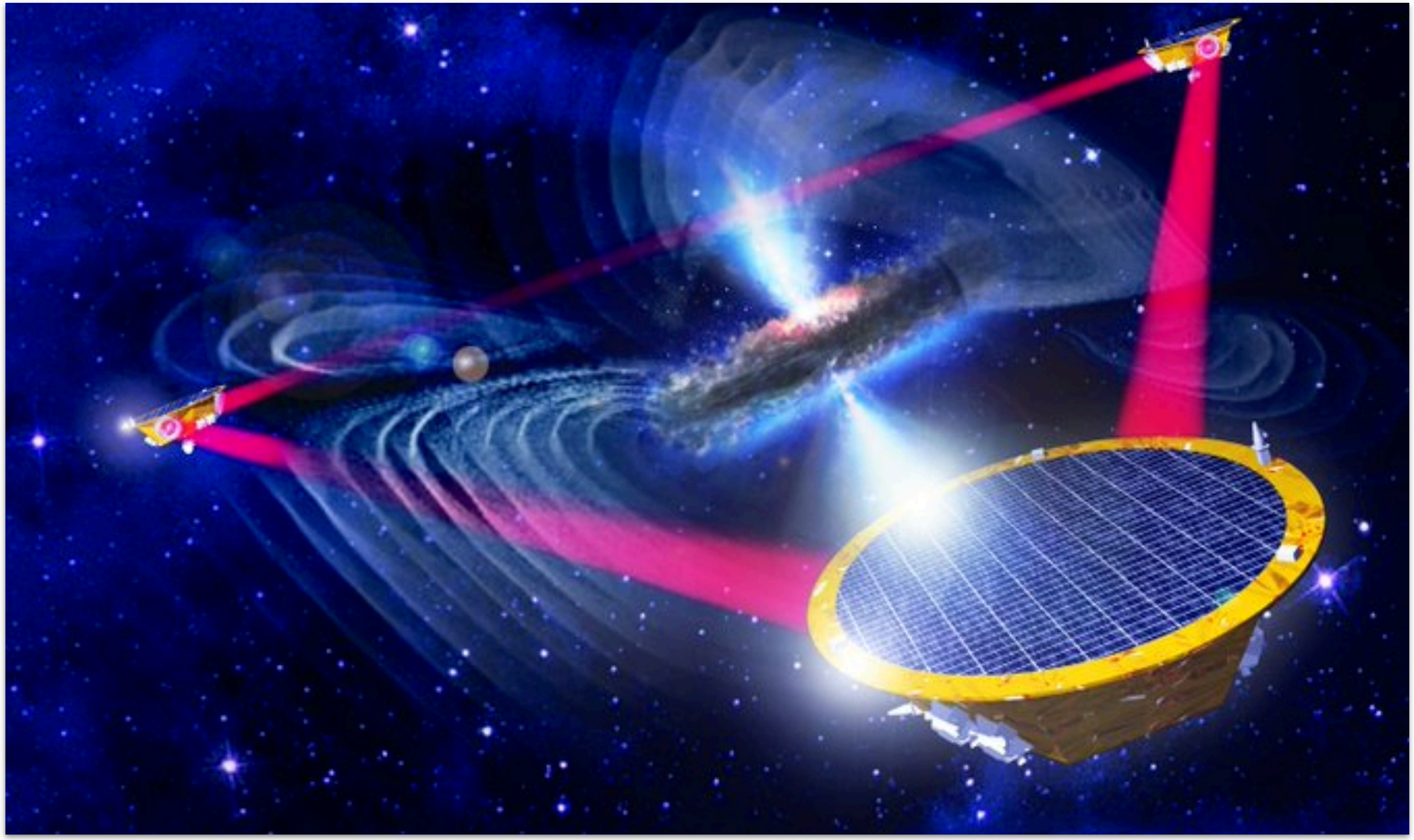
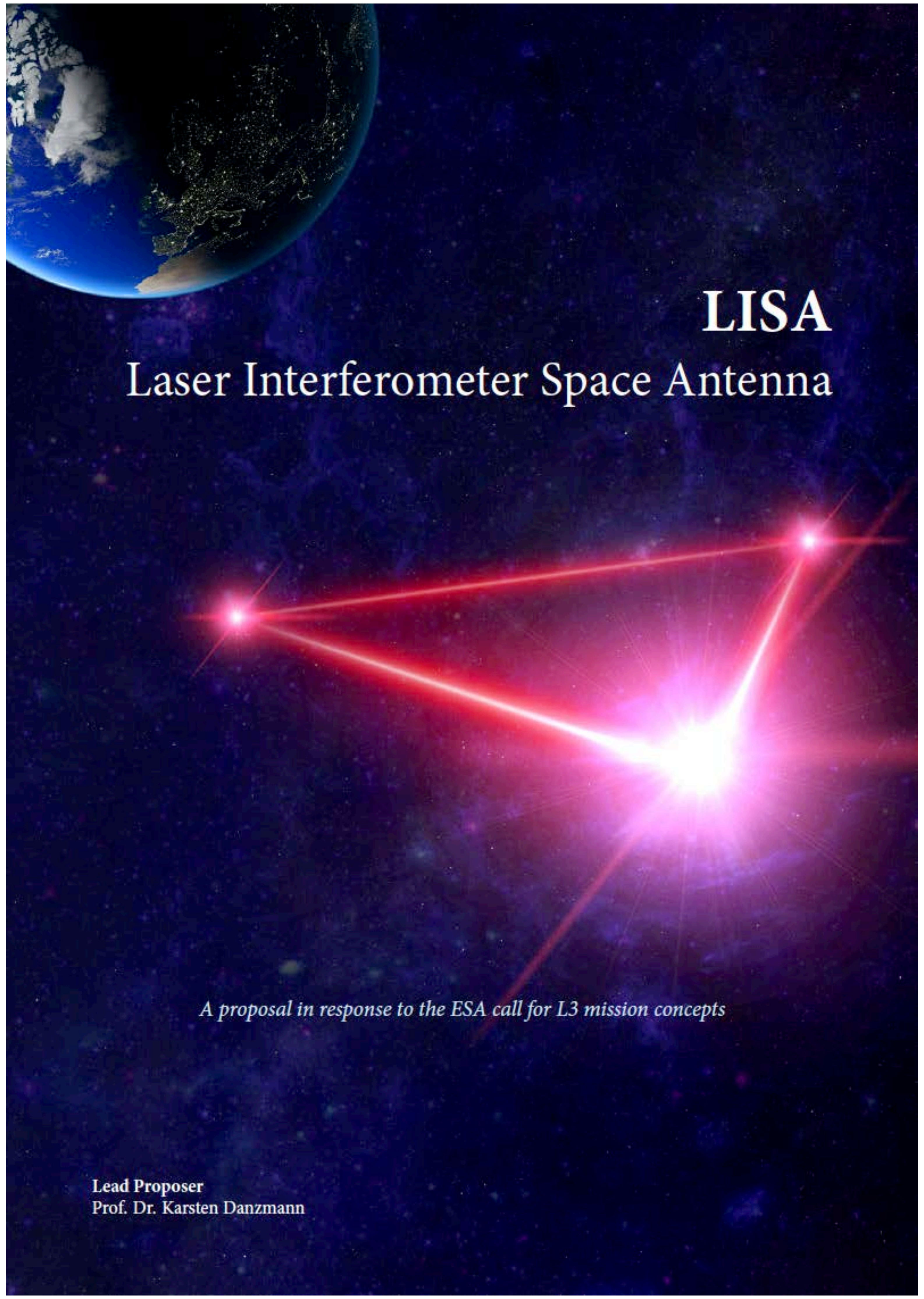


