Newtonian Noise Measurement with TOrsion-Bar Antenna

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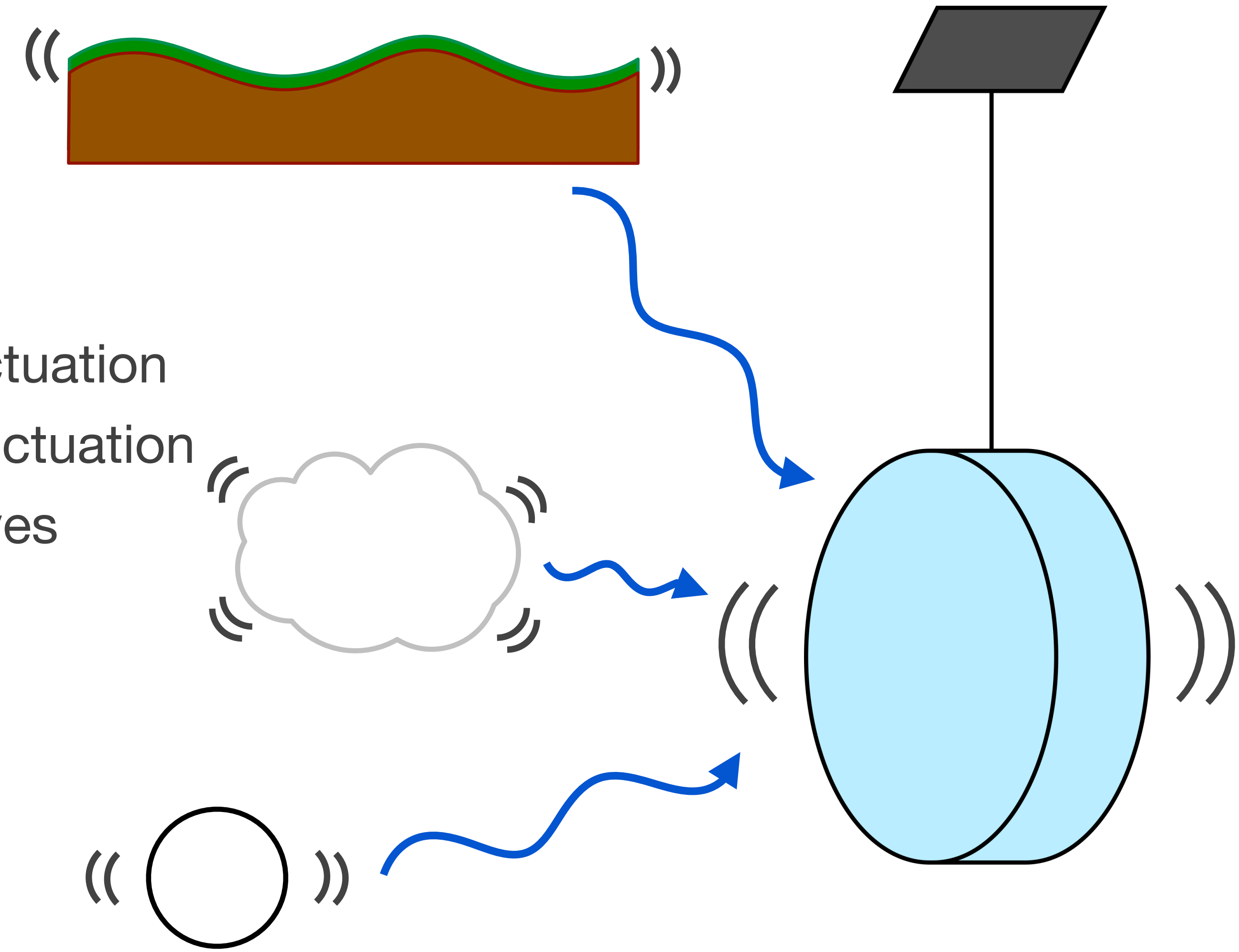
The Univ. of Tokyo

9/11/21 KAGRA FWG open meeting @ online

Newtonian Noise

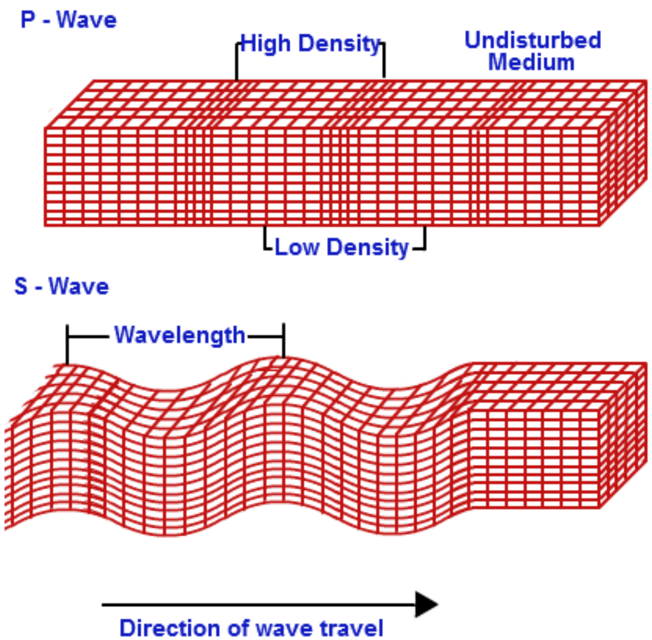
Newtonian noise: comes from local gravity gradient fluctuation

- Seismic waves
  - body wave
  - surface wave
  - etc.
- Atmospheric fluctuation
  - temperature fluctuation
  - infrasound waves
  - etc.
- Moving masses
  - water
  - human activity
  - etc.



Seismic Wave

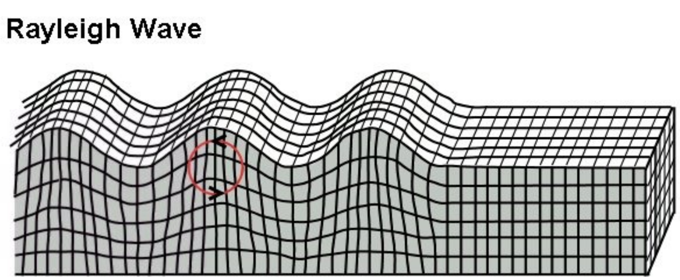
- Seismic waves:
  - body wave
    - P-wave: compressional wave
    - S-wave: shear wave
    - propagate though media



http://physics.tutorcircle.com/waves/p-wave.html

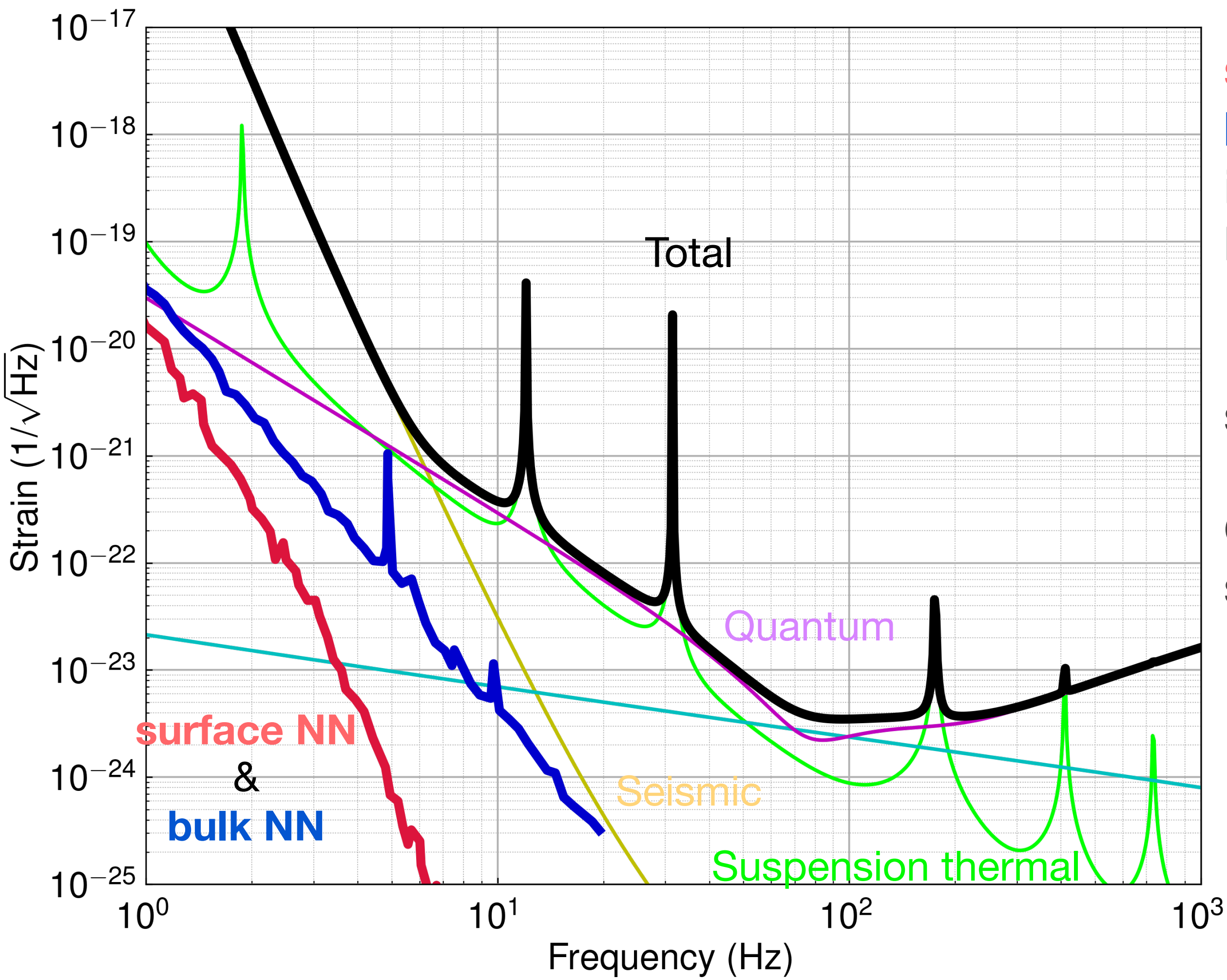
  - surface waves
    - Rayleigh wave
    - propagates on the surface of media

- can be divided by
  surface and bulk contribution



https://earthquake.usgs.gov/learn/glossary/images/rayleigh_web.jpg

NN in KAGRA



surface NN and
bulk NN
in KAGRA site
based on Somiya+ (2012)

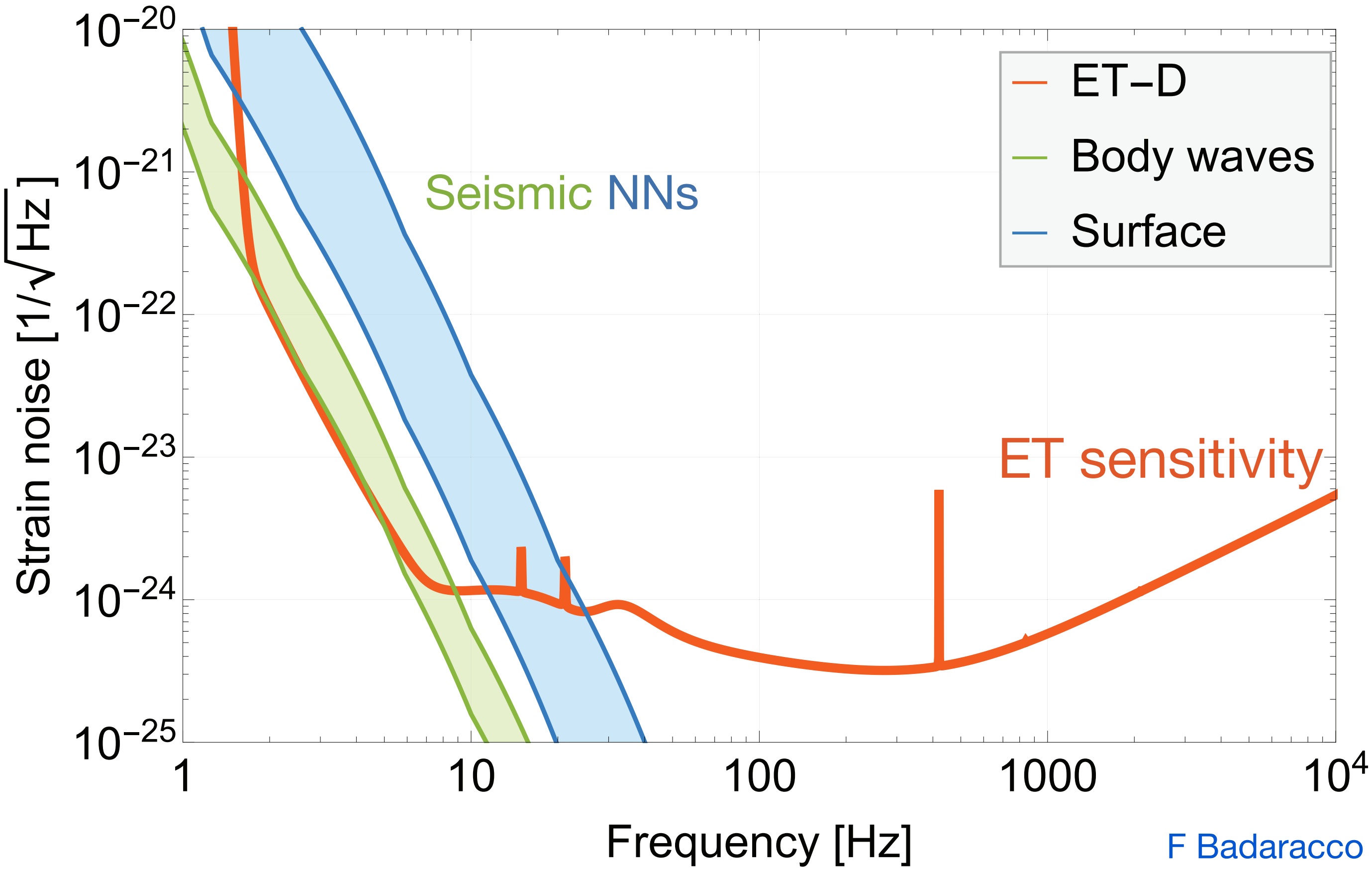
Estimated to be enough small for seismic

