Université
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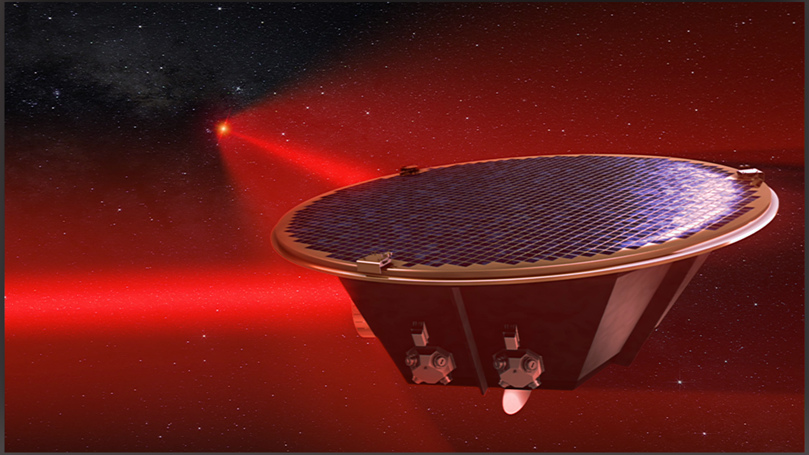
From the Galaxy to Cosmic Dawn:
Peering into millihertz gravitational waves with LISA

Quentin Baghi (APC)

Journées Scientifiques du PNGRAM - Nice - 8 novembre 2023

Layout

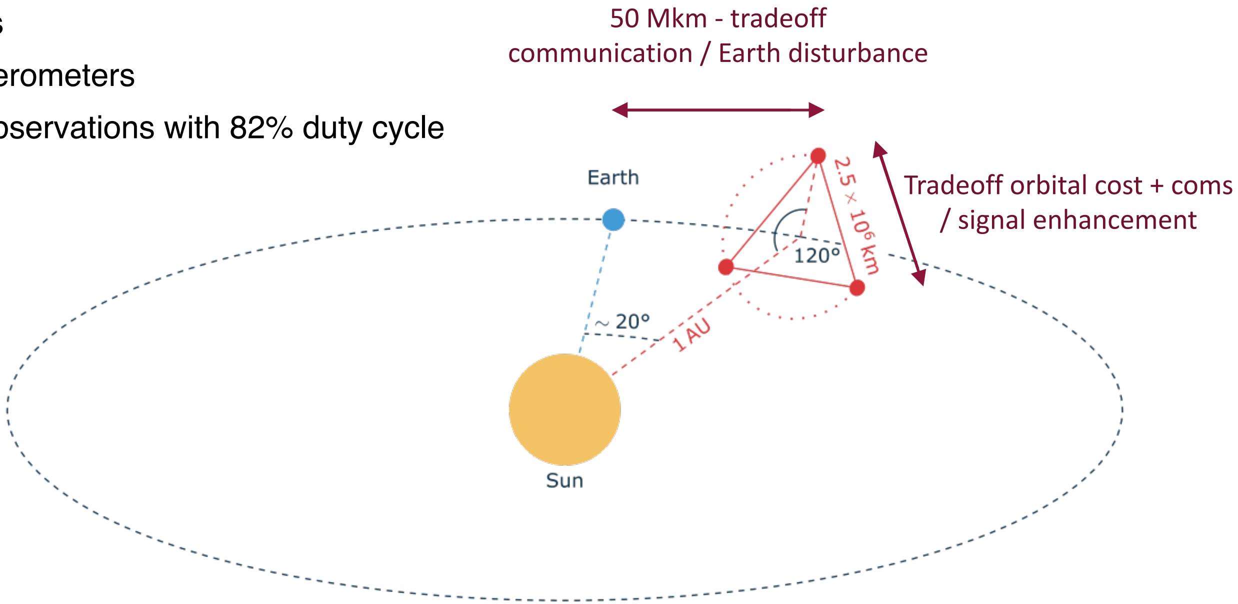


1. Mission concept
2. Science objectives and related challenges
3. Fundamental physics with LISA
4. Towards the future

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

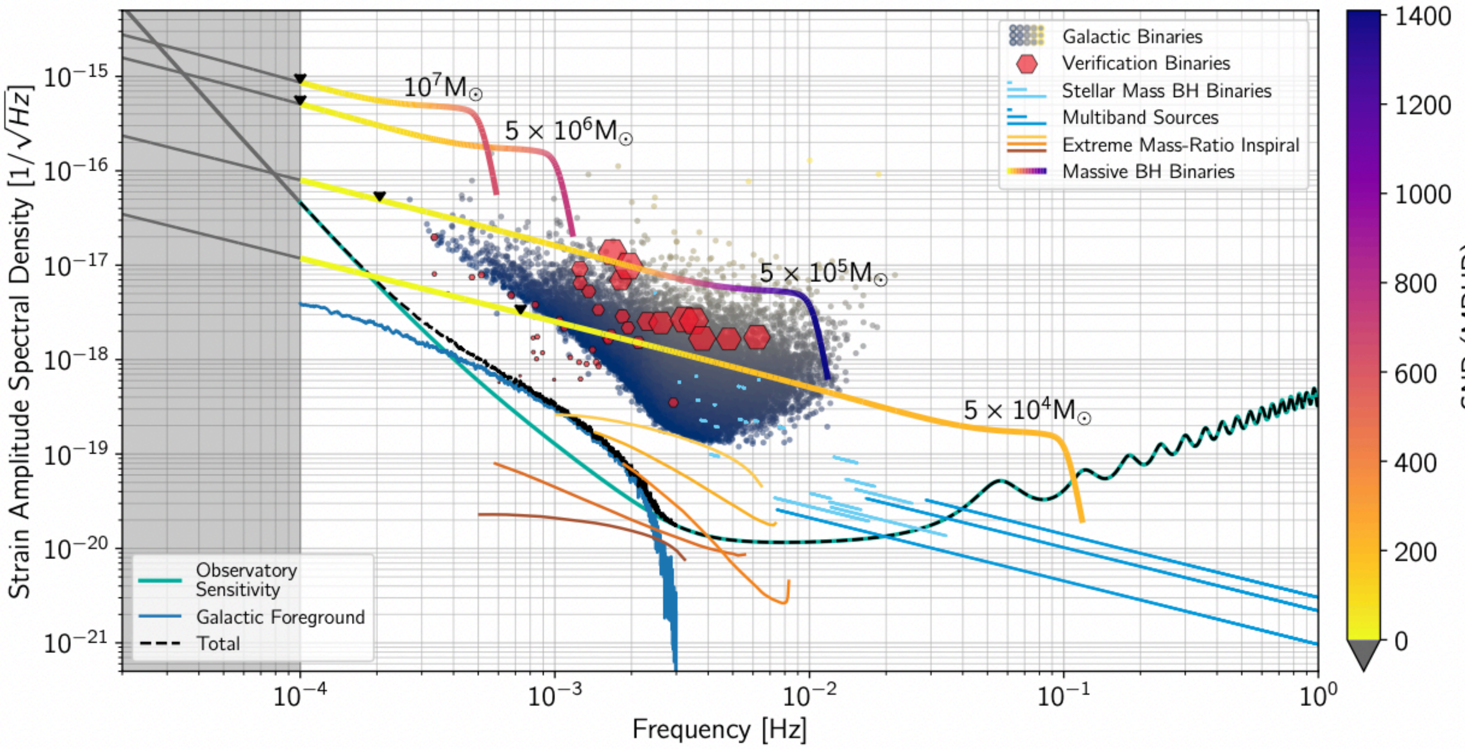
1. Mission concept

- 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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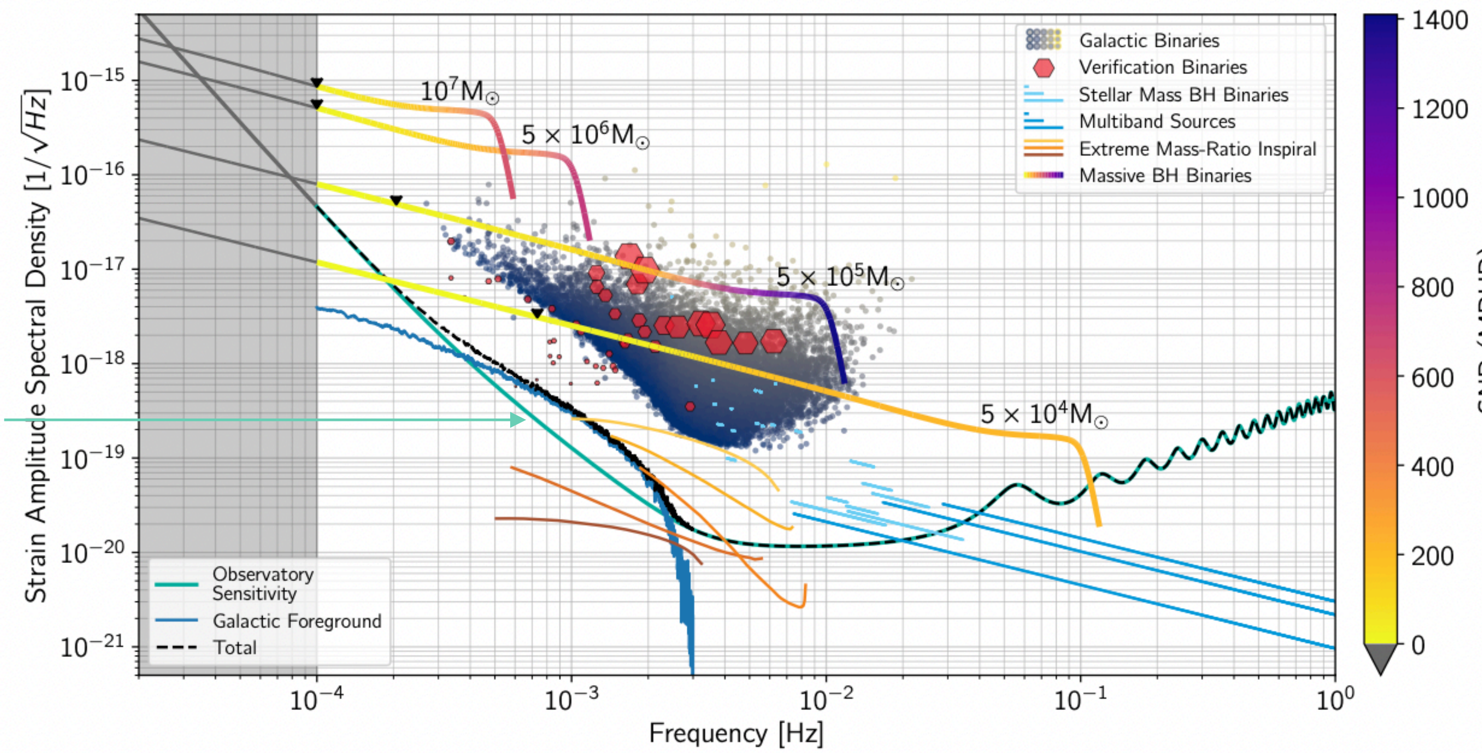
Sensitivity: noise PSD / GW response



