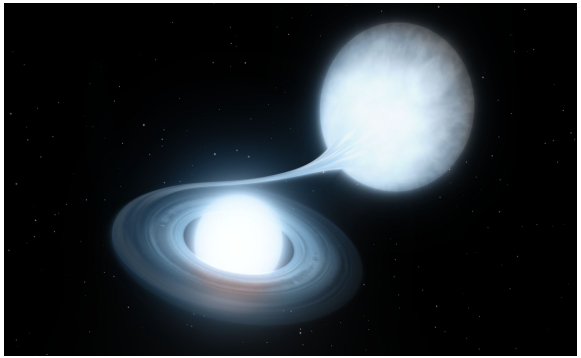
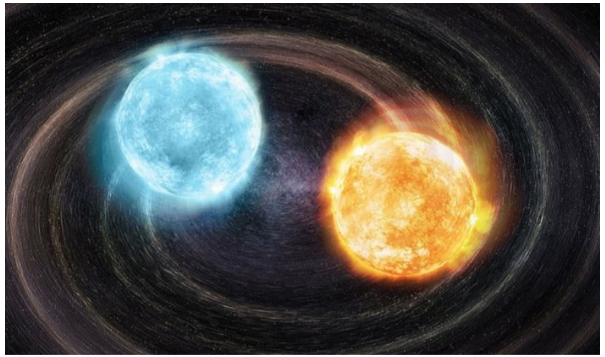
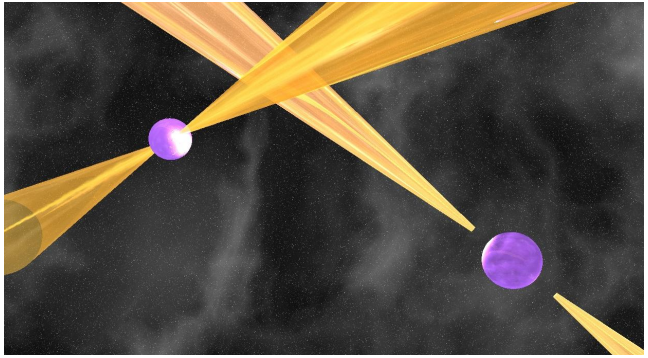
How the ideal LISA catalog of Galactic Binaries may look like from an astronomer's perspective?

By Valeriya Korol (Max Planck Institute for Astrophysics, Garching)

With inputs from the MPA binaries group including Ruggiero Valli, Alejandro Vigna-Gomez, Rob Farmer, Martyna Chruslinska, Stephen Justam; and Gijs Nelemans, Na'ama Hallakoun, Ingrid Pelisoli, Tom Prince and Thomas Kupfer