Other source could affect sensitivity

Mirror thermal

NN in 3G Detectors

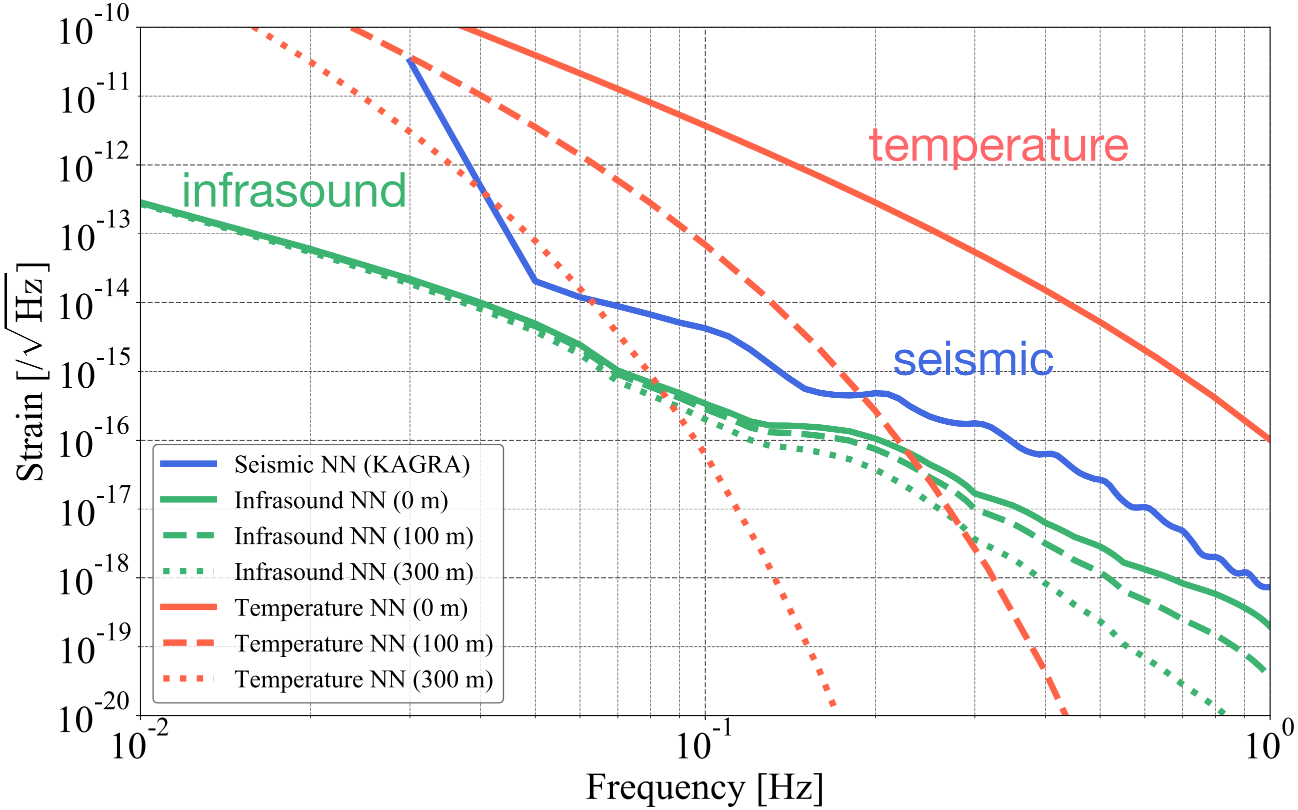
- For 3G detectors NN could be a dominant noise source in low frequencies



F Badaracco and J Harms 2019

Strategy

- Basically NN cannot be distinguished from GW signal
- Coupling path is simple, but modeling is complicated



credit: T.Shimoda

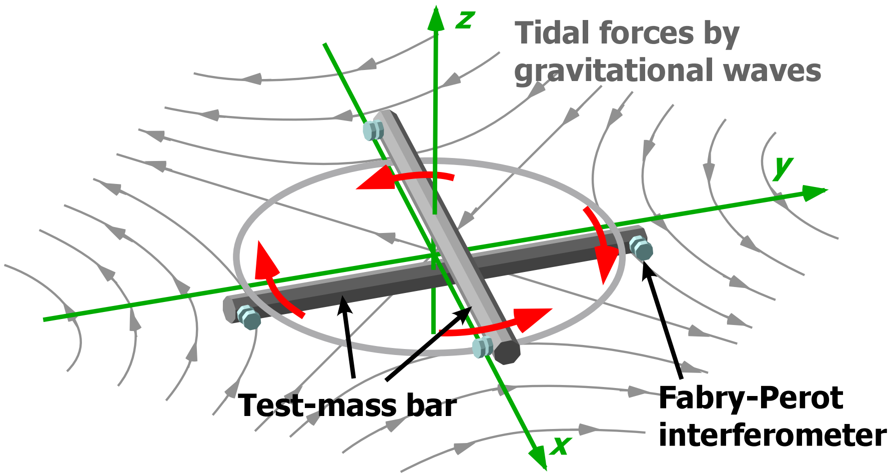
▸ Model test by direct measurement

Torsion Bar Antenna (TOBA)

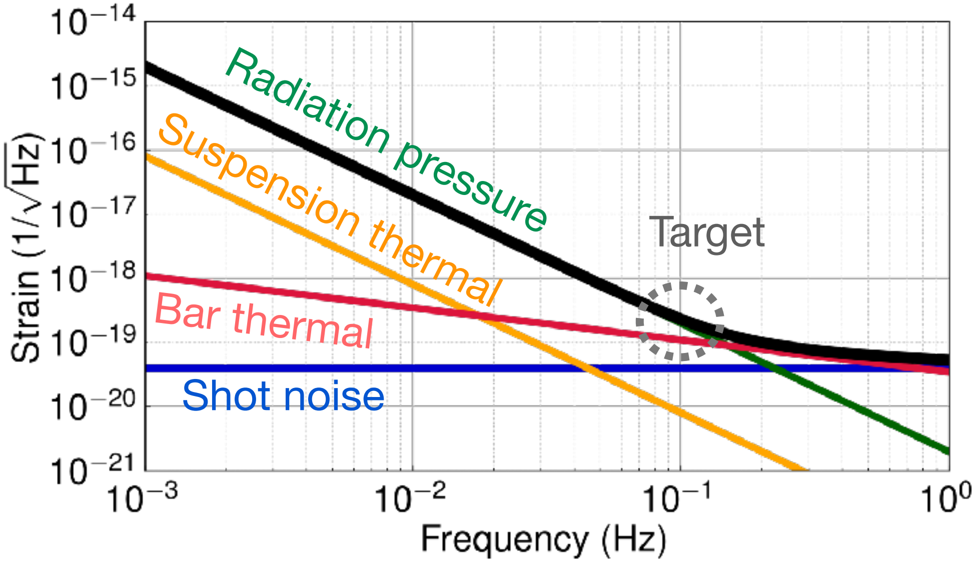
TOBA : TOrsion-Bar Antenna

- Gravitational wave detector using two torsion pendulums
- GW detector = Gravity Gradiometer
- Resonant frequency of torsion pendulum ~ mHz

  → Sensitive to **low frequency** (~ 0.1Hz)
- Target sensitivity **h ~ 10^{-19} / √Hz** @ 0.1 Hz with **10 m** bars



M. Ando+ (2010)



Design sensitivity of TOBA

Development Plan

Phase-I (2009)	Phase-II (2015)	**Phase-III (Now)**	Final (Target)

Principle Test

$10^{-8}/\sqrt{Hz}$ @ 0.1 Hz
(Established)

- Room Temp.
- 25cm TM(s)

Cryogenic Test

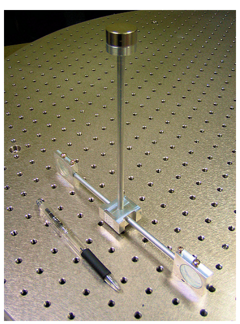
$10^{-15}/\sqrt{Hz}$ @ 0.1 Hz
(Design)

- **Cryo. Temp.** (**4K**)
- 35cm TMs

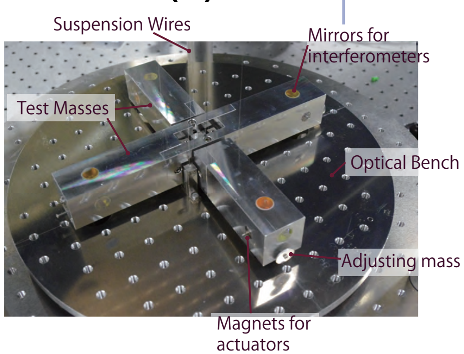
Goal

$10^{-19}/\sqrt{Hz}$ @ 0.1 Hz
(Target)

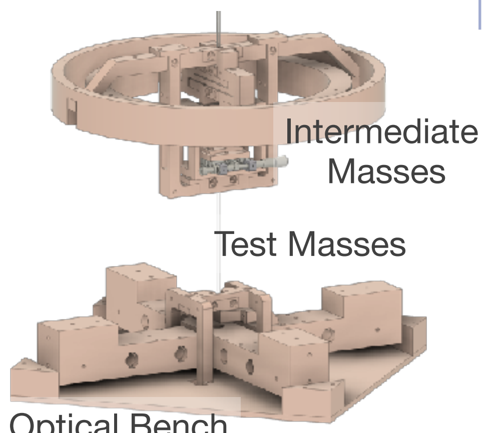
- **Cryo. Temp.** (**4K**)
- **10m** TMs

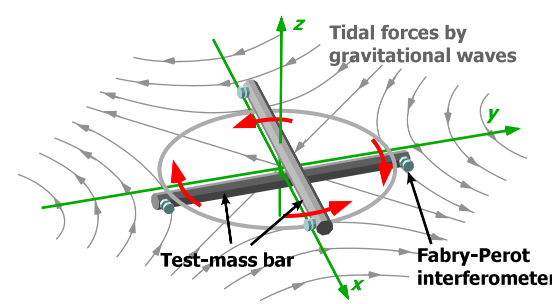


K. Ishidoshiro
Ph.D Thesis



A. Shoda
Ph.D Thesis

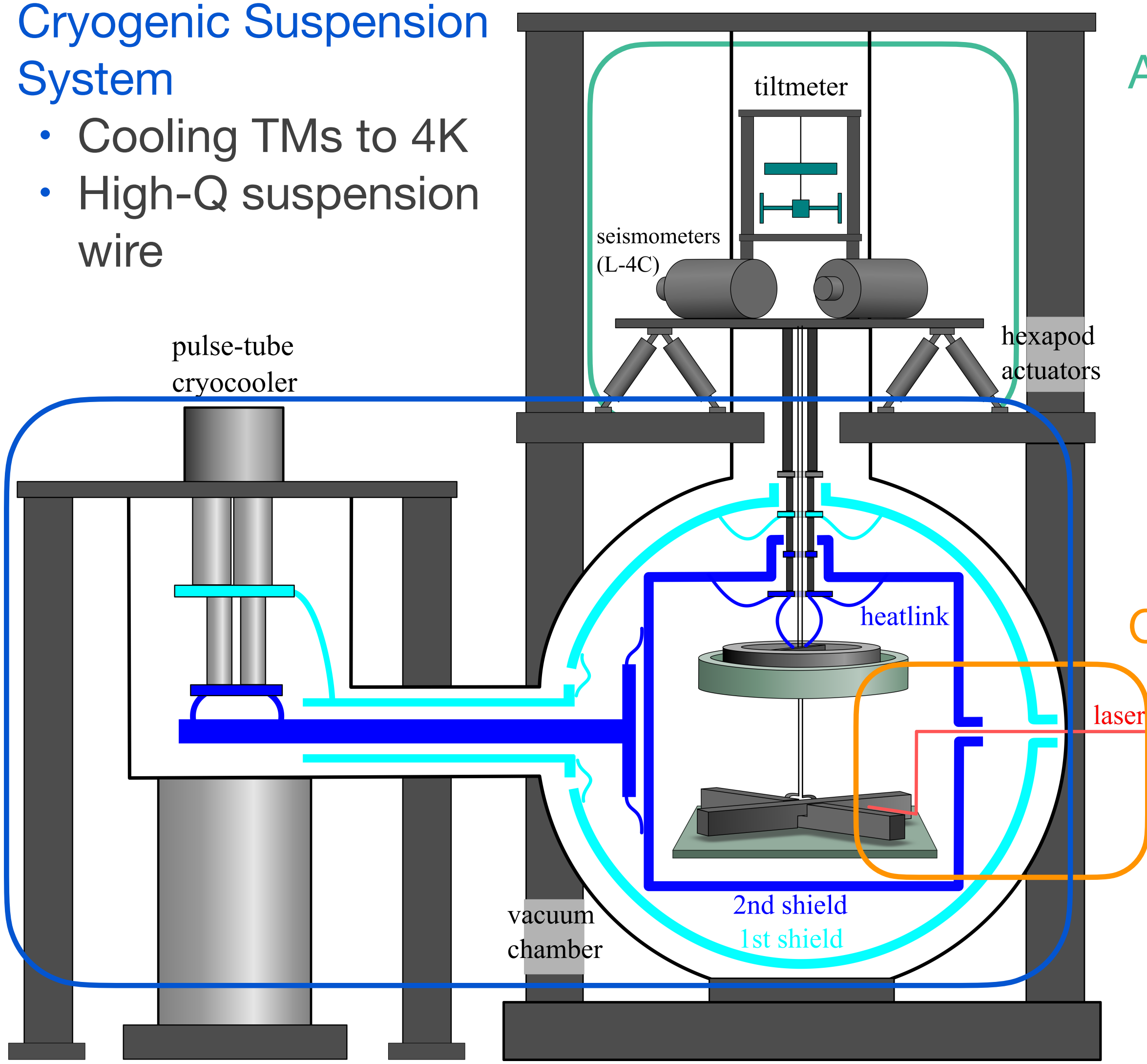




Setup of Phase-III TOBA

Cryogenic Suspension System

- Cooling TMs to 4K
- High-Q suspension wire



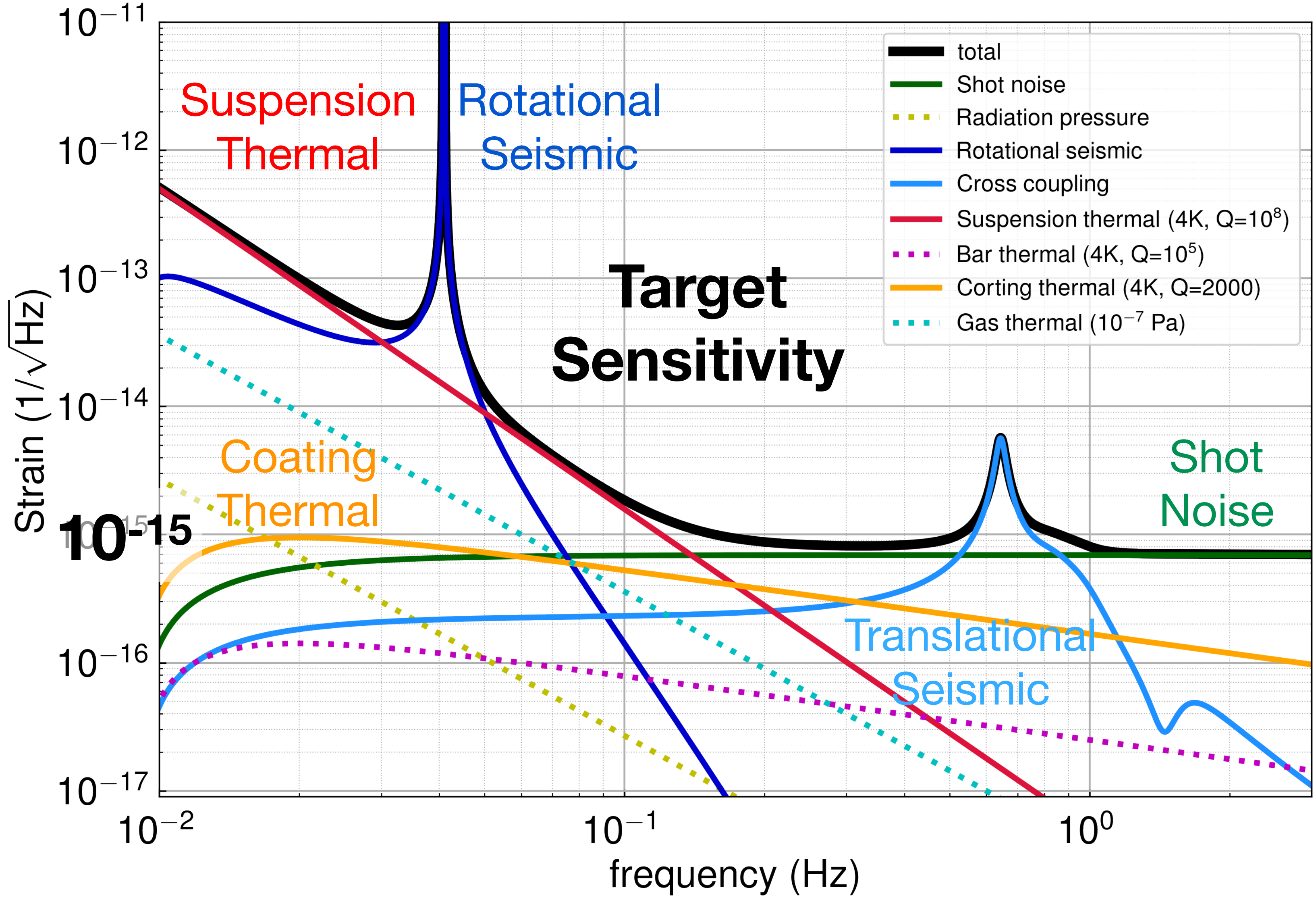
Active Vibration Isolation System

- Reduction of vibration at the suspension point
- Reduction of vibration induced cryocooler