LISA

Guido Mueller

MPI for Gravitational Physics
University of Florida

LISA



LISA

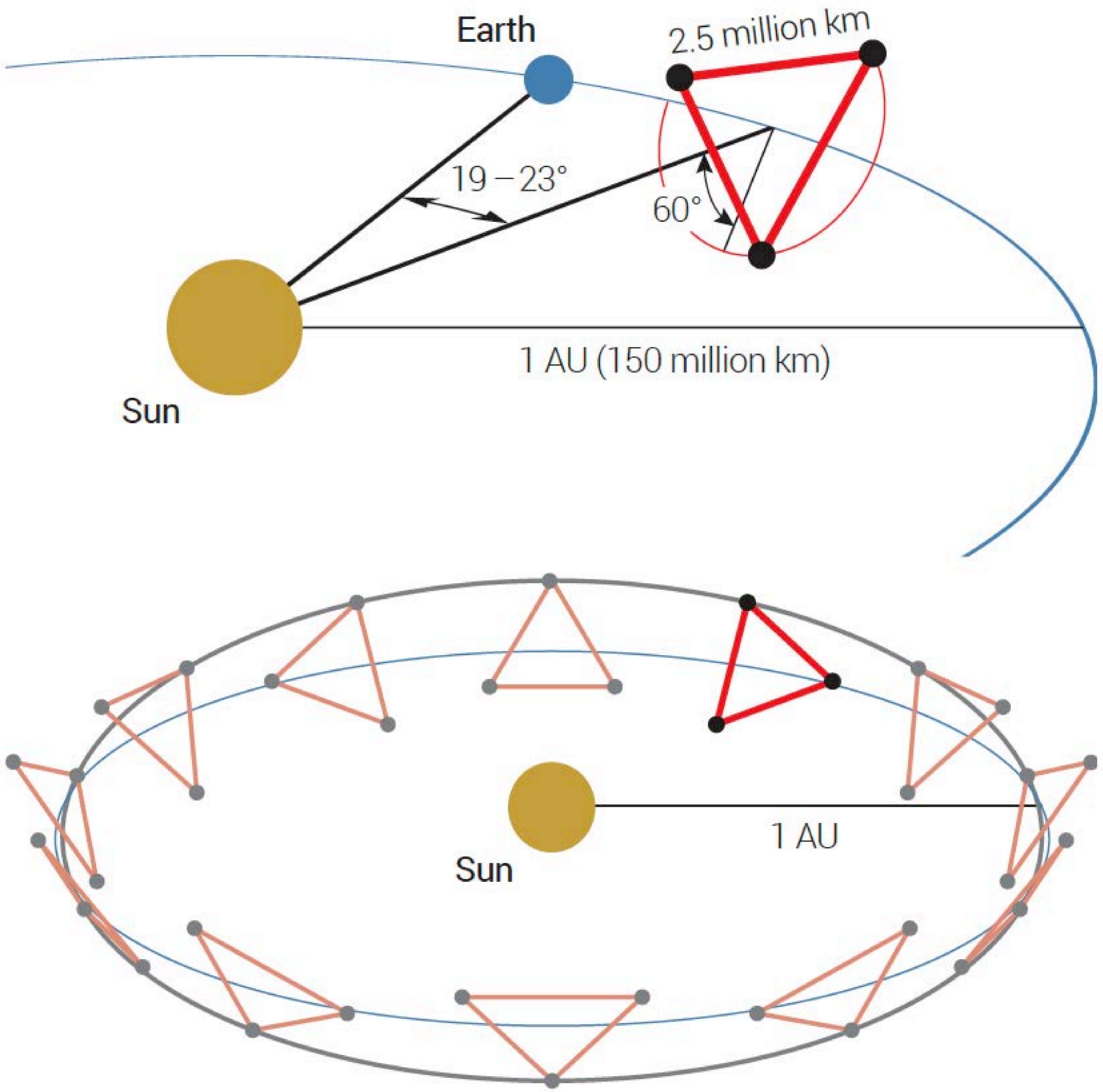
- Proposed in 2017 in response to ESA's call for L3 mission concept
  - by LISA Consortium, lead: Karsten Danzmann (AEI Hannover)
- Enabled by two major breakthroughs:
  - LIGO discovery 2015
  - LISA Pathfinder success in 2016/17
- ESA-led project
  - NASA partner
  - ESA member states contribute directly
- Currently in Phase B1:
  - Demonstration of all critical functions
  - Identify responsible partner for every deliverable —> sign MLA
  - Adoption: January 2024
- Launch: 2035

LISA

Basic concept

- 3 S/C in triangular formation
  - 2.5 Gm arm length
- Free falling test masses
- Laser interferometric readout
- Very long history

1974 first discussions (Weiss, Bender, Misner, Pound)
1984 LAGOS: laser antenna for GW observations in space (Bender, Faller, Hall, Hils, Vincent)
1993 LISA (Danzmann) and Sagittarius (Hellings) proposed to ESA's Horizon 2000, studied together as LISAG
1996 six-spacecraft, heliocentric design chosen as cornerstone for Horizon 2000+, for launch — 2017–2023
1997 JPL study (Bender, Stebbins, Folkner): joint NASA–ESA, three s/c design, for launch — 2005–2010
1998 pre-phase A report (yellow book)
2000 U.S. decadal: LISA 2nd among moderate projects
2001 U.S. LISA project formed; LISA Pathfinder begins
Confidential
2003 TRIP review
2004 formal NASA–ESA agreement, for launch — 2012–2013
2006 first Mock LISA Data Challenge
2007 Beyond Einstein review: 1st science, launch — 2017–2020
2010 astro2010+: high priority, but cannot do it on ESA timeframe



LISA Science Objectives

SO 1 Study the formation and evolution of compact binary stars in the Milky Way Galaxy

SI 1.1 Elucidate the formation and evolution of Galactic Binaries by measuring their period, spatial and mass distributions

SI 1.2 Enable joint gravitational and electromagnetic observations of galactic binaries (GBs) to study the interplay between gravitational radiation and tidal dissipation in interacting stellar systems

SO 2 Trace the origin, growth and merger history of massive black holes across cosmic ages

SI 2.1 Search for seed black holes at cosmic dawn

SI 2.2 Study the growth mechanism of MBHs before the epoch of reionization

SI 2.3 Observation of EM counterparts to unveil the astrophysical environment around merging binaries

SI 2.4 Test the existence of intermediate-mass black holes (IMBHs)

SO 3 Probe the dynamics of dense nuclear clusters using extreme mass-ratio inspirals (EMRIs)

SI 3.1 Study the immediate environment of Milky Way like massive black holes (MBHs) at low redshift

SO 4 Understand the astrophysics of stellar origin black holes

SI 4.1 Study the close environment of Stellar Origin Black Holes (SOBHs) by enabling multi-band and multi-messenger observations at the time of coalescence

