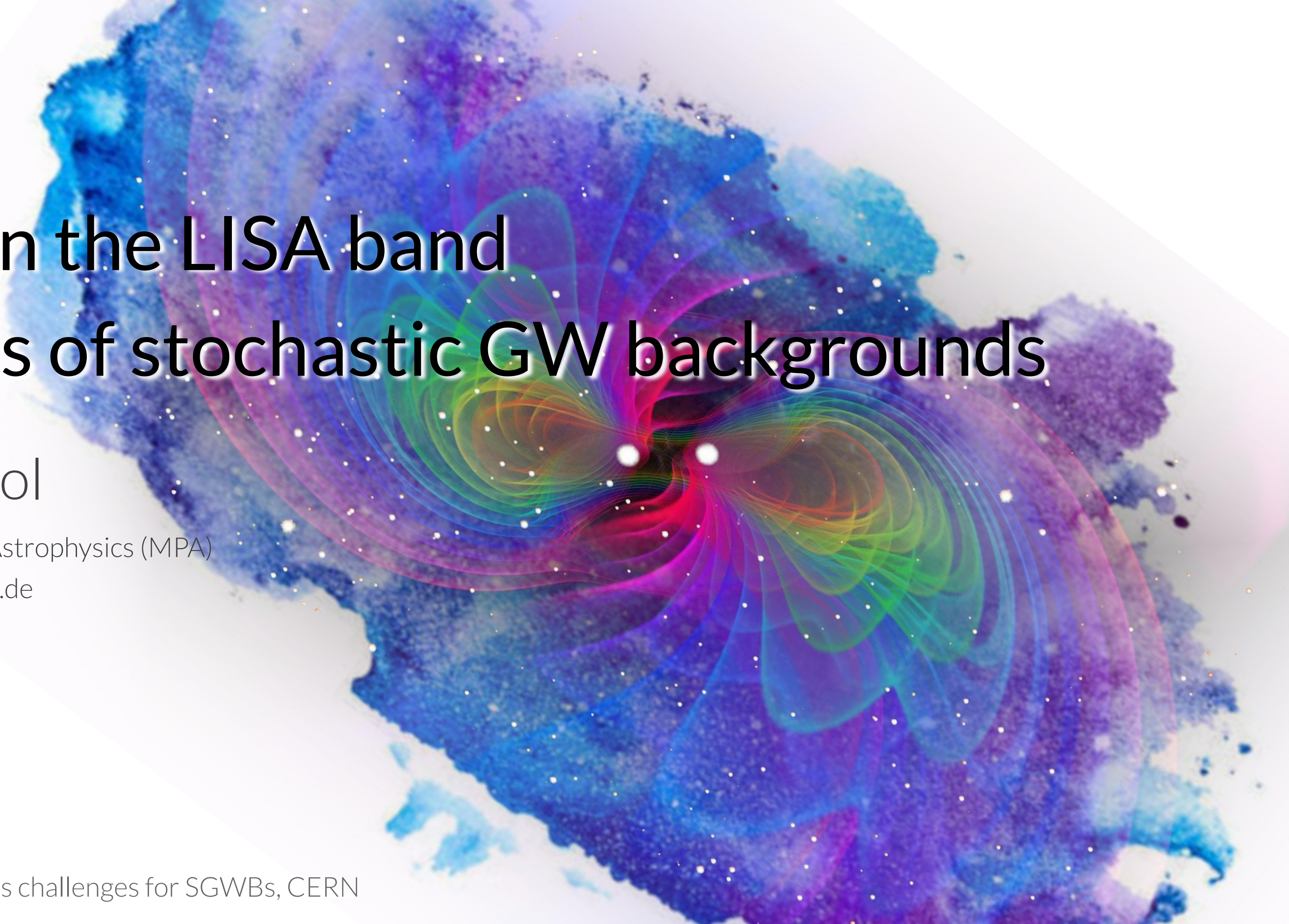

Binaries in the LISA band as sources of stochastic GW backgrounds

Valeriya Korol

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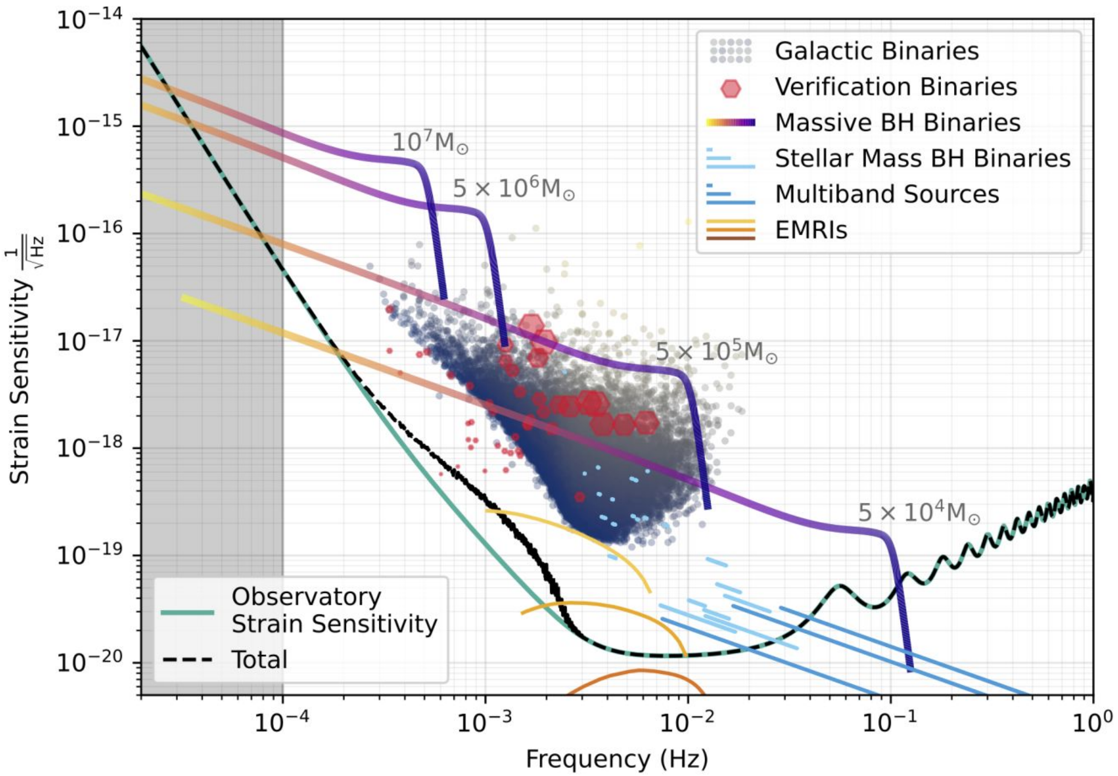
www.valeriakorol.com

LISA
CONSORTIUM

19.07.2023 | Data analysis challenges for SGWBs, CERN

Classes of LISA astrophysical sources



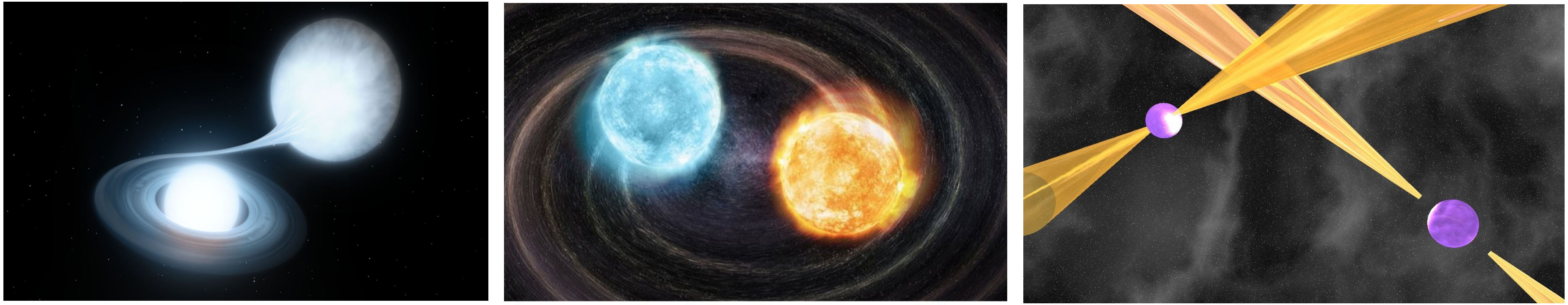
All classes of LISA sources have the potential to generate a Stochastic Gravitational Wave Background (SGWB)

…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.

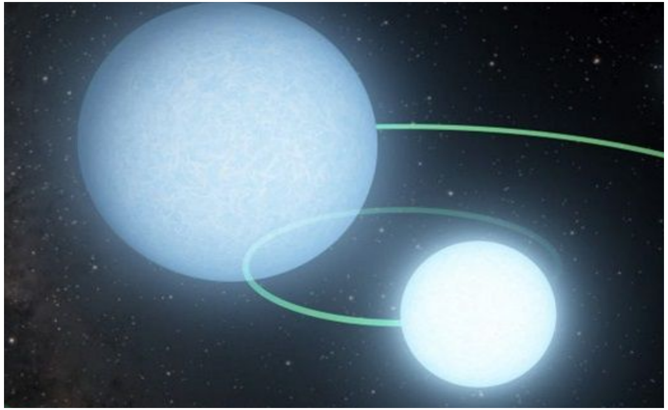
The SGWB carries global information about the source population, which complements the details gathered from individually resolved sources.

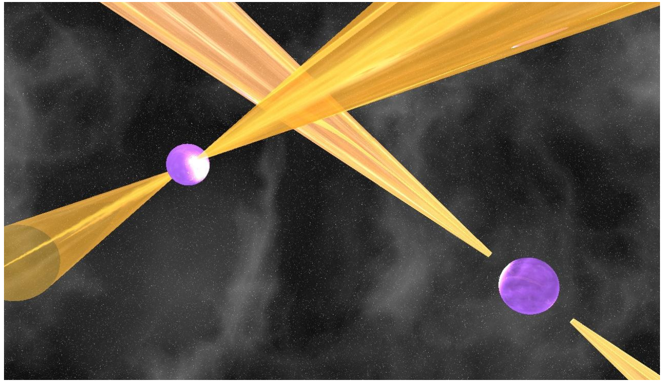
Figure credit: Riccardo Buscicchio; LISA Definition Study Report to be submitted to ESA for the LISA mission by 2024