Optical System

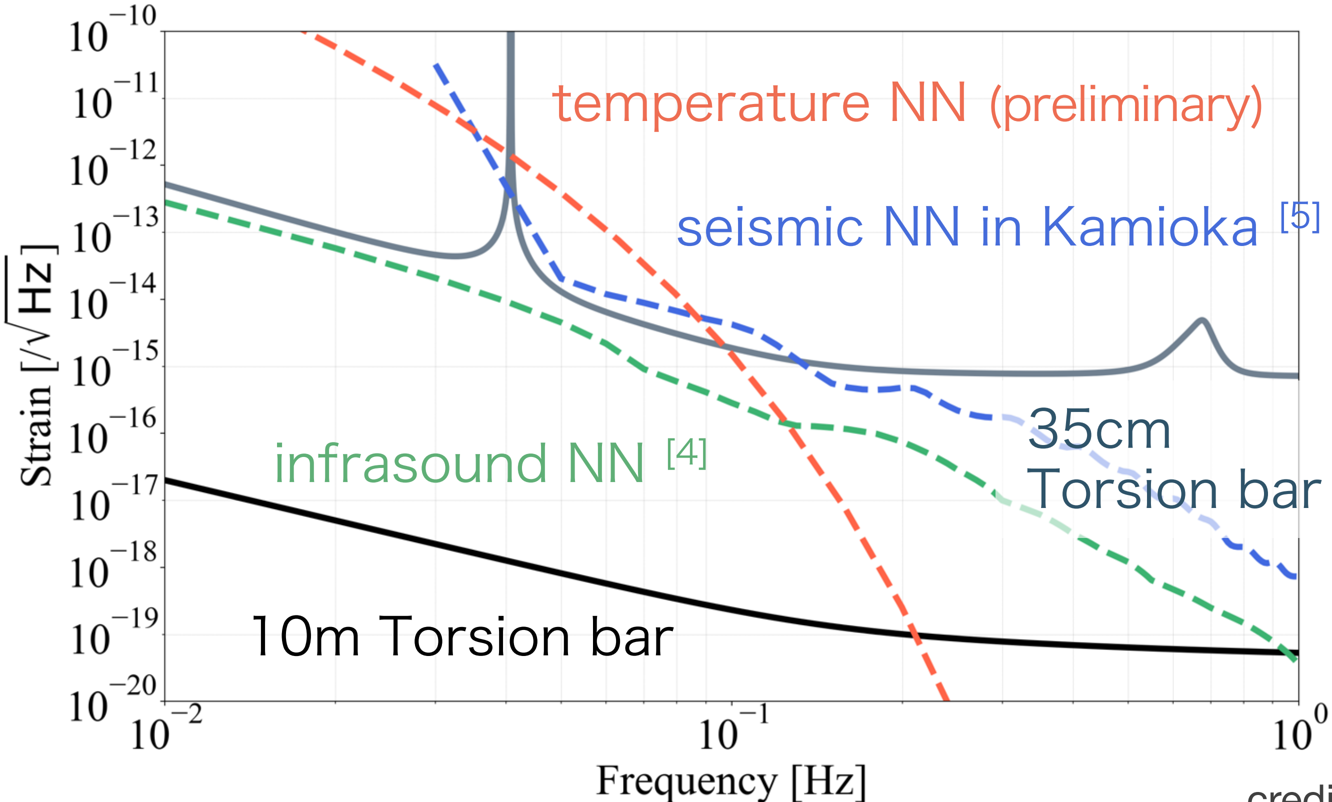
- Rotation measurement by high-sensitive wave front sensor
- Monolithic interferometer for reducing readout noise

Design Sensitivity



Direct Measurement of NN with TOBA

- TOBA sensitivity vs NN estimation



credit: T.Shimoda

- Phase-III TOBA can measure NN directly below 0.1 Hz
- Higher S/N for Final TOBA

Development Items

- Cryogenic Suspension System
  - Cooling System → Cooled down to **6.1 K**
  - High-Q suspension fiber

- Optical System
  - New angular sensor with higher sensitivity
  - Monolithic interferometer under cryogenic temp.

- Active Vibration Isolation
  - Reduction of translational seismic noise

    → Reduced by **1/1000** at most
  - Reduction of vibration induced by cooler

Cryogenic Suspension System

Cryogenic Cooler

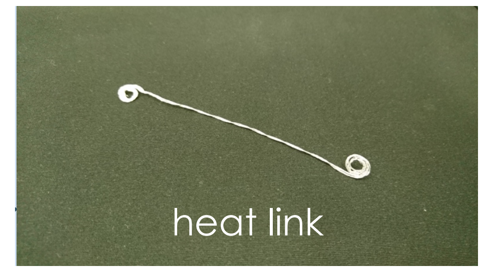
- Cool down TMs to 4 K
- Two radiation shields (50 K & 4 K)

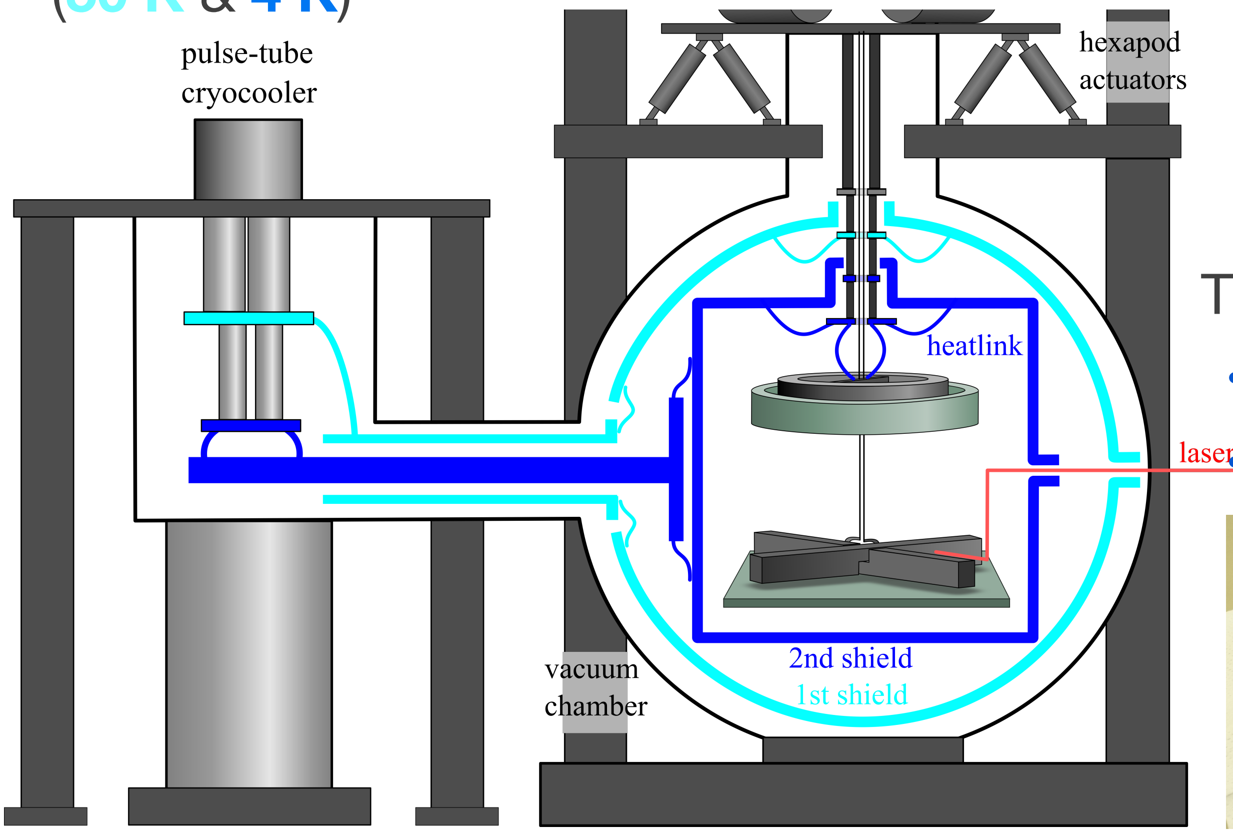
Suspension wire

- Si wire
- High Q value (>10^8)

Heat Links

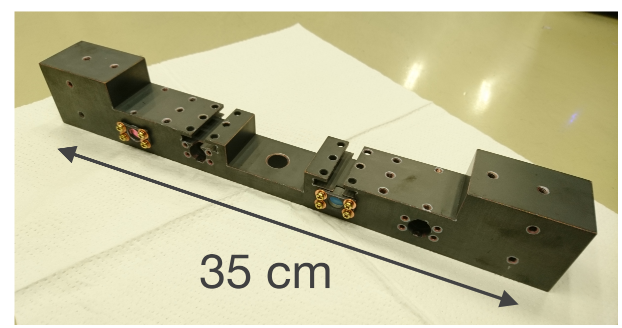
- High-purity aluminum
  - Conductive cooling





TMs

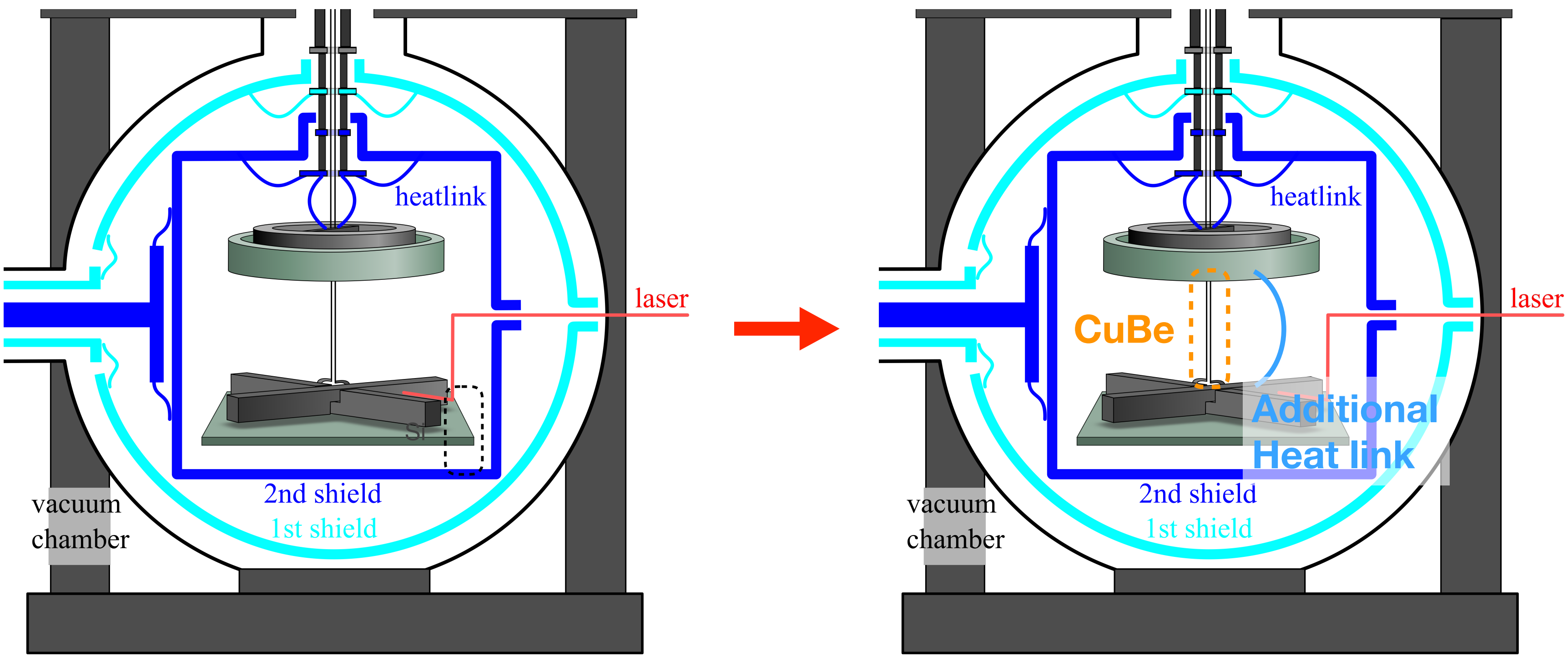
- Copper
- Surface is oxidized



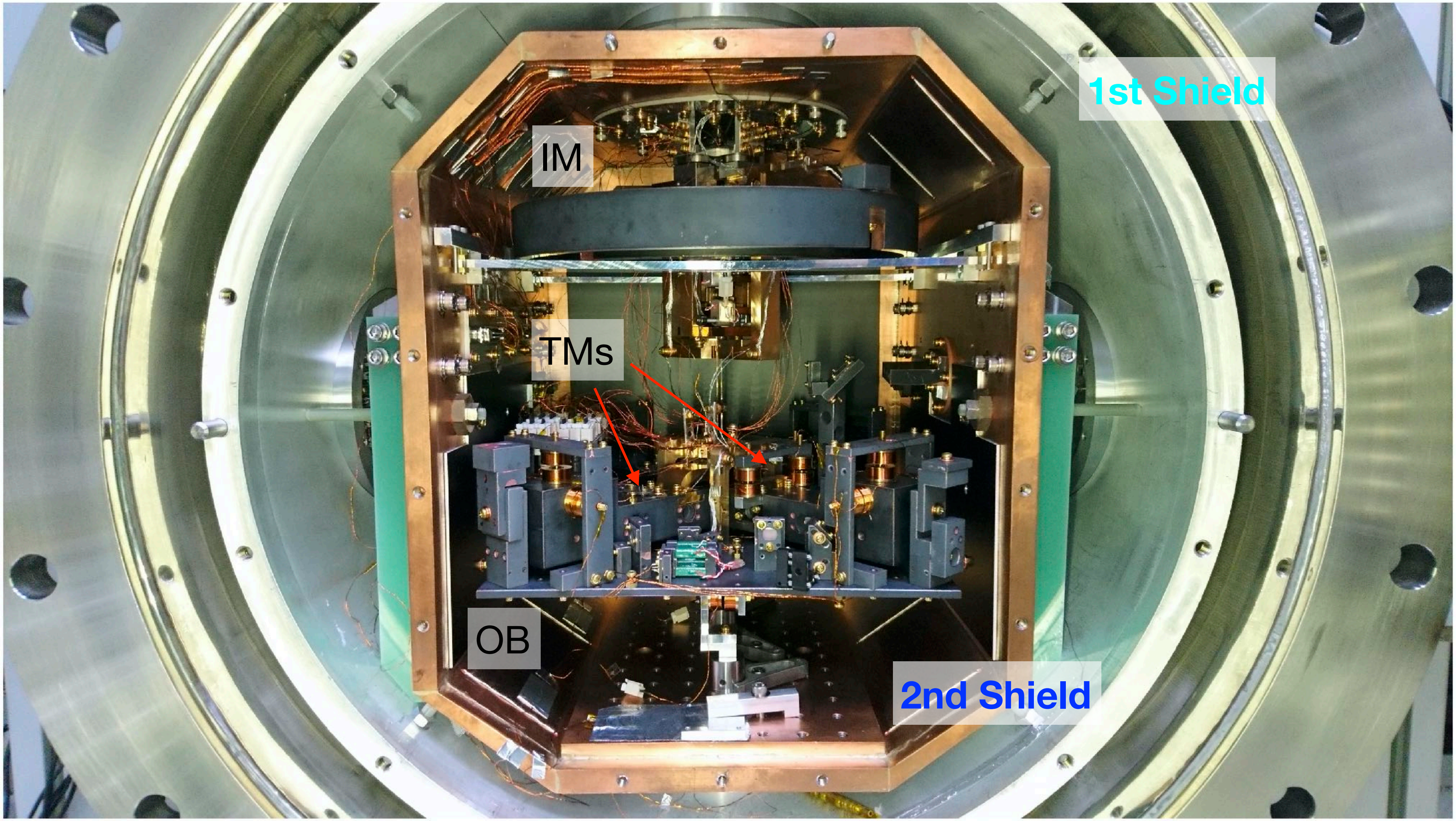
Current Suspension System

Test for cryogenic, simplified configuration

- Silicon fiber → CuBe wire
- Heatlinks between IM and TMs
- Readout: only optical levers

