Measurement of gravitationally induced phase shift on entangled photons

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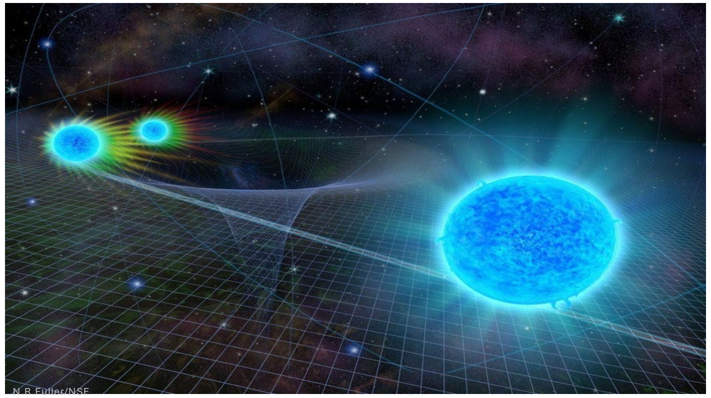
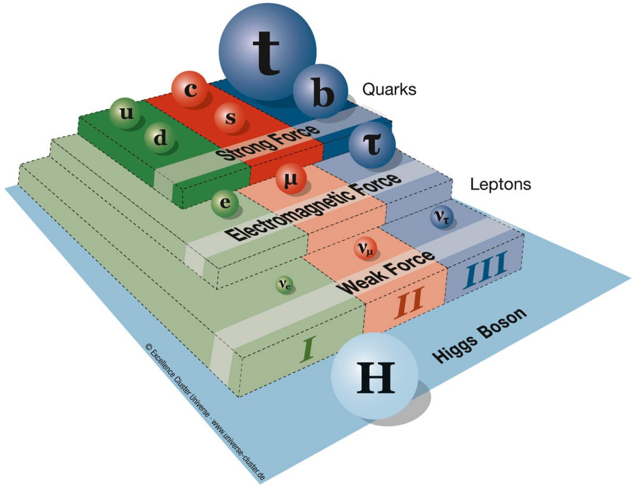
Introduction

LAWS OF OUR UNIVERSE

Macroscopic Scale: General Relativity



Microscopic Scale: Quantum Field Theory

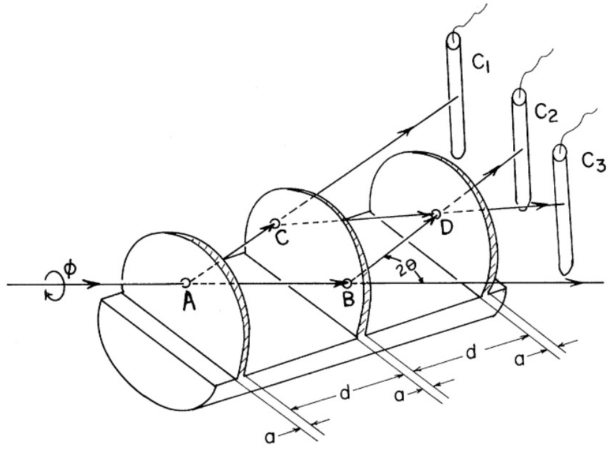


OPEN CHALLENGE – a clear signature of <u>gravitational time dilation</u> in a system where the full formalism of GR and quantum mechanics must be applied simultaneously to explain the outcome

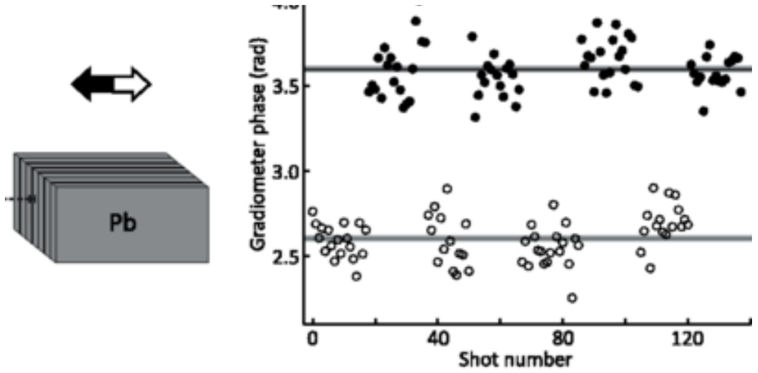
Introduction

A quantum system whose wavefunction is spread across two different gravitational potentials, either through superposition or path entanglement, is an ideal platform for observing this effect.

- Interferometry using neutrons (1975): measurement of the gravitational phase-shift on **massive neutrons**



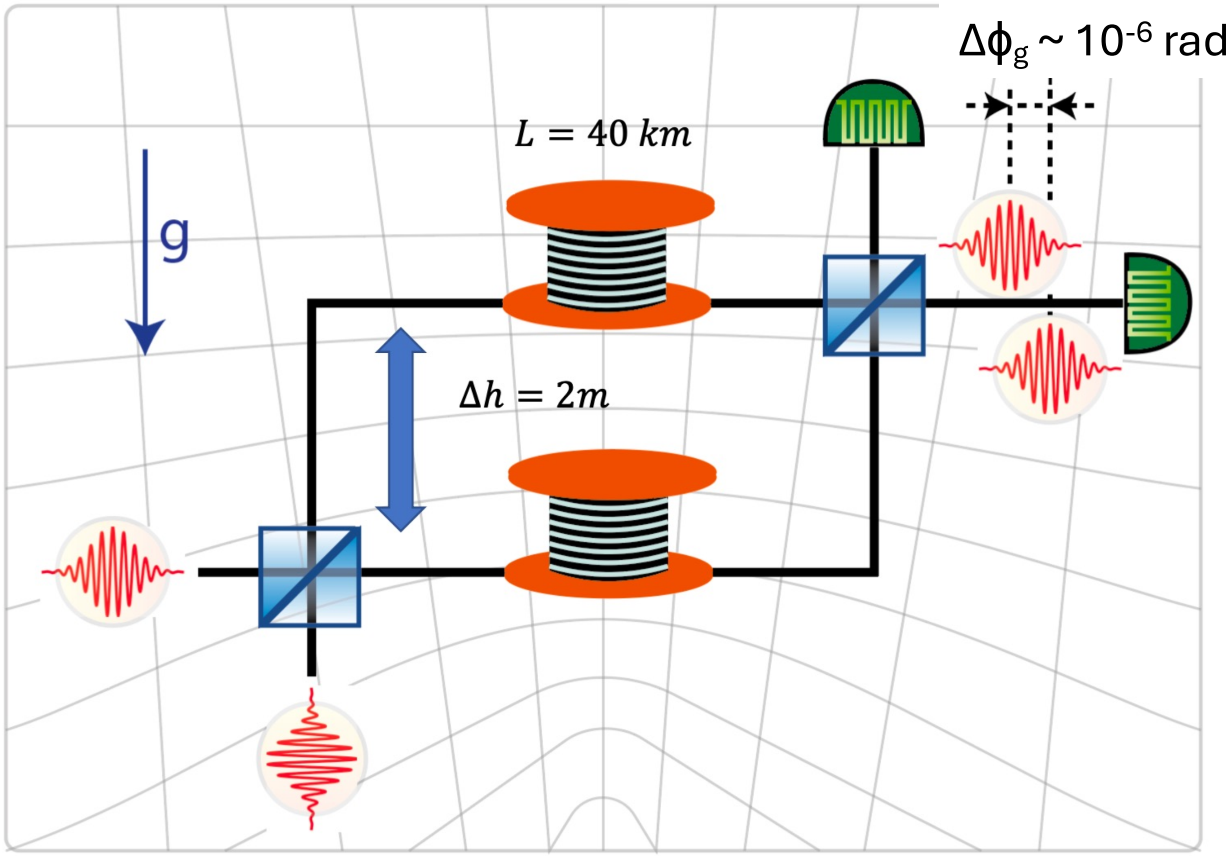
- Interferometry using atoms (2017): measurement of the gravitational phase-shift on **massive atom fountains**



Experiments using <u>massive particles</u> can be understood in terms of Newtonian gravity !

Experimental Overview

Goal: to measure the effect of gravity on entangled quantum states of light



$\Delta\phi_g \sim 10^{-6}$ rad → $\Delta\phi_g = \frac{2\pi lghn}{\lambda c^2}$

Experimental Overview

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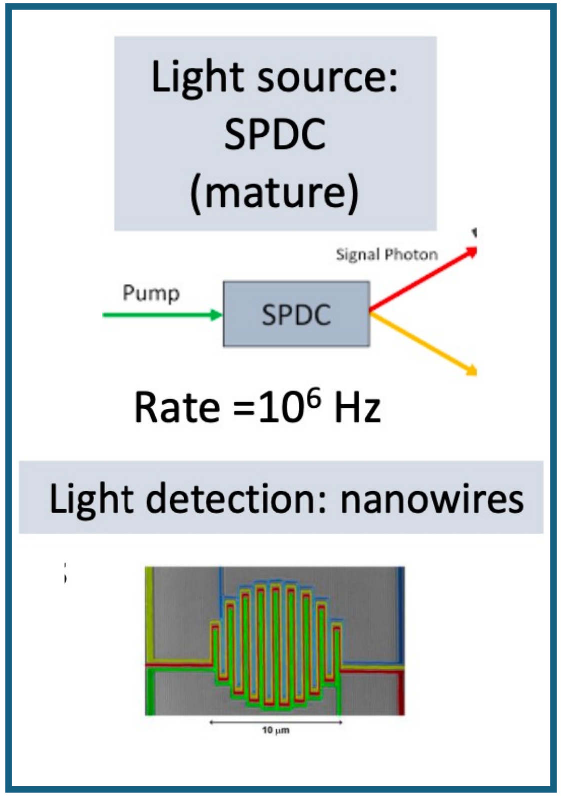
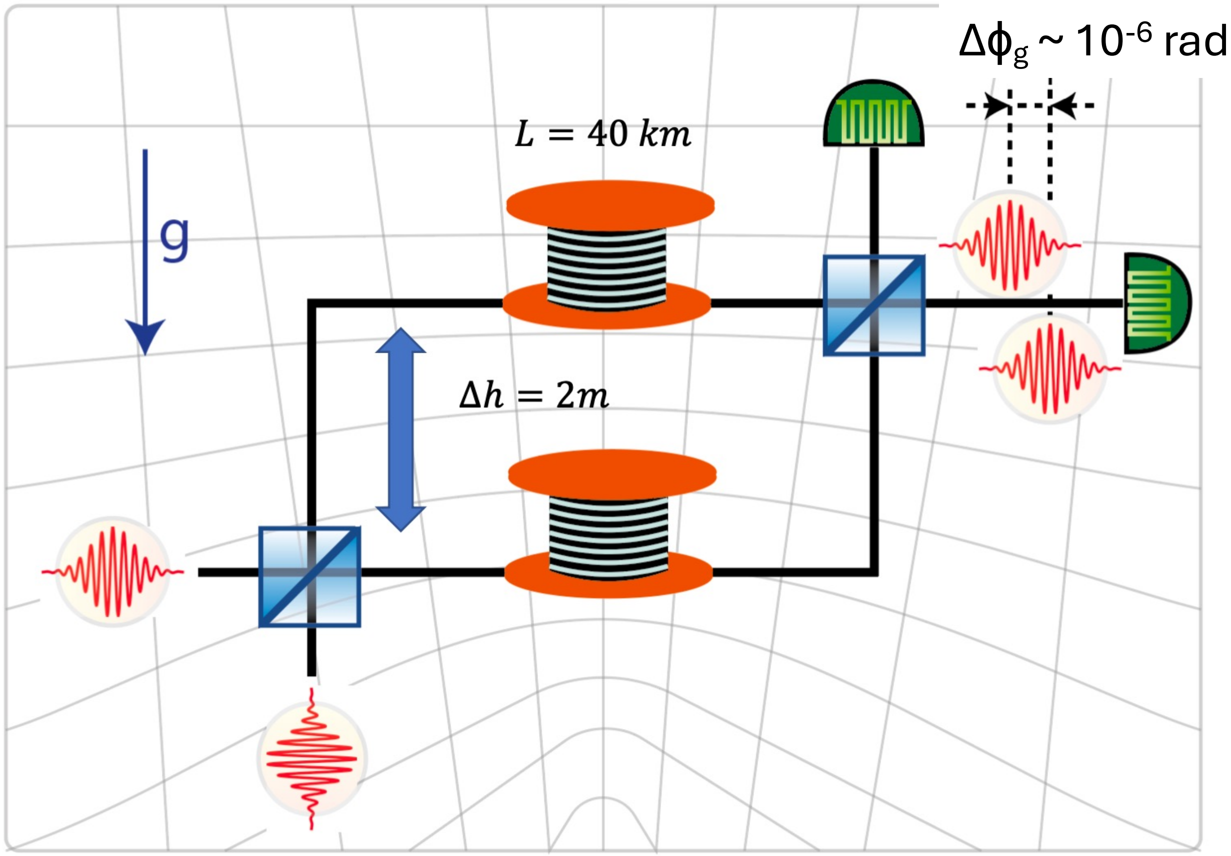


From Philip Walther's group in Vienna

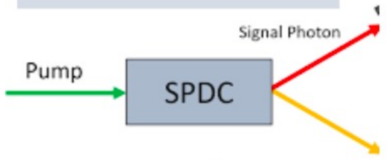


$\Delta\phi_g \sim 10^{-6}$ rad → $\Delta\phi_g = \frac{2\pi l g h n}{\lambda c^2}$

