Université Paris Cité

Space-based detectors: LISA

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4th MaNiTou Summer School on Gravitational Waves - July 4th, 2025

Layout

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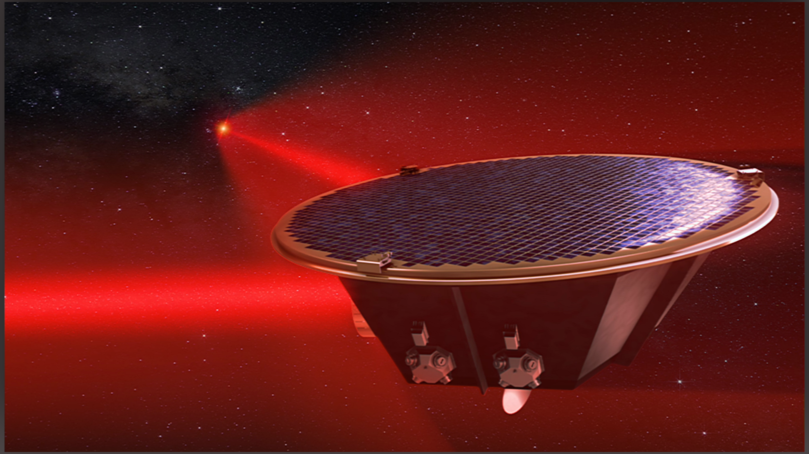
2. Science objectives and related challenges
3. Measurement principles
4. Towards the future

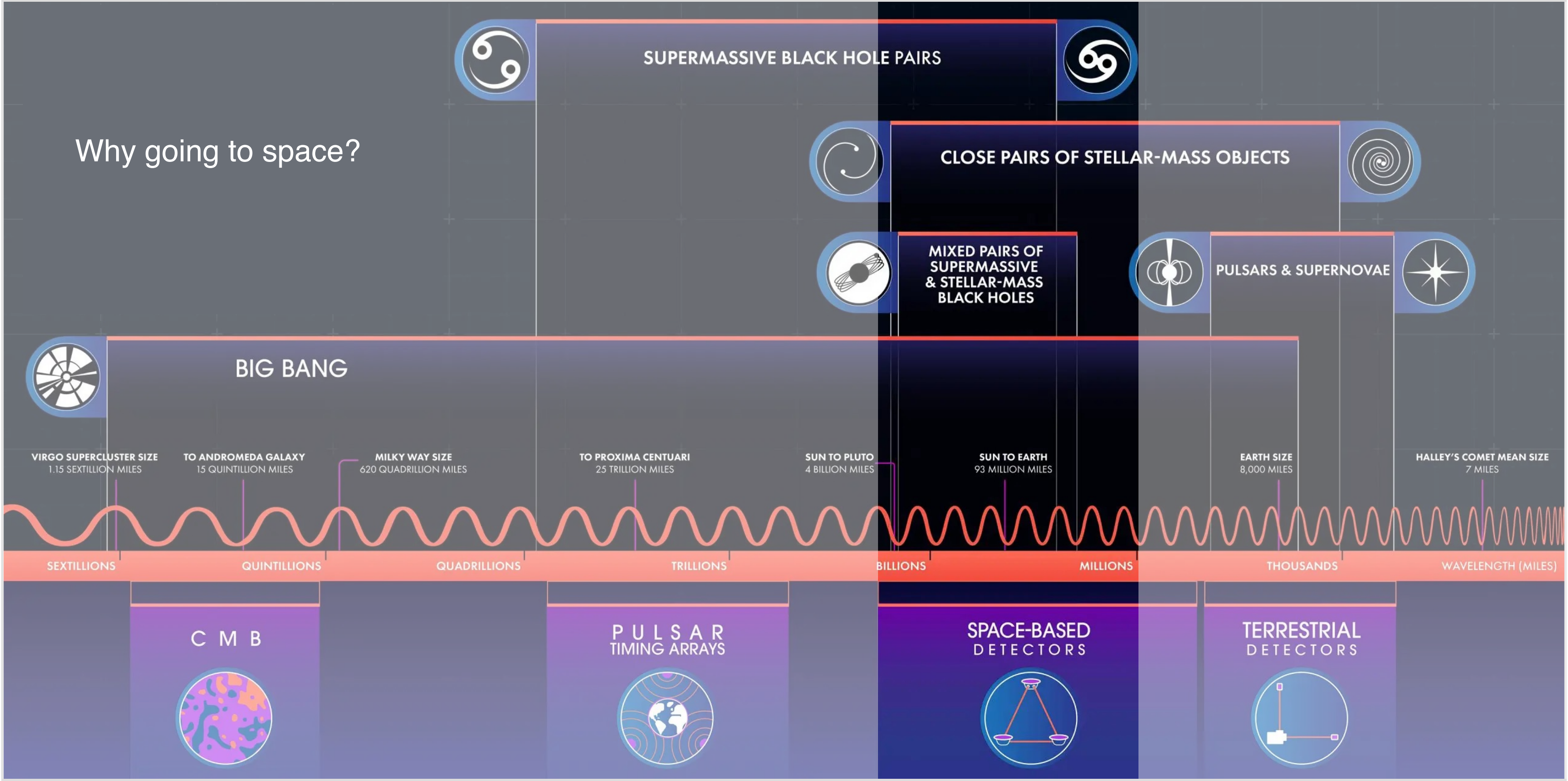


1. Mission concept

1. Mission concept

LISA

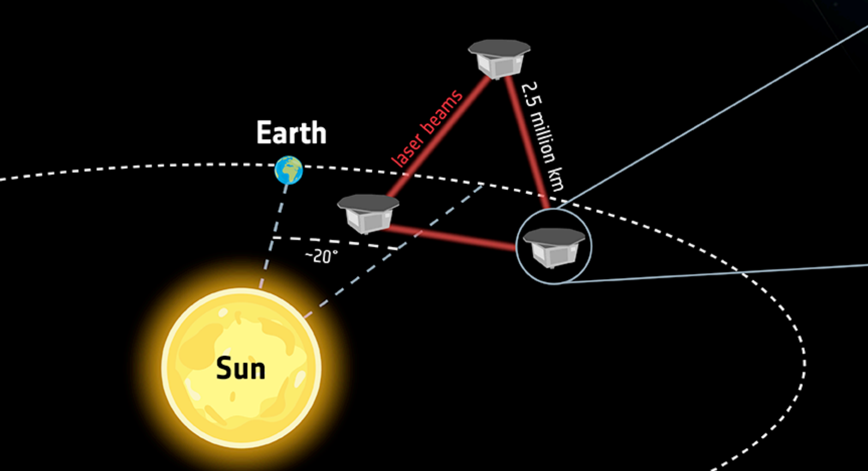
Why going to space?

