ARC Centre of Excellence for Gravitational Wave Discovery

Torsion-Pendulum Gravitational Force Sensor

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Australian National University

GWADW 2019 - Elba

LIGO and its Pendulums

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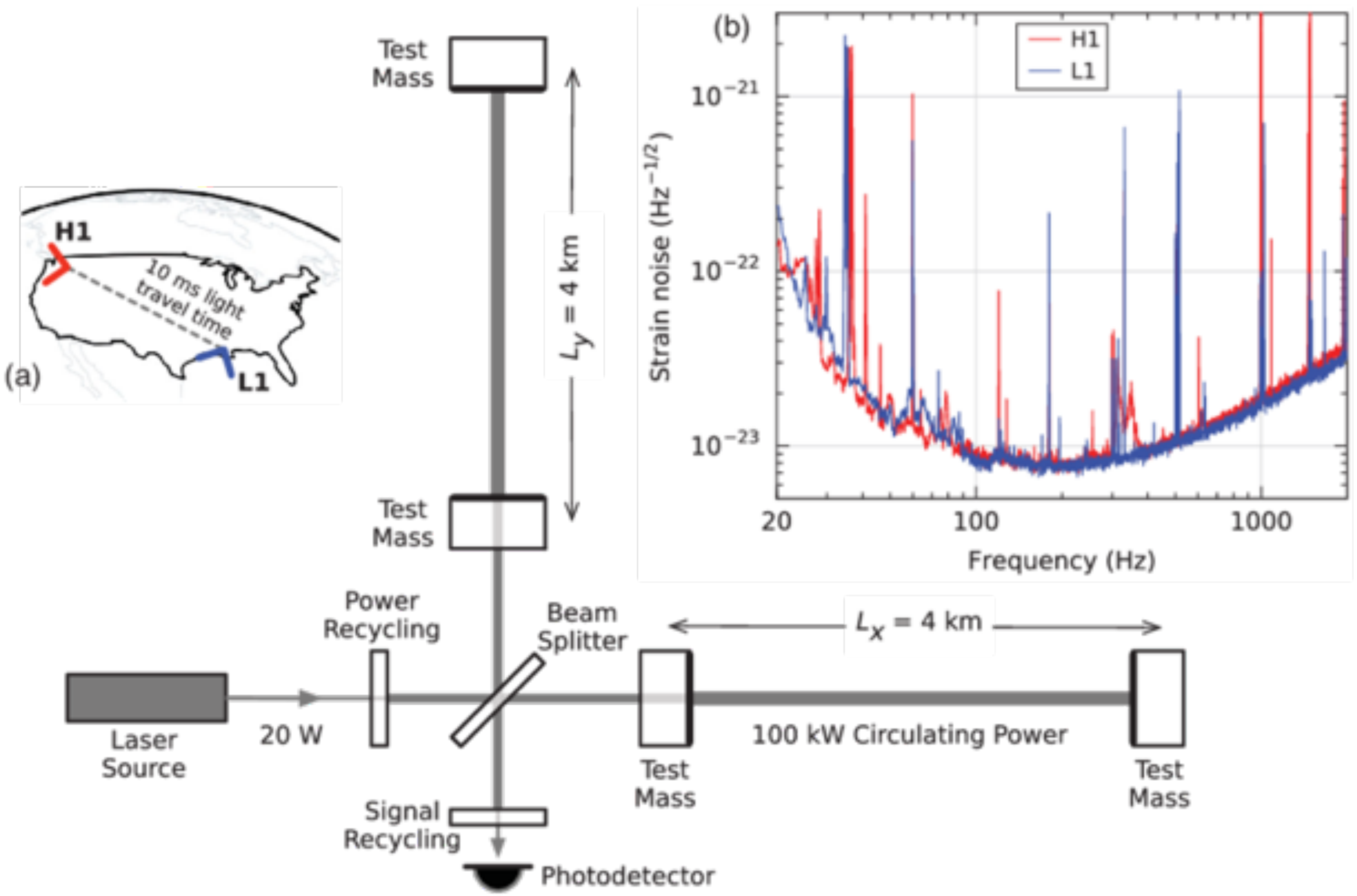

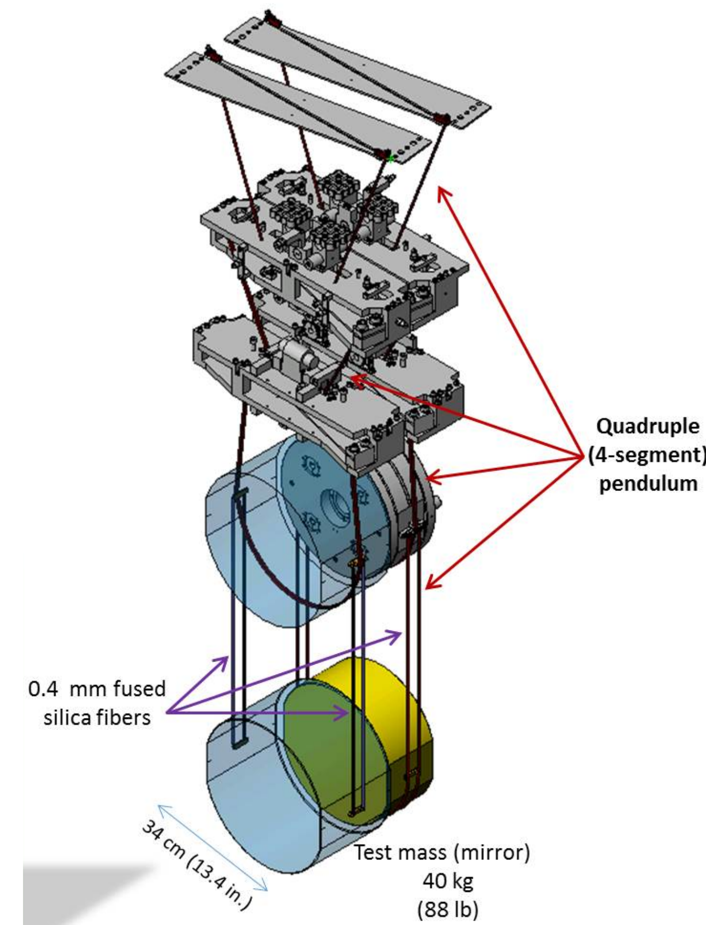

Advanced LIGO Suspension

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Newtonian noise

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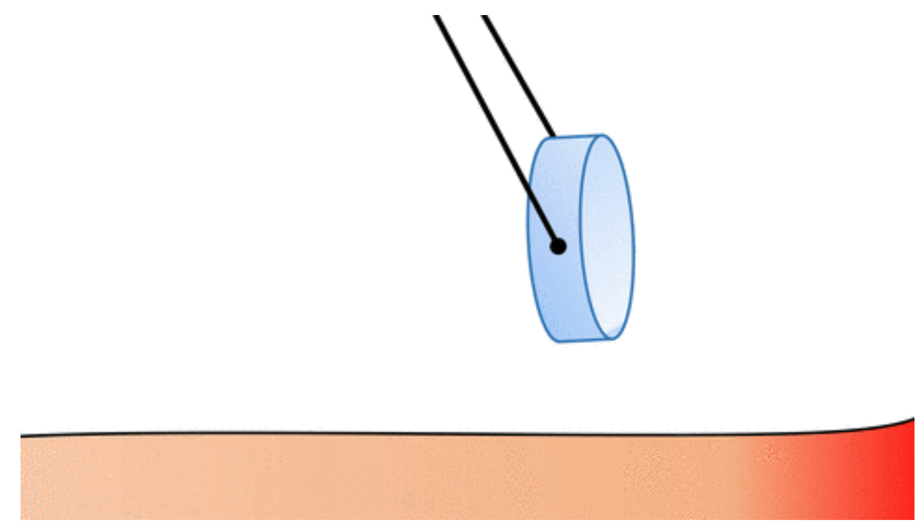
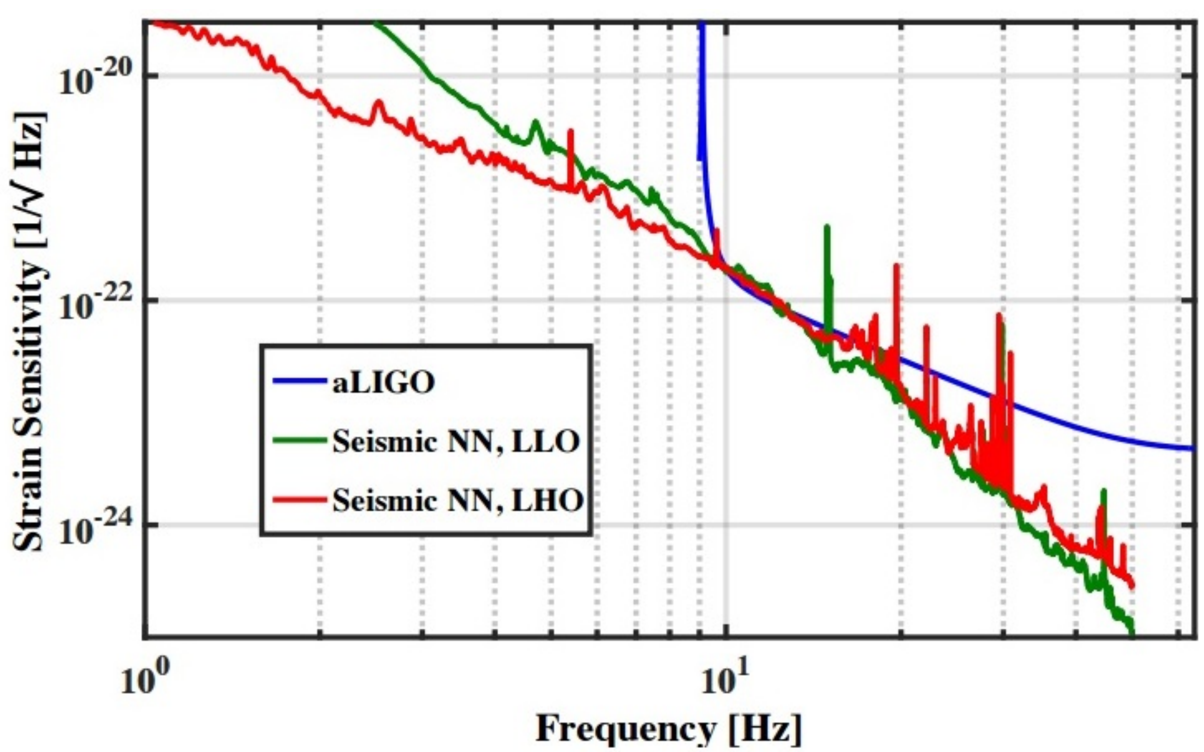
- Also know as gravity-gradient noise.
- Local density fluctuation generate force field which interact with the interferometer test masses.
- Seismic or atmospheric induced.
- Cannot be shielded.
- Future detectors becoming limited by Newtonian noise at low frequencies.
- Technologies under investigation to mitigate the Newtonian noise coupling





Donatella Fiorucci, et al, Phys. Rev. D **97**, 062003

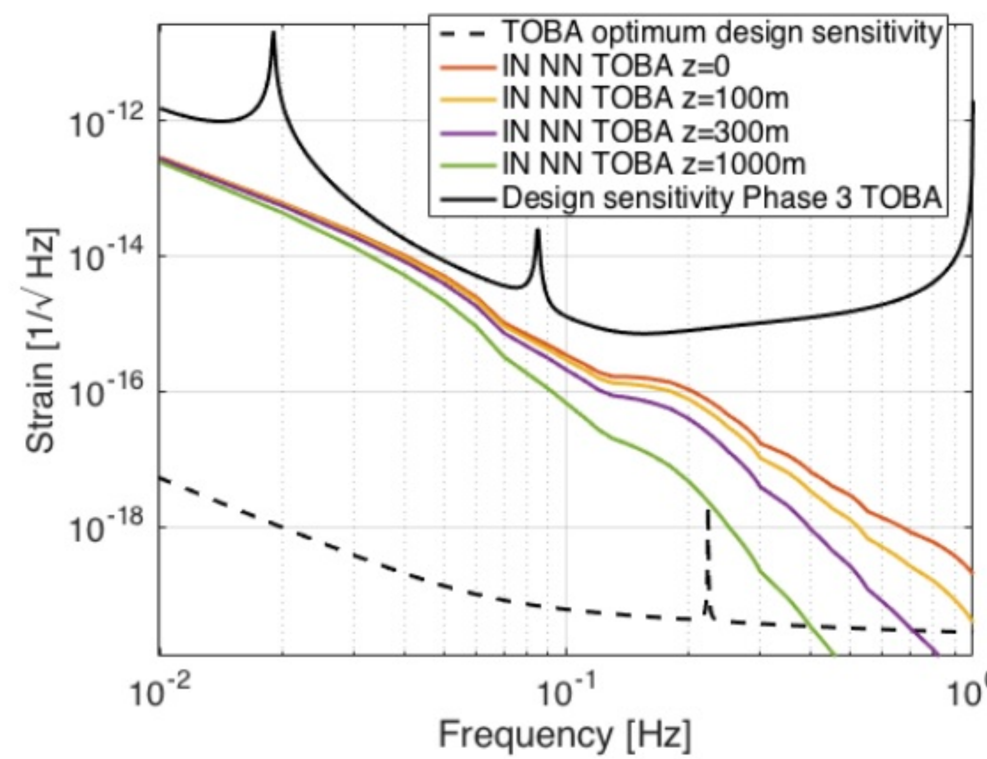


FIG. 12. TOBA infrasound NN for different detector depth. The dashed sensitivity curve corresponds to the optimum TOBA configuration. The solid black curve corresponds to the next stage TOBA configuration sensitivity.