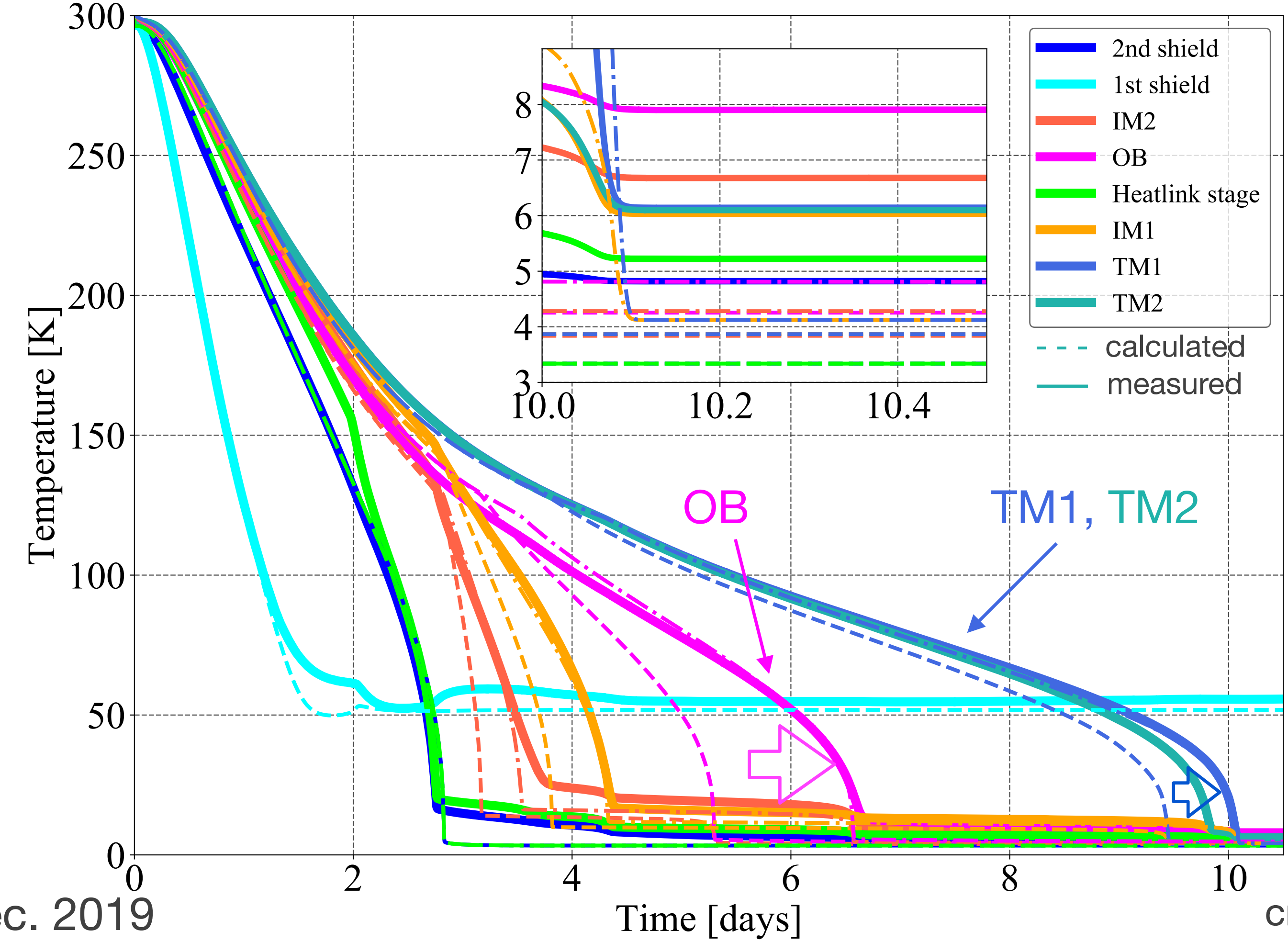


Current Setup



Cooling Result

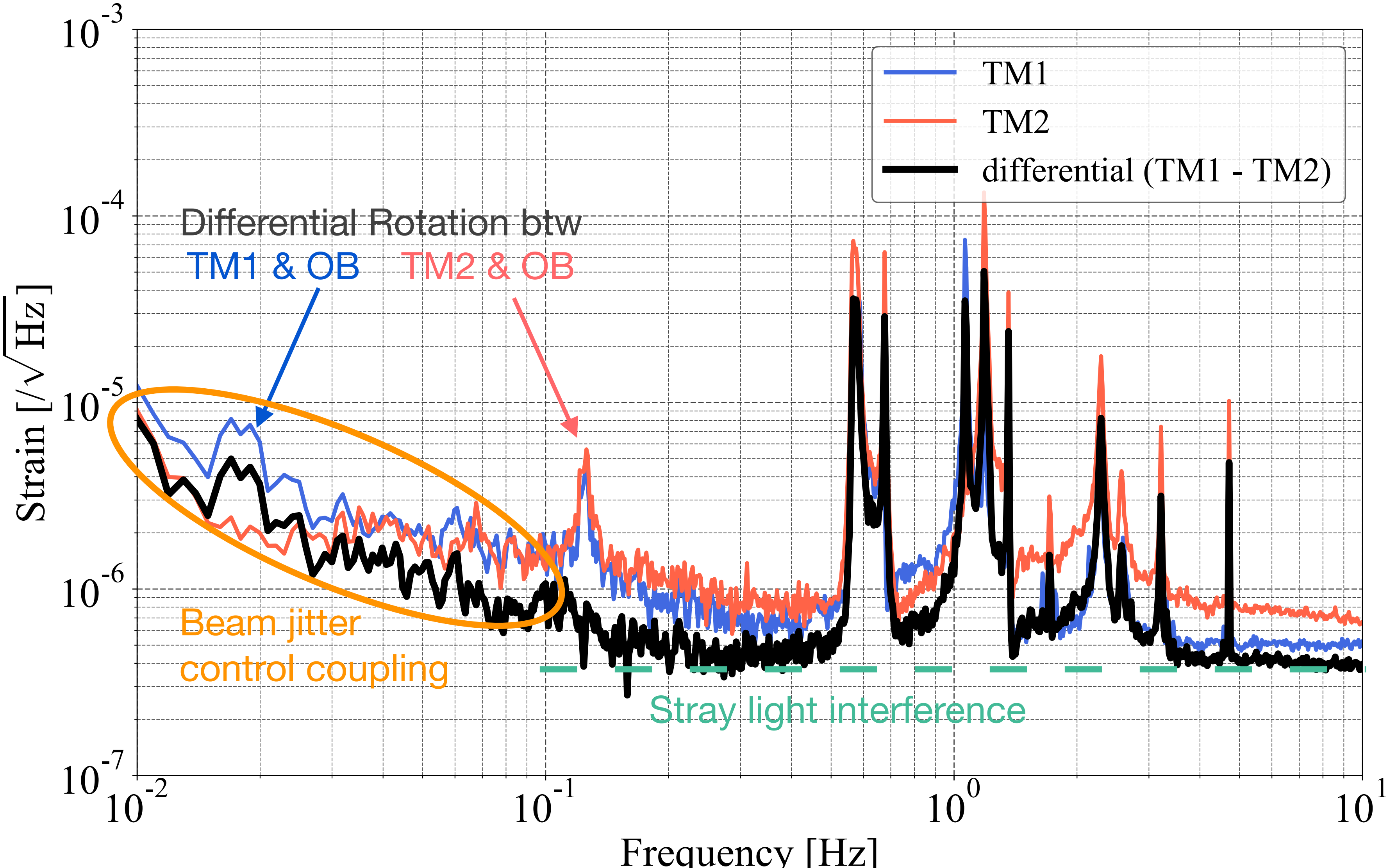
- **Cool down to 6.1 K**
- Slower cooling speed → Bad heat contact?



Result in Dec. 2019

credit: T.Shimoda

Sensitivity of differential motion



Result in Dec. 2019

credit: T.Shimoda

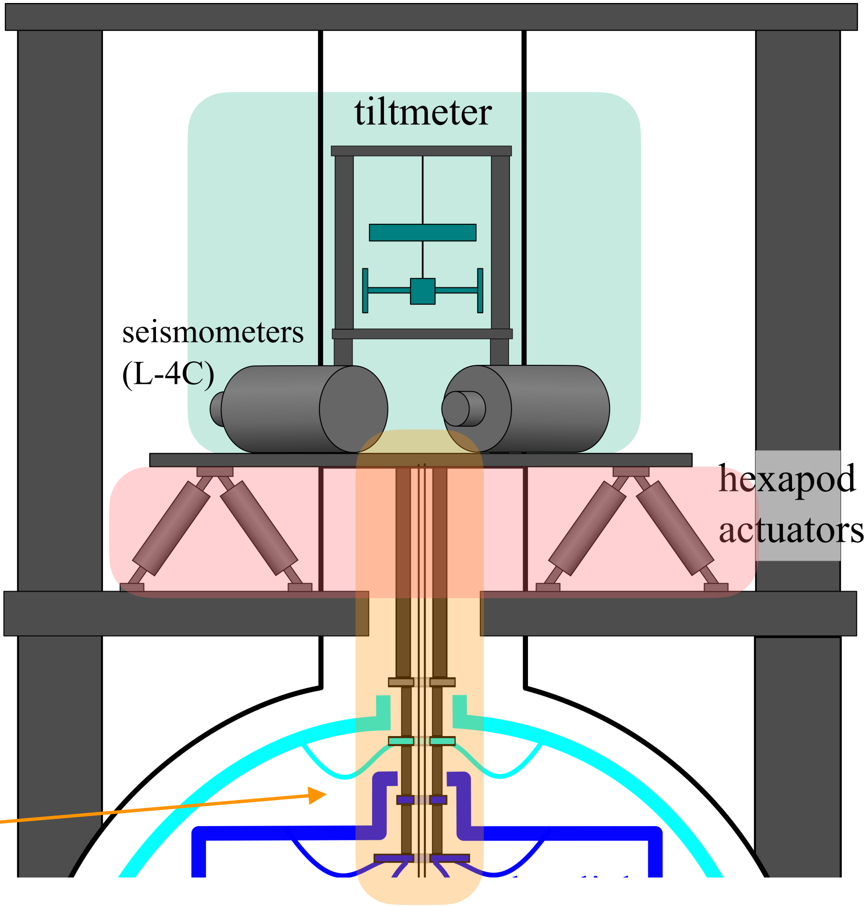
Active Vibration Isolation System

- Reduction of seismic vibration
  - Coupling from horizontal vibration
    - 10^{-7} m/√Hz @ 0.1 Hz
  - Nonlinear coupling
    - 10^{-10} m/√Hz @ 1 Hz

Measure motion at the suspension point by seismometer & tilt meter

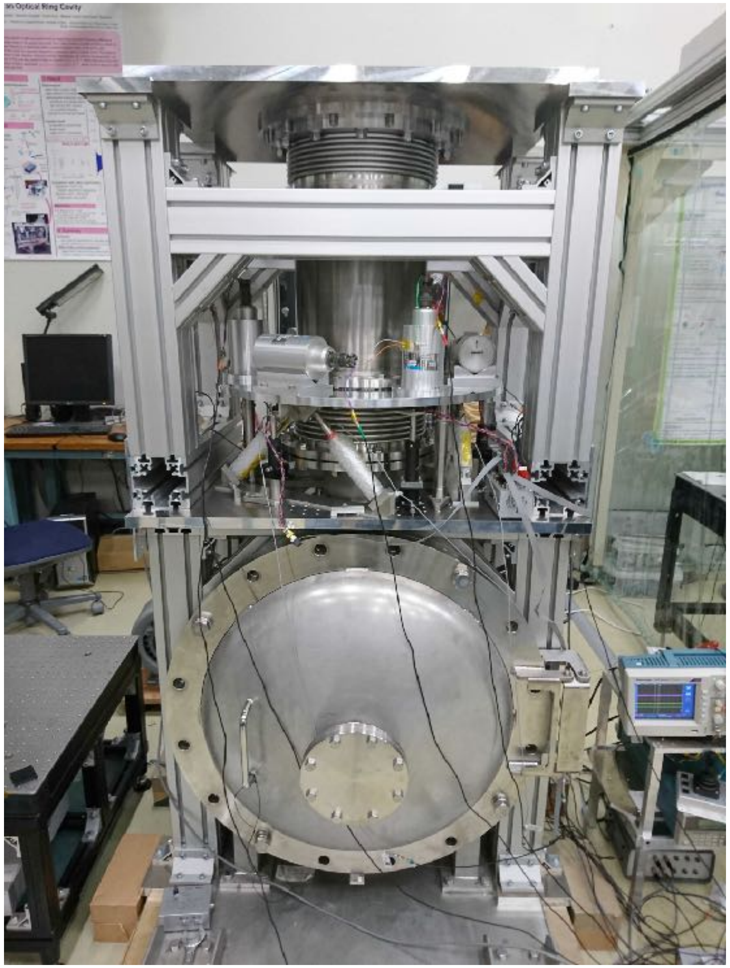
Feedback the signal to actuators to cancel out the motion