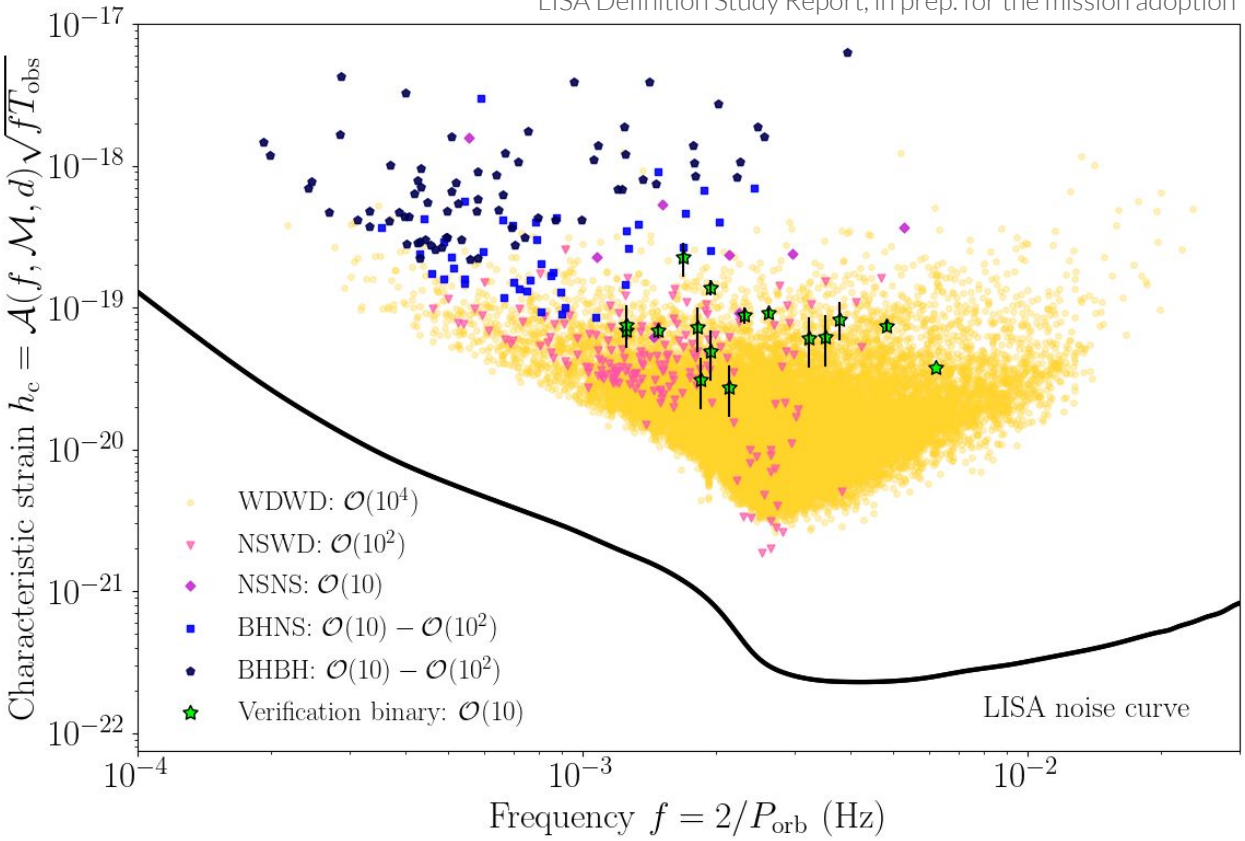




14th June 2023, Towards LISA catalogs meeting, Nice

Variety of LISA Galactic binaries and expected number of detections

LISA Definition Study Report, in prep. for the mission adoption



Isolated binary evolution

Source	N	$N^{\rm detected}$
WD+WD	$\sim 10^8$	6000–10,000
NS+WD	$\sim 10^7$	100–300
BH+WD	$\sim 10^6$	0–3
NS+NS	$\sim 10^5$	2–100
BH+NS	$\sim 10^4 - 10^5$	0–20
BH+BH	$\sim 10^6$	0–70

Evolution in clusters

Source	N	$N^{\rm detected}$
WD+WD	$\sim 2 \times 10^4$	4–20
NS+WD	$\sim 10^3$	3–6
BH+WD	$\sim 10^2$	2–4
NS+NS	~ 40	1
BH+NS	~ 4	0
BH+BH	$\sim 2 \times 10^2$	4–7

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

#1 science objective for LISA: **Study the formation and evolution of compact binary stars and the structure of the Milky Way**

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1. Formation and evolution pathways of EM dark compact binary stars in the Milky Way and in neighboring galaxies
    - How do binary stars evolve into close double compact systems?
    - What is the current merger rate of white dwarfs, neutron stars and stellar-mass black holes in the Milky Way?

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    - What is the spatial distribution of EM dark compact binary stars detected by LISA?
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3. The interplay between gravitational waves and tidal dissipation
   - What fraction of detached ultra-compact binaries evolve into interacting binaries and avoid merger?
   - What is the role of mass transfer, tides and GW in the merger of systems, and what does it tell us about the explosion mechanism of type Ia supernovae?

