Title: Millihertz Gravitational Waves: Challenges and opportunities in the LISA Era

Speakers: Lorenzo Speri

Collection/Series: Strong Gravity

Subject: Strong Gravity

Date: January 30, 2025 - 1:00 PM

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Abstract:

In January 2024, the Laser Interferometer Space Antenna (LISA) mission was officially adopted by the European Space Agency, marking a new era in gravitational wave astronomy. LISA will be the first space-based gravitational wave detector, designed to explore the cosmos in the millihertz frequency range. This talk will present the mission's key scientific objectives and how the scientific community is preparing for the exploitation of LISA data. I will discuss the anticipated source types and the fundamental questions they could help answer. Then, we will focus on Extreme Mass Ratio Inspirals (EMRIs), a class of sources where small compact objects orbit the massive black holes at the centers of galaxies. These systems hold immense scientific potential for the LISA mission, as they encode a detailed map of the spacetime around the massive black hole. I will discuss how future detections of EMRIs can be used to constrain parameters related to accretion disks and modifications of General Relativity. Finally, I will highlight the path forward in preparing for LISA's launch and how to get involved in contributing to the mission scientific success.

Millihertz Gravitational Waves:
Challenges and opportunities in the LISA Era

Perimeter Institute, Strong Gravity Seminar

Lorenzo Speri

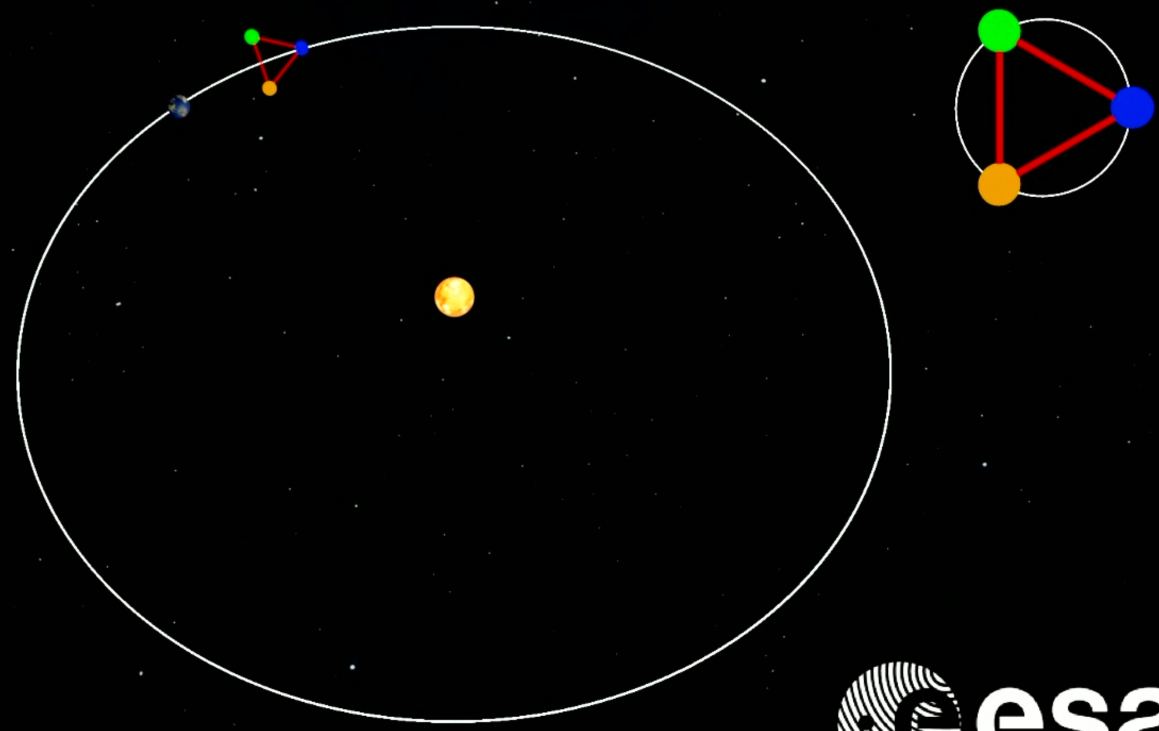


Image credit: Strub

Talk Outline

1. Gravitational Wave Data Analysis

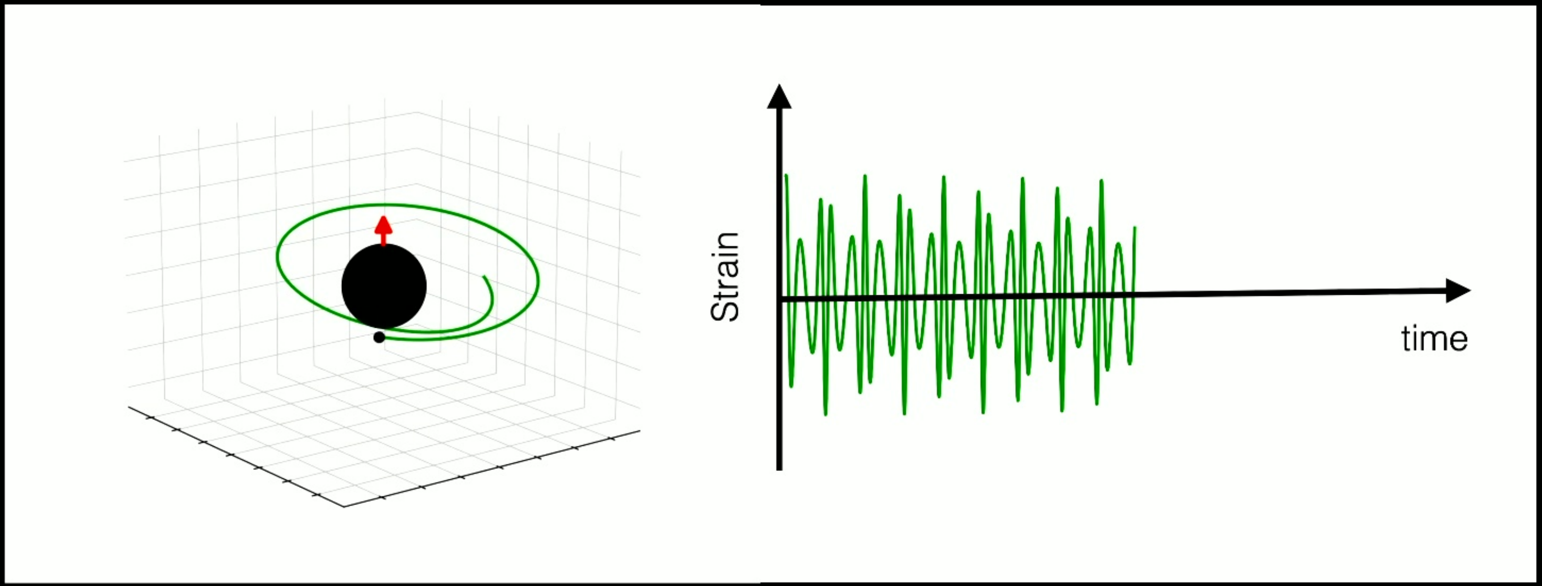
2. The Laser Interferometer Space Antenna

3. Prospects and challenges of the LISA mission

4. Extreme Mass Ratio Inspirals

5. Conclusions

Gravitational Waves



Frequency evolution ⟷ Binary orbital dynamics

How do we find GW signals?

Data = Signal (parameters) + Noise

$$\text{Signal}\,(a, f, \dot{f}\,) = a\,\cos\left[2\pi t\,(f + \dot{f}t)\right]$$

$$\text{log-likelihood} \propto -\frac{|\,\text{Data} - \text{Signal}\,|^2}{2\,\sigma_n^2}$$

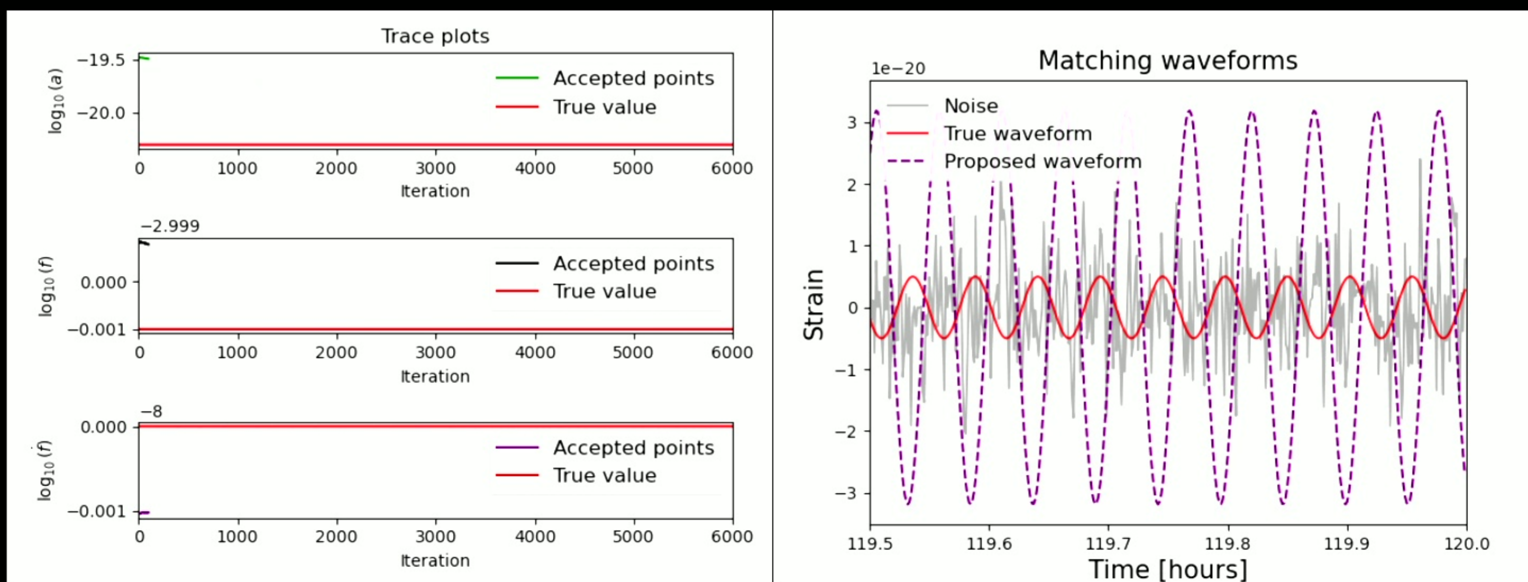


Image credit: O. Burke

How do we estimate GW parameters?