- Reduction of vibration induced by cooler

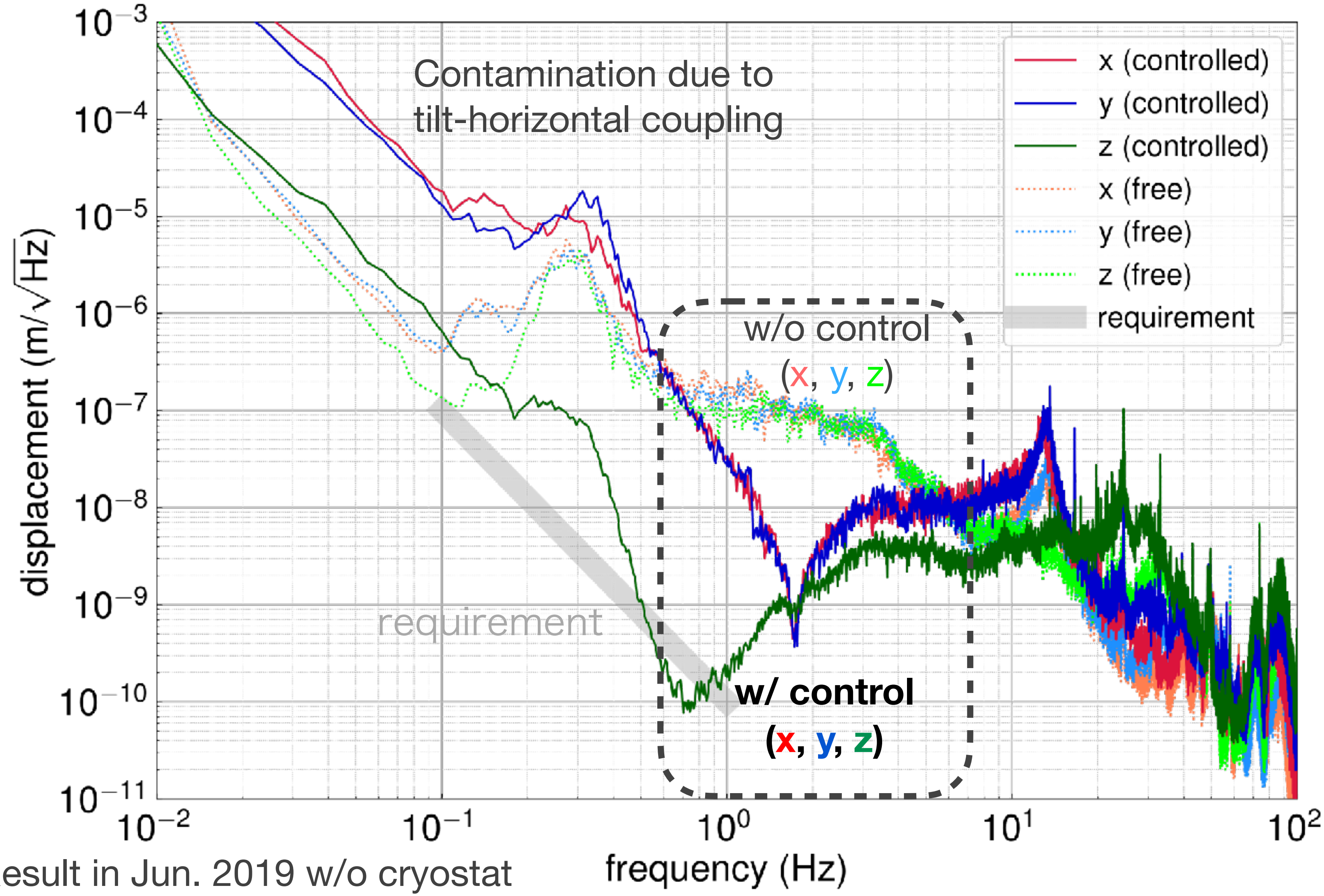


Active Vibration Isolation System

- Tested w/o the suspension and the cryostat
- Tiltmeter is not install



- Sensor: L4C (inertial) x6, PS (local) x6
- Actuator: PZT (range: ~60μm) x6



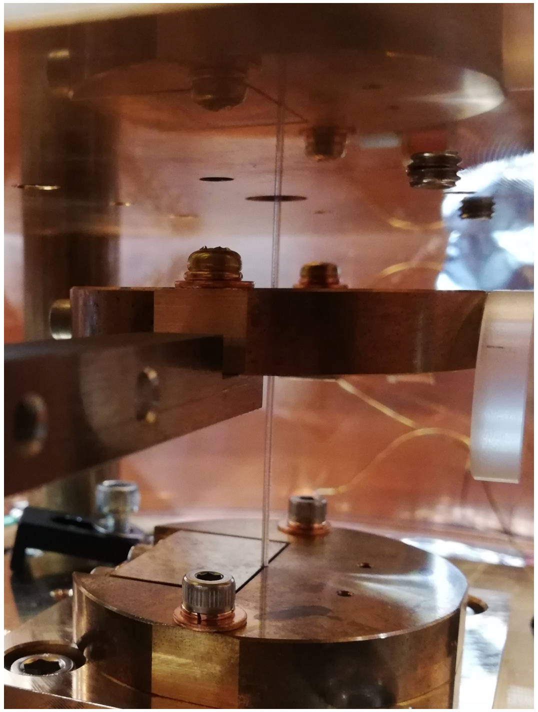
Result in Jun. 2019 w/o cryostat

High-Q Suspension Fiber

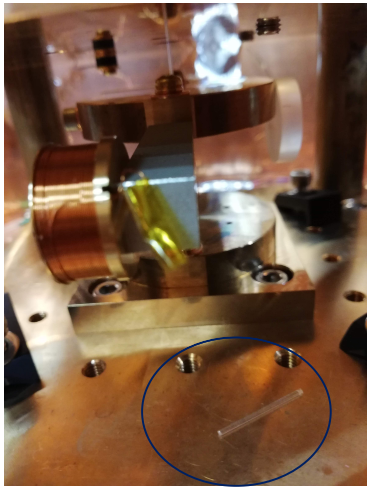
- Measurement of torsional Q of Sapphire fiber

- Coefficient of expansion is larger for CuBe than sapphire

Before cooling:



After cooling:



Broken piece

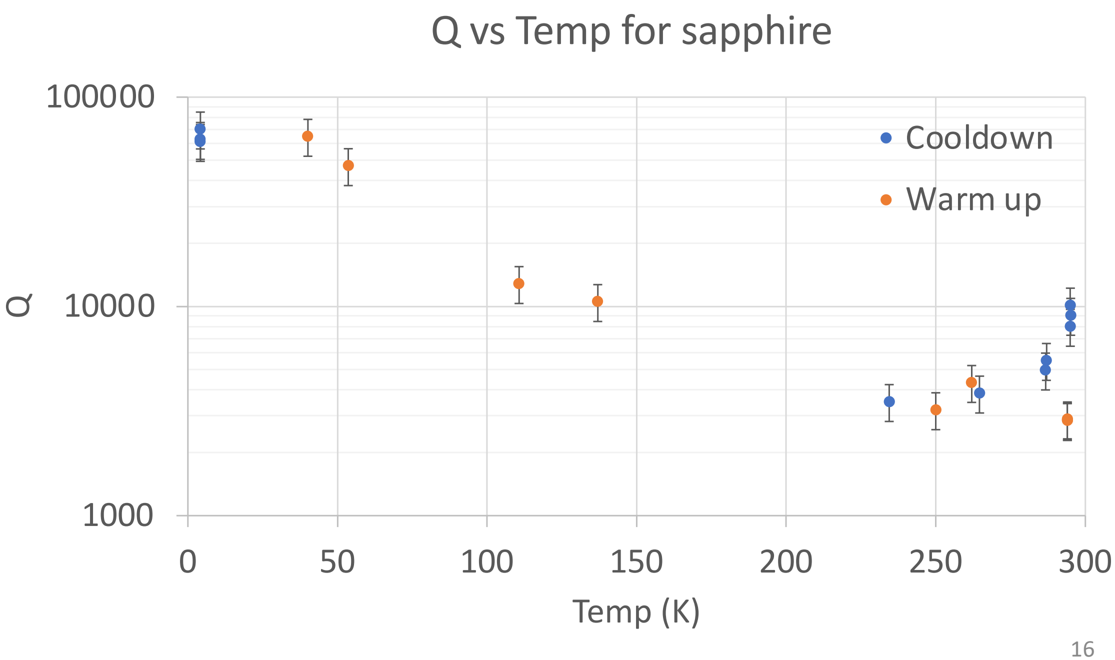
15

credit: C. P. Ooi

High-Q Suspension Fiber

- Achieved to 7x104 at 4 K
- Currently seemed to be limited by loss at the clamp

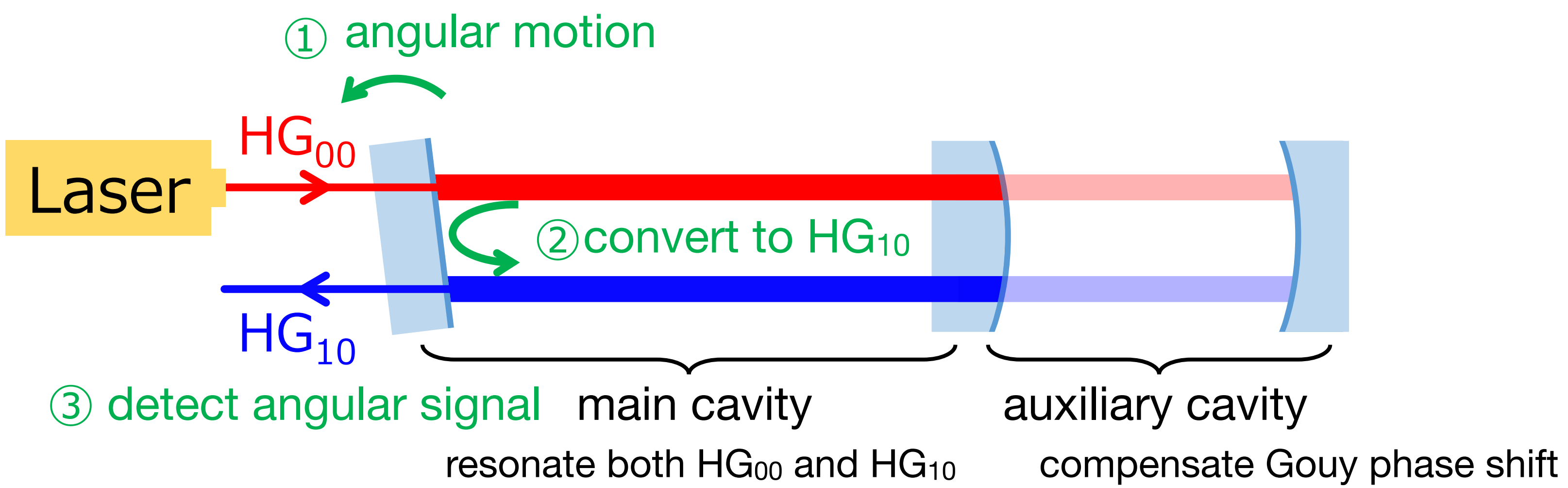
- Q ranged from 3 000 to 70 000 at 4 K
- Single clamp mode
  - Due to breakage
- Adjustments have been made to shift the pendulum frequency from the torsion frequency
  - Cannot be ruled out as source of interference



credit: C. P. Ooi

High Sensitive Angular Sensor

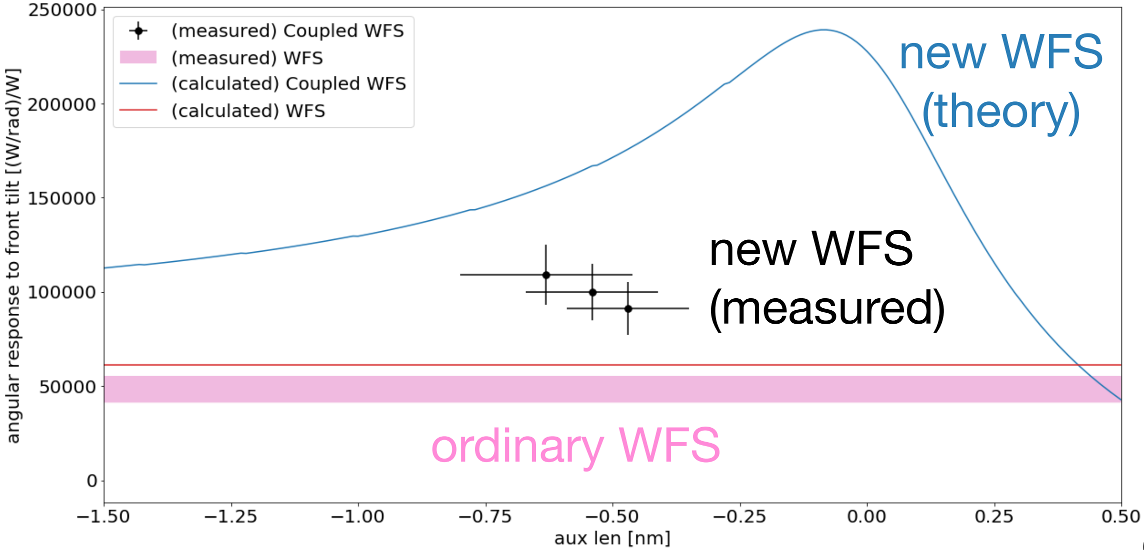
- An improved wave front sensor



- Enhance angular signal by resonating both HG00 and HG10
  - Ordinary it's impossible due to Gouy phase shift
  - Compensate it by an auxiliary cavity

