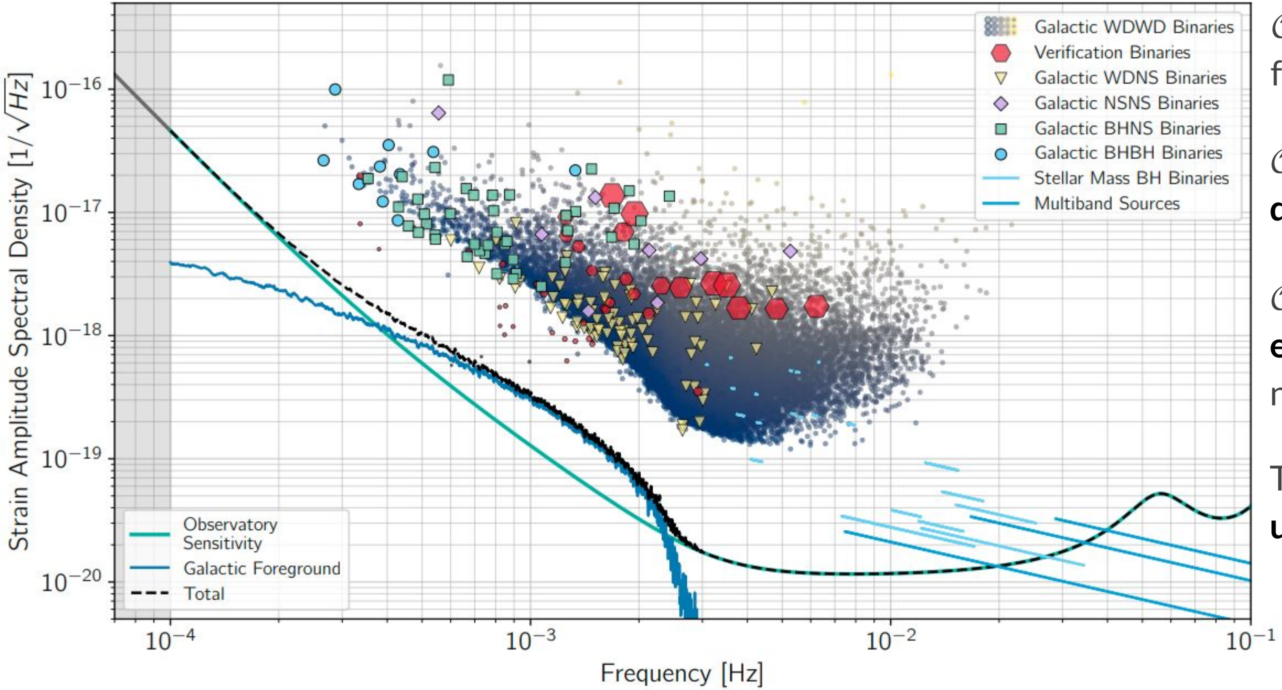
Towards a realistic forecast detection of Primordial GW Backgrounds
11 December 2024, Valencia

Galactic GW foreground(s)

Valeriya Korol
Max Planck Institute for Astrophysics
korol@mpa-garching.mpg.de

Compact binary stars **in the Milky Way**



$\mathcal{O}(10^7)$ **overall in the Milky Way** with f>0.1 mHz

$\mathcal{O}(10^3\text{-}10^4)$ detected as **individual quasi-monochromatic GW sources**

$\mathcal{O}(10)$ are already **known from electromagnetic observations** (Solar neighborhood)

The remainder will blend into an **unresolved stochastic GW foreground**

LISA Definition Study Report, Colpi et al. 2024, arXiv: 2402.07571

Key science questions

How do **binary stars evolve** into close double compact systems?

What is their current **merger rate** in the Milky Way and the Local Group?

What is the role of **binary interactions** (e.g. tides, mass transfer/accretion) and GWs in the merger of systems?

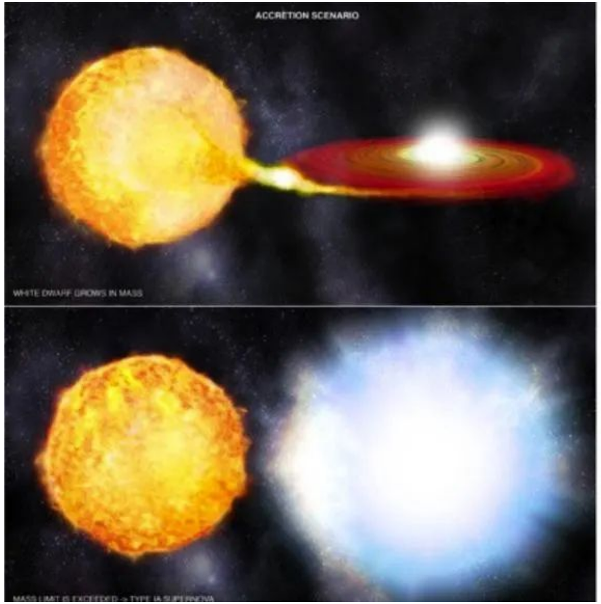
What can we learn from LISA sources about the **Milky Way** as a whole?

LISA Definition Study Report, Colpi et al. 2024, arXiv: 2402.07571

Expected insights on **Type Ia supernovae**

A decades-long debate:
What are the progenitors of Type Ia supernovae?

Single-degenerate channel



or

Double-degenerate channel

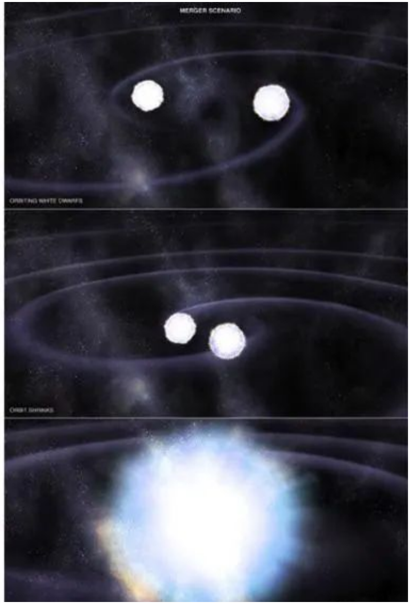
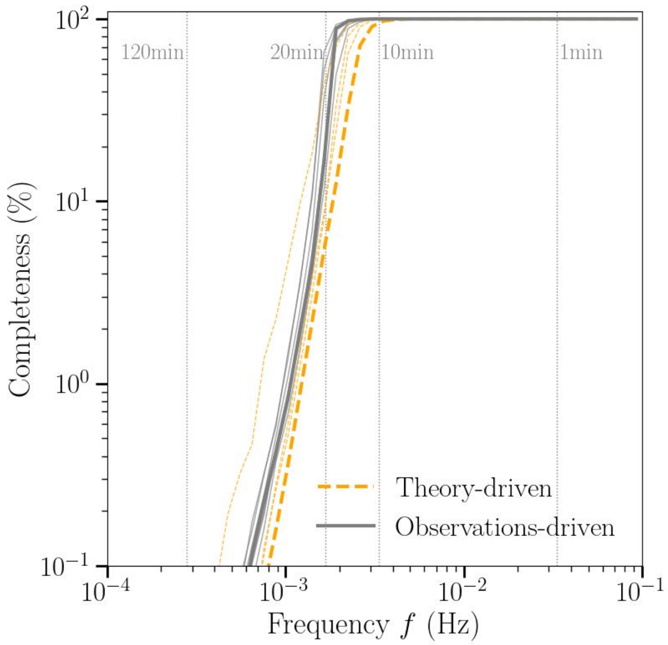


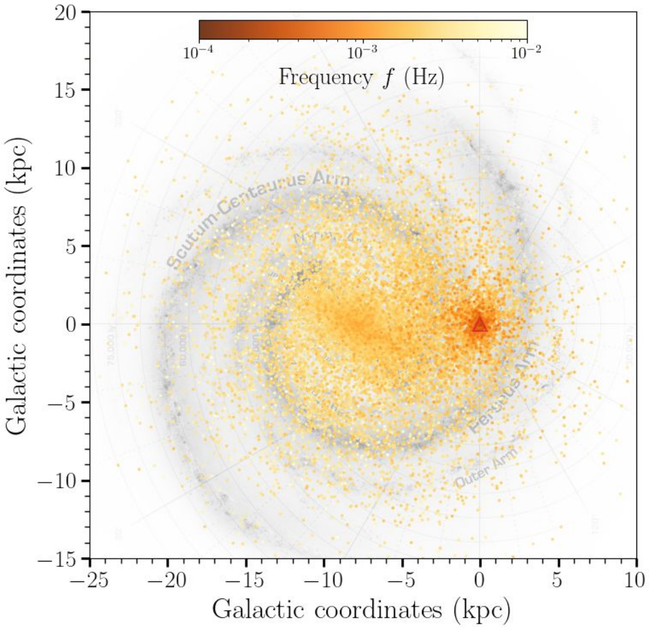
Image credits: NASA / CXC / M. Weiss

This is an oversimplified picture, there are many many nuances to be considered!
Many reviews are published: Livio & Mazzali et al. 2018, Liu et al. 2023; Blondin et al. 2024; Ruiter & Seitenzahl 2024 and many others

LISA's constraints on the double-degenerate Type Ia progenitors

Complete sample up to orbital periods of ~15 min **across the entire Milky Way!**





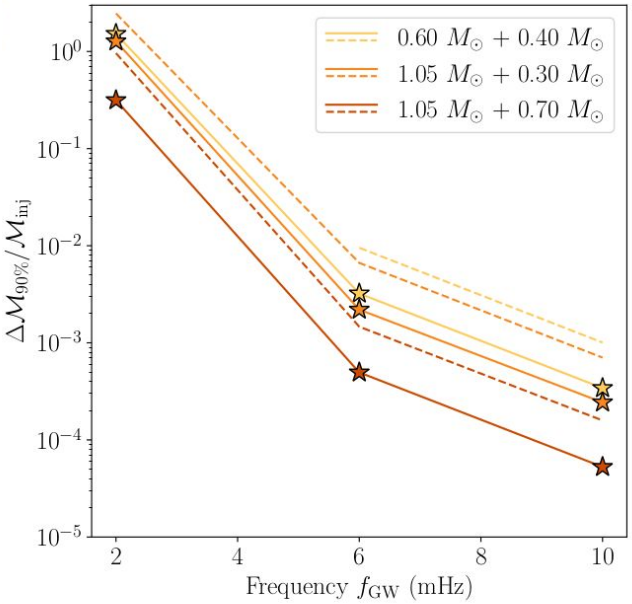
✓ **Chirp mass measurement**

✓ **Merger rate estimates**

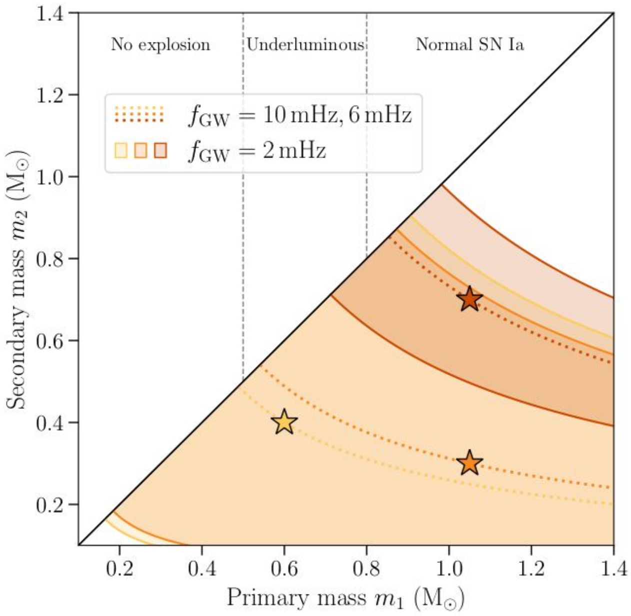
Based on WD+WD catalogs from: Korol et al. 2017; Wilhelm, Korol et al. 2021; Korol, Hallakoun et al. 2022;
See also Lamberts et al. 2019; Breivik et al. 2020; Li et al. 2020; Tang et al. 2024 and many previous studies

LISA's constraints on the double-degenerate Type Ia progenitors

At GW frequencies near to the merger (< 0.01 Hz) **chirp mass constraints at 0.01-0.001%**



Chirp mass constraint translates into a **lower bound on the primary mass** making it possible to forecast the possibility and the type of thermonuclear transient.