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L3 catalogs represent one of the final, crucial, steps in facilitating these objectives

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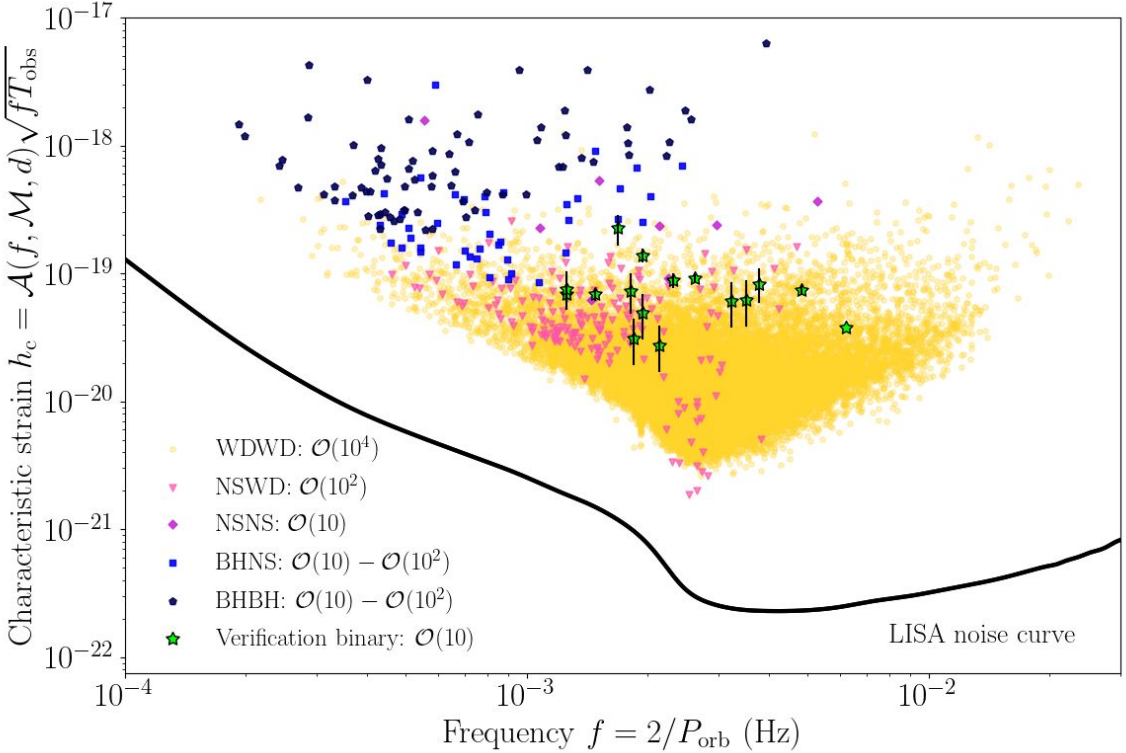
What would it take to study (1) The formation and evolution pathways of Galactic Binaries?



We must distinguish and classify the different types of binary systems.

This classification will allow us to approach each type with tailored methodologies, leading to a deeper and more nuanced understanding of their respective formation processes and evolutionary paths.