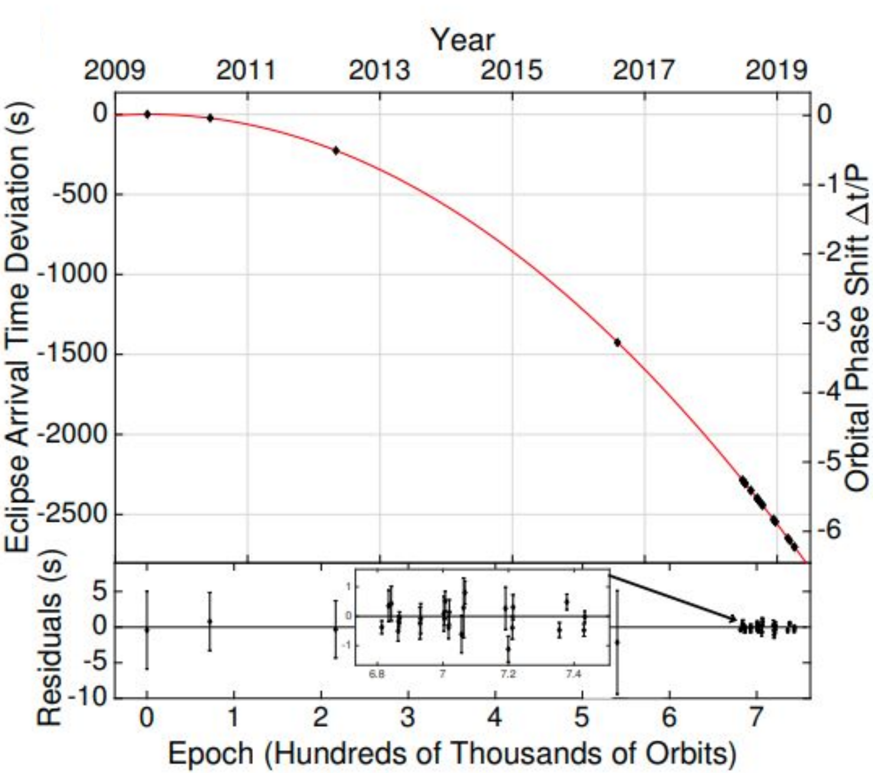
Galactic binaries and multiples



Compact binary stars are guaranteed LISA sources

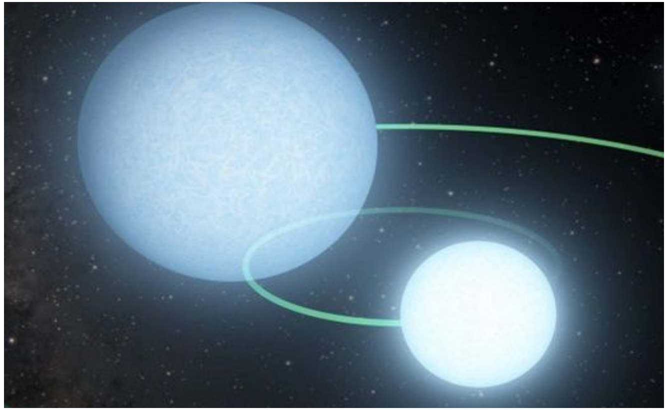


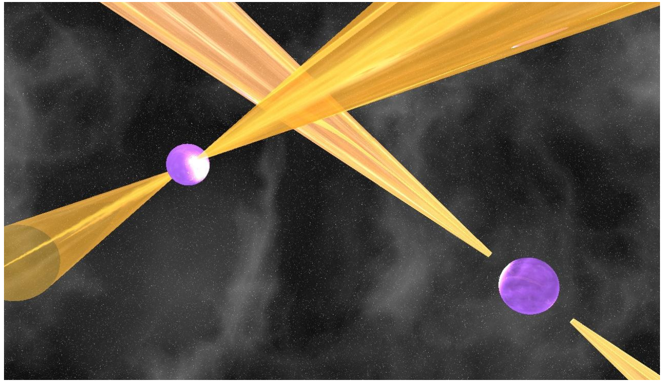


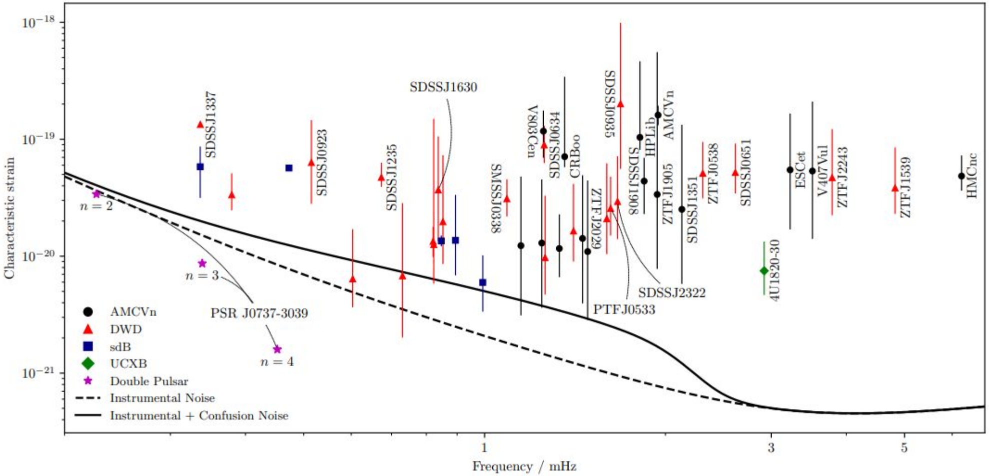


Burdge et al. 2019

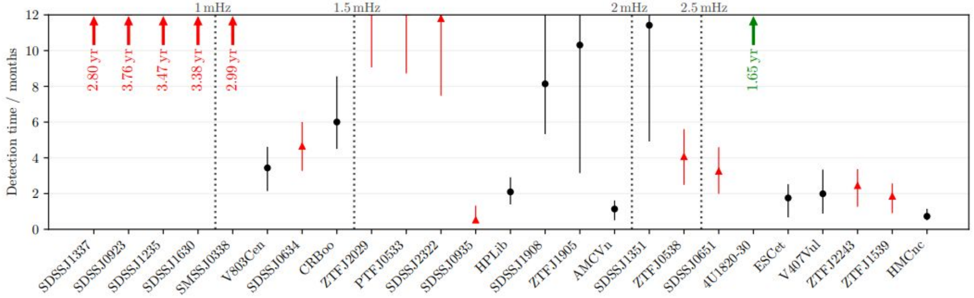
Compact binary stars are guaranteed LISA sources







Finch et al./w Korol et al. 2023

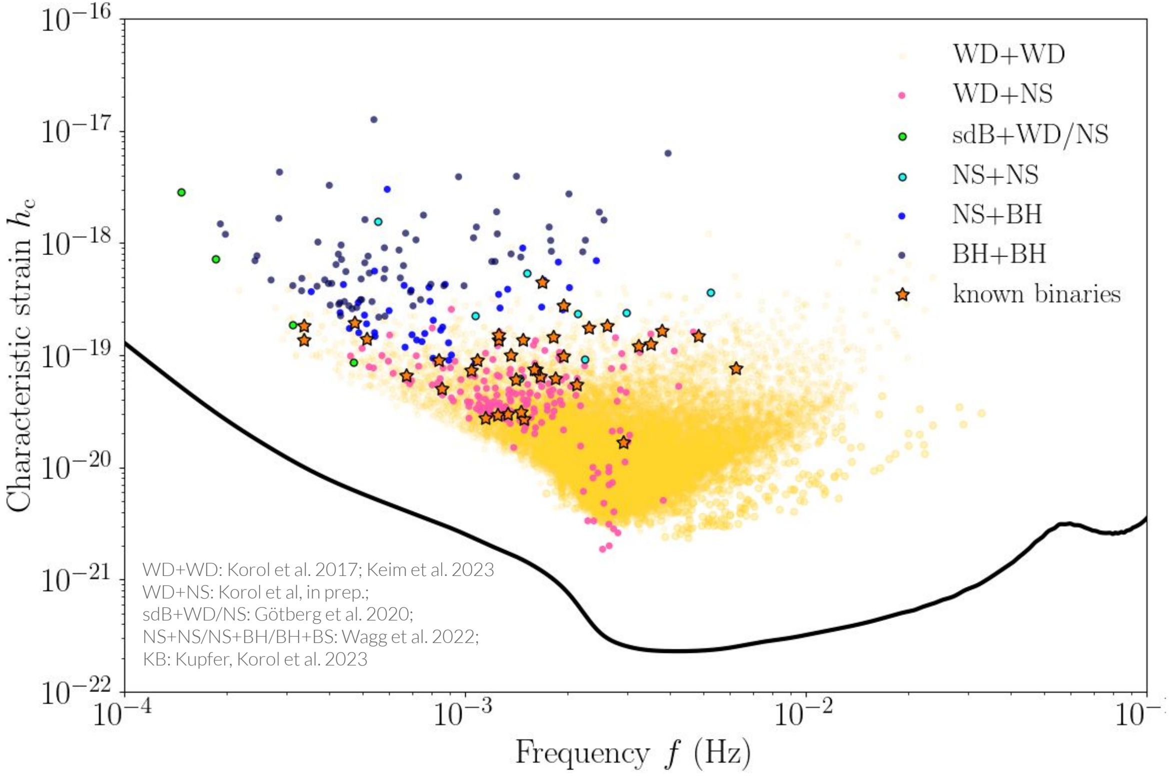


List of candidate LISA verification binaries Kupfer, Korol et al. (2023)

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

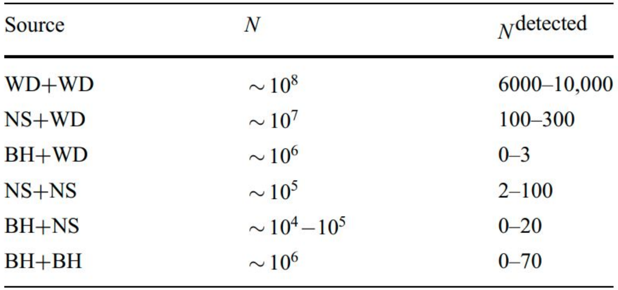
Variety of LISA Galactic binaries and expected number of detections

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



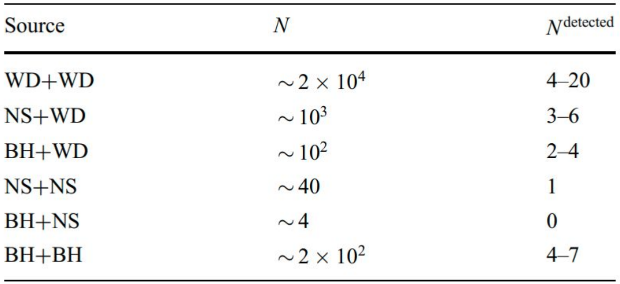
WD+WD: Korol et al. 2017; Keim et al. 2023
WD+NS: Korol et al, in prep.;
sdB+WD/NS: Götberg et al. 2020;
NS+NS/NS+BH/BH+BS: Wagg et al. 2022;
KB: Kupfer, Korol et al. 2023

Isolated binary evolution



Source	N	N^{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

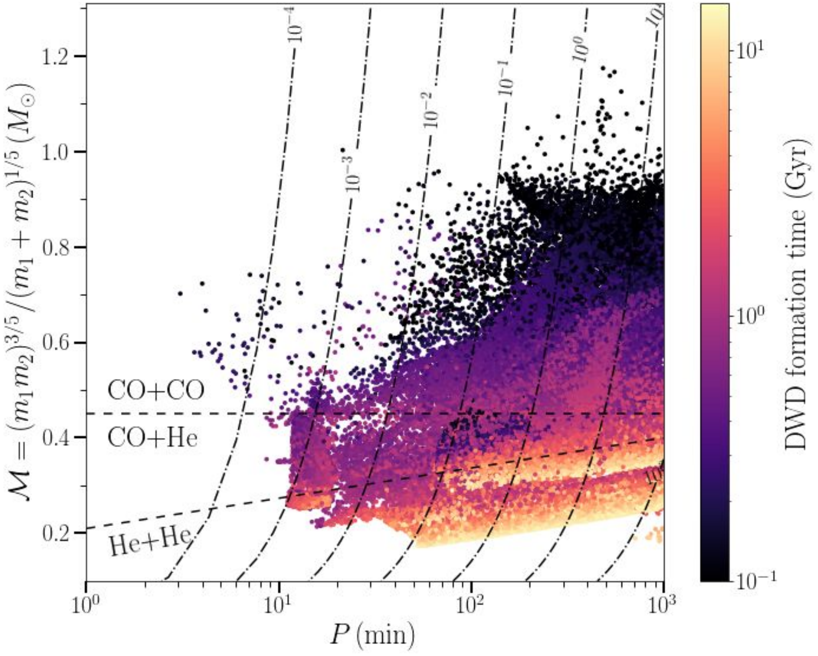


Source	N	N^{detected}
WD+WD	$\sim 2 \times 10^4$	4–20
NS+WD	$\sim 10^3$	3–6
BH+WD	$\sim 10^2$	2–4
NS+NS	~ 40	1
BH+NS	~ 4	0
BH+BH	$\sim 2 \times 10^2$	4–7

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

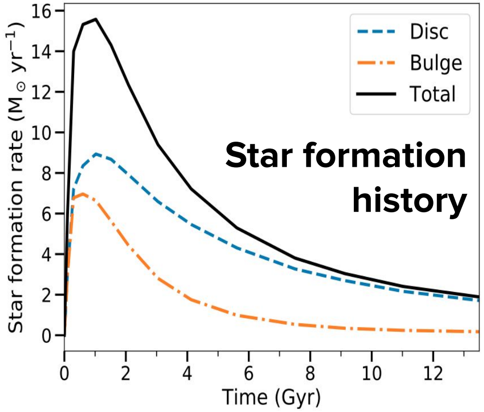
How we forecast LISA observations of Galactic binaries?
Binary population synthesis approach

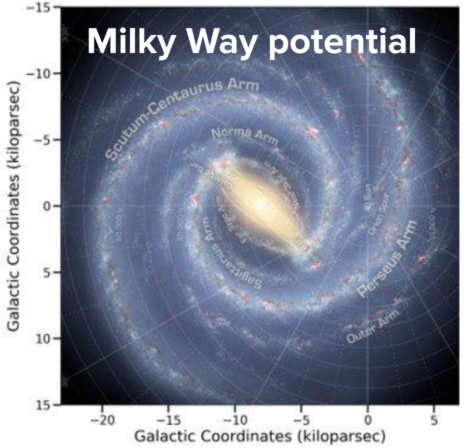
When forecasting LISA observations, we mainly rely on the binary population synthesis (BPS) technique.