SI 4.2 Disentangle SOBHs binary formation channels

LISA Science Objectives

SO 5 Explore the fundamental nature of gravity and black holes

SI 5.1 Use ring-down characteristics observed in massive black hole binary (MBHB) coalescences to test whether the post-merger objects are the black holes predicted by General Theory of Relativity (GR)

SI 5.2 Use EMRIs to explore the multipolar structure of MBHs

SI 5.3 Testing for the presence of beyond-GR emission channels

SI 5.4 Test the propagation properties of gravitational waves (GWs)

SI 5.5 Test the presence of massive fields around massive black holes with masses larger than $10^3\ M_\odot$

SO 6 Probe the rate of expansion of the Universe

SI 6.1 Measure the dimensionless Hubble parameter by means of GW observations only

SI 6.2 Constrain cosmological parameters through joint GW and electro-magnetic (EM) observations

SO 7 Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics

SI 7.1 Characterise the astrophysical stochastic GW background

SI7.2 Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background

SO 8 Search for GW bursts and unforeseen sources

SI 8.1 Search for cusps and kinks of cosmic strings

SI 8.2 Search for unmodelled sources

Science Requirements Document (SRD) turns these Science Objectives into mission requirements formulated as:

- Strain linear spectral density
- Mission lifetime and duty cycle
    - 4 yr minimum, > 75% on
    - 10 year goal
- Polarisation resolution
- Requests for joint GW/EM observations
- Data Timing and latency
- Protected periods
- Data gaps
- …

