. In addition, DM may also give rise to completely new LISA signals, like transient and persistent GWs from ultralight boson clouds around fast-spinning BHs. In some models, DM particles could even directly couple to LISA. One of the main scientific goals of LISA, as detailed in WPSI.7, is to test the cornerstones of general relativity, such as Lorentz symmetry, parity invariance, the massless nature of gravitons, the existence of additional fields mediating the gravitational interactions and/or of extra dimensions. Last but not least, in WPSI.8 we discuss LISA's unique potential to test whether the Kerr solution really describes the BHs we observe in the Universe. This is important because the existence of BHs is connected to some of the deepest puzzles in modern physics, including the information loss paradox, the search for a high-energy (possibly quantum) completion of general relativity, the problem of singularities and the search for exotic fields, some of which could be DM candidates. Some of this physics could be observed as deviations from the standard waveform predictions of general relativity in the inspiral and/or ringdown, using EMRI waveforms to measure the multipolar structure of spinning supermassive objects, or (e.g.) by observing "echoes" in the post-merger signal.

Table 7.1 summarizes the Science Investigation Work Packages.

WP	Description	Priority
WPSI.1	Formation, evolution and electromagnetic counterparts of massive black hole mergers	3
WPSI.2	Demographics, formation, evolution and electromagnetic counterparts of stellar-mass compact objects	3
WPSI.3	Extreme- and intermediate-mass ratio inspirals: detection, characterization, population	3
WPSI.4	Estimation of cosmological parameters	3
WPSI.5	Characterization of stochastic backgrounds	3
WPSI.6	Elucidating dark matter	3
WPSI.7	Foundations of the gravitational interaction	3
WPSI.8	Testing the nature of black holes	3

Table 7.1: Science Investigation Work Packages, based on key LISA Science Objectives.

7.1 WPSI.1: Formation, evolution and electromagnetic counterparts of massive black hole mergers

The LISA observatory has as prime objective to shed light into the processes of formation of the first seed BHs formed in primeval halos (WPSI.1.1) upon which the MBHs ubiquitous in today's galaxies have grown. LISA will let us peer deep into the young Universe, when the first dark matter halos collapse and the first stars are forming, providing exquisite information on the mass spectrum of the earliest MBHs. LISA will also explore the hierarchical build up of MBHs by detecting the loud signal of coalescing MBHs of about a million solar masses across all cosmic ages to probe their concordant evolution with galaxies (WPSI.1.2). These are two major science deliverables of the mission, associated to WPSI.1.1 and WPSI.1.2, and require the building of astrophysically motivated modelling pipelines to tell apart competing models for the evolution of these sources. As MBH binaries may trigger or be associated to electromagnetic counterparts in radio, optical or X-rays, the interpretation of these counterparts deserves a separate WP (WPSI.1.3).

7.1.1 Studies of seed black holes and BH formation mechanisms

Black holes of $10^6 - 10^9\,\mathrm{M}_\odot$ are ubiquitous in today's massive active and quiescent galaxies [128, 104], and evidence is growing that BHs of about $10^5\,\mathrm{M}_\odot$ or less inhabit dense nuclear star clusters at the centers of bulge-less, disc galaxies [29, 133]. Furthermore, accreting SMBHs of $> 10^9\,\mathrm{M}_\odot$ are observed as luminous quasars (the so-called "hyper-luminous" AGN, with luminosities $> 10^{47}$ erg/s) at $z > 5$, close to the reionization epoch and beyond, up to $z \sim 7.5$ [30]. These systems, however, are probably just the tip of the iceberg of an underlying population of fainter (less-massive) high-z AGN [126], more poorly known in terms of BH demographics, birth and growth.

The detection of SMBHs ($> 10^6\,\mathrm{M}_\odot$) at redshifts as large as $z > 7$ suggests that their ancestors – BHs of smaller mass, often called "seeds" – must have formed even earlier ($z > 10$) inside primeval dark matter halos. The mass spectrum of the seeds upon which the giants have grown, as well as the growth mechanisms through which they become supermassive, are still unconstrained [160, 100].

Several possible seed formation scenarios have been proposed so far: *(i)* primordial BHs (PBHs) with masses ranging between 0.01 and $10^5\,\mathrm{M}_\odot$, that may have formed in the very early Universe from peaks in primordial curvature fluctuations; *(ii)* light seeds of about $\sim 10^2\,\mathrm{M}_\odot$ BHs, remnants of the first generation of massive, metal-poor/free stars (the so-called Population III stars) forming in the first structures emerging at the cosmic dawn, $z \sim 20-30$, when the Universe was less than ~ 180 Myr old [119, 97]; *(iii)* intermediate mass (or medium-weight) seeds of about $200 - 10^4\,\mathrm{M}_\odot$, that may have formed at later epochs ($z > 10$) in gas-rich, yet metal-poor, dense star clusters through runaway collisions of massive (even pre-main sequence) stars, fragmenting gas clumps or smaller BHs [121, 147, 118]; *(iv)* heavy seeds, up to $\sim 10^5 - 10^6\,\mathrm{M}_\odot$, forming in dark matter halos with virial temperatures above 10^4 K from the fast accretion of supermassive proto-stars collapsing directly into a BH – the so-called direct collapse BH (DCBH) scenario – promoted by H_2 photodissociation [39, 115], dynamical heating [146] or massive nuclear inflows during major gas-rich galaxy mergers [127].

Accretion of the surrounding cold gas and mergers with other BHs are thought to drive the growth of the seeds [100]. Alongside gas accretion, in either sub- and/or super-Eddington regimes, galaxy encounters are frequent in the hierarchical structure formation scenario, and seed BHs are expected to participate in the process of clustering of cosmic structures, possibly growing also via mergers [161]. Thus, during galaxy assembly ruled by mergers, the formation of "binary" seeds and "binary" massive BHs appears inevitable, and an increasing number of low-z quasar pairs is being discovered [79]. The clear prediction is that galaxy collisions are preferred sites where BHs of all flavors, from the seeds to the giants, form, grow, pair and coalesce, becoming among the loudest sources of GWs in the Universe.

LISA will shed light into the seed BH formation processes, as it can detect the inspiral signal of binary BH coalescences with masses down to $10^3\,\mathrm{M}_\odot$ (as measured in the source frame) out to $z \sim 20$, and the inspiral, merger, and ringdown of BH binaries with masses in the interval between about 10^4 and $10^7\,\mathrm{M}_\odot$, even beyond $z = 20$.

7.1.1.1 Overview and Goals

The aim of this WP is to collect, connect and coordinate theoretical studies and observations on the formation and growth of the first BHs at high redshift, the so called "seeds." One of the main goals is to deliver catalogues of seed BH coalescence events (investigating the mass spectrum, rates etc.) in the mass interval relevant to LISA at high z: $M \sim 10^3 - 10^6\,\mathrm{M}_\odot$. The goals of the WP are to find and develop the relevant expertise (in addition to codes and pipelines) within the Consortium, in order to:

- Identify the population of the earliest MBHs, coalescing before the epoch of cosmic reionization, and draw conclusions on the physical origin of the BH seeds at cosmic dawn.
- Infer the rates of the earliest BH seed coalescences, and draw conclusions on their occupation fraction in galactic halos.
- Investigate the existence of MBHs of about 10^5–$10^6\,\mathrm{M}_\odot$ at $z \sim 15$–20, and draw conclusions on the formation pathways of SMBHs shining as bright QSOs up to $z \sim 7$.
- Carry out a comprehensive investigation to identify GW signals from colliding BH seeds of different origins at high redshifts.
- Set limits on the time lapse between formation and coalescence of the observed MBH merger events to indirectly infer (as yet unknown) rates of MBHs sinking via dynamical processes in high-redshift dark matter halos.
- Explore whether heavy BH seeds continue to merge in halos during the epoch of shining of the brightest QSOs (at $z \sim 7$) down to cosmic high noon (at $z \sim 2$, when the bulk of the star formation takes place in all the galaxies), to draw preliminary conclusions on channels of potential delayed/continuous formation, on the long-term growth of seeds, and/or delayed pairing.
- Investigate new BH formation channels driven by current and future GW detections, and their implications for high-z SMBH formation scenarios.

7.1.1.2 Deliverables

List of pre-launch deliverables (related to simulated data):

- Catalogues of the (simulated) earliest merging (seed) BHs of different origins (PBHs, light, medium-weight and heavy seeds) in the mass interval between about 10^3 and $10^6\,\mathrm{M}_\odot$ and in different environments. To be converted into waveforms catalogues to simulate the LISA sky and to be used in model selection pipelines (inference pipelines).
- Mock catalogues of seed BHs and their host galaxy properties at high redshift. Studies of possible criteria to detect, distinguish and select seed populations from the observational point of view (e.g. best observational strategies and/or selection criteria in surveys).
- Model selection pipelines to determine the properties of the earliest seed BHs. Combination of parametric semi-analytic models and observed distributions to pin down relevant parameters and discriminate between BH formation models/populations.

Post-launch deliverables, related to LISA findings/observations in terms of consortium publications of key results and implications for models/theory of seeds formation. The following list is connected to the item "Publication and archive of LISA finding" in the Timeframe section.

- Publications describing the properties of the earliest (observed) $10^3 - 10^4\,\mathrm{M}_\odot$ merging BHs and implications of LISA findings on the medium-weight seeds formation scenario.
- Publications describing the properties of the earliest (observed) $10^4 - 10^6\,\mathrm{M}_\odot$ merging BHs and implications of this findings on models of monolithic collapse of gas clouds for the formation of heavy BH seeds.
- Publications describing the properties of the earliest (observed) merging BHs and implications on the scenario invoking the formation of PBHs.
- Publications comparing the (observed) mass spectrum of the earliest BHs with the low-redshift BHs in the corresponding mass range, as inferred from the observations of EMRIs.
- Publications on the effect of weak lensing on the estimate of luminosity distance of detected high-redshift signals.

7.1.1.3 Description of work

The interpretation of LISA observations will be supported by theoretical studies combining state-of-the-art semi-analytical models (which are preferable for statistical purposes) with advanced numerical/hydrodynamical simulations (with increasing resolution) already available in the literature developed by Astro-WG members in collaboration with the scientific community at large. This approach will enable us to study in details how and when the first binary BHs form and evolve inside early galaxies, along the formation of cosmic structures.

The achievement of the aforementioned goals will rely on the development of flexible parametric semianalytic models (SAMs), to allow the exploration of the vast parameter space connected to the birth and growth of MBHs along the cosmic history. The SAMs will include parametric prescriptions for all the relevant physics driving the formation of MBH seeds, their evolution and the dynamics of MBH binaries and multiplets, extracted from analytical as well as numerical simulations at different scales, either available in the literature or generated in liaison with the Astro-WG when specifically needed. The SAMs will include:

- Implementation/improvement of physically motivated prescriptions for the different formation mechanisms of seed BHs according to high-z environmental properties building up on existing models/simulations available in the literature/community.
- A systematic treatment of the dynamics of seed BHs in binary/multiple systems. This will use models already available, integrated by new high-resolution (small-scales) numerical simulations covering a wide space of physical parameters in different environments when necessary.
- Implementation of physically motivated prescriptions to trace the cosmological evolution of binary BH seeds (formation, growth, merger timescales, etc.), extracted from targeted high-redshift hydro simulations already available in the literature, or ran ad hoc if/when necessary.
- Modeling of the statistical properties of "cosmological" BHs in binaries, triplets and quadruplets extracted from the SAMs (mass, spin and redshift distributions versus cosmic time; merger rates).

The SAMs will provide the basis to carry out a number of preliminary studies within the Consortium, including:

- Creation of catalogs of realistic MBHB populations to inject in mock LISA data, and to test source and parameter recovery.

- Match of merging binaries to their hosts and generation of catalogs of host properties, to be used as input for MM studies.

- Creation of a likelihood function to match observations with the parametric SAM model. Embedding into a Bayesian framework to address the "inverse problem."

- Preliminary studies addressing the inverse problem with mock LISA observations: (i) studies of the role of different seed populations and of high-z seed mergers in the formation/growth of $z > 6$ SMBHs; (ii) recovery of merger time delays and constraints on MBHB dynamics; (iii) recovery of spin distributions in connection to accretion history.

- Development of observational strategies based on theoretical predictions, to uncover high-z seed host galaxies (possibly distinguishing the birth environment of different seed populations) using future facilities operating in different energy bands, such as ELT, JWST, Athena and SKA, jointly with LISA.

- Studies of the potential match in redshift space between EM signals from forming BH seed and GW signals from merging seeds combining model predictions (e.g. BH accretion rates and host galaxy properties) with radiation emission/transport models available in the literature, or developed within the Astro-WG if needed.

7.1.1.4 Timeframe and workforce requirement

The work described above will be the result of a running effort. SAMs will be initially developed building up on the most updated existing theoretical findings and will be continuously updated as better prescriptions become available from more realistic/refined simulations either coming spontaneously from the community or stimulated directly by the needs of the WP. We foresee the timeframe/workforce requirement to be:

- For development and implementation of seed formation models, including survey of the literature, identification of state of the art models, etc: ~ 3 years (0.3/0.4 FTE).

- For development and implementation of MBH binary and multiplet dynamics: ~ 2 years (0.3/0.4 FTE).

- For creation of a likelihood function: ~ 3 years (0.3/0.4 FTE).

- For preliminary studies addressing the inverse problem with mock LISA observations: $\sim 4-5$ years (0.3/0.4 FTE), starting from year 3. This requires a "beta version" of a SAM and an associated likelihood function.

- For the development of EM/GW observational strategies in different energy bands: $\sim 3-4$ years (0.3/0.4 FTE), starting from year 3. This is conditional to the development of appropriate EM models.

- For the theoretical studies of the potential match of EW and GW signals in redshift space: $\sim 4-5$ years (0.3/0.4 FTE), starting from year 3. This relies on interfacing model outputs with radiative transfer codes (need additional time to adapt input/output data format, test, run RT software and/or develop ad hoc tools by the WG.)

Storage space requirement for (simulated) data catalogues and tools (codes and routines): $\sim 50-100$ TB total disk space on computer clusters and > 50 TB for storage systems, including backup and redundant storage).

7.1.1.5 Possible subpackages

- Theoretical and numerical studies of the formation and dynamics of massive (metal free/poor) stars, stellar origin BHs (light and medium-weight seeds) and heavy seeds in the high-z Universe.
- Numerical studies of the dynamics of seed BHs (binary/multiple BH interactions) in galaxy collisions at high redshift.
- Development of cosmological models and simulations for the formation, evolution, and clustering of dark matter halos with improved (sub-grid) prescriptions for BH seed formation and dynamics.
- Construction and maintenance of (simulated) BH seeds and binary/merging seed catalogues.
- Development of model selection pipelines to discriminate between competing models/seed populations.
- Development of models to analyze the possible signatures of PBHs in LISA sources.