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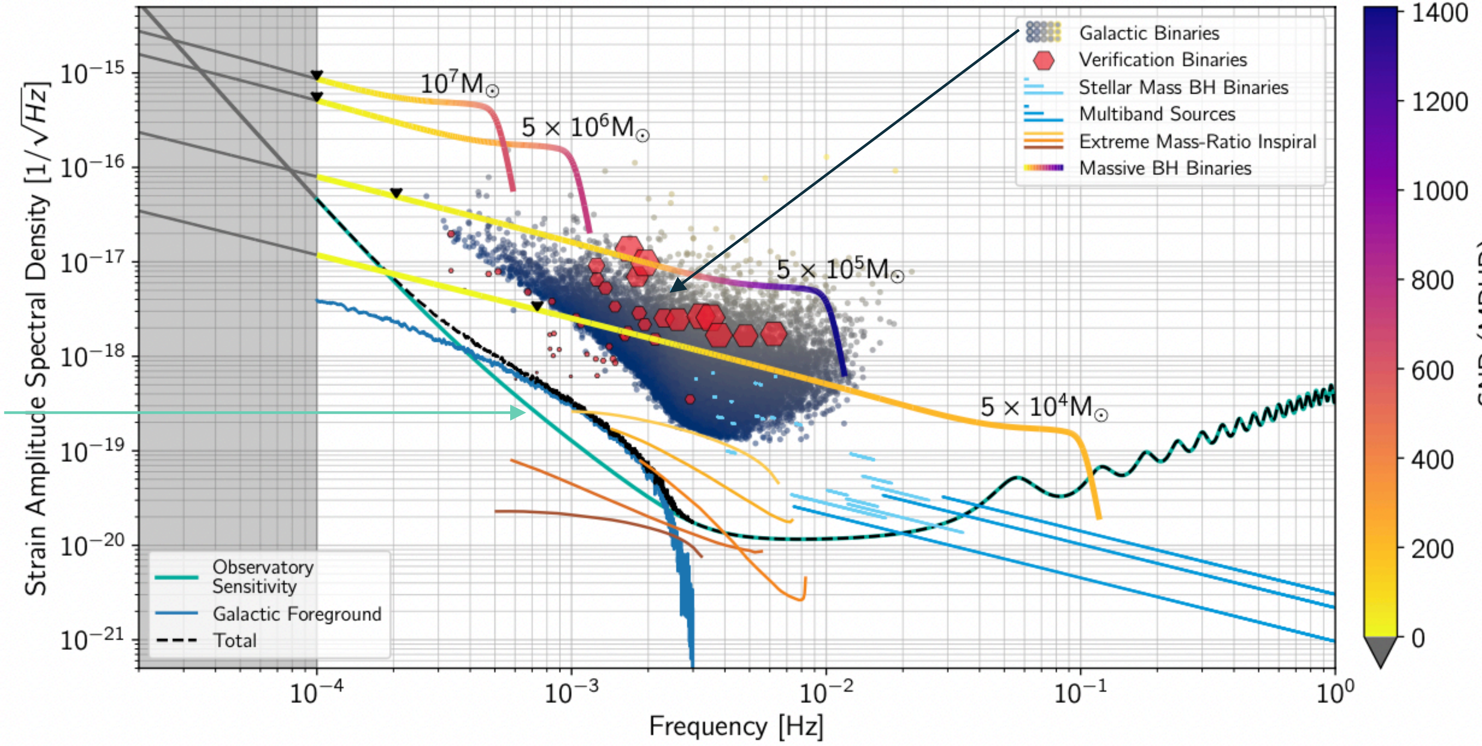

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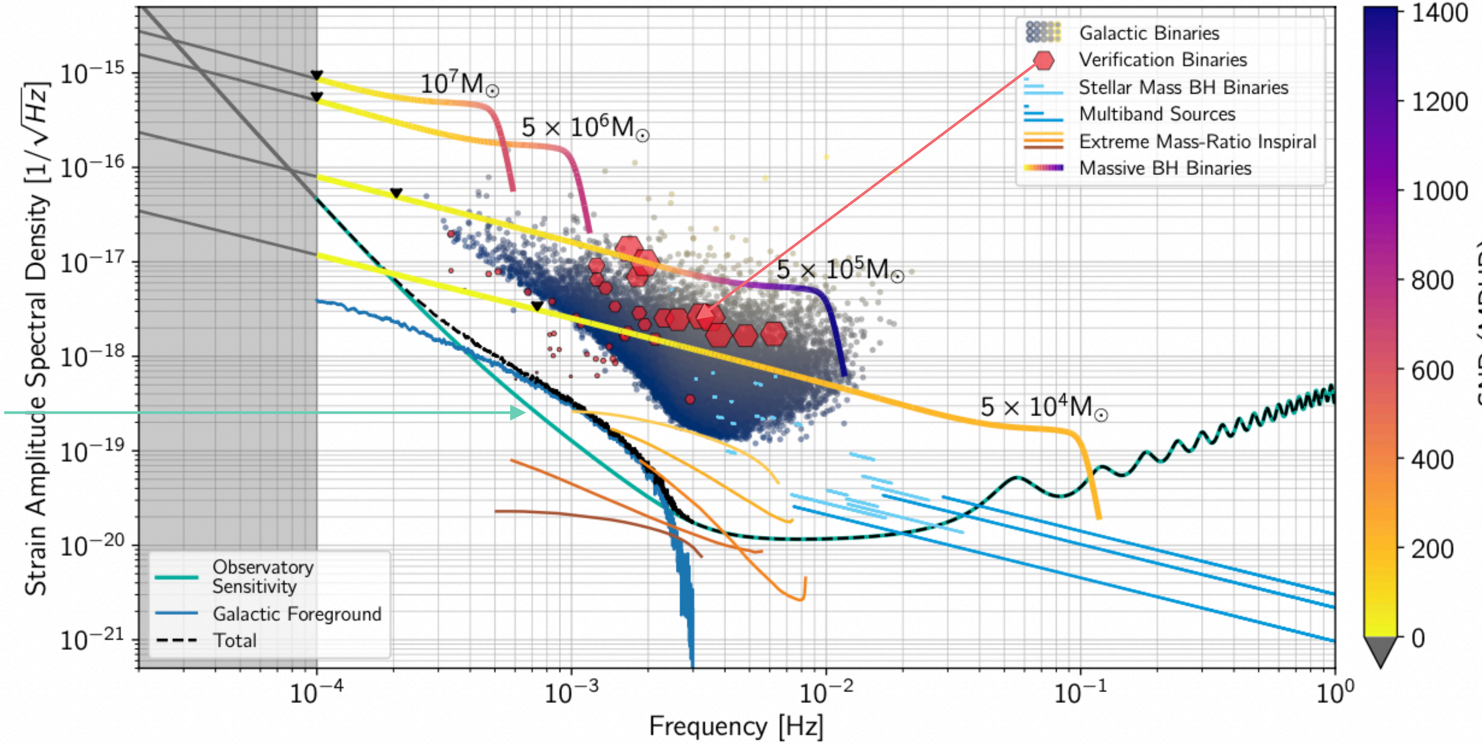

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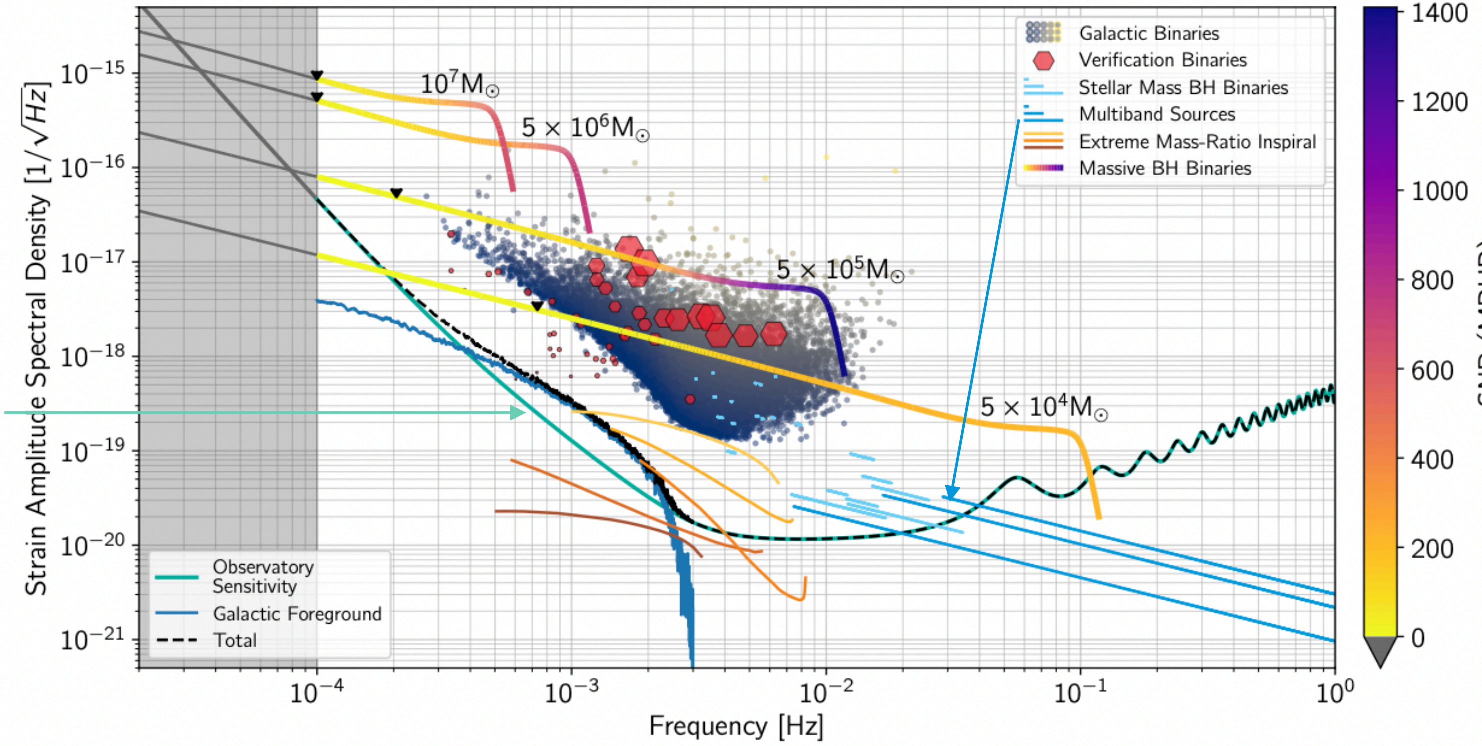

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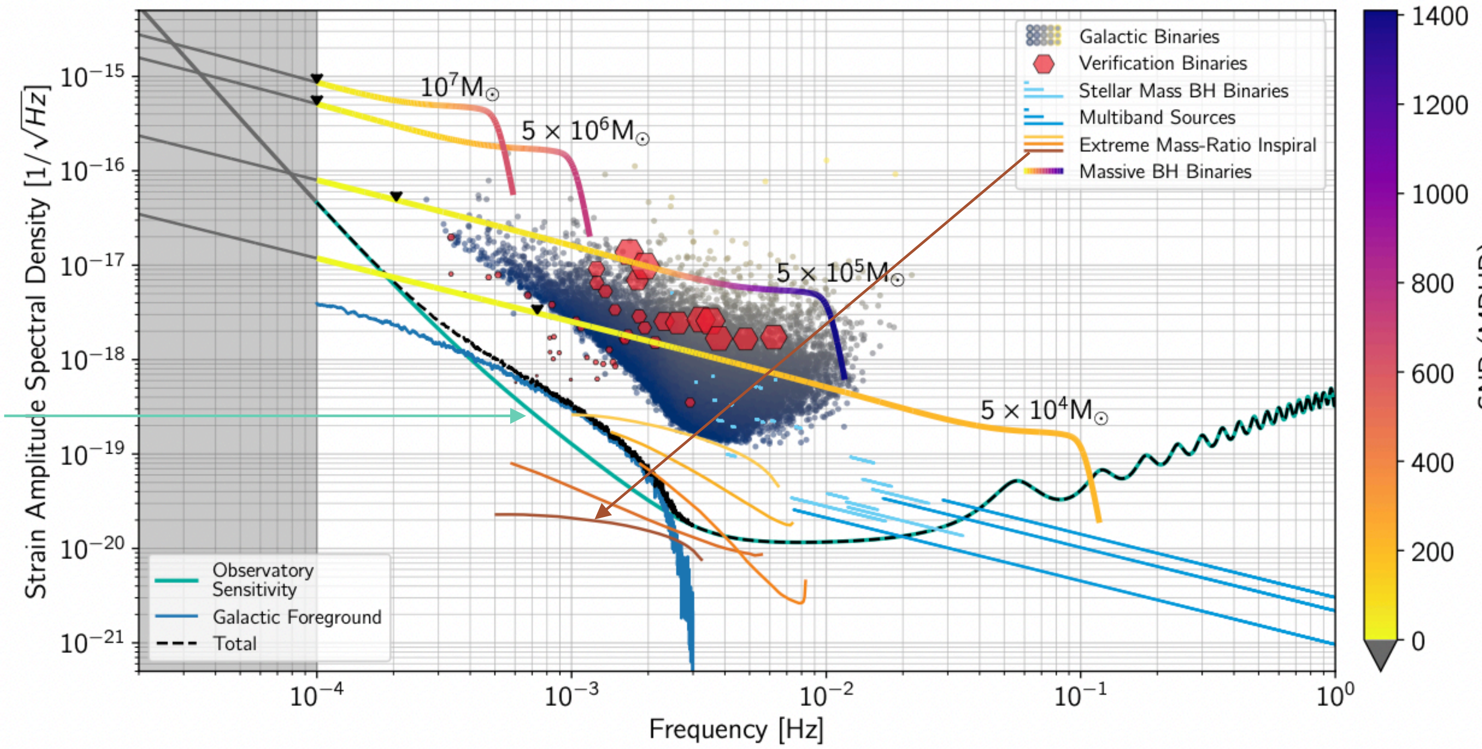