No explosion: $m_1 > 0.5\ M_\odot$

Thermonuclear explosion but **less luminous than a SN Ia**: $0.5\ M_\odot < m_1 < 0.8\ M_\odot$

"Normal" SN Ia: $m_1 > 0.8\ M_\odot$

(based on 1D and 3D hydro-dynamical simulations: Sim et al. 2010; Shen et al. 2015, 2024; Morean-Fraile et al. 2024)

Based on the Balrog code (Uni. of Birmingham)
See e.g. Buscicchio et al. 2019, 2021; Roebber et al. 2020; Klein et al. 2022

There is a **4-7% chance** of a Type Ia occuring in our own Galaxy within LISA's lifetime (10 yr)

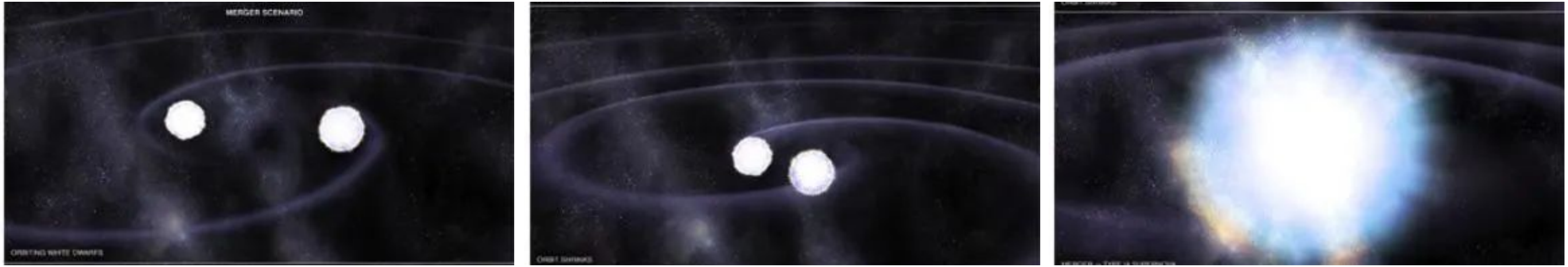
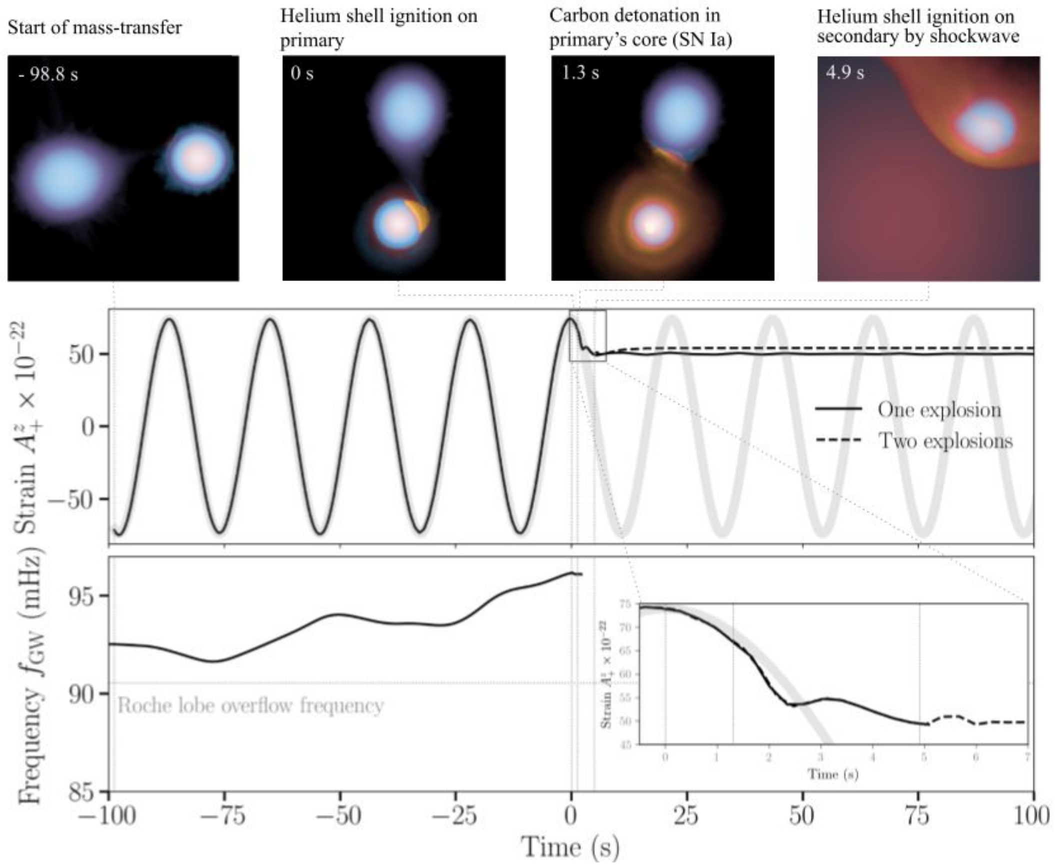


Image credits: NASA / CXC / M. Weiss

Assuming that type Ia supernovae are produced via a double detonation mechanism



3D hydro-dynamical simulation of a **1.05 M⊙ + 0.7 M⊙ carbon-oxygen white dwarf binary** by Pakmor et al. 2022

Korol et al. 2024, arXiv:240703935;
Also Seto et al. 2023, Dan et al. 2011

EM

Only EM

Indication towards a **single-degenerate** scenario, where GWs signal in the LISA band is not expected or a **double degenerate** merger with a delay time larger that the LISA's mission lifetime.

(Neutrinos detection is possible)

GWs → prompt EM (→ no GWs)

Direct confirmation of the **double-degenerate** scenario, Type Ia supernovae produced via dynamical explosions such as **double detonation**.

(Neutrinos detection is unlikely)

GW

What will we learn from a multi-messenger detection?

GWs → no or delayed EM (→ no GWs)

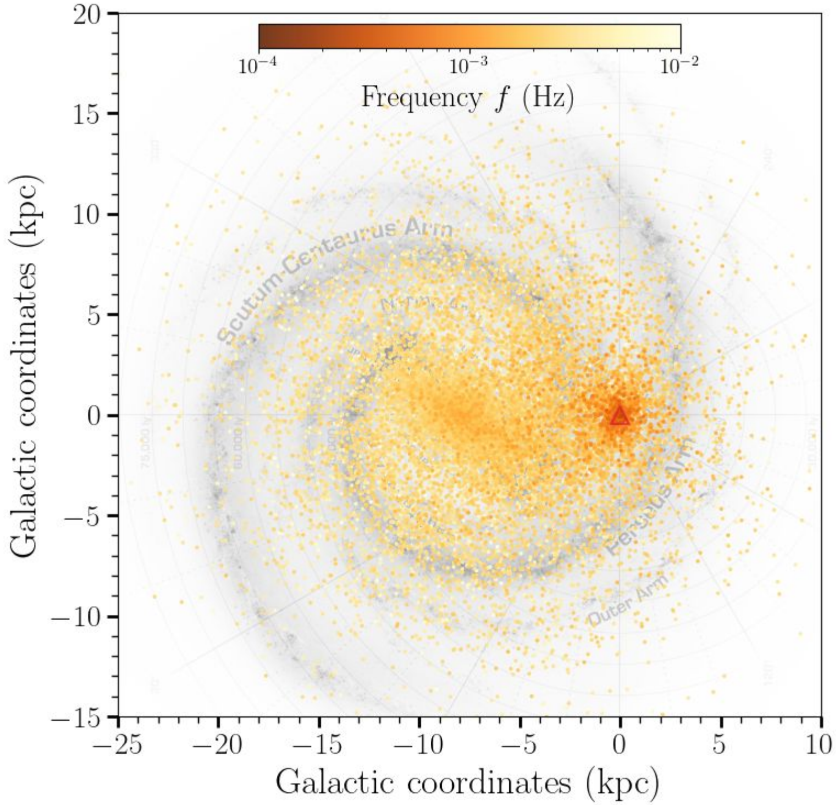
Direct confirmation of the **double-degenerate** scenario, Type Ia supernovae produced via **classical super-Chandrasekhar merger scenario** (delays up to 10^4 yrs).

(Neutrinos detection is possible)

Expected insights on the Milky Way

Credit: NASA's Goddard Space Flight Center with Ira Thorpe

Making a **gravitational wave map** of the of the Milky Way



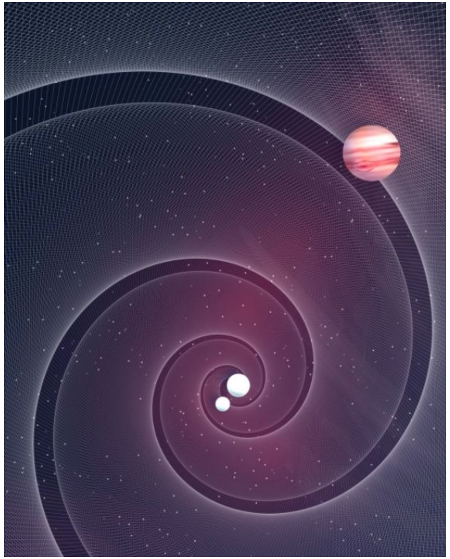
LISA's precision in locating WD+WD binaries will constrain structural parameters of the Milky Way, providing new insights into its shape:

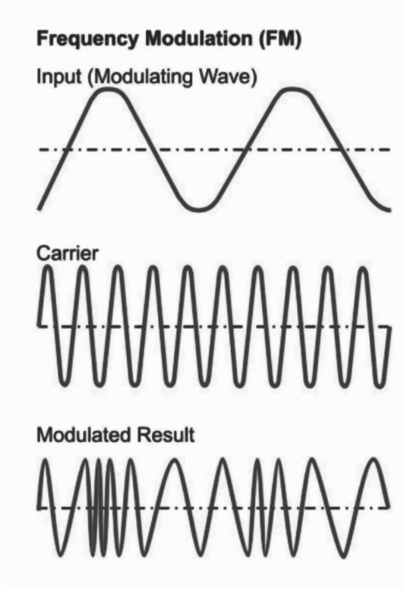
- Bulge Scale Radius: **2%** precision
- Disk Scale Radius: **3%** precision
- Disk Scale Height: **16%** precision
- Bar Axis Ratio: **10%** precision
- Bar Length: **1%** precision
- Bar Orientation Angle: **<1°**

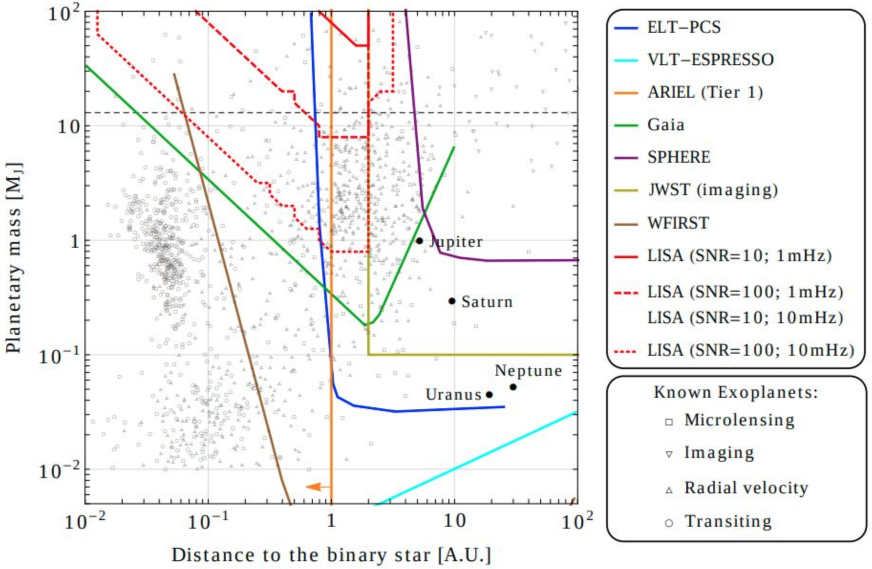
Korol et al. 2019; Wilhelm et al. 2021;
See also earlier work by Adams & Cornish 2010

