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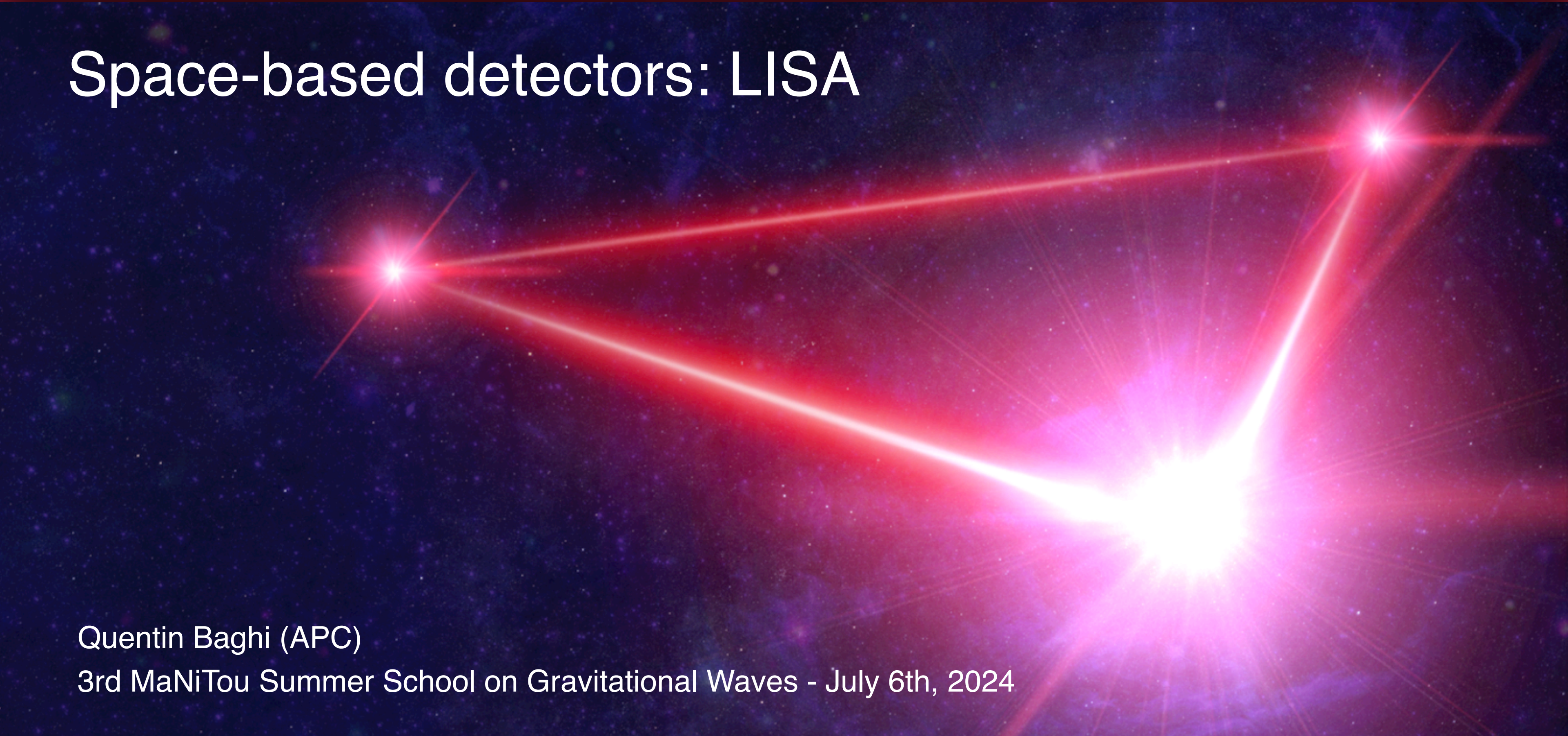
Space-based detectors: LISA

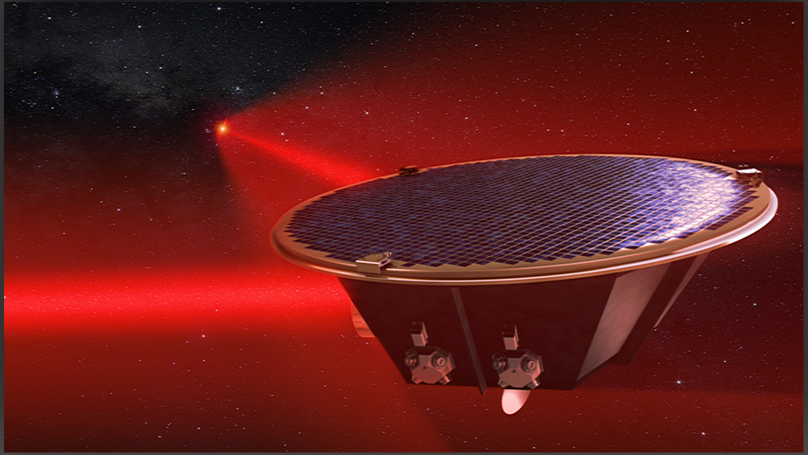


Quentin Baghi (APC)

