Binaries in the LISA band as sources of stochastic GW backgrounds

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All classes of LISA sources have the potential to generate a Stochastic Gravitational Wave Background (SGWB) ...either because they have a low signal-to-noise ratio (due to low mass or large distance) or because they are so numerous that they overlap in both time and frequency domains.

The SGWB carries global information about the source population, which complements the details gathered from individually resolved sources.
Galactic binaries and multiples
Compact binary stars are guaranteed LISA sources
Compact binary stars are guaranteed LISA sources

List of candidate LISA verification binaries Kupfer, Korol et al. (2023)

https://gitlab.in2p3.fr/LISA/lisa-verification-binaries
Variety of LISA Galactic binaries and expected number of detections

**Isolated binary evolution**

<table>
<thead>
<tr>
<th>Source</th>
<th>$N$</th>
<th>$N_{\text{detected}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD+WD</td>
<td>$\sim 10^8$</td>
<td>6000–10,000</td>
</tr>
<tr>
<td>NS+WD</td>
<td>$\sim 10^7$</td>
<td>100–300</td>
</tr>
<tr>
<td>BH+WD</td>
<td>$\sim 10^6$</td>
<td>0–3</td>
</tr>
<tr>
<td>NS+NS</td>
<td>$\sim 10^5$</td>
<td>2–100</td>
</tr>
<tr>
<td>NS+NS+NS+BH</td>
<td>$\sim 10^4$</td>
<td>0–20</td>
</tr>
<tr>
<td>BH+BH</td>
<td>$\sim 10^6$</td>
<td>0–70</td>
</tr>
</tbody>
</table>

**Evolution in clusters**

<table>
<thead>
<tr>
<th>Source</th>
<th>$N$</th>
<th>$N_{\text{detected}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD+WD</td>
<td>$\sim 2 \times 10^4$</td>
<td>4–20</td>
</tr>
<tr>
<td>NS+WD</td>
<td>$\sim 10^3$</td>
<td>3–6</td>
</tr>
<tr>
<td>BH+WD</td>
<td>$\sim 10^2$</td>
<td>2–4</td>
</tr>
<tr>
<td>NS+NS</td>
<td>$\sim 40$</td>
<td>1</td>
</tr>
<tr>
<td>BH+NS</td>
<td>$\sim 4$</td>
<td>0</td>
</tr>
<tr>
<td>BH+BH</td>
<td>$\sim 2 \times 10^2$</td>
<td>4–7</td>
</tr>
</tbody>
</table>

LISA Astro white paper, Amaro-Seoane et al. (2023)

WD+WD: Korol et al. 2017; Keim et al. 2023
WD+NS: Korol et al. in prep.;
sdB+WD/NS: Göttberg et al. 2020;
NS+NS/NS+BH/BH+BS: Wagg et al. 2022;
KB: Kupfer, Korol et al. 2023
How we forecast LISA observations of Galactic binaries? Binary population synthesis approach

When forecasting LISA observations, we mainly rely on the binary population synthesis (BPS) technique.

Toonen et al. 2012, based on SeBa BPS code
See also: Nelemans et al. (2001), Ruiter et al. (2010), Yu & Jaffery (2010), Lamberts et al. (2018), Breivik et al. (2020), Li et al. (2020), Wagg et al. (2022) and many others
How we forecast LISA observations of Galactic binaries? An observationally-driven approach

We can construct a representative double white dwarf (DWD) population based on constraints on the binary separation distribution and DWD fraction from multi-epoch spectroscopic surveys SDSS and SPY.
How we forecast LISA observations of Galactic binaries? An observationally-driven approach

Model assumptions:

- The primary WD mass follows the same distribution as single WDs
- Mass ratio follows a flat distribution
- Constant star formation
- The distribution of DWD separations at formation follows a power-law with index $\alpha$

By comparing the data to the models where we vary these underlying assumption it is possible to constrain the power law index $\alpha$ of the DWD separation distribution and DWD/WD fraction.