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TORsion PEndulum Dual Oscillator

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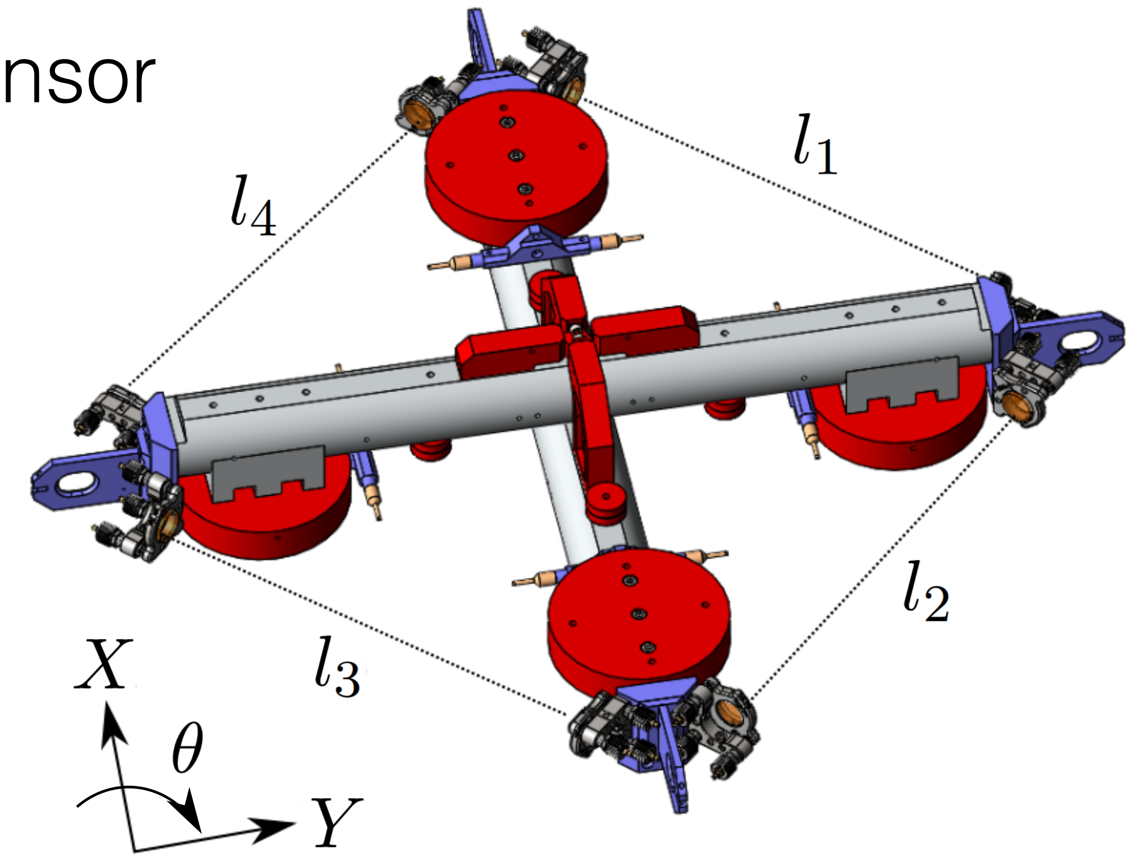
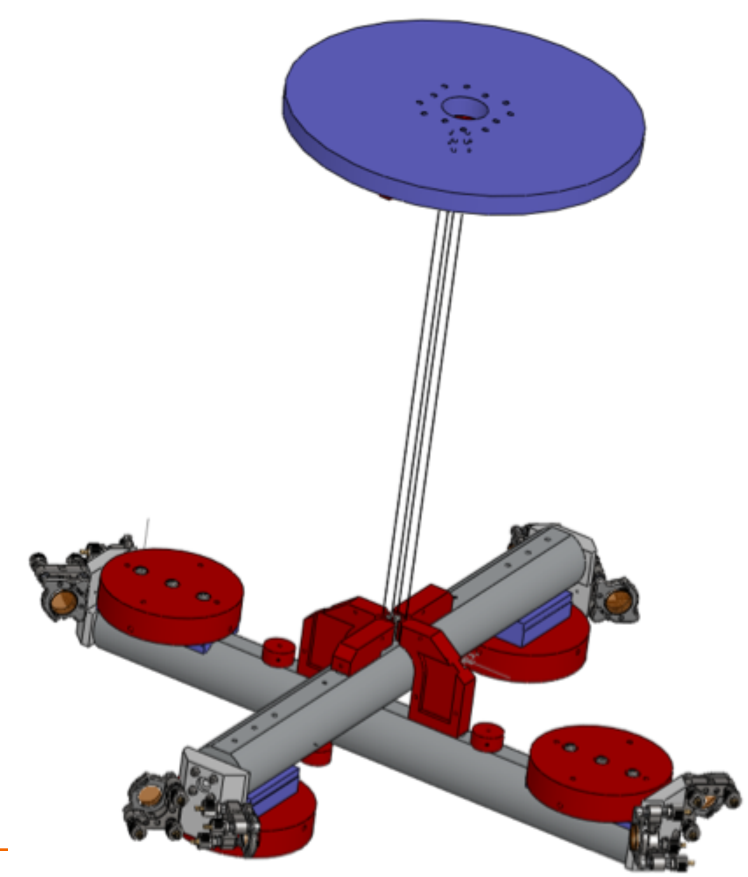
- Low-Frequency Gravitational Force Sensor
  - Frequency 10 mHz -10 Hz
- Terrestrial Newtonian Noise
- Earth-quake early warning

- Two torsion balance
  - Centres of Mass coincide
  - Co-linear axes of rotation
  - Identical tuned moments of inertia
- Read out with optical cavities
- Target sensitivity ~1e-15 /rtHz at 0.1 Hz
- Prototype Build

- (David McManus, Nathan Holland, Perry Forsyth)





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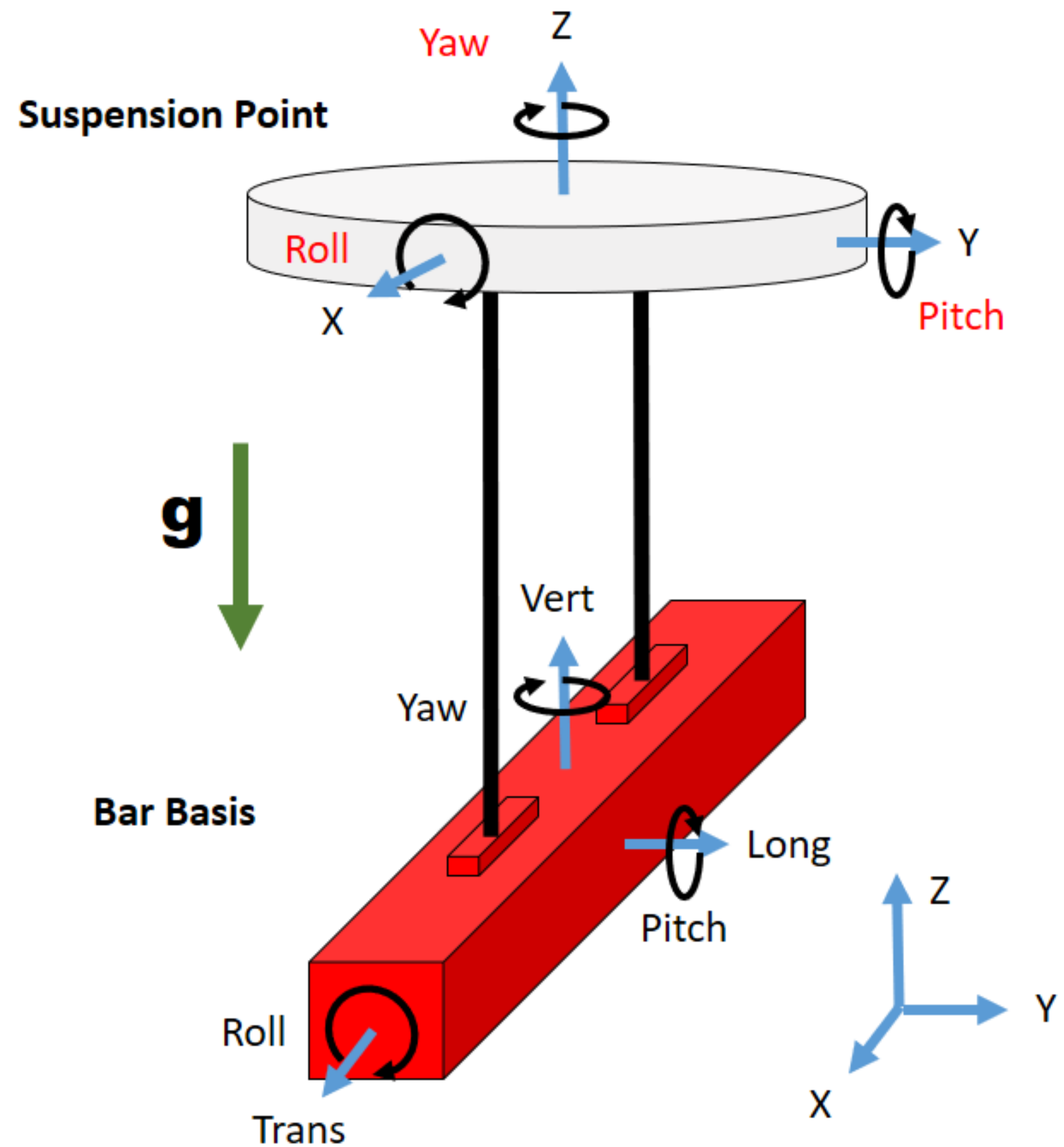
Torsion Mechanics

We built a model that includes:

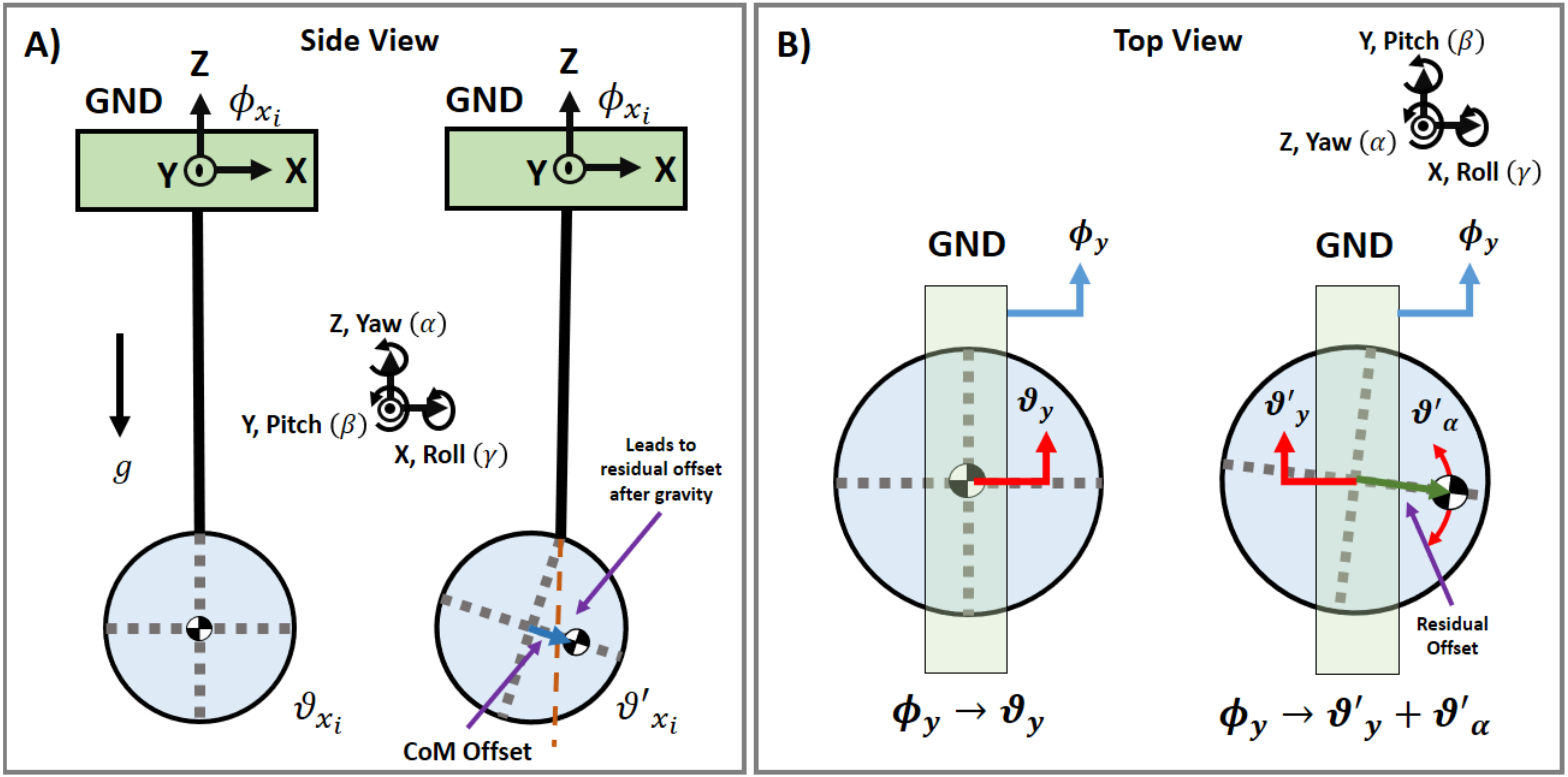
- The displacement of the CoM to the attachment point on each bar
- The bending and stretching of each individual wire
- The constraints applied by having two wires
- The loss angles (Q) of the suspension wire material
- Ideal values from the CAD model of the system
- Cartesian and generalized forces