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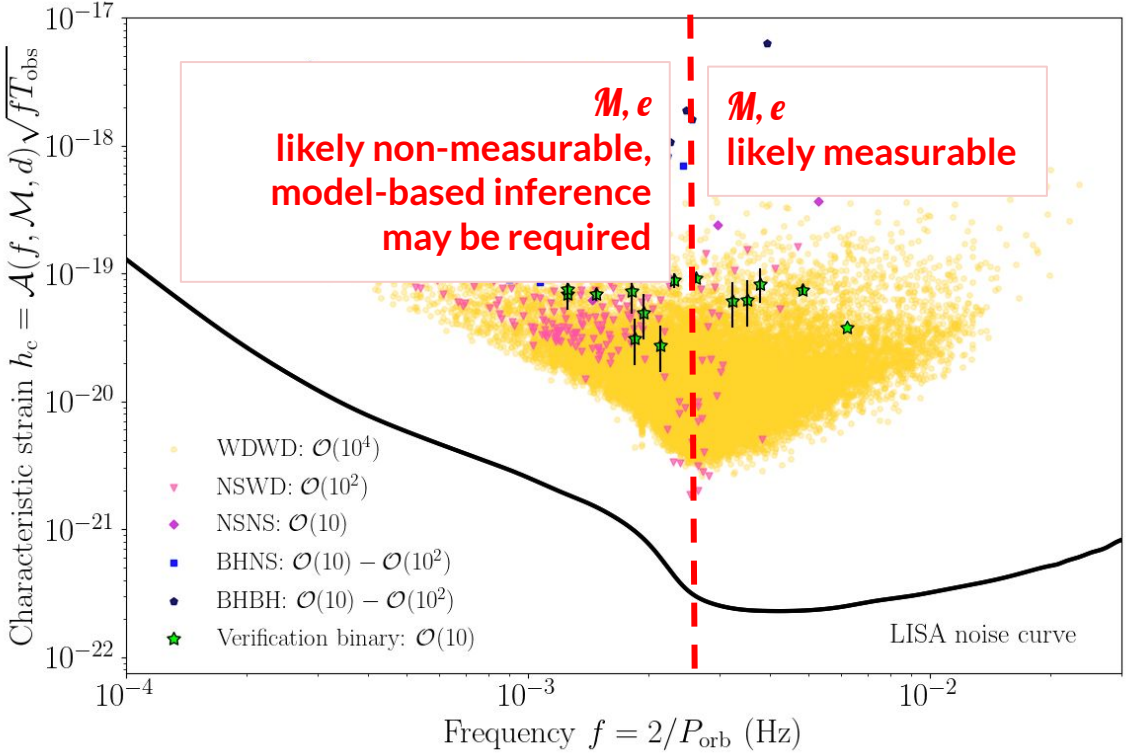

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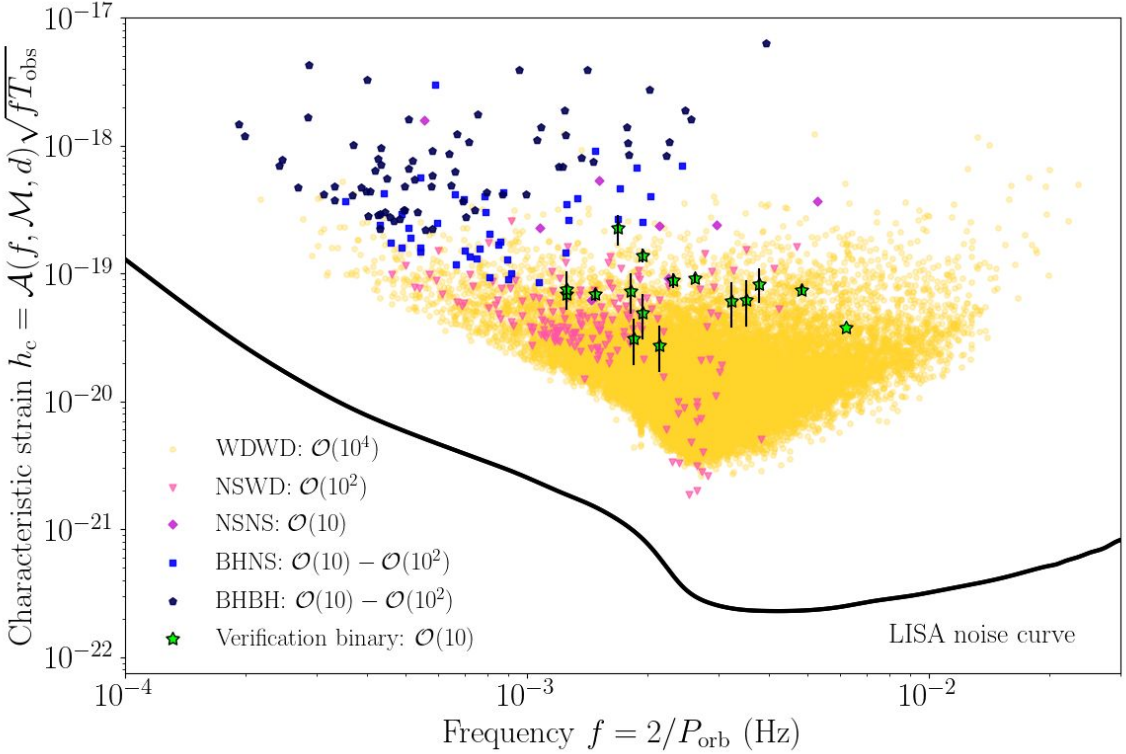
We must distinguish and classify the different types of binary systems.

