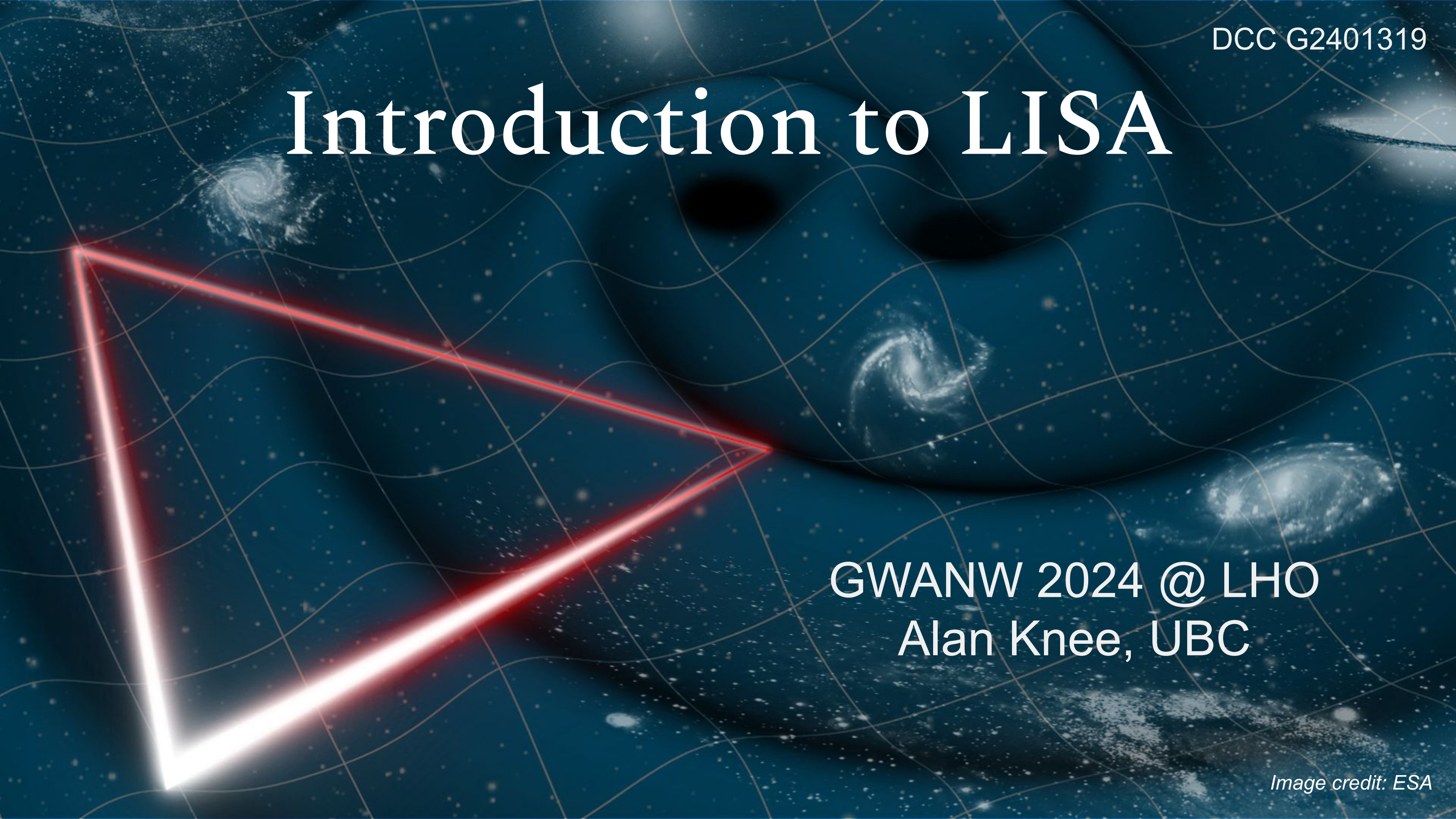
DCC G2401319

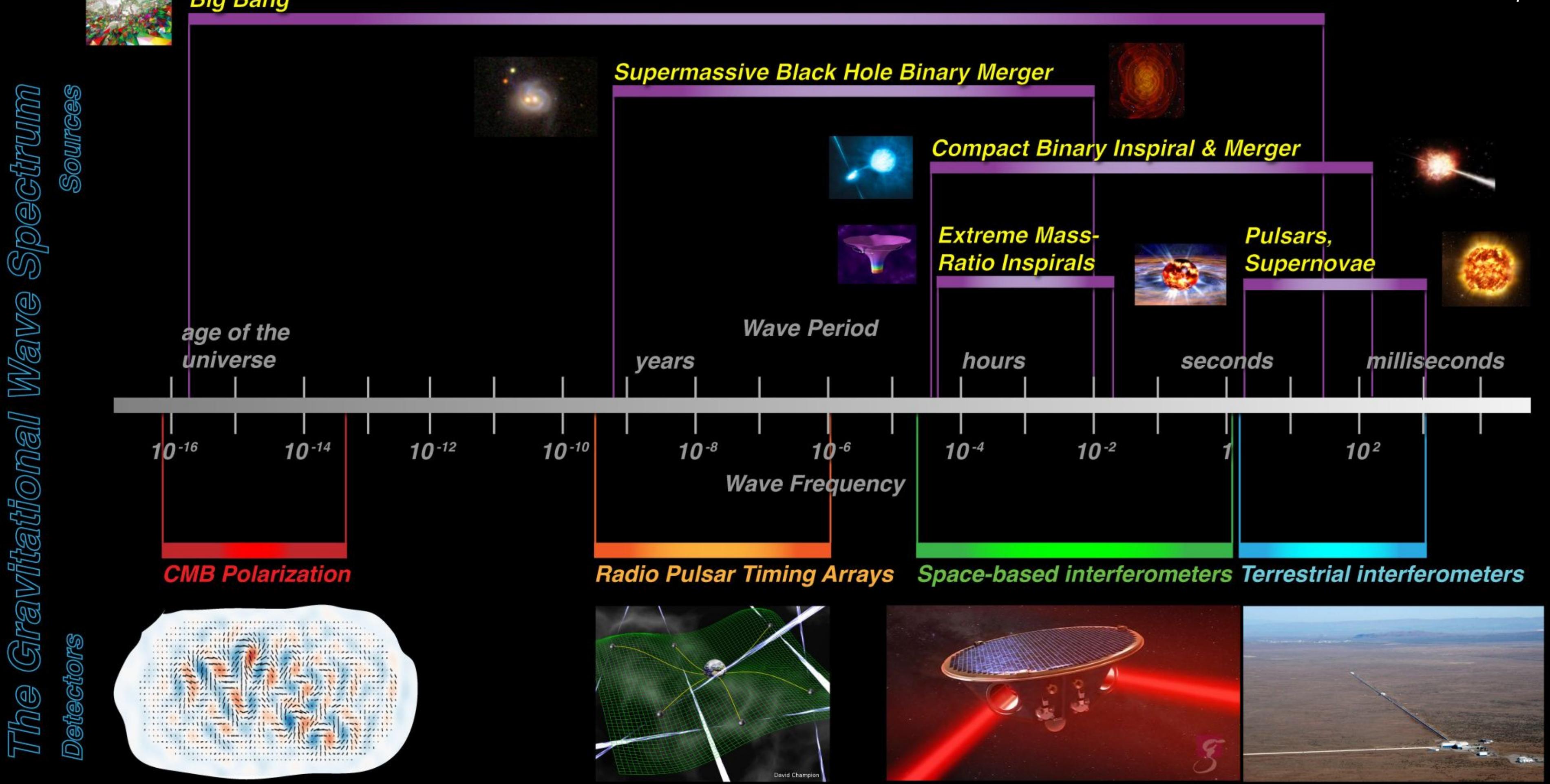
Introduction to LISA



GWANW 2024 @ LHO

Alan Knee, UBC

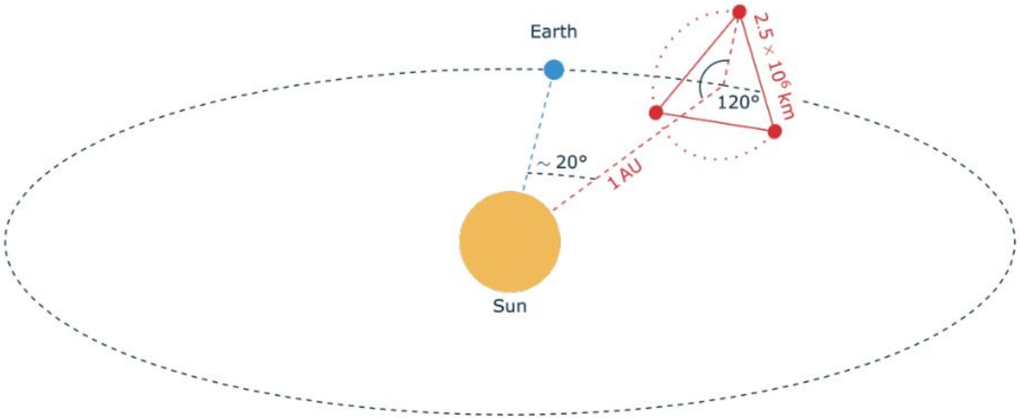
Image credit: ESA



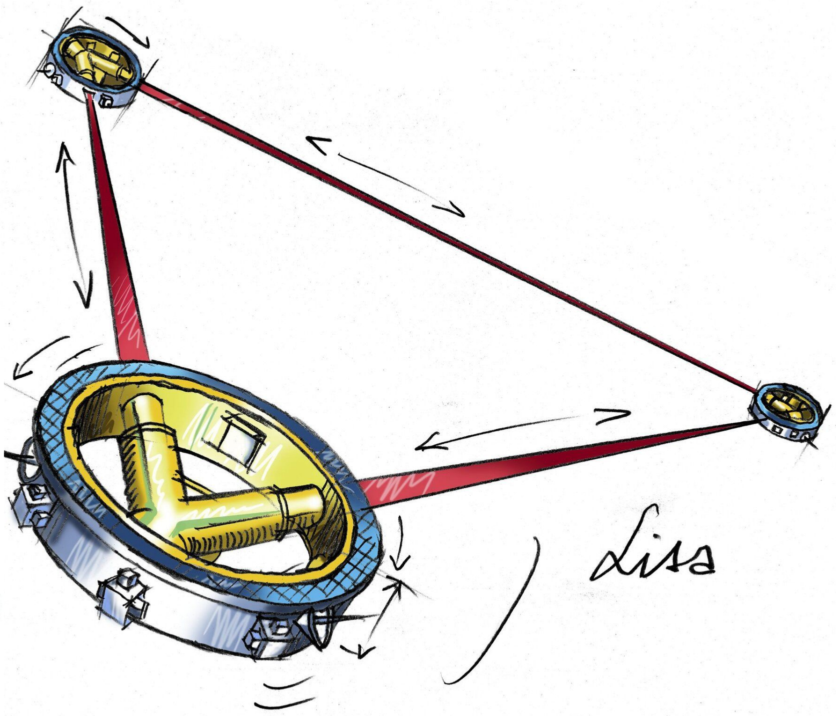
Credit: NASA/J. I. Thorpe

Laser Interferometer Space Antenna (LISA)

- 3 spacecraft on heliocentric orbits, forming triangular constellation
- 2.5 million km arm length
- Sensitive band: $10^{-4}\,\mathrm{Hz} - 0.1\,\mathrm{Hz}$
- 4 yr nominal mission lifetime
- Led by ESA, partnered with NASA



Credit: LISA Definition Study Report



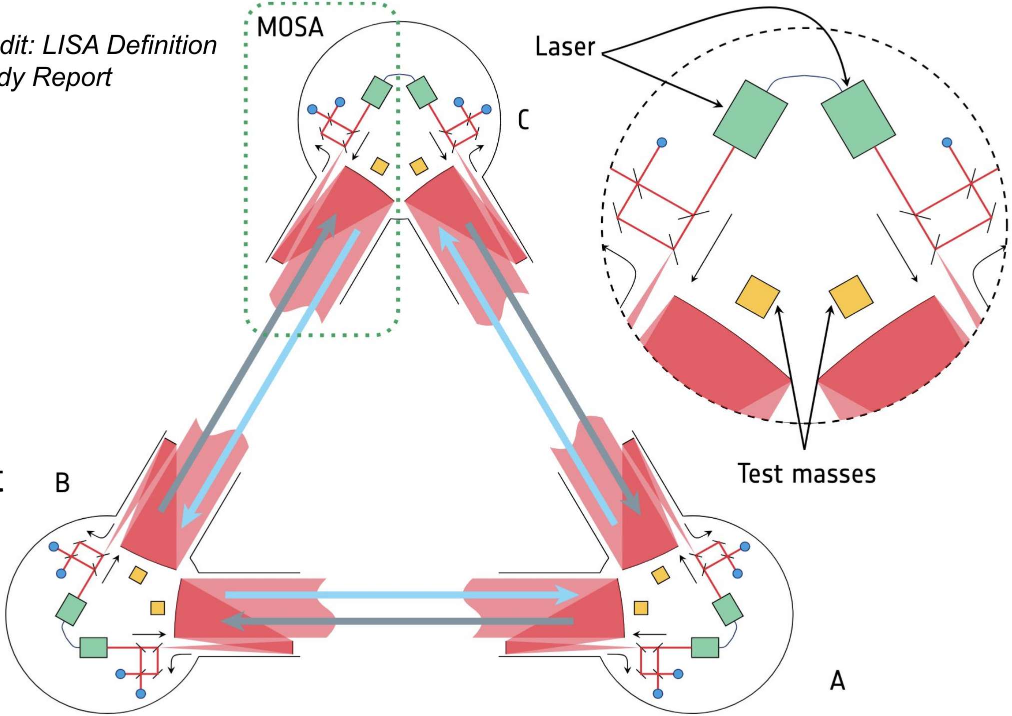
Credit: ESA/C. Vijoux

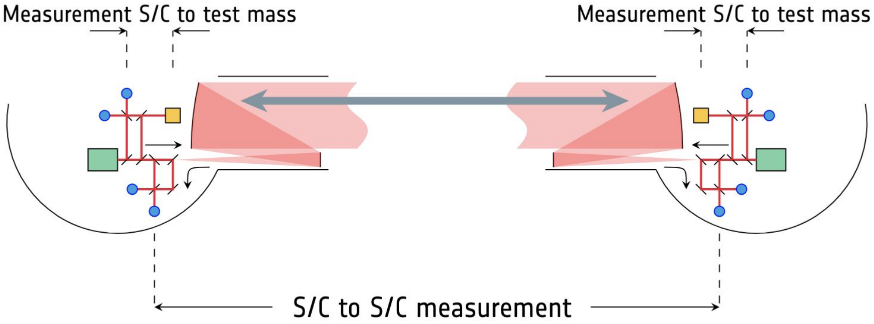
Credit: AEI/Milde Marketing/exozet effects

How does LISA work?

- Each spacecraft houses two lasers + two free-floating test masses
- 6 laser “links” total
- Interfere pairs of incoming/local lasers to measure relative displacement of test masses → GW strain

Credit: LISA Definition Study Report





- Test mass interferometer (TMI) for test mass displacement relative to local optical bench
- Inter-satellite interferometer (ISI) for spacecraft-to-spacecraft measurement

What LISA will see

Question – How does GW frequency depend on the mass and radius of a binary?

What LISA will see

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- Kepler's third law:

$$f_{\mathrm{GW}} = 2f_{\mathrm{orb}} = \sqrt{\frac{GM}{\pi^2 R^3}}$$

- Wider radius = lower frequency, LISA will see binaries with orbital periods of minutes to hours
- Higher mass = higher frequency
- **Question** – How come LIGO does not see massive black hole mergers?