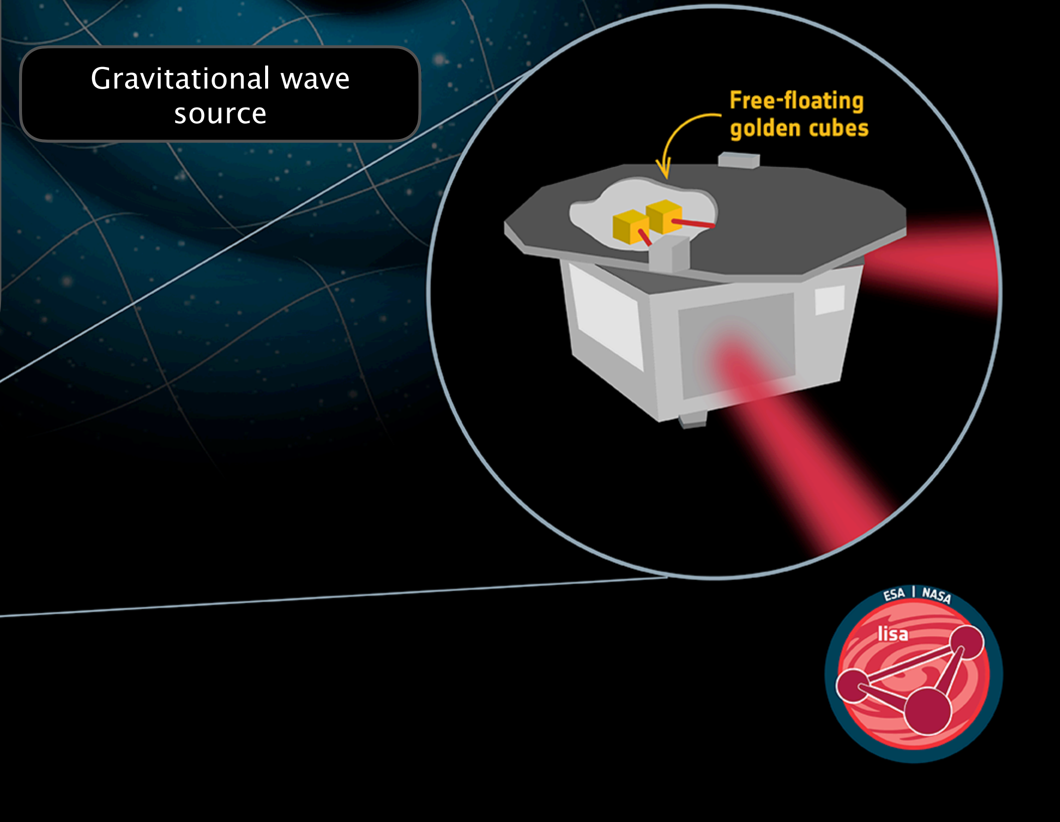


1. Mission concept

LISA - LASER INTERFEROMETER SPACE ANTENNA

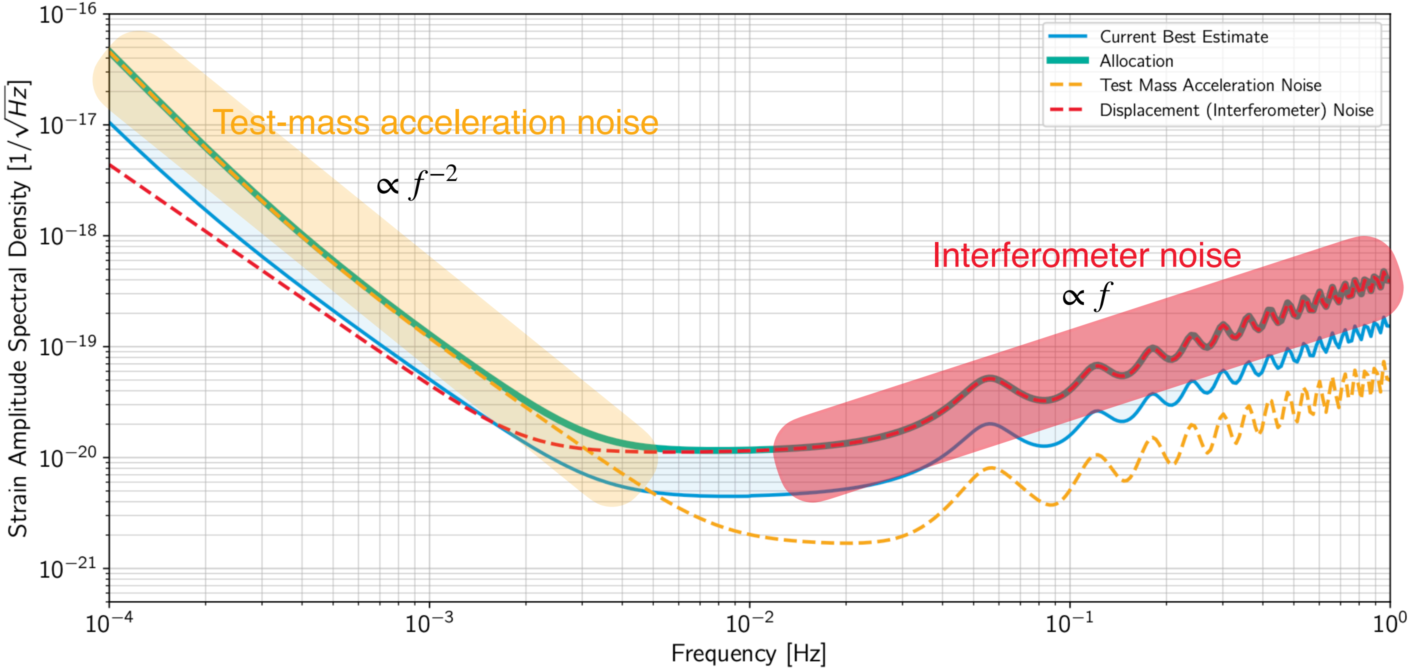
- Measures mHz gravitational waves at $[10^{-4}, 1]$ Hz
- It uses a network of laser interferometers connecting 6 free-floating test-masses
- A constellation of 3 satellites separated by 2.5 Mkm
- 10 picometer precision on the optical path difference





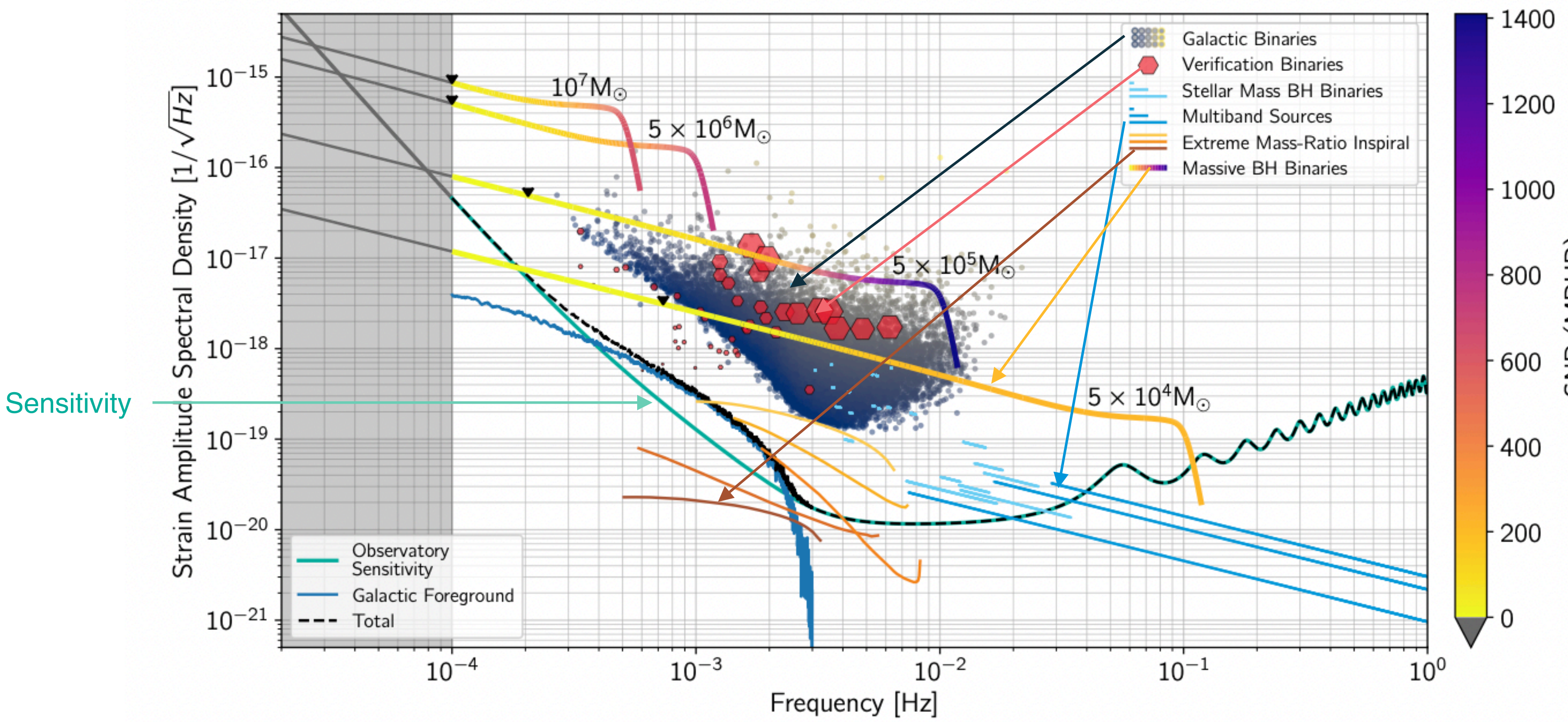
1. Mission concept

- LISA's sensitivity $S_h(f) = \dfrac{T_{\mathrm{acc}}(f)S_{\mathrm{acc}(f)} + T_{\mathrm{disp}}(f)S_{\mathrm{disp}}(f)}{R_{\mathrm{GW}}(f)}$ ← Noise power spectral density; ← Instrument's response to GWs



