

Updates on Cryogenic Interferometric Inertial Sensors & Low Vibration Cryogenic facility

Morgane Zeoli

Supervisors: Christophe Collette, Joris van Heijningen, Giacomo Bruno

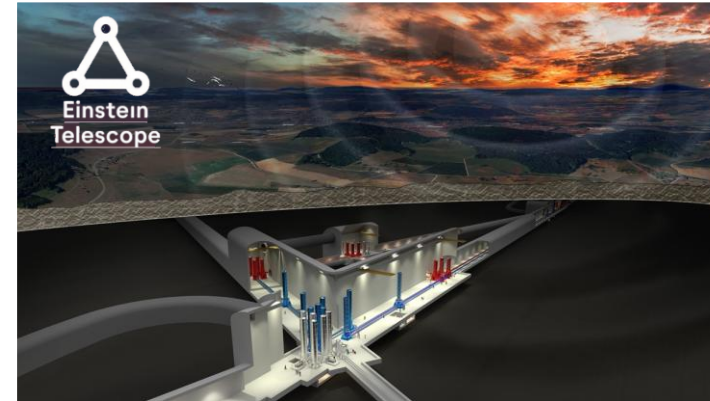
Why cryogenic inertial sensors

Kagra (2022)

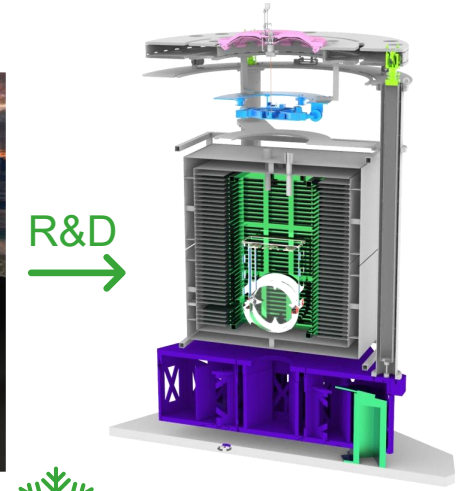


Need for a highly sensitive cryogenic inertial sensor

Einstein Telescope (2020)



E-TEST ETEST (2023)



R&D
→

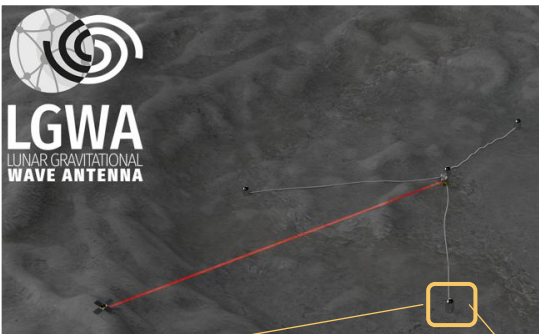


Cryogenic payload

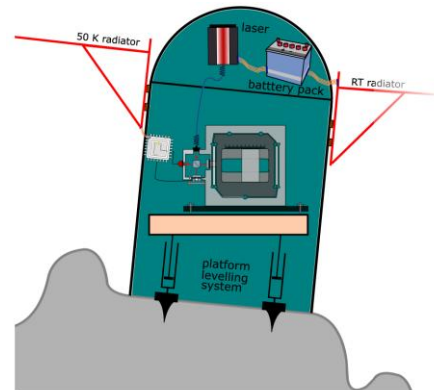
Highly performant
vibration isolation
systems



LGWA (2023)



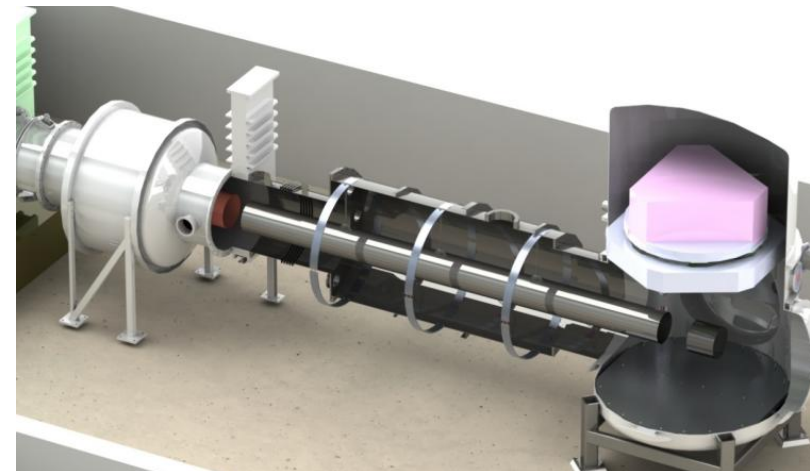
Star-configuration array
of seismic station in a
40K environment



LGWA Soundcheck

1st step

LIGO Voyager (2024)



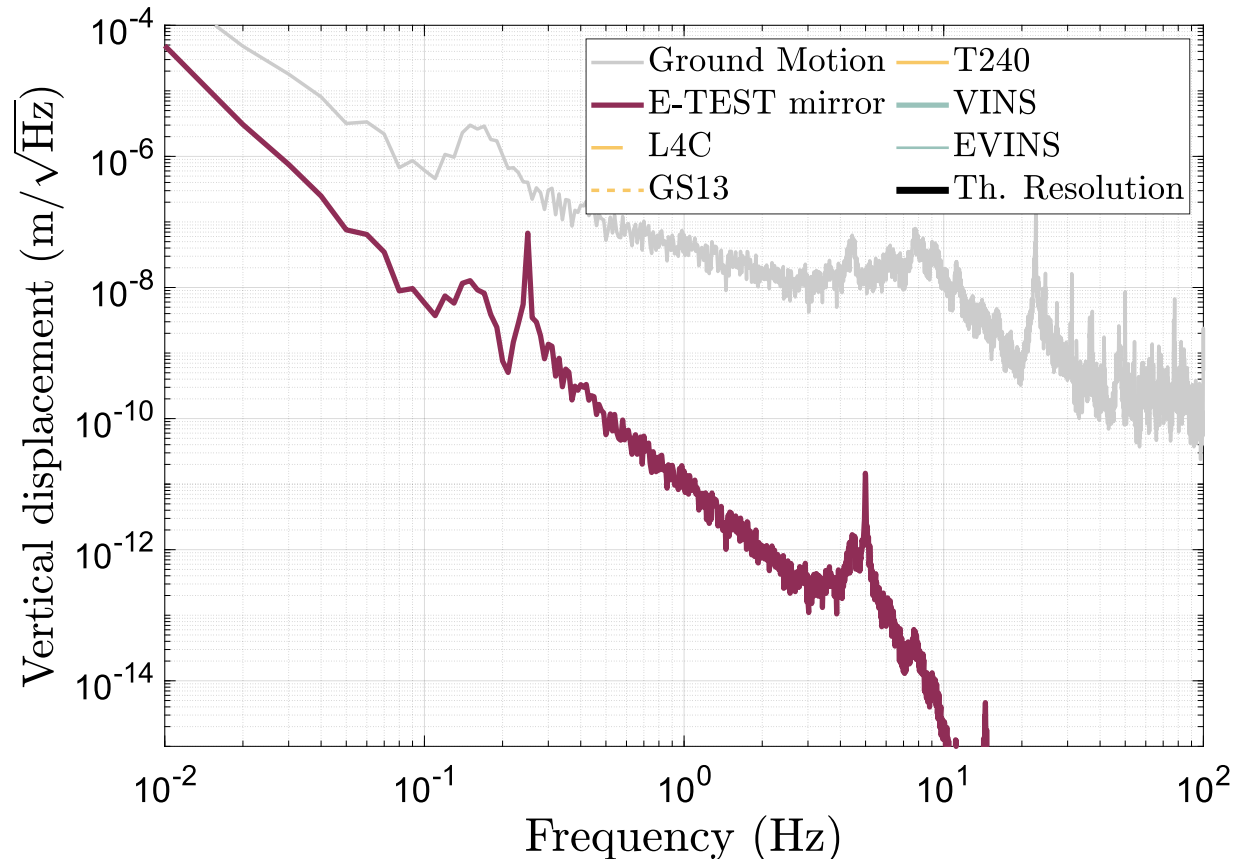
Goal and requirements



E-TEST is a prototype suspension, combining passive and active isolation techniques, of a 100 kg silicon mirror cooled down radiatively to 25 K in a suspended cryostat

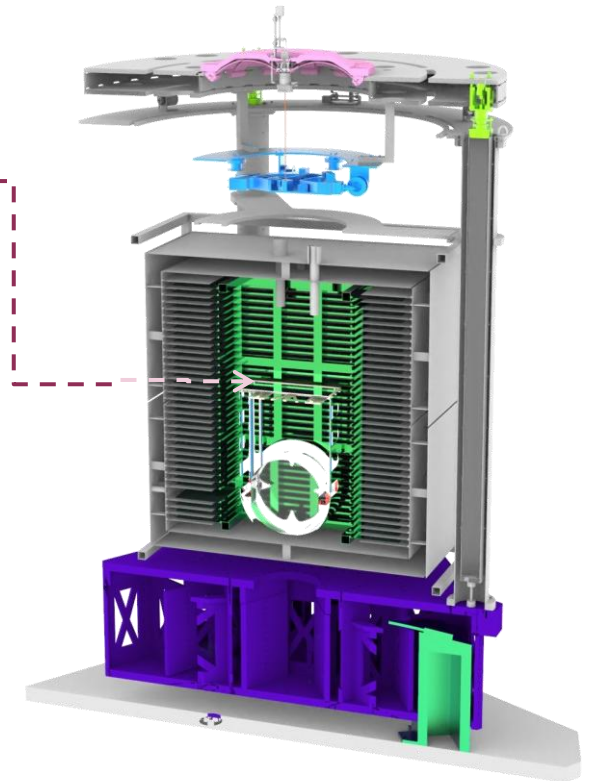
Monitor residual motion at the last isolation stage, in the cryostat

Develop and validate **cryogenic compatible inertial sensors** with a sensitivity of 2×10^{-14} m/√Hz from 2/3 Hz at 20K
from 2/3 Hz at 20K



Typical ground motion

Target residual motion at E-TEST mirror level



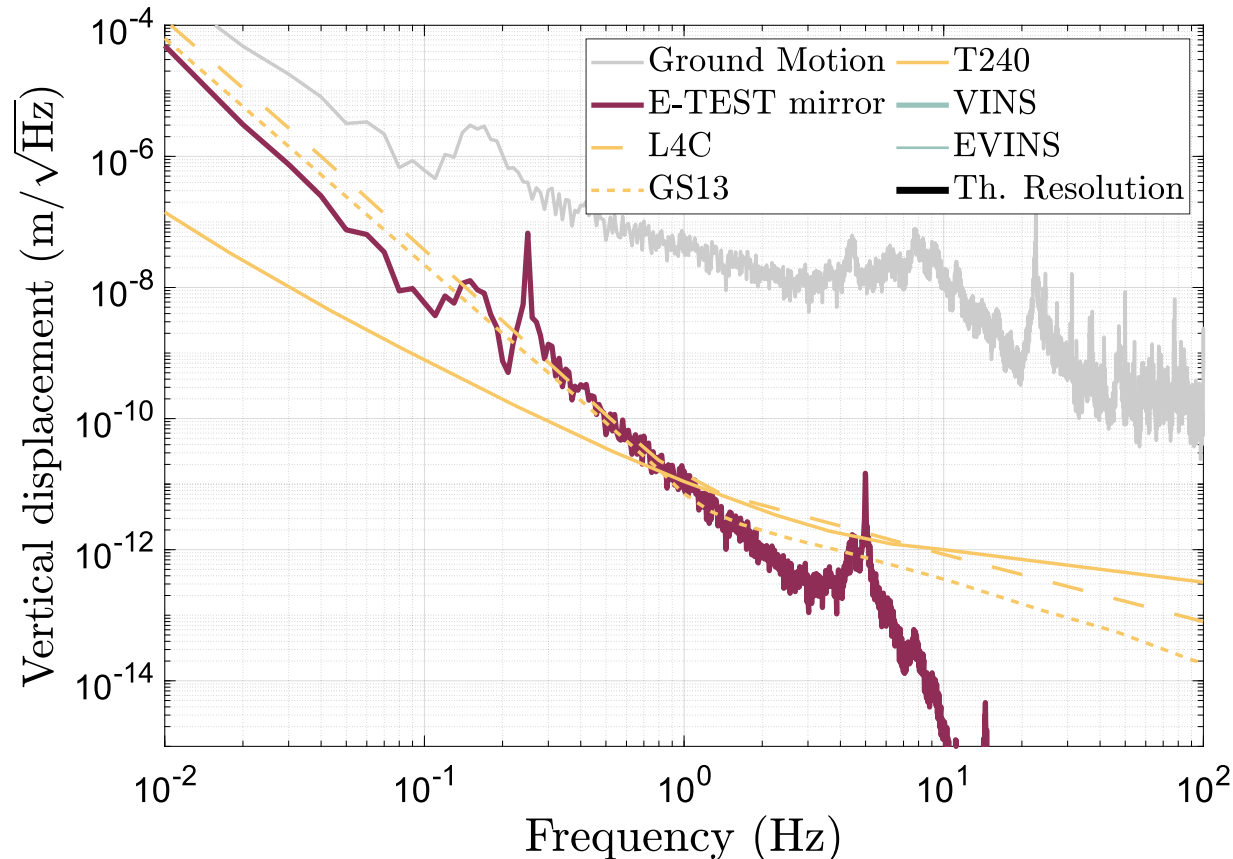
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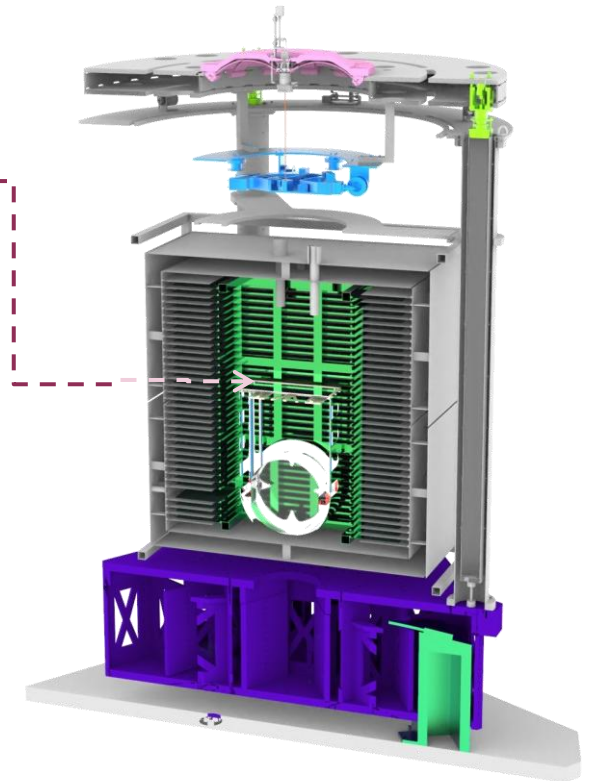
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Commercial sensor (not vacuum nor cryo compatible)



