Universität Hamburg
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GRAVITATIONAL WAVE DETECTION

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Mitigating low-frequency noise

Role of tilt, software tools, controller optimization

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GWADW workshop

24 May 2023

Outline

Low-frequency noise

Tilt & Sensors

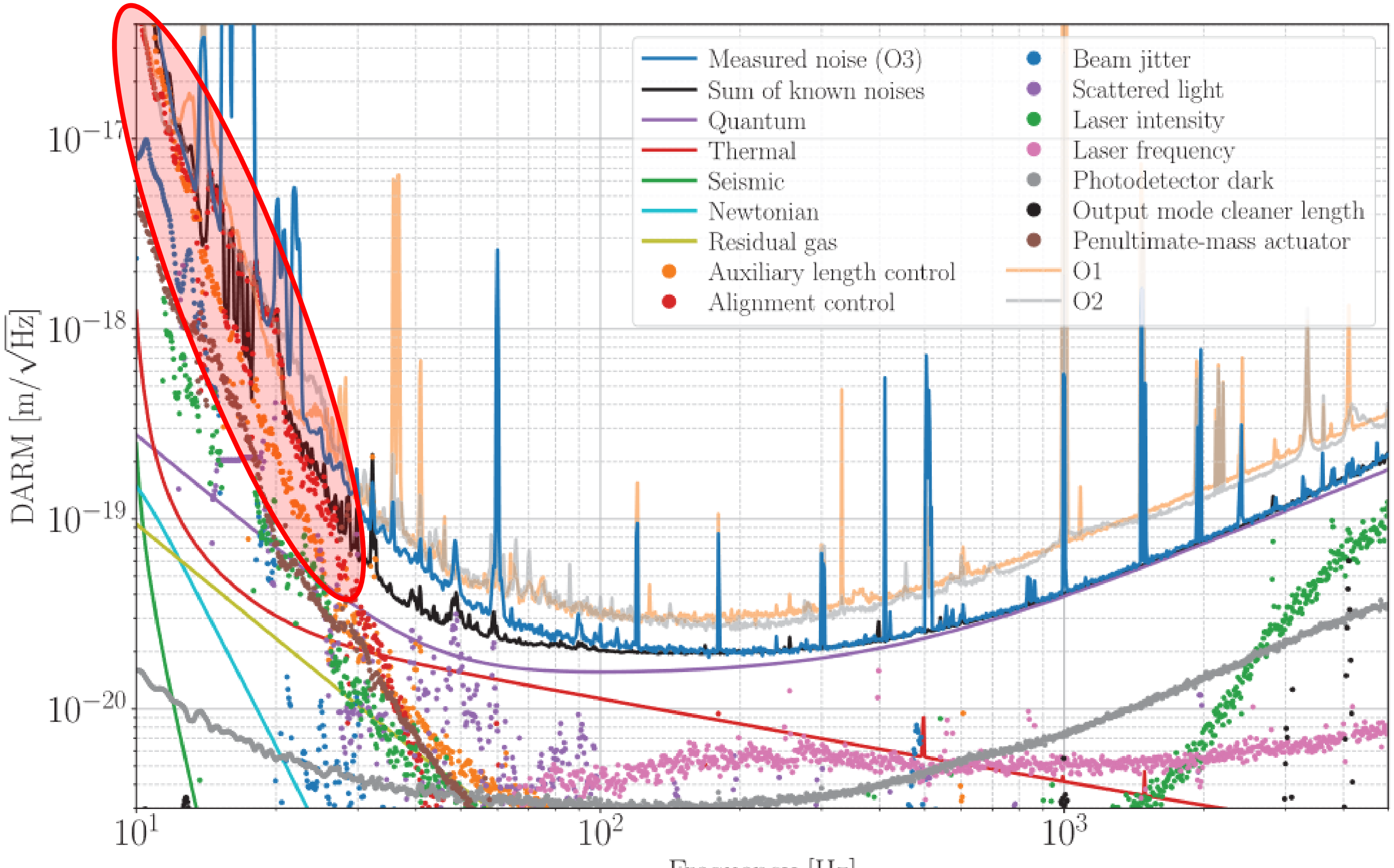
Seismic isolation & Control

Modelling Software

Low-frequency noise

Low-frequency noise

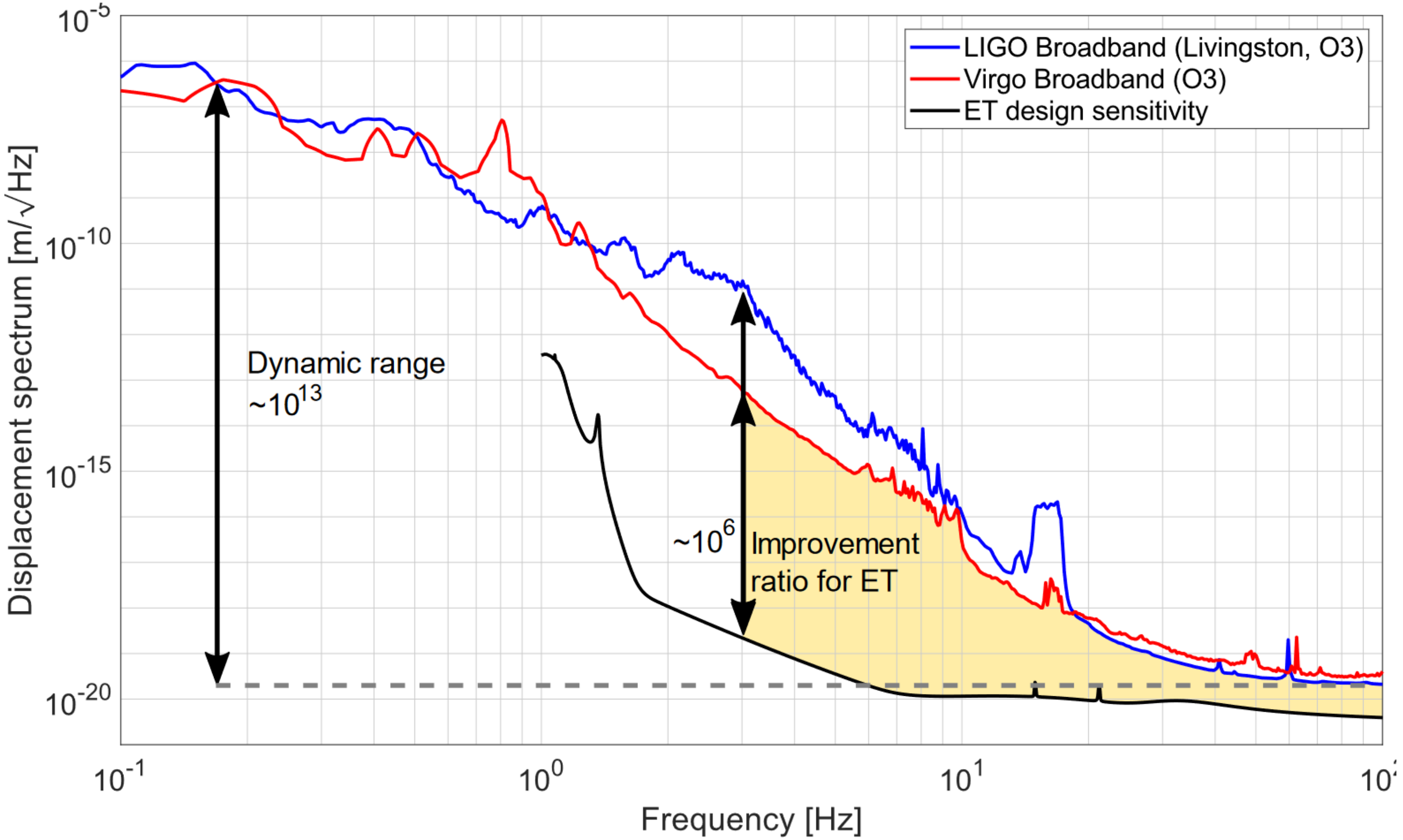
- Limiting sensitivity of current GW detectors