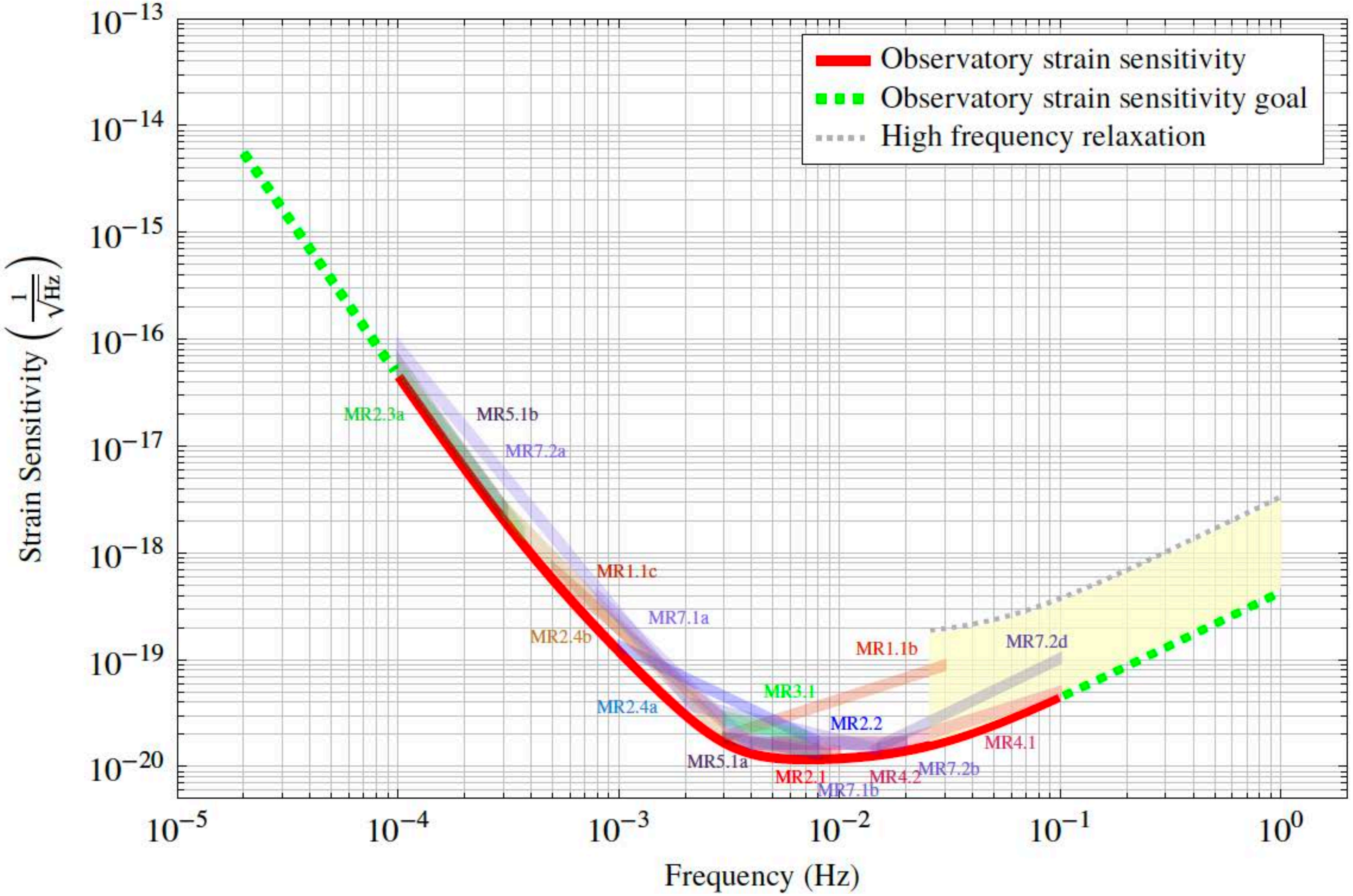


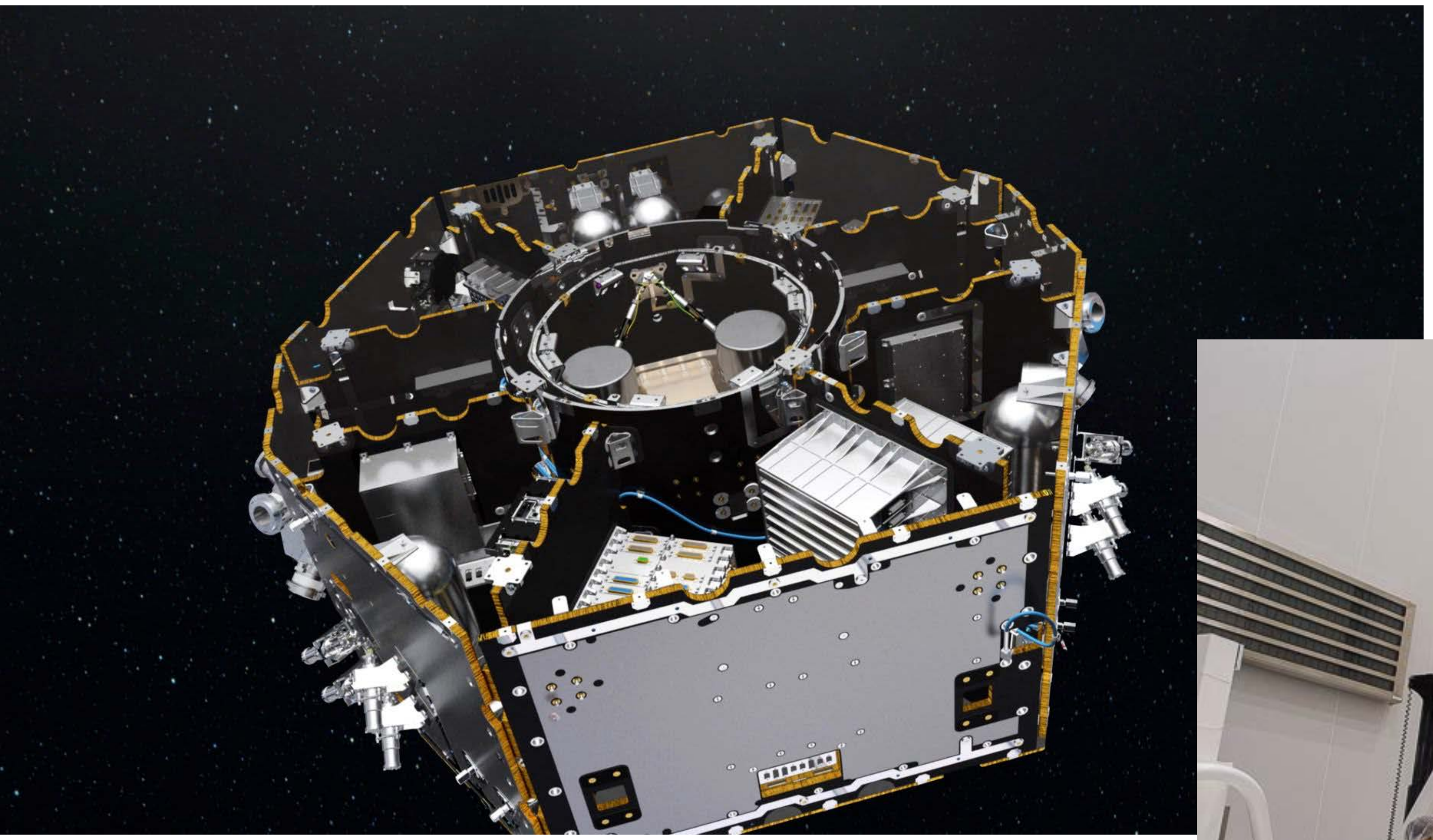
Figure 1: Red solid line: Sky, inclination and polarisation-averaged constraints on the strain sensitivity of the observatory, derived from the measurement requirements for each observational requirement (coloured lines). The green dotted lines above 0.1 Hz and below 0.1 mHz indicate *mission goals*. The grey dashed line indicates the envelope of the sensitivity at high frequency due to nulls in the observatory response arising from the relationship between armlength and gravitational wavelngth. (see Section 3.3 for details).

