Development Update For The TorPeDO Experiment:

A Newtonian Noise Sensor For 3G Observatories

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

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G2101010

Newtonian Noise

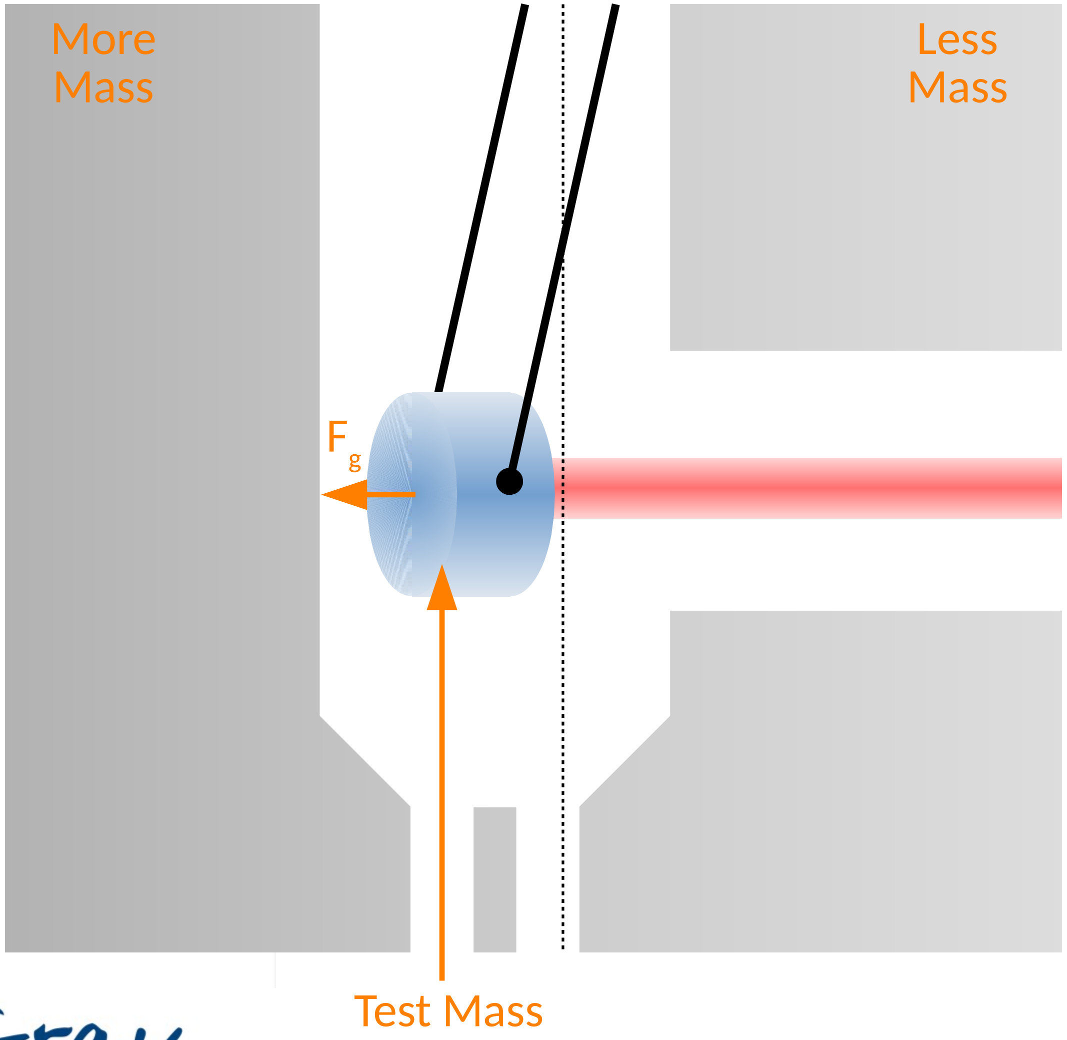
Direct gravitational attraction due to local density fluctuations.

Impossible to shield from.

- Is a fundamental noise source for GW detectors.

Has 2 primary causes:

- Seismic – surface waves.
- Atmospheric – thermal gradients and infrasound.



A Problem for 3G Detectors

3G detectors, ET and CE, propose pushing their detection bands down to several Hz.

