Sub-femtometer precision displacement sensing using heterodyne cavity-tracking

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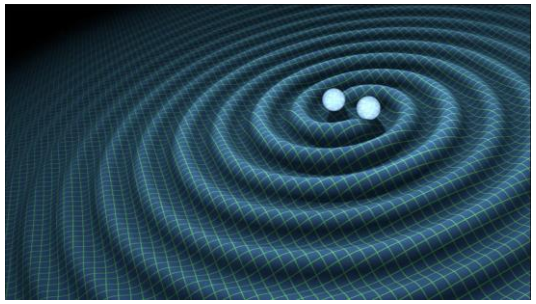

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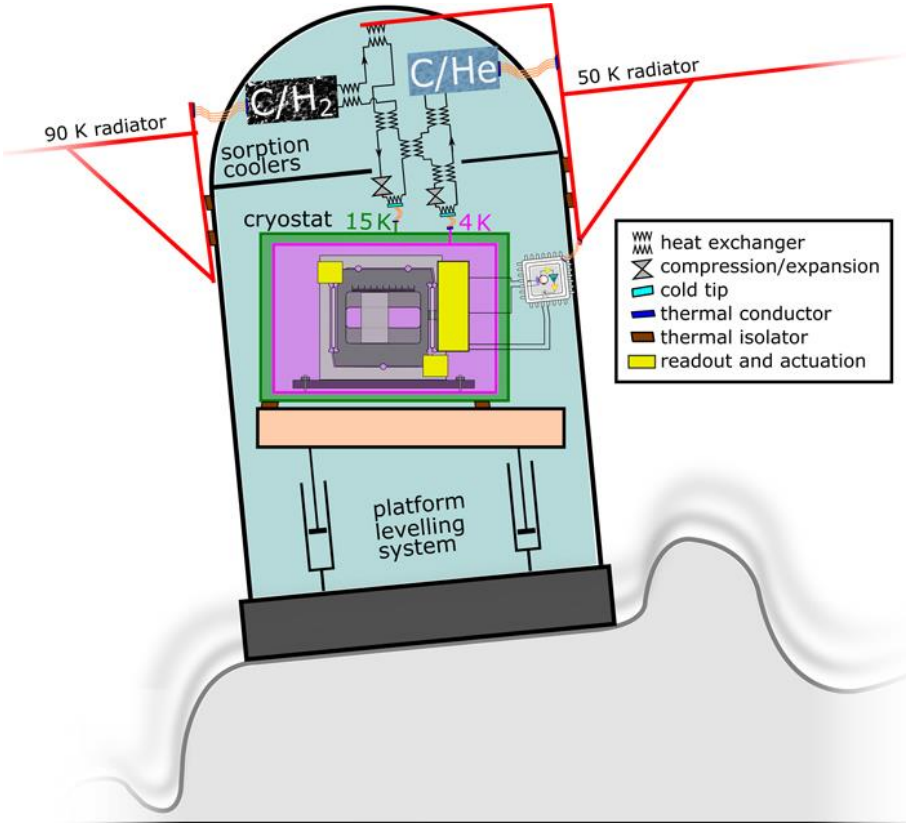
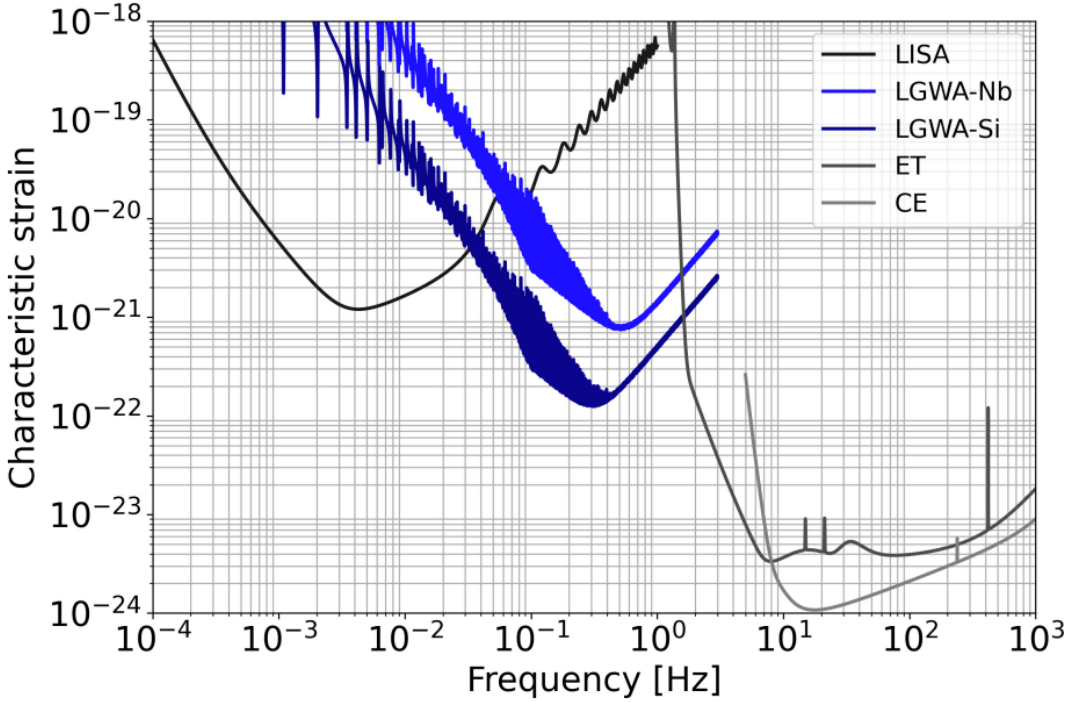
LGWA

Lunar Gravitational-wave Antenna



Source: J. van Heijningen et al., J. Appl. Phys. 133, 244501 (2023)



Source: P. Ajith et al., JCAP01 (2025) 108

- Sub-femtometer precision displacement readout is the prime requirement

LISA: Laser Interferometer Space Antenna; ET: Einstein Telescope; CE: Cosmic Explorer

Interferometry options – An overview

Types	Sub-types	Remarks
Locked IFO	Two-beam IFO (Michelson, Mach-Zehnder…)	Limited to sub-fringe, needs either closed-loop control or movable reference arm
	Optical cavity based	
High dynamic range IFO (Towards multi-fringe)	Homodyne Quadrature Interferometry (HoQI)	pm/√Hz sensitivity, suitable for 'LGWA Soundcheck'
	Deep Frequency Modulation Interferometry (DFMI), Resonantly enhanced DFMI	Reaching fm/√Hz readout noise floor, limited by the fact that power is being measured
	Heterodyne cavity-tracking	Potential candidate for LGWA

A slide from 2 years before…
(11 Oct 2023, LGWA meeting @ Catania)

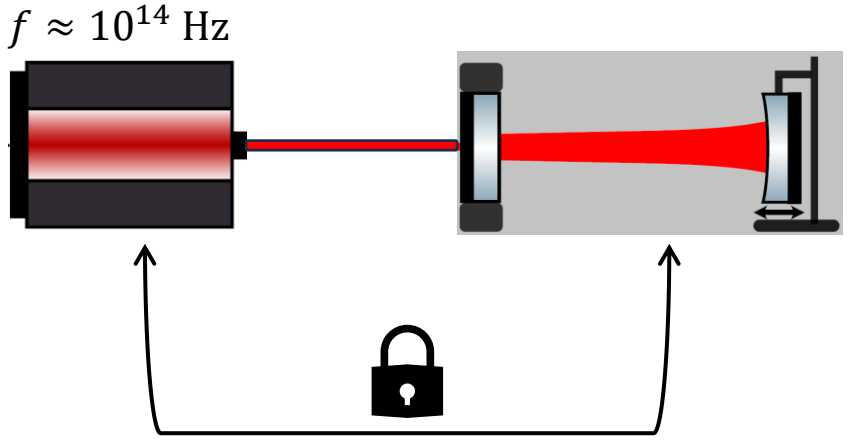
This talk!