Assumptions:

- Ridged body mechanics. (Bars don't bend)
- Small angle approximation
- Linear system

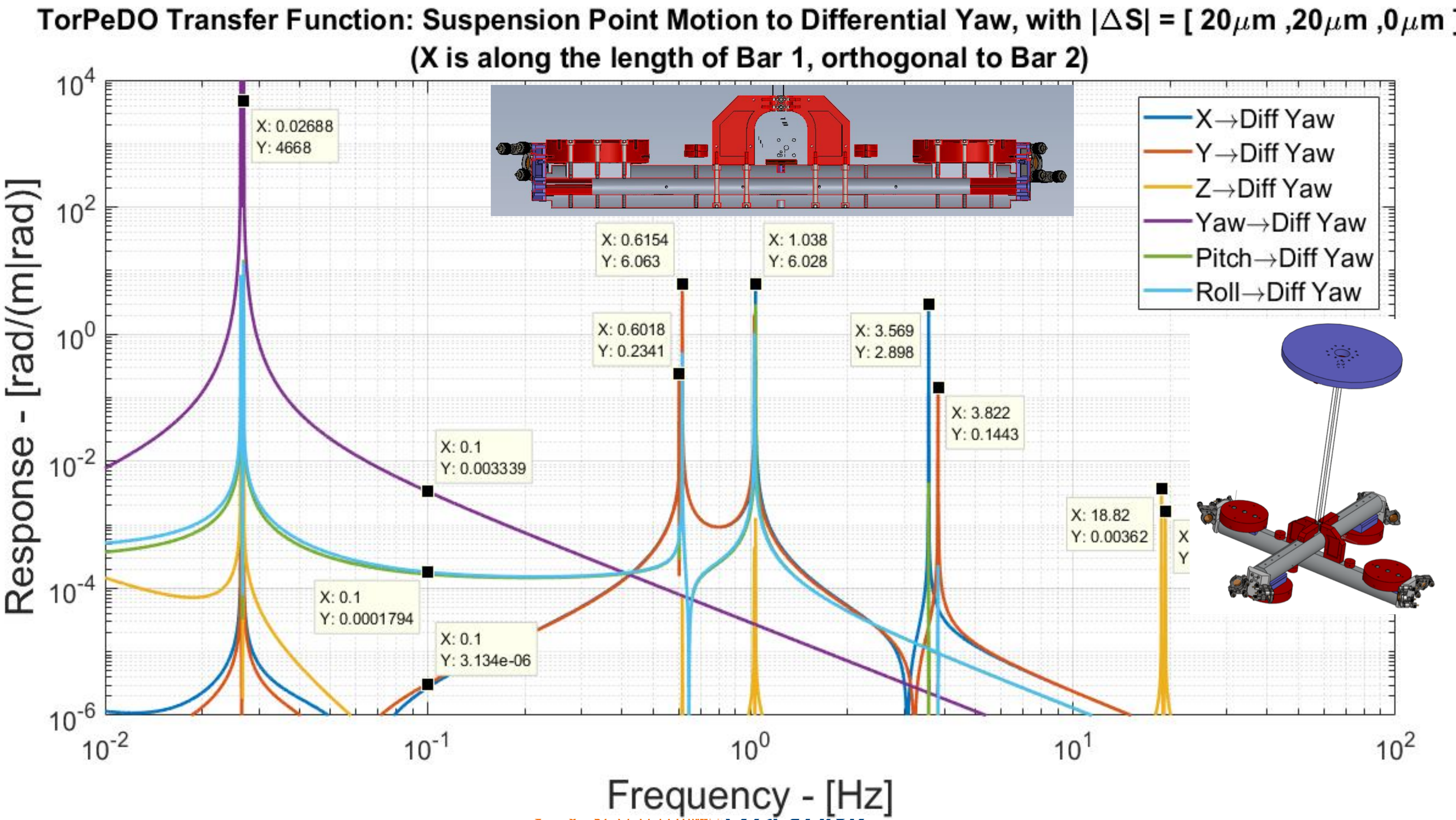


Centre-of-Mass Offset

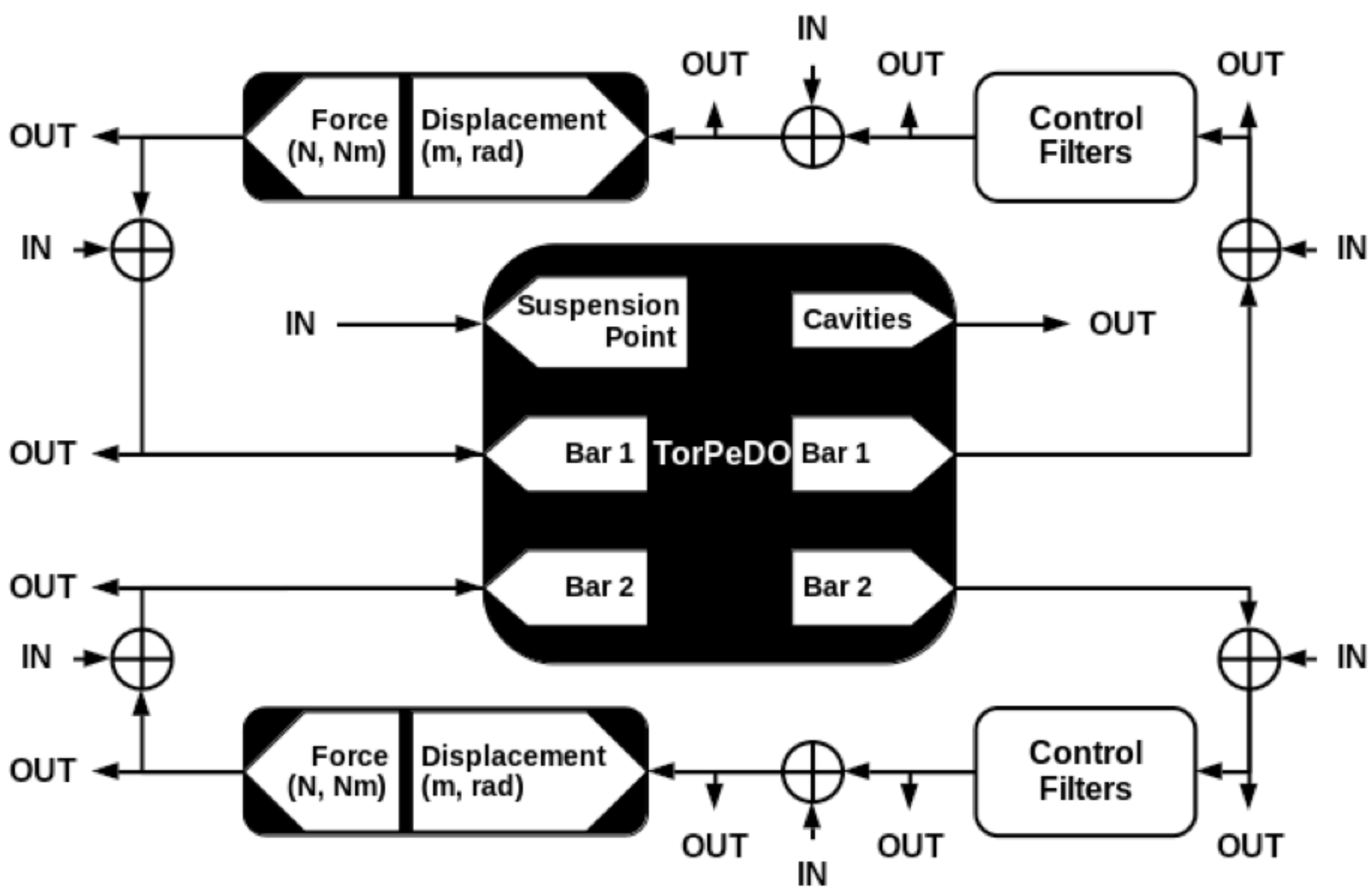


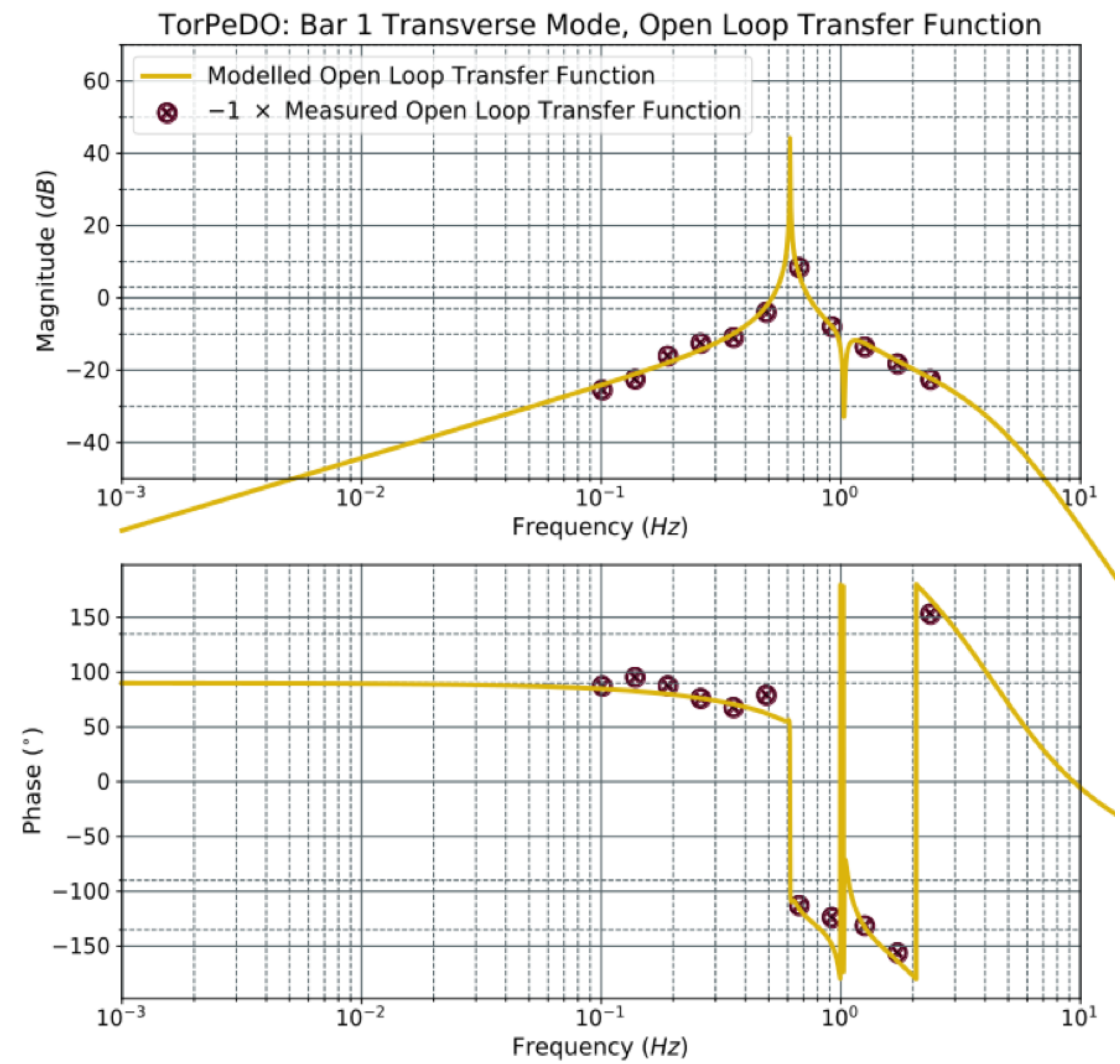
Reduced cross coupling after tuning

- Moving 200g mass by 1mm provide ΔS COM tuning down to 20 μm



Controls Modelling



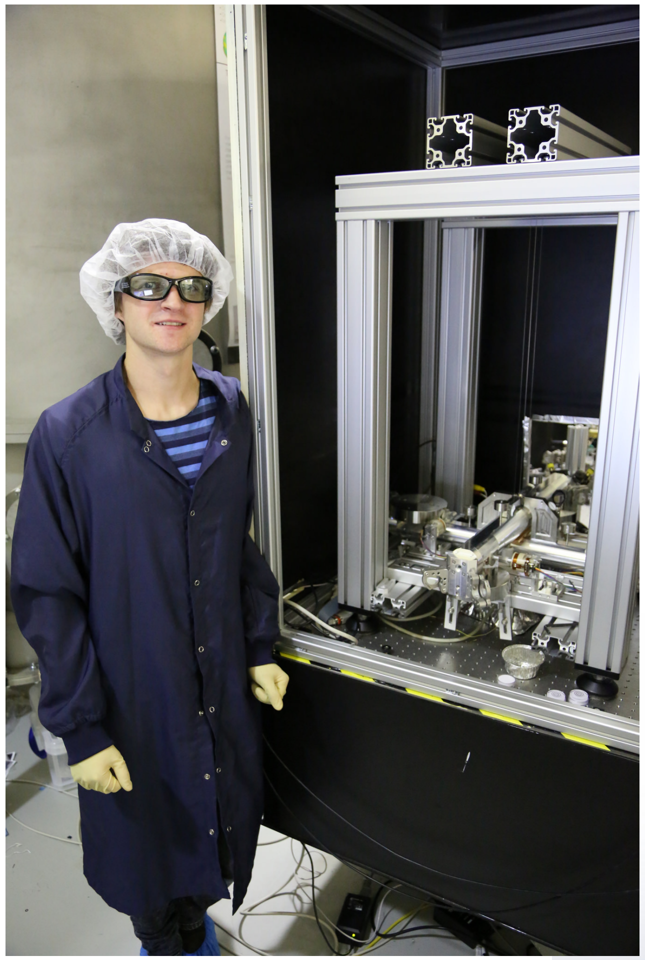


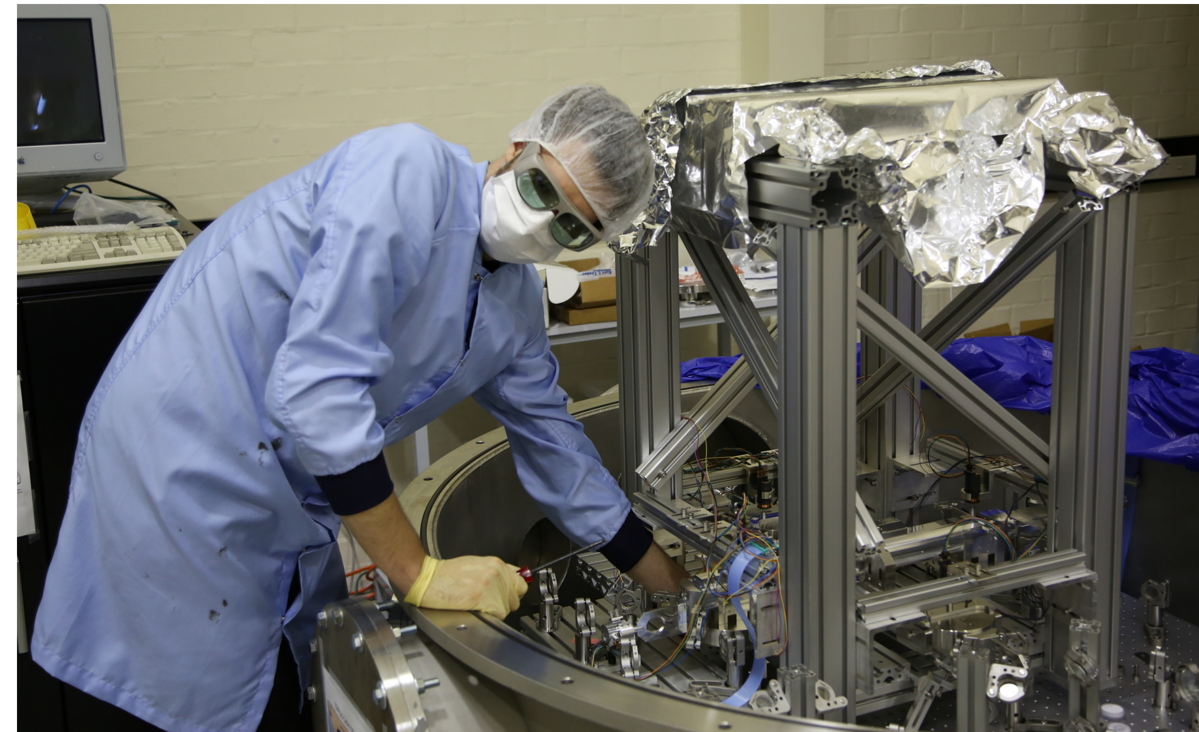
Suspension controls modelling. This will be used to:

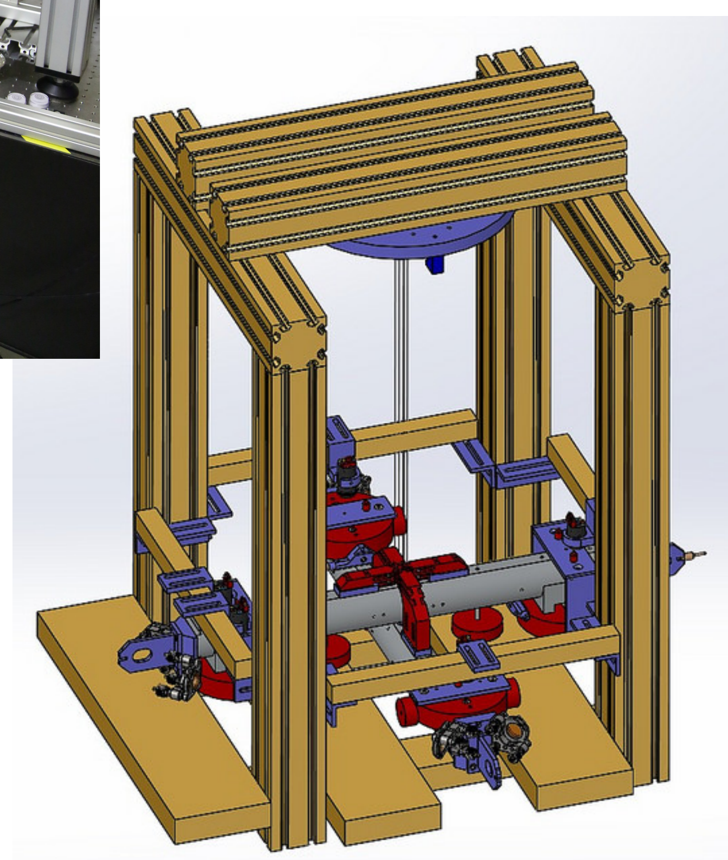
- Evaluate local damping performance.
- Inform improvements to local damping.