Experimental Overview

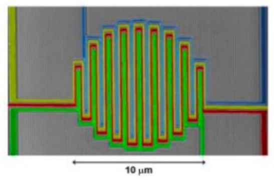
Goal: to measure the effect of gravity on entangled quantum states of light

Light source: SPDC (mature)

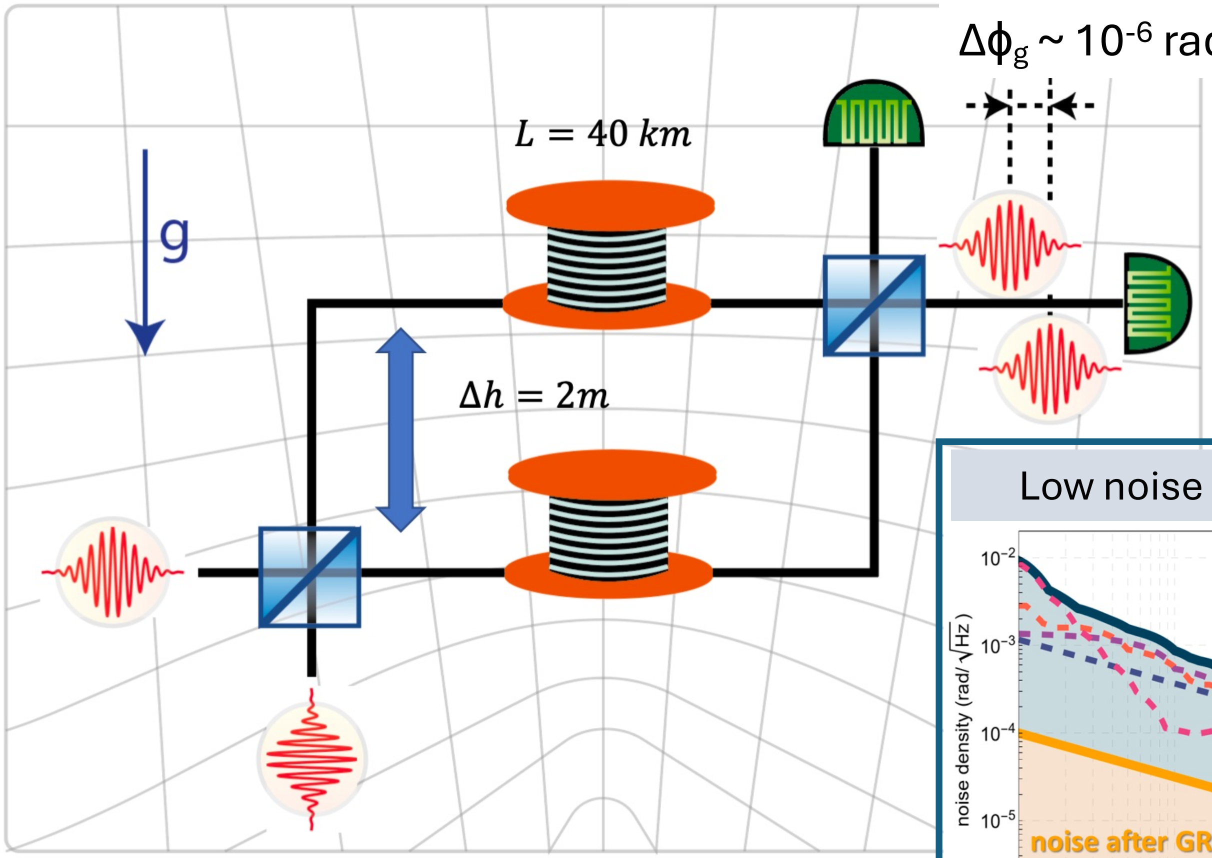


Rate $=10^6$ Hz

Light detection: nanowires



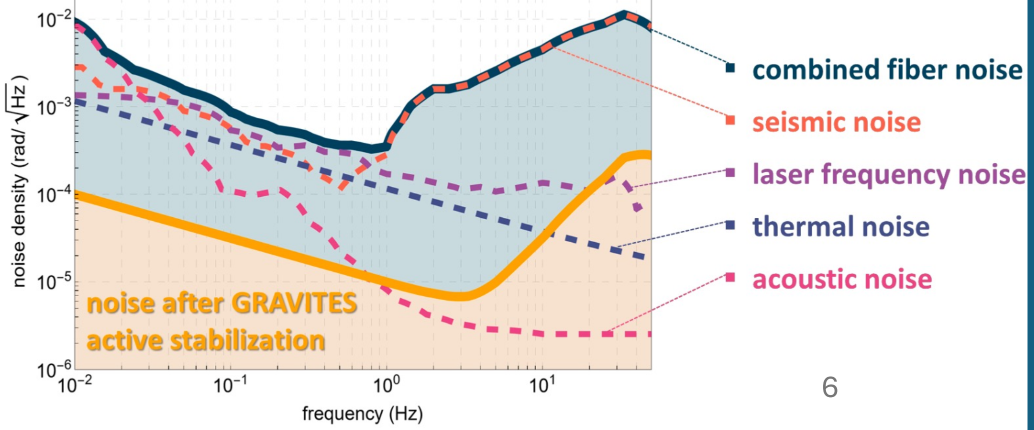
From Philip Walther's group in Vienna



$\Delta\phi_g \sim 10^{-6}$ rad → $\Delta\phi_g = \frac{2\pi l g h n}{\lambda c^2}$

From our group at MIT

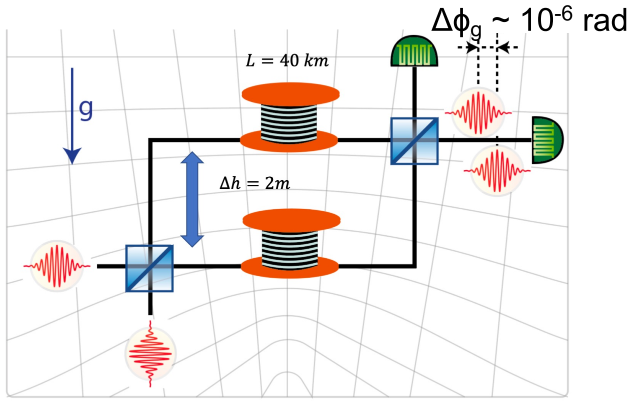
Low noise fiber interferometer



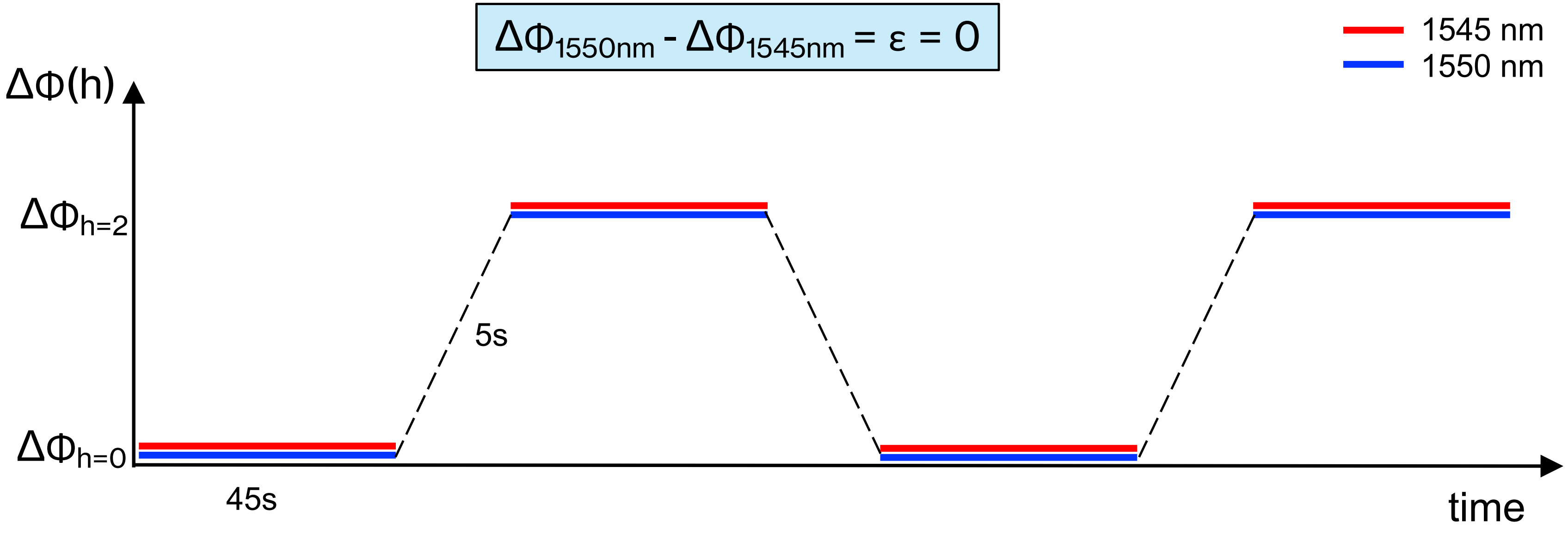
Experimental Goal at MIT

- <u>Differential measurement</u> at two wavelengths with moving stage
  - ➢ Control wavelength 1545nm
  - ➢ Main field wavelength 1550nm

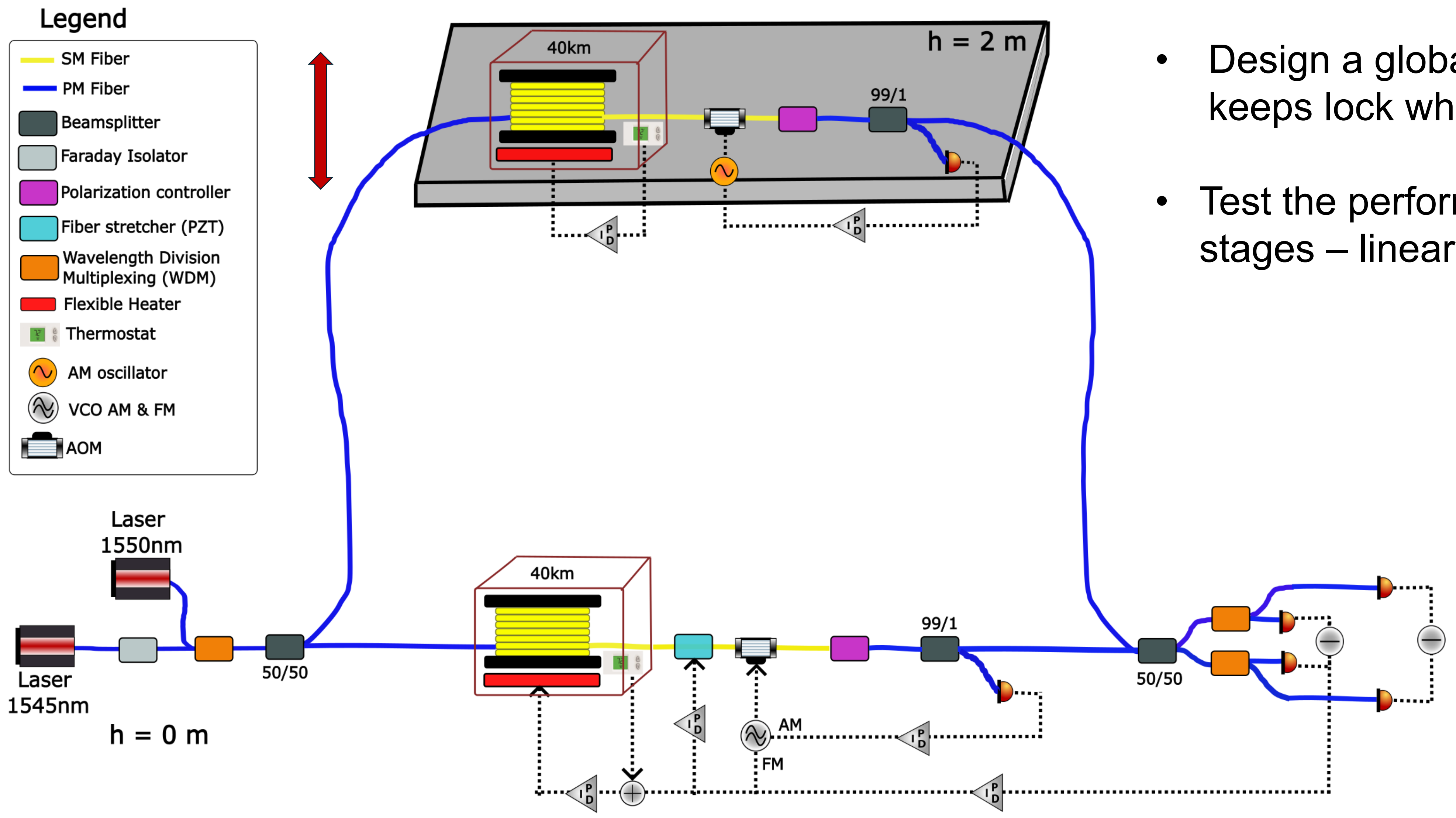
- We expect to measure a differential phase shift of zero