7.1.1.6 Dependencies

- Dependent on waveforms and parameter estimation codes for MBH and IMBH mergers (WAVWP and DPEWP).
- Connection and overlap with studies of MBH binaries on large scales (WPSI.1.2), of EM counterparts (WPSI.1.3, WPSI.4, WPMMA.1, WPMMA.2), and identification of high-z seed host galaxies using future facilities such as ELT, JWST, Athena and SKA, jointly with LISA (WPSI.4, WPMMA.3.3).
- Connection and overlap with studies of weak lensing effects on the estimate of luminosity distance for high-redshift signals (WPSI.4).
- Connection and overlap with studies of EMRIs/IMRIs (WPSI.3).
- Connection with stellar-mass LISA sources (WPSI.2).
- Connection with tests of the nature of black holes (WPSI.8) and studies of the SGWB from PBHs (WPSI.5).
- Connection with CATWP: tools for (modelled and unmodelled) source catalogues release/interface (CATWP).
- Contribution to Data products 2 (catalogue of MBH mergers), 3 (catalogue of IMBH mergers and IMRIs), 4 (catalogue of EMRIs), 5 (catalogue of SOBBHs).
- Related to Data products 0 (combined catalogue of all sources), 6 (catalogue of other modelled transients), 7 (catalogue of unmodelled transients) and to External Data products 3 (pulsar timing data) and 5 (catalogues of galaxies and quasars).

7.1.1.7 List of projects

In this Section we list possible (relatively short-term) projects related to the goals of WPSI.1.1.

- Population III BH binaries. Survey and, where necessary, integration of theoretical and numerical studies of Pop III star formation and dynamics, to distill recipes to be included in the WPT SAMs.

- Dynamics of SOBHs. Collect studies of mass segregation and possible runaway stellar/BH mergers in dense nuclear star clusters at high redshifts, to understand the properties of (merging) SOBHs (in comparison with MBHs) and improve WPT SAMs prescriptions.
- Direct collapse BH (DCBH) scenario. Analyze the plethora of existing/ongoing theoretical studies of the fragmentation of massive (metal-free/poor) gas clouds and the formation of heavy BH seeds in the high-redshift Universe, with improved astrochemistry and radiative transport, to build a comprehensive view of the heavy seed formation process to be described in the WPT SAMs.
- Merger-driven DCBH formation. Extraction of a recipe for the formation of MBHs via direct collapse during gas inflows induced by gas- and metal-rich galaxy major mergers at high redshift ($z > 6$) based on available theoretical studies.
- Seed BH properties and implications for LISA. Collecting different literature/community studies of light, medium-weight and heavy seed properties as a function of redshift and environmental (host galaxy) properties: mass spectrum (birth mass function), spin, number density etc., to compare and connect through/within the WPT SAMs, the different MBH formation scenarios and their implications for LISA detections.
- Forming “cosmological” BH binaries (BHBs). Comparing/surveying theoretical studies of the formation of seed BH binaries pairing during halo-halo collisions and via dynamical interactions of multiple systems within single halos (“in situ”) at high z, to assess BHB populations studies (e.g. mass spectrum, occupation fraction, mass ratios and the dependence on the seed formation channel), relevant for WPT SAMs.
- Growing “cosmological” BHBs. Collecting (or conducting if missing) comprehensive studies of the accretion/growth of seed BHBs (before merger) at early cosmic epochs and implications for the BHB mass spectrum evolution.
- Dynamics of “cosmological” seed binaries. Studies and comparison of the merger rates, probability and typical timescales (hence redshift distribution and detectability) of seed BHs pairing in halo-halo collisions within the WPT SAMs and with other models available in the literature (possibly outside the community). Including rapidly/efficiently growing light seed binaries (Population III star remnant BHs) entering the LISA band.

7.1.2 Studies of SMBH binaries and connection to galaxy assembly

7.1.2.1 Overview and goals

In the aftermath of a collision between two galaxies, the SMBHs residing at their centres sink via stellar and gas-dynamical processes or multiple (3–4 body) interactions, eventually forming a close Keplerian binary fated to coalesce [38]. If, according to the current paradigm of galaxy formation, dark matter halos grow through clustering [51], then SMBH binary coalescences appear inevitable. In this perspective, SMBH binaries pin-point the places where galaxies assemble and grow. LISA can detect the coalescence of SMBH binaries with SNR of 50 and higher, in the mass interval between 10^4 and a few 10^7 $M_\odot$, across all cosmic ages – from $z \sim 20$, through the epoch of the rare brightest QSOs at $z \sim 7$, down to cosmic noon, when the star formation history and AGN activity have their maxima, and the local Universe.

The most important goals of this work package are listed below:

- Study the distribution in redshift of the MBHB coalescences, to draw conclusions on possible delays between time of formation of the binary and time of coalescence, to learn about the dissipative mechanisms driving MBHs toward coalescence, and study the delay-time distributions by matching the data with population synthesis models.
- From the rate of MBHB coalescences, draw conclusions on the merger rate of galaxies and on the relative contribution between major and minor mergers from the distribution of their mass ratios.
- Analyze the set of observed MBH coalescences, to draw conclusions on their growth mechanisms through accretion and mergers with other MBHs from the observed masses, mass ratios, and spin distributions.
- From the spin distribution of the merging MBHs, draw conclusions on the nature of the accretion process (e.g. whether the accretion flow is preferentially coherent or chaotic).
- Compare the population of merging MBHs with the MBHs sites of EMRI events, and draw conclusions on the population of “quiescent” MBHs versus the population of “interacting” MBHs.
- Learn whether MBH mergers retain memory of large initial eccentricities that might indicate interactions with a third MBH and activation of Kozai–Lidov resonances or chaotic three-body encounters.
- In case of a joint EM + GW detection, correlate the properties of the EM signal with the properties of the two merging MBH, and compare with those that did not show a counterpart to draw conclusions on their environment.

7.1.2.2 Deliverables

Pre-launch deliverables:

- Studies of SMBH pairing
  - at cosmological scales (to study the effect of large-scale structure);
  - at galactic scales (to study the effect of baryons);
  - at circumnuclear/circumbinary scales (to study, e.g. spin evolution).

Post-launch deliverables:

- Models of (i) MBH growth mechanisms (accretion versus coalescences), in relation to the distribution of LISA-detected masses, mass ratios, and spins; (ii) the delay between binary formation and coalescence, in relation to the redshift distribution of LISA-detected coalescences; (iii) the LISA-detected coalescence rate and distribution of mass ratios of SMBHs, in relation to the (minor and major) merger rate of galaxies; (iv) the LISA-detected spin distribution of coalescing SMBHs and EMRIs, in relation to the nature of the accretion process (e.g. coherent versus chaotic accretion flow; interacting versus quiescent); and (v) the LISA-detected populations of SMBH coalescences and EMRIs in relation to the population of interacting and quiescent SMBHs.

- Distributions, from the set of observed MBH coalescences, of (i) *masses* (including comparisons to those resulting from EM observations, possibly at selected epochs, within narrow redshift bins), to learn about the overall growth of MBHs); (ii) *mass ratios*, to infer properties of the underlying host galaxies; (iii) *spins* (including comparisons with the spins of nearby isolated MBHs and with those of MBHs hosting EMRIS), to discuss the implications of the nature of the accretion flows; and (iv) residual *eccentricities*.

- Description of how the parameters of the observed GW events (masses, mass ratios, spin orientations, and residual eccentricities) fit within global scenarios of galactic collisions resulting from state-of-the-art simulations.

7.1.2.3 Description of work

- Continued development of numerical algorithms and sub-grid models to improve the quality of simulations (hydrodynamical, N-body cosmological/isolated simulations; direct N-body simulations).

- Extract catalogues of simulated MBH pairs and binaries from numerical simulations, both those already available in the literature – developed by Astro-WG members or by the scientific community at large – and new simulations with increased resolution:

  - Cosmological N-body, hydrodynamical simulations of SMBHs in high-redshift galaxy mergers.

  - Cosmological N-body, hydrodynamical simulations of SMBHs in low-redshift galaxy mergers.

  - Isolated N-body, hydrodynamical simulations of SMBH binaries with initial conditions consistent with updated cosmological simulations.

  - Direct N-body simulations of low-redshift (gas-poor) galaxy mergers: interactions between SMBHs and stars.

- Provide simulations for population inference studies, which however are *beyond the scope of this specific sub-WP.*

7.1.2.4 Timeframe and workforce requirements

- Construction of a catalogue of mass, mass ratio, spin, and residual eccentricity distributions of observed MBH coalescences: L + ∼2 years (1.0 FTE).

- Improvement of numerical algorithms and sub-grid models; running and analysis of numerical simulations (cosmological, N-body, hydrodynamical; isolated, N-body, hydrodynamical; and direct N-body): ∼10 years (0.5 FTE).

- Development of novel population synthesis models for MBHBs using cosmological simulations and improved sub-grid physics. Carry out periodic upgrades and refinement of the models, to update recipes in relation to advances in knowledge on how galaxies grow and evolve from the then-current observations, e.g. with ALMA and JWST: ∼10 years (0.5 FTE).

- Construction of an archive of "galaxy mergers" to instruct on the search and identification of the GW signals: ∼3 years (0.5 FTE).
- Development of the pipeline to address the inverse problem: ∼5 years (0.5 FTE).

7.1.2.5 Possible subpackages

- Studies of SMBH binaries at high redshift.
- Studies of SMBH binaries at low redshift.
- Studies of SMBH pairing at large scales.
- Studies of SMBH pairing at small scales.

7.1.2.6 Dependencies

- Waveform and PE codes for SMBH binaries (WAV3.2, DPE.3).
- Source catalogues (CATWP).
- Collaboration with the LISA Astrophysics Working Group communities working on population synthesis models, on AGN, and on galaxy formation.
- Large overlap with WPSI.1.1 and WPSI.1.3.
- Overlap with WPSI.3 (EMRIs/IMRIs).
- Overlap with WPMMA.1, WPMMA.2, WPMMA.3.3.

7.1.2.7 List of projects

- Theoretical and numerical studies of MBH pairing and binary formation and of MBH growth and activity, for different epochs, environments, and scales:

  - Theoretical and numerical models of MBH growth mechanisms (accretion versus coalescences).

  - Theoretical and numerical models of the delay between binary formation and coalescence.

  - Theoretical and numerical models of coalescence rate and distribution of mass ratios of SMBHs.

  - Theoretical and numerical models of the spin distribution of coalescing SMBHs and EMRIs.

- Extraction of catalogues of simulated MBH pairs and binaries from existing numerical simulations (both cosmological and isolated; N-body, hydrodynamical and direct N-body; high and low redshift).

7.1.3 Analysis of joint EM+GW MBHB events

7.1.3.1 Overview and Goals

Coincident detections of EM and GW signals from coalescences of MBHBs are considered an observational grand challenge. They have the potential to provide unparalleled understanding of the evolution of MBHs in the context of the large scale structure in the universe [104, 96]. The outcome of this scientific endeavour directly depends on our ability to identify MBHB systems characterized by both messengers. The feasibility of such observations is determined by the properties of accreting MBHBs and of the environments in which they reside, as well as by the technical capabilities of EM and GW observatories. Furthermore, our understanding of the assembly of MBHs along the cosmic history will uniquely depend on our ability to interpret these observations and determine the properties of the MBHs and their hosts. The synergistic EM and GW observations and their analysis are therefore key to achieving the full LISA potential. The focus of this work package is on the modelling and interpretation of EM counterparts to GW mergers of MBHBs, as well as on the development and curation of archives of modeled and observed EM+GW events.

The most important goals of this work package are listed below.

- Identify and study MBHB hosts to high redshifts.
- Understand properties of the close environments of merging MBHs and constrain the underlying physics of their emission, e.g.: what is the spectral energy distribution of the emitted light? Is there evidence of jets? Can we extract the properties of the accretion flow?
- Determine whether EM counterparts can provide independent constraints on the MBHB parameters and quantify which MBHB systems will benefit the most from coincident GW-EM detections.
- Connect the nature of EM emission with the parameters of merging MBHs. E.g. are the MBHs associated with EM counterparts preferentially highly spinning? Are their spins aligned?
- Compare findings with state of the art models (e.g. full GRMHD simulations) and develop a coherent picture of the MBHB evolution and signatures in the inspiral-merger-post merger phase.

7.1.3.2 Deliverables

- Guidelines to the broader scientific community, involved in development of models and simulations of EM+GW signatures of inspiraling and merging MBHBs, on results pertinent to the Consortium. The guidelines can be formulated in terms of the sensitivity, relevant figures of merit, and anticipated precision of the LISA measurements. The initial case studies can originate within the Consortium, to set the standard and provide an example, but the overall development can be done within the broader scientific community.
- A template bank of EM counterparts (multiwavelength light curves and spectra) compiled from the above simulations and models adhering to a uniform set of criteria defined by the Consortium, mirroring the gravitational waveform template bank.
- Tests of multimessenger potential on mock LISA and EM data. Publication of the results.
- Theoretical framework for interpretation of the joint EM and GW datasets in terms of the source parameters. Delivery of a pipeline for astrophysical inference.

- Publication of joint GW-EM observations of individual LISA events (requires MOUs with partner EM observatories).
- Archive of all joint GW-EM detections with all the relevant data (requires MOUs with partner EM observatories).

7.1.3.3 Description of work

- Continued collaboration with the broader scientific community in development of targeted theoretical models and predictions that will lead to the first unambiguous identification of an GW-EM event.
- Development and maintenance of a template bank of EM counterparts to GW.
- After the first detection, determination which EM signatures are more likely to be observed than others and subsequent prioritization of observational strategies.
- Streamlining of this procedure and recommendations to the observational community in preparation for subsequent / multiple detections of GW-EM events.
- Interpretation of the first unambiguous identification of an GW-EM event.
- Determination which subgroup of theoretical models and pipelines are necessary (or missing) for astrophysical inference and interpretation of the GW-EM signatures and subsequent prioritization of modeling strategies.
- Streamlining of this procedure in preparation for analysis of subsequent detections of multiple GW-EM events.
- Concurrent publication of joint GW-EM observations of individual LISA events.
- Development and curation of a comprehensive archive of GW-EM detections.

7.1.3.4 Timeframe and workforce requirements

- Theoretical studies of EM counterparts: ongoing (0 FTEs).
- First simulations (case studies) of MBHBs in gas including radiative transfer: $\sim 3+$ years (at least 1 FTE).
- Development and maintenance of a template bank of modeled EM counterparts to GW events: $\sim 5+$ years (at least 1 FTE).
- Development of a pipeline for astrophysical inference from joint observations: 3+ years (at least 2FTEs).
- First tests of multimessenger potential on mock EM and GW data using the above pipeline: $\sim 3+$ years (at least 2 FTEs involved in the EM and GW side of modeling, respectively).
- Interpretation and publication of the first GW-EM event: L+0 years (at least 2 FTEs involved in the EM and GW side of PE, respectively).
- Interpretation, publication and archiving of subsequent GW-EM events: L+1 years (at least $2-3$ FTEs from this point on to provide redundancy and capacity to work on multiple events in parallel).

7.1.3.5 Possible subpackages

- Theoretical and numerical studies of EM counterparts to merging MBHBs.
- Construction and maintenance of a template bank of modelled EM counterparts (multi-wavelength light curves and spectra) and corresponding GW waveforms.
- Pipeline for inference of physical properties of MBHBs and their environments from the GW-EM datasets.
- Construction and maintenance of the archive of joint GW-EM detections.

7.1.3.6 Dependencies

- Connection with DPE.1, DPE.3, WPMMA.1, WPMM.2, WPMMA.3.3,3.4 for the identification of EM counterparts and the development of codes for mock simulations of GW signals plus EM counterparts.
- Waveforms and PE codes for MBHBs (WAV.3, DPE.3).
- Source catalogues (CATWP).
- MOU with partner observatories and protocols (CAT.2, CAT.3, WPMMA.4).
- Significant overlap with studies of the MBHB population along the cosmic history (WPSI.1.1, WPSI.1.2).
- Collaboration with analytical and numerical modellers of MBHBs in gas rich environments on all scales.

