EMRI Search and Inference within the LISA Global Fit - Part I

Report of Contributions

https://indico.in2p3.fr/e/emri-1

Contribution ID: **1** Type: **not specified**

Test abstract

This is a test

Author: Dr BAGHI, Quentin (APC | Université Paris Cité)

Presenter: Dr BAGHI, Quentin (APC | Université Paris Cité)

Contribution ID: **2** Type: **not specified**

Inexpensive Inference of Missing Physics in Gravitational Wave Sources

Tuesday 24 June 2025 14:30 (30 minutes)

The upcoming LISA observatory will measure parameters of sources like EMRIs with exquisite precision, providing a unique avenue to test General Relativity (GR) and the matter-rich environment in galactic centers. Such "beyond-vacuum-GR" effects modify the inspiral, and if neglected from the analysis, can significantly bias ($\geq 10\sigma$) parameter recovery as shown by previous studies. Yet, the rich landscape of proposed beyond-vacuum-GR effects modifying the "null" vacuum-GR hypothesis makes inference through conventional methods like Markov Chain Monte Carlo (MCMC) practically infeasible. We propose bias-corrected importance sampling, a generic inference framework for nested hypotheses, making it particularly suitable for the inference and test of beyond-vacuum-GR effects in GW signals. I will discuss the effectiveness of the technique for EMRIs and compare it against MCMC. Finally, in the context of the proposed LISA global-fit pipeline, I will motivate why such methods may be necessary for feasible and systematic inference of beyond-vacuum-GR effects.

Authors: KEJRIWAL, Shubham (National University of Singapore); DUQUE, Francisco (Max Planck Institute for Gravitational Physics); CHUA, Alvin (National University of Singapore); GAIR, Jonathan (AEI Potsdam)

Presenter: KEJRIWAL, Shubham (National University of Singapore)

Contribution ID: **3** Type: **not specified**

A test for LISA foreground Gaussianity and stationarity. Extreme mass-ratio inspirals

Tuesday 24 June 2025 16:50 (20 minutes)

Extreme Mass Ratio Inspirals (EMRIs) are key observational targets for the Laser Interferometer Space Antenna (LISA) mission. Unresolvable EMRI signals contribute to the formation of a gravitational wave background (GWB).
Characterizing the statistical features of the GWB from EMRIs is of great importance, as EMRIs will ubiquitously affect large segments of the inference scheme.
In this work, we apply a frequentist test for GWB Gaussianity and stationarity, exploring three astrophysically-motivated EMRI populations. We construct the resulting signal by combining state-of-the-art EMRI waveforms and a detailed description of the LISA response with time-delay interferometric variables.
Depending on the brightness of the GWB, our analysis demonstrates that the resultant EMRI foregrounds show varying degrees of departure from the usual statistical assumptions that the GWBs are both Gaussian and Stationary.
If the GWB is non-stationary with non-Gaussian features, this will challenge the robustness of Gaussian-likelihood model, when applied to global inference results, e.g. foreground estimation, background detection, and individual-source parameters reconstruction.

Author: PIARULLI, Manuel (L2IT, Université Toulouse III - Paul Sabatier)

Co-authors: SESANA, Alberto (University of Birmingham); POZZOLI, Federico (Università degli Studi Milano-Bicocca); BONETTI, Matteo (University of Milano-Bicocca); BURKE, Ollie (University Avenue, Glasgow, UK); Dr BUSCICCHIO, Riccardo (Universitá di Milano-Bicocca)

Presenter: PIARULLI, Manuel (L2IT, Université Toulouse III - Paul Sabatier)

Contribution ID: **4** Type: **not specified**

Roadmap for the Inclusion of Extreme Mass Ratio Inspirals in the LISA Global Fit

Extreme Mass Ratio Inspirals (EMRIs) present one of the key challenges in the data analysis of future data from the Laser Interferometer Space Antenna (LISA). Their long signal duration and the large number of harmonics make the search and parameter estimation of these sources particularly challenging. There are two main challenges associated with EMRI data analysis: the size of the posterior is several orders of magnitude smaller than the size of the prior search, and the search surface adopting standard detection statistics presents several local maxima, making the identification of EMRIs especially difficult.

I will discuss current strategies for overcoming these problems, review the latest results from machine learning methods, semi-coherent searches, and phenomenological approaches. Additionally, I will outline the timeline and roadmap for successfully including EMRIs in the global fit of LISA, aiming to realize the rich scientific potential of these sources.

