Albert Einstein Institute
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LISA

Laser Interferometer Space Antenna

M Hewitson
for the LISA Consortium
ASTROD Workshop #2, Taiwan
May 2017

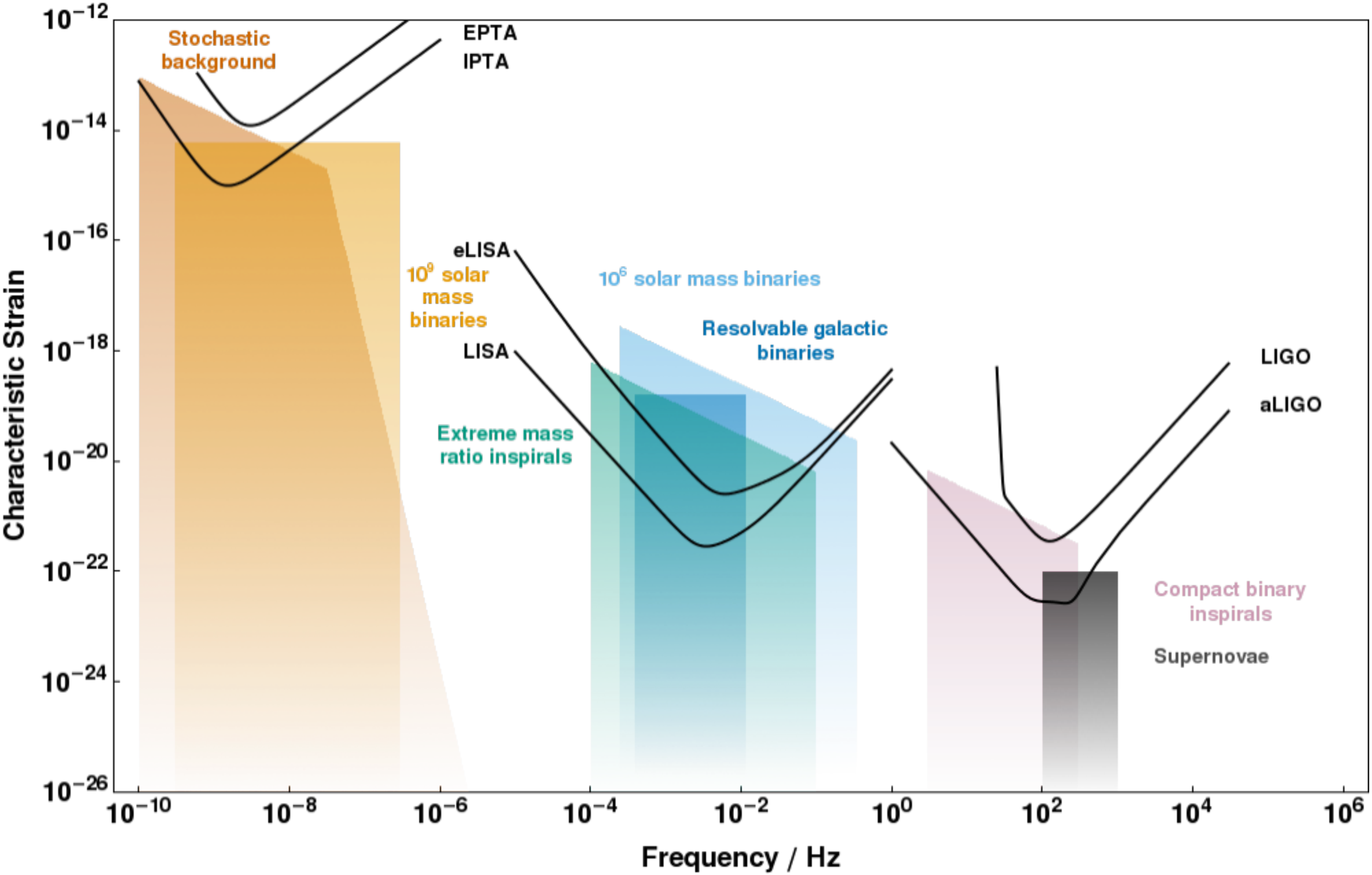
Contents

- Why space?
- LISA Science
- LPF Heritage
- L3 proposal
  - observatory design, consortium etc
  - sensitivity curve
  - science performance
- The path to LISA
  - schedule, CDF, Phase A, consortium etc

Why Gravitational Wave Observation from Space?

- Push down to much lower frequencies: mHz
  - expect rich science from:
    - super-massive BH binaries out to high redshift
    - the orbiting of solar mass black holes around super-massive black holes in galactic centres (EMRIs)
- Ground-based instruments limited by seismic and gravity gradient noise
- Fractional length stability of ground-based instruments is difficult to achieve at these frequencies
  - e.g., temperature and structural fluctuations
- Increase arm-length to improve strain sensitivity
  - go to space

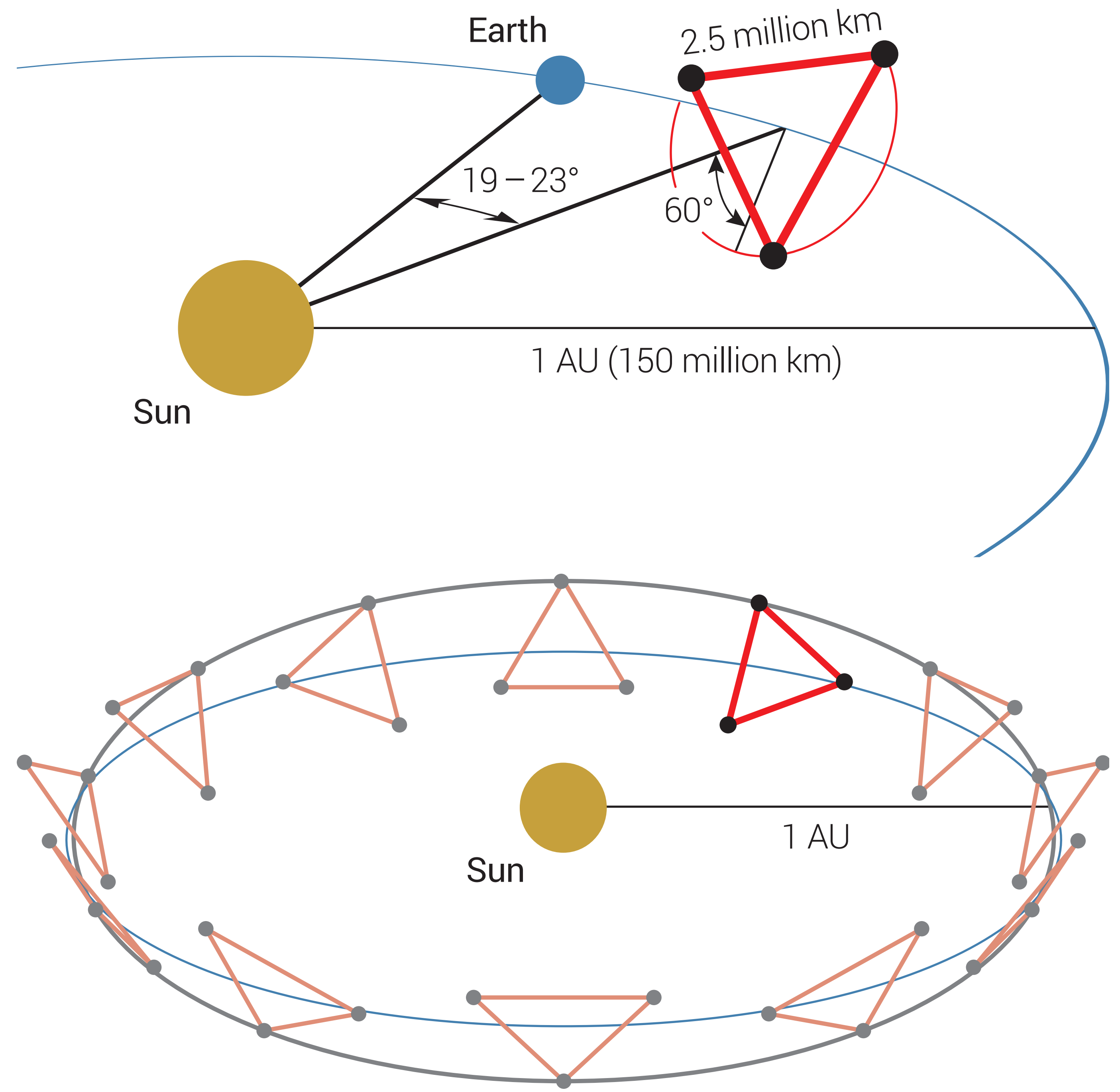
GW Spectrum



Stochastic background
EPTA
IPTA
eLISA
10^9 solar mass binaries
LISA
10^6 solar mass binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
LIGO
aLIGO
Compact binary inspirals
Supernovae
Characteristic Strain
Frequency / Hz
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

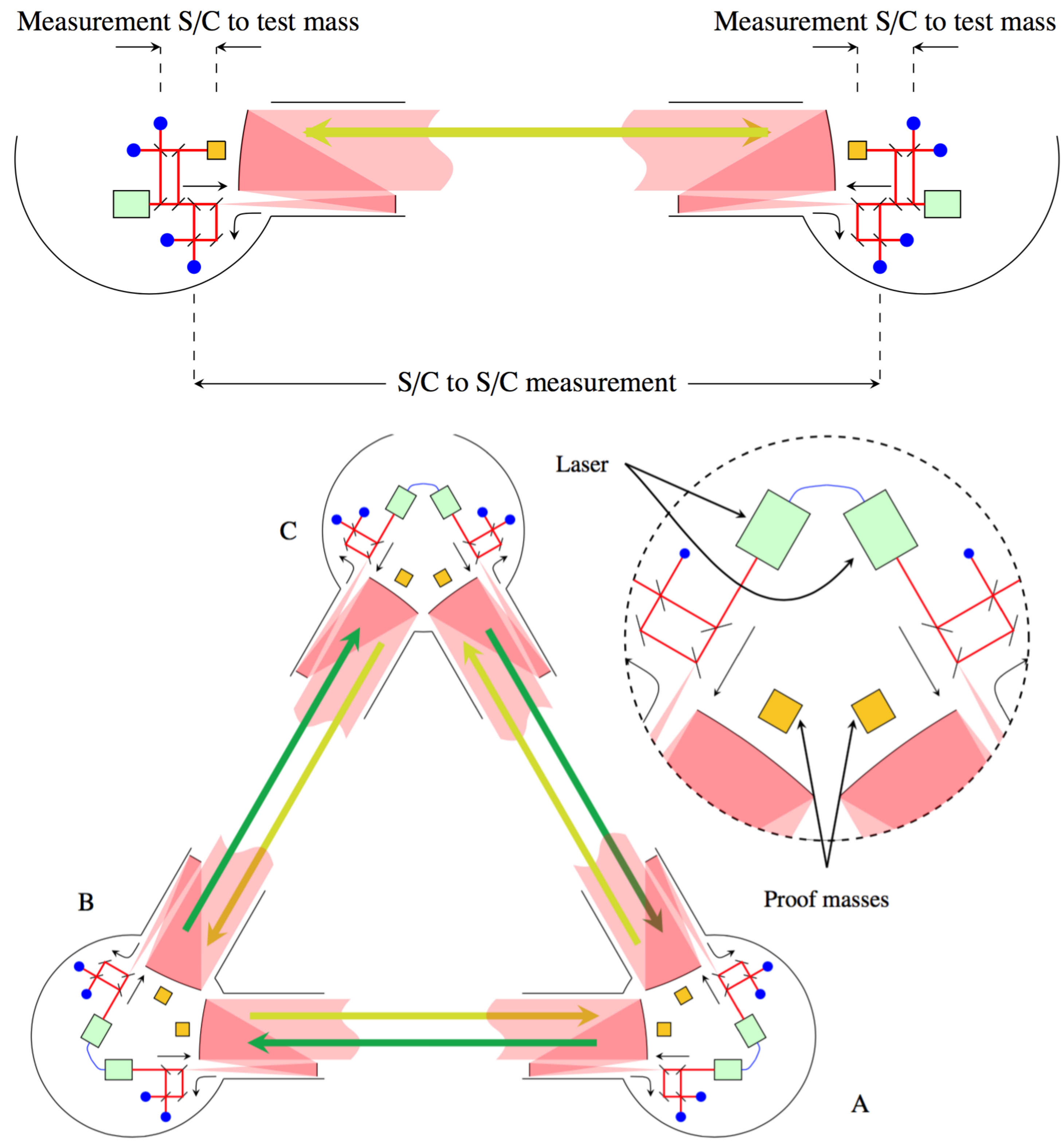
The LISA Concept

- Probe the change in proper time between **free-falling** test masses caused by GWs
- Free-falling test masses are housed in **drag-free** spacecraft separated by a few million km
- Proper time is inferred by the time of flight of photons exchanged between the satellites
- We have **multiple transponder links** from which we can form Michelson-like signals