$$\Delta\Phi_{1550nm} - \Delta\Phi_{1545nm} = \varepsilon = 0$$

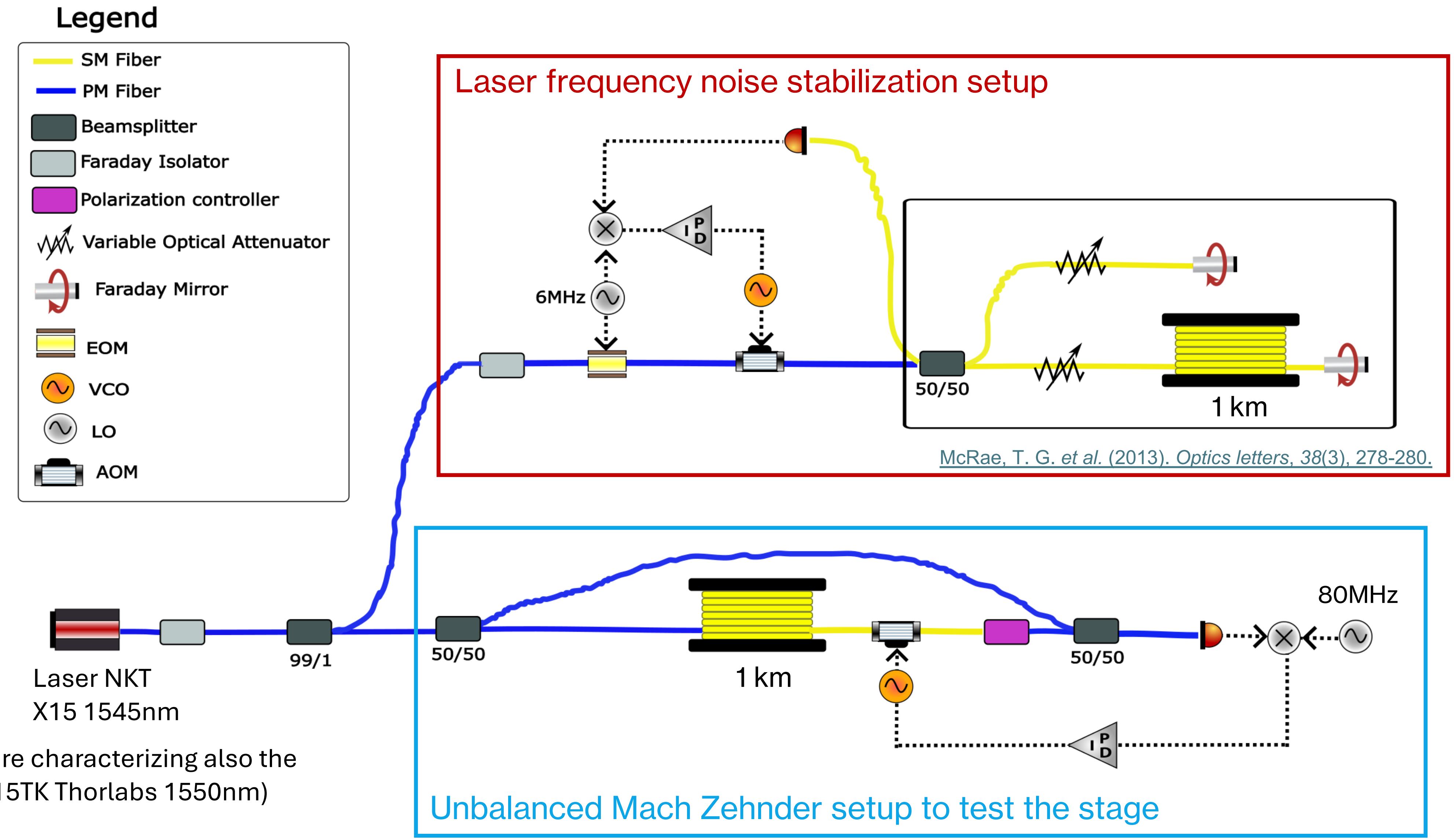


Experimental Goal at MIT



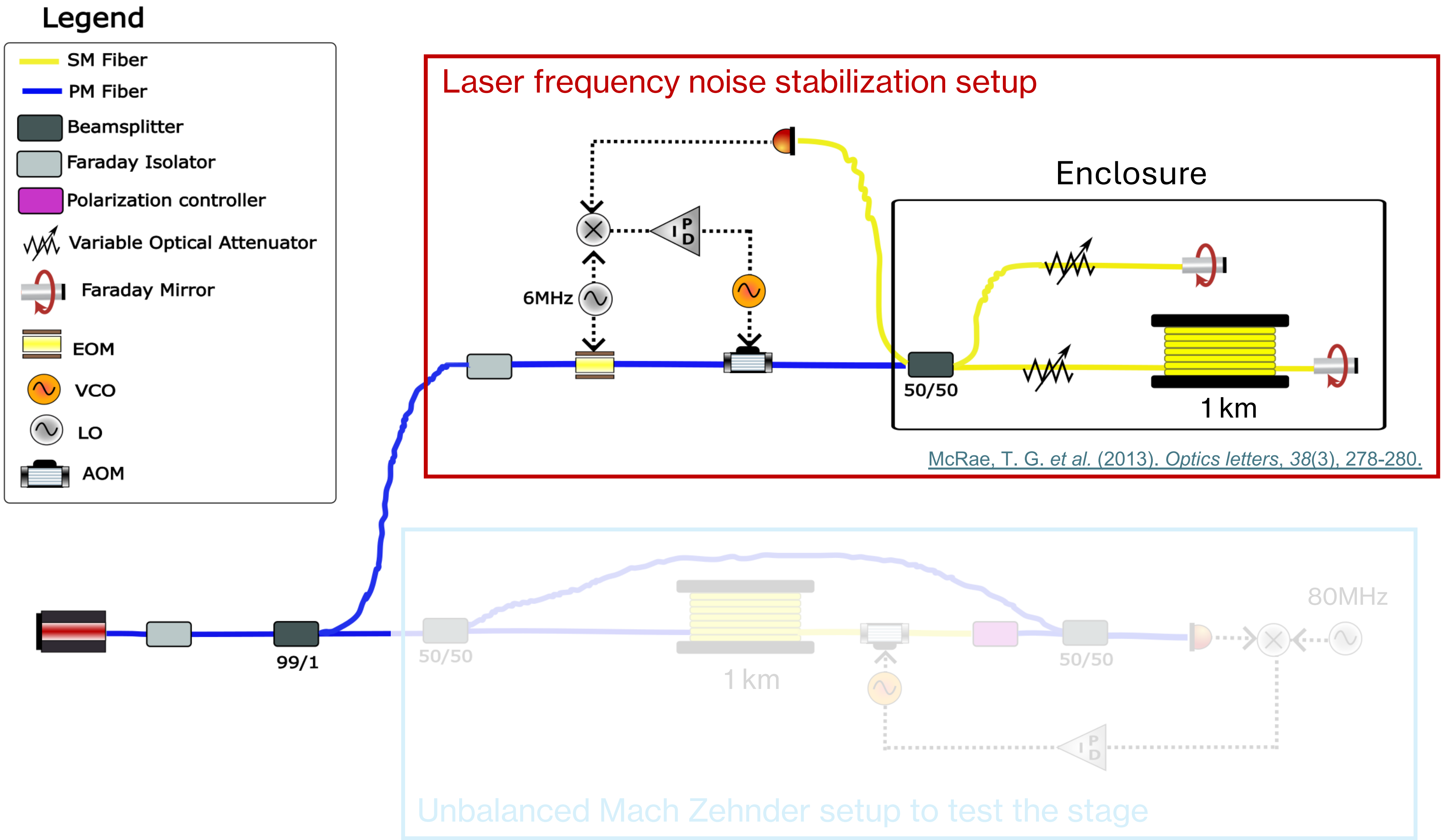
- Design a global control scheme that keeps lock while moving the stage
- Test the performances of different stages – linear and/or rotatory

Experimental Setup at MIT

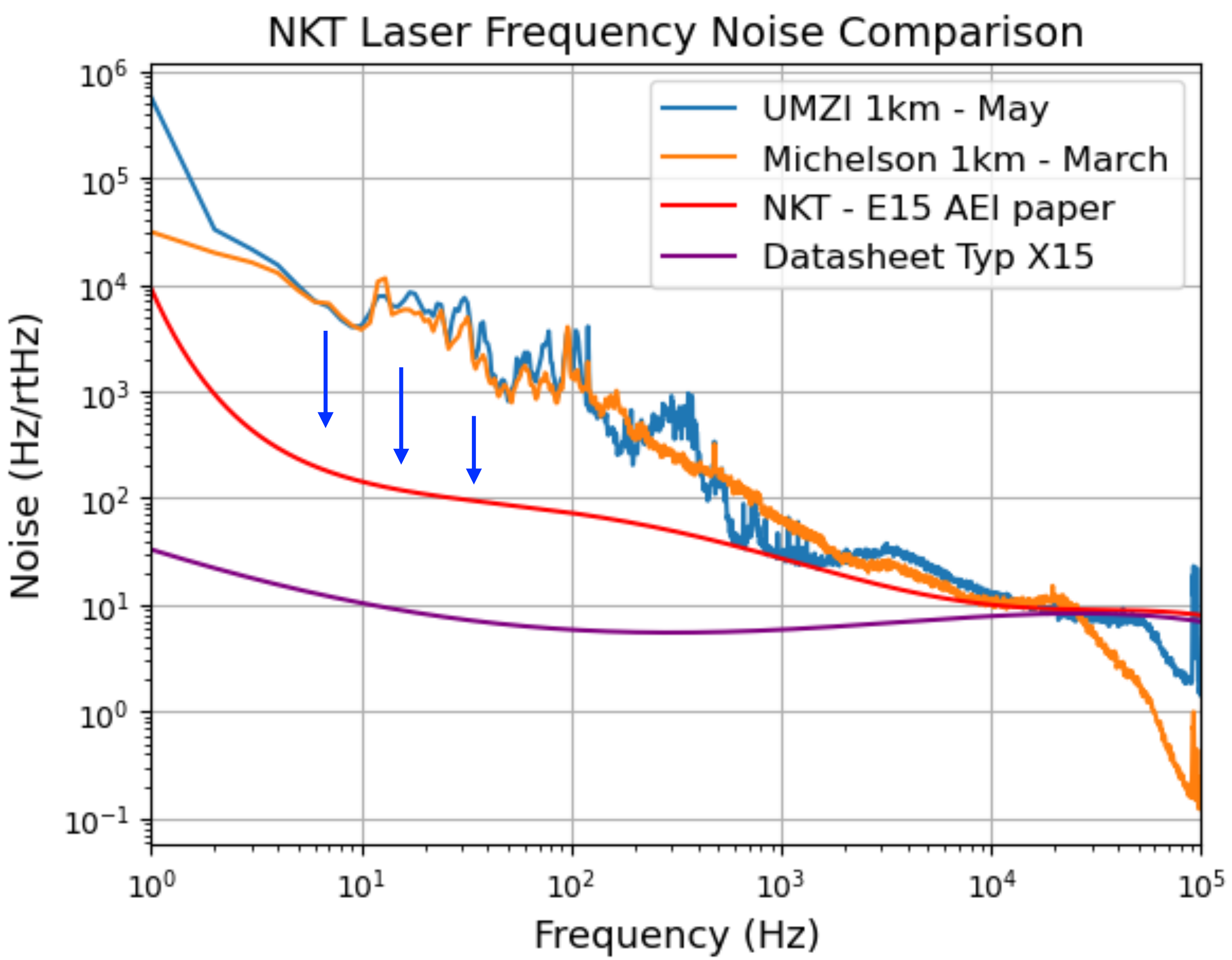


(we are characterizing also the ULN15TK Thorlabs 1550nm)