- Provide earlier warning of astrophysically interesting sources (e.g. BNS mergers).
- Detect larger mass BBH mergers.

To achieve required sensitivity Newtonian noise needs to be removed from the strain data.

Seismometer arrays are being investigated, by several groups, for cancellation of seismic Newtonian noise.

Investigation of atmospheric Newtonian noise, and cancellation schemes, are a much less active area.

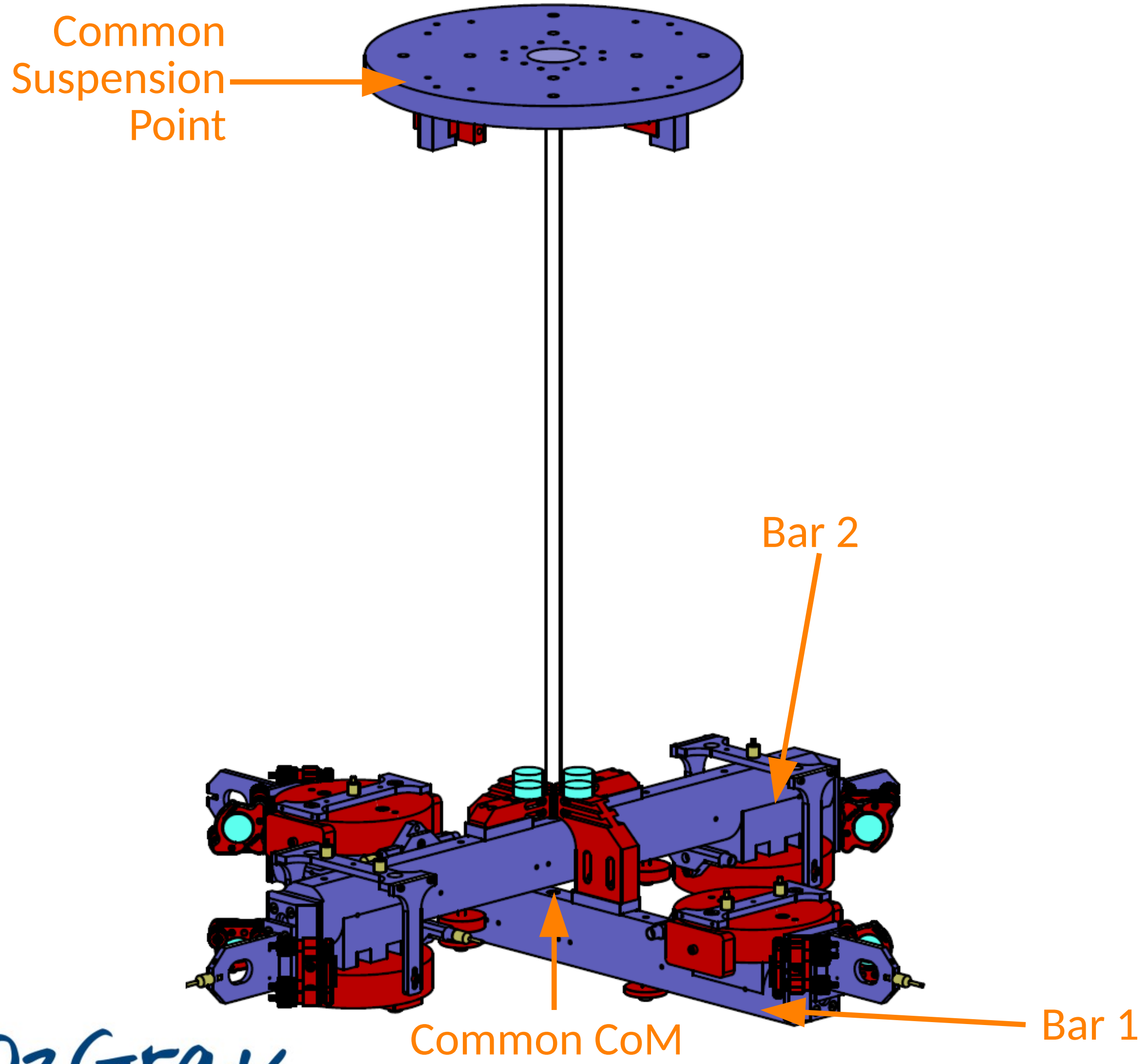
TorPeDO Mechanical Design

Designed as a direct Newtonian noise sensor for 3G facilities.