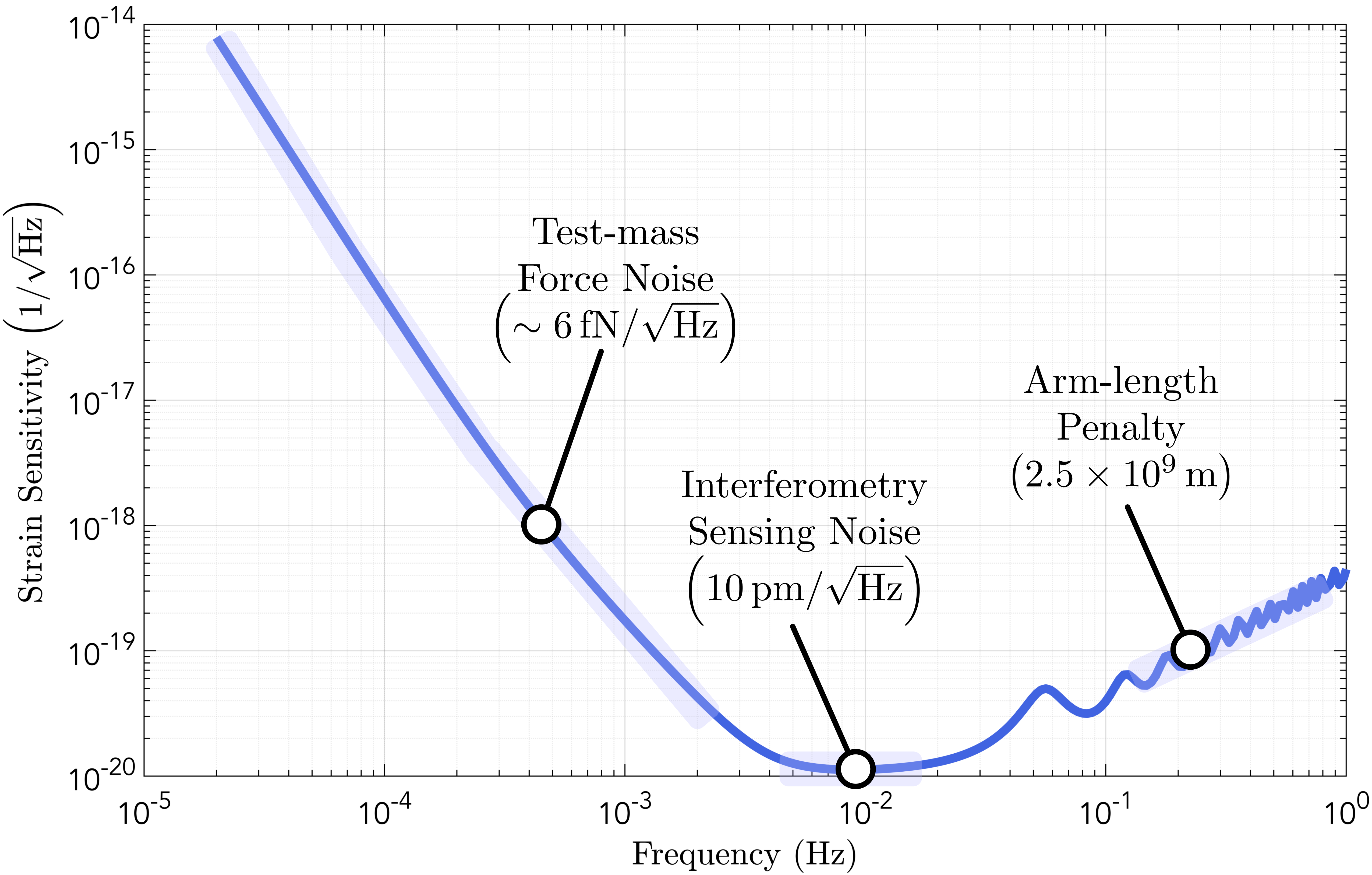


The measurement concept

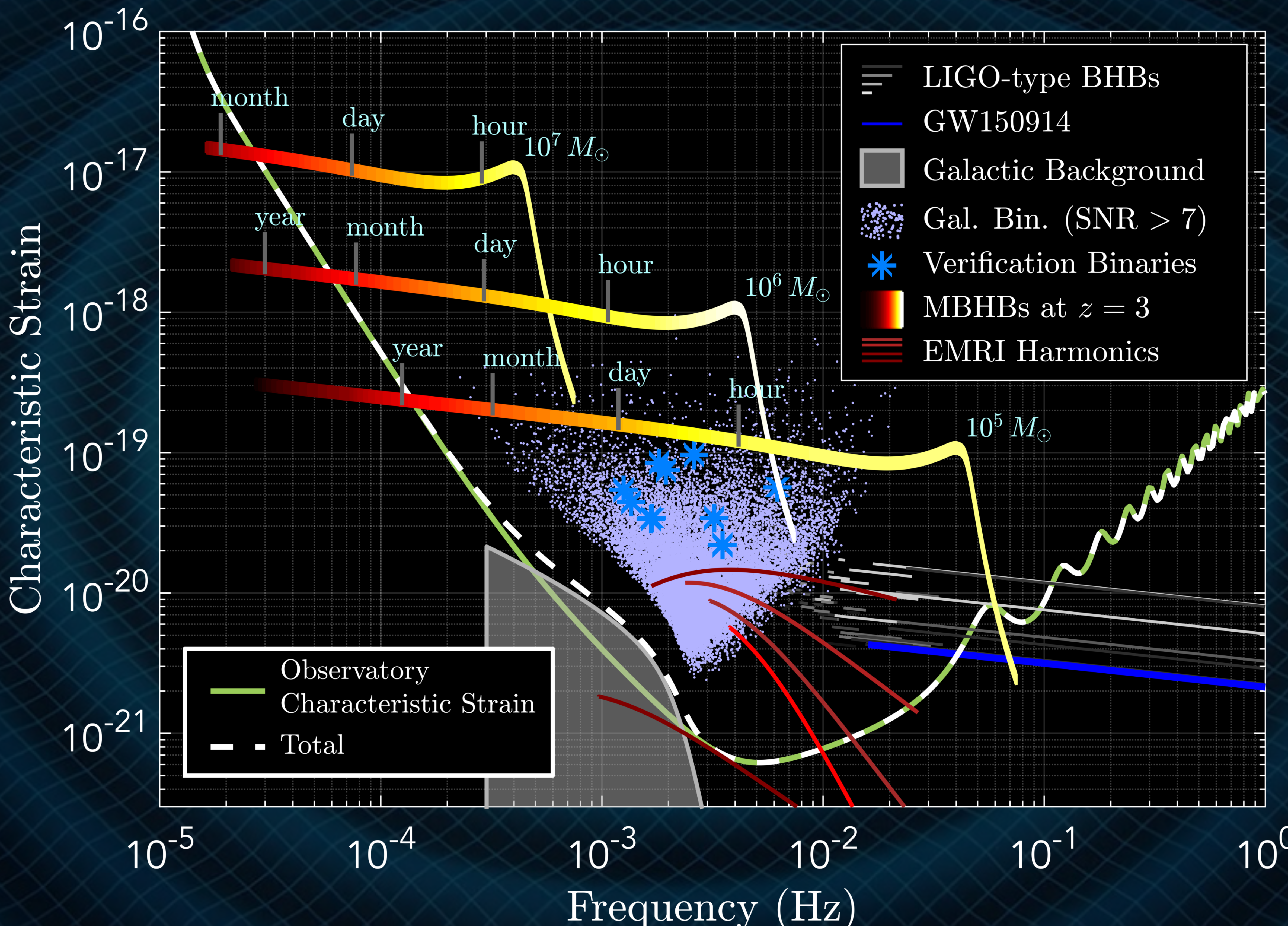
- test-mass to test-mass measurement is synthesised from:
  - test-mass to SC
  - SC to SC
  - SC to test-mass
- Combine 6 links on ground
- **T**ime **D**elay **I**nterferometry



LISA Performance



LISA Science

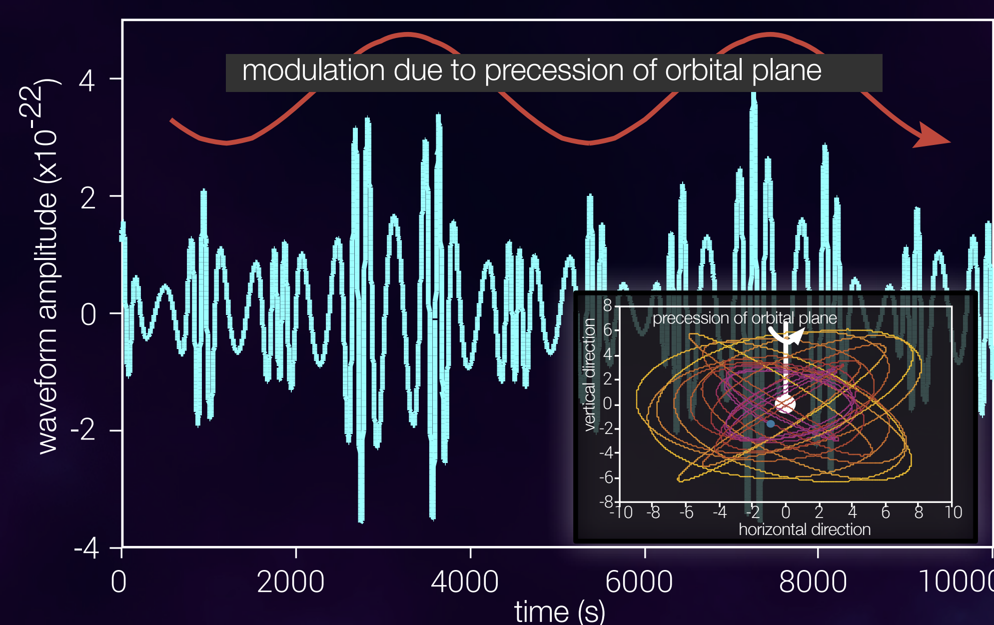


LISA Science — Massive Black Holes

- Masses 10^2 to 10^8 $M_\odot$
- Questions:
  - When did the first Black Holes appear in pre-galactic halos and what is their mass and spin?
  - How did Black Holes form, assemble and evolve from cosmic dawn to present time, due to accretion and mergers?
  - What role did Black Holes play in re-ionisation, galaxy evolution and structure formation?
  - What is the precise luminosity distance to loud standard siren black hole binaries?
  - What is the distance – redshift relation and the evolution history of the universe?
  - Does the Graviton have mass?

LISA Science — Extreme Mass Ratio Inspirals

- EMRIs (1 to 10 $M_\odot$ into 10^4 to 5×10^6 $M_\odot$)
  - How are the stellar dynamics in dense galactic nuclei?
  - How does dynamical relaxation and mass segregation work in dense galactic nuclei?
  - What is the occupation fraction of black holes in low-mass galaxies?
  - How large are deviations from Kerr Metric, and what new physics causes them?
  - Are there horizonless objects like boson stars or gravastars?
  - Are alternatives to GR viable, like Chern-Simons or scalar tensor theories or braneworld scenarios?



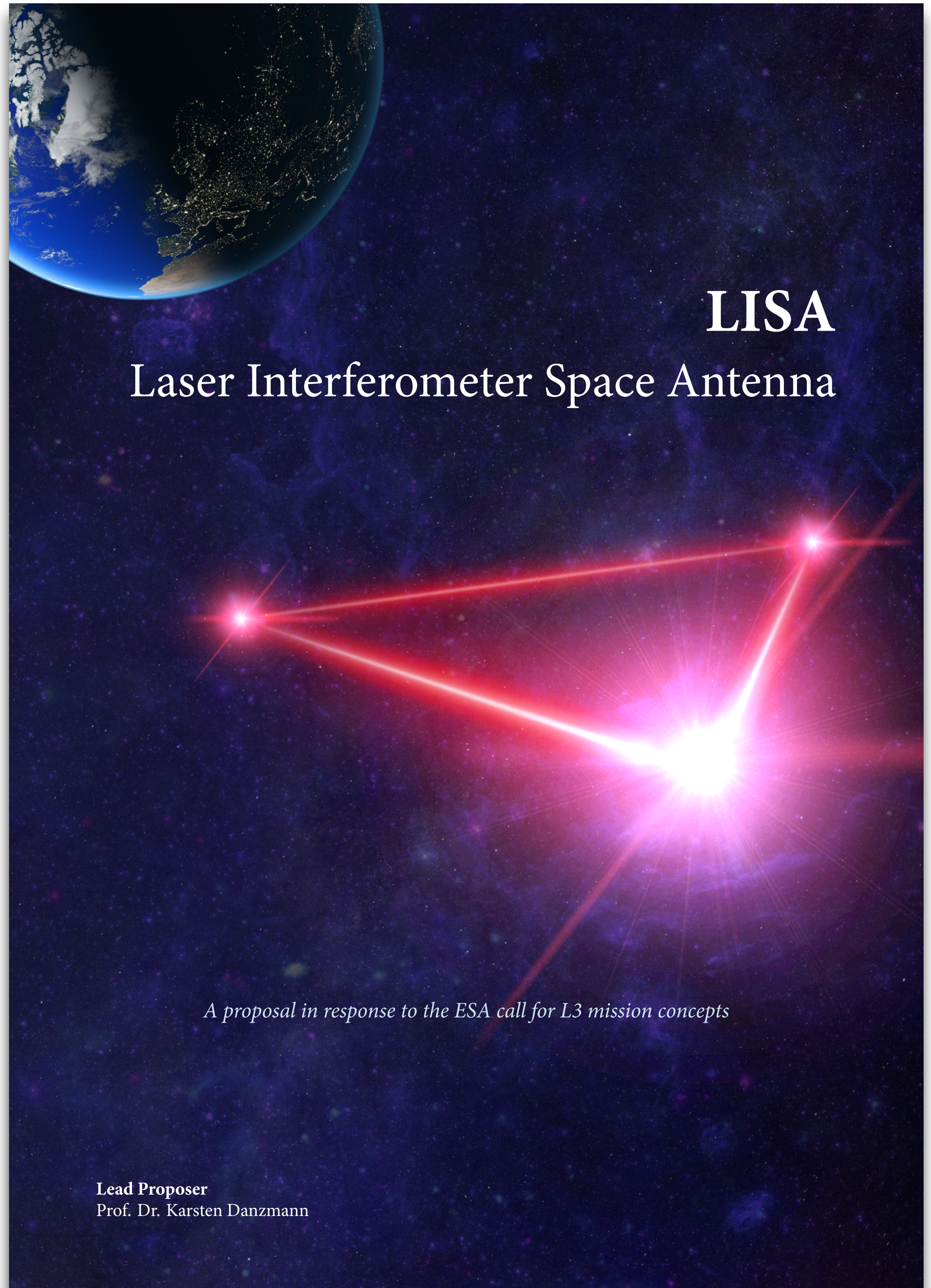
LISA Science — Ultra-Compact Binaries

- Binaries in the Milky Way
  - What is the explosion mechanism of type Ia supernovae?
  - What is the formation and merger rate of compact binaries?
  - What is the endpoint of stellar evolution?

