Université Paris Cité

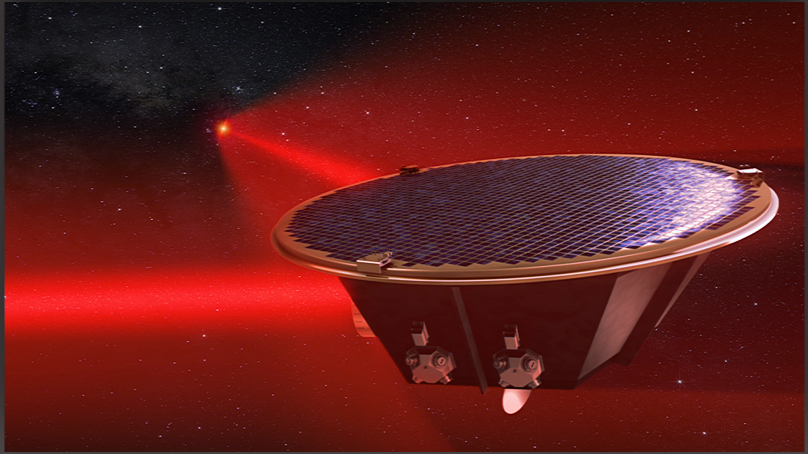
LISA Red Book: peering into millihertz gravitational waves

Quentin Baghi (APC)

Assemblée Générale du GdR Ondes Gravitationnelles - 17 octobre 2023

Layout

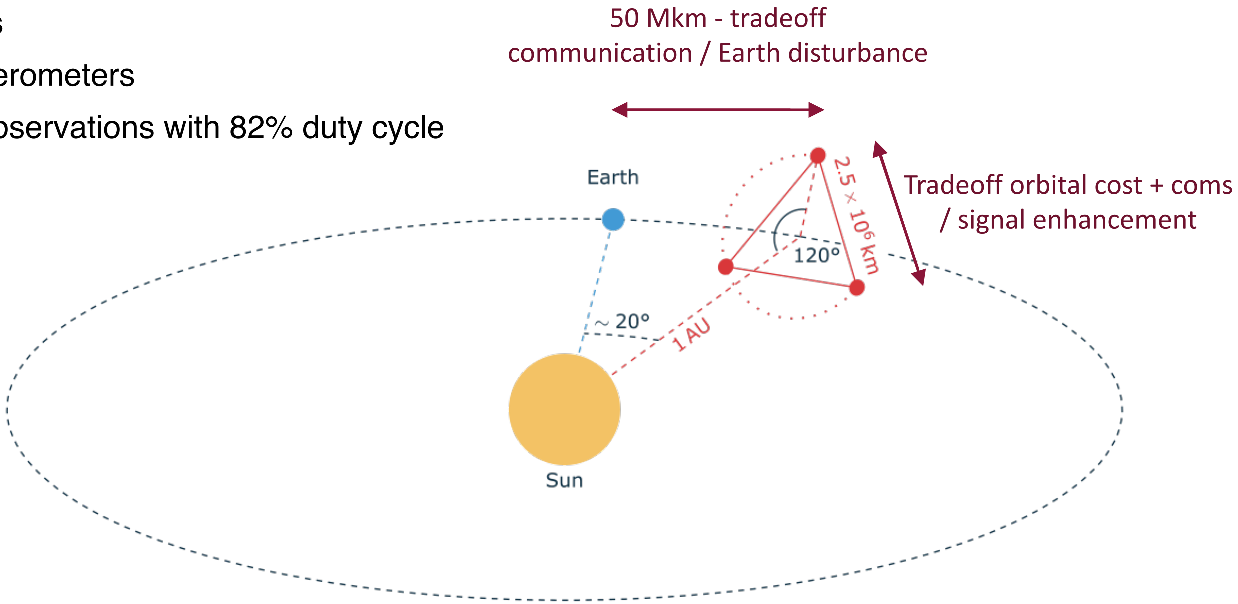
1. Mission concept
2. Science objectives and related challenges
3. Towards the future



Part of the definition study report, or Red Book = summary of the work that has been undertaken on LISA mission definition phase

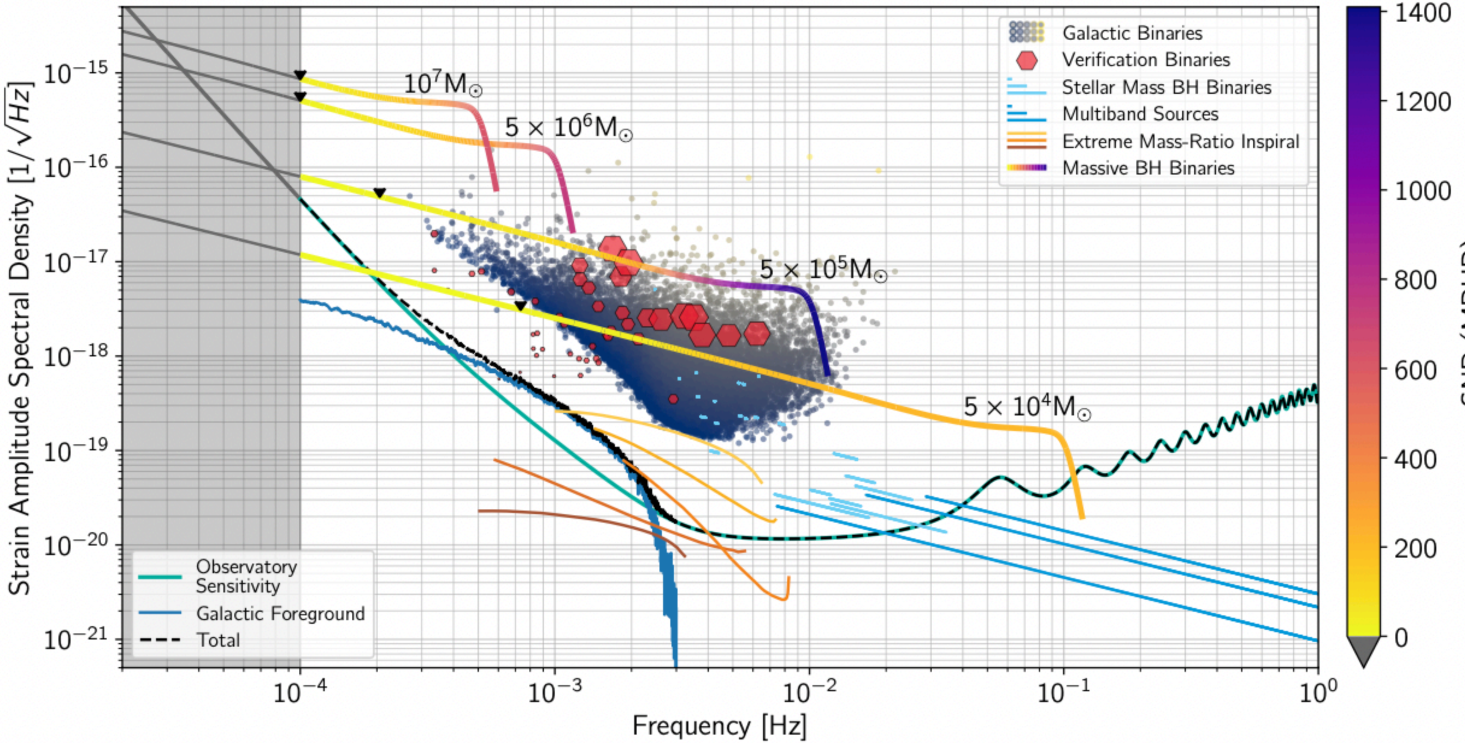
1. Mission concept

- Measures mHz gravitational waves [10^{-4}, 1] Hz
- 3 spacecraft (S/C) forming a triangle with 2.5×10^6 km arms
- Housing 6 test masses
- Network of laser interferometers
- 4.5 years of science observations with 82% duty cycle



1. Mission concept

— Target gravitational wave sources



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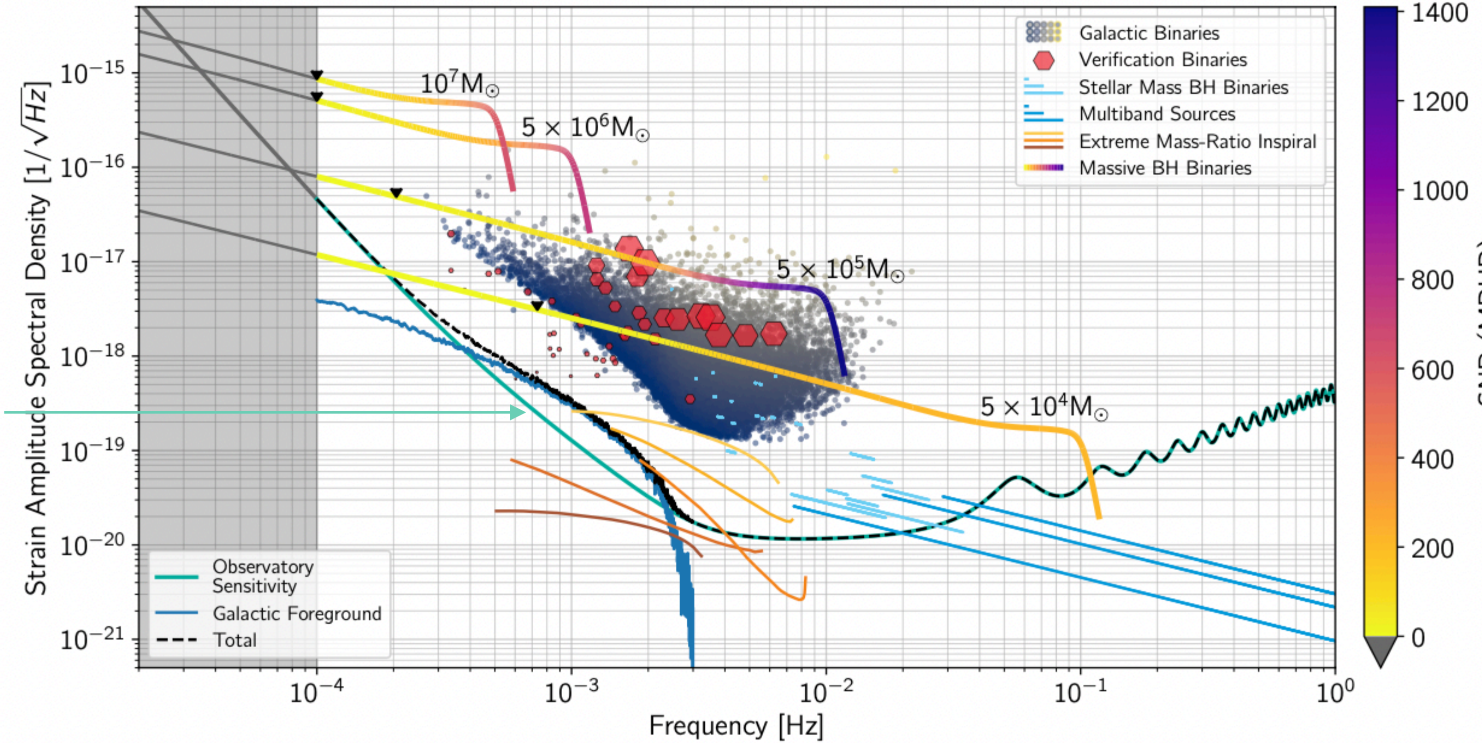
Sensitivity: noise PSD / GW response