7.1.3.7 List of Projects

- Theoretical and numerical studies of EM counterparts to merging MBHBs (ongoing).
- Inference of physical properties of MBHBs and their environments from the GW-EM datasets (ongoing).
- Investigation of which MBHB systems will benefit the most from coincident GW-EM detections (ongoing).

7.2 WPSI.2: Demographics, formation, evolution and electromagnetic counterparts of stellar-mass compact objects

According to the stellar initial mass function, the Milky Way hosts about $\sim 10^{10}$ white dwarfs (WDs), $\sim 10^{8}$ neutron stars (NSs) and $\sim 10^{7}$ black holes (BHs). A fraction of them are members of binary systems and might be accessible to LISA as individual sources or as part of a foreground emission. The Galactic GW signal observed by LISA will be dominated by WD binaries: 11000 of them are expected to be observed in just one year [107, 105, 148, 113, 52]. Approximately two dozen of these WD binaries will be globular-cluster sources [108]. Moreover, a number of binaries are accessible to electromagnetic (EM) facilities: we expect hundreds to thousands of joint GW-EM observations of WD binaries with LISA and Gaia or LSST [107, 106, 53].

7.2.1 Verification Binaries

7.2.1.1 Overview and Goals

There are roughly 20 WD binaries known from EM surveys [112, 60] that are expected to be observable by LISA. These already well studied binaries can be considered as verification binaries (VBs) for LISA: they will be used to validate instrument performance and to assist data analysis. In addition, current and forthcoming surveys (Gaia, LSST, ZTF, BlackGEM, GOTO, etc.) are expected to discover a dozen of WD binaries before LISA's launch. These new binaries will be added to the sample of VBs. VBs that can be completely characterized before LISA's launch will enable precise tests of theoretical models for tides and mass transfer in compact binaries [53]. The most important goals of this work package are listed below.

- Perform high precision tests of astrophysical models in detached and interacting ultra-compact binaries.
- Use VBs for instrument calibration and validation of analysis.

7.2.1.2 Deliverables

- Pipeline software which produces GW information as a function of source parameters (see e.g. [117]).
- Publication of VB catalog with GW-EM information that is appended based on new discoveries and finalized at the end of the mission.
- Astrophysical implications from the "pristine sample" of fully characterized VBs. Publication of results.

7.2.1.3 Description of work

- Continued development of pipelines to predict GW signals for VBs.
- As EM surveys discover and characterize new VBs, update public catalog and continue theoretical studies of astrophysical implications of new discoveries.
- Assess quality of known VBs (prior to launch) and newly discovered VBs as time/phase references for other analyses (e.g. bridging gaps in the data).
- Once all VBs are observed and characterized with GWs (end of mission), produce final "pristine sample".
- Analyze predicted and observed GW signatures of VBs to improve precision characteristics of the population of Galactic binaries.

7.2.1.4 Timeframe and workforce requirements

- Pipeline development for GW characterization: ongoing (1 FTE).
- VB catalog development and maintenance: begin as soon as possible (0.3 FTE).
- Astrophysical constraints based on VB discoveries: ongoing - L+1 years (0.5 FTE).
- Analysis of predicted and observed GW signatures: L+1 years (0.5 FTE).

7.2.1.5 Possible subpackages

- EM catalog maintenance (pre-launch).
- Tests of theoretical models in binary evolution (tides, mass transfer, common envelope).
- GW characterization pipeline.

7.2.1.6 Dependencies

- Significant overlap with resolved Galactic binaries (WPSI.2.3).
- Depends on tool development for data analysis frameworks and libraries (DAFT.3, DAFT.5), assessing mission design (DAFT.4), and data quality indicators (DAFT.3).
- Source catalogs (CATWP).
- WPMMA.1, WPMMA.2, WPMMA.3.1,.3.2

7.2.1.7 List of projects

- Inference of GW properties for current and discovered VBs (ongoing).
- Theoretical studies of interacting compact binaries (ongoing).
- Implications of observed VB population for theoretical GB formation channels (3-L+1 years).

7.2.2 Multi-band GW sources

7.2.2.1 Overview and Goals

GW150914, the first direct detection of GWs by ground-based interferometers [3], has opened exciting perspectives for the possibility of multiband GW observations [151]. While GW150914 appears to be quite an exceptional event (relatively nearby, $z \sim 0.1$, and with total mass $\gtrsim 60 M_\odot$), under reasonably optimistic assumptions, LISA may be able to observe several BBHs from weeks to years before their merger. Advanced LIGO and Virgo (or more likely their upgrades and/or third-generation ground-based detectors) will capture these events during their merger. Several additional multiband events can be recovered by starting from ground-based detections and then looking back into LISA data for sub-threshold events [166].

Capturing a multiband event with LIGO has several exciting implications for GW astronomy. An early LISA detection can lead to better sky localisation ($\sim 1\text{deg}^2$) for EM follow-up. Measuring BBH eccentricity in the LISA frequency range can provide a significant clue to interpret the binary formation channel [134, 135, 55, 18, 83, 109]. The most important goals of this work package are listed below.

- Constrain binary evolution using ground- and space-based gravitational wave observations.
- Determine formation channels for binaries containing NS and BH components.

7.2.2.2 Deliverables

- Public catalog of GW events which are observable by both LISA and LIGO-Virgo-KAGRA.
- Pipeline software which uses different models (e.g. for eccentricity) to generate the GW signal in LISA based on ground-based detections of GW mergers.
- Predictions of BNS/NSBH/BBH populations based on current understanding of formation and evolution of these binaries. Publication of the results.
- Astrophysical implications for the joint analysis of ground- and space-based BNS/NSBH/BBH populations. Publication of the results.

7.2.2.3 Description of work

- Maintain catalogs of GW mergers from ground-based detectors (LIGO-Virgo-KAGRA).
- Develop pipeline to model GW signals and uncertainties in LISA band based on the best known parameters from LIGO-Virgo-KAGRA GW sources.
- Simulate the expected LISA catalog of BNS/NSBH/BBHs based on ground-based GW observations only.
- Compare GW-based simulated catalogs to population simulations to infer formation channels of BNS/NSBH/BBH populations.
- Characterize the likelihood of joint detections by LISA and ground-based detectors based on different formation scenarios.
- Analyze joint ground-based and space-borne observations to characterize the similarities and differences of the population.
- Investigate connections between catalogs from ground-based and space-borne GW observatories and characterize the implications of the differences.

7.2.2.4 Timeframe and worforce requirements

- Development/maintenance of a catalog of ground-based GW mergers: begin as soon as possible (0.3 FTE).
- Simulation of LISA catalogs based on ground-based GW observations: ongoing - L+1 years (1 FTE).
- Analysis of joint space-borne and ground-based observations: L+3 years (0.7 FTE).

7.2.2.5 Possible subpackages

- Multiband observations of stellar-mass compact objects.

7.2.2.6 Dependencies

- Resolved Galactic binaries and extra-Galactic binaries should be connected to observed GW mergers from ground-based observatories (WPSI.2.3, WPSI.2.4).
- Source catalogs (CATWP).
- MOUs with LIGO-Virgo-KAGRA and other Earth-based detectors, WPMMA.4.
- WPMMA.1, WPMMA.2.3., WPMMA3.3.

7.2.2.7 List of Projects

- Predictions of stellar-mass compact objects observable by LISA based on LIGO-Virgo-KAGRA observations (1-3 years).
- Predictions of multi-band population of BBHs.
- Inference of stellar-mass compact object formation channels from joint ground-based and space-borne observations (L+3-5 years).
- Inference of redshift-dependent compact object populations (L+3-5 years).

7.2.3 Resolved sources

7.2.3.1 Overview and goals

Resolved stellar-mass binaries represent a unique target for LISA science. The formation channels of WD binaries [132], as well as NS and BH binaries [122], are a matter of intense debate. The large sample of Galactic binaries that LISA can detect in our Galaxy (including possibly the first detection of a Galactic BBH or NSBH binary) will help to shed light on this open question. In addition, the observation of several thousand WD binaries will give a significant contribution to the characterization of the Milky Way's structure and to the measurement of the mass of our Galaxy. The most important goals of this work package are listed below.

- Constrain binary evolution for WD binaries, including those with stripped stars, NS, and BH companions.
- Characterise the Galactic population of BH and NS binaries.
- Discover extra-Galactic stellar-mass sources.
- Constrain the Galactic structure and that of the Local Group.

7.2.3.2 Deliverables

- Up-to-date population synthesis software. This includes, but is not limited to COSMIC [52]; MOBSE [123, 90, 89]; SeBa [143, 158]...
- Simulated catalogs of Galactic and extra-Galactic populations to be used in LDCs.
- Analysis pipeline to construct Mock LISA observations from simulated catalogs.
- Catalogs of LISA sources from ground-based GW surveys.
- Catalogs of LISA sources that are, can be or have been detected by EM surveys.
- Astrophysical implications of WD binary formation and evolutionary channels. Publication of the results.
- Astrophysical implications of BH and NS binary formation and evolutionary channels. Publication of the results.

7.2.3.3 Description of work

- Develop and maintain population synthesis software (e.g., but not limited to, COSMIC [52]; MOBSE [123, 90, 89]; SeBa [143, 158]...) to incorporate state-of-the-art understanding of the formation and evolution of stellar-mass LISA sources.
- Simulate the Galactic population of stellar-mass LISA sources, including binaries containing compact objects, white dwarfs, and stripped stars which emit GWs in the LISA band.
- Develop a standardized LISA analysis pipeline to predict realistic GW catalogs and foregrounds from simulated populations.
- Integrate and update realistic assumptions for Galactic mass distributions and star formation history based on EM data, cosmological simulations, and eventually GW data.
- Investigate the impact on astrophysical implications for monochromatic sources which will not have distance measurements from GWs

- Establish ability to find Galactic binaries in EM data based on GW information alone.
- Establish ability to confirm extra-Galactic sources.
- Develop and maintain catalog of resolved Galactic and extra-Galactic population.

7.2.3.4 Timeframe and workforce requirements

- Development of population synthesis software, simulations of Galactic catalogs, maintenance of simulated catalogs for LDCs (ongoing, 1 FTE).
- Development of analysis pipeline to produce mock LISA catalogs from simulated Galactic catalogs (ongoing, 1 FTE).
- Development of updated Galactic mass distributions, analysis of simulated Galactic catalogs to study demography and formation channels (3-5 years, 0.5 FTE).
- Development of pipeline for EM searches based on GWs alone: 3-5 years (1 FTE).
- Analysis of resolved Galactic binaries to constrain formation channels and Galactic structure (L+3 years, 0.5 FTE).

7.2.3.5 Possible subpackages

- Galactic and Galactic neighborhood structure.
- Demography, formation and evolution of stellar-mass, resolved sources.

7.2.3.6 Dependencies

- Connect resolved Galactic binaries to observed GW mergers (WPSI.2.2).
- Source catalogs (CATWP).
- Depends on tool development for data analysis frameworks and libraries (DAFT.3, DAFT.5).
- Depends on detection and parameter estimation of Galactic binaries (CATWP).
- WPMMA.1, WPMMA.2, WPMMA.3.1,.3.2

7.2.3.7 List of projects

- Generate synthetic Galactic catalogs of stellar mass sources using different binary evolution models to predict resolved source populations (1-5 years).
- Determine observational feasibility and scientific gains from multi-messenger observations of DWDs (1-3 years).
- Determine demography of resolved sources including parameter distributions, source number, and spatial distributions (L+1-5 years).
- Connect DWD populations observed by LISA to Type Ia supernovae (L+1 years).
- Use observed resolved populations to determine formation channels for WD, NS, and BH binaries (L+1-5 years).
- Establish the result of mass transfer in WD binaries (L+4-5 years).
- Measure Galactic structure with resolved DWD sources (L+1-5 years).
- Compare demography of Galactic and extra-Galactic resolved sources (L+1-5 years).

7.2.4 Foreground from stellar-mass sources

Due to the large number of compact binaries in the Milky Way, their population gives rise to a millihertz gravitational-wave foreground detectable by LISA. A measurement of the Galactic foreground can provide crucial information on the demography of WD binaries and on the structure of the Milky Way [42, 113, 54].

7.2.4.1 Overview and Goals

The most important goals for this work package are:

- Constrain the structure of the Galaxy based on the magnitude and shape of the irreducible, unresolved foreground.
- Determine statistical binary population constraints using the magnitude and shape of the foreground.

7.2.4.2 Deliverables

- Up-to-date population synthesis software. This includes, but is not limited to COSMIC [52]; MOBSE [123, 90, 89]; SeBa [143, 158]...
- Synthetic Galactic foregrounds based on simulated populations.
- Synthetic Galactic foregrounds based on parametric models.
- Pipeline to construct the synthetic foreground based on simulated catalogs.
- Analysis pipeline to examine the Galactic foreground and determine its parameters such as spectral shape.
- Analysis pipeline to infer Galactic structure & binary population characteristics based on the derived characteristics of the foreground.

7.2.4.3 Description of work

- Develop and maintain population synthesis software (e.g., but not limited to, COSMIC [52]; MOBSE [123, 90, 89]; SeBa [143, 158]) to incorporate state-of-the-art understanding of the formation and evolution of stellar-mass LISA sources.
- Investigate methods to produce realistic Galactic foreground simulations based on simulated populations and/or parametric models.
- Simulate the Galactic foreground.
- Establish the effect of different population models and methods on the predictions of the foreground. Assess any degeneracies between the models.
- Assess the prospects and methods for utilizing the foreground in order to place constraints on Galactic structure and binary populations.

7.2.4.4 Timeframe and workforce requirements

- Simulations of Galactic foreground and development of foreground detection pipeline. < 2 years (0.4 FTE).
- Analysis of simulated Galactic foregrounds from different population models. Determine which constraints can be placed on the Galactic population from GW observations of the Galactic foreground. 5 – 10 years (0.5 FTE).
- Analysis of observed Galactic foreground. Measure Galactic structure and mass. Post launch (0.7 FTE).

7.2.4.5 Possible subpackages

- Galactic and Galactic neighborhood structure.
- Demography, formation, and evolution of stellar-mass sources.

7.2.4.6 Dependencies

- Significant overlap with resolved Galactic binaries (WPSI.2.3).
- Serves as input for studies of the stochastic GW background (WPSI.5).
- Depends on tool development for data analysis frameworks and libraries (DAFT.3, DAFT.5), assessing mission design (DAFT.4), and data quality indicators (DAFT.3).
- Depends on detection and parameter estimation of Galactic binaries (DPE.2).
- Source catalogs (CATWP).
- WPMMA.1, WPMMA.2, WPMMA.3.1,.3.2.

7.2.4.7 List of projects

- Predict the shape of the foreground for several binary evolution models (1-3 years).
- Measure the shape of the foreground and compare to predicted models to determine demography of unresolved population (L+5 years).