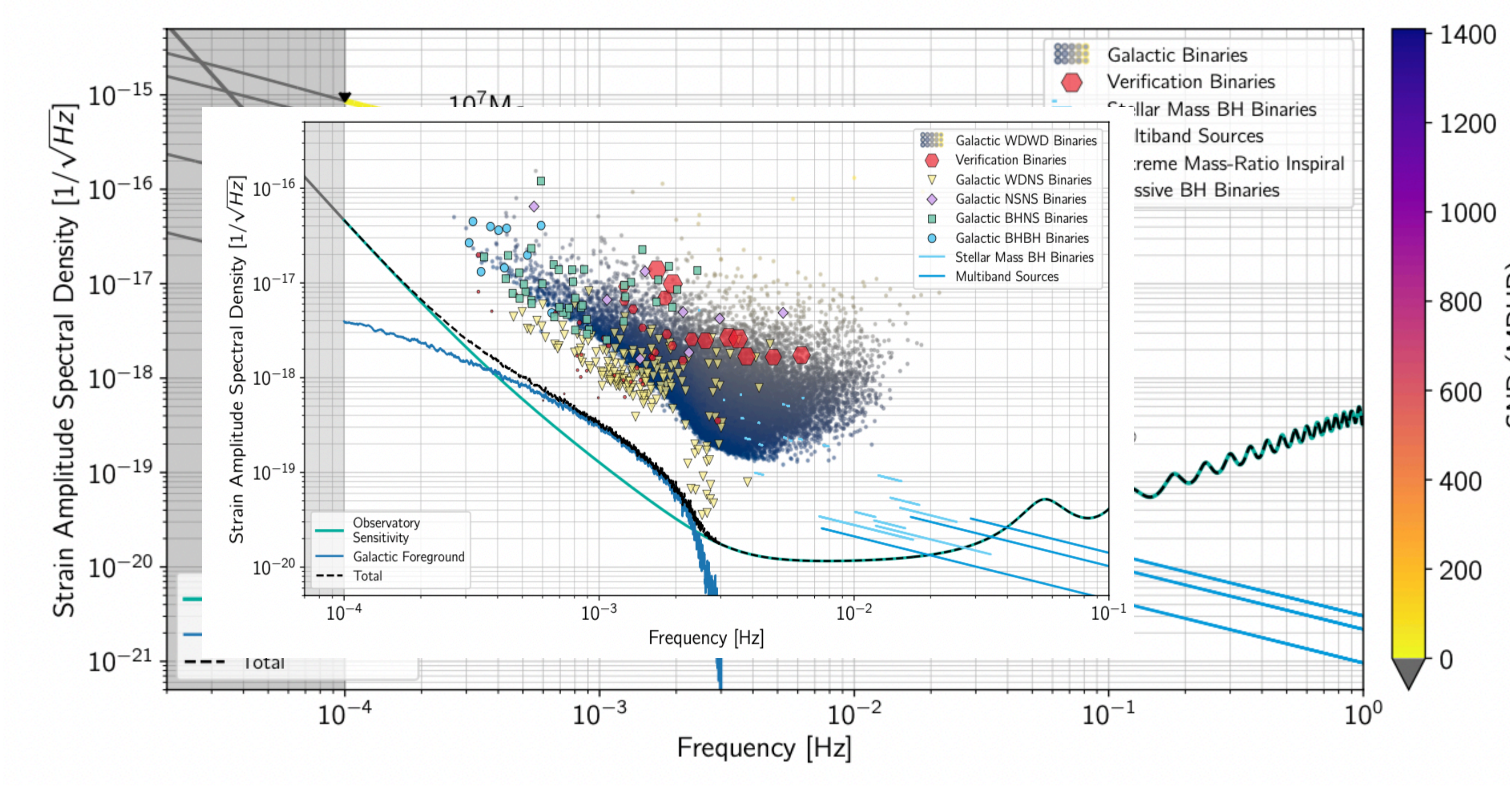
1. Mission concept

- Target gravitational wave sources



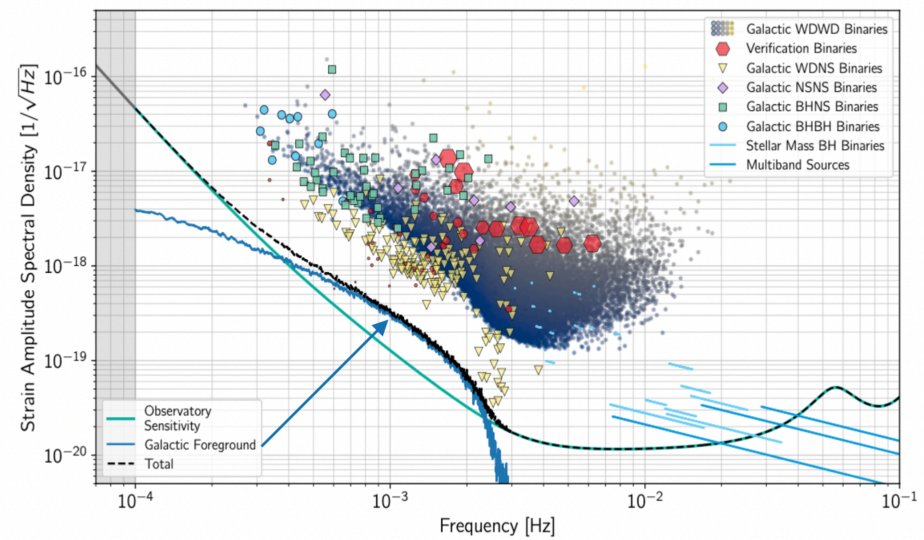
2. Science Objectives

2. Science objectives: Study compact binary stars evolution and Galaxy structure



2. Science objectives: Study compact binary stars evolution and Galaxy structure

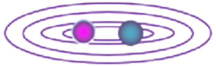
- Most numerous sources ~ 10^7 with ~10^4 detectable

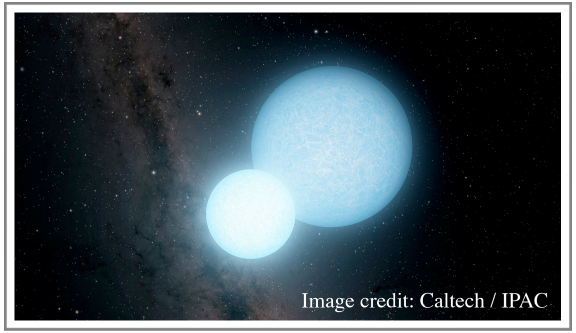


- Most of them are detached and interactive white dwarfs → stellar remnants
- Unresolved sources form a confusion foreground

2. Science objectives: Study compact binary stars evolution and Galaxy structure

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





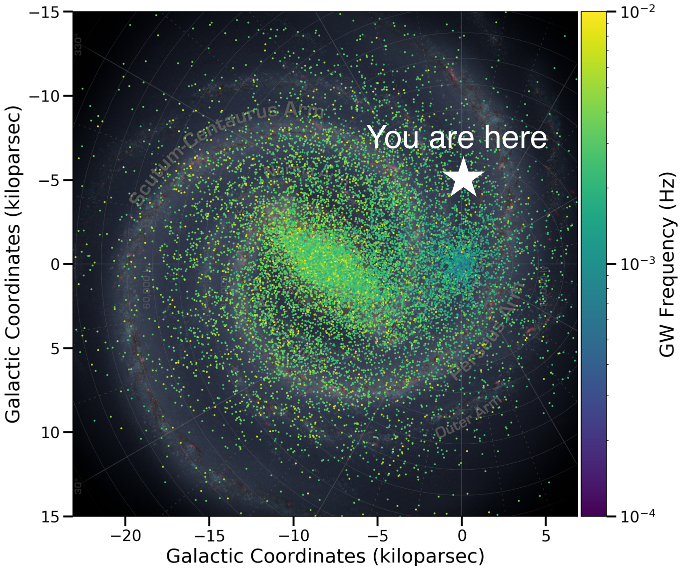
GB sources detected by LISA + confusion foreground

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

See Astrid Lambert's lecture on Saturday!

2. Science objectives: Study compact binary stars evolution and Galaxy structure

- What is the spatial distribution of ultra-compact binaries?
- How do they inform us about the structure of the Galaxy?



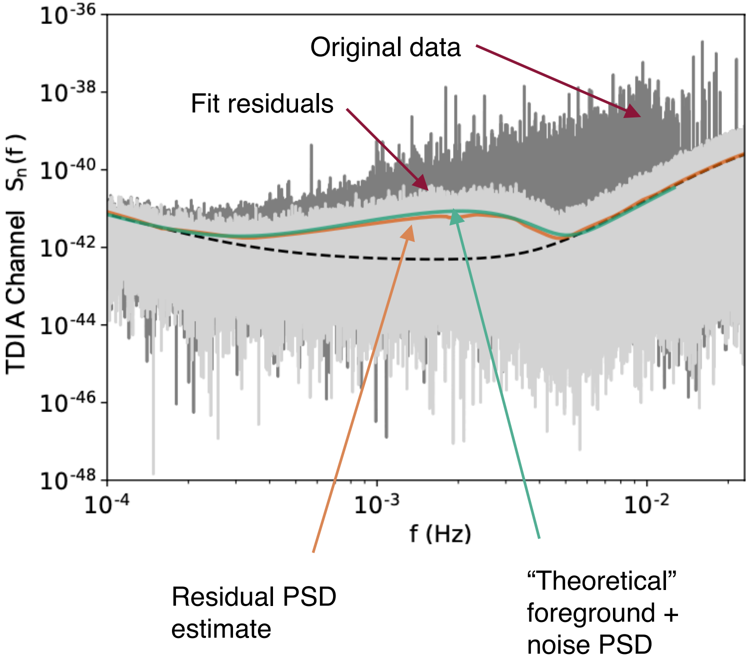
GB sources detected by LISA

↓

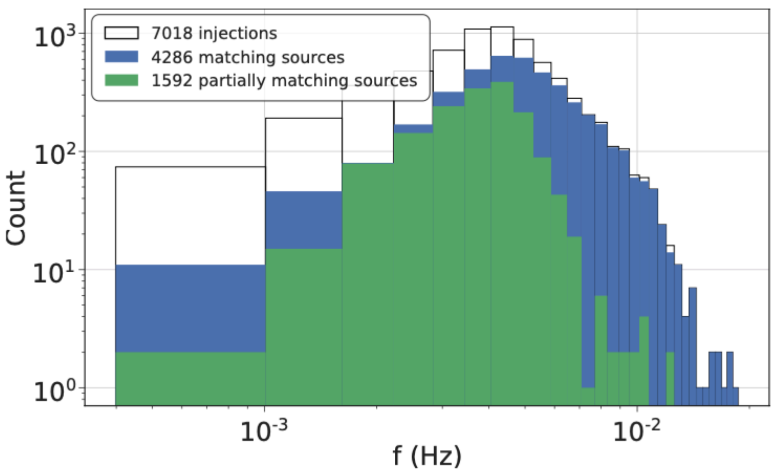
Sky locations and distances for a few 10^3 ⇒ 3D distribution of binaries ⇒ Geometric structure and stellar mass distribution of Galaxy

2. Science objectives: Study compact binary stars evolution and Galaxy structure

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



Prototype pipelines results with LISA Data Challenges 2 data

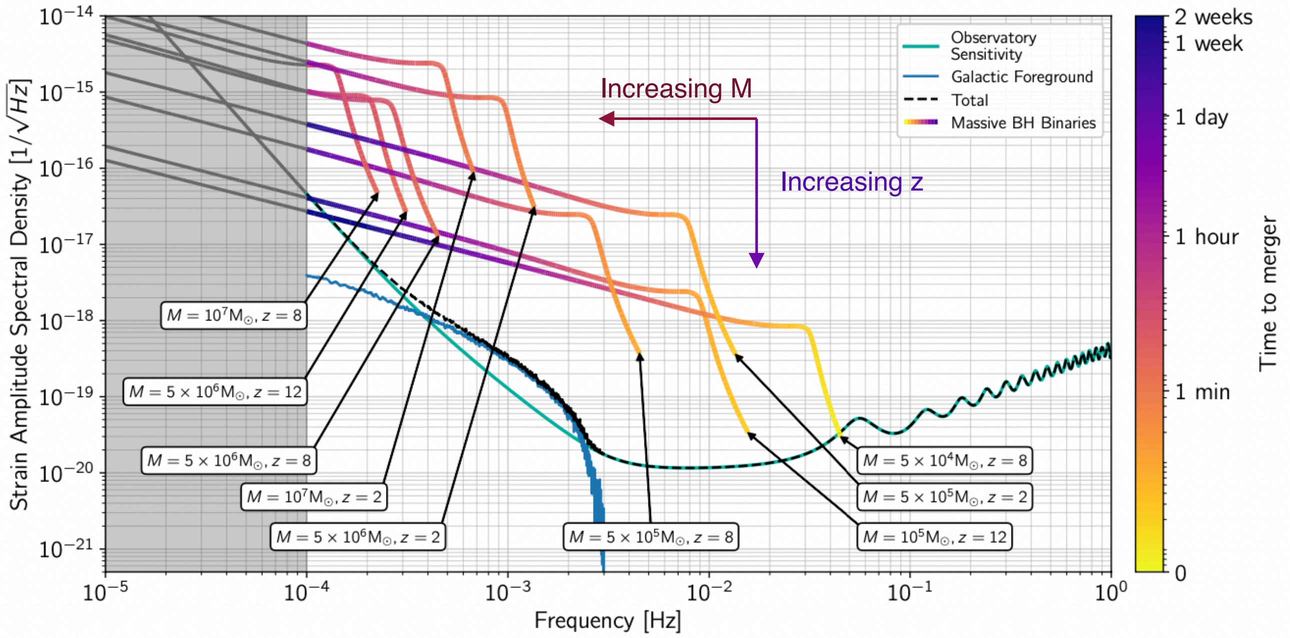


Galactic binary source frequency

[APC team LDC 2a results]