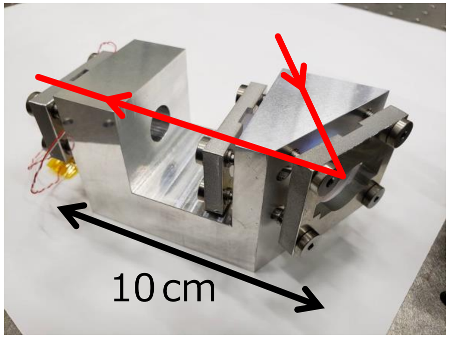
High Sensitive Angular Sensor

- Demonstration was done
  - Still need further improvement



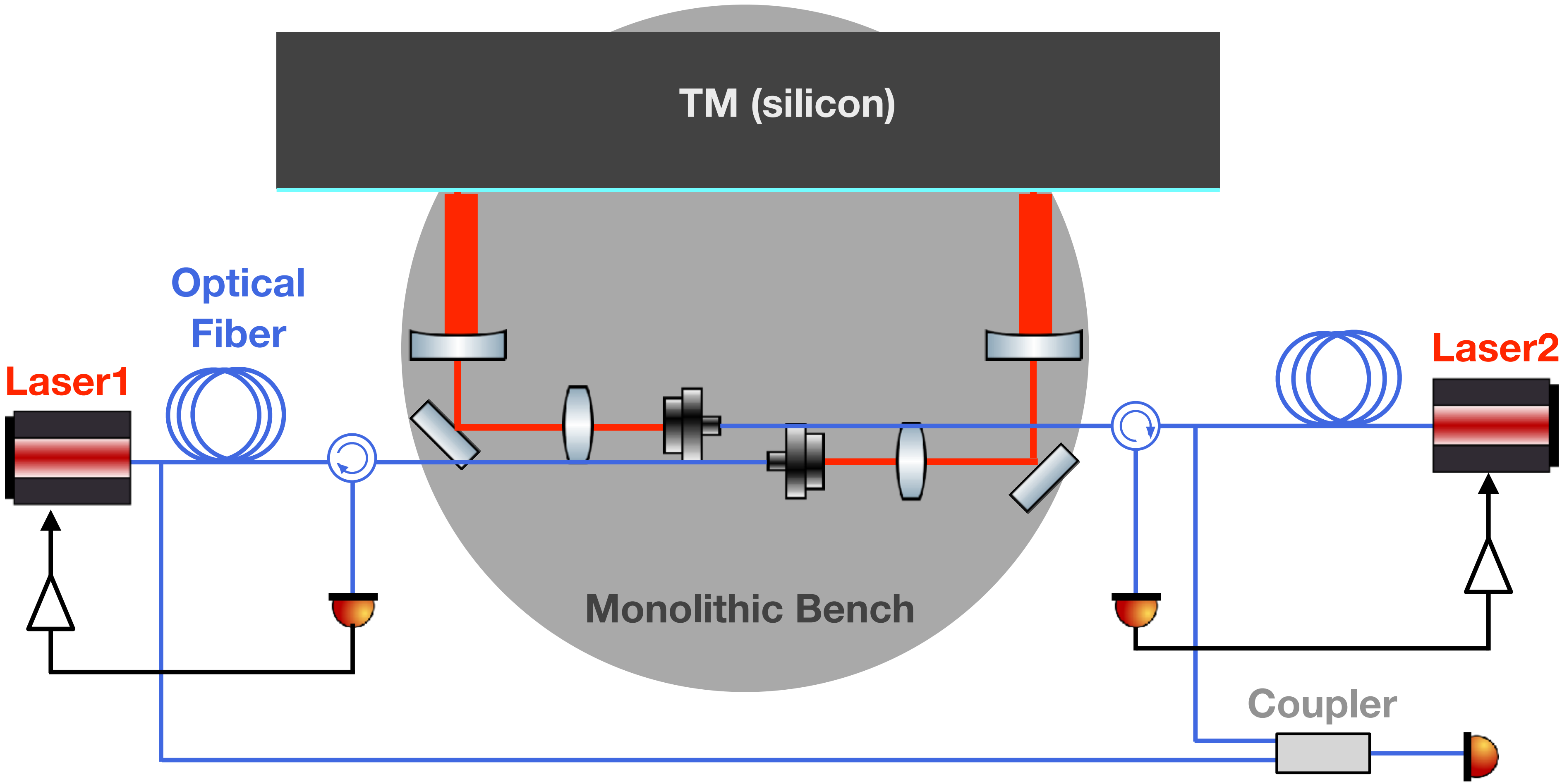
credit: Y. Miyazaki

- A new prototype is under development



credit: Y. Oshima

Monolithic Interferometer

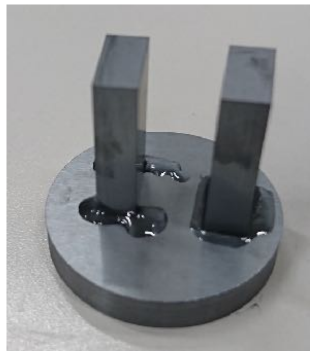


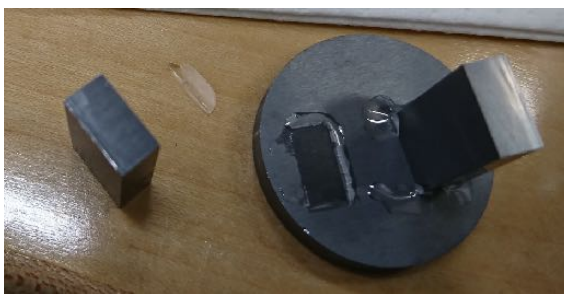
- Read displacement of each arm cavity independently (2 laser)
- Feedback to each laser's frequency
- Measure beat frequency to read differential motion

Monolithic Interferometer

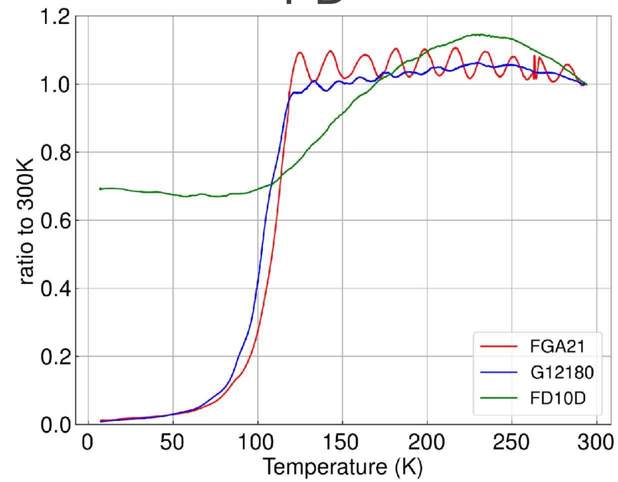
- Component selection is on going

Bonding

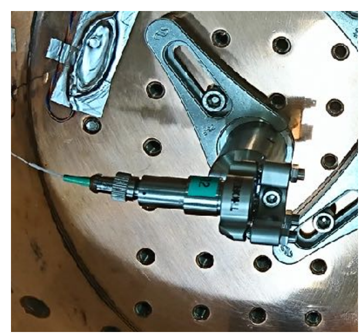


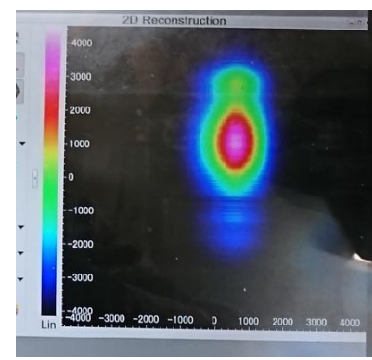


PD



Collimator



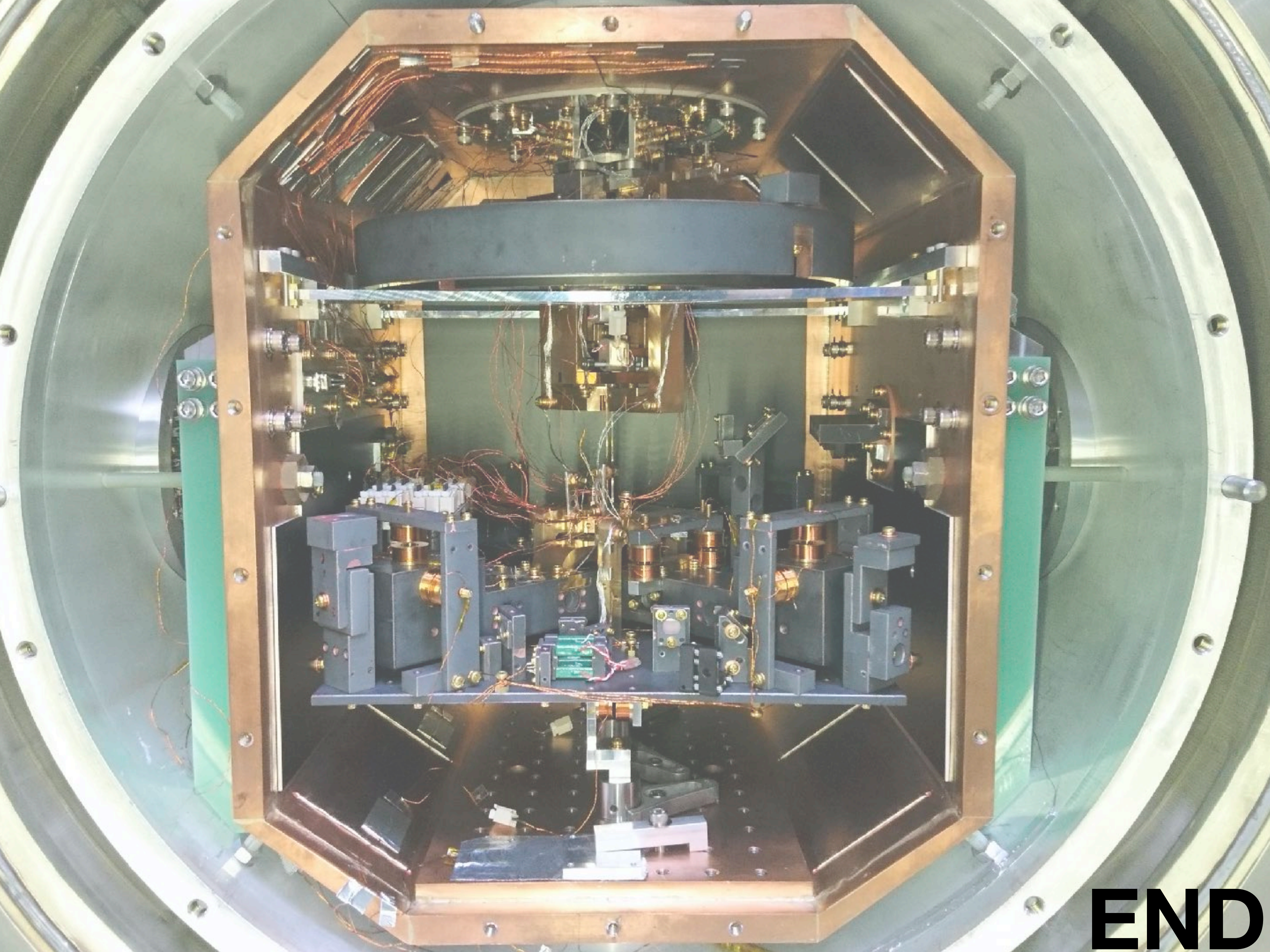


Summary

- Direct measurement of Newtonian Noise with TOBA
  - ◉ S/N > 10^3 in f < 0.1 Hz
  - ◉ Put upper limit 10^{-21} @ 10 Hz on NN of KAGRA

- Current achievement
  - ◉ Cryogenic → basically demonstrated
    - ▶ Need some improvements (cooling speed, achieved temp.)
  - ◉ Active isolation vibration → 3 DoF controlled
    - ▶ Decouple tilt motion from horizontal translation

- On-going issues
  - ◉ Development of high-Q silicon fiber
  - ◉ Demonstration of coupled WFS
  - ◉ Cryogenic monolithic interferometer

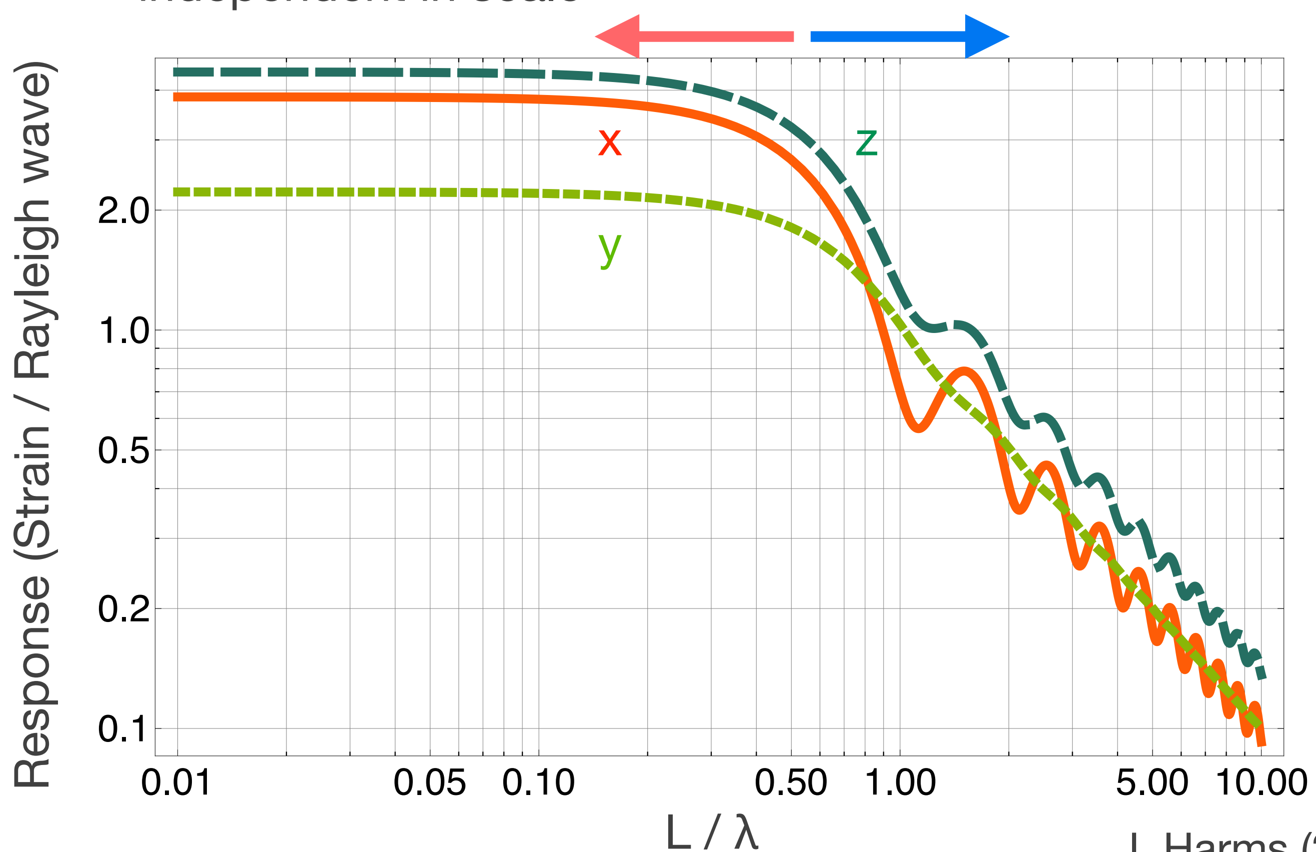


END

Seismic NN in Different Scale

- Response from Rayleigh waves to NN (arm: x direction)

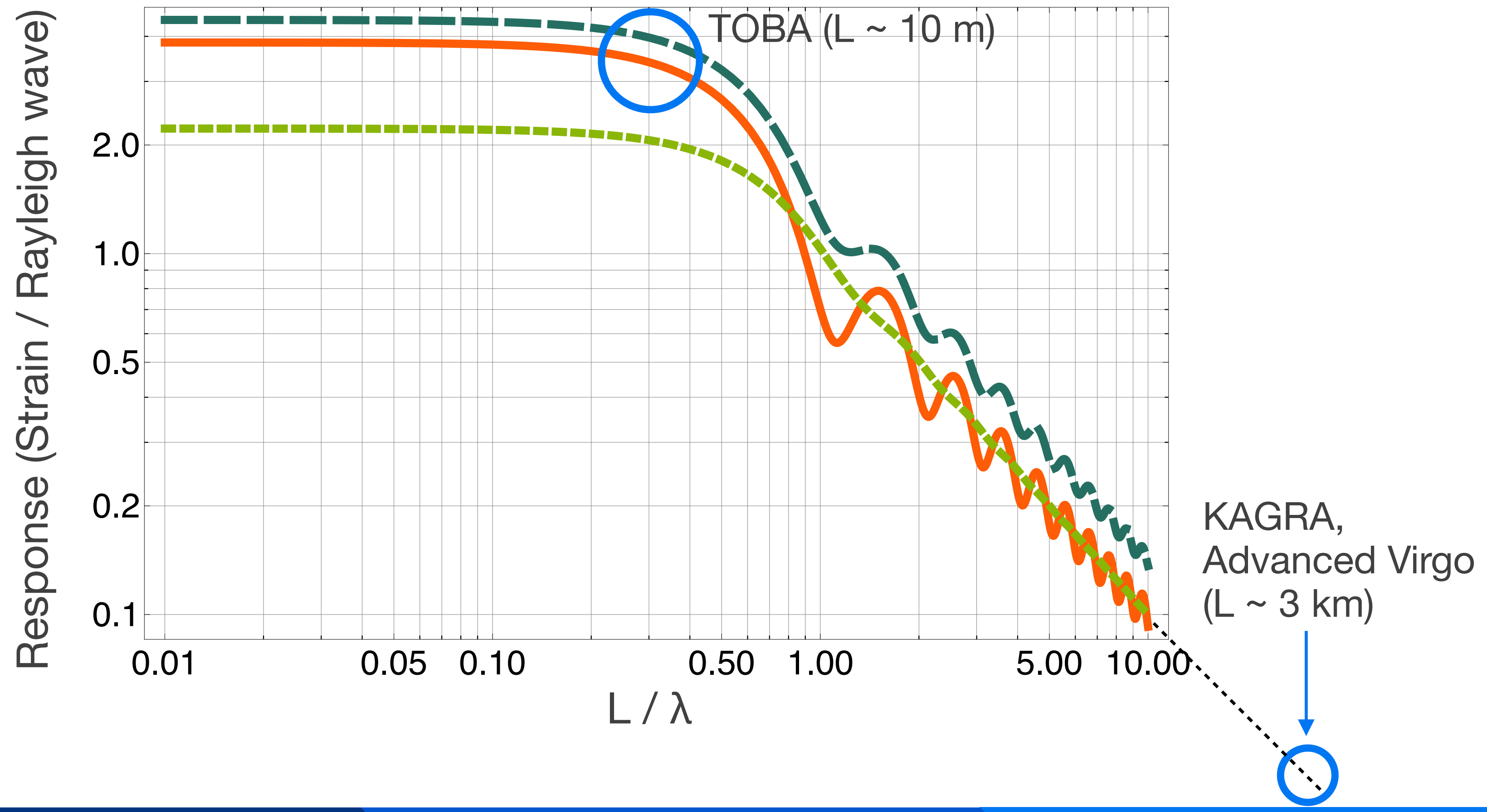
NN is coherent in detector scale
▸independent in scale