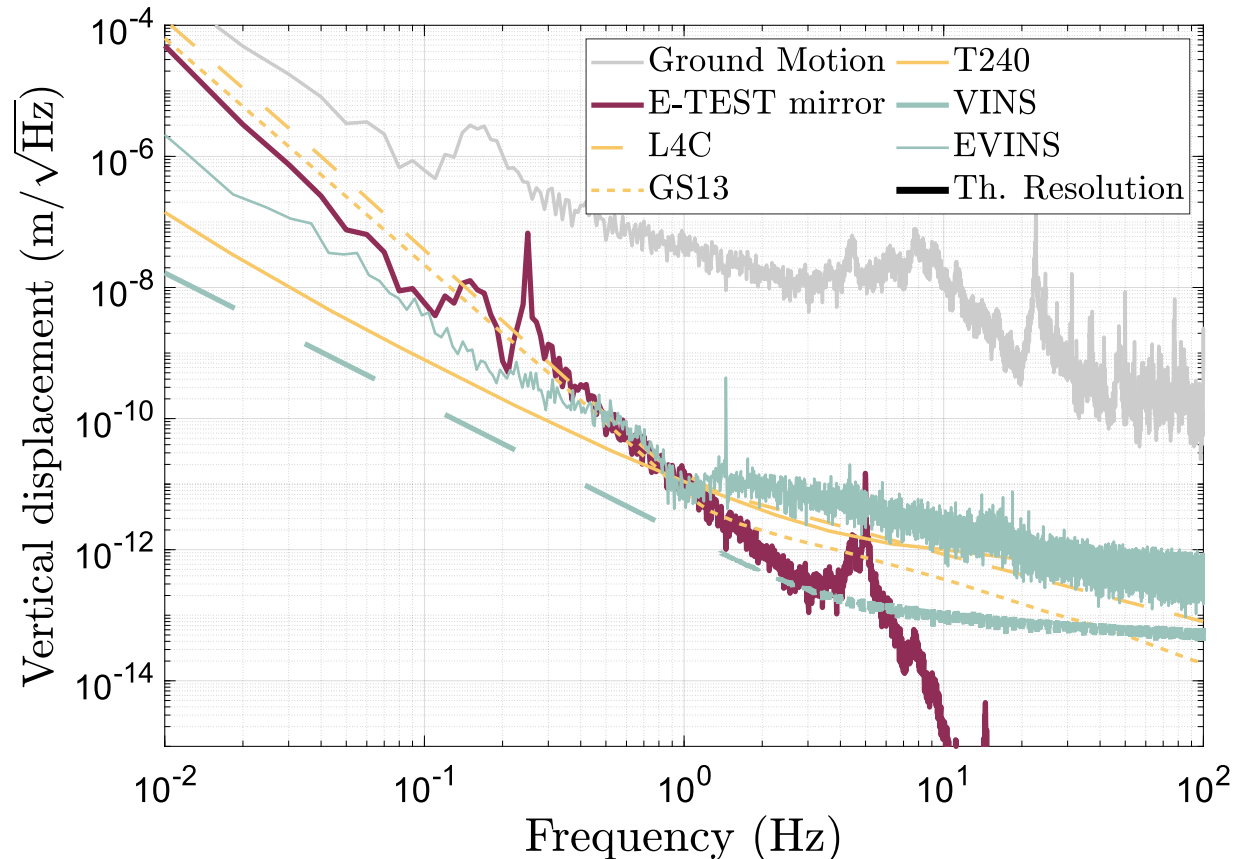
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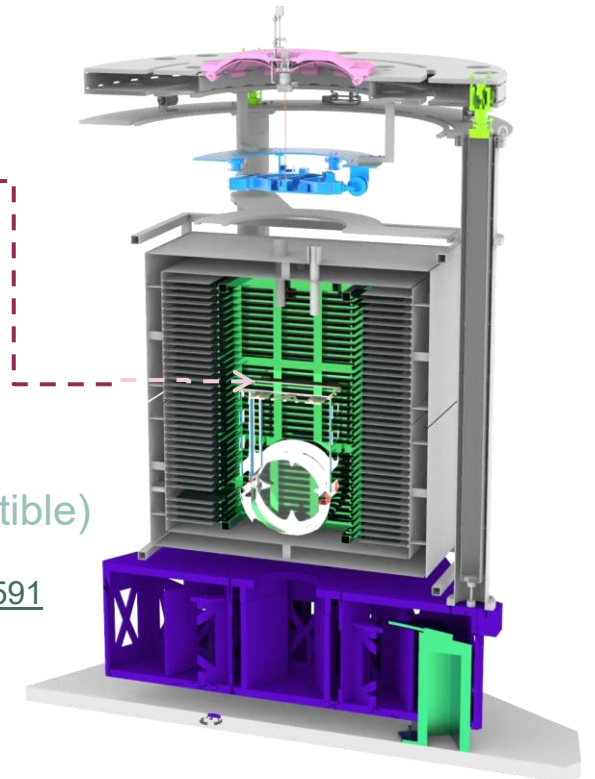
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PML legacy (not cryo compatible)

VINS (Binlei Ding): [PhD thesis](#)

EVINS (Anthony Amorosi): [G2502591](#)



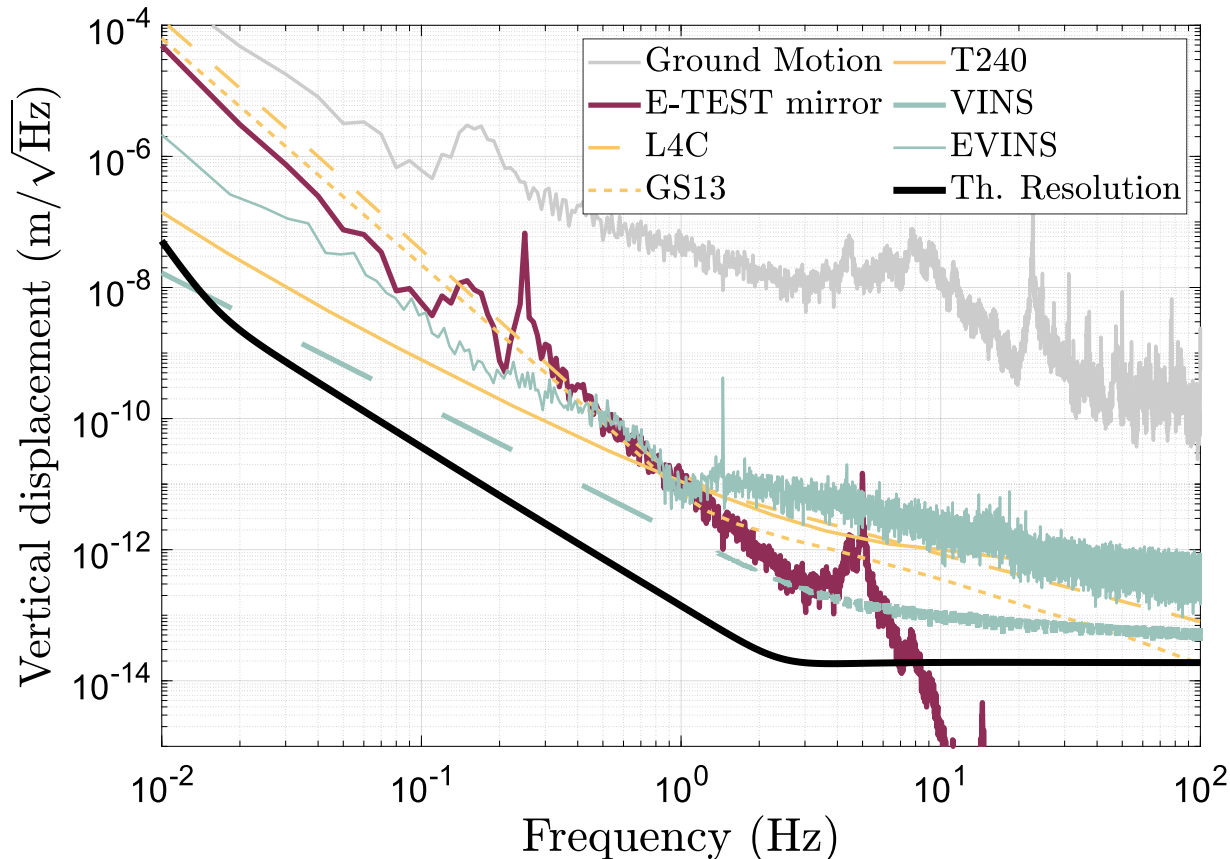
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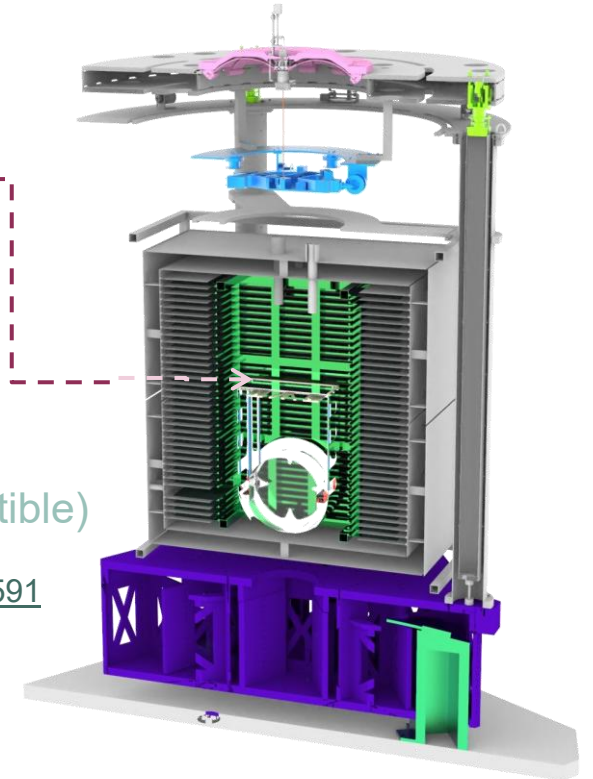
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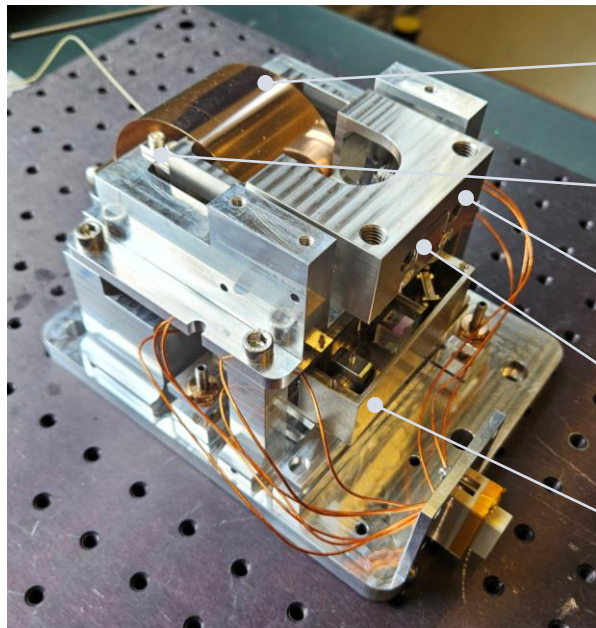
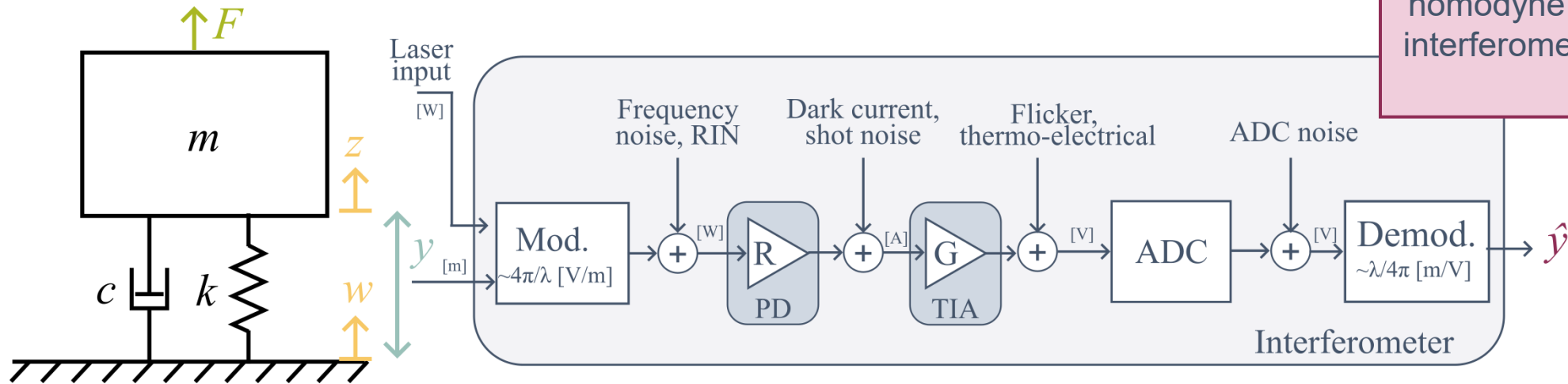
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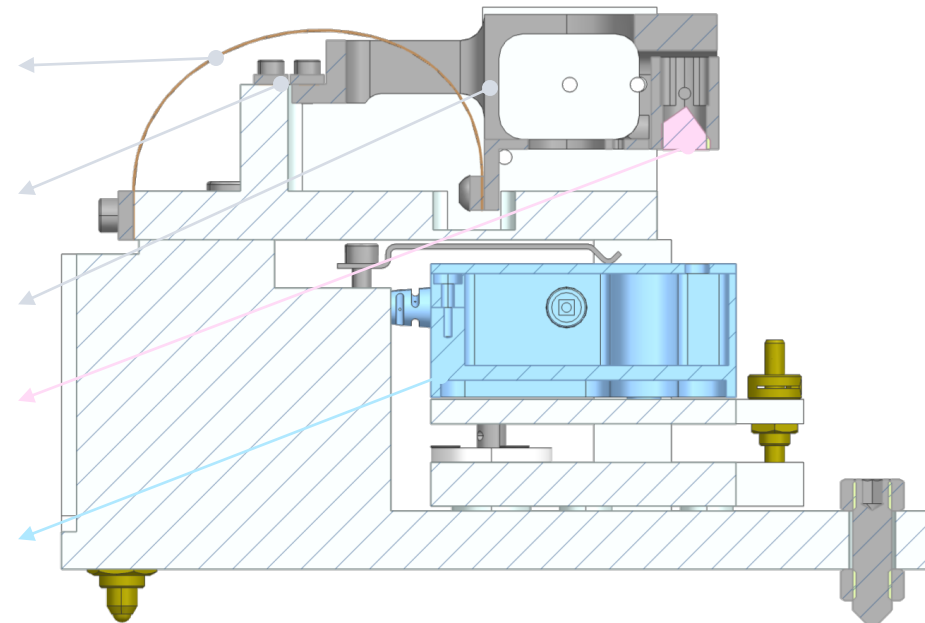
Objective resolution for the cryogenic sensor