This classification will allow us to approach each type with tailored methodologies, leading to a deeper and more nuanced understanding of their respective formation processes and evolutionary paths.

Key to distinguishing different types of binary systems is the measurement of the binaries' chirp mass and eccentricity.

What would it take to study (2) The Milky Way stellar mass distribution



To effectively utilize Galactic Binaries as Milky Way mass tracers the **precise determination of sky positions and distances are crucial.**

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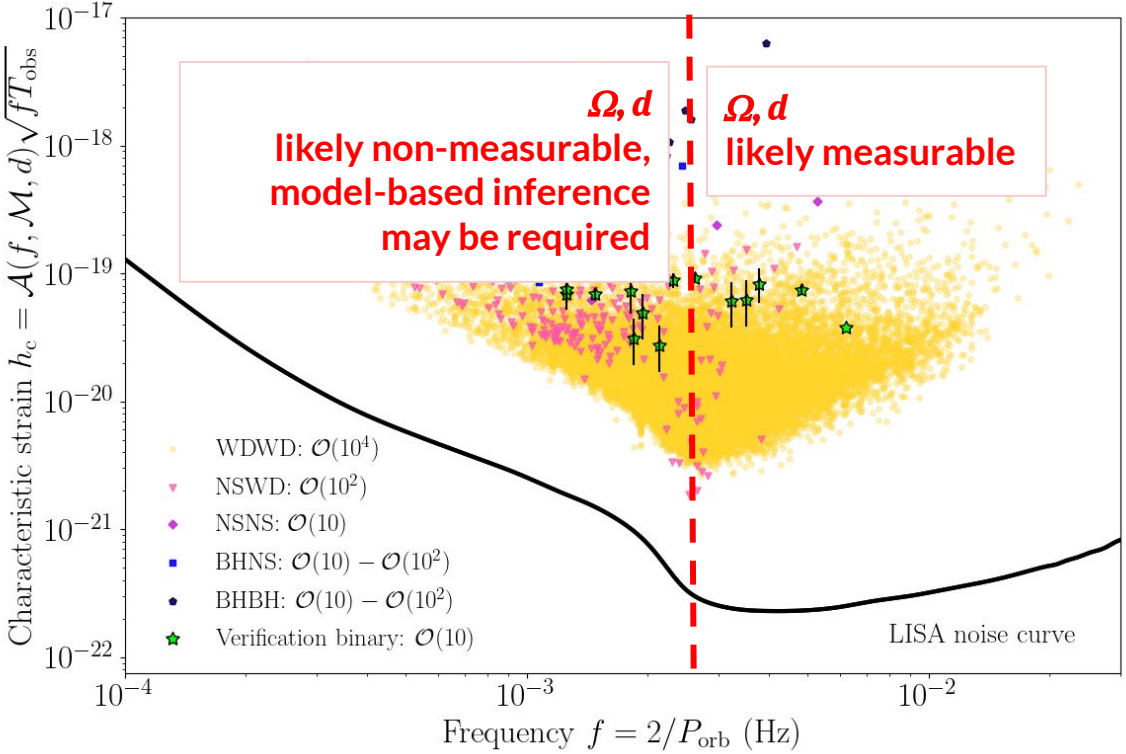