Courtesy of Na’ama Hallakoun
How we forecast LISA observations of Galactic binaries?  
An observationally-driven approach

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- Power-law index $\alpha = -1.3$
- DWD fraction = 9.5% for separations of less than 4 au

PDFs for generating this DWD population:  
https://gitlab.in2p3.fr/korol/observationally-driven-population-of-galactic-binaries
BPS vs observationally-driven predictions

BPS models predict 6k–25k of individually resolved DWD signals vs 60k predicted by the observation-based model. Note also that the shape of the unresolved signal is also different.
What will we learn from the unresolved Galactic GW foreground?

In strain units, we define the model for the stochastic component of the signal due to unresolved Galactic binaries, as:

$$S_{gal} = \frac{A}{2} f^{-n_s^S} e^{-(f/f_1)\alpha} \{1 + \tanh \left( (f_{knee} - f) / f_2 \right) \},$$

(3)

where $A$ is the amplitude of the signal, $n_s^S$ is the low frequency spectral tilt\(^1\), while the exponential term (with the two parameters $f_1$ and $\alpha$) models the “loss of stochasticity” due to the smaller density of sources at higher frequencies. Finally, the tanh term (with the two parameters $f_{knee}$ and $f_2$) represents a signal cut-off due to individual removal of bright sources. From the above, we recognize that
What will we learn from the unresolved Galactic GW foreground?

It is intuitive to imagine that the total energy emitted in GWs by the Galactic DWD population is related to their total number and, hence, to the total stellar mass of the Galaxy. This is analogous to how the total light emitted by a galaxy is set by its stellar mass. In particular, the total mass of the Galaxy can be connected the shape of the stochastic confusion signal measured by LISA.
What will we learn from the unresolved Galactic GW foreground?

The shape of the Galaxy doesn't significantly alter the shape of foreground, at least in terms of the energy density as a function of frequency.

Georgousi, Karnesis et al. w Korol (2022)
See also Benacquista & Holley-Bockelmann (2006), Breivik et al. (2020)
What will we learn from the unresolved Galactic GW foreground?

When we consider a fixed total stellar mass for the population, the modeling of binary interactions - particularly the common envelope phase - becomes a critical factor. How we encode these interactions significantly influence the characteristics of binaries emitting in the LISA band and therefore shape the detectable foreground.

\[ S_{\text{gal}} = \frac{A}{2} f^{-n_s} e^{-(f/f_i)^{\alpha}} \{ 1 + \tanh \left[ \frac{(f_{\text{knee}} - f)}{f_2} \right] \} \]

Ashlin Varghese's project as part of the Kavli Summer School 2023 (MPA, Garching)

In collaboration with Nikolaos Karnesis et al.
Extragalactic stellar-mass BH binaries
Understanding the astrophysics of stellar-mass BHBs with LISA

LISA can observe individual stellar-mass Black Hole Binaries (BHBs) up to several hundreds of years before coalescence, enabling measurements that are complementary to those made with ground based detectors.

LISA Astro white paper, Amaro-Seoane et al. (2023)
Before the era of (observational) GW astronomy, our black hole sample was largely limited to a few dozens, primarily detected via X-ray radiation within our own Galaxy.

With the arrival of LVK observations, we now have a population of \( \sim 100 \) stellar-mass Black Hole binaries (BHBs), featuring masses as large as \( \sim 100 \, M_\odot \).

This sample is projected to grow up to \( 10^3 \) detections by the time LISA begins operations.

A key strength of the LVK sample lies in its common selection effects, facilitating the direct extrapolation of LISA observations from this observed sample.
Lehoucq et al. (2023) studied SGWB from BHBs and BNSs based on the LVK/EM samples and based on binary population synthesis models:

- **BHB baseline analytical**: Powerlaw+peak mass distribution and merger rate follows star formation rate
- **BNS baseline analytical**: NS mass distribution from Galactic observations, assuming validity at all redshifts.
- **BHB/BNS COSMIC default**: BH/NS mass and delay time distributions from COSMIC with default setting

Key findings: BHBs are likely dominant SGWB contributors; BNS contribution is highly uncertain (need far more BNS merger detections). Approx. 10 BBHs but no BNSs detectable by LISA in 4-year observation period.