[Phys. Rev. D 102, 062003]

Low-frequency noise

- Even bigger problem for next generation: several orders of magnitude improvement required
- Can't make the "noise wall" arbitrarily steep → need good improvement even below detection band



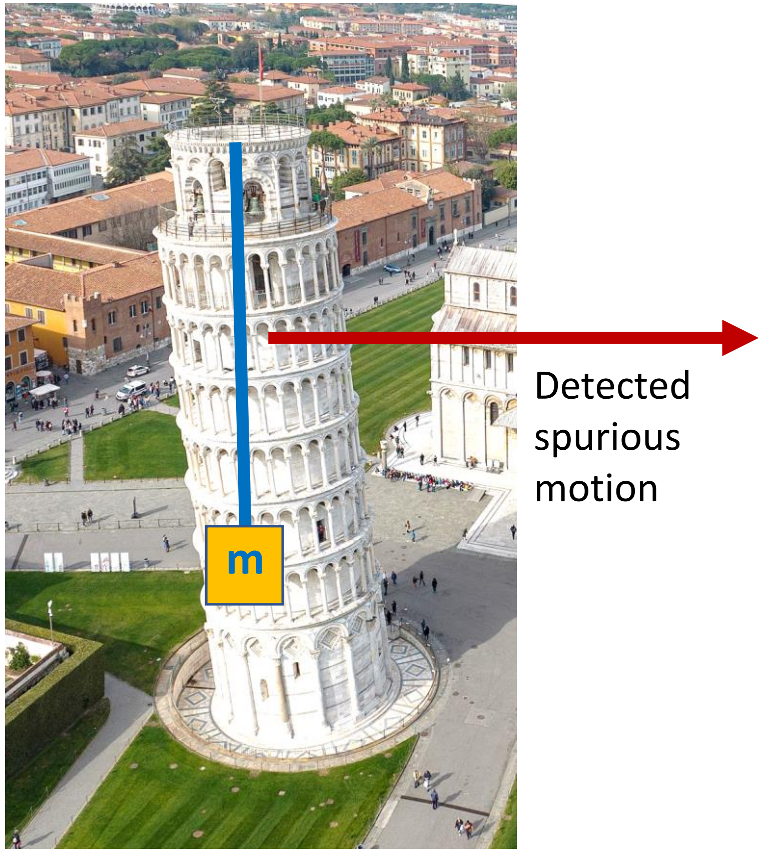
Source: Conor Mow-Lowry

Tilt & sensors

Low-frequency noise: ground motion and tilt

- **Imperfect compensation of seismic motion** in the isolation chain
- Limited by **sensor performance**
- **Platform tilt** produces spurious translational readings
- This and other noises get **imprinted onto the motion** of isolated platform by actuation

Effect of tilt on inertial sensor:



Low-frequency noise: ground motion and tilt

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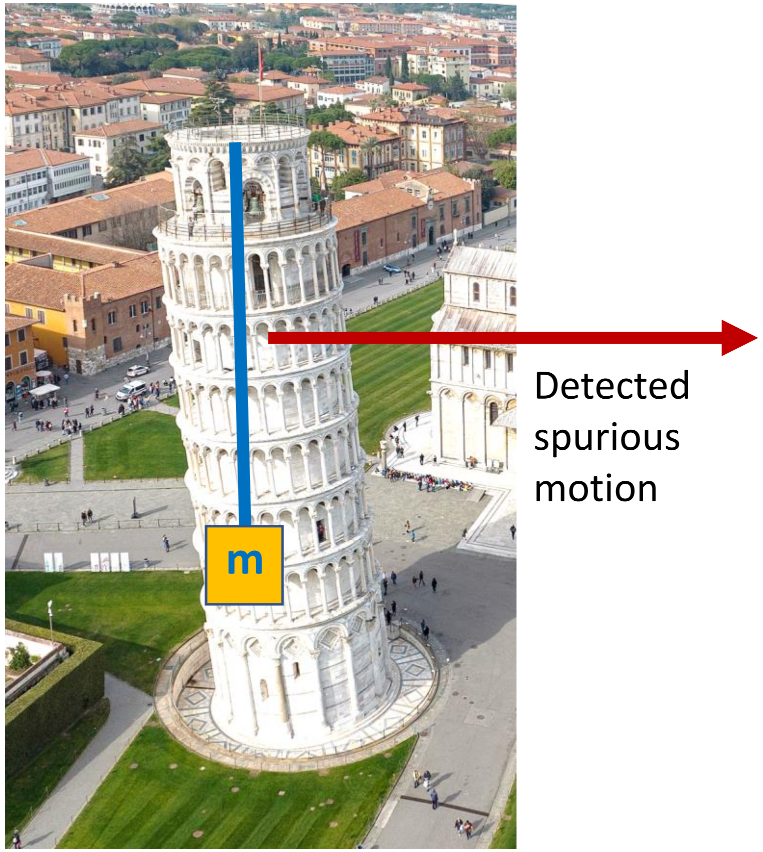
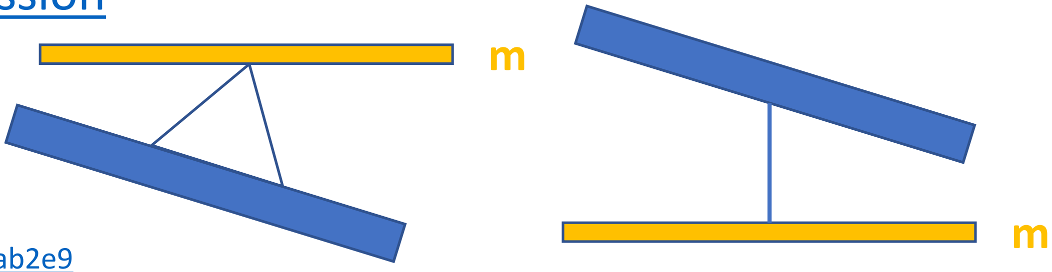
Some solutions:
- **Tilt sensors** (on the ground, e.g. BRS @ LIGO[1], or suspended beam[2])
- Better translational local sensors based on **interferometry**, e.g. HoQi[3]
- See also: [yesterday's session]

Effect of tilt on inertial sensor:



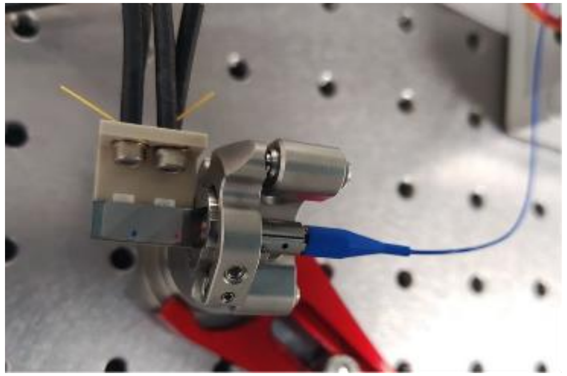


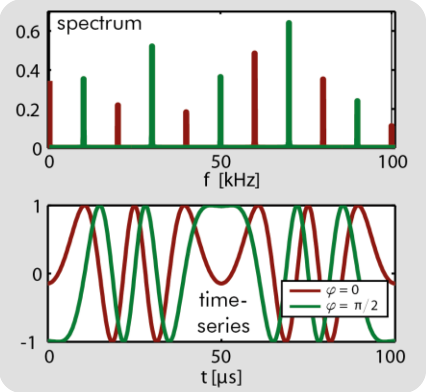
1. https://doi.org/10.1063/1.4862816
2. https://doi.org/10.1063/5.0118606
3. https://doi.org/10.1088/1361-6382/aab2e9