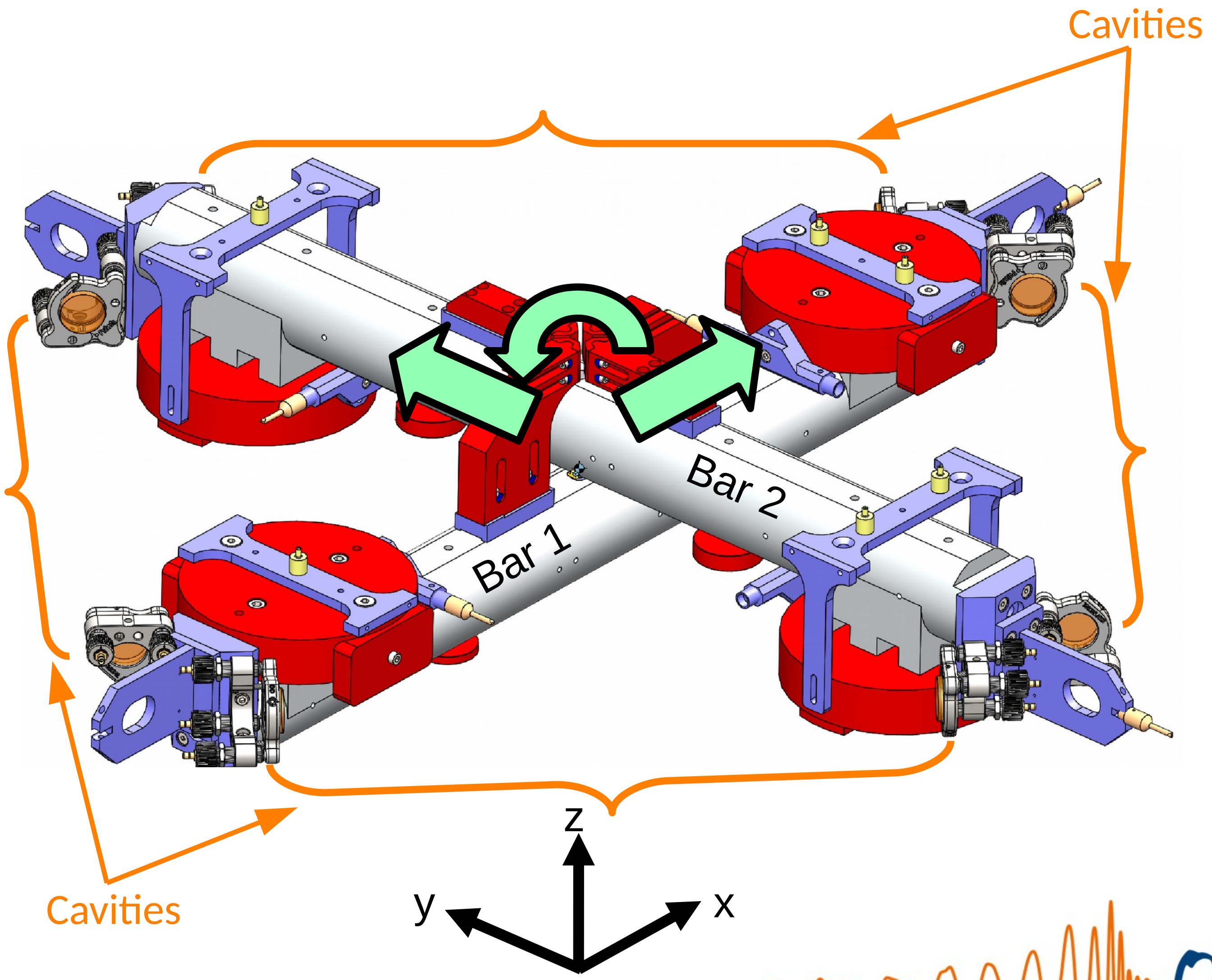
Torsion **Pe**ndulum **D**ual **O**scillator

- 2× Torsion pendula, with 25 mHz torsion frequency.
- Common centre of mass & rotation, reduce the sensitivity to common motion.
- 2 wires per pendulum – easier to use but more cross coupling.