Author: Dr SPERI, Lorenzo (European Space Agency)

Presenter: Dr SPERI, Lorenzo (European Space Agency)

Session Classification: Data Analysis I

Contribution ID: **5** Type: **not specified**

Millisecond waveforms for eccentric extreme mass ratio inspirals into spinning black holes

The Laser Interferometer Space Antenna is expected to observe numerous gravitational-wave sources in the mHz band. One promising source class are extreme mass ratio inspirals (EMRIs) of a stellar-mass compact object into a massive black hole (MBH). Accurate EMRI waveforms are essential for data analysis, but this is challenging to achieve due to the need to accurately track the phasing of many harmonic modes over tens of thousands of orbital cycles. Rapid EMRI template generation is the ongoing aim of the FastEMRIWaveforms (FEW) project, which demonstrated millisecond waveform generation for eccentric inspirals into spin-zero black holes. However, MBHs are expected to be rapidly spinning, which greatly impacts EMRI waveforms for these systems. In this talk, I will present a significant extension to FEW that incorporates MBH spins of up to 0.999. I will first describe the modifications to the framework required to achieve this, followed by a discussion of EMRI science prospects for eccentric and spinning systems with a fully relativistic waveform model for the first time. I will conclude with an overview of the next steps for FEW development, including early results for the generation of EMRIs directly in the time-frequency domain, which has the potential to further accelerate FEW by more than an order of magnitude.

Author: CHAPMAN-BIRD, Christian (University of Birmingham)

Presenter: CHAPMAN-BIRD, Christian (University of Birmingham)

Session Classification: Waveform tools

Contribution ID: **7** Type: **not specified**

Accelerated MBH population estimation from EMRI detections

Tuesday 24 June 2025 16:30 (20 minutes)

Multiple detections of extreme mass ratio inspirals (EMRIs) offer a unique opportunity to probe the population of massive black holes (MBHs). Maximizing the scientific potential of these observations requires a robust inference framework capable of handling computational challenges in likelihood evaluation and observational biases. In this work, we present a Bayesian hierarchical inference framework designed to constrain the MBH population parameters. We introduce a feed-forward neural network, achieving ~5 orders of magnitude speed-up in signal-to-noise ratio (SNR) computations for EMRI waveforms. These SNR calculations are a bottleneck in the likelihood evaluation and SNR-based selection effect, which we have included in our analysis. We validate our method using phenomenological, astrophysically motivated MBH population models. Our results demonstrate the framework's ability to tightly constrain mass and spin distributions and the branching fractions associated with different MBH formation channels, further driving investigation into the origins and evolution of MBHs.

Authors: SINGH, Shashwat (University of Glasgow); Dr CHAPMAN-BIRD, Christian (University of Birmingham); Dr BERRY, Christopher (University of Glasgow); Dr VEITCH, John (University of Glasgow)

Presenter: SINGH, Shashwat (University of Glasgow)

Contribution ID: **8** Type: **not specified**

Don’t reinvent the wheel: including Extreme Mass Ratio Inspirals in the LISA global fit

Wednesday 25 June 2025 14:00 (20 minutes)

LISA data analysis poses many challenges.
The presence of persistent, long-lived, and overlapping sources in the data stream requires a global fit to all the parameters of all the source models simultaneously.
The number and variety of signals, together with the dimensionality of the parameter space, call for large computational resources and extremely optimized pipelines capable of leveraging the unique properties inherent to each source type.
Recent works in literature introduced global fit algorithms for analyzing the LDC2A dataset, which consists of Massive Black Hole binaries, Galactic Binaries, and instrumental noise.
In this work, we take the first steps towards introducing Extreme Mass Ratio Inspirals (EMRIs) in the GPU-accelerated pipeline “Erebor.”
These signals represent one of the toughest challenges we have to face to fully exploit the scientific potential of the LISA mission, both from the modeling and analysis sides.
While the current state-of-the-art EMRI tools have recently enabled fully Bayesian parameter estimation studies through Markov Chain Monte Carlo (MCMC) methods, the inclusion of these sources in large-scale frameworks remains an open problem.
Here, we combine these tools with our pipeline’s intrinsic modularity and flexibility, showcasing how straightforward it is to include (or remove) a block from our global fit “wheel.”
While we do not focus on developing a working search pipeline for these sources, we show how to use search results to seed the global MCMC in the joint parameter estimation stage.
This will prepare us to tackle datasets of increasing realism and difficulty, starting with the next LISA Data Challenge.