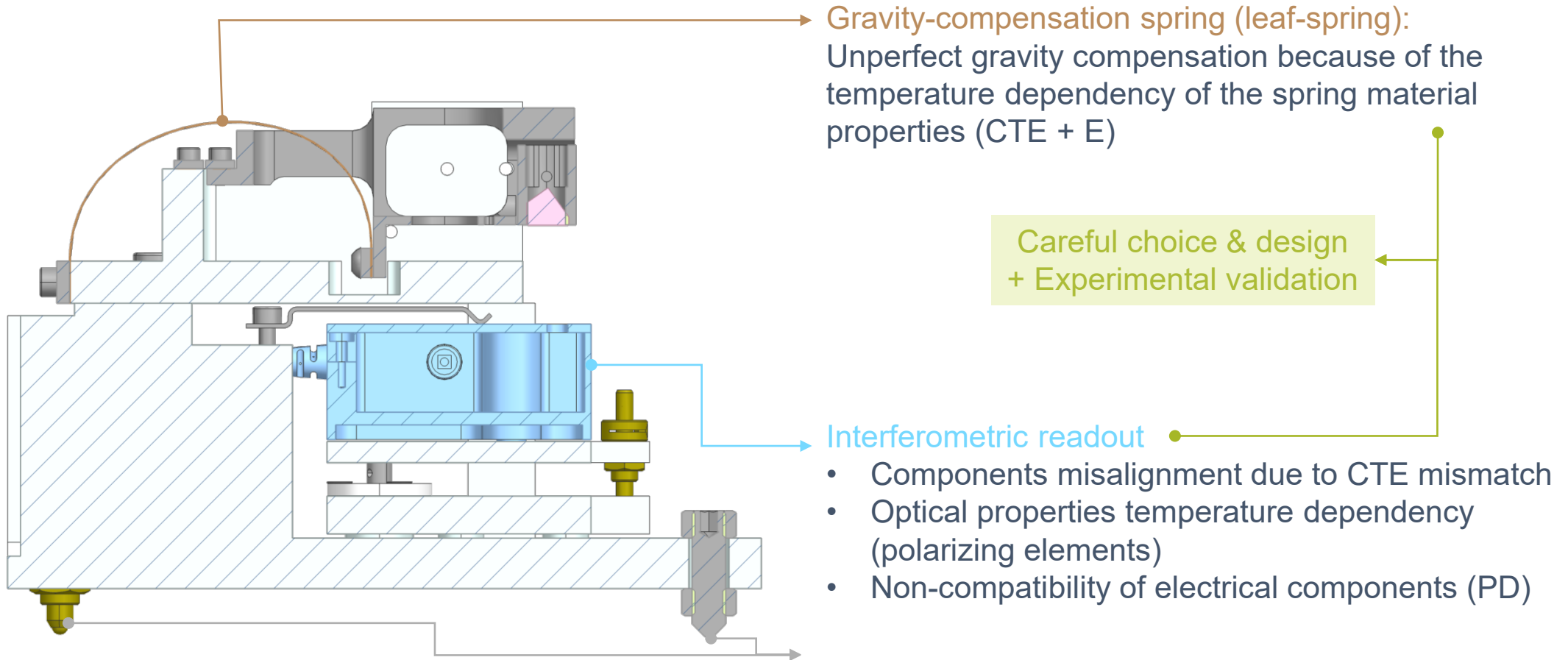
Vertical cryogenic inertial sensor



- Leaf-spring suspension (BeCu)
 - Double-clamped blade hinge (BeCu)
 - Inertial mass
 - Corner cube
 - Homodyne quadrature interferometric readout
- Amorosi 2025

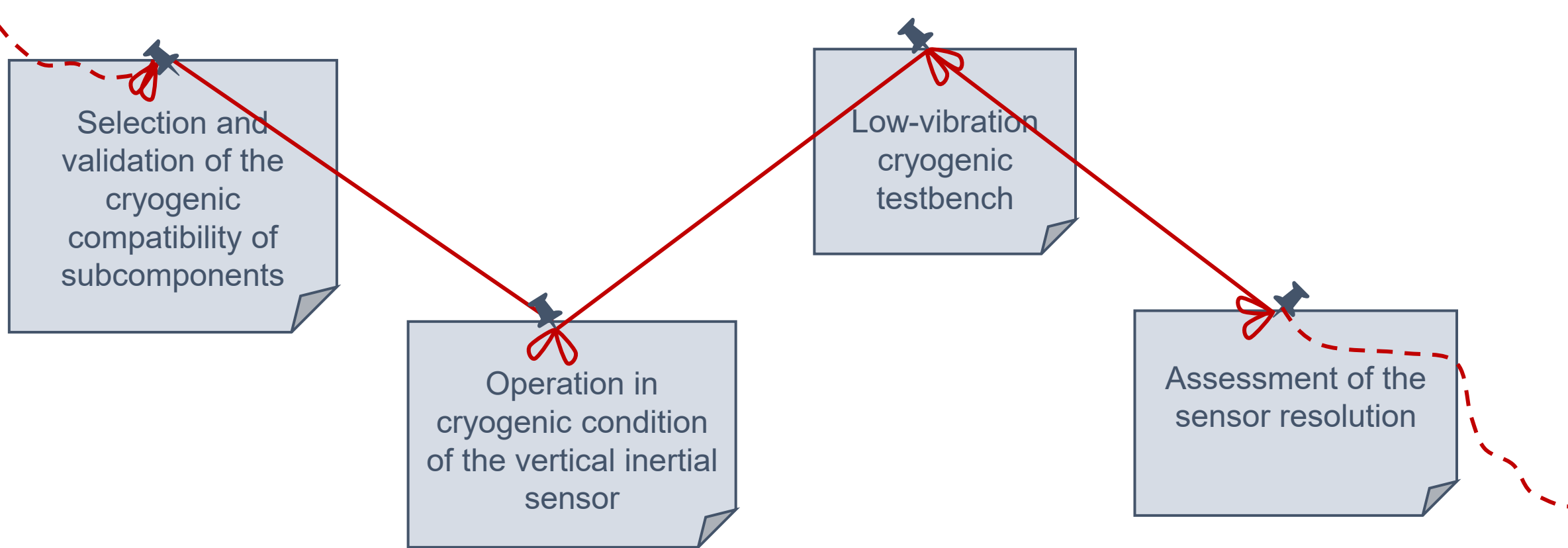


Challenges related to cryogenic temperatures



CTE: coefficient of thermal expansion
E: young modulus
PD: photodiodes

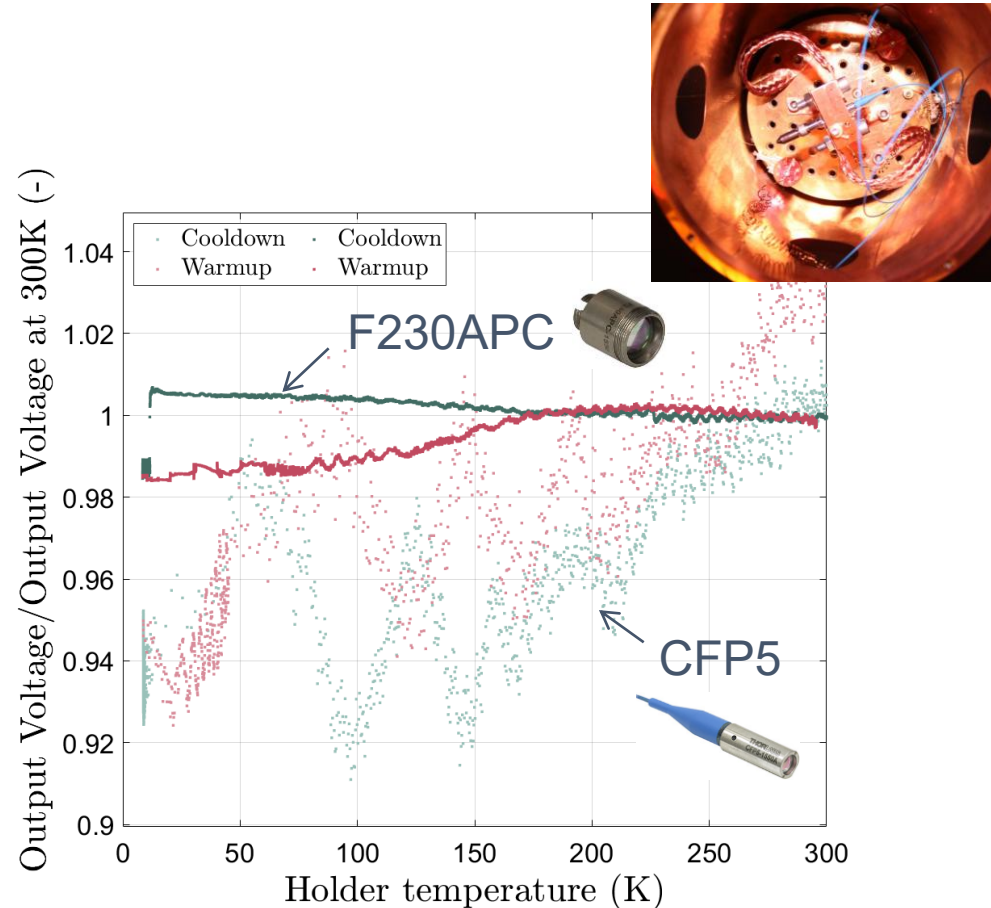
Methodology



Interferometric readout – Critical optical elements validation

Kulbusch, Zeoli et al (2024)

Collimators

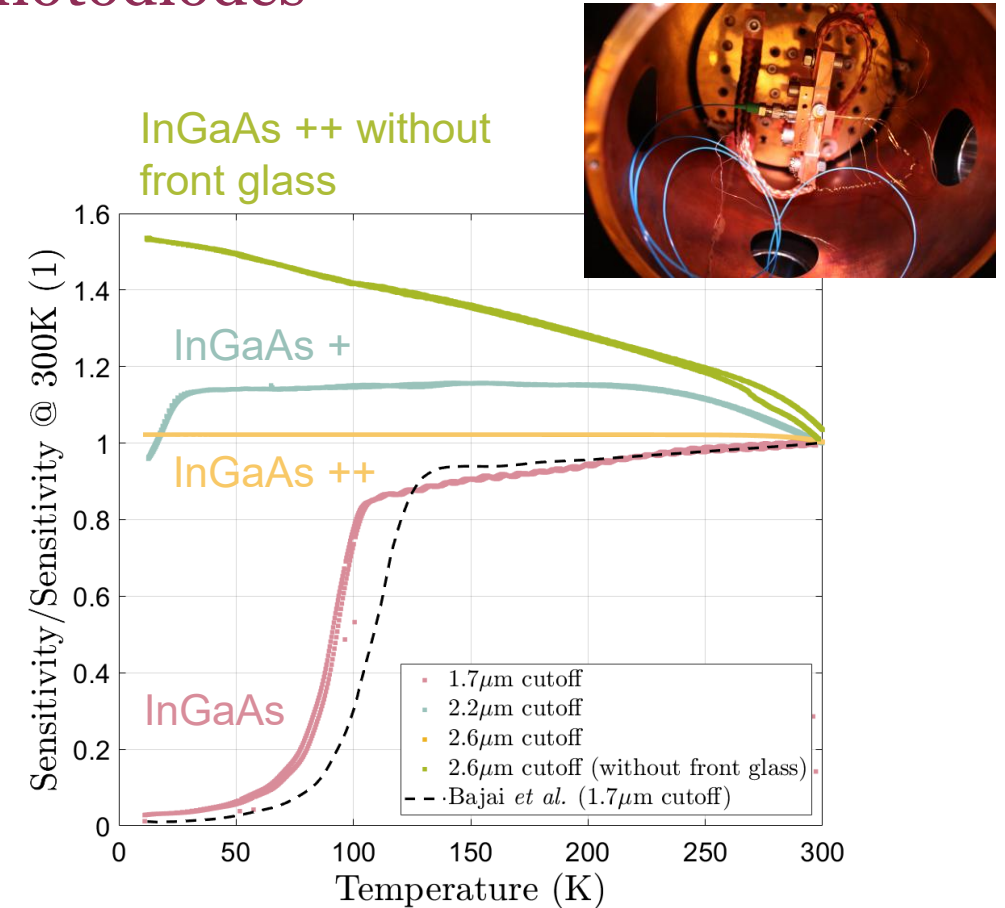


More sensitive to
temperature
fluctuations



Relative decrease in
voltage <2.2%

Photodiodes



Selected: extended InGaAs 2.6 μm cutoff

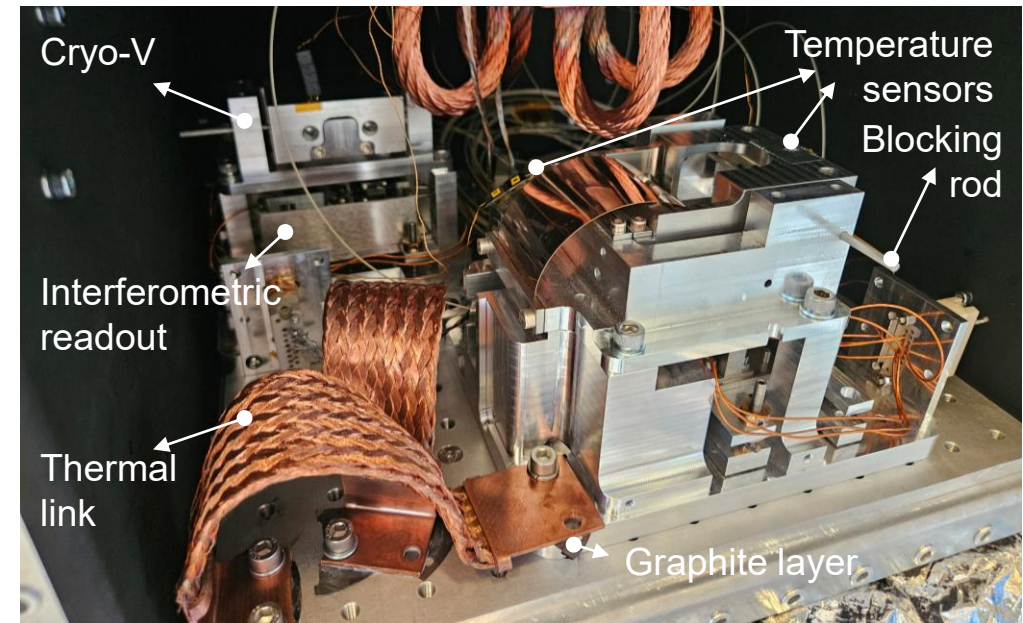
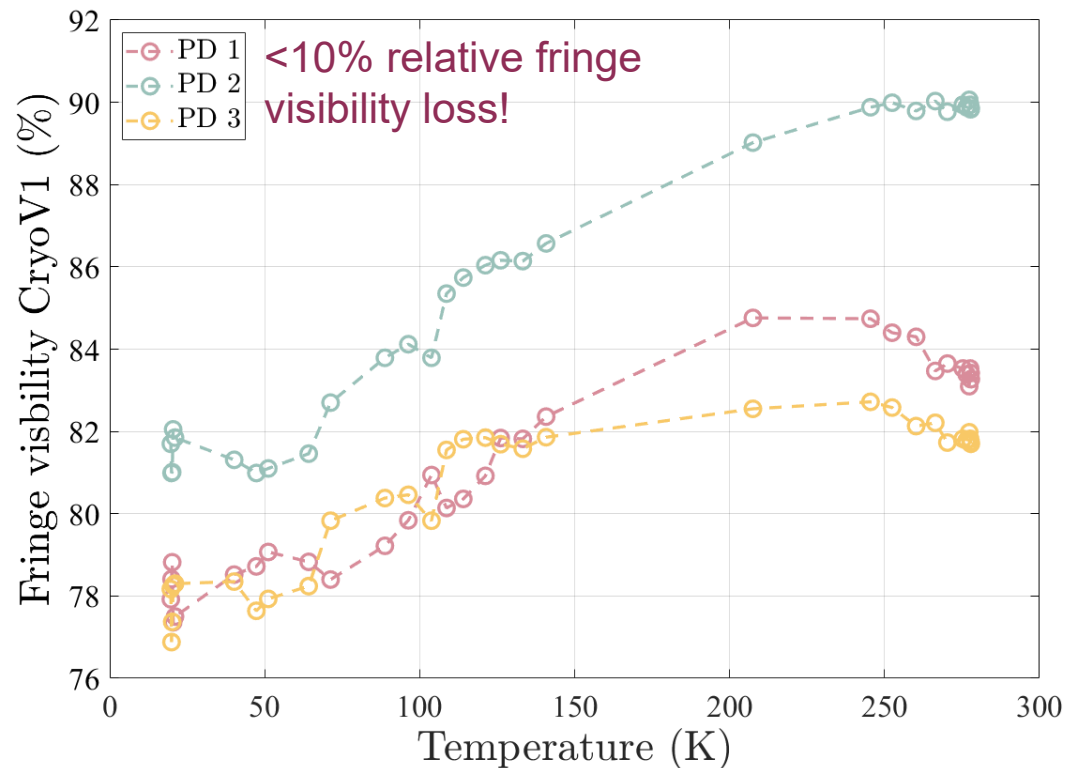
Bajpai (2022)