Soft in all 6 degrees of freedom.



TorPeDO Sensor Overview



4× Fabry-Pérot cavities:

- FSR ≈ 400 MHz.
- FWHM ≈ 2.4 MHz.

Locked with PDH locking.

Oriented within the *xy plane*.

- Differential x (DIFFX), differential y (DIFFY), and **differential z rotation** (DRZ)

Full Interferometric Sensing Scheme

The optical cavities sense a projection of the differential motion between the bars.

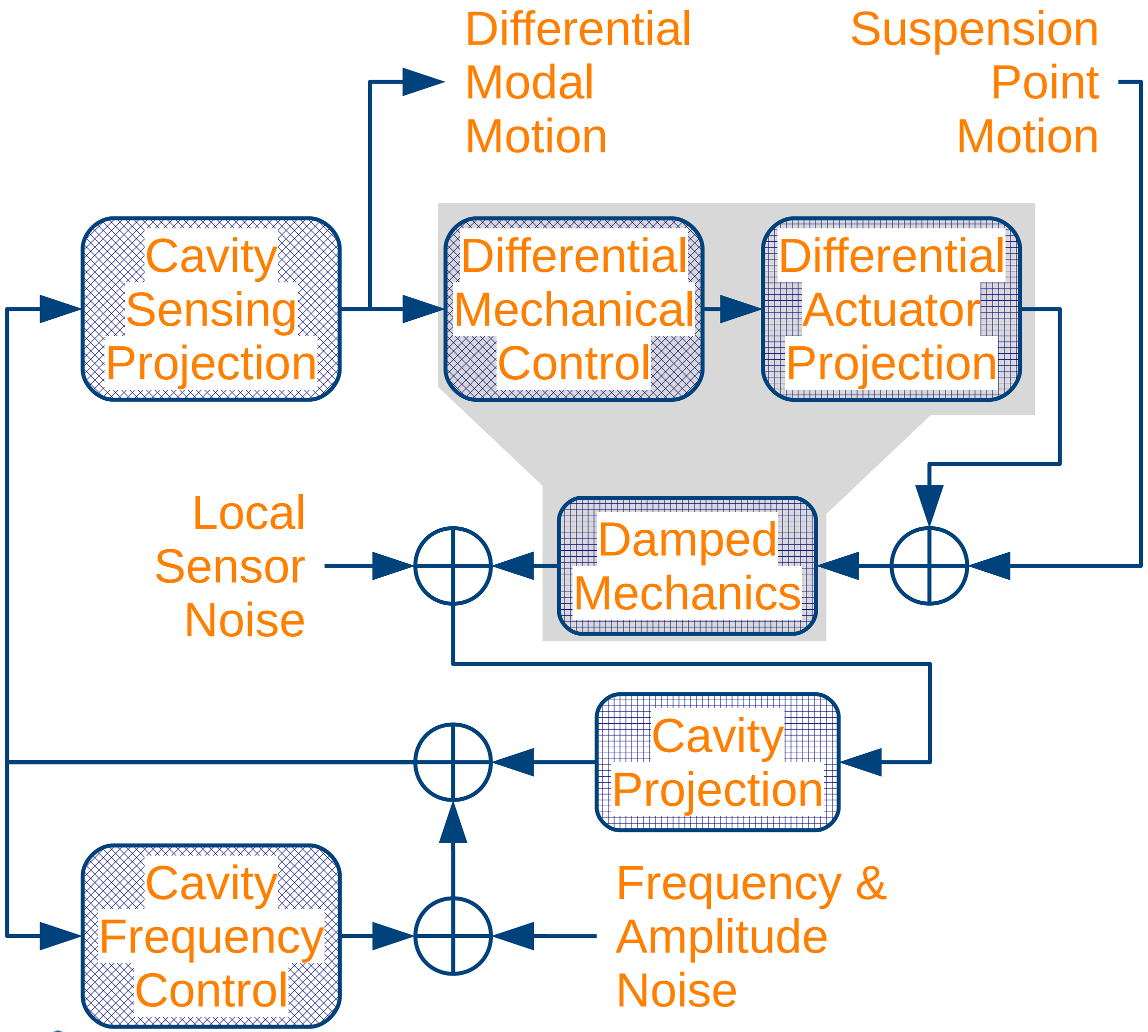
- Resolve the modes of interest with a linear combination of optical cavities.