Authors: SANTINI, Alessandro (Max Planck Institute for Gravitational Physics (AEI)); KATZ, Michael (NASA Marshall Space Flight Center); Dr KARNESIS, Nikolaos (AUTh); KORSAKOVA, Natalia (SYRTE/Observatoire de Paris); GAIR, Jonathan (AEI Potsdam)

Presenter: SANTINI, Alessandro (Max Planck Institute for Gravitational Physics (AEI))

Contribution ID: **9** Type: **not specified**

Looking for a better space for EMRI waveform

Wednesday 25 June 2025 14:20 (20 minutes)

I am going to talk about the possibilities of finding an optimal representation for the EMRI waveform. We can follow the idea of the singular value decomposition (or similar methods, such as principle component analysis (PCA)), when we project the data on the new basis along the direction which are more representative of the data. In this way the dimensions that do not contribute much to reconstruction of the data can be dropped out. This simple technique of the linear algebra can be extended to the methods used in artificial intelligence (AI) such as autoencoders. They can be seen as the extension of the linear approach to nonlinear spaces. We are going to explore the variety of these methods up to the most modern ones such as transformers, which have in recent year revolutionised AI field.

Author: KORSAKOVA, Natalia (ARTEMIS)

Presenter: KORSAKOVA, Natalia (ARTEMIS)

Contribution ID: **10** Type: **not specified**

Millisecond waveforms for eccentric extreme mass ratio inspirals into spinning black holes

Monday 23 June 2025 11:30 (45 minutes)

The Laser Interferometer Space Antenna is expected to observe numerous gravitational-wave sources in the mHz band. One promising source class are extreme mass ratio inspirals (EMRIs) of a stellar-mass compact object into a massive black hole (MBH). Accurate EMRI waveforms are essential for data analysis, but this is challenging to achieve due to the need to accurately track the phasing of many harmonic modes over tens of thousands of orbital cycles. Rapid EMRI template generation is the ongoing aim of the FastEMRIWaveforms (FEW) project, which demonstrated millisecond waveform generation for eccentric inspirals into spin-zero black holes. However, MBHs are expected to be rapidly spinning, which greatly impacts EMRI waveforms for these systems. In this talk, I will present a significant extension to FEW that incorporates MBH spins of up to 0.999. I will first describe the modifications to the framework required to achieve this, followed by a discussion of EMRI science prospects for eccentric and spinning systems with a fully relativistic waveform model for the first time. I will conclude with an overview of the next steps for FEW development, including early results for the generation of EMRIs directly in the time-frequency domain, which has the potential to further accelerate FEW by more than an order of magnitude.

Presenter: CHAPMAN-BIRD, Christian (University of Birmingham)

Contribution ID: **11** Type: **not specified**

Roadmap for the Inclusion of Extreme Mass Ratio Inspirals in the LISA Global Fit

Monday 23 June 2025 10:30 (30 minutes)

Extreme Mass Ratio Inspirals (EMRIs) present one of the key challenges in the data analysis of future data from the Laser Interferometer Space Antenna (LISA). Their long signal duration and the large number of harmonics make the search and parameter estimation of these sources particularly challenging. There are two main challenges associated with EMRI data analysis: the size of the posterior is several orders of magnitude smaller than the size of the prior search, and the search surface adopting standard detection statistics presents several local maxima, making the identification of EMRIs especially difficult.

I will discuss current strategies for overcoming these problems, review the latest results from machine learning methods, semi-coherent searches, and phenomenological approaches. Additionally, I will outline the timeline and roadmap for successfully including EMRIs in the global fit of LISA, aiming to realize the rich scientific potential of these sources.

Author: Dr SPERI, Lorenzo (European Space Agency)

Presenter: Dr SPERI, Lorenzo (European Space Agency)

Contribution ID: **12** Type: **not specified**

Sequential simulation-based inference for extreme mass ratio inspirals

Monday 23 June 2025 15:30 (30 minutes)

Extreme mass ratio inspirals are a key target for next generation space-based gravitational wave detectors because they have a rich phenomenology that could offer new astrophysics and fundamental physics insights. However, their dynamics are complicated to model, their signals remain in band for long durations, and they will be buried amongst a large population of other sources in the milliHertz frequency band with a background of non-stationary and non-Gaussian noise. Searching for these systems and measuring their parameters therefore presents a difficult challenge.

Simulation-based inference methods could offer solutions to some of these challenges. I will show how sequential simulation-based inference, specifically truncated marginal neural ratio estimation, can efficiently narrow down the volume of the complex 11-dimensional search parameter space by a factor of a million and provide 1-dimensional marginal proposal distributions for non-spinning extreme-mass-ratio inspirals. I will highlight the benefits of this approach with respect to traditional likelihood-based methods, and discuss the broader context in which such a pipeline will need to be embedded as well as how and when environmental effects should be considered.

