Master (M2) internship 2025:
Accelerated and differentiable LISA space mission instrument response for fast parameter inference of gravitational waves

Keywords: *Fast Bayesian inference, 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).

Internship project

The 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 detecting events from incomplete data necessary. 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.

This project's central challenge will consist of developing a fast and differentiable LISA instrument response in the JAX framework. The LISA response will be the fast inference pipeline's (LLAP) cornerstone. The differentiable nature of the response will allow us to exploit gradient information. Therefore, this enables using gradient-based sampling algorithms like Langevin diffusions or Hamiltonian Monte Carlo methods. The next part of the project will consist of adapting these sampling algorithms for LISA's fast gravitational wave inference problem. Depending on the student's advancement, we aim to continue exploring the usage of variational inference techniques and machine learning-assisted methods to accelerate the sampling (e.g., normalising flows).

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 project. 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 project aligns with IRFU's activity in developing and delivering solutions to 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 following an M2 master or an engineering diploma degree, with a specialisation on signal processing/statistics/machine learning or astrophysics. Basic knowledge of Bayesian inference, signal processing, and machine learning is expected. The candidate should be comfortable with software development (at least in Python) and, ideally, be familiar with deep learning frameworks (e.g. JAX). Experience with open-source and collaborative development tools (e.g. GitHub) is a plus. The research team is international, so speaking French is not a requirement.

Practical details

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

– Ideal start date: 1st April 2025.

– The deadline for applications: 31st January 2025.

– Ideal duration: 5 or 6 months.

– To apply, send by email the application documents, a CV and your transcript of records (*relevé de notes*), with an email subject starting with [LISA-internship].

Co-supervisors:

– Dr. Tobías I. Liaudat (tobias.liaudat@cea.fr) [Personal page link]

– Dr. Jean-Baptiste Bayle (jean-baptiste.bayle@cea.fr)