LISA Science — Stochastic Signals

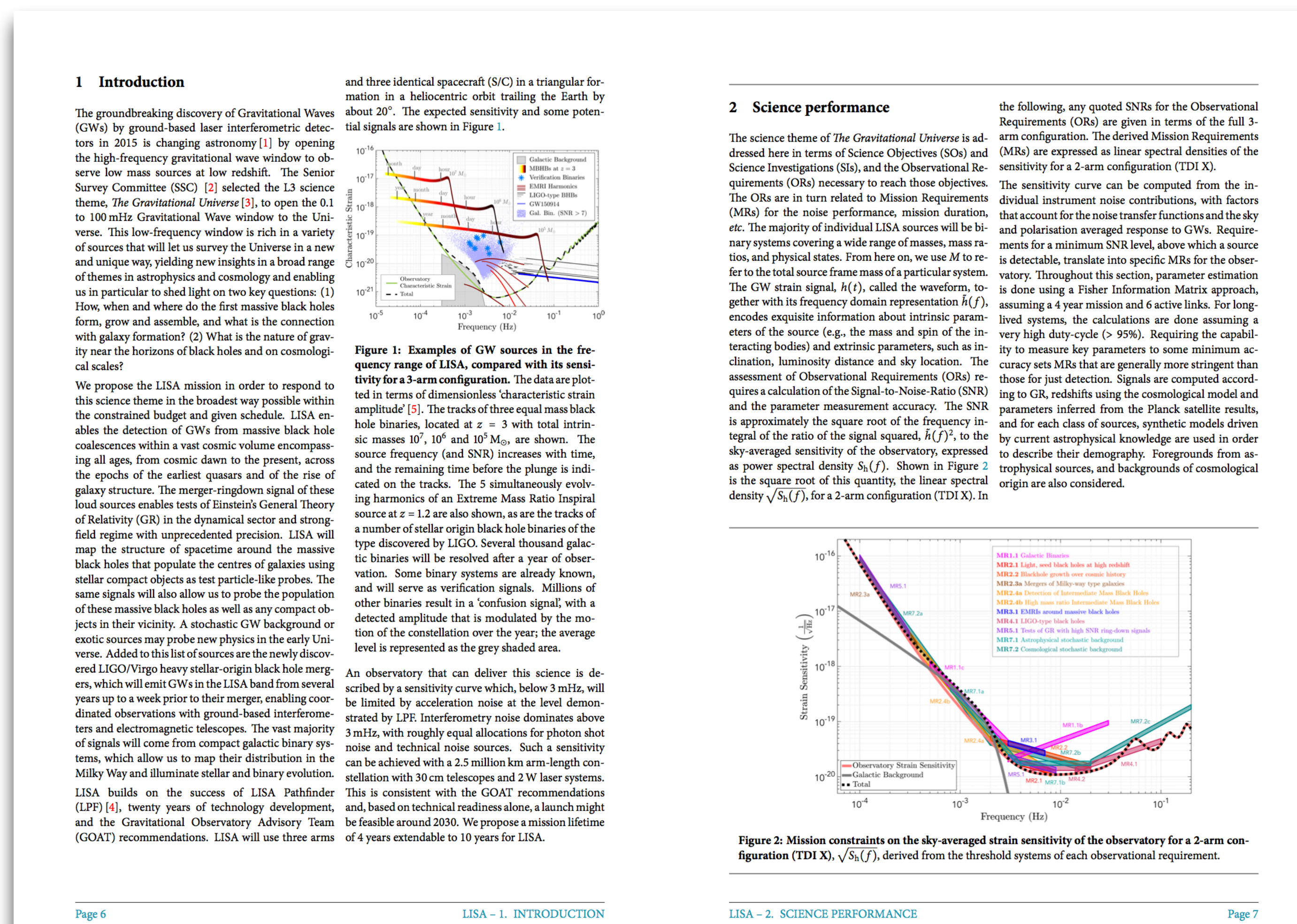
- Cosmological
  - Directly probe Planck scale epoch at 1 TeV to 1000 TeV before decoupling of microwave background
  - Were there phase transitions and of which order?
  - Probe Higgs field self coupling and potential, and search for supersymmetry.
  - Are there warped sub-millimetre extra-dimensions?
  - Can we see braneworld scenarios with reheating temperatures in the TeV range?
  - Do topological defects like Cosmic Strings exist?
- Astrophysical

LISA Proposal for ESA's L3 mission slot



www.lisamission.org

https://www.lisamission.org/proposal/LISA.pdf



1 Introduction

The groundbreaking discovery of Gravitational Waves (GWs) by ground-based laser interferometric detectors in 2015 is changing astronomy [1] by opening the high-frequency gravitational wave window to observe low mass sources at low redshift. The Senior Survey Committee (SSC) [2] selected the L3 science theme, *The Gravitational Universe* [3], to open the 0.1 to 100 mHz Gravitational Wave window to the Universe. This low-frequency window is rich in a variety of sources that will let us survey the Universe in a new and unique way, yielding new insights in a broad range of themes in astrophysics and cosmology and enabling us in particular to shed light on two key questions: (1) How, when and where do the first massive black holes form, grow and assemble, and what is the connection with galaxy formation? (2) What is the nature of gravity near the horizons of black holes and on cosmological scales?

We propose the LISA mission in order to respond to this science theme in the broadest way possible within the constrained budget and given schedule. LISA enables the detection of GWs from massive black hole coalescences within a vast cosmic volume encompassing all ages, from cosmic dawn to the present, across the epochs of the earliest quasars and of the rise of galaxy structure. The merger-ringdown signal of these loud sources enables tests of Einstein's General Theory of Relativity (GR) in the dynamical sector and strong-field regime with unprecedented precision. LISA will map the structure of spacetime around the massive black holes that populate the centres of galaxies using stellar compact objects as test particle-like probes. The same signals will also allow us to probe the population of these massive black holes as well as any compact objects in their vicinity. A stochastic GW background or exotic sources may probe new physics in the early Universe. Added to this list of sources are the newly discovered LIGO/Virgo heavy stellar-origin black hole mergers, which will emit GWs in the LISA band from several years up to a week prior to their merger, enabling coordinated observations with ground-based interferometers and electromagnetic telescopes. The vast majority of signals will come from compact galactic binary systems, which allow us to map their distribution in the Milky Way and illuminate stellar and binary evolution.

LISA builds on the success of LISA Pathfinder (LPF) [4], twenty years of technology development, and the Gravitational Observatory Advisory Team (GOAT) recommendations. LISA will use three arms and three identical spacecraft (S/C) in a triangular formation in a heliocentric orbit trailing the Earth by about 20°. The expected sensitivity and some potential signals are shown in Figure 1.

Figure 1: Examples of GW sources in the frequency range of LISA, compared with its sensitivity for a 3-arm configuration. The data are plotted in terms of dimensionless 'characteristic strain amplitude' [5]. The tracks of three equal mass black hole binaries, located at $z = 3$ with total intrinsic masses 10^7, 10^6 and $10^5\,M_\odot$, are shown. The source frequency (and SNR) increases with time, and the remaining time before the plunge is indicated on the tracks. The 5 simultaneously evolving harmonics of an Extreme Mass Ratio Inspiral source at $z = 1.2$ are also shown, as are the tracks of a number of stellar origin black hole binaries of the type discovered by LIGO. Several thousand galactic binaries will be resolved after a year of observation. Some binary systems are already known, and will serve as verification signals. Millions of other binaries result in a 'confusion signal', with a detected amplitude that is modulated by the motion of the constellation over the year; the average level is represented as the grey shaded area.

An observatory that can deliver this science is described by a sensitivity curve which, below 3 mHz, will be limited by acceleration noise at the level demonstrated by LPF. Interferometry noise dominates above 3 mHz, with roughly equal allocations for photon shot noise and technical noise sources. Such a sensitivity can be achieved with a 2.5 million km arm-length constellation with 30 cm telescopes and 2 W laser systems. This is consistent with the GOAT recommendations and, based on technical readiness alone, a launch might be feasible around 2030. We propose a mission lifetime of 4 years extendable to 10 years for LISA.

Page 6 LISA – 1. INTRODUCTION

2 Science performance

The science theme of *The Gravitational Universe* is addressed here in terms of Science Objectives (SOs) and Science Investigations (SIs), and the Observational Requirements (ORs) necessary to reach those objectives. The ORs are in turn related to Mission Requirements (MRs) for the noise performance, mission duration, *etc*. The majority of individual LISA sources will be binary systems covering a wide range of masses, mass ratios, and physical states. From here on, we use M to refer to the total source frame mass of a particular system. The GW strain signal, $h(t)$, called the waveform, together with its frequency domain representation $\tilde{h}(f)$, encodes exquisite information about intrinsic parameters of the source (e.g., the mass and spin of the interacting bodies) and extrinsic parameters, such as inclination, luminosity distance and sky location. The assessment of Observational Requirements (ORs) requires a calculation of the Signal-to-Noise-Ratio (SNR) and the parameter measurement accuracy. The SNR is approximately the square root of the frequency integral of the ratio of the signal squared, $\tilde{h}(f)^2$, to the sky-averaged sensitivity of the observatory, expressed as power spectral density $S_h(f)$. Shown in Figure 2 is the square root of this quantity, the linear spectral density $\sqrt{S_h(f)}$, for a 2-arm configuration (TDI X). In the following, any quoted SNRs for the Observational Requirements (ORs) are given in terms of the full 3-arm configuration. The derived Mission Requirements (MRs) are expressed as linear spectral densities of the sensitivity for a 2-arm configuration (TDI X).

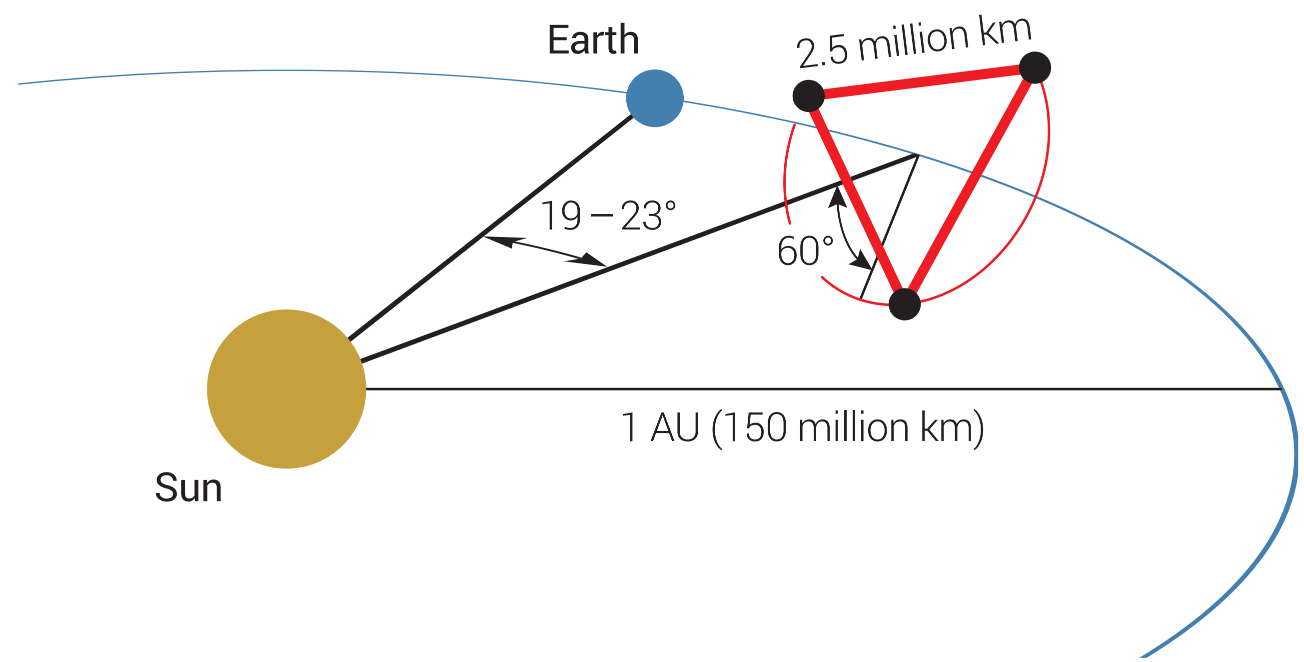
The sensitivity curve can be computed from the individual instrument noise contributions, with factors that account for the noise transfer functions and the sky and polarisation averaged response to GWs. Requirements for a minimum SNR level, above which a source is detectable, translate into specific MRs for the observatory. Throughout this section, parameter estimation is done using a Fisher Information Matrix approach, assuming a 4 year mission and 6 active links. For long-lived systems, the calculations are done assuming a very high duty-cycle (> 95%). Requiring the capability to measure key parameters to some minimum accuracy sets MRs that are generally more stringent than those for just detection. Signals are computed according to GR, redshifts using the cosmological model and parameters inferred from the Planck satellite results, and for each class of sources, synthetic models driven by current astrophysical knowledge are used in order to describe their demography. Foregrounds from astrophysical sources, and backgrounds of cosmological origin are also considered.

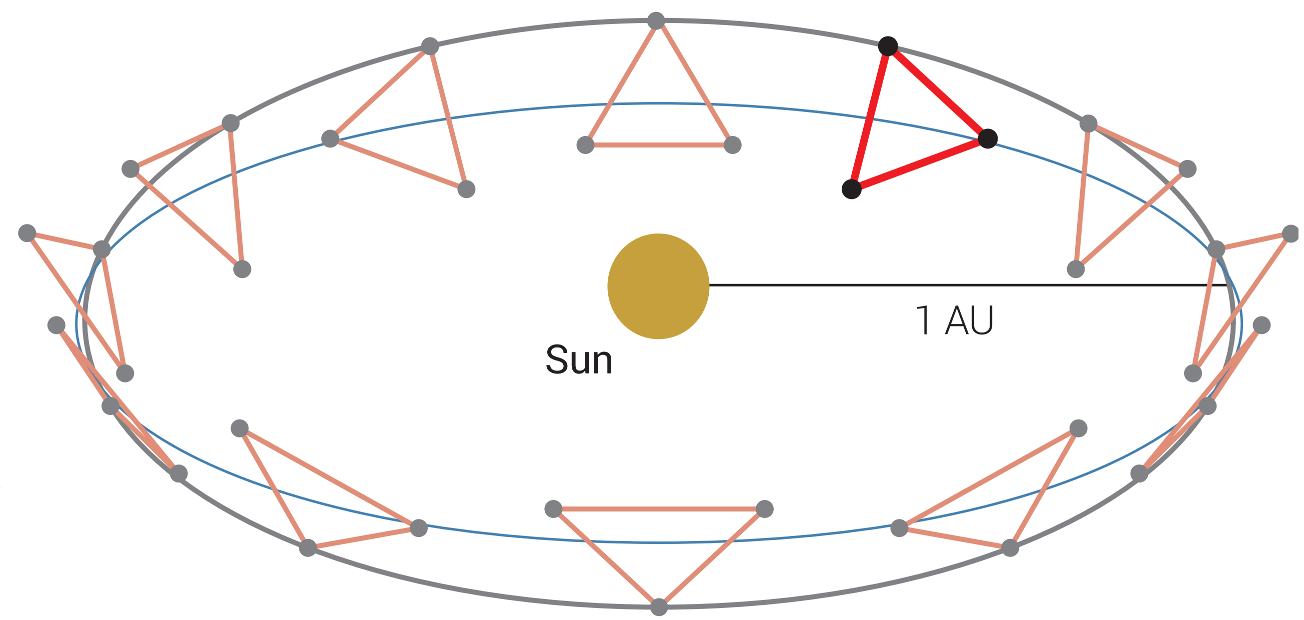
Figure 2: Mission constraints on the sky-averaged strain sensitivity of the observatory for a 2-arm configuration (TDI X), $\sqrt{S_h(f)}$, derived from the threshold systems of each observational requirement.