An appropriate choice of actuator projection can reduce sensor noise re-injection.

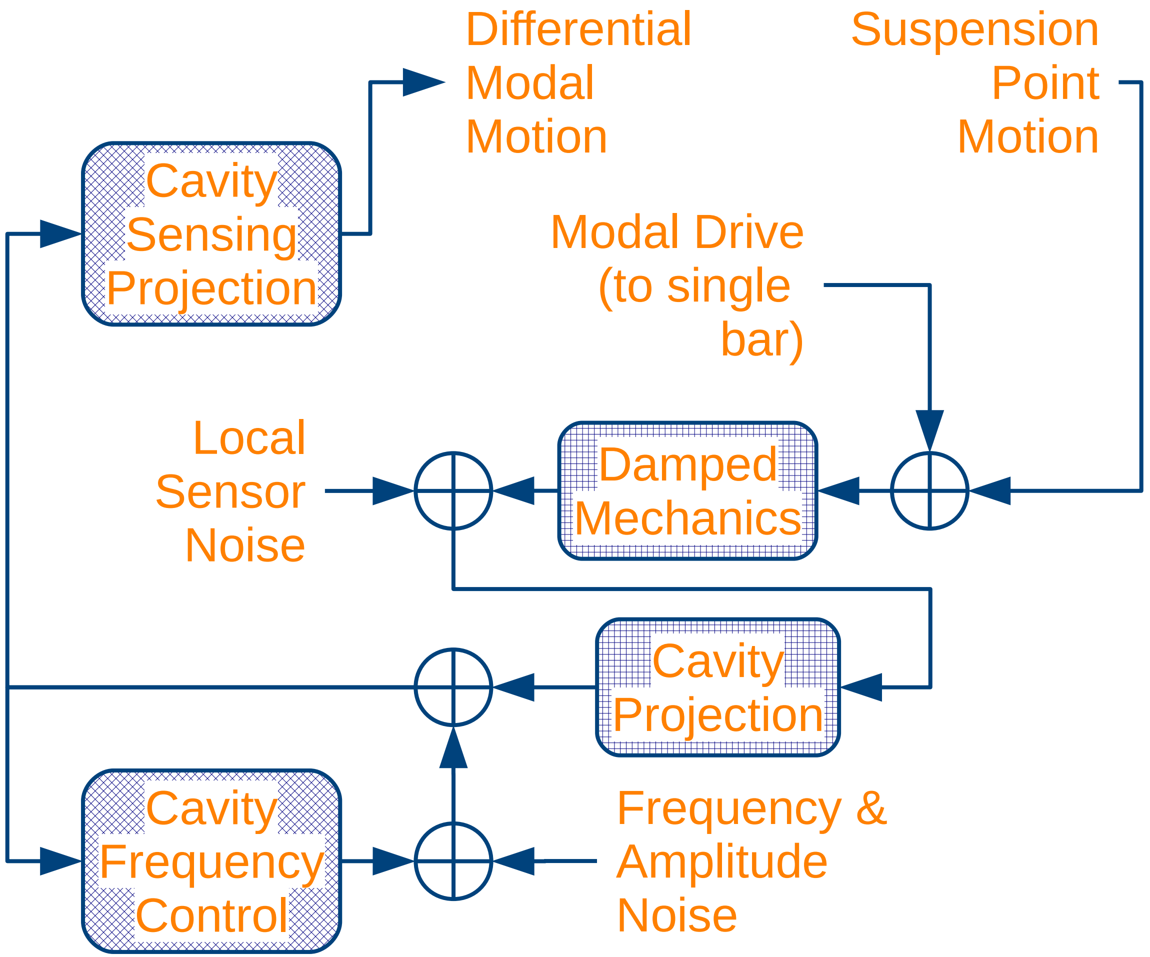
- Originates from local control of pendula.

Mechanics are damped to reduce the RMS motion of the resonant peaks.

