PhD project (2025-2028): Fast parameter inference of gravitational waves for the LISA space mission

Keywords: *Fast Bayesian inference, Event identification, Signal processing, Gravitational waves, Machine learning*

Context

In 2016, the announcement of the first direct detection of gravitational waves ushered in an era in which the universe will be probed in an unprecedented way. At the same time, the complete success of the LISA Pathfinder mission validated certain technologies selected for the LISA (Laser Interferometer Space Antenna) project. The year 2024 started with the adoption of the LISA mission by the European Space Agency (ESA) and NASA. This unprecedented gravitational wave space observatory will consist of three satellites 2.5 million kilometres apart and will enable the direct detection of gravitational waves at undetectable frequencies by terrestrial interferometers. ESA plans a launch in 2035.

In parallel with the technical aspects, the LISA mission introduces several data analysis challenges that need to be addressed for the mission's success. The mission needs to prove that with simulations, the scientific community will be able to identify and characterise the detected gravitational wave signals. Data analysis involves various stages, one of which is the rapid analysis pipeline, whose role is to detect new events and characterise the detected events. The last point concerns the rapid estimation of the position in the sky of the source of gravitational wave emission and their characteristic time, such as the coalescence time for a black hole merger.

These analysis tools form the low-latency analysis pipeline. As well as being of interest to LISA, this pipeline also plays a vital role in enabling multi-messenger astronomy, consisting of rapidly monitoring events detected by electromagnetic observations (ground-based or space-based observatories, from radio waves to Gamma rays).

PhD project

The PhD project focuses on the development of event detection and identification tools for the low-latency alert pipeline (LLAP) of LISA. This pipeline will be an essential part of the LISA analysis workflow, providing a rapid detection of massive black hole binaries, as well as a fast and accurate estimation of the sources' sky localizations as well as coalescence time. These are key information for multi-messager follow-ups as well as for the global analysis of the LISA data.

While rapid analysis methods have been developed for ground-based interferometers, the case of space-based interferometers such as LISA remains a field to be explored. Adapted data processing will have to consider how data is transmitted in packets, making it necessary to detect events from incomplete data. Using data marred by artefacts such as glitches or missing data packages, these methods should enable the detection, discrimination and analysis of various sources: black hole mergers, EMRIs (spiral binaries with extreme mass ratios), bursts and binaries from compact objects. A final and crucial element of complexity is the speed of analysis, which constitutes a strong constraint on the methods to be developed.

To this end, the problems we will be tackling during this thesis will be:

1. The fast parameter inference of the gravitational waves, noticeably, the sky position, and the coalescence time. Two of the main difficulties reside in the multimodality of the posterior probability distribution of the target parameters and the stringent computing time requirements. To that end, we will consider different advanced inference strategies including:
   (a) Using gradient-based sampling algorithms like Langevin diffusions or Hamiltonian Monte Carlo methods adapted to LISA's gravitational wave problem,
   (b) Using machine learning-assisted methods to accelerate the sampling (e.g. normalising flows),

    (c) Using variational inference techniques.

2. The early detection of black hole mergers.
3. The increasing complexity of LISA data, including, among others, realistic noise, realistic instrument response, glitches, data gaps, and overlapping sources.
4. The online handling of the incoming 5-minute data packages with the developed fast inference framework.

This thesis will be based on applying Bayesian and statistical methods for data analysis and machine learning. However, an effort on the physics part is necessary, both to understand the simulations and the different waveforms considered (with their underlying hypotheses) and to interpret the results regarding the detectability of black hole merger signals in the context of the rapid analysis of LISA data.

Scientific environment

The candidate will be hosted at the CEA's Institut de Recherche sur les Lois Fondamentales de l'Univers (IRFU) as part of a transverse research team on gravitational waves, with activities ranging from instrumental involvement in the LISA mission to the astrophysical or cosmological consequences of exploiting the signals (Antoine Petiteau, Marc Besançon), via the development of algorithms, simulations (Jean-Baptiste Bayle) and data analysis (Jérôme Bobin, Hervé Moutarde, Tobías Liaudat) that form the core of the proposed thesis topic. The candidate will have the opportunity to take an interest in all aspects of the host team's activity and interact with each member. This PhD project will strongly contribution to Irfu's activity in developing and delivering solutions to the LISA's LLAP. The candidate will be able to benefit from the expertise of the growing machine learning and artificial intelligence community on the Saclay plateau.

Computational resources The successful candidate will have access to the Jean Zay supercomputer and to the IRFU's CPU/GPU computer cluster.

The applicant profile

The successful candidate should be comfortable with software development (at least in Python) and, ideally, be familiar with deep learning frameworks (e.g. PyTorch, JAX). Experience with open-source and collaborative development tools (e.g. GitHub) is desirable. Basic knowledge of statistical inference, signal processing, and machine learning is expected. Previous experience with gravitational wave data analysis would be beneficial. The research team is international, so speaking French is not a requirement.

Collaborations / Partnerships

The candidate will be a member of the LISA collaboration and participate in the CU L2A group coordinating the low-latency alert pipeline effort. He/she will interact with members of the Groupement de Recherche (GdR) Ondes Gravitationnelles and collaborate regularly with physicists and engineers from the Astroparticles and Cosmology (APC) laboratory in Paris. The candidate is expected to present results within the LISA consortium and at international conferences.

Contact

The PhD position will be based in the ALEPH group at the IRFU institute from the CEA Paris-Saclay research centre, which is located 20km south of central Paris in the Paris-Saclay cluster. The group is focuses on signal (and image) processing and machine learning applied to astrophysics applications and is heavily involved in LISA.

Co-supervisors:

- Dr. Tobías I. Liaudat (tobias.liaudat@cea.fr)
- Dr. Jérôme Bobin (jerome.bobin@cea.fr)

The deadline for applications is the 30 Mars 2025.