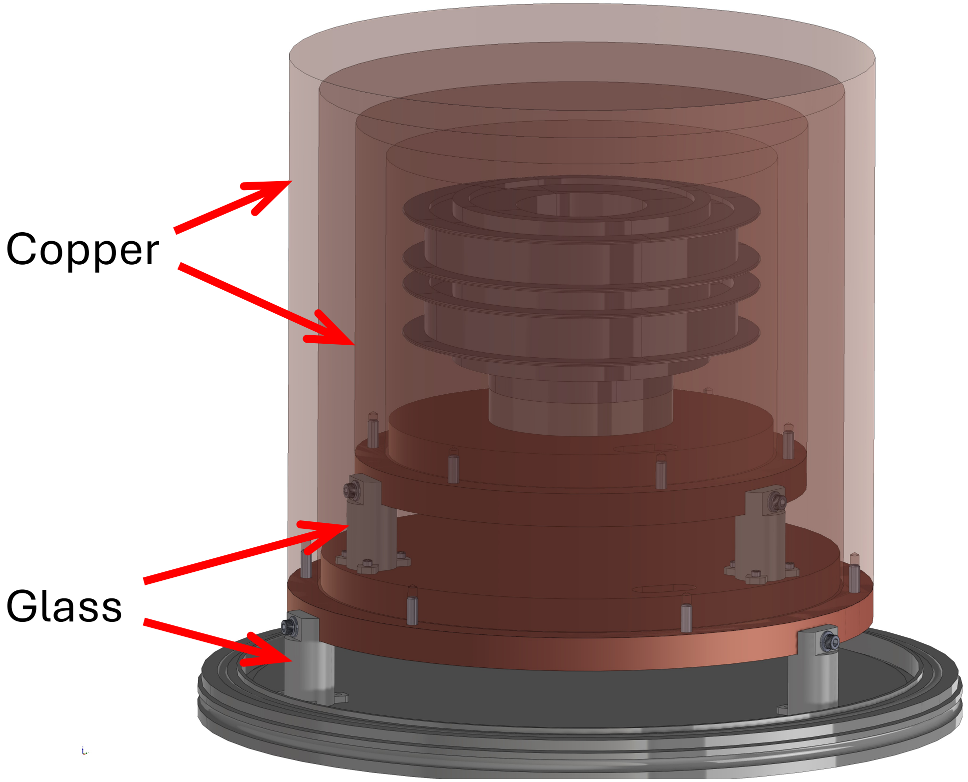
Experimental Setup at MIT



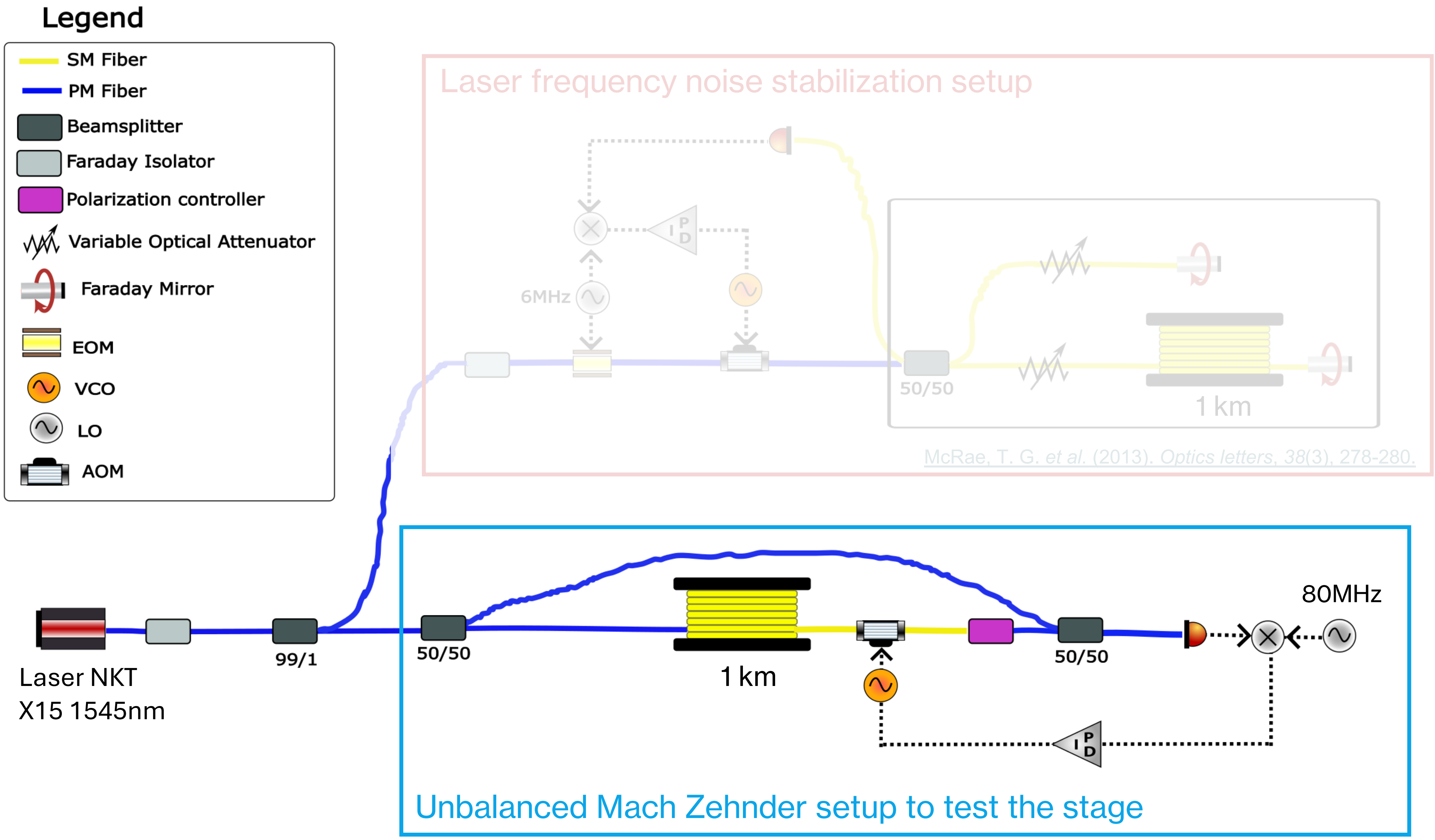
Laser Frequency Noise Stabilization Setup



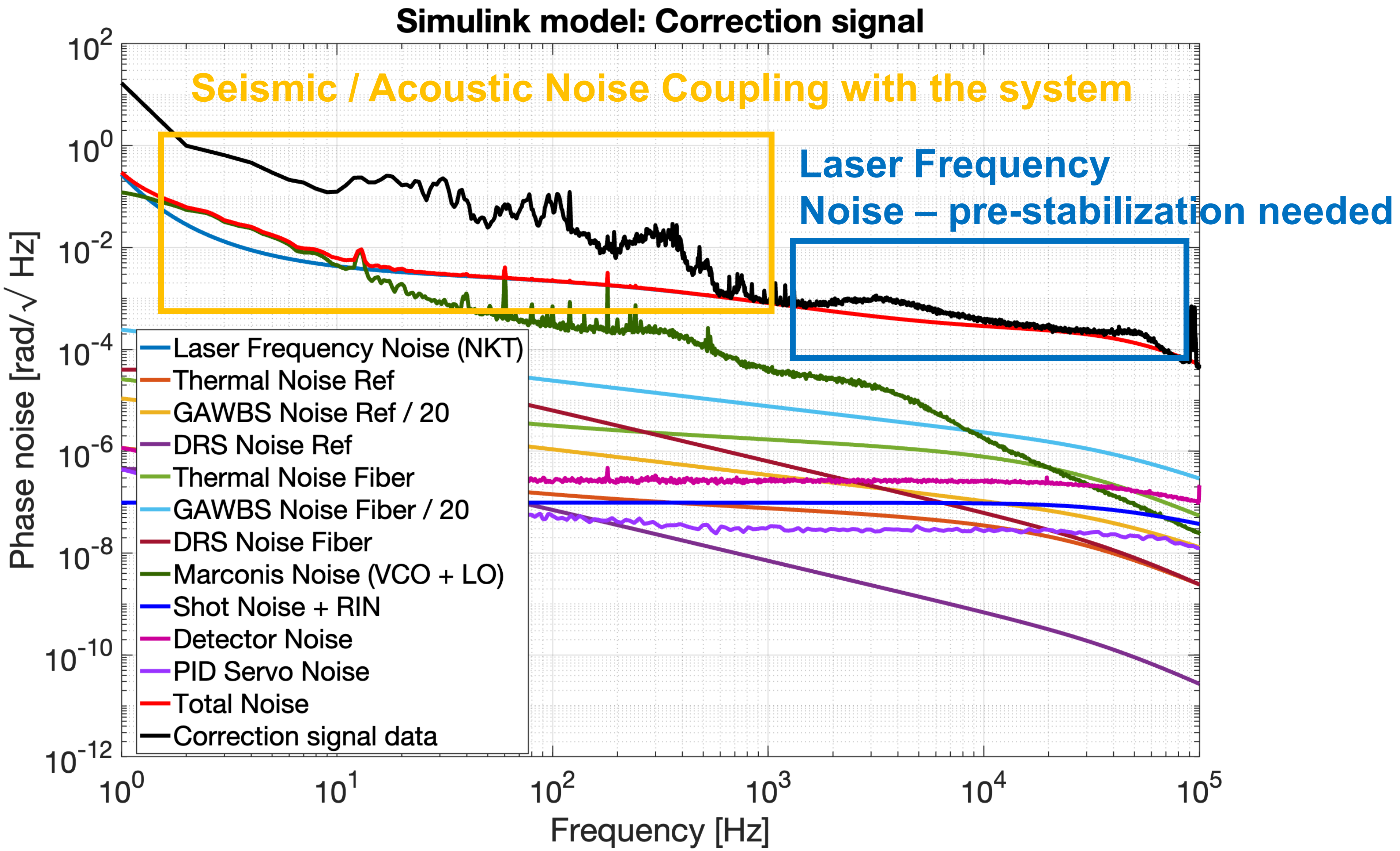
Enclosure designed to have a tens of hours time constant.