Toonen et al. 2012, based on SeBa BPS code

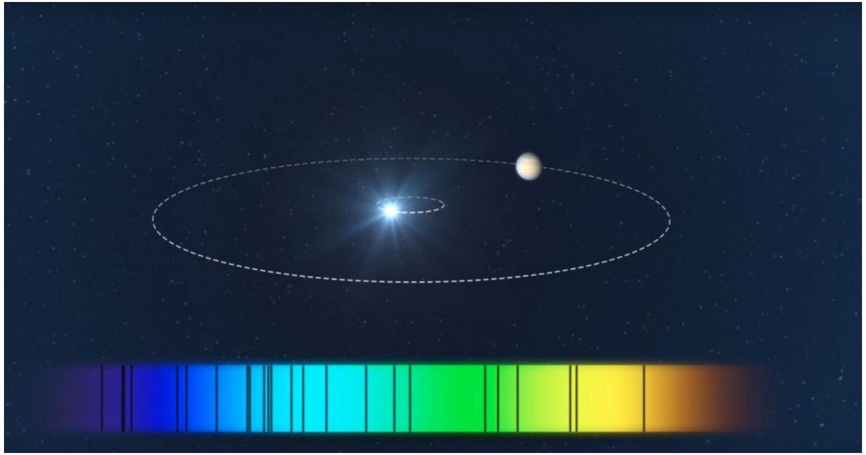
See also: Nelemans et al. (2001), Ruiter et al. (2010), Yu & Jaffery (2010), Lamberts et al. (2018), Breivik et al. (2020), Li et al. (2020), Wagg et al. (2022) and many others



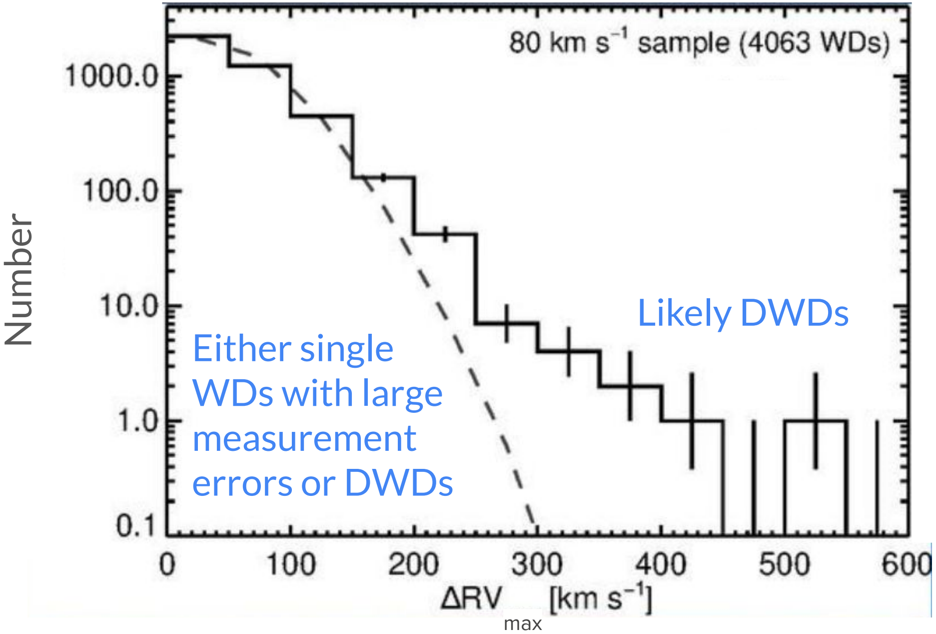


How we forecast LISA observations of Galactic binaries?
An observationally-driven approach

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



Credit: ESO/L. Calçada



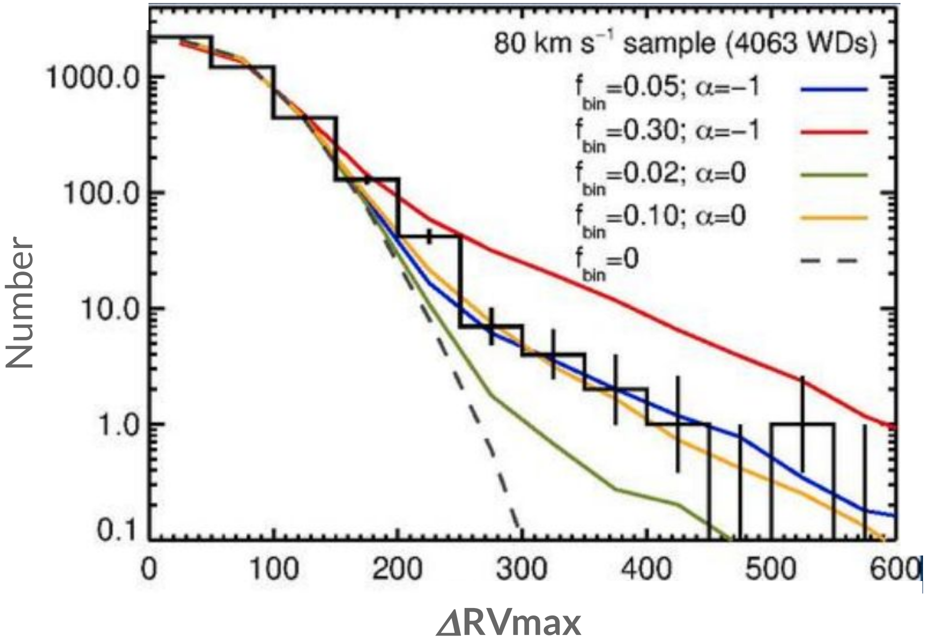
Courtesy of Na'ama Hallakoun
See Maoz et al. (2012), arXiv:1202.5467
and Maoz & Hallakoun (2017), arXiv:1609.02156

How 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 α**

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



Courtesy of Na'ama Hallakoun
See Maoz et al. (2012), arXiv:1202.5467
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How we forecast LISA observations of Galactic binaries? An observationally-driven approach

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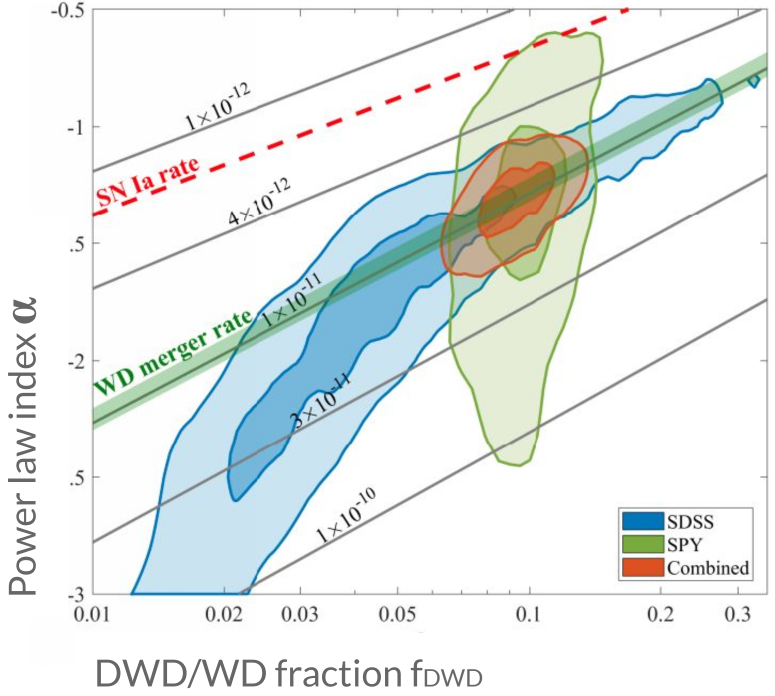
By comparing the data to the models where we vary these underlying assumption it is possible to constrain the power law index **α** of the DWD separation distribution and DWD/WD fraction.

- Power-law index **α** = -1.3
- DWD fraction = 9.5 % for separations of less than 4 au

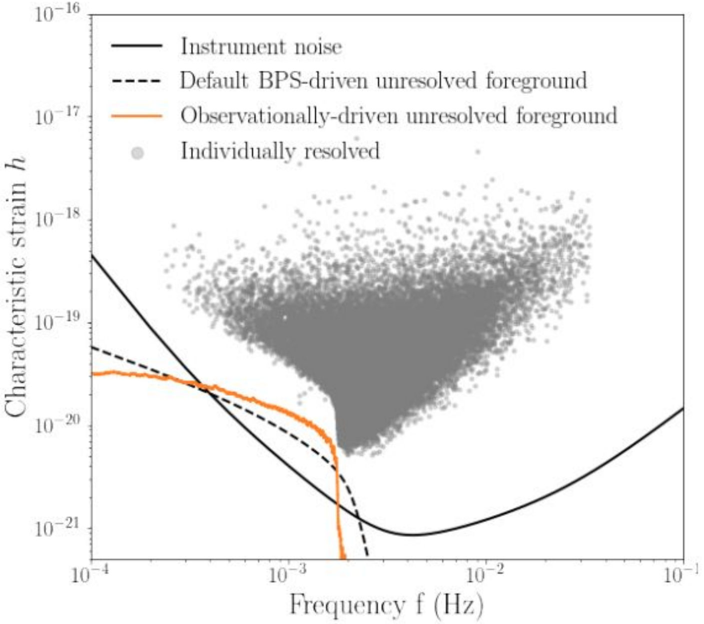


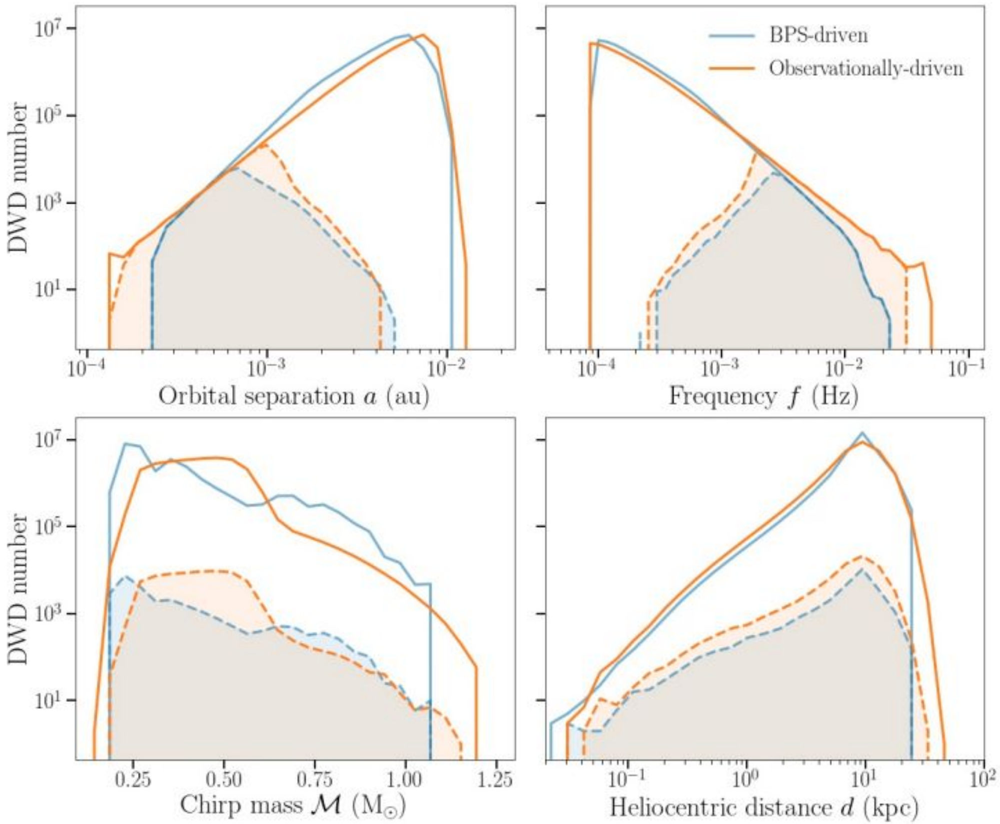
Maoz, Hallkoun et al. (2018)

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

BPS vs observationally-driven predictions

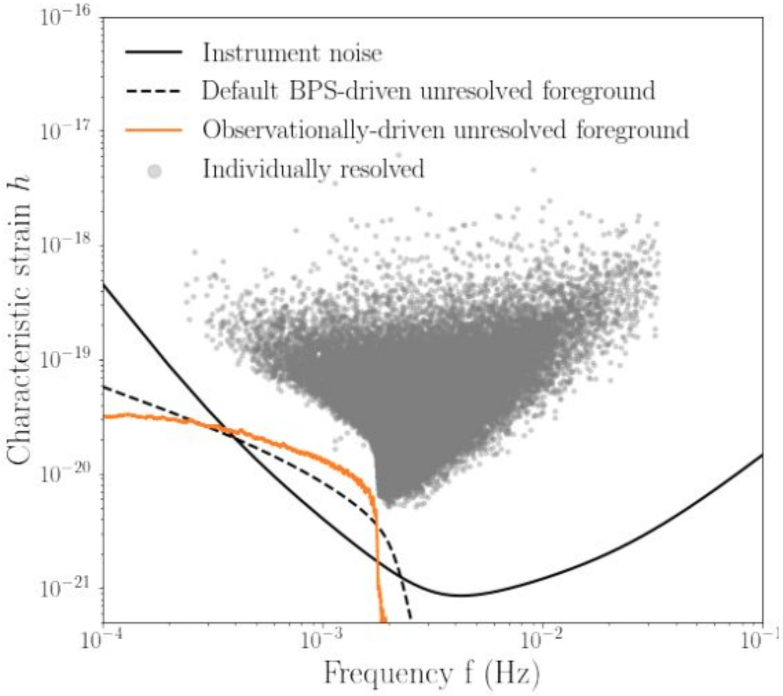
BPS models predict **6k-25k** of individually resolved DWD signals vs **60k** predicted by the observation-based model. Note also that the shape of the unresolved signal is also different.