7.3 WPSI.3: Extreme-, intermediate- and extremely-large mass ratio inspirals: detection, characterization, populations

Extreme mass ration inspirals (EMRIs) are systems comprised of a central MBH and an inspiralling stellar-mass compact object [15, 12, 43]. The most extreme mass ratio inspirals (XMRIs) consist of a MBH and a sub-solar mass companion such as a brown dwarf or a primordial black hole [13]. On account of their mass ratios, these types of inspiral are slow, and the observed signal contains many cycles, of the order of the mass ratio itself. This allows them to be used to make precision measurements. Intermediate-mass ratio inspirals (IMRIs) can either consist of an IBH inspiralling into a MBH, or a stellar-mass object inspiralling into an IMBH. They form the bridge between MBHBs and EMRIs, and stellar-mass BBH and IMBHBs, respectively. Their intermediate mass ratios also provide slow inspirals, although not to the same extent as EMRIs. The astrophysical interpretation of EMRI, IMRI and XMRI systems involves understanding how these binary systems form. For those involving an MBH, this includes the origins of both their central MBHs (expected to evolve in a galactic centre) and less massive companion (a component of a nuclear star cluster), while for IMRIs consisting of a stellar-mass BH and an IMBH, similar questions can be answered for the origins of IMBHs and their surrounding environments (which may be a globular cluster or dwarf galaxy nucleus). By combining a large population of EMRI, IMRI and XMRI observations, we may reconstruct the properties of the population and identify key tracers indicating the processes that govern the environments in the centres of galaxies and the formation of BHs across the spectrum from IMBHs to MBHs.

7.3.1 EMRIs: Extreme-mass ratio inspirals

EMRIs consist of a binary formed by one compact object in the stellar-mass range, and one massive black hole [15, 12, 43]. These binaries therefore have mass ratios of $\sim 10^{-4}$–10^{-7}. The stellar-mass component would be drawn from the population of the nuclear star cluster surrounding the MBH, and therefore provide insight into the demographics of nuclear star clusters surrounding MBHs. The measured properties of the MBH will provide an insight into the population of MBHs: these will be complementary to measurements from MBHBs, as formation of MBHBs is expected to disrupt the stellar cusp distribution around the MBH from which the compact objects are drawn [26, 144, 16, 12]. For EMRIs in systems where there is a thick disc surrounding the MBH, the viscous drag experienced by the compact object can leave an imprint on the signal, enabling probes of the environment. Multimessenger observations could provide further insight into the environments where EMRIs form.

7.3.1.1 Overview and Goals

The aim of this WP is to enhance our understanding of the sources of EMRIs, specifically how these sources form and how these constrains the properties of their host environments and the growth of BHs. To achieve this we will collect observations of EMRIs, and connect these to observations of other compact-object binaries to provide a synoptic view of the entire BH mass spectrum. In order to interpret this catalogue of observations, it is necessary to have theoretical models for the formation and evolution of the sources. Therefore, it will be necessary to coordinate development work predicting the populations of sources for different input physical assumptions.

The goals of the WP are to find and develop the relevant expertise (in addition to codes and pipelines) within the Consortium, in order to:

- Infer the event rate of EMRIs.
- Characterize the potential background of unresolvable EMRIs, and combine this with observations of resolvable EMRIs to characterize the full population.

- Determine the mass function of EMRI-hosting MBHs.
- Determine the spin distribution of EMRI-hosting MBHs.
- Determine the redshift distribution of EMRIs.
- Determine the distribution of EMRI orbital parameters including eccentricity and inclination.
- Infer the presence of any environmental effects that leave an imprint on the waveform, e.g., viscous drag, perturbations from nearby stars [14], a stellar-mass binary as the secondary component [76], electric charges, magnetic fields, firewalls and dark matter (see [33]). Use these results to understand the physical environment of individual EMRI systems and the overall population.
- Combine the above results to understand the environments in which EMRIs form, the mechanisms by which they form (for example. two-body relaxation vs. tidal separation [129]), the composition of nuclear star clusters, and the evolution of EMRI-hosting MBHs.
- Use any electromagnetic observations (either of the source system, or through surveys of galaxies) to identify the host galaxy, and so understand where EMRIs form.
- Combine EMRI, XMRI, IMRI and MBHB observations to create a complete understanding of the BH population, their formation and evolution over cosmic time.

7.3.1.2 Deliverables

Prelaunch (to be continued postlaunch as new results appear in the literature):

- Models describing expected EMRI populations for comparison to observations.
- Parameterized models fit to EMRI observations to describe the intrinsic populations.

Postlaunch (requiring use of LISA observations):

- A first interpretation of EMRI observations, and their implications for the physics of MBHs and their environments, placing in context observational results with regards to the published literature and model predictions.
- A catalogue of EMRIs with parameters informed by the hierarchical analysis of the population.

7.3.1.3 Description of work

The interpretation of LISA observations will be facilitated comparing the data with theoretical studies modelling the predicted population, as well as using model-agnostic parameterised models. To perform inferences about the true astrophysical population and their formation, it will be necessary to develop analysis codes that can estimate the properties of the population, and develop astrophysical predictions which can match the level of accuracy of these inference results. Production of astrophysical population models, using both semianayltic prescriptions and detailed numerical modelling will be done Astro-WG members in collaboration with the larger scientific community. The necessary steps in completing the inference to intrepid EMRI observations will be to:

- Link the properties of the merger rate as a function of mass, spin and redshift to constrain the overall formation rate of EMRIs, and interpret this in context of predictions for different formation histories.

- Link the properties of the merger rate as a function of orbital properties (eccentricity, inclination) to various formation mechanisms for EMRIs.
- Identify measurable environmental effects, such as viscous drag, perturbing objects, dark matter halos, etc., and how these can be used to perform a census of EMRI hosts.
- Produce catalogues of EMRIs with different astrophysics assumptions, and build simple parametric models to emulate the main features of these, in order to provide input to data analysis pipelines.
- Identify how electromagnetic observations can be used to constrain our understanding of EMRI formation, either through observation of counterparts to the source system or through identification of the host galaxy.
- Combine observations of EMRIs, IMRIs, XMRIs and MBHBs to chart the evolution of MBHs across cosmic time, and reconstruct their dominant seed formation and growth mechanisms.

7.3.1.4 Timeframe and workforce requirements

- Link merger-rate properties to EMRI formation: 3 years (0.5 FTE).
- Identify measurable environmental effects: 5 years (0.4 FTE).
- Produce EMRI catalogues and parametric models: 5 years (0.4 FTE).
- Identify how electromagnetic observations can be used to constrain EMRI formation: 5 years (0.2 FTE).
- Combine LISA observations to chart MBH evolution: L+3 years (4 FTE).

Storage space requirement for (simulated) data catalogues and inference data products: $\sim$ 100 TB, shared with models and results for other binaries.

7.3.1.5 Possible subpackages

7.3.1.6 Dependencies

Within WPSI:

- Compare population parameters for the MBHB population (WPSI.1, WPSI.2) with the population of MBHs in EMRI systems in order to characterize the full spectrum of MBH systems.
- Understanding of deviations from pure Kerr spacetimes (WPSI.8) for MBHs: these could either indicate the presence of matter (WPSI.3, this WP) or new fundamental physics due to violations of general relativity (WPSI.7) or an exotic compact object (WPSI.8).
- Cross correlation of EMRI and localizations with galaxy catalogues is useful for (i) understanding the environment of EMRI formation (WPSI.3, this WP); (ii) multimessenger follow-up (WPSI.1.3), and (iii) measurement of cosmological parameters (WPSI.4).

Between WPSI and WAVWP, DAFTWP, LAPWP, CATWP:

- Accurate waveforms (WAVWP) are needed for detection and measurement of EMRIs. These are fundamental in searching for and characterising EMRI signals.

- Waveform models (WAVWP) and/or data analysis methods (DPEWP) for EMRIs with environmental effects (WPSI.6, WPSI.8) are also needed, in order to detect and measure these effects.

- Data analysis pipelines able to (i) detect EMRIs (WAVWP, DPEWP), (ii) infer individual source parameter properties (WAVWP, DPEWP), and (iii) hierarchically infer the population parameters (CATWP). These are essential to provide the observations upon which this workpackage is based.

- Data analysis pipelines to identify unresolvable backgrounds of EMRIs, and characterize the properties of this background (DPEWP, CATWP, WPSI.5).

- Quantitative assessment of instrument sensitivity and calibration accuracy necessary to assess selection effects of detection pipelines and accuracy of source parameter inferences (DPEWP). These are necessary input to reliably characterize the population of EMRIs.

7.3.1.7 List of projects

- Development of models predicting the number of EMRIs as a function of MBH properties and redshift. Uncertainties in the inputs to these models will enable the calculation the range of potential rates. Through comparison to observations, this will enable these uncertain processes to be constrained.

- Quantification of selection effects for detection pipelines.

- Construction of parameterized phenomenological models which can capture the key properties of the expected distributions over mass, spin, and eccentricity without having to rely on specific physical predictions.

- Construction of a hierarchical inference framework to infer population parameters.

- Assessing precision of population parameter inferences as a function of the number of detections, the length of the mission, and the observing duty cycle.

- Assessing biases on population inferences introduced from waveform modelling error and instrument calibration. (Overlaps with WAVWP, DPEWP.)

- Quantifying detectability of environmental effects in EMRI waveforms, and exploring degeneracies with other non-Kerr properties (such as hairy black holes). (Overlaps with WPSI.7, WPSI.8.)

- Prototyping data releases for the production of the catalogue.

7.3.2 IMRIs: MBH + IMBH binaries

IMRIs consisting of an IMBH and a MBH have mass ratios of $\sim 10^{-2}$–10^{-4}. These systems bridge the gap between EMRIs and MBHBs, and thereofre combining all these observations is necessary to provide a complete census of the MBH binary popuation. These IMRIs would record the number of minor mergers MBHs undergo, and enable an insight into how MBHs and their surround nuclear star clusters grow: IMBHs may indicate that the nuclear star cluster has assembled from smaller clusters (globular clusters or the nuclear clusters of dwarf galaxies, see e.g. [68, 67, 125, 66, 85, 17]). The presence of an IMBH would perturb the inner regions of a nuclear star cluster, potentially destroying the cusp from which EMRIs are drawn.

7.3.2.1 Overview and Goals

The aim of this WP is to enhance our understanding of the sources of IMRIs, specifically how these sources form and how these constrains the properties of their host environments and the growth of BHs. To achieve this we will collect observations of IMRIs, and connect these to observations of other compact-object binaries to provide a synoptic view of the entire BH mass spectrum. In order to interpret this catalogue of observations, it is necessary to have theoretical models for the formation and evolution of the sources. Therefore, it will be necessary to coordinate development work predicting the populations of sources for different input physical assumptions.

The goals of the WP are to find and develop the relevant expertise (in addition to codes and pipelines) within the Consortium, in order to:

- Infer the event rate of IMRIs.
- Characterize the potential background of unresolvable IMRIs, and combine this with observations of resolvable IMRIs to characterize the full population.
- Determine the mass function of IMRI-hosting MBHs.
- Determine the spin distribution of IMRI-hosting MBHs.
- Determine the redshift distribution of IMRIs.
- Determine the mass and spin of IMBHs observed in IMRIs.
- Infer the presence of any environmental effects that leave an imprint on the waveform, e.g., perturbations from nearby stars [11]. Use these results to understand the physical environment of individual IMRI systems and the overall population.
- Combine the above results to understand the environments in which IMRIs form, and the evolution of IMRI-hosting MBHs.
- Use any electromagnetic observations (either of the source system, or through surveys of galaxies) to identify the host galaxy, and so understand where IMRIs form.
- Combine EMRI, XMRI, IMRI and MBHB observations to create a complete understanding of the MBH population, their formation and evolution over cosmic time.
- Combine observations of IMRIs and IMBHBs to create a complete understanding of the IMBH population, their formation and evolution over cosmic time.

7.3.2.2 Deliverables

Prelaunch (to be continued postlaunch as new results appear in the literature):

- Models describing expected IMRI populations for comparison to observations.
- Parameterized models fit to IMRI observations to describe the intrinsic populations.

Postlaunch (requiring use of LISA observations):

- A first interpretation of IMRI observations, and their implications for the physics of MBHs and their environments, placing in context observational results with regards to the published literature and model predictions.
- A catalogue of IMRIs with parameters informed by the hierarchical analysis of the population.

7.3.2.3 Description of work

The interpretation of LISA observations will be facilitated comparing the data with theoretical studies modelling the predicted population, as well as using model-agnostic parameterized models. To perform inferences about the true astrophysical population and their formation, it will be necessary to develop analysis codes that can estimate the properties of the population, and develop astrophysical predictions which can match the level of accuracy of these inference results. Production of astrophysical population models, using both semianalytic prescriptions and detailed numerical modelling will be done Astro-WG members in collaboration with the larger scientific community. The necessary steps in completing the inference to intrepid IMRI observations will be to:

- Link the properties of the merger rate as a function of MBH mass, spin and redshift to constrain the overall formation rate of IMRIs, and interpret this in context of predictions for different formation histories.
- Link the properties of the merger rate as a function of IMBH mass and spin, and interpret this in the context of the evolution with redshift for different formation and growth mechanisms.
- Produce catalogues of IMRIs with different astrophysics assumptions, and build simple parametric models to emulate the main features of these, in order to provide input to data analysis pipelines.
- Identify how electromagnetic observations can be used to constrain our understanding of IMRI formation, either through observation of counterparts to the source system or through identification of the host galaxy.
- Combine observations of EMRIs, IMRIs, XMRIs and MBHBs to chart the evolution of IMBHs and MBHs across cosmic time, and reconstruct their dominant seed formation and growth mechanisms.

7.3.2.4 Timeframe and workforce requirements

- Link merger-rate properties to IMRI formation: 3 years (0.5 FTE).
- Identify measurable environmental effects: 5 years (0.1 FTE).
- Produce IMRI catalogues and parametric models: 5 years (0.4 FTE).

- Identify how electromagnetic observations can be used to constrain IMRI formation: 5 years (0.1 FTE).
- Combine LISA observations to chart MBH evolution: L+3 years (4 FTE).

Storage space requirement for (simulated) data catalogues and inference data products: $\sim$ 100 TB, shared with models and results for other binaries.

7.3.2.5 Possible subpackages

7.3.2.6 Dependencies

Within WPSI:

- Population parameters for the IMBHB and MBHB populations to compare with the population of IMBHs and MBHs in IMRI systems in order to characterize the full spectrum of binary systems.
- Cross correlation of IMRI and localizations with galaxy catalogues is useful for (i) understanding the environment of IMRI formation (this WP); (ii) multimessenger follow-up, and (iii) measurement of cosmological parameters.

Between WPSI and WAVWP, DPEWP and CATWP, WPMMA:

- Accurate waveforms are needed for detection and measurement of IMRIs. These are fundamental in searching for and characterising IMRI signals.
- Data analysis pipelines able to (i) detect IMRIs, (ii) infer individual source parameter properties, and (iii) hierarchically infer the population parameters. These are essential to provide the observations upon which this workpackage is based.
- Data analysis pipelines to identify unresolvable backgrounds of IMRIs, and characterize the properties of this background.
- Quantitative assessment of instrument sensitivity and calibration accuracy necessary to assess selection effects of detection pipelines and accuracy of source parameter inferences. These are necessary input to reliably characterize the population of IMRIs.
- Multi-messenger information: WPMMA.1, WPMMA.2, WPMMA.3.4

7.3.2.7 List of projects

- Development of models predicting the number of IMRIs as a function of MBH properties and redshift. Uncertainties in the inputs to these models will enable the calculation the range of potential rates. Through comparison to observations, this will enable these uncertain processes to be constrained.
- Quantification of selection effects for detection pipelines.
- Construction of parameterized phenomenological models which can capture the key properties of the expected distributions over mass, spin, and eccentricity without having to rely on specific physical predictions.
- Construction of a hierarchical inference framework to infer population parameters.
- Assessing precision of population parameter inferences as a function of the number of detections, the length of the mission, and the observing duty cycle.