Expected insights on **exoplanets**

LISA's WD+WD as tracers of other stellar populations

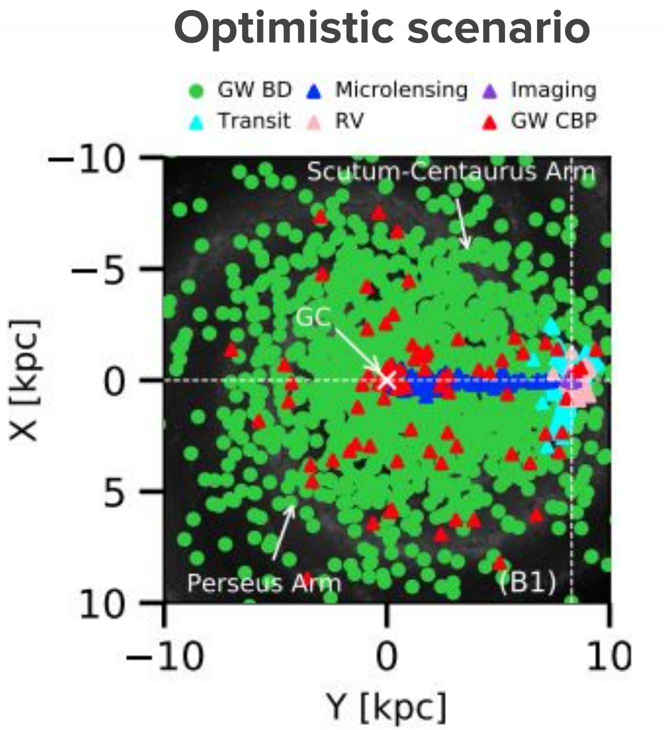


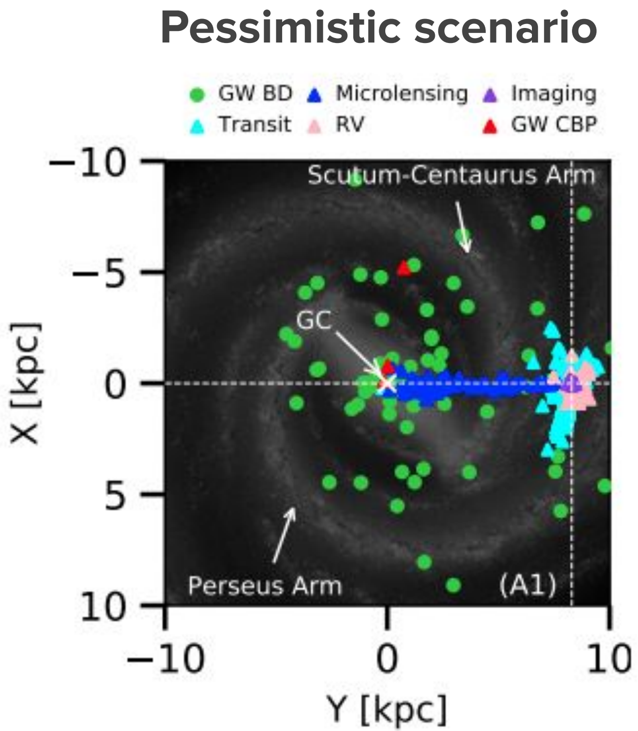




Tamanini & Danielski 2018
See also Seto et al. 2008

Detecting a new population of exoplanets with LISA across the entire Milky Way





Danielski, Korol et al. 2019; Katz et al. /w Korol 2022

How do we make LISA forecasts?

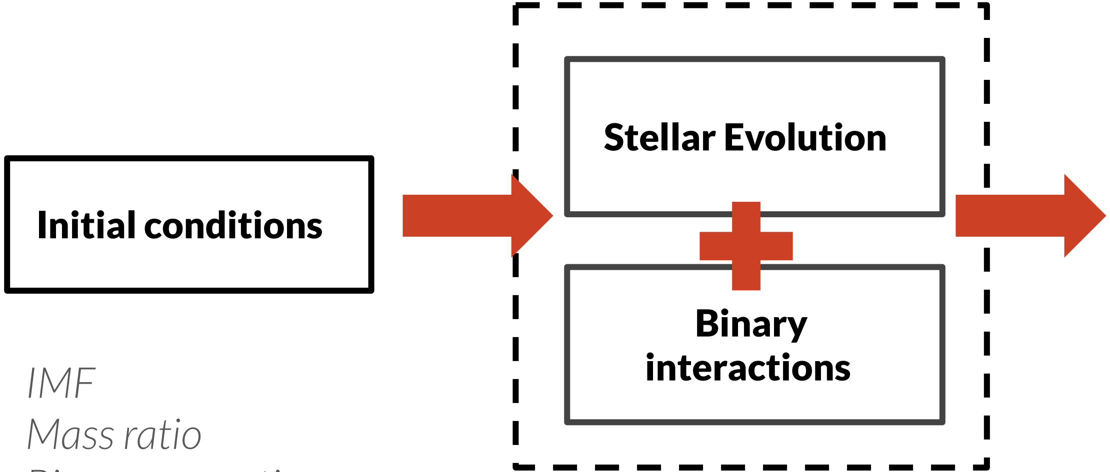
Option 1: Theory-driven approach

How do we make LISA forecasts?

Option 1: Theory-driven approach

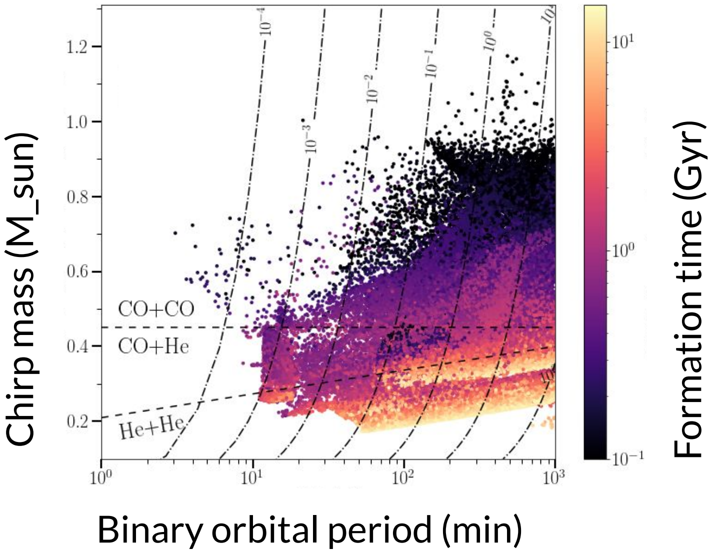
Step 1

Binary Population Synthesis



IMF
Mass ratio
Binary separation
Eccentricity
Binary fraction
Metallicity
…

Mass transfer
Accretion
Tides
…



↑Toonen et al. 2012; BPS models based on the SeBa code
See also: Nelemans et al. 2001, Ruiter et al. 2010, Yu & Jeffery 2010, Nissanke et al. 2012, Lamberts et al. 2018, Breivik et al. 2020, Li et al. 2020 and many others

Binary Population Synthesis Codes

participating in the **UCB catalogs** Astro WG projects coordinated by A. Bobrick & K. Breivik

POSYDON

BSE
Lamberts et al. 2019
Li et al. 2020

bpass
Tang et al. 2024

BINCODEX

ComBinE

COMPAS
Lau et al. 2021
Wagg et al. 2022

binary_c

SeBa
Nelemans et al. 2001
Nissanke et al. 2012; Korol et al. 2017

SEvN

METISSE

COSMIC
Breivik et al. 2020
Thiele et al. 2023
Toubiana et al. 2024

Binary Population Synthesis Codes

Credit: Giuliano Iorio (ICCUB)

UCB catalogs Astro WG project

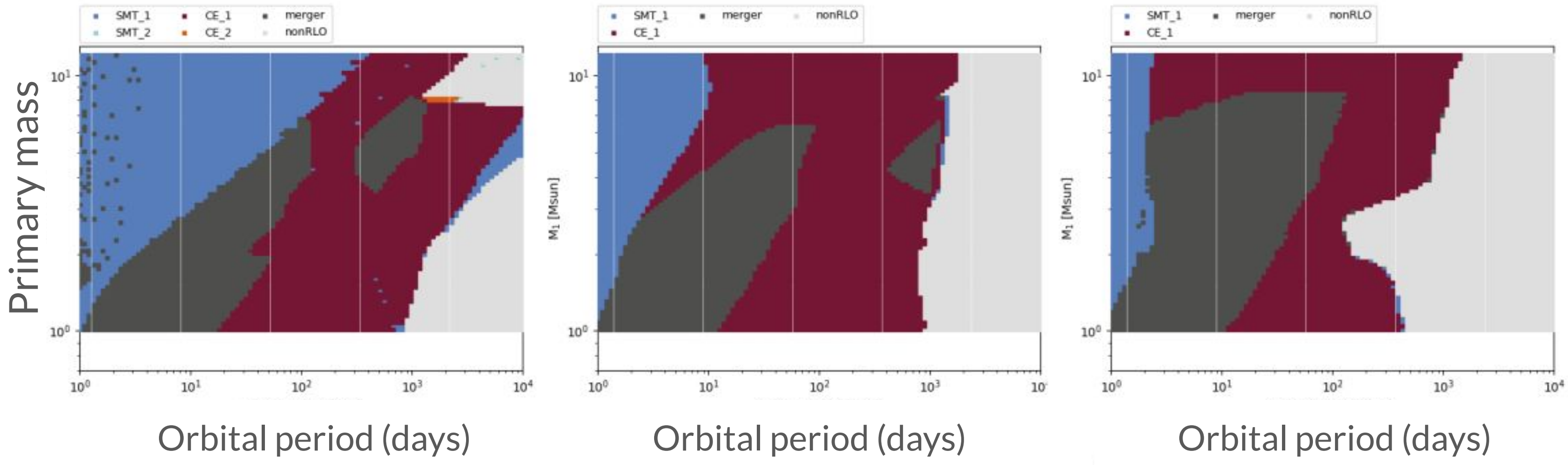
What is the Galactic population of LISA WD+WD binaries to the best of our knowledge?

Expected outputs

- Public repository of synthetic catalogs (Australian Data Central and LISA DDPC)
- Two publications
  - ***Astrophysical uncertainties*** (Bobrick et al. 2025): variance assuming perfect implementation
  - ***Code uncertainties*** (Breivik et al. 2025): variance assuming perfect astrophysics knowledge
- BinCodex: Standardised binary evolution output format
  Valli, Graziani et al. 2023, arXiv:2311.03431
- Analysis tools repository

UCB catalogs Astro WG project

What does the population look like after the first interaction?



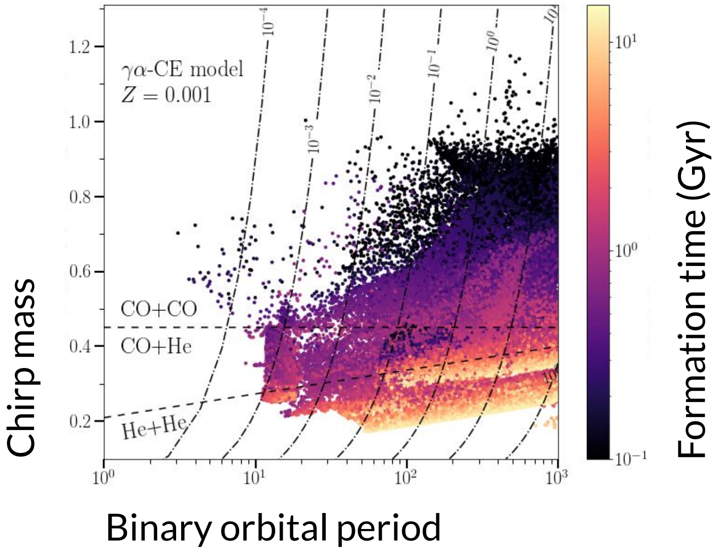
COMPAS **COSMIC** **COSMIC + METISSE**

Credit: K. Breivik, R. Willcox

How do we make LISA forecasts?