Lehoucq et al. (2023); see also Babak et al. (2023)
Massive black hole binaries
LISA will discover Massive Black Holes (MBHs) across a largely unexplored segment of the mass spectrum: $10^4 - 10^7 \, M_\odot$, and unveil their origins and evolution along cosmic history.

These MBHs are the least well-known in terms of basic demographics, birth, grows, dynamics and connection to the host galaxy.

Knowledge will be acquired through the measurement of the MBH masses and spins, and the luminosity distance imprinted in the GW signal.

Figure credit: Elisa Bortolas, inspired by Volonteri et al. (2021) review
Discovering seed BHs at cosmic dawn

- **Primordial origin BHs**: high-contrast density perturbations during early Universe phase transitions, forming even before galaxies, with initial mass up to $10^6 \, M_\odot$.
- **PopIII BHs (light seeds)**: From the collapse of the first metal-free (Pop III) stars at high redshifts, masses between $10 \, M_\odot$ and a few $10^2 \, M_\odot$.
- **Direct collapse BHs (heavy seeds)**: From the direct collapse of supermassive stars around $z \sim 10^{-15}$ in massive halos, masses up to $10^6 \, M_\odot$.
- **Nuclear clusters**: from stellar collisions in metal-poor star clusters, masses up to several $10^3 \, M_\odot$.

![Diagram of BHs and redshift](image)

Figure credit: Melanie Habouzit; LISA Astrophysics white paper, Amaro-Seoane et al. (2023) Observed via EM radiation
LISA’s cosmic horizon

Figure credit: Riccardo Buscicchio based on Bonetti et al. (2019); LISA Definition Study Report to be submitted to ESA for the LISA mission by 2024
Studying the growth mechanism and merger history of MBHs

Figure credit: Silvia Bonoli & Alessandro Lupi, Elisa Bortolas
LISA Astrophysics white paper, Amaro-Seoane et al. (2023)
Studying the growth mechanism and merger history of MBHs

Anticipated rates 2-100 peaking at z~2-4 (with a tail up to z~14)

Figure credit: Silvia Bonoli & Alessandro Lupi†, Elisa Bortolas→
LISA Astrophysics white paper, Amaro-Seoane et al (2023)
What are the implications of the PTA stochastic GW background detection for LISA?

PTA detection of stochastic GW background informs LISA observations.

LISA detection rates, extrapolated from PTA data:
- $<134$ MBH binary mergers/year (total mass: $10^7 - 10^8 \, M_\odot$)
- $<2$ MBH binary mergers/year (total mass: $>10^8 \, M_\odot$)

Continuous PTA efforts will refine predictions and boost LISA's scientific reach.

Steinle et al. (2023)
Do they produce a background for LISA?

Possibly, if MBHs have formed from low-mass remnants of Population III stars, not all can be resolved by LISA.

E.g., Sesana et. al. (2007), Bonetti et al. (2021), Barausse et al. (2020)
Extreme and Intermediate mass ratio inspirals:

GW analogues to S-stars orbiting our own supermassive black hole Sgr A*
Extreme and Intermediate mass ratio inspirals

- EMRIs typically involve a stellar-mass compact object (white dwarf, neutron star, black hole) inspiraling into a MBH with a mass of $\sim 10^4$ - $10^7$
- GWs from these events lie well within LISA's optimal sensitivity range, at $\sim 3$ mHz
- Range of cases is large