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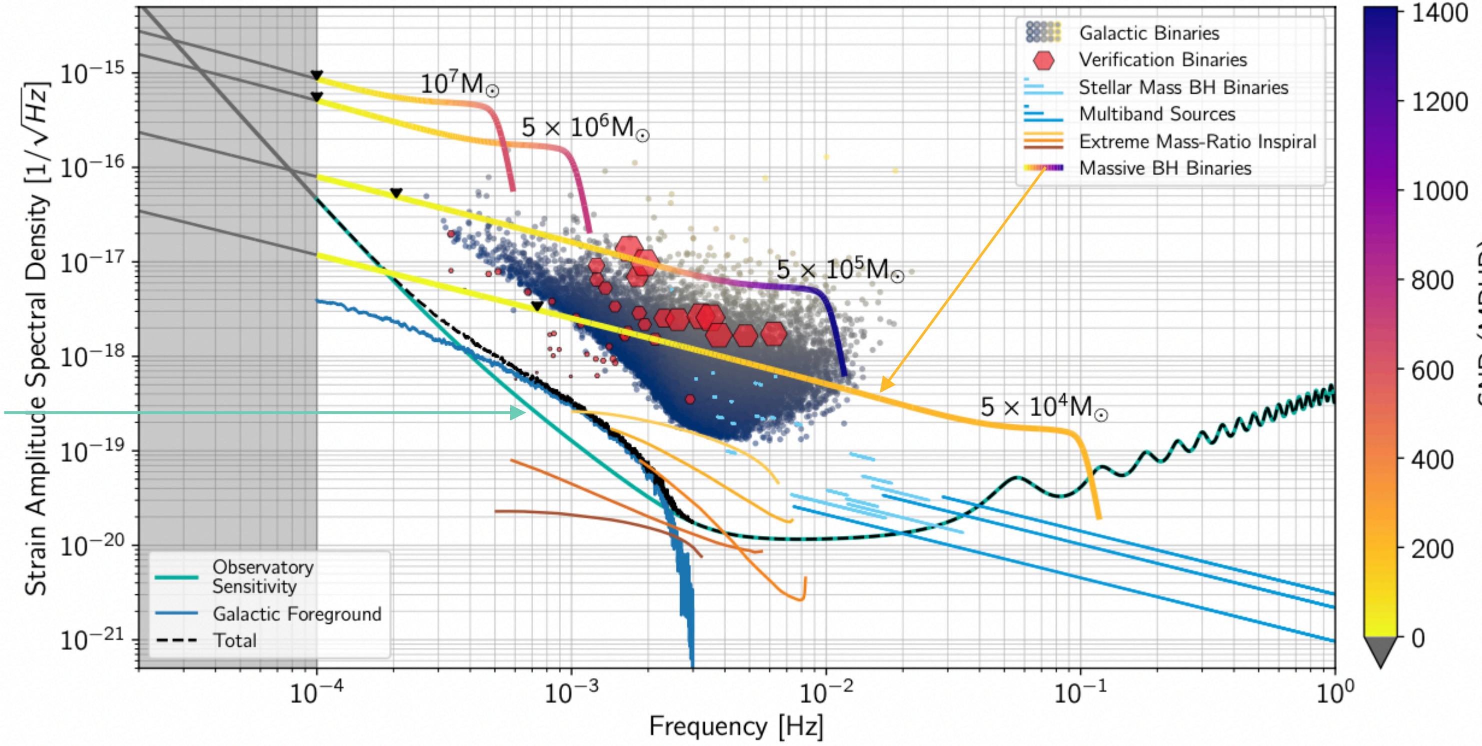
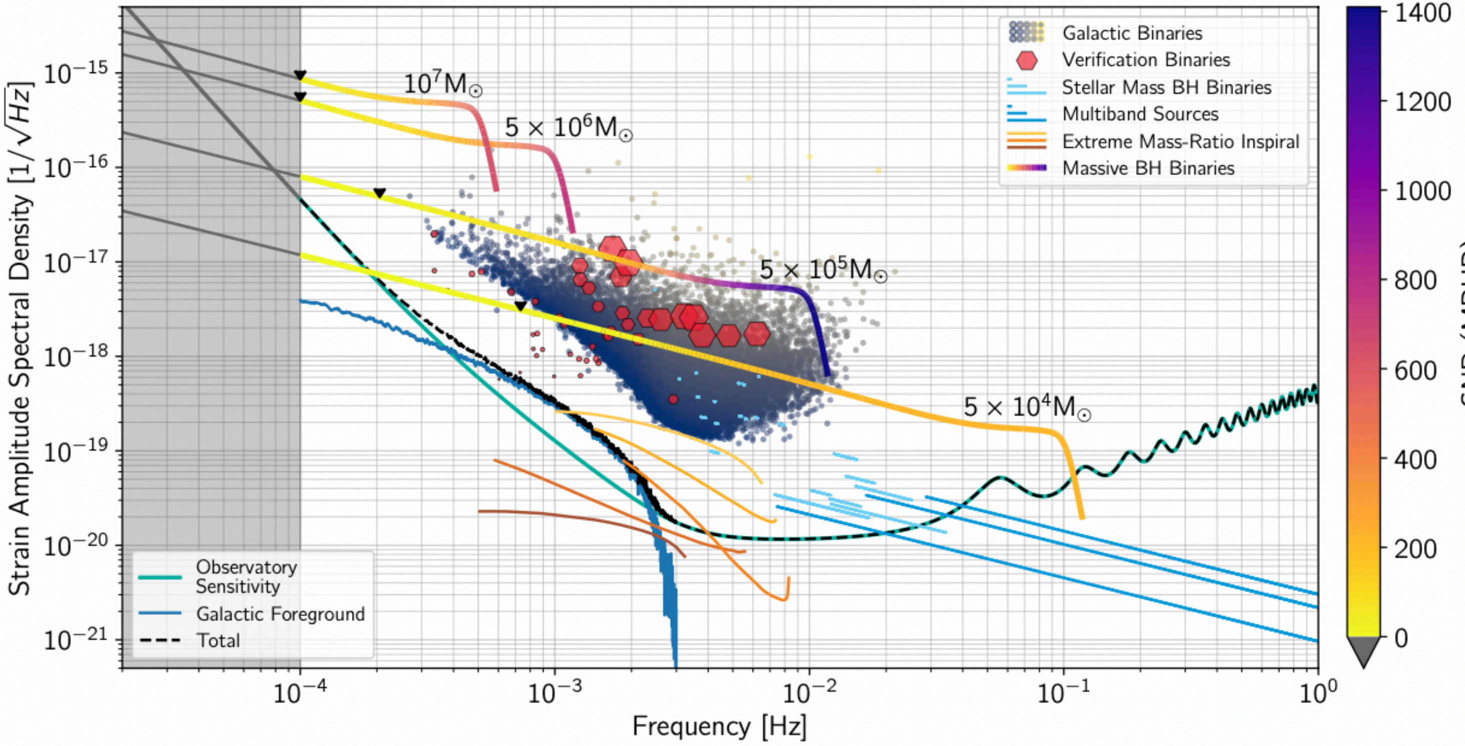


2. Science objectives

— SO1: Study compact binary stars evolution and Galaxy structure



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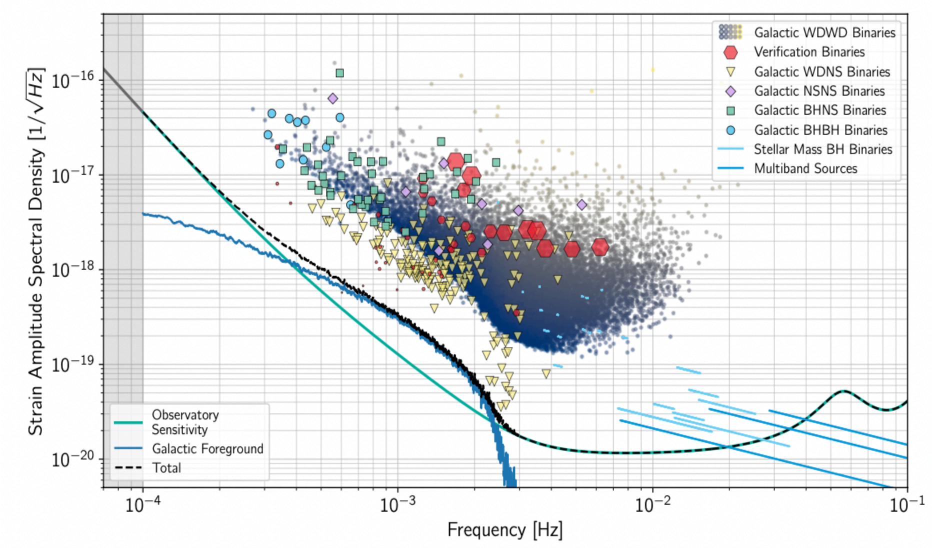

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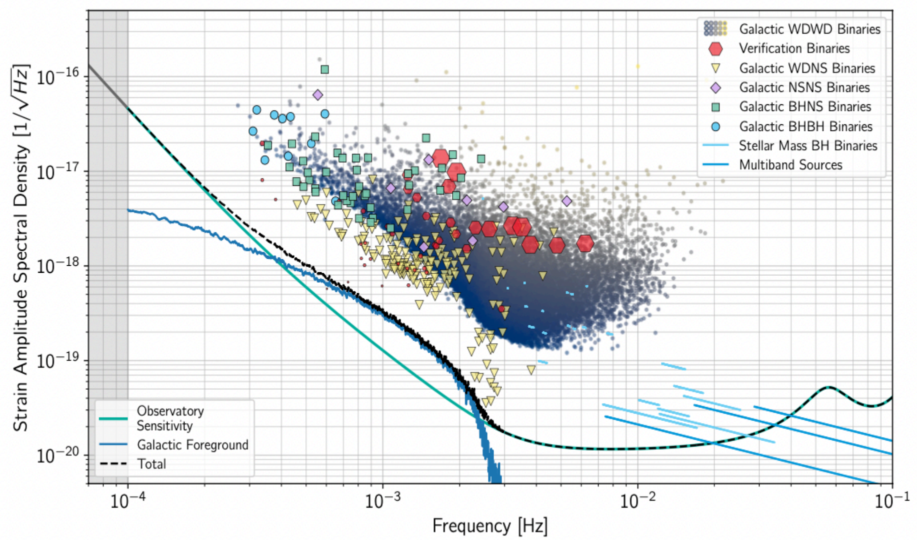
SO1: Study compact binary stars evolution and Galaxy structure

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



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— Unresolved sources form a confusion foreground

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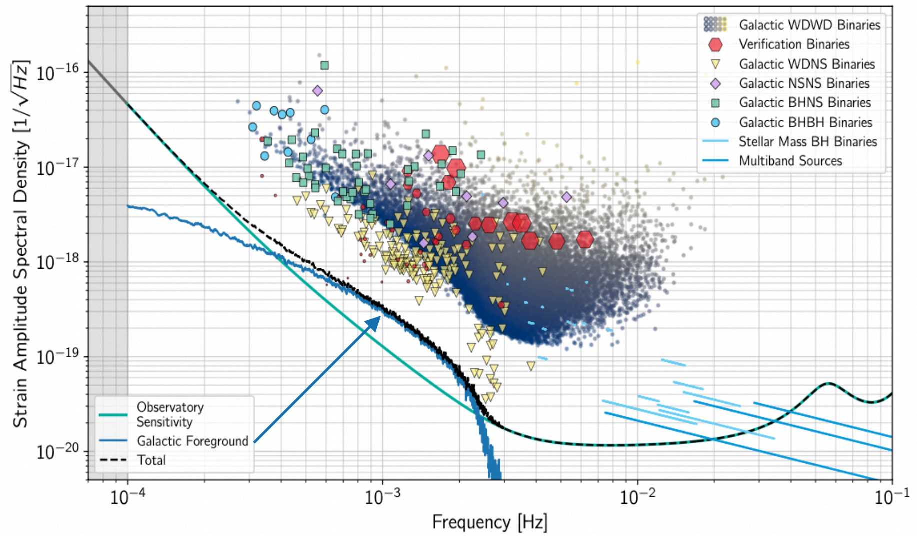

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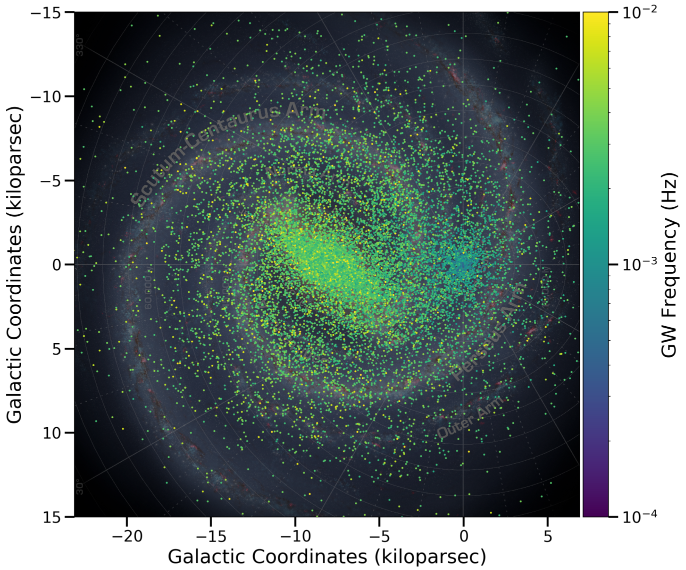
— What is the spatial distribution of ultra-compact binaries?