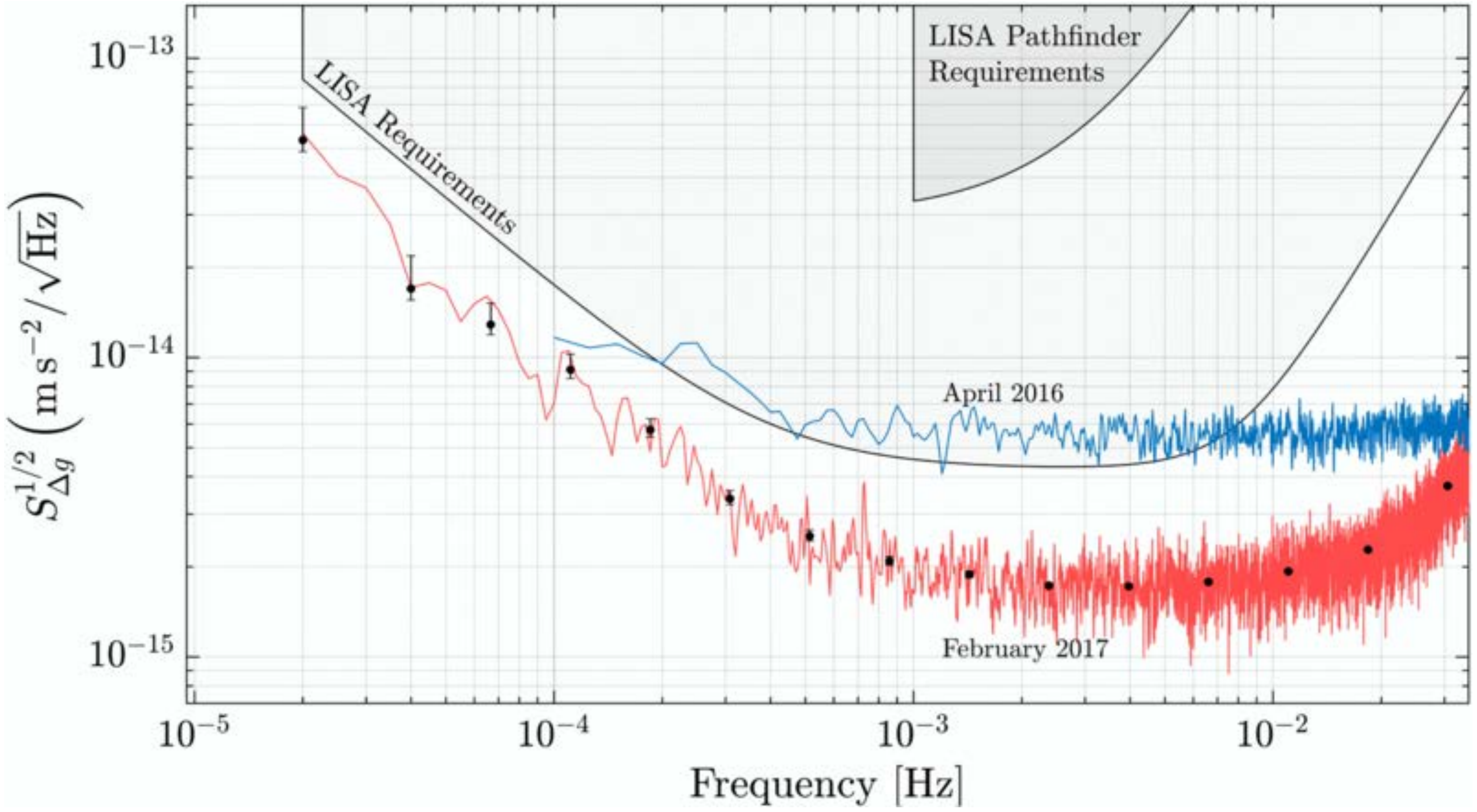
Mission requirements status

LISA Pathfinder: Launched December 2015

Goal: To demonstrate free fall within one order of magnitude of LISA

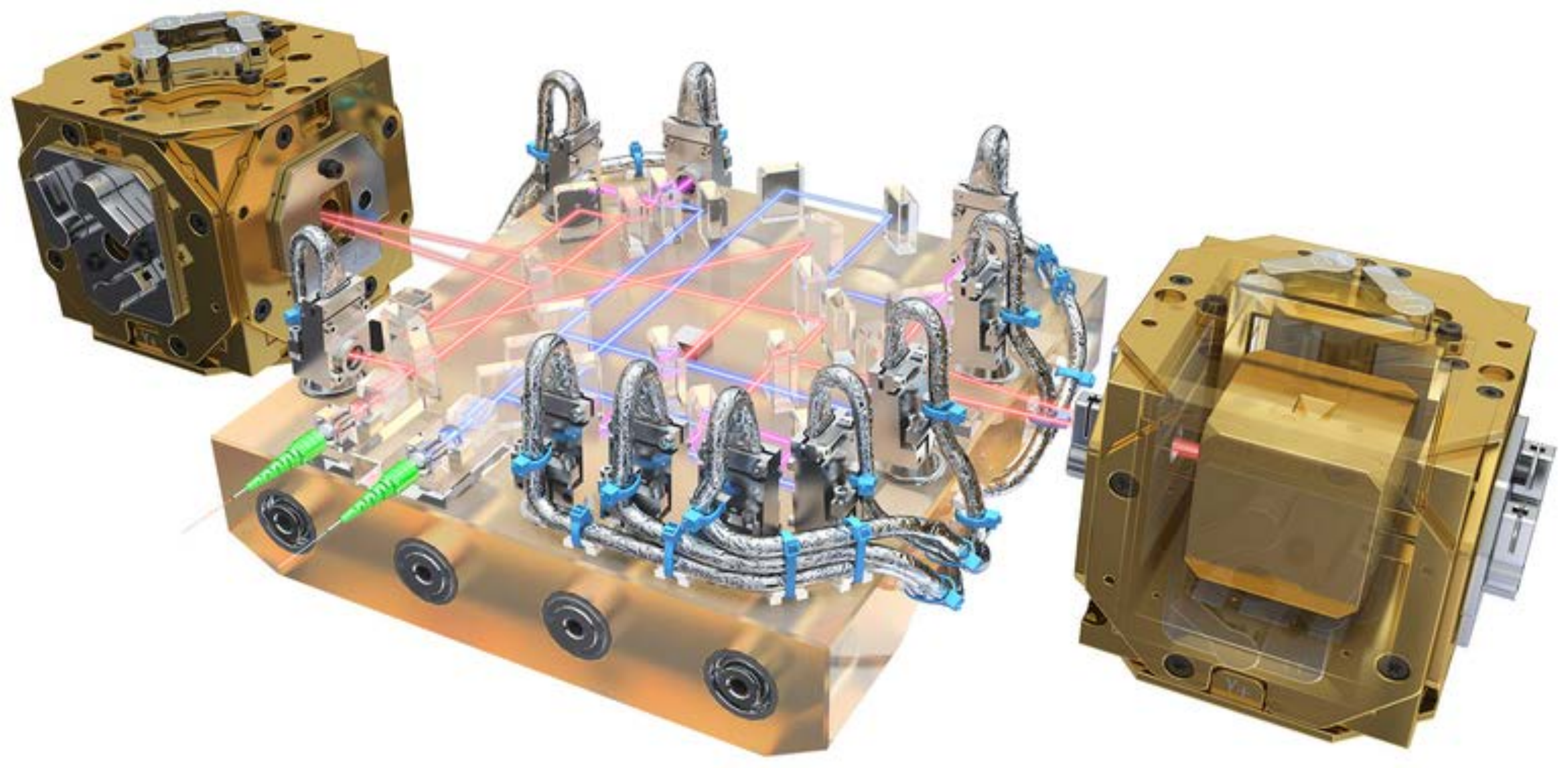
Result: Better than required for LISA!





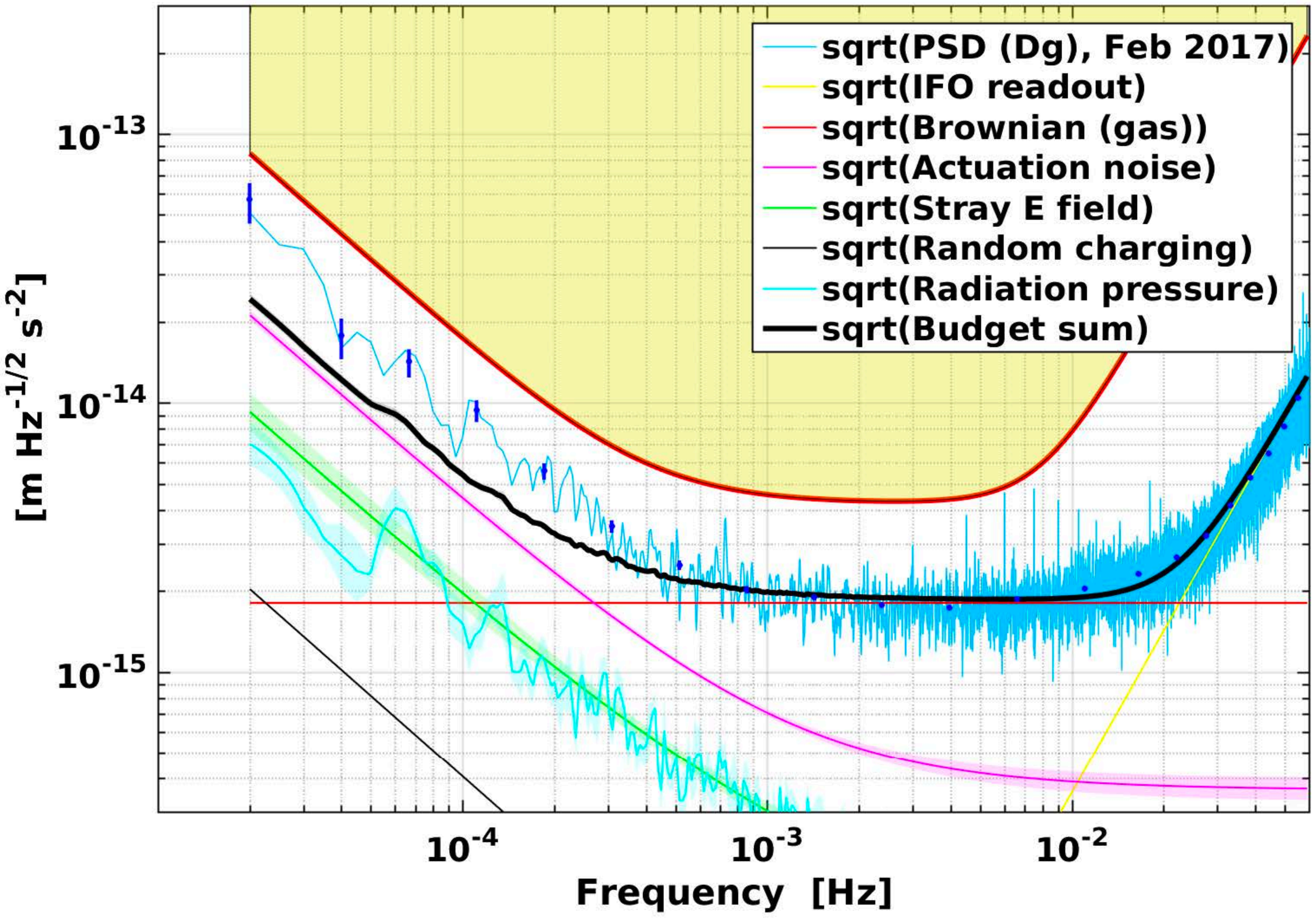
Mission requirements status

LISA Pathfinder:
Launched December 2015



Actuation noise:

- Actuation required because of local gravitational field
  - In part limited by mass balance inside S/C
- Residual gas pressure
  - Amplified by small gaps between TM and housing