Option 1: Theory-driven approach

Step 2



Milky Way model

Stellar distribution

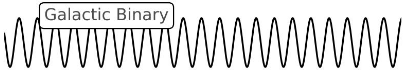
+

Star formation history

Parametric approach
Semi-analytic
Hydrodynamic

Binaries' present-day GW properties:

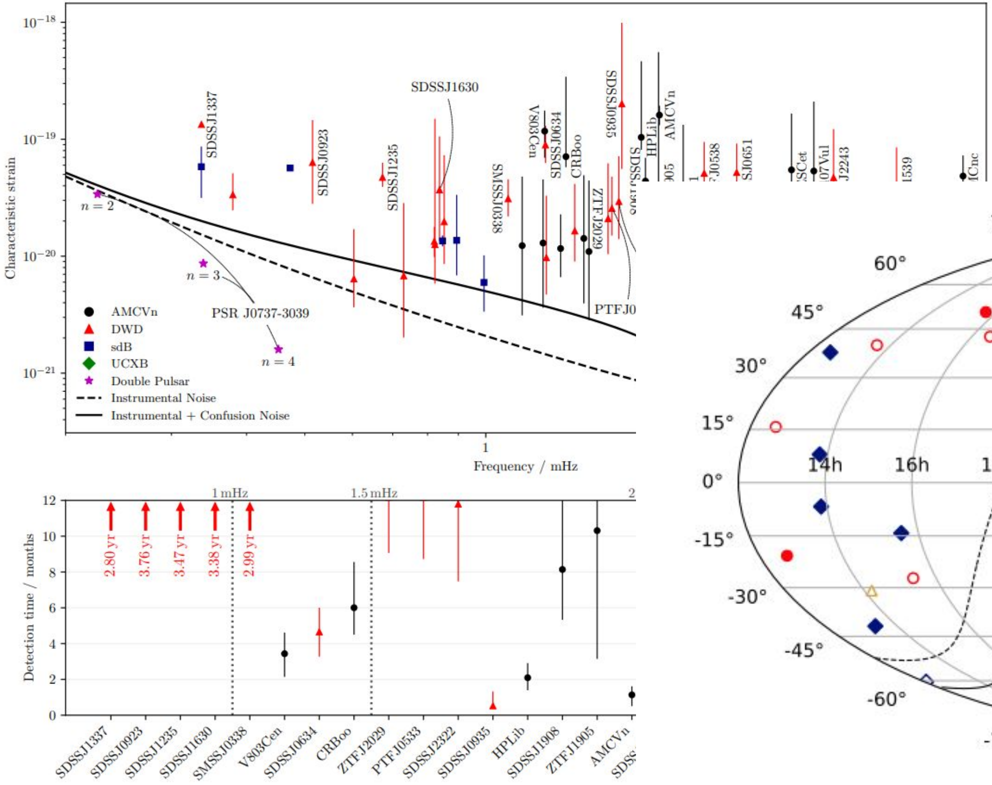
$$\{\mathcal{A}, f_0, \dot{f}_0, \lambda, \beta, \iota, \psi, \phi_0\}$$



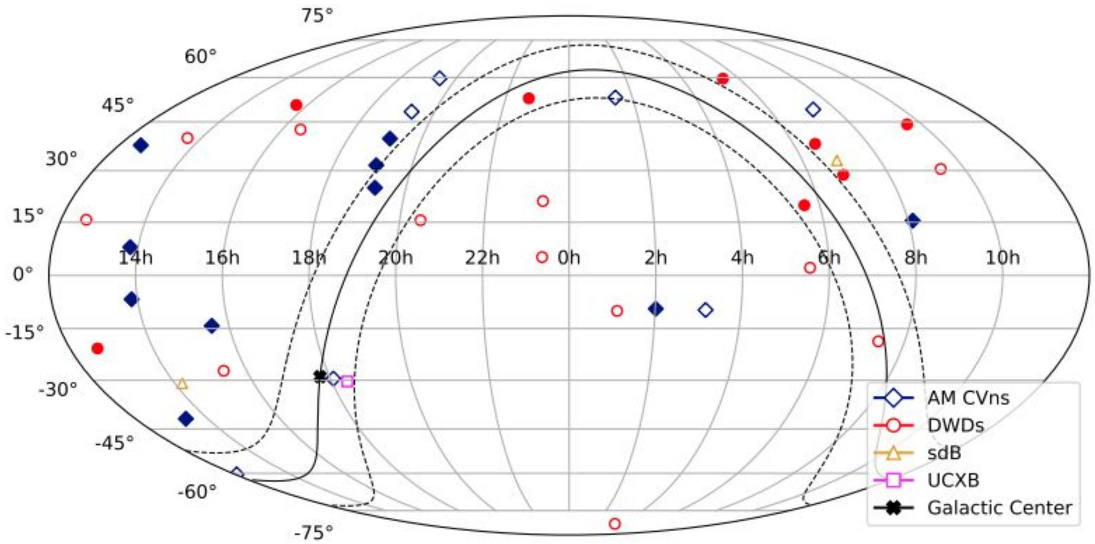
How do we make LISA forecasts?

Option 2: Observations-driven approach

Can we use LISA's "verification binaries "?



Finch et al. 2023



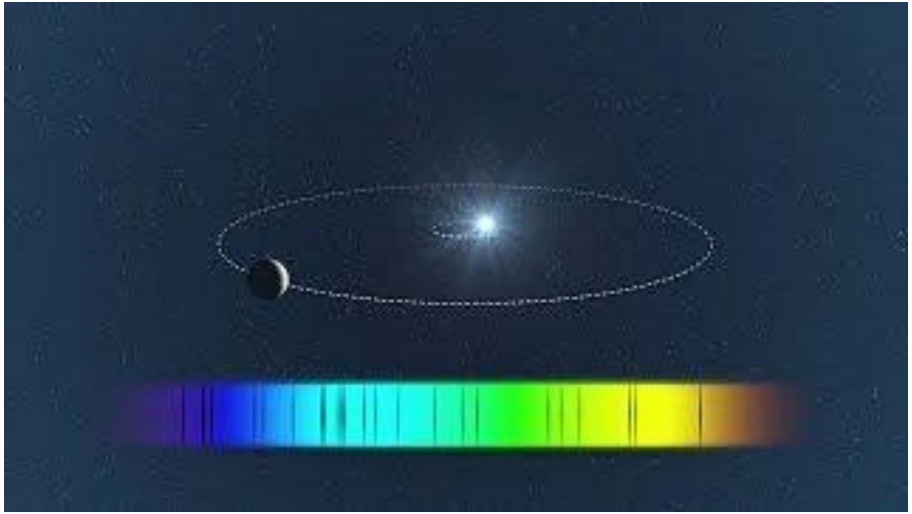
List of candidate LISA verification binaries Kupfer, Korol et al. (2024)

https://gitlab.in2p3.fr/LISA/lisa-verification-binaries

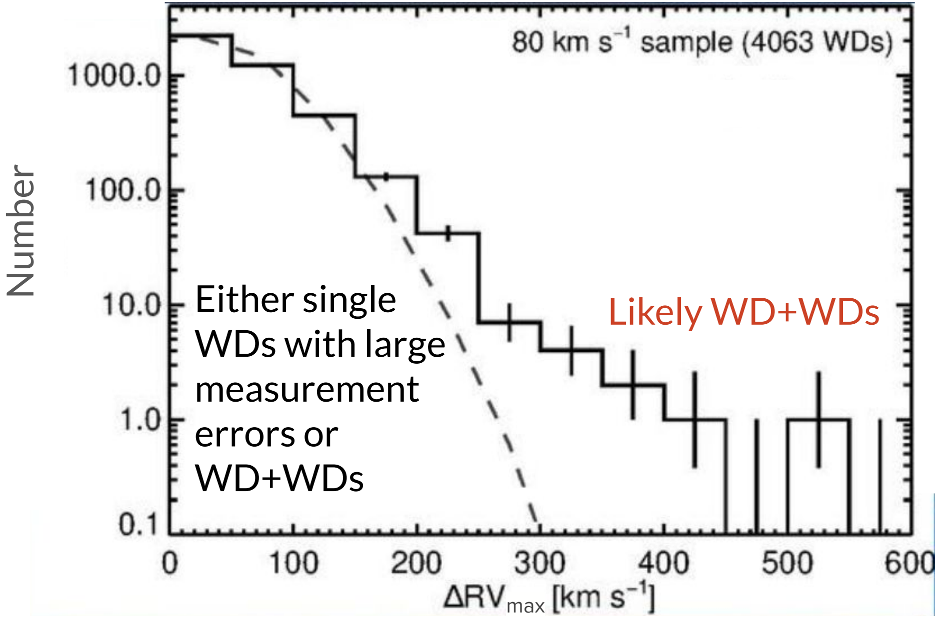
How do we make LISA forecasts?

Option 2: Observations-driven approach

We can construct a representative Galactic WD+WD population based on constraints on the binary separation distribution and WD+WD fraction from multi-epoch spectroscopic surveys SDSS and SPY (lower orbital frequencies)



Credit: ESO/L. Calçada



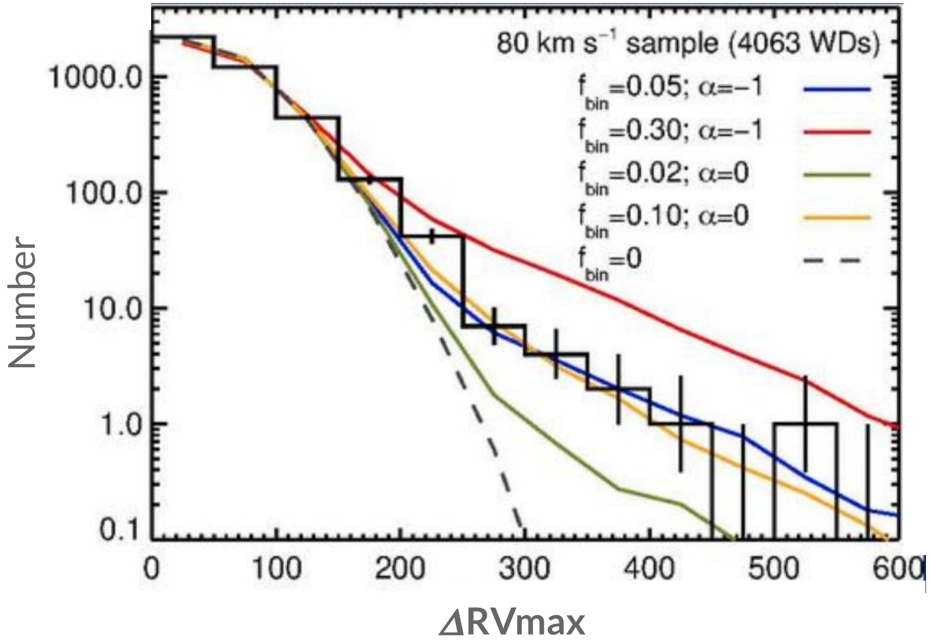
Courtesy of Na'ama Hallakoun
See Maoz et al. (2012), arXiv:1202.5467
and Maoz & Hallakoun (2017), arXiv:1609.02156

How do we make LISA forecasts?