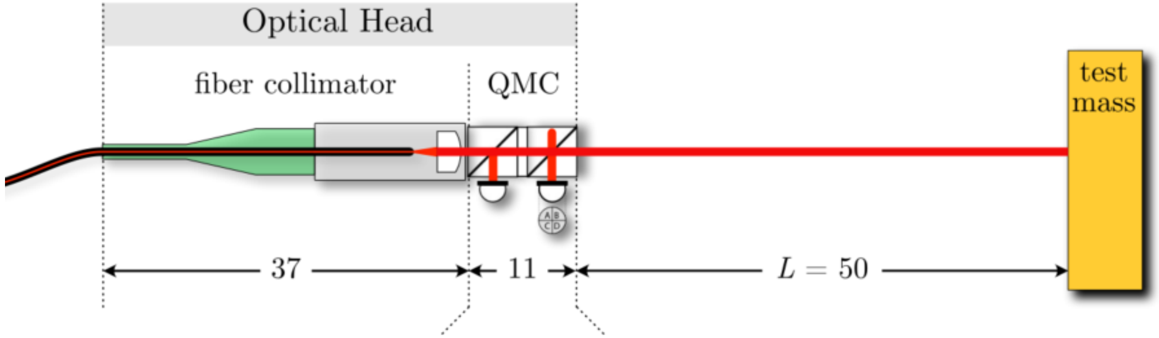
Our group

Compact Balanced Readout Interferometer (COBRI) sensors

- Local displacement readout or inertial sensors
- Based on **Deep Frequency Modulation Interferometry (DFMI)** [poster #105 by Oliver]
- Very compact: fits into half inch mirror mount
- Expected sensitivity ~**10^{-14} m/ √Hz**







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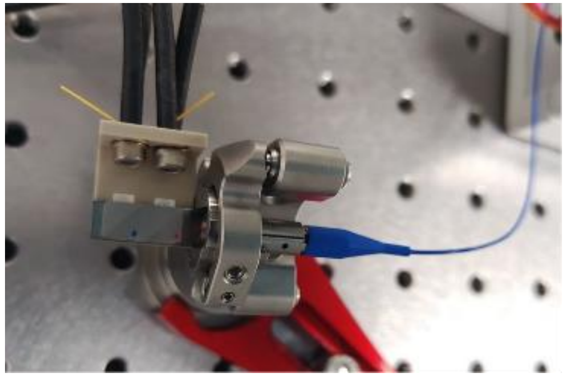
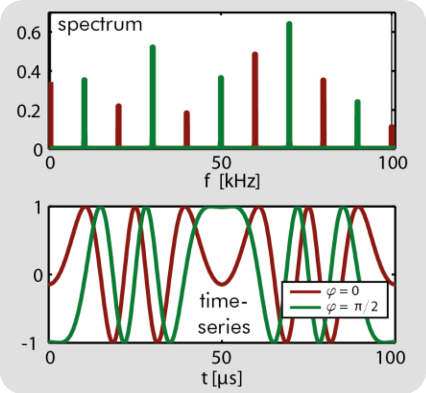
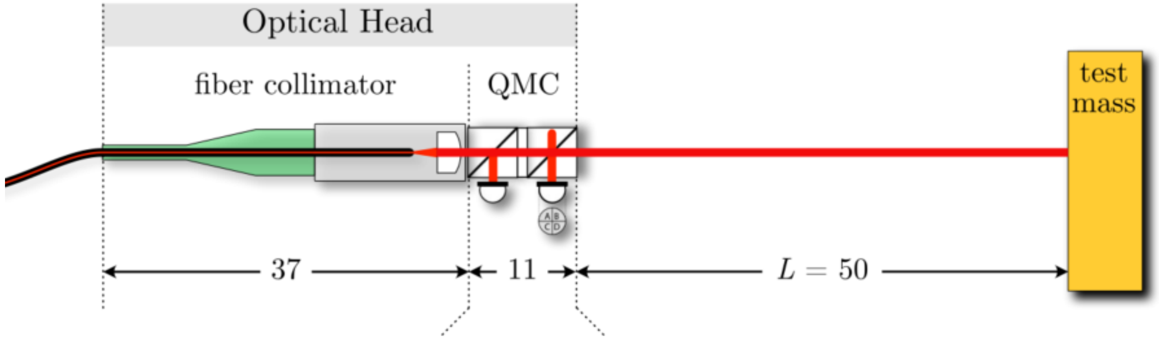
- Very compact: fits into half inch mirror mount
- Expected sensitivity ~**10^{-14} m/ √Hz**
- Two other readout techniques currently investigated to go below **10^{-15}/√Hz**:
  - Resonantly enhanced DFMI
  - Heterodyne cavity readout [poster #24 by Shreevathsa]







Seismic isolation & Control

Our group

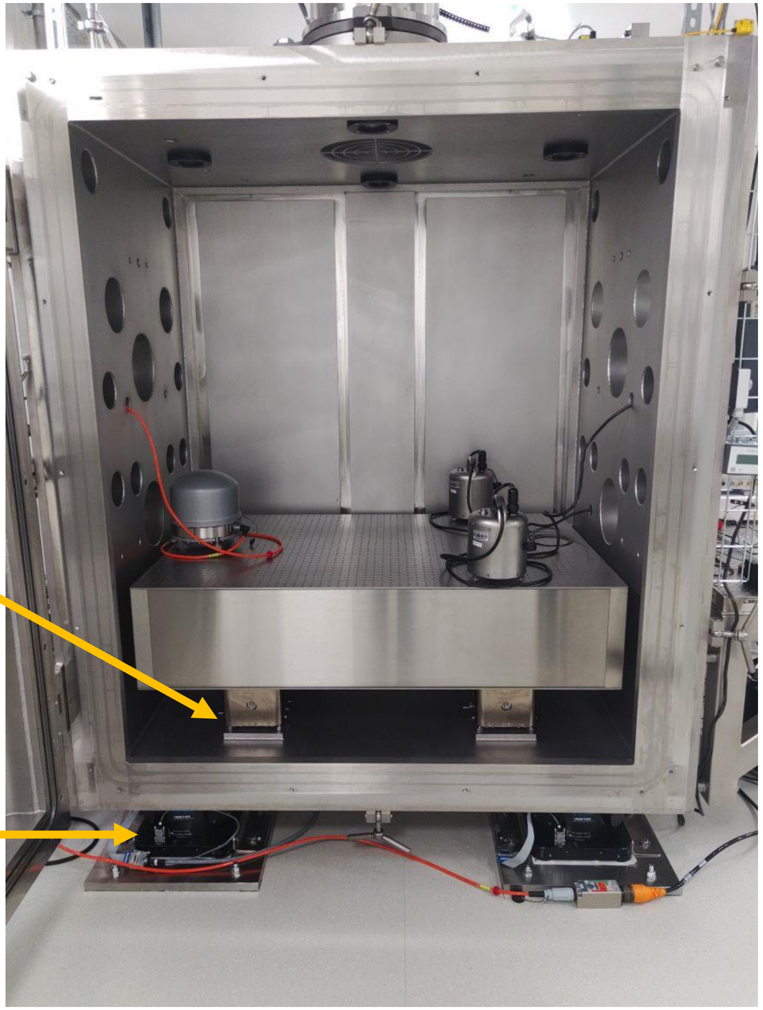
VATIGrav: seismically isolated platform for testing sensor designs in vacuum

Vacuum goal <10^{-6} mbar

- Reached: $1.9*10^{-6}$ mbar

Passive isolation for optical table inside

Active seismic isolation from the ground (STACIS III)