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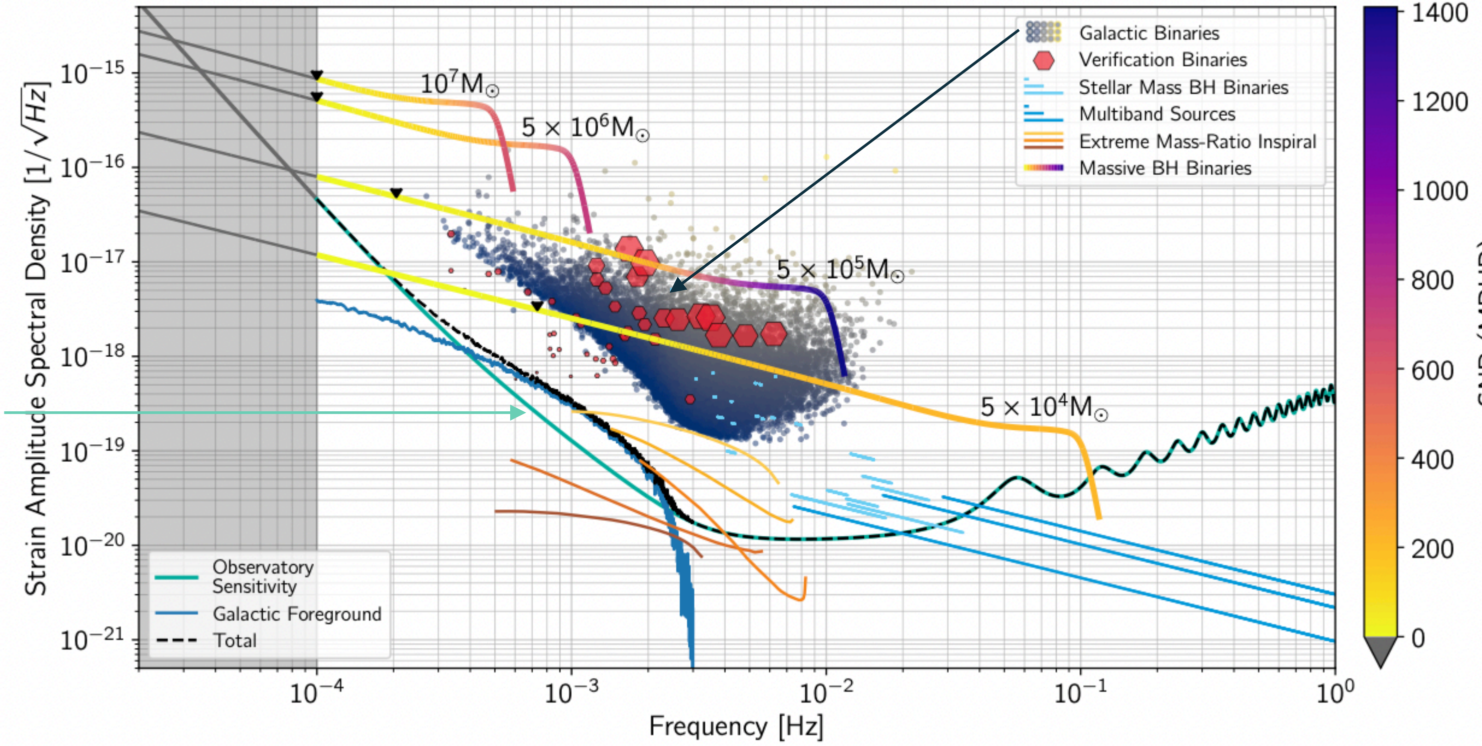

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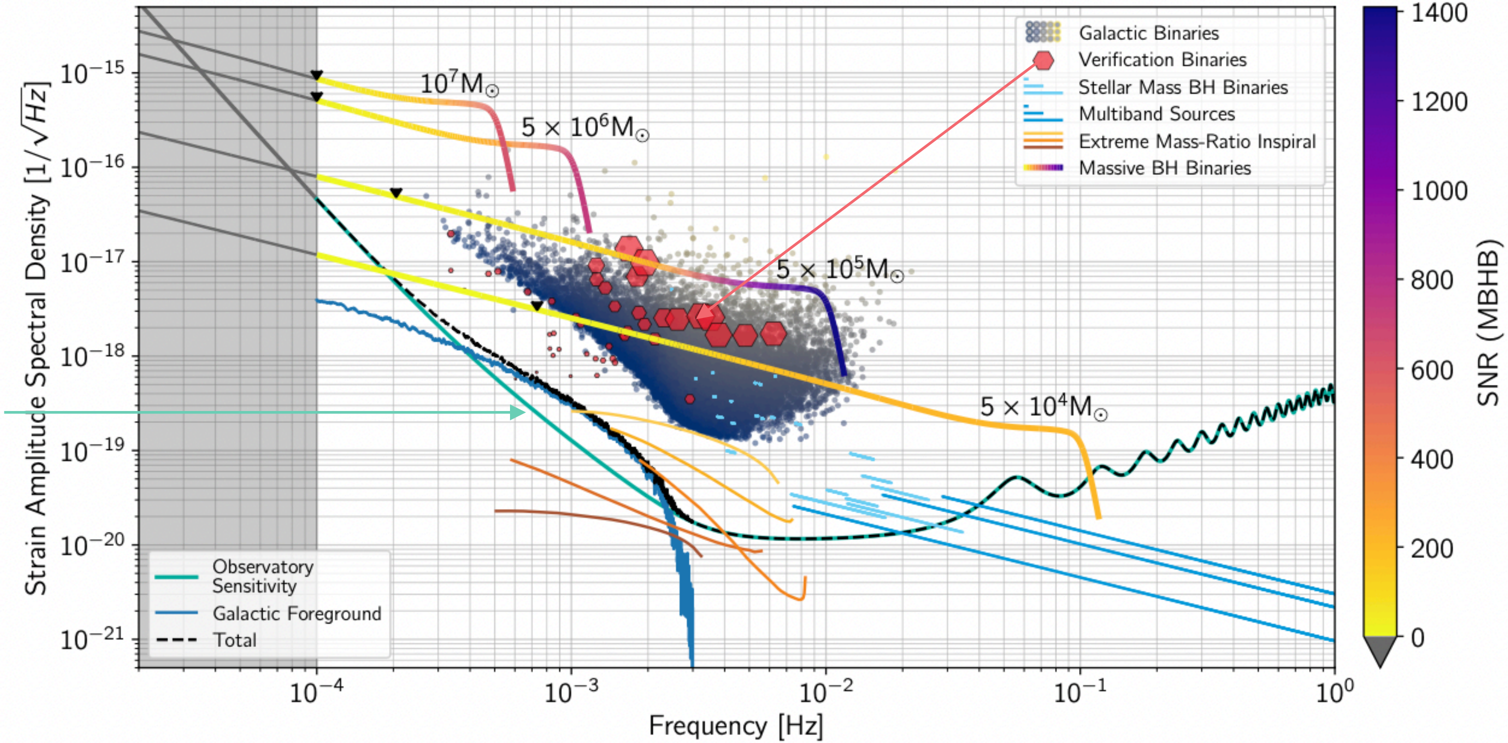

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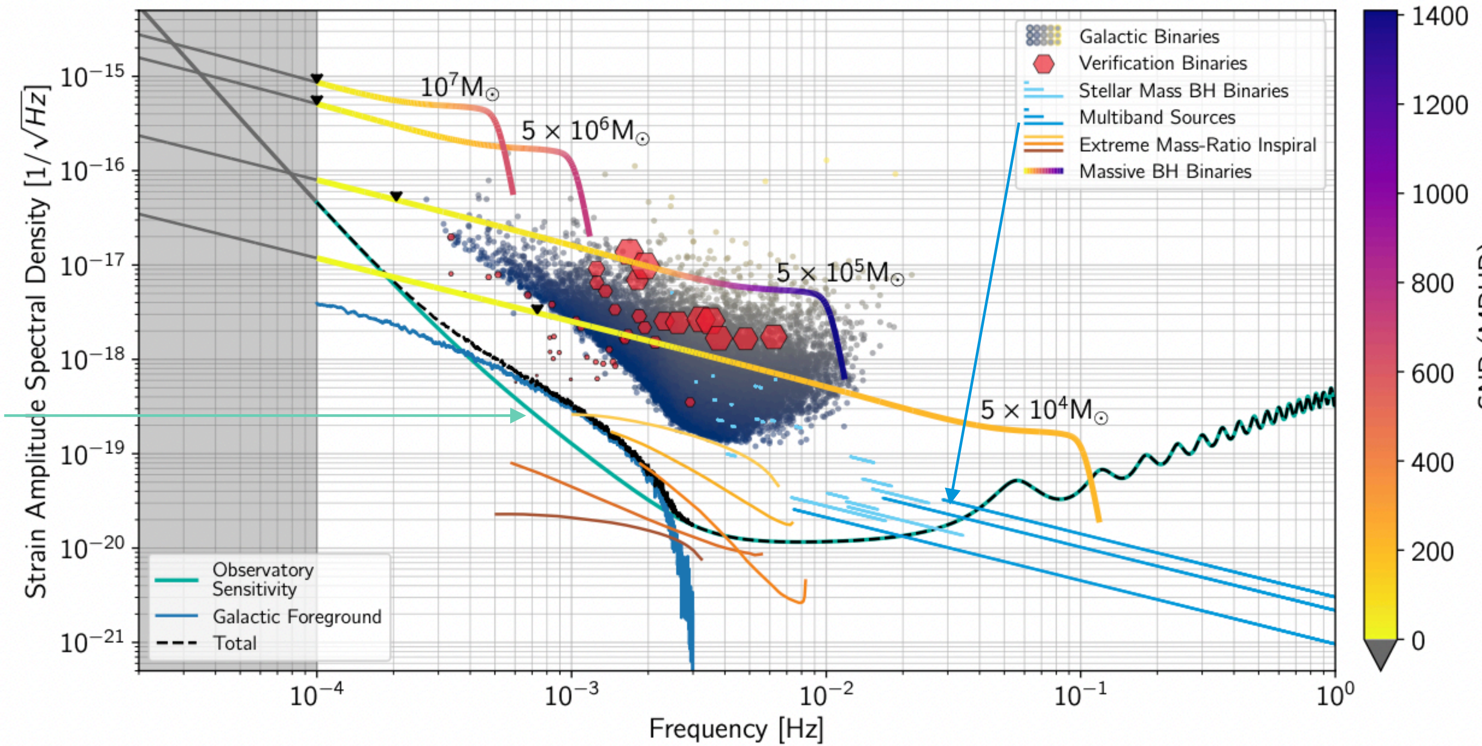

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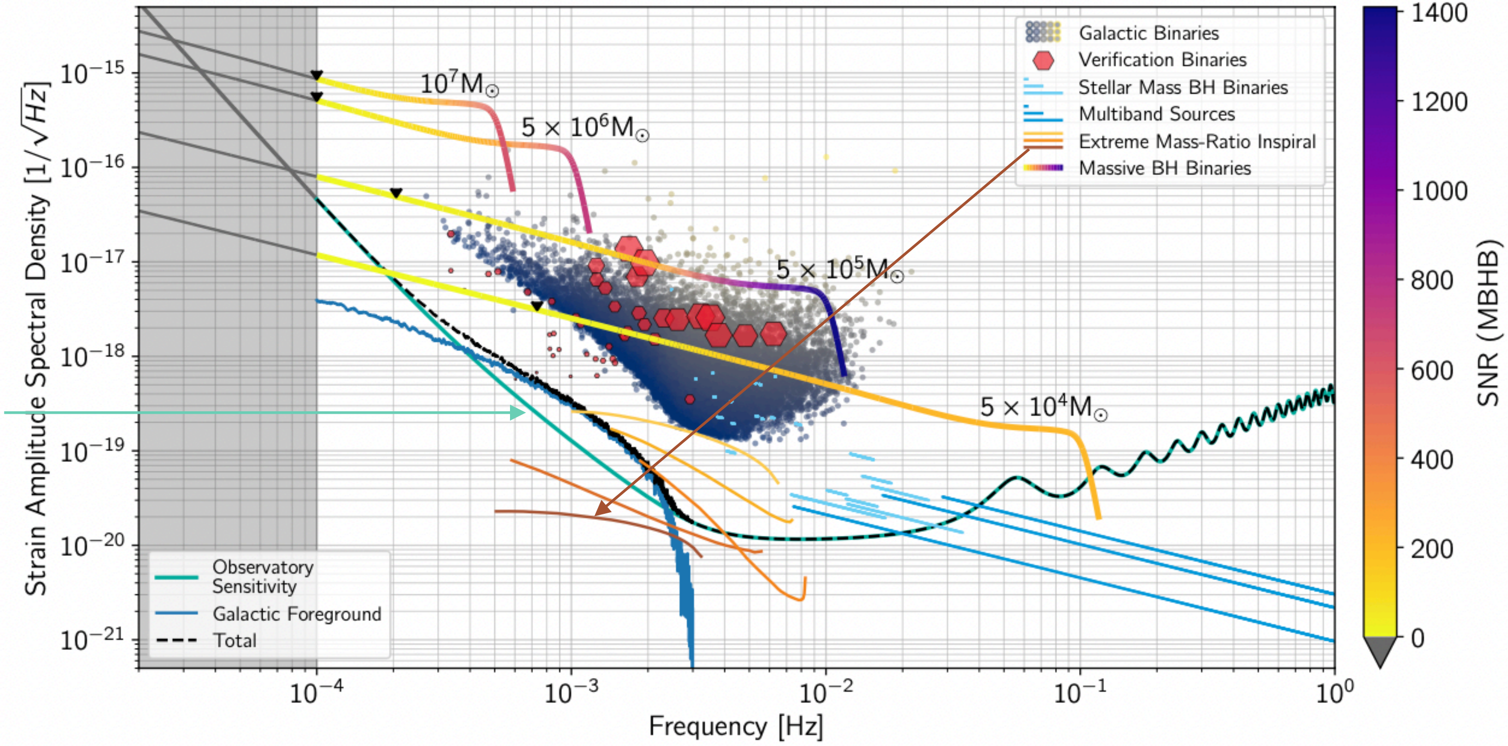