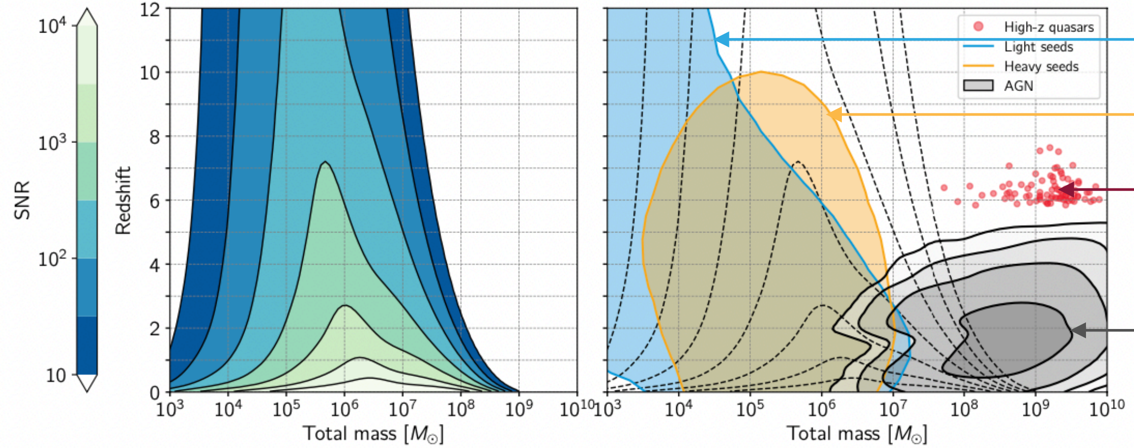
2. Science objectives: Trace the origin, growth and merger histories of massive black holes

- LISA will detects black hole 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!



2. Science objectives: Trace the origin, growth and merger histories of massive black holes

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

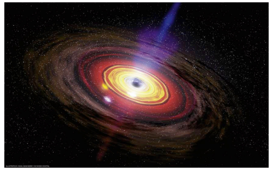


Simulated MBHB resulting from light seeds

Simulated MBHB resulting from heavy seeds

Quasars observed at z ~ 7 with EM observations

Current distribution of AGN population



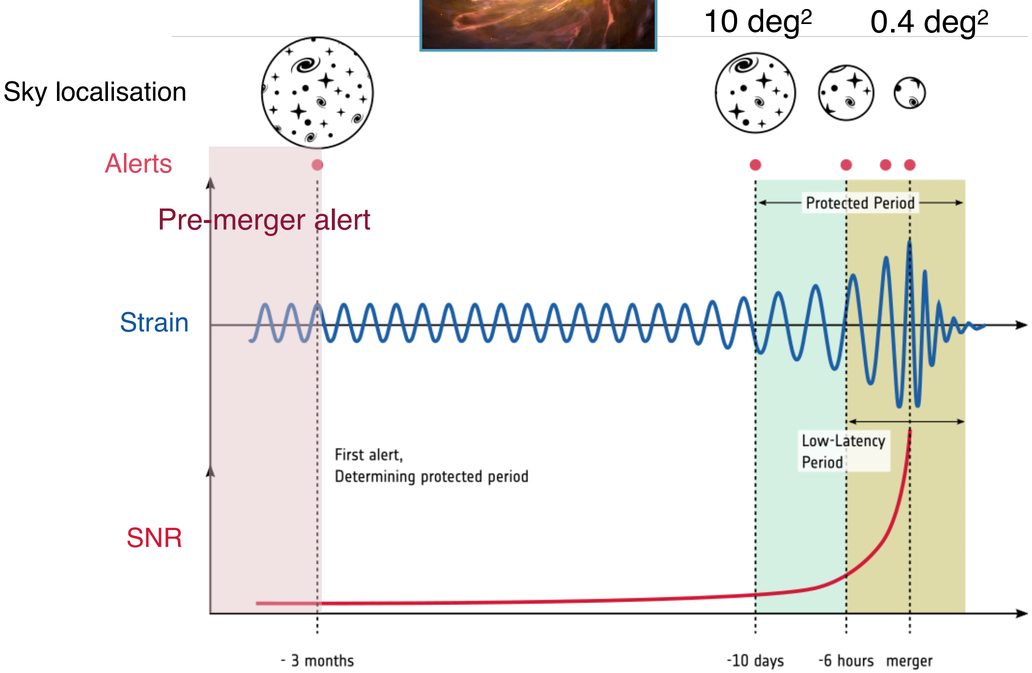
Measurement of MBH masses and redshifts → Help distinguish between different possible seeds

Light seeds = result from gravitational **collapse of first metal-free stars** in early dark matter haloes

Heavy seeds = result from **direct collapse of supermassive stars** in massive dark matter haloes

2. Science objectives: 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 before and after the merger?
- What is the role of accretion?



→ Plan observations ahead of time

→ Secure **protected periods**

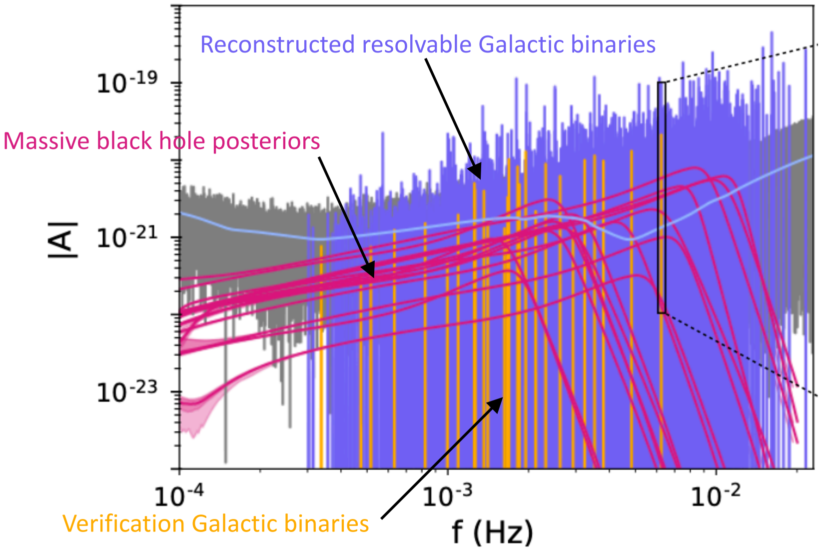
→ **Low-latency alert** pipeline

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

2. Science objectives: Trace the origin, growth and merger histories of massive black holes

- Source type mixing requires to develop a “global fit” approach

Prototype pipelines results with LISA Data Challenges 2 data

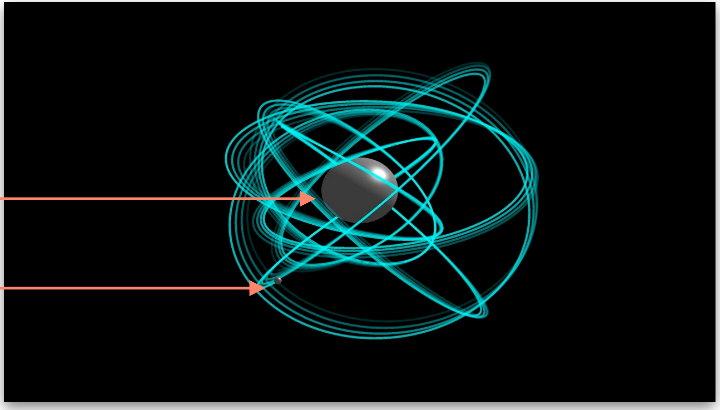


2. Science objectives: Probe the properties and immediate environments of Black Holes using EMRIs

- 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 $10^{-6} < q < 10^{-4}$

Example: 1 massive black hole with 10^6 $M_\odot$

1 black hole with 10 $M_\odot$



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

- 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

2. Science objectives: Probe the properties and immediate environments of Black Holes using EMRIs

- Challenge for data analysis: many harmonics and cycles, complicated waveform
- Challenge for (fast) waveform modelling: disparate time and length scales