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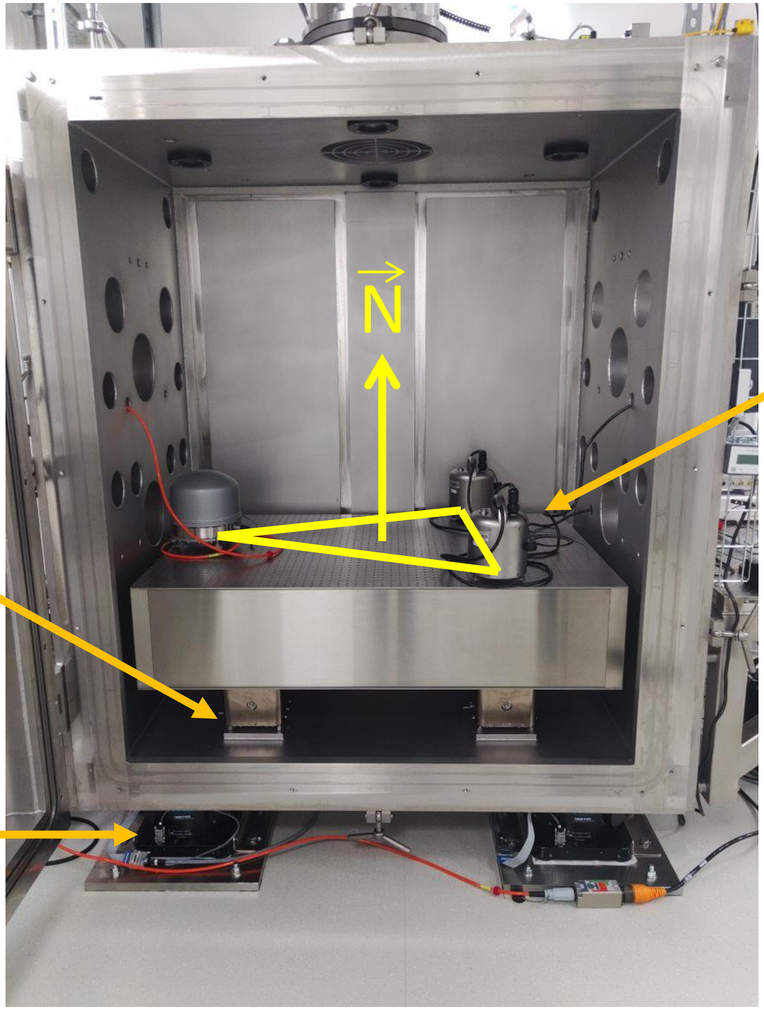
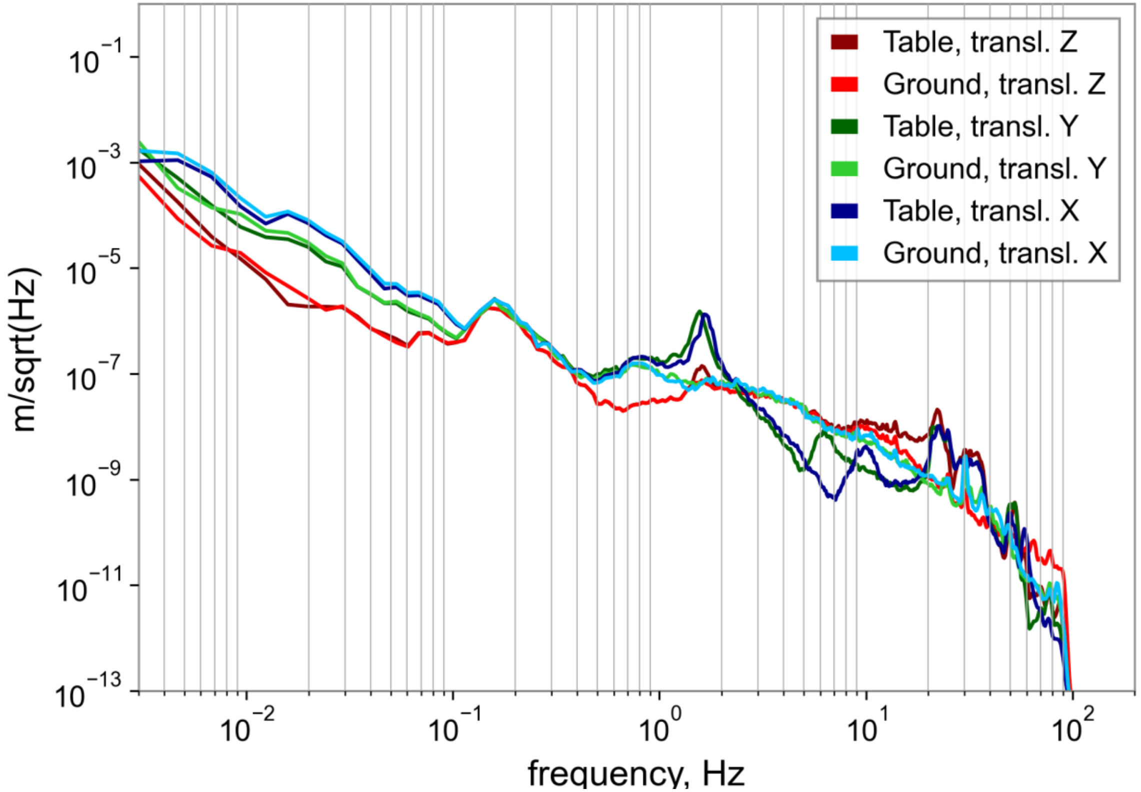