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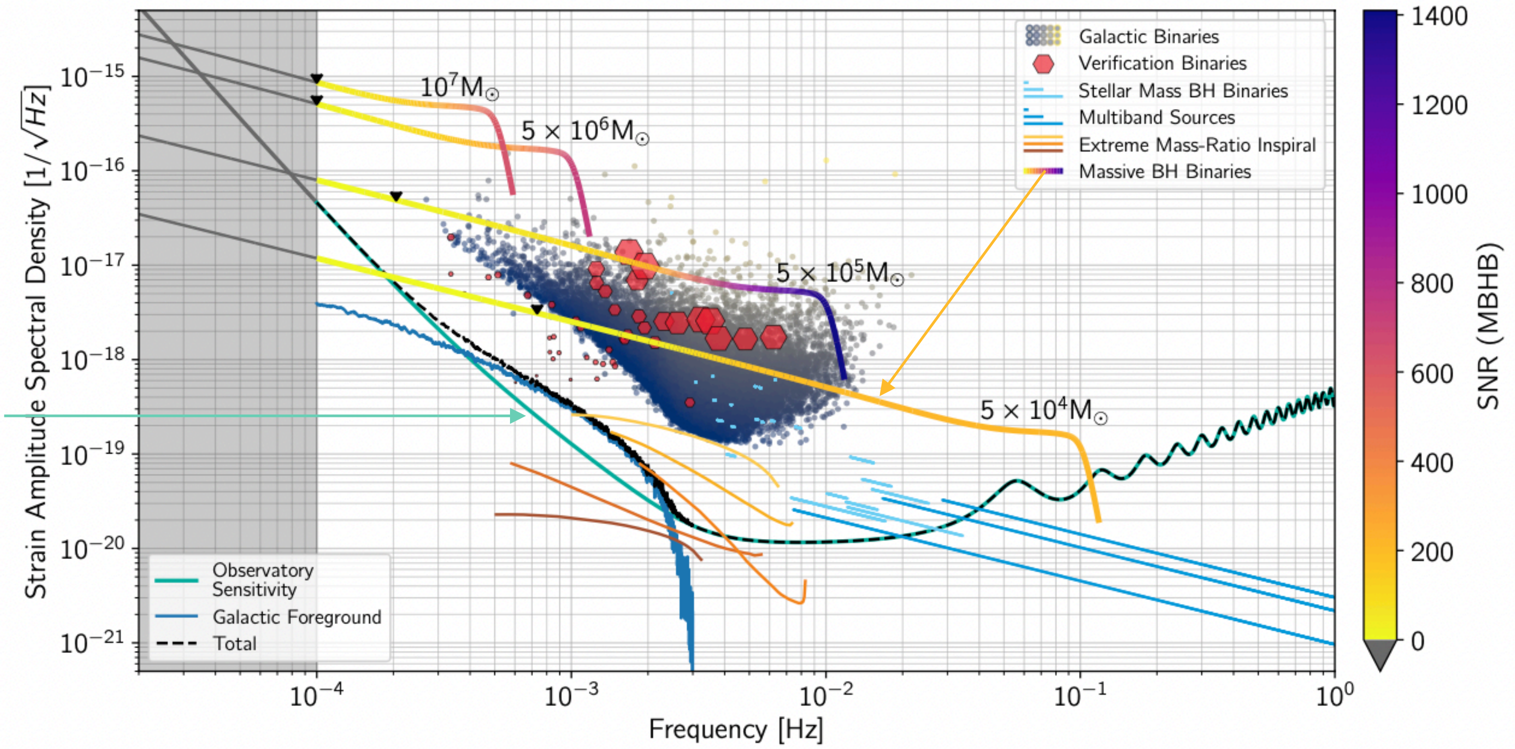
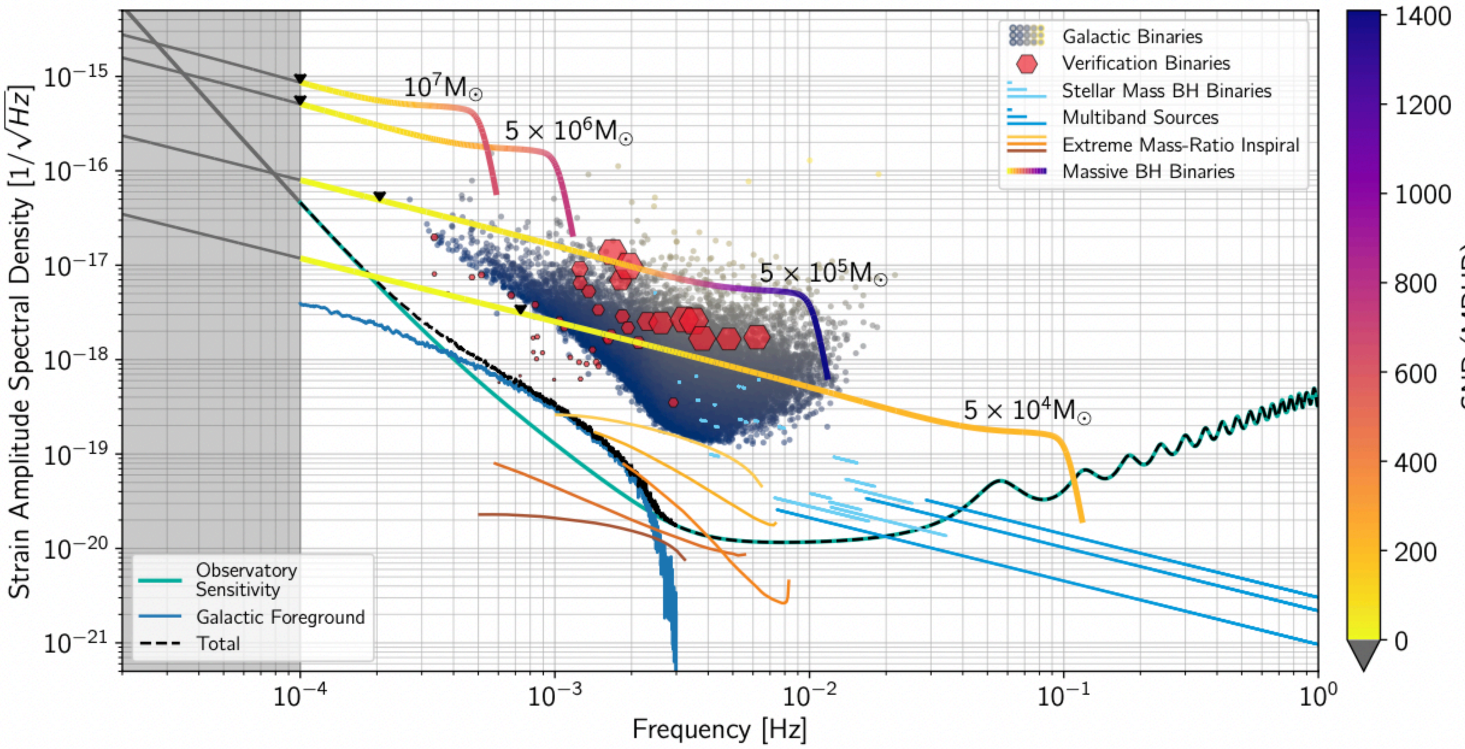


2. Science objectives

— SO1: Study compact binary stars evolution and Galaxy structure



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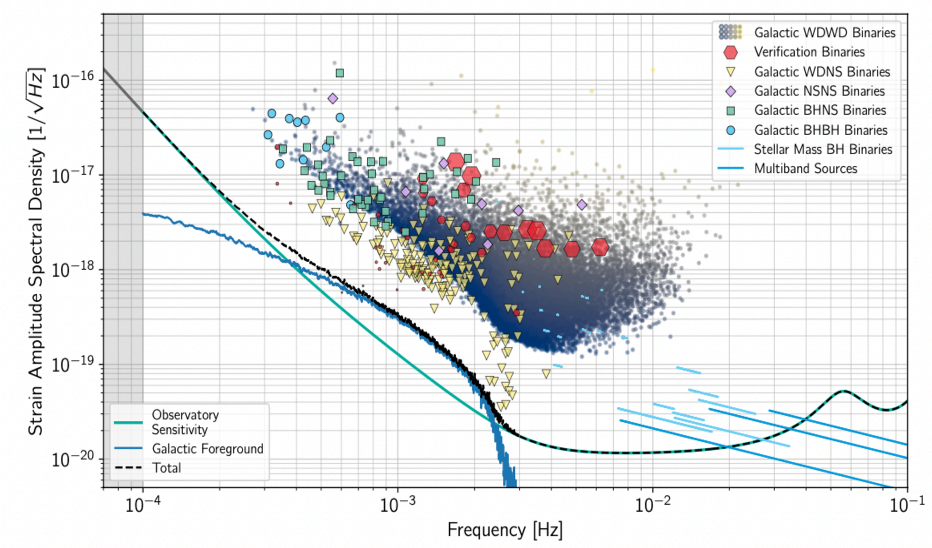

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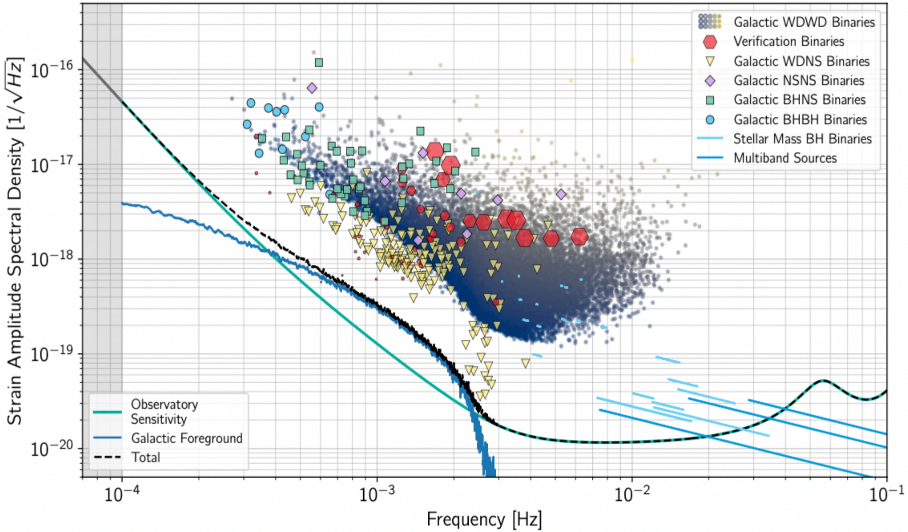
SO1: Study compact binary stars evolution and Galaxy structure

— Most numerous sources ~ 10^7 with ~10^4 detectable



— Most of them are detached and interactive white dwarves → stellar remnants

— Unresolved sources form a confusion foreground

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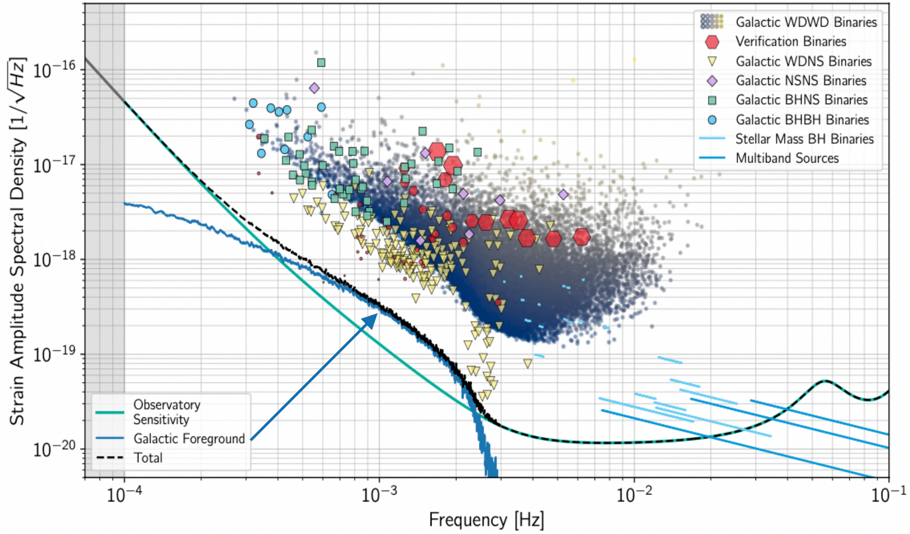

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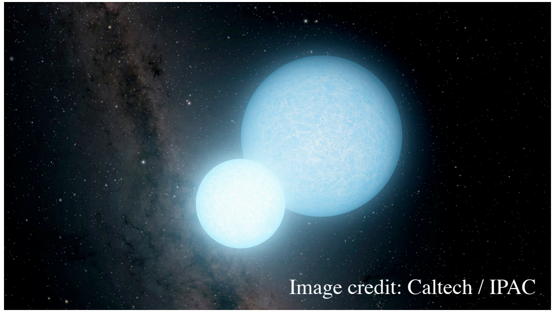

Image credit: Caltech / IPAC

GB sources detected by LISA + confusion foreground

Population of compact binaries in the Milky Way vs frequency

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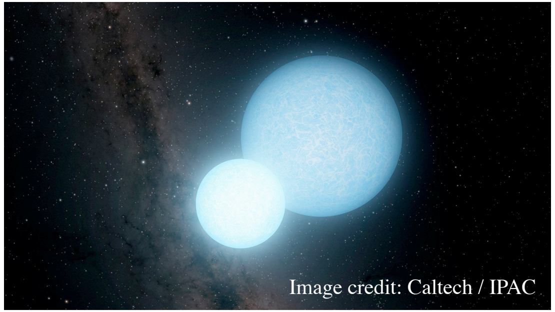