Presenter: COLE, Philippa

Contribution ID: **13** Type: **not specified**

Astrophysics of Extreme Mass Ratio Inspirals

Tuesday 24 June 2025 10:00 (30 minutes)

Extreme Mass Ratio Inspirals (EMRIs) are compact binary systems characterized by very small mass ratios (between 10^{-9} and 10^{-4}), and they represent one of the primary gravitational wave (GW) sources for the forthcoming Laser Interferometer Space Antenna (LISA).
In the standard formation scenario, EMRIs originate in dense nuclear star clusters when a compact object is captured by a central massive black hole (MBH) due to frequent two-body interactions among orbiting bodies.
Alongside this widely studied mechanism, several alternative formation channels have been proposed—such as evolution within active galactic nucleus (AGN) disks, tidal separation of binaries, or perturbations from massive bodies.

In this talk, I will review the leading formation scenarios, with a focus on their predicted orbital features and the significant astrophysical uncertainties that affect them. I will then focus on specific aspects of the two-body capture

Presenter: BONETTI, Matteo (University of Milano-Bicocca)

Contribution ID: **14** Type: **not specified**

Electromagnetic observations of EMRIs: modeling and data analysis of quasi-periodic eruptions

Tuesday 24 June 2025 10:30 (30 minutes)

Quasi-periodic eruptions (QPEs) are intense repeating soft X-ray bursts with recurrence times about a few hours to a few days from galactic nuclei. More and more analyses show that QPEs are the result of collisions between an EMRI and an accretion disk around a supermassive black hole (SMBH) in galactic nuclei (EMRI+disk model). In this talk, I will first review exisisting QPE observations and the evidence for the EMRI+disk model,then report a Bayesian framework we have constructed for analyzing QPE data, and show that QPEs (EM signals of EMRIs) are a sensitive probe to the EMRI orbits and the SMBH spacetime.

Presenter: Dr PAN, Zhen (T.D. Lee Institute, Shanghai Jiao-Tong University)

Contribution ID: **15** Type: **not specified**

Dynamics and dephasing of EMRI systems in realistic accretion discs.

Tuesday 24 June 2025 14:00 (30 minutes)

I will present a brief overview of the state-of-the-art in the topic of environmental effects for gas embedded EMRI systems, focusing on the potential and the challenges of extracting GW phase shifts from realistic signals. I will demonstrate how pushing the modelling of EMRI interaction with the gas medium beyond the commonly adopted migration torque and dynamical friction prescriptions can reveal richer observables. In particular, I will share some recent results on epicyclical resonances between the EMRI orbit and the accretion disc torques. They suggest that mildly eccentric EMRIs in accretion discs will dephase by 10 to 100 times more that what was previously expected.

Presenter: Dr ZWICK, Lorenz (Niels Bohr International Academy Copenhagen)

Contribution ID: **16** Type: **not specified**

Robust EMRI parameter estimation in the presence of noise non-Gaussianities

Wednesday 25 June 2025 10:00 (30 minutes)

Presenter: Dr KARNESIS, Nikolaos (AUTh)

Contribution ID: **17** Type: **not specified**

Identification and parameter estimation of gravitational-wave signals from extreme-mass-ratio inspirals with LISA

Wednesday 25 June 2025 10:30 (30 minutes)

We present an innovative search method for gravitational wave signals from EMRIs. With the precise identification of the signal, we are able to compute the posterior distribution of EMRI signals. This leads the path to the global fit of EMRI signals overlapping with other sources of gravitational wave signals.

Author: STRUB, Stefan (ETH Zurich)

Presenter: STRUB, Stefan (ETH Zurich)

Contribution ID: **18** Type: **not specified**

A full stellar mass inspiral search: Building the road to the EMRI search

Monday 23 June 2025 16:00 (30 minutes)

The search for EMRIs is hindered by two main problems, the extremely compact posterior and the degenerate parameter space with numerous secondary peaks. This talk addresses the former by demonstrating a complete search pipeline for stellar-mass binary inspirals; these systems exhibit similarly compact posteriors. While the stellar-origin binaries are an important LISA source in their own right, these signals are also a good testing ground for the development of EMRI search algorithms. We present results from the first full search pipeline for stellar mass binary inspirals in LISA data, which is also capable of dealing with data gaps and cyclo-stationary noise. The results of applying this search to the LISA data challenge "Yorsh"are presented, with associated false alarm probabilities for each detected source. A time-frequency approach is used to significantly reduce the cost of the search; full searches over parameter space can be completed within a week. I will also discuss how this approach can be adapted for the EMRI search.

Presenter: BANDOPADHYAY, Diganta (University of Birmingham)

Contribution ID: **19** Type: **not specified**

The DDPC global fit infrastructure

Wednesday 25 June 2025 14:40 (20 minutes)

Presenters: PITTE, Chantal Laure (SISSA); DENG, Senwen (APC)