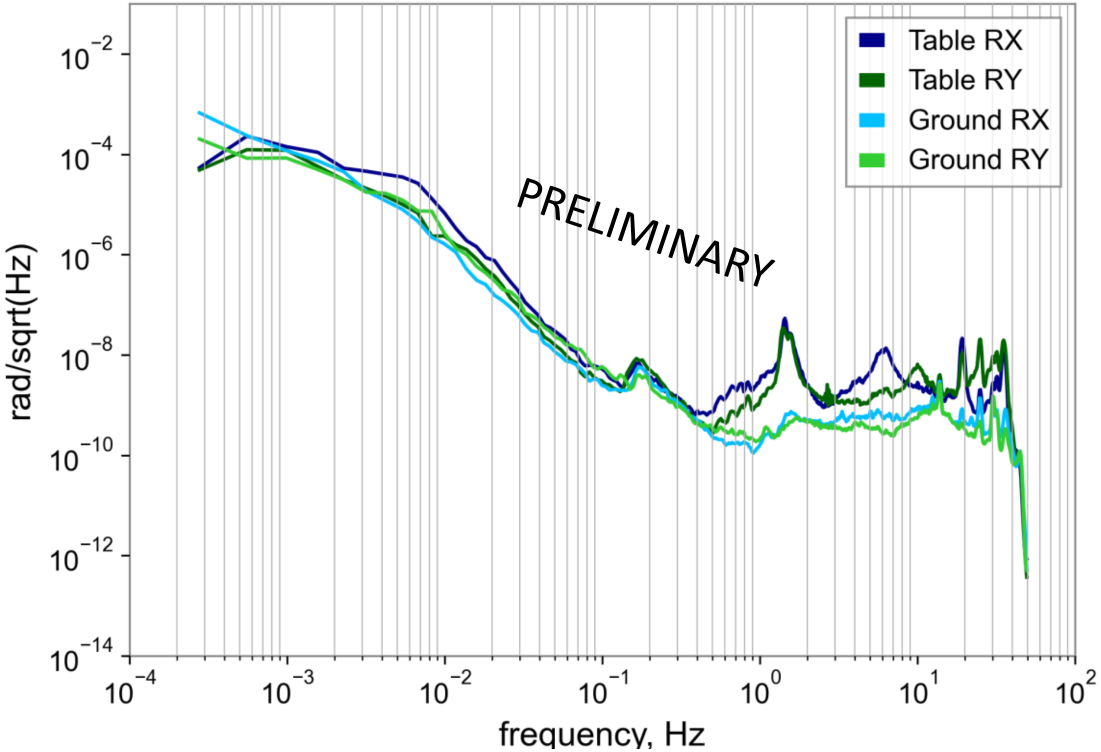
Currently: Translation/tilt measurement

Measurements of translation and tilt

Active isolation

OFF

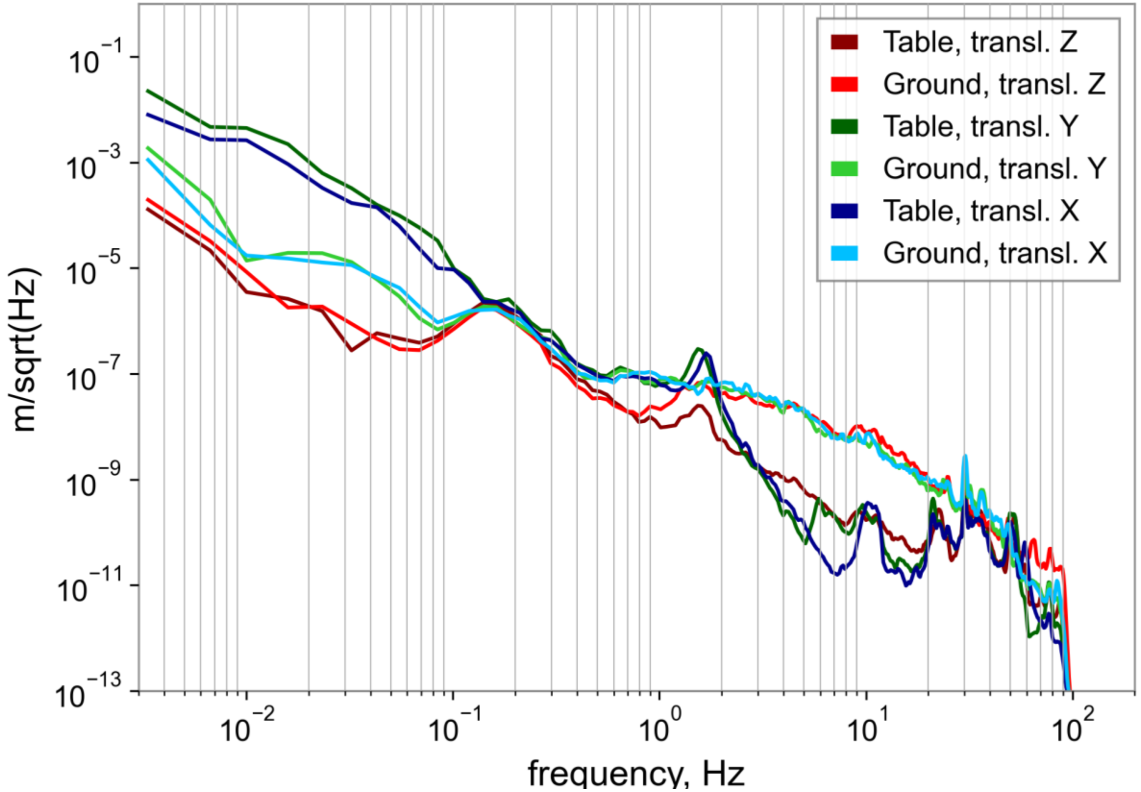


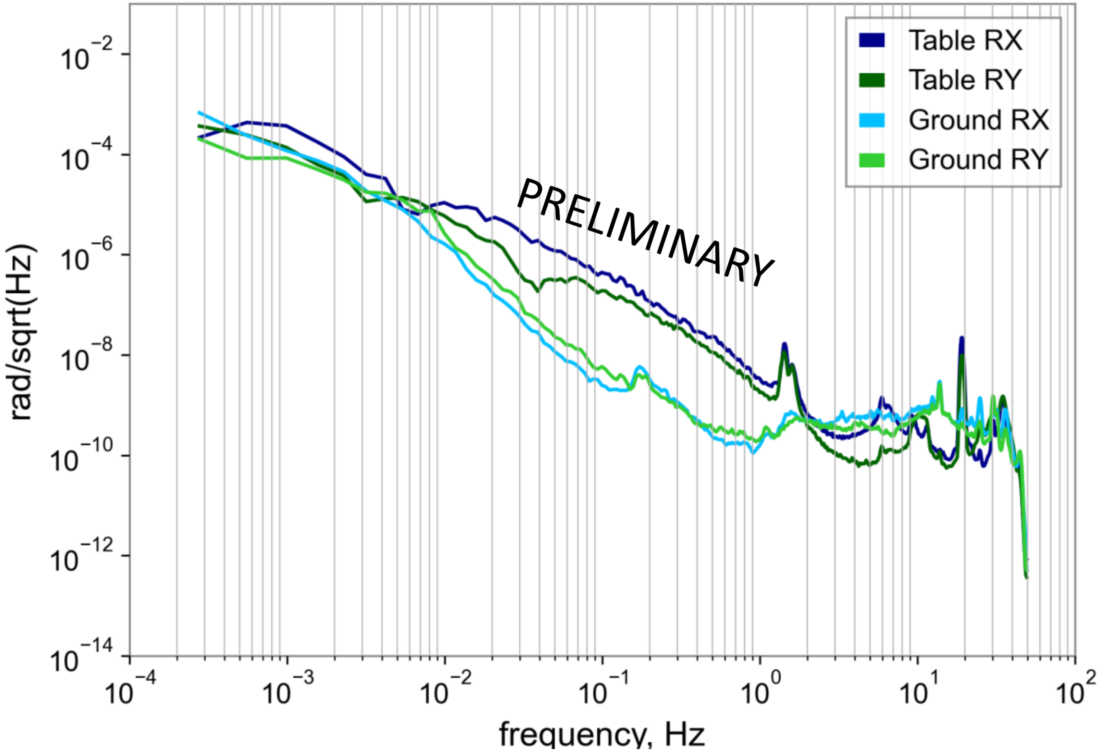


Measurements of translation and tilt

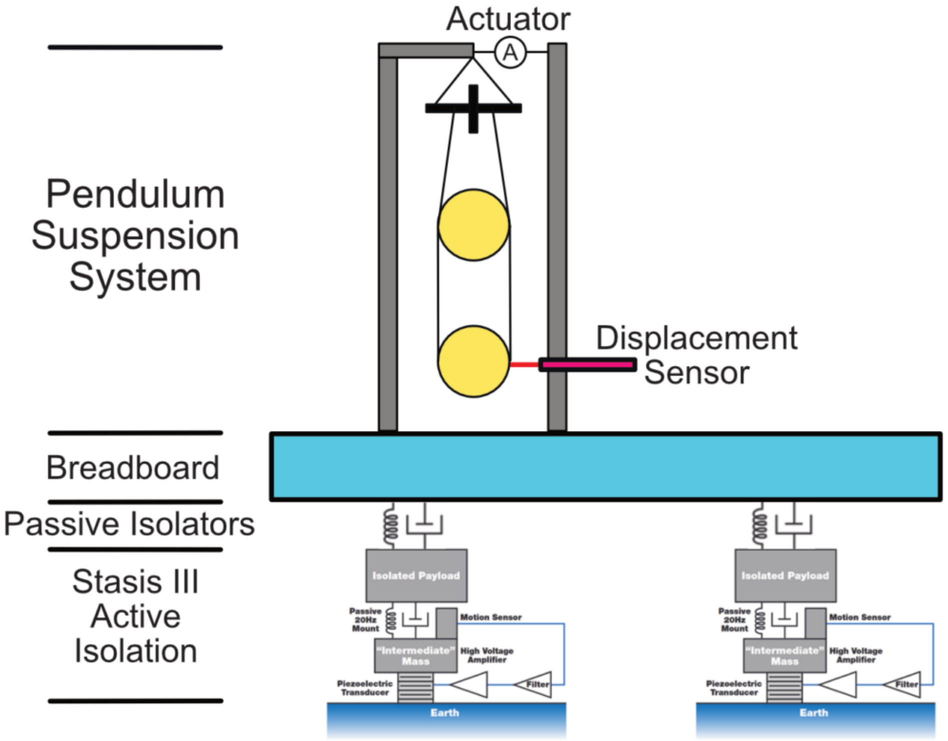
Active isolation

ON



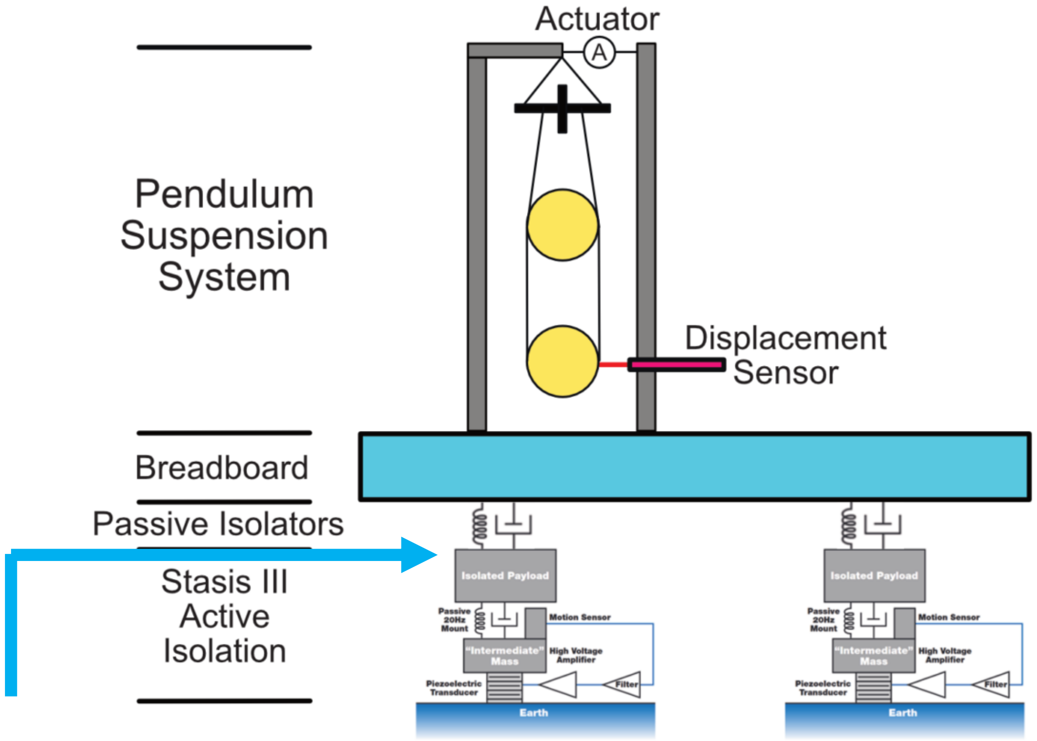


Path to improvement



Path to improvement

Translation and
tilt feedforward

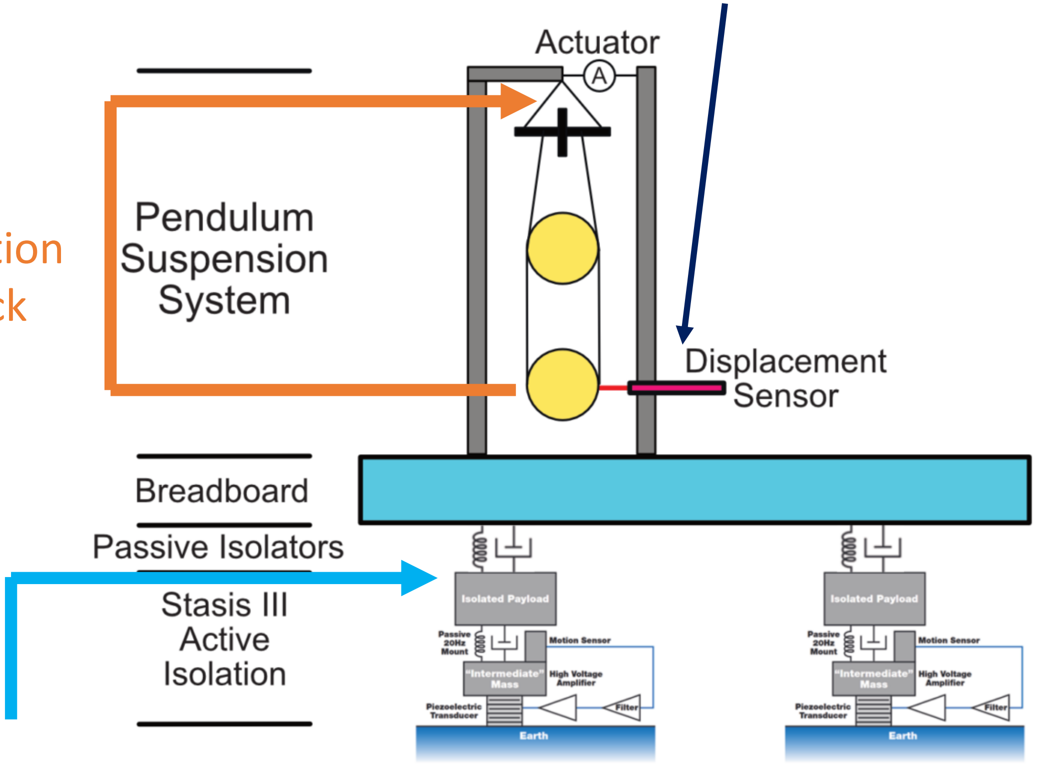


Path to improvement

COBRIs on suspensions +
test mass = inertial sensor

Translation feedback

Translation and tilt feedforward



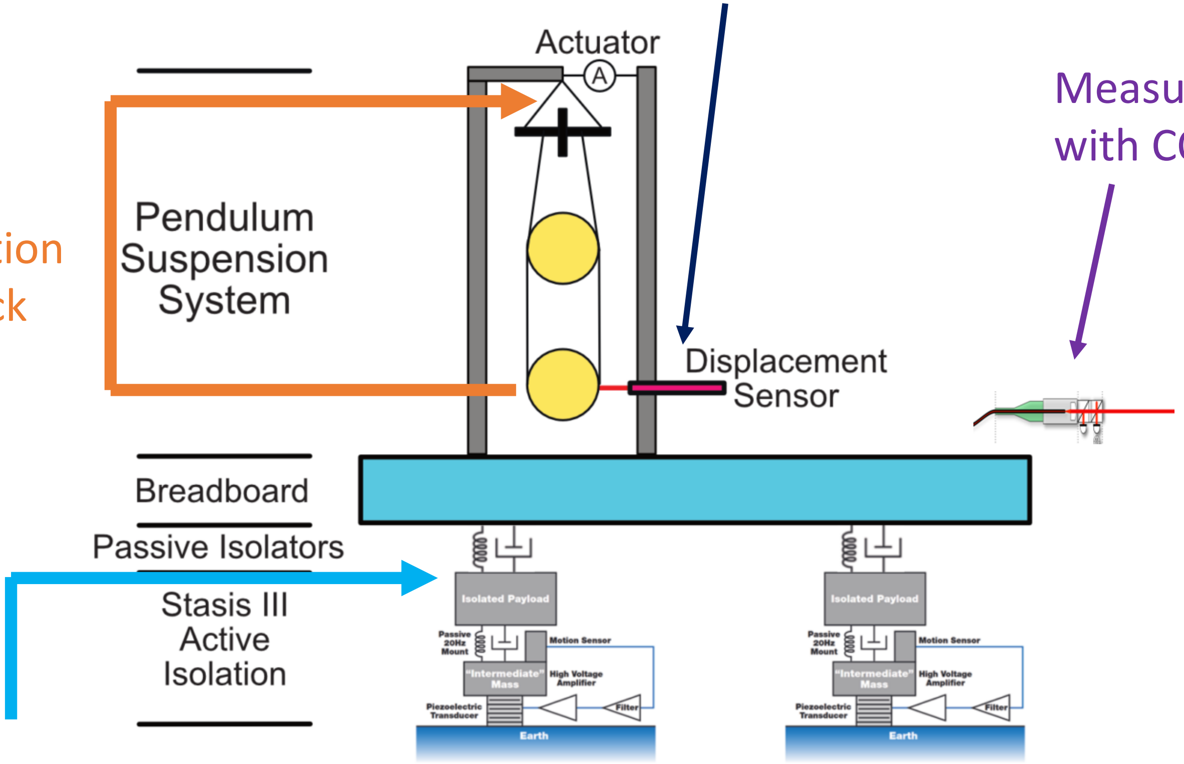
Path to improvement

COBRIs on suspensions +
test mass = inertial sensor

Measure displacement
with COBRIs wrt the wall

Translation
feedback

Translation and
tilt feedforward



Path to improvement

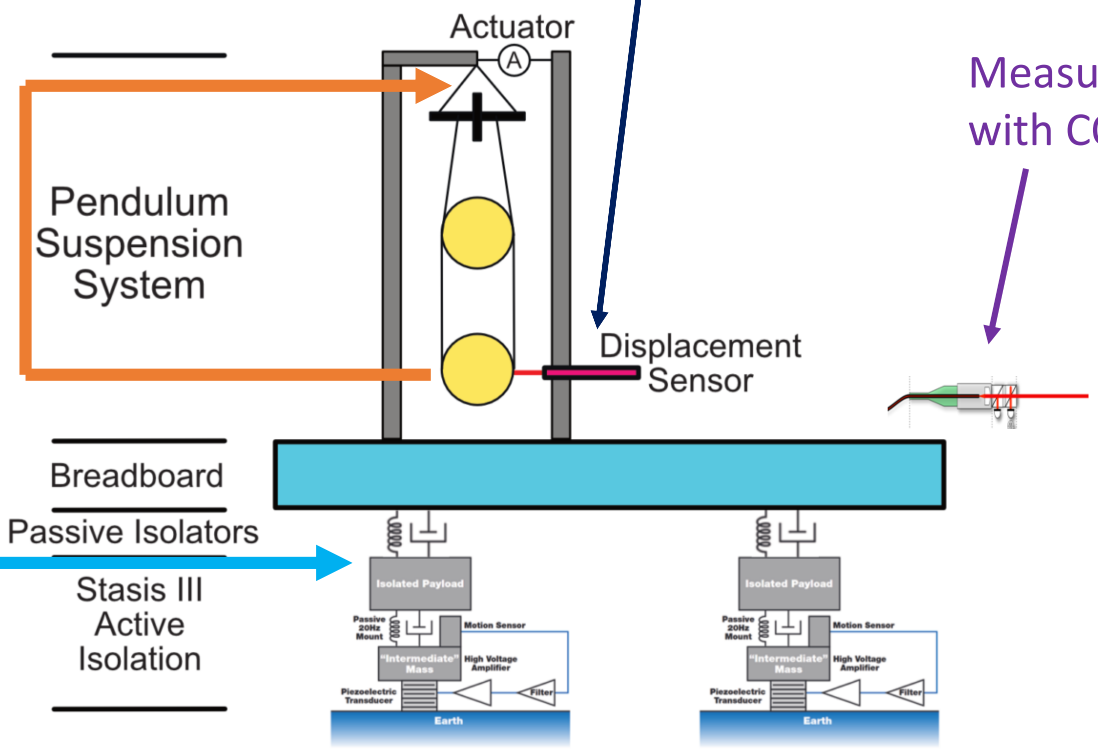