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⇒

Constrain merger rate of white dwarves, neutron stars and black holes

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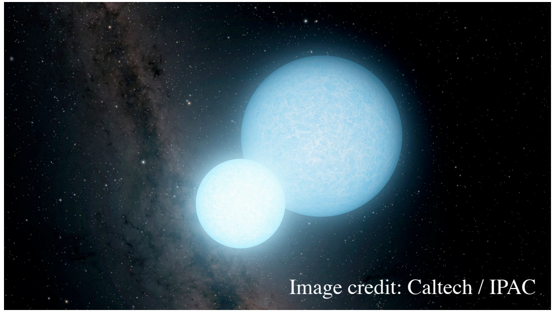

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Population of compact binaries in the Milky Way vs frequency ⇒ Constrain merger rate of white dwarves, neutron stars and black holes ⇒ Implication on explosive events (kilo and supernovae)

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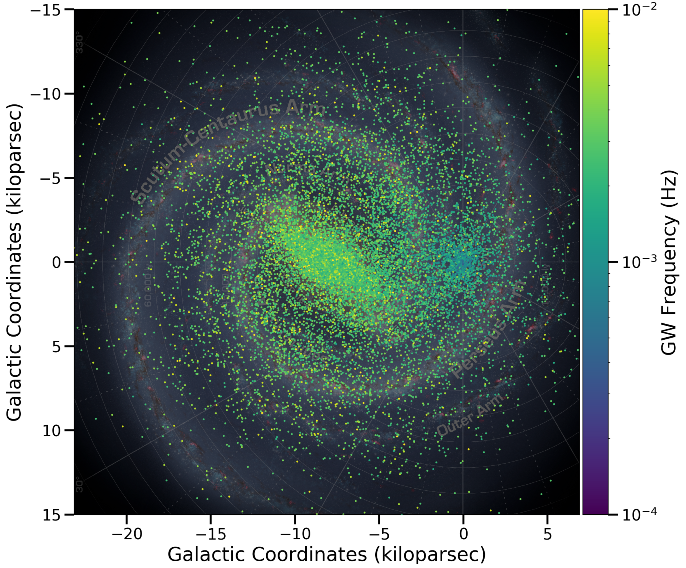
— What is the spatial distribution of ultra-compact binaries?

— How do they inform us about the structure of the Galaxy?



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Sky locations and distances for a few 10^3 ⇒ 3D distribution of binaries ⇒ Geometric structure and stellar mass distribution of Galaxy

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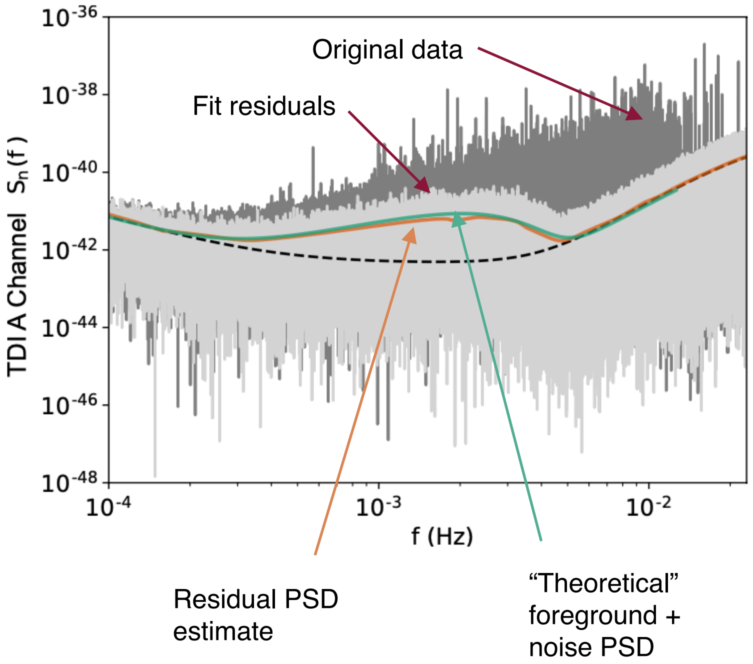
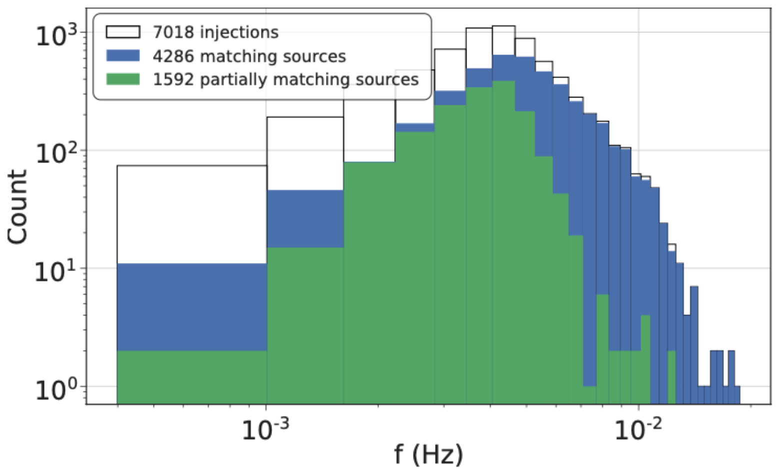
— This is a challenge for data analysis: tens of thousands of continuous, overlapping sources



Prototype pipelines results with LISA Data Challenges 2 data



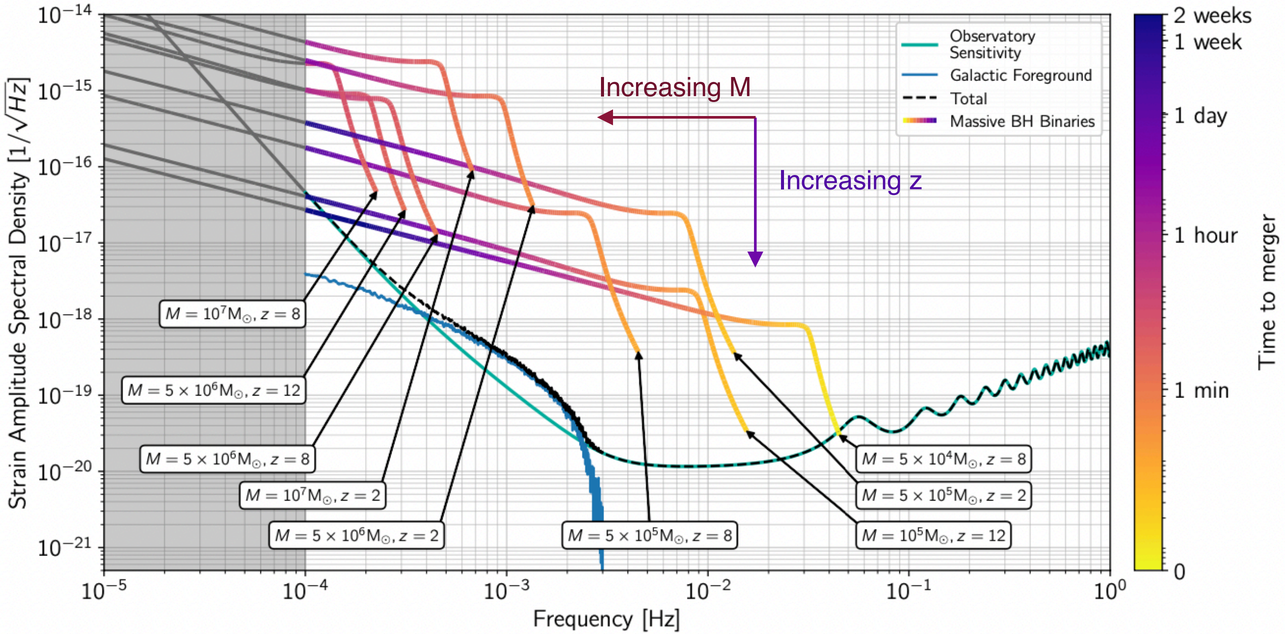
Galactic binary source frequency

[APC team LDC 2a results]

2. Science objectives

SO2: Trace the origin, growth and merger histories of massive black holes

- LISA will detects BHs mergers with $10^5 < M < 10^7$ solar masses
- Up to large redshifts: z = 15 and beyond
- Formidable tool to study the origin and evolution of BHs!



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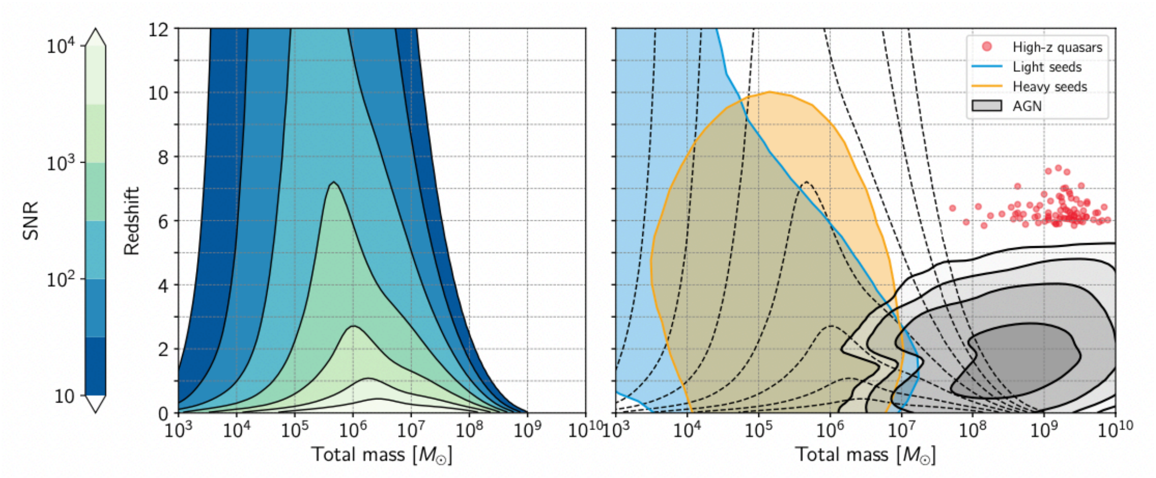
SO2: Trace the origin, growth and merger histories of massive black holes

— How did massive black holes form? What are their seeds?



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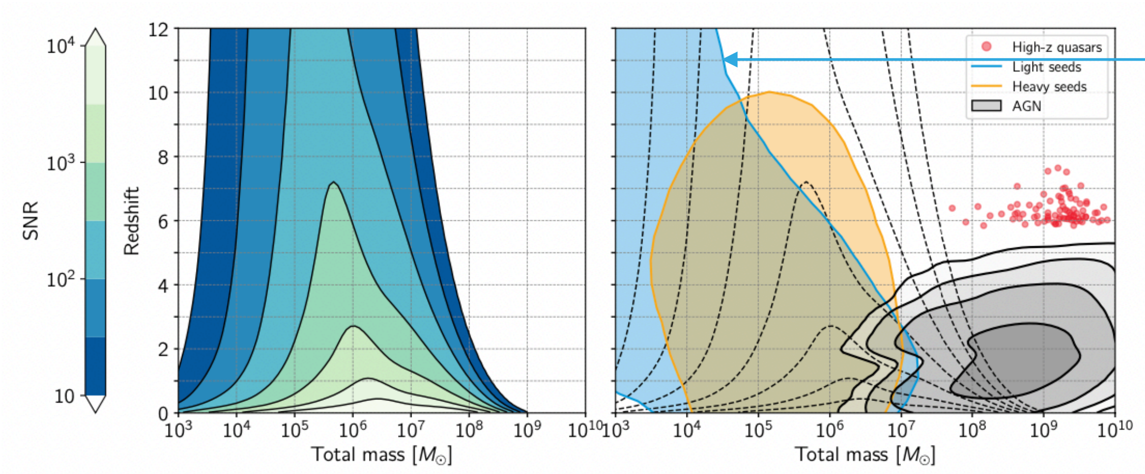

Simulated MBHB resulting from light seeds

Light seeds = result from gravitational **collapse of first metal-free stars** in early dark matter haloes (Carole Perigois's talk)

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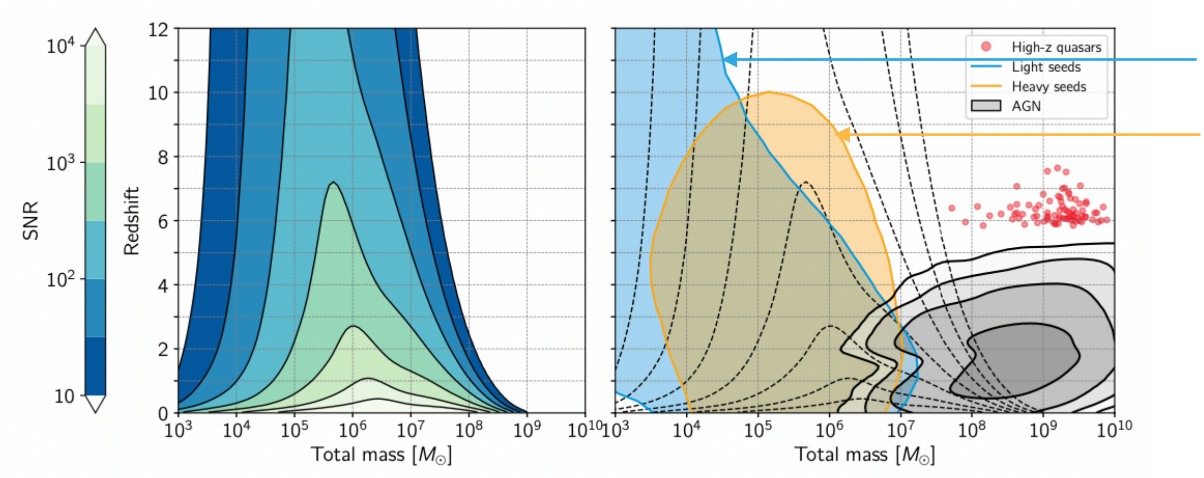