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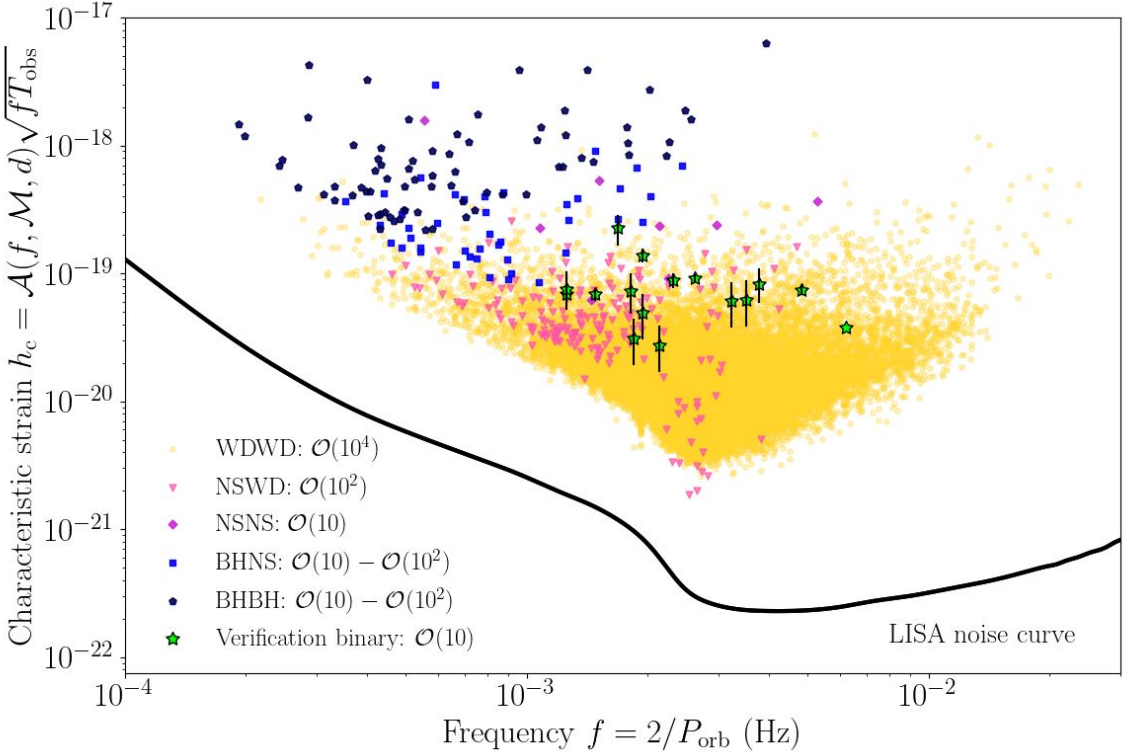
What would it take to study (3) Interplay between gravitational waves and tidal dissipation



To probe the interplay between gravitational waves and processes like tides and mass transfer in binary evolution, two key factors are crucial: **the ability to measure the rate of change of frequency (ḟ) of the gravitational waves and the capability for EM follow-up observations.**

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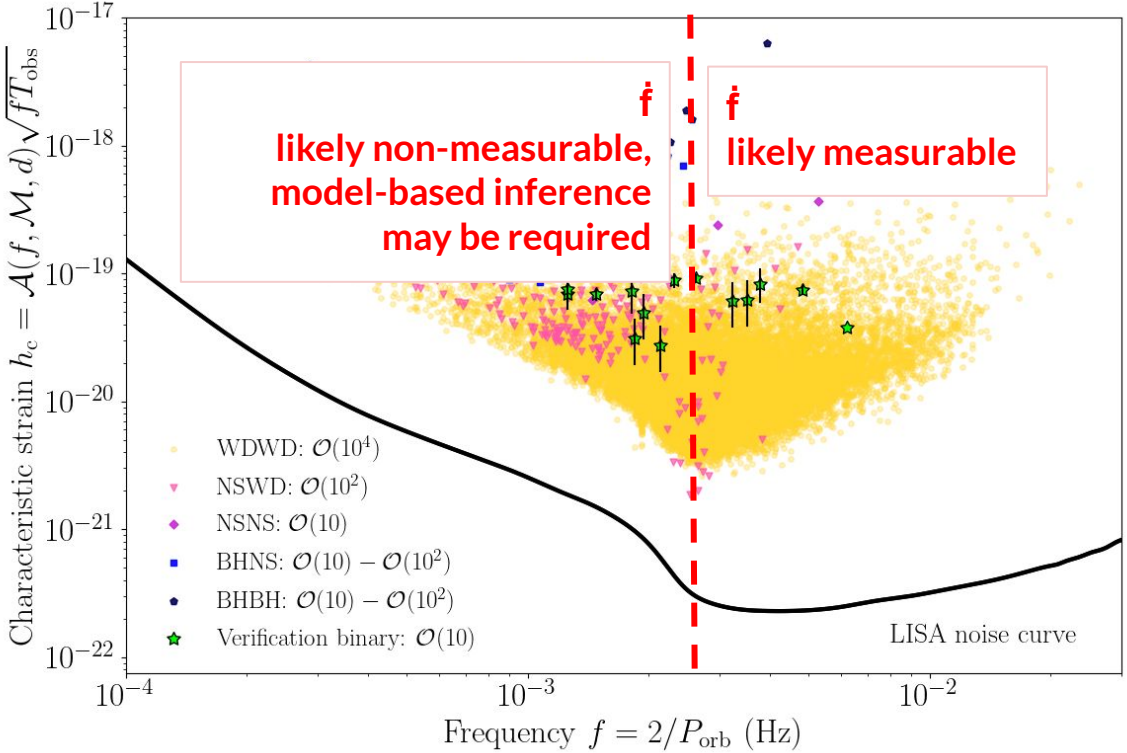