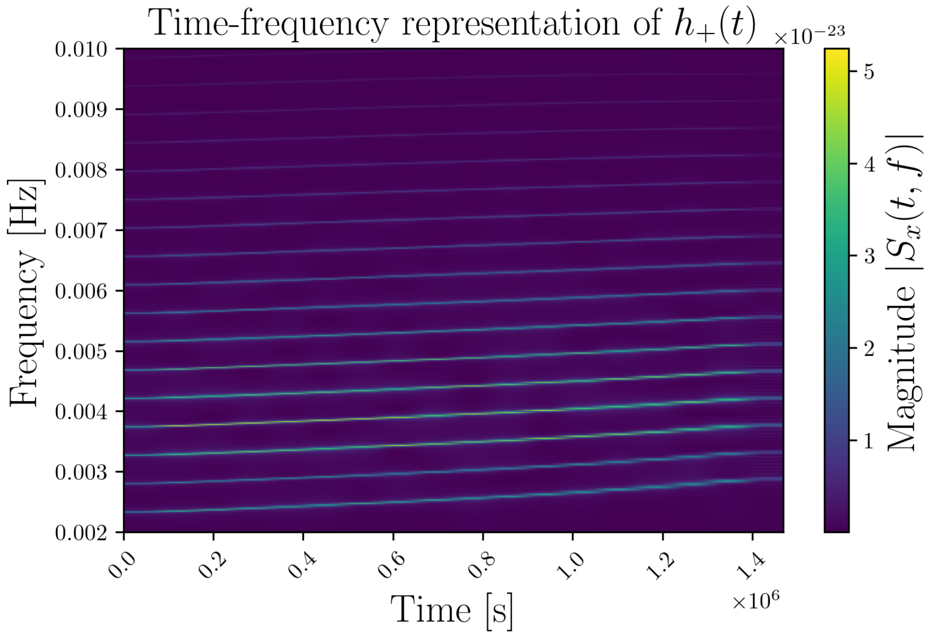
- Current fast **Kludge models** should be enough to detect EMRIs
- Accurate parameter estimation requires better models described by **gravitational self-force** (BH perturbation theory)

→ Need for extending waveforms models to spinning, eccentric, and inclined systems

→ Need adapted inference strategies

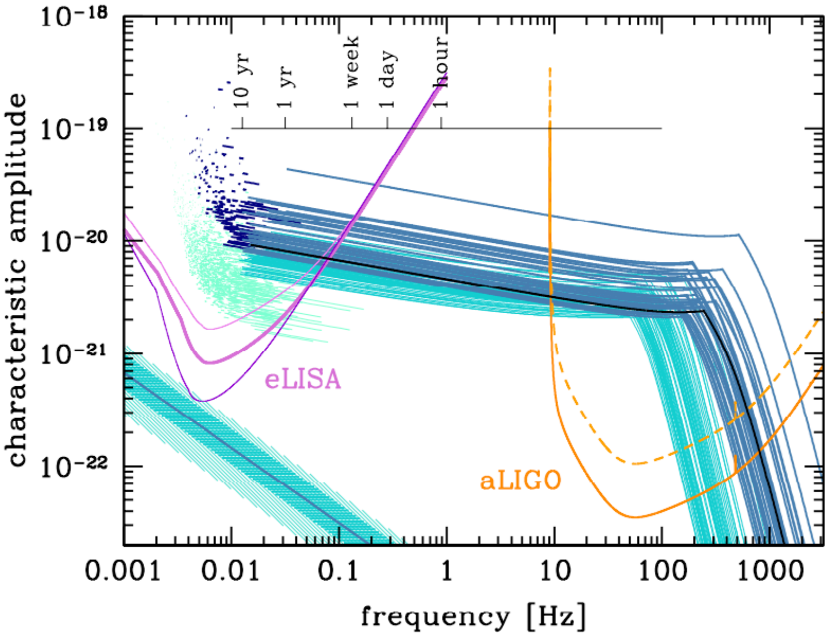
Ongoing developments in the FastEMRIWaveforms package

[C. Chapman-Bird, L. Speri, Z. Nasipak, O. Burke, M. Katz, et al.]



2. Science objectives: 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.

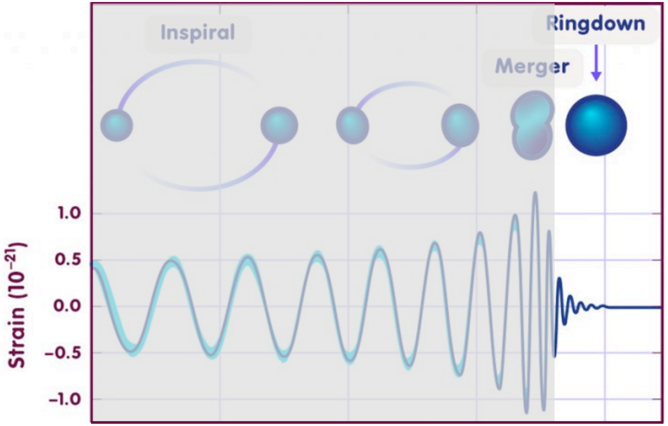


[Sesana 2016]

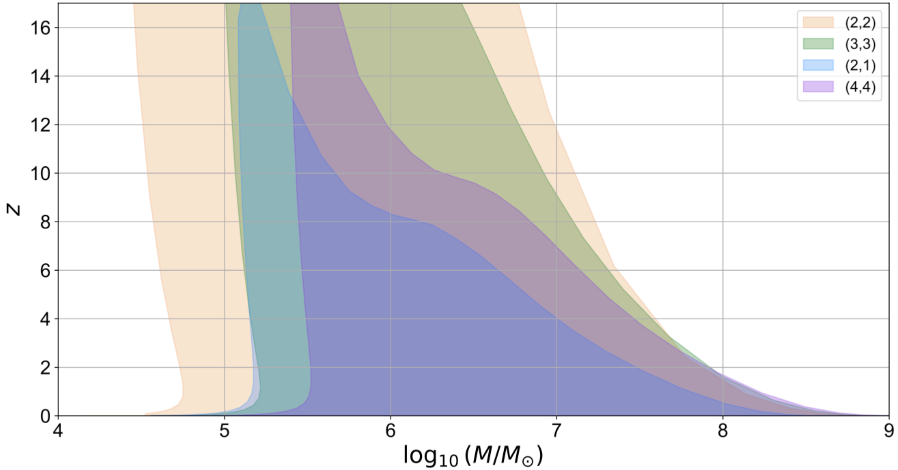
2. Science objectives: Explore the fundamental nature of gravity and Black Holes

- Test GR in the strong field regime
- Test validity of GR Kerr solution for merger remnants

$$h(t) = \sum_{l,m} h_{lm}(t)$$



[LIGO/Virgo Collaboration]



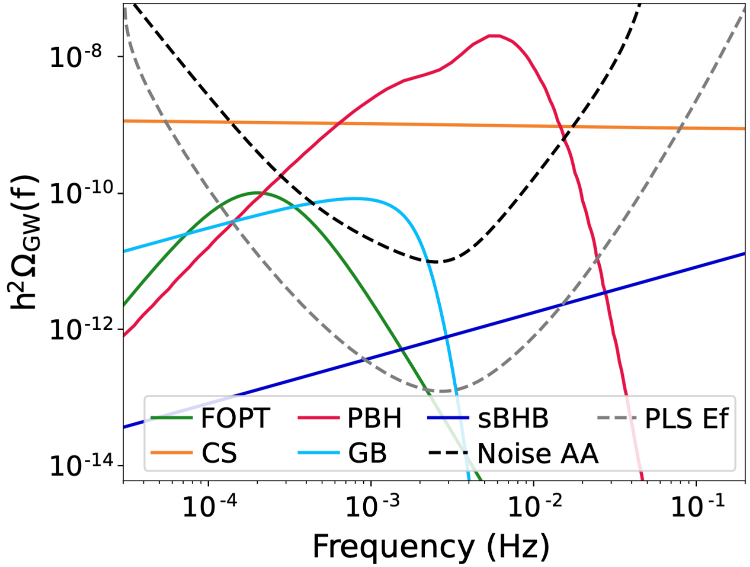
2. Science objectives: Cosmology

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

- We can probe the expansion of the universe at $z > 2$ with **bright sirens:** massive black hole binaries with electromagnetic counterparts
- We can probe the expansion of the universe at $z < 1$ with **dark sirens**: EMRIs

SO7: Understand stochastic GW backgrounds

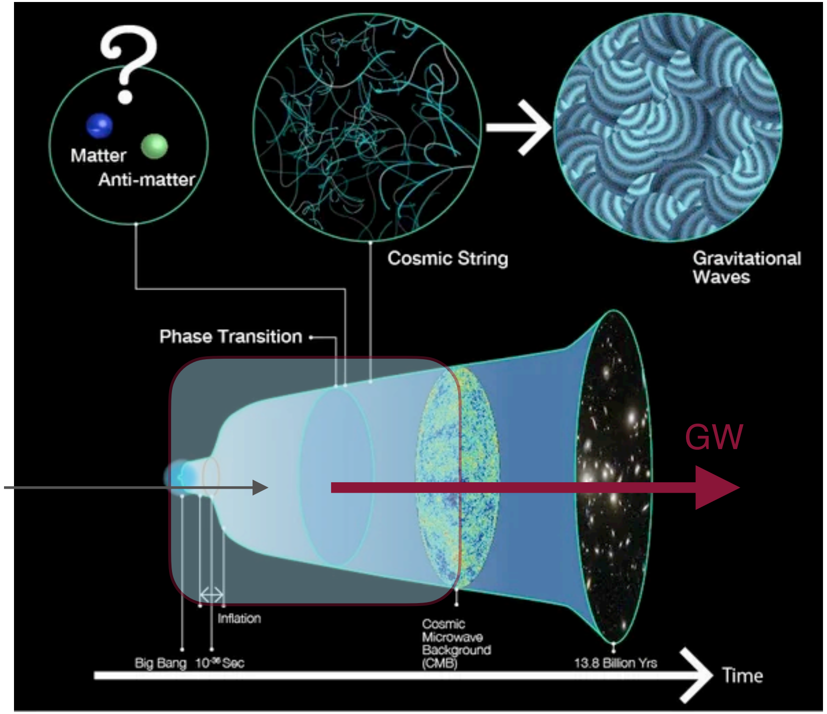
- It would be a **groundbreaking discovery** if we detected a stochastic GW background of cosmological origin
- Unique probe of early-universe physics and TeV-scale particle physics)
- But very challenging data analysis task!