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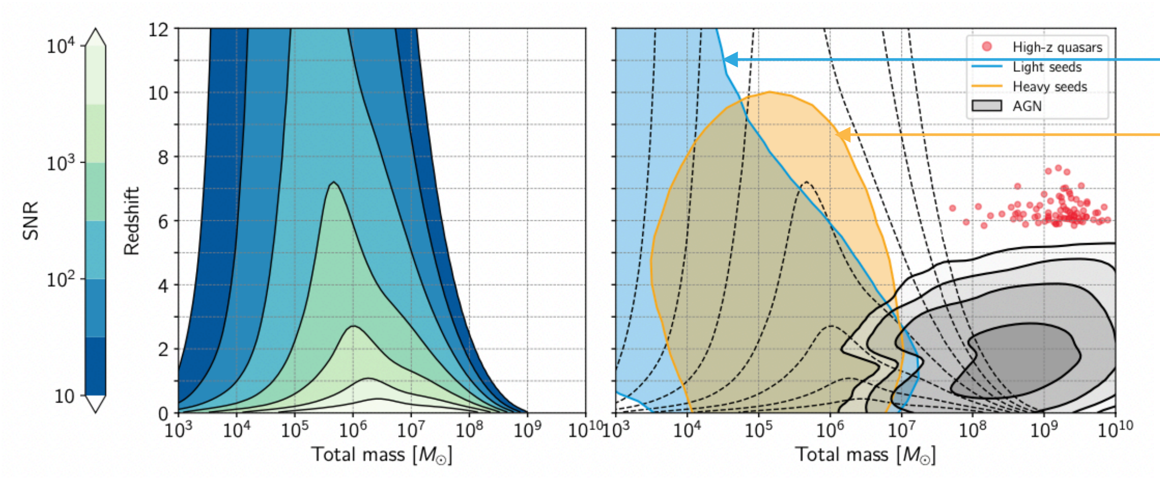

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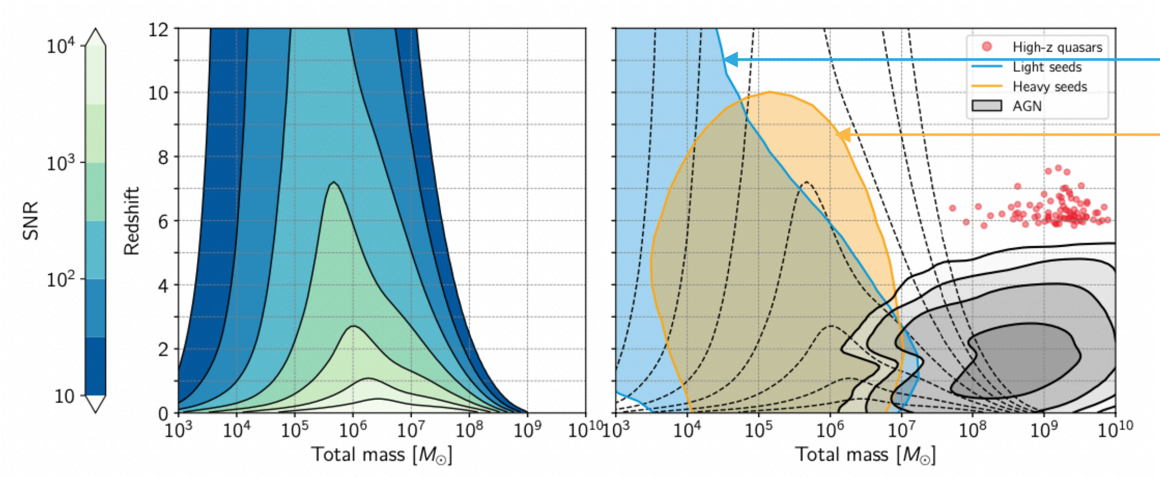

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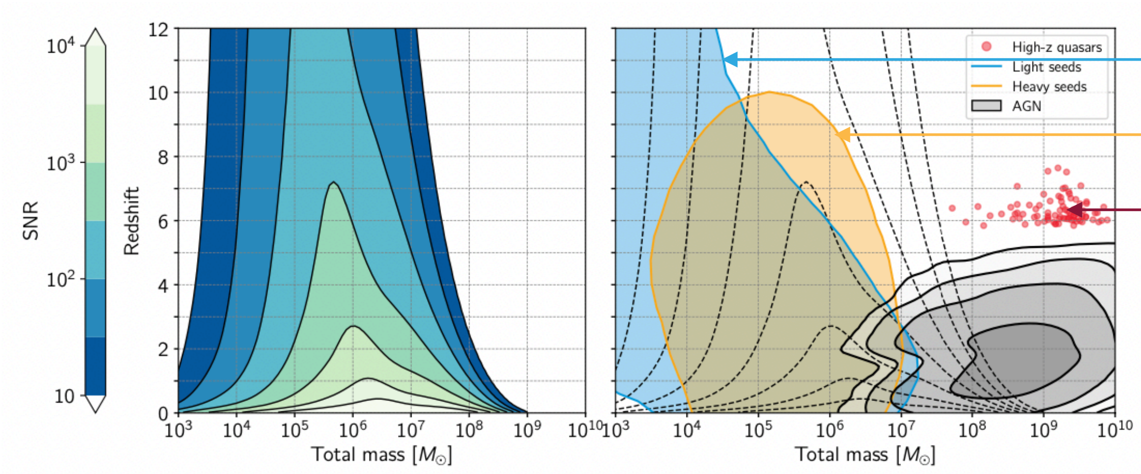

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Quasars observed at z ~ 7 with EM observations

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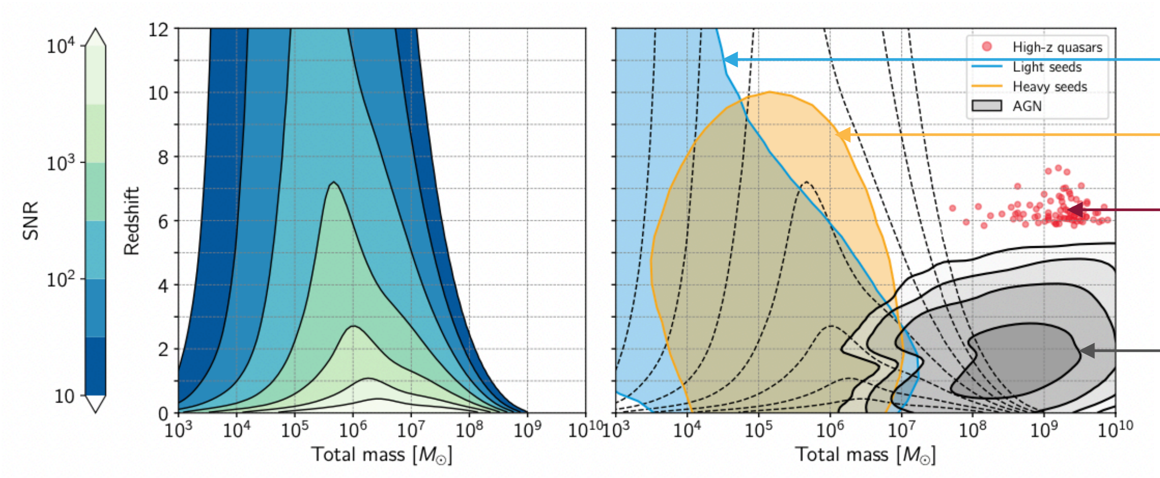

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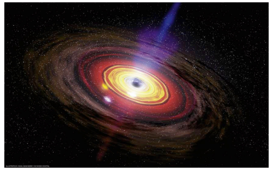
Current distribution of AGN population



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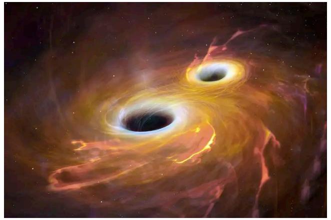
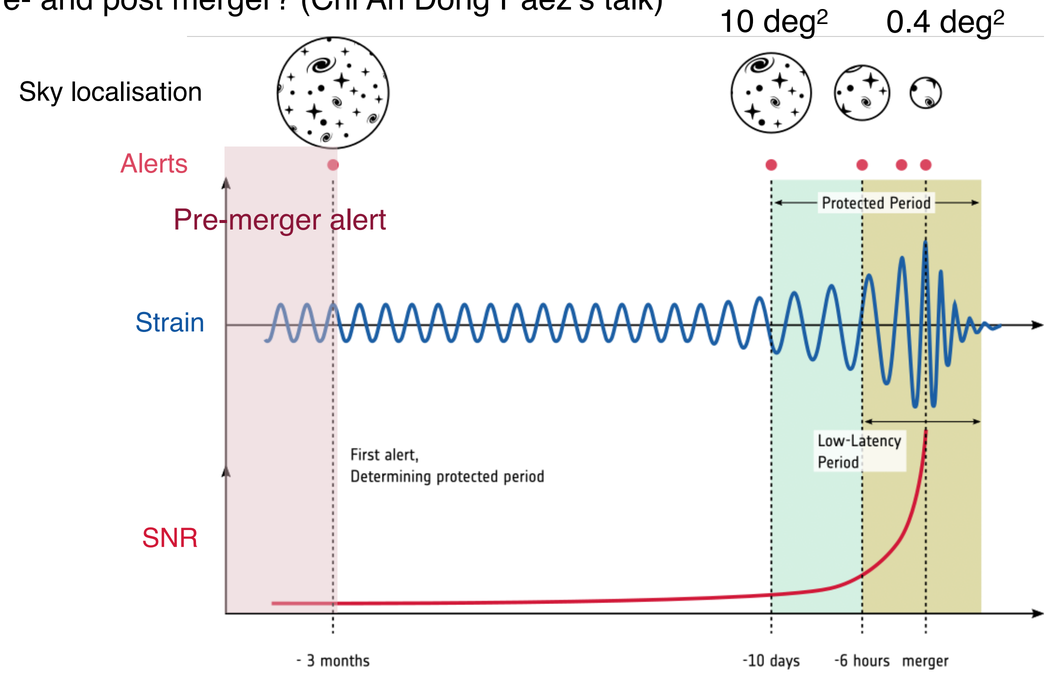
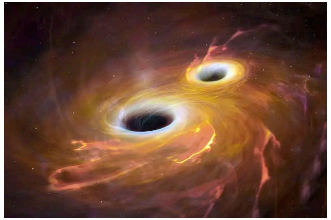
- Can we identify the host galaxies of detected coalescences?
- Can we detect EM counterparts pre- and post merger? (Chi An Dong Páez's talk)
- What is the role of accretion?