Interferometric readout – Alignment & compatibility

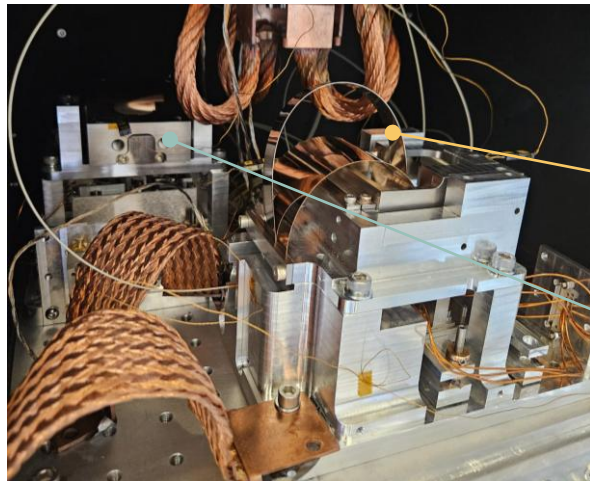
Alignment quality figure of merit:
Fringe visibility (FV) of the raw fringes measured
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$$FV = \frac{V_{PD}(\max) - V_{PD}(\min)}{V_{PD}(\max) + V_{PD}(\min)}$$

The interferometer
alignment is maintained
down to 20K



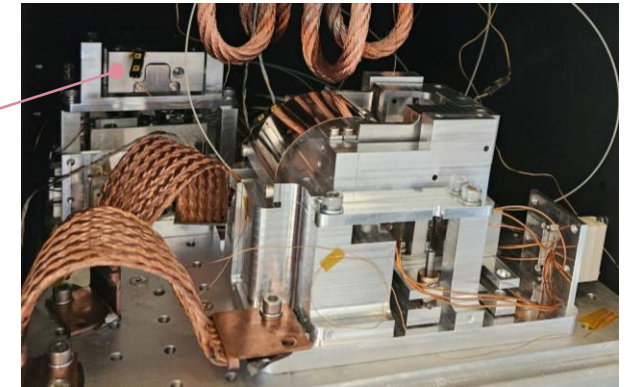
Gravity-compensation spring (leaf-spring):



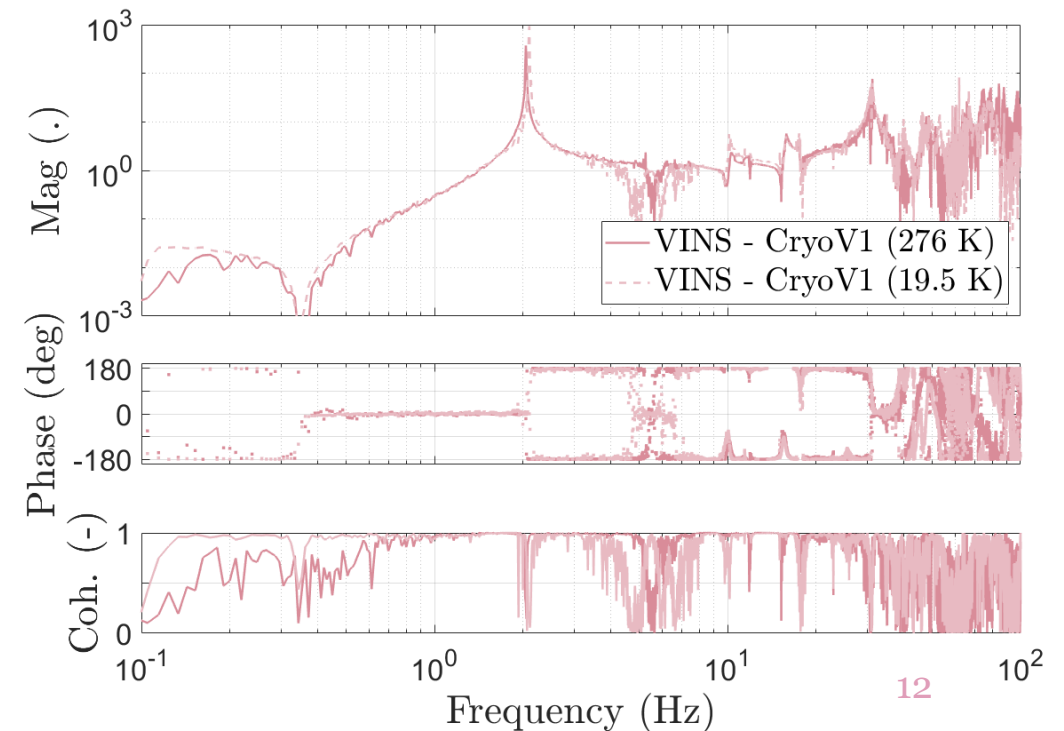
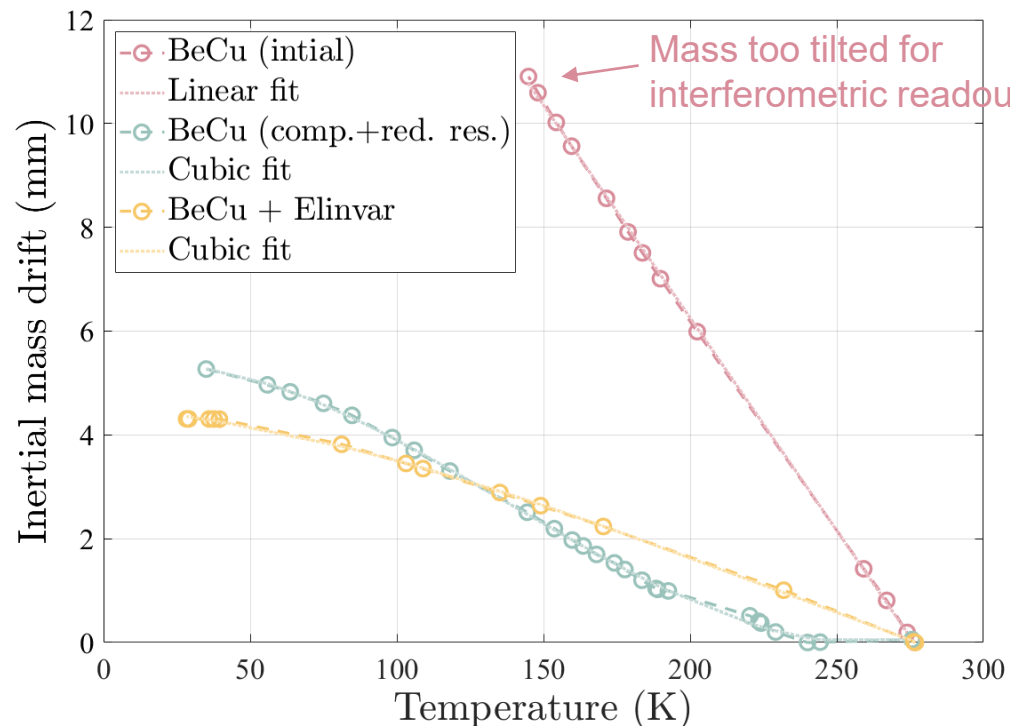
Initial suspension (BeCu): $-81.98 \mu\text{m/K}$ (lin)
Critical drift up

BeCu + Elinvar: $-20.14 \mu\text{m/K}$ (quad.)
Opposite temperature dependency of E

BeCu compensated: $\sim -32.7 \mu\text{m/K}$ (cube.)
the mass lies on its down stop to compensate the expected drift



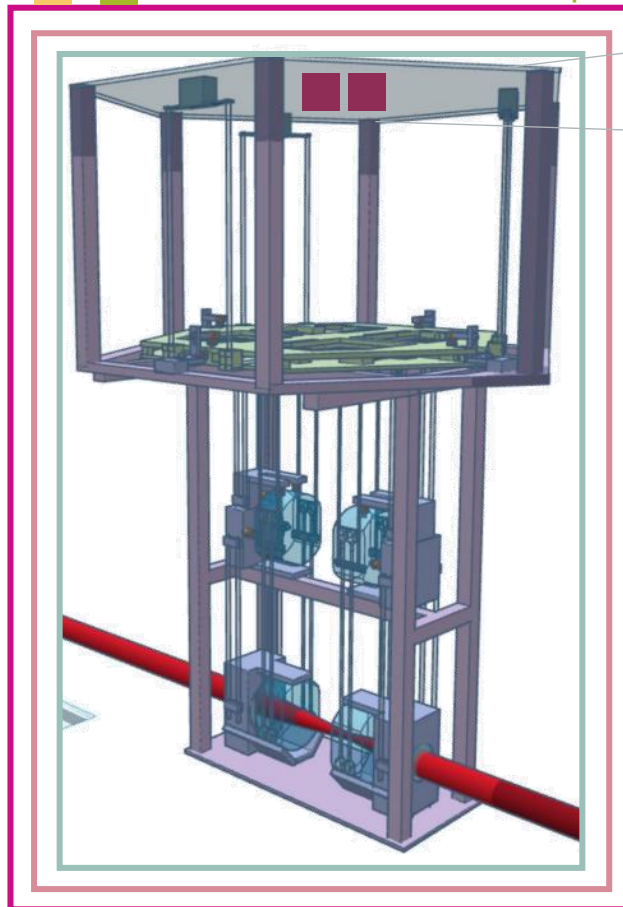
Validation with witness sensor (VINS) on the ground!



Sensor validation at University of Glasgow (IGR)

A multistage seismic isolation system providing passive vertical and longitudinal isolation for the test mass cavity to reduce seismic noise to a level where the cavity can be locked and thermal noise can reasonably be investigated ([ET-0279A-25](#))

Witness sensors: Guralp + Accelerometer

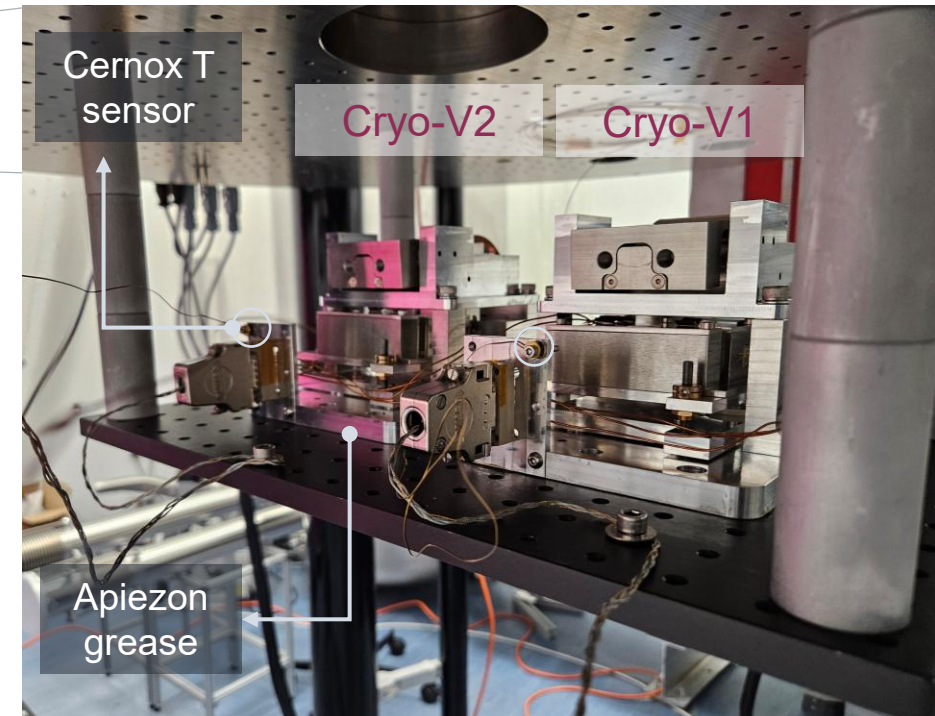


Vacuum tank
4K Cold plate

50K shield
4K cold shield
Common
platform

Double
pendulum
test mass
chain

Prestabilized
laser input

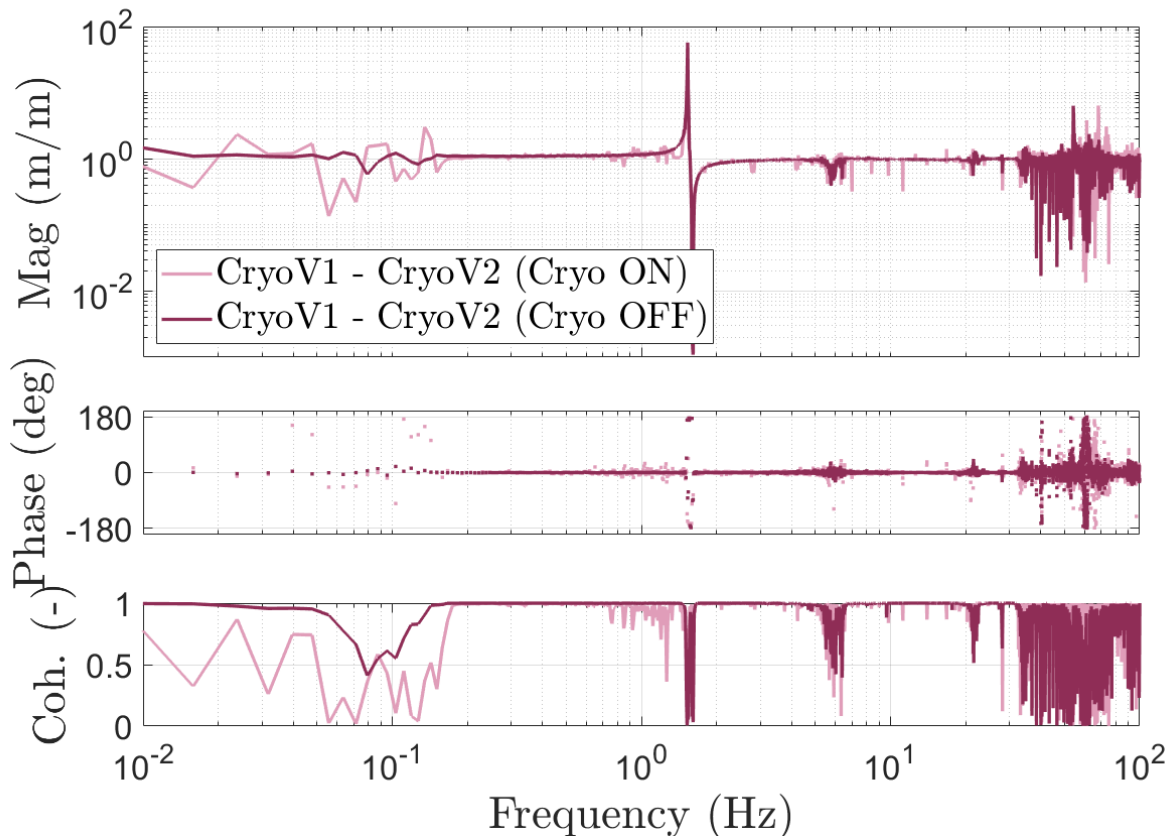


- Measure the vertical vibration induced by the vacuum and cryogenic systems on the cold plate
- Validate the Cryo-V in a large-scale cryo environment