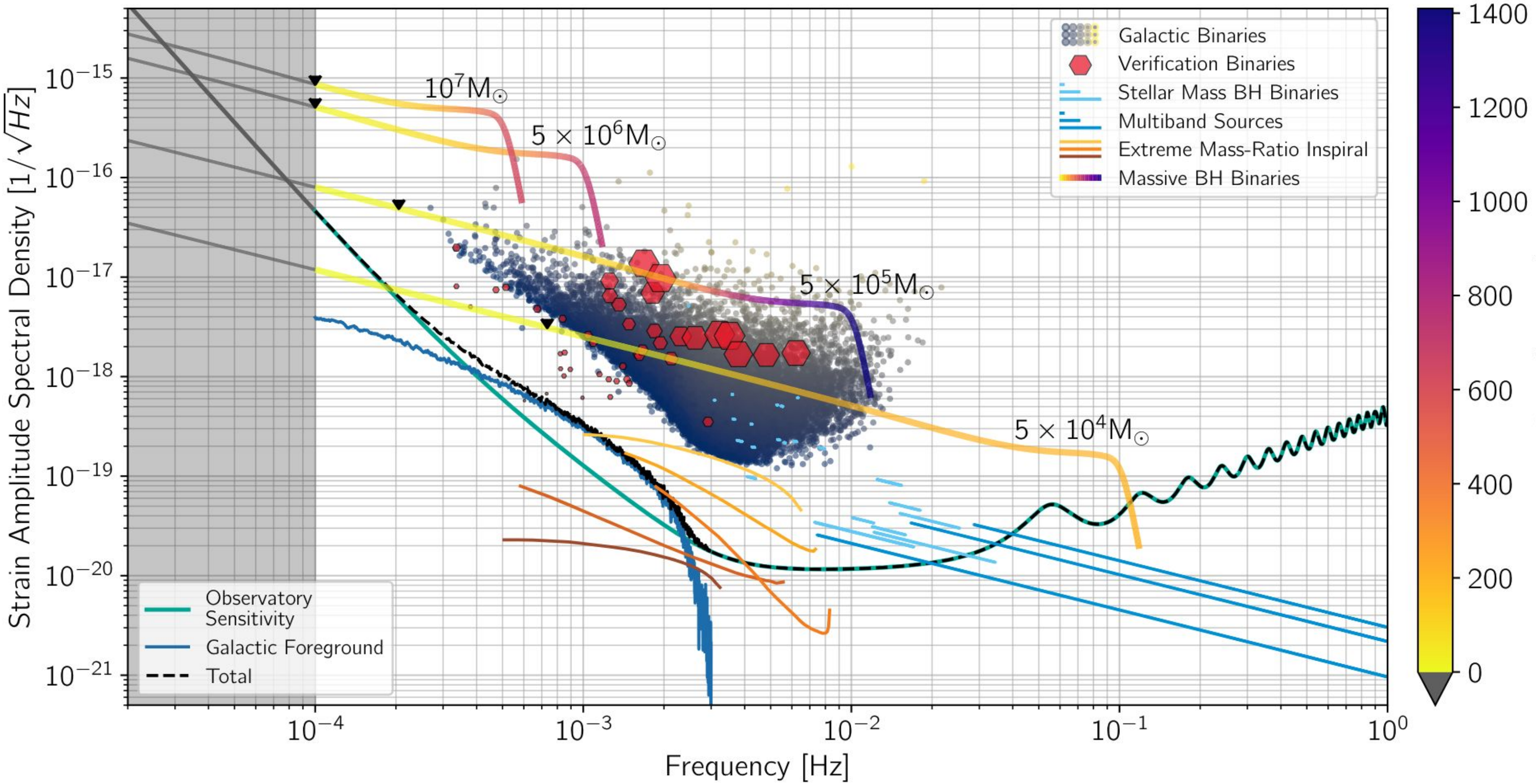
What LISA will see

Question – How come LIGO does not see massive black hole mergers?

- More massive black holes have larger Schwarzschild radii

$$R_s = \frac{2GM}{c^2}$$

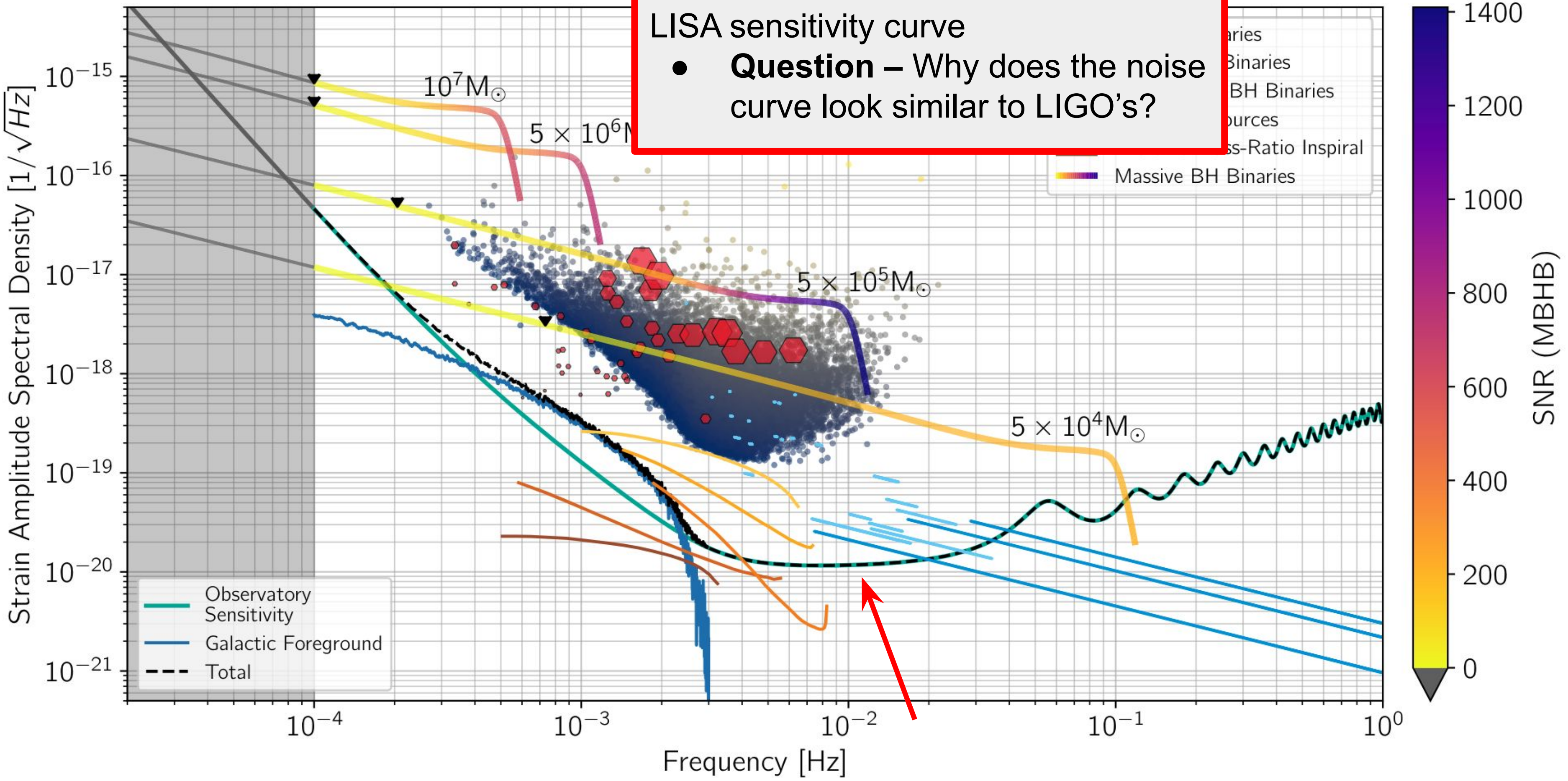
- Two black holes will contact each other long before reaching LIGO band
- Merger happens at lower GW frequencies, in the LISA band