Option 2: Observations-driven approach

Model assumptions:

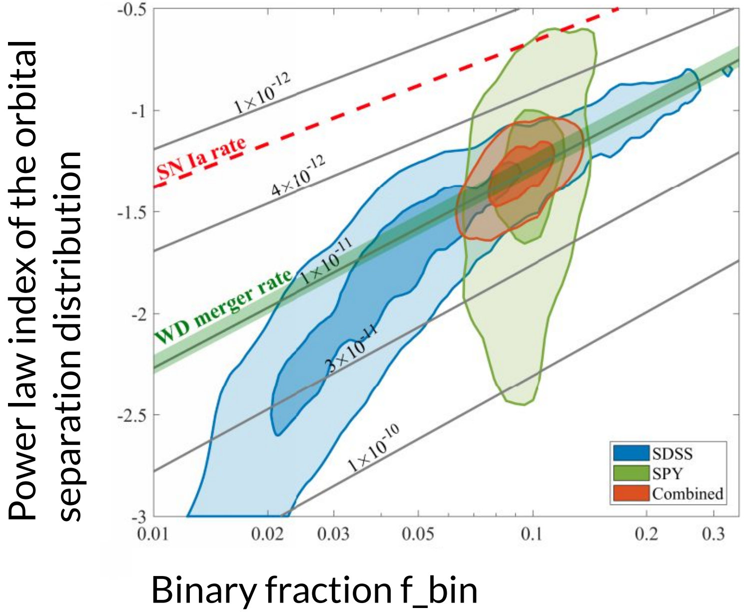
- The primary WD mass follows the same distribution as single WDs
- Mass ratio follows a flat distribution
- Constant star formation
- The distribution of WD+WD separations at formation follows a power-law with index **α**



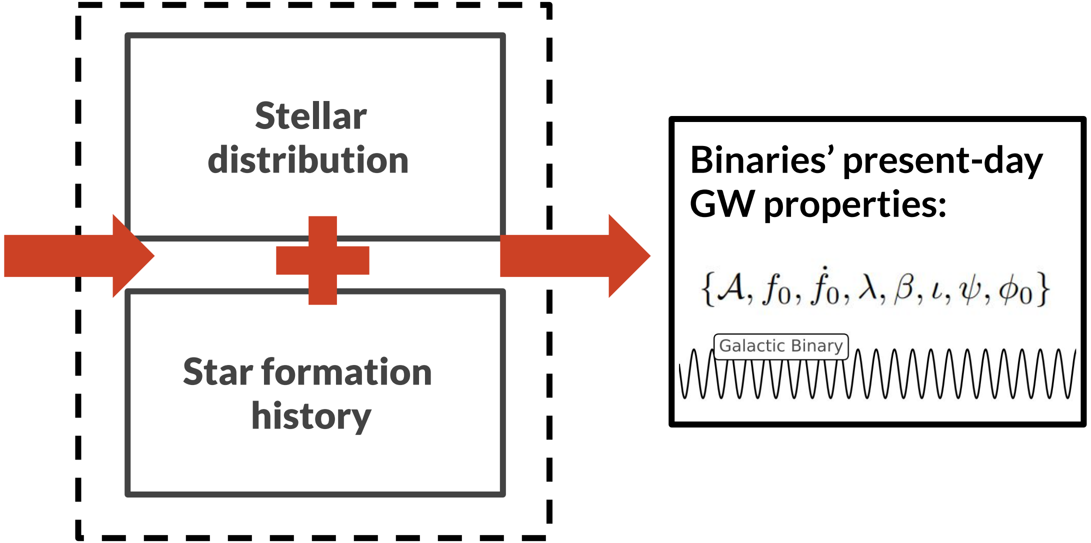
Courtesy of Na'ama Hallakoun
See Maoz et al. (2012), arXiv:1202.5467
and Maoz & Hallakoun (2017), arXiv:1609.02156

How do we make LISA forecasts?

Option 2: Observations-driven approach

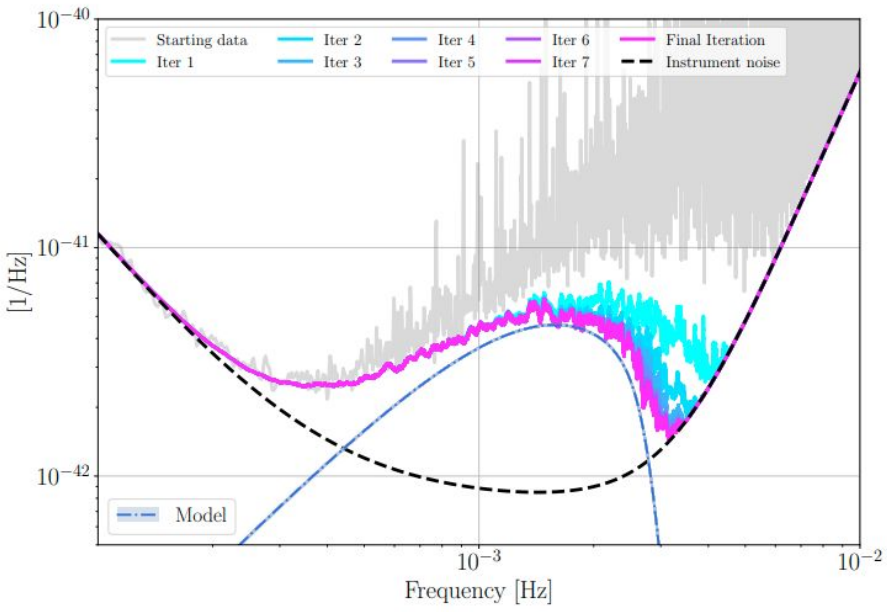


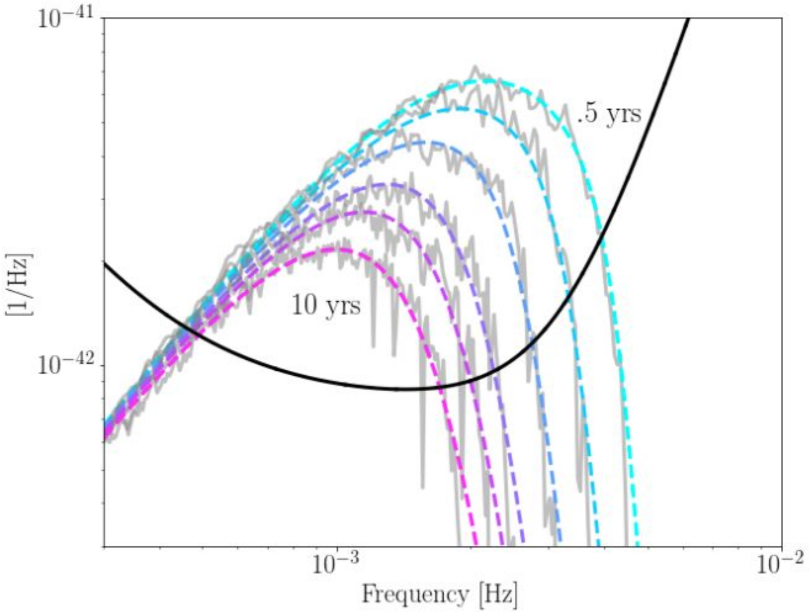
Milky Way model



Korol et al. 2022, based on Maoz et al. 2012; Maoz & Hallakoun 2017

Iterative SNR-based algorithm for estimating Galactic confusion foreground

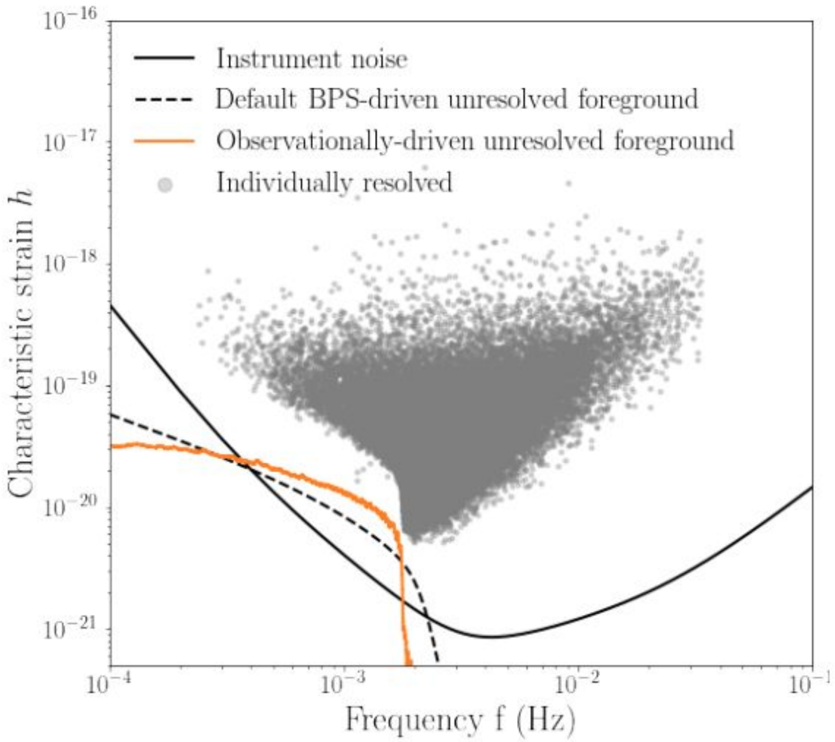




Karnesis et al. 2021

See earlier papers by Timpano et al. 2006; Crowder & Cornish 2007; Nissanke et al. 2012

Comparing **theory-driven** and **observations-driven** forecasts



Korol et al./w Karnesis 2022

Both predict a total of **20x10^6** WD+WD binaries within the LISA frequency band

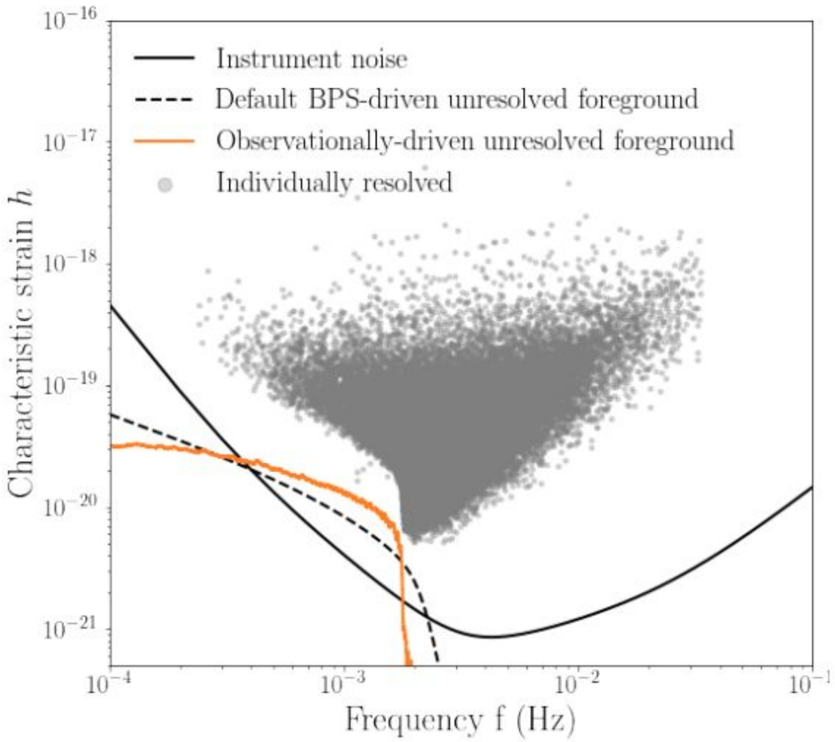
A factor of 3-6 difference in the number of resolved sources

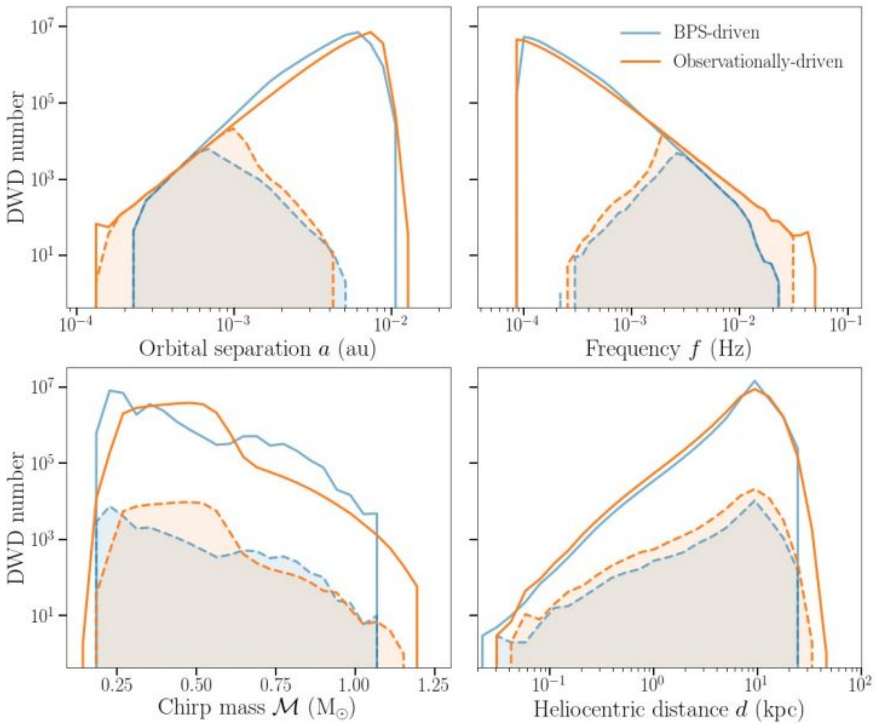
The **shape of unresolved stochastic signal** varies between the two.