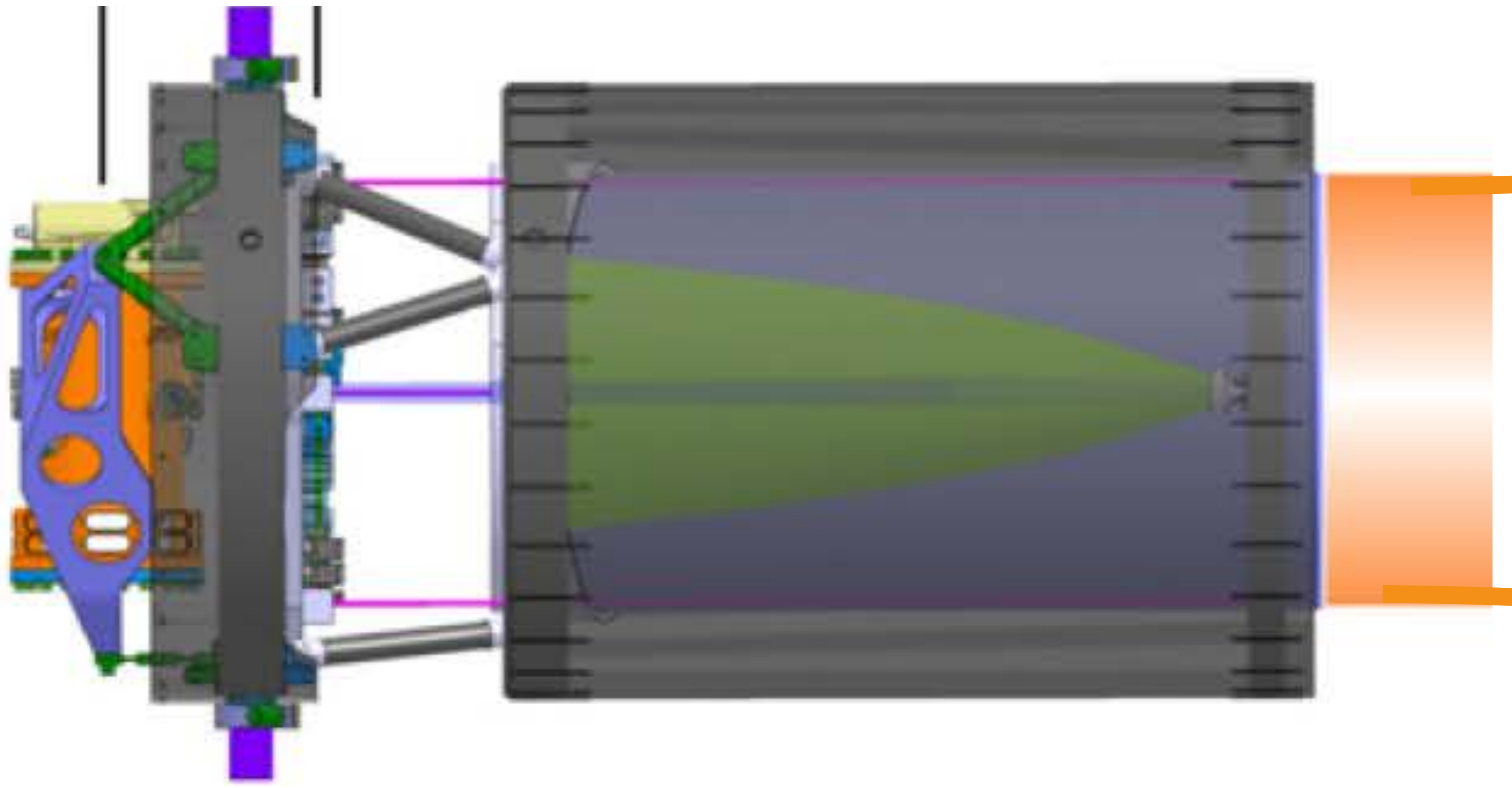


LTPDA 3.0.12.ops (R2015b), 2017-07-11 00:44:52.225 UTC, LPF_DA_Module: 8a04b9f, ltpda: 88427c3, iplotPSD

Final result shows not only superior performance but also deep understanding of limiting noise sources.

Mission requirements status

Shot noise:



Diameter: 30cm

$P_{out} = 2\,\mathrm{W}$

Beam size at S/C: 12 km

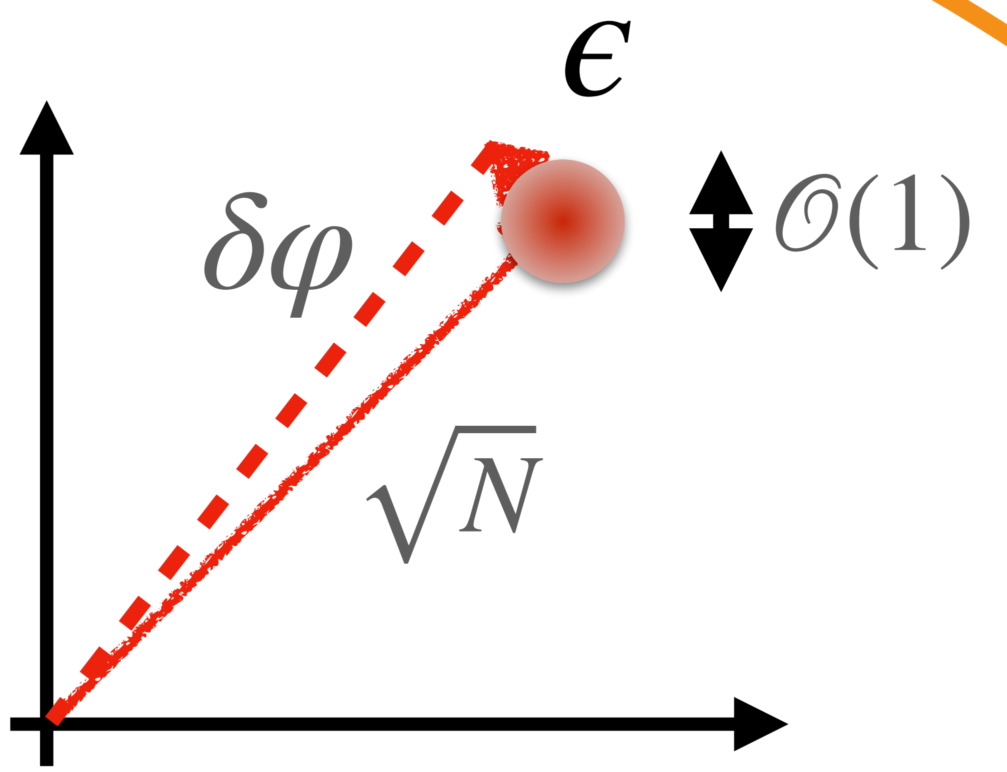
Diameter: 30cm

$P_{rec} \leq 1\,\mathrm{nW}$

Diffraction spreads the beam

- Received power at far S/C below nW

➡ Shot noise limit: $\delta l_{SN} \approx 2 \frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$



➡ Requirement: $\delta l_{SCI} \approx 10 \frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$ to include optical losses and technical noise sources