3rd MaNiTou Summer School on Gravitational Waves - July 6th, 2024

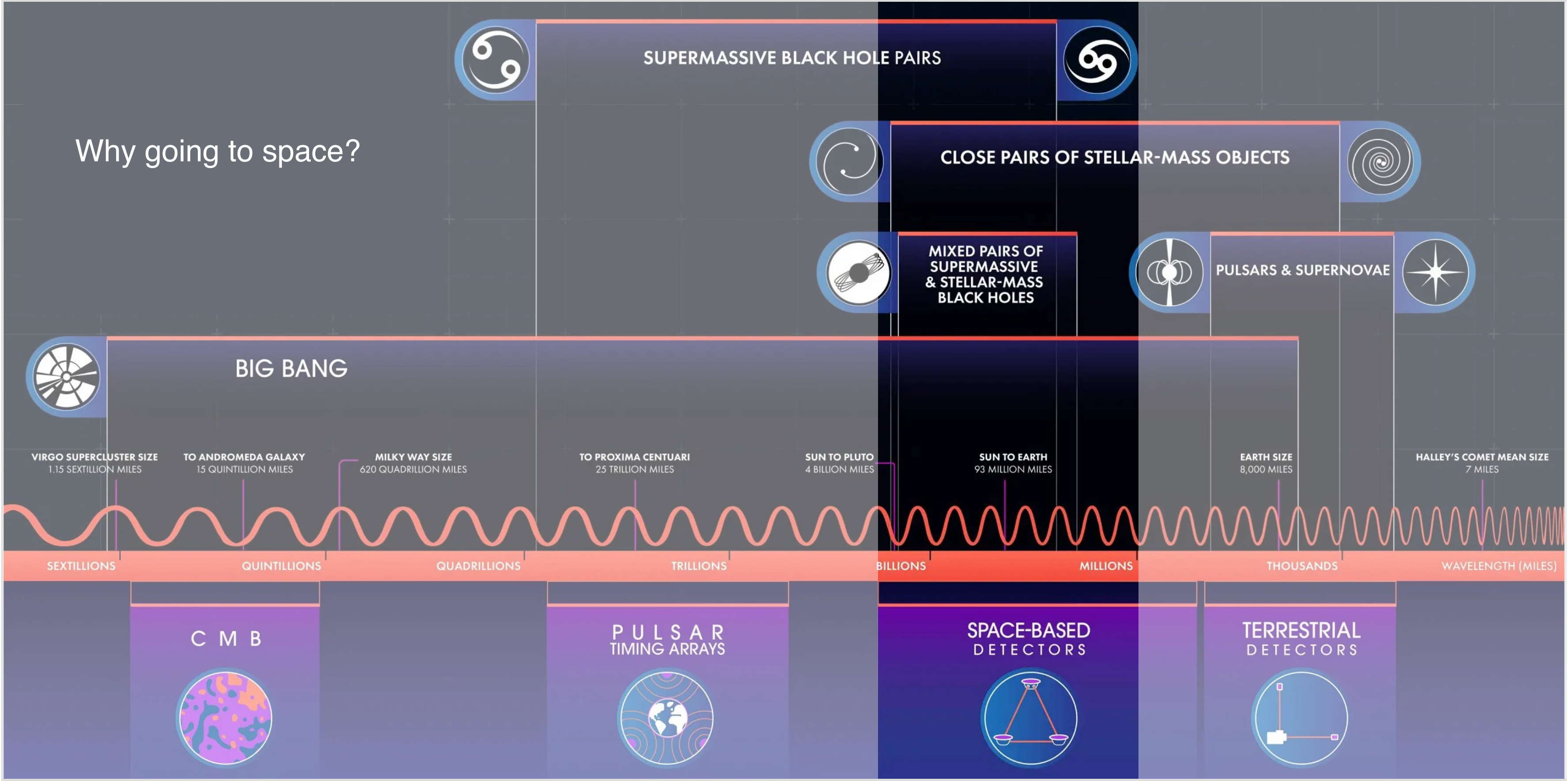
Layout

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



1. Mission concept

LISA



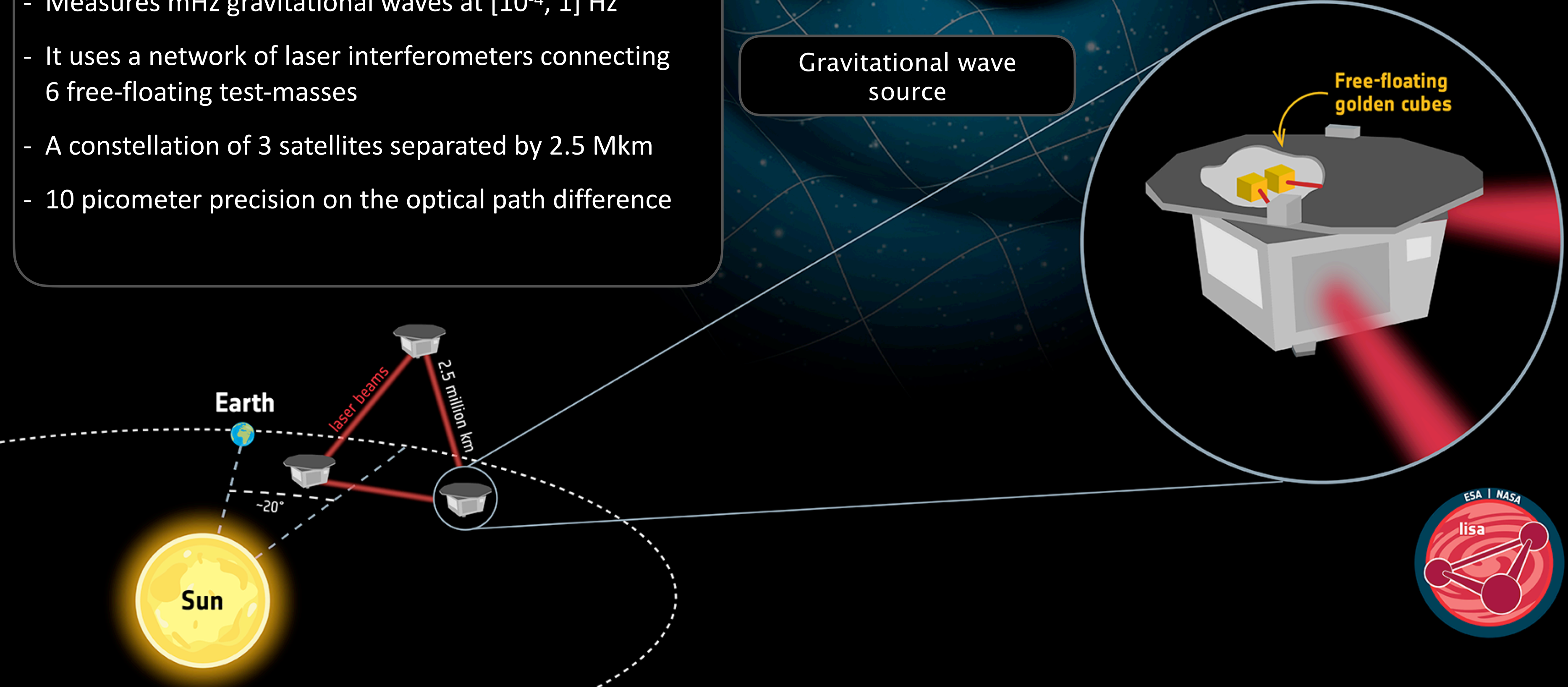
Why going to space?

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

Gravitational wave source

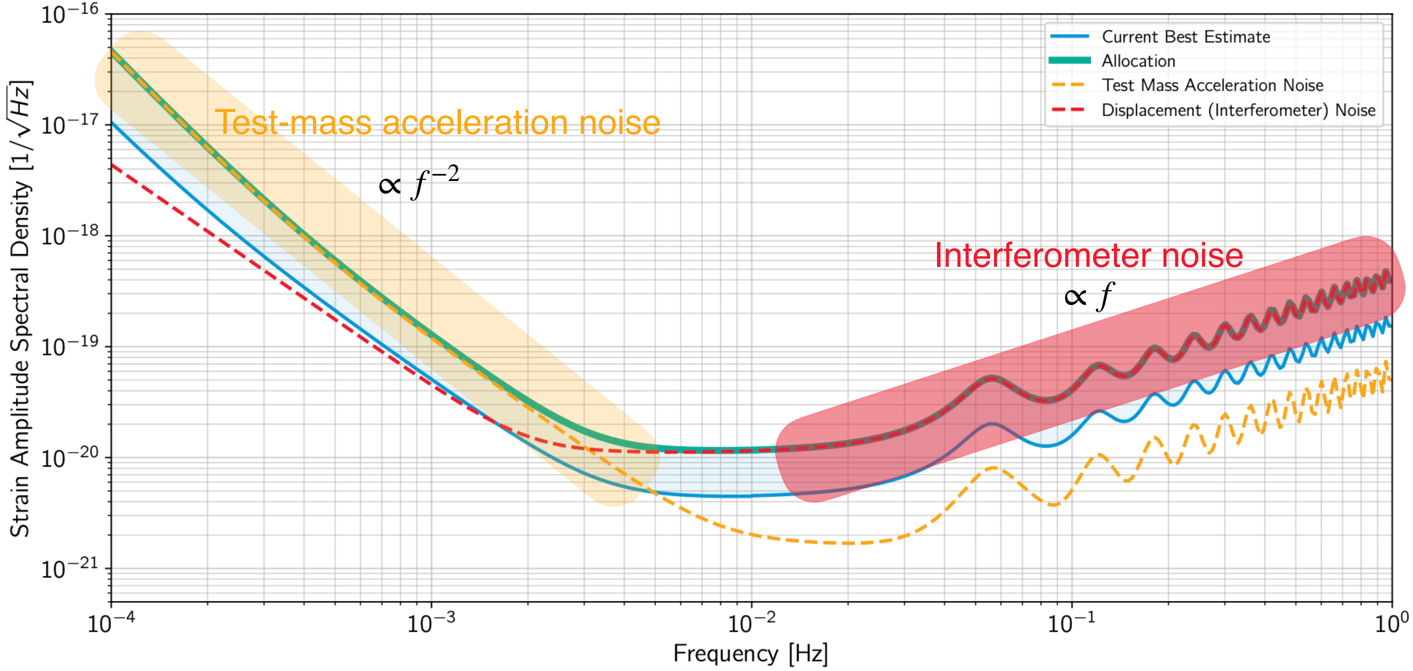


1. Mission concept

— LISA's sensitity $S_h(f) = \dfrac{T_{\mathrm{acc}}(f)S_{\mathrm{acc}(f)} + T_{\mathrm{disp}}(f)S_{\mathrm{disp}}(f)}{R_{\mathrm{GW}}(f)}$