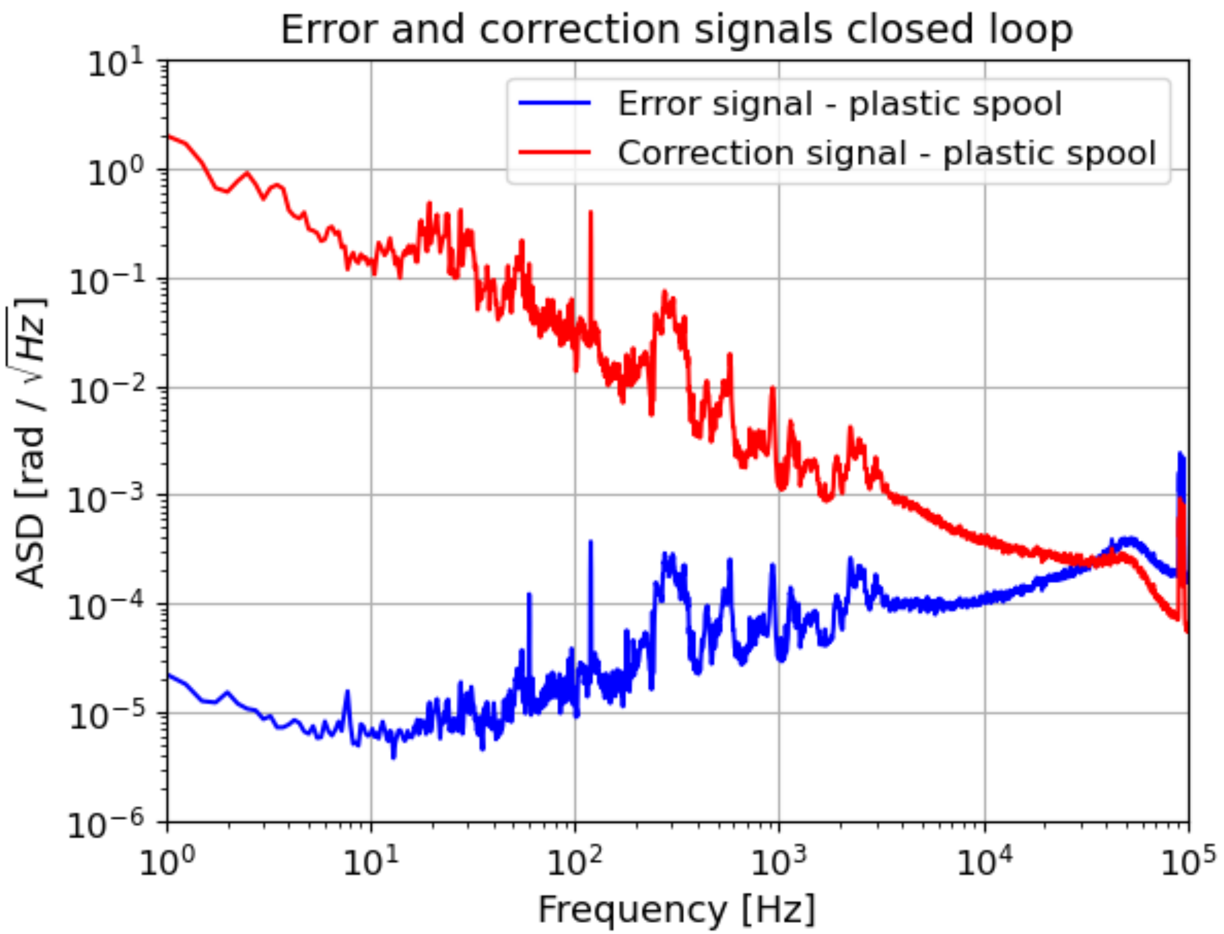
Experimental Setup at MIT

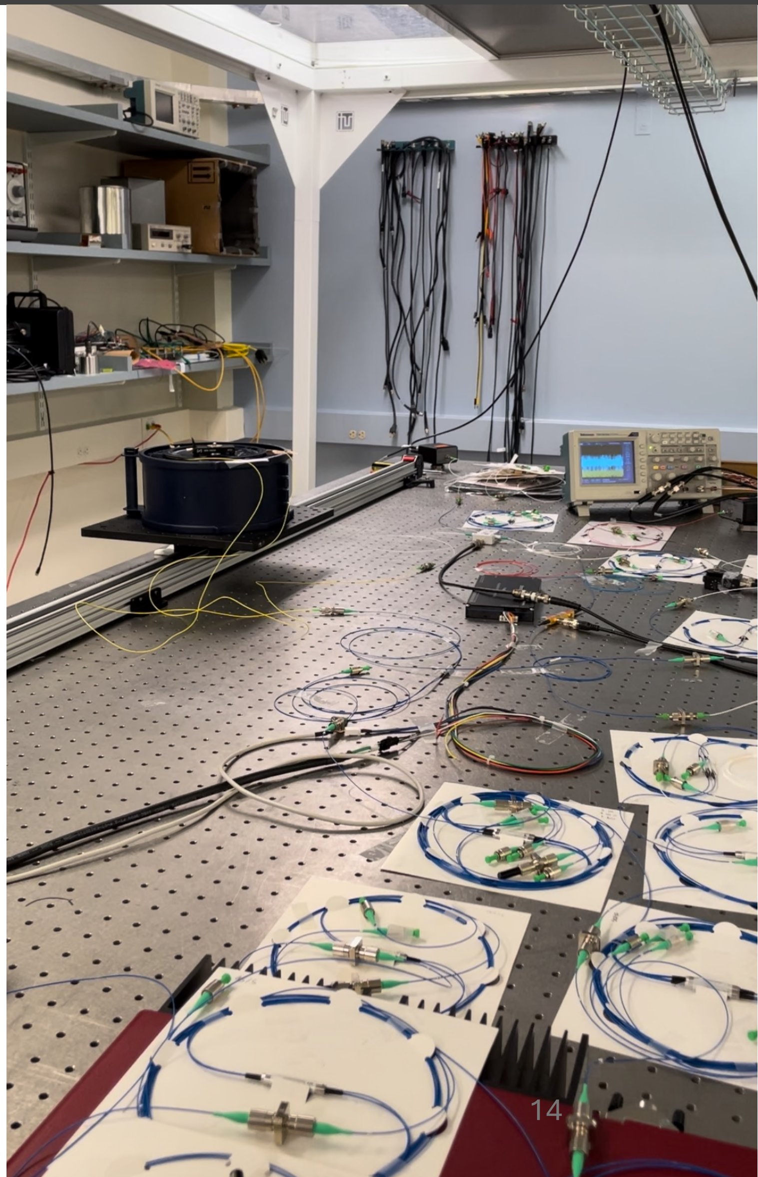


Noise Budget UMZI 1km

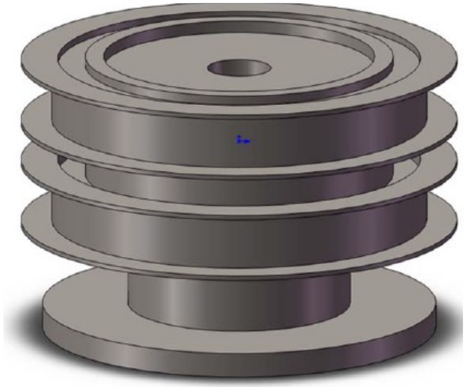


Measurements with Plastic Spool



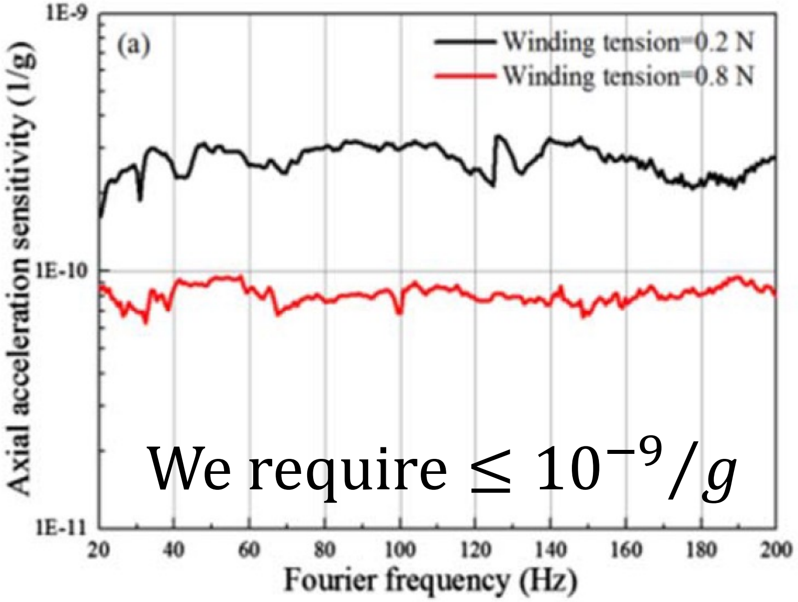


Vibration Insensitive Spool

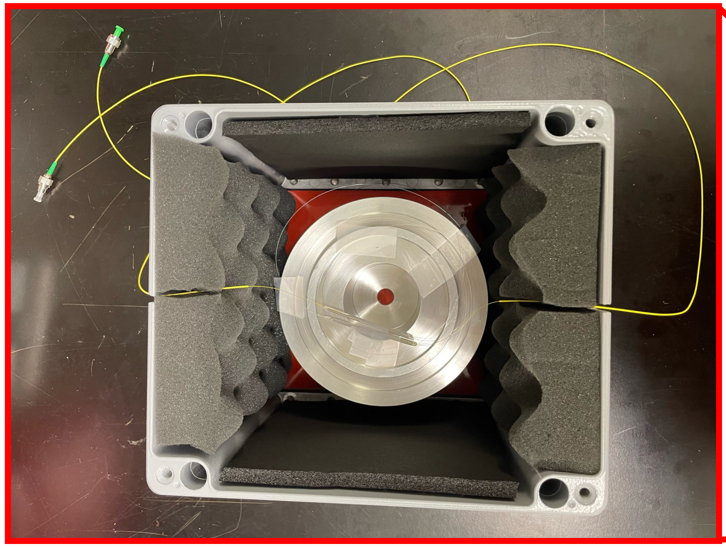


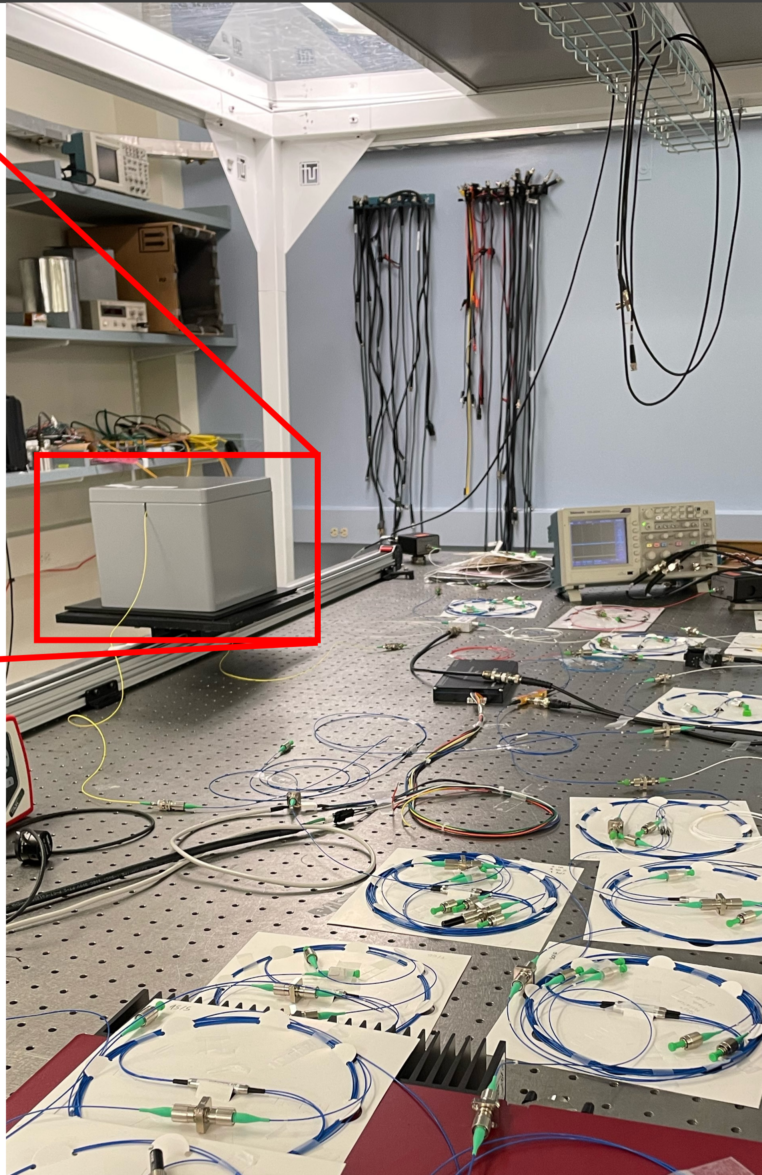
FEA with COMSOL

Adapted from *J. Huang et al. COL* ***17****, 081403 (2019)*



We require $\leq 10^{-9}/g$

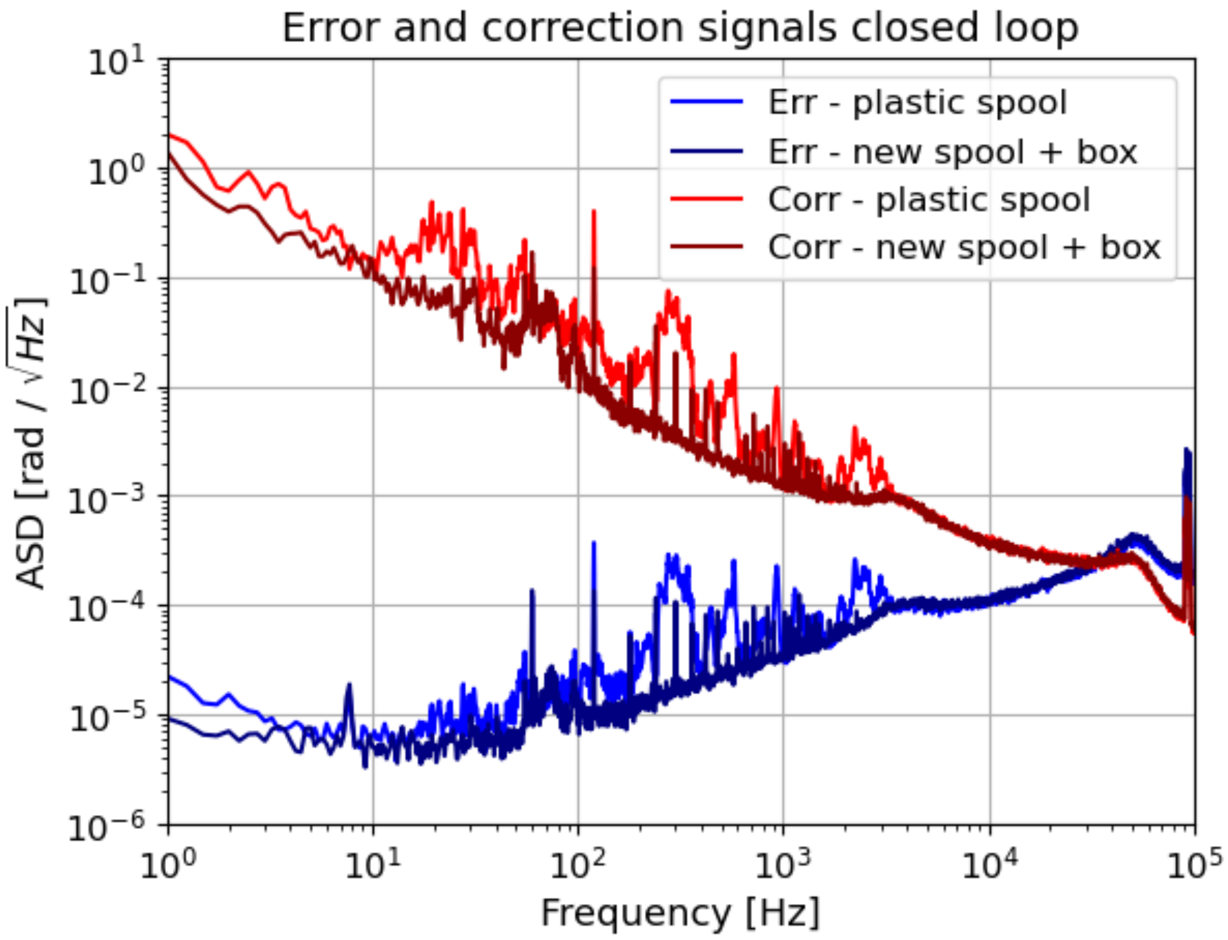




Vibration insensitive spool 1km:

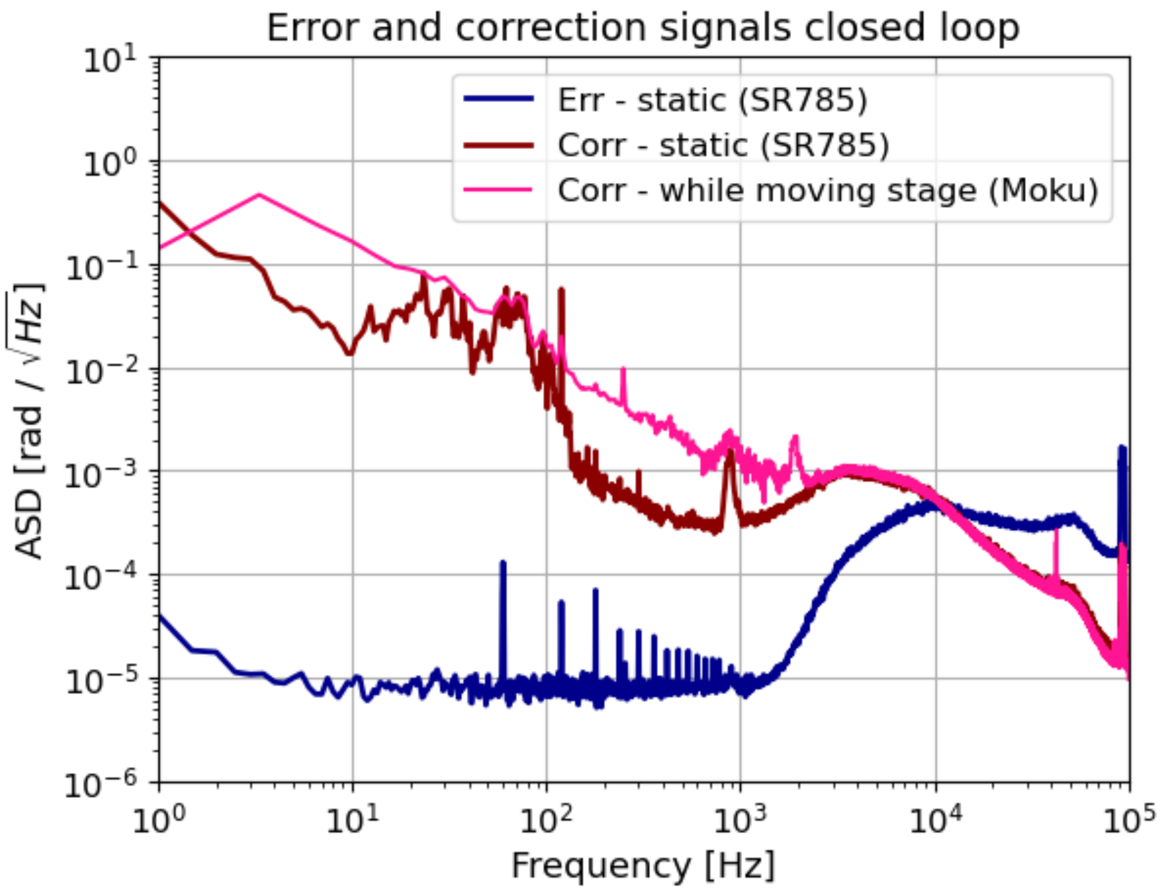
- Designed with COMSOL
- Machined & cleaned
- Fiber re-winded around it
- Spliced
- Insert in a homemade box

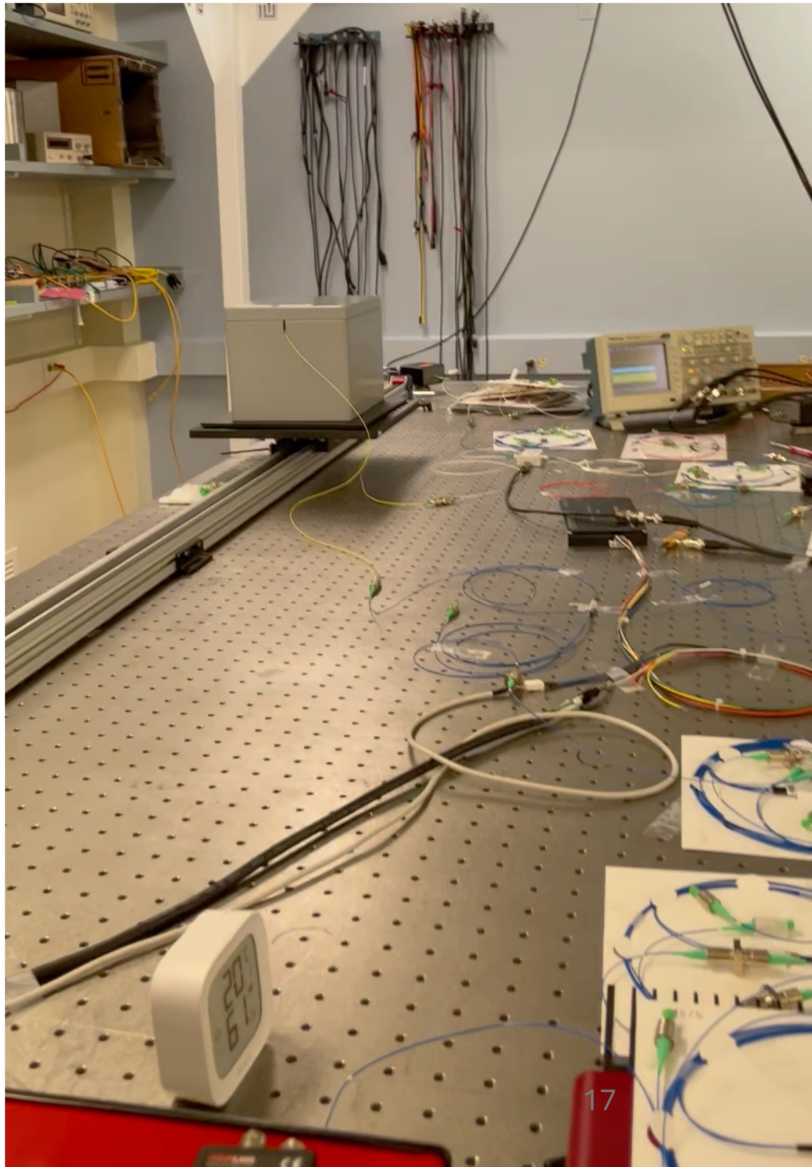
Measurements with New Spool



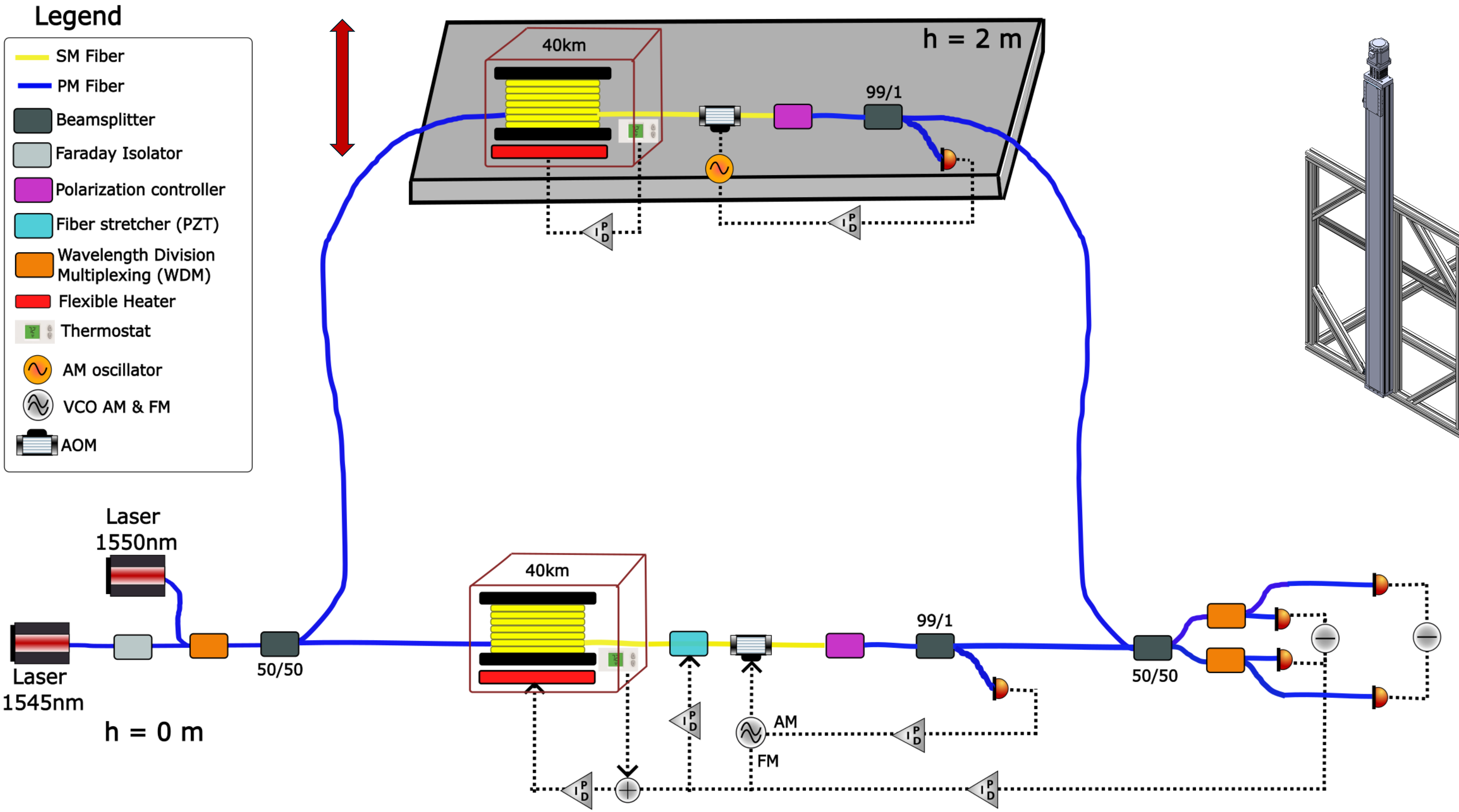
Measurements with New Spool Moving

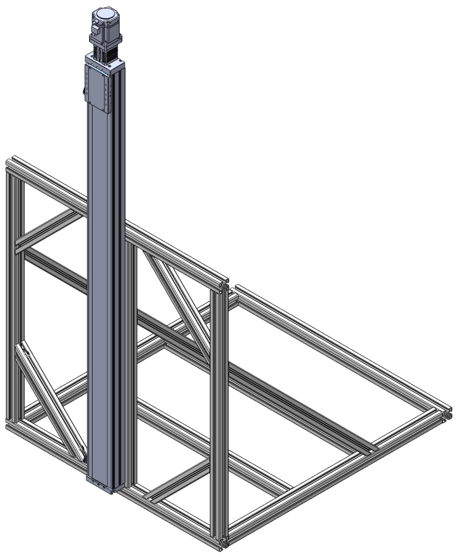
New servo board (two integrators: 3kHz, 5kHz) & different VCO setting