To probe the interplay between gravitational waves and processes like tides and mass transfer in binary evolution, two key factors are crucial: **the ability to measure the rate of change of frequency ($\dot{f}$) of the gravitational waves and the capability for EM follow-up observations.**

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We should also prepare for non-standard sources

- Triples and higher order multiples
- Exoplanets/brown dwarfs tertiaries around LISA sources
- Common envelope events
- Helium-star binaries
- Type Ia explosions
- ...

LISA Astrophysics white paper, RRL (2023)

Envisaging L3 catalogs: astronomers' wish list

Comprehensive Listings: The L3 catalog should include a list of all detected binaries, complete with GW parameters and (very desirably) their EM-friendly analogues (e.g., providing conversion from {f,$\dot{\mathbf{f}}$,A} to {P,M,d}, to other sky coordinate systems, etc.).

It should quantify the uncertainties (preferably, as posterior distributions - likely to be most critical for low-frequency sources) and provide correlations between these parameters.

Additionally, tags specifying the source types (or probabilities for a source to be of a certain type, e.g. WD+WD, NS+NS; or even subtypes, e.g. HeWD+HeWD, COWD+COWD), which will probably an important addition when going from L2 to L3.

Envisaging L3 catalogs: astronomers' wish list

Fit Quality Parameter(s): The catalog should include 'goodness of fit' parameter(s) (e.g Gaia's Renormalized Unit Weight Error (RUWE) parameter), which indicates how well each source fits the expected standard waveform.

In addition, it is important to include a measure of how likely the source being resolved or being sources.

Such parameters would be important for evaluating the reliability and the uniqueness of each entry. Particularly, it is also helpful in identifying outliers—such as highly eccentric binaries, triples, and higher order multiples—which are often astrophysically interesting than "standard" sources.

Envisaging L3 catalogs: astronomers' wish list

Bias and Completeness Assessments: Information assessing selection biases and completeness of the catalog should accompany the data release.

A tool with which you can check the probability of detection (and thus inclusion in the catalog) of a source with certain properties could be useful for this.

Envisaging L3 catalogs: astronomers' wish list

Search Capabilities: The ability to search for binaries with specific properties and ability to pull out the L2 `global fit' result (e.g. LIGO web app shown in Jonah's talk).

It would be great to have the ability to select sources from a 3D map or from a mass-period parameters space.