- Assessing biases on population inferences introduced from waveform modelling error and instrument calibration. (Overlaps with WAVWP, DPEWP.)
- Quantifying detectability of environmental effects in IMRI waveforms.
- Prototyping data releases for the production of the catalogue.

7.3.3 IMRIs: IMBH + stellar-mass object

Contrary to MBH and IMBH IMRIs, the IMBH and stellar-mass compact objects IMRIs are likely to be found in smaller stellar systems such as globular clusters or ultra-compact dwarf galaxies around IMBHs. As a consequence of their less extreme mass ratios, the modelling of IMRI waveforms is difficult to model, falling between the EMRI regime where perturbation theory can be readily applied, and comparable mass binaries where numerical relativity is feasible. Similarly event rates requires a more complex theory than EMRIs: the central IMBH cannot be modelled as a feature of the centre of a nuclear star cluster, but only as a dynamical component of its host, necessitating detailed simulations [103]. IMBH and stellar-mass BHs IMRIs potentially shed light on the seeds of MBHs, and the spectrum of BHs from stellar mass to intermediate mass.

IMBH and stellar-mass IMRIs are potentially detectable with high frequency ground-based GW detectors [11]. It may therefore be feasible to make multiband observations where either the same source is observed in multiple detectors, or independent observations are combined in order to uncover the properties of the full population. If the companion stellar-mass object is a white dwarf, it will be tidally disrupted outside of the event horizon of the IMBH, which could also provide us with an electromagnetic counterpart [150].

7.3.3.1 Overview and Goals

The aim of this WP is to enhance our understanding of the sources of IMRIs, specifically how these sources form and how these constrains the properties of their host environments and the growth of BHs. To achieve this we will collect observations of IMRIs, and connect these to observations of other compact-object binaries to provide a synoptic view of the entire BH mass spectrum. In order to interpret this catalogue of observations, it is necessary to have theoretical models for the formation and evolution of the sources. Therefore, it will be necessary to coordinate development work predicting the populations of sources for different input physical assumptions.

The goals of the WP are to find and develop the relevant expertise (in addition to codes and pipelines) within the Consortium, in order to:

- Infer the event rate of IMRIs.
- Characterize the potential background of unresolvable IMRIs, and combine this with observations of resolvable IMRIs to characterize the full population.
- Determine the mass function of IMBHs and stellar-mass BHs which form IMRIs.
- Determine the spin distribution of IMBHs and stellar-mass BHs which form IMRIs.
- Determine the redshift distribution of IMRIs.
- Determine the mass and spin of IMBHs observed in IMRIs.
- Use electromagnetic observations of tidal disruption events to characterise the stellar-mass components of IMRIs, and infer the population of objects surrounding IMBHs.

- Combine the above results with observations of IMRIs from ground-based GW detectors to obtain the most precise measurements of the IMRI population.
- Combine stellar-mass binary, IMRI and IMBHB observations to create a complete understanding of the stellar-mass compact object and IMBH population, their evolution over cosmic time, and the implications for the formation and evolution of these binaries (including the evolution of stars and the dynamics of dense stellar environments).
- Combine observations of BHs across the entire mass spectrum to uncover the formation and growth mechanisms for IMBHs and MBHs, and how these relate to their environments.

7.3.3.2 Deliverables

Prelaunch (to be continued postlaunch as new results appear in the literature):

- Models describing expected IMRI populations for comparison to observations.
- Parameterized models fit to IMRI observations to describe the intrinsic populations.

Postlaunch (requiring use of LISA observations):

- A first interpretation of IMRI observations, and their implications for the physics of IMBHs and their environments, placing in context observational results with regards to the published literature and model predictions.
- A combined analysis with results from ground-based GW observations to provide a more detailed understanding of the IMRI population.
- A catalogue of IMRIs properties linked to potential tidal disruption events, and if counterparts are found, updated constraints folding in multimessenger observations.
- A catalogue of IMRIs with parameters informed by the hierarchical analysis of the population.

7.3.3.3 Description of work

The interpretation of LISA observations will be facilitated comparing the data with theoretical studies modelling the predicted population, as well as using model-agnostic parameterised models. To perform inferences about the true astrophysical population and their formation, it will be necessary to develop analysis codes that can estimate the properties of the population, and develop astrophysical predictions which can match the level of accuracy of these inference results. Production of astrophysical population models, using both semianayltic prescriptions and detailed numerical modelling will be done Astro-WG members in collaboration with the larger scientific community. The necessary steps in completing the inference to intrepid IMRI observations will be to:

- Use observations, or lack thereof, from ground-based GW observations to constrain the population of IMRIs.
- Link the properties of the merger rate as a function of mass, spin and redshift to constrain the overall formation rate of IMRIs, and interpret this in context of predictions for different formation histories.
- Link the properties of the merger rate as a function of orbital properties (eccentricity, inclination) to various formation mechanisms for IMRIs. The feasibility of this may depend on the availability of accurate waveforms.

- Identify measurable environmental effects, such as perturbing objects, and how these can be used to perform a census of IMRI hosts.
- Produce catalogues of IMRIs with different astrophysics assumptions, and build simple parametric models to emulate the main features of these, in order to provide input to data analysis pipelines.
- Identify how electromagnetic observations can be used to constrain our understanding of IMRI systems, and in particular how tidal disruption events can inform our understanding of the nature of white dwarfs.
- Quantify the potential for multiband GW observations, and determine what additional information on the population and their astrophysical origins can be determined through combination of observations.
- Combine observations of stellar-mass binaries, IMRIs, and IMBHBs to chart the evolution of stellar-mass and intermediate mass binaries across cosmic time, and understand how these binaries form and evolve.

7.3.3.4 Timeframe and workforce requirements

- Use ground-based observations to constrain IMRI population: 3 years (0.1 FTE).
- Link merger-rate properties to IMRI formation: 3 years (0.5 FTE).
- Identify measurable environmental effects: 5 years (0.1 FTE).
- Produce IMRI catalogues and parametric models: 5 years (0.4 FTE).
- Identify how electromagnetic observations can be used to constrain IMRI formation: 5 years (0.2 FTE).
- Quantify the potential for multiband IMRI observations: 5 years (0.3 FTE).
- Combine LISA observations to chart SOBH and IMBH evolution: L+3 years (4 FTE).

Storage space requirement for (simulated) data catalogues and inference data products: $\sim$ 100 TB, shared with models and results for other binaries.

7.3.3.5 Possible subpackages

7.3.3.6 Dependencies

Within WPSI:

- Population parameters for the IMBHB and stellar-mass binary populations to compare with the population of IMBHs and stellar-mass compact objects in IMRI systems in order to characterize the full spectrum of binary systems.
- Cross correlation of IMRI and localizations with galaxy catalogues is useful for (i) understanding the environment of IMRI formation (this WP); (ii) multimessenger follow-up, and (iii) measurement of cosmological parameters.

Between WPSI and WAVWP, DPEWP and CATWP, WPMMA:

- Accurate waveforms are needed for detection and measurement of IMRIs. These are fundamental in searching for and characterising IMRI signals.

- Data analysis pipelines able to (i) detect IMRIs, (ii) infer individual source parameter properties, and (iii) hierarchically infer the population parameters. These are essential to provide the observations upon which this workpackage is based.

- Data analysis pipelines to identify unresolvable backgrounds of IMRIs, and characterize the properties of this background.

- Quantitative assessment of instrument sensitivity and calibration accuracy necessary to assess selection effects of detection pipelines and accuracy of source parameter inferences. These are necessary input to reliably characterize the population of IMRIs.

- Multi-messenger information: WPMMA.1, WPMMA.2, WPMMA.3.4.

7.3.3.7 List of projects

- Development of models predicting the number of IMRIs as a function of the IMBH properties, in particular of its mass, so as to assess different theoretical models of globular clusters harbouring IMBHs. These should include available constraints from ground-based GW observations.

- Quantification of selection effects for detection pipelines.

- Construction of parameterized phenomenological models which can capture the key properties of the expected distributions over mass, spin, etc. without having to rely on specific physical predictions.

- Construction of a hierarchical inference framework to infer population parameters.

- Characterising the population of IMRIs which lead to tidal disruption events with observable electromagnetic counterparts, and how information from electromagnetic observations can be used to infer source properties.

- Assessing precision of population parameter inferences as a function of the number of detections, the length of the mission, and the observing duty cycle.

- Assessing biases on population inferences introduced from waveform modelling error and instrument calibration.

- Prototyping data releases for the production of the catalogue.

7.3.4 XMRIs: Extremely-large mass ratio inspirals

Substellar objects in our Galaxy such as brown dwarfs have an event rate which has been estimated to be one order of magnitude larger than regular EMRIs, i.e. a stellar-mass black hole plunging into an MBH. However, because their mass ratio is much higher, $q \sim 10^{-8}$, they can live in the LISA band for at least 10^6 yr or longer with SNRs that range between 10 and up to $\sim 10^4$ due to their proximity to us (8 kpc, at the Galactic Centre). From the point of view of LISA, they are monochromatic sources. Because backreaction depends on the mass ratio, their trajectories are closer to regular geodesics than EMRIs [13, 93].

7.3.4.1 Overview and Goals

The aim of this WP is to enhance our understanding of the sources of XMRIs, specifically how these sources form and how these constrains the properties of their host environments and the growth of BHs. To achieve this we will collect observations of XMRIs, and connect these to observations of other compact-object binaries to provide a synoptic view of the entire BH mass spectrum. In order to interpret this catalogue of observations, it is necessary to have theoretical models for the formation and evolution of the sources. Therefore, it will be necessary to coordinate development work predicting the populations of sources for different input physical assumptions.

The goals of the WP are to find and develop the relevant expertise (in addition to codes and pipelines) within the Consortium, in order to:

- Infer the event rate of XMRIs.
- Characterize the potential background of unresolvable XMRIs.
- Use the above results to probe the population of subsolar objects surrounding MBHs, and place constraints the the number of brown dwarfs or primordial black holes.
- Use XMRI observations to estimate the properties of Sagittarius A*, and place it in context of the MBH population.

7.3.4.2 Deliverables

Prelaunch (to be continued postlaunch as new results appear in the literature):

- Models describing expected XMRI populations for comparison to observations.
- Parameterized models fit to XMRI observations to describe the intrinsic populations.

Postlaunch (requiring use of LISA observations):

- A first interpretation of XMRI observations, their likely sources (brown dwarf or primordial black hole), and their implications for the environments surrounding MBHs.
- A catalogue of XMRIs with parameters informed by the hierarchical analysis of the population.

7.3.4.3 Description of work

The interpretation of LISA observations will be facilitated comparing the data with theoretical studies modelling the predicted population, as well as using model-agnostic parameterised models. To perform inferences about the true astrophysical population and their formation, it will be necessary to develop analysis codes that can estimate the properties of the population, and develop astrophysical predictions which can match the level of accuracy of these inference results. Production of astrophysical population models, using both semianayltic prescriptions and detailed numerical modelling will be done Astro-WG members in collaboration with the larger scientific community. The necessary steps in completing the inference to intrepid XMRI observations will be to:

- Derive robust predictions for XMRI rates as a function of their eccentricity and other orbital parameters.
- Assess the impact of Galactic XMRIs, which may potentially be extremely high SNR (up to $\sim 10^4$), on the detectability of other sources, by providing catalogues generated with different astrophysical assumptions for use in development of data analysis pipelines.
- Identify properties of the XMRI population which would provide insights into the formation of these systems, for example to distinguish primordial black hole XMRIs from brown dwarf XMRIs.
- Establish the potential for electromagnetic counterparts to XMRIs, and how electromagnetic observations could improve our understanding of a source.
- Use observations of XMRIs to measure the properties of our Galaxy's MBH, and combine with observations of EMRIs, IMRIs and MBHBs to constrain the MBH population and their surroundings.

7.3.4.4 Timeframe and workforce requirements

- Derive robust predictions for XMRI rates: 3 years (0.4 FTE).
- Assess the impact of Galactic XMRIs on the detectability of other sources: 3 years (0.5 FTE).
- Identify properties of the XMRI population that provide insights into XMRI formation: 5 years (0.3 FTE).
- Establish the potential for electromagnetic counterparts to XMRIs: 5 years (0.1 FTE).
- Use observations of XMRIs to measure the properties of our Galaxy's MBH: L+1 years (2 FTE).
- Combine LISA observations to constrain the MBH population and their surroundings: L+3 years (1 FTE).

Storage space requirement for (simulated) data catalogues and inference data products: $\sim$ 100 TB, shared with models and results for other binaries.

7.3.4.5 Possible subpackages

7.3.4.6 Dependencies

Within WPSI:

- Population parameters for the MBH population to compare with the individual MBHs observable with XMRIs.
- Understanding of deviations from pure Kerr spacetimes for MBHs: these could either indicate the presence of matter (this WP) or new fundamental physics (violations of general relativity or a non-black hole compact object).

Between WPSI 7 and WAVWP, DAFTWP, LAPWP:

- Accurate waveforms are needed for detection and measurement of XMRIs (WAVWP and DPEWP). These are fundamental in searching for and characterising XMRI signals. The waveforms are slowly evolving, but could potentially be loud (SNR of 10^4), meaning that even small errors could lead to systematic errors.

- Data analysis pipelines able to (i) detect XMRIs, (ii) infer individual source parameter properties, and (iii) hierarchically infer the population parameters. These are essential to provide the observations upon which this workpackage is based. XMRIs may be a significant foreground for other sources (WPSI.5), so it must be possible to detect other sources without XMRI contamination.

- Data analysis pipelines to identify unresolvable backgrounds of XMRIs, and characterize the properties of this background (WPSI.5).

- Quantitative assessment of instrument sensitivity and calibration accuracy necessary to assess selection effects of detection pipelines and accuracy of source parameter inferences. These are necessary input to reliably characterize the population of XMRIs.

- Multi-messenger information: WPMMA.1, WPMMA.2, WPMMA.3.4

7.3.4.7 List of projects

- Development of models predicting the number of XMRIs of Galactic and extragalactic origin, and whether these are resolvable or form a background. Uncertainties in the inputs to these models will enable the calculation the range of potential rates. Through comparison to observations, this will enable these uncertain processes to be constrained.

- Quantification of selection effects for detection pipelines, and the impact of loud XMRIs on the detection of other sources.

- Construction of a hierarchical inference framework to infer population parameters.

- Assessing precision of population parameter inferences as a function of the number of detections, the length of the mission, and the observing duty cycle.

- Assessing biases on population inferences introduced from waveform modelling error and instrument calibration.

- Investigate the potential for multimessenger observations, and how these could be combined to provide a complete picture of a source.

- Prototyping data releases for the production of the catalogue.