Likelihood x Prior / Evidence = Posterior Distribution

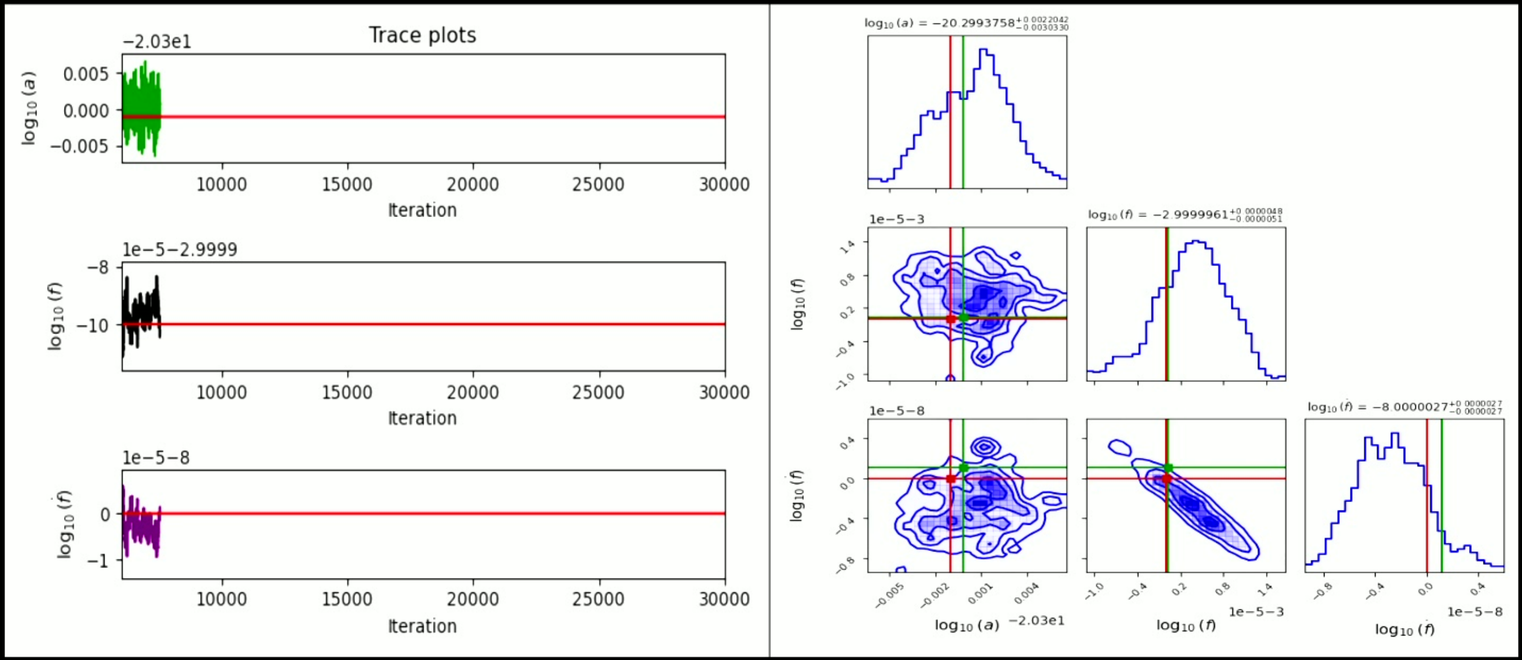


Image credit: O. Burke

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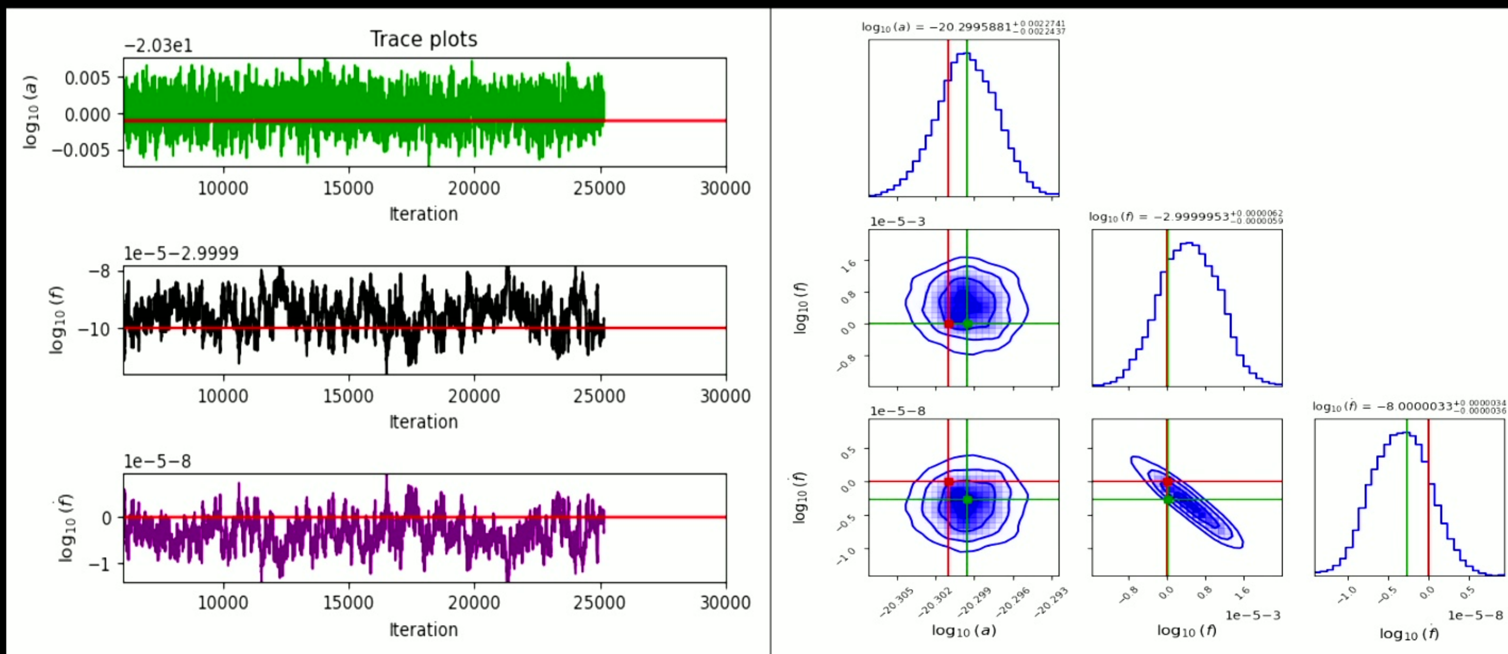
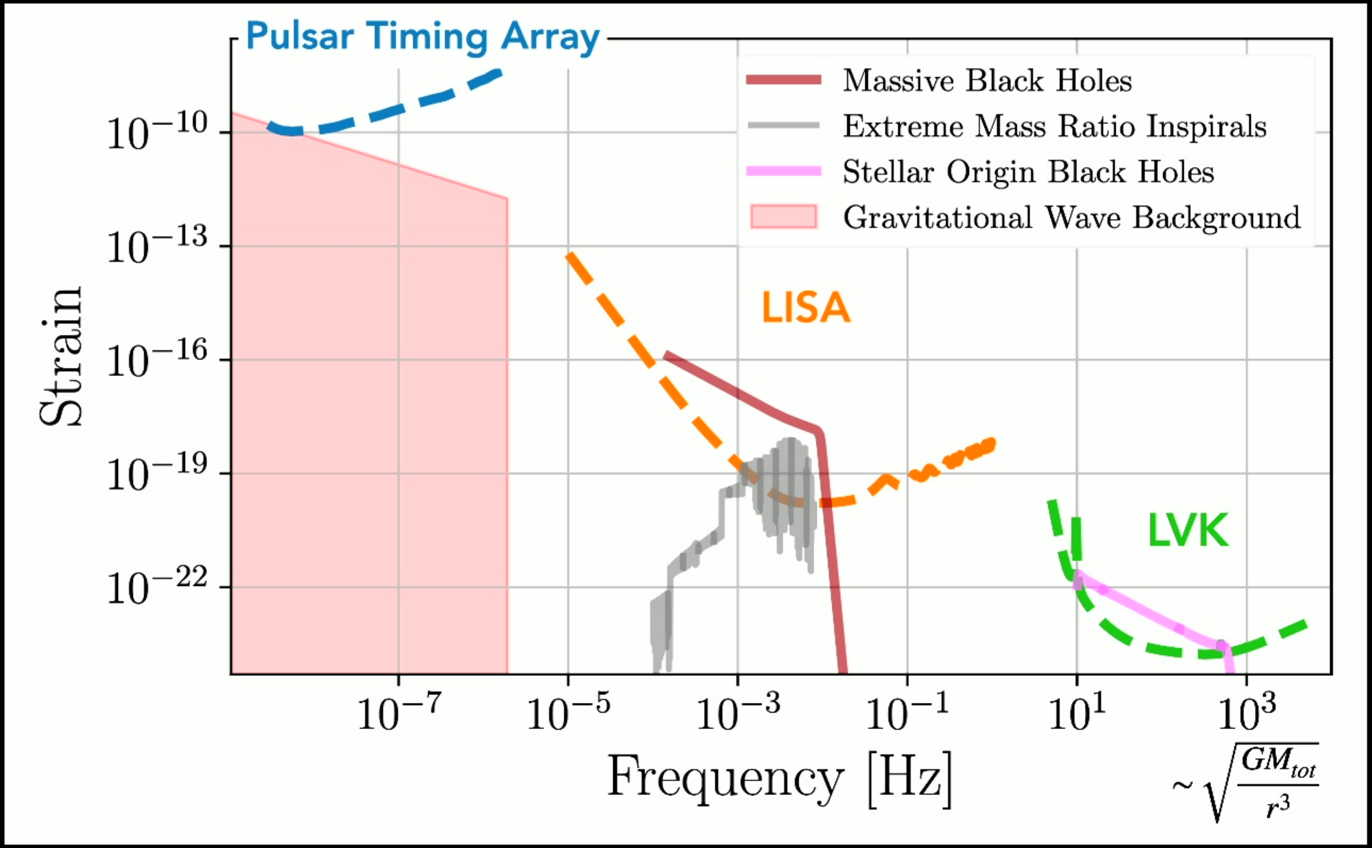