What's our sensing concept?

- Construct an optical cavity consisting of the "proof mass"
- Make frequency of a laser follow the resonance of that cavity
- Relative length fluctuation of the cavity ⇒ relative frequency fluctuation of the laser
- Heterodyne readout: compare the laser frequency with a reference
- One-way motion of the proof mass:

$$\Delta L = \frac{\Delta f}{f} \cdot L$$

Heterodyne cavity-tracking



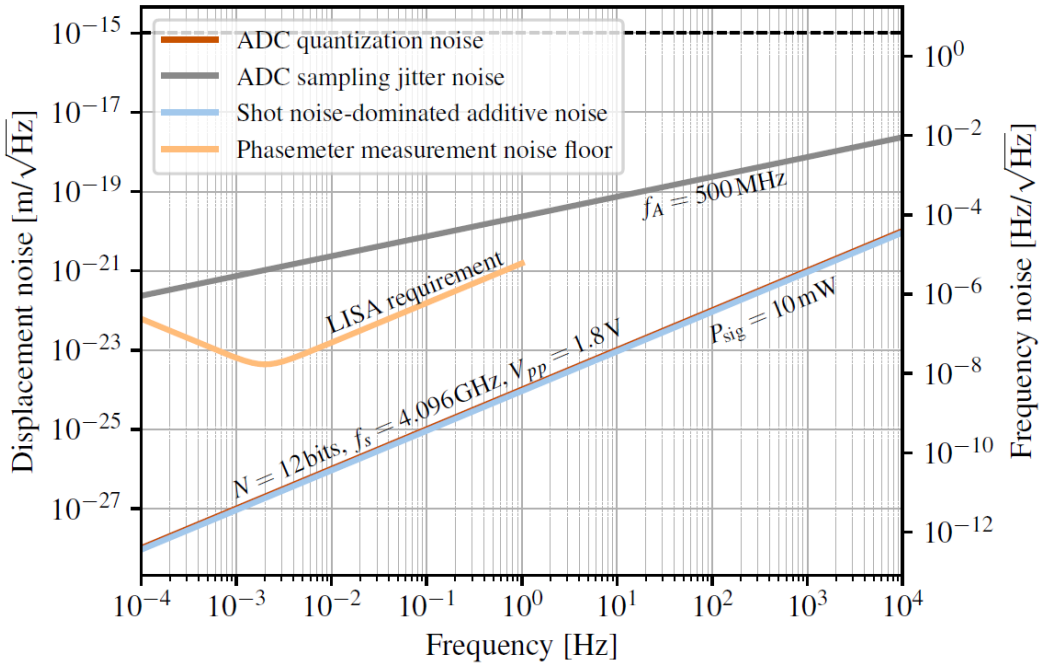
Δf: heterodyne beat note; f: absolute laser frequency; L: physical length of the cavity

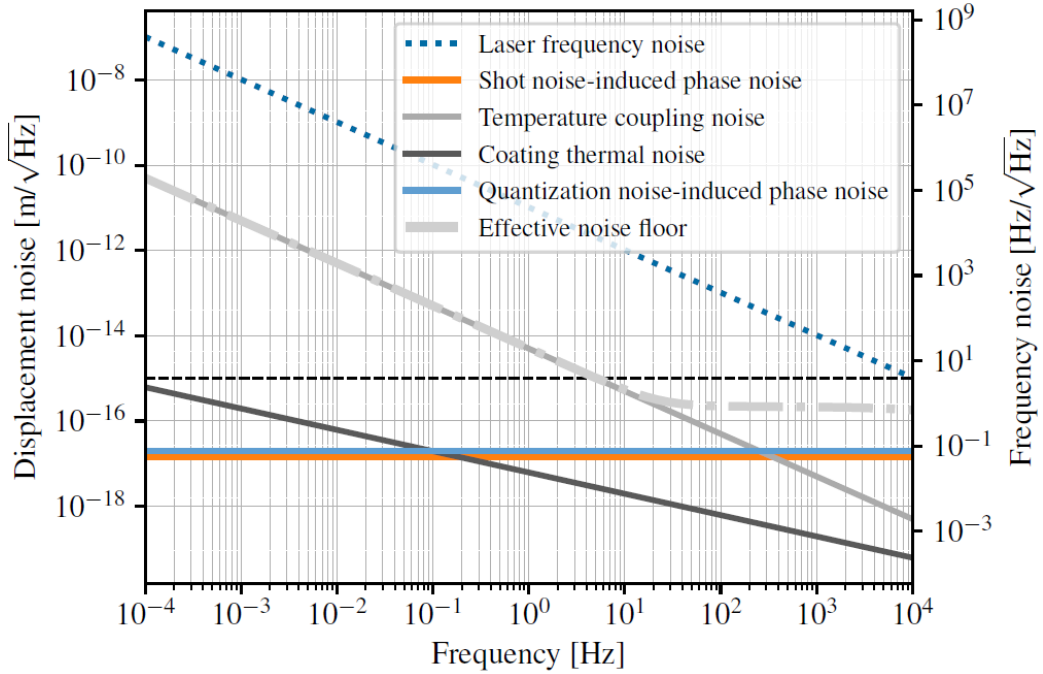
What precision is achievable?

Two points where noise can couple to the system:

- While measuring the beat frequency
- While locking the laser to the dynamic cavity

Heterodyne cavity-tracking represents the most precise readout that can be realized with laser interferometry for local displacement sensing

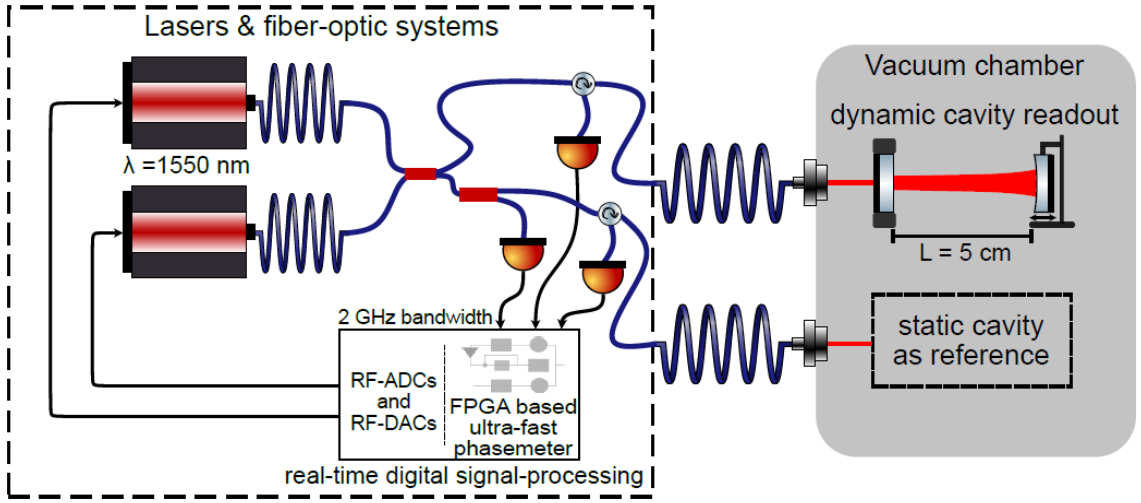




Ref.: SCS, *PhD thesis* (2025)