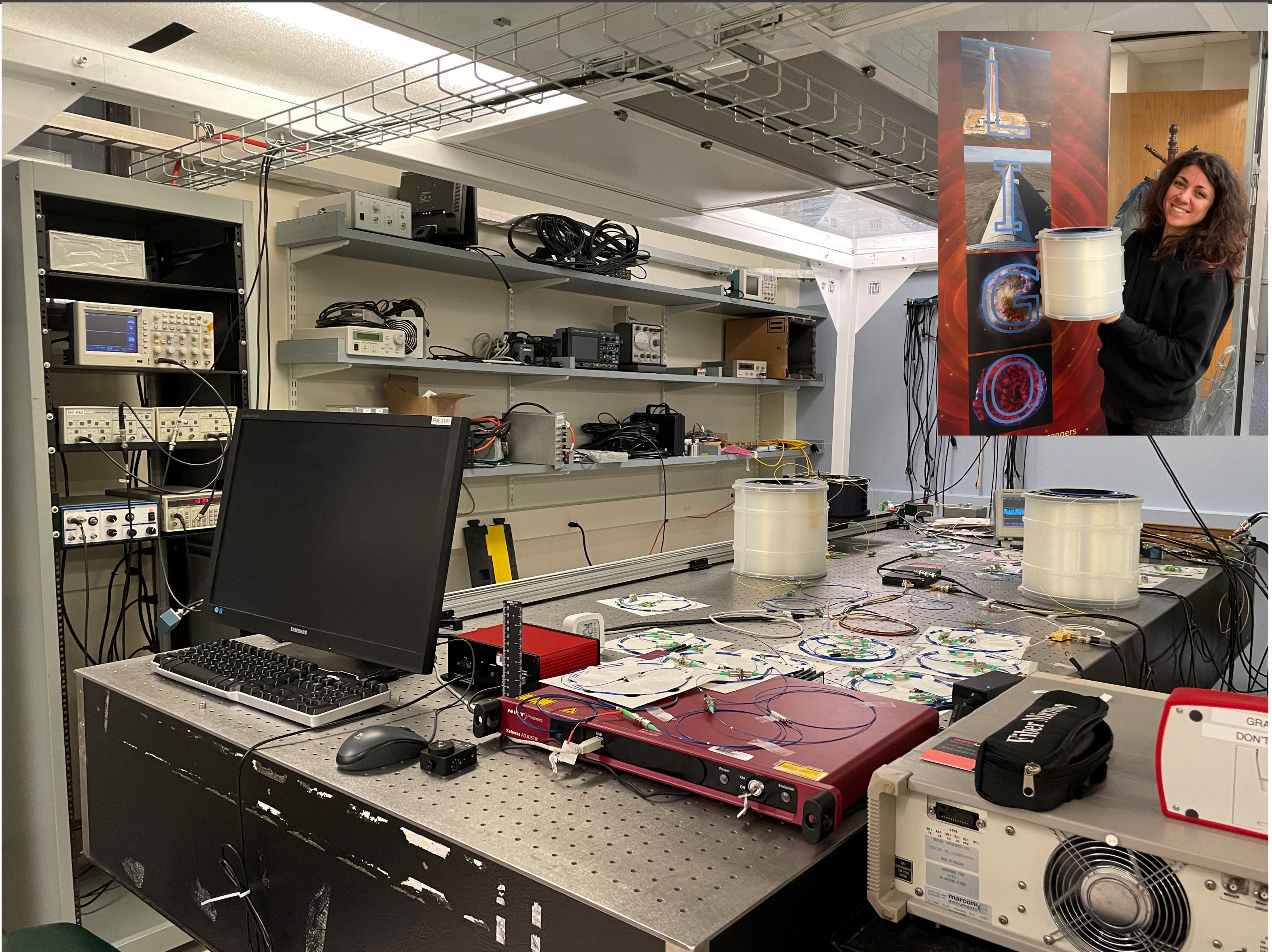


Balanced MZI with 40km

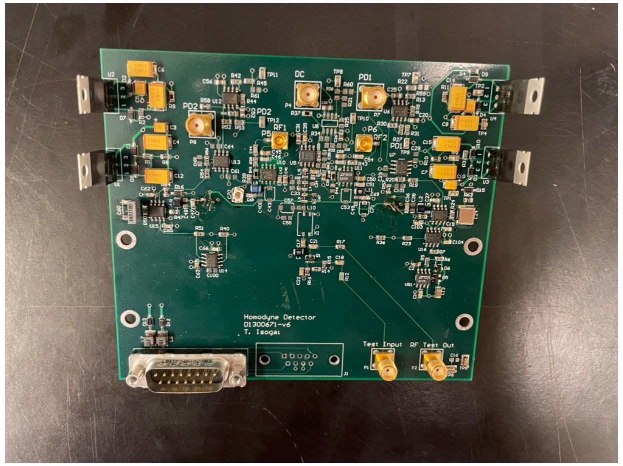


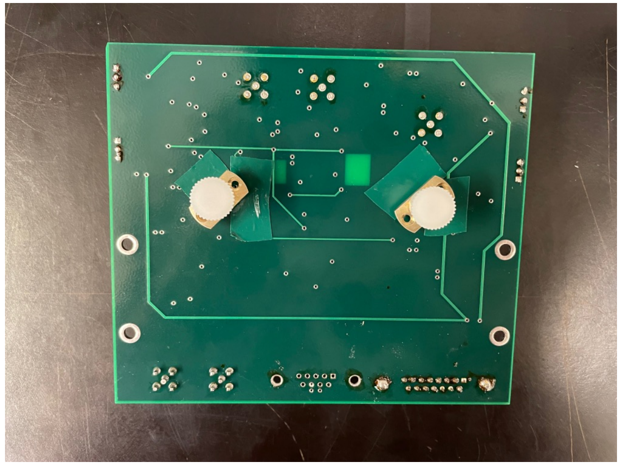


Balanced MZI with 40km



Homodyne detector ready – adapted from aLIGO HD





Conclusions & Next Steps

- Setup to test moving stages ready
- Laser Frequency Noise pre-stabilization setup almost ready

Next steps:

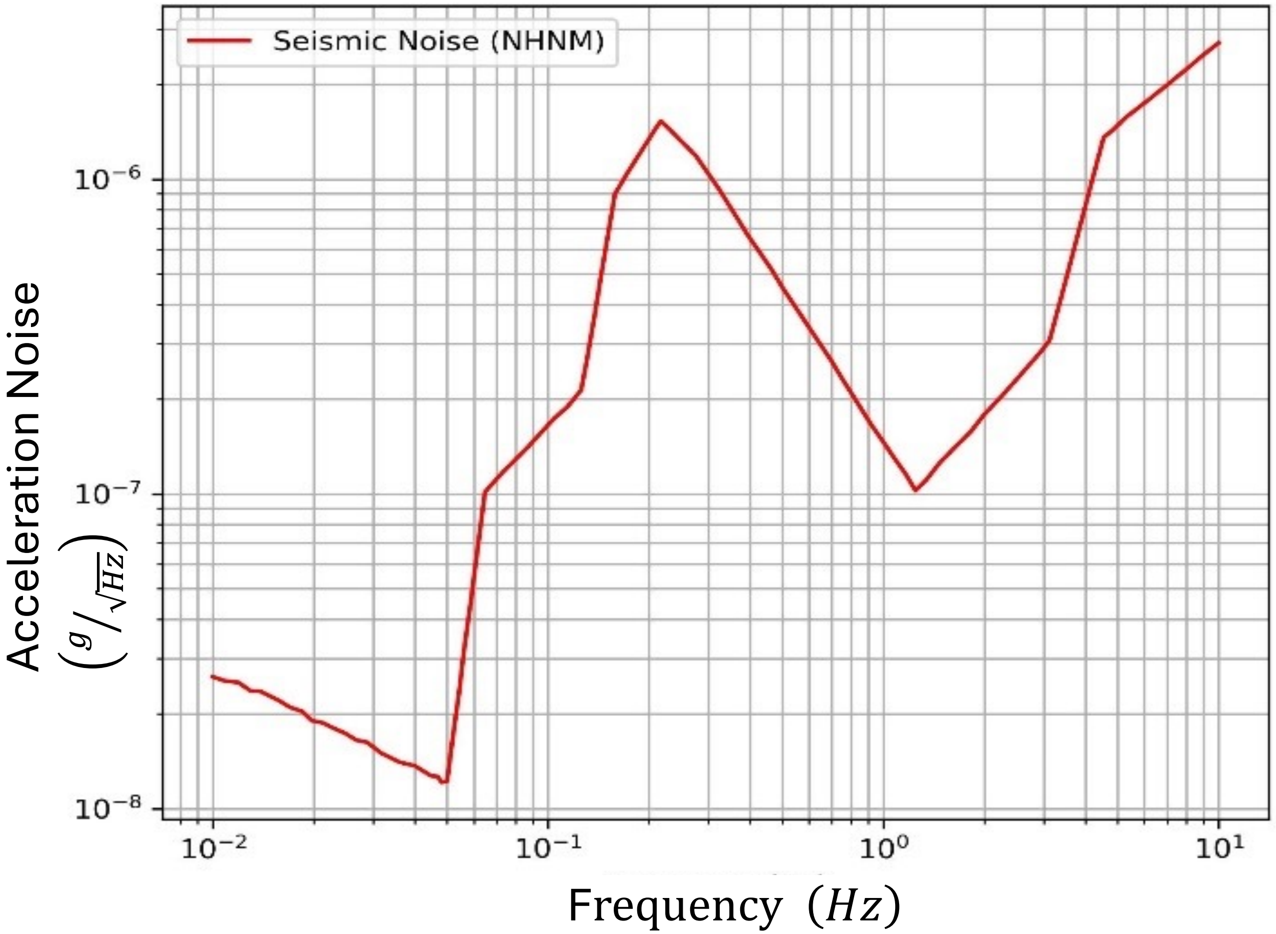
- Perform the differential phase shift measurement with coherent light at MIT
- Move the 40km interferometer & moving stage to Vienna
- Measure the effect of gravity on a path entangled state of light for the first time

↓

initial milestone for more complex experiments aimed at measuring relativistic effects such as probing the impact of spacetime curvature on entangled photons through experiments conducted in space

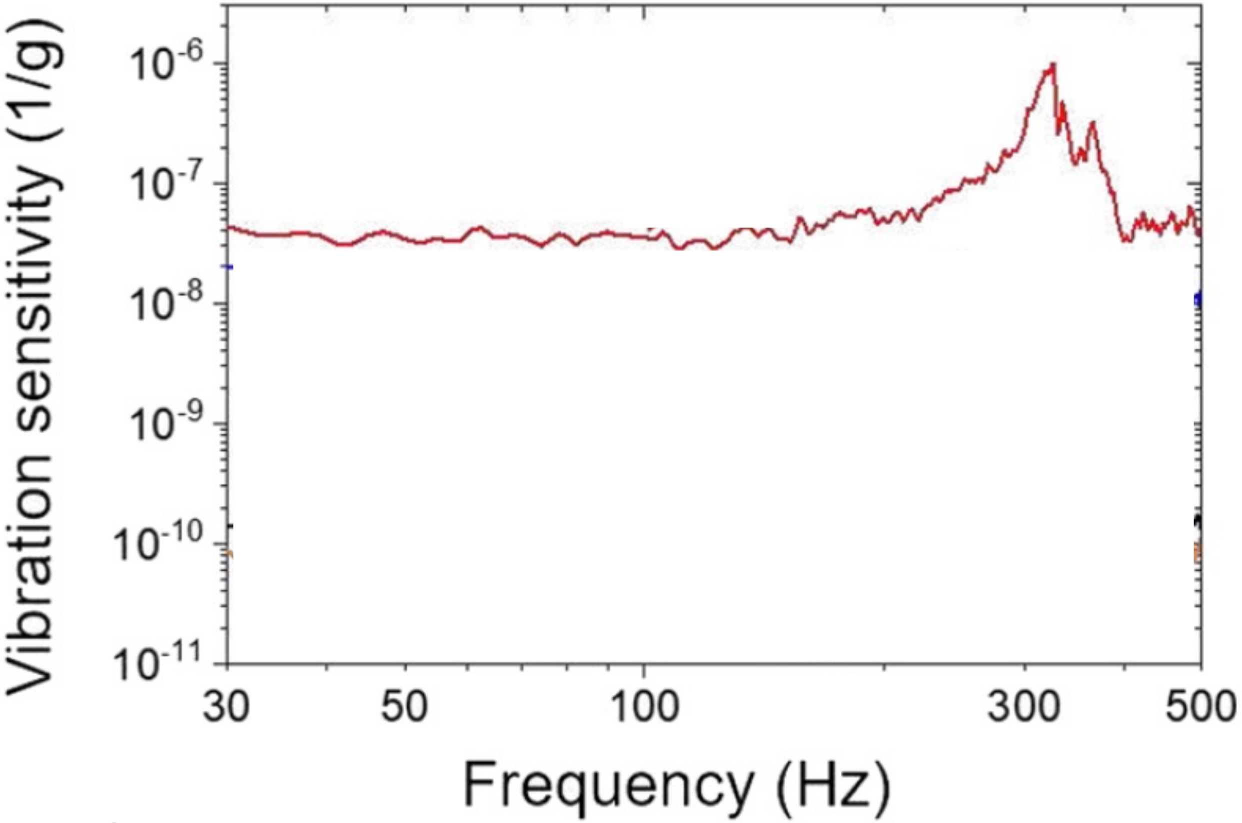
EXTRA SLIDES

Reduction of Seismic Noise Coupling



Seismic vibrations accelerate the fiber spool

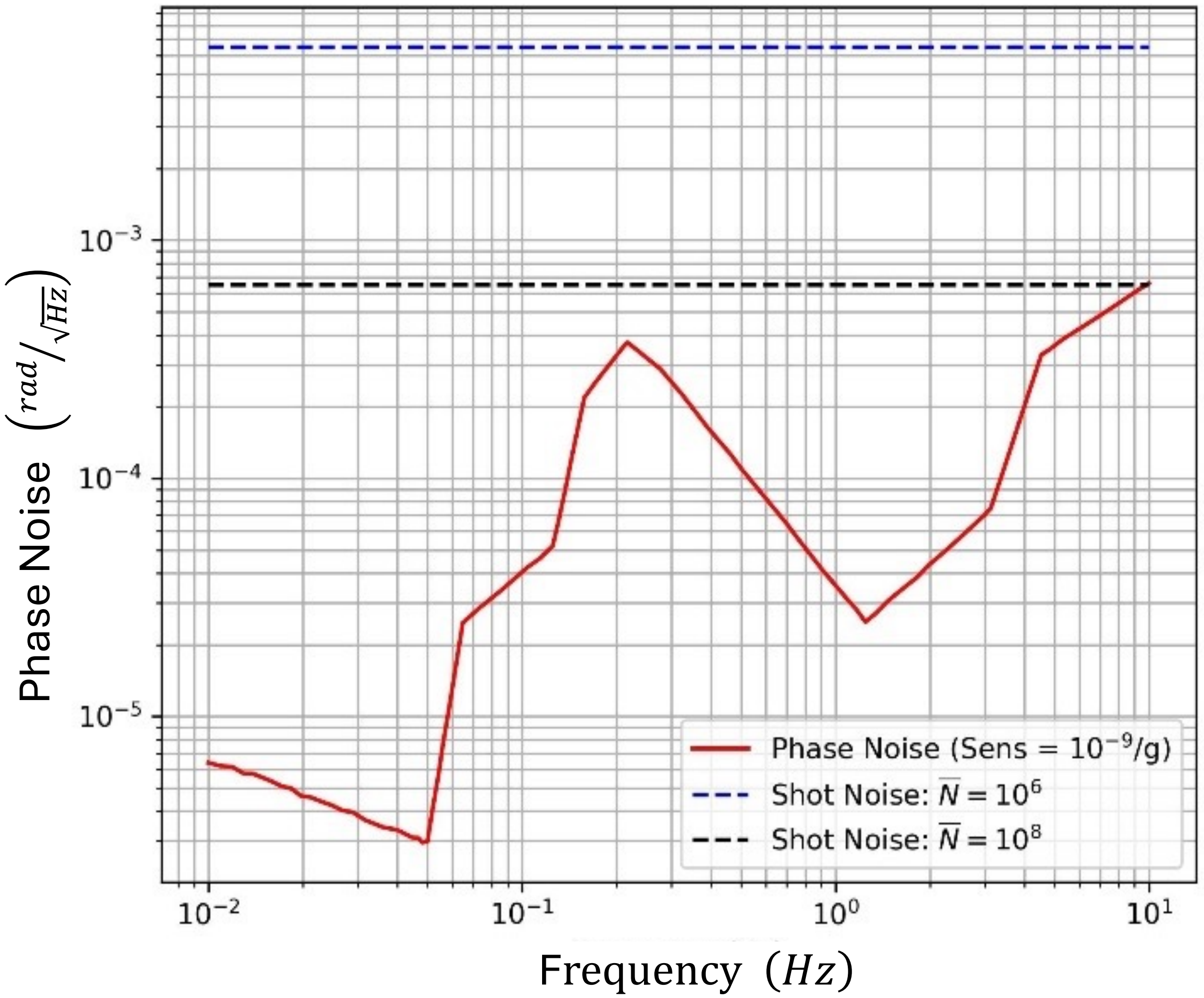
Standard Plastic Spool [1]

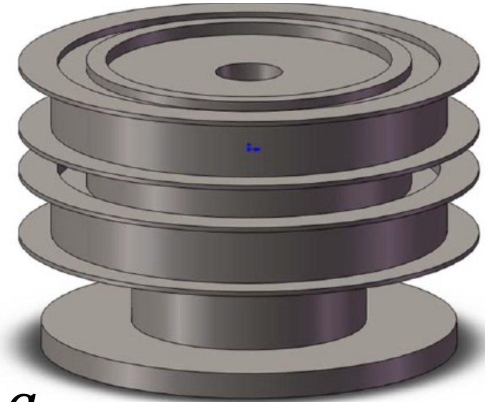


Spool deforms under acceleration.
Causes fractional length change in fiber.