Sensor operation at 5.17 K

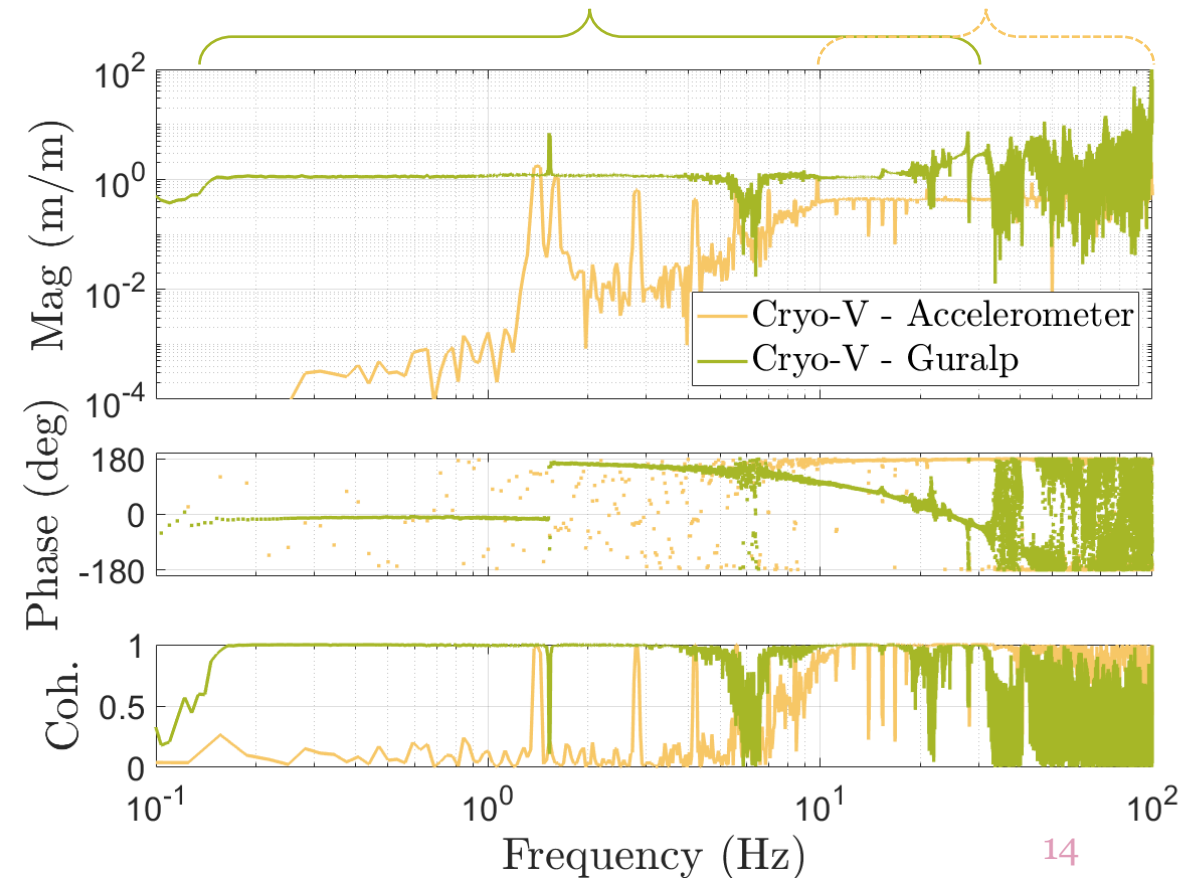
The sensors are
properly operating
down to **5.17K**

The 2 Cryo-V output signal have a coherence close to 1 in the 0.01 – 100 Hz range



Guralp: coherent from
0.1 to 30Hz

Accelerometer: coherent
from 12Hz onward

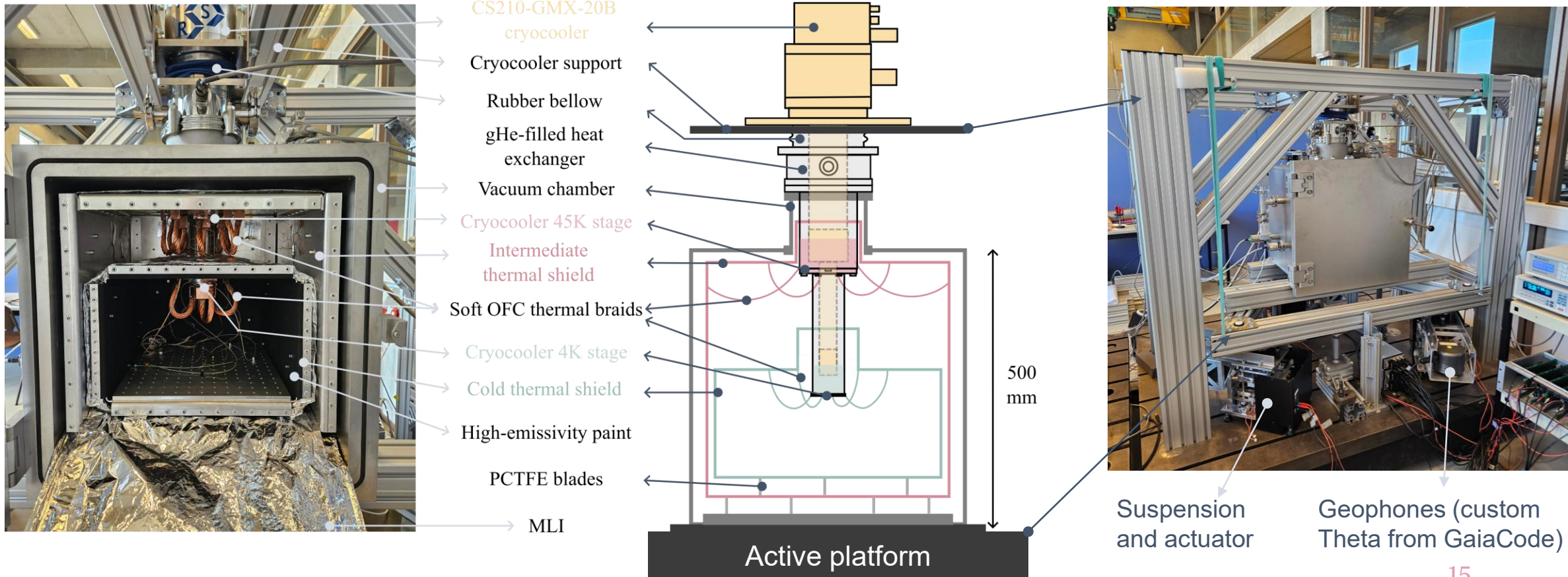


Low-vibration cryo testbench

Testbench to measure the sensor **resolution** in cryogenic conditions

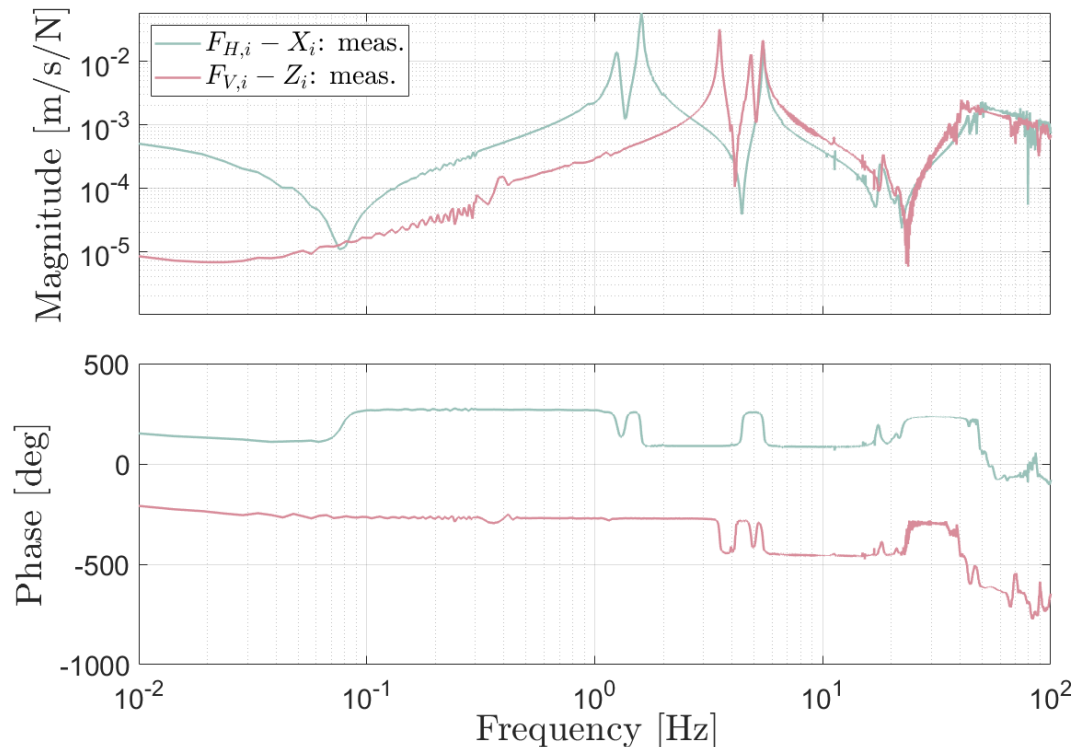
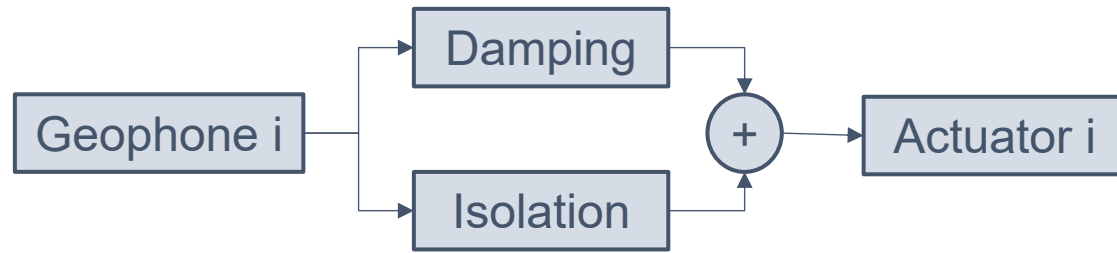
Combination of passive and active isolation

Target temperature	10 - 20 K
Cooling power	1 W at 4 K
Vibration level	- 10 nm RMS in [0.01-10] Hz - 10 nm/$\sqrt{\text{Hz}}$ from 0.1 Hz - pm/$\sqrt{\text{Hz}}$ level from 3 Hz
Volume	Host 3 sensors (20x20x20cm)

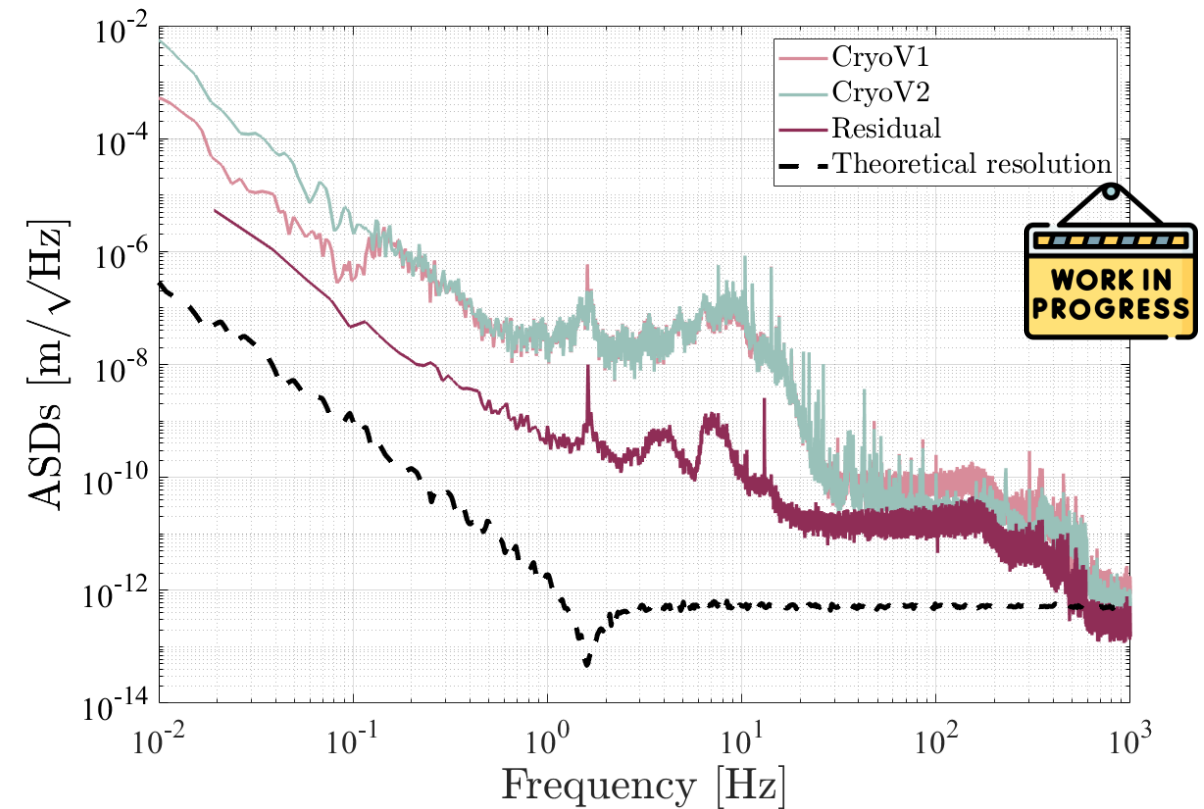


First measurement of the sensor resolution at 19K

Decentralized control in local coordinates

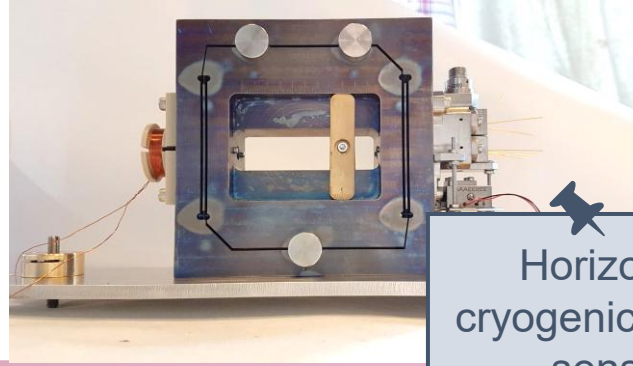


Preliminary Huddle test obtained at 27 K, with horizontal & vertical damping, and isolation, measured with a MicrolabBox II

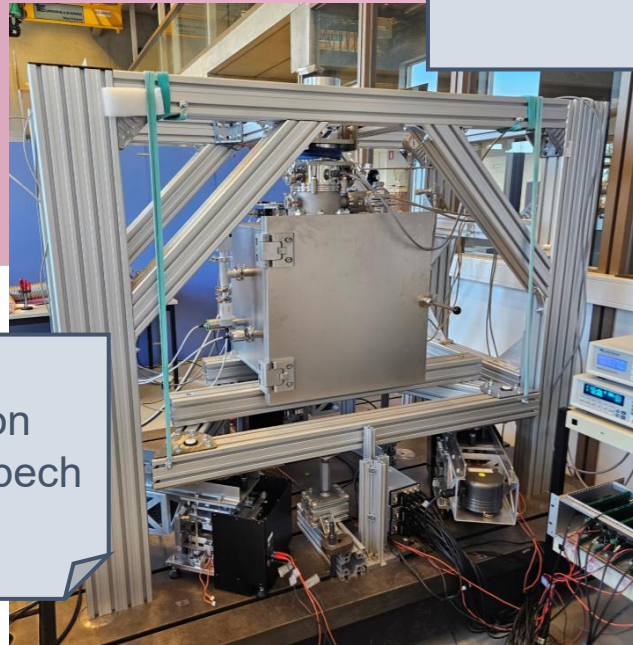


Conclusion and next activities

- ✓ We have redesigned and adapted state-of-the-art sensors to cryogenic conditions
- ✓ Validated the cryogenic compatibility of **sub-components** ([Kulbusch, Zeoli et al \(2024\)](#))
- ✓ Validated the operation of the vertical cryogenic inertial sensor at 5K