2. Science objectives: Understand stochastic GW backgrounds

- Stochastic GW backgrounds could be fabricated before the Universe's first light

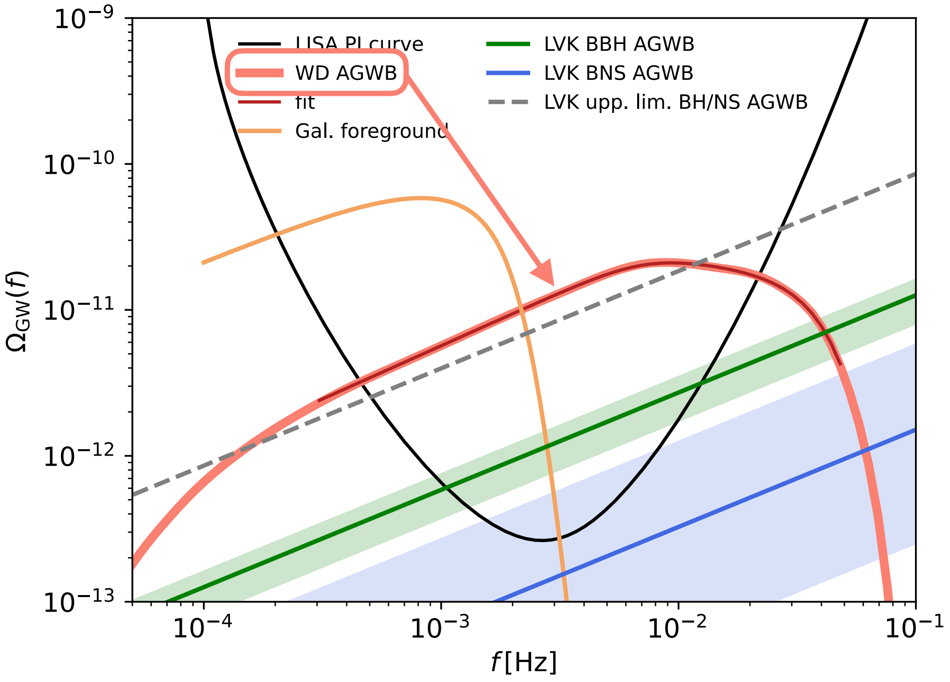
Region inaccessible through light



Credit: R. Hurt/Caltech-JPL, NASA, and ESA

2. Science objectives: Understand stochastic GW backgrounds

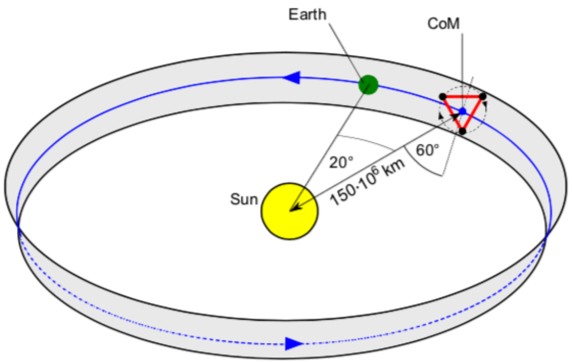
- Stochastic GW backgrounds could also come from binary populations in the universe!



[Staelens & Nelemans 2024]

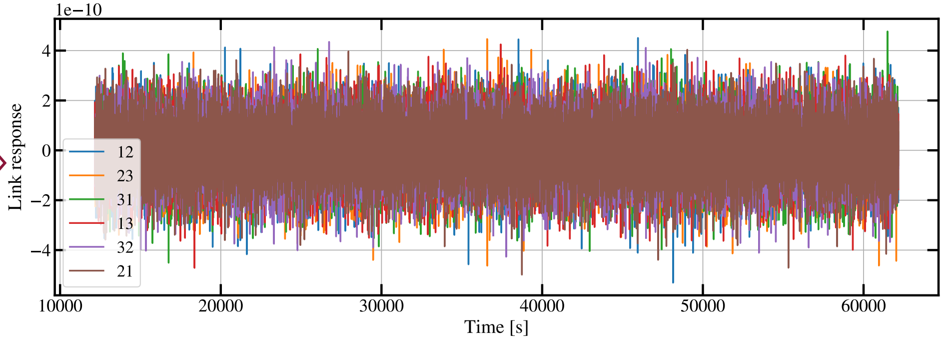
2. Science objectives: Understand stochastic GW backgrounds

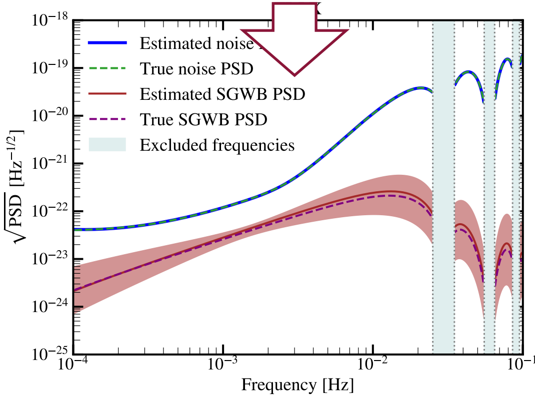
- Extracting them is a challenge: they must be distinguished from instrumental noise and Galactic foreground