Mission requirements

- Free falling test masses

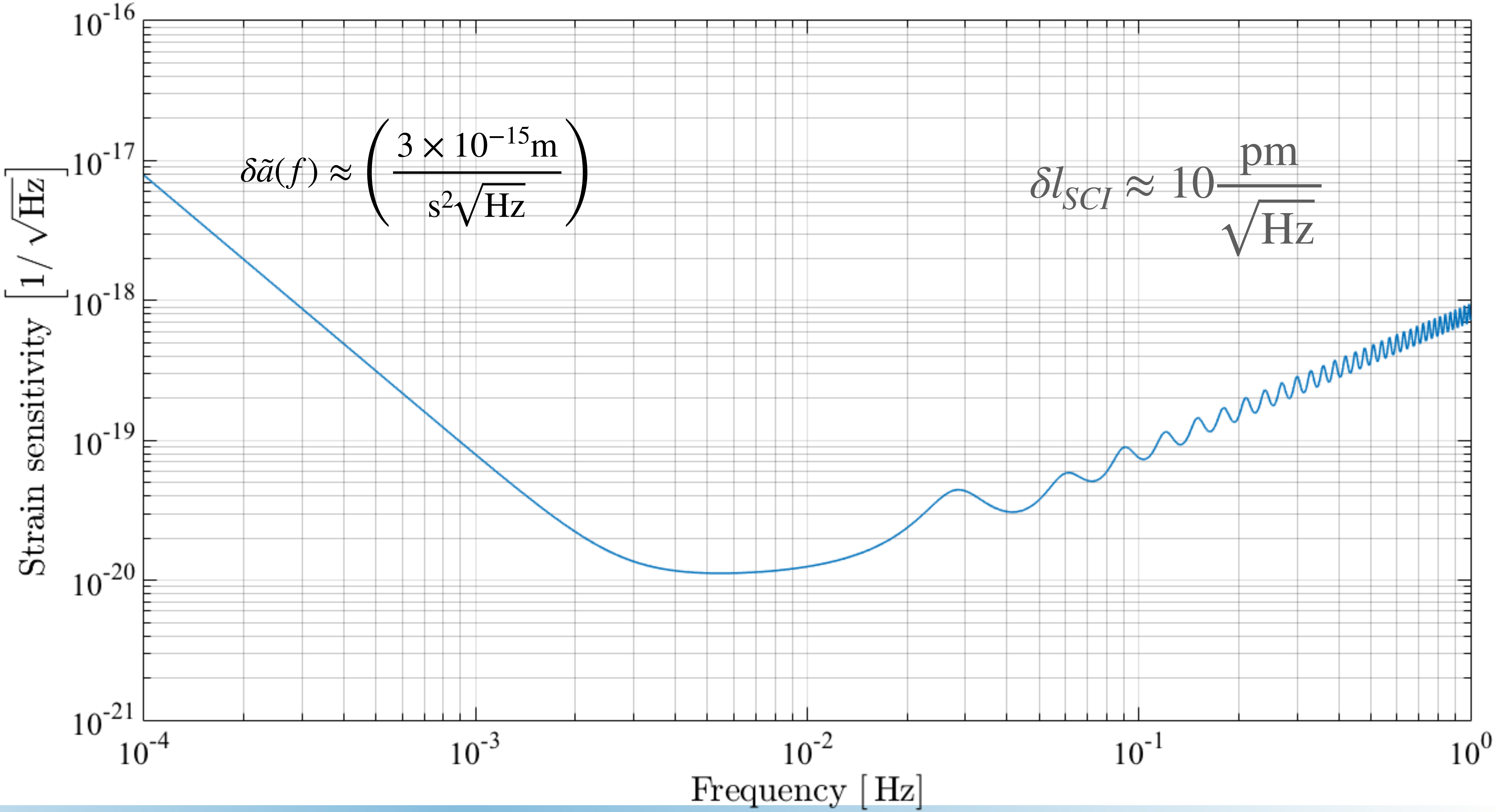
$$\delta \tilde{a}(f) \approx \left(\frac{3 \times 10^{-15} \mathrm{m}}{\mathrm{s}^2 \sqrt{\mathrm{Hz}}} \right)$$

- Single link noise:

$$\delta l_{SCI} \approx 10 \frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$$

LISA Design sensitivity

(One link)



Other issues

- Stray light
  - Micrometeorites, dust, outgassing
- Backlink phase noise
- Clock comparison
  - Laser phase modulation fidelity
- Tilt to length coupling
  - Minimize and subtract
- Lock acquisition
- ….

Implementation Schedule
Major Milestones

Review	Date	Instrument Level
Adoption	January 2024	
Prime Kick-Off	End 2024	
Mission SRR	April 2025	Ongoing
Mission PDR	Nov 27/Feb 28	TBD
Mission CDR	Jan 2031	Late 2027
Target	2035	

- Adoption follows MAR (Mission Adoption Review: Will start this fall)
- SRR: Systems Requirements Review (I-SRR just started)
- PDR: Preliminary Design Review
- CDR: Critical Design Review

LISA Schedule

	Proposal Phase	Phase 0	Phase A	Phase B1	Phase B2/C/D	Phase E
Decision milestones	**Science Program Committee (SPC) Informed** Selected for study			We are here **Science Program Committee (SPC) Decision** Mission Adoption		
Mission phase		Concurent Design Facility (CDF)				
Main actors during this mission phase	**Group of scientists proposes the idea to ESA**	**Assessment Phase** *Is this mission technically possible?* *What needs to be developed?* *What are the first requirements?*	**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	Proposal Selection	Mission Definition Review (MDR)	Mission Consolidation Review (MCR) Mission Formulation Review (MFR)	Mission Adoption Review (MAR)	Launch	
Final Documents	Proposal	CDF Report	Industrial & Inst Data Packs: (Technical & Programmatic) Industrial & Inst Data Packs: (Tech & Programmatic)	Data Pack: (Tech & Programmatic) & Red Book		
LISA	JAN 2017	DEC 2017	DEC 2019 DEC 2021	2024		

LISA + CE/ET

Detection of Gravitational memory effect in LISA using triggers from ground-based detectors

Sourath Ghosh,[1] Alexander Weaver,[1] Jose Sanjuan,[2] Paul Fulda,[1] and Guido Mueller[1,3]
[1] *Physics Department, University of Florida, USA*
[2] *Department of Aerospace Engineering, Texas A&M University, USA*
[3] *Max Planck Institute for Gravitational Physics (Albert-Einstein-Institut) Hannover, Germany*
(Dated: February 10, 2023)

Detector(d)	$\frac{\mathrm{SNR}^d}{\mathrm{SNR}^{\mathrm{LIGO\ O3}}}$	Time for memory detection[yrs]			
		LISA	AMIGO	ALIA	Folkner
CE	8.69	26	2.3×10^{-1}	9×10^{-2}	1.4×10^{-1}
ET	18.94	6	4.8×10^{-2}	1.9×10^{-2}	3.1×10^{-2}
LIGO A$^{\#}$	4.13	120	1.0	0.4	0.7
LIGO O3	1	2000	17	7	11
CE+ET	18.94	6	4.8×10^{-2}	1.9×10^{-2}	3.1×10^{-2}