Both stochastic signals can be described by

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

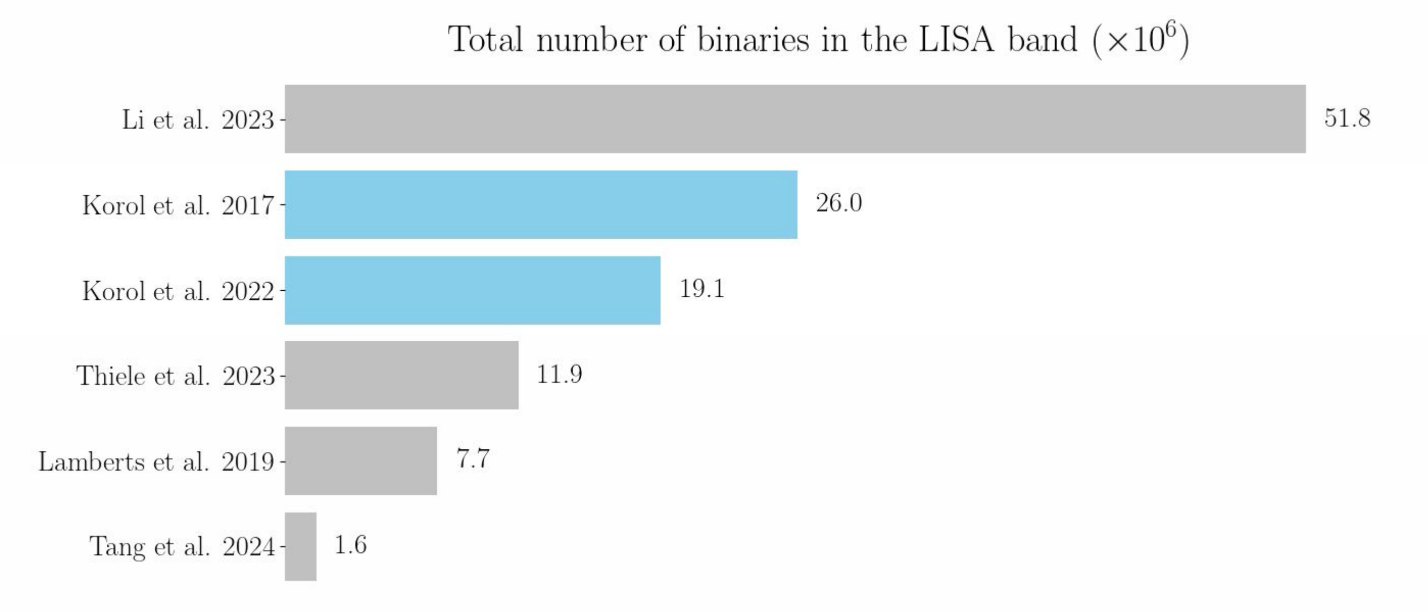
Comparing **theory-driven** and **observations-driven** forecasts





Korol et al./w Karnesis 2022

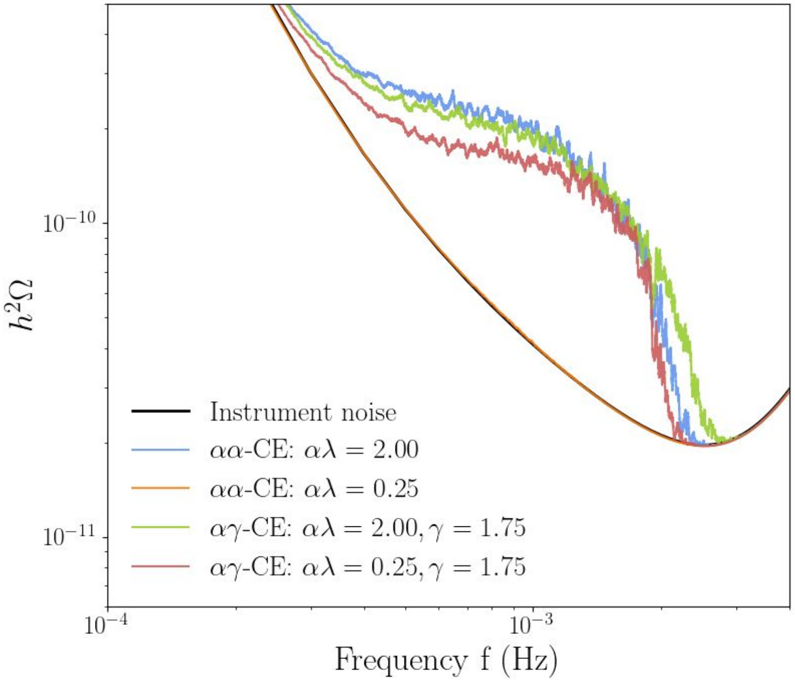
We are currently expanding the comparison

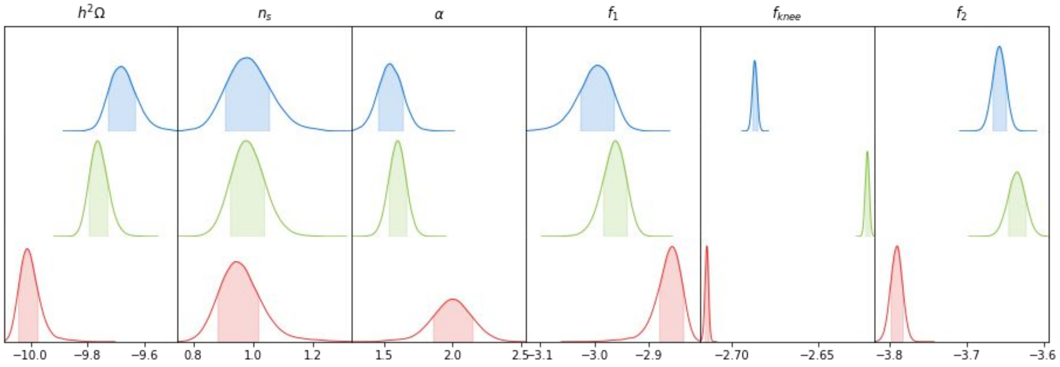


The results will be published as part of the LISA Figures of Merit paper in 2025

The catalogs as well as the resulting foregrounds will be made available through the University of Thessaloniki

Differences in the LISA-detectable population and the unresolved stochastic foreground **are primarily due to changes in binary evolution physics**





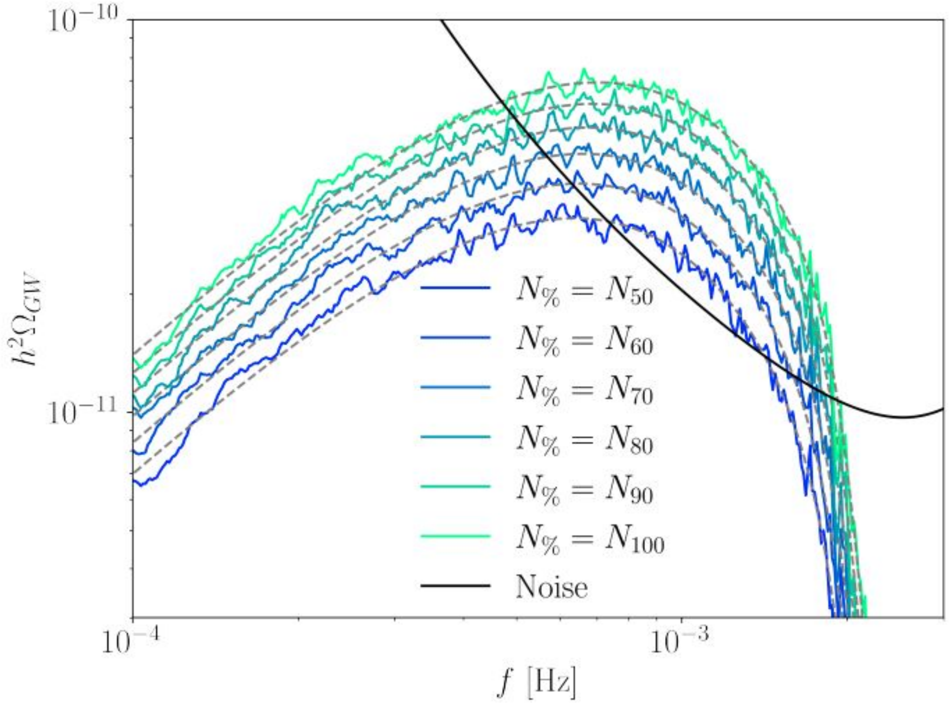
$$S_{\rm gal} = \frac{A}{2} f^{-n_s^S} e^{-(f/f_1)^\alpha} \left\{1 + \tanh\left[(f_{\rm knee} - f)/f_2\right]\right\}$$

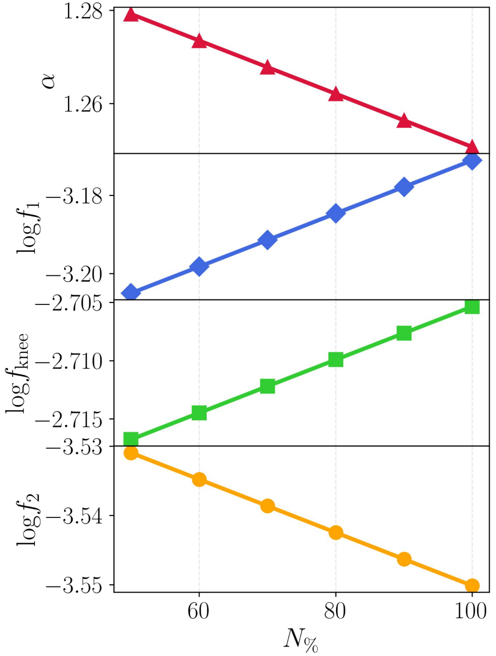
Ashlin Varghese's project as part of the Kavli Summer School 2023 (MPA, Garching)

In collaboration with Nikolaos Karnesis et al.

Fixing the binary evolution model while varying the Galactic model

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

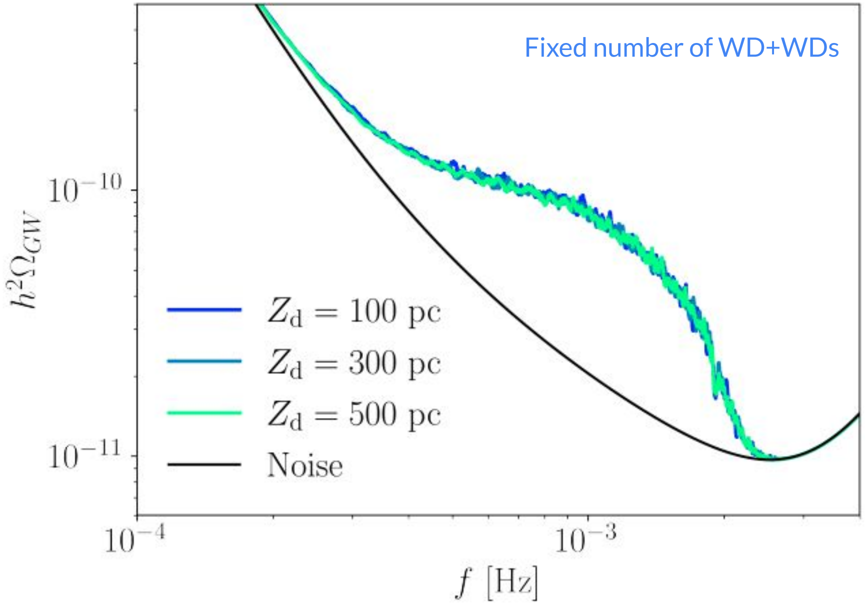




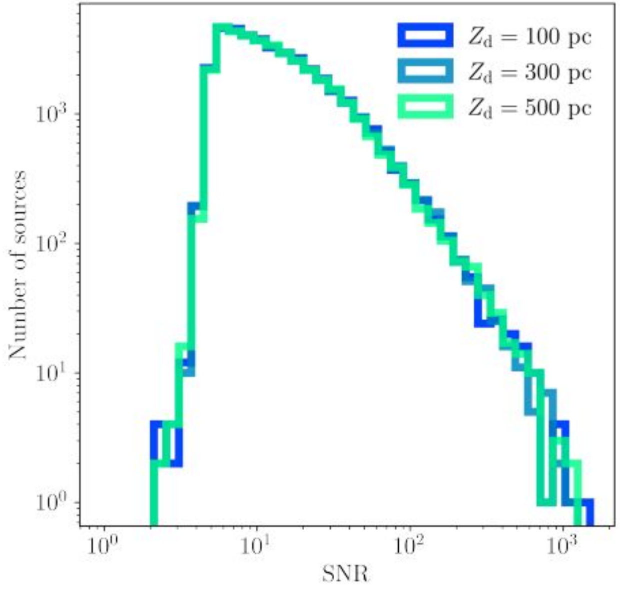
Georgousi, Karnesis et al.\w Korol (2022)