Horizontal
cryogenic inertial
sensor



Low-vibration
cryogenic testbench

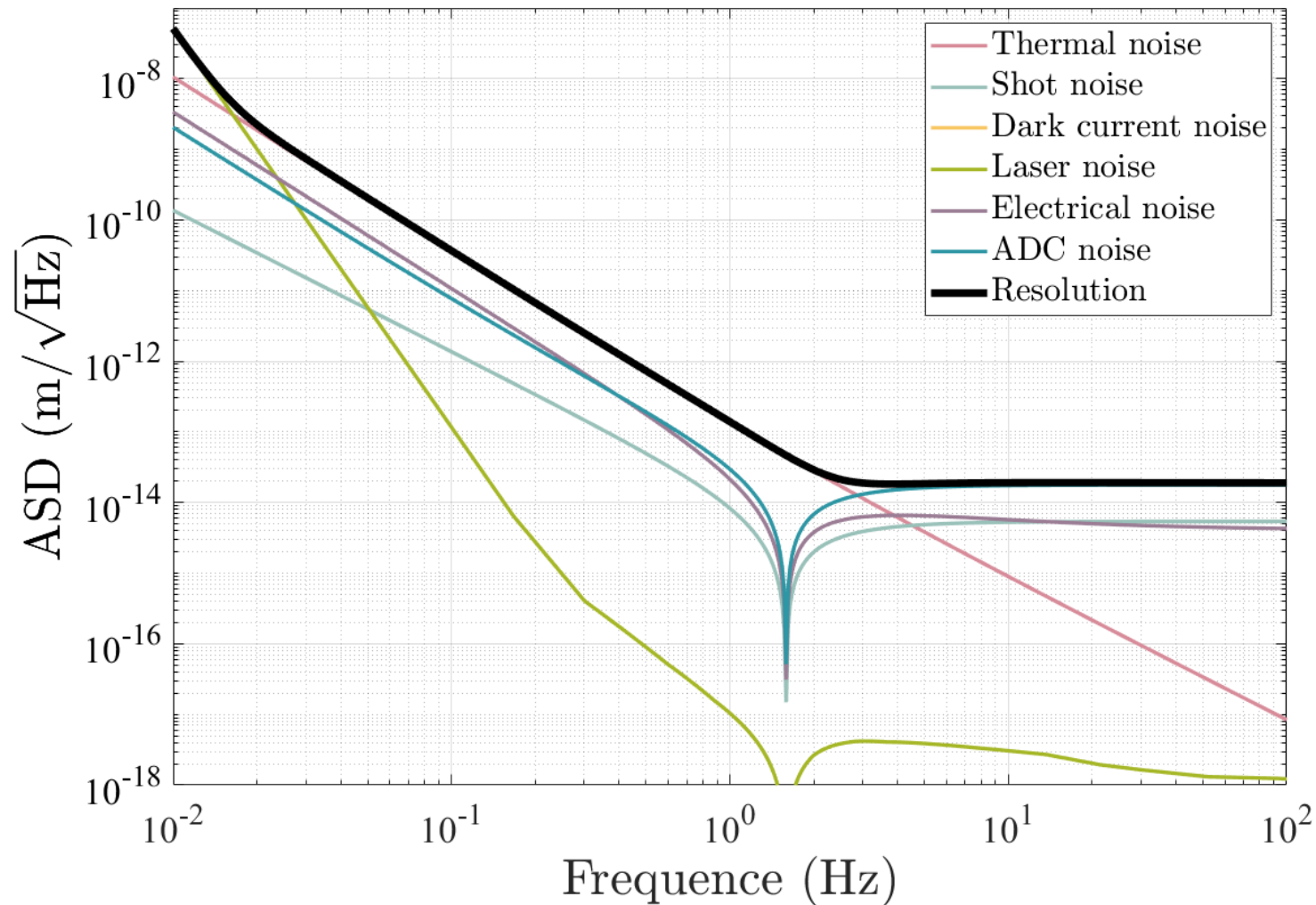
Experimental
measurement of
resolution



Integration in large
facilities (E-TEST)

Backup

Noise budget

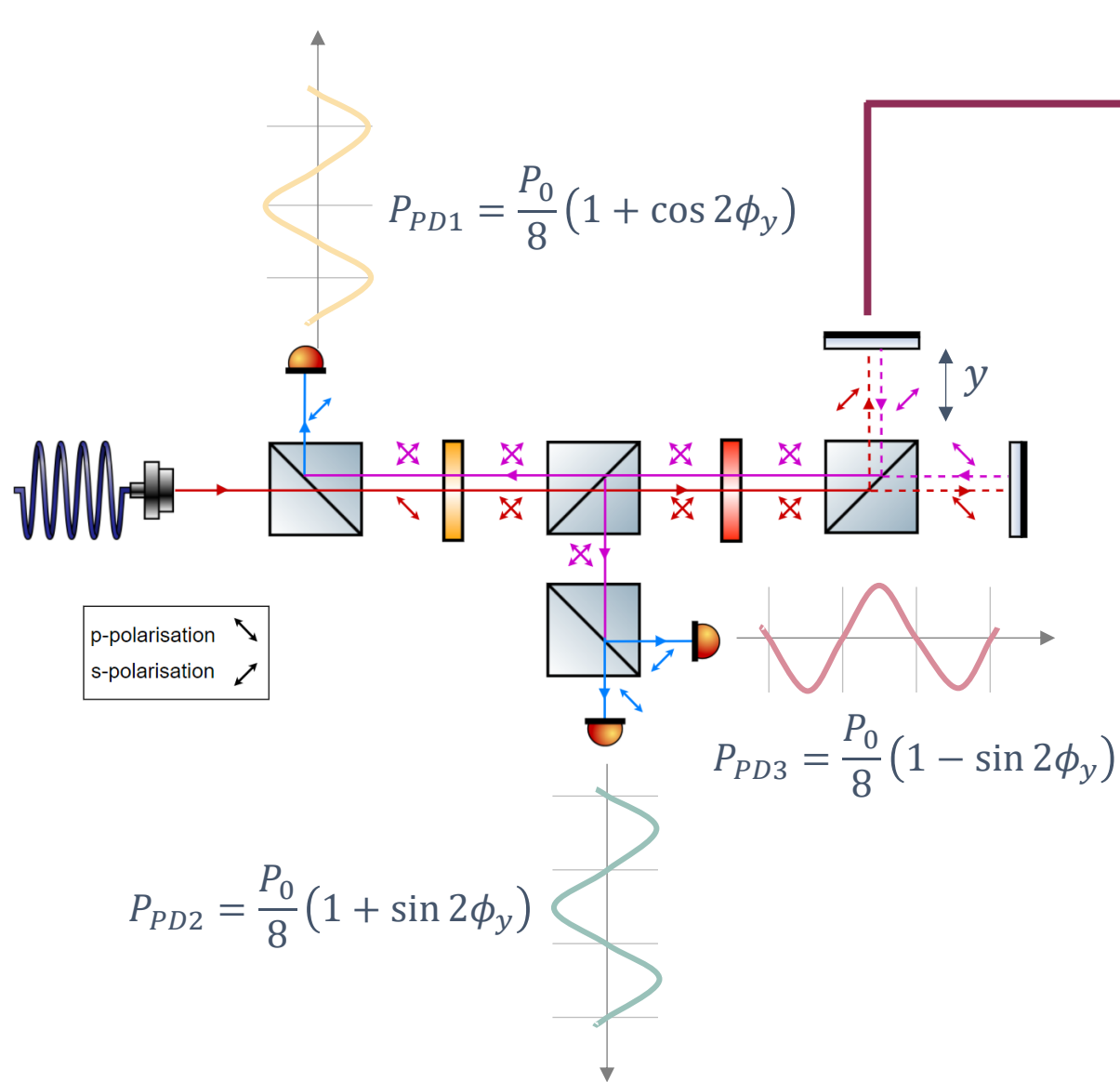


Structural noise at 20 K

Koheras BASIK X15

Centaur from Nanometrics (24bits, 20Vpp)

↕ Vertical cryogenic inertial sensor

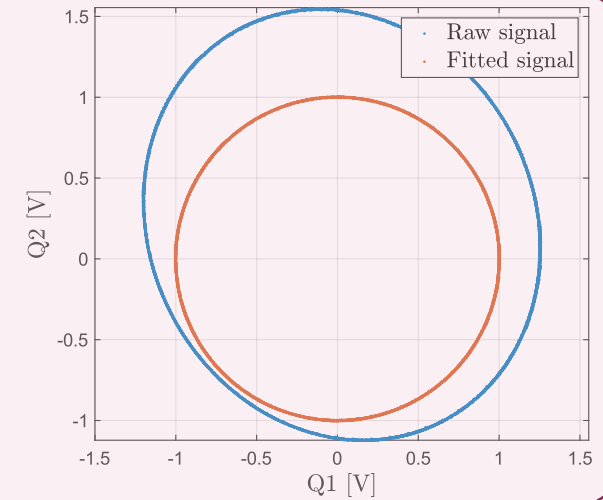


Common-mode
noise rejection

$$Q_1 = P_{PD1} - P_{PD3}$$

$$Q_2 = P_{PD1} - P_{PD2}$$

Online-ellipse
fitting and
normalization

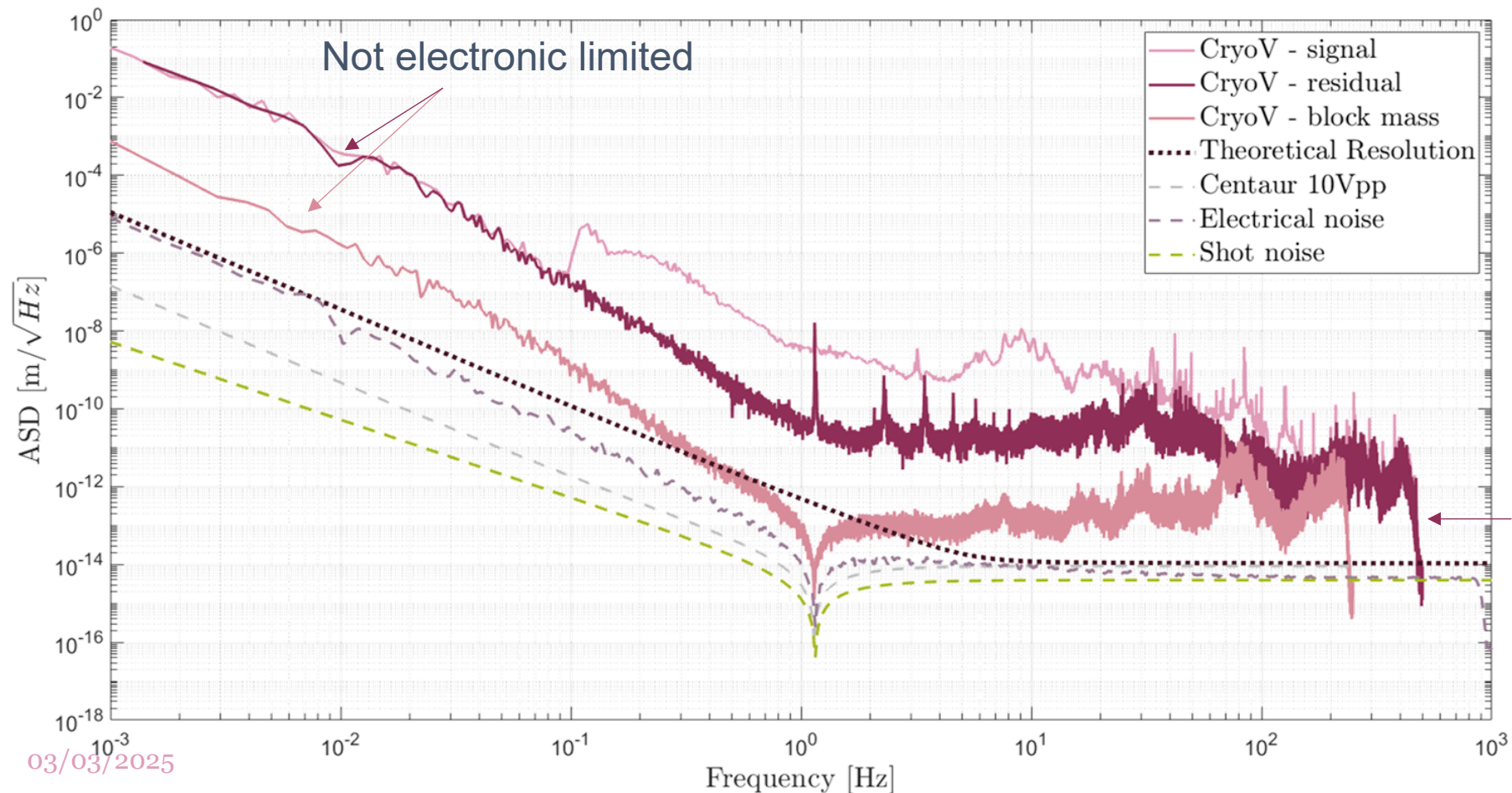


Fringe demodulation

$$y = \frac{\lambda}{4\pi\rho} \left(\arctan \left(\frac{Q_2}{Q_1} \right) - \frac{\pi}{4} \right)$$