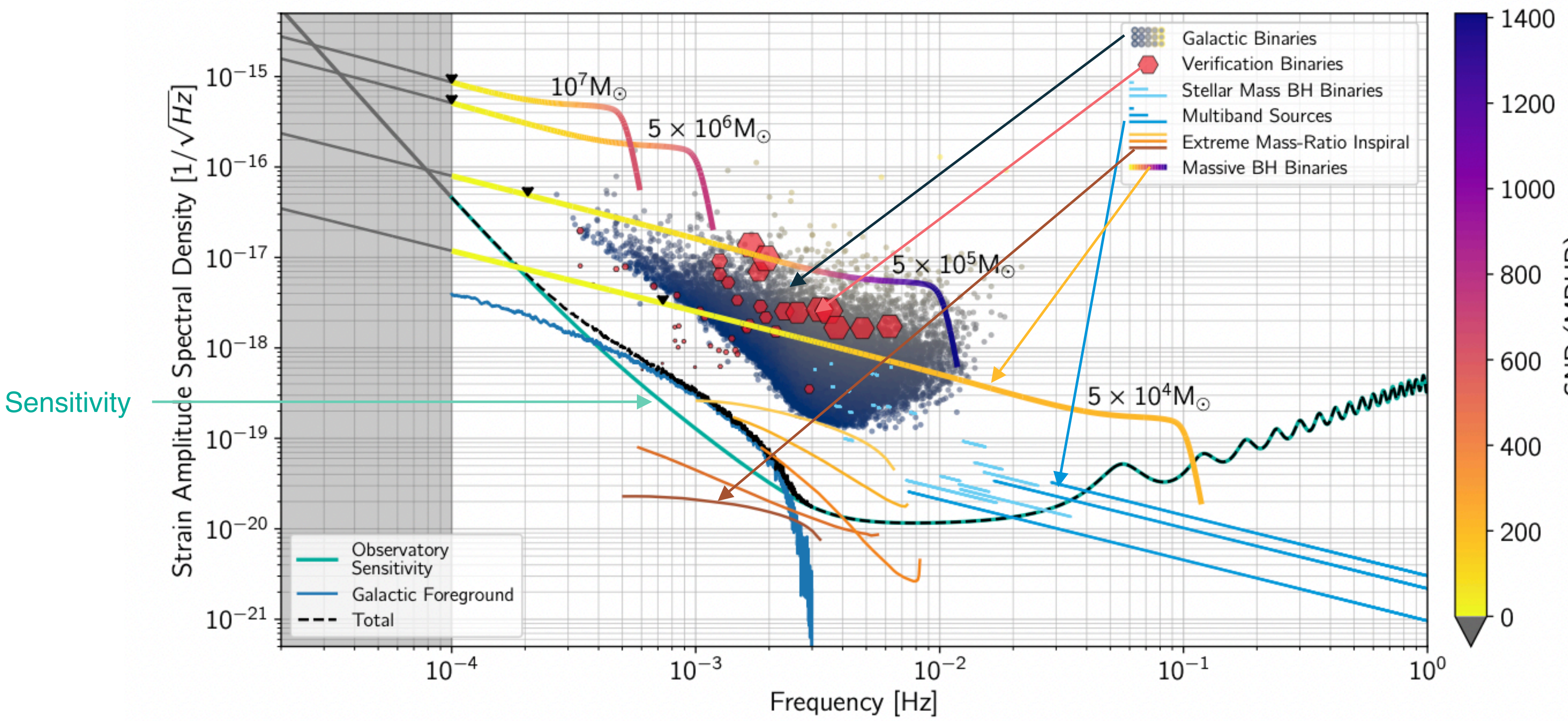
← Noise power spectral density

← Instrument's response to GWs

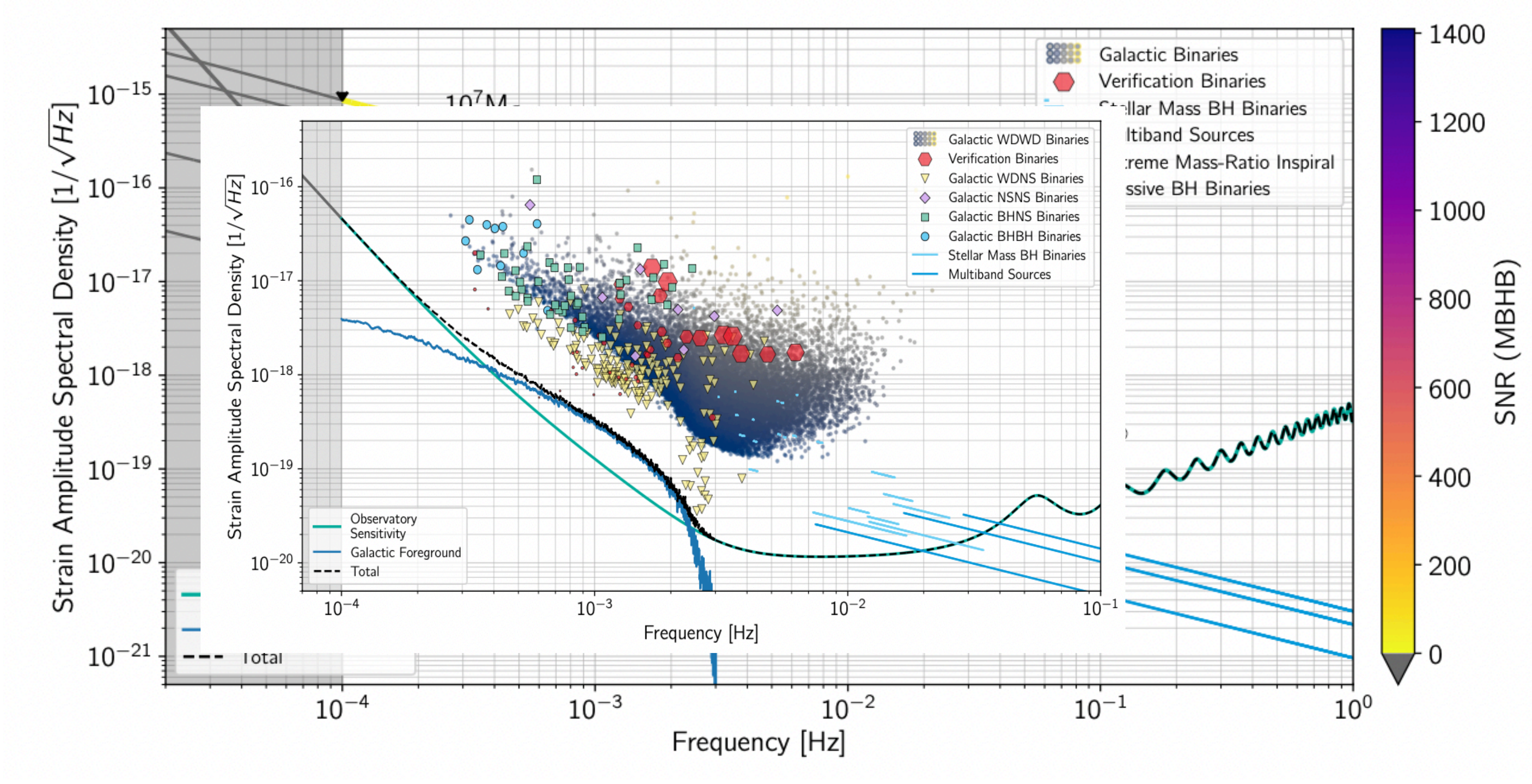


1. Mission concept

— Target gravitational wave sources

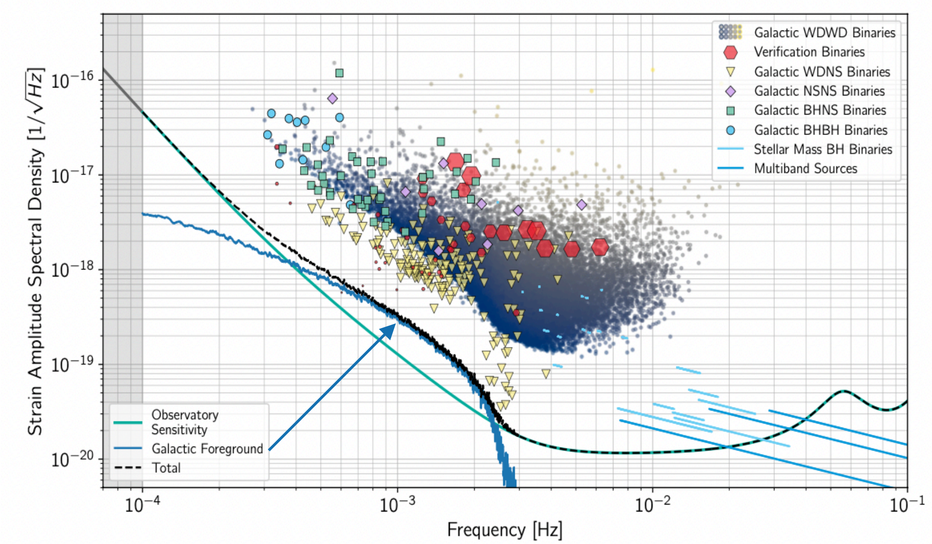


2. Science objectives: Study compact binary stars evolution and Galaxy structure



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

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

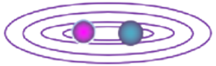


— Most of them are detached and interactive white dwarves → stellar remnants

— 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?



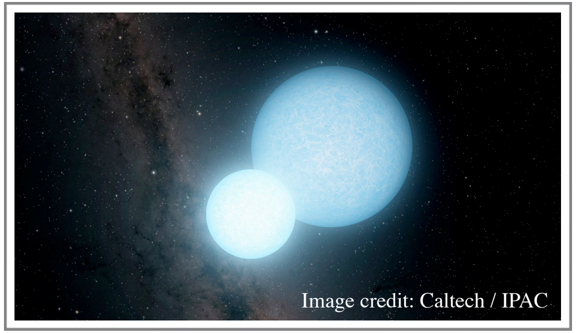
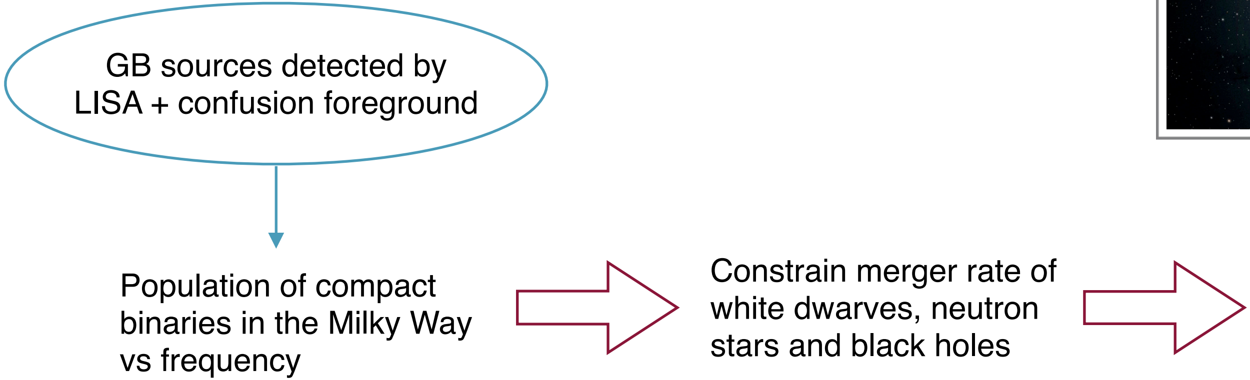


Image credit: Caltech / IPAC



GB sources detected by LISA + confusion foreground

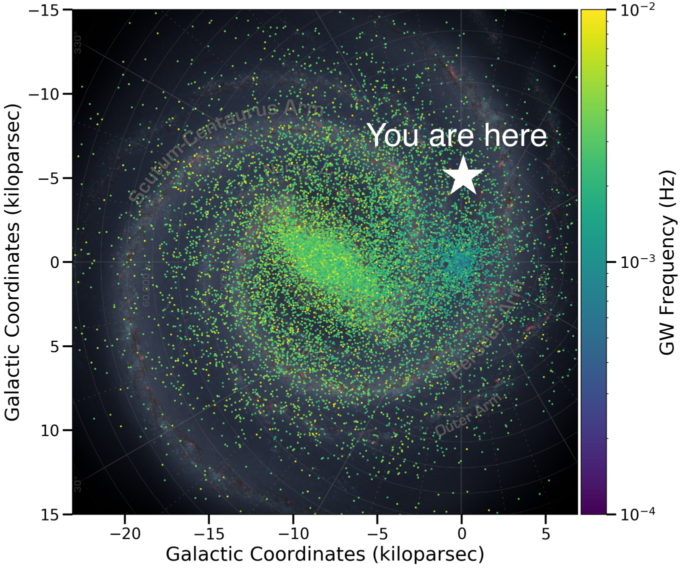
Population of compact binaries in the Milky Way vs frequency

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

Implication on explosive events (kilo and supernovae)

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

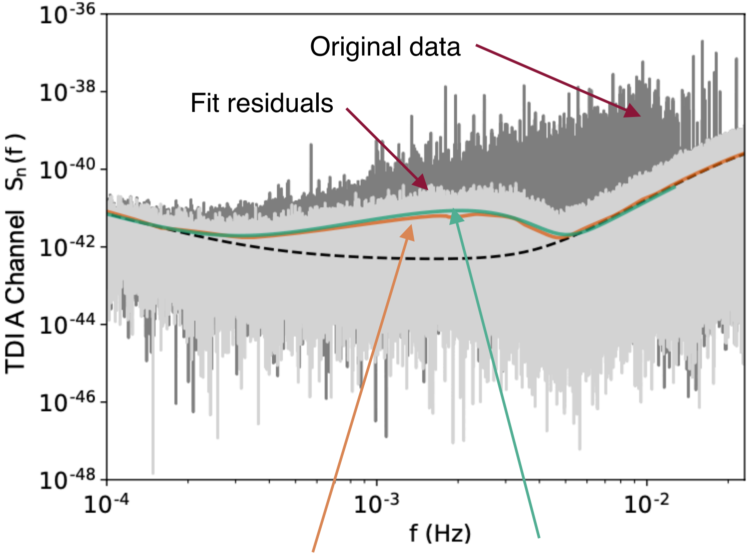
Sky locations and distances for a few 10^3