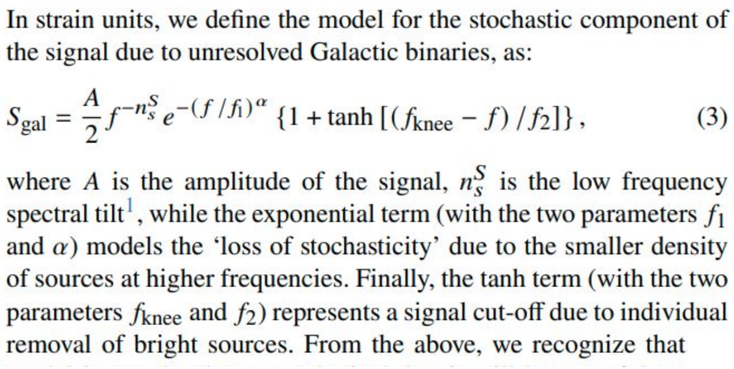




Korol et al./w Karnesis (2022)

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:

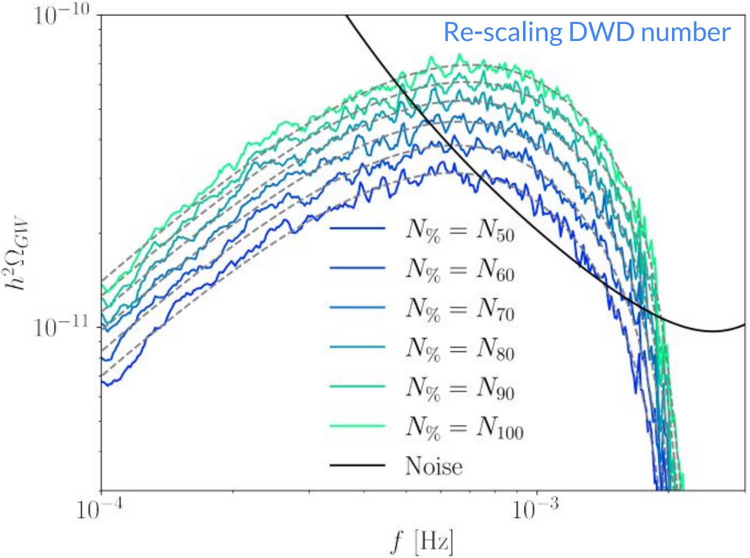
$$S_{\rm gal} = \frac{A}{2} f^{-n_s^S} e^{-(f/f_1)^\alpha} \left\{1 + \tanh\left[(f_{\rm knee} - f)/f_2\right]\right\}, \quad (3)$$

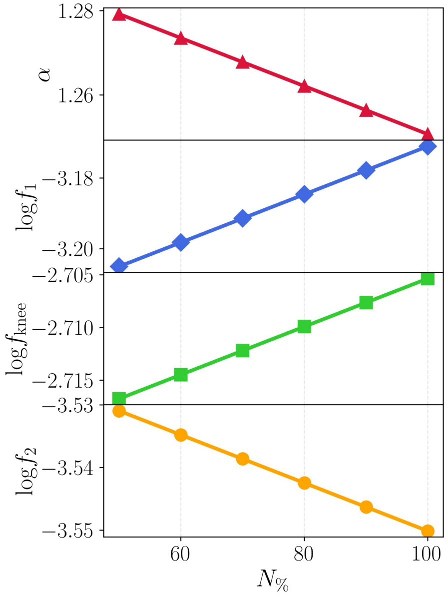
where A is the amplitude of the signal, n_s^S is the low frequency spectral tilt[1], while the exponential term (with the two parameters f_1 and α) models the 'loss of stochasticity' due to the smaller density of sources at higher frequencies. Finally, the tanh term (with the two parameters $f_{\rm knee}$ and f_2) represents a signal cut-off due to individual removal of bright sources. From the above, we recognize that

Korol et al./w Karnesis (2022)

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.





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

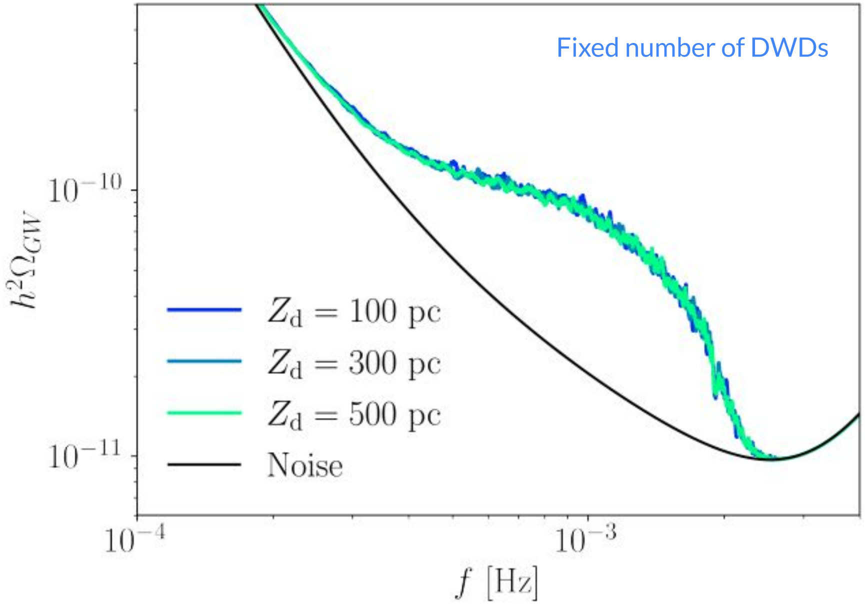
$N_\%$	$m_{\rm G}$ [$\times 10^{10} M_\odot$]	Relative error 1σ
N_{50}	4.1	0.017
N_{60}	4.92	0.013
N_{70}	5.74	0.010
N_{80}	6.56	0.008
N_{90}	7.38	0.007
N_{100}	8.2	0.006

Georgousi, Karnesis et al.\w Korol 2022

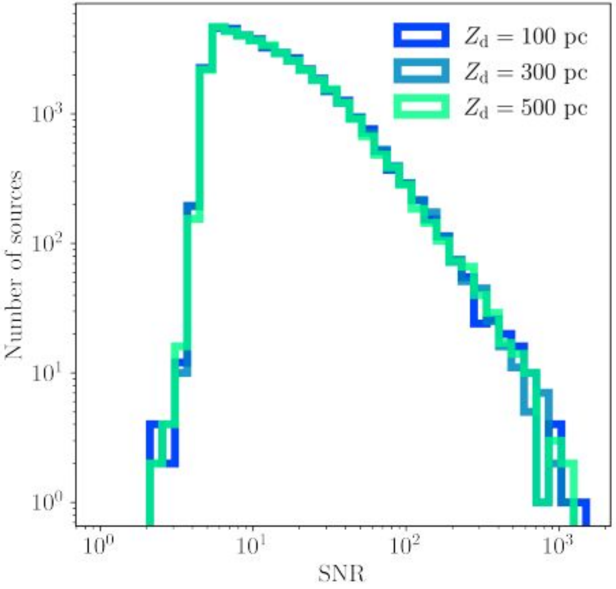
What will we learn from the unresolved Galactic GW foreground?

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.

Unresolved



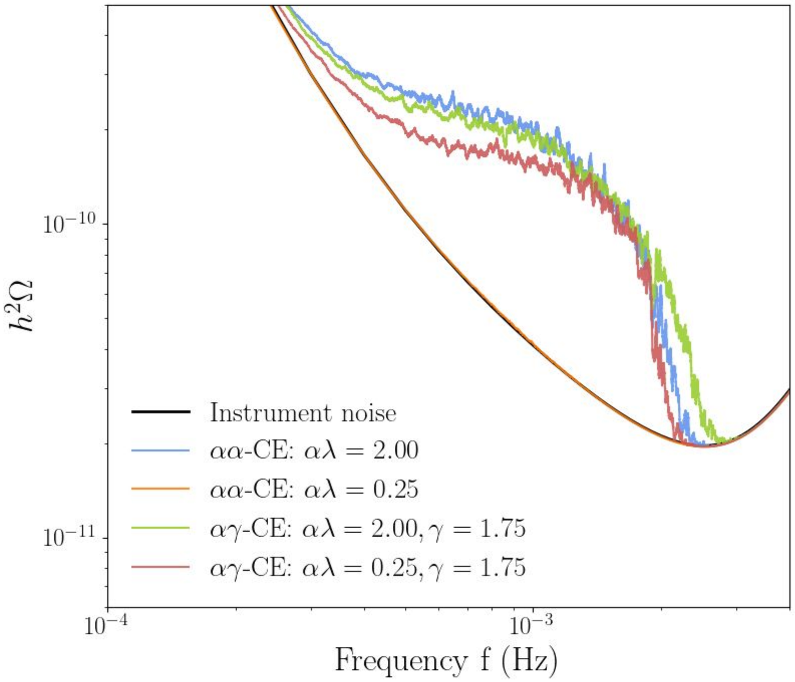
Resolved

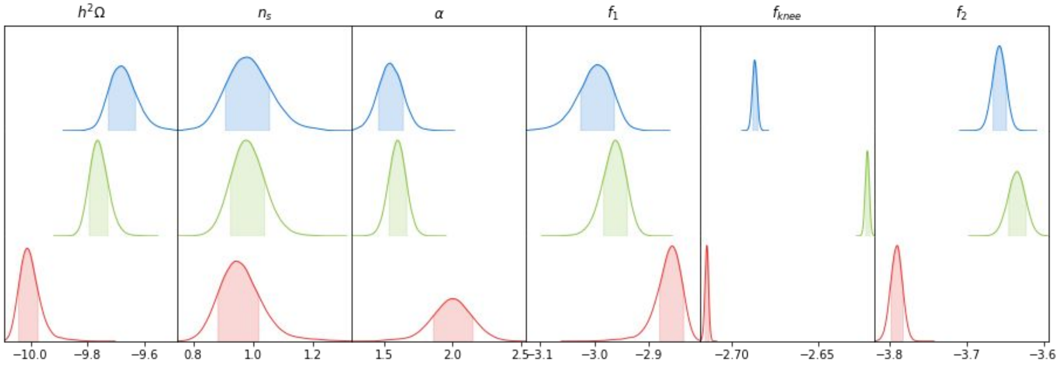


Georgousi, Karnesis et al.\w Korol (2022)
See also Benacquista & Holley-Bockelmann (2006), Breivik et al. (2020)

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.