LISA – 2. SCIENCE PERFORMANCE Page 7

Mission Profile and Orbit

- Breathing angles ± 1 deg
- Doppler shifts ± 5 MHz
- Launch on dedicated Ariane 6.4
  - Transfer time ~400 days
  - Direct escape V_∞ = 260 m/s
  - Propulsion module and S/C composite





Operations concept

- Checkout and testing during cruise
- Initial acquisition
- Main science mode: all TMs in free-fall along lines of sight between S/Cs
  - DFACS with uN thrusters
  - Minimum deliberate disturbance (~100% duty cycle)
  - No station keeping
  - Daily communication with observatory of ~ 8 hours
    - 35 kbit/s, 334 MB / Day
    - data links on laser light between S/C (~15 kbit/s)
    - X band
- Maintenance activities
  - antenna repointing every 9 days
  - laser frequency plan adjustments

Defining the target sensitivity curve

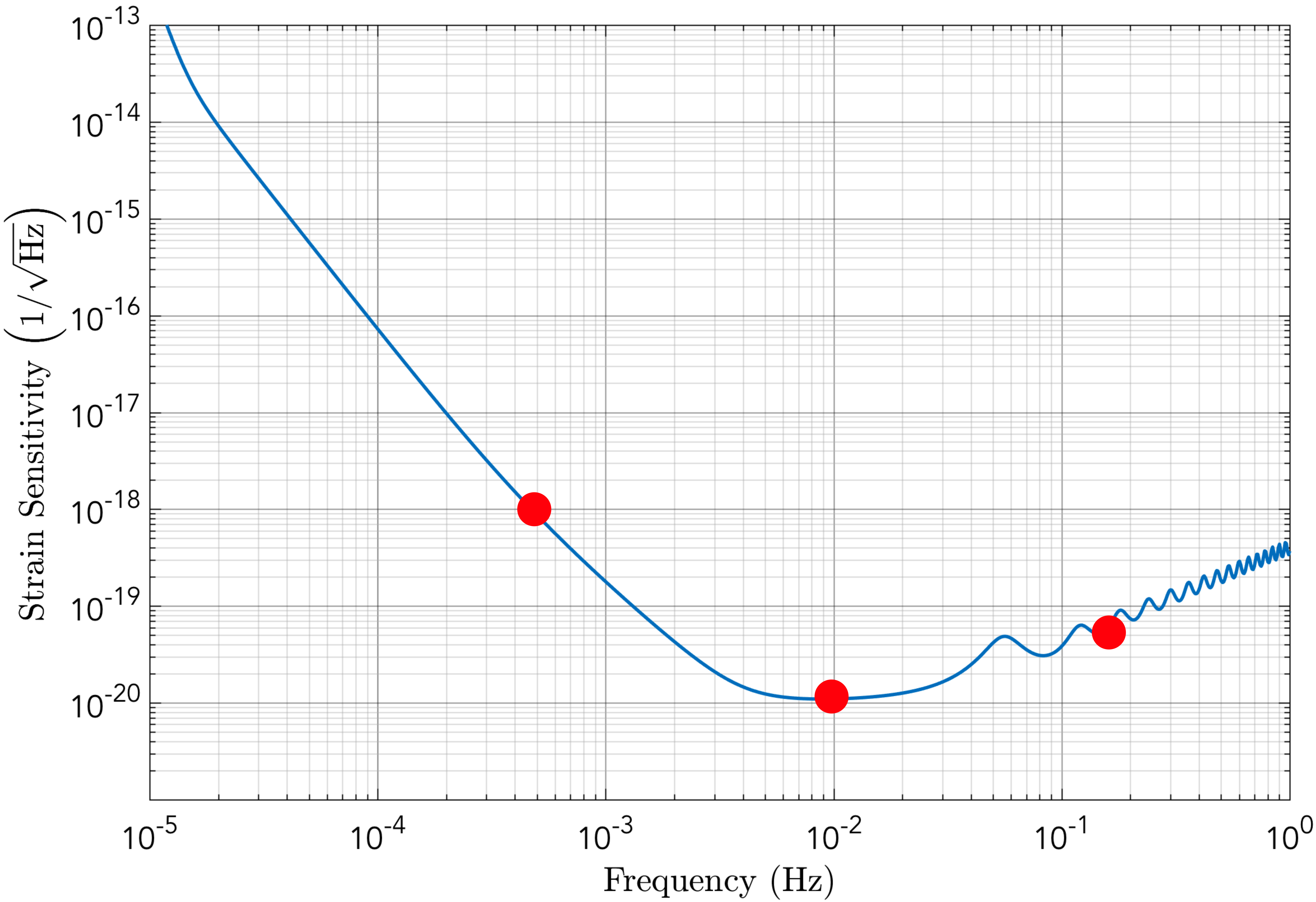
- Started with a bottom-up definition
  - LPF measured acceleration contributions
  - Current best estimates for OMS noise source
- This evolved to include margin
- Observatory configuration was defined early in the process

Observatory configuration

- 3 arms was baseline from the start, based on GOAT report
- Telescope diameter triggered much thought
  - size ranged from 20 to 40 cm
  - 30cm was chosen
    - monolithic construction at this size should not be a cost driver
    - this diameter doesn't drive SC volume
    - not completely shot-noise limited, so increasing doesn't help that much (see arm-length discussion)
- Laser output power: 2W
  - considered achievable goal given currently flying lasers and current levels of testing
- Arm-length
  - possible range considered: 1 to 5 Gm
  - 2.5 Gm is loosely considered a threshold in technical complexity of mission
  - not much high-frequency gain above 2.5 Gm

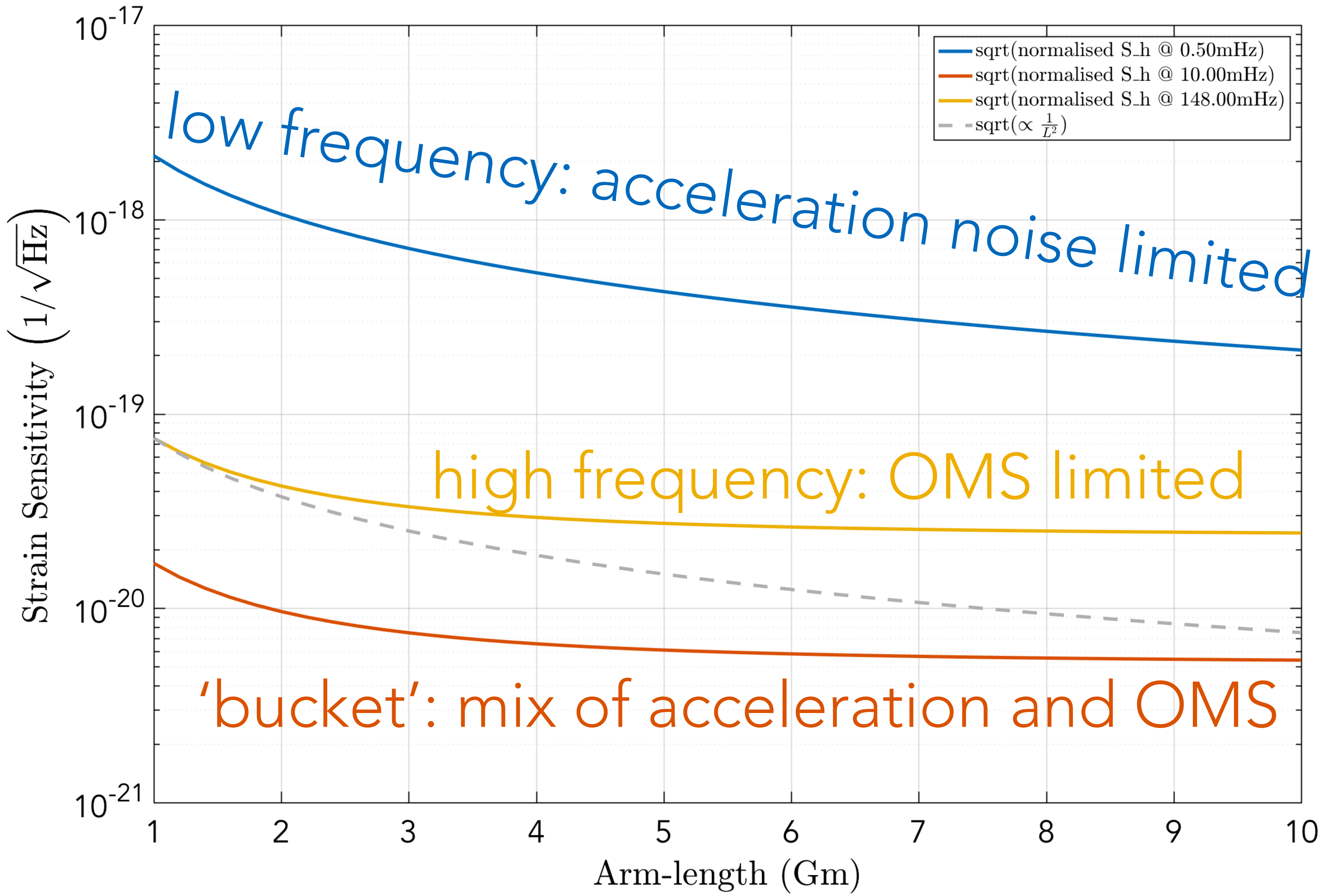
https://www.cosmos.esa.int/web/goat

Arm-length



Strain Sensitivity $\left(1/\sqrt{\mathrm{Hz}}\right)$
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Frequency (Hz)