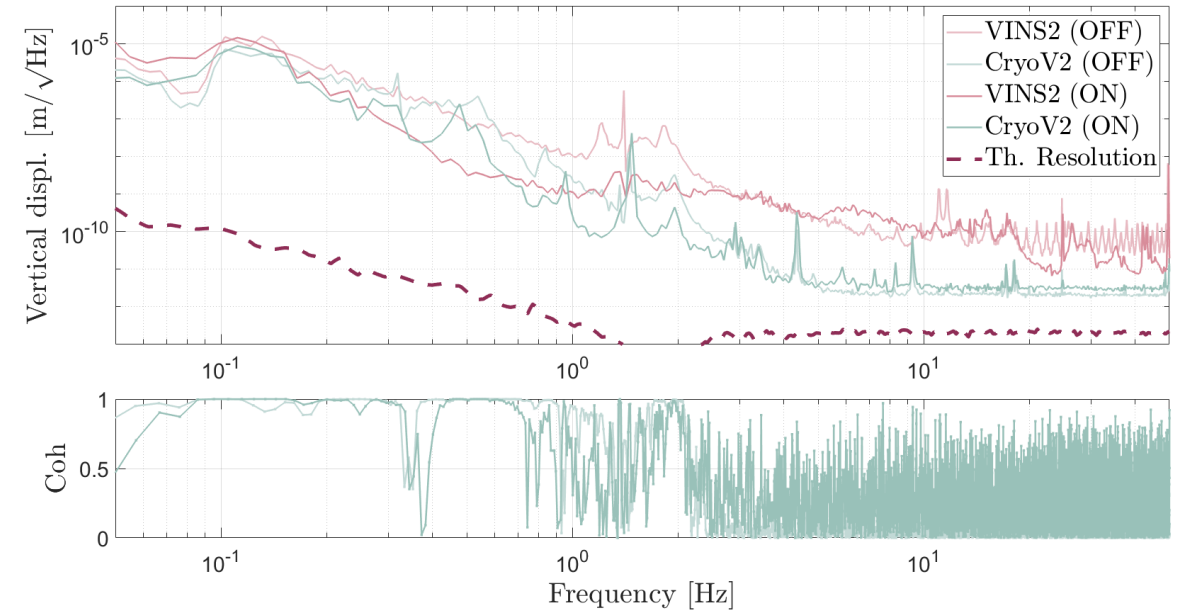
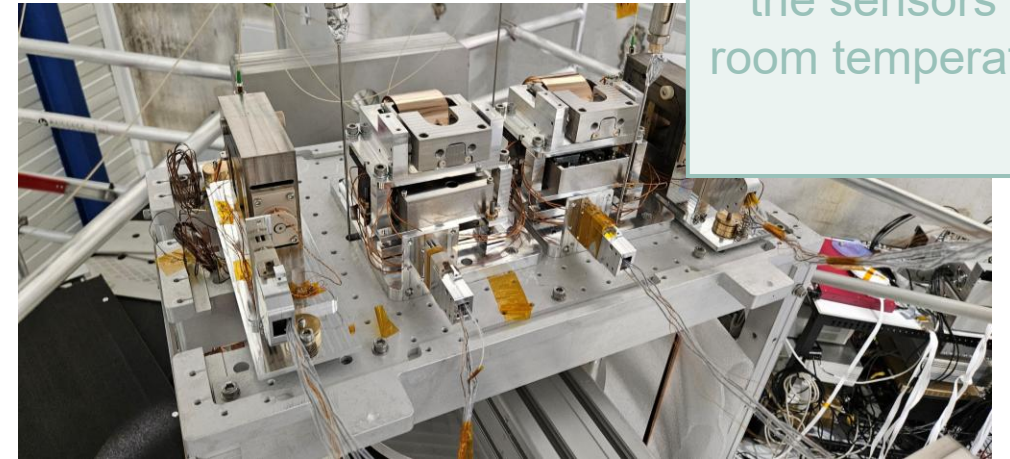
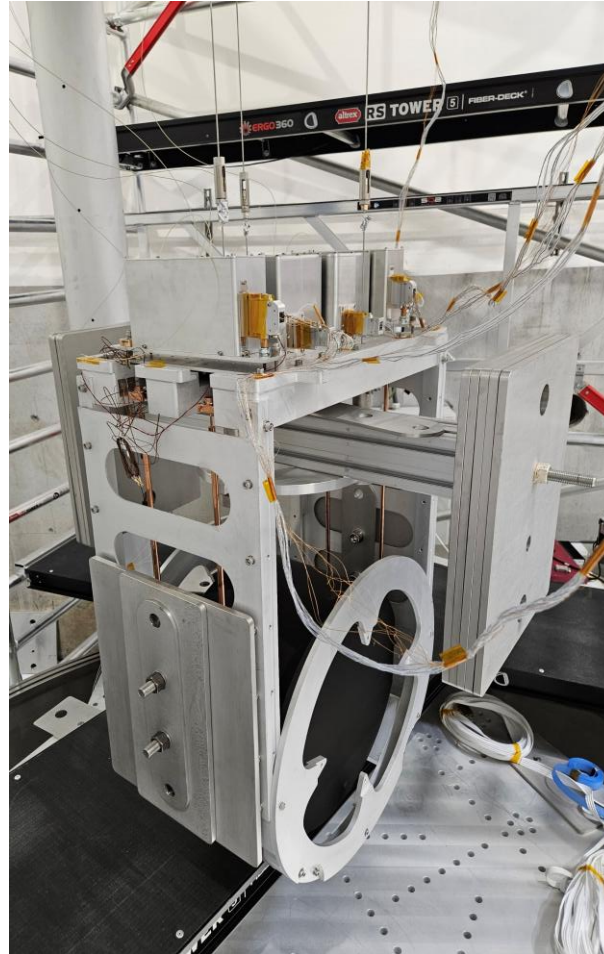
Cryo-V experimental noise budget RT (Lab)

- Sensors signal recorded during the nigh (from 23h-5h)
- As expected, two orders of magnitude are subtracted
- The slope at low frequencies is quite steep... (15 μ m drift?)



Cryo-V in ETEST isolated environment (RT)

Measurement of the resolution of the sensors at room temperature

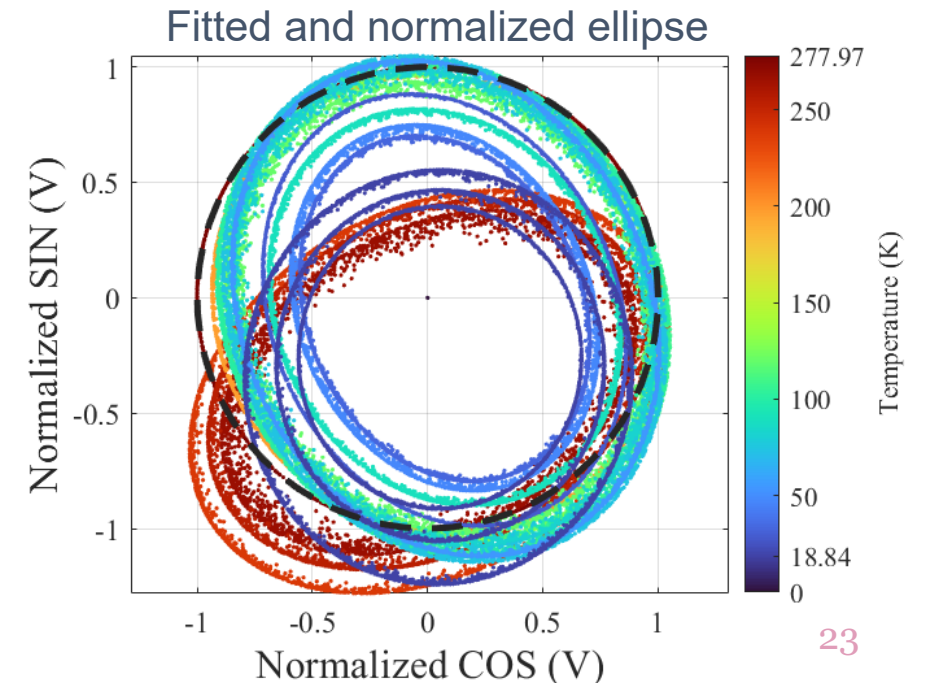
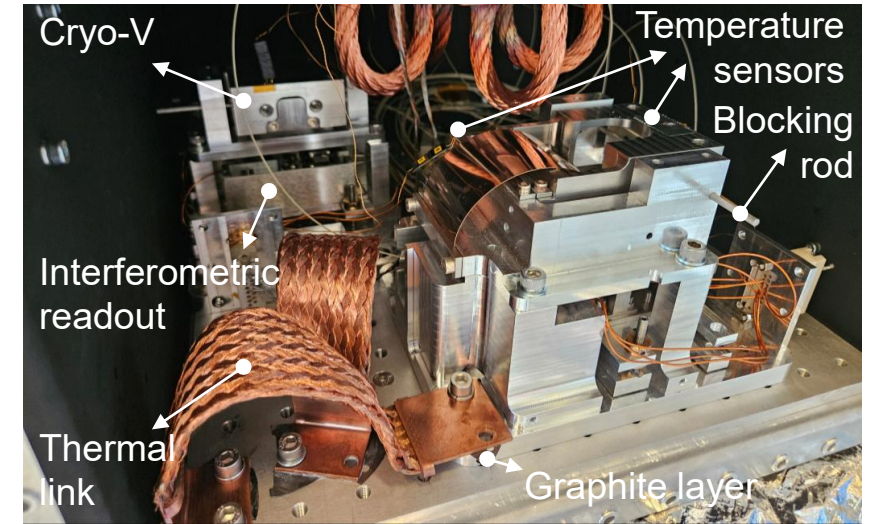
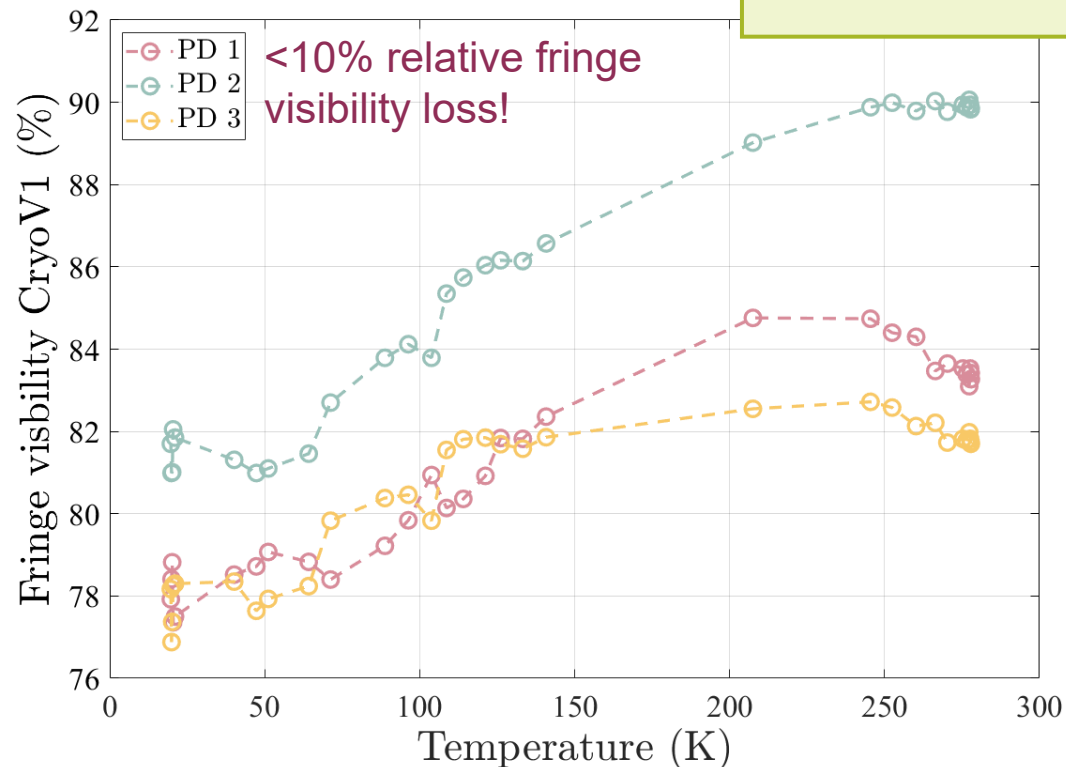


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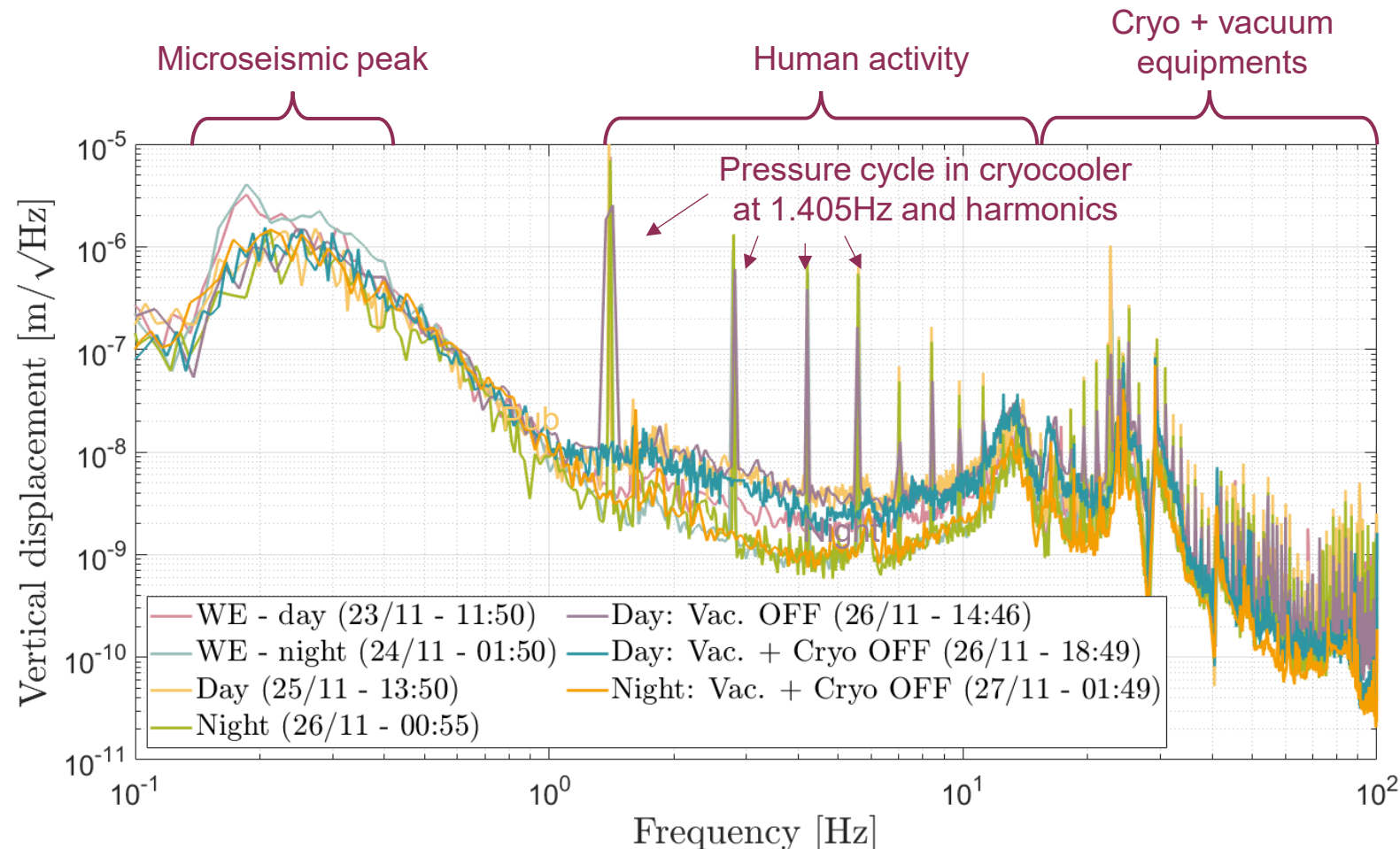
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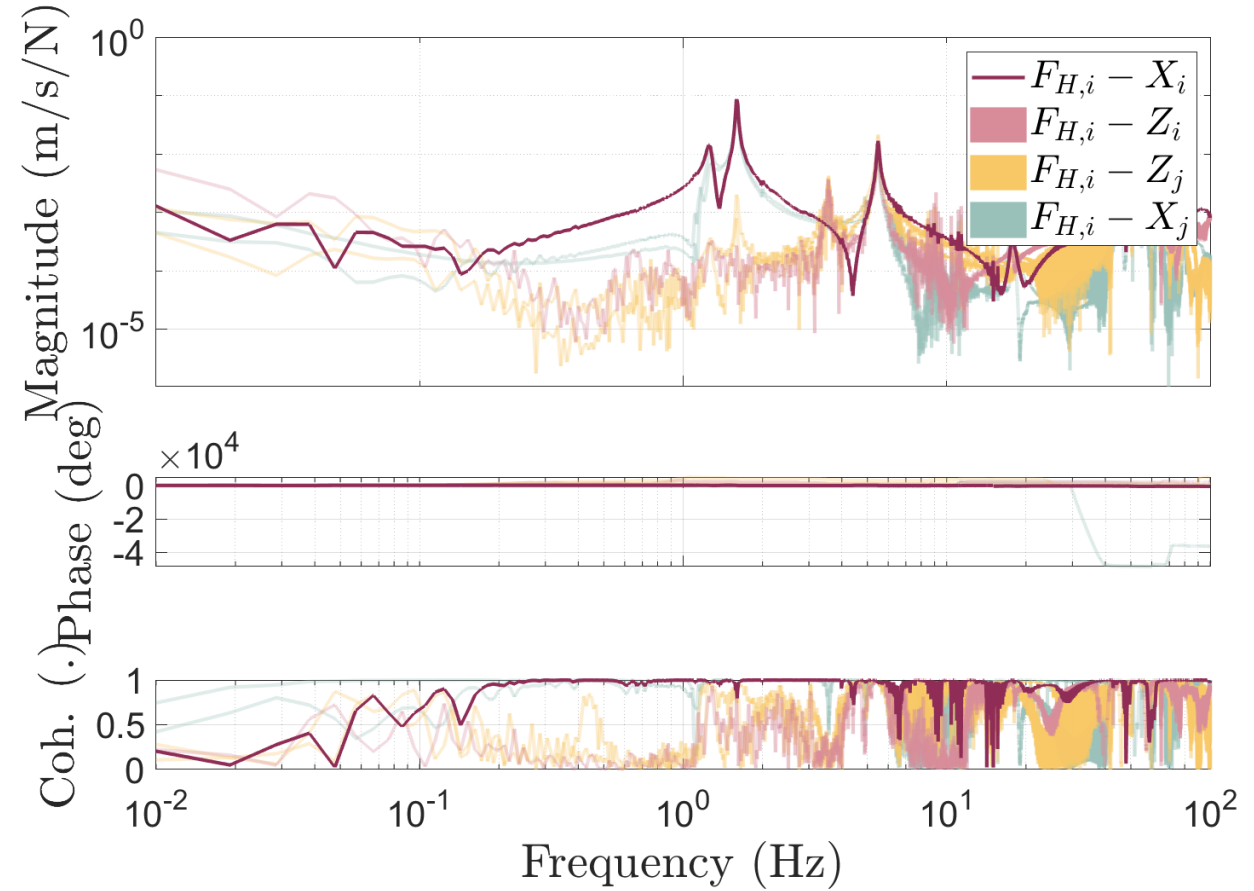
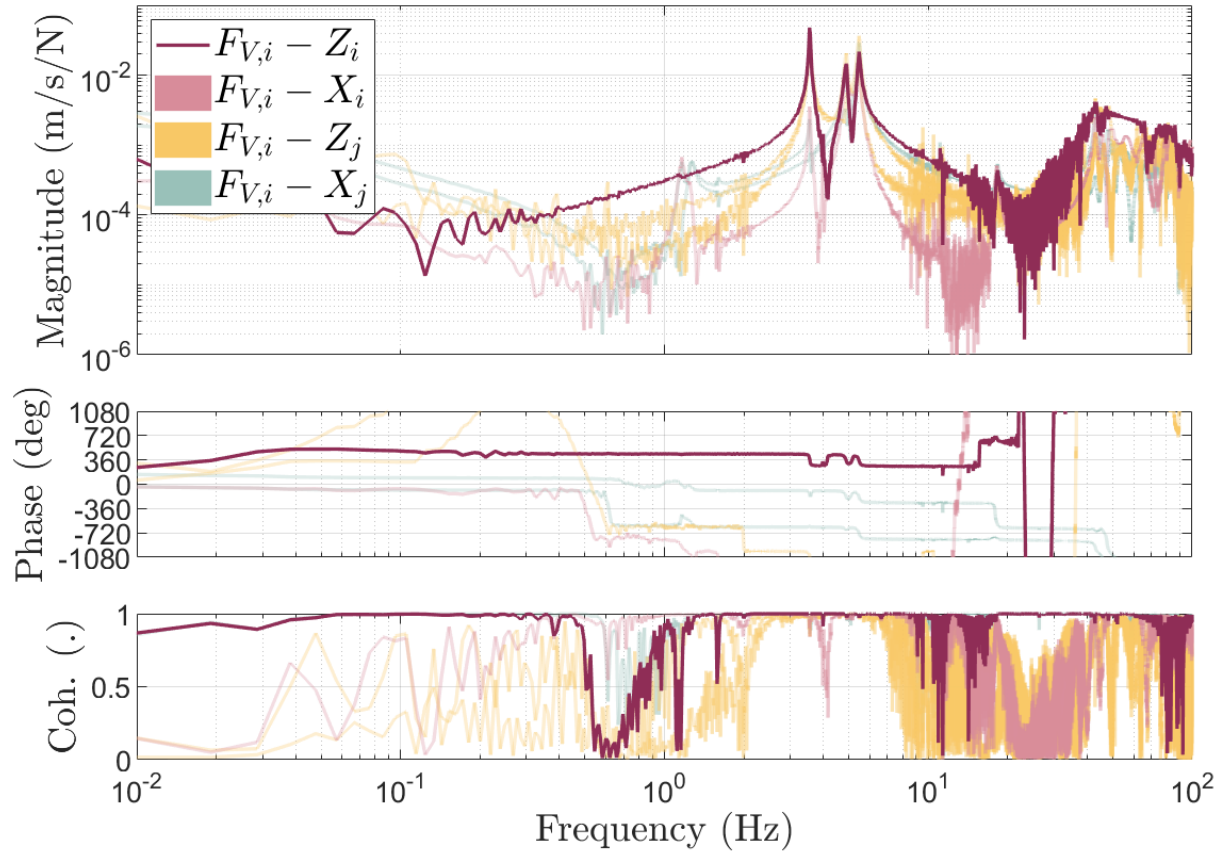