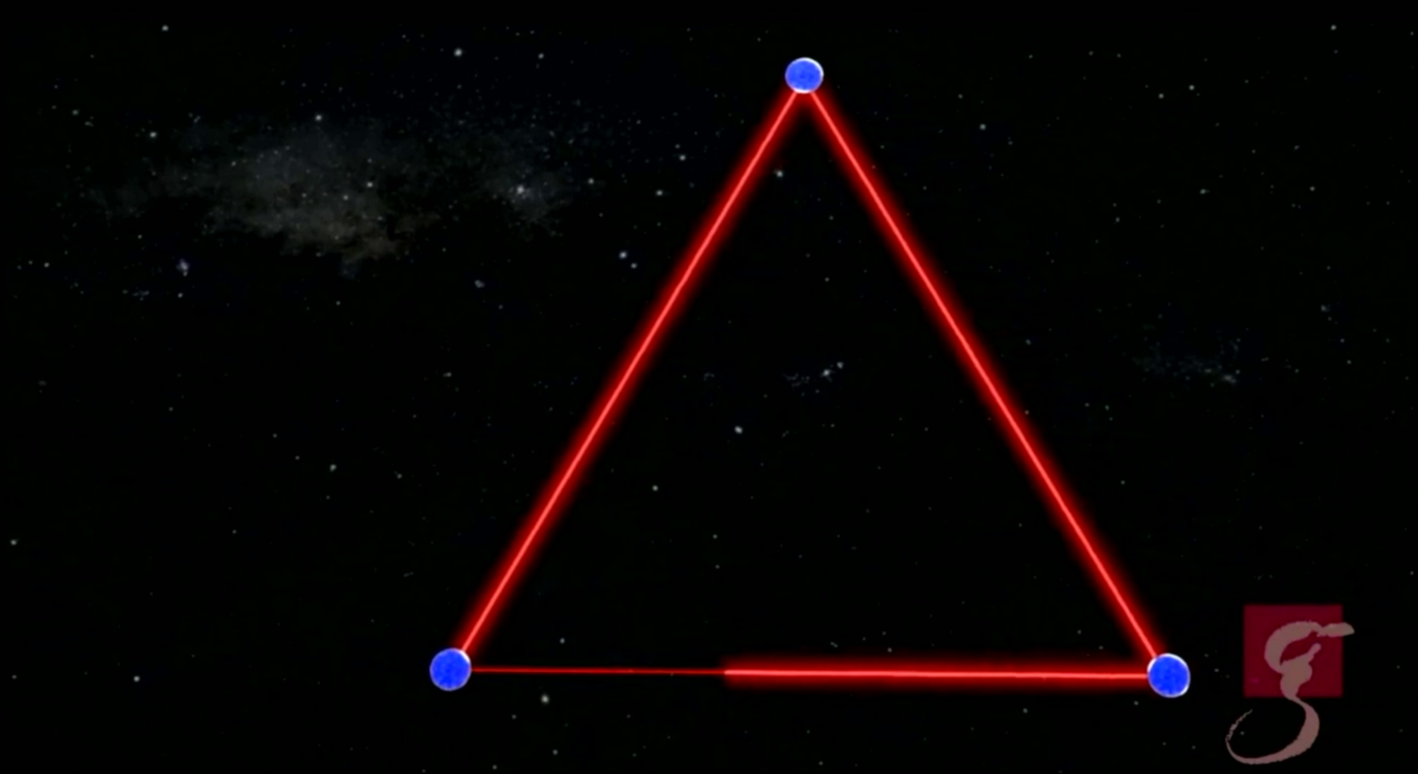
Image credit: O. Burke

Gravitational Wave Spectrum

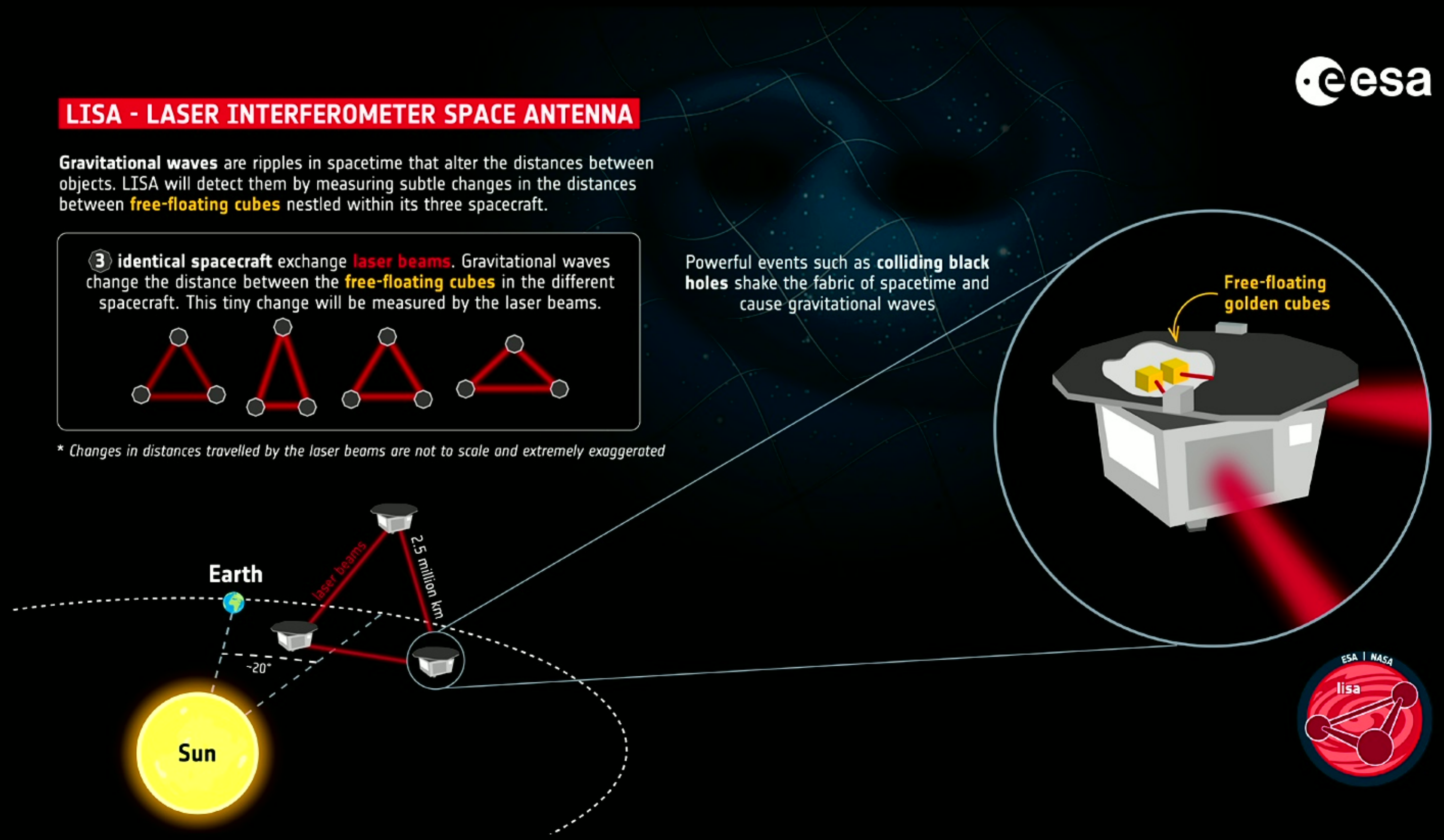
GW Strain h induces a change in the detector arms $\frac{\Delta L}{L} \sim h_{GW}$



The Laser Interferometer Space Antenna



The Laser Interferometer Space Antenna



The Laser Interferometer Space Antenna

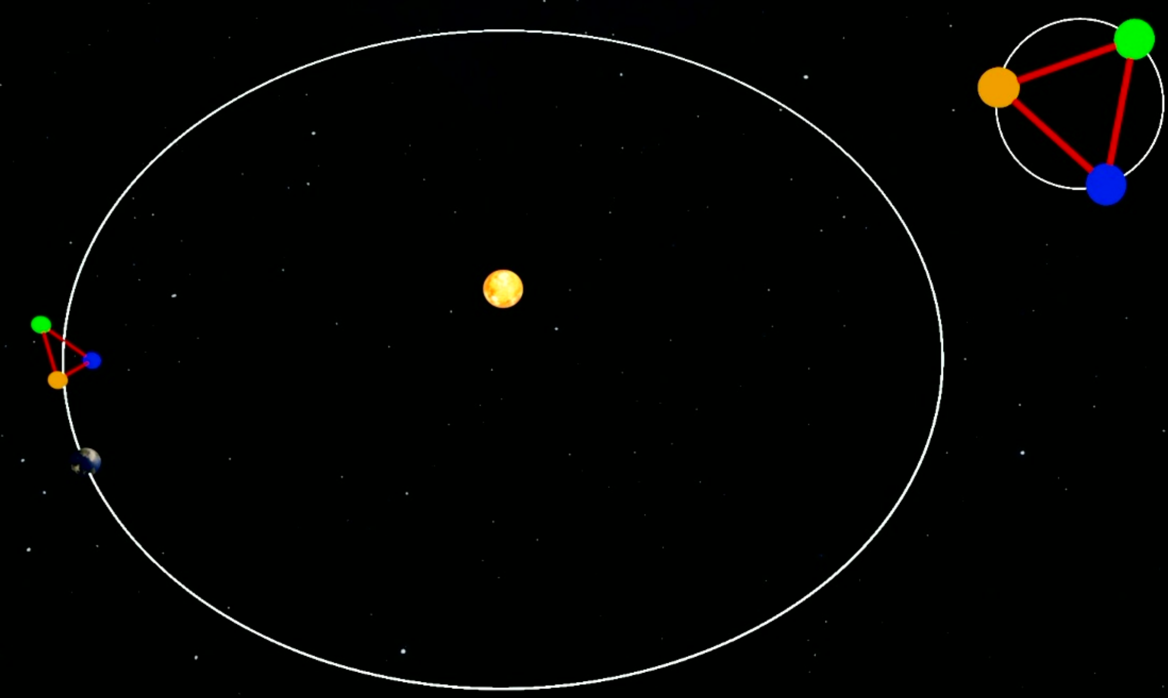
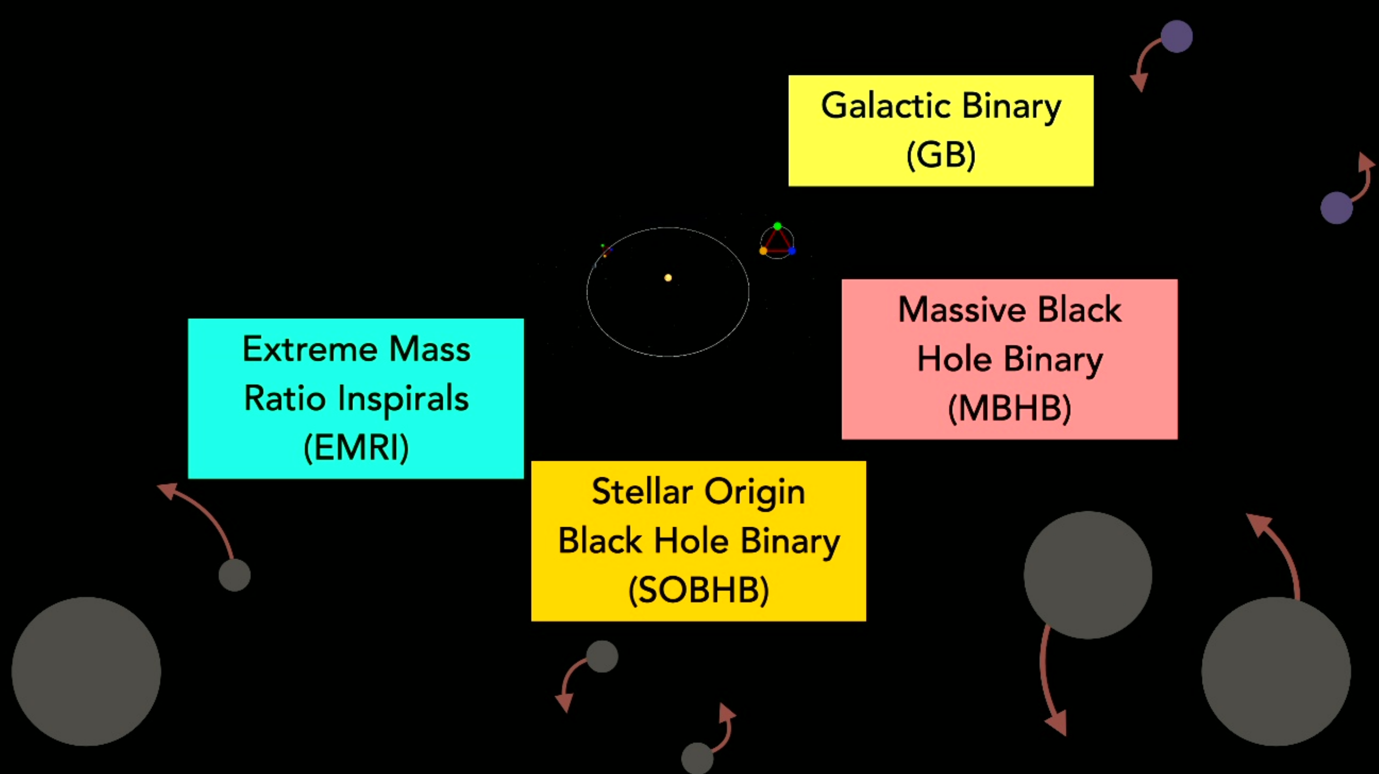
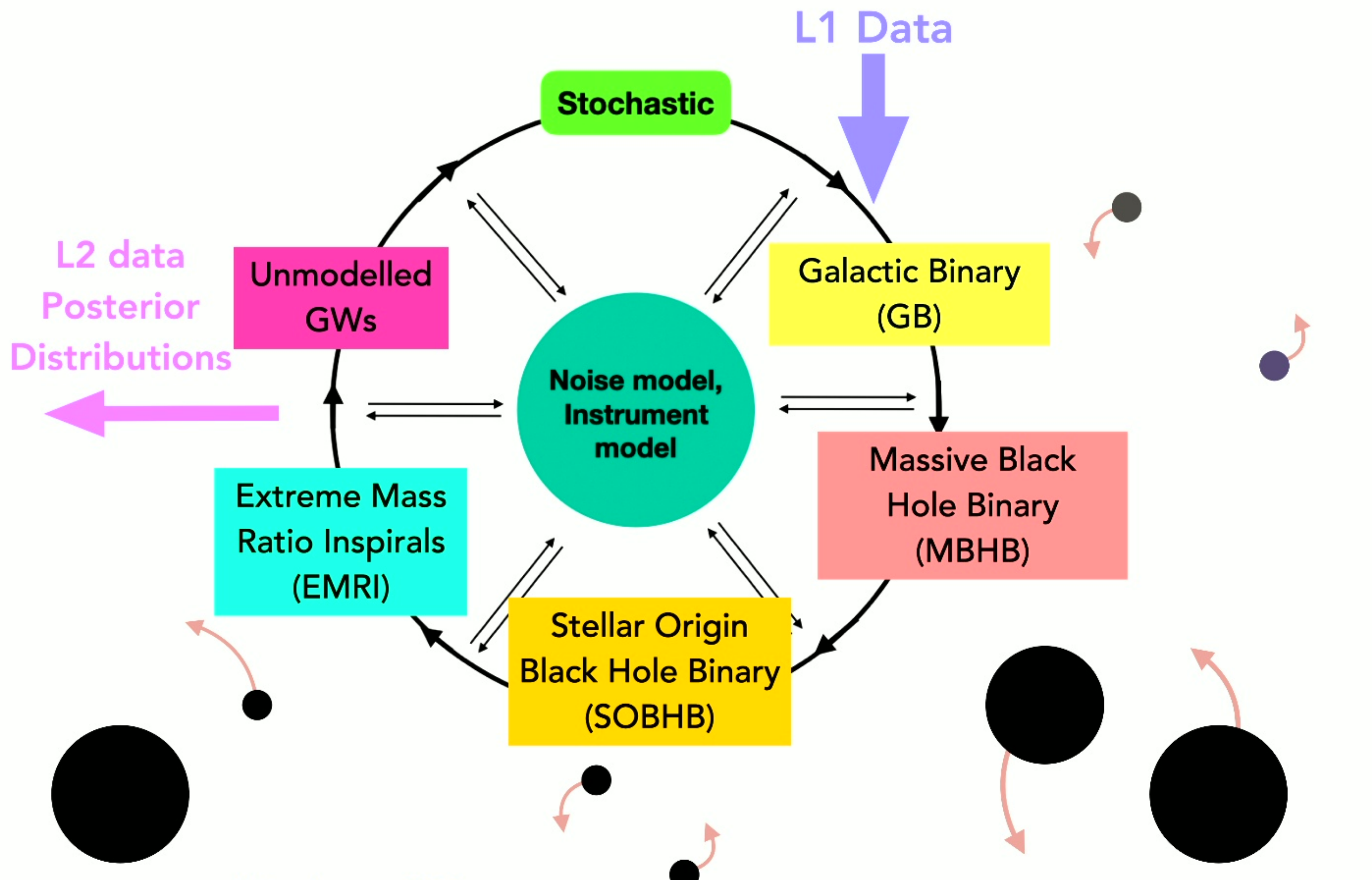