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



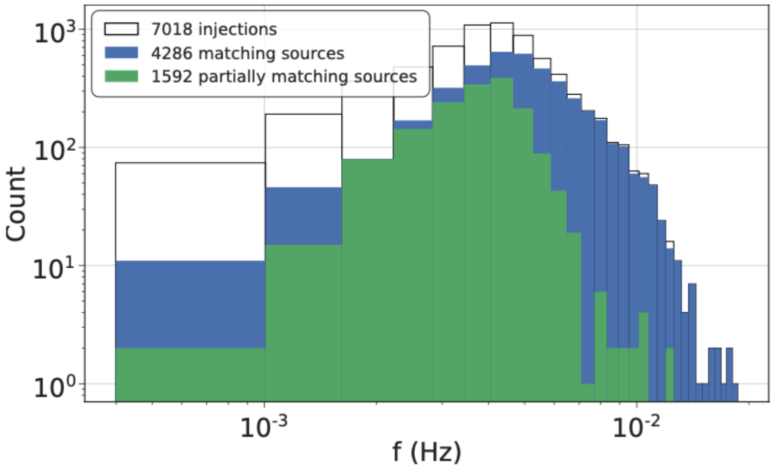
Original data

Fit residuals

Residual PSD estimate

“Theoretical” foreground + noise PSD

Prototype pipelines results with LISA Data Challenges 2 data

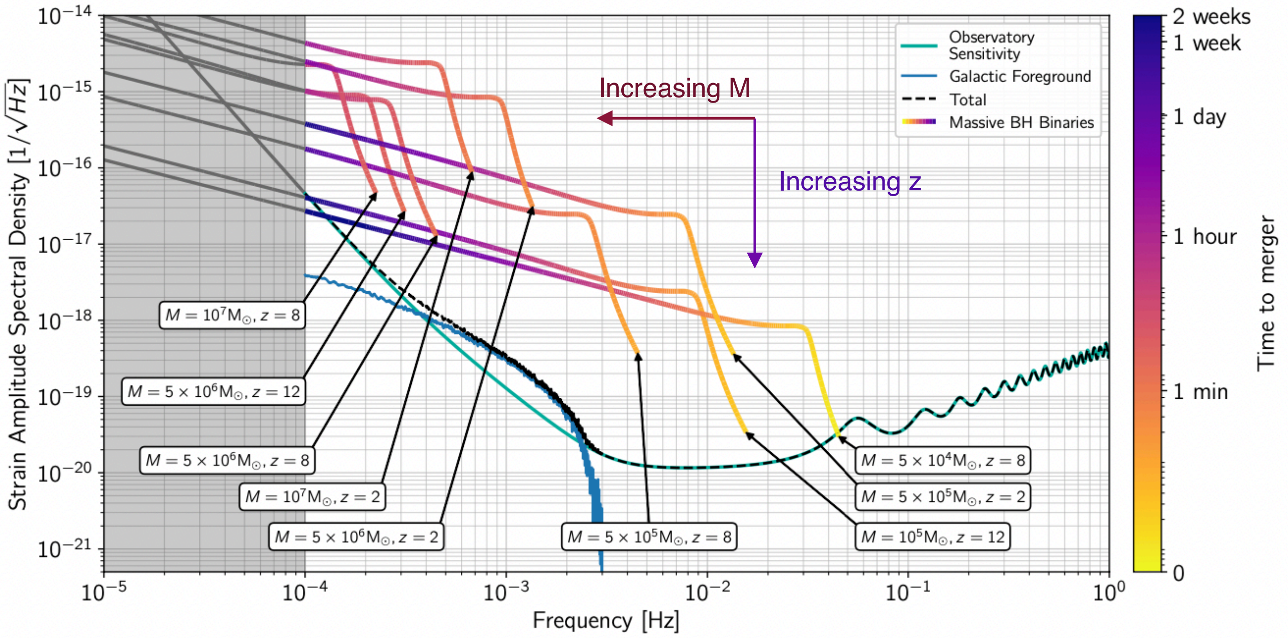


Galactic binary source frequency

[APC team LDC 2a results]

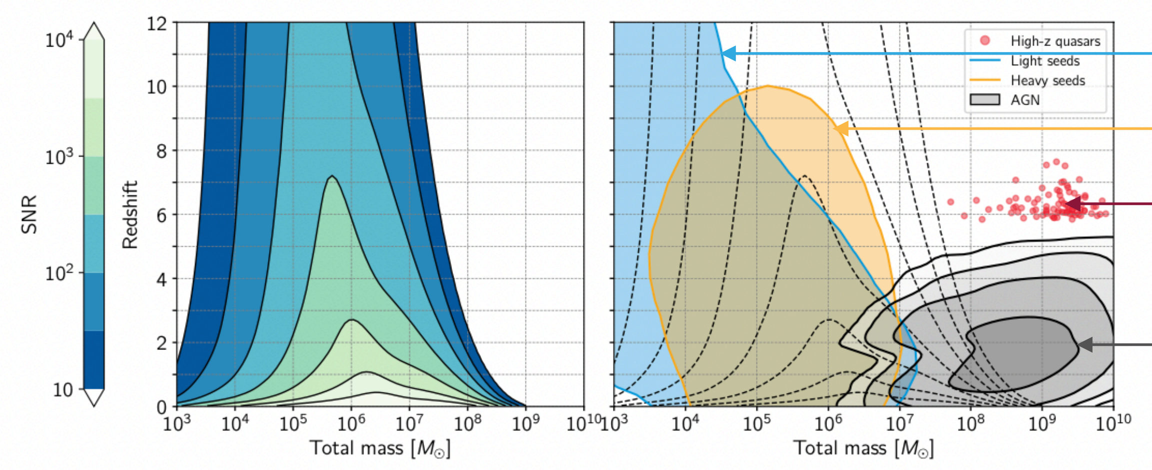
2. Science objectives: Trace the origin, growth and merger histories of massive black holes

- LISA will detects 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!



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

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

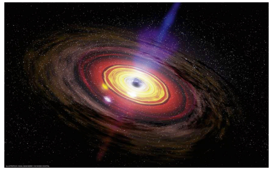


Simulated MBHB resulting from light seeds

Simulated MBHB resulting from heavy seeds

Quasars observed at z ~ 7 with EM observations

Current distribution of AGN population



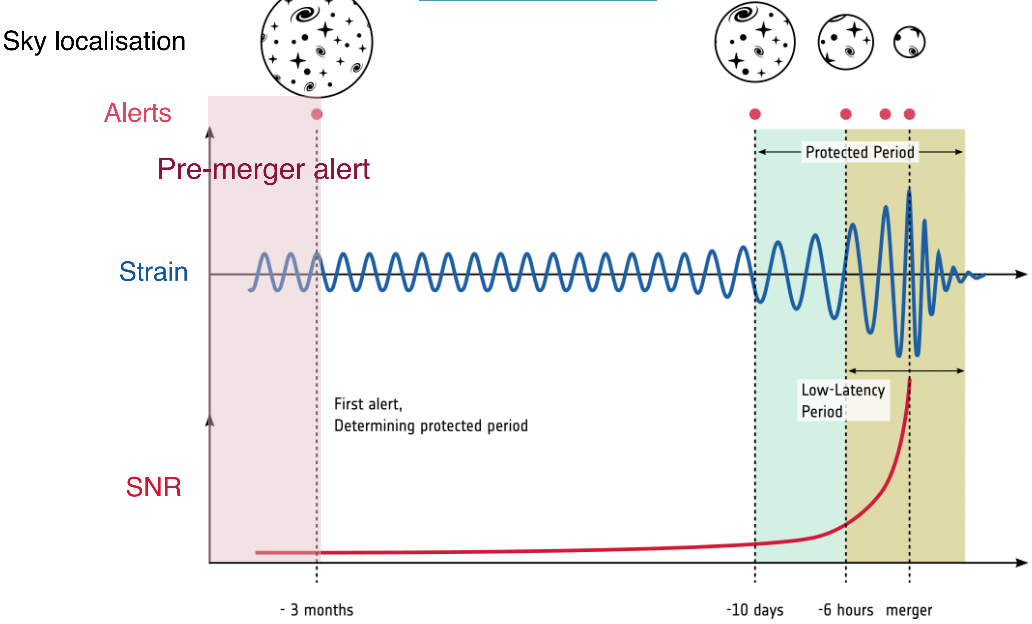
Measurement of MBH masses and redshifts → Help distinguish between different possible seeds

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 pre- and post merger?
- What is the role of accretion?