7.4 WPSI.4: Estimation of cosmological parameters

7.4.1 Overview and Goals

The luminosity distance of compact binaries can be directly inferred from the measured GW signal, implying that GW sources can be used as cosmological distance indicator (standard sirens). This, in combination with complementary redshift information, can be used to test the distance-redshift relation and thus to put constraints on the cosmological parameters of standard (ΛCDM) and alternative cosmological models. The main challenge with these analyses consists in obtaining a redshift measurements of the GW source.
There are two main ways to obtain redshift information:

- Identify an electromagnetic counterpart (*counterpart method* or *bright sirens*): this can be done if an EM counterpart is observed or if the localization region is sufficiently constrained to contain only one galaxy. In this case to each GW event corresponds a unique redshift value (usually measured from the host galaxy).

- Use galaxy catalogs (*statistical method* or *dark sirens*): one assigns multiple redshift values to each GW event by looking at galaxies within the localization region, whose properties are recovered from a galaxy catalog or from a dedicated EM survey. The information collected with many GW events is then combined to find the true value of the cosmological parameters. This method does not require the identification of the host galaxy, but it needs fairly complete galaxy catalogs around the localization region of the GW event.

The goals of this WP are the following:

- Map the expansion of the universe and probe possible cosmological models beyond ΛCDM [DEL4].

- Evaluate all possible systematic uncertainties affecting LISA cosmological measurements (weak lensing, waveform uncertainties, ...) [DEL3].

- Assess the implications of LISA cosmological measurements with respect to other GW observations and EM probes, especially at high redshift ($z \gtrsim 2$) [DEL7].

- Explore new ways to conduct cosmological measurements (e.g. lensing, cross-correlation with LSS, MBHBs as dark sirens and other connections with AGN hosts?, ...) [DEL6].

- Test deviations from general relativity at cosmological scales (e.g. through effects on the propagation of GWs) [DEL5]. **To be done in collaboration with the fundamental physics WPs: WPSI.7, WPSI.8.**

7.4.2 Deliverables

- DEL1: Mock data catalogues of LISA bright sirens: e.g. MBHB mergers with counterparts or events with identified unique host galaxy. This deliverable needs as input the catalogues of MBHB mergers detected by LISA and, possibly, also catalogues of other sources (SOBHBs, EMRIs, IMBHs?): these are developed in CATWP and maybe also in WPSI.1.

- DEL2: Definition of the relevant parameters and figures of merit of the cosmological models that will be tested (ΛCDM, early dark energy, modified gravity scenarios, ...), to optimise the LISA testing ability.

- DEL3: Assess all possible systematic uncertainties affecting the LISA cosmological analyses (e.g. weak lensing, calibration, waveforms, ...) and identify analytical or numerical methods to estimate their contribution on relevant parameters of LISA detected events (e.g. luminosity distance, sky localisation, ...).

- DEL4: Data analysis pipelines for measuring the parameters of the cosmological models identified in DEL1 with LISA standard sirens:
  - DEL4.1: Code returning constraints on cosmological model parameters with bright standard sirens. The code will need as input the catalogues of LISA sources with known redshift, e.g. through the identification of the host galaxy, developed in DEL1 (e.g. MBHBs).
  - DEL4.2: Code returning constraints on cosmological parameters with dark standard sirens. The code will need as input catalogues of GW sources developed in CATWP and possibly also in WPSI.2 ans WPSI.3 (SOBHBs, EMRIs, IMBHs?), as well as galaxy catalogues obtained by external EM partners or publicly available. **Possible strong overlap with WPMM - to be checked**.
  - DEL4.3: Code combining the information of both bright and dark sirens. This deliverable depends on DEL4.1 and DEL4.2.

- DEL5: Data analysis pipelines for testing deviations from standard GR propagation of GWs at cosmological distances (**to be performed in collaboration with fundamental physics WPs: WPSI.7 and WPSI:8**):
  - DEL5.1: Definition of the deviations from standard GR propagation that need to be considered, and choice of the corresponding parameters to be tested (ongoing within CosWG).
  - DEL5.2: Code returning constraints on deviations from the GR propagation of GWs at cosmological distances with bright standard sirens. The code will be based upon an extension of the one developed in DEL4.1.
  - DEL5.3: Investigate whether dark sirens have the potential to test deviations from GR, and if so develop a code returning constraints on deviations from the GR propagation of GWs at cosmological distances with dark standard sirens. The code might be based upon an extension of the one developed in DEL4.2. If relevant, also develop constrains on deviations from GR by extending the combined bright and dark sirens code developed in DEL4.3

- DEL6: Define and develop other possible data analysis products for extracting cosmological information by combining GW-EM datasets (e.g. lensing, cross-correlation with LSS, ...).
  - DEL6.1: If the result of DEL6 indicates that this is needed, develop a code that combines LISA measurements with EM datasets, and other GW probes, to exploit other ways to extract cosmological information (e.g. lensing, cross-correlation with LSS, ...). The realization of this deliverable will depend on the outcome of the theoretical/computational work to be performed within DEL6 (**to be performed in collaboration with WPMM?**).

- DEL7: Compare and combine LISA cosmological measurements with (expected) EM measurements. Assess the potential of LISA to improve and extend EM analyses, especially at high redshift ($z \gtrsim 2$).

- Once preliminary versions of the codes for DEL4 to 6 are developed, they will be reviewed, approved and released. Follow-up work will be needed to further refine them into subsequent versions until the delivery of final release of data analysis pipelines (before the start of LISA science operations).

7.4.3 Timeframe and workforce requirements

- DEL1: within ∼2 years, or within ∼1 year from the acquisition of new catalogues of LISA sources (e.g. new MBHB) from CATWP and possibly from WPSI.1. **Required FTEs: 3.0** (ideally 0.5 FTEs to review current literature, 1.5 FTEs to develop analytical/numerical codes for estimating the emission and detection of EM counterparts, and 1.0 FTEs in astrophysical/numerical/observational expertise).

- DEL2: within ∼2 years. **Required FTEs: 1.5** (ideally 1.0 FTEs spread over different expertise in theoretical cosmology, and 0.5 FTEs on GW data analysis expertise).

- DEL3: within ∼2 years. **Required FTEs: 2.0** (ideally 0.7 FTEs on cosmological systematics, e.g. weak lensing, 0.8 FTEs on waveform/measurements systematic, e.g. calibration uncertainties, 0.5 FTEs on astrophysical systematic, e.g. peculiar velocities or source environment effects).

- DEL4.1: ∼3 years, or within 1 year since the completion of DEL1. **Required FTEs: 1.0** (ideally 0.5 FTEs to write the codes/pipeline, 0.3 FTEs in statistical cosmology expertise, and 0.2 FTEs in complementary GW/astro/observational expertise).

- DEL4.2: within ∼4 years, or within 2 years since the acquisition of new catalogues of LISA sources (e.g. SOBHBs, EMRIs, ...) from CATWP and possibly from WPSI.2 and WPSI.3. The longer period is envisaged to assess all systematic, arising in both GW measurements and galaxy catalogues. **Required FTEs: 3.0** (ideally 1.0 FTEs to write the codes/pipelines, 1.0 FTEs on galaxy catalogs expertise, 0.4 FTEs on statistical cosmology, 0.4 FTEs on GW data analysis, and 0.2 FTEs on astrophysical expertise).

- DEL4.3: within ∼4.5 years, or 0.5 years after DEL4.1 and DEL4.2 have been completed. **Required FTEs: 0.5** (ideally 0.3 FTEs to write the codes/pipeline, 0.1 FTEs on data analysis, and 0.1 FTEs on statistical cosmology).

- DEL5.1: within ∼3 years, or as soon as DEL4.1 is completed. **Required FTEs: 1.5** (ideally 1.2 FTEs spread over different expertise in theoretical cosmology, especially modified gravity and dark energy, and 0.3 FTEs in data analysis/GW measurements).

- DEL5.2: within ∼4 years, or 1 year after both DEL4.1 and DEL5.1 have been completed. **Required FTEs: 1.5** (ideally 1.0 FTEs to write codes/pipeline, and 0.5 FTEs on modified gravity/cosmology/data analysis/GWs expertise).

- DEL5.3: within ∼6 years, or within 2 years after both DEL5.1 and DEL4.2 have been completed. **Required FTEs: 1.0+1.5** (ideally 1.0 FTEs to investigate the feasibility of the objectives and possibly 1.5 FTEs to write the codes/pipelines together with required expertise).

- DEL6: within ∼ 3 to 5 years. **Required FTEs: 1.5** (ideally 1.0 FTEs in statistical cosmology and LSS, 0.5 FTEs in GW data analysis).

- DEL6.1 (if relevant): within ∼6 years, or ∼1 year after DEL6 has been completed. **Required FTEs: 2.0** (ideally 1.0 FTEs to write the codes/pipelines, and 1.0 FTEs in statistical cosmology and data analysis expertise).

- DEL7: within ∼6 years, or 1.5 years after DEL4.3 has been completed. **Required FTEs: 1.0** (ideally 0.5 FTEs to write codes/pipelines, 0.5 FTEs in cosmological expertise).

7.4.4 Description of work

- DEL1: Develop mock data catalogues for MBHBs, SOBHBs, EMRIs, and IMBHs.
- DEL2: Use the products of DEL1 and DEL4 to estimate the figures of merit for different cosmological parameters and different cosmological models.
- DEL3: List the possible sources of systematic uncertainties, properly add them into the products of of DEL1 and DEL4 and estimate their effects on the accuracy of cosmological parameter measurements.
- DEL4: Develop codes that return the cosmological parameter measurements with bright and dark sirens, with the possibility of combining the measurements from both sirens.
- DEL5: Develop codes to compare the propagation distances of GW and EM signals from MBHBs so that GR can be tested. Investigate and develop codes that can test GR without EM counterparts.
- DEL6: Investigate other methods that extract cosmological information by cross correlating GW-EM data. Develop codes for the methods that allow to extract information on the cosmological model in a comparable or better way than those developed in DEL4.
- DEL7: Take the projections of other cosmological experiments and combine/compare with our projections in DEL2. Estimate the additional contribution from LISA.

7.4.5 Possible subpackages

- Theoretical work package: DEL2 and DEL5.1
- Systematic work package: DEL3
- Bright sirens work package: DEL1, DEL4.1, DEL5.2
- Dark sirens work package: DEL4.2, DEL5.3
- Combination and comparison (also with EM observations) work package: DEL4.3, DEL5.3, DEL7
- Lensing and LSS work package: DEL6, DEL6.1

7.4.6 Dependencies

7.4.6.1 General requirements

- Catalogues of GW sources (SOBHBs, EMRIs, MBHBs, IMBHs?, ...) with parameter estimation (distance, sky location, mass, inclination angle measurement uncertainties, ...)
- Galaxy catalogues from EM observations, including the sky coordinates, redshift, and color magnitudes of the galaxies with uncertainties.
- Redshift measurements for MBHB mergers with associated EM counterpart (e.g. trough the identified host galaxy, through 21-cm line?, ...).

7.4.6.2 Dependencies on specific (sub-)WPs

- For the development of this subWP one needs to use the catalogues developed in CATWP and possibly also WPSI.1, WPSI.2, WPSI.3 (MBHB, SOBHB, EMRIs, IMBHB?)
- For the development of this subWP one needs to investigate the dependence of cosmological measurements on the astrophysics of MBHBs, in particular in connection to MBH formation and evolution theories and models used to predict the emission and detection of EM counterparts: connected to WPs CAT, DPE, WPSI.1, WPMMA.1, WPMMA.2, WPMMA.3, and in collaboration with the Astrophysics WG.
- For the development of this subWP one needs to develop theoretical and data analysis tools to test deviations from GR in the propagation of GWs over cosmological distances: connected to WPSI.7 and WPSI.8, and in collaboration with the Fundamental Physics WG.
- This subWP depends also on galaxy catalogues: connected to WPMMA's activities.

7.4.7 List of projects

Completed projects

- Preliminary cosmological analysis with LISA MBHB mergers as bright sirens [154, 153].
- Preliminary cosmological analysis with LISA SOBHBs as dark sirens [80].
- Preliminary analyses of simple beyond-ΛCDM models with LISA MBHB mergers as bright sirens [65, 61].
- First analysis on constraints of modified GW propagation with LISA MBHB mergers as bright sirens [40] [CosmoWG project].

Ongoing projects

- First exploratory analysis of cosmological constraints using LISA EMRIs as dark sirens (contact: Nicola Tamanini).
- Refined cosmological analysis with LISA MBHB mergers as bright sirens, including proper Bayesian merger and ringdown parameter estimation and new figures of merit for cosmology (contact: Nicola Tamanini, Chiara Caprini).
- First combined cosmological exploratory analysis with all available LISA standard sirens (MBHBs, EMRIs, SOBHBs) (contact: Nicola Tamanini).
- Second analysis on constraints of modified GW propagation with LISA MBHB mergers as bright sirens, including frequency-depended modification on the waveform [CosmoWG project, contact: Gianmassimo Tasinato, Tessa Baker].

Possible future projects

- Refinement of the estimation of the MBHB EM counterpart production and detection (in collaboration with WPMM and WPSI.1).
- Theoretical investigations of beyond-ΛCDM and modified gravity models relevant for LISA, i.e. for which LISA can provide unique constraints, e.g. at high redshift. In collaboration with WPSI.7, WPSI.8.

- Assessment of weak-lensing as systematic uncertainty and its effect on cosmological measurements, and as a possible new way to obtain cosmological information (e.g. cross-correlating with LSS). Impact of possible de-lensing techniques on LISA cosmological measurements.
- Detailed definition of a Bayesian framework for LISA dark sirens, including high redshift systematic (e.g. evolution of number of galaxies).

7.5 WPSI.5: Characterization of stochastic backgrounds

7.5.1 Overview and goals

The superposition of many unresolved sources appears as a stochastic signal in the detector. A stochastic gravitational wave background (SGWB) can be of astrophysical origin: in the LISA band we expect at least three types of astrophysical SGWB: from unresolved GBs (white dwarfs), unresolved SOBHBs (which could also be of primordial origin), and unresolved NSBs. Astrophysical SGWB from unresolved EMRIs and supermassive black hole binaries are also possible. The SGWB can also be of cosmological origin, generated by a variety of processes operating in the very early universe. Sources susceptible of emitting in the LISA band include: primordial first order phase transitions at the electroweak scale and beyond, topological defects, specific models or mechanisms of particle production during inflation, PBHs with masses of the order of 10^{-12} solar masses.

A list of the relevant topics for this WP is given in the following. Note that this list is not prioritised, while deliverables (next section) are.

- In the case of a detection, the measurement of the properties of the SGWB (spectral shape, statistical properties, polarization, angular anisotropies) will be crucial in identifying the main source of the SGWB and allow for a targeted search for sub-dominant components with distinct properties. **Need input from the LIG concerning the noise model**

- SGWB of astrophysical origin - GB: the background from unresolved GB is expected to be well above LISA sensitivity curve and is non-isotropic. Measuring this background will allow to study the population properties (such as their total number and distribution of orbital parameters) and confront them with constraints from electromagnetic observations (such as SNIa rates) and galactic sources resolved by LISA. Moreover, this SGWB acts as a foreground to all other sources, and it is therefore crucial to fully characterize it in order to allow the detection of extragalactic and cosmological backgrounds. **Possible strong overlap with DPEWP**.