Experimental setup

Heterodyne cavity-tracking



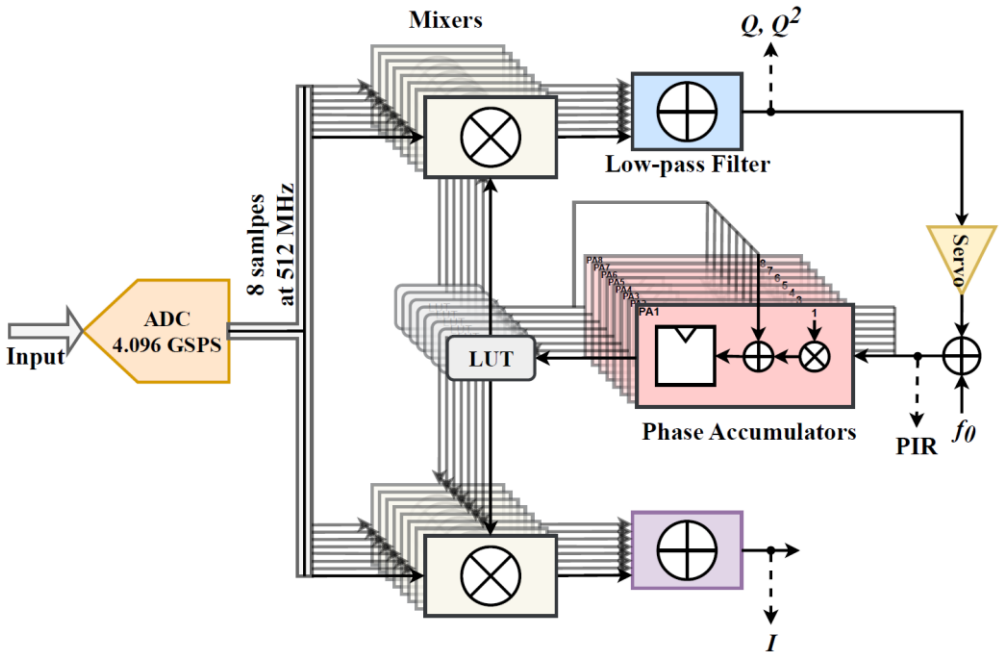
- Proof mass motion is encoded in the heterodyne beat frequency, Δf
- Max. operating range is decided by the detection bandwidth (BW):

$$\Delta L_{\max} = \frac{\lambda}{2} \cdot \frac{\mathrm{BW}}{\mathrm{FSR}} = L \cdot \frac{\mathrm{BW}}{f}$$

  with FSR: free-spectral range of the cavity, $\frac{c}{2L}$
- Example: $1\ \mu\mathrm{m}$ movement of the proof mass will shift the beat note by $\sim 3.87\ \mathrm{GHz}$!

GHz Phasemeter

Realized using Zynq UltraScale+ RFSoC



- Integrated circuit that combines RF signal processing with DSP on a single chip
- RF-ADC sampling at 4.096 GHz

- Multi-demodulation and phase accumulation stages
- Signal bandwidth of 2.048 GHz
- DSP speed of 512 MHz
- Highest stable tracking bandwidth of 2 MHz

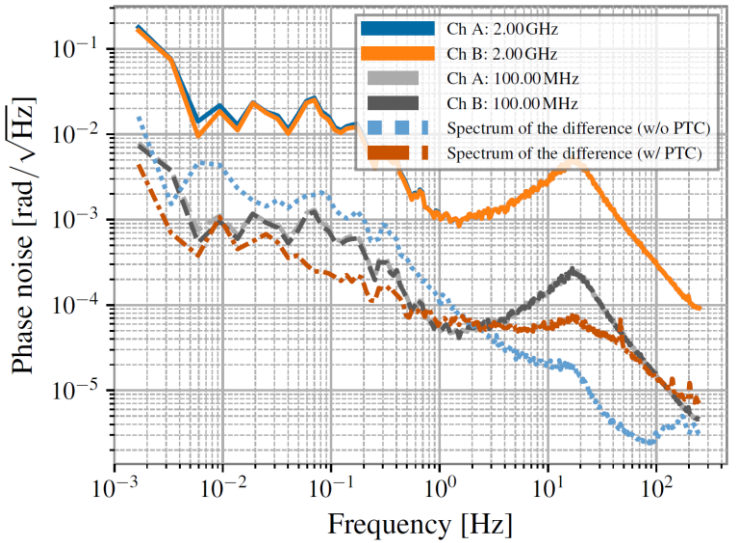
RFSoC: radio-frequency system-on-chip; DSP: digital signal processing

PIR: phase increment register; LUT: look-up table

SCS et al., IEEE Trans. Instrum. Meas. 74, 2001108 (2025)

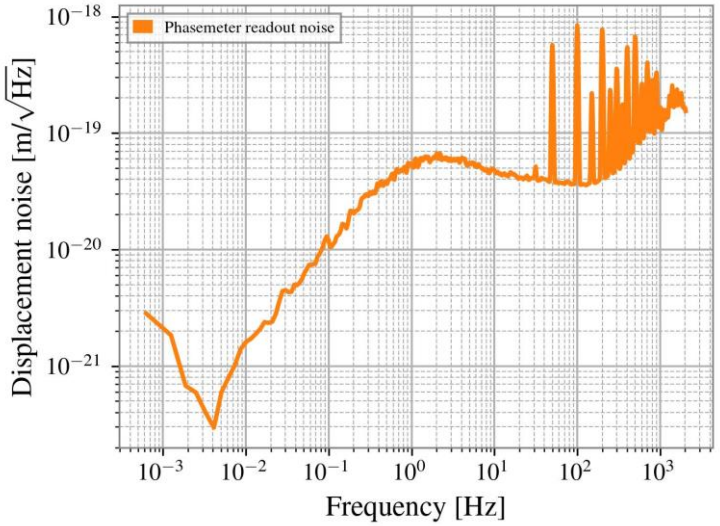
GHz Phasemeter

The highest bandwidth, highly stable, and fastest frequency-tracking instrument



Key features:

- Input signal bandwidth of 2.048 GHz
- 8 phasemeter channels (each with two GHz PLLs)
- PLL tracking bandwidth of 2 MHz
- Acquisition range of 4.1 MHz
- Tracking speed of above 240 GHz/s



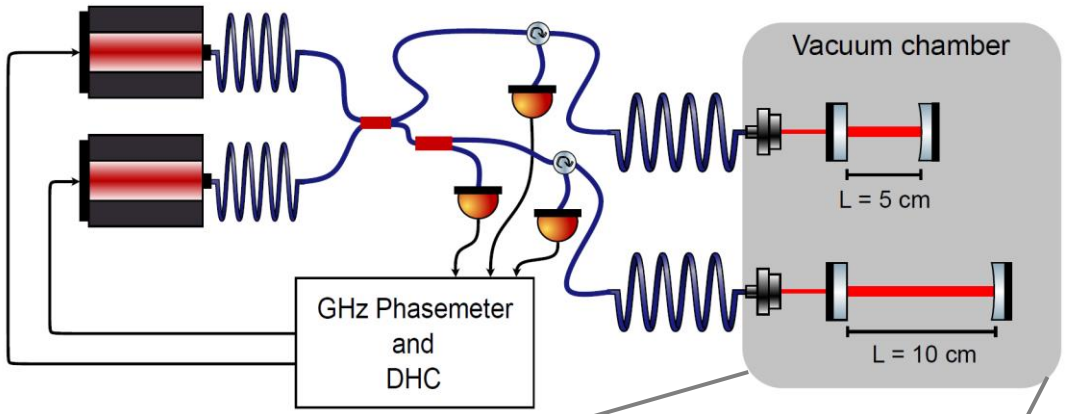
PLL: phase-locked loop; PTC: pilot tone correction

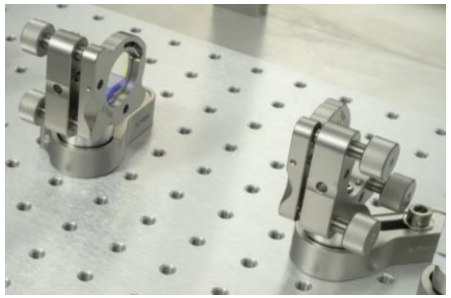
SCS et al., IEEE Trans. Instrum. Meas. 74, 2001108 (2025)