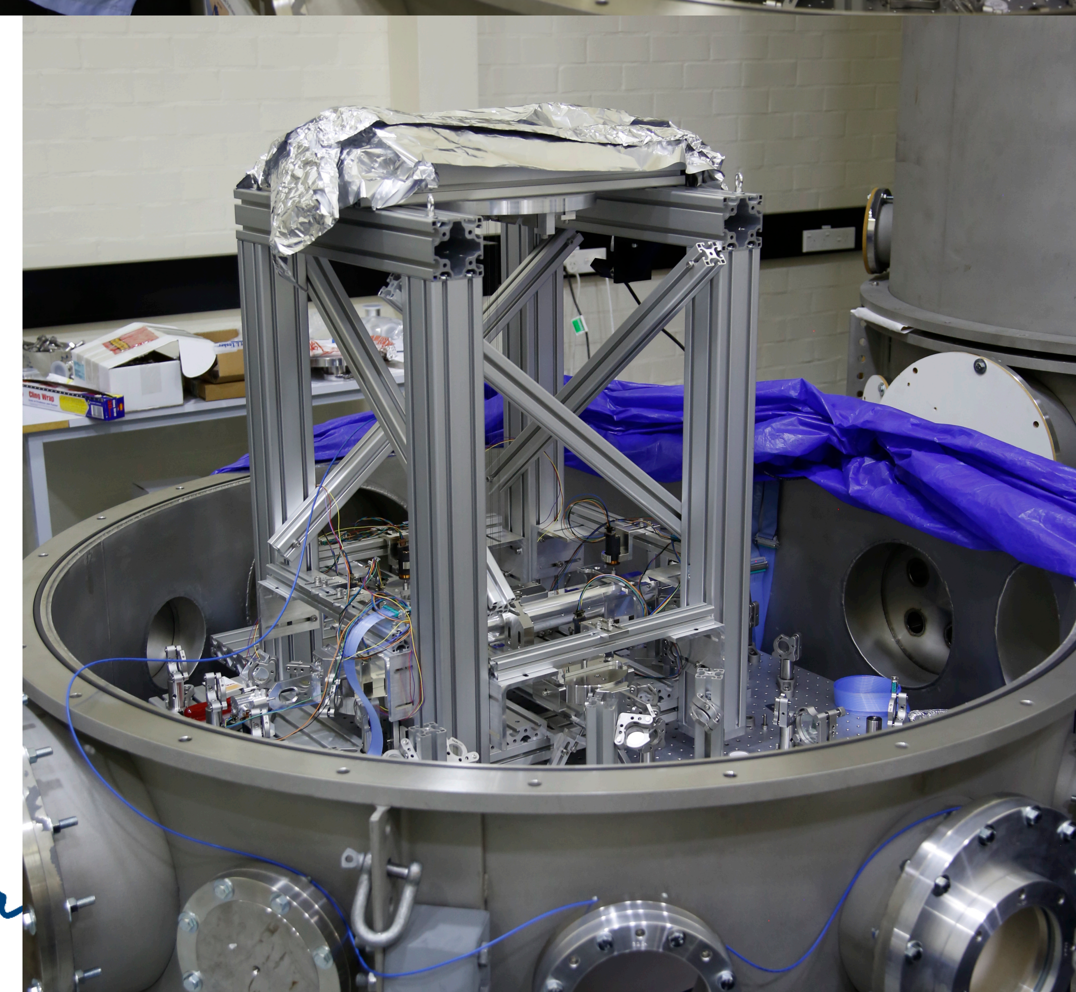
Torpedo Experiment Status

Moved into vacuum chamber

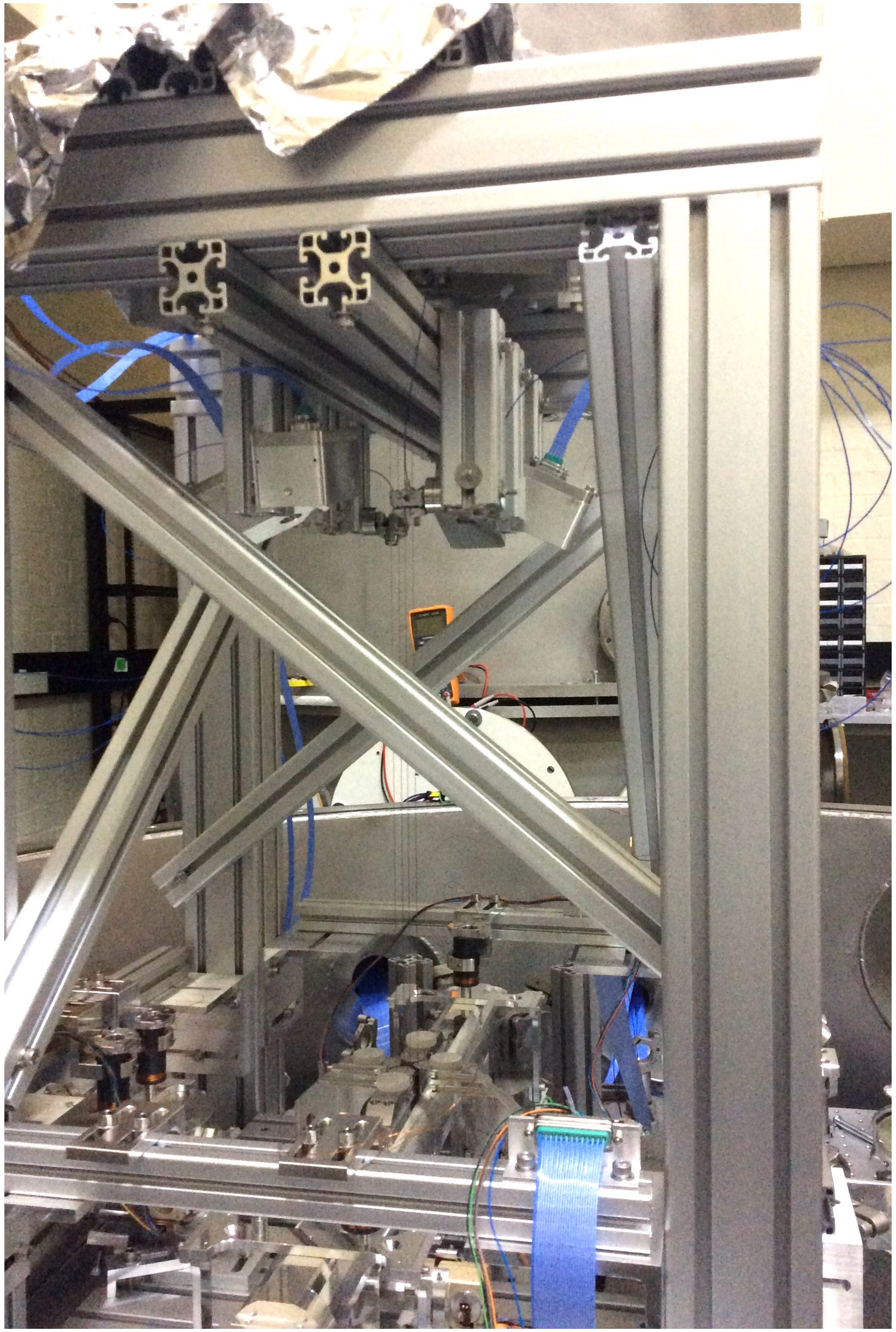


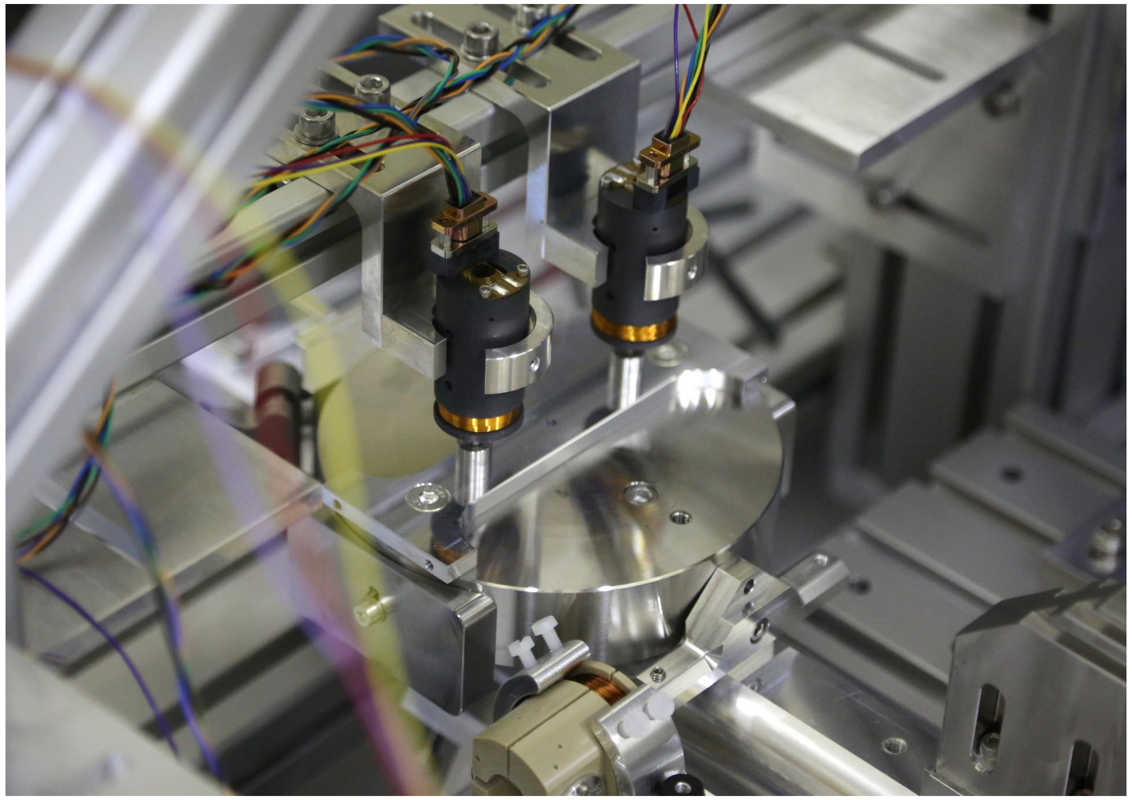


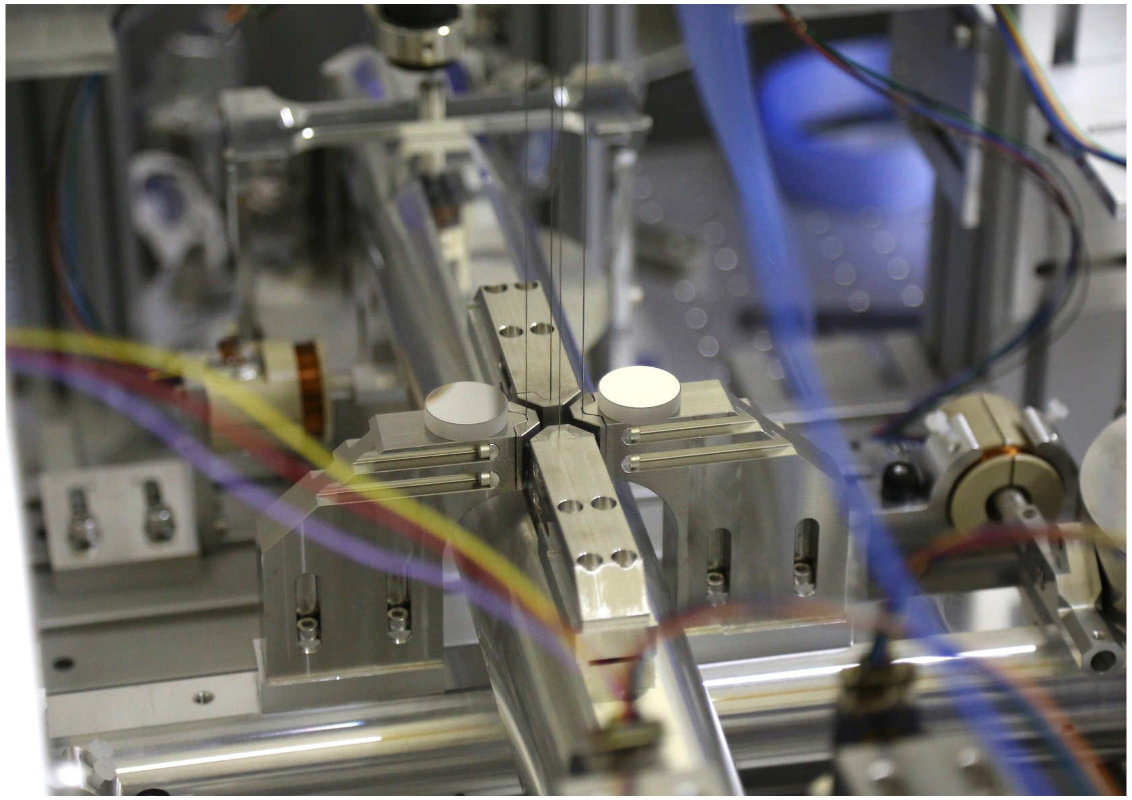




Locking cavities







Layout

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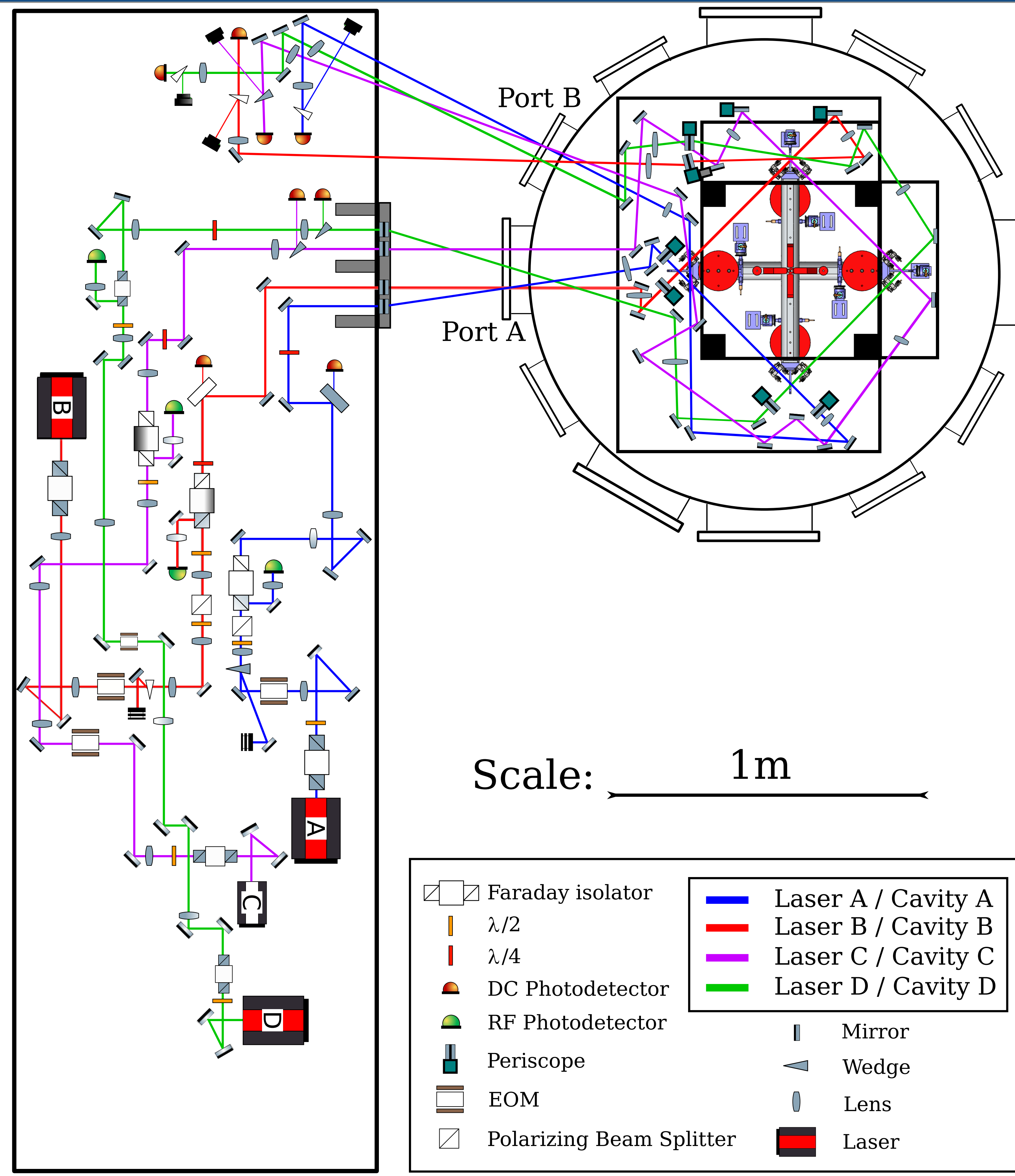