Image credit: Strub

The Laser Interferometer Space Antenna



The LISA Global Fit



Littenberg+ 2020

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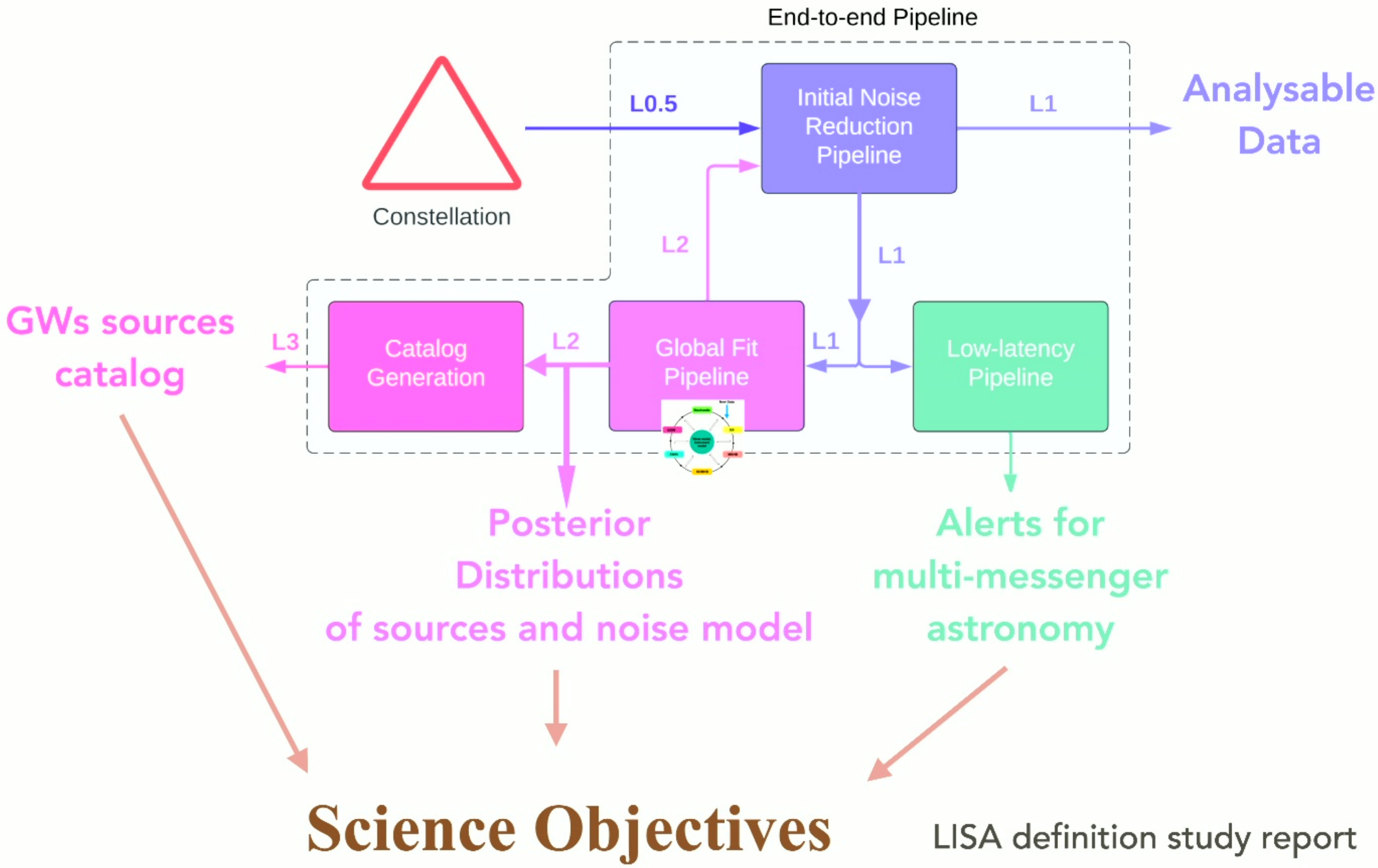
LISA data analysis



LISA definition study report
Colpi+2024

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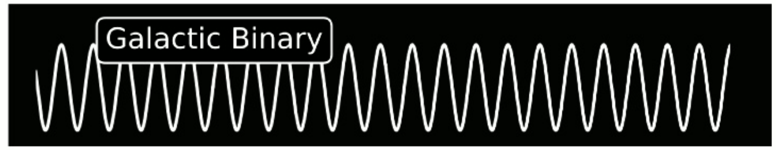
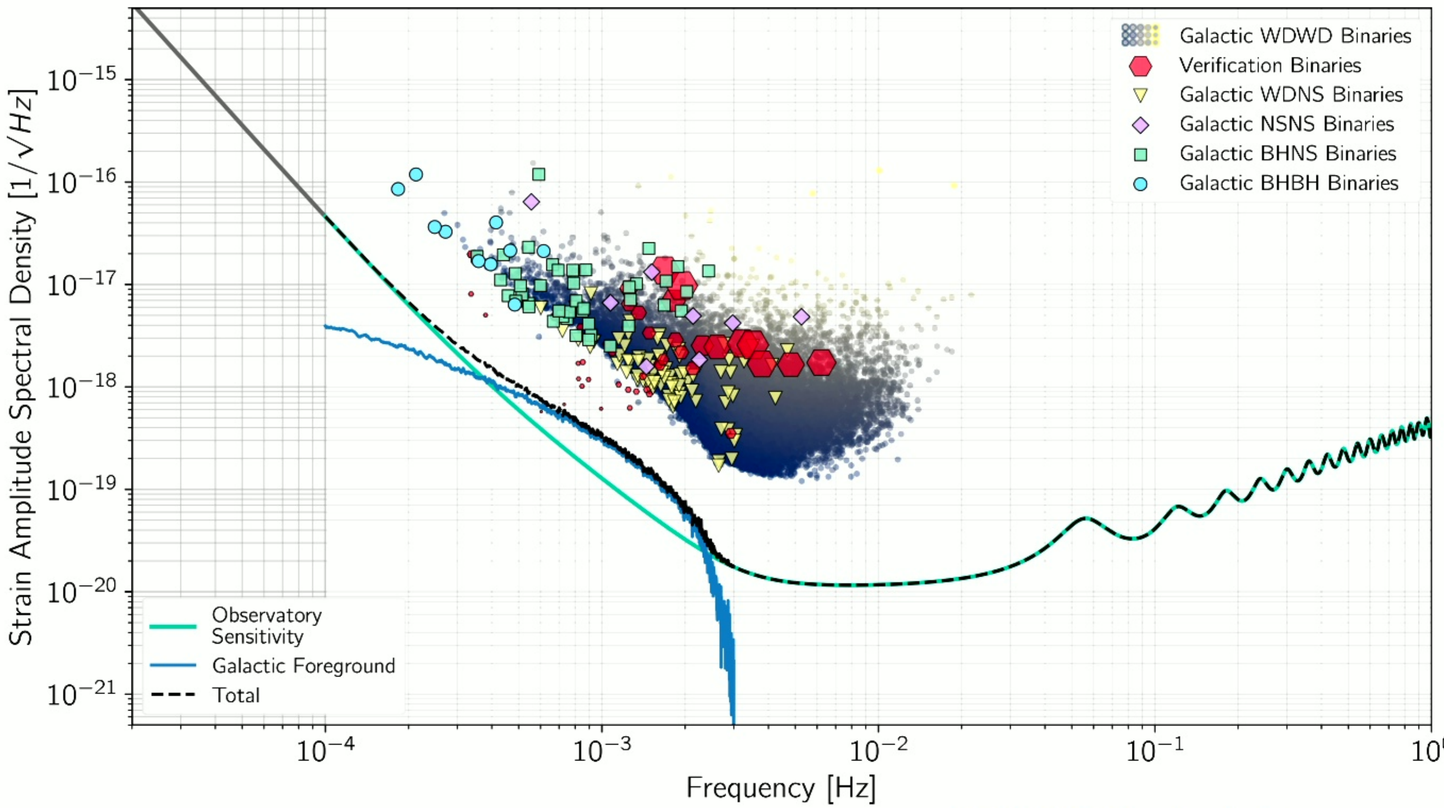
Prospects: Science Objectives