Cavity frequency control extends the locking bandwidth, up to ≈ 20 kHz.



Reduced Sensing Scheme



Remove the differential mechanical feedback.

- Greatly simplifies cavity control scheme, to SISO.
- Sacrifices some noise improvements.

Allows commissioning of:

- *Cavity sensing projection*, and then;
- *Differential actuator* projection.
- Then we can migrate back to the full scheme.

Yields the current performance.

- Just not the best that can be achieved.

Cavity Suppression Loops

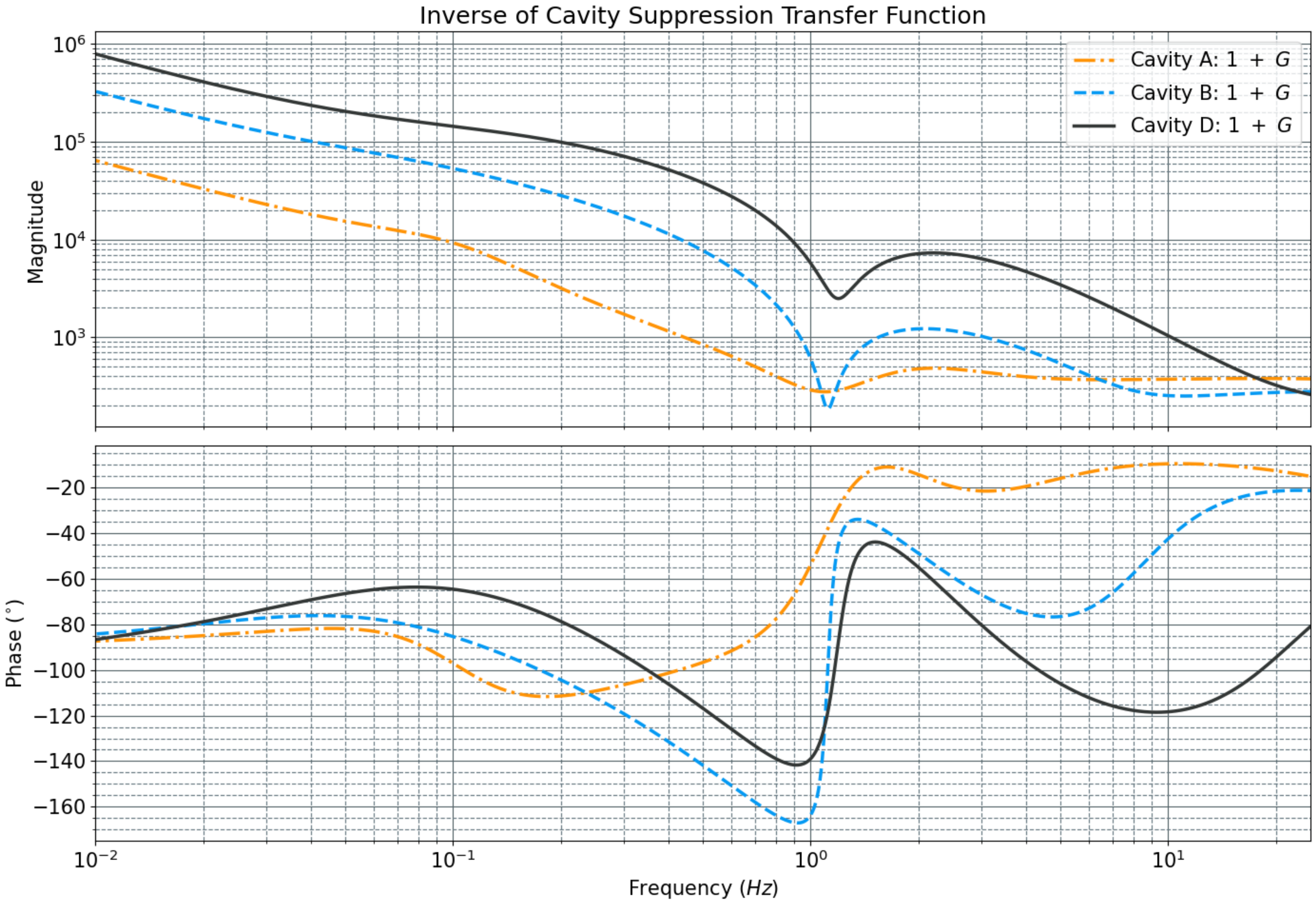
Fitted from measured data.