Envisaging L3 catalogs: astronomers' wish list

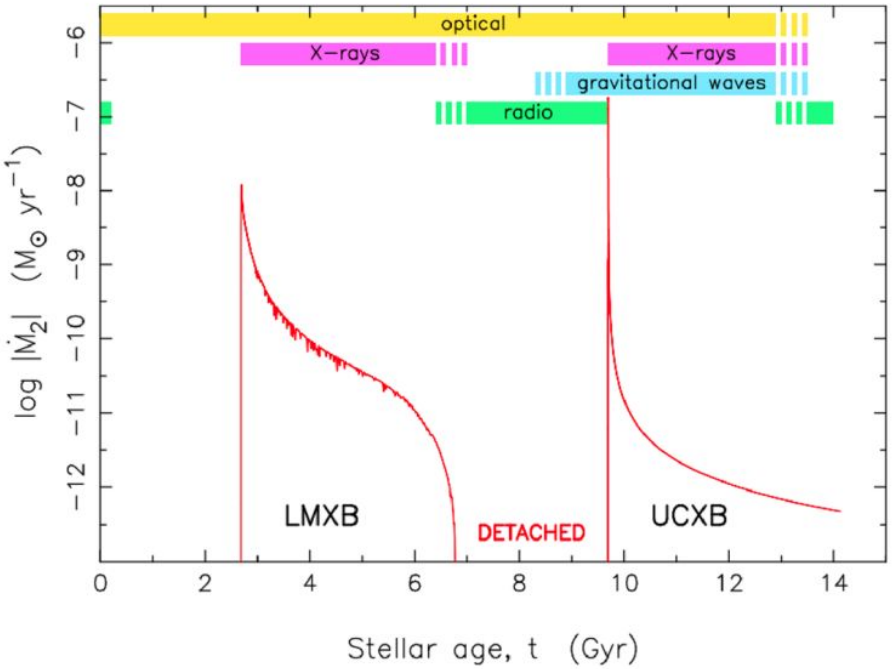
Integration with other surveys: Automatic links to data from other instruments, possibly with adaptable matching criteria, to enable comprehensive multi-messenger studies.

Envisaging L3 catalogs: astronomers' wish list

Re-analysis and Transparency: The L3 catalog will represent one potential (and hopefully optimal) method to analyse L2 data. There will undoubtedly be those who wish to undertake their own analyses (e.g. focusing on outliers).

Therefore, it is important that comprehensive information is provided on how the transition from L2 to L3 is accomplished. This will allow the community to use the L3 catalog as a benchmark or example to validate their own models and methodologies, promoting robust and diverse explorations of the data.

Target “consumers” of the L3 catalog



Given the significant variety of Galactic Binaries and the fact that certain types emit across the entire electromagnetic spectrum, we expect a broad range of “consumers” for the L3 catalog.

These include:

- **Gravitational wave astronomers**
- **Theorists**
- **Observers across the EM Spectrum**
- **Milky Way stellar content researchers**
- Probably others

Tauris (2018), LISA Astro white paper (2023)

Envisaging L3 catalogs: astronomers' wish list summary

1. **Comprehensive Listings**: A list of all detected binaries, complete with estimated parameters (GW but also EM friendly analogs, e.g. {f,A,fdot} →{P,M,d}) and correlations between parameters, uncertainties, and tags specifying source types—or probabilities for a source to be of a certain type (WDWD, NSNS, etc…).
2. **Fit Quality Parameter(s)**: A 'goodness of fit' parameter indicating how well each source fits expected standards (e.g. Gaia's RUWE parameter), helping when interested in outliers (e.g. highly eccentric binaries, triples and higher order multiples).
3. **Bias and Completeness Assessments:** Information assessing selection biases and completeness of the catalog should accompany the release of the L3 catalog. A tool with which you can check the probability of detection (and thus inclusion in the catalog) of a source with certain properties could be useful for this.
4. **Search Capabilities:** The ability to search for binaries with specific properties and to recover the original `global fit' result. It would be great to have the ability to select sources from a 3D map or from a mass distribution.
5. **Integration with Other Data:** Automatic links to data from other instruments, possibly with adaptable matching criteria, to enable comprehensive multi-wavelength studies.
6. **Re-analysis and Transparency:** The L3 catalog is a potential blueprint for analysing L2 data. Providing a clear account of how we transitioned from L2 to L3 (including scripts, notebooks) will enable others in the community to verify their own models and encourage diverse data explorations.