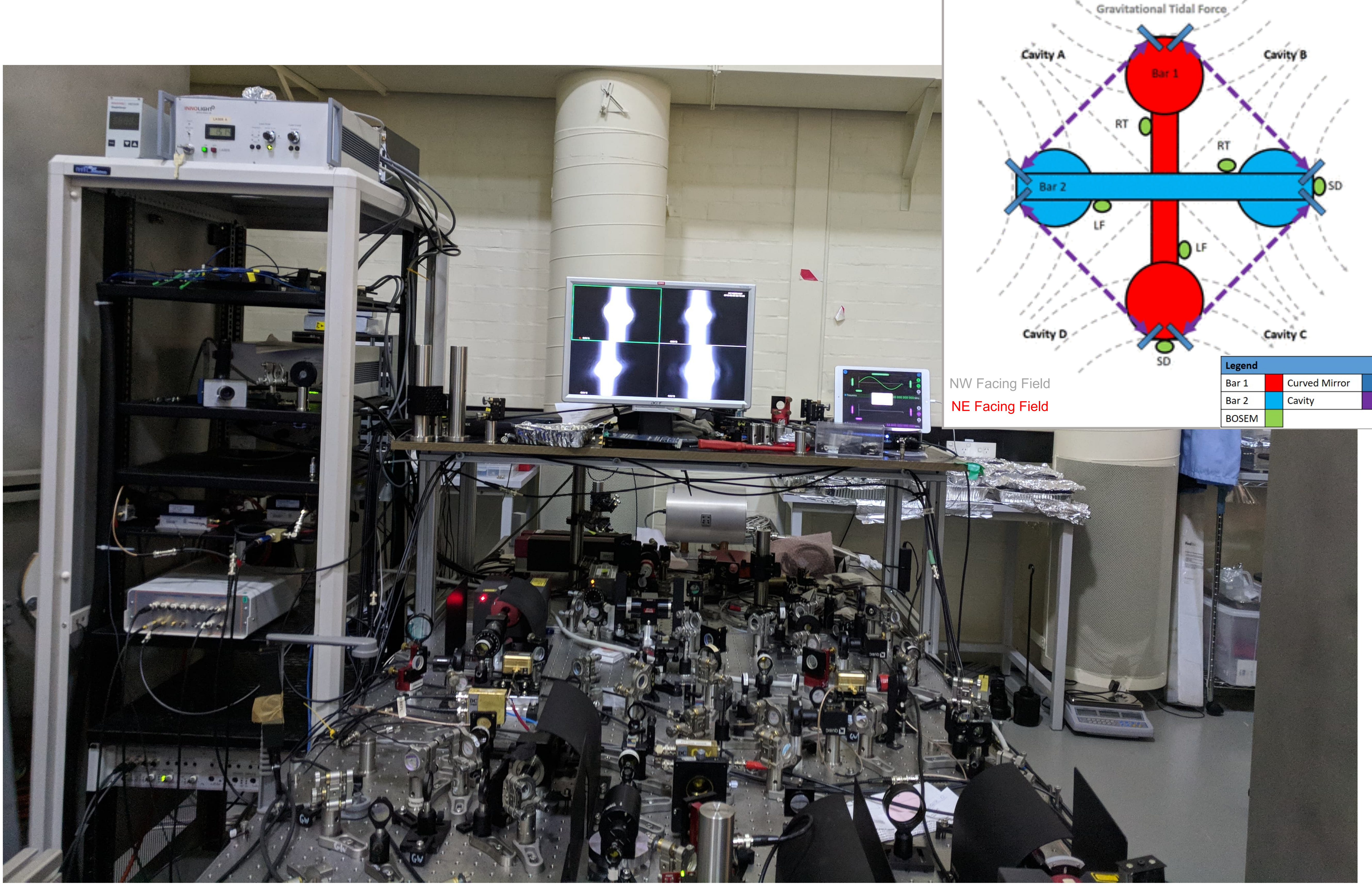
- Four independent lasers
- PDH readout from individual cavities
  - >10 Hz laser locked to cavity
  - <10 Hz feedback to mechanics
- LIGO CDS control to acquire and maintain resonance.





Three cavities on resonance with active high gain feedback, fourth laser frequency f/back only. Mixed input matrix config.