Example of a MBHB $10^5 < M < 10^6$ solar masses at $z < 0.3$

2. Science objectives



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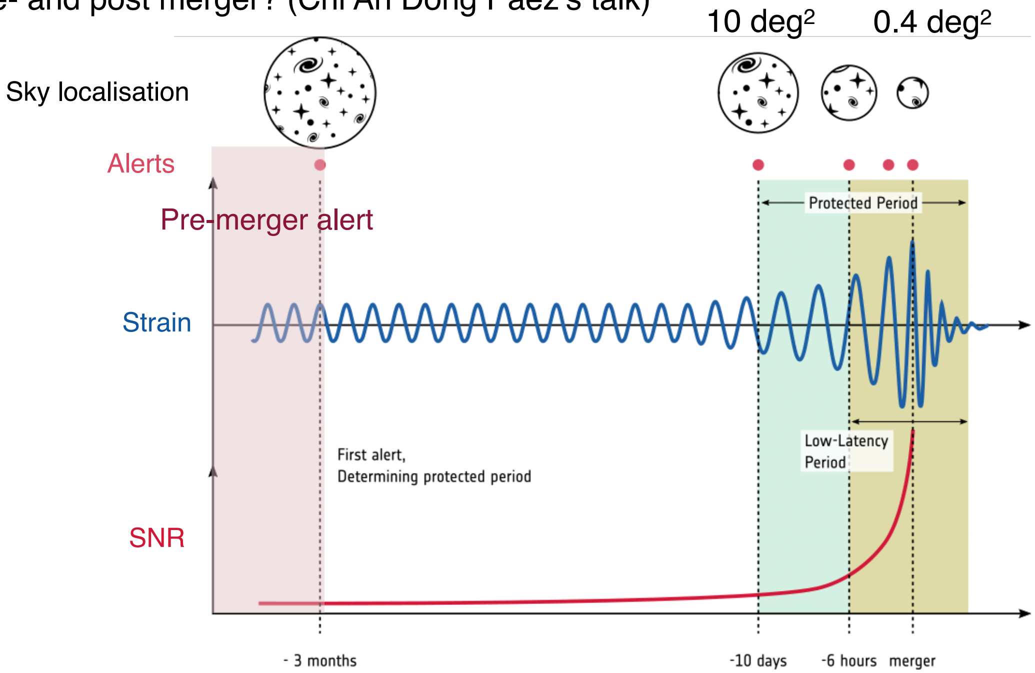

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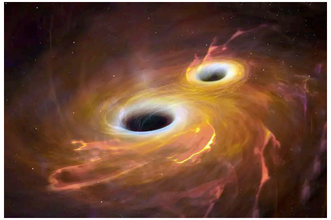

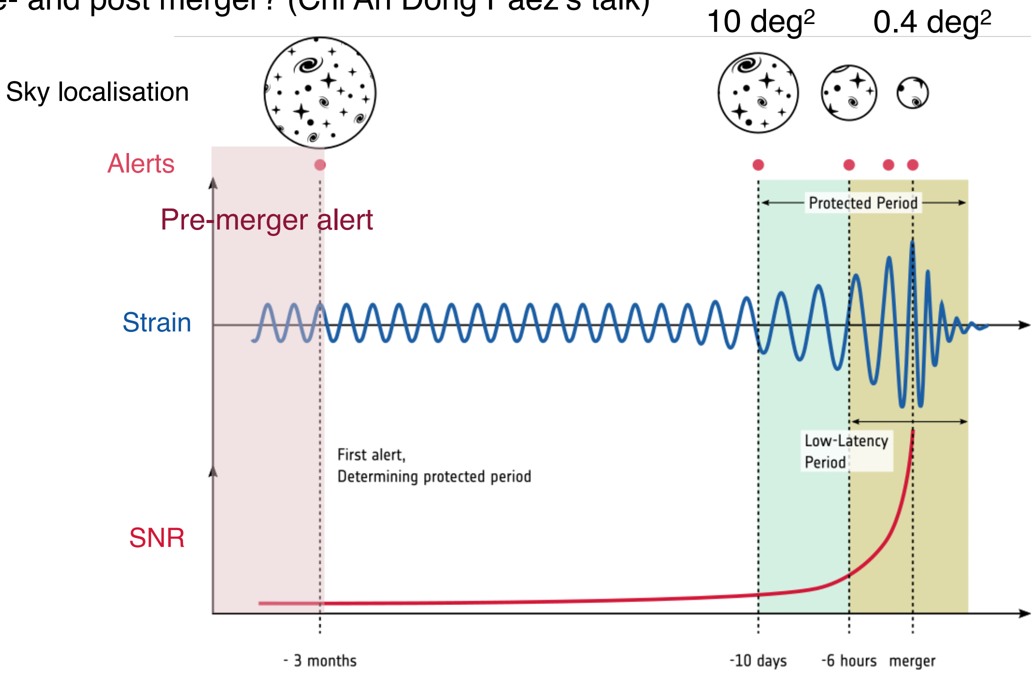

→ Plan observations ahead of time

→ Secure **protected periods**

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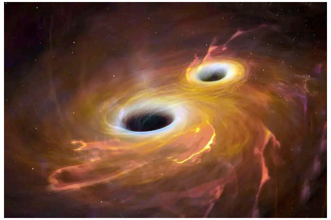

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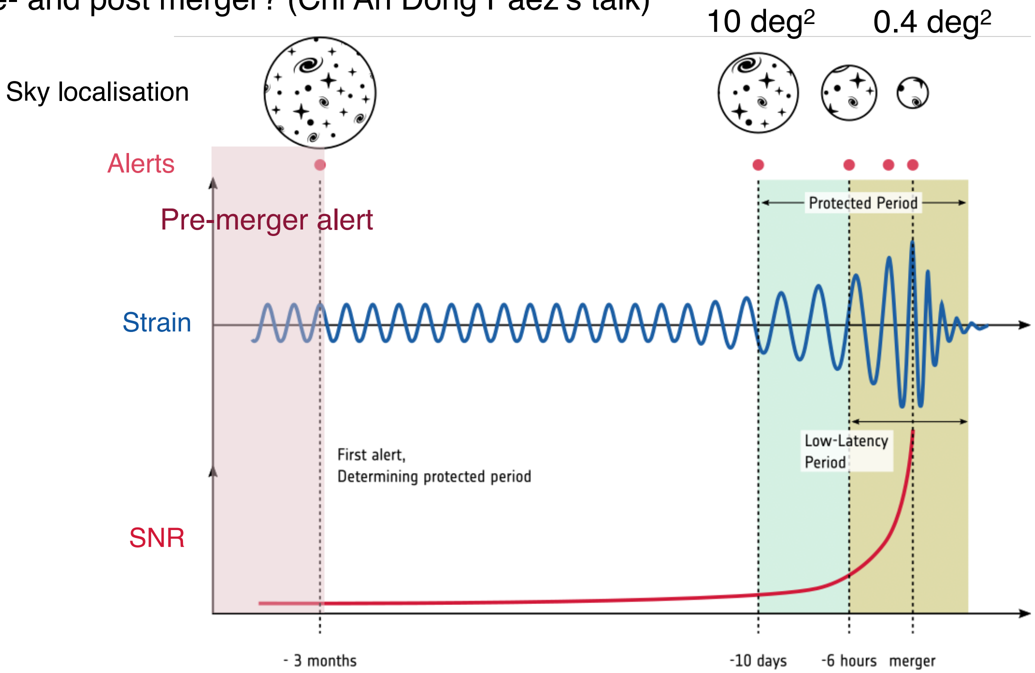
→ **Low-latency alert** pipeline



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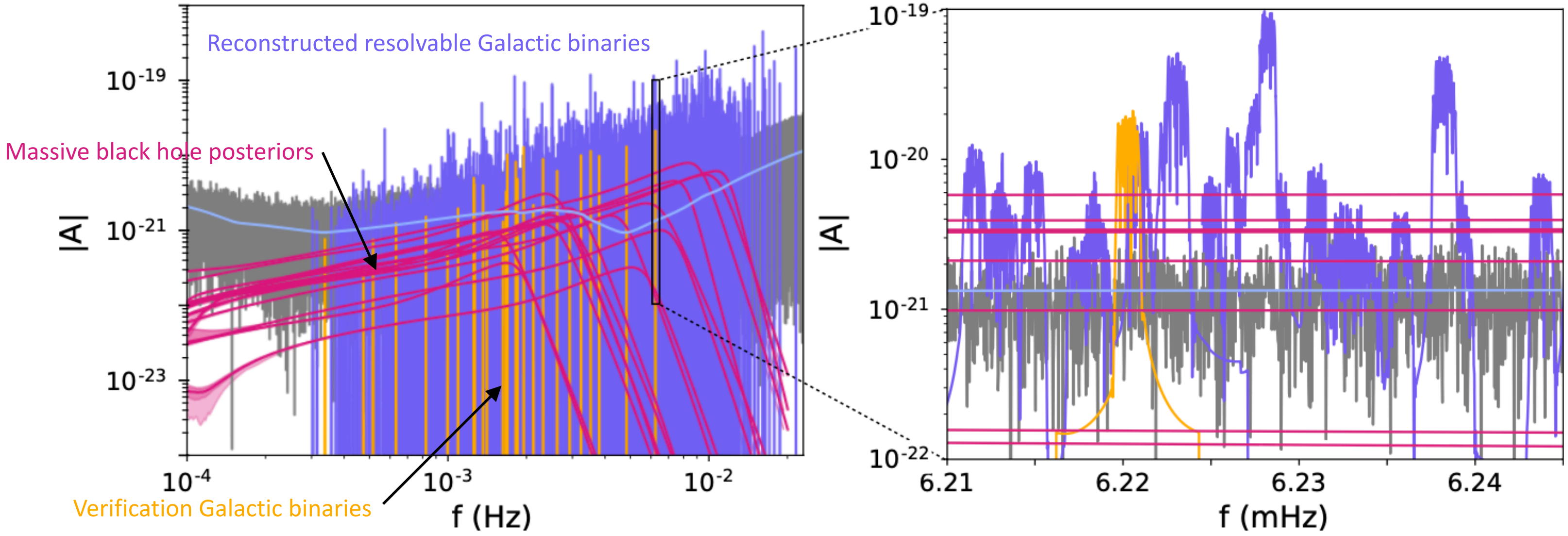
— Source type mixing requires to develop a "global fit" approach (see Senwen Deng's talk)

Prototype pipelines results with LISA Data Challenges 2 data



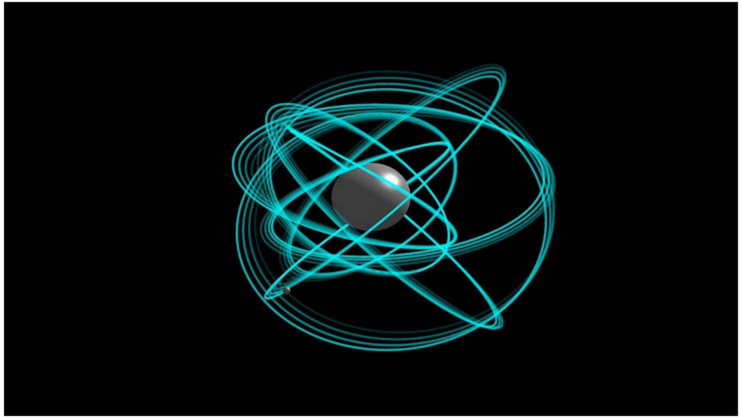
[Littenberg & Cornish 2023]

2. Science objectives

SO3: Probe the properties and immediate environments of Black Holes using EMRIs and IMRIs

- In which stellar environments do MBHs live?
- What are the spin & mass distributions of MBHs?

We can use extreme-mass ratio inspirals (EMRIs) with mass ratios $10^{-6} < q < 10^{-4}$



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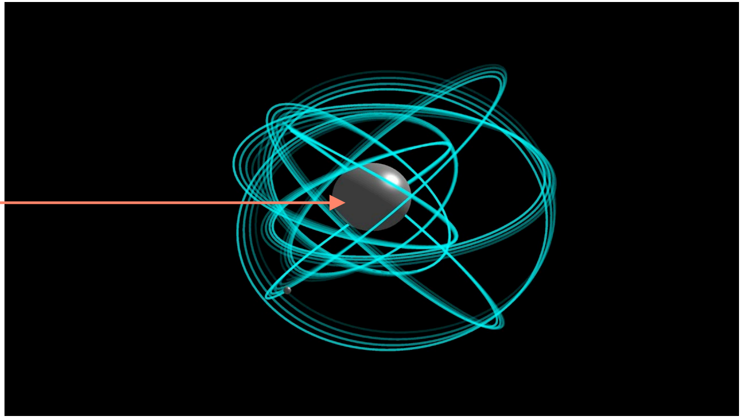

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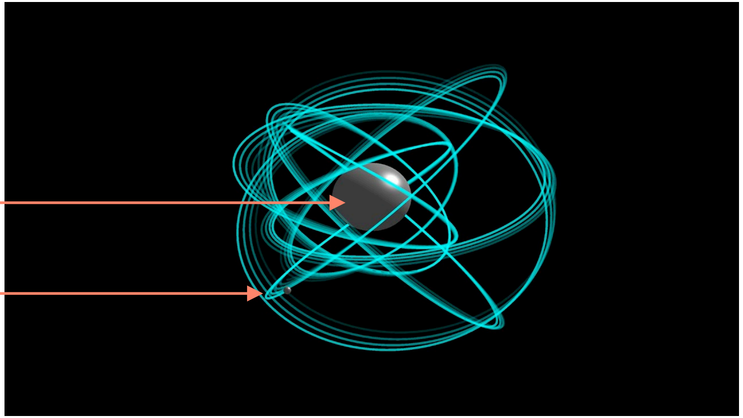

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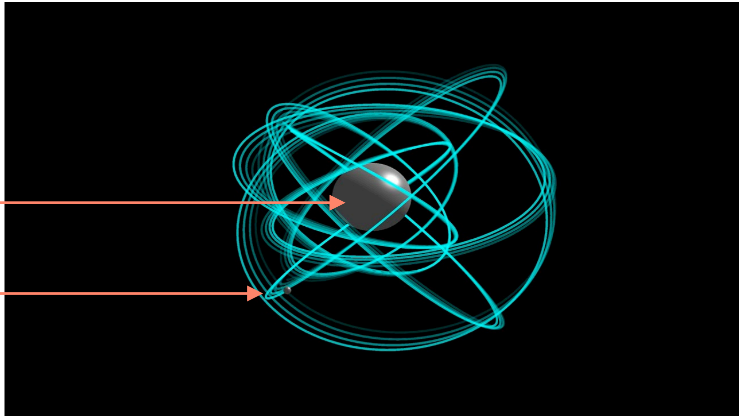