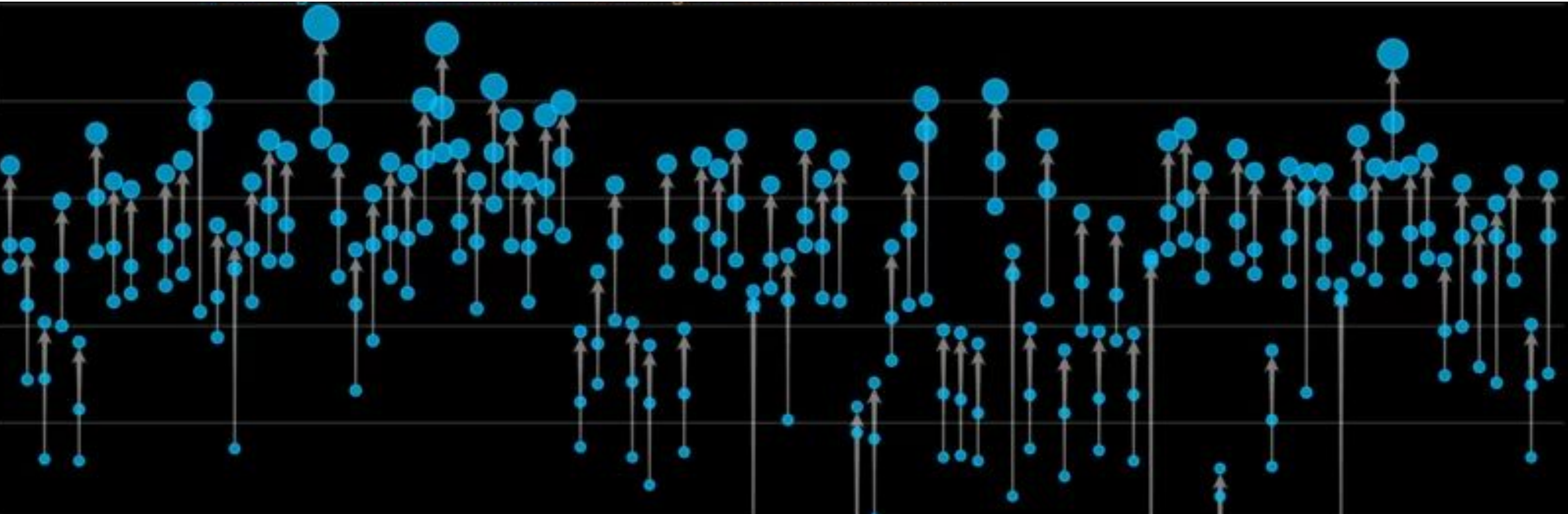


$$S_{\mathrm{gal}} = \frac{A}{2} f^{-n_s^S} e^{-(f/f_1)^{\alpha}} \{1 + \tanh[(f_{\mathrm{knee}} - f)/f_2]\}$$

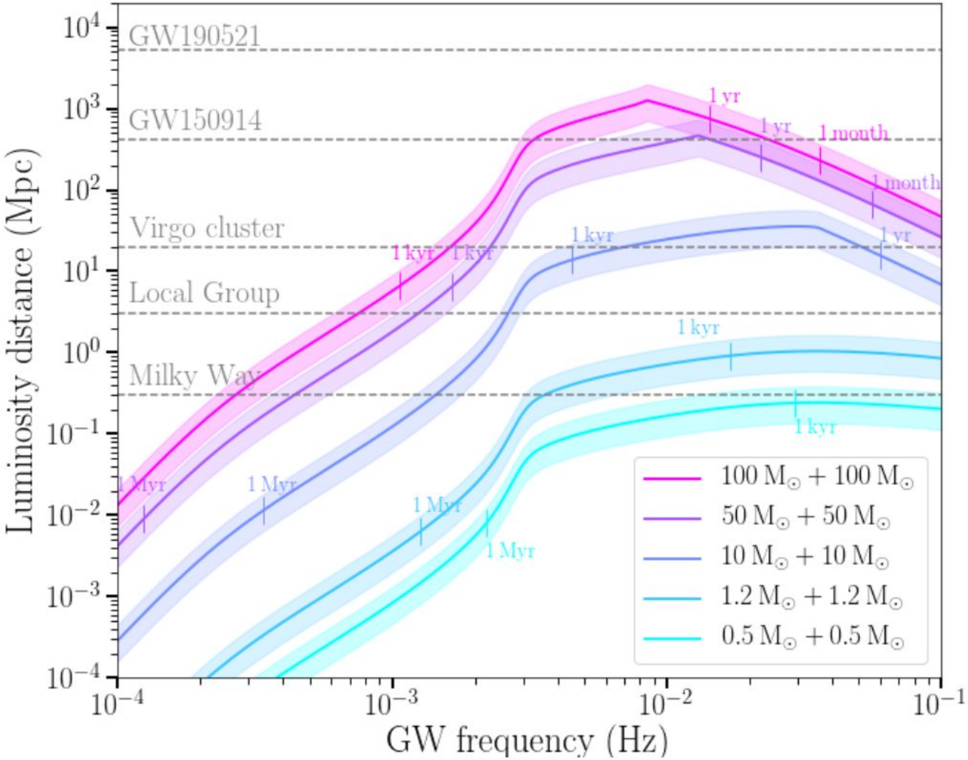
Ashlin Varghese's project as part of the Kavli Summer School 2023 (MPA, Garching)

In collaboration with Nikolaos Karnesis et al.

Extragalactic stellar-mass BH binaries



Understanding the astrophysics of stellar-mass BHBs with LISA

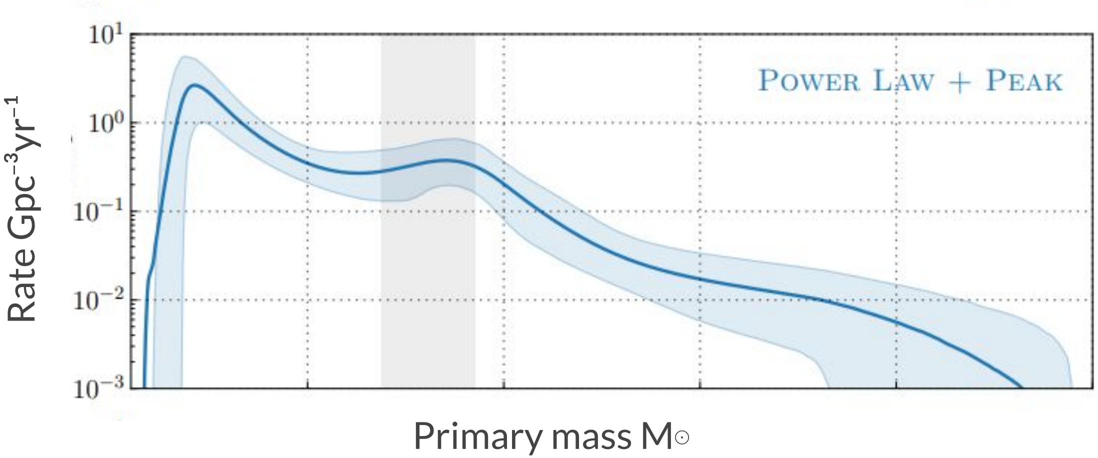


LISA can observe individual stellar-mass Black Hole Binaries (BHBs) up to several hundreds of years before coalescence, enabling measurements that are complementary to those made with ground based detectors.

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

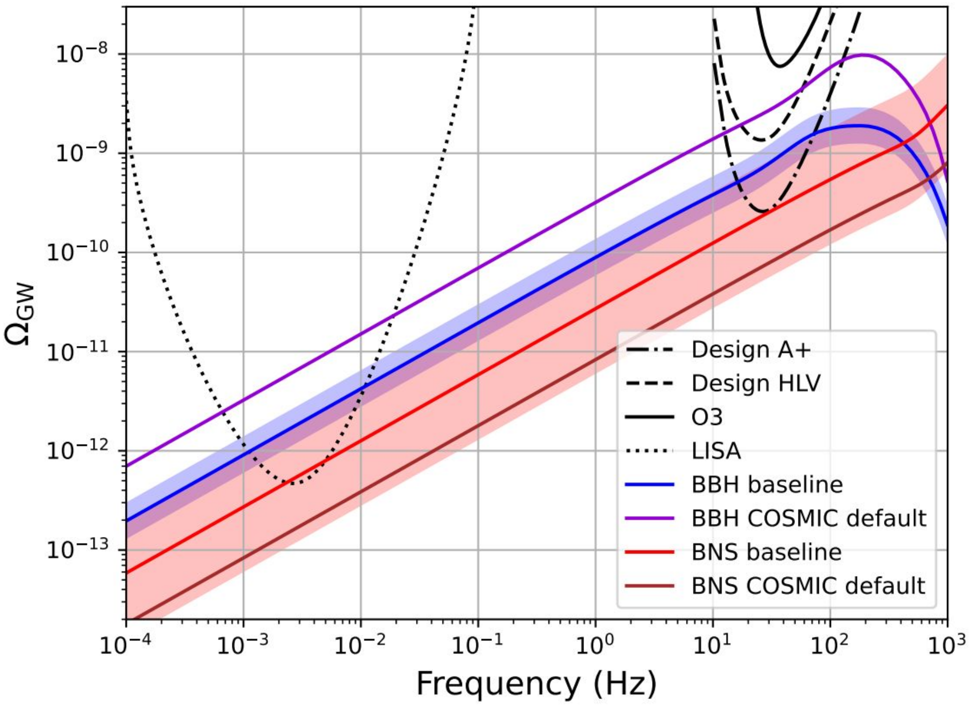
Understanding the astrophysics of stellar-mass BHBs with LISA

- 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 ~100 stellar-mass Black Hole binaries (BHBs), featuring masses as large as ≈ 100 M⊙.
- 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.



LIGO and Virgo Scientific Collaboration (2021)

Predicting extragalactic stellar-mass BHB foreground



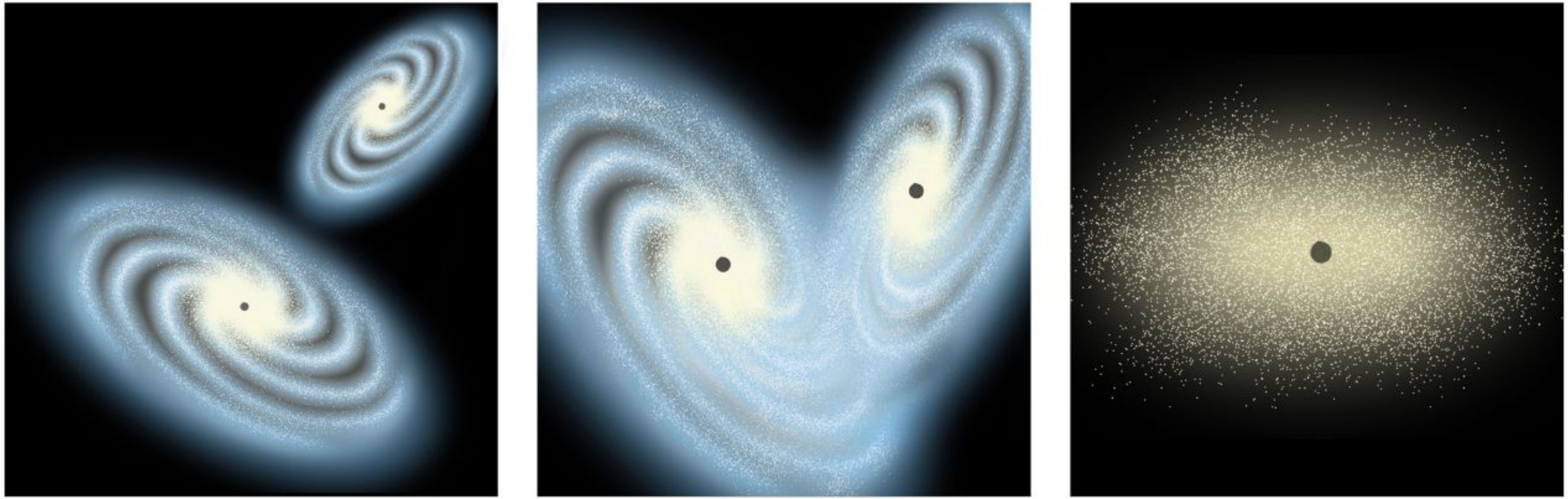
Lehoucq et al. (2023) studied SGWB from BHBs and BNSs based on the LVK/EM samples and based on binary population synthesis models:

- 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

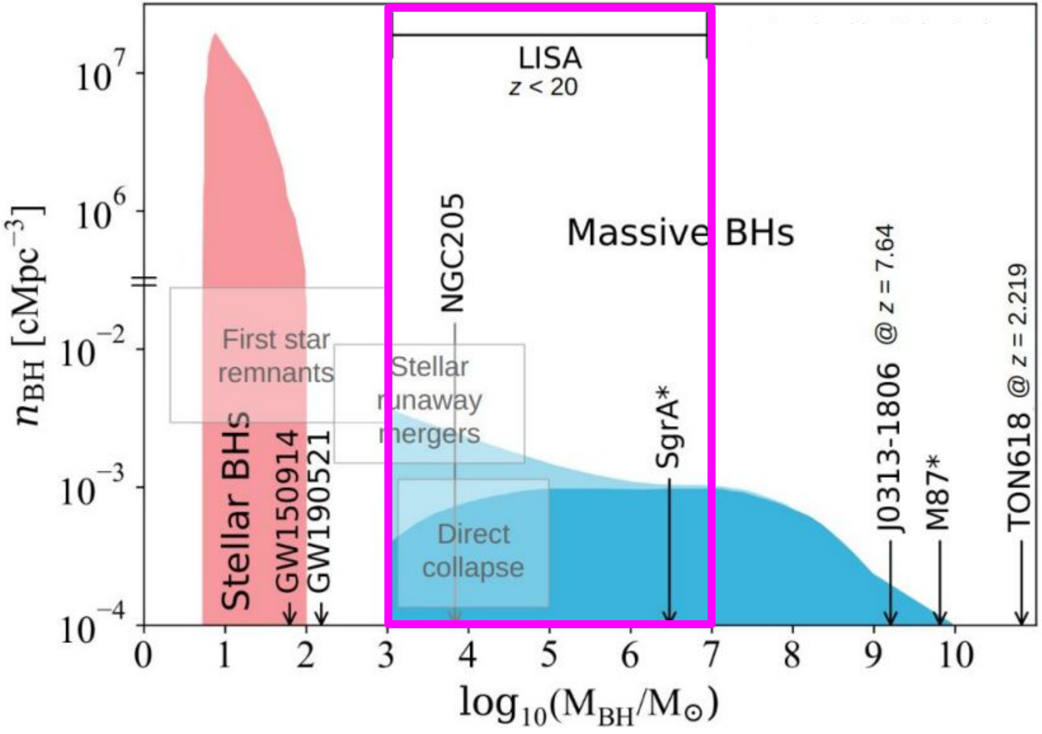
Key findings: BHBs are likely dominant SGWB contributors; BNS contribution is highly uncertain (need far more BNS merger detections). Approx. 10 BBHs but no BNSs detectable by LISA in 4-year observation period.