Scanning the sky

Interferometric measurements



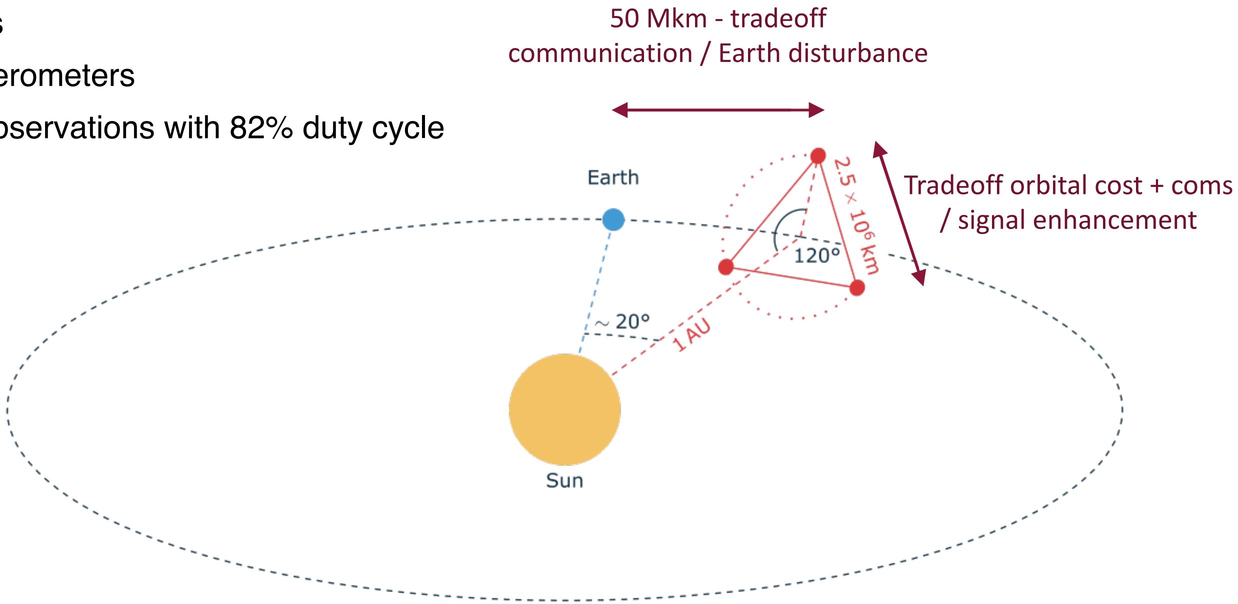


Reconstructed spectra

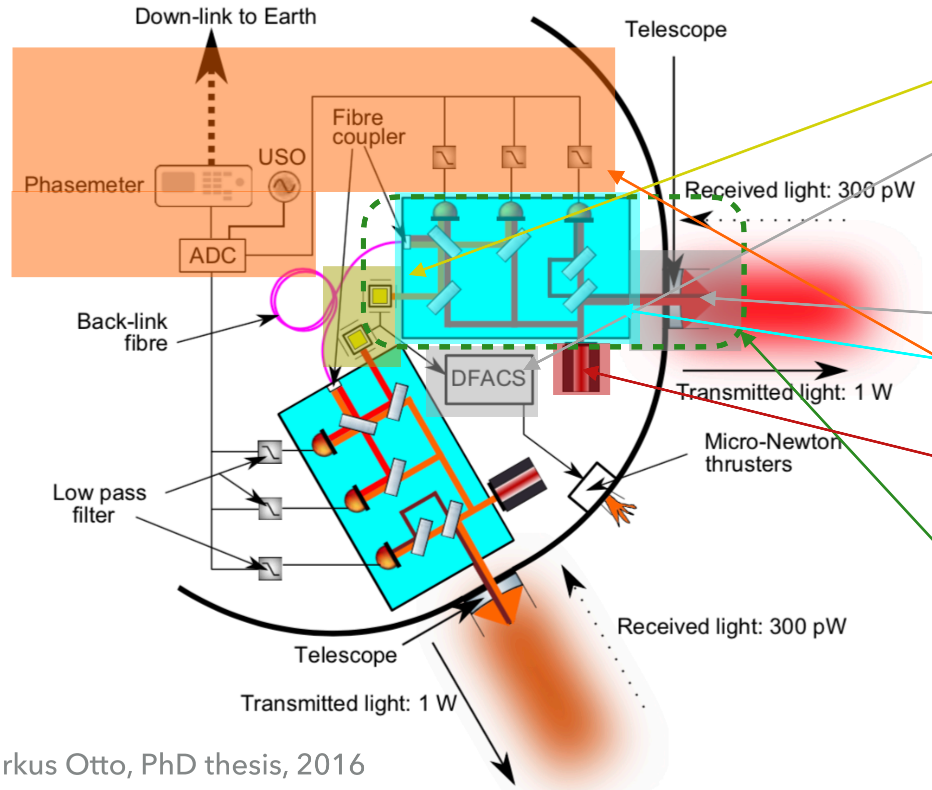
3. Measurement principles

3. Measurement principles

- 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



3. Measurement principles: components



Gravitational reference system

- Test-masses
- Surrounding hardware and avionics

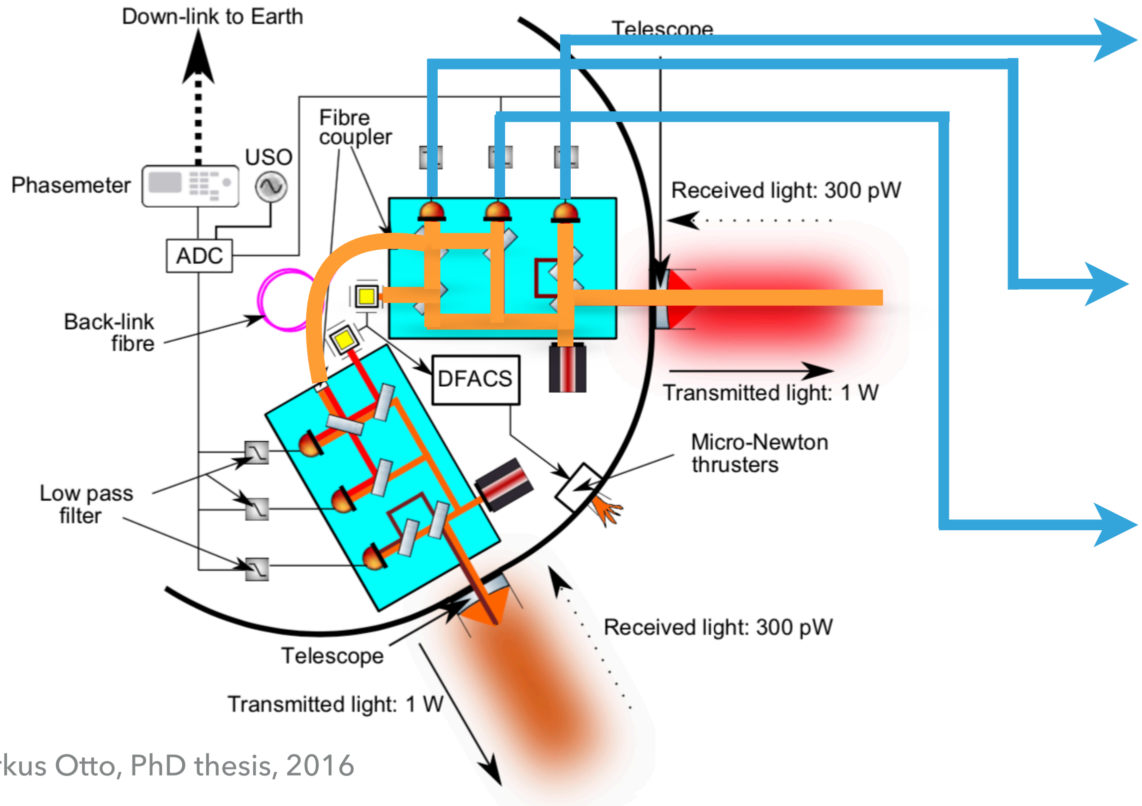
Optical metrology system

- Telescope
- Optical bench
- Phase measurement system
- Laser system

Moving Optical Sub-Assembly (MOSA)

Credit: Markus Otto, PhD thesis, 2016

3. Measurement principles: onboard interferometry



Science interferometer: Distant S/C laser beam - local oscillator

"Spacecraft to spacecraft"

Test-mass interferometer: Local oscillator after bouncing on TM - adjacent oscillator

"Spacecraft to test-mass"

Reference interferometer: Local oscillator - adjacent oscillator

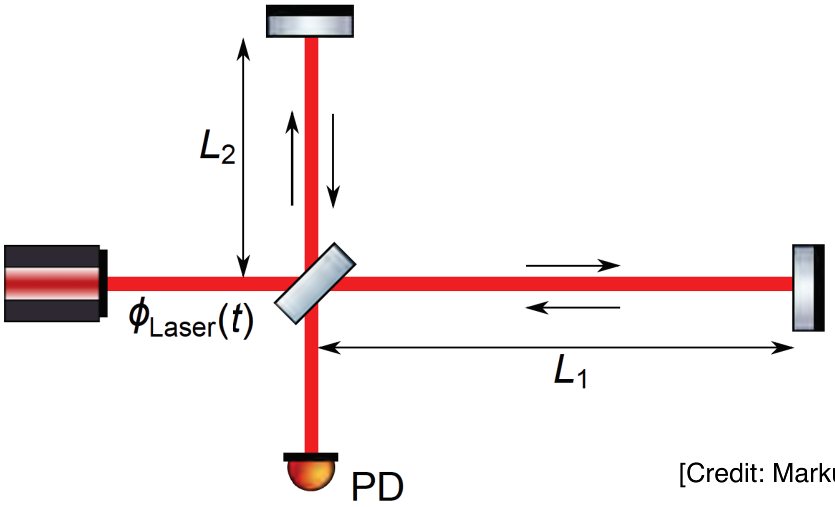
"Laser to laser"

Credit: Markus Otto, PhD thesis, 2016

3. Measurement principles: onboard interferometry

- How do we do in space?
- In a classic Michelson interferometer, we detect the differential phase of two light rays with a phasemeter
- The position noise due to the arm length mismatch is

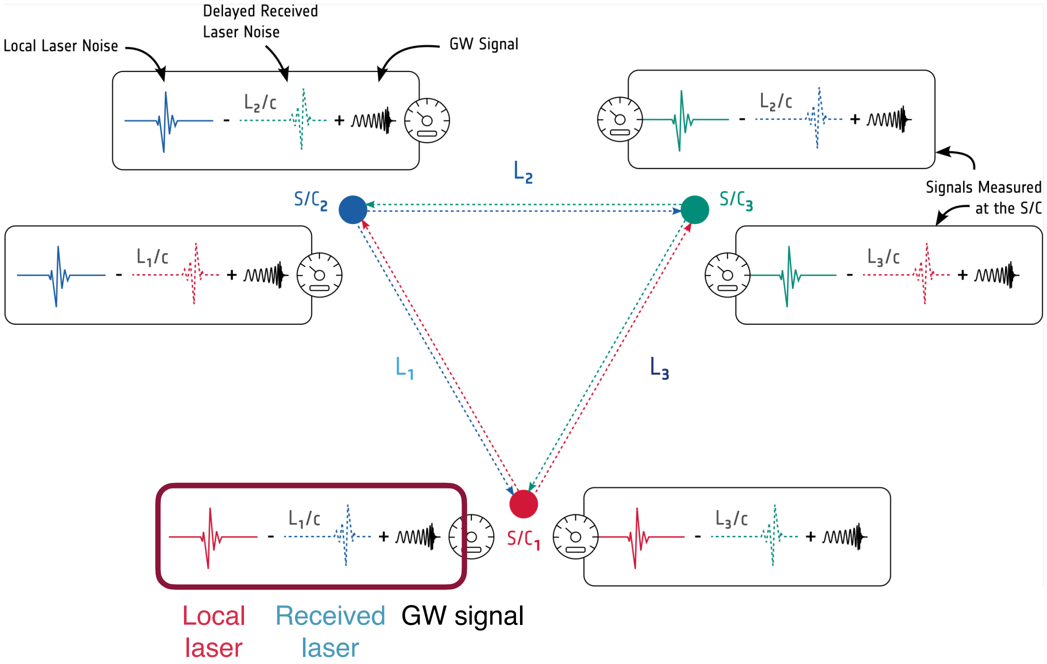
$$\sqrt{S_x} = |L_2 - L_1| \frac{\sqrt{S_\nu}}{\nu_0}$$



[Credit: Markus Otto, PhD thesis, 2016]

3. Measurement principles: onboard interferometry

- 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



3. Measurement principles: onboard interferometry

- But in LISA, each science interferometer length mismatch is of the order of millions of kms.
- Each link has its own laser source.
- This induces a huge noise due to laser frequency random fluctuations, even with the best lasers.

Laser frequency noise

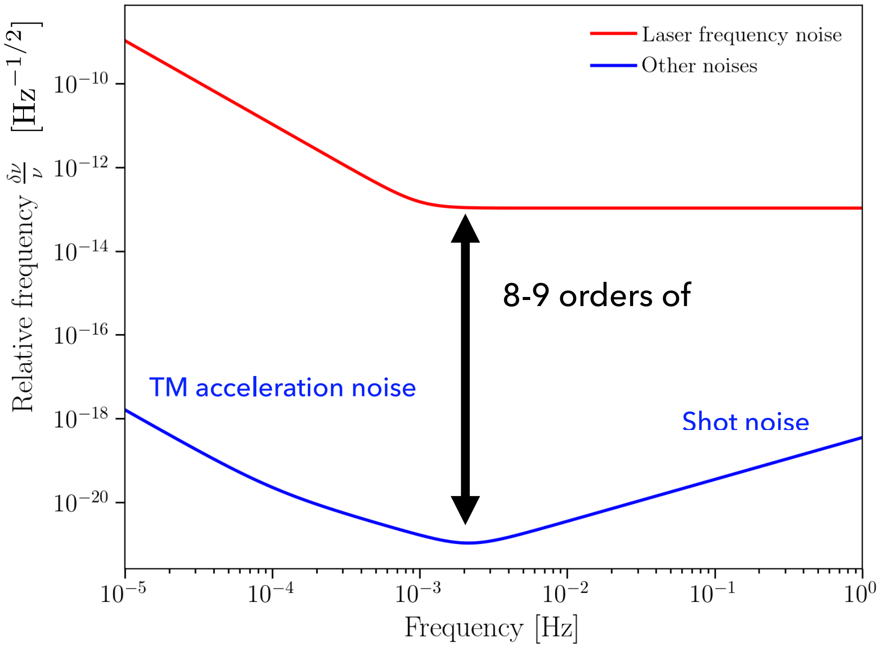
$$\sqrt{S_\nu} \approx 300 \frac{\mathrm{Hz}}{\sqrt{\mathrm{Hz}}} \text{ @3 mHz}$$

Gravitational strain noise

$$\sqrt{S_h} = 2\frac{\sqrt{S_x}}{L} \sim 2 \times 10^{-12}\,\mathrm{Hz}^{-1/2}$$