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



GB sources detected by LISA

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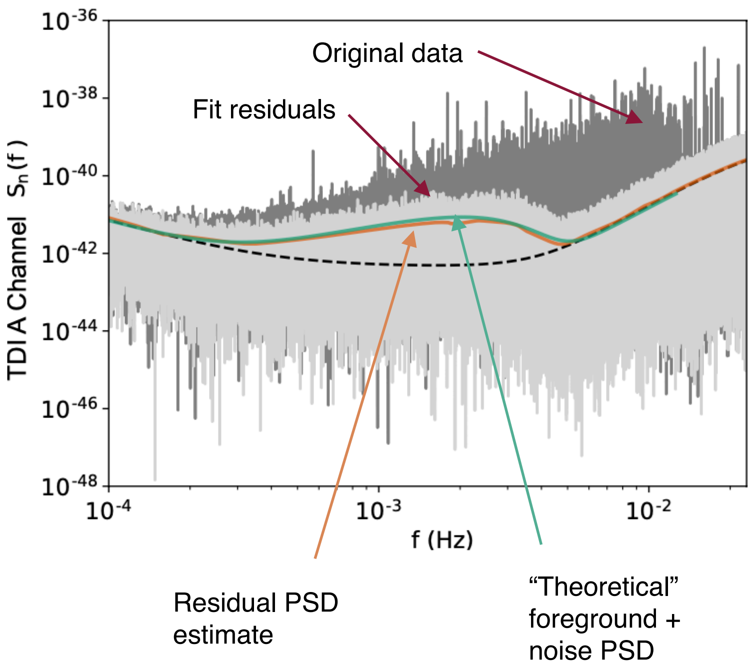
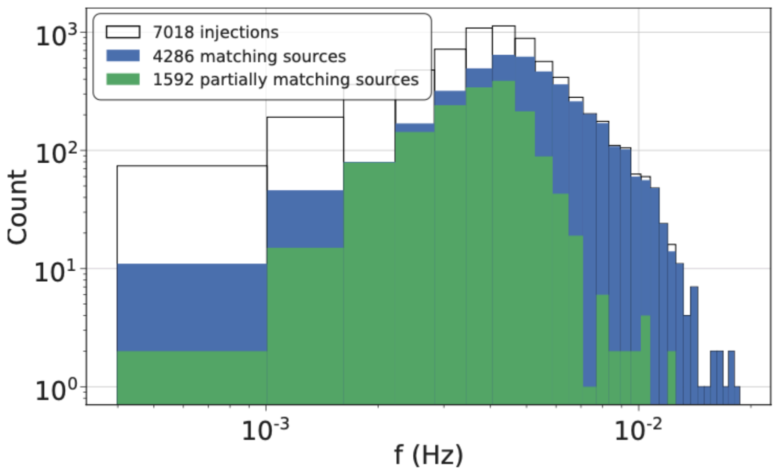
— This is a challenge for data analysis: tens of thousands of continuous, overlapping sources



Prototype pipelines results with LISA Data Challenges 2 data



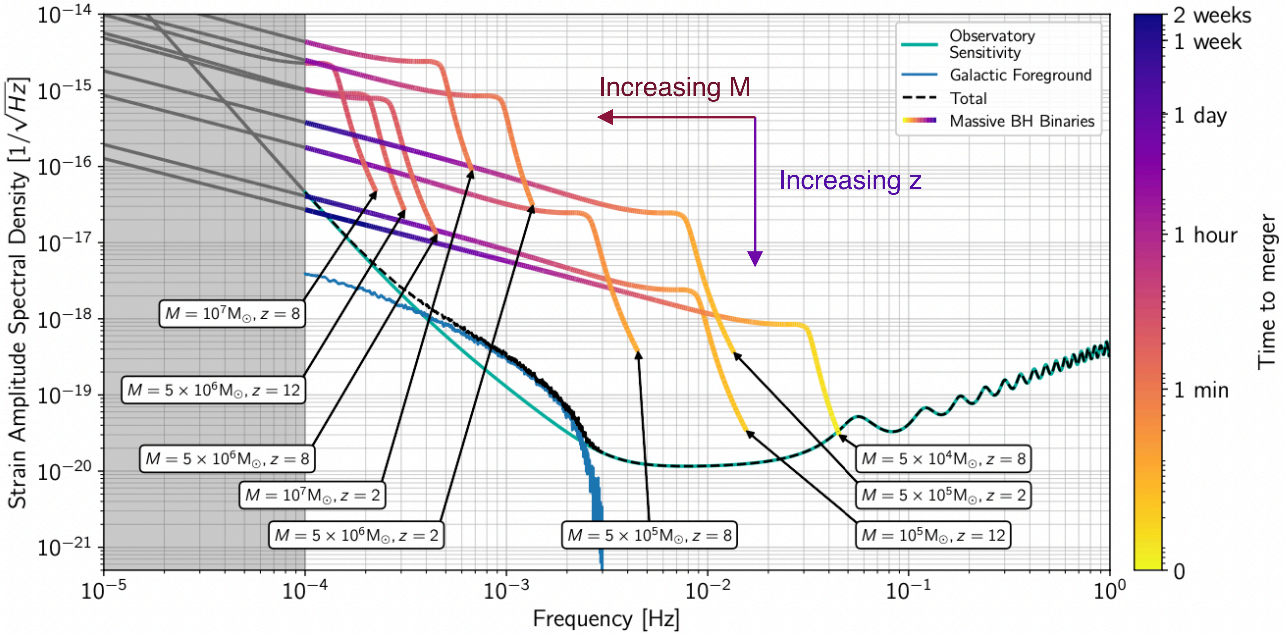
Galactic binary source frequency

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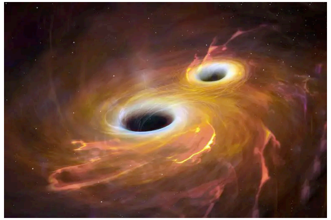
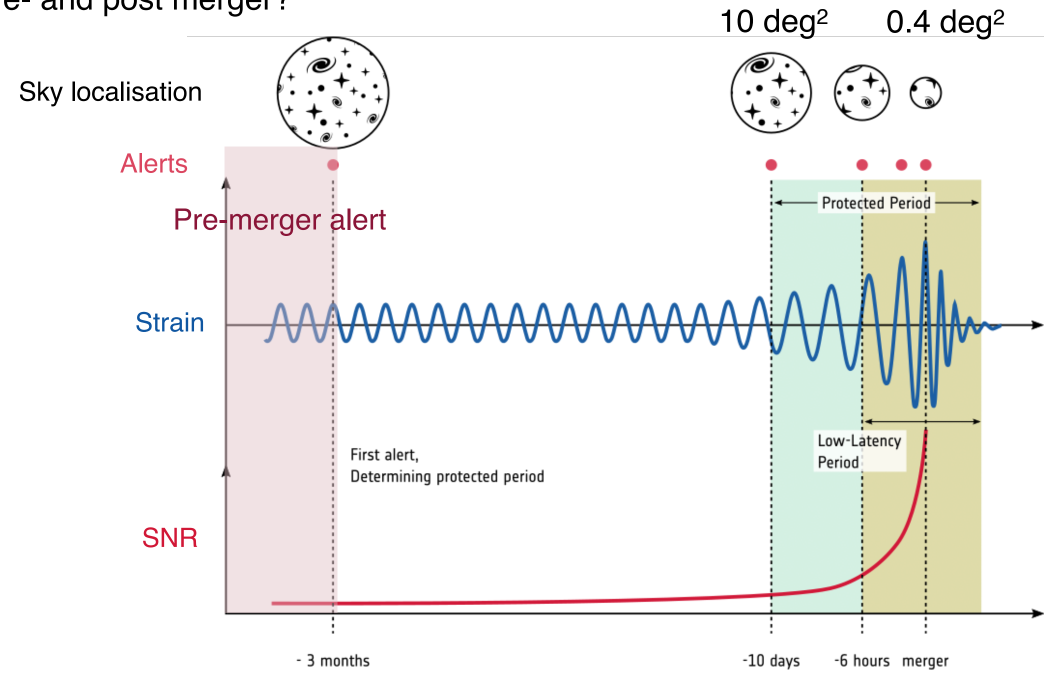
SO2: Trace the origin, growth and merger histories of massive black holes

- Can we identify the host galaxies of detected coalescences?
- Can we detect EM counterparts pre- and post merger?
- What is the role of accretion?





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

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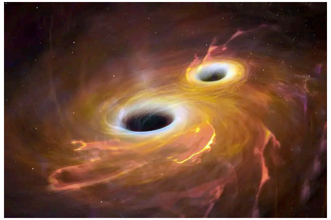

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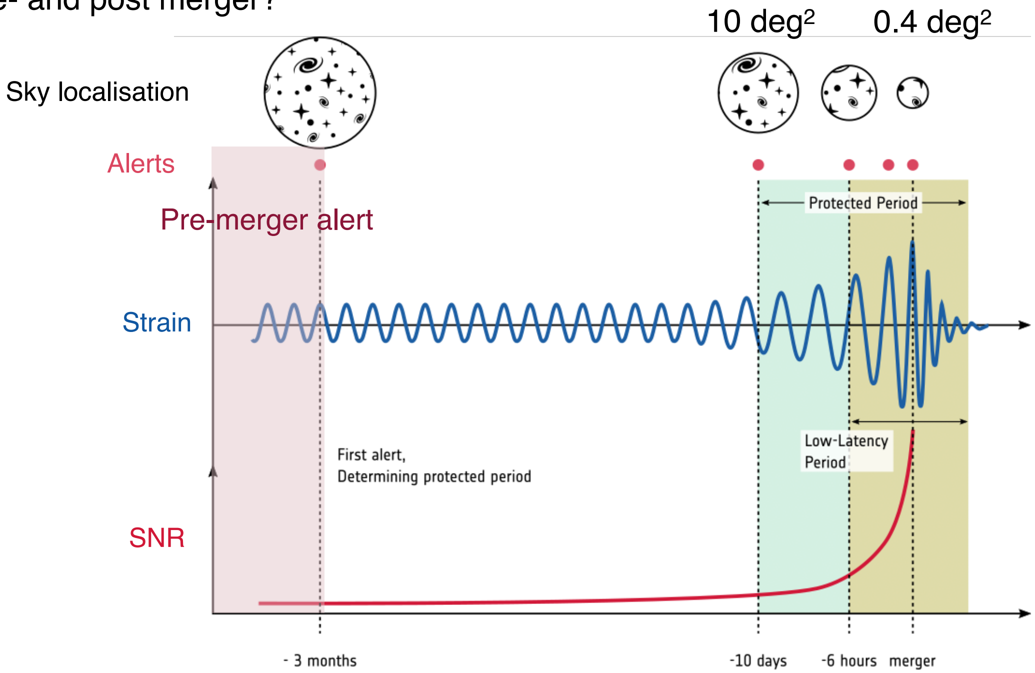

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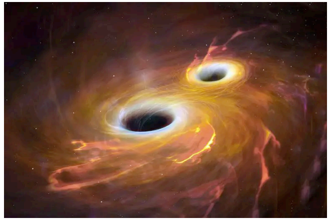
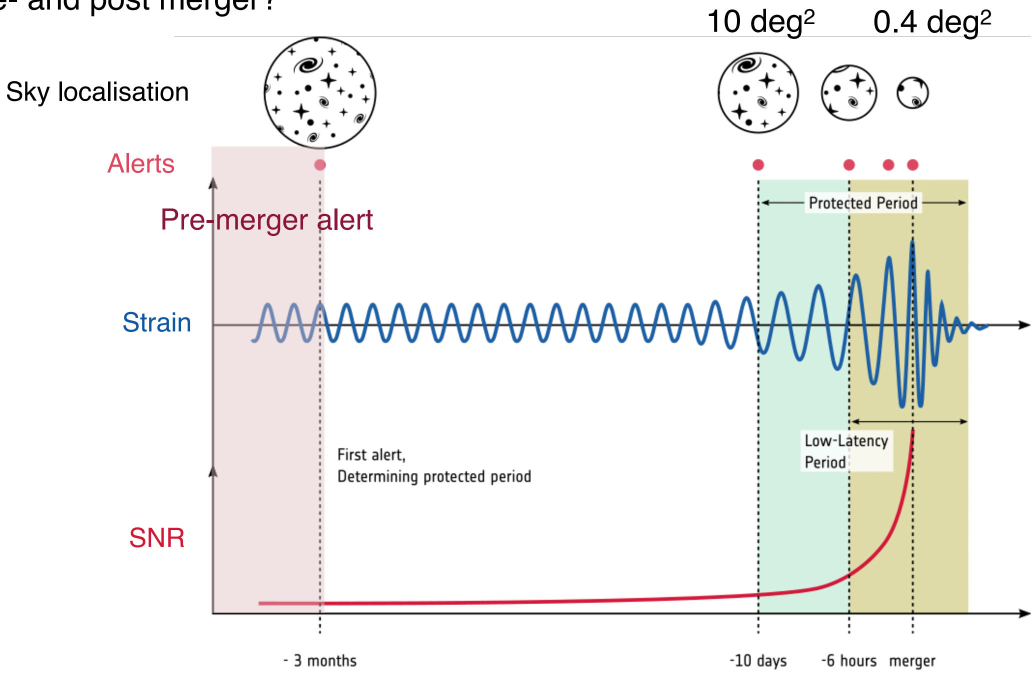


→ Plan observations ahead of time

→ Secure **protected periods**



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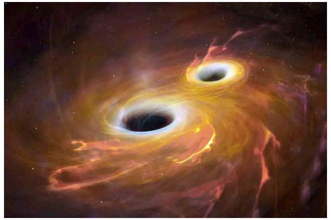

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— Can we identify the host galaxies of detected coalescences?