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
<th>Mass ratio</th>
<th>Constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>light IMRI</td>
<td>light intermediate mass-ratio inspiral</td>
<td>$10^{-5}$ - $10^{-2}$</td>
<td>IMBH &amp; stellar-mass compact object</td>
</tr>
<tr>
<td>heavy IMRI</td>
<td>heavy intermediate mass-ratio inspiral</td>
<td>$10^{-5}$ - $10^{-2}$</td>
<td>MBH &amp; IMBH</td>
</tr>
<tr>
<td>EMRI</td>
<td>extreme mass-ratio inspiral</td>
<td>$10^{-8}$ - $10^{-5}$</td>
<td>MBH &amp; stellar-mass compact object</td>
</tr>
<tr>
<td>b-EMRI</td>
<td>binary-extreme mass-ratio inspiral</td>
<td>$10^{-8}$ - $10^{-5}$</td>
<td>MBH &amp; binary stellar-mass compact object</td>
</tr>
<tr>
<td>XMRI</td>
<td>extremely large mass-ratio inspiral</td>
<td>$\leq 10^{-8}$</td>
<td>MBH &amp; sub-stellar object</td>
</tr>
</tbody>
</table>

LISA Astro white paper, Amaro-Seoane et al. (2023)
Extreme and Intermediate mass ratio inspirals

The predicted rates are uncertain: from a few to thousands over LISA’s mission duration.

However, even the most pessimistic models confirm EMRIs as a probable source of GWs for LISA to detect.

<table>
<thead>
<tr>
<th>Inspiral type</th>
<th>Rate (yr$^{-1}$)</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMRI</td>
<td>$10^{-1} - 10^3$</td>
<td>$\sim 100$</td>
</tr>
<tr>
<td>light IMRI</td>
<td>6–60</td>
<td>$10^{-1} - 10^3$</td>
</tr>
<tr>
<td>heavy IMRI</td>
<td>2–20</td>
<td>10–100</td>
</tr>
<tr>
<td>XMRI</td>
<td>$\sim$ few tens (at any given moment)</td>
<td>$10^{-1} - 10^4$</td>
</tr>
</tbody>
</table>

LISA Astro white paper, Amaro-Seoane et al. (2023)
EMRI background

The amplitude of EMRI background is related to the EMRI rate (although not necessarily linearly), its spectral shape will be determined by the efficiency of various formation channels throughout cosmic history.

Recent estimates suggest that, the majority of EMRI models could result in potentially detectable foreground, which may significantly contribute to the overall LISA noise budget in the 1-10 mHz frequency range.
Bonus slides
Asteroseismology

Power density \[\text{ppm}^2/\mu\text{Hz}\]

Frequency \[\mu\text{Hz}\]

\[\ell = 2\] (quadrupole)
Analyzing Stellar Oscillation Data

\[ \Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d \ln f} \]

\[ \Omega_{GW}(f) \propto \frac{A^2 \eta I^2}{\chi^2 H_0^2} f \]

- \( \Omega_{GW} \): energy density of GWs
- \( f \): frequency
- \( A \): amplitude
- \( \eta \): mode damping
- \( I \): mode inertia
- \( \chi \): mode dilatation
- \( H_0 \): Hubble constant

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Bellinger & MPA team, in prep.

Freeman Dyson (1969), Siegel & Roth (2010, 2014)
Analyzing Stellar Oscillation Data

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- energy density of GWs
- frequency
- amplitude
- mode damping
- mode inertia
- mode dilatation
- Hubble constant

PRELIMINARY

\begin{align*}
\Omega_{\text{GW}} & \quad \text{frequency [Hz]} \\
10^{-1} & \quad 10^0 \\
10^{-2} & \quad 10^1 \\
10^{-3} & \quad 10^2 \\
10^{-4} & \quad 10^3 \\
10^{-5} & \quad 10^4
\end{align*}

Gaia astrometry

Asteroseismology

Pulsar timing

LISA (2038)

LIGO/Virgo

\[ \ast \]

Bellinger & MPA team, in prep.

\[ \ast \]

Freeman Dyson (1969), Siegel & Roth (2010, 2014)
Icebreakers
Which astro SGWB is the most exiting?

1. Galactic
2. Extragalactic stellar-mass binary black holes
3. Extreme mass ratio inspirals
4. Pop III BH seeds at high redshift
Which astro SGWB we will detect first?

1. Galactic
2. Extragalactic stellar-mass binary black holes
3. Extreme mass ratio inspirals
4. Pop III BH seeds at high redshift