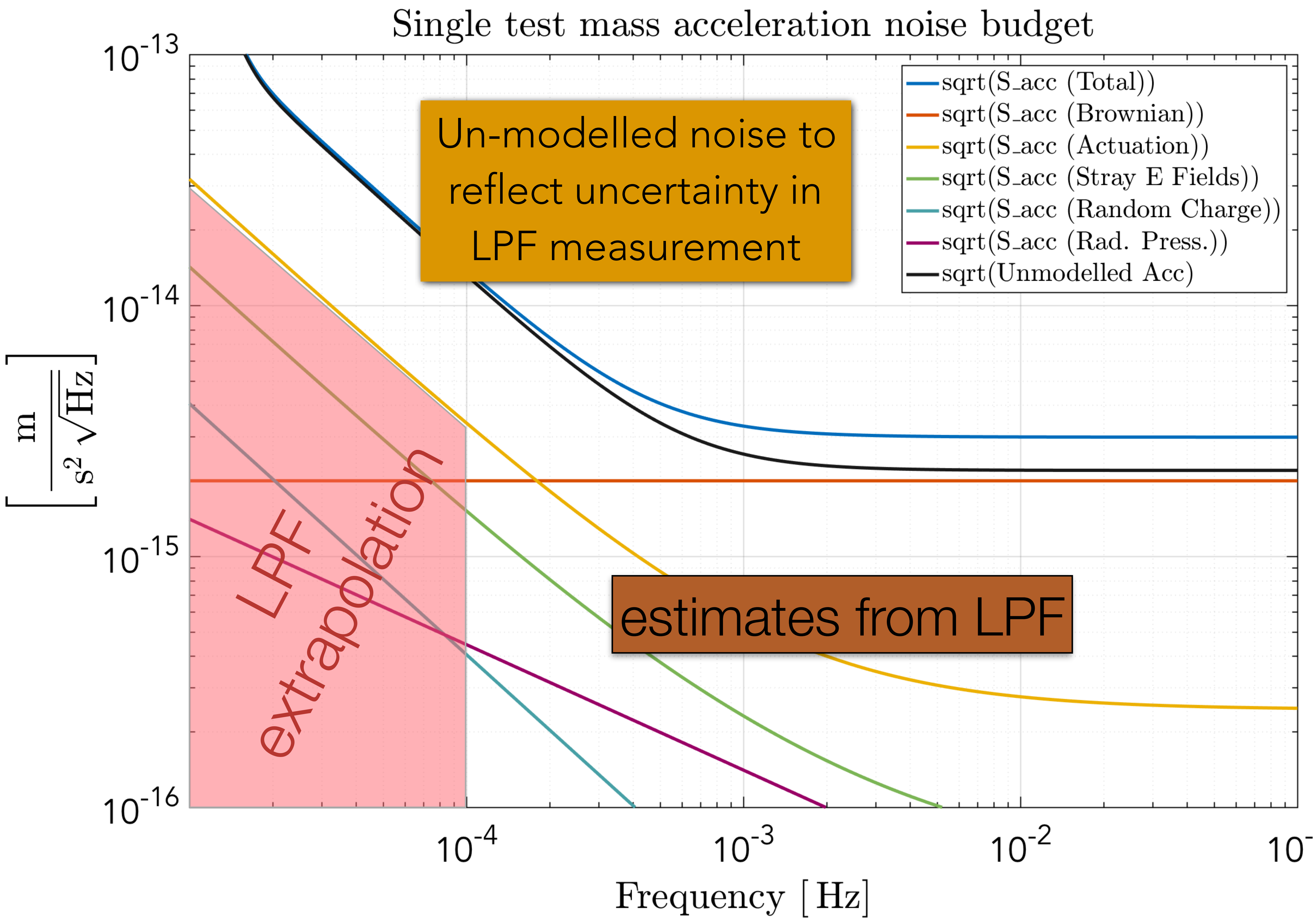
Sensitivity versus Arm-length



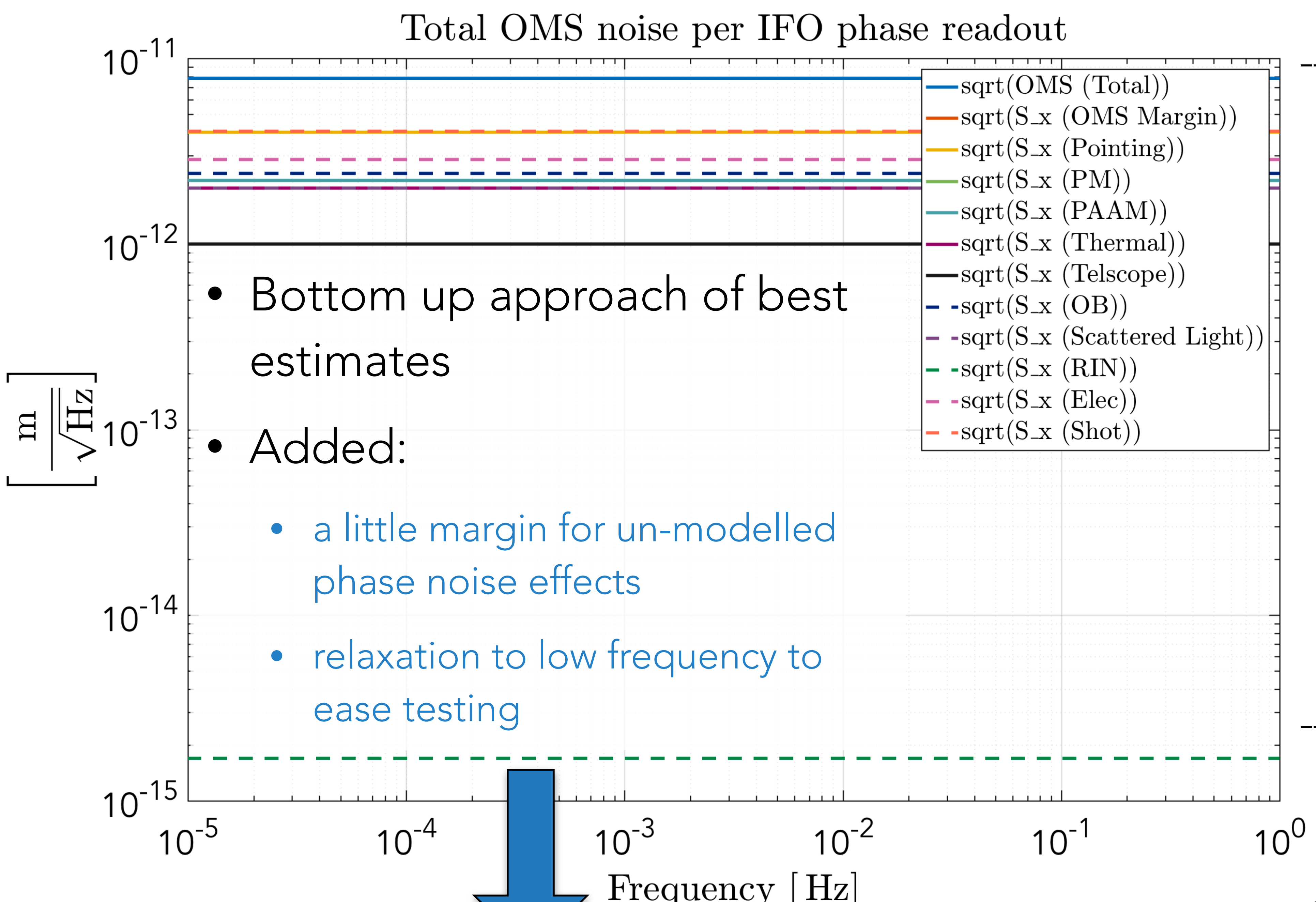
Acceleration noise in LPF

figure removed

Acceleration noise



OMS Noise

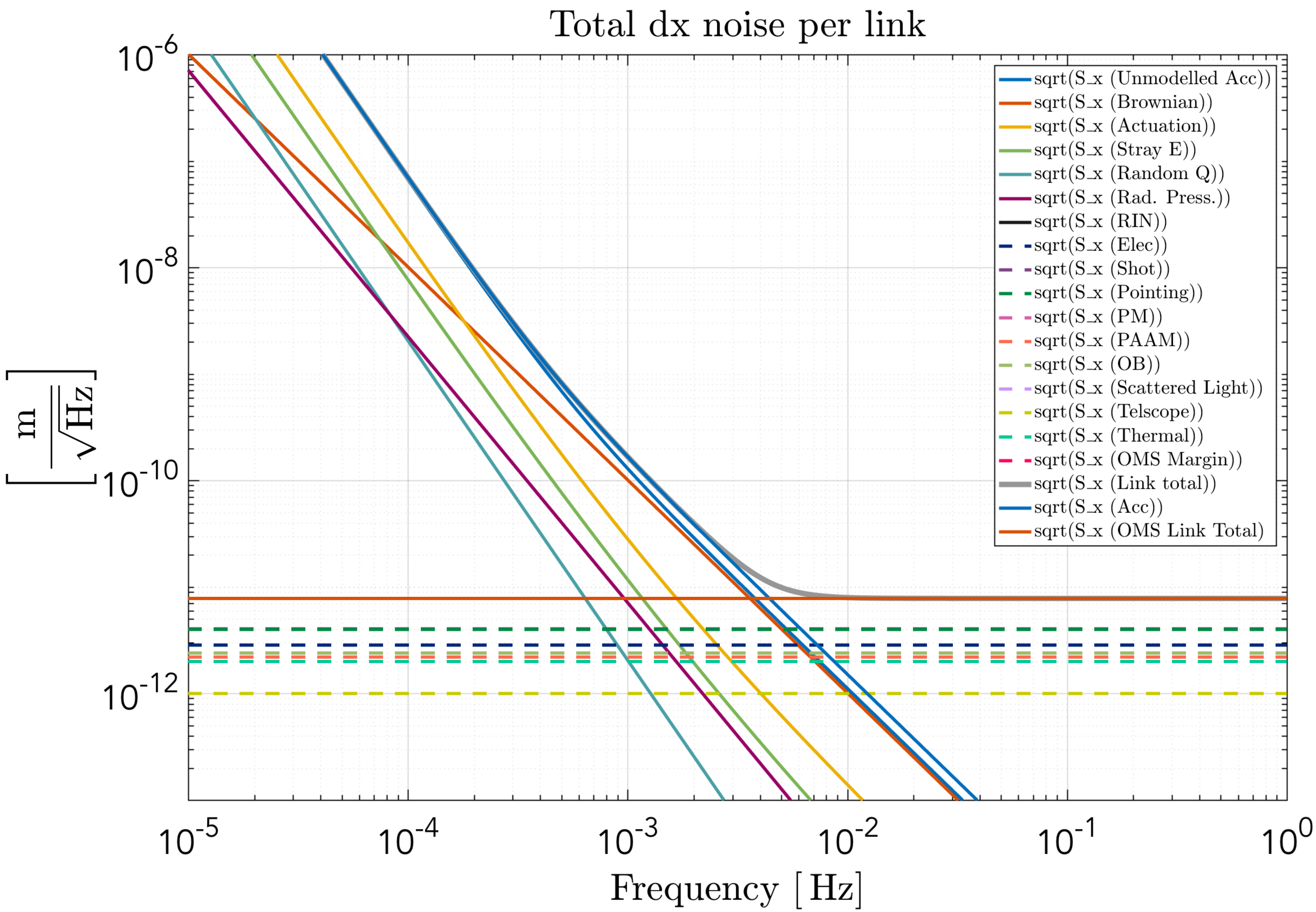


- Bottom up approach of best estimates
- Added:
  - a little margin for un-modelled phase noise effects
  - relaxation to low frequency to ease testing

$$S_{\mathrm{IFO}}^{1/2} \leq 10 \cdot 10^{-12} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \cdot \sqrt{1 + \left(\frac{2\,\mathrm{mHz}}{f}\right)^4}$$

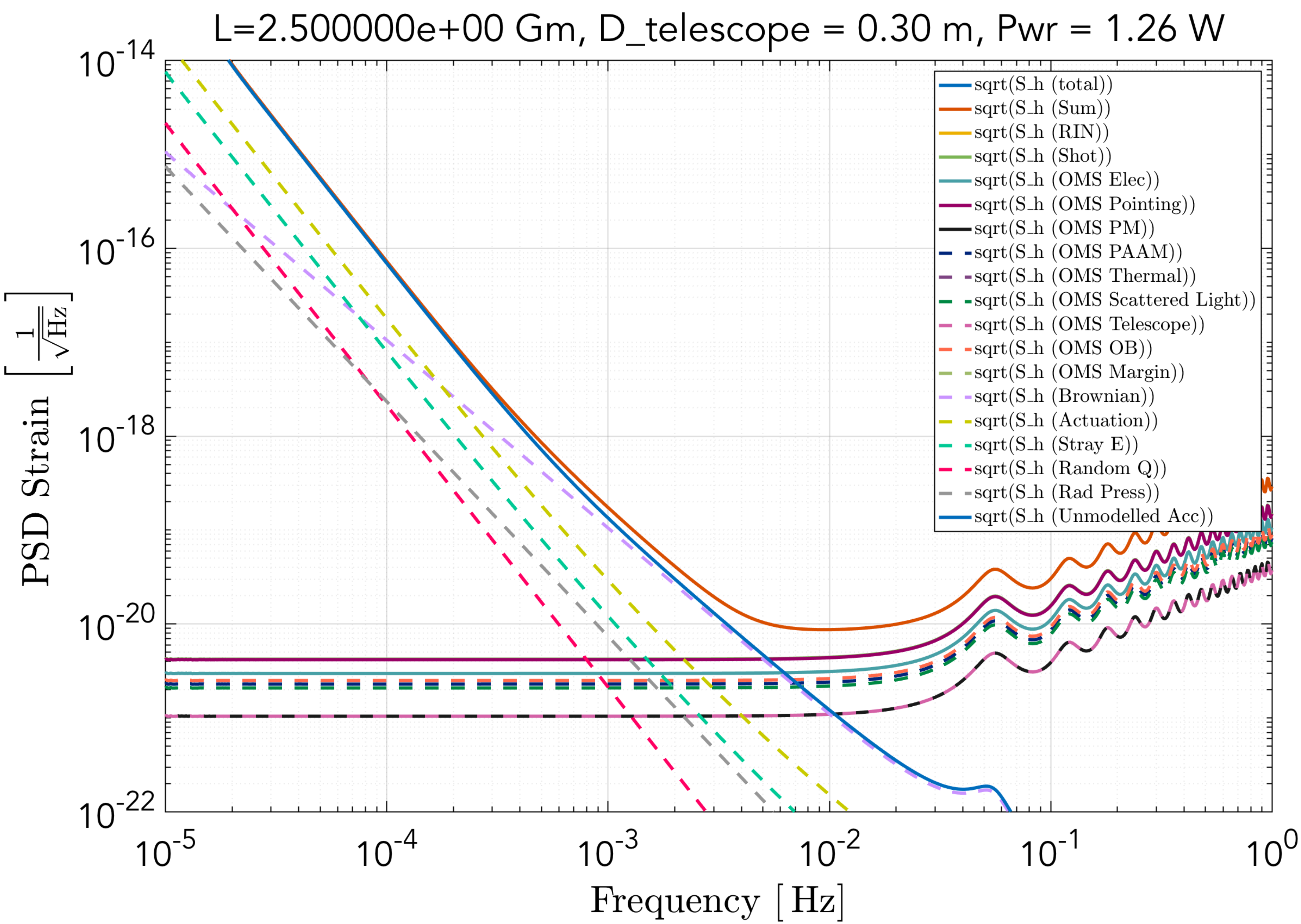
```
----------- LISA Observatory 01 -----------
                   Name:
            description:
             armlength: 2.50 [Gm]
                  Dtel: 0.30 [m]
                Plaser: 2.00 [W]
                  Ptel: 1.26 [W]
                    w0: 13.38 [cm]
                  Irec: 10.25 [nA/m^2]
                  Prec: 507.36 [pW]
                Plocal: 1.67 [mW]
                   Zpd: 636.62 [Ohm]
                   Rpd: 0.69 [A/W]
                   Cpd: 10.00 [pF]
                Ndiode: 4 []
               Npdsegs: 4 []
                 f_het: 25.00 [MHz]
               eta_het: 0.80 []
               eta_opt: 0.70 []
                   RIN: 1e-08 []
                  TM_Q: 1e+07 [e]
            lambda_eff: 1.3e+03 [e/s]
                DeltaX: 5 [mV]
      sqrt(S_brownian): 2 [fm s^-2 Hz^-0.5]
           sqrt(S_Ipd): 1.25 [pA/sqrt(Hz)]
           sqrt(S_Upd): 2 [nV/sqrt(Hz)]
-------------- OMS Noise ----------------
   sqrt(S_dx_margin): 0 [m/sqrt(Hz)]
      sqrt(S_dx_RIN): 0.0017 [pm/sqrt(Hz)]
     sqrt(S_dx_elec): 2.9 [pm/sqrt(Hz)]
     sqrt(S_dx_shot): 4.1 [pm/sqrt(Hz)]
       sqrt(S_dx_PM): 1 [pm/sqrt(Hz)]
     sqrt(S_dx_PAAM): 2.2 [pm/sqrt(Hz)]
 sqrt(S_dx_pointing): 4 [pm/sqrt(Hz)]
sqrt(S_dx_telescope): 1 [pm/sqrt(Hz)]
       sqrt(S_dx_OB): 2.4 [pm/sqrt(Hz)]
  sqrt(S_dx_thermal): 2 [pm/sqrt(Hz)]
  sqrt(S_dx_scatter): 2 [pm/sqrt(Hz)]
-----------------------------------------
   sqrt(S_OMS_total): 7.82 [pm/sqrt(Hz)]
-----------------------------------------
-----------------------------------------
```