Source: LISA Definition Study Report

LISA sensitivity curve

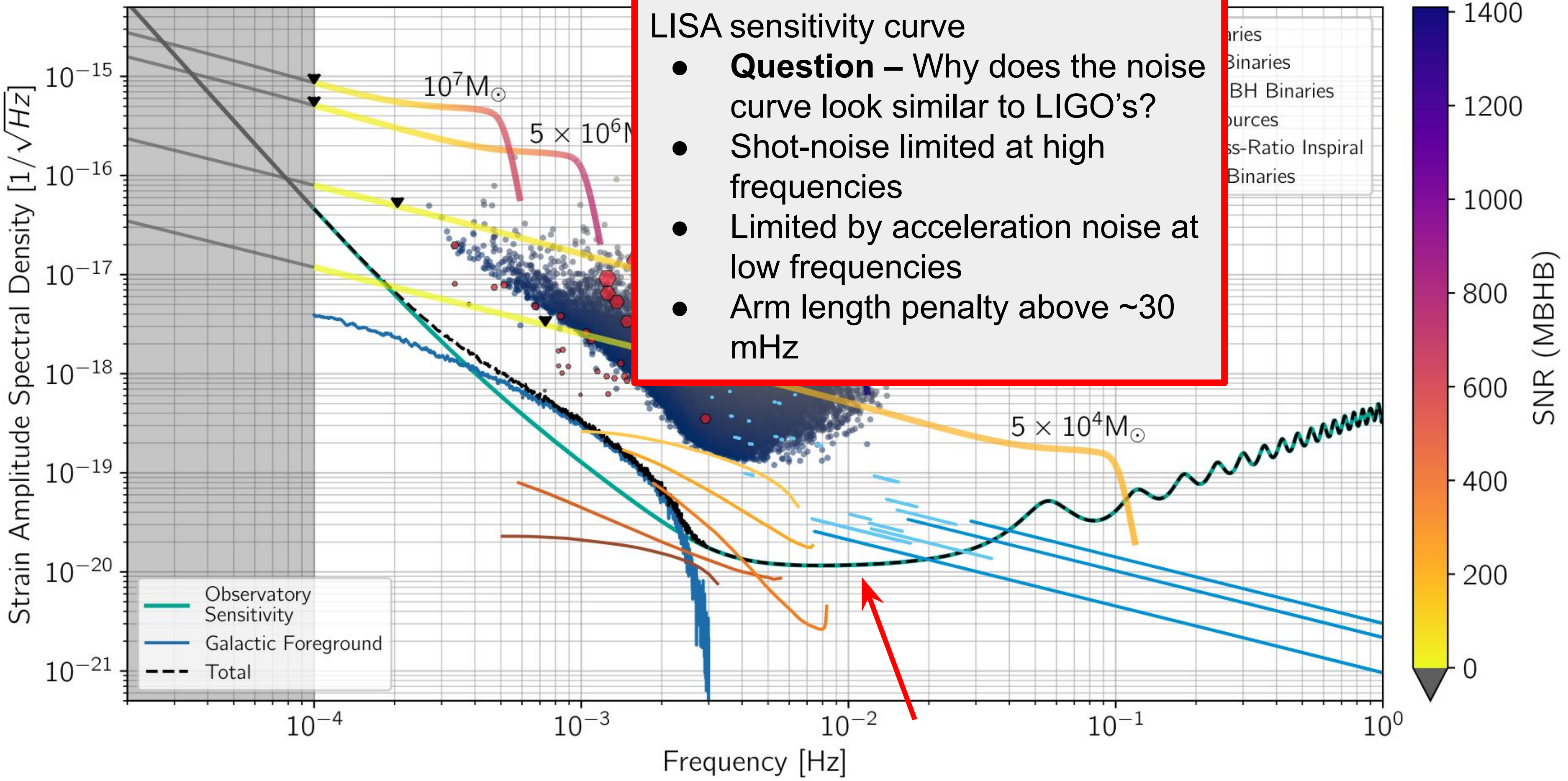
- **Question –** Why does the noise curve look similar to LIGO’s?



Source: LISA Definition Study Report

LISA sensitivity curve

- **Question –** Why does the noise curve look similar to LIGO's?
- Shot-noise limited at high frequencies
- Limited by acceleration noise at low frequencies
- Arm length penalty above ~30 mHz



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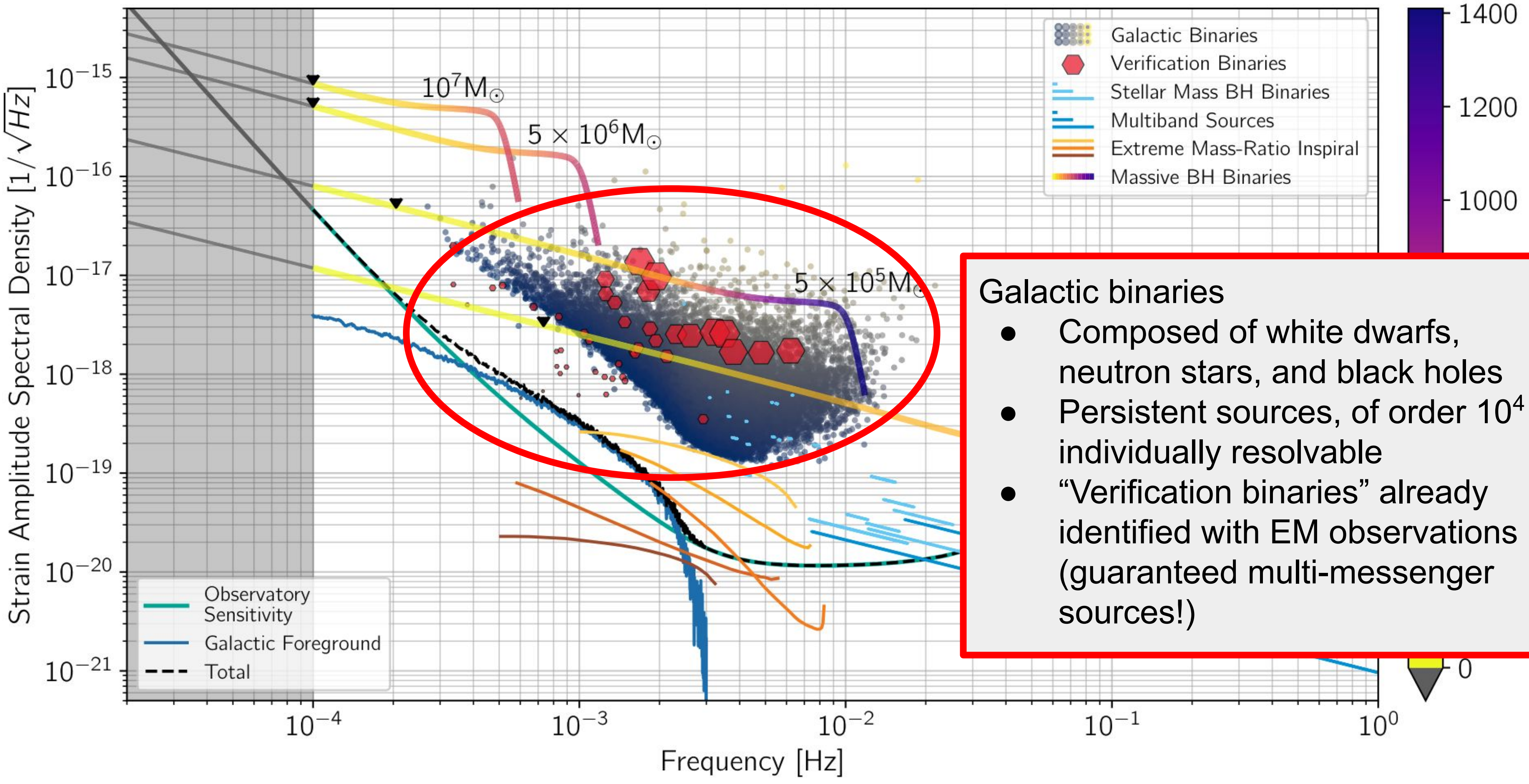
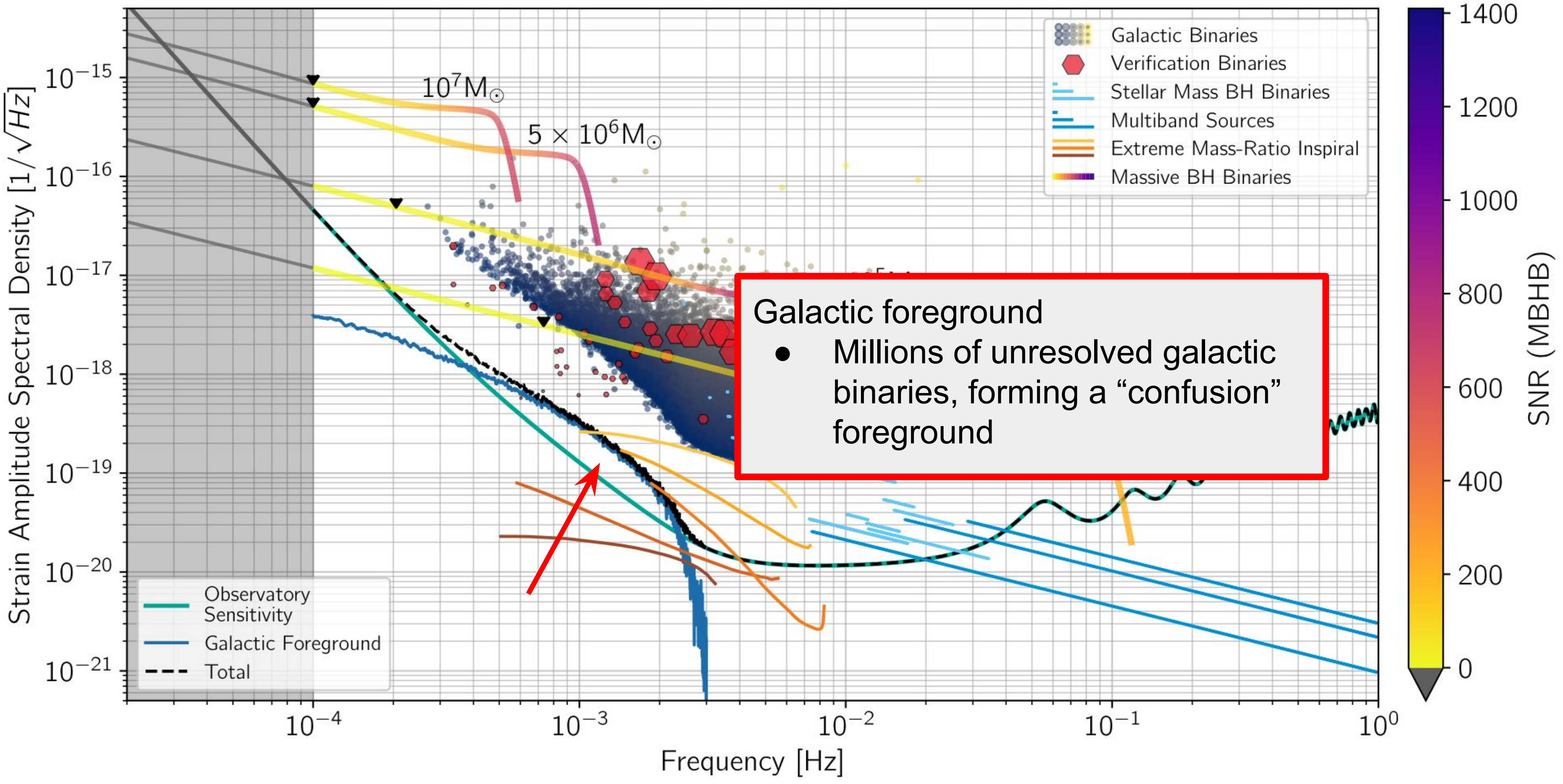