1. Study the formation and evolution of **compact binary stars** and the structure of the Milky Way Galaxy
2. Trace the origins, growth and merger histories of **massive Black Holes** across cosmic epochs
3. Probe the properties and immediate environments of Black Holes in the local Universe using **extreme mass-ratio inspirals** and **intermediate mass-ratio inspirals**
4. Understand the astrophysics of **stellar-origin Black Holes**
5. Explore the **fundamental nature of gravity** and Black Holes
6. Probe the rate of **expansion of the Universe** with standard sirens
7. Understand **stochastic gravitational wave backgrounds** and their implications for the early Universe and TeV-scale particle physics
8. Search for gravitational wave bursts and **unforeseen sources**

LISA Definition Study Report

Galactic Binaries



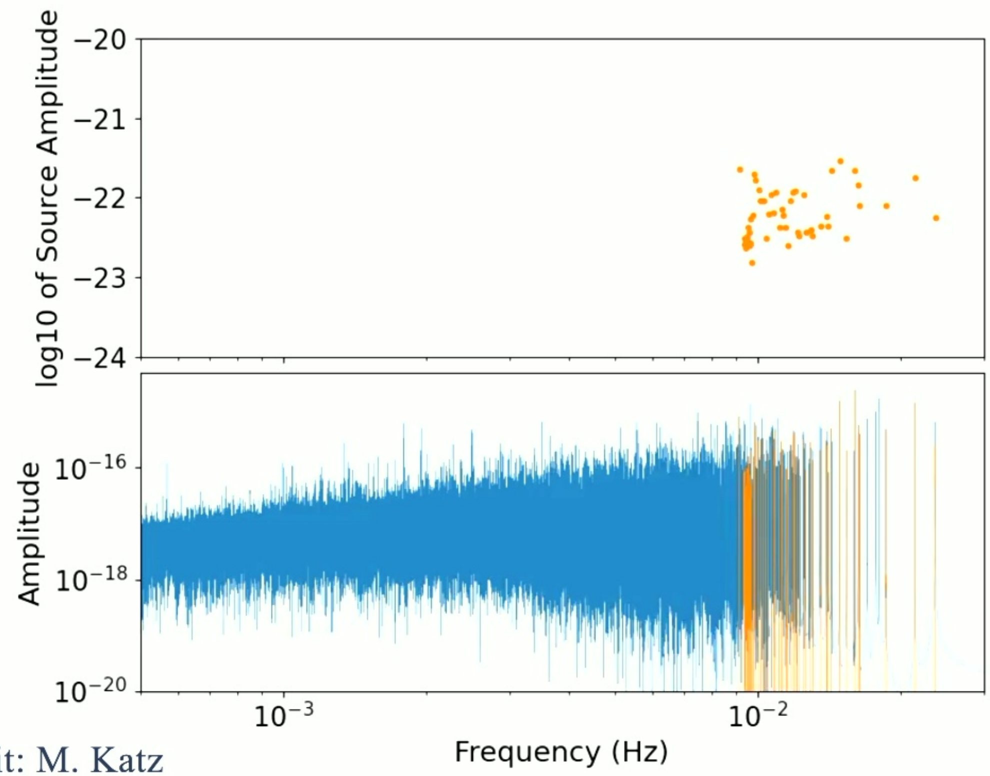


LISA Definition Study Report

Galactic Binaries

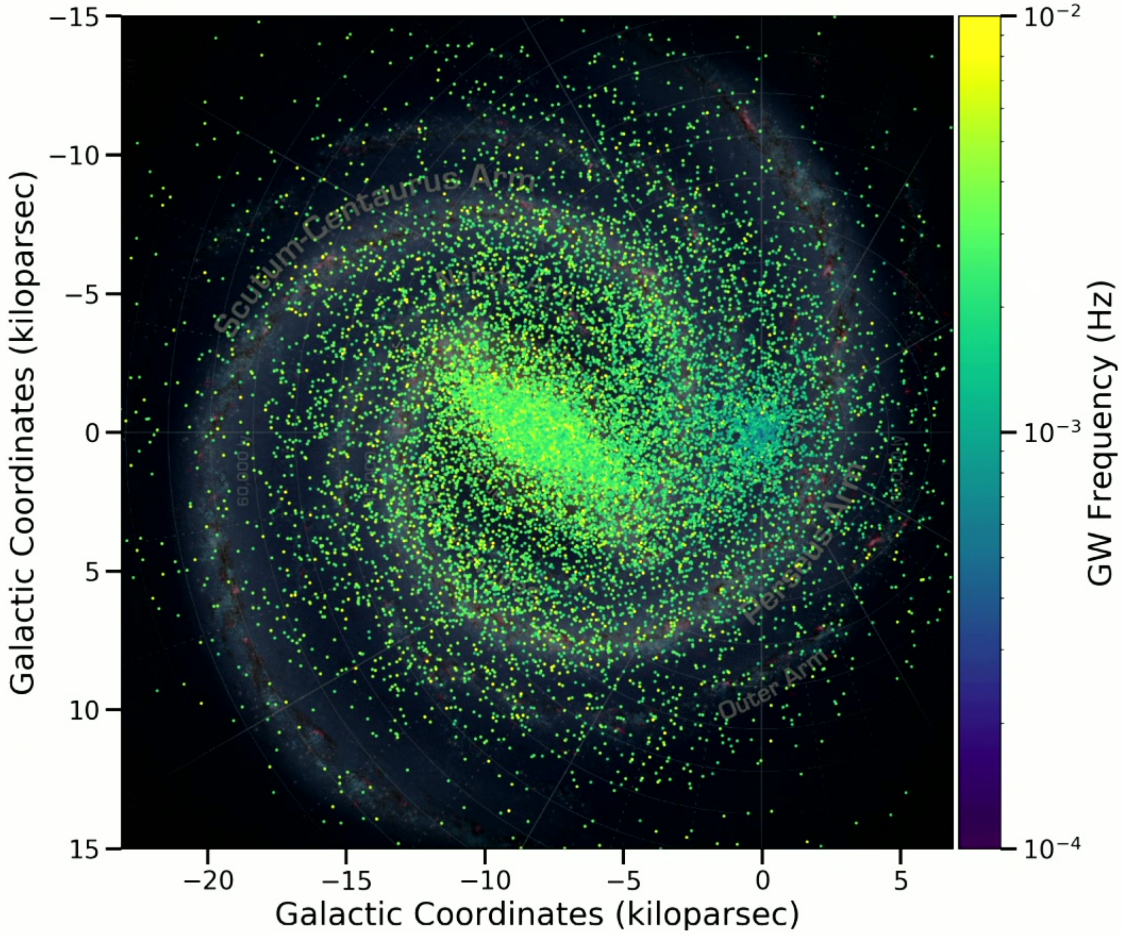
always in band quasi-monochromatic signals