→ Plan observations ahead of time

→ Secure **protected periods**

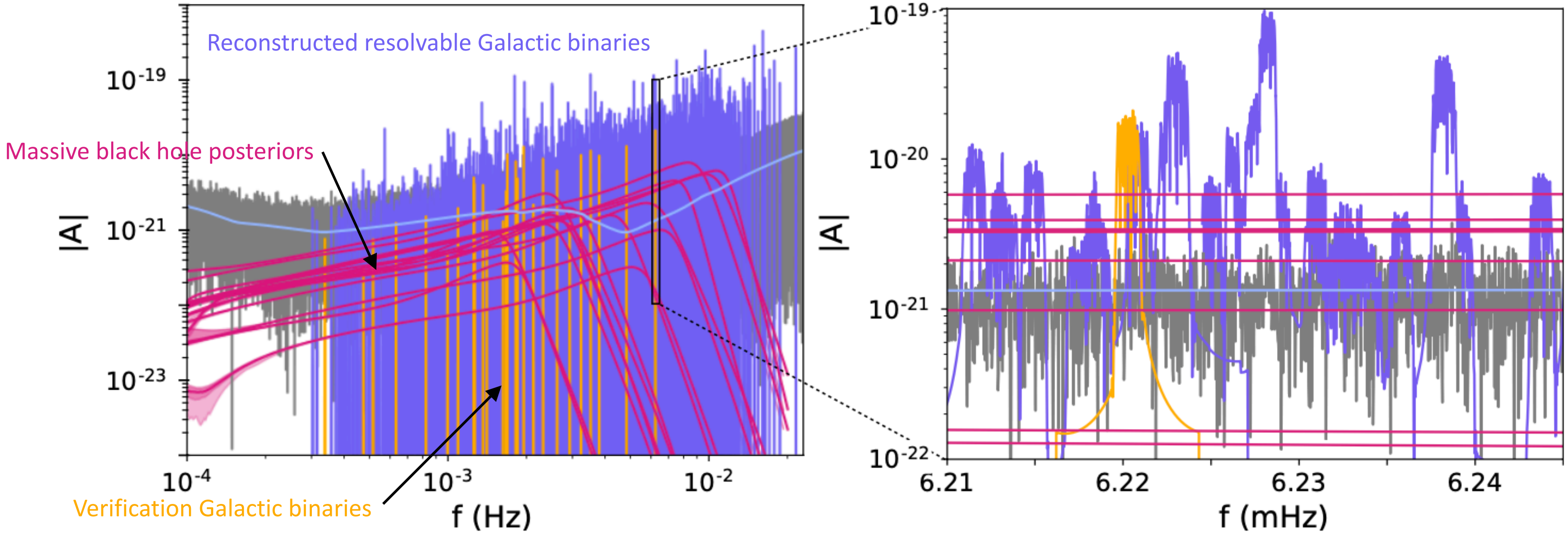
→ **Low-latency alert** pipeline

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



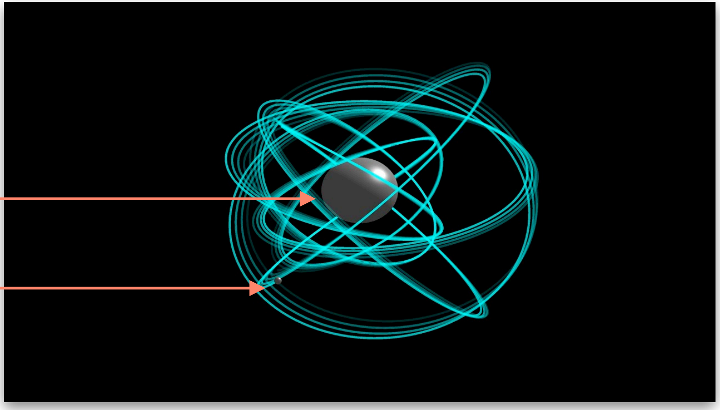
[Littenberg & Cornish 2023]

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

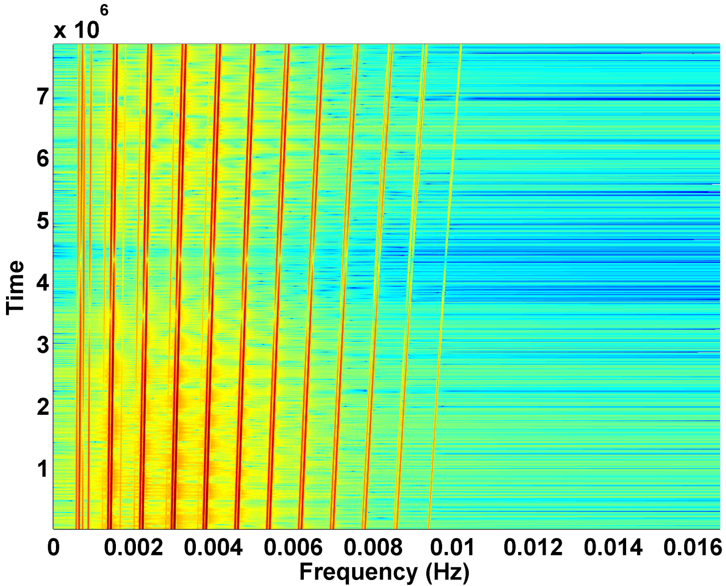
— Challenge for data analysis: many harmonics and cycles, complicated waveform

— 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 to spinning, eccentric and inclined systems

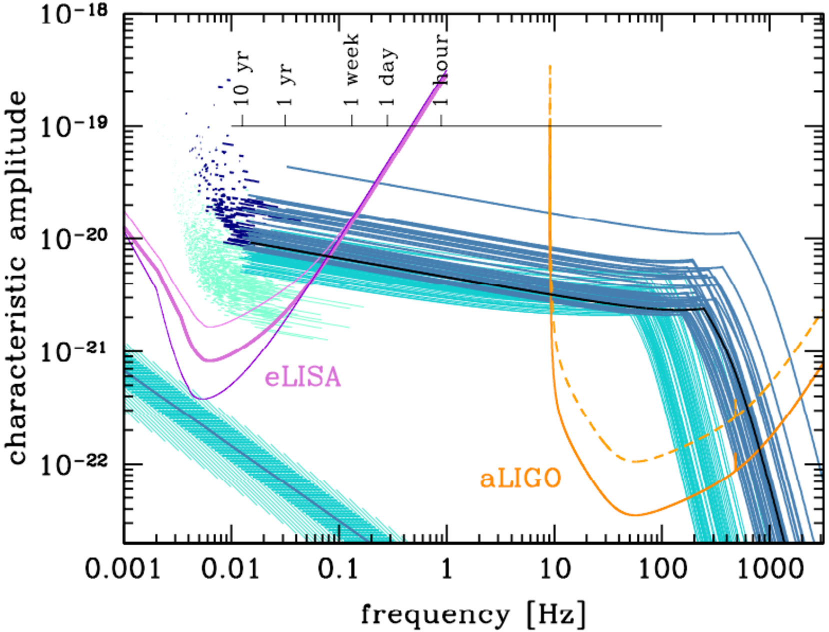
→ Need **adapted inference strategies**



[Babak 2017]

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.

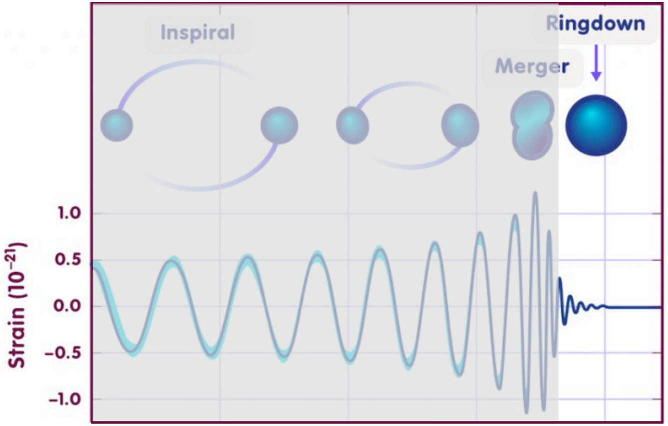


[Sesana 2016]

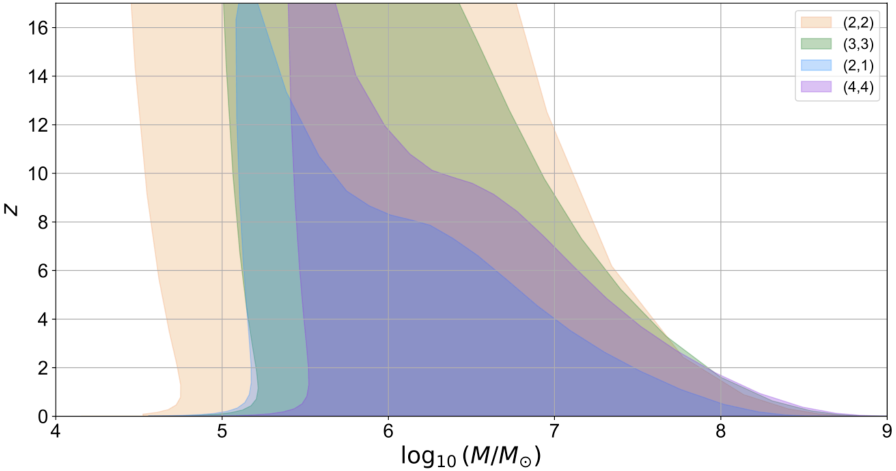
2. Science objectives: Explore the fundamental nature of gravity and Black Holes

- 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]



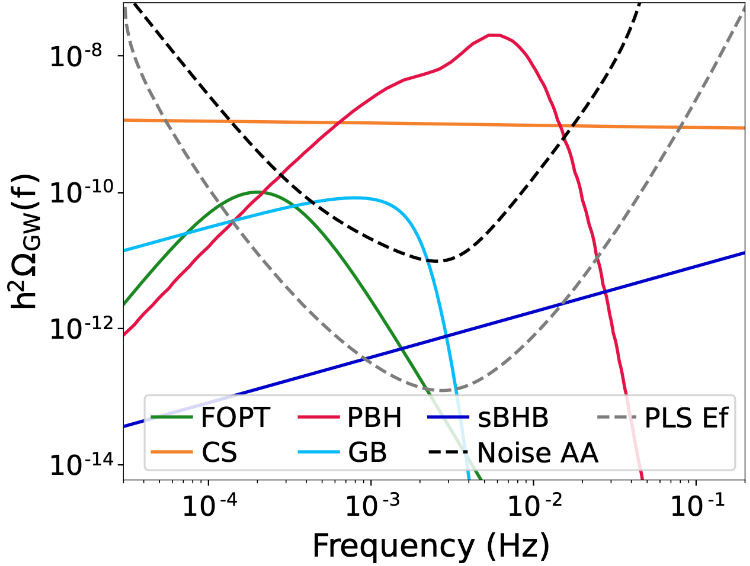
2. Science objectives: Cosmology

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 EM counterparts
- We can probe the expansion of the universe at $z < 1$ with **dark sirens**: EMRIs