Galactic binaries

- Composed of white dwarfs, neutron stars, and black holes
- Persistent sources, of order 10^4 individually resolvable
- “Verification binaries” already identified with EM observations (guaranteed multi-messenger sources!)

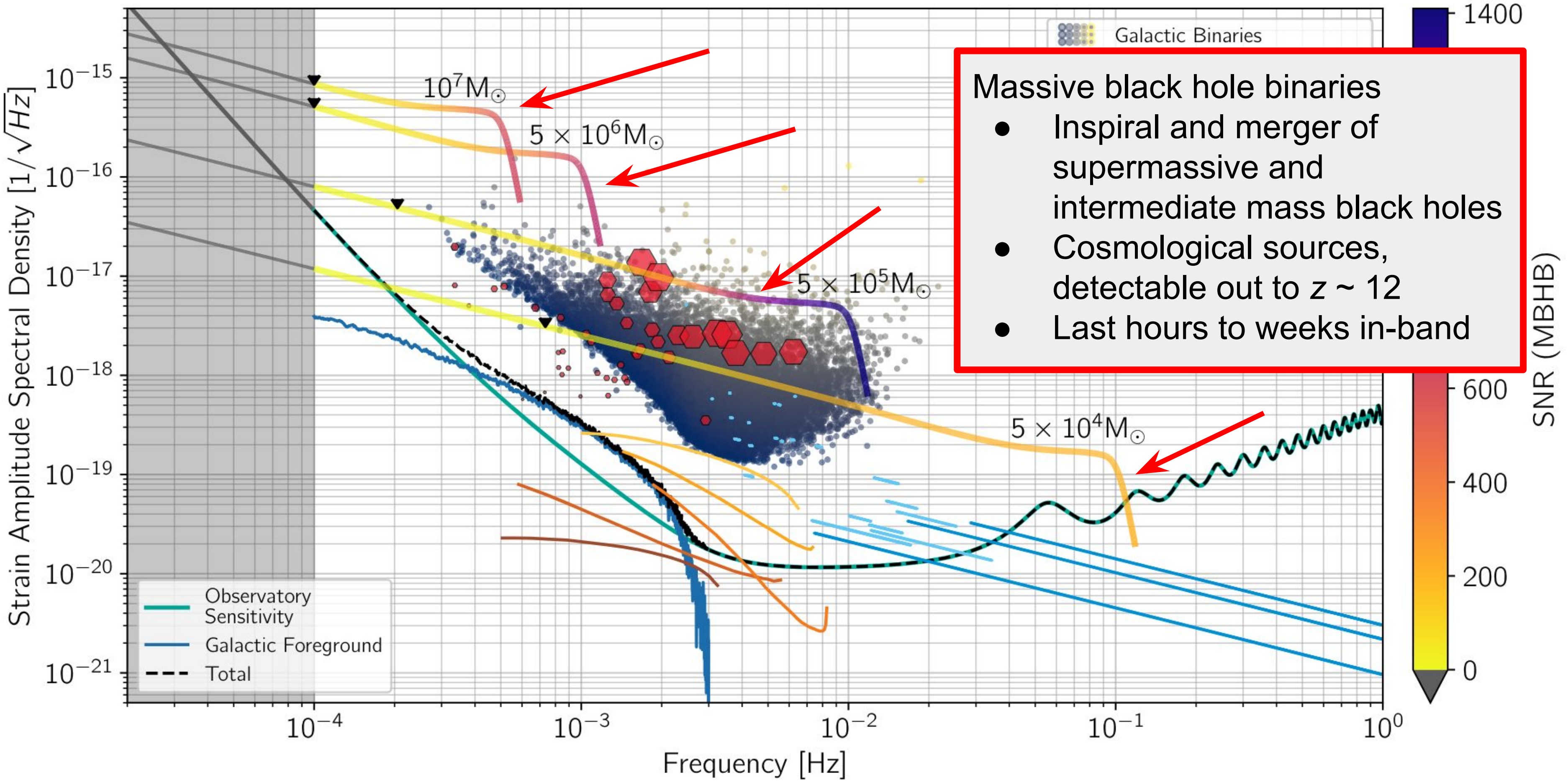
Source: LISA Definition Study Report



Galactic foreground

- Millions of unresolved galactic binaries, forming a “confusion” foreground

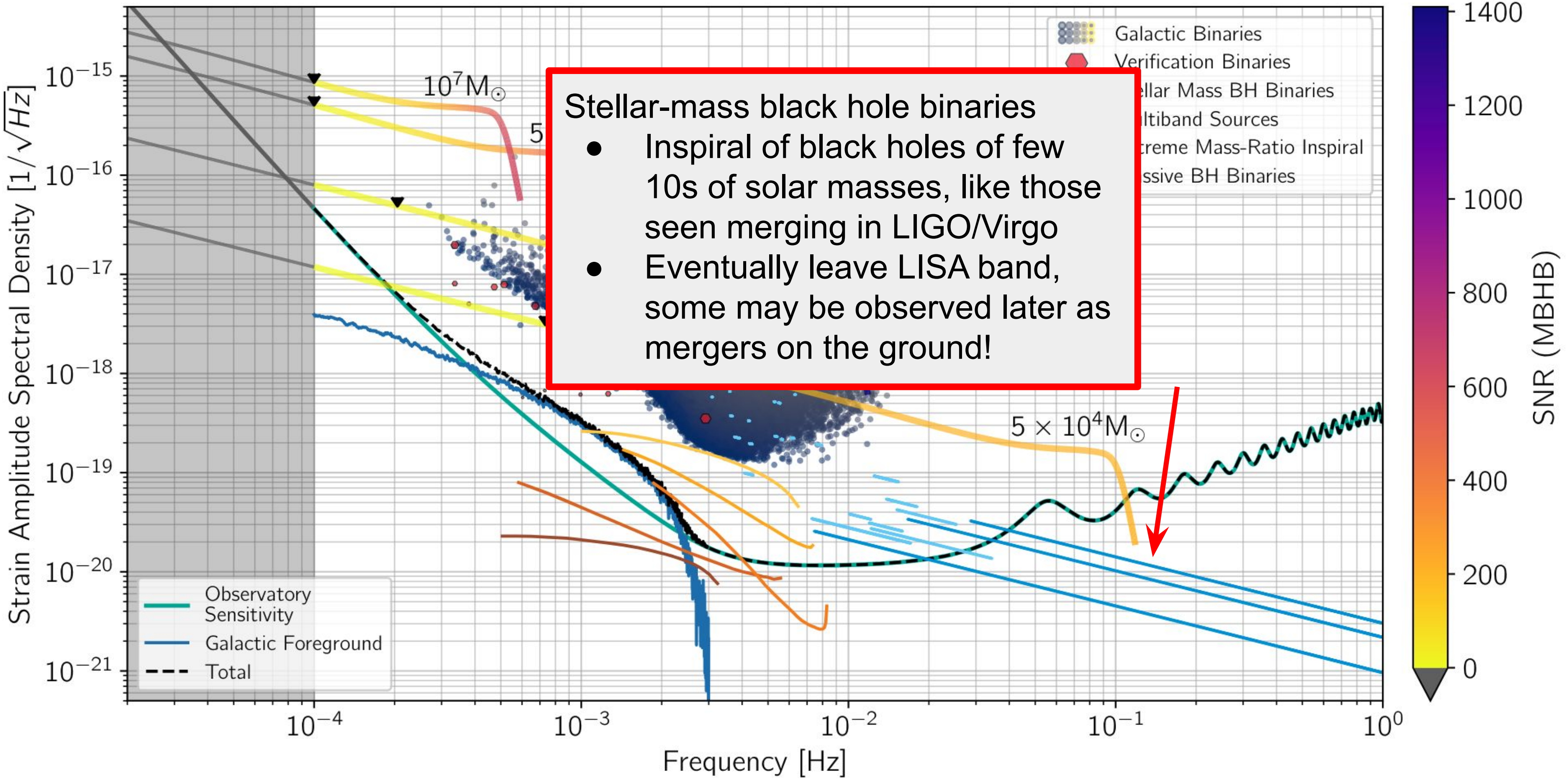
Source: LISA Definition Study Report