Starting at 3 mHz, takes 1 year to plunge = 10^5 waveform cycles

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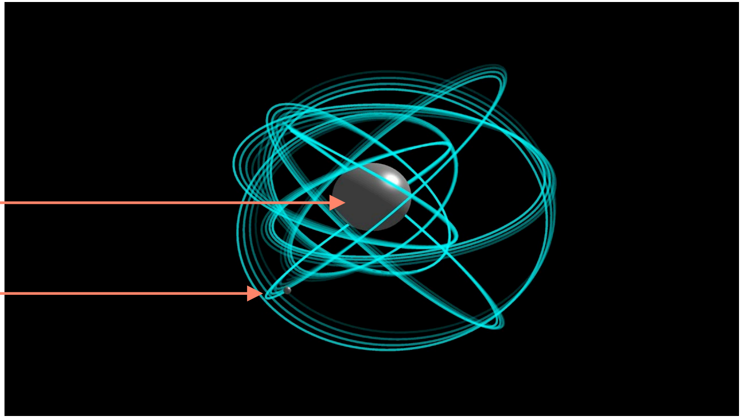

- LISA could detect EMRIs at typical z ~ 3

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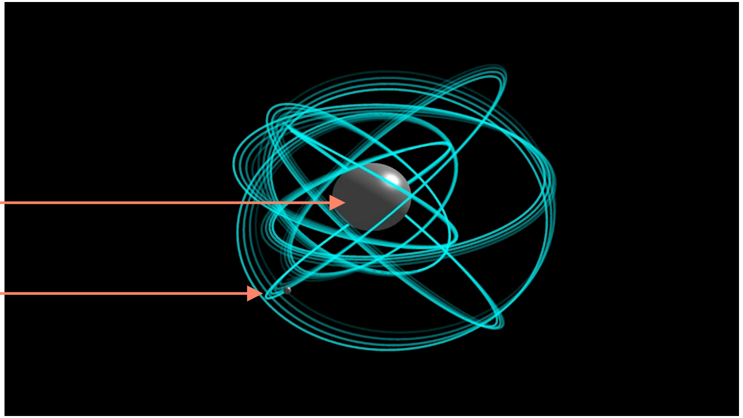

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→ Probe astrophysical environments of **quiescent** massive black holes → co-evolution with host galaxies

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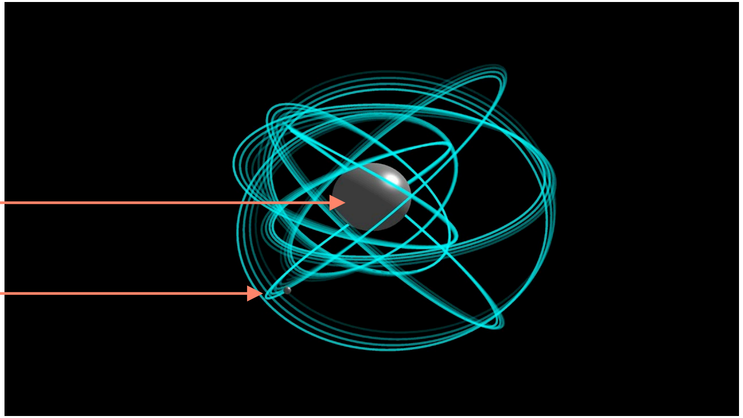

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→ Measure cosmological parameters

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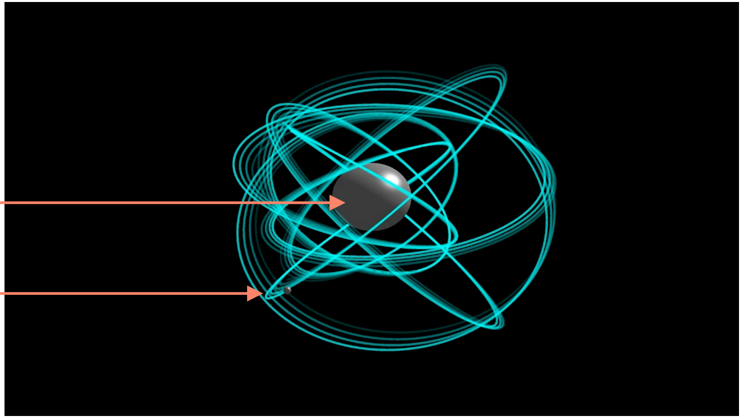

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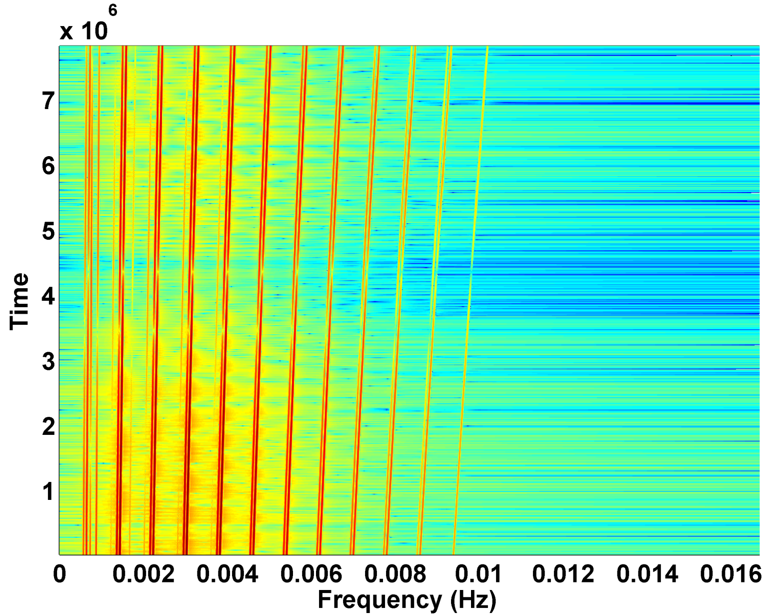
- LISA could detect EMRIs at typical z ~ 3
  - Probe astrophysical environments of **quiescent** massive black holes → co-evolution with host galaxies
  - Measure cosmological parameters
  - Test fundamental physics: test whether massive compact objects observed in the center of galaxies are spinning black holes described by GR’s Kerr metric

2. Science objectives

SO3: Probe the properties and immediate environments of Black Holes using EMRIs and IMRIs

— Challenge for data analysis: many harmonics and cycles, complicated waveform

— Challenge for (fast) waveform modelling: disparate time and length scales



[Babak 2017]

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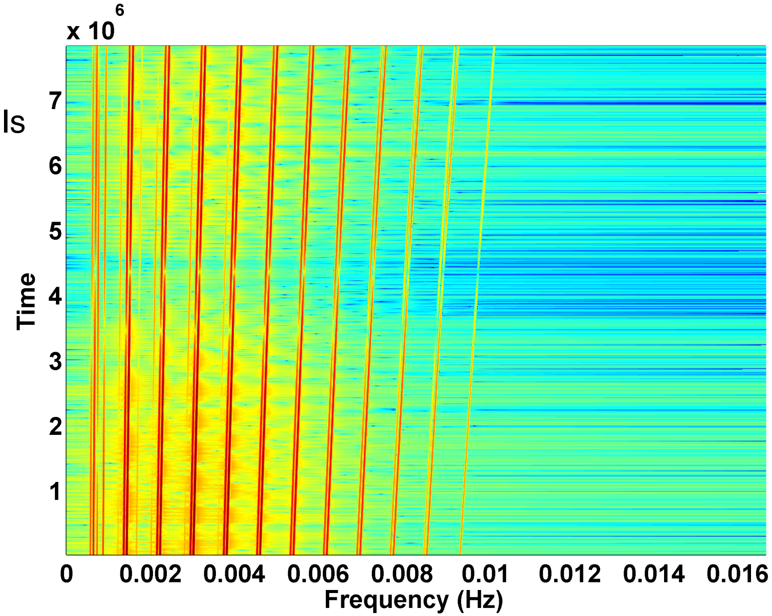

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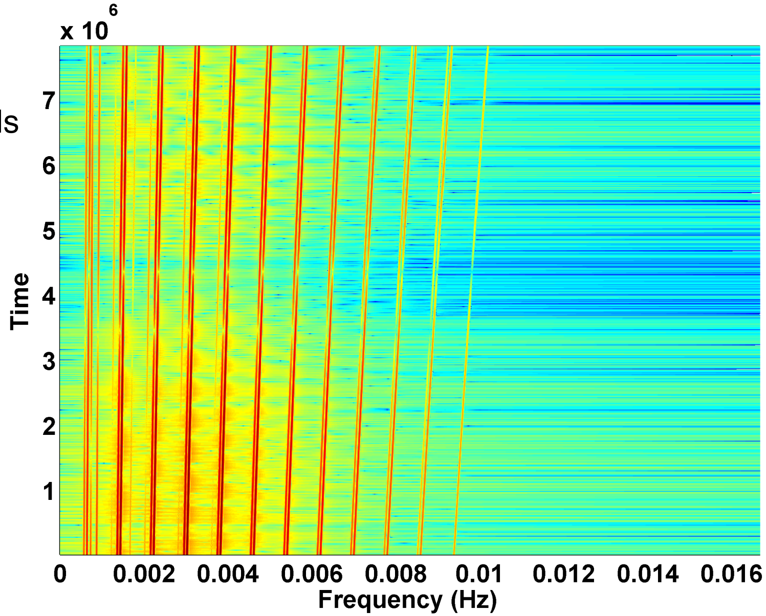
→ Need for **extending waveforms models** to to spinning, eccentric and inclined systems (Ollie Burke's talk)

→ Need **adapted inference strategies**



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SO4: Understand the astrophysics of stellar-mass black holes

- How are they born?
- Complementary to ground-based observations: LISA will observe sBHBs < hundreds of years before they merge.

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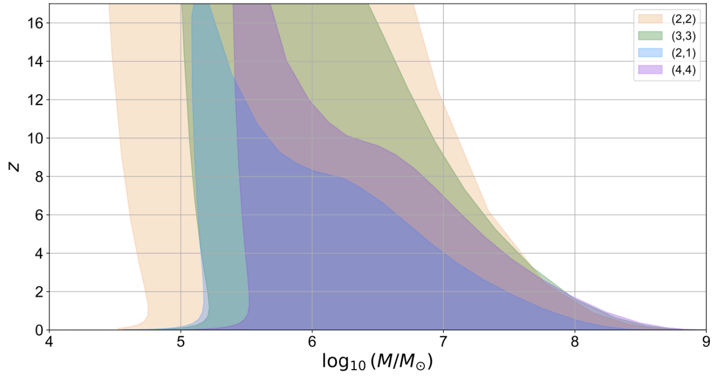
SO5: Explore the fundamental nature of gravity and Black Holes

— Test GR in the strong field regime

— Test validity of GR Kerr solution for merger remnants → see Chantal Pitte's talk



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SO6: Probe the rate of expansion of the Universe with standard sirens

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— We can probe the expansion of the universe at $z > 2$ with **bright sirens:** massive black hole binaries with EM counterparts

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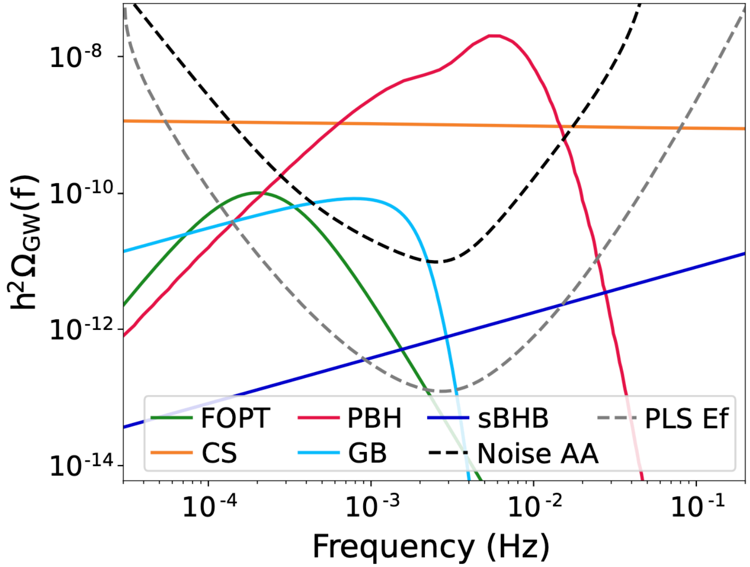
SO7: Understand stochastic GW backgrounds

— Would be **groundbreaking discovery** if we detect a stochastic GW background of cosmological origin (Alberto Roper Pol's talk)

— Unique probe of early-universe physics and TeV-scale particle physics)

— But very challenging data analysis task! (see Quang Nam Dam's talk)



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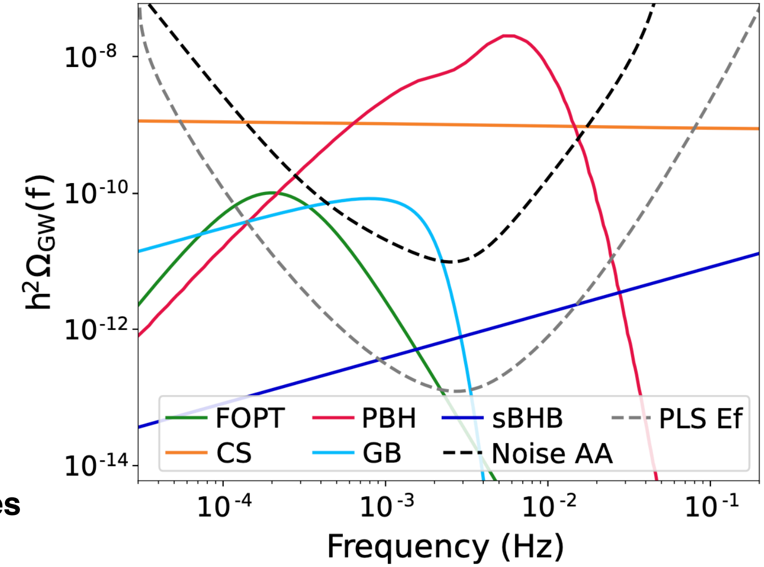

SO8: Search for GW bursts and unforeseen sources

Conclusion: bright future and many challenges

Decision milestones

Science Program Committee (SPC) Decision
Mission Adoption

Mission phase

Phase A | Phase B1 | Phase B2/C/D | Phase E

Main actors during this mission phase

Feasibility Phase
Two competing prime contractors
Developing first designs of the mission

Refinement Phase
Refine Mission Definition
Get ready for Implementation
Choose final Design
Write the big mission document - the Red Book

Implementation
One Prime Contractor chosen
Now we build the mission!