Lehoucq et al. (2023); see also Babak et al. (2023)

Massive black hole binaries



Tracing the origins, growth and merger histories of MBHs



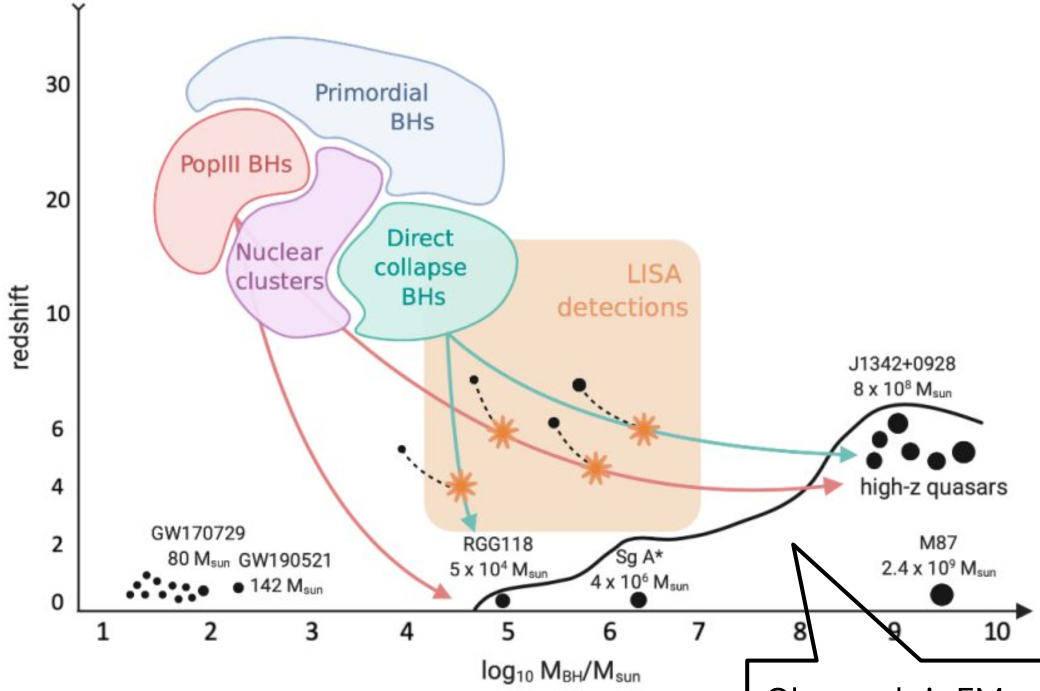
LISA will discover Massive Black Holes (MBHs) across a largely unexplored segment of the mass spectrum: $10^4 - 10^7$ M$_\odot$, and unveil their origins and evolution along cosmic history.

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



Observed via EM radiation

- **Primordial origin BHs**: high-contrast density perturbations during early Universe phase transitions, forming even before galaxies, with initial mass up to 10^5 M⊙.
- **PopIII BHs (light seeds)**: From the collapse of the first metal-free (Pop III) stars at high redshifts, masses between 10 M⊙ and a few 10^2 M⊙.
- **Direct collapse BHs (heavy seeds)**: From the direct collapse of supermassive stars around z ~ 10−15 in massive halos, masses up to 10^5 M⊙.
- **Nuclear clusters**: from stellar collisions in metal-poor star clusters, masses up to several 10^3 M⊙.

Figure credit: Melanie Habouzit; LISA Astrophysics white paper, Amaro-Seoane et al. (2023)

LISA’s cosmic horizon

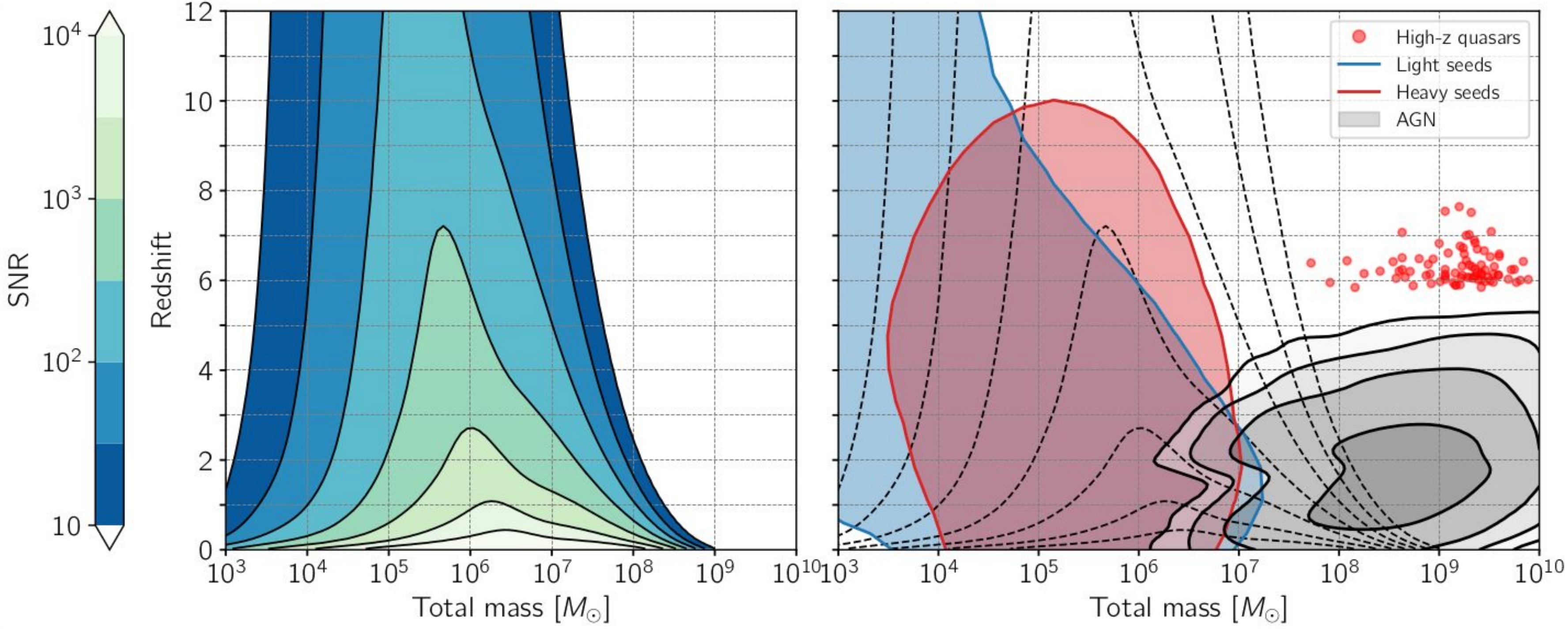
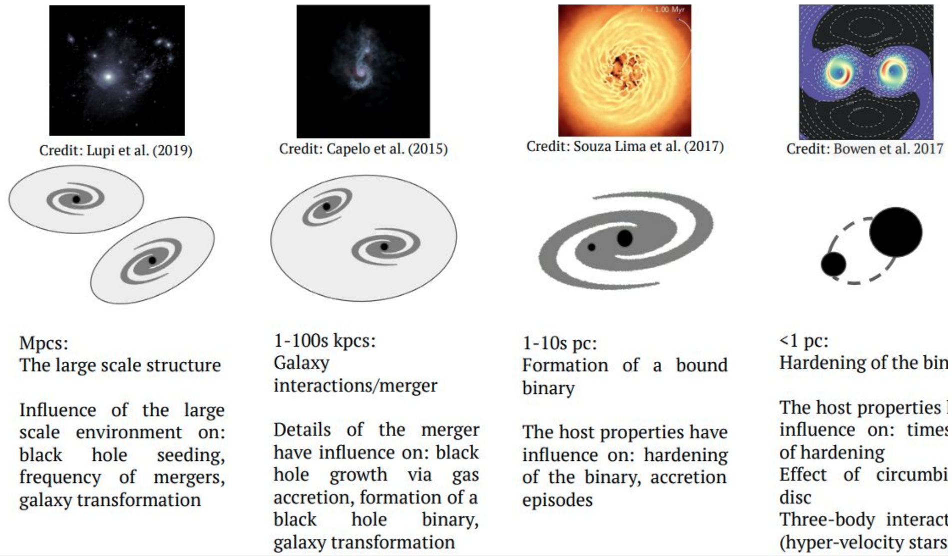


Figure credit: Riccardo Buscicchio based on Bonetti et al. (2019); LISA Definition Study Report to be submitted to ESA for the LISA mission by 2024

Studying the growth mechanism and merger history of MBHs



Credit: Lupi et al. (2019)

Mpcs:
The large scale structure

Influence of the large scale environment on: black hole seeding, frequency of mergers, galaxy transformation

Credit: Capelo et al. (2015)

1-100s kpcs:
Galaxy interactions/merger

Details of the merger have influence on: black hole growth via gas accretion, formation of a black hole binary, galaxy transformation

Credit: Souza Lima et al. (2017)

1-10s pc:
Formation of a bound binary

The host properties have influence on: hardening of the binary, accretion episodes

Credit: Bowen et al. 2017

<1 pc:
Hardening of the bin

The host properties
influence on: time
of hardening
Effect of circumbi
disc
Three-body interact
(hyper-velocity stars

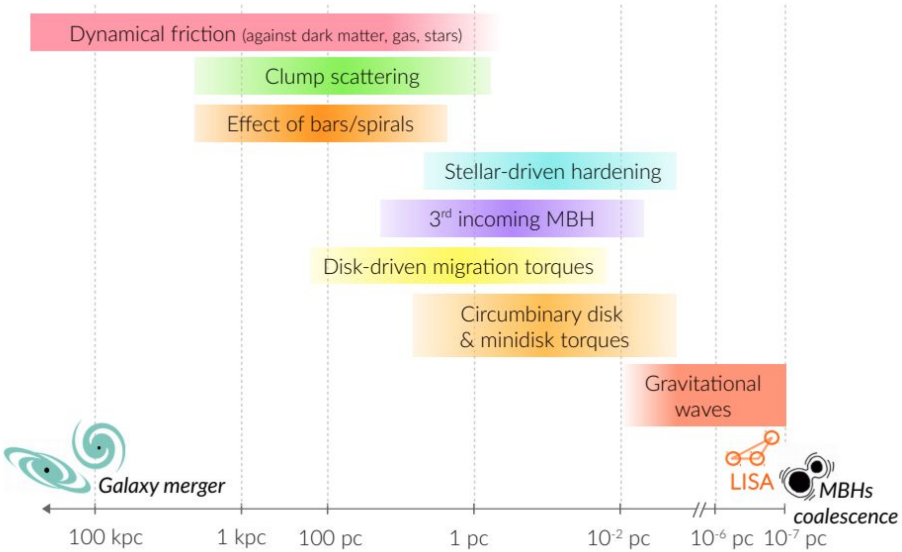


Figure credit: Silvia Bonoli & Alessandro Lupi ↑, Elisa Bortolas→
LISA Astrophysics white paper, Amaro-Seoane et a.l (2023)