J. Harms (2015)

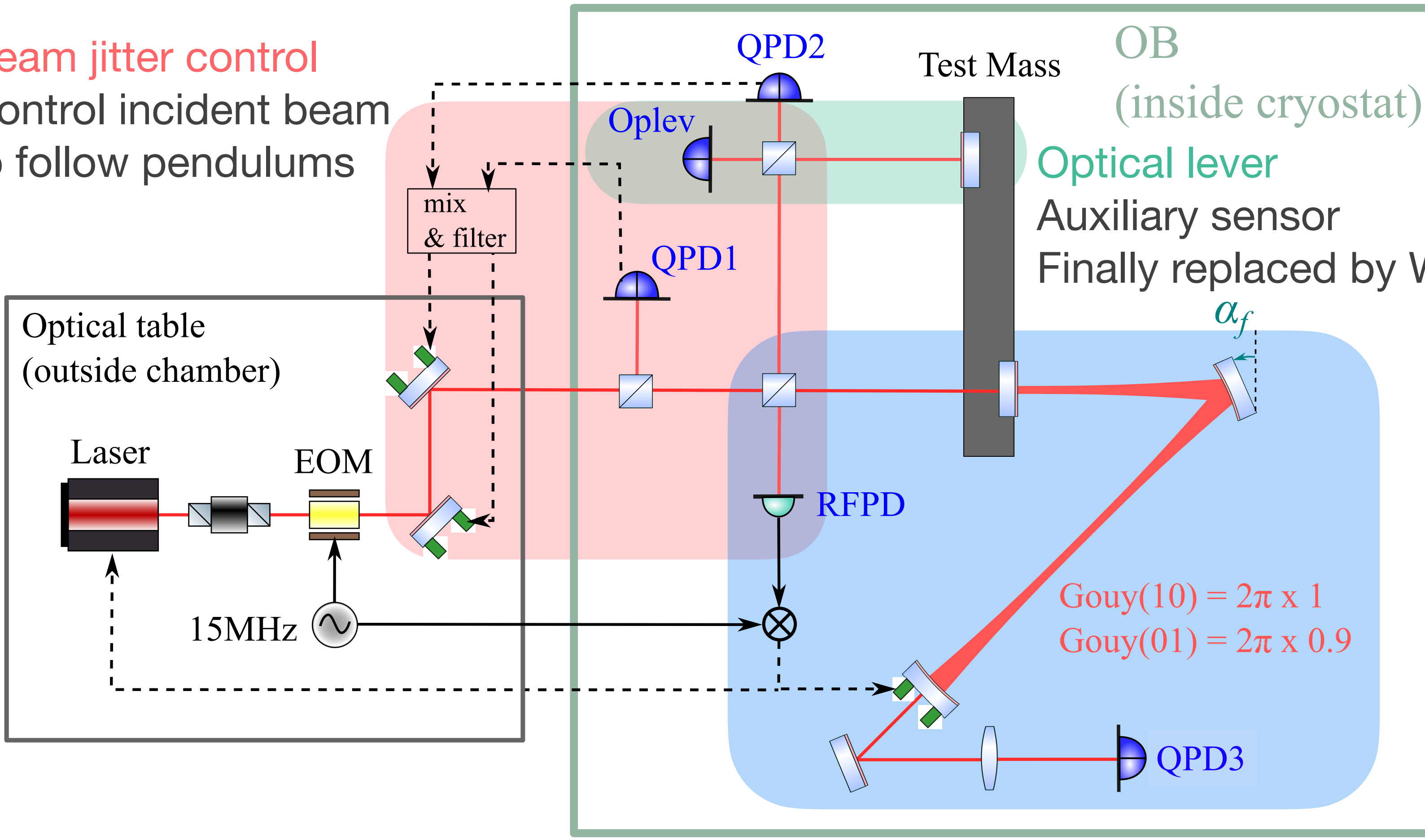
Seismic NN in Different Scale

- Rayleigh wave length: λ ~ 30 m @ 10 Hz (v ~ 300 m/s)
- TOBA: L ~ 10 m ↔ KAGRA, Advanced Virgo: L ~ 3km
  - ▸**more sensitive** ET: L ~ 10 km



Optical System

Beam jitter control
Control incident beam
to follow pendulums



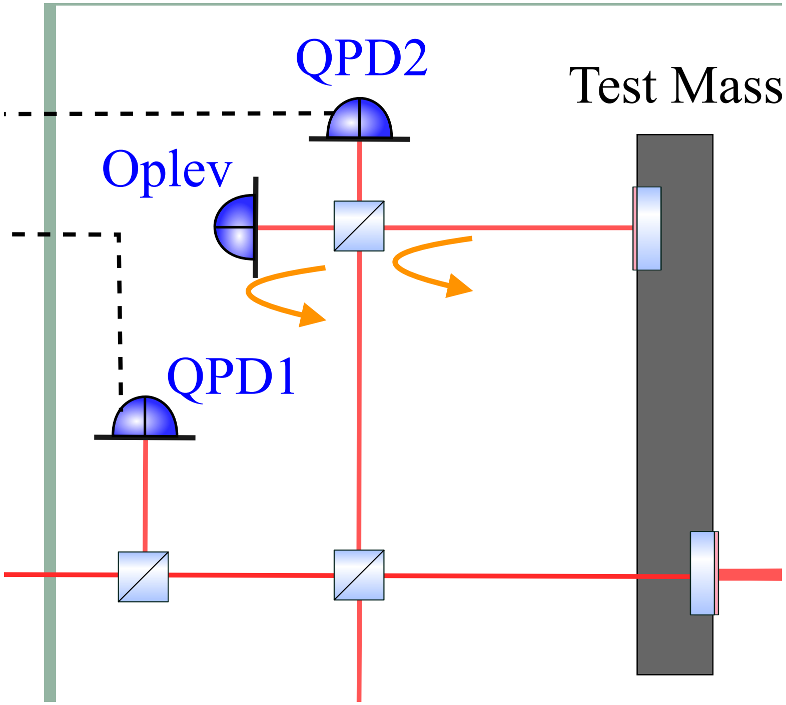
Optical lever
Auxiliary sensor
Finally replaced by WFS

High sensitive angular sensor
Measure HG10 mode
induced by rotational motion

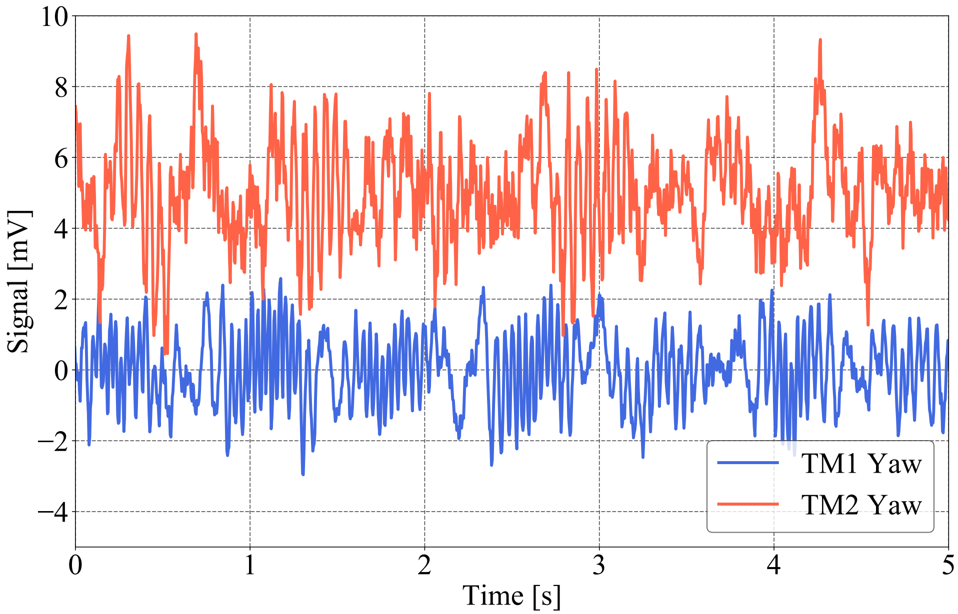
Stray Light Problem

Front reflection at

- Cube BS
- QPD surface
  - Stray light

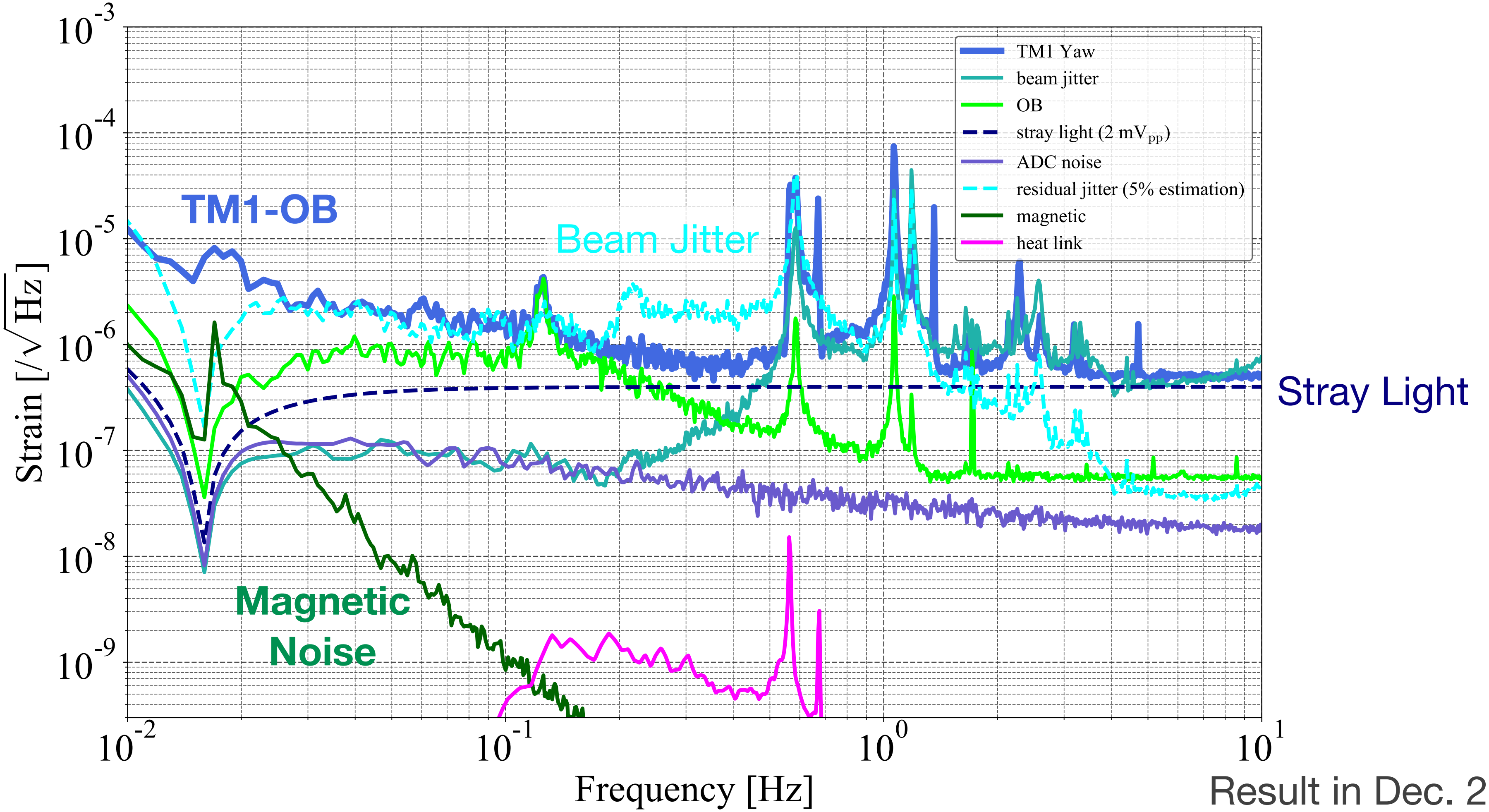


Interference with stray light contaminates oplev signal



Sensitivity of one TM

- Limited by **beam jitter**, **interference of stray light**
- Unexpected noise: **magnetic noise** due to eddy current flowing TM

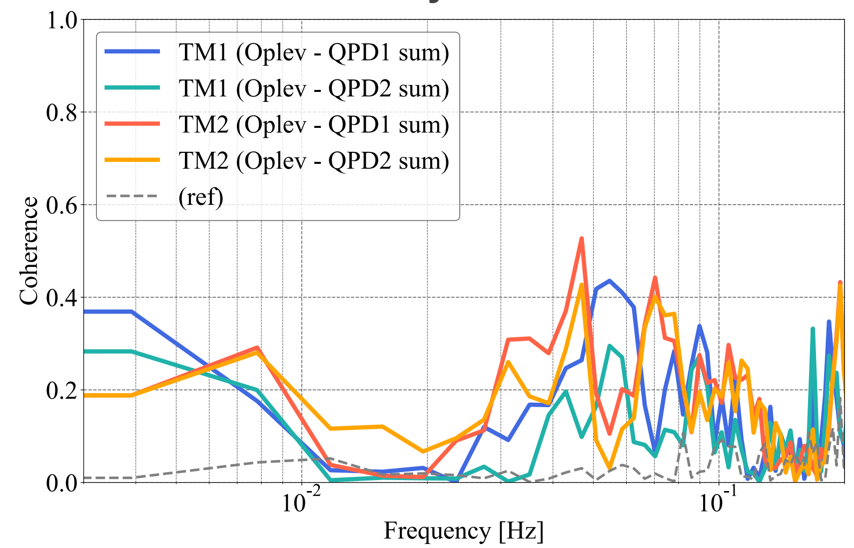


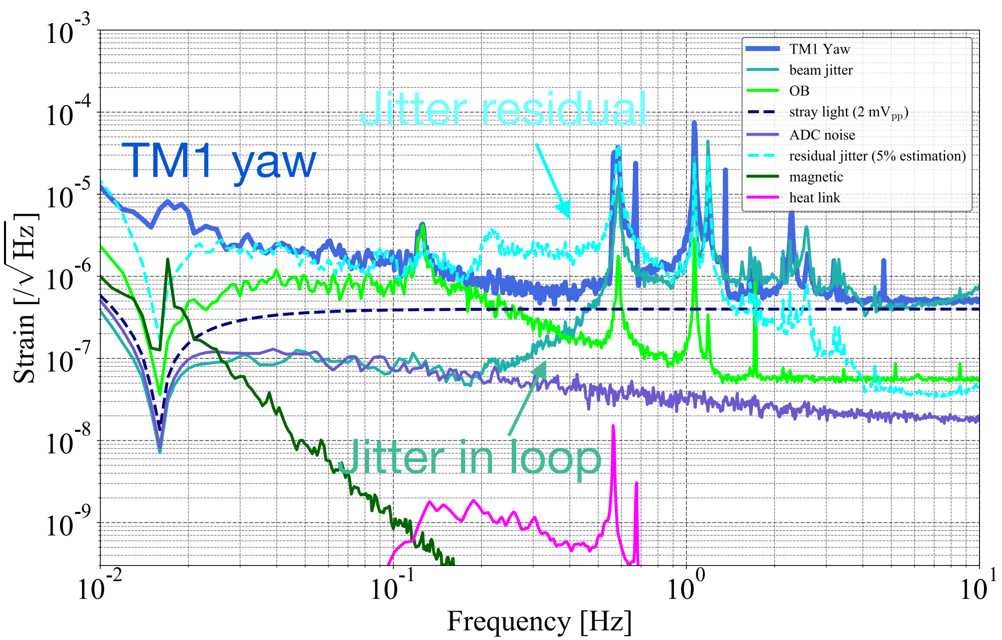
Result in Dec. 2019

Beam Jitter Control Noise

- Some coherence btw TM oplev yaw & Jitter QPD sum
  - Beam jitter control signal shakes beam additionally
  - Contaminates oplev signal