Current Noise Performance

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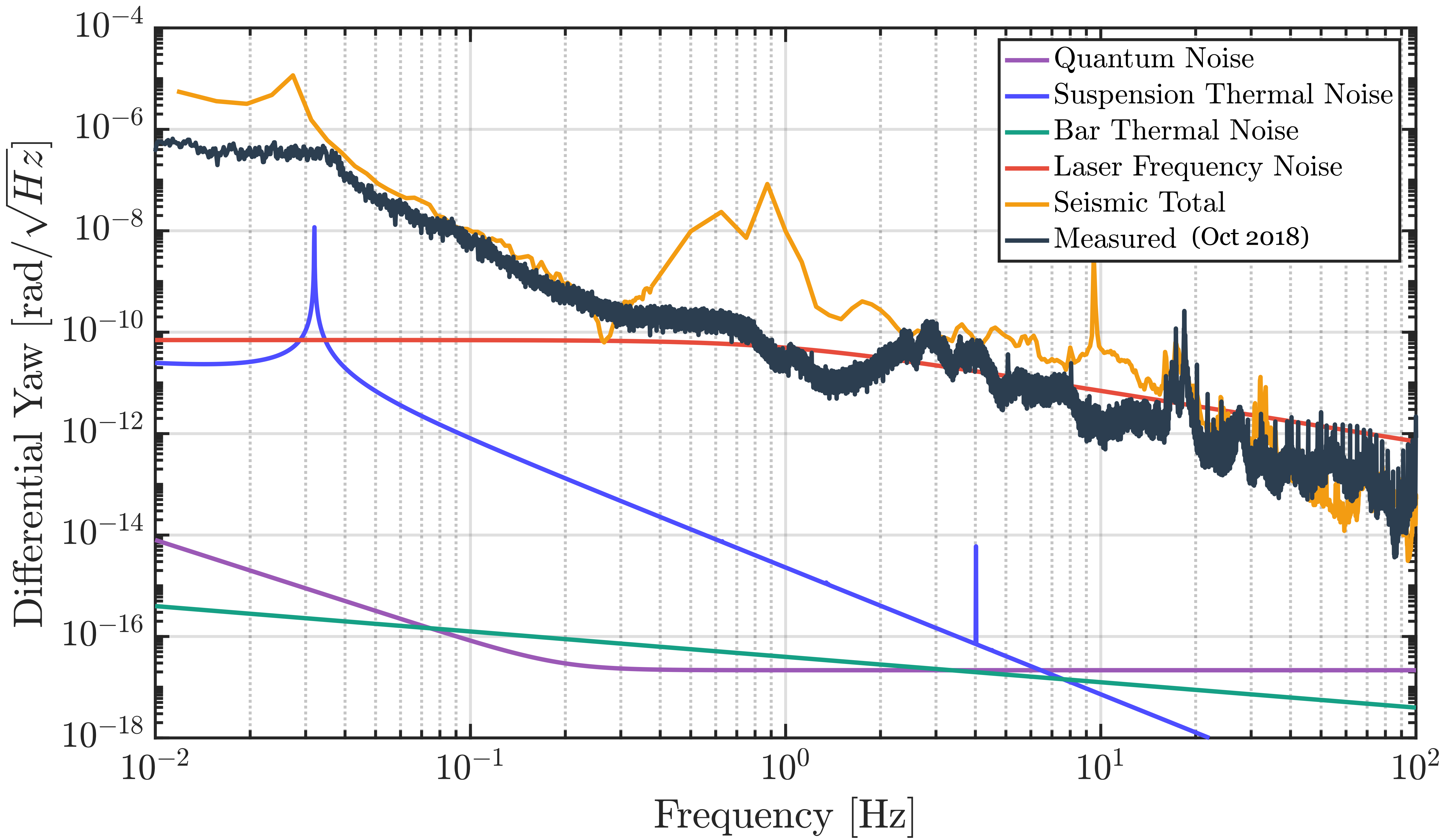

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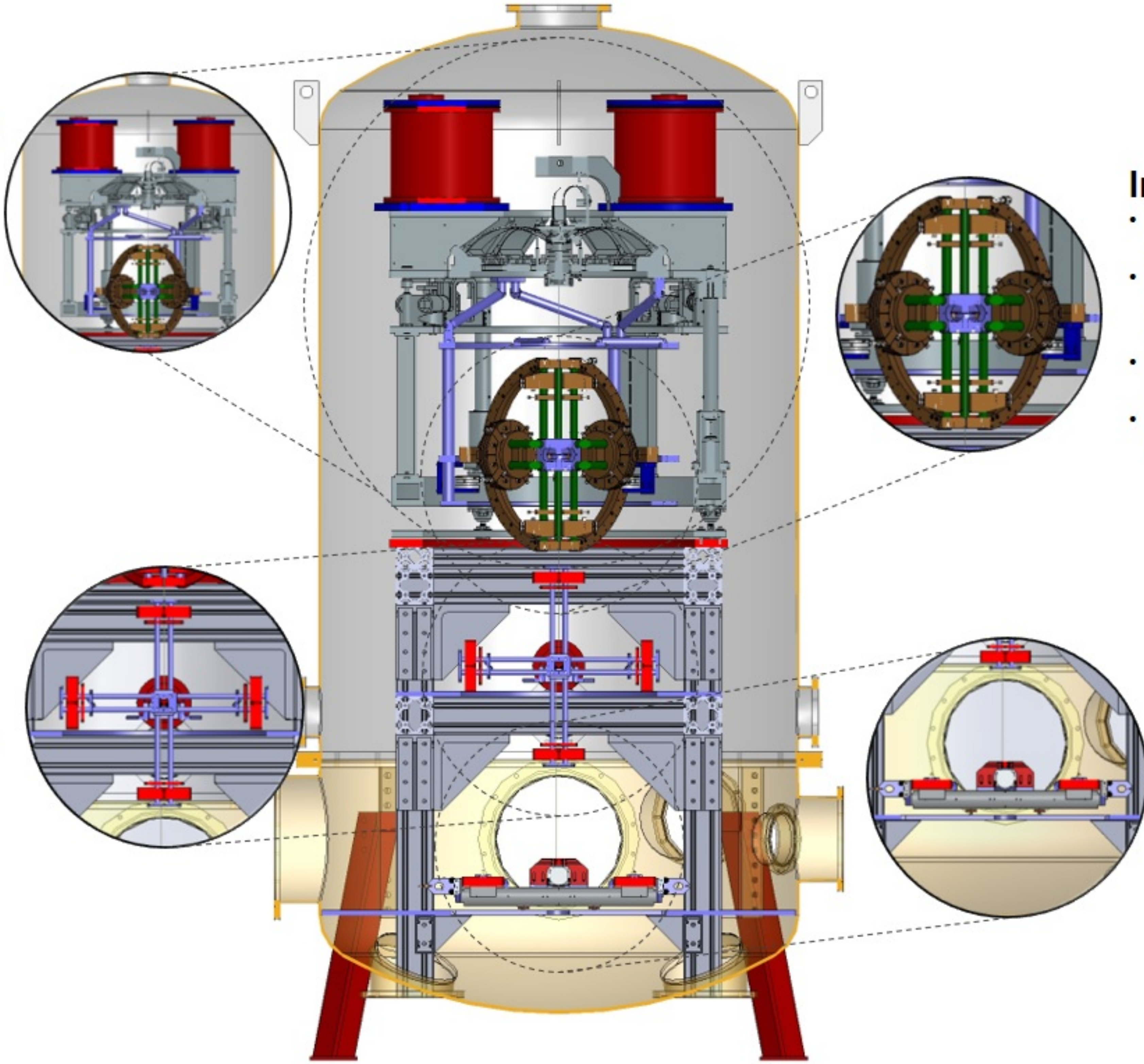
Seismic Isolation&Suspension Chain

Inverted Pendulum

- MultiSAS base
- Uses 3 Trilliums to isolate linear motion
- Soft platform for actuation
- Contains GAS filter for vertical isolation.

Intermediate Mass

- 140kg 6-way cross / hollow sphere hybrid
- Large inertia combined with single wire suspension provides high passive isolation.
- Spherical structure raises the frequency of internal modes.
- 6-way cross allows for fine tuning of CoM and moment of inertia.



Penultimate Mass

- 40kg 6-way cross.
- Acts as suspension point for TorPeDO system.
- High moment of inertia per mass provides additional isolation for rotation.

TorPeDO System

- Two dual wire torsion pendulums.
- Operation between 30mHz to 10Hz.
- Optical differential yaw readout.