Fixing the binary evolution model while varying the Galactic model

Unresolved

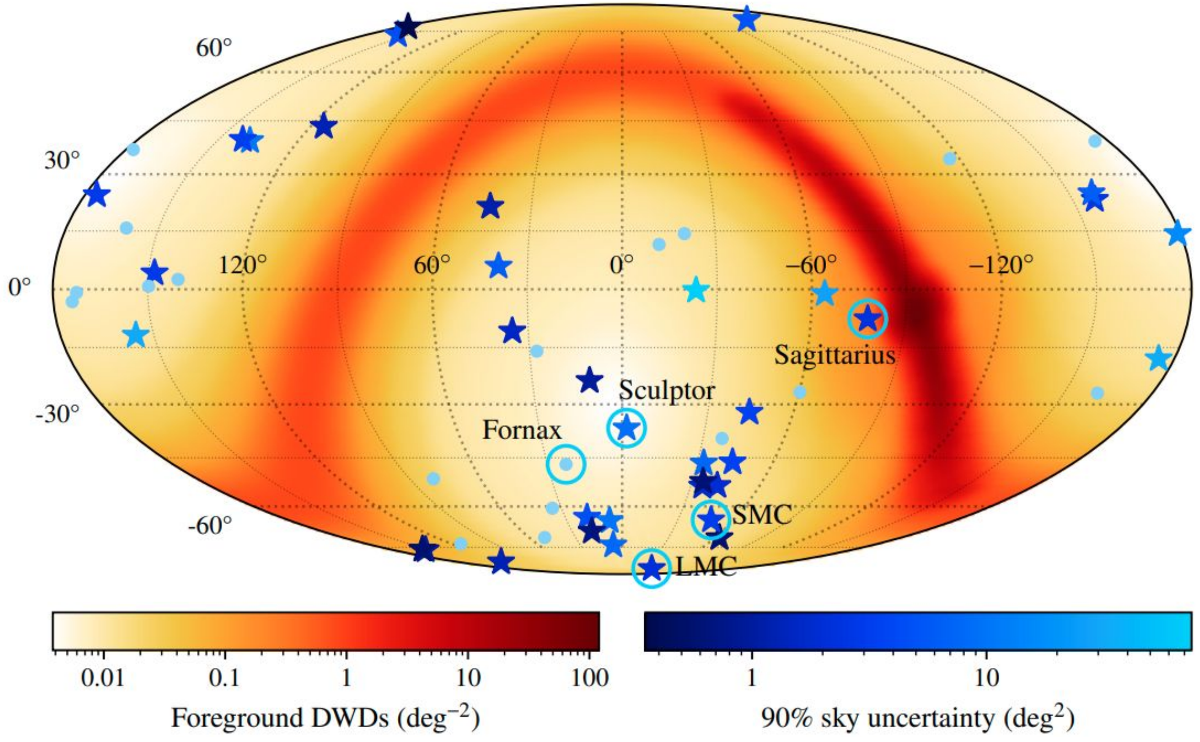


Resolved



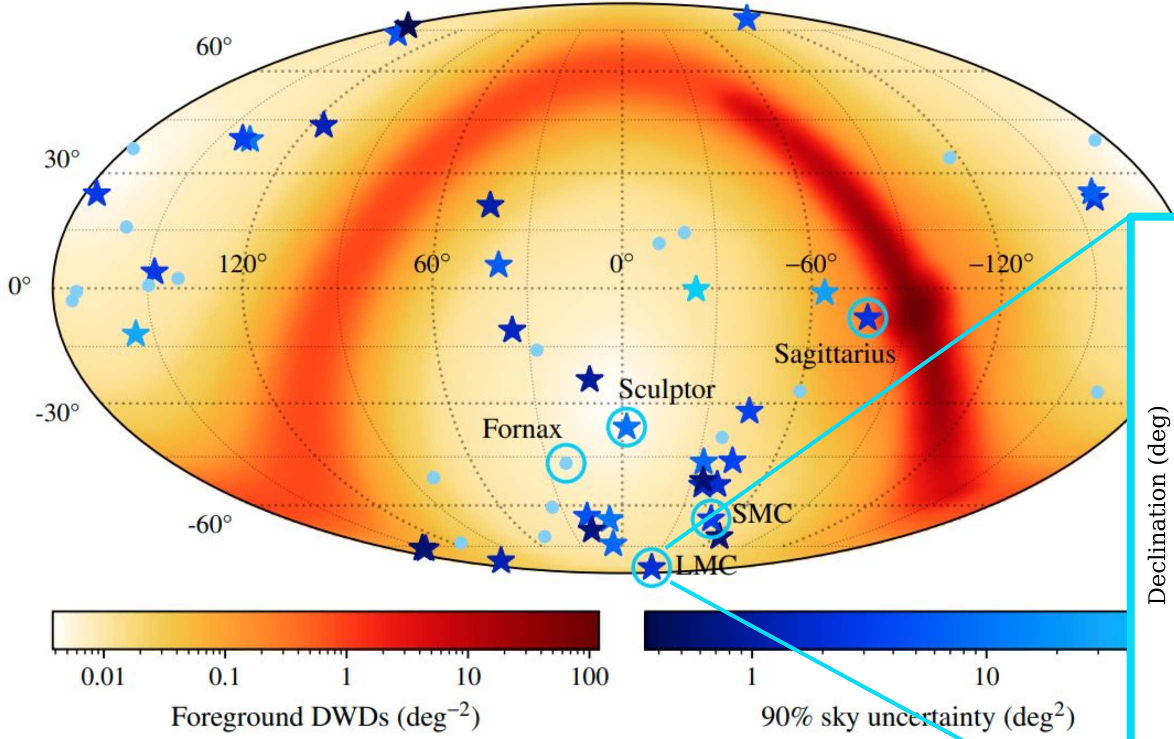
Georgousi, Karnesis et al.\w Korol (2022)
See also Benacquista & Holley-Bockelmann (2006), Breivik et al. (2020)

The Galactic stochastic foreground will be anisotropic



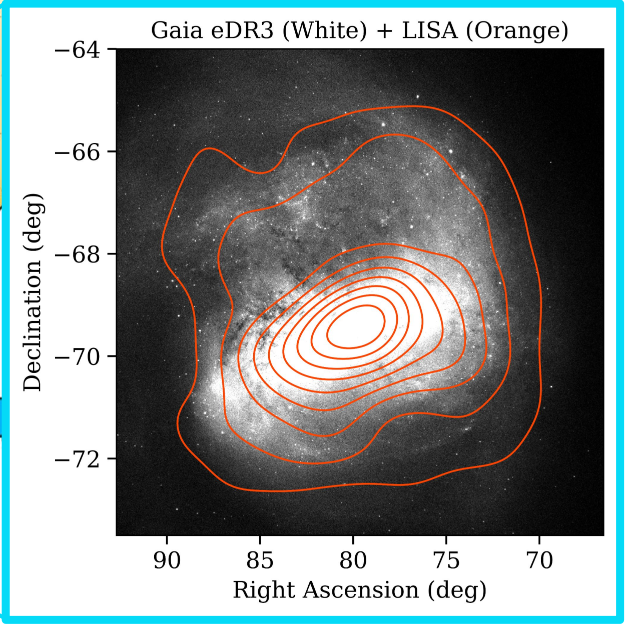
Roebber et al. 2020; Korol et al. 2020, 2021

The Galactic stochastic foreground will be anisotropic

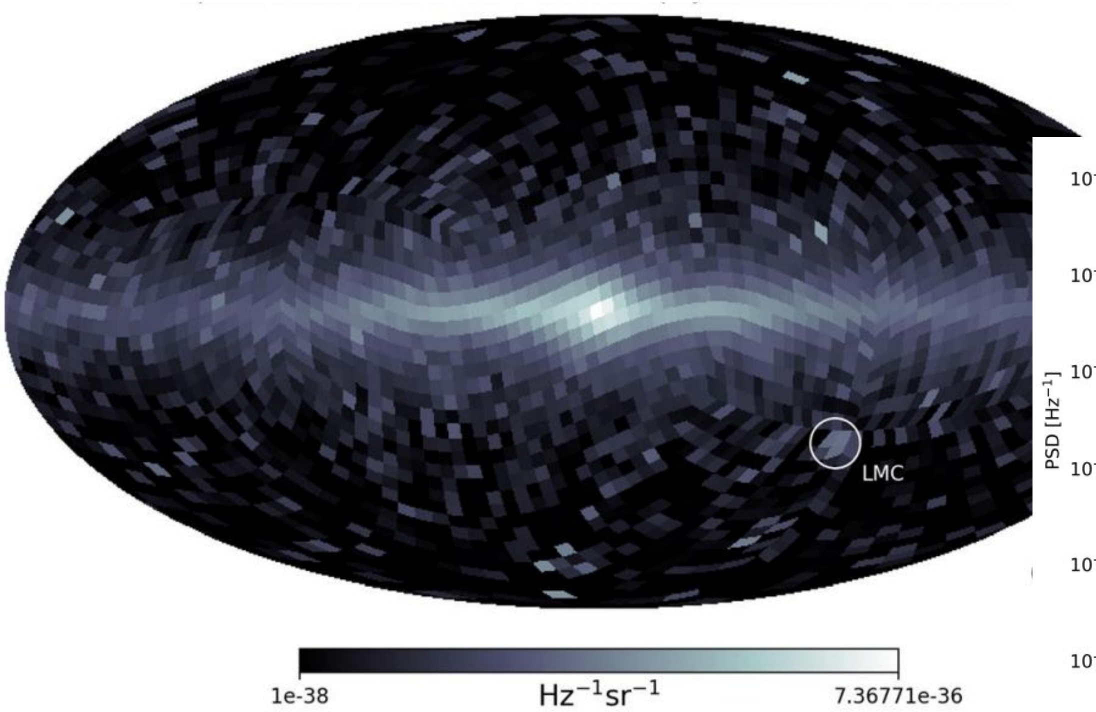


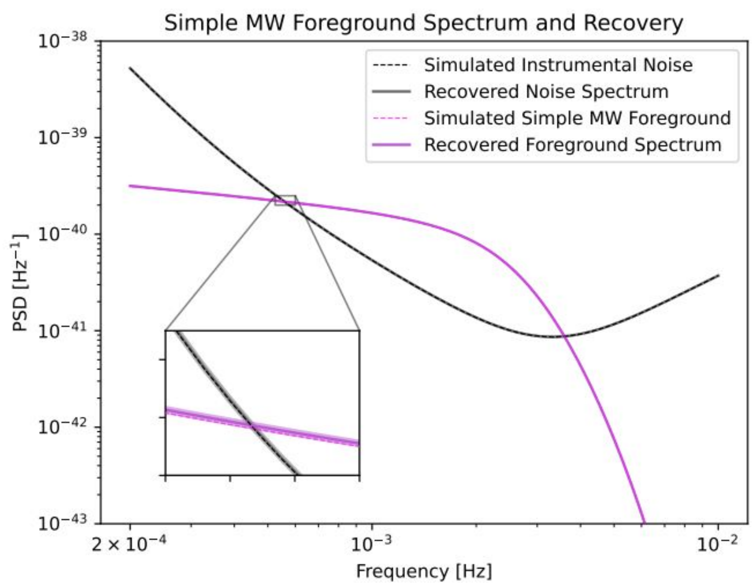
Roebber et al. 2020; Korol et al. 2020, 2021