Massive black hole binaries

- Inspiral and merger of supermassive and intermediate mass black holes
- Cosmological sources, detectable out to $z \sim 12$
- Last hours to weeks in-band

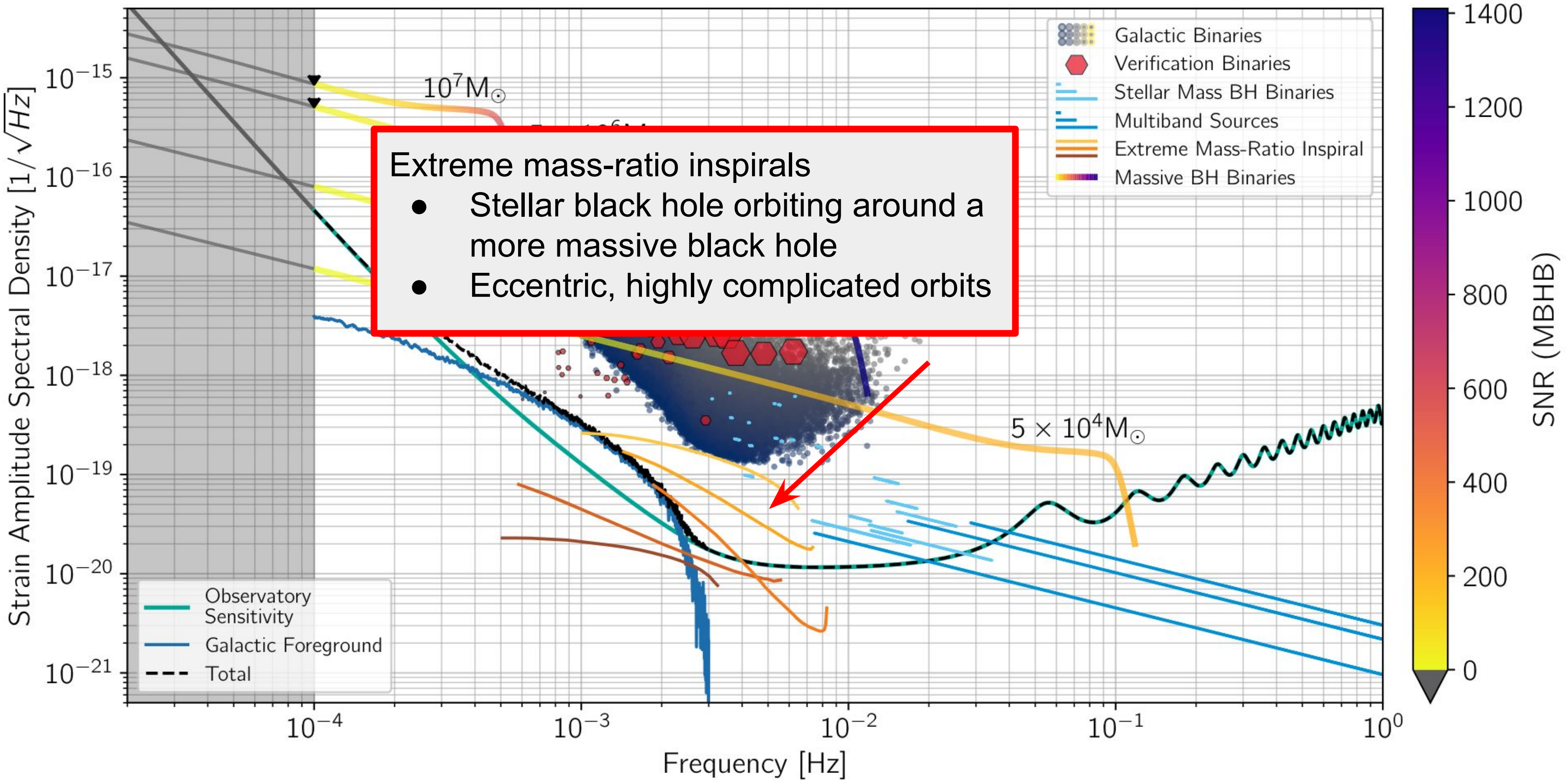
Source: LISA Definition Study Report



Stellar-mass black hole binaries

- Inspiral of black holes of few 10s of solar masses, like those seen merging in LIGO/Virgo
- Eventually leave LISA band, some may be observed later as mergers on the ground!