In the Lab

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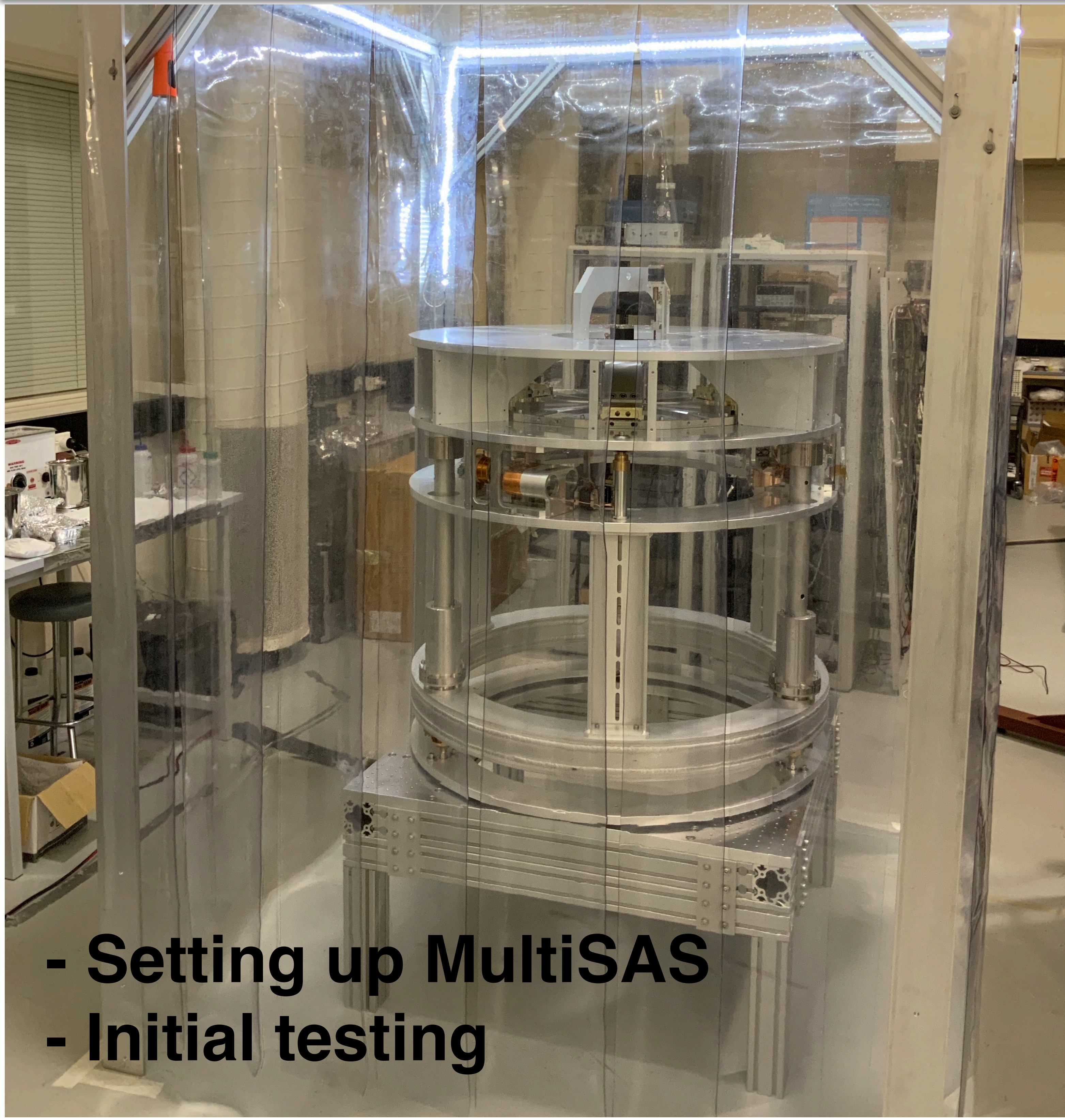
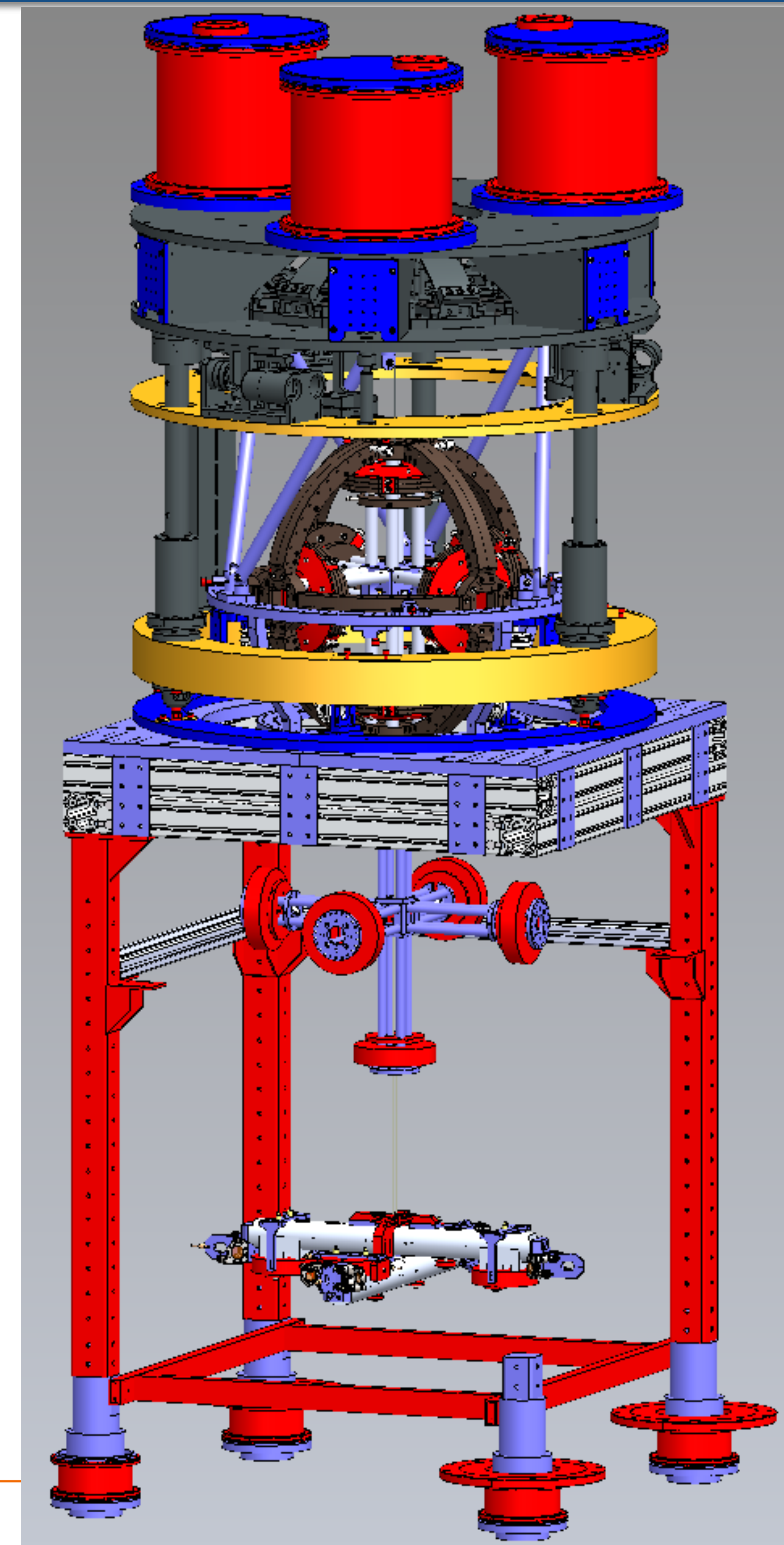
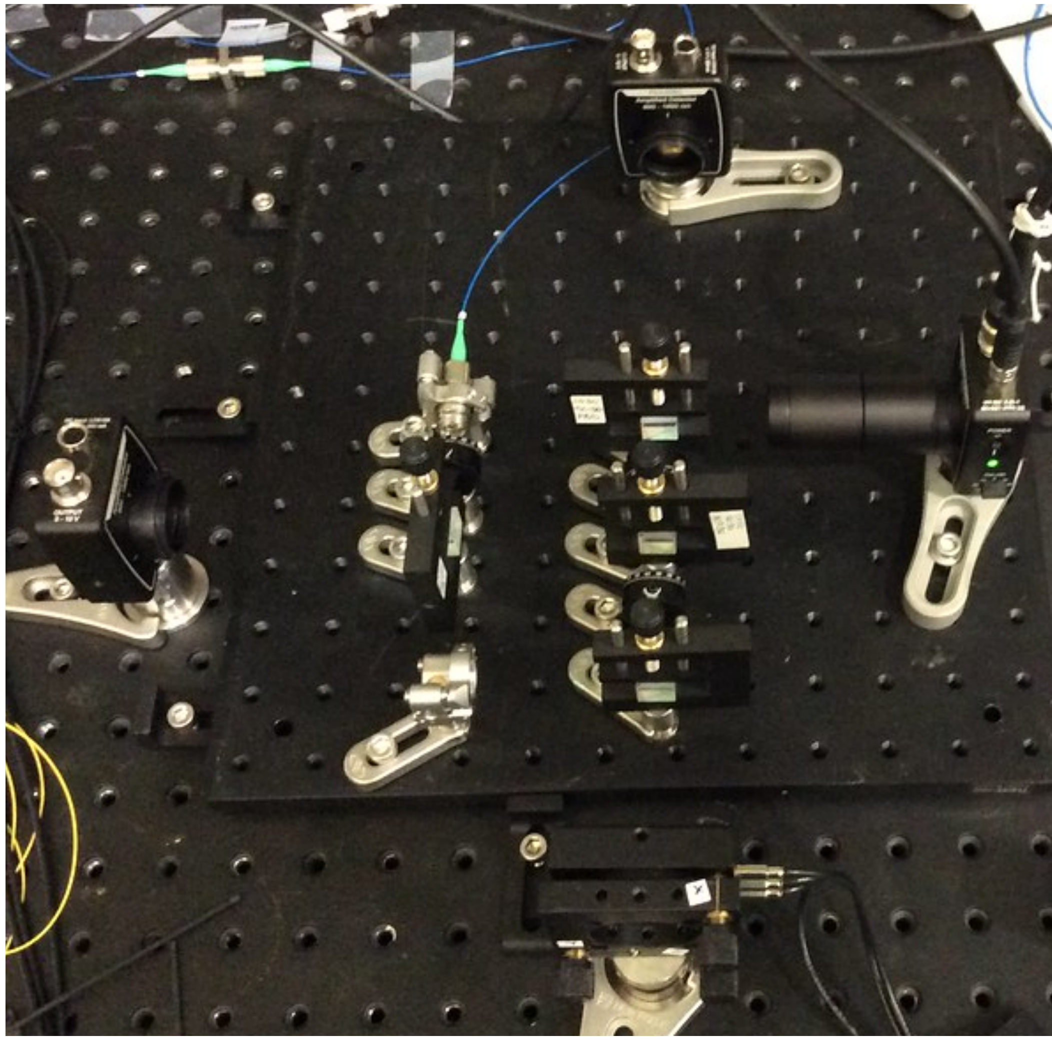


- Setting up MultiSAS
- Initial testing



Local Sensor

- Target 1 pm/rtHz 10 mHz to 100 Hz
- Build a HoQI
  - Fringe visibility ~90%
  - Tracks motion
  - Electronics limited
- Investigating DEHI
  - Large working distance (>0.5m)
  - ~1 pm/rtHz nose floor



Target Noise Budget

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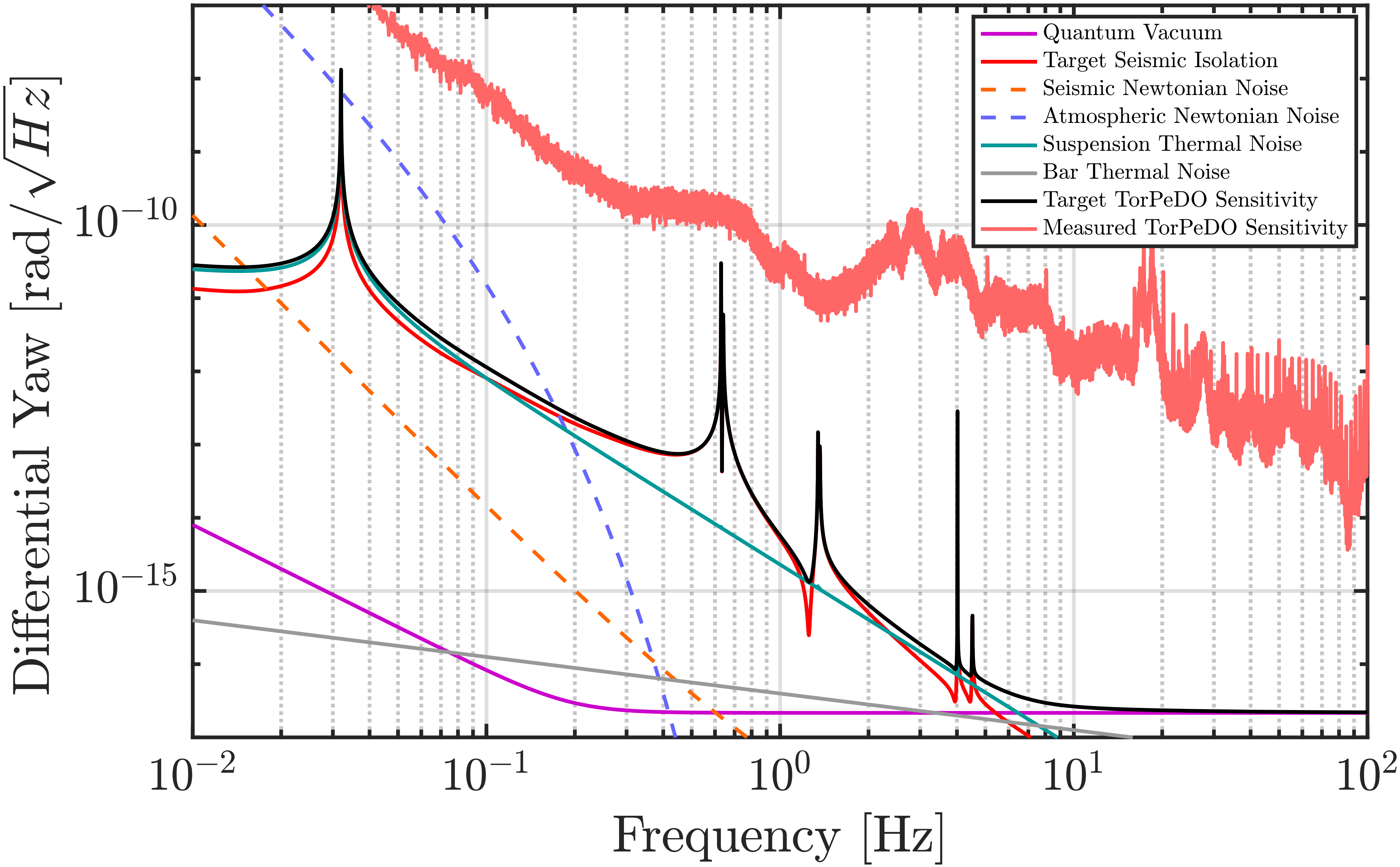
- Torpedo Suspension Point controlled down to 1 pm/√Hz
- Replace Tungsten suspension wires with Fused Silica.



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Earthquake Early Warning

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- ✦ Use Gravitational Wave Detector technology for the detection of earthquakes
- ✦ Use gravity gradient and changes in local ‘g’ to register and estimate earthquakes
- ✦ Let’s examine using a low-frequency torsion gravitational force sensor to register earthquakes.

1. J. Chiba, T. Obata and Y. Nemoto, in “IEEE International Carnahan Conference on Security Technology, Crime Countermeasures”, **9 publications** from 1990 to 1998 on ‘Large/Big Seismic Waves sensed by GWD’.
2. J. Harms, ***Low-frequency terrestrial gravitational-wave detectors***. Phys. Rev. D, 88:122003, Dec 2013.
3. J. Harms, ***Transient gravity perturbations induced by earthquake rupture***. Geophysical Journal International, 201(3):1416–1425, 2015.
4. M. Vallee, ***Observations and modeling of the elastogravity signals preceding direct seismic waves***. Science, 358(6367):1164–1168, 2017.
5. J.P. Montagner, ***Prompt gravity signal induced by the 2011 Tohoku-Oki earthquake.*** Nature Communications 13349 2016.
6. K. Juhel, ***Earthquake early warning using future generation gravity strainmeters***. Journal of Geophysical Research: Solid Earth, 123(12):10,889–10,902, 2018.

Earthquake Why Early Warning

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- Earthquake early warning of ~20-30s prior seismometer based warning systems
  - Warn people to take cover
  - Move people to safe position

- Trigger automatic responses
  - Slow down/stop trains
  - Close valves and pipelines
  - Save/move vital computer data

- Limitations
  - chance of false/wrong alerts: need to account for finite rupture size
  - no warning in blind zone (~30 km around epicenter)

Pablo Ampuero (Caltech Seismolab)

Earth Quake Characterisation

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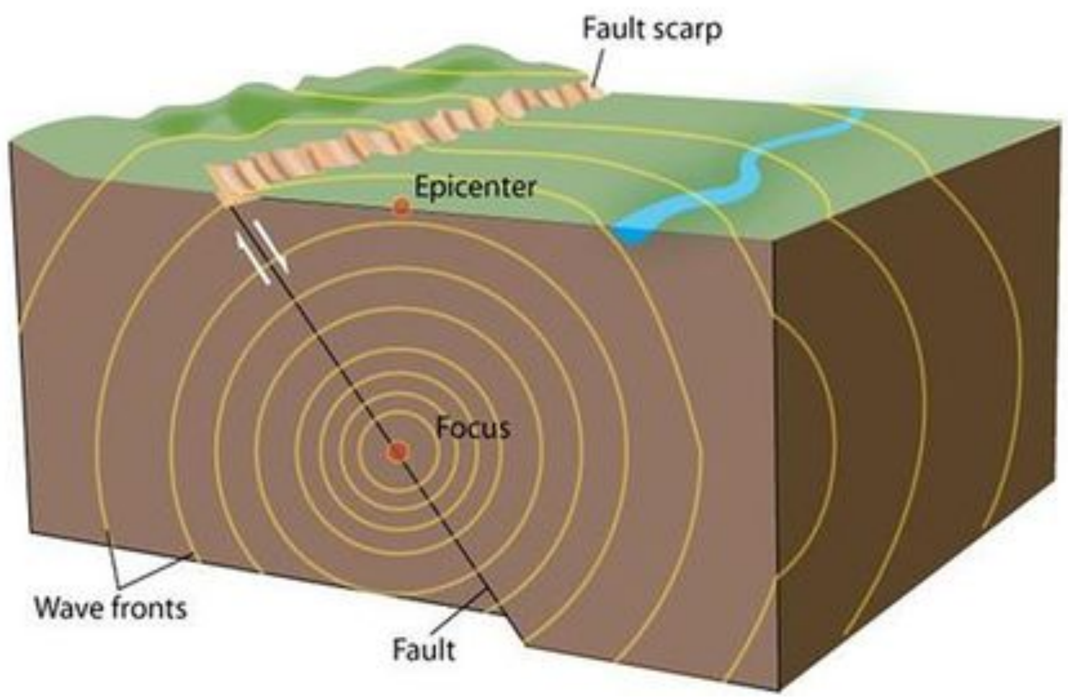


✦ Seismic moment from a slip-stick event.