Keim, Korol et al. 2023



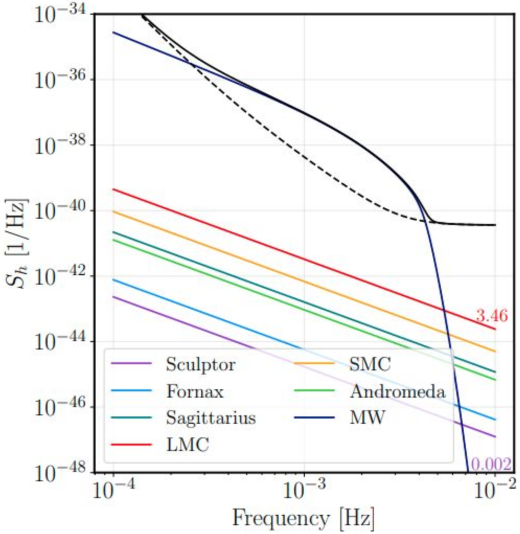
Example of a **templated anisotropic analysis** of the LISA Galactic foreground

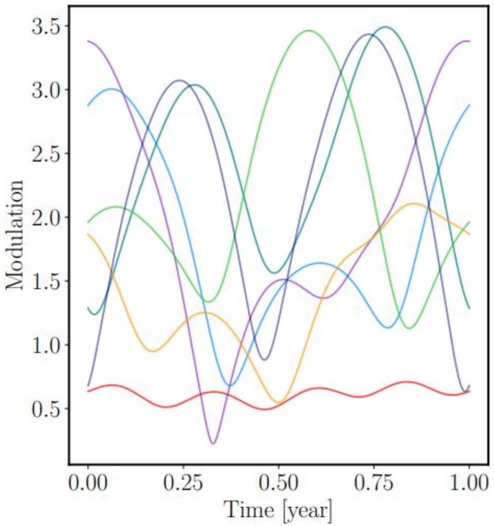




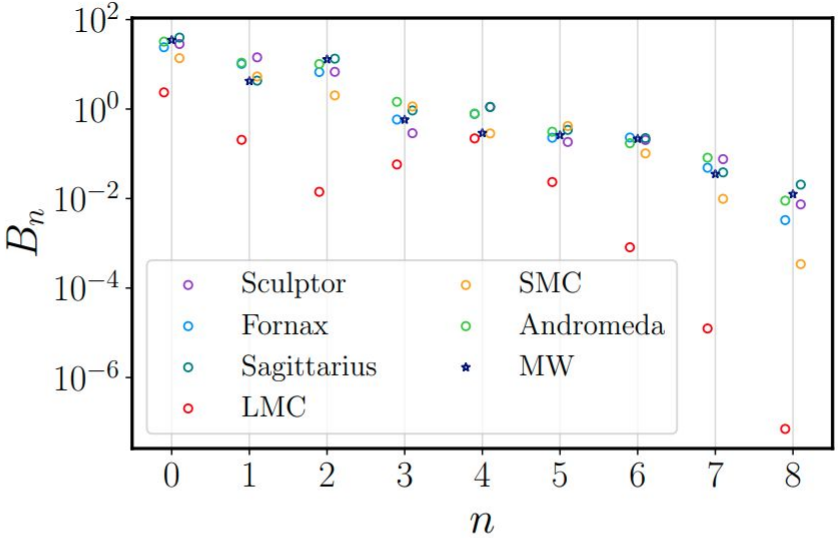
Criswell et al. 2024; Rieck et al. 2024 based on the BLIP pipeline with pixel-basis anisotropic templates by Banagiri et al. 2021

Example of cyclostationary analysis of the LISA Galactic Foreground





Fourier Coefficient of Modulation

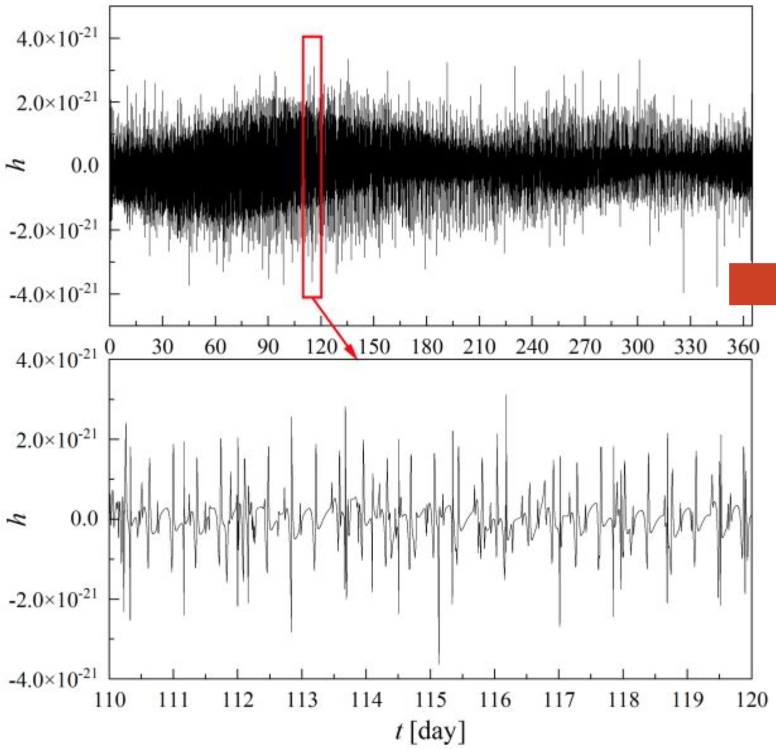


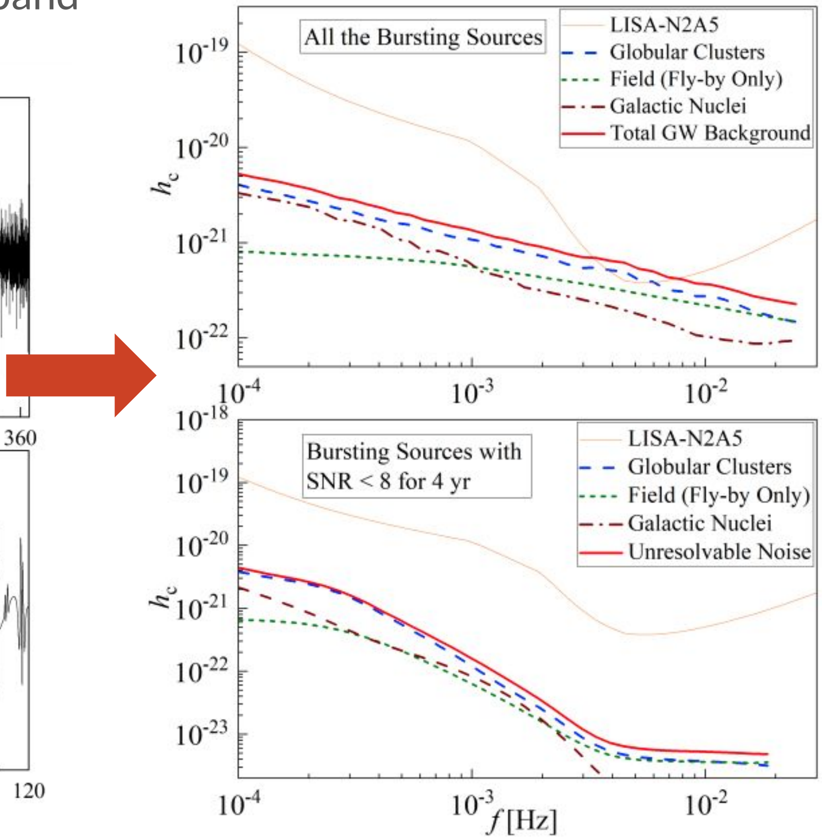
The modulation is primarily influenced by latitude, while the impact of size is a secondary effect.

Pozzoli et al. 2024

What about other Galactic GW sources?

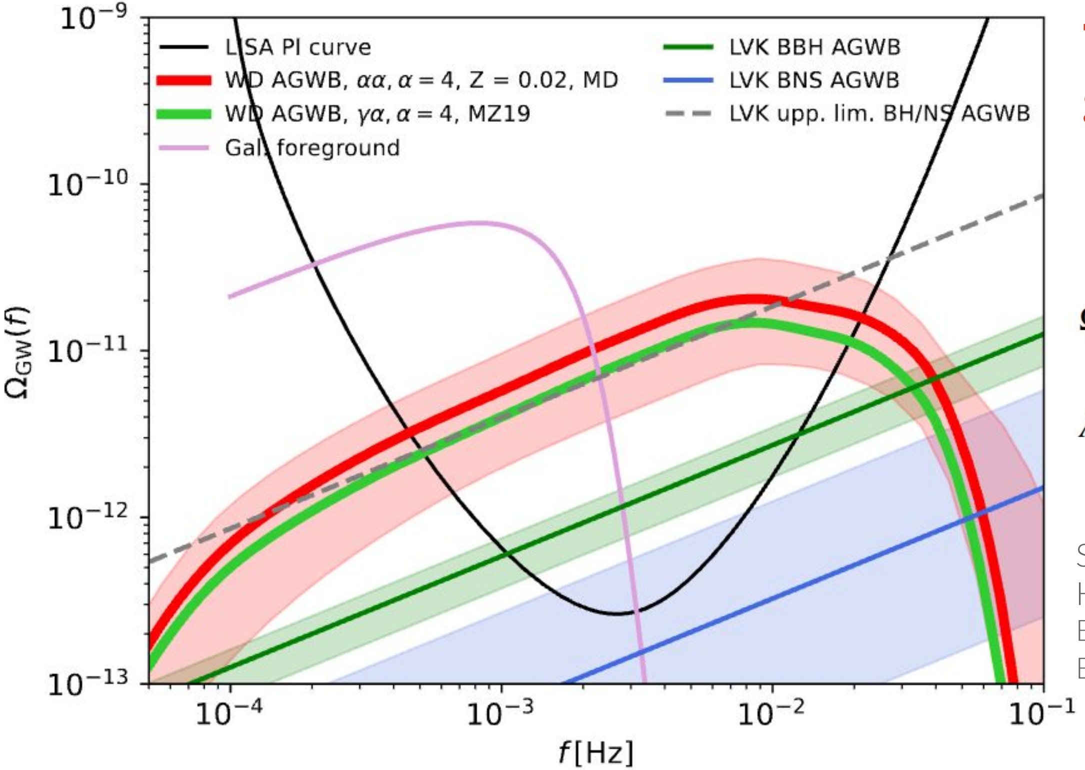
Stochastic gravitational wave background from highly-eccentric stellar-mass binaries in the milli-hertz band





Xuang et al. 2024
arXiv:2403.04832

The astrophysical GW foreground is dominated by WD+WD binaries in the Galaxy below 2–3 mHz and extragalactic WD+WD binaries below 30 mHz



The extragalactic signal is generated by 2×10^{17} WD+WD binaries! (most within redshift ~1)

$$\Omega_{\mathrm{GW}}(f) = A\left(\frac{f}{\hat{f}}\right)^{0.741}\left[1+\left(\frac{f}{\hat{f}}\right)^{4.15}\right]^{-0.255} \cdot \exp\left(-Bf^3\right)$$

$A = 1.72 \times 10^{-11}$, $B = 1.54 \times 10^4$ and $\hat{f} = 7.2\,\mathrm{mHz}$

Staelens & Nelemans 2023, arXiv:2310.19448
Hofman & Nelemans 2024, arXiv:2407.10642
Boileau et al. in prep
Based on Farmer and Phinney 2003

Summary

- LISA's Galactic foreground will yield tons of science, even though it represents "noise" for early universe sources
- The foreground depends on the realization of the entire galaxy
- So far, the community has published on BPS-based predictions; uncertainties in binary evolution are likely the major source of uncertainty in the foreground
- An observations-based model is also available, allowing to skip the uncertainties of BPS-based methods, though it may be oversimplified
- The Galactic foreground is anisotropic, shaped by the Milky Way and also contributions from satellite galaxies
- Beyond 30 mHz, it is likely dominated by extragalactic white dwarfs