Total single link contribution

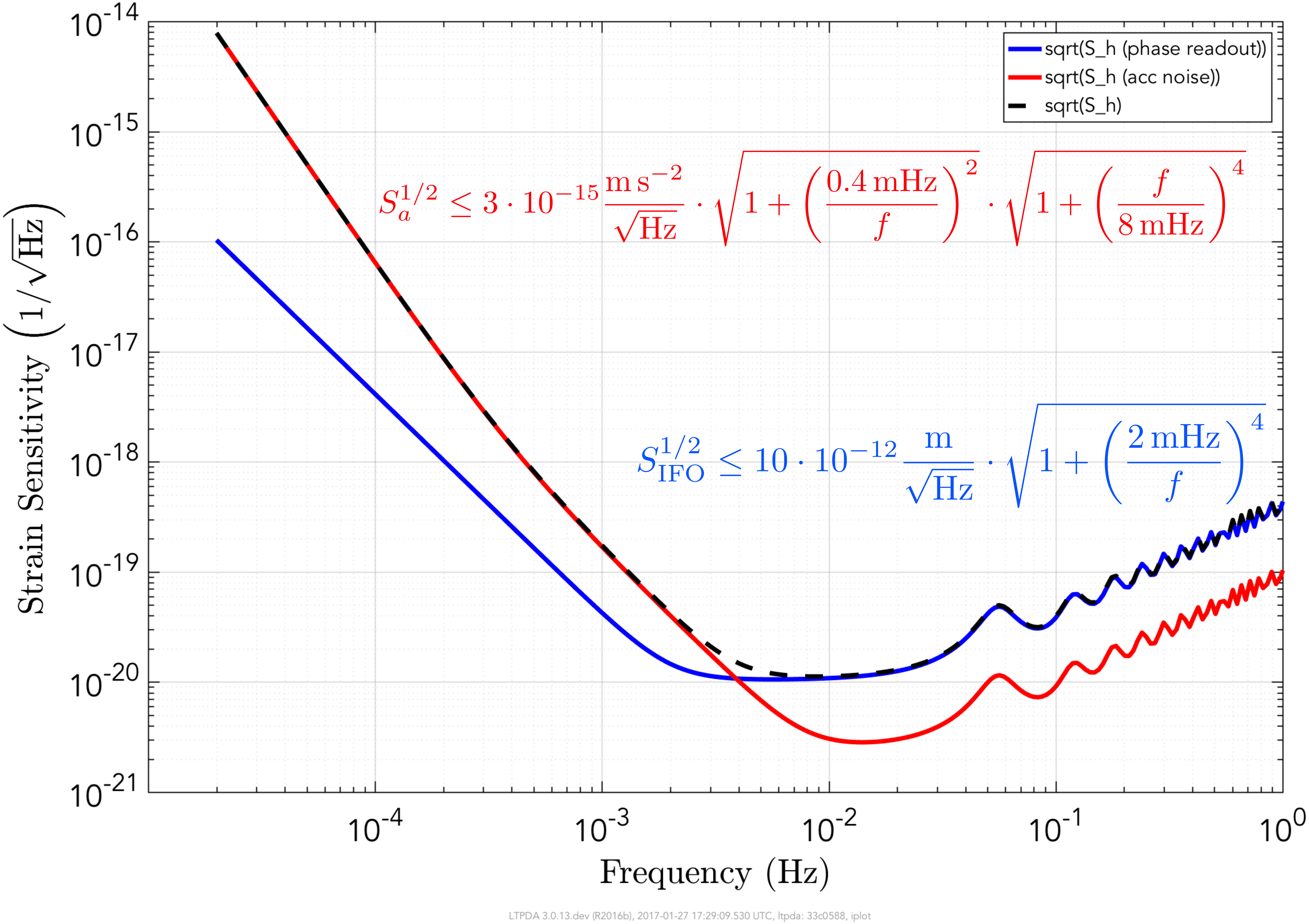


Link = 1 x phase readout + 4 x force noise

Full observatory break-down

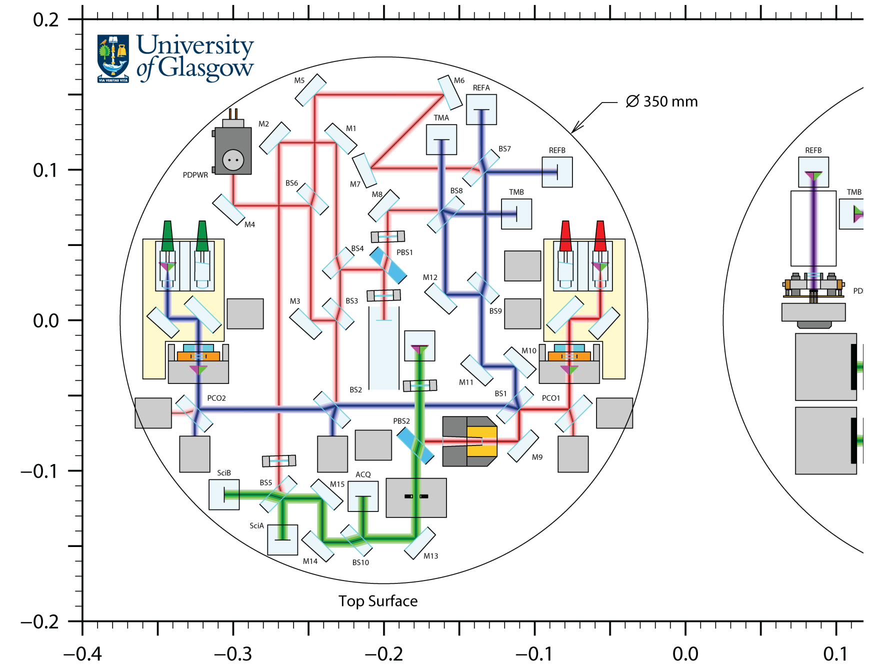


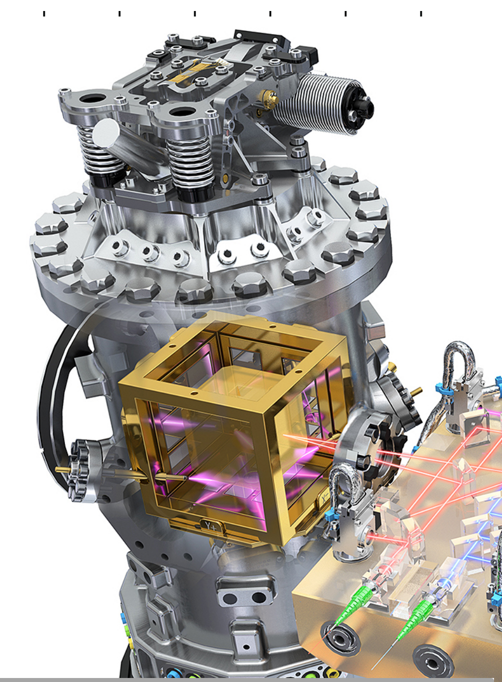
Condensed description

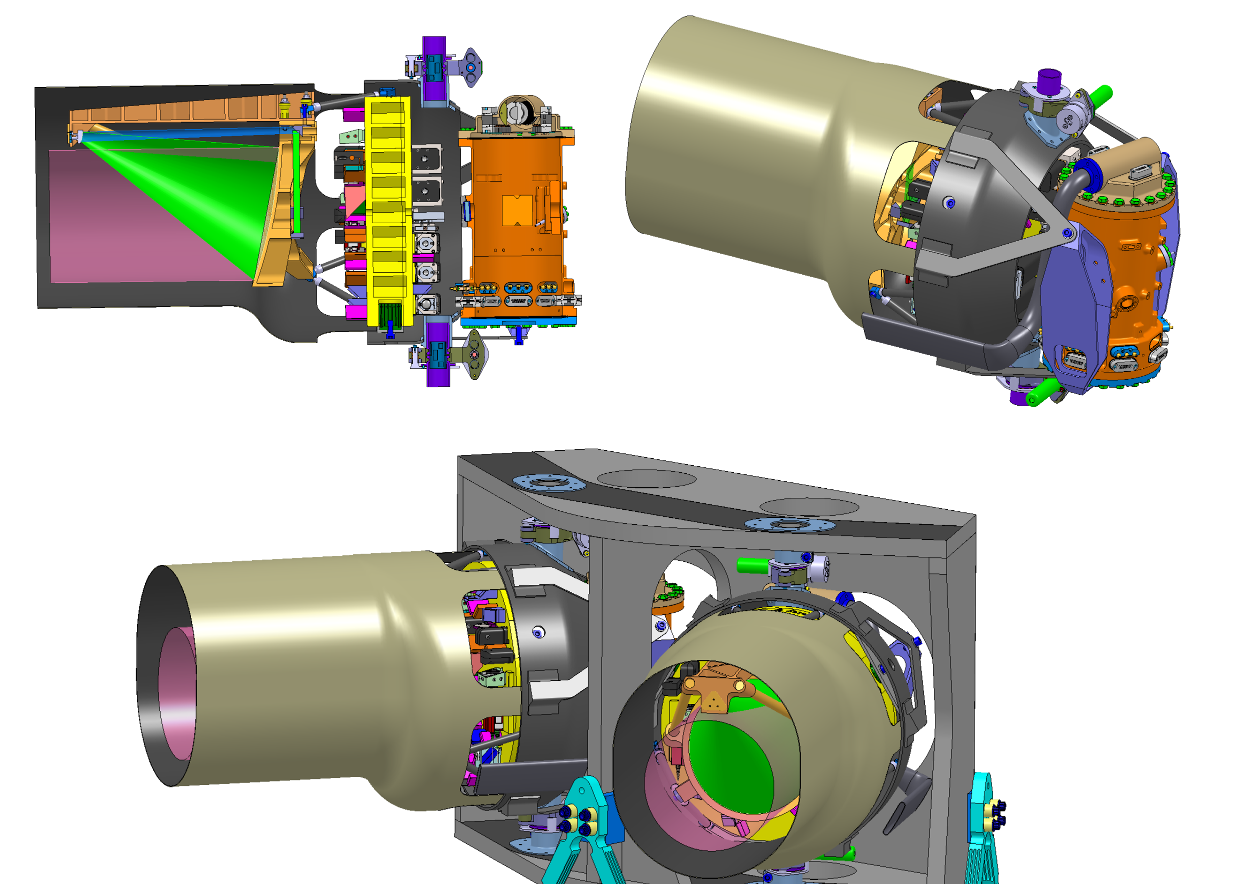


Payload concept (per S/C)

- 2 LPF Gravitational Reference Sensors
    - TM, EH, FEE, caging mechanism, discharge system
- 2 Optical Benches
    - imaging of received light, local and science IFOs, back-link/phase reference
- 2 Telescopes and mounting structures
- Breathing mechanism

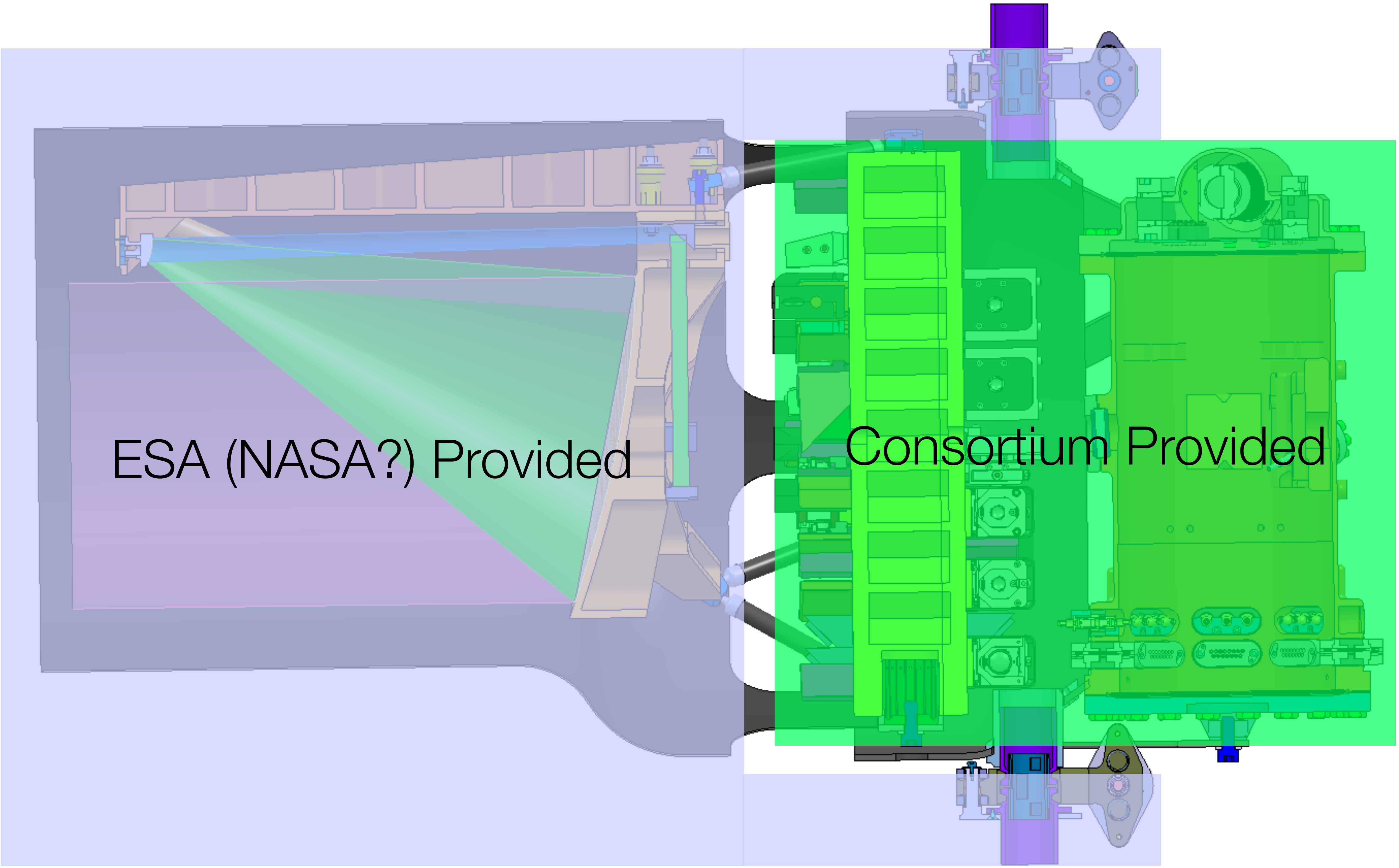




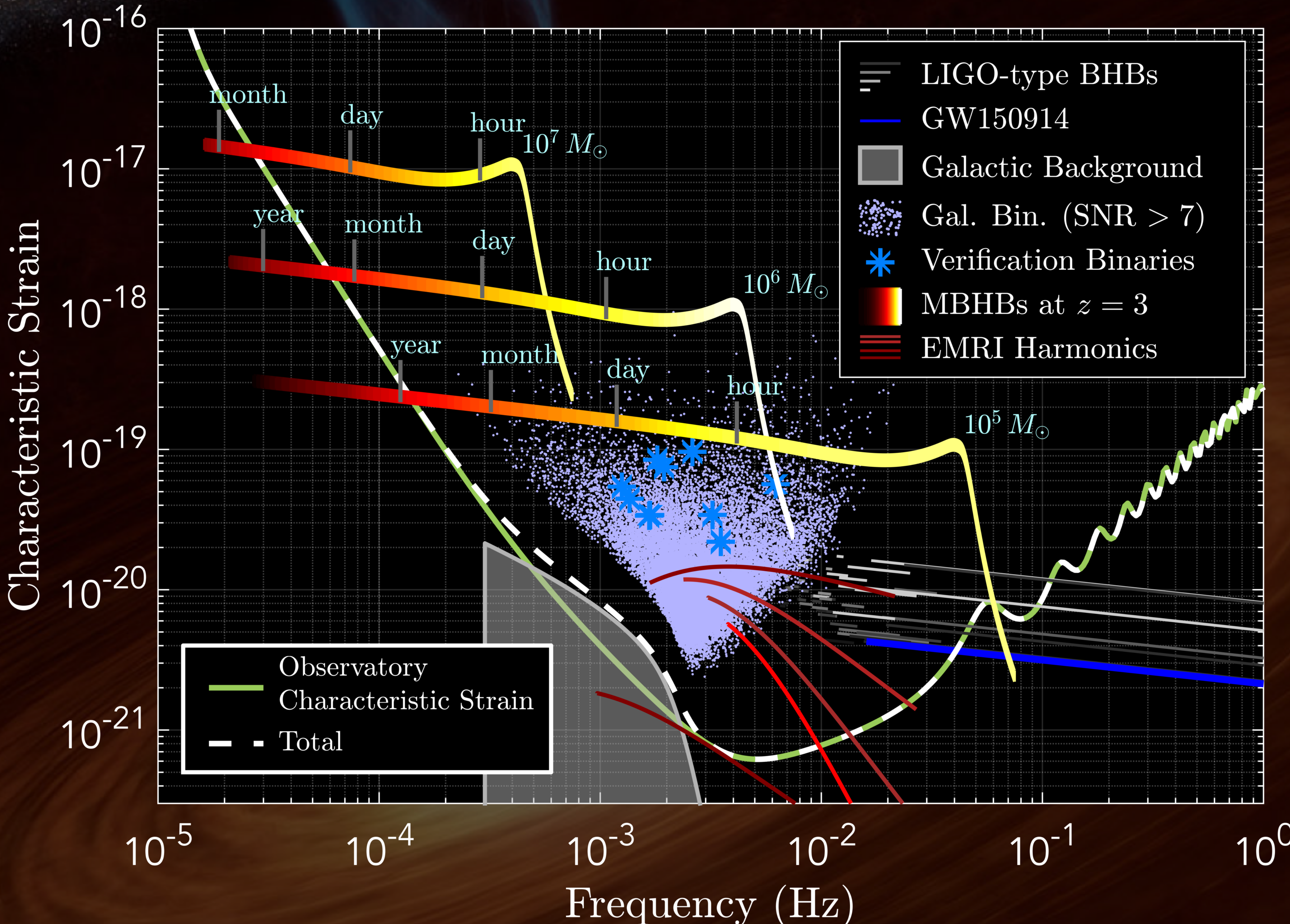


Images courtesy of Airbus D&S GmbH, Friedrichshafen

Payload concept (per S/C)