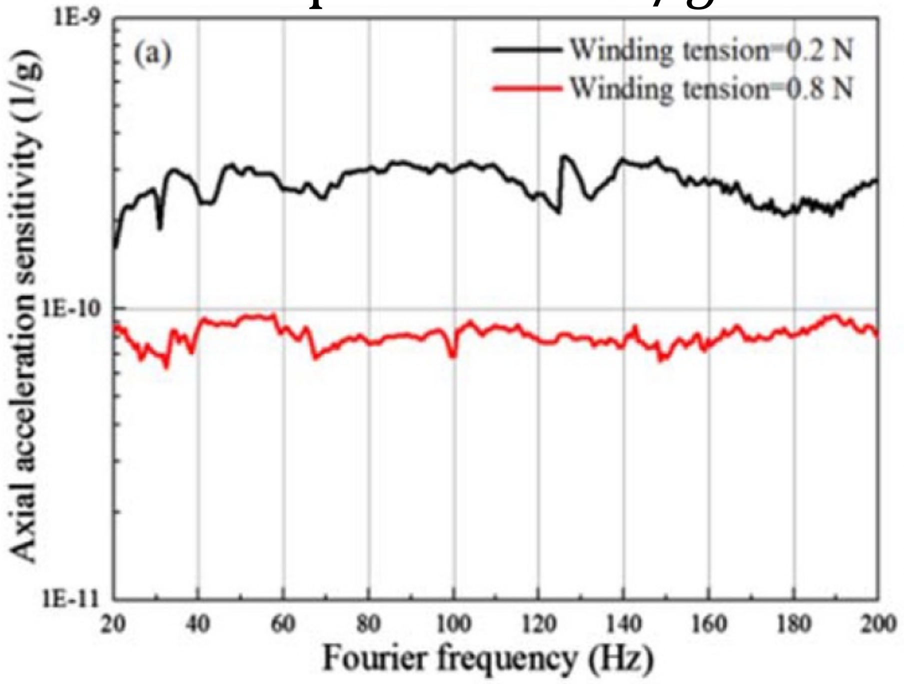
[1] I. Jeon et al. APL Photon. **8**, 120804 (2023)

Acceleration Sensitivity Goal for 40 km Fiber Spools



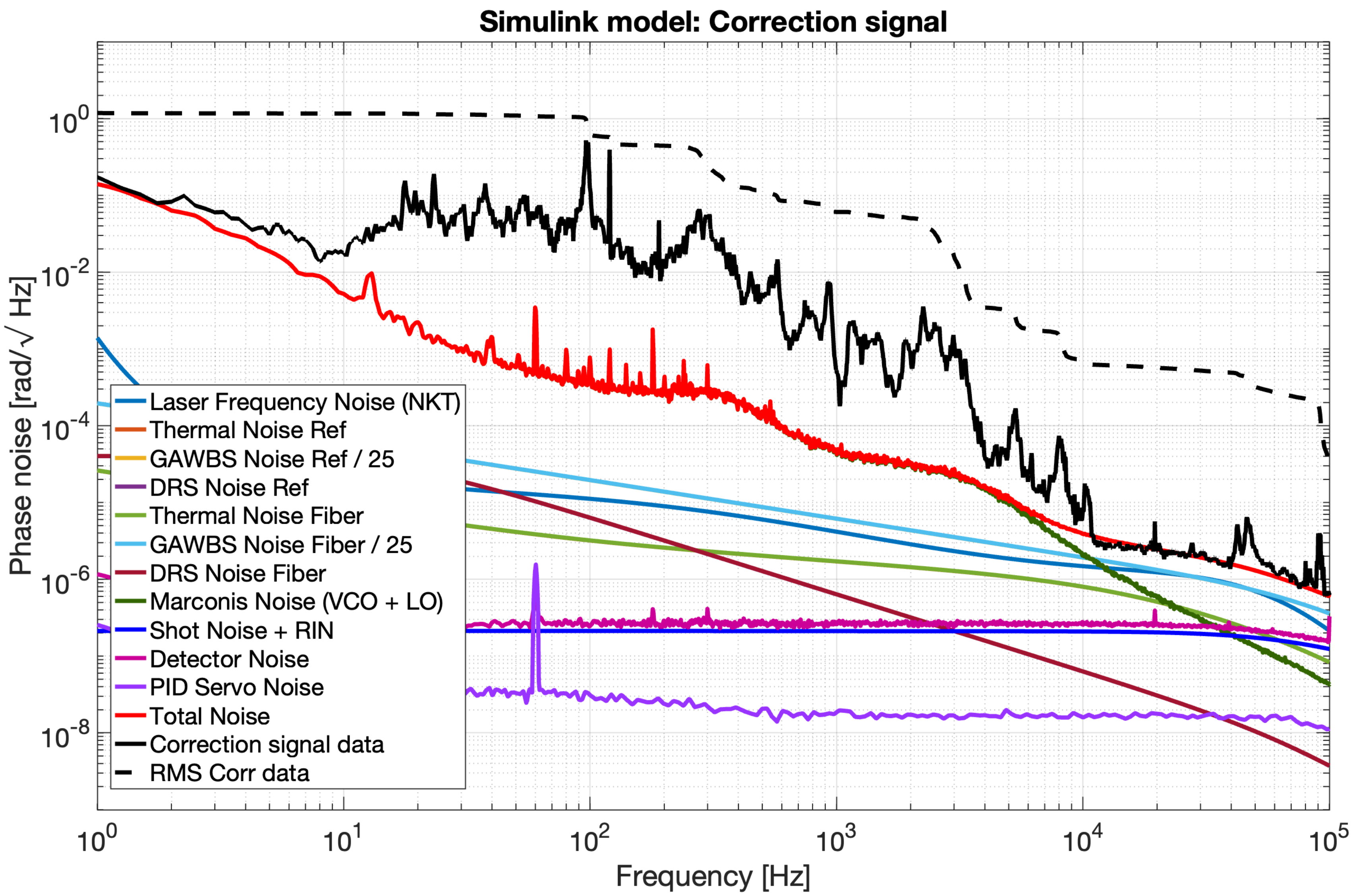


We require $\leq 10^{-9}/g$



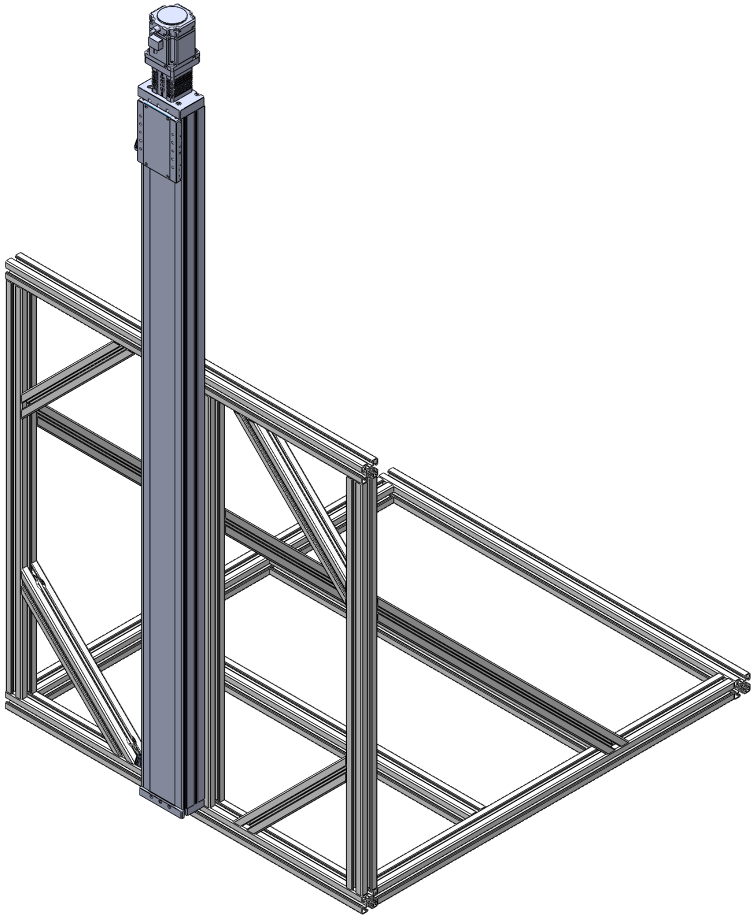
*J. Huang et al. COL **17**, 081403 (2019)*

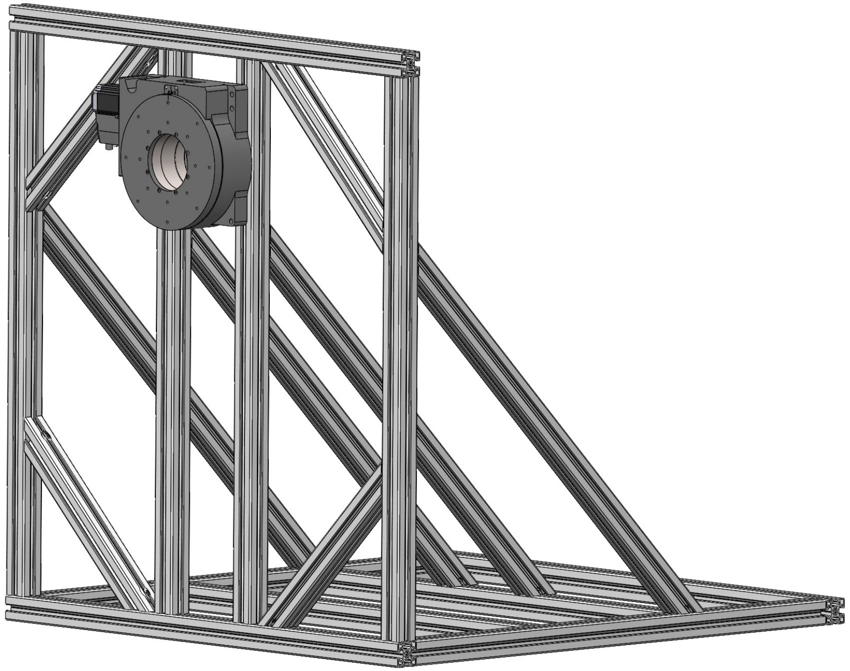
Balanced MZI with 40km



Linear & Rotatory Stage Options

We bought a linear stage (Fuyu) with higher loading weight and a rotatory stage (Zaber).
They can support 40kg spool + isolation support. We will test them soon.





Credit Elio Angile

Abstract

Gravitational time dilation refers to the phenomenon in which time passes at different rates across regions with different gravitational potentials and it represents a fundamental prediction of General Relativity.
Pound and Rebka's groundbreaking work in 1959 provided the first experimental evidence of this effect, using gamma-ray spectroscopy in a terrestrial laboratory [1]. To date, no one has seen a clear signature of gravitational time dilation in a system where the full formalism of GR and quantum mechanics must be applied simultaneously to explain the outcome. A quantum system whose wavefunction is spread across two different gravitational potentials, either through superposition or path entanglement, is an ideal platform for observing this effect.
Photon interferometry is particularly promising since experiments using massive particles, such as the Colella, Overhauser and Werner experiment [2], can be understood in terms of Newtonian gravity unless internal degrees of freedom are used to track the proper time evolution [3].
With this ultimate goal in mind, we are developing an experiment to study the gravitationally induced phase shift of photons prepared in path entangled states between two arms of a fiber interferometer separated by a height of 2 meters [4]. We will describe the apparatus under development to achieve the exceptional sensitivity required to resolve any changes in the gravitational phase shift that may arise due to the dual quantum mechanical and relativistic nature of our system. This would be the first experiment to measure the effect of gravity on a path entangled state of light, marking the initial milestone for more complex experiments aimed at measuring relativistic effects such as probing the impact of spacetime curvature on entangled photons through experiments conducted in space [5, 6].

[1] R. V. Pound and G. A. Rebka. Physical Review Letters 4 (1960), pp. 337–341.
[2] R. Colella, A. W. Overhauser, and S. A. Werner. Physical Review Letters 34.23 (1975), p. 1472
[3] M. Zych, F. Costa, I. Pikovski, and C. Brukner. Nat. Comm. 2 (2011) 505.
[4] C. Hilweg et al. New Journal of Physics 19.3 (2017), p. 033028.
[5] M. Mohageg, L. Mazzarella, C. Anastopoulos et al. EPJ Quantum Technology 9, 25 (2022)
[6] T. B. Mieling, C. Hilweg, P. Walther. Physical Review A 106 (2022) 3, L031701