SO7: Understand stochastic GW backgrounds

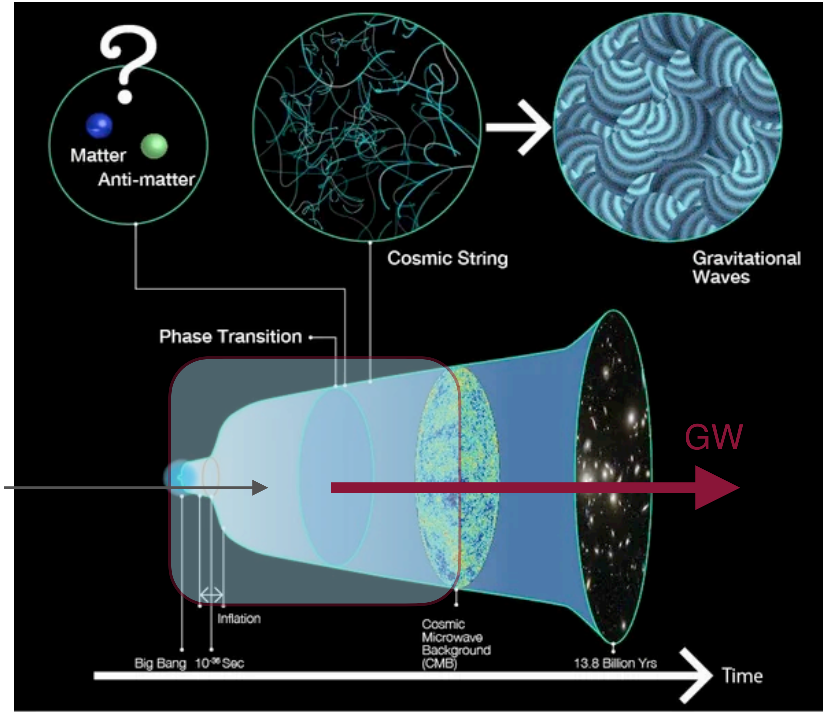
- It would be a **groundbreaking discovery** if we detected a stochastic GW background of cosmological origin
- Unique probe of early-universe physics and TeV-scale particle physics)
- But very challenging data analysis task!



2. Science objectives: Understand stochastic GW backgrounds

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

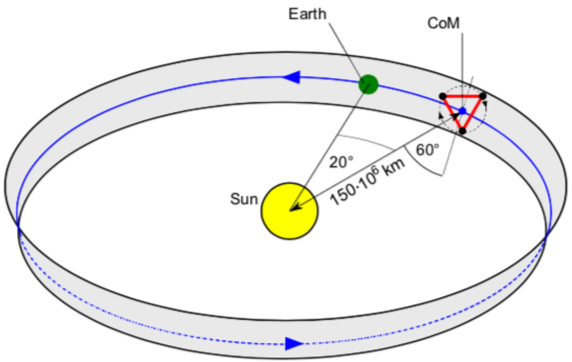
Region inaccessible through light



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

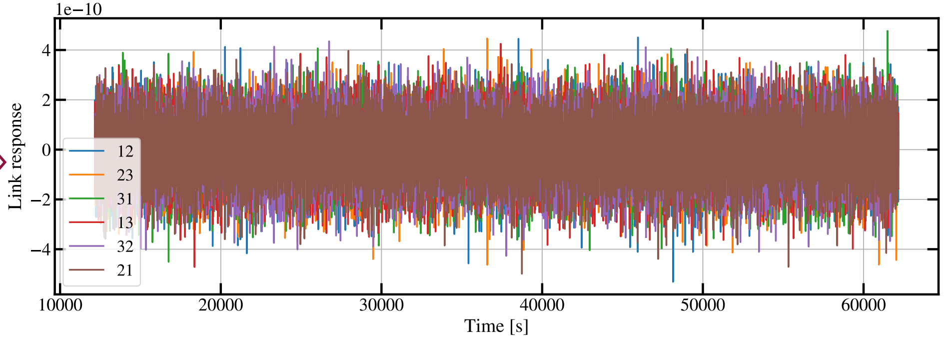
2. Science objectives: Understand stochastic GW backgrounds

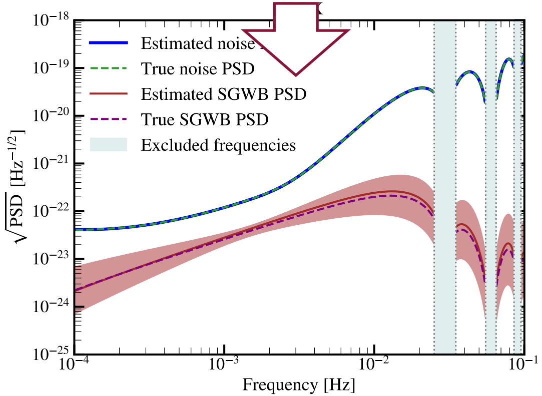
— Extracting them is a challenge: they must be distinguished from instrumental noise and Galactic foreground



Scanning the sky

Interferometric measurements

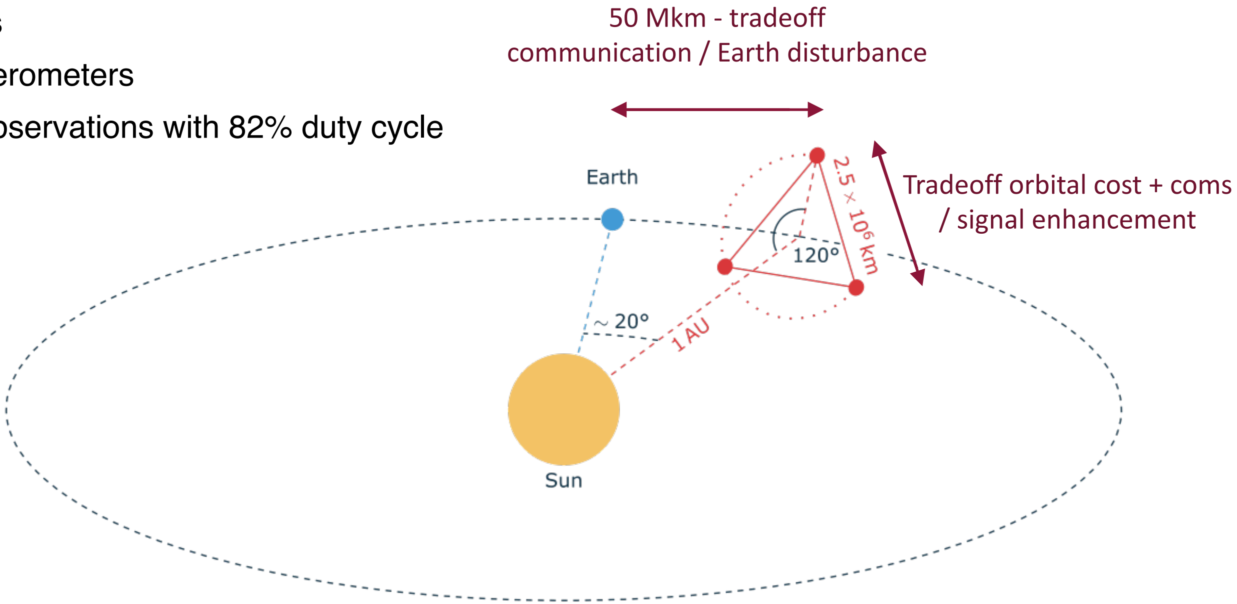




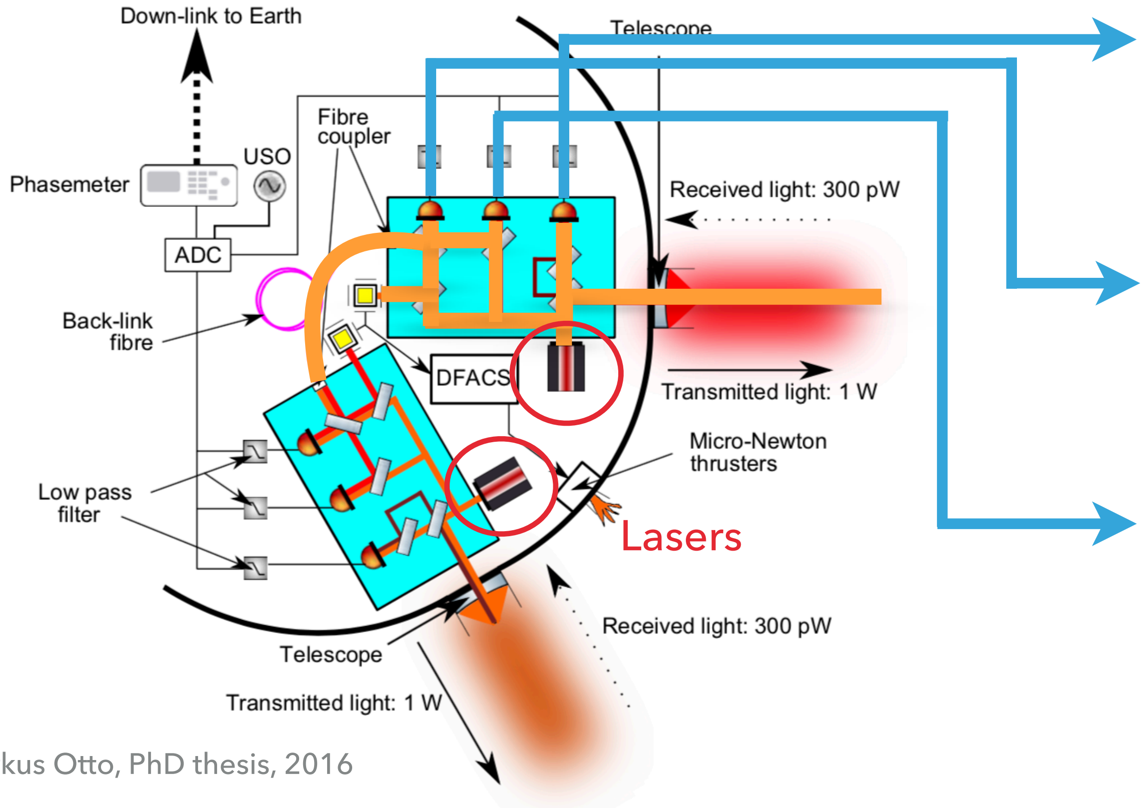
Reconstructed spectra

3. Measurement principles

- Measures mHz gravitational waves [10^{-4}, 1] Hz
- 3 spacecraft (S/C) forming a triangle with 2.5 x 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: onboard interferometry