- SGWB of astrophysical origin - extragalactic SOBHB, EMRI, NSB: unresolved extragalactic sources create a SGWB with a well-defined spectral shape, but whose amplitude depends on the merger rate of SO binary systems, and its evolution with redshift. Detection or upper limit on this SGWB and comparison with the measurement from ground-based GW detectors will allow to constrain the SO binary population. This signal may also act as a foreground for cosmological sources.

- PBH: the PBH abundance is constrained for a wide range of masses, with a noticeable exception in the 10^{-12} solar mass window, where they can constitute the totality of the dark matter. The most standard mechanism for PBHs production is from enhanced density perturbations. These perturbations unavoidably source a SGWB well above the LISA sensitivity. Therefore LISA will probe this dark matter candidate

- SGWB of cosmological origin – phase transitions and topological defects: phase transitions can result in a SGWB, both at the transition itself and by the evolution of topological defects formed at the transition. In particular, a strong electroweak phase transition is present in several extensions of the Standard Model of particle physics. This can allow to probe fundamental physics in a complementary way to accelerator searches.

- SGWB of cosmological origin – inflation: while the SGWB produced by the inflationary expansion itself is well below the LISA sensitivity, a variety of inflationary mechanisms can produce a significantly larger, and potentially visible signal. For instance, sourced perturbations in axion inflation can be naturally large at interferometer scale. LISA constitutes a unique opportunity to explore primordial perturbations and GW produced about 25 e-folds before the end of inflation.

7.5.2 Deliverables

- DEL1: Prediction of the SGWB signal
  - DEL1.1: Theoretical prediction of the SGWB signal in the LISA band: this must include both cosmological and astrophysical SGWB, must be broad and kept up to date, and must include an estimation of the expected uncertainty of the templates
  - DEL1.2: Mock SGWB data catalogues: simulated data of SGWB signal plus instrumental noise. The data catalogues can be produced as they are needed, following the progresses in the other deliverables. Depending on the WP requirements, they can include several features as the SGWB power spectrum, its anisotropies, its statistics, its chirality, as well as different instrument noise characteristics (e.g. possible non-gaussianity). This deliverable is necessary for DEL2. **This deliverable needs the input of the LIG and/or LDPG to characterise the noise**.
- DEL2: Data analysis pipelines performing the reconstruction of the SGWB signal from the simulated data
  - Reconstruction of the SGWB spectral shape
    - DEL 2.1: agnostic reconstruction: codes returning the reconstruction of the instrumental noise and SGWB spectral shape without assumptions on the origin of the signal
    - DEL2.2: template based: codes performing the parameter estimation of the SGWB power spectrum and instrumental noise for several cosmological and astrophysical signals. This deliverable depends on DEL1.1
  - Reconstruction of the SGWB characteristics beyond the power spectrum
    - DEL 2.3: anisotropy: codes extracting the angular distribution of the SGWB signal
    - DEL 2.4: chirality: codes extracting the chirality of the SGWB signal
- DEL3: Forecasts on the SGWB production processes: assess how the (non-)detection of the SGWB constrains/confirms the production processes and the underlying physics
  - DEL3.1: SGWB of astrophysical origin: study the potential of LISA to constrain sources population models (GB, NSB, SOBHB, EMRIs) **This deliverable needs the input of the astrophysical WPs regarding population models: CATWP, WPSI.2, WPSI.3**.
  - DEL3.2: SGWB of cosmological origin: study the potential of LISA to constrain models of the universe at high energy, in particular PBHs (in collaboration with WPSI.6), phase transitions and inflation

Side remark: We note that deviations in the SGWB templates due to non-standard pre-BBN cosmology, and their link to tests of cosmological parameters, are important aspects, but we defer them to the work of the scientific community within the Cosmology WG. The same holds for the investigation of any dependence between the SGWB from binary (or triplets, ...) and the cosmological model, like the correlation with binary formation processes, the correlation with the structure formation and its anisotropies, and so on. Note as well that the list of SGWB given in the Overview and Goals isn't exhaustive, other SGWB sources have been put forward in the literature, as for example ultra-light boson condensates (c.f WPSI.6).

7.5.3 Timeframe and workforce requirements

- DEL 1: 4+10 FTEs
  - DEL 1.1: we can expect a broad catalogue within 2 years, but this will have to be updated as theory develops, on a yearly basis
  - DEL 1.2: requires coordination with the data analysis group (estimate: 5 years)
- DEL 2: requires coordination with the data analysis group. 26 FTEs
  - DEL 2.1: codes exist (1906.09244 and 1906.09027), they need to be integrated into the pipelines (estimate: 1 year) and they need to be tested in data challenges (2 years, or following the calendar of the LDC)
  - DEL 2.2: write the code, integrate in the pipelines, test with the data challenges (3 years, or following the calendar of the LDC)
  - DEL 2.3: 5 years
  - DEL 2.4: 3 years (like 2.2)
- DEL 3: qualitative studies exist, a more quantitative analysis requires DEL 1 and DEL 2. 4 FTEs
  - DEL 3.1 : 1 year once DEL 1 and DEL 2 exist
  - DEL 3.2 : 1 year once DEL 1 and DEL 2 exist

7.5.4 Description of work

- DEL 1. Astro: Given population models, predict SGWB. Cosmo: For the most common sources, predict SGWB. In coordination with data analysis team, generate mock data catalogues.
- DEL 2. develop methods (theory), write codes, implement in pipelines, test in data challenges
- DEL 3. given DEL 1 and 2, derive constraints on parameter spaces and draw conclusions on the physics.

7.5.5 Possible subpackages

- **subWP on astrophysical SGWB**: For each astrophysical SGWB source, accurately predict the amplitude, spectral shapes and other possible features of the corresponding SWGB, depending on the source characteristics. (DEL 1.1, later DEL 3)
- **subWP on cosmological SGWB**: For each cosmological SGWB source, accurately predict the amplitude, spectral shapes and other possible features of the corresponding SWGB, depending on the source characteristics. (DEL 1.1, later DEL 3)
- **subWP on SGWB detection**: Develop pipelines to infer SGWB parameters, principal components, and other characteristics (non-gaussianity, angular dependence, polarization…). Develop strategies to extract sub-dominant signals, subtracting the high-SNR galactic background (DEL 1.2 and DEL 2)

7.5.6 Dependencies

7.5.6.1 General requirements

- astrophysical sources, population models, catalogues (SOBHB, WD binaries, NS binaries, EMRIs)
- Take into account the potential of future Earth-based detectors such as the Einstein Telescope and Cosmic explorer to reduce, by accurate detections of resolved events, the level of the astrophysical SGWB.
- Take into account possible predictions/detections of the SGWB from future Earth-based detectors and from new discoveries or constraints at particle physics experiments.
- interface with data analysis groups for implementing codes and pipelines and mock SGWB data for the template-based and non-template-based searches

7.5.6.2 Dependencies on specific (sub-)WPs

Within the WPSI:

- WPs about sources that can be hidden by the known astrophysical SGWB: SOBHBs (WPSI.2), GBs (WPSI.2), EMRIs (WPSI.3), [also see cosmic strings (WAV1.7)].
- Constraints on backgrounds generated by primordial black holes should take into account the observed population of black holes: WPSI.1, WPSI.2, WPSI.3.

Between WPSI and WPs : WAV, DPE and DAFT:

- Estimation of the instrument noise and its time evolution (via ground tests, null-stream TDI channels as Sagnac, and other techniques available).
- For the proper characterisation of the SGWB, the subtraction of other LISA sources must be accurate enough to minimise residuals. This involves the waveform WAVWP and the data analysis DPEWP.
- WPs about noise characterisation such as DAFT.4-DAFT.3.
- Constraints on backgrounds generated by cosmic strings should take into account any detected/modelled transients consistent with bursts from cosmic string cusps: DPE.9.

7.5.7 List of projects

Completed projects

- Preliminary theoretical templates and LISA capabilities for some selected inflationary models [36].
- Preliminary theoretical templates and preliminary LISA capabilities for cosmological phase transitions [62, 63].
- Preliminary theoretical templates and preliminary LISA capabilities for cosmic strings [23].
- Preliminary agnostic reconstruction of a SGWB power spectrum [64].

Ongoing projects

- CosWG analyses of the template-based parameter reconstruction of the signals from phase transitions, topological defects, inflation (contact: Germano Nardini)
- SGWBinner code developed within the CosWG (contact: Mauro Pieroni)
- CosWG analysis of anisotropies in the SGWB: map making (contact: Arianna Renzini), and forecasting the ability of LISA to detect it (contact: Angelo Ricciardone))
- CosWG analysis of the signal from PBH (contact: Sebastien Clesse and Juan Garcia-Bellido)

7.6 WPSI.6: Elucidating Dark Matter

Out of all the matter in the universe, only ∼15% is composed of regular baryonic particles. The other ∼85% is dark matter (DM), a poorly-understood substance that has so far evaded detection [155]. This famous elusiveness stems from the lack of obvious interaction between DM and the particles known within the standard model of particle physics. In spite of this, whatever its specific characteristics, DM must certainly couple to gravity. LISA has the unique potential to take advantage of this universal interaction to shed light on the nature and properties of DM, and thus solve one of the foremost scientific questions of the century. The goal of probing DM is related to Science Objectives 5-8 in the LISA Science Requirements Document.

LISA will be able to probe DM through a variety of observables [32, 49]. The presence of DM may be revealed through the study of a large population of signals from binary black holes (BHs), whose mass and spin distributions may have been affected by interactions with DM [21, 20, 19, 138, 58, 57, 37, 59] (see Ref. [56] for a review). LISA will be able to detect minute dephasings in the waveforms from individual sources, helping identify traces of environmental DM effects (such as drag or accretion [34, 101]) and to distinguish between BHs and potential self-gravitating DM structures (like boson stars [116, 73], see also WPSI.8 below). DM may also give rise to completely new LISA signals, like transient and persistent gravitational waves (GWs) from ultralight boson clouds around fast-spinning BHs [21, 20, 19, 138, 58, 57, 37, 59, 56]. LISA may also be sensitive to direct couplings between DM particles and the instrument itself [131, 82, 94, 141]. Moreover, LISA will be very important to investigate the possibility that DM is made out of primordial BHs (this particular aspect has a rich phenomenology at cosmological times and hence will be led by WPSI.4 and WPSI.5).

Activities in this work package (WP) will involve developing analysis pipelines for the extraction of DM information from LISA data, as well as creating a theoretical framework for interpreting observations. The WP also aims to engage the community of relevant experts to predict LISA observables under specific DM models. Much of the work will call for close coordination with other WPs, in particular WPSI.4 and WPSI.5, WPSI.7 and WPSI.8.

7.6.1 Overview and goals

- Detect or constrain DM through direct searches for transient and persistent GW signals from ultralight-boson condensates.
- Use populations of binary BHs to probe the large-scale structure and dynamic properties of DM, and establish connections to cosmology.
- Explore potential impact of DM on gravitational waveforms from compact binaries.
- Collaborate with other WPs to understand potential stealth bias from confounding factors, like baryonic physics.
- Study the possibility of using LISA as a direct DM detector, assessing feasibility and merit of potentially-required alterations of instrumental or data-collection operations.

7.6.2 Deliverables

- Analysis pipeline for the detection and characterization of continuous GWs from ultralight-boson condensates, including the followup of binary mergers.
- Parameter estimation infrastructure for the identification of DM stochastic backgrounds. To be carried in strong collaboration with the Cosmo WP.
- Infrastructure for producing constraints on ultralight bosons from individual BH mass and spin measurements.

- Binary BH waveforms encoding deviations from the vacuum general-relativistic prediction due to DM. Disambiguation with respect to baryonic matter effects.
- Hierarchical inference infrastructure for the analysis of populations of compact-binary signals within the context of DM models (e.g. measuring DM properties from distribution of BH masses and spins as a function of redshift).
- Theoretical and analytical framework for translating generic parameterized constraints (e.g. as obtained in searches for beyond-Einstein physics) into DM statements.
- Analysis pipeline for the detection and characterization of bosenova bursts.
- Characterization of the influence of local DM on LISA data. This will be done for different DM-standard model interactions, and different DM models.

7.6.3 Description of work

Activities in this work package will involve developing data analysis pipelines, creating a theoretical framework and community of experts for interpretation, and the production of specific predictions for LISA observables under specific models of dark matter. Much of the work will call for close coordination with other work packages, in particular WPSI.7, WPSI.8, WPSI.3 and WPSI.4.

7.6.4 Timeframe and workforce requirements

- Near-term goals (< 2 years):
  - Obtain projected range and rates of ultralight-boson GWs based on a realistic implementation of searches for continuous waves in LISA data (1.5 FTEs).
  - Simulate extraction of ultralight-boson stochastic background, and its separation from astrophysical or primordial elements (3 FTEs). To be done in collaboration with Cosmo WP.
  - Characterize the possible effects in the free-fall trajectories of the test masses and laser propagation between the satellites produced by the local DM for a variety of DM models (2 FTEs).
- Medium-term goals (< 5 years):
  - Understand how to identify generic DM effects on the waveform as due, e.g., to drag in DM environments or modification in the propagation of the laser beams (4 FTEs).
  - Create infrastructure to hierarchically extract DM information from populations of compact-binary detections (3 FTEs).
  - Leverage numerical simulations to inform analyses for bosenovas and other phenomenology of self-interacting ultralight bosons (2 FTEs).
  - Perform realistic simulations of the uses of LISA as a DM direct detection experiment. Understand possible improvements of the mission to maximize the potential of LISA in this direction.
- Long-term goals (< 10 years):
  - Obtain waveforms from simulations of compact binary coalescences in DM environments (6 FTEs)
  - Develop production-level search and parameter estimation infrastructure (10 FTEs).

7.6.5 Possible subpackages

- Compact binary waveform modeling (develop waveforms with specific DM imprints, like drag).

- Compact binary parameter estimation (implement generic waveform models that encompass the specific effects above, and integrate them with new or existing inference infrastructure).

- Directed searches for continuous DM signals (develop or adapt all-sky and directed searches).

- Directed searches for modeled and unmodeled transients (e.g. from bosenovas).

- Stochastic background modeling and search (develop predictions for spectral shape of ultralight-boson stochastic backgrounds and interface with searches).

- Compact binary rates and populations (obtain predictions for DM models, and repurpose or create infrastructure to make joint inferences from observations).

- LISA as a DM Detector.

7.6.6 Dependencies

Within WPSI:

- This package overlaps closely with WPSI.7 - Testing the Foundations of General Relativity and WPSI.8 Testing the nature of BHs, WPSI.3 and WPSI.4 (Cosmology). These five packages exist under the theme of Fundamental Physics with LISA and will interact with the Fundamental Physics Working Group.

- These five sub-packages will share similar data analysis pipelines, for example an ability to augment the standard waveform models with beyond-GR and/or environmental effects, and perform parameter estimation to constrain or measure these effects. They will require hierarchical modeling pipelines to post-process and combine these results to test specific theories against entire source populations from LISA. The connection to the Cosmology subpackages has several flavours (population of primordial black holes that can constitute part of the DM, complementary views on bosonic ultra-light candidates, etc.).

- The packages will differ in the expertise needed to interpret these data products, and to generate waveform models in specific beyond-GR theories or incorporating specific matter effects. In case of overlap, interactions among the co-chairs will contribute to distribute tasks and maximising efficiency.

Between WPSI and WPs: WAV, DAFT, DPE, MMA:

- The waveforms of WAVWP are dependencies for any of the packages in the Fundamental Physics theme.