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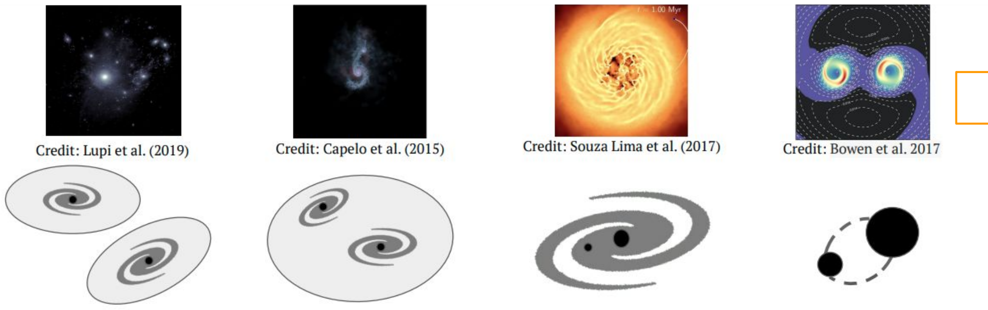

Credit: Lupi et al. (2019)

Credit: Capelo et al. (2015)

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<1 pc:
Hardening of the binary

The host properties have influence on: timescale of hardening
Effect of circumbinary disc
Three-body interactions (hyper-velocity stars)

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

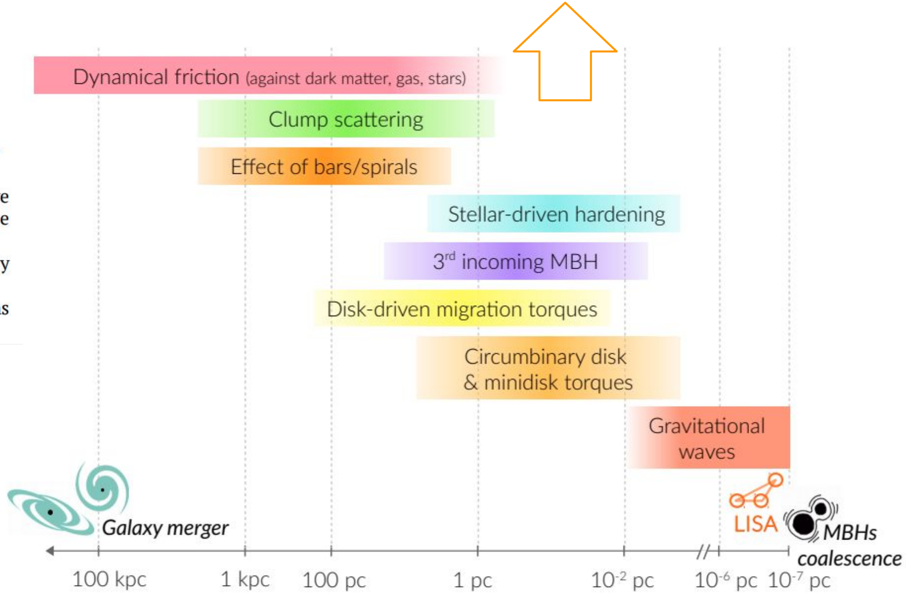
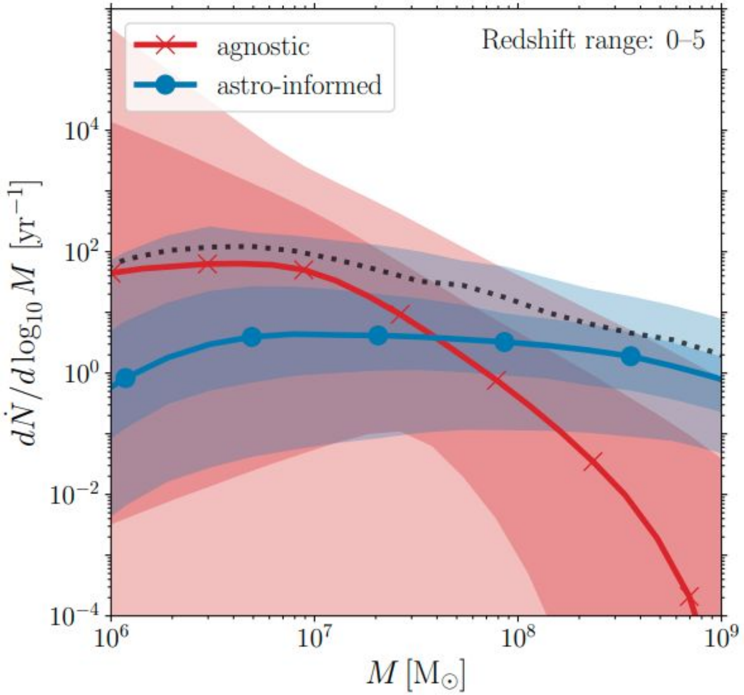


Figure credit: Silvia Bonoli & Alessandro Lupi ↑, Elisa Bortolas→
LISA Astrophysics white paper, Amaro-Seoane et a.l (2023)

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)

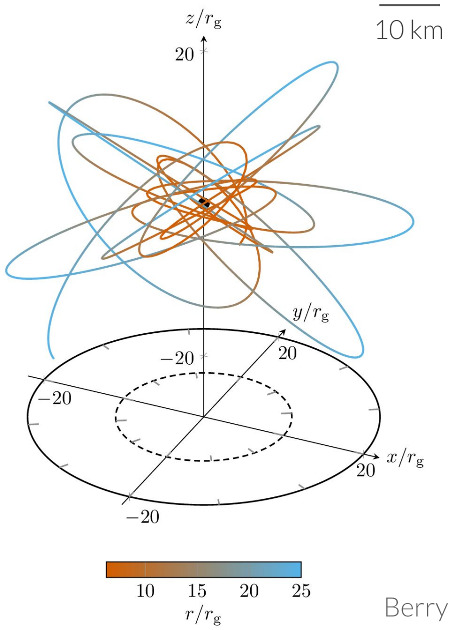
Do they produce a background for LISA?

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

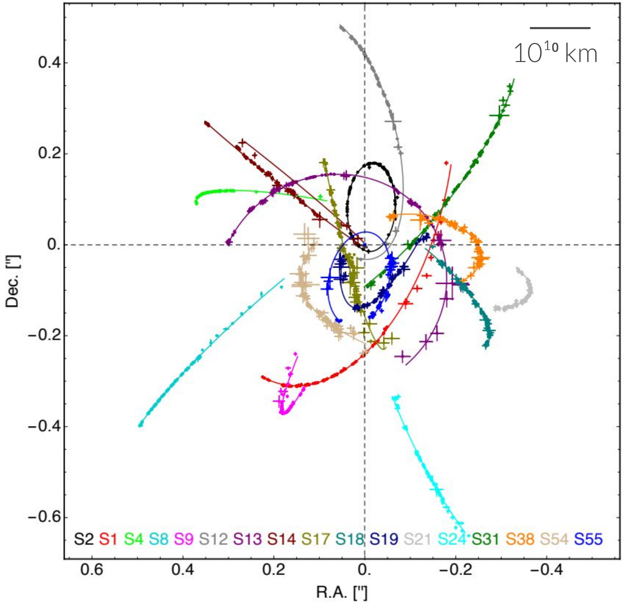
E.g., Sesana et. al. (2007), Bonetti et al. (2021), Barausse et al. (2020)

Extreme and Intermediate mass ratio inspirals:

GW analogues to S-stars orbiting our own supermassive black hole Sgr A*

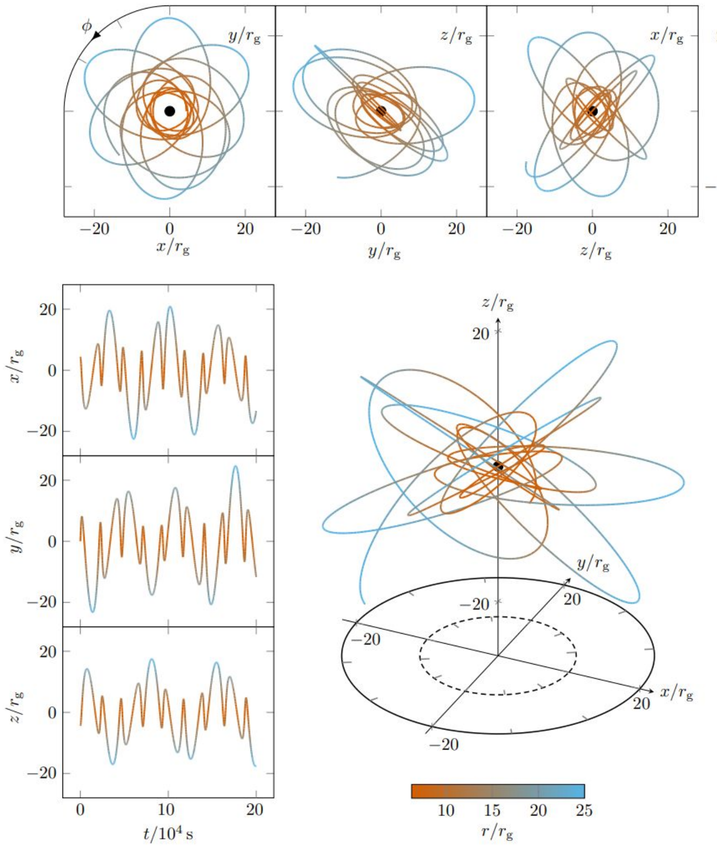


Berry et al. 2019



Gillessen et al. (2017)

Extreme and Intermediate mass ratio inspirals



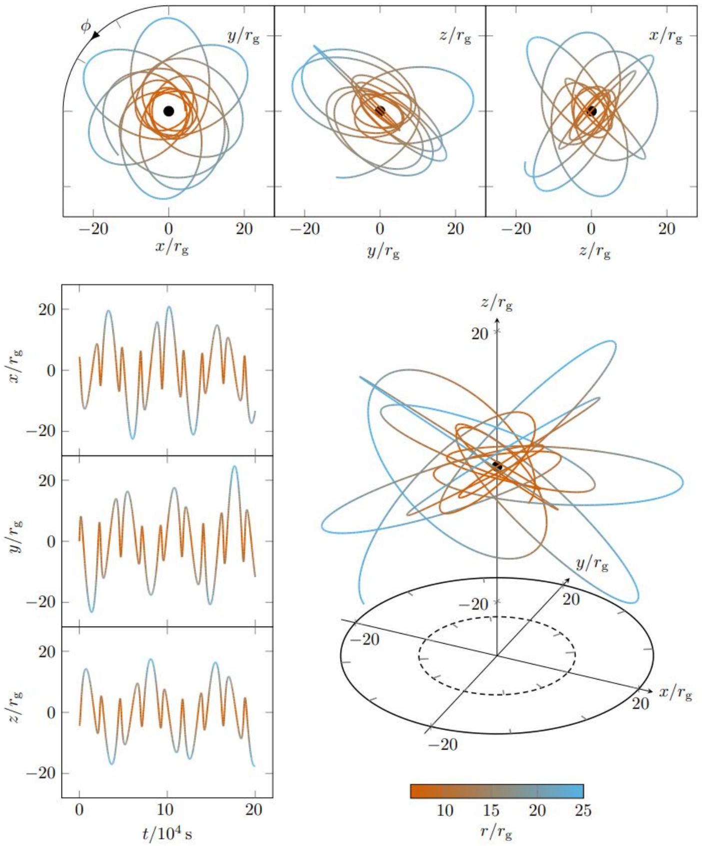
Berry et al. 2019

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

Acronym	Meaning	Mass ratio	Constituents
light IMRI	light intermediate mass-ratio inspiral	10^{-5}–10^{-2}	IMBH & stellar-mass compact object
heavy IMRI	heavy intermediate mass-ratio inspiral	10^{-5}–10^{-2}	MBH & IMBH
EMRI	extreme mass-ratio inspiral	10^{-8}–10^{-5}	MBH & stellar-mass compact object
b-EMRI	binary-extreme mass-ratio inspiral	10^{-8}–10^{-5}	MBH & binary stellar-mass compact object
XMRI	extremely large mass-ratio inspiral	$\lesssim 10^{-8}$	MBH & sub-stellar object