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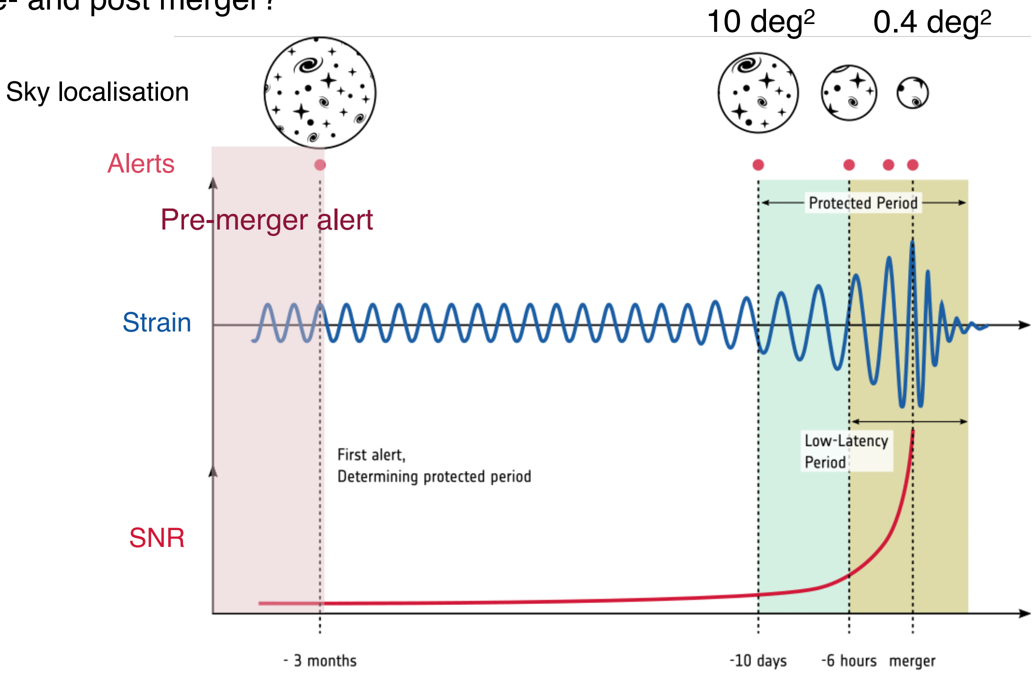
→ Plan observations ahead of time

→ Secure **protected periods**

→ **Low-latency alert** pipeline



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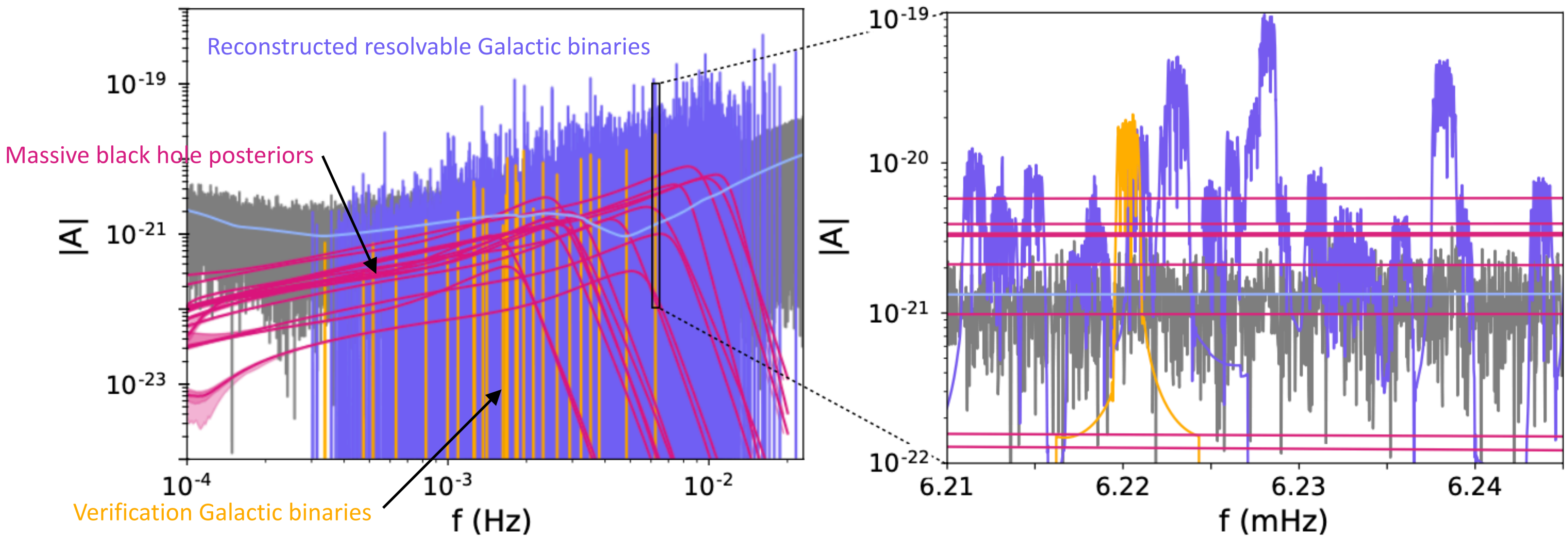
— Source type mixing requires to develop a "global fit" approach

Prototype pipelines results with LISA Data Challenges 2 data



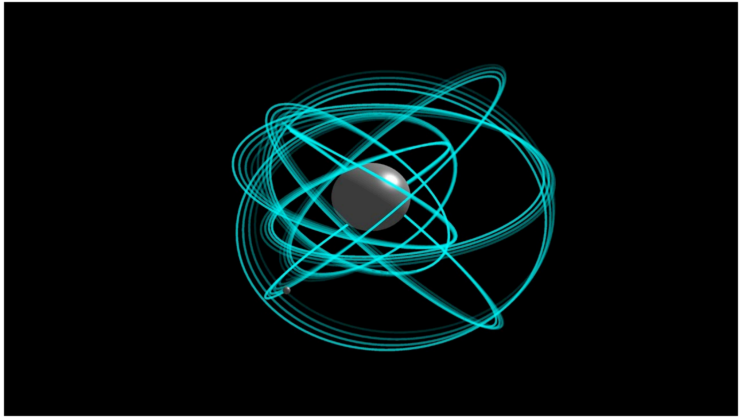
[Littenberg & Cornish 2023]

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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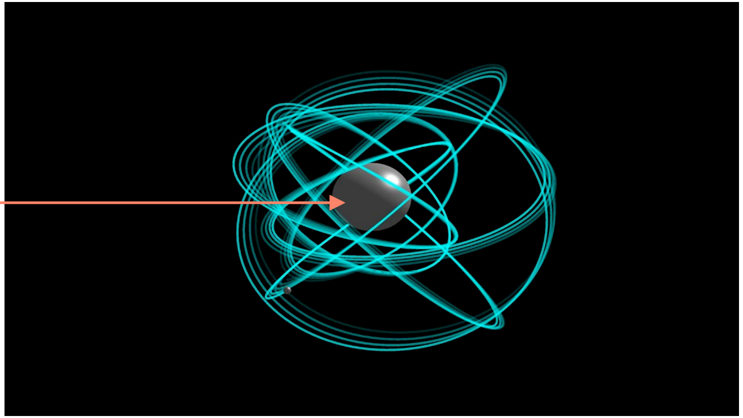

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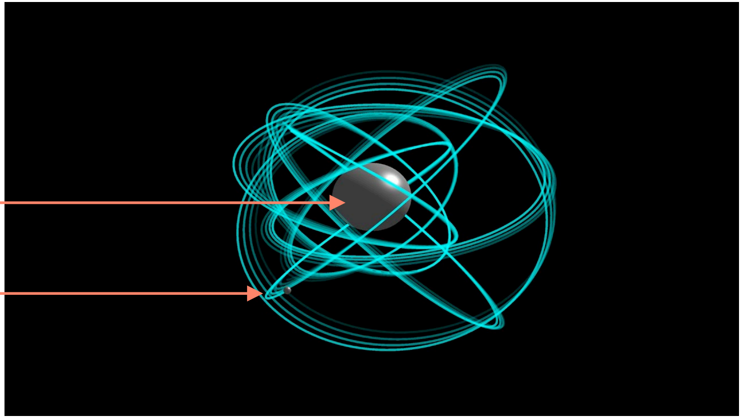

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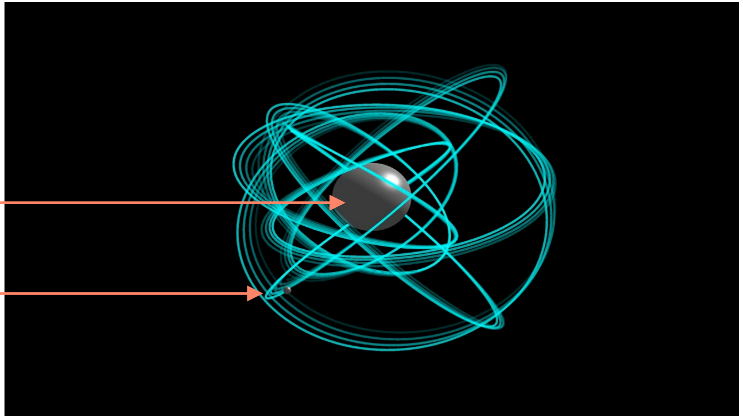

Starting at 3 mHz, takes 1 year to plunge = 10^5 orbital cycles

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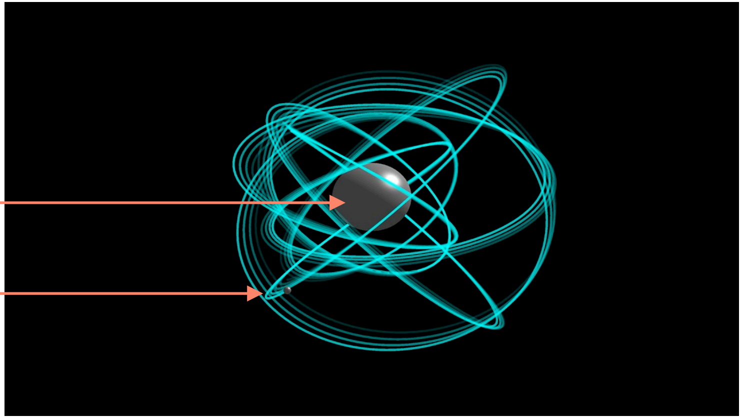

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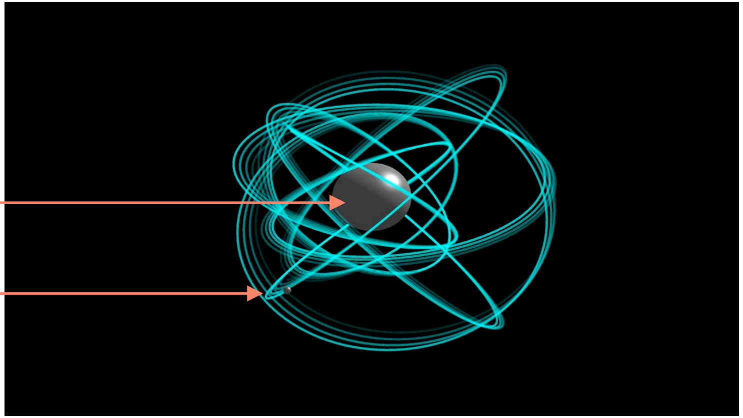