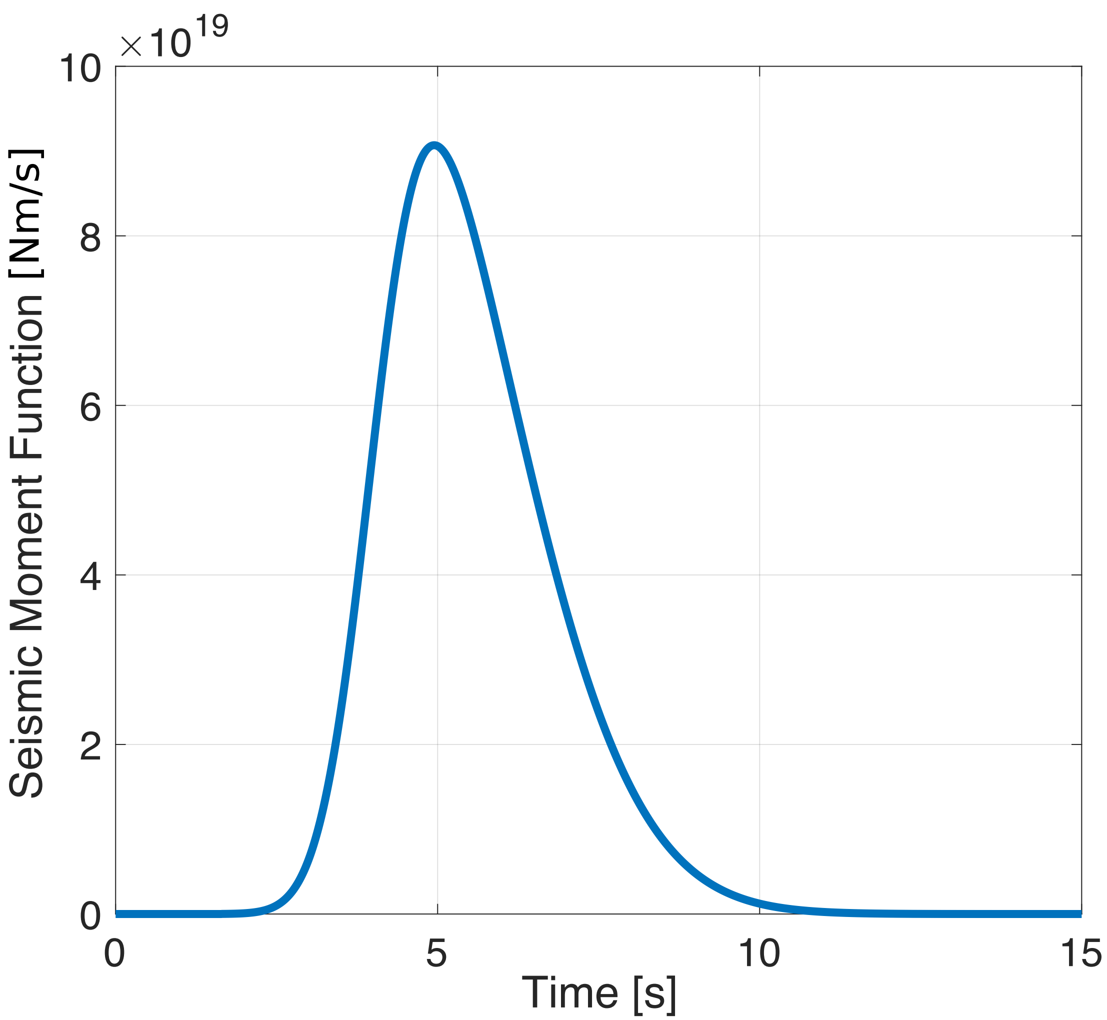
$$M_0 = \mu D A$$

μ is shear modulus, **D** slip displacement and **A** rupture surface area.

✦ EQ difficult to characterise
- Complex underlying physical processes.

✦ Seismic moment over time shows the evolution of an earthquake

$$M_s[t] = \frac{dM_0}{dt}$$



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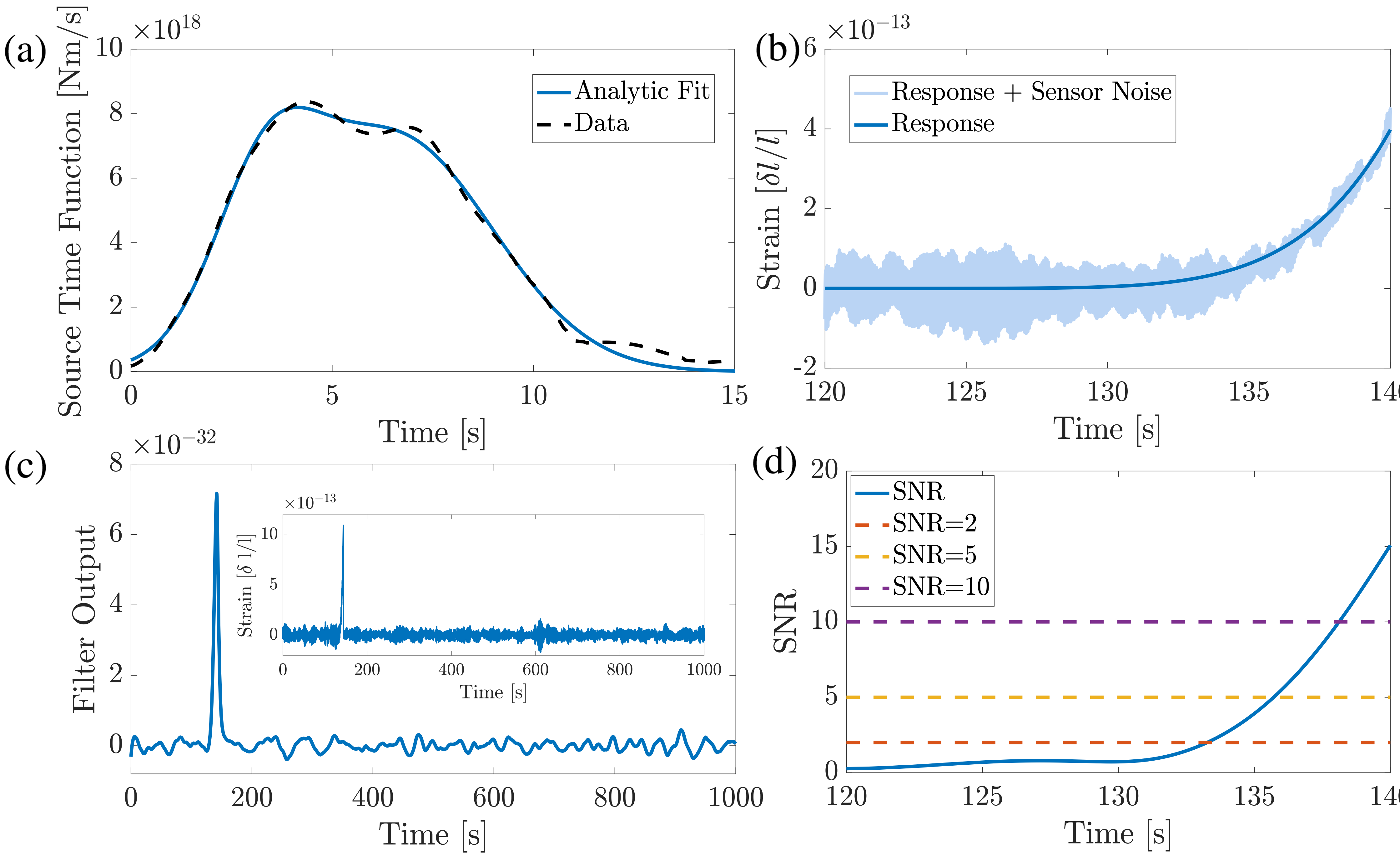
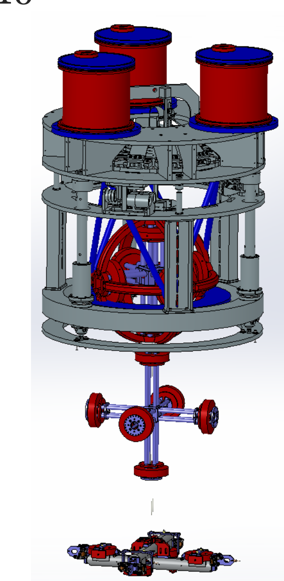
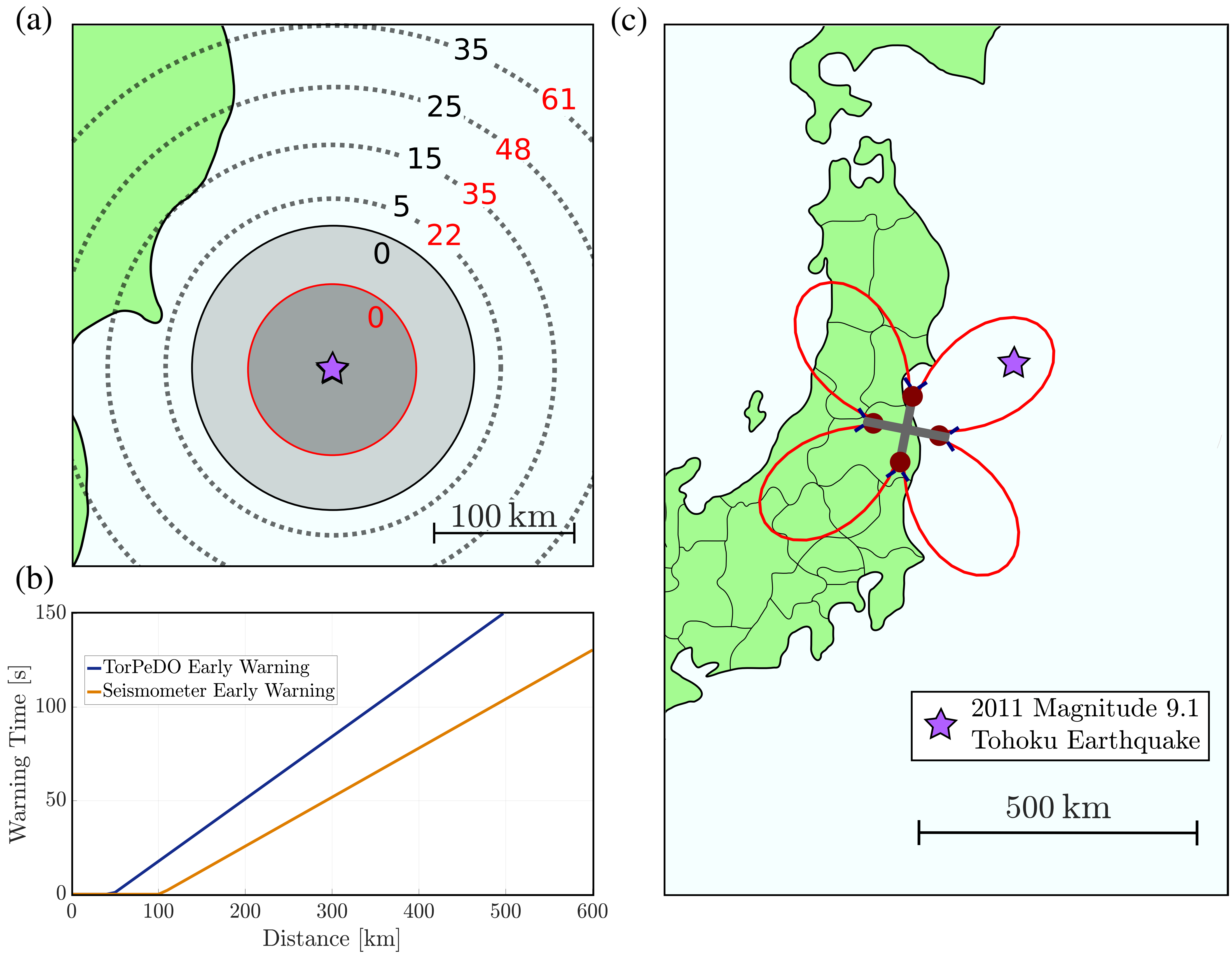




- M7.1 earthquake at 300 km
- Simplified, homogeneous space, first order approximation of acceleration force onto Torpedo
- We start with some shaped noise generated from our target sensitivity.
- We insert our signal estimate inside the noise, and try and extract it with a matched filter



Comparison between TorPeDO earthquake early warning and Japan's early warning system for the 2011 Tohoku M9.1 earthquake. The numbered red rings show predicted TorPeDO early warning provided at this distance in seconds. The black rings show the early warning of the seismometer based system.

End