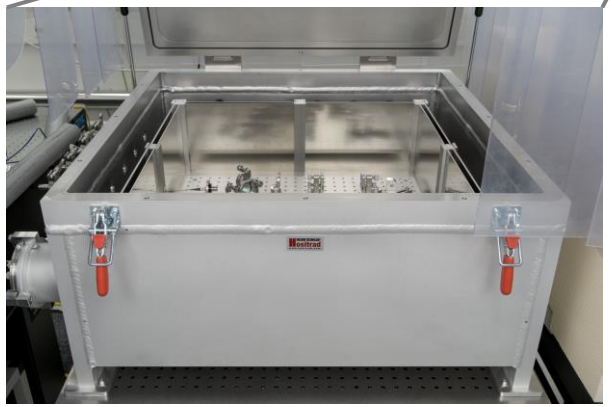
Displacement sensitivity

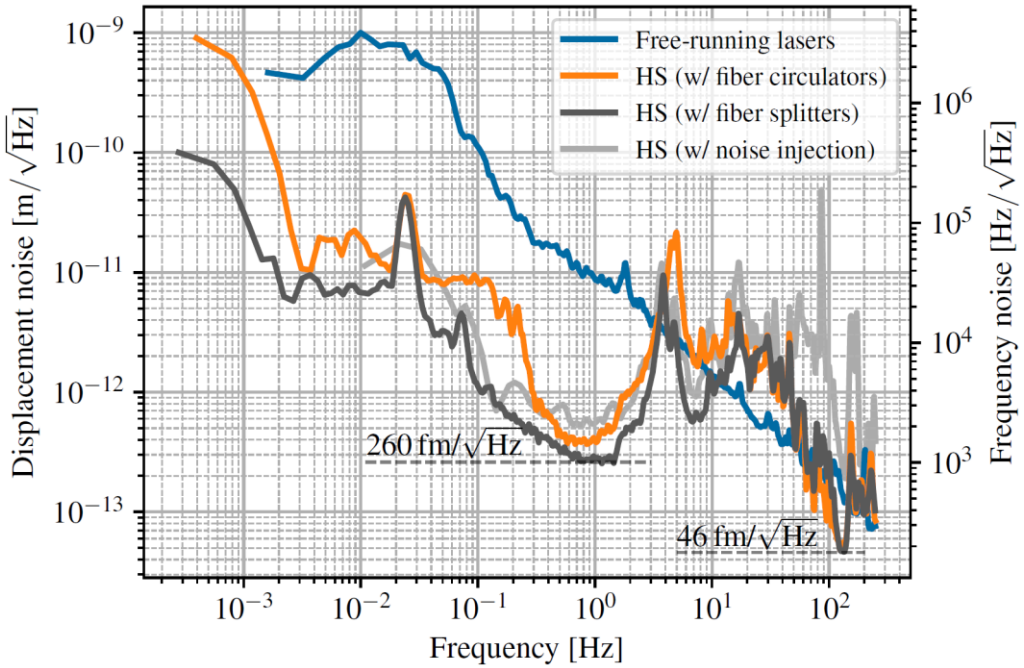
Mirror mount-based cavities in vacuum & heterodyne stabilization

SCS et al., Opt. Exp. 33, 4044-4054 (2025)







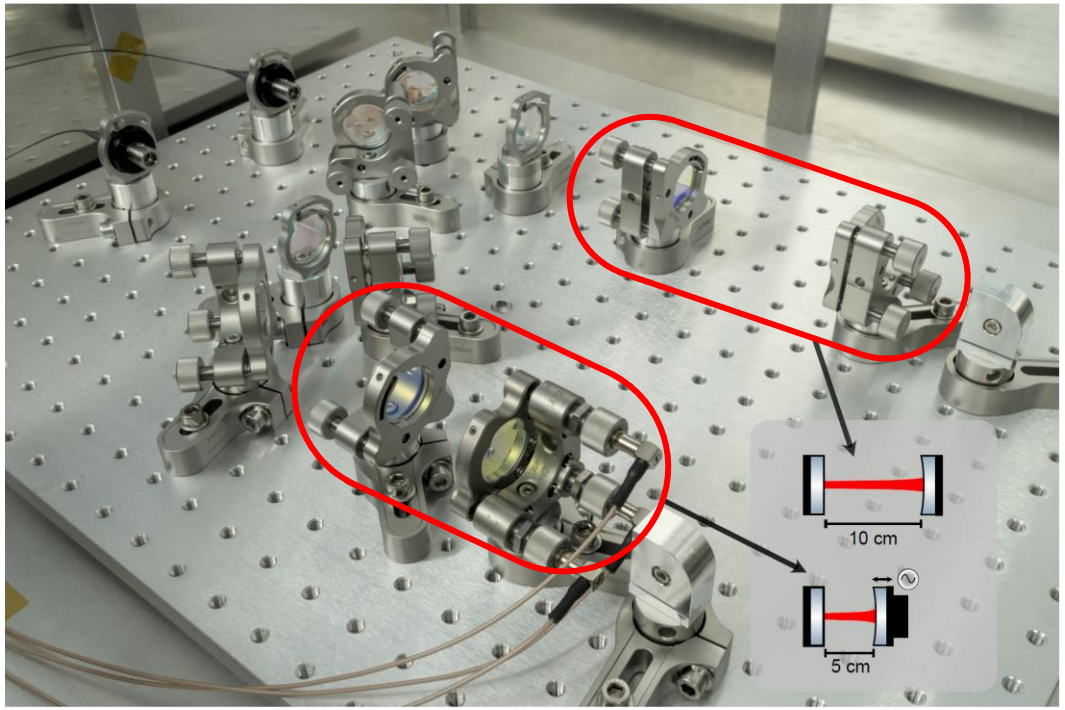


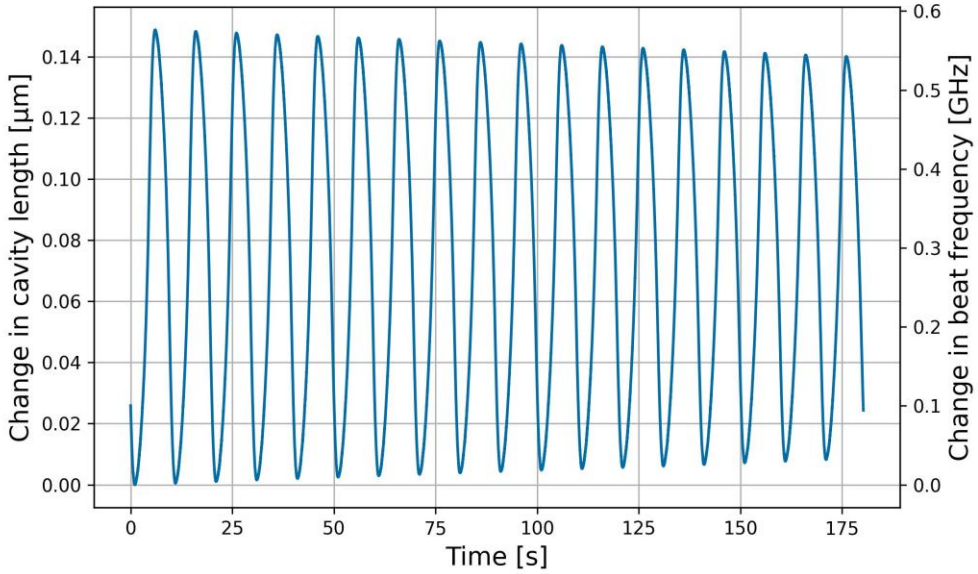
Limitations:

- Mechanical instability of the cavities
- Parasitic beams due to fiber-based setup

DHC: Digital Heterodyne Controller; HS: heterodyne stabilization

Operating range

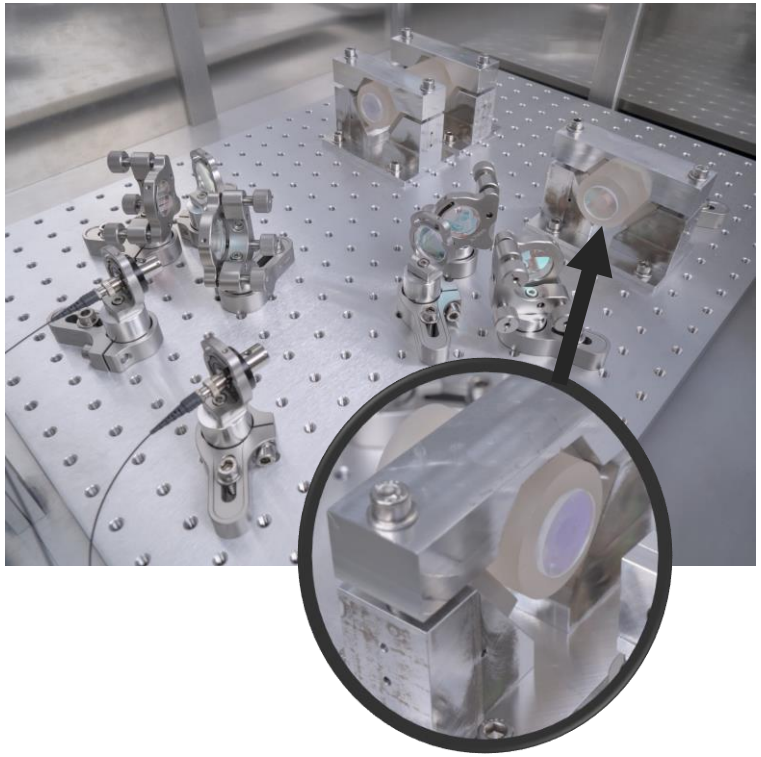


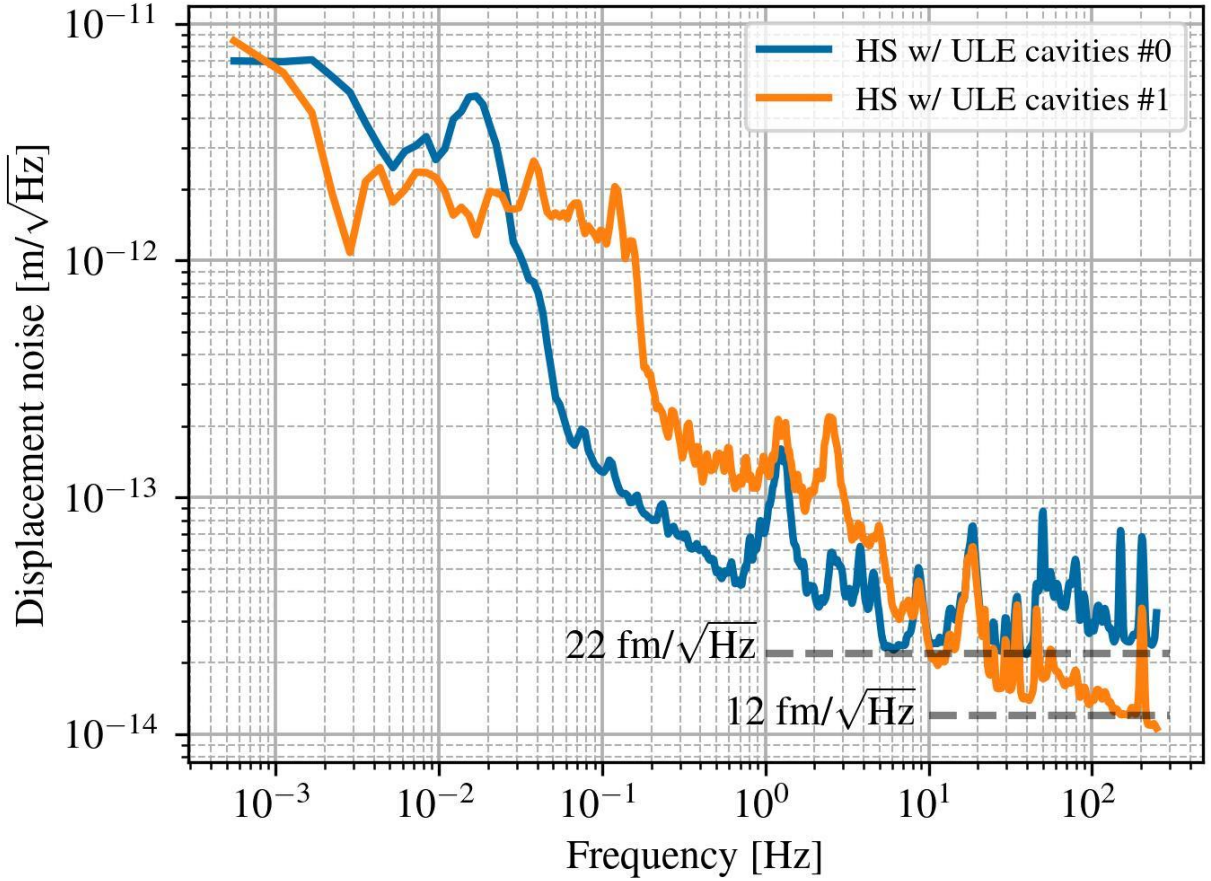


SCS et al., Opt. Exp. 33, 4044-4054 (2025)