Coherence btw
TM oplev yaw & QPD sums





5% residual assumption

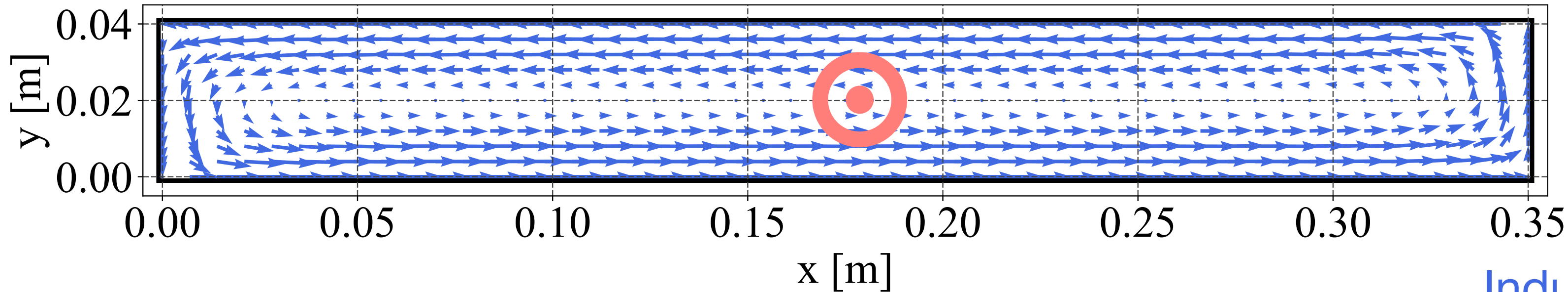
- can be explained the noise budget well

Magnetic Noise Due to Eddy Current

- Ambient magnetic fluctuation induces eddy current
  - TM has magnetic dipole moment $\tilde{\boldsymbol{\mu}}$

Induced magnetic dipole moment

$\tilde{\boldsymbol{\mu}}$

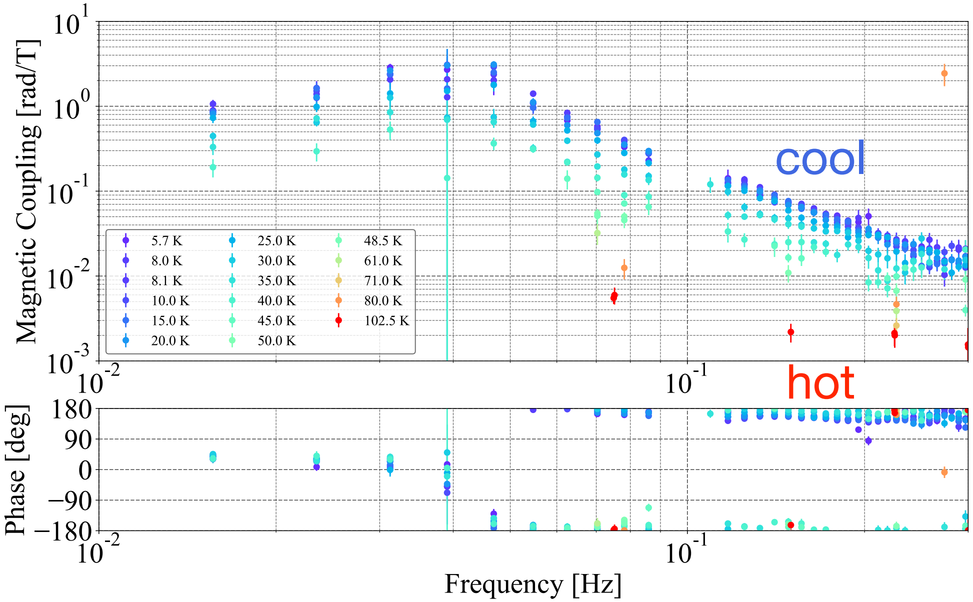


Induced
eddy current

  - This $\tilde{\boldsymbol{\mu}}$ induces torque noise $\tilde{\boldsymbol{\mu}} \times \boldsymbol{B}$ with DC magnetic field $\boldsymbol{B}$

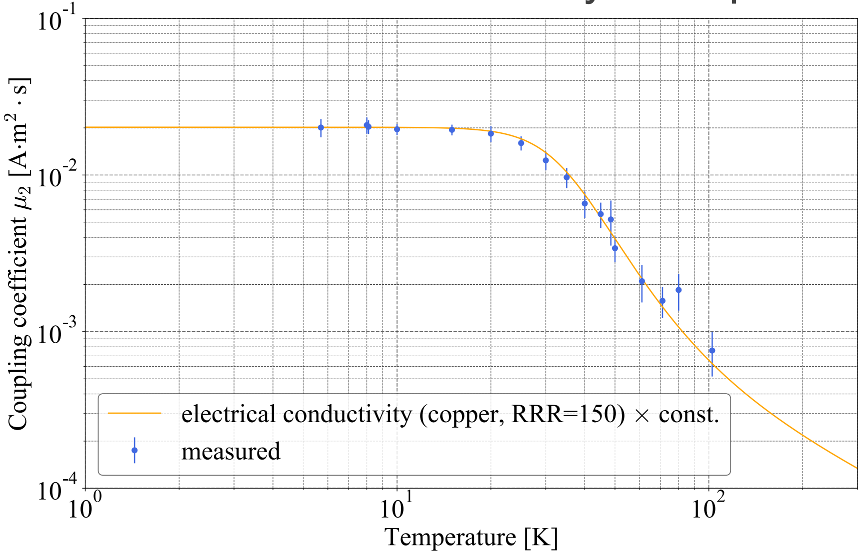
Magnetic Noise Due to Eddy Current

- Induced eddy current ∝ electric conductivity
- For metals electric conductivity gets larger when cooled down
  - ▶ Coupling gets larger at lower temperature



Transfer function
from magnetic fluctuation to TM yaw

Electrical conductivity of coper



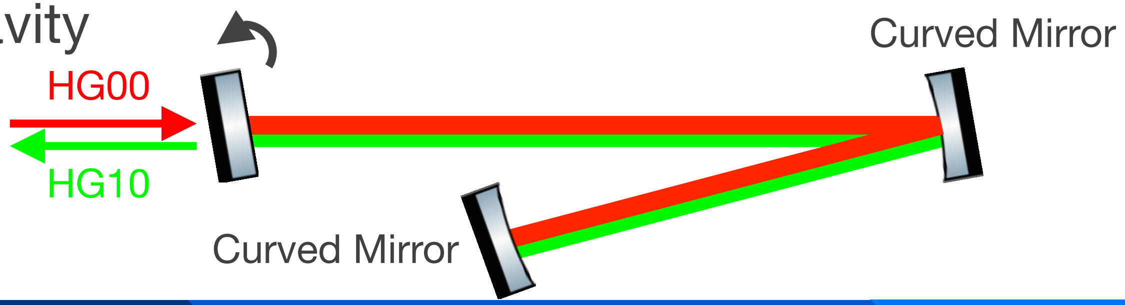
High Sensitive Angular Sensor

Cavity-enhanced wave front sensor (new idea)

- Compensate Gouy phase difference between HG00 and HG10
  - HG10 mode resonates as well as HG00
  - Induced HG10 is enhanced
  - Higher sensitivity than normal WFS

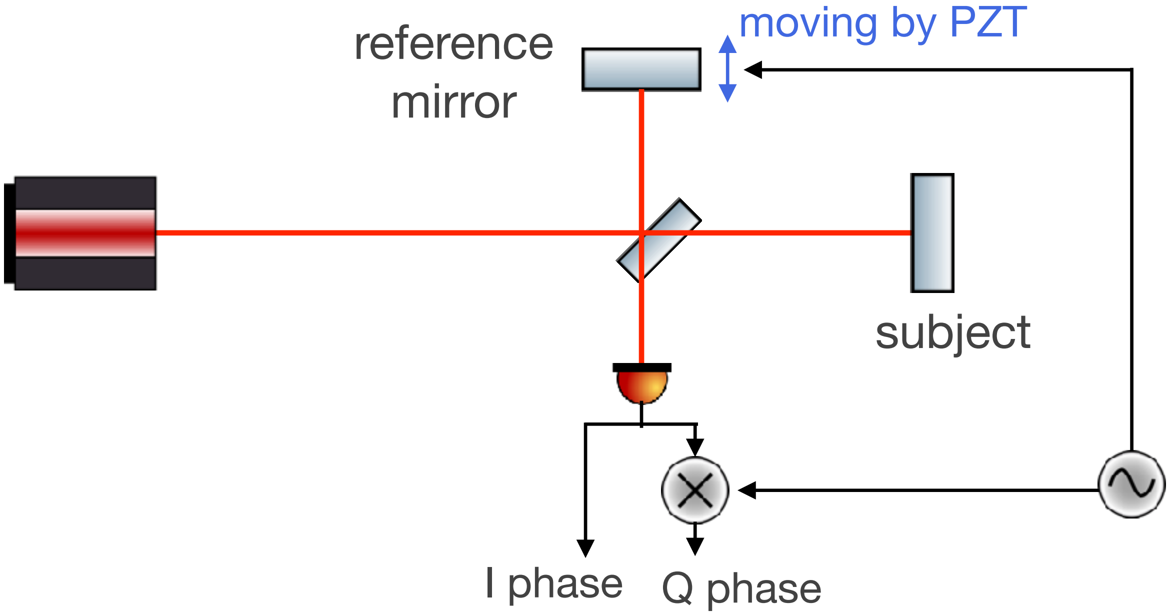
    5×10^{-16} rad/√Hz @ 0.1 Hz
- How to compensate
  - Auxiliary cavity

  - Folded cavity

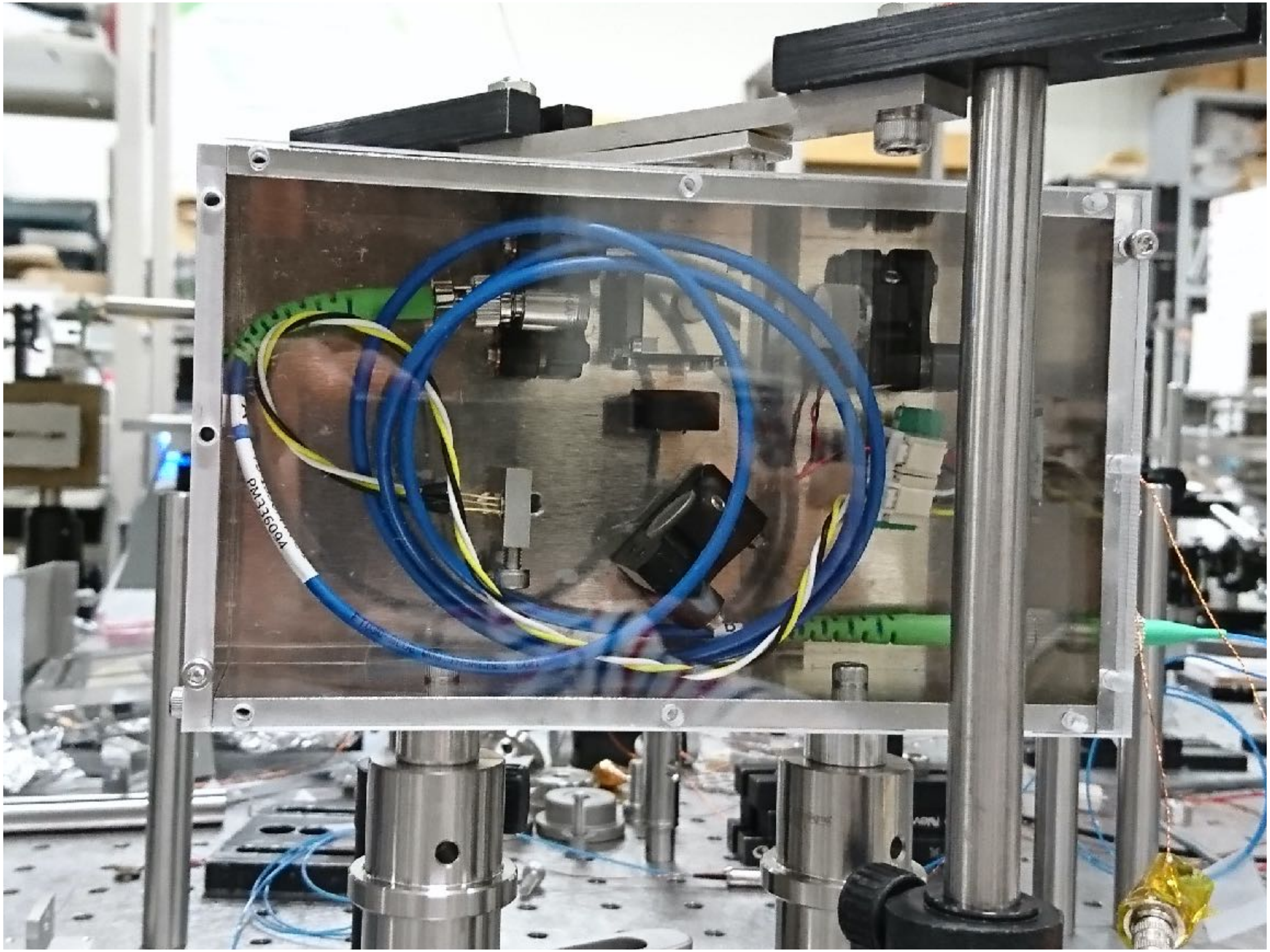


Local Quadrature Interferometer

- Quadrature Interferometer for a local sensor of AVIS
- Michelson interferometer with a dithered reference mirror
  - Resolution: same as Michelson interferometer
  - Range: ∞ (ideally)
- No polarization optics
- Generate quadrature signal by moving reference mirror



Picture



Performance