Reviews	Mission Definition Review (MDR)	Mission Consolidation Review (MCR)	Mission Formulation Review (MFR)	Mission Adoption Review (MAR)	Launch
Final Documents	CDF Report	Industrial & Inst Data Packs: (Technical & Programmatic)	Industrial & Inst Data Packs: (Tech & Programmatic)	Data Pack: (Tech & Programmatic) & Red Book	
Date	DEC 2017	DEC 2019	DEC 2021	2024	

Conclusion: bright future and many challenges

We are here

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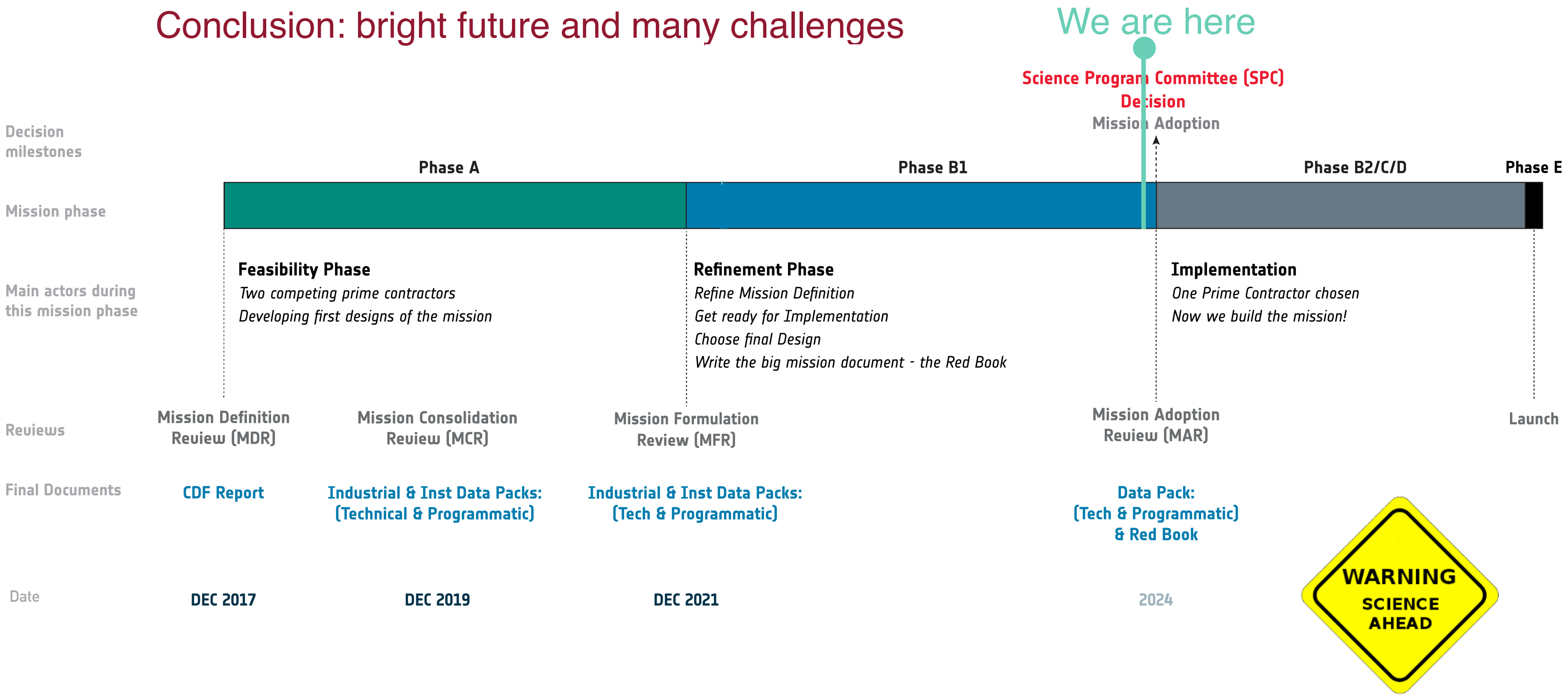
Conclusion: bright future and many challenges



Conclusion: bright future and many challenges

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Science Program Committee (SPC) Decision
Mission Adoption

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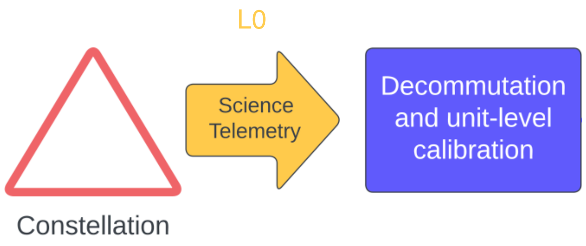
Thank you for you attention!

Back-up slides

3. Science observations

LISA's operational concept: perform a *time-resolved*, *all-sky* survey of gravitational waves sources in the millihertz band.



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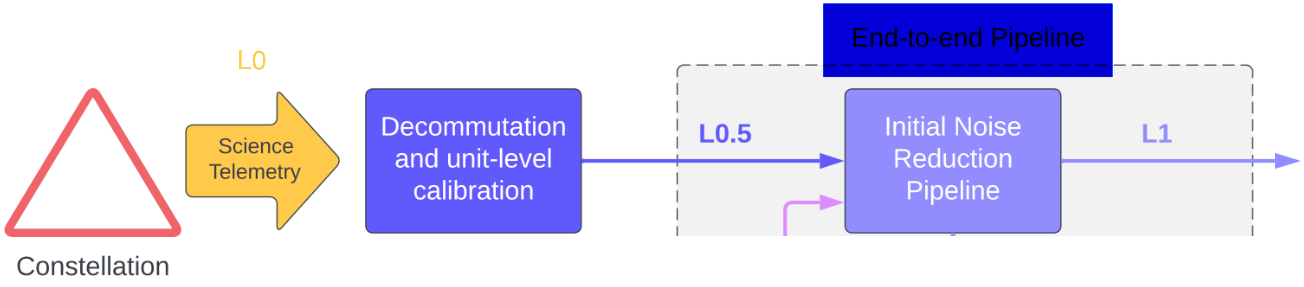

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- L0.5: processed and reformatted
- L1: noise-reduced TDI data

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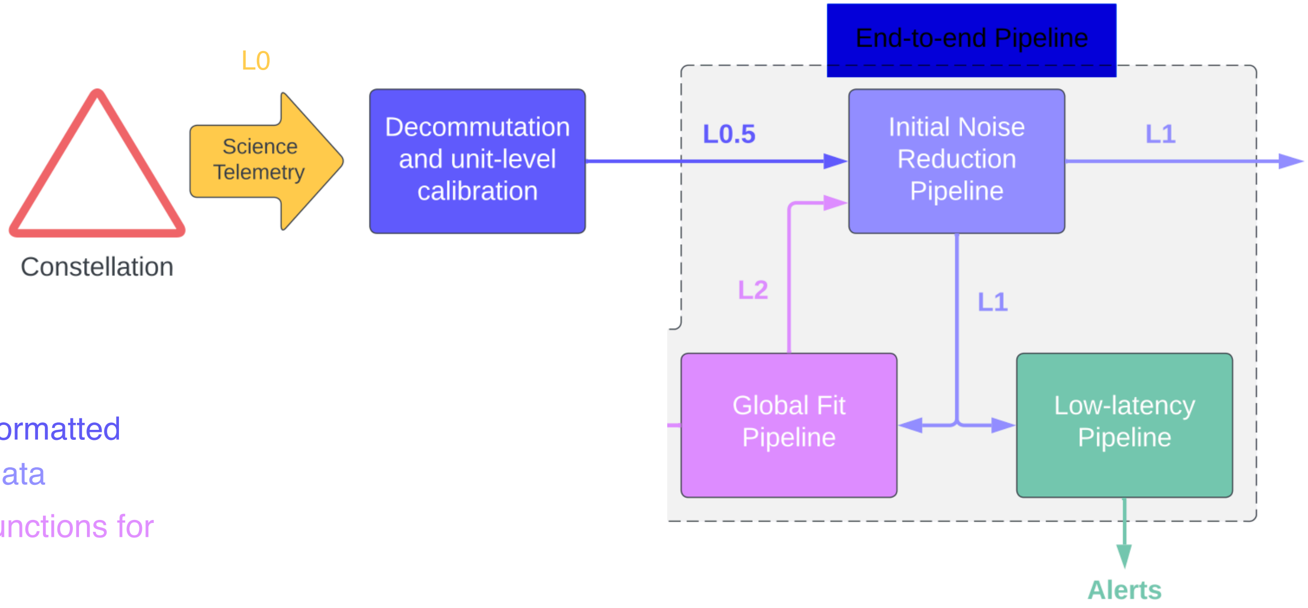

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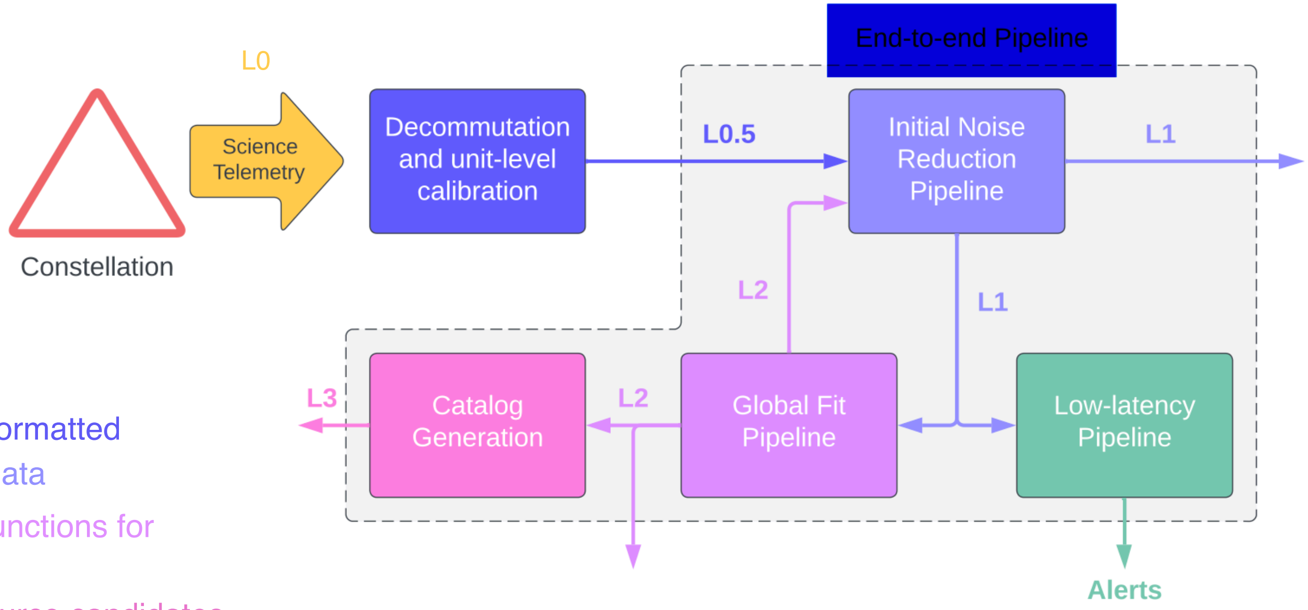

- L0: raw telemetry
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- L1: noise-reduced TDI data
- L2: probability density functions for identified GW sources
- L3: Catalogue of GW source candidates

3. Science observations

- LISA long arm lengths makes it infeasible to have a classic Michelson configuration
- Instead, each link has its own laser source
- Interferometric measurement between the outgoing beam and light coming from distant spacecraft

Combining measurements received from the constellation with suitable time delays suppresses laser frequency noise = **time-delay interferometry**