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

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

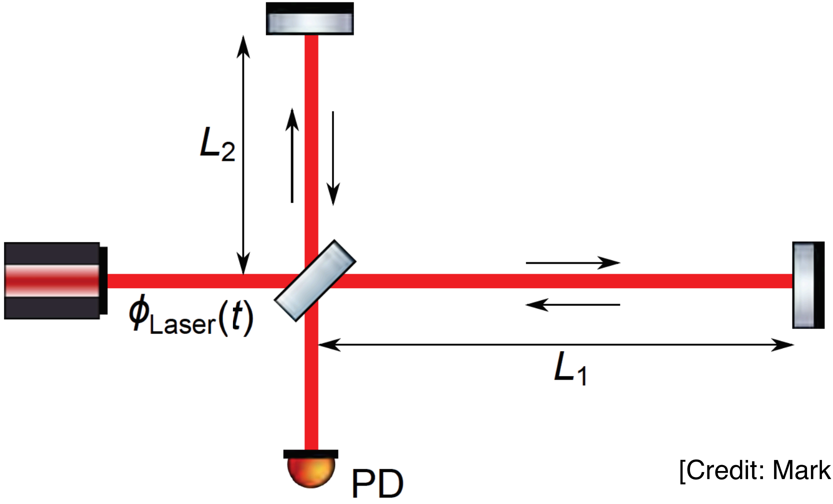
Reference interferometer: Local oscillator - adjacent oscillator

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

- In LISA, each science interferometer length mismatch is of order of million 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

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

▼

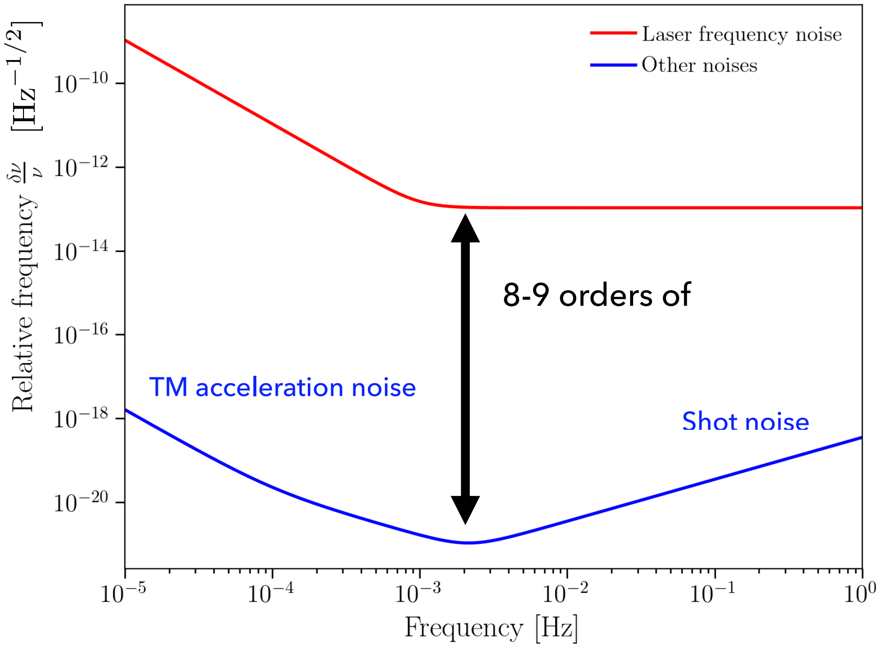
Gravitational strain noise

$$\sqrt{S_h} = 2\frac{\sqrt{S_x}}{L}$$

$$\sim 2 \times 10^{-12}\,\mathrm{Hz}^{-1/2}$$

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

Too large to detect GWs!