Setting science requirements



Example

SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages

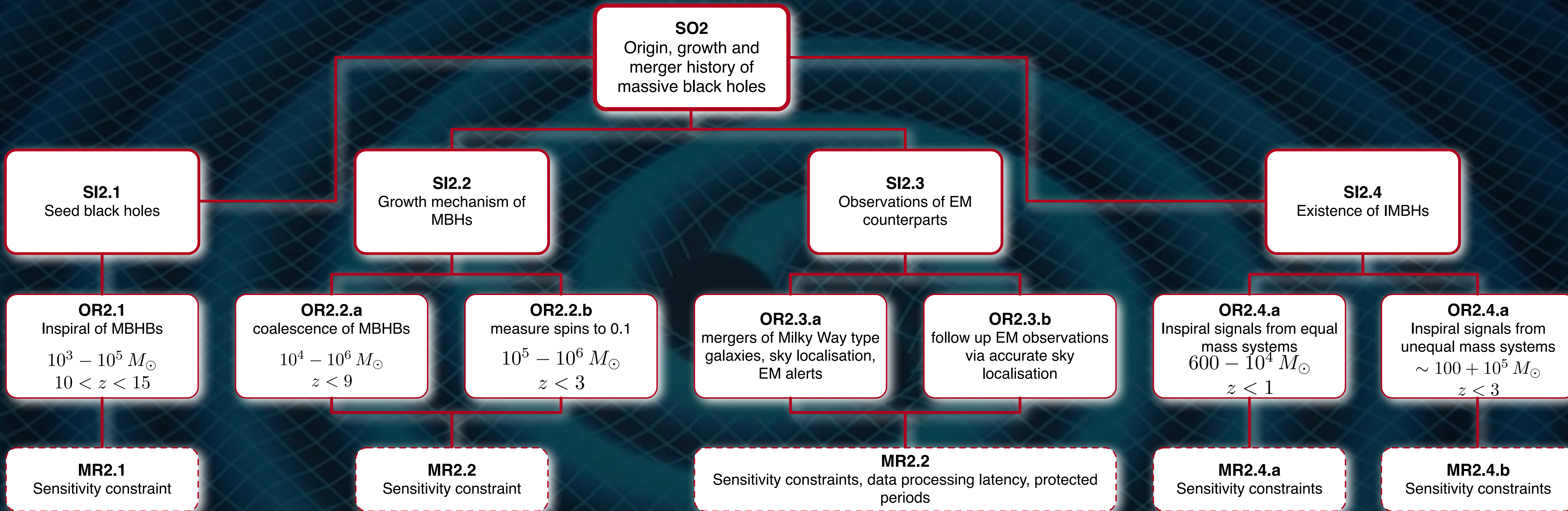
SI2.1: Search for seed black holes at cosmic dawn

SI2.2: Study the growth mechanism of MBHs from the epoch of the earliest quasars

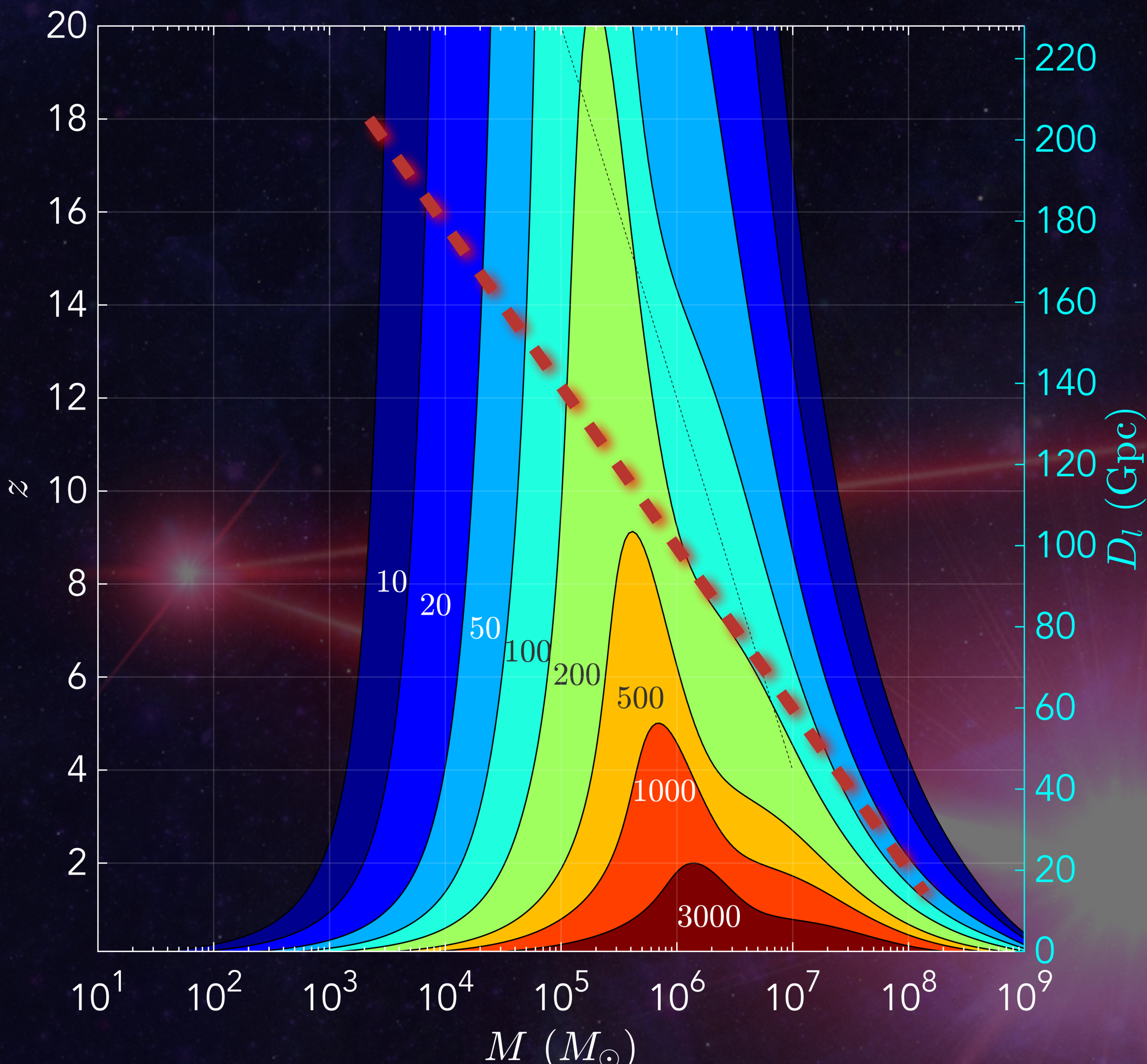
SI2.3: Observation of EM counterparts to unveil the astrophysical environment around merging binaries

SI2.4: Test the existence of Intermediate Mass Black Hole Binaries (IMBHBs)

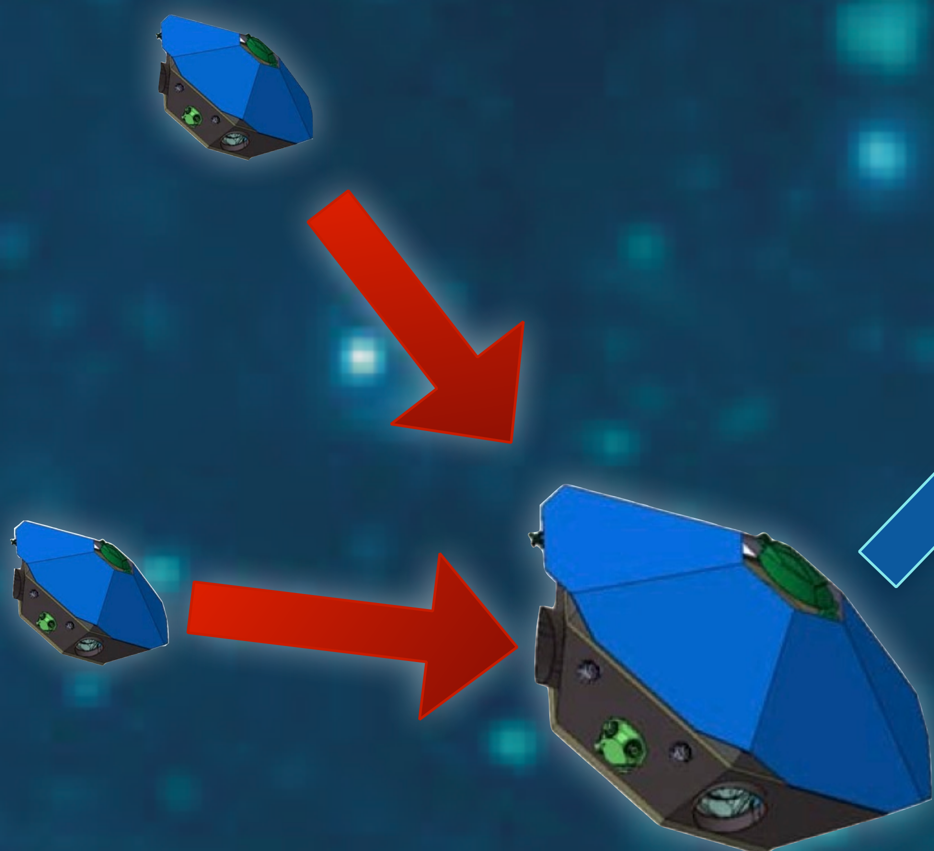
SO2 breakdown



Mass/Redshift plane



Data Processing (1)



Calibration

Preprocessing

TDI Processing

Astrophysics DA

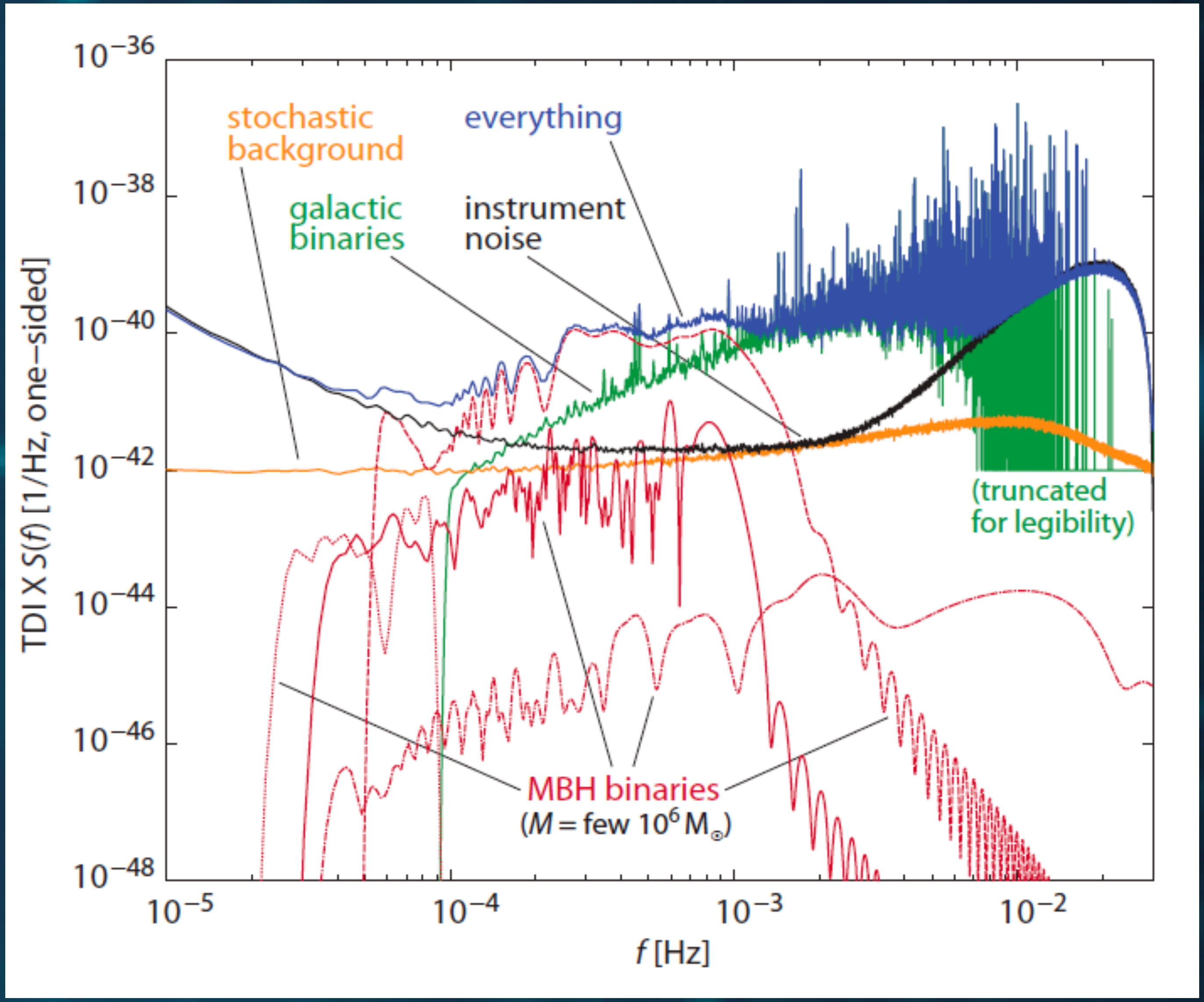
Source Catalogues

Data Processing (2)

- The many data streams needed to extract the science of LISA are sent to ground at low sample rate (few Hz)
- A number of post processing steps are needed to
  - make accurate measurements of the arm length (as a function of time)
  - correct timing jitter
  - noise subtractions, data cleaning, calibrations
- Use **T**ime **D**elay **I**nterferometry to compute physical variables sensitive to GWs
  - cancel laser frequency noise, spacecraft jitter, etc
  - additional data conditioning

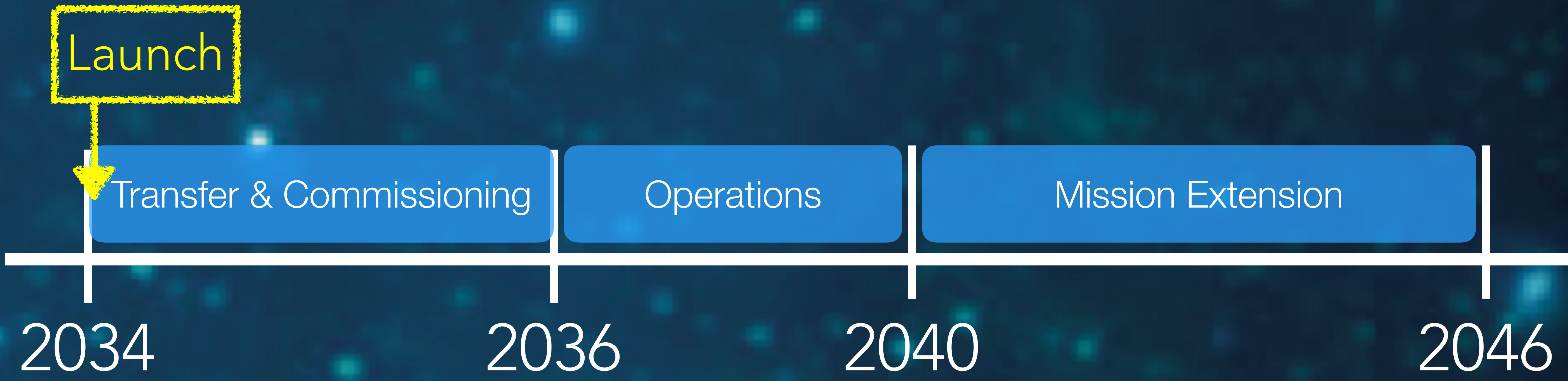
The challenge of LISA data analysis

- LISA is signal dominated!
- Multiple signals are always present in the data
- Need to disentangle all those signals to extract information about the sources
- Mock LISA Data Challenges
  - international community working on the problem