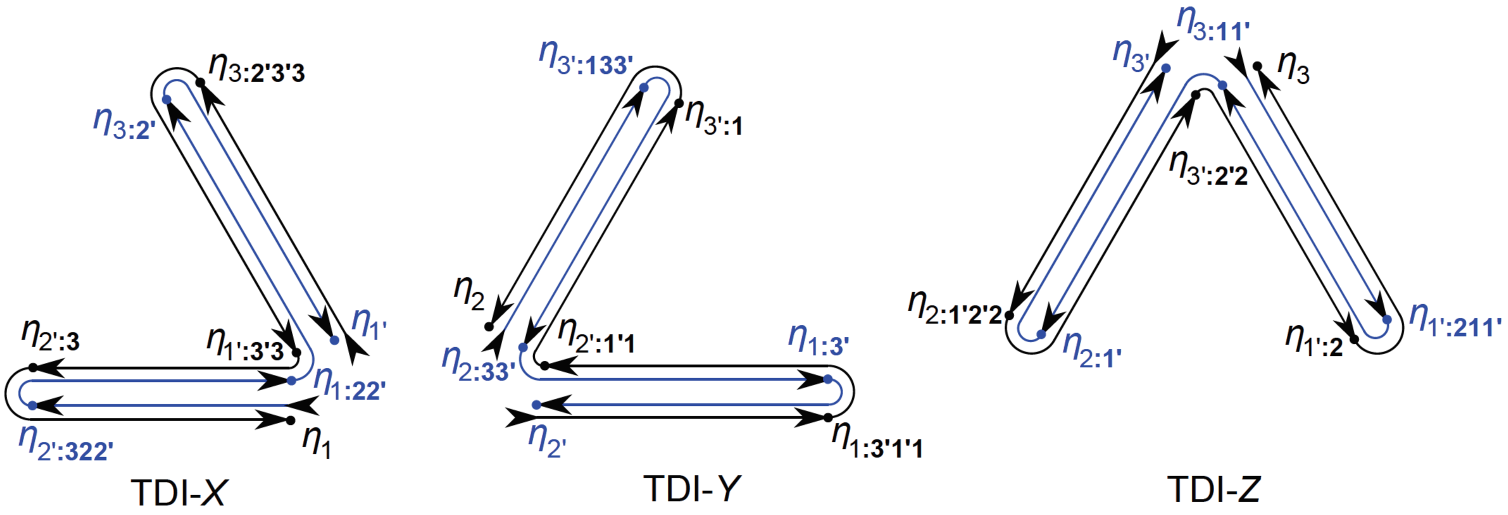
$$\gg 10^{-21}\,\mathrm{Hz}^{-1/2}$$

Too large to detect GWs!



3. Measurement principles: time-delay interferometry

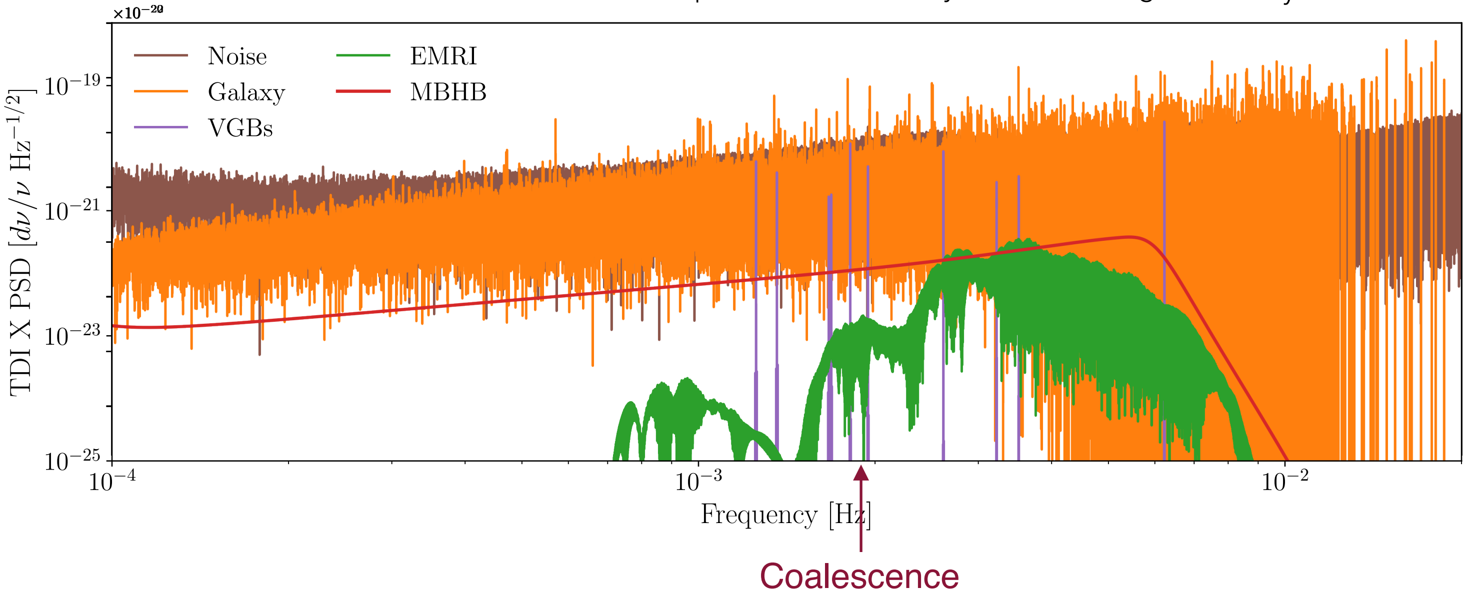
- The interferometry is done as a **post-processing step**.
- A linear combination of delayed phasemeter measurements tailored to cancel laser noise
- This algorithm is called **time-delay interferometry** (TDI) [Tinto & Armstrong 1999]
- Some of these combinations are equivalent to synthetically reproducing a photon path inside a Michelson interferometer



3. Measurement principles: data analysis

- The challenge of data analysis

A few Galactic binaries + Extreme mass ratio inspiral + massive binary black hole merger + Galaxy + noise



3. Measurement principles: data analysis

- The favored strategy to analyse the TDI data is based on Bayesian statistics

$$p\left(\boldsymbol{\theta}, k \,|\, \boldsymbol{d}\right) = \frac{p\left(\boldsymbol{d} \,|\, \boldsymbol{\theta}, k\right) p(\boldsymbol{\theta}, k)}{p(\boldsymbol{d})}$$

Model parameters

Number of model components

Data vector, for example d=(X, Y, Z)

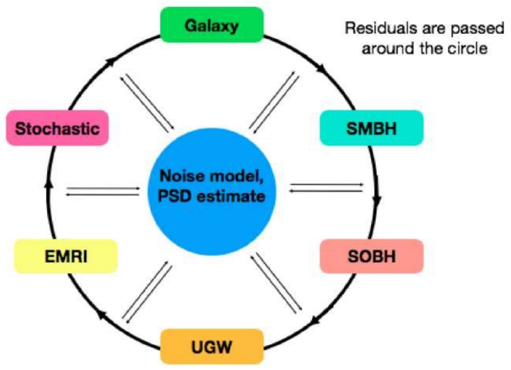
- Where one must define a likelihood function: for example, Gaussian

$$p\left(\boldsymbol{d} \,|\, \boldsymbol{\theta}, k\right) = \frac{1}{\sqrt{(2\pi)^N |\boldsymbol{\Sigma}(\boldsymbol{\theta})|}} \exp\left\{ \left(\boldsymbol{d} - \boldsymbol{h}(\boldsymbol{\theta}, q)\right)^{\dagger} \boldsymbol{\Sigma}(\boldsymbol{\theta}, p)^{-1} \left(\boldsymbol{d} - \boldsymbol{h}(\boldsymbol{\theta}, q)\right) \right\}$$

GW signals: $\boldsymbol{h}(\boldsymbol{\theta}, q) = \sum_{j=1}^{q} \boldsymbol{h}_j(\boldsymbol{\theta}_j)$ Stochastic processes: $\boldsymbol{\Sigma}(\boldsymbol{\theta}) = \sum_{i=1}^{p} \boldsymbol{\Sigma}_i(\boldsymbol{\theta}_i)$

$$k = p + q$$

3. Measurement principles: data analysis



Blocked Gibbs scheme: iterative sampling over subset of parameters

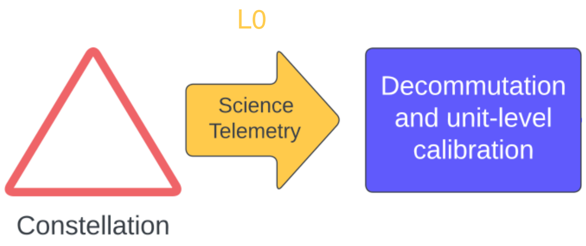
1. Sample for $p\left(\boldsymbol{\theta}_{\mathrm{MBHB}} \middle| \boldsymbol{y}, \boldsymbol{\theta}_{\mathrm{others}}\right)$
2. Sample for $p\left(\boldsymbol{\theta}_{\mathrm{GB}} \middle| \boldsymbol{y}, \boldsymbol{\theta}_{\mathrm{others}}\right)$
3. Sample for $p\left(\boldsymbol{\theta}_{\mathrm{EMRI}} \middle| \boldsymbol{y}, \boldsymbol{\theta}_{\mathrm{others}}\right)$

$\cdots$

K. Sample for $p\left(\boldsymbol{\theta}_{\mathrm{noise}} \middle| \boldsymbol{y}, \boldsymbol{\theta}_{\mathrm{others}}\right)$

3. Measurement principles: operations

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



- L0: raw telemetry
- L0.5: processed and reformatted
- L1: noise-reduced TDI data
- L2: probability density functions for identified GW sources
- L3: Catalogue of GW source candidates

4. Conclusion

Conclusion: bright future and many challenges

Thank you for you attention!