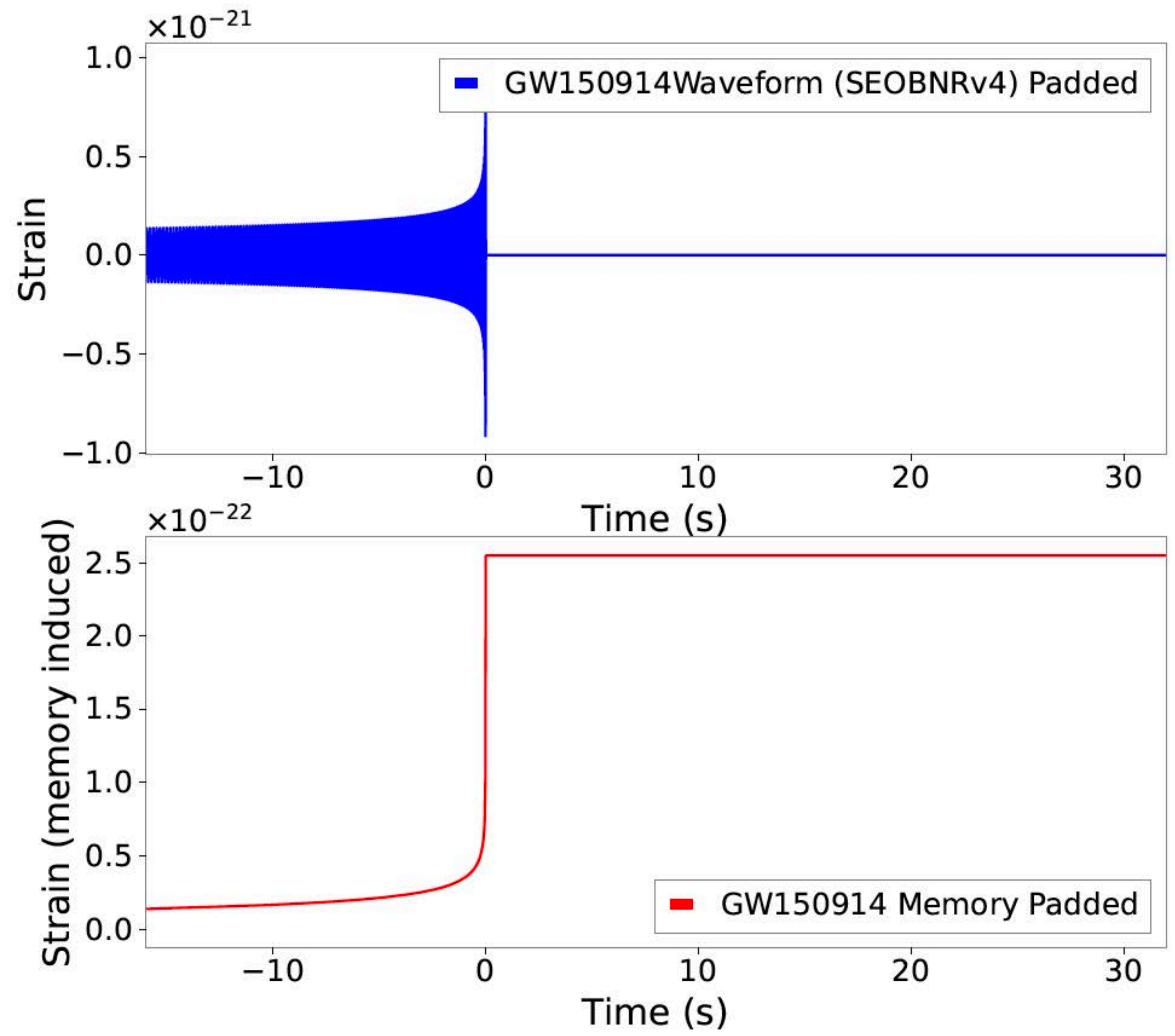
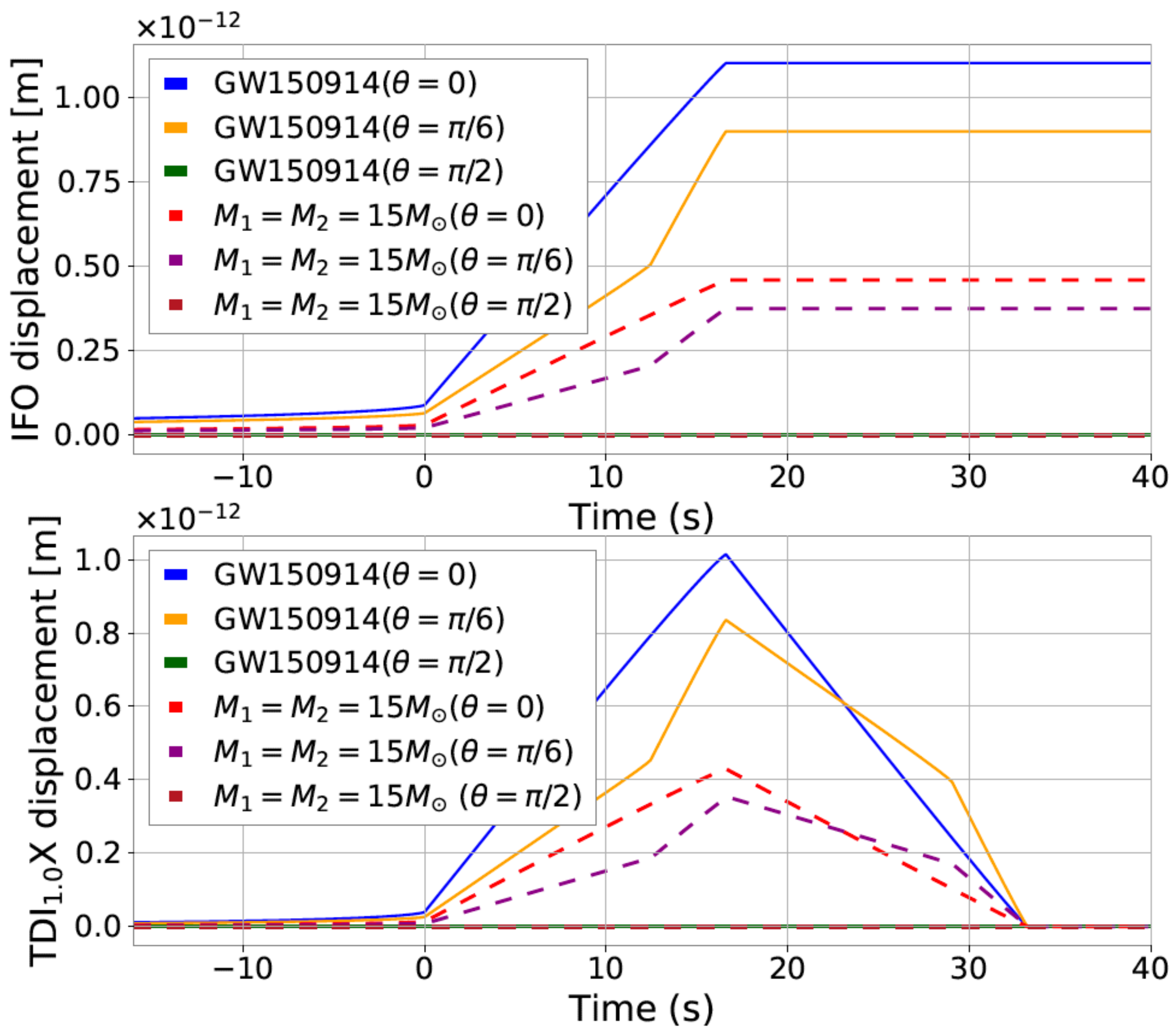


FIG. 2. Top panel: GW150914 strain waveform (SEOBNRv4 approximant), Bottom panel: The induced memory strain sourced by the gravitational wave radiation.



A different type of 'multimessenger':

- ET/CE signals trigger search for memory effect in LISA
- Step function in LISA
- … a long way to go …