Displacement sensitivity

ULE glass-based cavities in vacuum & heterodyne stabilization

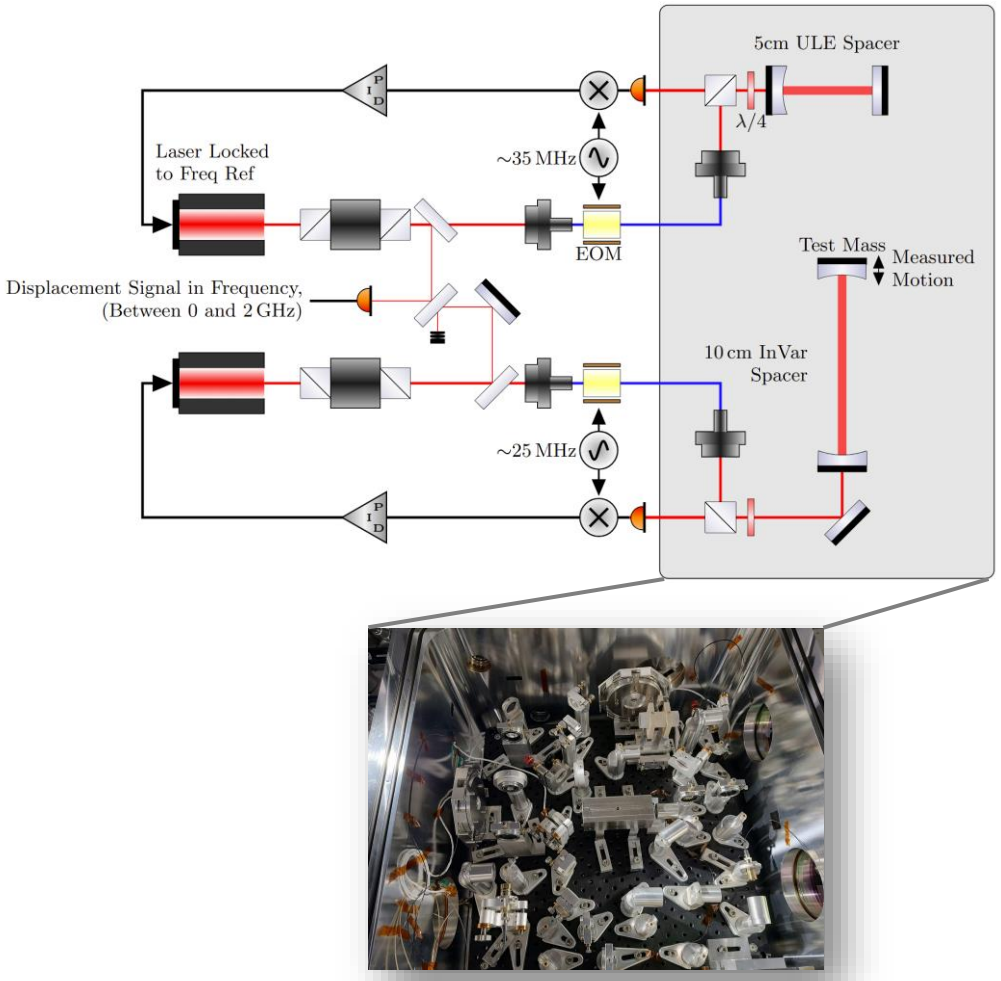


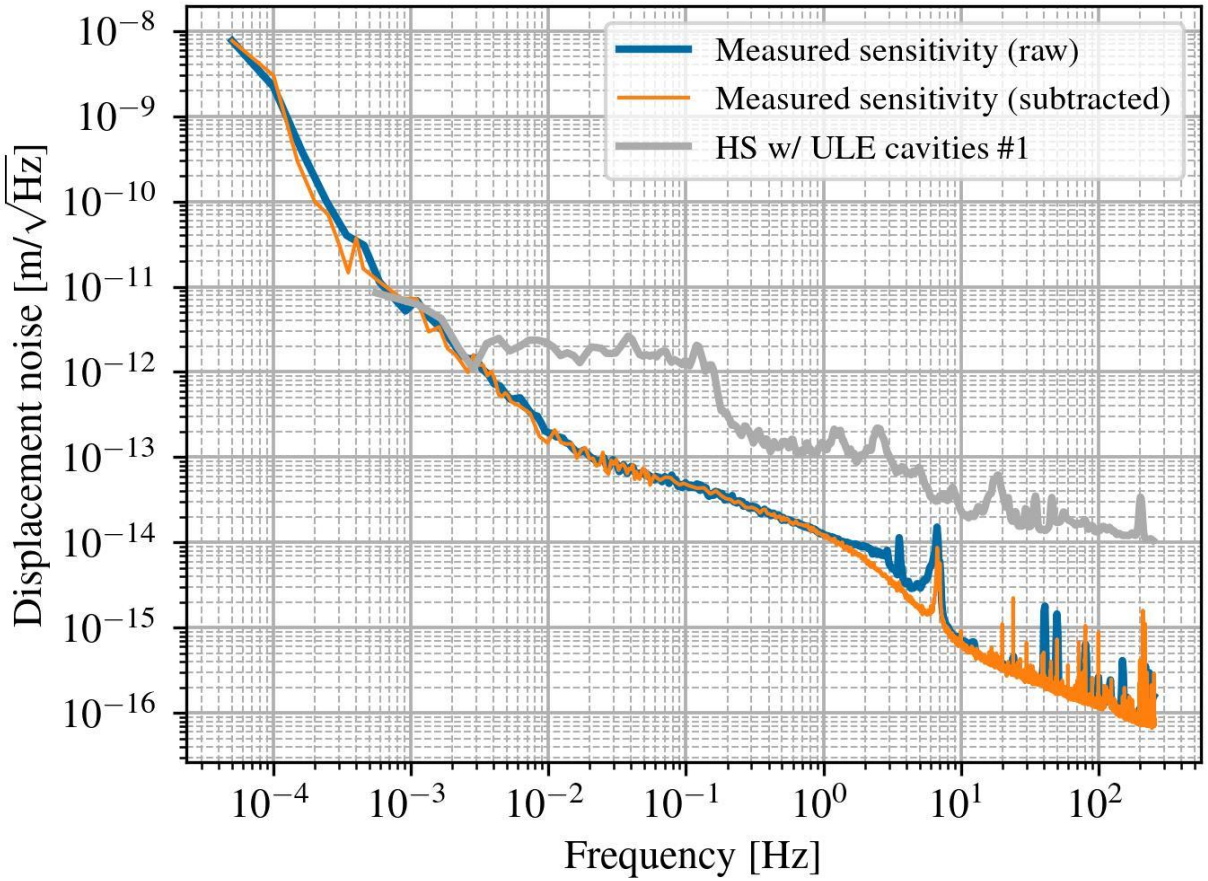


ULE: Ultra-Low Expansion; HS: heterodyne stabilization

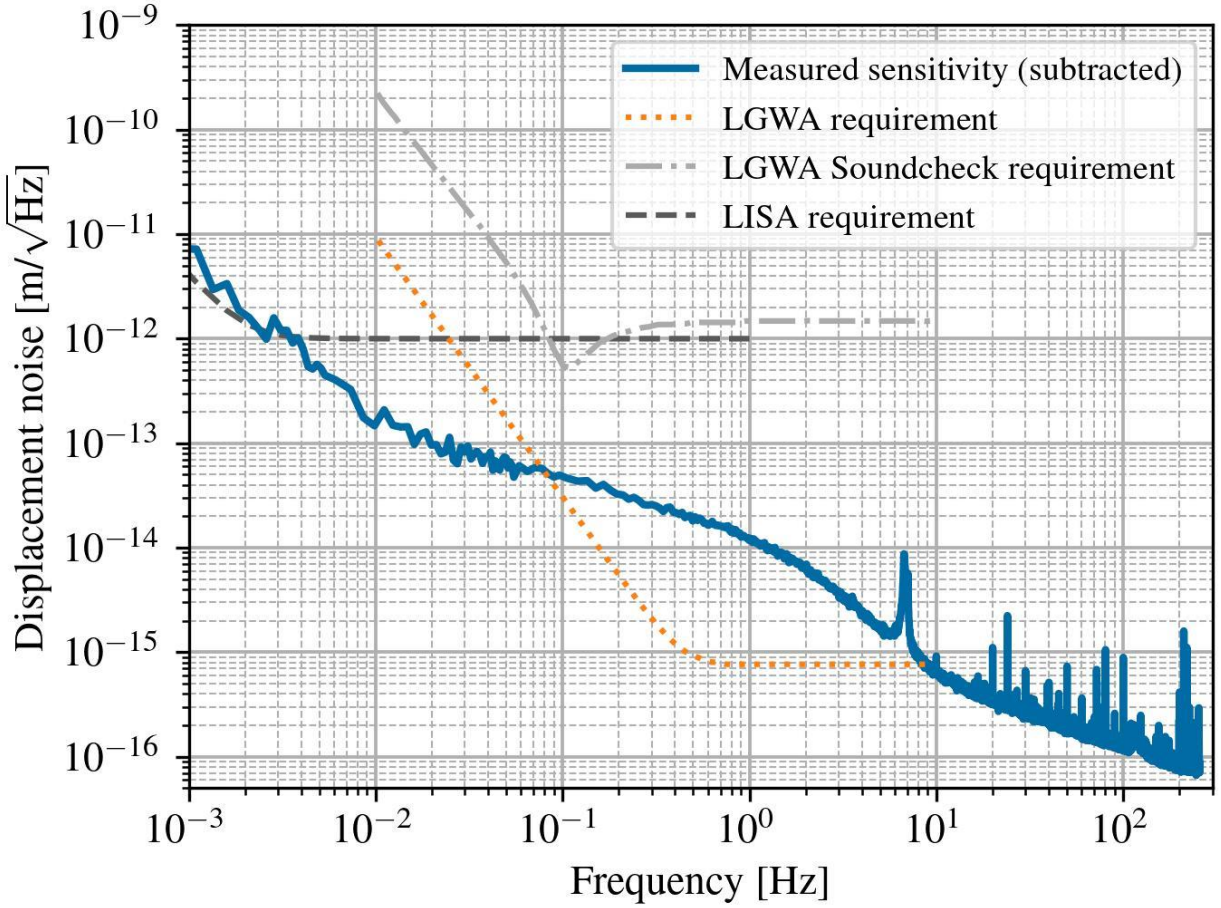
Displacement sensitivity

Free-beam setup with Pound-Drever-Hall locking





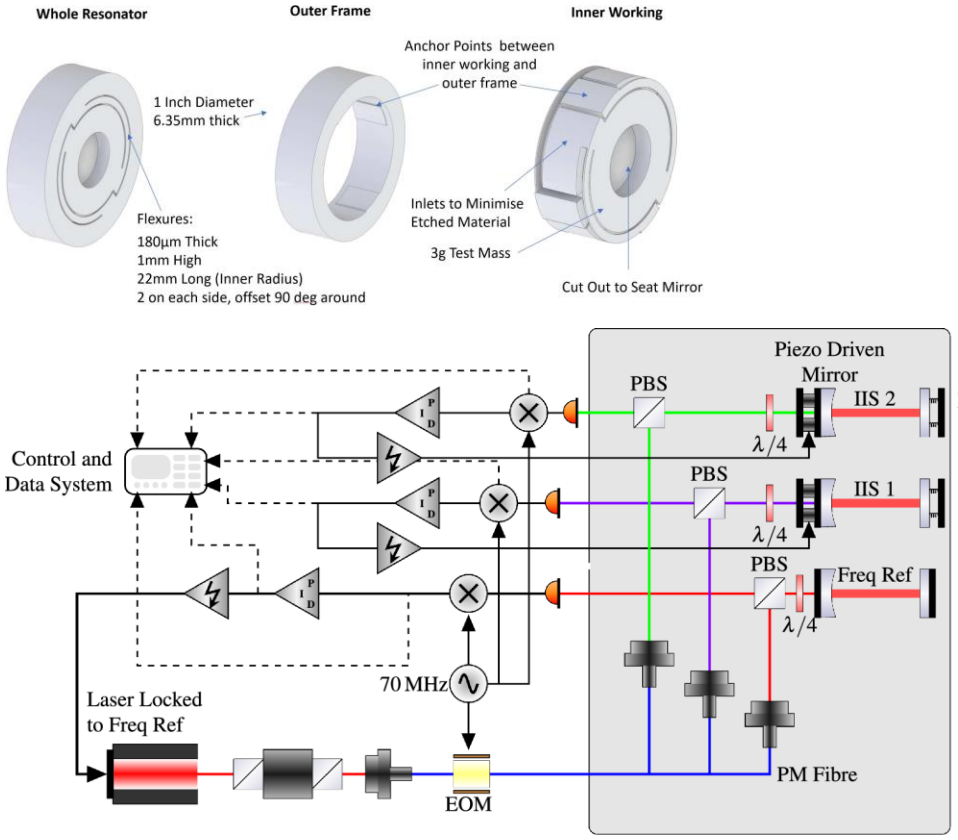
What does this mean for LGWA?



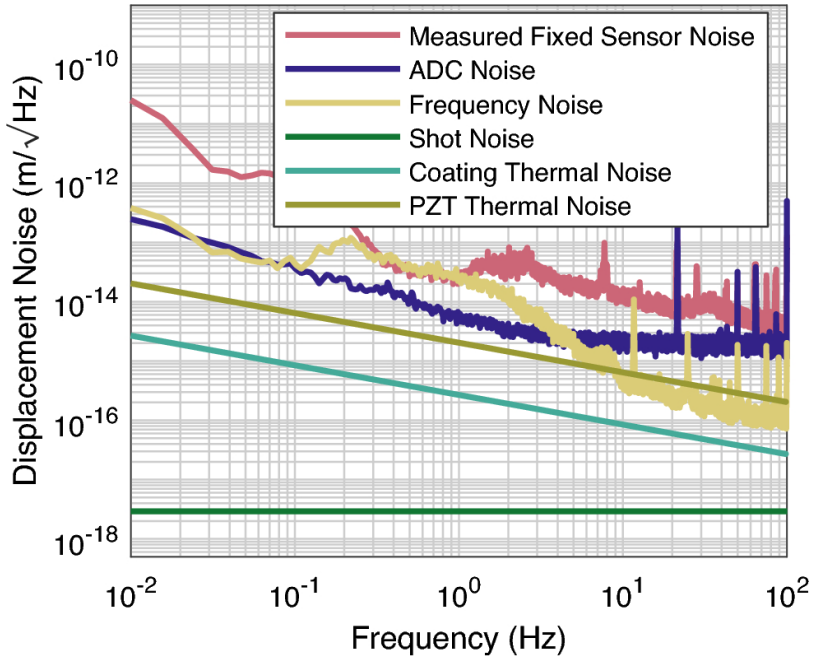