Path to launch

Post launch


Launch
Transfer & Commissioning
Operations
Mission Extension
2034
2036
2040
2046

LISA in ESA's Concurrent Design Facility

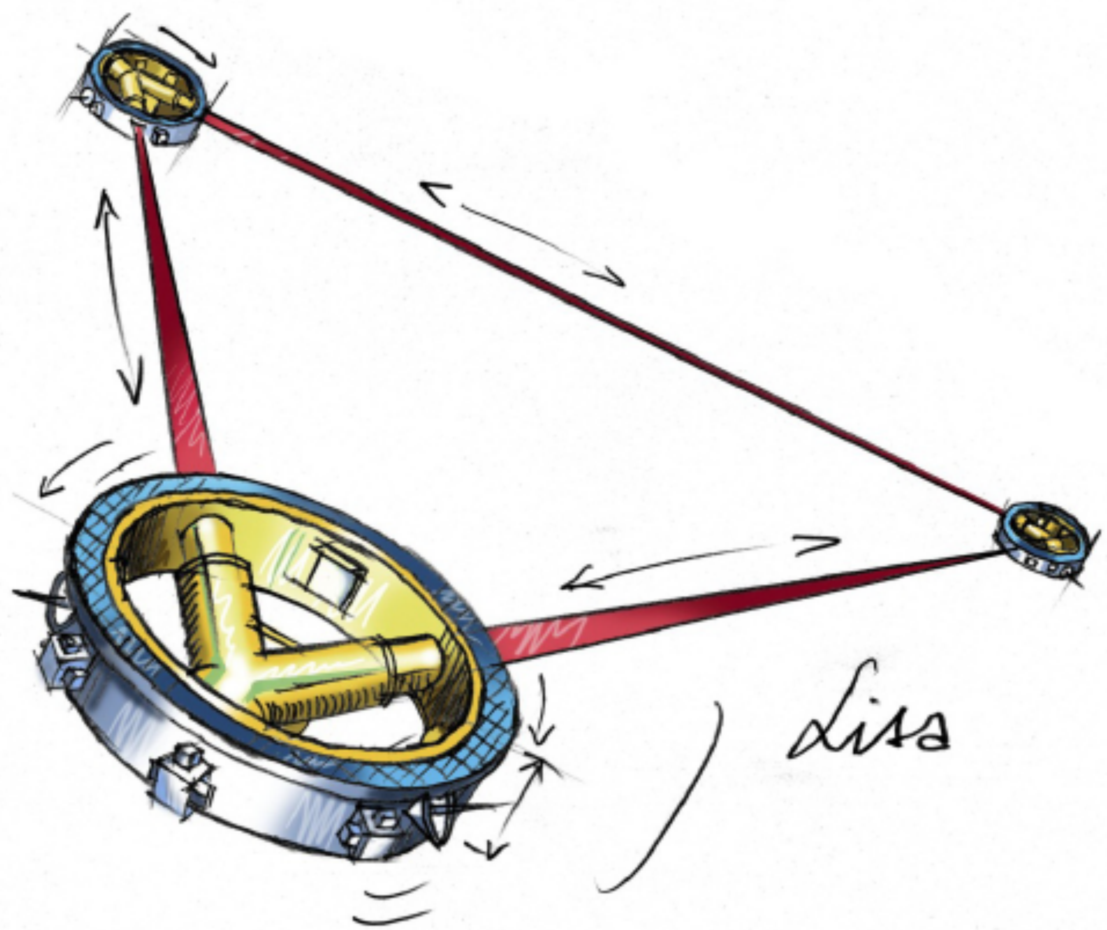
esa

LISA
Study Introduction

Systems

Session 1
ESTEC, 08-03-2017

Prepared by the CDF* Team



(*) ESTEC Concurrent Design Facility

ESA UNCLASSIFIED – For Official Use - Privileged

concurrent design facility

LISA in ESA's Concurrent Design Facility

- Large study team at ESA
  - ~40 engineers
- Support from Consortium

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LISA in ESA's Concurrent Design Facility

STUDY SCHEDULE

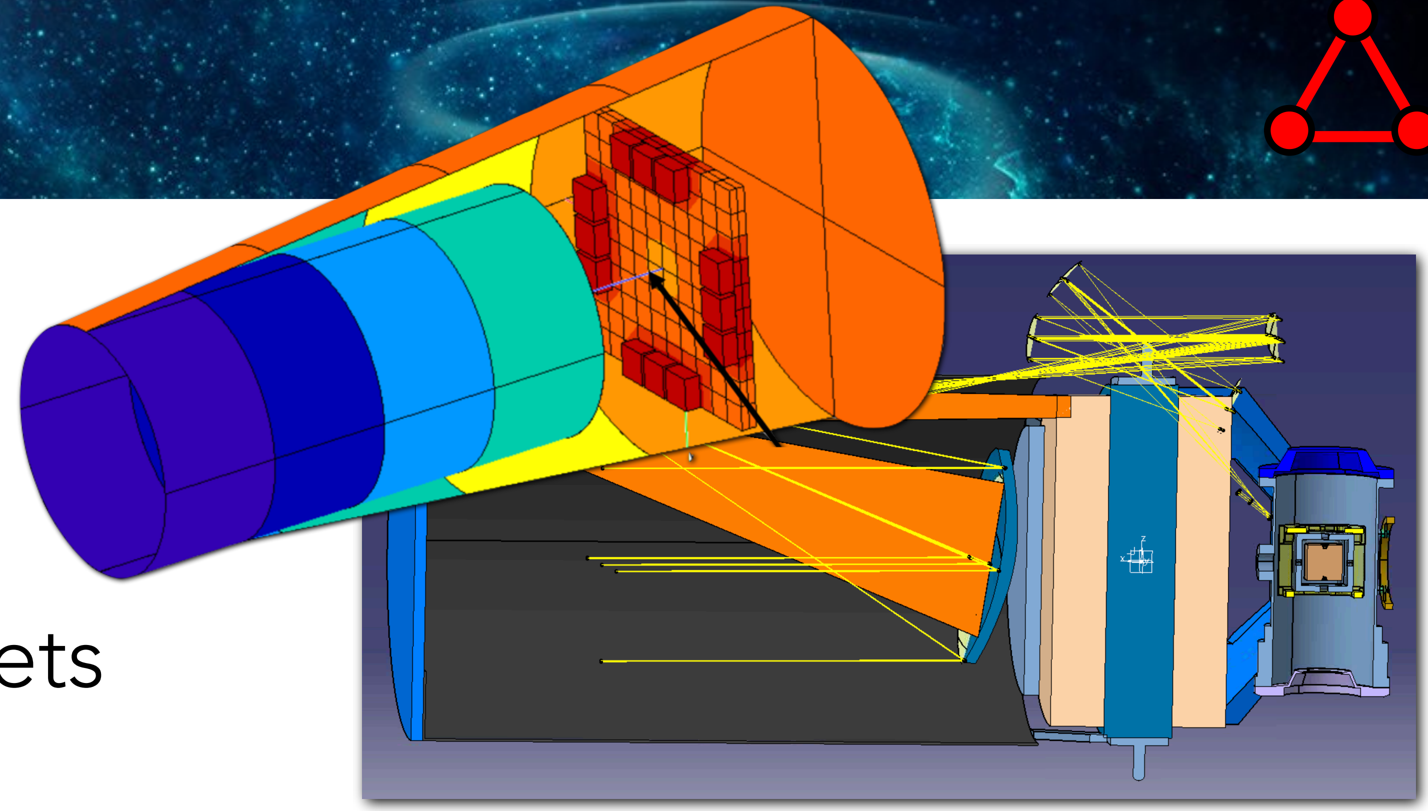
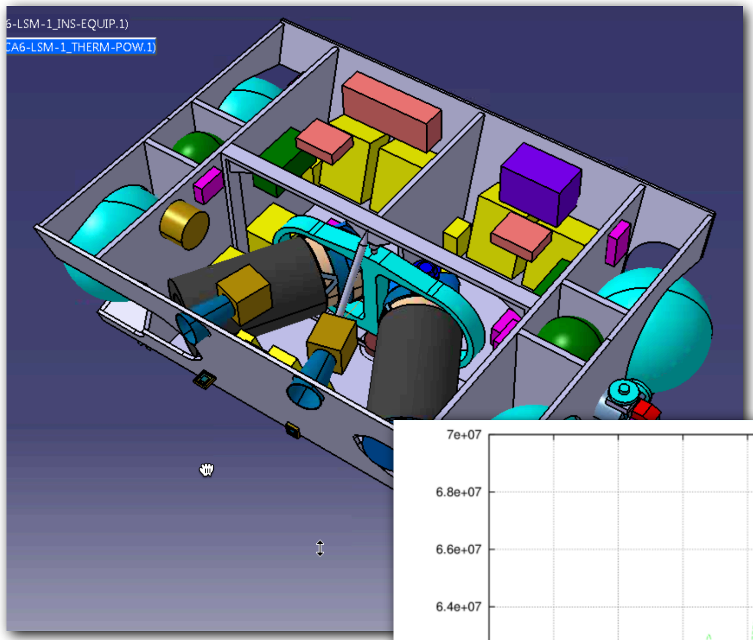
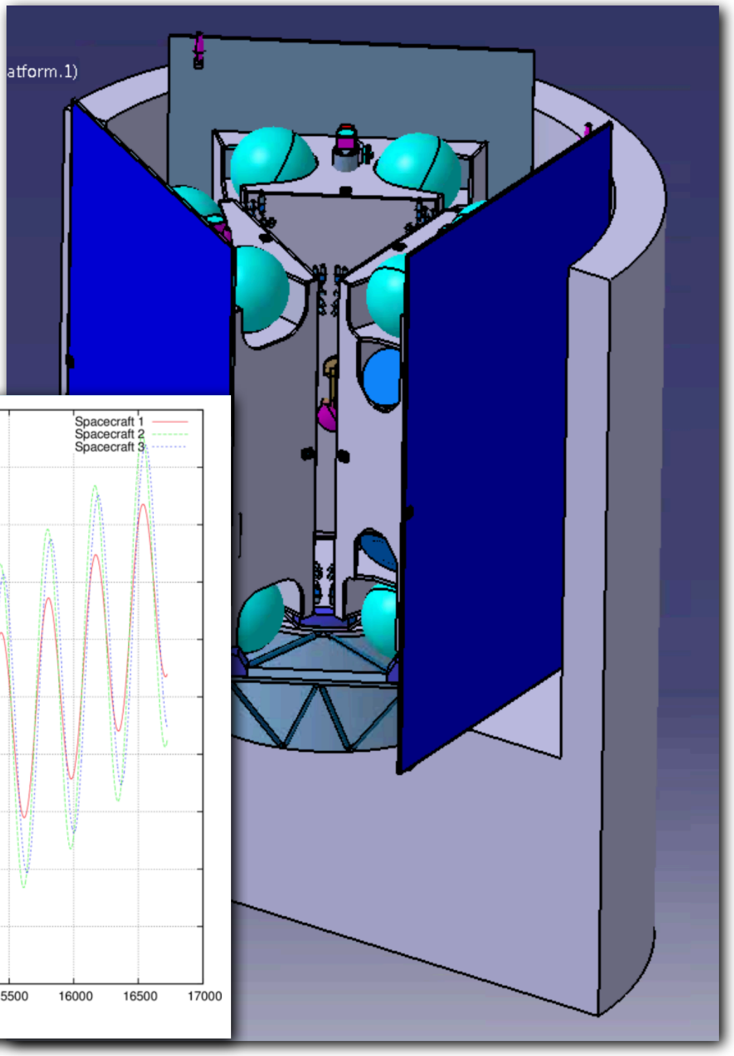
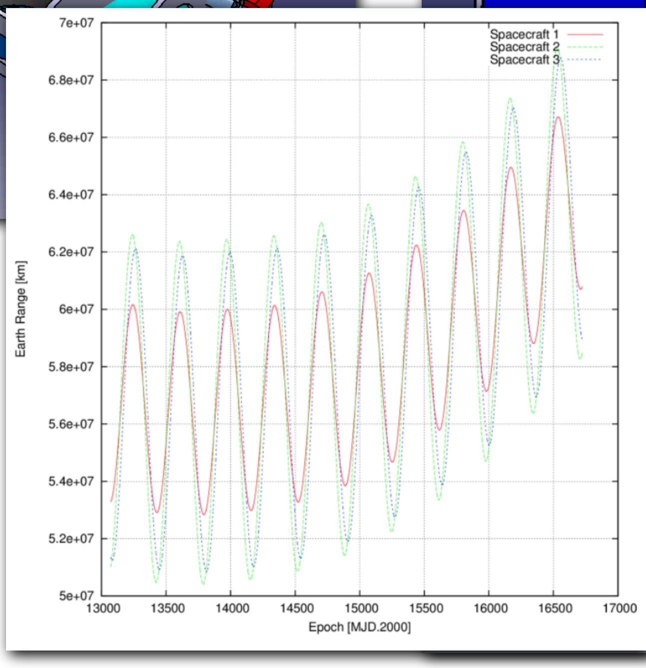
SESSION	DAY	DATE	TIME
Kick Off	Wednesday	08/03/2017	13:30-17:30 CET
#2	Friday	10/03/2017	9:30-13:30 CET
#3	Wednesday	15/03/2017	9:30-13:30 CET
#4	Friday	17/03/2017	9:30-13:30 CET
#5	Wednesday	22/03/2017	13:30-17:30 CET
#6	Friday	24/03/2017	13:30-17:30 CET
#7	Wednesday	29/03/2017	9:30-13:30 CET
#8	Friday	31/03/2017	9:30-13:30 CET
#9	Wednesday	05/04/2017	13:30-17:30 CET
#10	Friday	07/04/2017	9:30-13:30 CET
#11	Wednesday	12/04/2017	9:30-13:30 CET
#12	Wednesday	03/05/2017	9:30-13:30 CET
Internal Final Presentation	Friday	05/05/2017	9:30-16:30 CET

LISA| Slide 5 ESA UNCLASSIFIED – For Official Use - Privileged System

concurrent design facility

In the CDF…

- Overall mission analysis
  - orbits, launch, transfer, etc
- Power, mass, volume budgets
- Overall architecture
- Data handling
- Payload definition
- DFACS
- Programmatics
- Structures
- Ground stations and operations

Summary

- L3 Proposal is in!
  - has been studied by ESA's advisory group
  - Phase 0 (CDF) is nearly complete
  - Payload Phase 0 starts soon
- We have a robust baseline mission which delivers the science of *The Gravitational Universe*
- Properly builds upon the heritage and experience of LPF
- We are ready to build LISA!