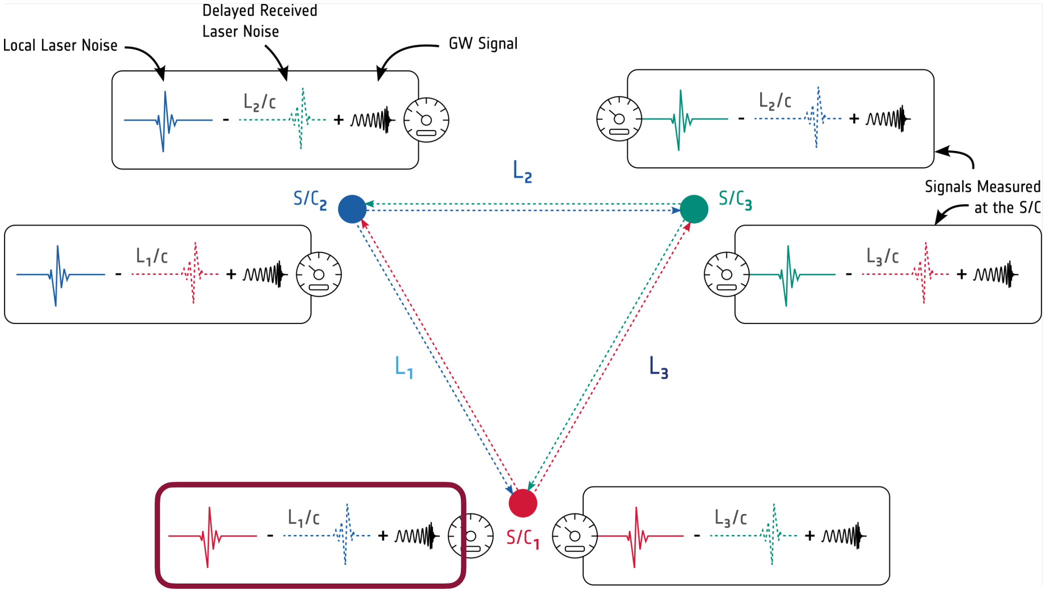
8-9 orders of

TM acceleration noise

Shot noise

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



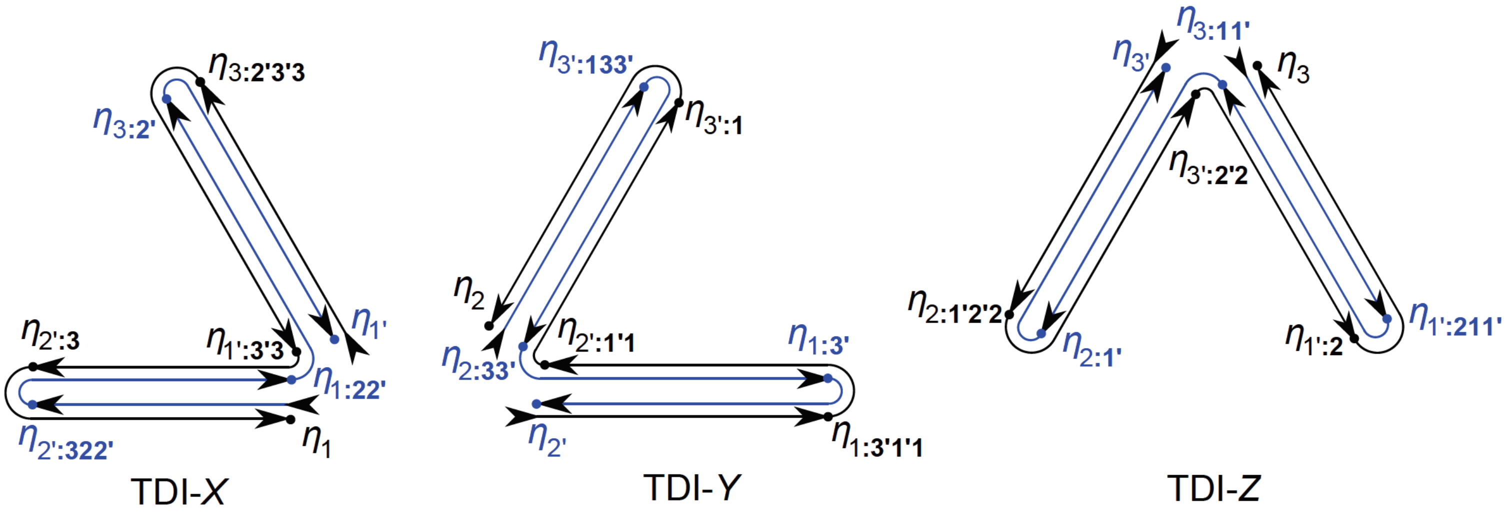
Local laser

Received laser

GW signal

3. Measurement principles: time-delay interferometry

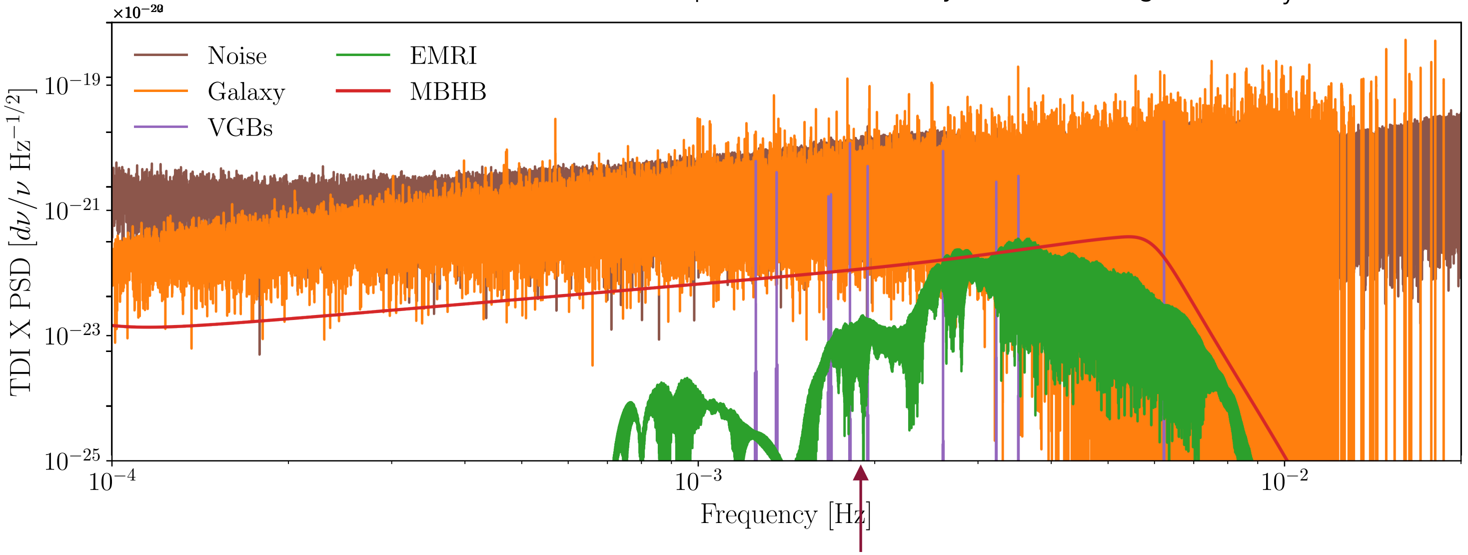
- The interferometry is done as a **post-processing step**.
- A linear combination of delayed phasemeter measurements tailored to cancel laser noise
- This algorithm is called **time-delay interferometry** (TDI) [Tinto & Armstrong1999]
- Some of these combinations are equivalent to a synthetically reproducing a Michelson interferometer photon path



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



Coalescence

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)

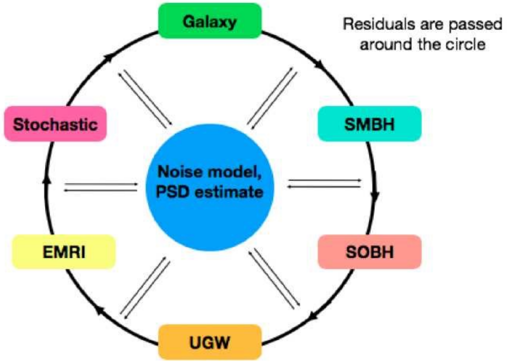
—Where one must define a likelihood function: for example, Gaussian

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

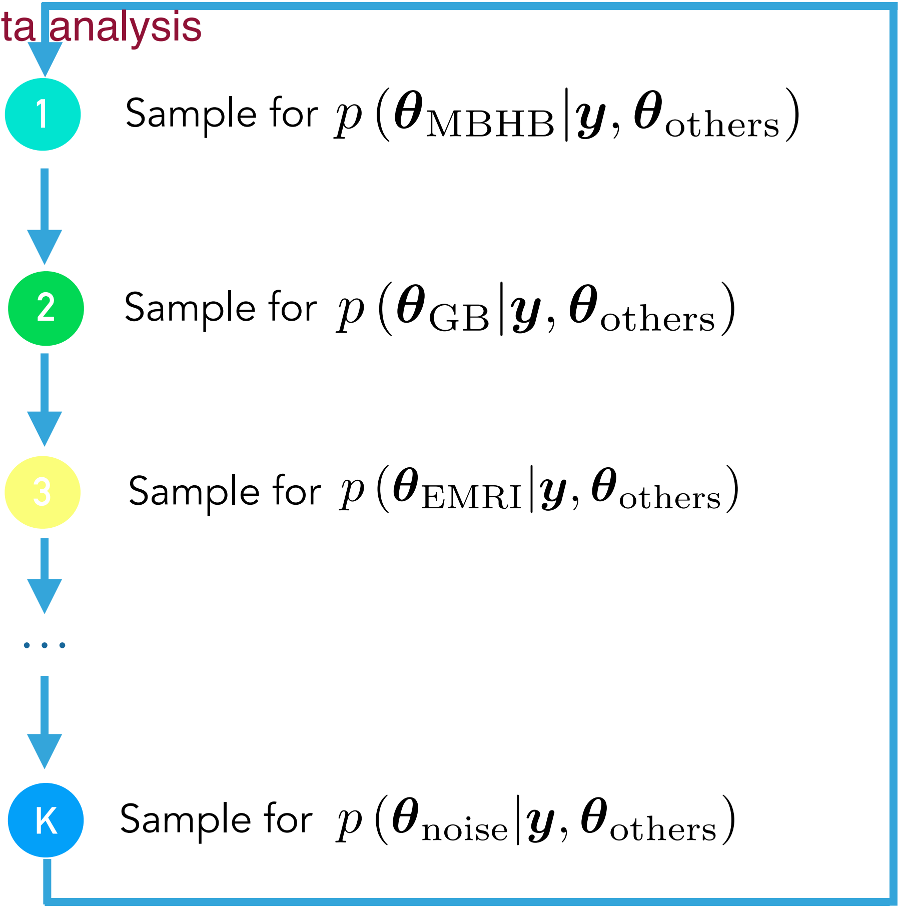
GW signals: $\boldsymbol{h}(\boldsymbol{\theta}, q) = \sum_{j=1}^{q} \boldsymbol{h}_j(\boldsymbol{\theta}_j)$ Stochastic processes: $\boldsymbol{\Sigma}(\boldsymbol{\theta}) = \sum_{i=1}^{p} \boldsymbol{\Sigma}_i(\boldsymbol{\theta}_i)$

$$k = p + q$$

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 $p\left(\boldsymbol{\theta}_{\mathrm{GB}} \middle| \boldsymbol{y}, \boldsymbol{\theta}_{\mathrm{others}}\right)$

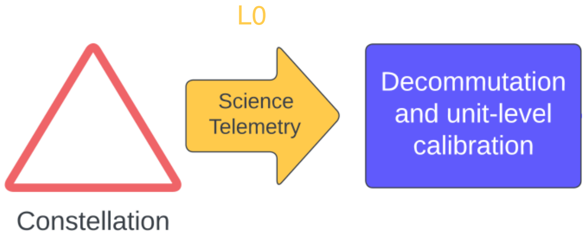
3. Sample for $p\left(\boldsymbol{\theta}_{\mathrm{EMRI}} \middle| \boldsymbol{y}, \boldsymbol{\theta}_{\mathrm{others}}\right)$

$\dots$

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

3. Measurement principles: operations

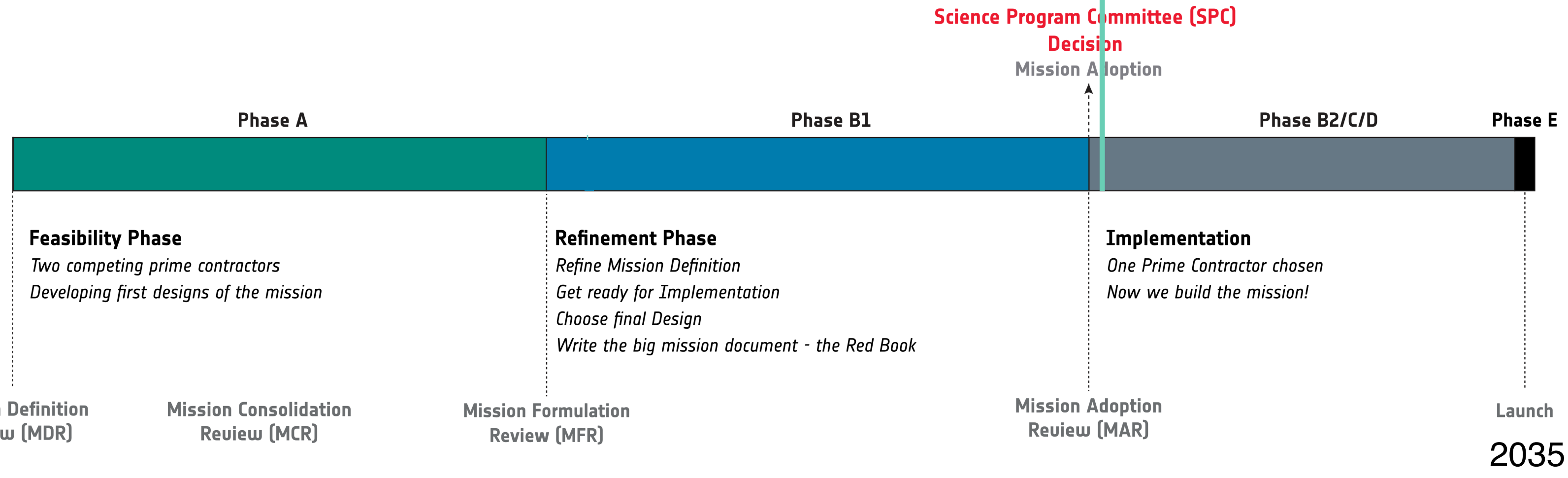
LISA’s operational concept: perform a *time-resolved*, *all-sky* survey of gravitational waves sources in the millihertz band.



- 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

Conclusion: bright future and many challenges

We are here



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	2035

Thank you for you attention!