— LISA could detect EMRIs at typical z ~ 3

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

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

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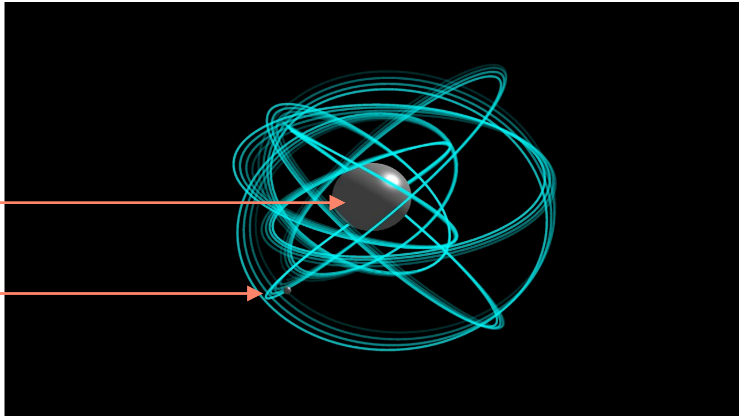

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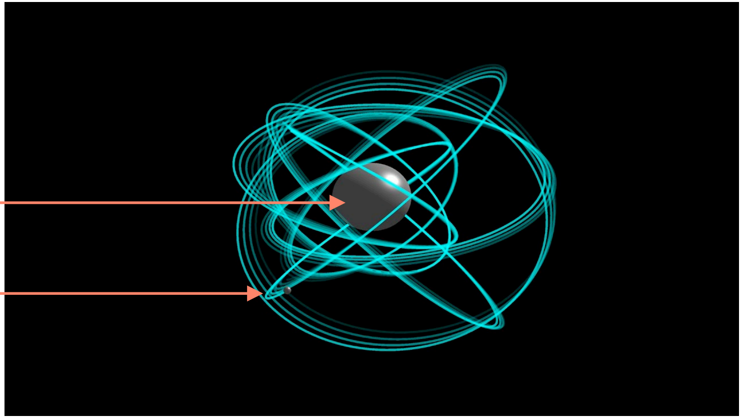

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- LISA could detect EMRIs at typical z ~ 3
  - → Probe astrophysical environments of **quiescent** massive black holes → co-evolution with host galaxies
  - → Measure cosmological parameters
  - → Test fundamental physics: test whether massive compact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

2. Science objectives

SO4: Understand the astrophysics of stellar-mass black holes

SO5: Explore the fundamental nature of gravity and Black Holes

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

SO7: Understand stochastic GW backgrounds

SO8: Search for GW bursts and unforeseen sources

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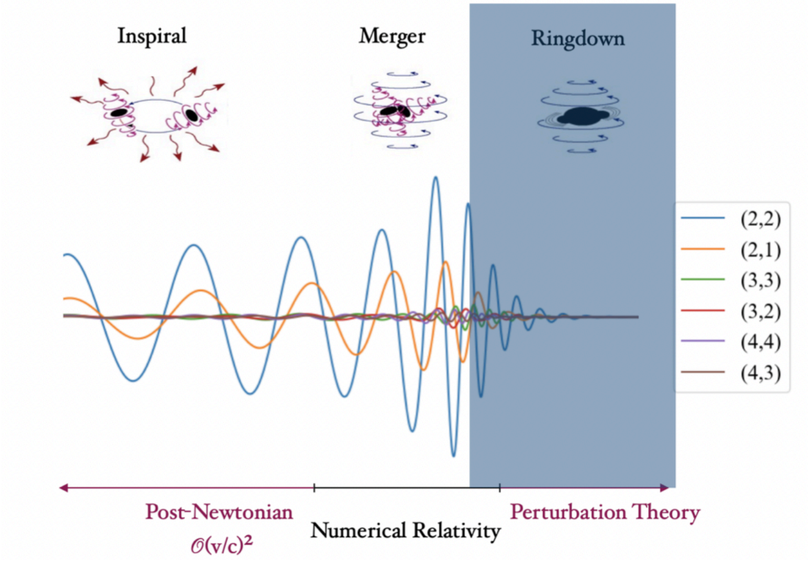
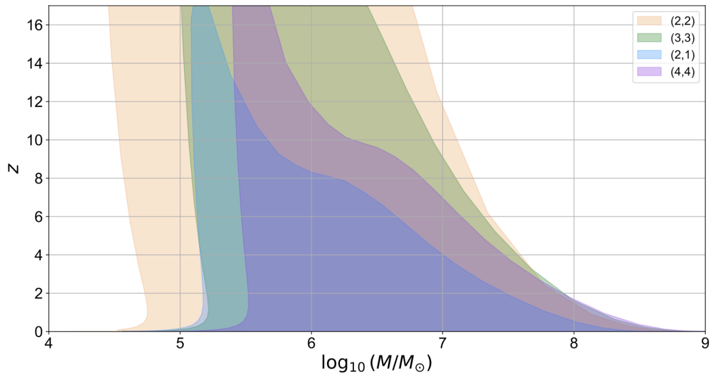
Overlaps with fundamental physics

3. Fundamental physics with LISA

- High signal-to-noise sources → precise tests of general relativity
- Test the nature of merger remnants with ringdown → black hole spectroscopy



[Chantal Pitte's courtesy]



Horizon redshift for the detection of fundamental ringdown quasi-normal modes

3. Fundamental physics with LISA

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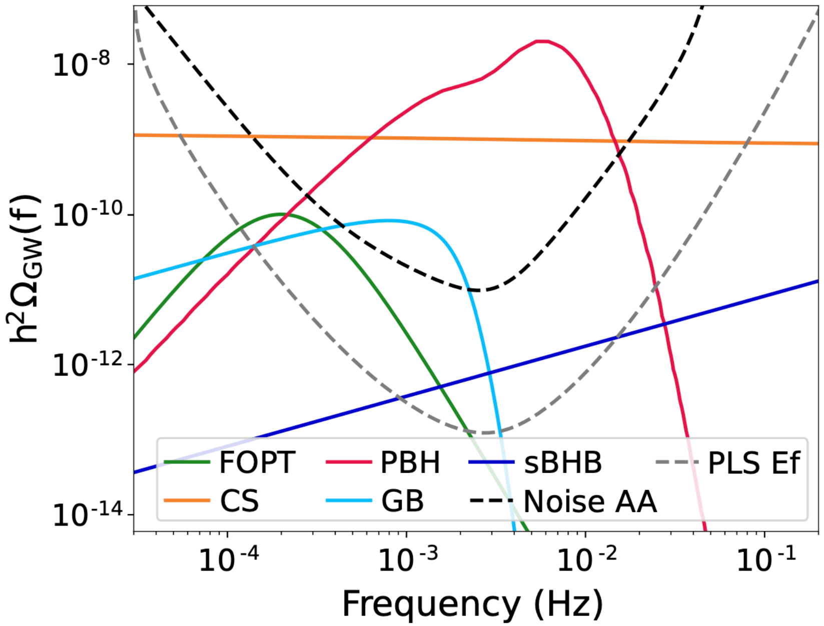
— Detecting a stochastic GW background of cosmological origin would be **groundbreaking discovery**



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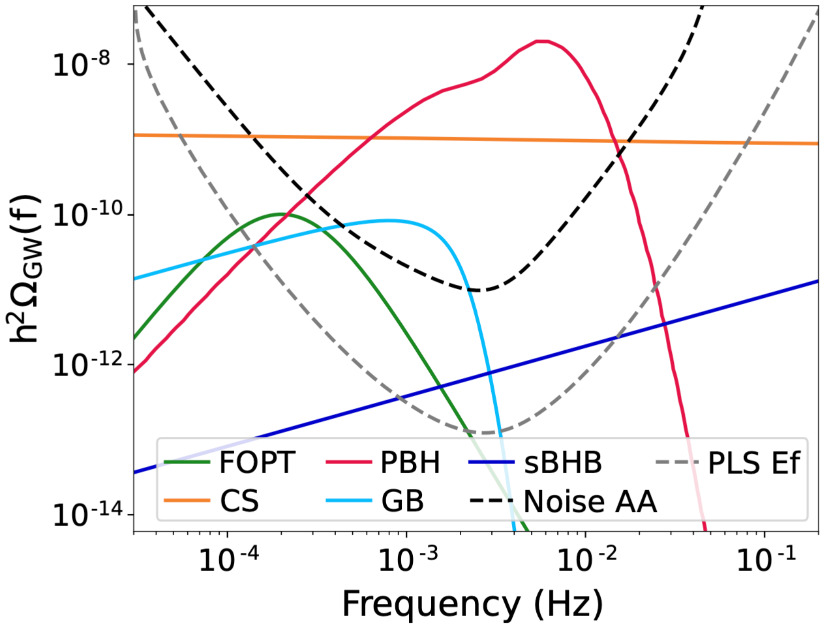

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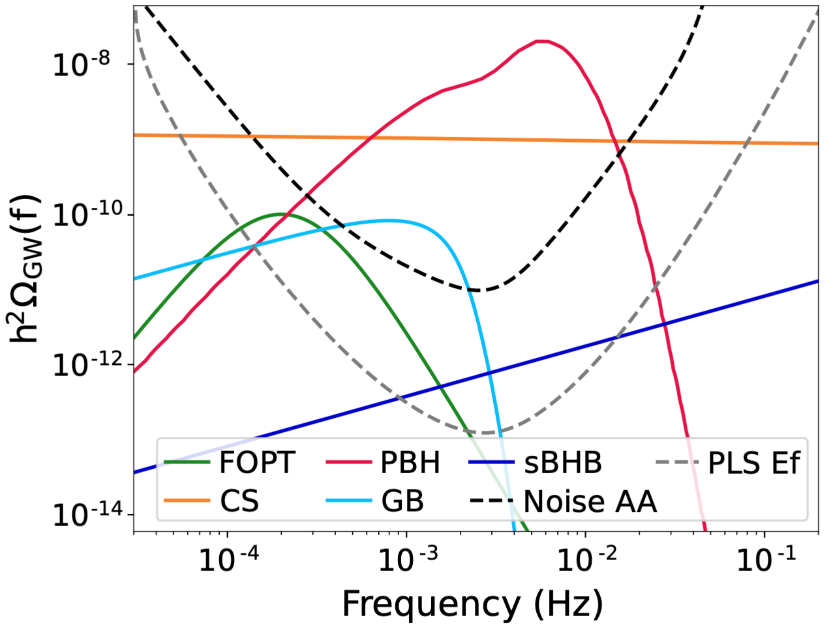
- But challenging data analysis task [Baghi et al. 2023]!



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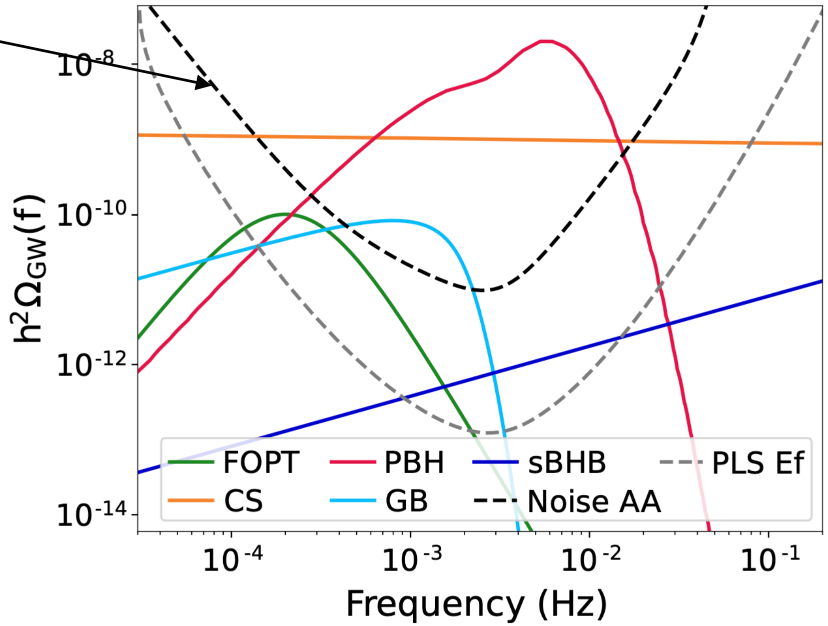
Energy density noise PSD