- We are well below the requirement for LGWA Soundcheck
- LGWA requirement curves are taken from Andric et al. (arXiv:2509.04730)
- Better thermal isolation and further suppression of scattered light might uncover sub-femtometer noise floor in the deci-Hz region as well

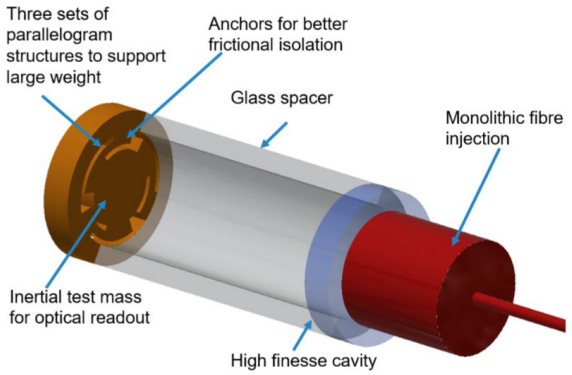
What's next?

Compact inertial sensor development

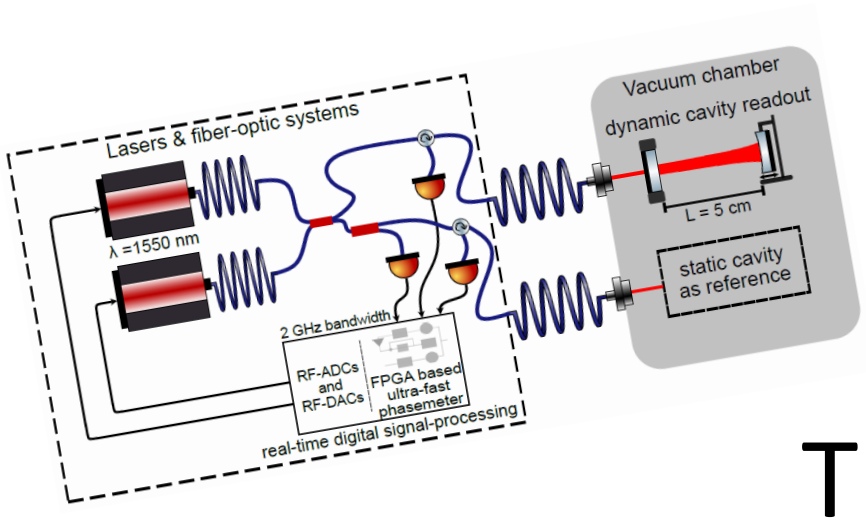


Source: Carter et al., Sci. Rep. 14, 17775 (2024)