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

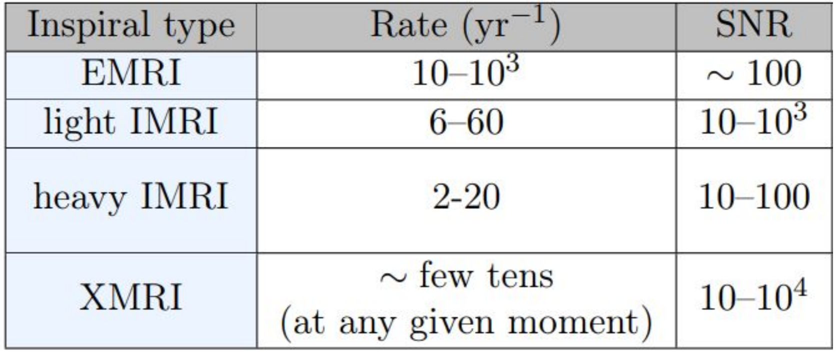
Extreme and Intermediate mass ratio inspirals



Berry et al. 2019

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



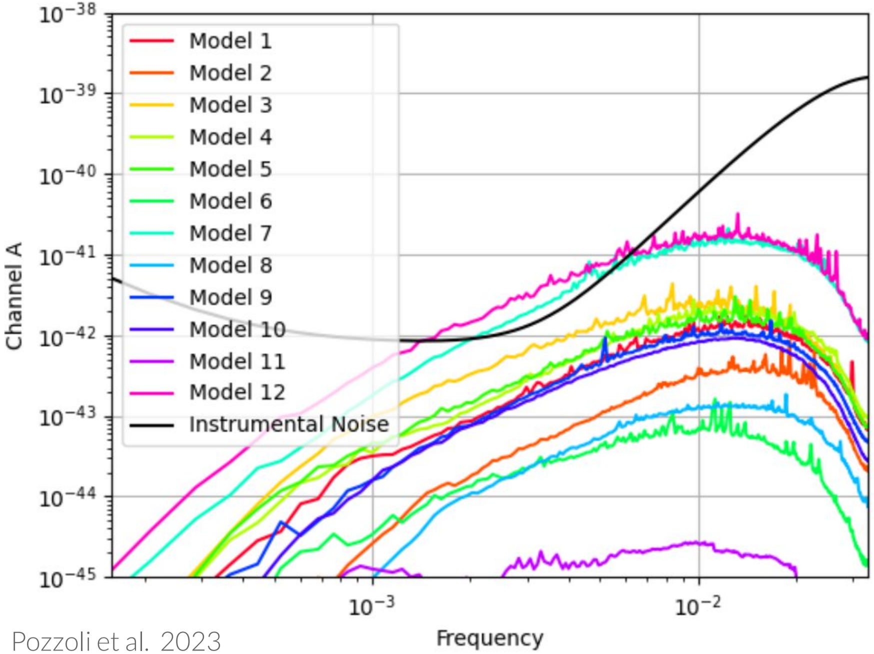
Inspiral type	Rate (yr^{-1})	SNR
EMRI	10–10^3	~ 100
light IMRI	6–60	10–10^3
heavy IMRI	2-20	10–100
XMRI	$\sim$ few tens (at any given moment)	10–10^4

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

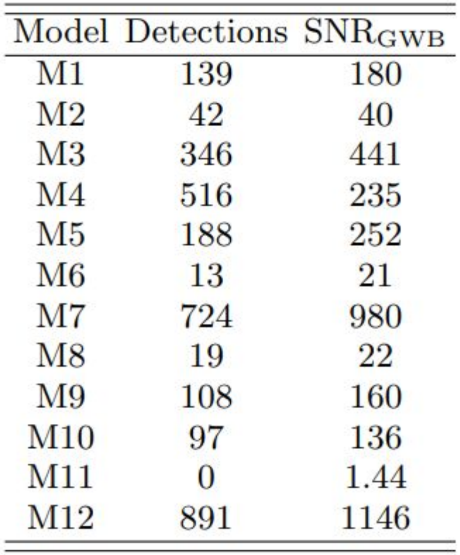
EMRI background

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.



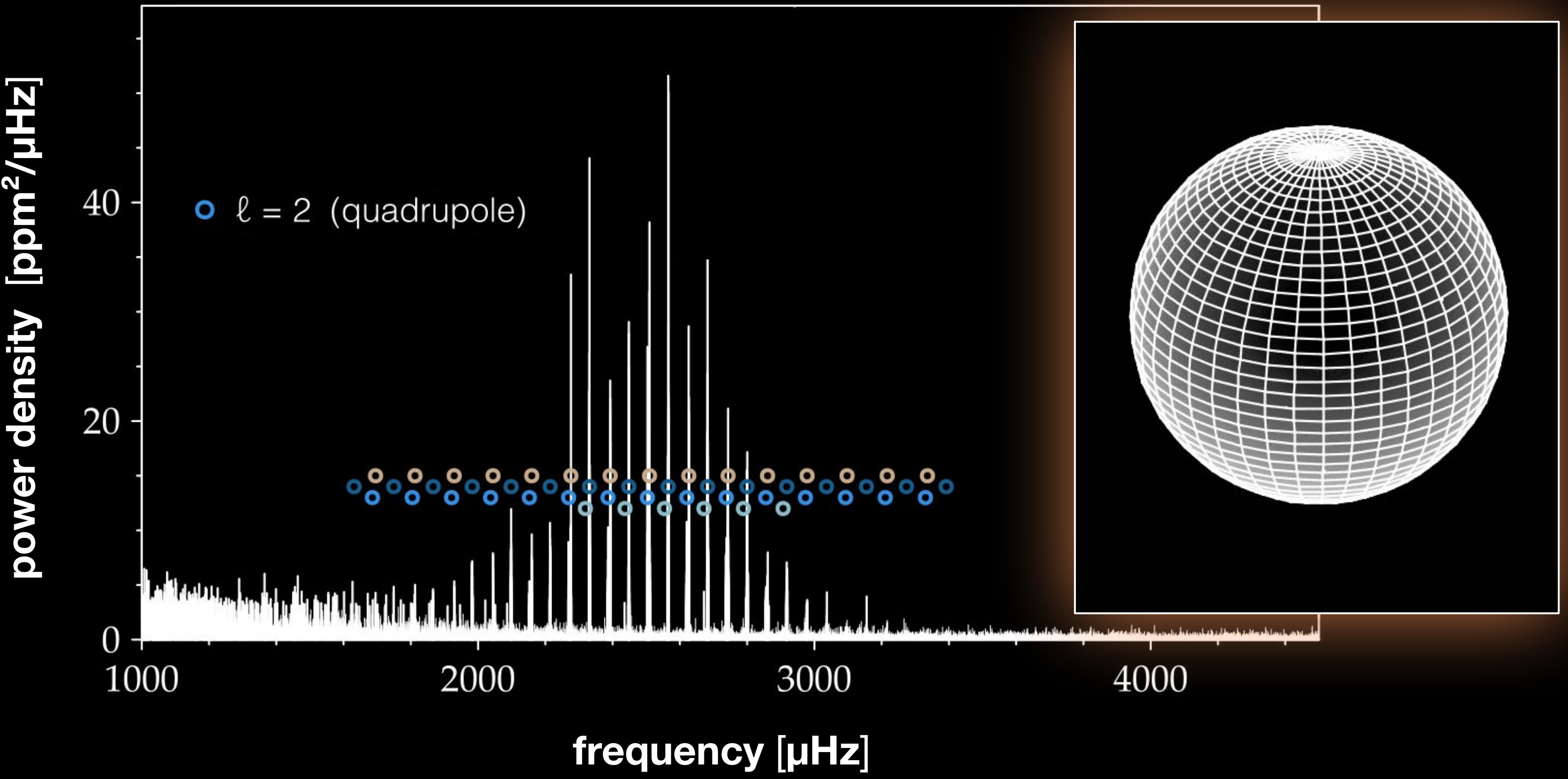
Pozzoli et al. 2023



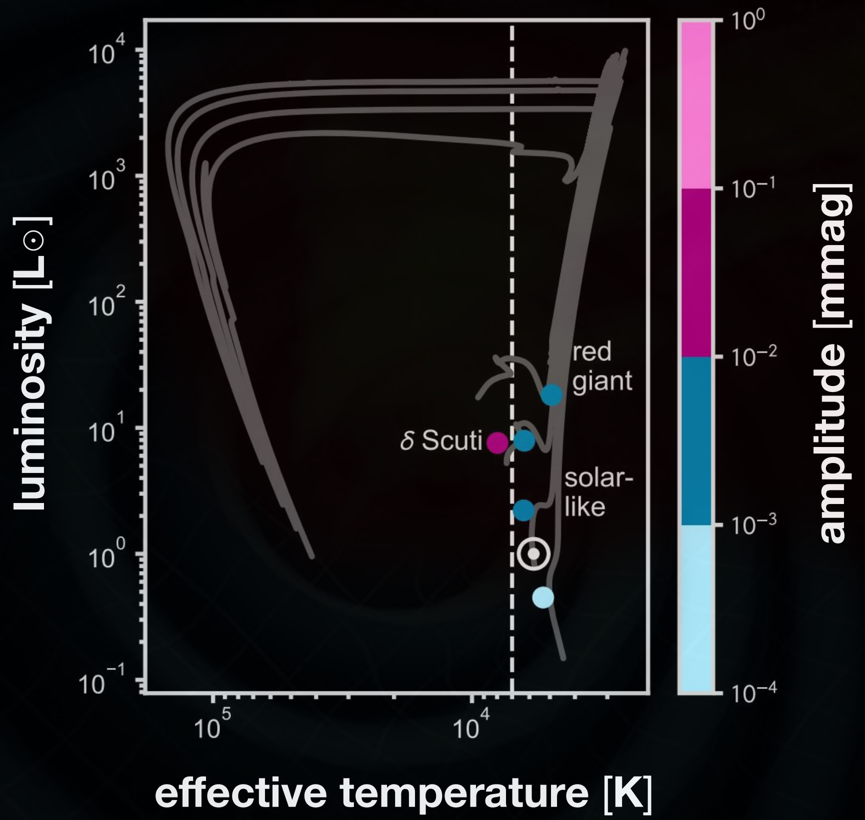
Model	Detections	$\mathrm{SNR_{GWB}}$
M1	139	180
M2	42	40
M3	346	441
M4	516	235
M5	188	252
M6	13	21
M7	724	980
M8	19	22
M9	108	160
M10	97	136
M11	0	1.44
M12	891	1146

Bonus slides

Asteroseismology



Analyzing Stellar Oscillation Data



Bellinger & MPA team, in prep.

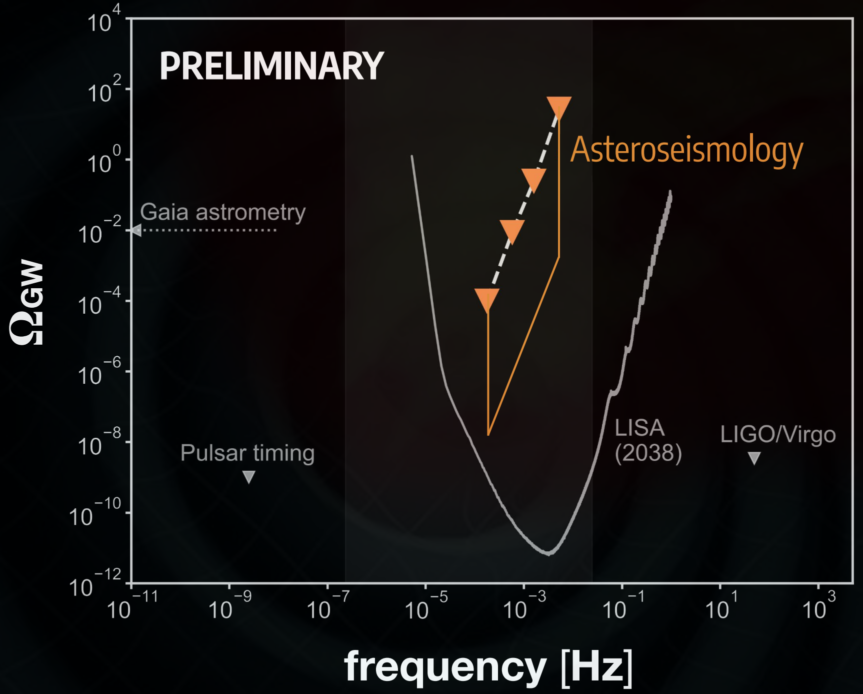
$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\mathrm{GW}}(f)}{\mathrm{d}\ln f}$$

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

	Ω_{GW}	energy density of GWs
observed	f	frequency
	A	amplitude
theory	η	mode damping
	I	mode inertia
	χ	mode dilatation
	H_0	Hubble constant

Freeman Dyson (1969), Siegel & Roth (2010, 2014)

Analyzing Stellar Oscillation Data



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Bellinger & MPA team, in prep.

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