Need to model:

- Effects of couplings between different DOFs in sensing and actuation
- Effects of sensor noise; optimize sensor placement
- Optimize the controller

COBRIs on suspensions + test mass = inertial sensor

Measure displacement with COBRIs wrt the wall

Translation feedback



Translation and tilt feedforward

Big(ger) picture

Same modelling needed + more for big IFOs

- For Einstein Telescope, LIGO, LISA..
- Many algorithms developed by the community over the years
  - “behind closed doors” of internal repos and private computers
- We need better organized modelling software:
  - **Compatible interfaces**
  - **Provenance**

See some thoughts on that in my/Oliver’s talk at ET Symposium

Common modelling tool(s)?

- We started a project to try to translate some of "community knowledge" to python and open source it
- Eager to learn about/collaborate on similar projects!

My inspirations: GWpy, python-control, Kontrol, Finesse3, … (incomplete list)

Spicypy project

Combining several tools to facilitate **signal processing**, **control systems modelling**, and the **interface between the two**.

LVK | Einstein Telescope | LISA | Laser physics, material science, …

- Open-source, transparent, collaborative development (hosted on gitlab.com, Apache License, contributors from 6 institutes and 4 countries…)
- Based on well-tested GWpy and python-control
- "Modern" approach: unit tests, examples and documentation

Summary

Low-frequency noise: difficult and important

Tilt affects Sensors → LF noise

Seismic isolation & Control

=> Intertwined, need to model & optimize

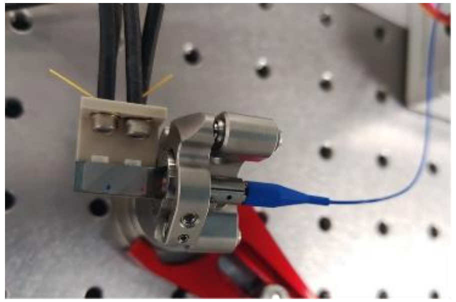
Modelling Software

=> Should be a common, open effort

VATIGrav

Spicypy

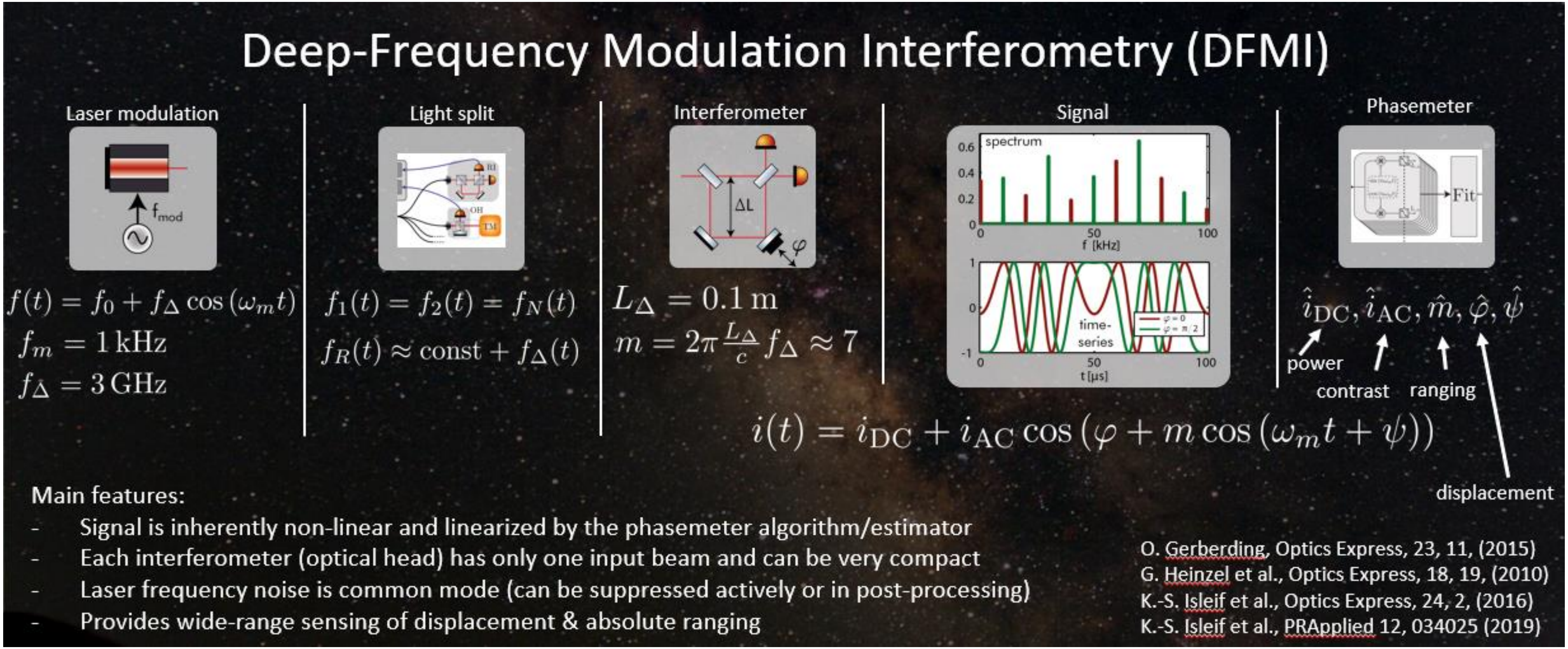
COBRI



Thank you!