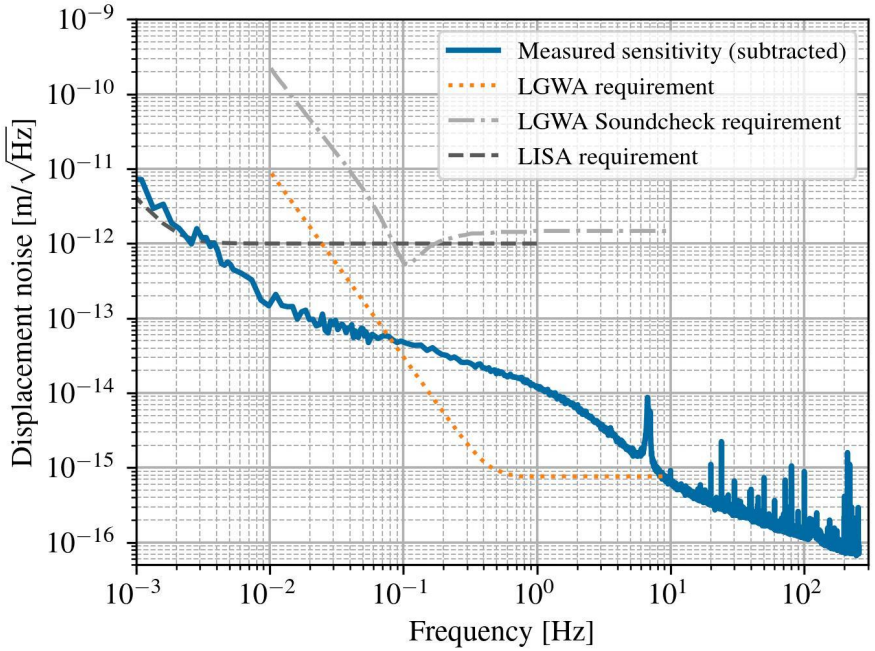


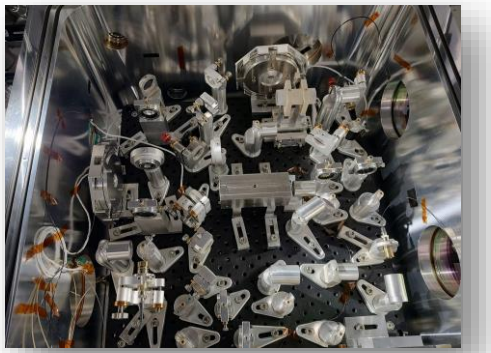
Source: Carter et al., IEEE INERTIAL (2020)



That's it!

Questions? Comments?

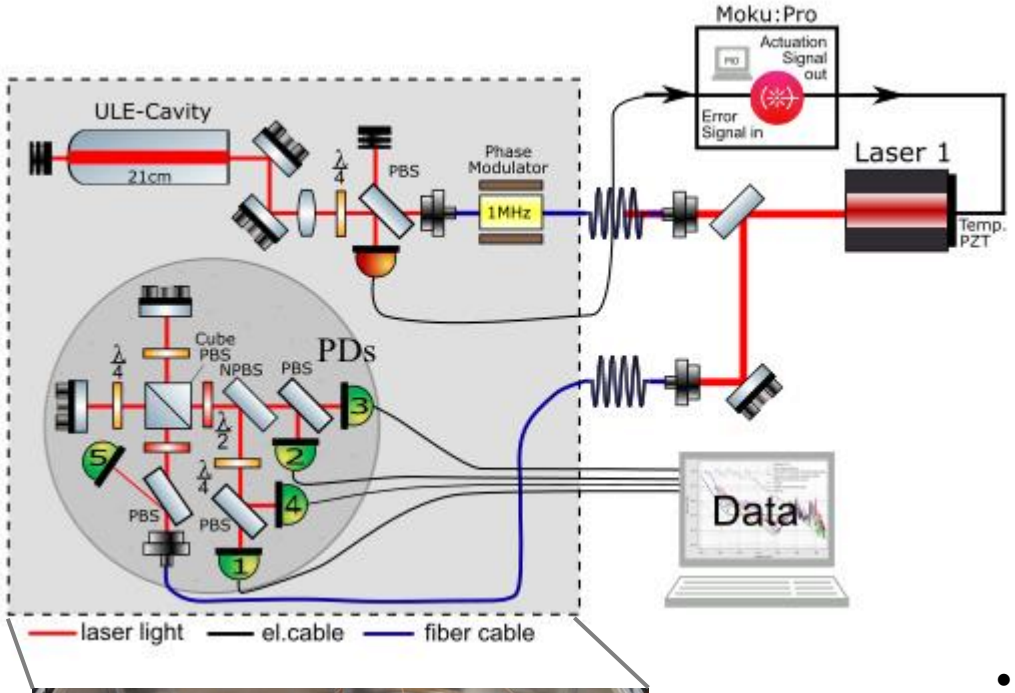


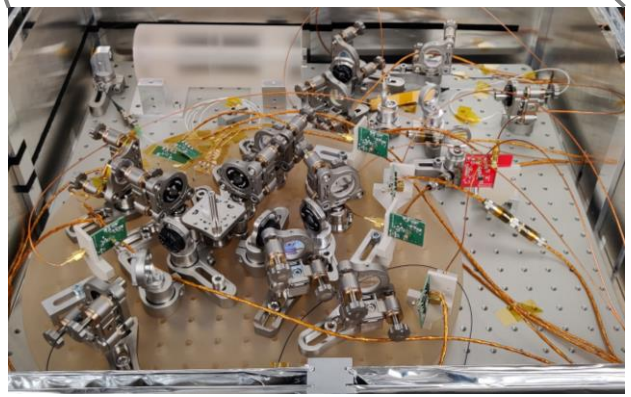


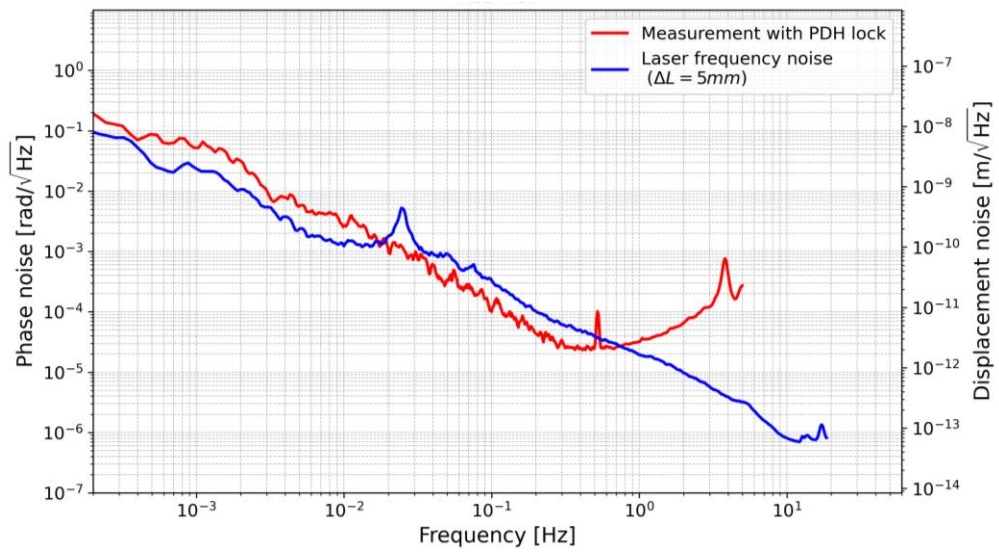
Additional slide

Low-frequency HoQI

Credits: Julian Priedemann and Marcel Beck







- Experimental setup is constructed using a toolset for adjustable picometer-stable interferometers
- More details about the toolset: M. Beck et al., Class. Quantum Grav. 42, 135001 (2025)
- Laser frequency noise suppression, intensity noise suppression in post-processing, Heydemann correction, …