10^6 sources $\qquad$ 10^4 resolvable



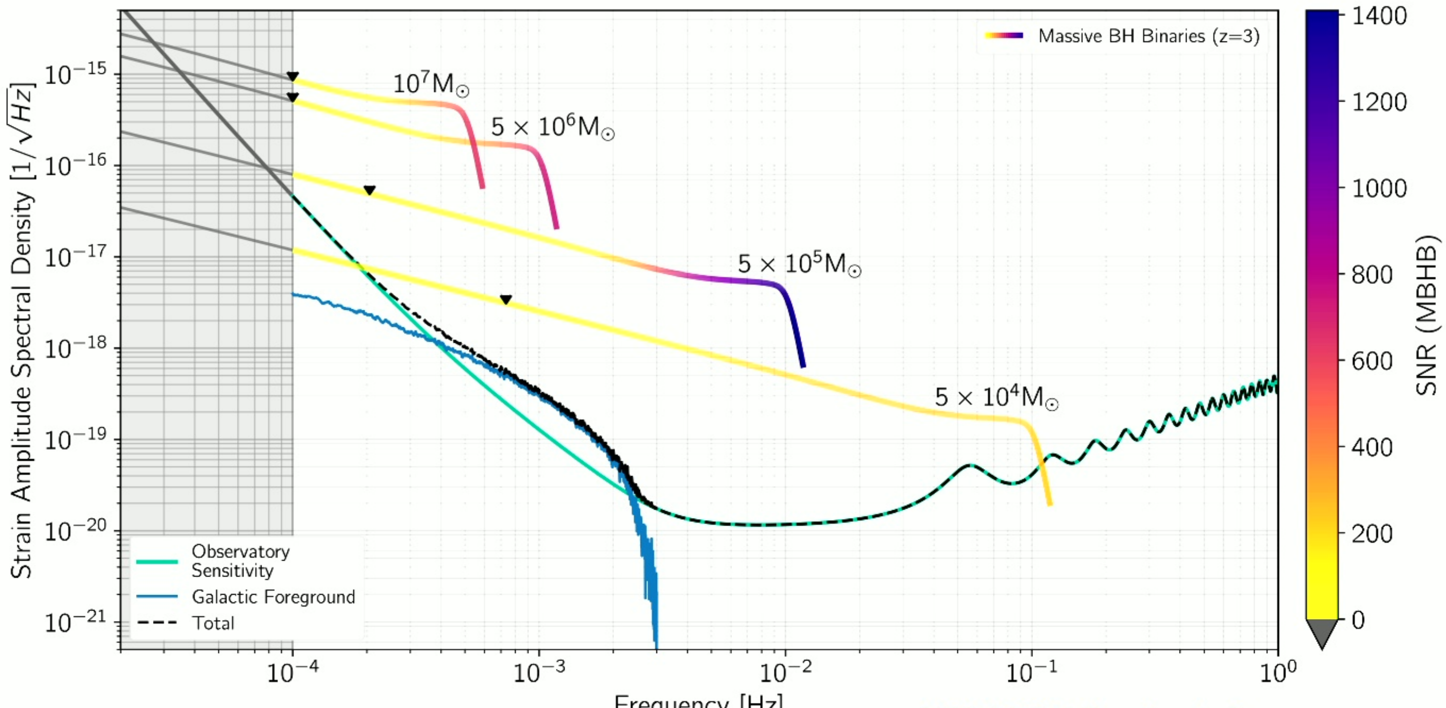
credit: M. Katz

SO1: Galactic Binaries



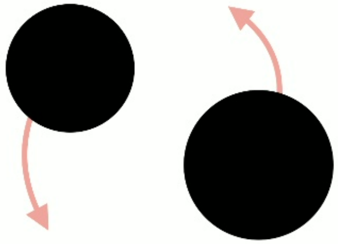
LISA Definition Study Report 19

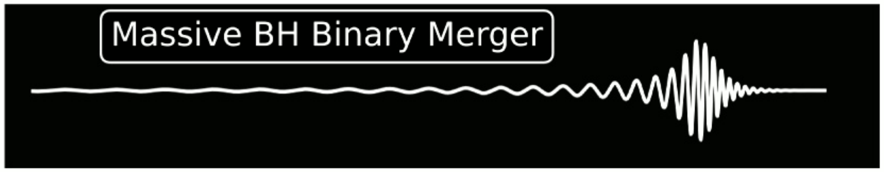
Massive Black Hole Binaries

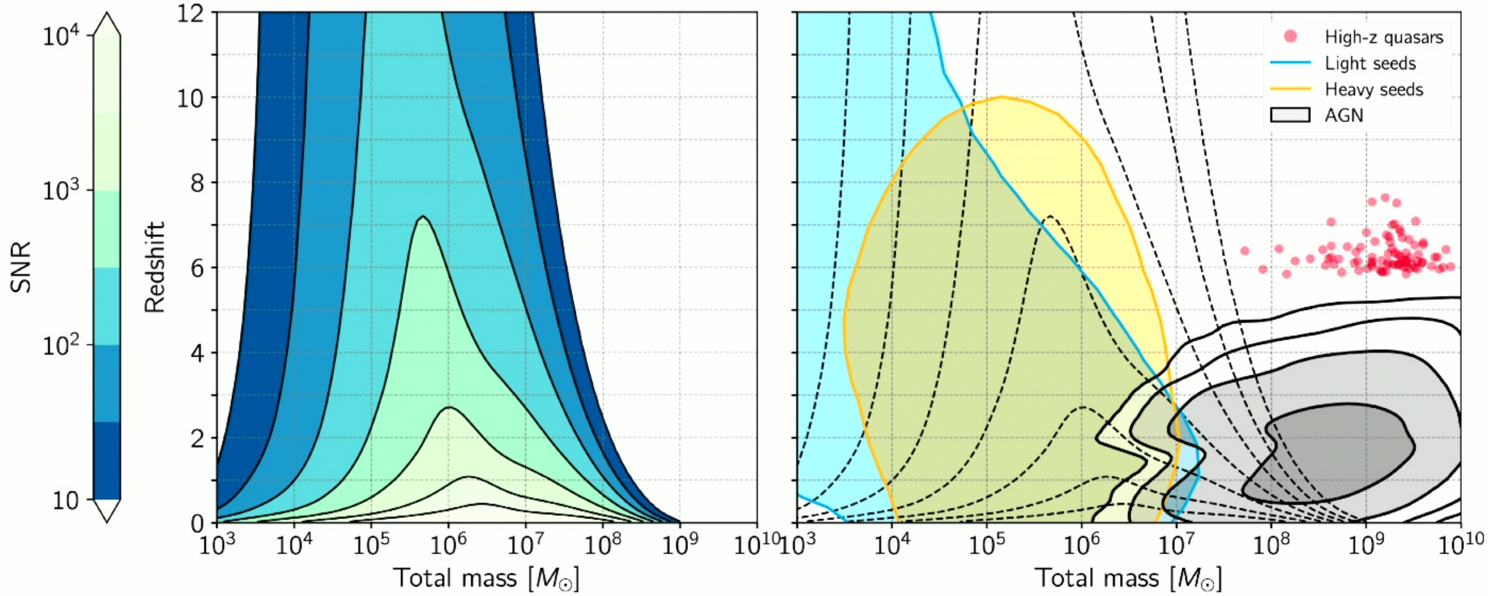


LISA Definition Study Report

SO2: Massive Black Hole Binaries



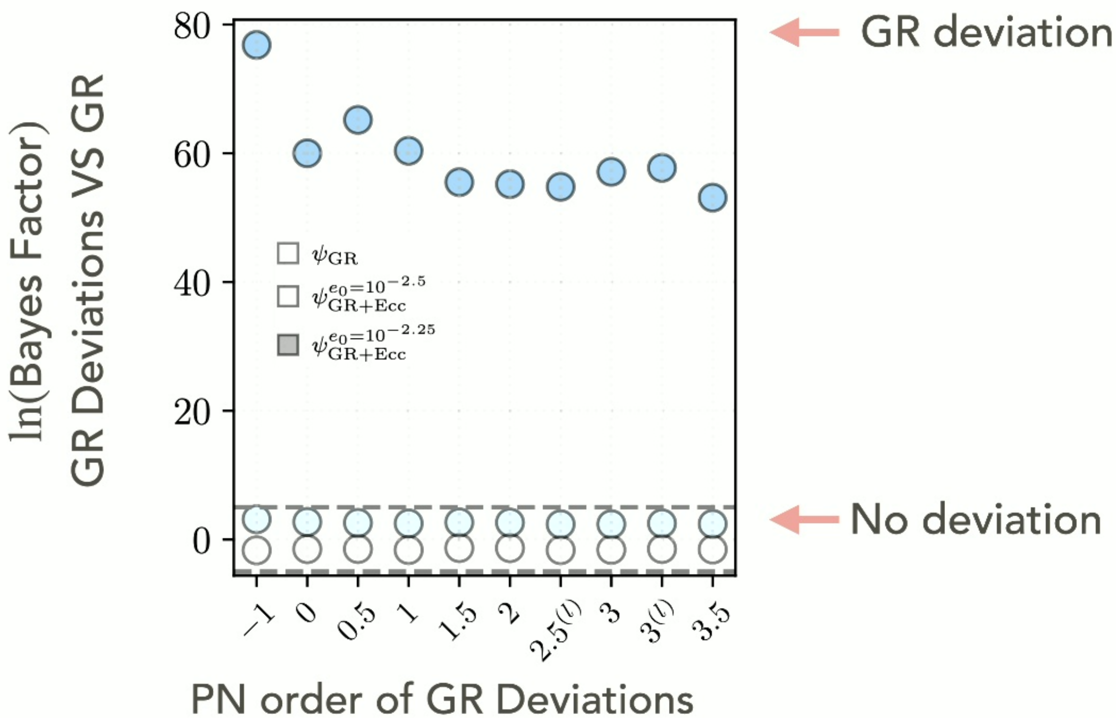




LISA Definition Study Report

MBHBs Waveform systematics

What would happen if we ignore eccentricity?



$M_z = 10^5\ M_\odot,\ q = 8,\ \chi_{1,2} = 0.9,\ t_c = 4$ years

Garg, **LS**, et al. 2024 arXiv:2410.02910

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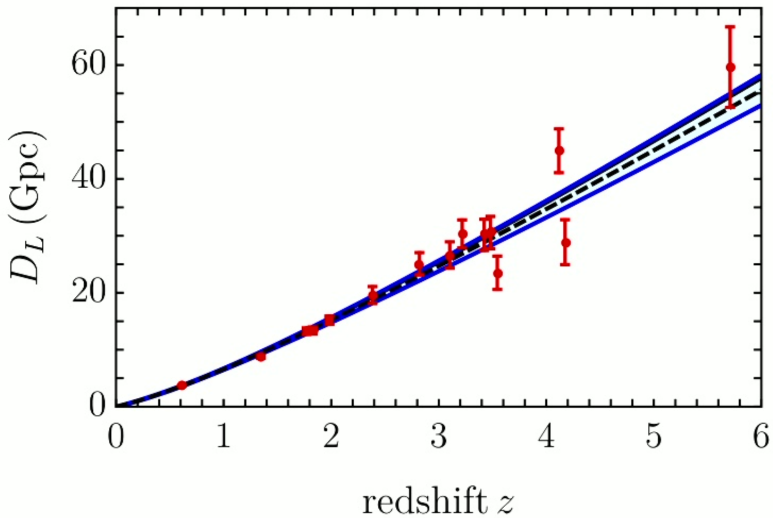
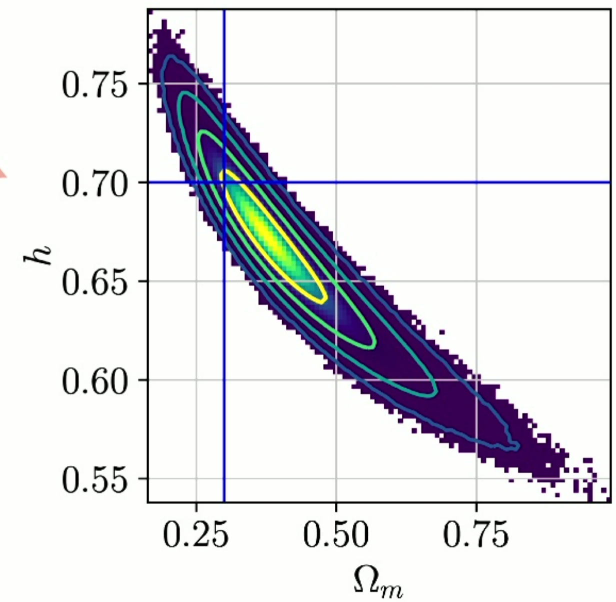
SO6: Probing the expansion of the universe



Massive Black Hole Binaries
Standard Sirens

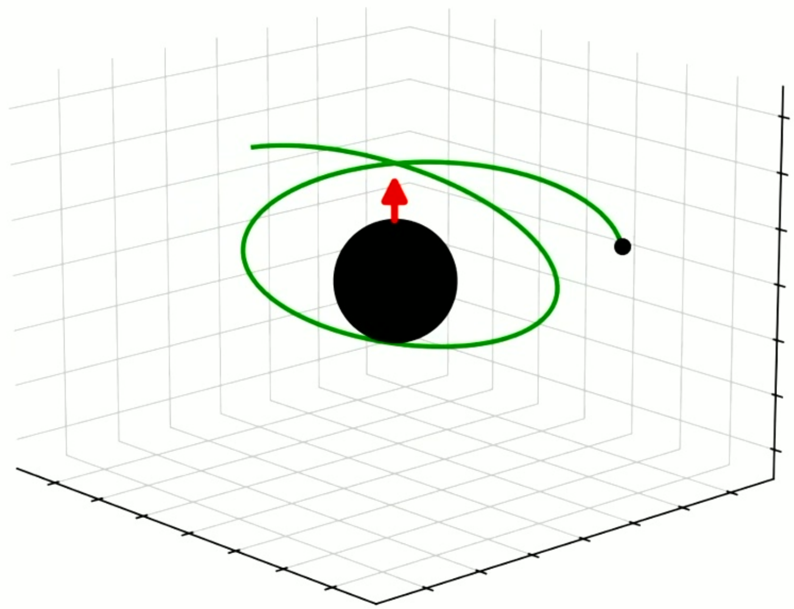


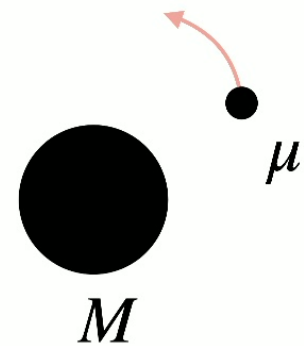
Mangiagli, LS, +2023
Speri+ 2021

Cosmology with LISA

arXiv:2204.05434

Extreme Mass Ratio Inspirals (EMRIs)