- The same is true of DAFTWP - Data analysis tools and DPEWP - Individual and global source identification. Any computational challenges presented by the activities of DPEWP will be more extreme when the models are modified to include DM and environmental effects.

- Some DM models predict simultaneous gravitational and electromagnetic signatures, motivating interactions with WPCAT and WPMMA- Multi messenger/band astronomy.

7.6.7 List of projects

This subpackage has been recently incorporated to the list of LISA Data Analysis Work Packages. There is no ongoing project at the moment, and the priority at this stage is to build the workforce to start organizing and addressing the previous objectives.

7.7 WPSI.7: Foundations of the gravitational interaction

Gravitation is still the most enigmatic of all interactions. It is poorly understood and tested at the shortest microscopic scales, where quantum effects are important. At large scales, the need to introduce DM and dark energy to explain all observations suggests that our understanding of gravity is also incomplete. LISA will provide unique guidance into the mysteries of gravity, by testing the cornerstones of the theory: are fundamental symmetries, such as Lorentz symmetry or parity invariance, fully respected by gravity? Is the gravitational interaction mediated by the metric only – i.e., by a massless spin-2 particle called the graviton? Can gravitons be massive? Are there new fields that partake in the gravitational interaction, either as classical remnants of a quantum description of gravity (e.g.compactification of extra dimensions), or as explanations to DM or dark energy? In practice, modified theories of gravity can offer quantitative and systematic answers to the questions above. By detecting or constraining modified theories of gravity and their dynamics, and with the right theoretical underpinning, we are probing the most fundamental principles of gravitation.

7.7.1 Overview and goals

The overarching goal is to test GR in the strong-field, highly relativistic regime, using LISA to inform theoretical physics on a variety of arenas [87, 173, 46, 48, 32]:

- Constraining the mass, propagation speed of gravitons and gravitational-wave oscillations [164, 44, 169, 130, 172, 41].
- To inform us on spacetime dimensionality, both in context of large, flat and warped extra dimensions [168, 172, 140, 71, 84].
- To provide limits on possible variations of the gravitational Newton coupling constant [171, 172, 152].
- To test gravitational parity violations and chirality [10, 170, 172].
- To test gravitational Lorentz violations [95, 172, 174].
- To test the Equivalence Principle violations [44, 169, 167, 172].
- To test the existence of other radiation channels [157, 32].
- Tests of gravity through nonlinear memory effect in binary coalescence [114]

7.7.2 Deliverables

- Accurate waveforms in modified theories of gravity where some numerical relativity simulations exist, such as Einstein-Maxwell-dilaton theory, Einstein-dilaton Gauss-Bonnet gravity and dynamical Chern-Simons gravity
- Accurate waveforms in modified theories of gravity where numerical relativity simulations currently do not exist, such as Horndeski theories, Einstein-æther theory, non-commutative gravity and extra-dimensional theories
- Fast (hybrid?) waveforms to perform parameter estimation
- Data analysis pipeline to test GR, including stacking multiple events
- Framework to translate parameterized constraints into specific theories / physical models
- Parameter estimation/bias in the presence of environmental effects (esp. for EMRIs)

7.7.3 Description of work

Activities in this work package will involve developing data analysis pipelines, creating a theoretical framework and community of experts for interpretation, and the production of specific predictions for LISA observables under specific models. Much of the work will call for close coordination with other work packages, in particular WPSI.7 and WPSI.8.

7.7.4 Timeframe and workforce requirements

In order of priority within each timeframe:

- Near-term goals (now–2 years):
  - Leading PN corrections in beyond-GR theories (1.5FTEs)
  - First simulations of BBH mergers in multiple theories beyond GR (4 FTEs)
  - Outline waveform accuracy requirements for successful ppE tests with LISA MBBHs (shared with WPSI 6 & 7) (1.5 FTEs)
  - Design interface of tests of GR with whole enchilada challenge (shared with WPSI 6 & 7) (4 FTEs)
  - Theoretical consistencies (2FTEs)
  - GW memory in non-GR theories (2 FTEs)
- Medium-term goals (2–5 years):
  - Develop initial pipeline for applying tests of GR to realistic LISA mock data (shared with WPSI 6 & 7) (8 FTEs)
  - Higher-PN corrections in beyond-GR theories (4 FTEs)
  - Accurate IMR waveform approximants beyond GR (5 FTEs)
  - Model-independent tests in the merger and post-merger phase (2 FTEs)
  - EMRI waveforms with beyond-GR effects and environmental effects (3 FTEs)
- Long-term goals (5–10 years):
  - Develop full pipeline for parameter estimation in beyond-GR theories (shared with WPSI 6 & 7) (10 FTEs). To be carried in strong collaboration with the Cosmo WP.
  - Identify the most promising beyond-GR theories and catalog the available constraints (7 FTEs)
  - Develop full ability to model LISA waveforms in the most promising beyond-GR theories (7 FTEs)
  - Develop pipeline for tests of GR with stacking multiple events (3 FTEs)

7.7.5 Possible subpackages

- Search for deviations from GR in the inspiral (generation effects)
- Search for deviations from GR in the merger/ringdown
- Waveform modeling in non-GR theories
- Violations of the Equivalence Principle and Lorentz invariance
- Probing the existence of extra dimensions

- Propagation effects (to be carried in strong collaboration with the Cosmo WP)
- Other model independent tests
- Astrophysical systematics due to environmental effects
- Data-analysis pipeline

7.7.6 Dependencies

General requirements:

- Population models of EMRIs, SOBHs, IMBHBs, IMRIs, multiband sources.
- Accurate waveforms for EMRIs and IMRIs in GR including environmental effects (that will be extended to include non-GR effects within this WP)
- Data analysis pipeline within GR (that will be extended to include non-GR effects within this WP)

Within WPSI:

- This package overlaps closely with WPSI.6 - Elucidating Dark Matter, with WPSI.8 Testing the nature of BHs and WPSI.4 and .5. These four packages exist under the theme of Fundamental Physics with LISA and will interact with the Fundamental Physics Working Group.
- These four sub-packages will share similar data analysis pipelines, for example an ability to augment the standard waveform models with beyond-GR and/or environmental effects, and perform parameter estimation to constrain or measure these effects. They will require hierarchical modeling pipelines to post-process and combine these results to test specific theories against entire source populations from LISA.
- The packages will differ in the expertise needed to interpret these data products, and to generate waveform models in specific beyond-GR theories or incorporating specific matter effects. In case of overlap, we envision constant interactions among the co-chairs to distribute tasks, for maximising efficiency.
- Analysis of EMRI population (WPSI.3), Analysis of IMBHBs and IMRIs (WPSI.1) and studies of SOBH populations (WPSI.2).

Between WPSI and WPs: MMA and WAV, DAFT and LAP:

- The waveforms of WAVWP are dependencies for any of the packages in the Fundamental Physics theme.
- The same is true of DAFTWP - Data analysis tools and DPEWP - Individual and global source identification. Any computational challenges presented by the activities of DPEWP will be more extreme when the models are modified to include dark matter and environmental effects.
- This activity has common interests with Multiband GW analysis (WPMMA.1, WPMM.2.3).

7.7.7 List of projects

completed

- probing dipole radiation, graviton mass, parity violation, etc. with multiband observations [35, 74, 75, 159]
- computing waveforms in compactified extra dimension spacetime [71, 84]
- gravitational-wave oscillations in a generic framework [41]

ongoing

- constructing full waveforms in string-inspired gravity
- computing waveforms in warped extra dimension spacetime
- computing gravitational-wave memory in scalar-tensor theories
- distinguishing non-GR and astrophysical effects

7.8 WPSI.8: Testing the nature of BHs

7.8.1 Overview and goals

One of the fundamental goals of LISA is to test the theory of general relativity (GR), and our understanding of matter in the most extreme conditions [87, 173, 46, 48, 32]. Many promising sources for LISA include massive, compact objects which – according to our current physical theories –must have collapsed to become BHs. A major science goal for LISA is to test whether these compact objects are in fact BHs, possessing event horizons, and whether these BHs are correctly described by GR [73]. This science goal is represented by Science Objective 5 ("Explore the fundamental nature of gravity and black holes") in the LISA Science Requirements Document [`https://www.cosmos.esa.int/web/lisa/lisa-documents`]. Motivations for testing the nature of compact objects are manifold [73] and include the information loss paradox, the search for a high-energy, possibly quantum, completion of GR, the problem of singularities in GR, and the search for exotic fields, some of them being also compelling dark-matter candidates.

A variety of methods for probing the nature of compact objects with GWs exists, but they primarily fall under the searches for deviations from standard waveform predictions, or the search for novel effects like echoes in the post-merger signal [70, 72, 8, 77, 163, 7]. Some famous approaches include: study the ringdown signal following the merger of BHs [45, 47], using EMRI waveforms to measure the multipolar structure of spinning supermassive objects [31, 24], and performing consistency tests with parameterized deviations from the inspiral-merger-ringdown waveforms [4, 88, 48].

The goals of this sub-WP are:

- Test the nature of compact objects, and particularly the GR "no-hair theorem"
- Test quantitatively for the presence of and study the dynamics of horizons
- Test the Cosmic Censorship Conjecture
- Search for exotic supermassive compact objects beyond BHs
- Account for systematics, especially possible environmental effects [34], on the above tests

The above goals are directly inspired by those listed in the LISA Proposal:

- SI 5.1: Use ring-down characteristics observed in MBHB coalescences to test whether the post-merger objects are the BHs predicted by GR
- SI 5.2: Use EMRIs to explore the multipolar structure of MBHs
- SI 5.3: Testing for the presence of beyond-GR emission channels

7.8.2 Deliverables

1. Full parametrized IMR waveforms which incorporate the possibility of exotic near-horizon physics, extreme compact objects other than BHs, and environmental effects, for both MBBHs, EMRIs, and IMBHs
2. Data-analysis pipeline yielding Bayes factors for the hypotheses of: i) deviations from the Kerr hypothesis, ii) new near-horizon physics, iii) environmental effects, as well as estimates of the corresponding parameters, based on individual/stacked sources and on measurements of the stochastic background
3. Framework to translate parametrized constraints into specific theories/physical models which predict objects other than Kerr BHs.
4. Framework for tests of no-hair and area theorems; development of a pipeline for those.

7.8.3 Description of work

Activities in this WP will involve developing and deploying data analysis pipelines, creating a theoretical framework and community of experts for interpretation, and the production and use of waveforms under specific models for how BHs may differ from the predictions of GR. Therefore, strong synergies among this WP and WAVWP [waveform modelling] as well as WPSI.6 and WPSI.7 are envisaged and welcome (see also Sec. 7.8.6).

7.8.4 Timeframe and workforce requirements

Within each timeframe goals are ordered by priority. D1-D4 refer to the above deliverables. FTEs refer to the whole timeframe duration.

- Near-term goals ($<$ 2 years):
  - Outline waveform accuracy requirements for successful ppE tests [172, 6] with LISA MBBHs (shared with WPSI.6 & .7) (D1, 1.5 FTEs)
  - Design interface of tests of GR and BH paradigm with whole enchilada challenge (shared with WPSI.6 & .7) (D1&D2, 4 FTEs)
  - First simulations of BBH mergers [165, 137, 136] in multiple theories beyond GR (D1, D3&D4, 4 FTEs)
  - Investigate role of overtones [27, 98, 91, 50] in LISA ringdown tests (D4, 1 FTE)
  - Build a catalogue of boson-star models [116, 73] (D1, D3&D4, 2 FTEs)
- Medium-term goals ($<$ 5 years):
  - Develop initial pipeline for applying tests of BHs to realistic LISA mock data (shared with WPSI.6 & WPSI.7) (D1&D2, 8 FTEs)
  - Develop accurate IMR waveform approximants beyond GR and for ECOs, including echoes [73, 156, 162, 120], tidal [69, 149, 139, 78] and spin effects [110, 111, 31, 142] (D1, 5 FTEs)
  - Complete framework for ringdown-based tests of the no-hair theorem [45, 47], including both parametrized deviations [124] and predictions in specific theories (D3&D4, 4 FTEs)
  - Produce EMRI waveforms with beyond-BH effects [31, 92, 142], especially for central objects with a different multipolar structure than Kerr BHs (D1,D3&D4, 6 FTEs)
  - Develop first-principles dynamical ECO models (D3&D4, 4 FTEs)
  - Understand how systematics from waveforms and environmental effects impact tests of the BH paradigm (D2, 3 FTEs)
- Long-term goals ($<$ 10 years):
  - Develop full pipeline for parameter estimation in beyond-GR theories and for performing and interpreting tests of the nature of compact objects (shared with WPSI.6 & .7) (D1&D2, 10 FTEs).
  - Identify the most promising alternatives to BHs and the most promising beyond-GR theories, investigate the most promising effects, and catalog the available constraints (D3&D4, 7 FTEs)
  - Develop full capability to model LISA waveforms for the most promising alternatives to BHs (D1, D3, D4, 7 FTEs)

7.8.5 Possible subpackages

- Simulations of coalescence beyond GR and for ECOs
- IMR waveforms beyond GR and for ECOs
- Ringdown and post-merger tests
- Parametrized and targeted inspiral tests
- Environmental effects on tests of the nature of BHs

7.8.6 Dependencies

Within WPSI: This package overlaps closely with WPSI.6 - Dark matter , with WPSI.3 - EMRIS, and especially with WPSI.7 - Testing the Foundations of General Relativity. These three packages exist under the theme of Fundamental Physics with LISA and will interact with the Fundamental Physics Working Group.

The above sub-packages will share some of the data analysis pipelines, for example the possibility to augment the standard waveform models with beyond-GR and/or environmental effects, and perform parameter estimation to constrain or measure these effects. They will require hierarchical modeling pipelines to post-process and combine these results to test specific theories against entire source populations from LISA.

The packages will differ in the expertise needed to interpret these data products, and to generate waveform models in specific beyond-GR theories or incorporating specific matter effects. However, the expertise needed for interpretation within WPSI.7 and WPSI.8 will strongly overlap, since the modifications to relativity that are explored in WPSI.7 will often impact the nature of BHs as explored in WPSI.8.

Between WPSI and WPs WAV, DAFT and DPE: The waveforms of WAVWP are dependencies for any of the packages in the Fundamental Physics theme. The same is true of DAFTWP - Data analysis tools and DPEWP - Individual and global source identification. Any computational challenges presented by the activities of DPEWP will be more extreme when the models are modified to include beyond-GR and environmental effects.

7.8.7 List of projects

Each of the timeframe goals (or combination thereof) listed in Sec. 7.8.4 are related to a specific project.

- Develop EOB/Phenom-like IMR waveforms for boson-star coalescence
- Build accurate and realistic GW echo templates
- Construct no-hair theorem and BH spectroscopy-based tests of GR which incorporate multiple modes, overtones, and which potentially combine multiple events
- Formulate a general parameterization of multipole moments for exotic compact objects “beyond Kerr,” and develop parametrized signal models when these multipoles are present
- Build a catalogue of boson-star models
- Construct accurate waveforms for tests of the nature of compact objects with tidal effects
- Investigate the size of astrophysical systematics and waveform-modeling errors in tests of the nature of BHs

- Simulate binary ECO coalescence in a fully dynamical, consistent model
- Develop an initial pipeline for applying tests of BHs to realistic LISA mock data

Acronyms and Glossary

LISA Laser Interferometer Space Antenna

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