Cold plate vibration level

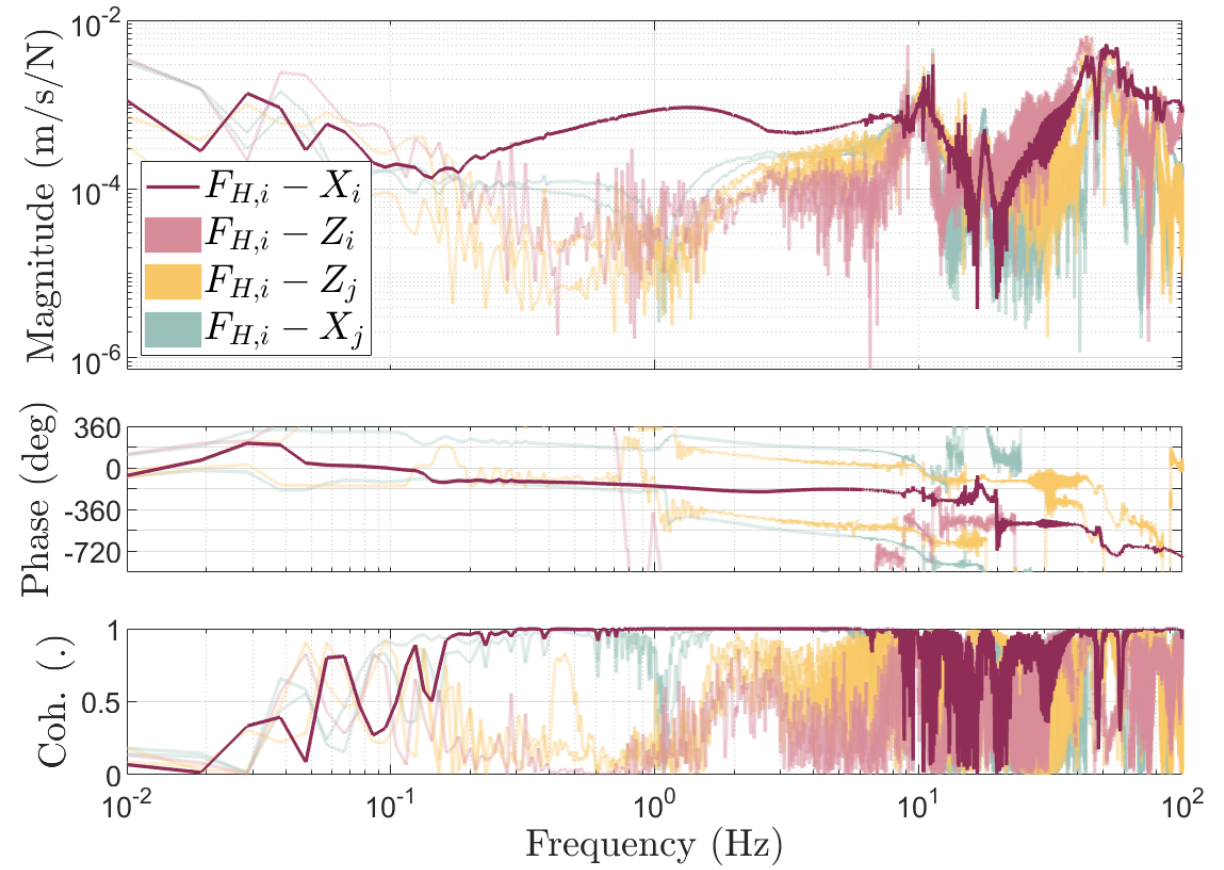
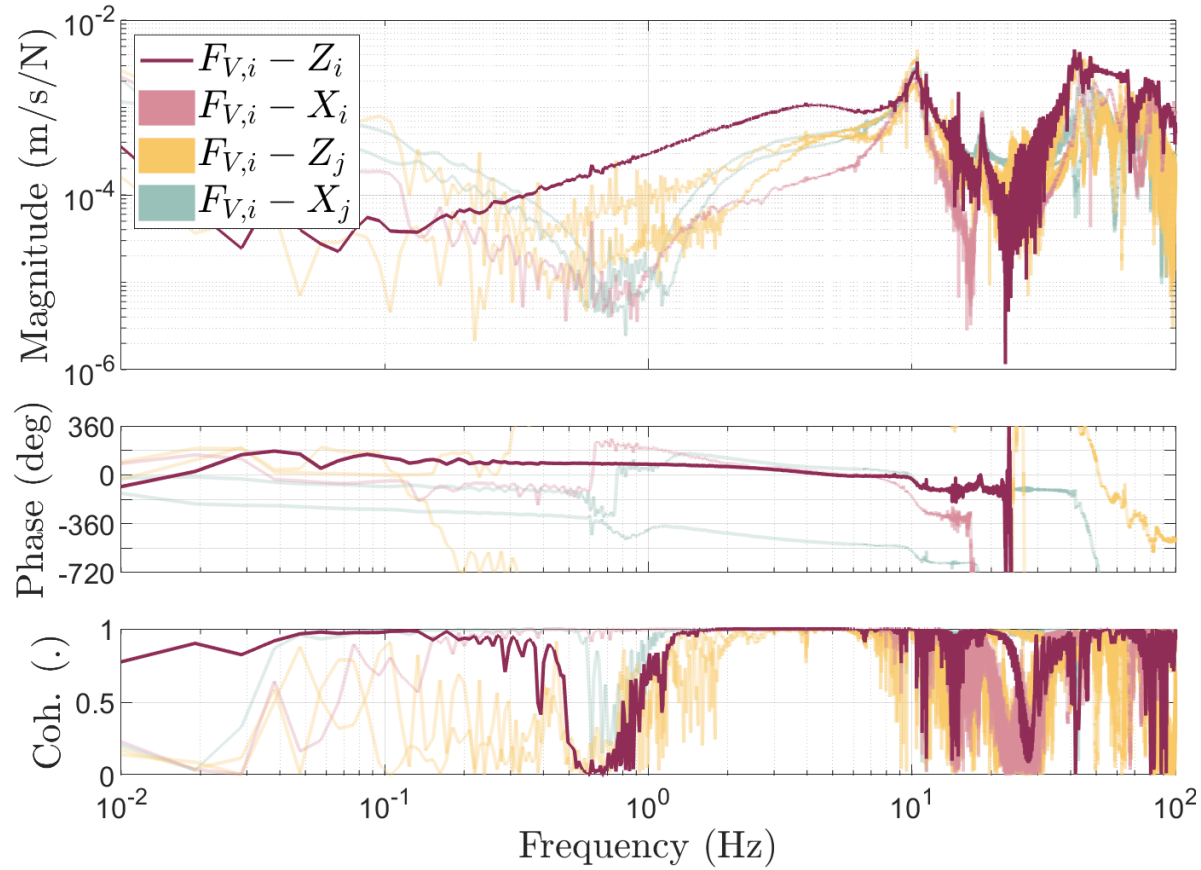
- Measurements conducted in various configurations to have a wide dataset for the design of the cavity suspension
- The only influence of the time of the day is between 1 and 10Hz
- The cryocooler vibrations impact low frequencies only via the pressure cycle resonance frequencies at 1.4Hz and its harmonics and higher frequencies



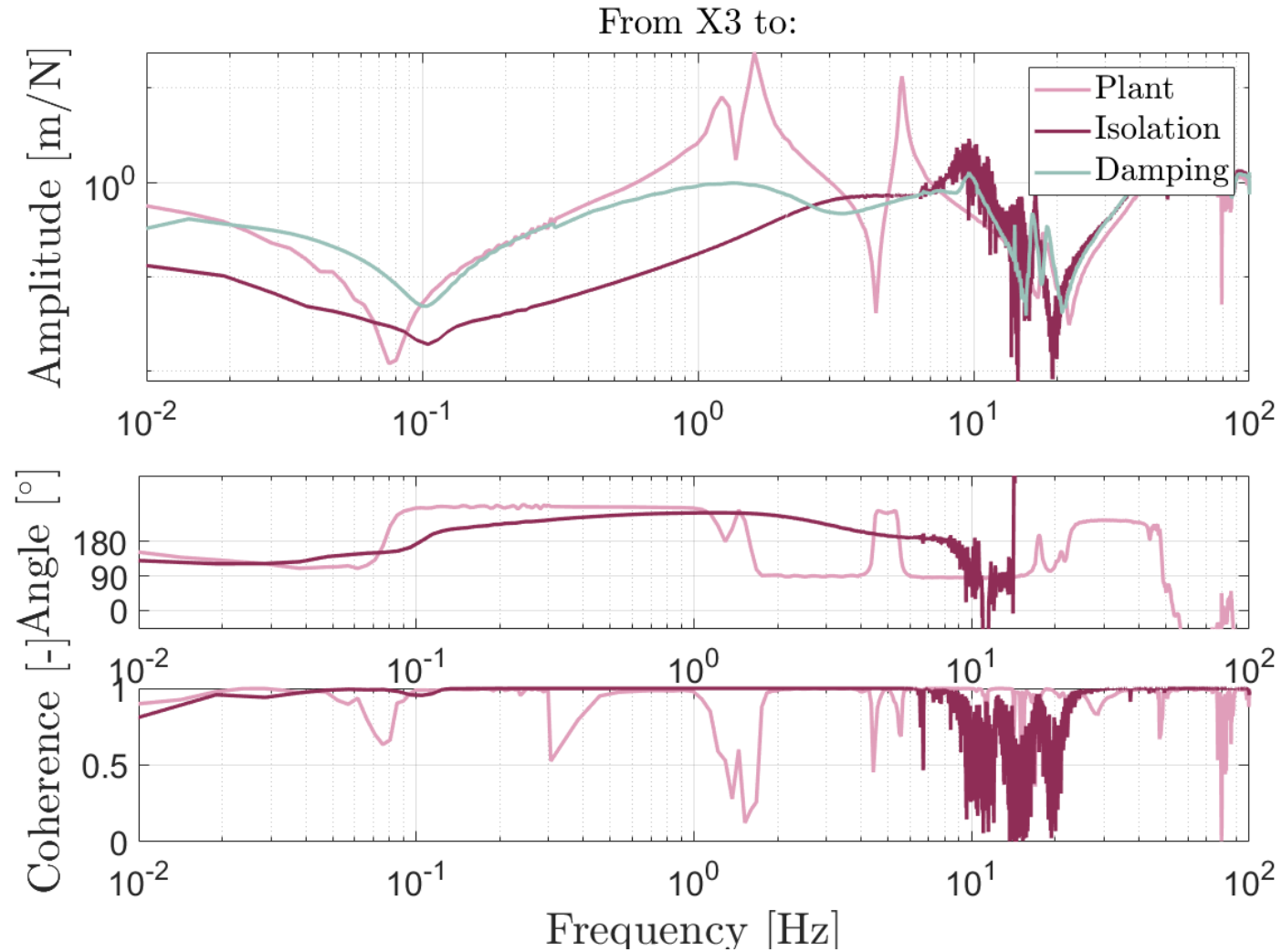
Active platform plant



Active platform decentralize damping



Active isolation



STELLAR cryogenic testbench