$$\epsilon = \frac{\mu}{M}$$

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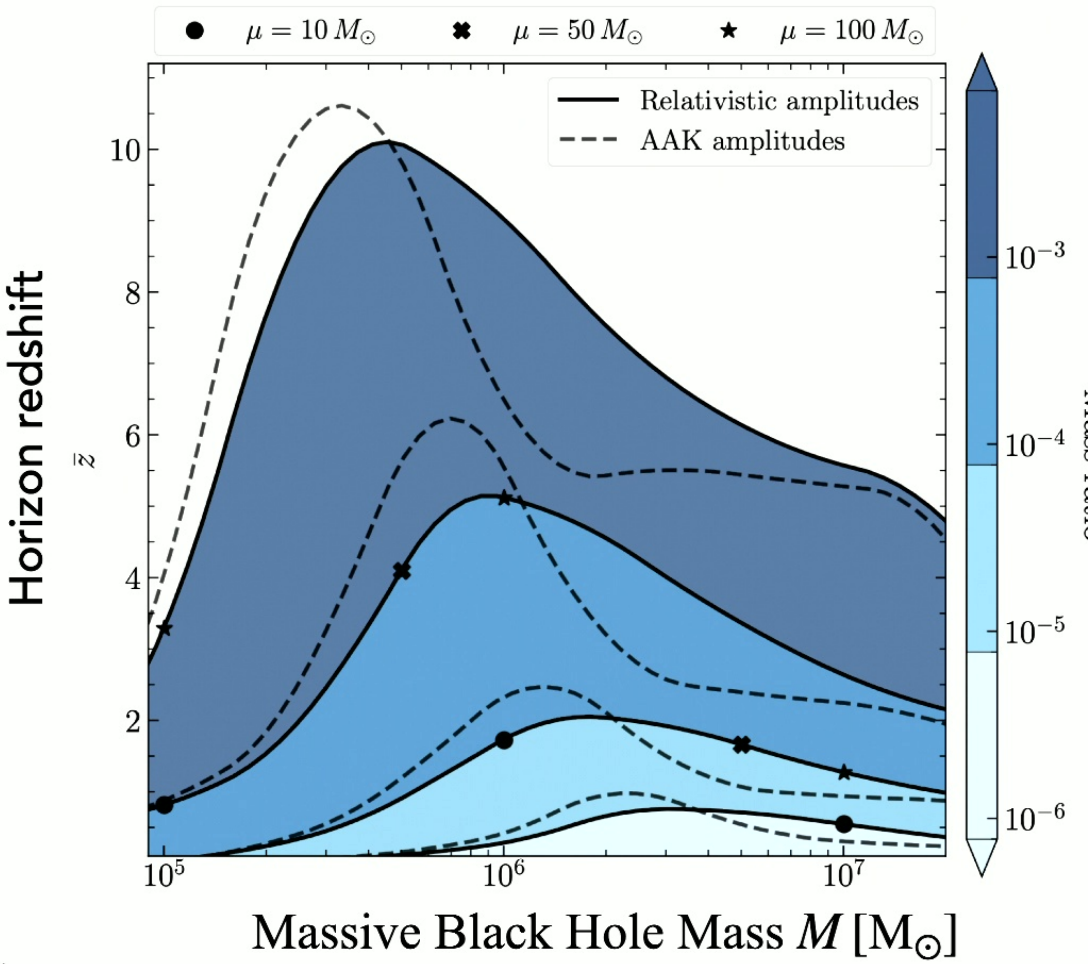
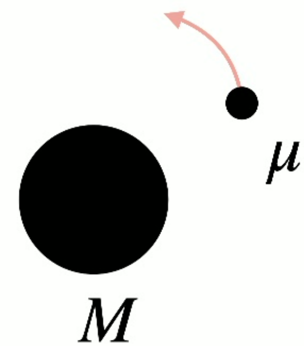
SO3: Extreme Mass Ratio Inspirals (EMRIs)





$$\epsilon = \frac{\mu}{M}$$

Khalvati, **LS**, et al. 2024
arXiv:2410.17310

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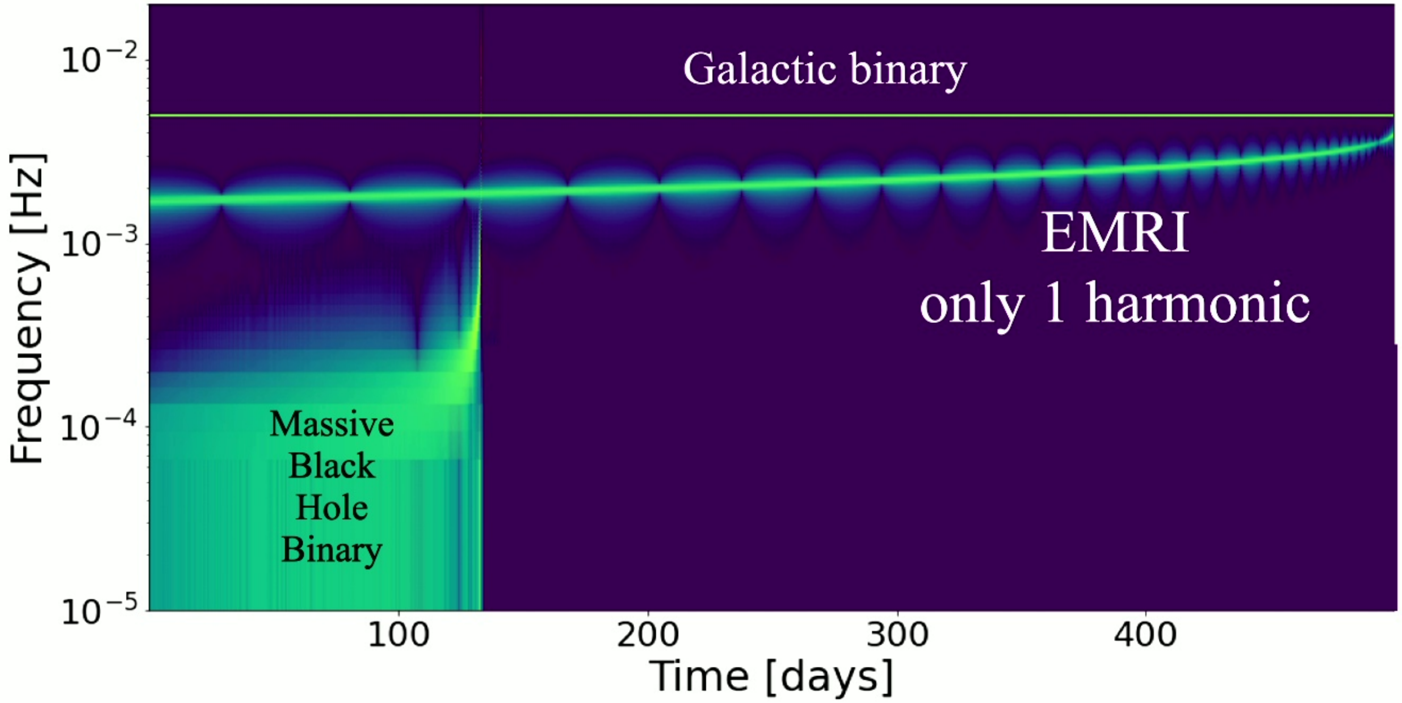
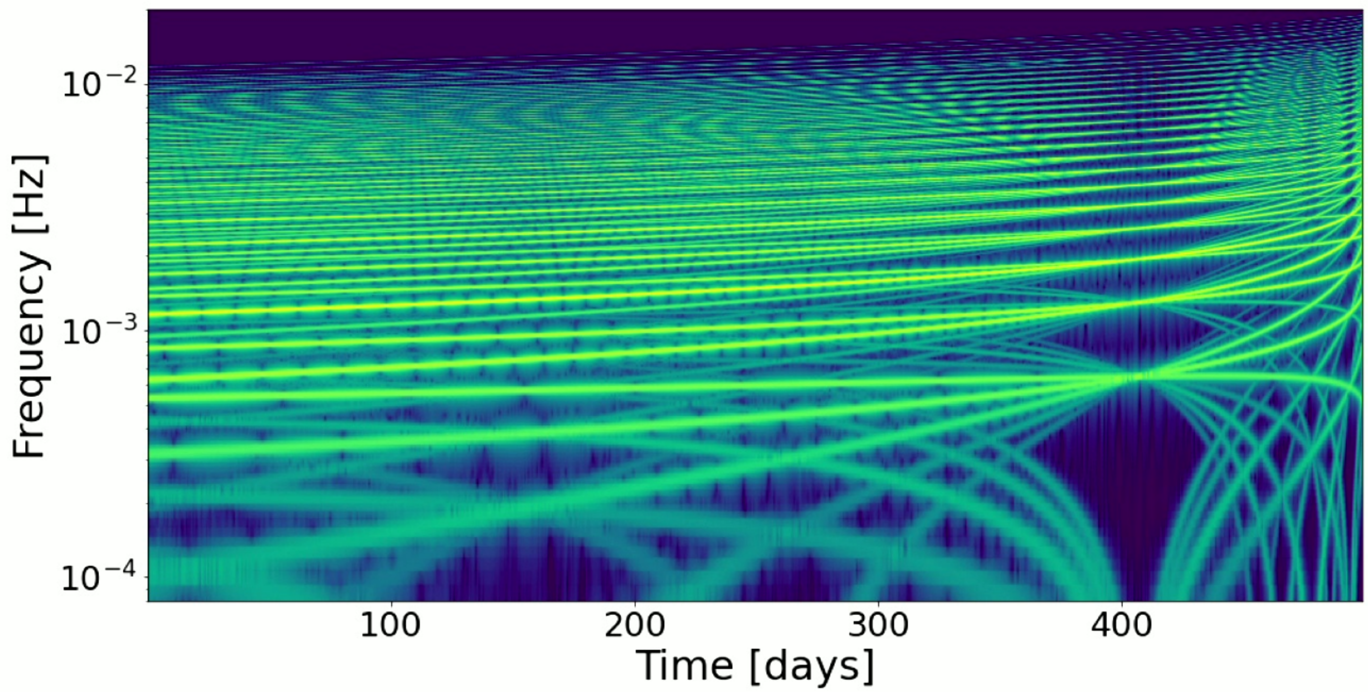
LISA Sources



EMRI Evolution Time Scale $T_{\rm ev} \sim 1/\epsilon$

EMRI Spectrogram



$$h = \sum_{V} A_V(t)\, \exp\Big[-i\Phi_V(t)\Big]$$

Harmonics ~ orbit complexity

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Fast EMRI Waveforms

$$h = \sum_{lmnk} \left\{ S_{lmnk}(\theta, \phi) \; A_{lmnk}(p(t), e(t), x_I(t)) \; e^{-i\Phi_{mnk}(t)} \right\}$$

Trajectory

ODE integration

$$\frac{d}{dt}(p, e, x_I) = \epsilon f_p(a, p, e, x_I)$$

$$\frac{d}{dt}\Phi_{\varphi,\theta,r} = \Omega_{\varphi,\theta,r}(a, p, e, x_I)$$