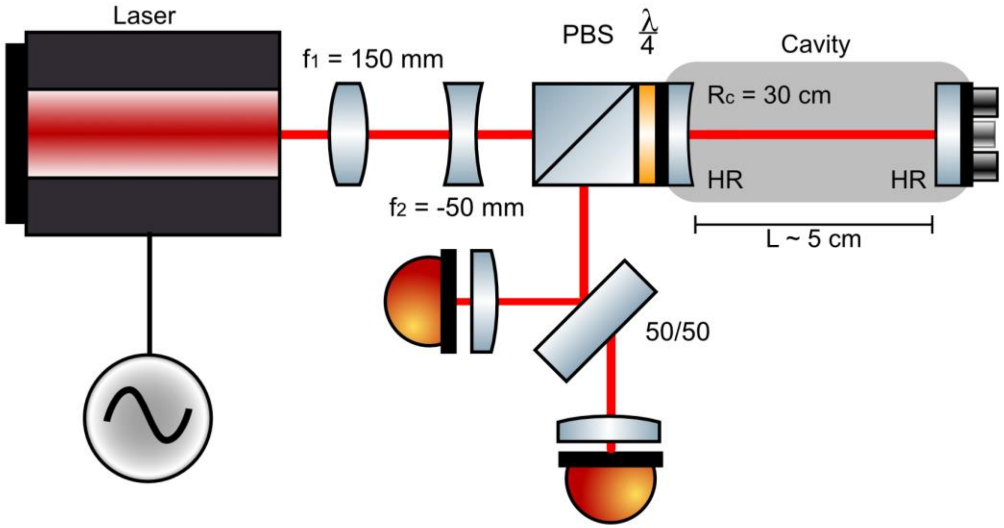
Backup

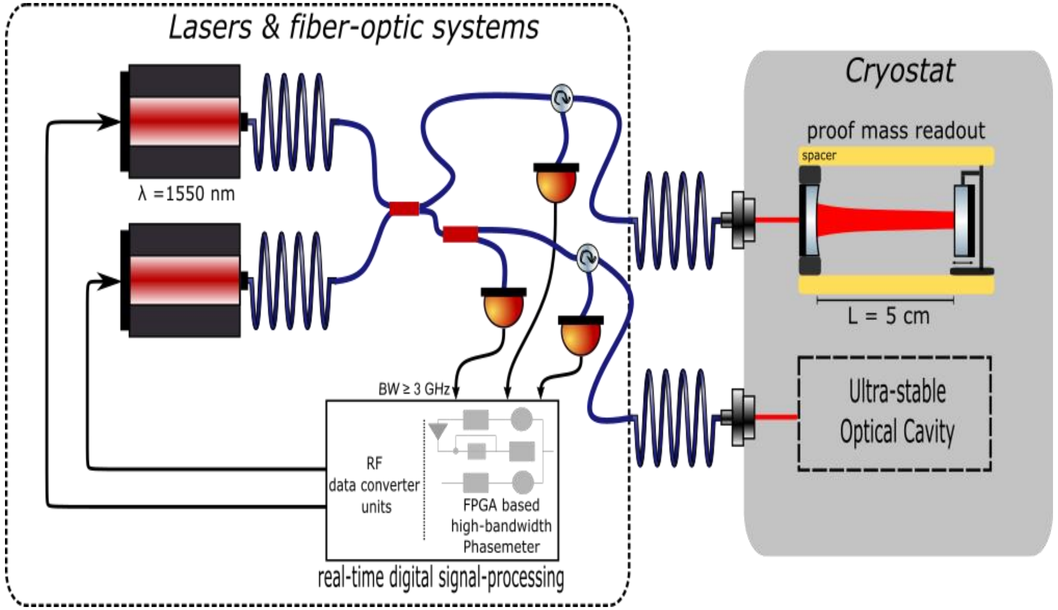
DFMI Concept



See [Oliver's talk at ET Symposium]

ReDFMI and Heterodyne cavity





Resonantly enhanced DFMI

$<10^{-15}$m/sqrt(Hz)
dozens of sensors per laser
absolute ranging

Heterodyne cavity tracking readout

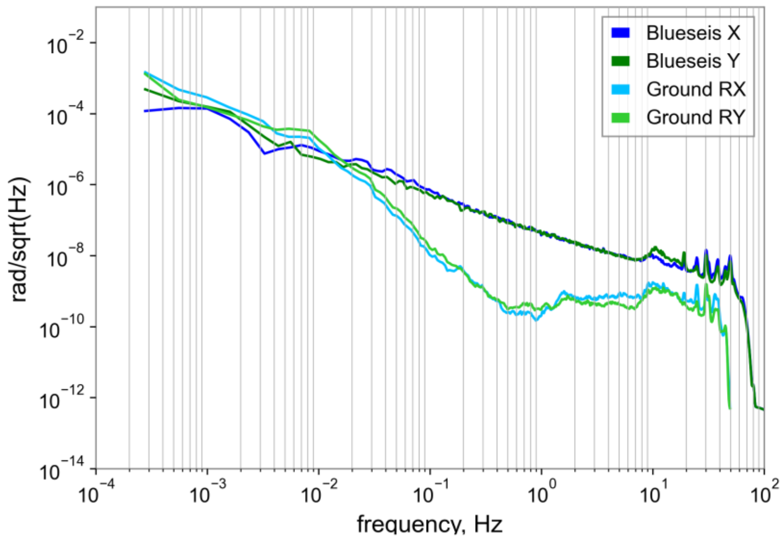
$<10^{-15}$m/sqrt(Hz)
one sensor per laser
best possible performance

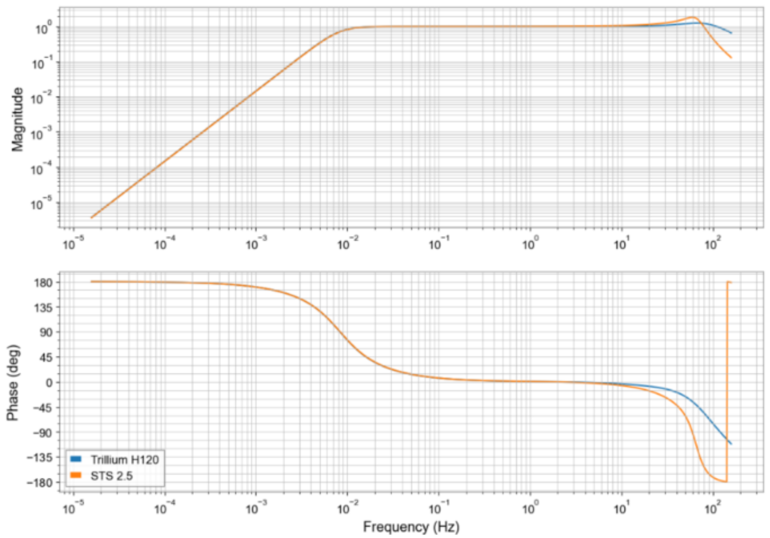
See [Oliver's talk at ET Symposium]

Caveats of tilt measurement

- Transfer function of seismometers is ignored, constant scaling in time domain (effect expected only in very low frequencies, otherwise TF ~1)
- Still working on calibration, absolute amplitudes may be off… Comparison with Blueseis 3A rotational seismometer:

- Due to limited number of seismometers can't measure at the same time on the ground and on the table, therefore using different measurements on the same plot
- Plan to use PPSD to generate more „averaged“ result





Transfer functions of STS 2.5 vs TH120:

- **Almost identical** in LF
- **Constant = 1 in wide freq range**