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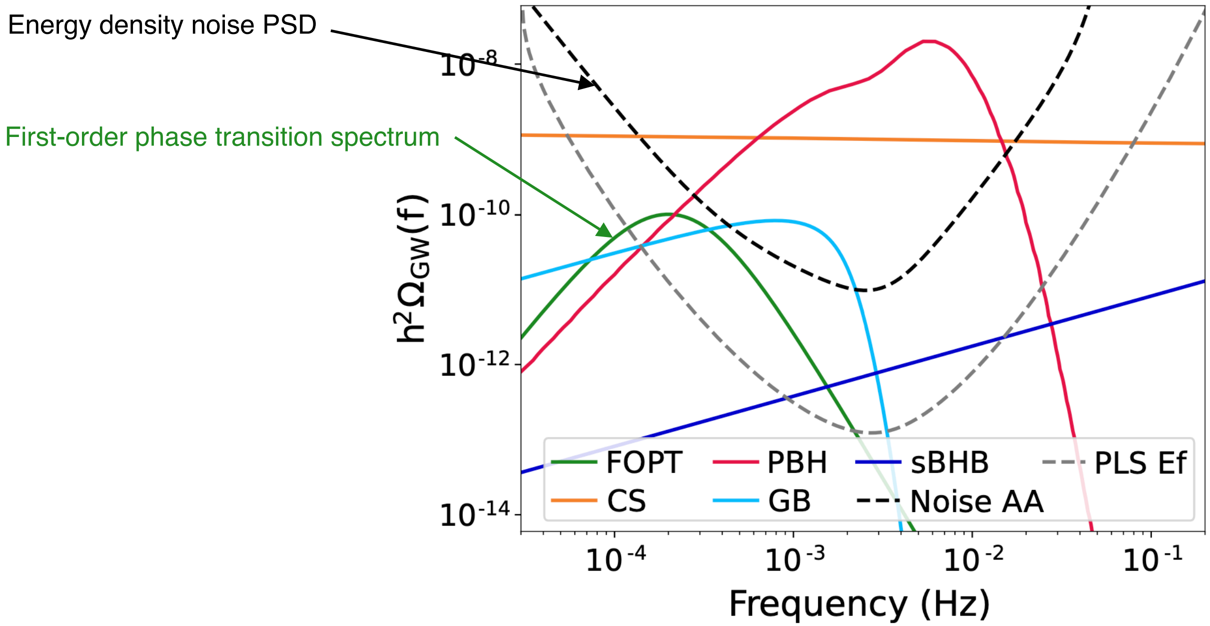

Conclusion: bright future and many challenges

Science Program Committee (SPC)
Decision
Mission Adoption

Decision milestones

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	2035

Conclusion: bright future and many challenges

We are here

Science Program Committee (SPC) Decision
Mission Adoption

	Phase A		Phase B1		Phase B2/C/D	Phase E
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!*	
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See also Ouali Acef and Maxime Vincent's talks!

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Mission Adoption

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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	2035

Thank you for you attention!

See also Ouali Acef and Maxime Vincent's talks!

Back-up slides

2. Science objectives

SO1: Study compact binary stars evolution and Galaxy structure

- How do binary compact stars interact?
- How do they evolve?

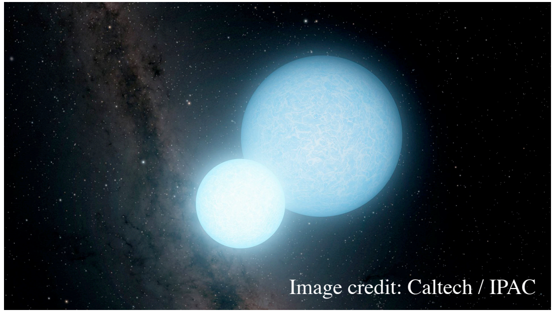
Image credit: Caltech / IPAC

GB sources detected by LISA + confusion foreground

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Population of compact binaries in the Milky Way vs frequency

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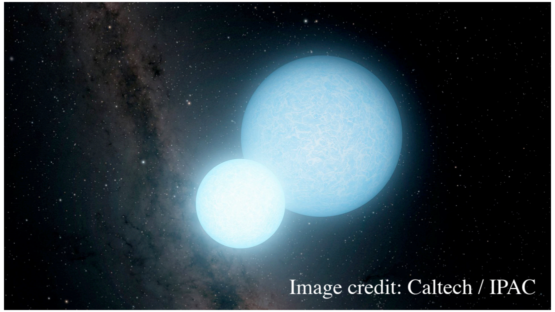

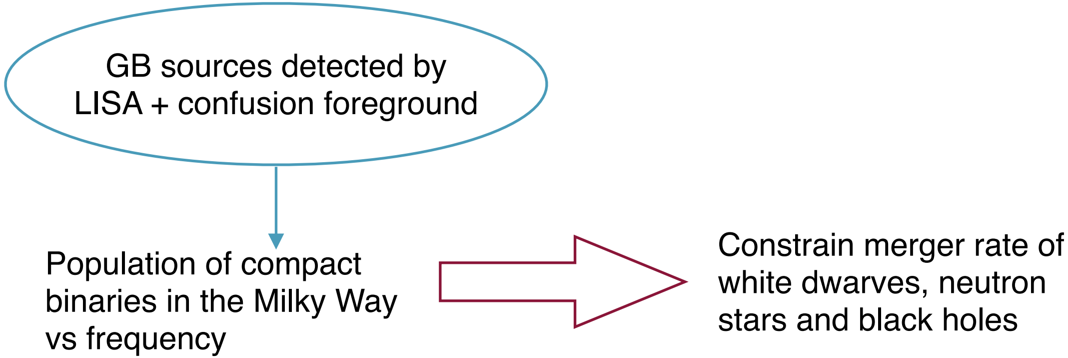

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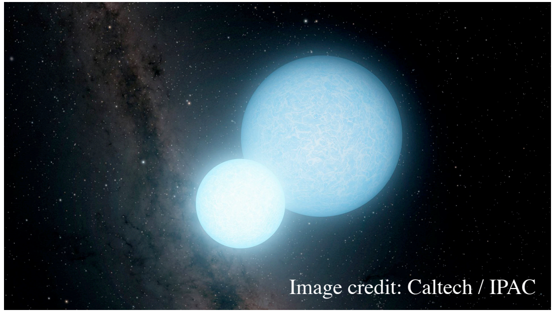

GB sources detected by LISA + confusion foreground

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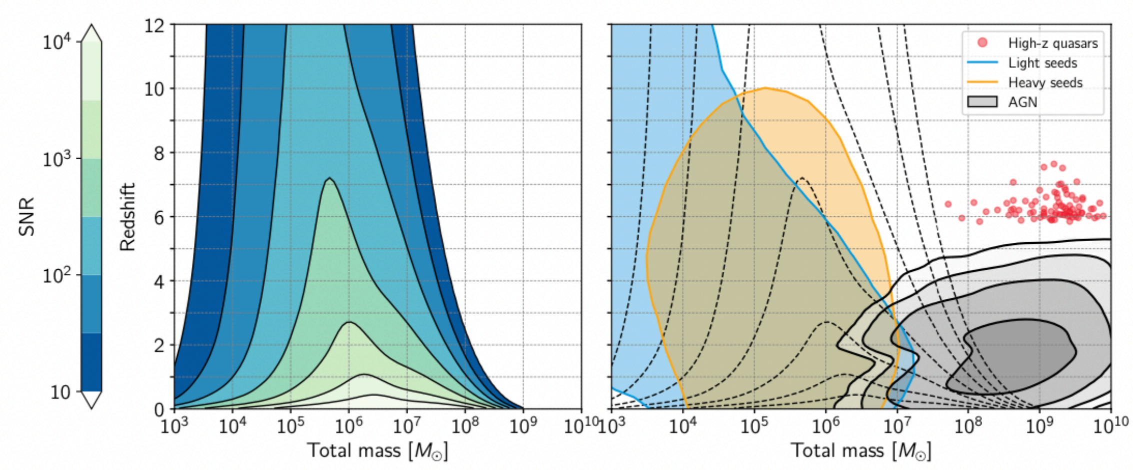
SO2: Trace the origin, growth and merger histories of massive black holes

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



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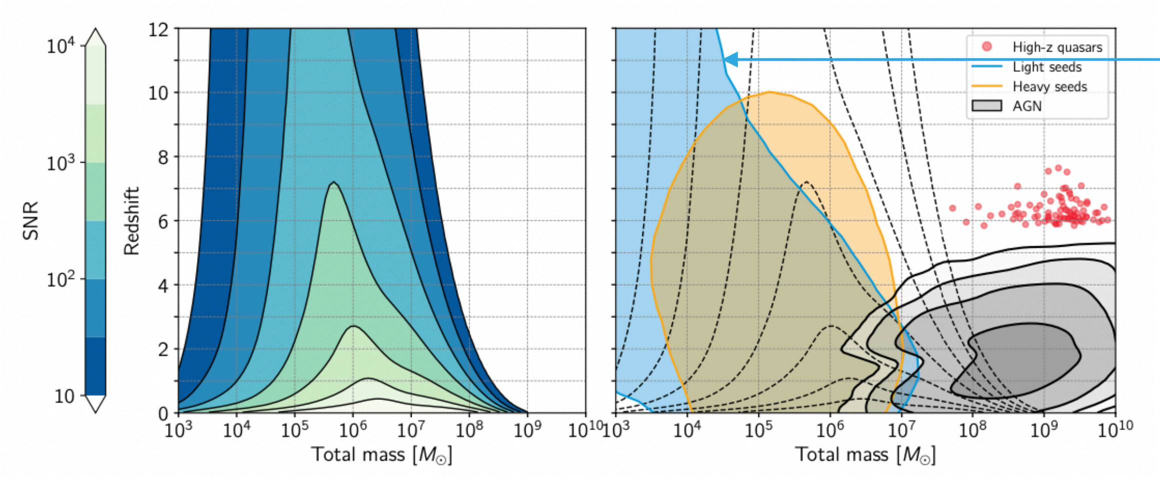

Simulated MBHB resulting from light seeds

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

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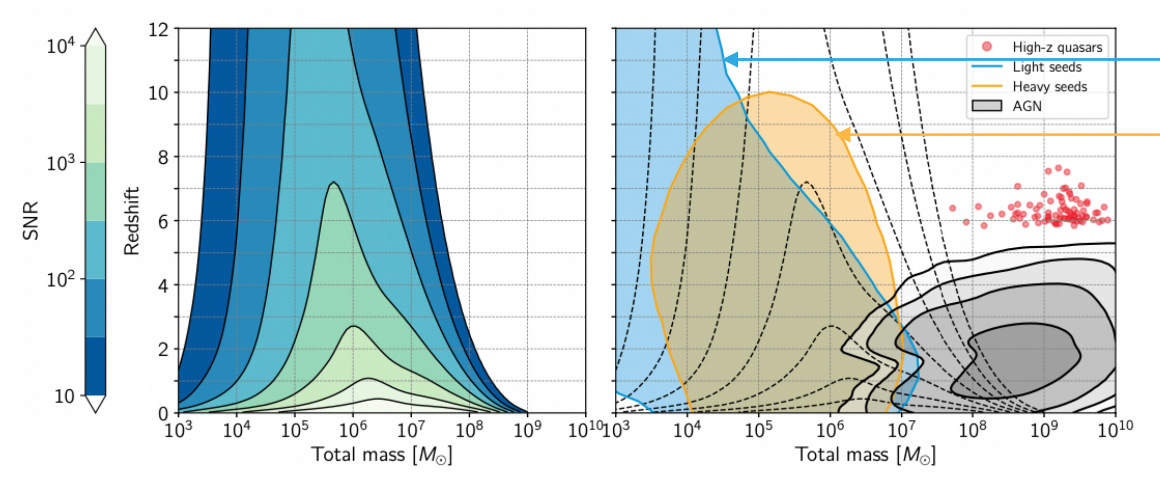

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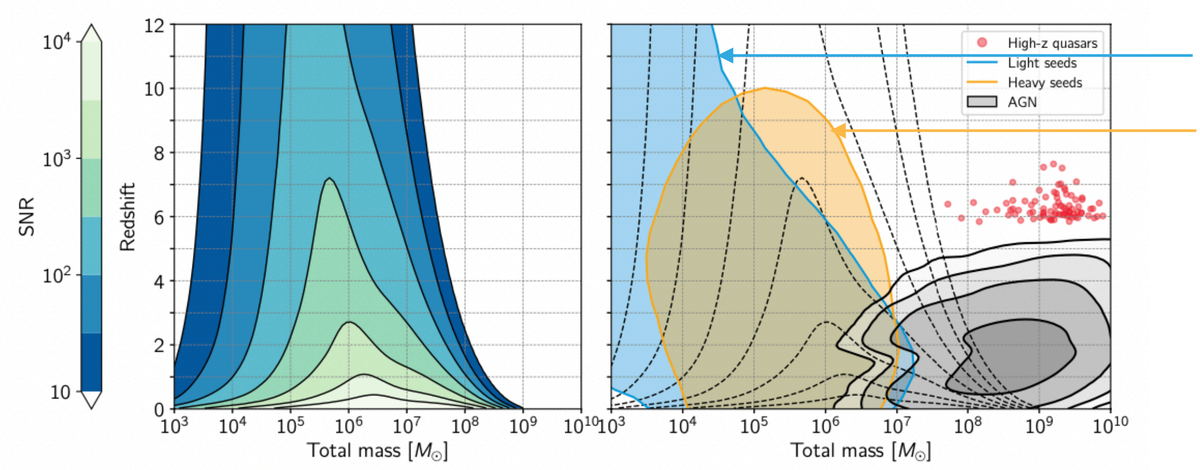