Source: LISA Definition Study Report



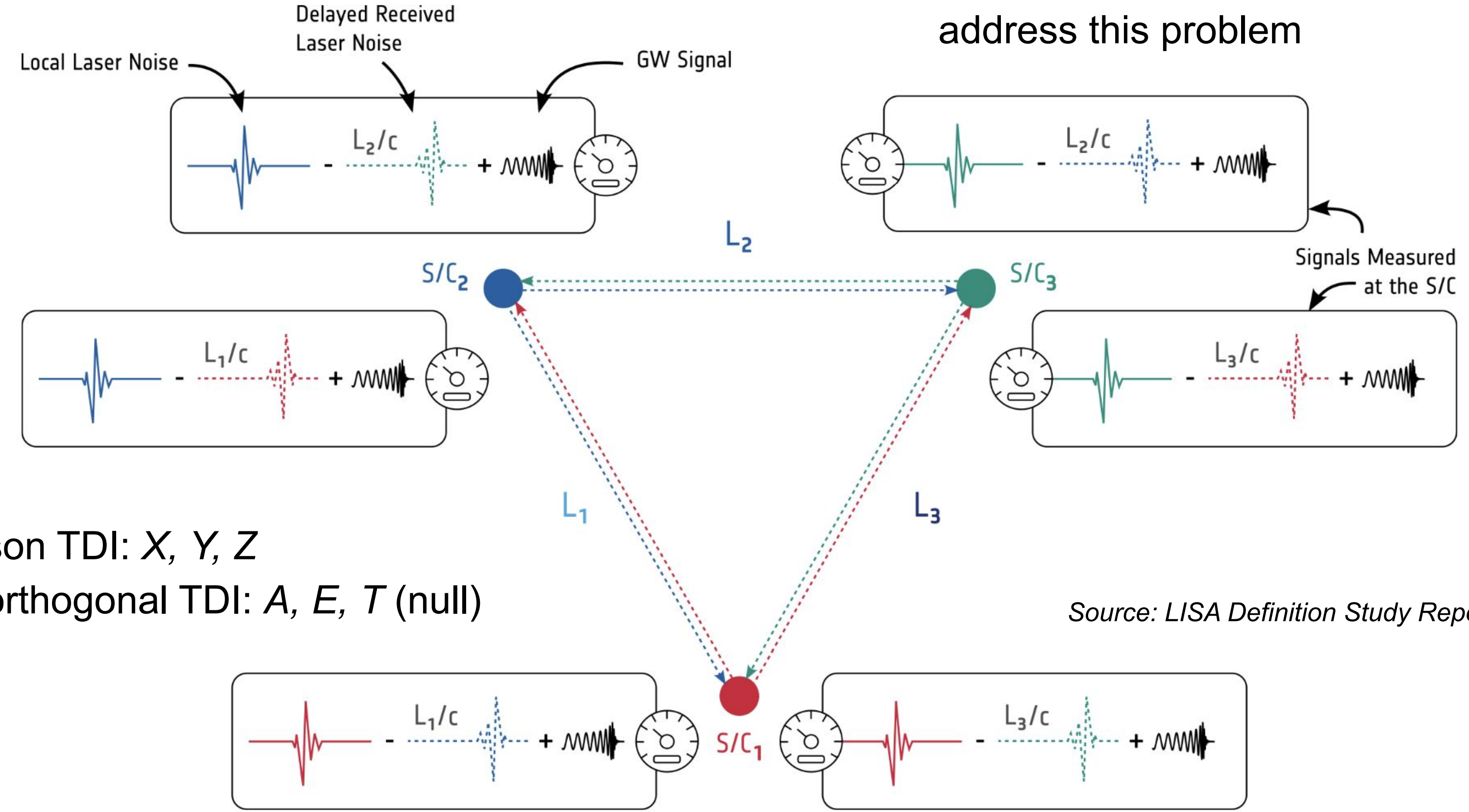
Extreme mass-ratio inspirals

- Stellar black hole orbiting around a more massive black hole
- Eccentric, highly complicated orbits

Source: LISA Definition Study Report

Time delay interferometry (TDI)

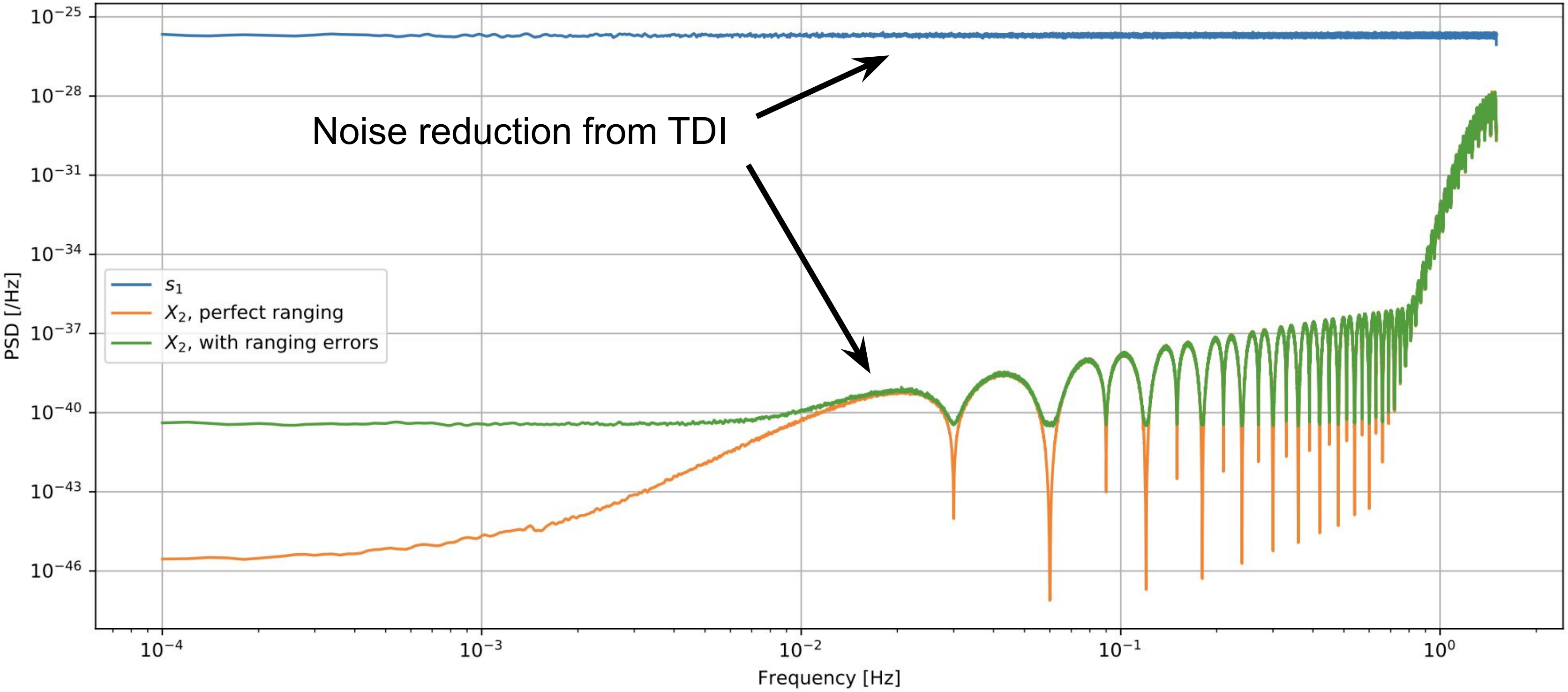
- One-way phase measurements dominated by laser frequency noise
- TDI technique developed to address this problem



- Michelson TDI: *X, Y, Z*
- Noise-orthogonal TDI: *A, E, T* (null)

Source: LISA Definition Study Report

Time delay interferometry (TDI)



Source: Jean-Baptiste Bayle PhD thesis

Signal from a galactic binary

- Galactic binaries are LISA's most numerous sources
- Modelled as sinusoids with a slow spin-up due to GW emission

$$h(t) = \mathcal{A}e^{i\Phi(t)} \qquad \Phi(t) = \phi_0 + 2\pi f t + \pi \dot{f} t^2$$

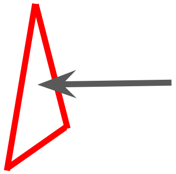
- **Question –** What else determines how the signal will be measured by LISA?