Amplitudes

Modes Interpolation

$$A_{lmnk}(a, p, e, x_I)$$

Chua+ 2020
Katz+ 2021
Speri+ 2023

Trajectory

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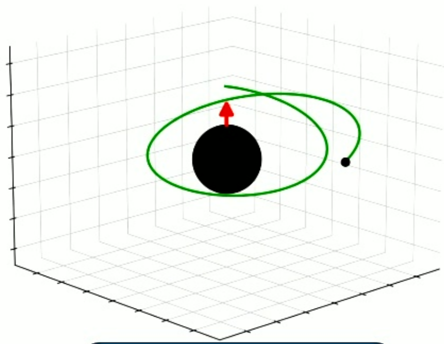
Fast EMRI Waveforms (FEW)



Chua+ 2020,Katz+ 2021,Speri+ 2023

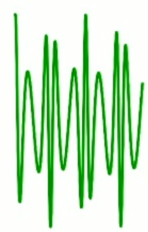
bhptoolkit.org/FastEMRIWaveforms

Trajectory

Amplitudes

Domain of Choice:
- Time Domain
- Frequency Domain
- Time-Frequency Domain

Waveform



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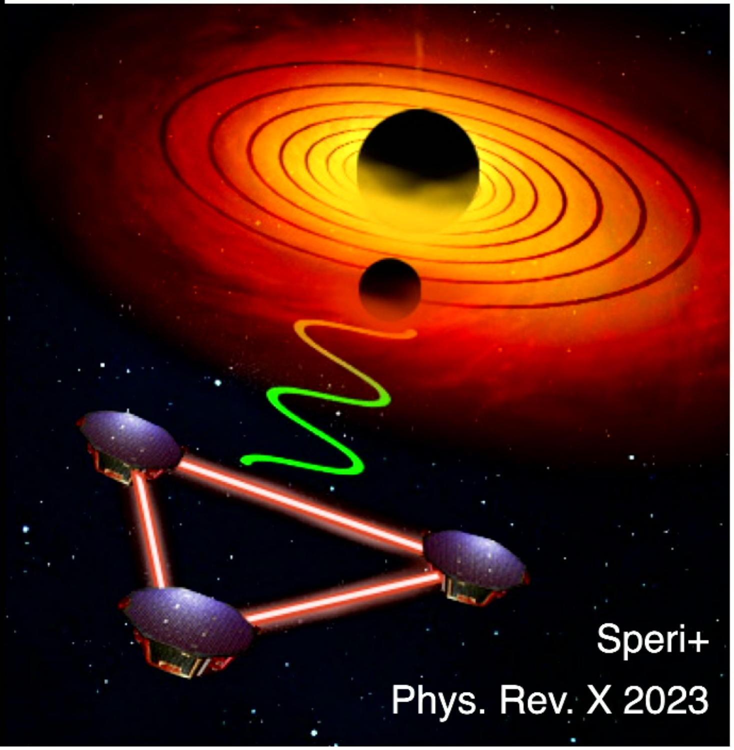
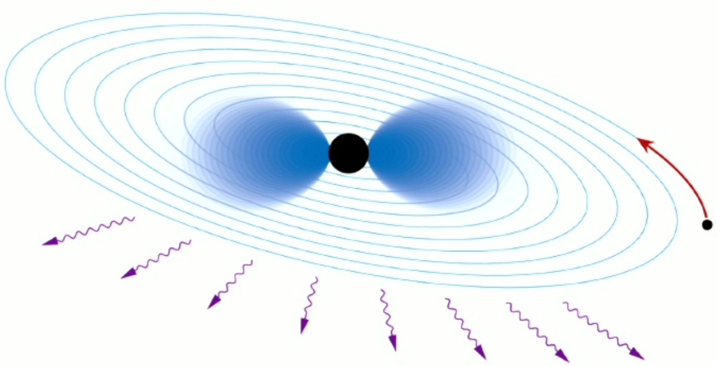
SO3: Probing environments around MBHs

Trajectory

$$\dot{E}_{\text{total}} = \dot{E}_{\text{environment}} + \dot{E}_{\text{GW}}$$





Baumann et al. PRL 2022

Cole et al. Nature Astron. 7 (2023) 8, 943-950

Khalvati, **LS**, et al. 2024 arXiv:2410.17310

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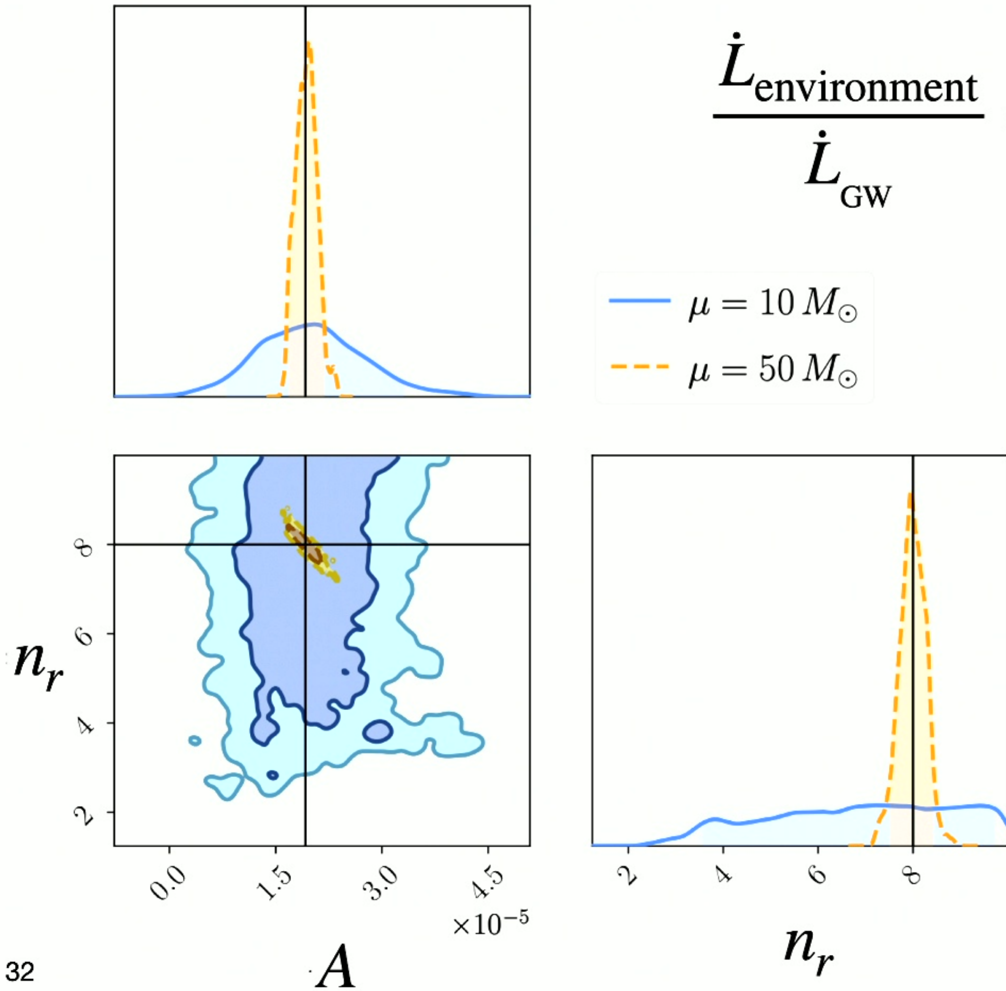
EMRIs in Accretion disks

$$\frac{\dot{L}_{\rm environment}}{\dot{L}_{\rm GW}} = A(f_{\rm Edd}, \Sigma)\, r^{n_r}$$



Speri+PRX 2023

Khalvati, **LS**, et al. 2024
arXiv:2410.17310

Copparoni+ in prep.

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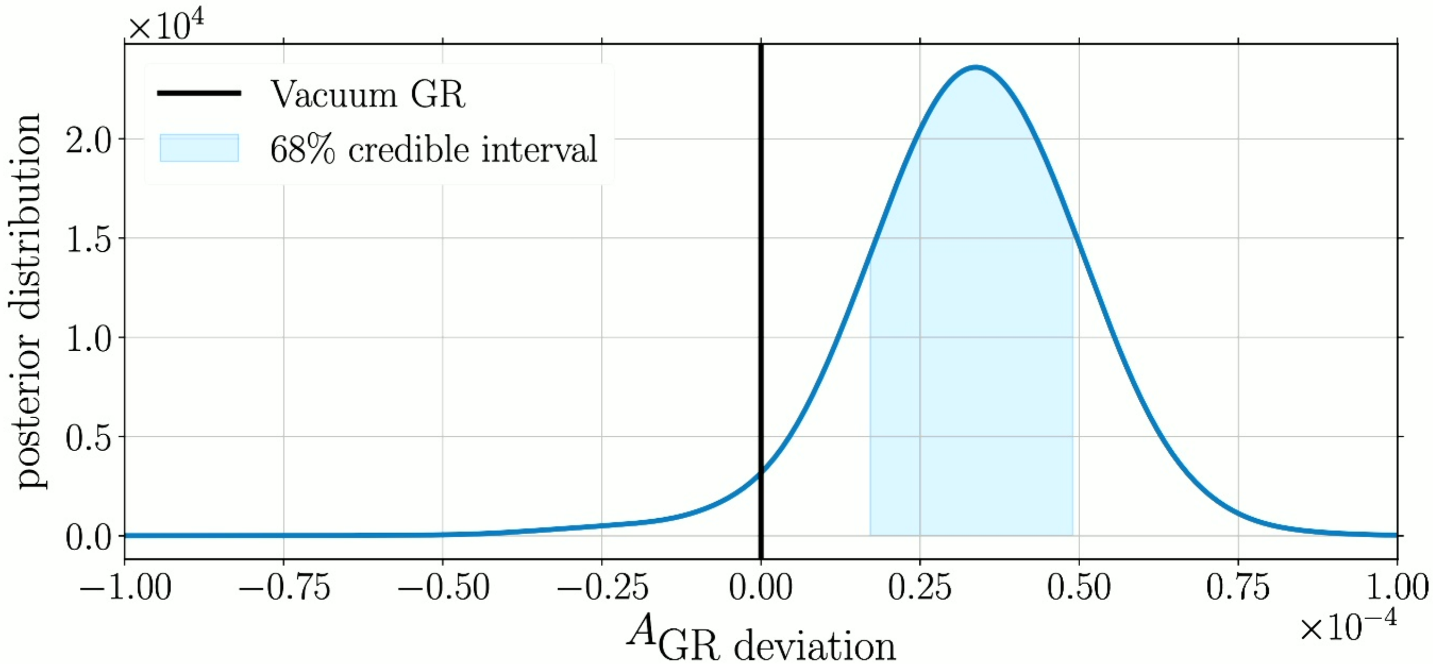
If environmental effects are ignored

Unmodelled environmental effects could be mistaken for GR violations



Speri+

Phys. Rev. X 2023

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Conclusions

Waveforms

→ Parameter space extension of models

→ Accuracy and speed

→ Beyond vacuum effects

Data analysis

→ Search of SOBHs and EMRIs

→ Multiple sources and global fit

→ Noise artifacts

→ Population analysis

We have the tools for addressing these questions!

LISA Data Generation and Analysis Workshop

https://indico.in2p3.fr/event/33255/

LISA Analysis Tools Workshop (LATW)

https://github.com/mikekatz04/LATW