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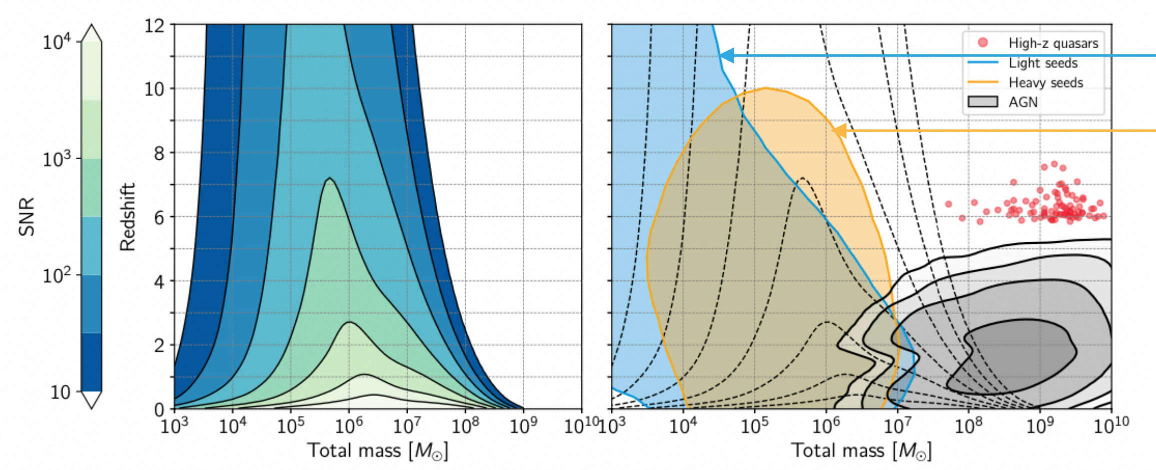

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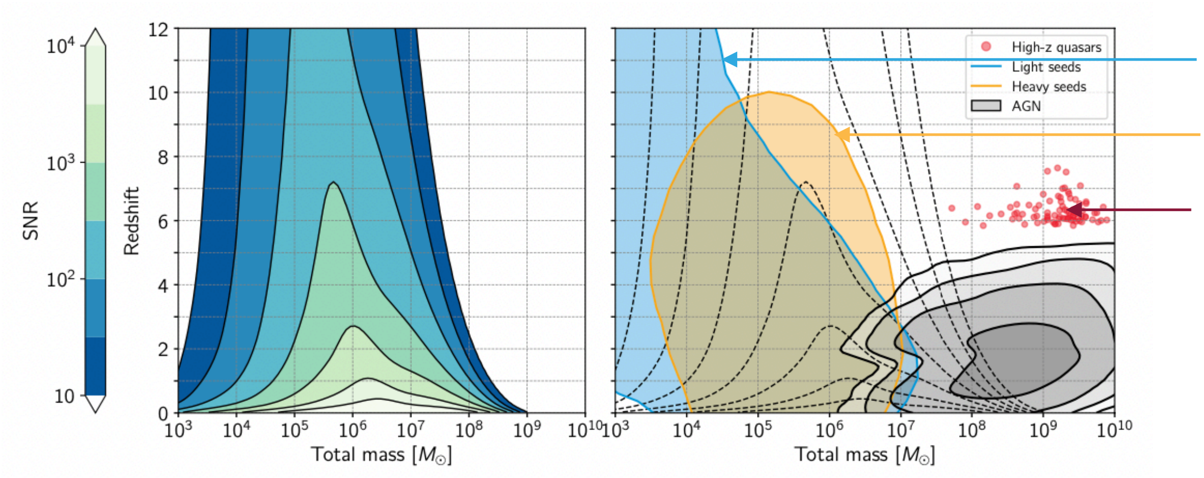

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Quasars observed at z ~ 7 with EM observations

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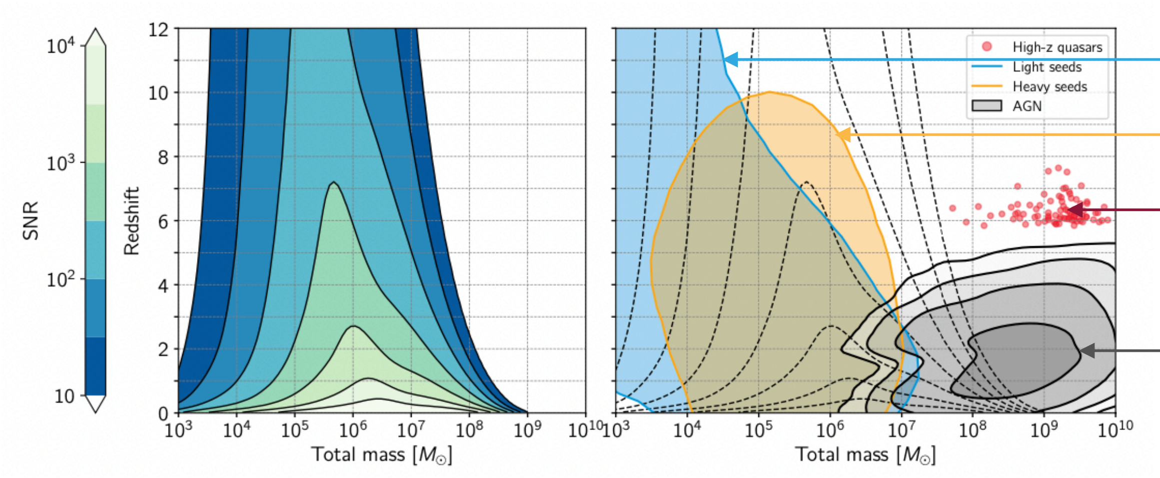
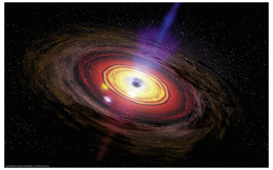


Simulated MBHB resulting from light seeds

Simulated MBHB resulting from heavy seeds

Quasars observed at z ~ 7 with EM observations

Current distribution of AGN population



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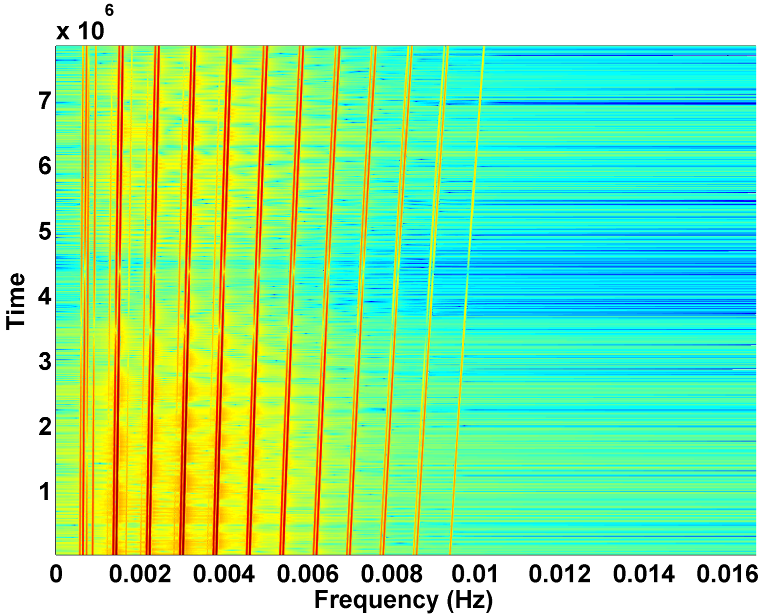
SO3: Probe the properties and immediate environments of Black Holes using EMRIs and IMRIs

- 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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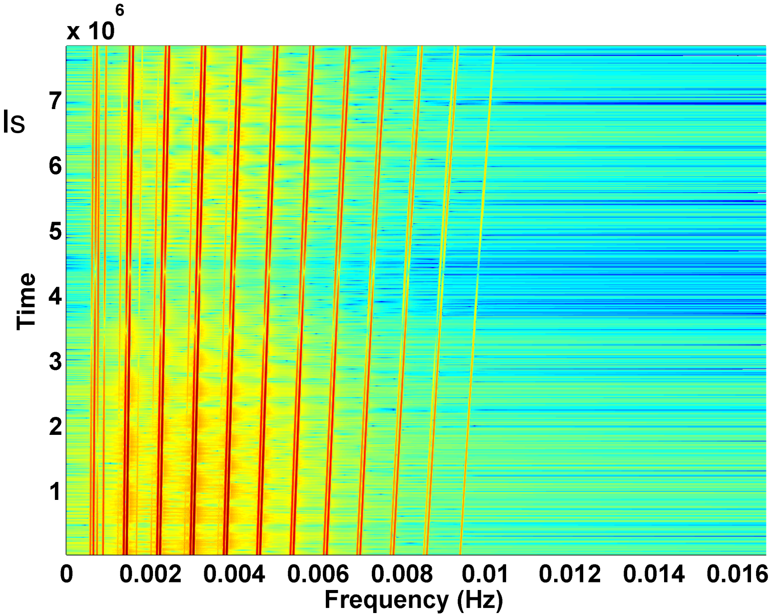

[Babak 2017]

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- Current fast Kludge models should be enough to detect EMRIs
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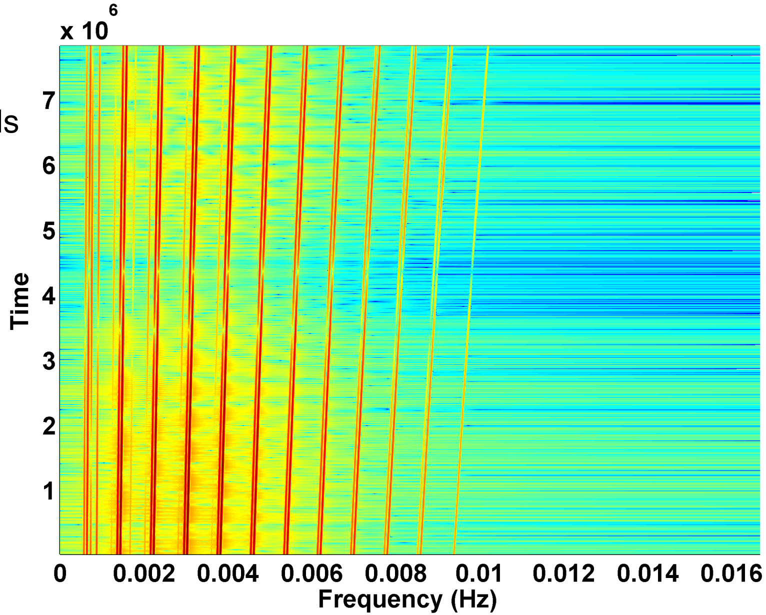
→ Need for **extending waveforms models** to to spinning, eccentric and inclined systems (Ollie Burke's talk)

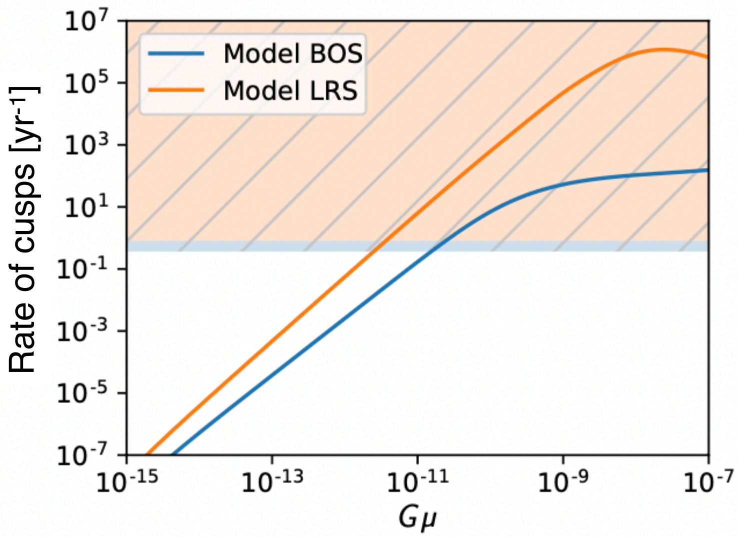
→ Need **adapted inference strategies**



[Babak 2017]

3. Fundamental physics with LISA

- And uncharted territories…
- Cosmic string cups and kinks?
- Unmodelled sources?



String tension

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**