Signal from a galactic binary

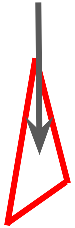
- Galactic binaries are LISA's most numerous sources
- Modelled as sinusoids with a slow spin-up due to GW emission

$$h(t) = \mathcal{A} e^{i\Phi(t)} \qquad \Phi(t) = \phi_0 + 2\pi f t + \pi \dot{f} t^2$$

- **Question –** What else determines how the signal will be measured by LISA?
- Also need to know the sky location of the source
- **Question –** What direction should the signal come from to maximize signal-to-noise?

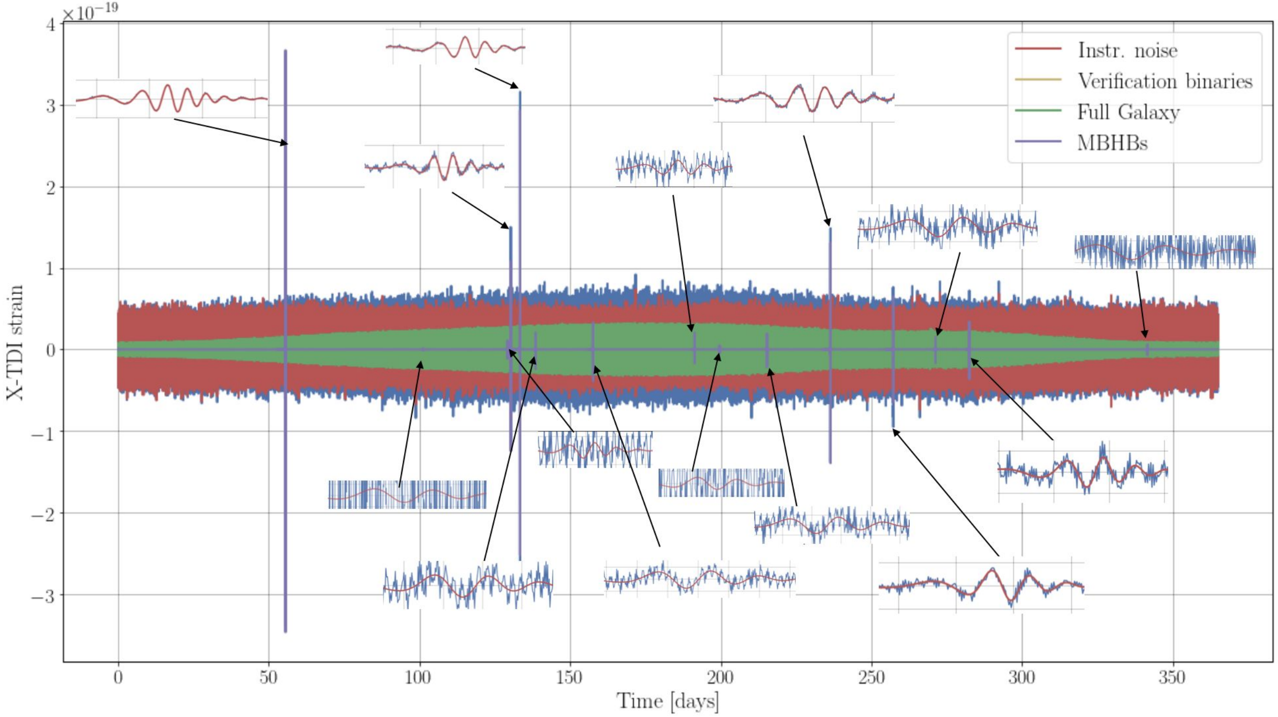


Orthogonal to plane of LISA



Parallel to plane of LISA

LISA data analysis



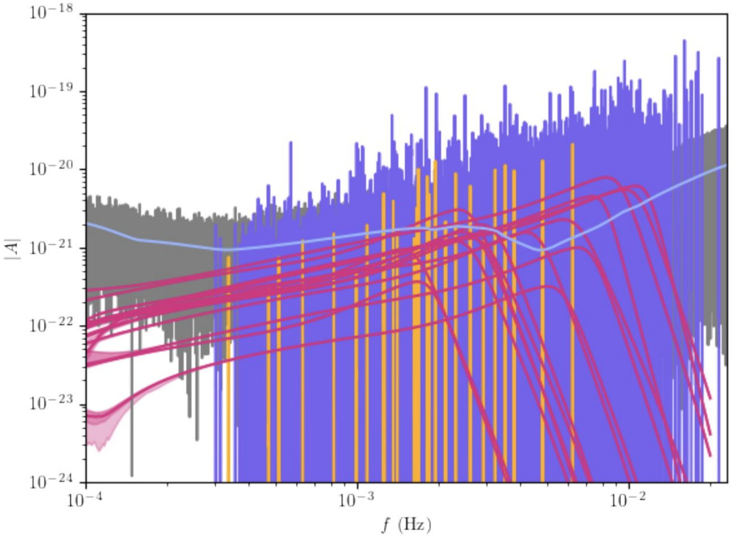
Source: LISA Data Challenge 2a

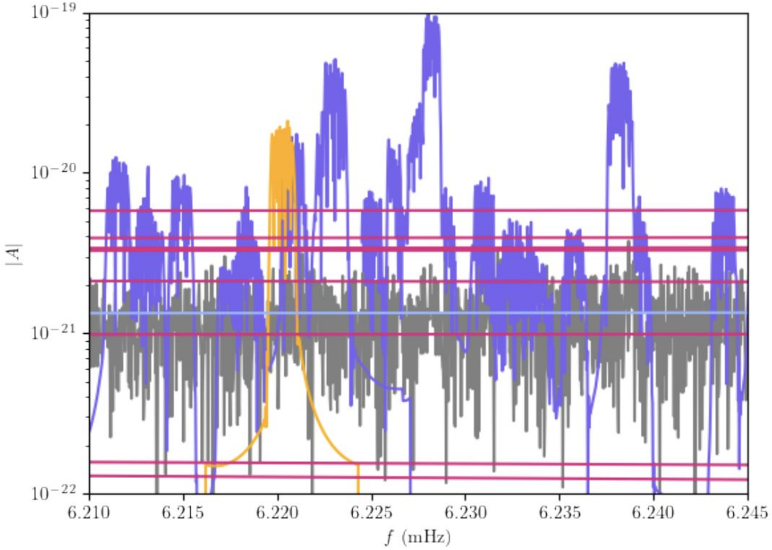
- High source count
- Transient and continuous signals
- Astrophysical and instrumental backgrounds
- Glitches, gaps

- How do we fit for all these sources? Need a **global fit**

LISA global fit

- Fit for all astrophysical sources and instrument noise simultaneously
- Outputs full catalog of sources w/ estimated parameters





Littenberg+23 [2301.03673]

LISA global fit

- Change in estimated residual noise with increasing observation time
- **Question –** Why does the galactic foreground appear to *decrease* over time?

Strub+24 [2403.15318]

LISA global fit

- Change in estimated residual noise with increasing observation time
- **Question –** Why does the galactic foreground appear to *decrease* over time?
- Certain foreground sources become individually resolvable, can be fitted out

Strub+24 [2403.15318]

Summary

- LISA will open up the mHz GW spectrum
- Enormous diversity of astrophysical sources, galactic and extragalactic
- Broad discovery space
    - Census of galactic compact binaries
    - Late-stage stellar evolution
    - Binary formation and evolution channels
    - Formation of massive black holes
    - Galaxy evolution
    - Cosmology
    - Tests of GR
- Global fit presents an interesting data analysis problem