- 0 Hz, integrator, pole is imposed.
- Fitted with transfer function SNRs.

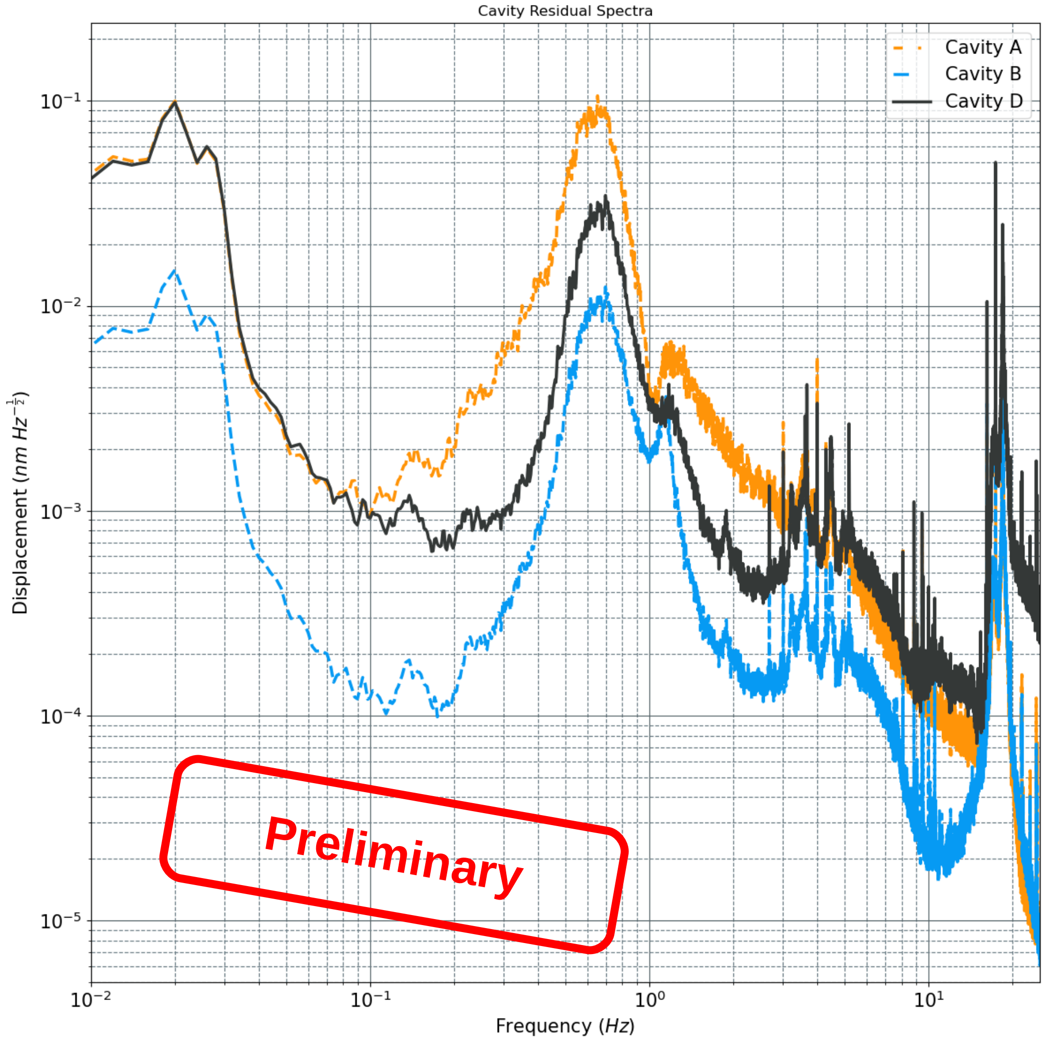
Laser Frequency feedback.

- Analogue PZT control fast < ≈ 20 kHz.
- Digital PZT control < 100 Hz.
- Laser crystal temperature control < ≈ 1 Hz.

Can be simplified to a SISO system.



Current Cavity Sensitivities

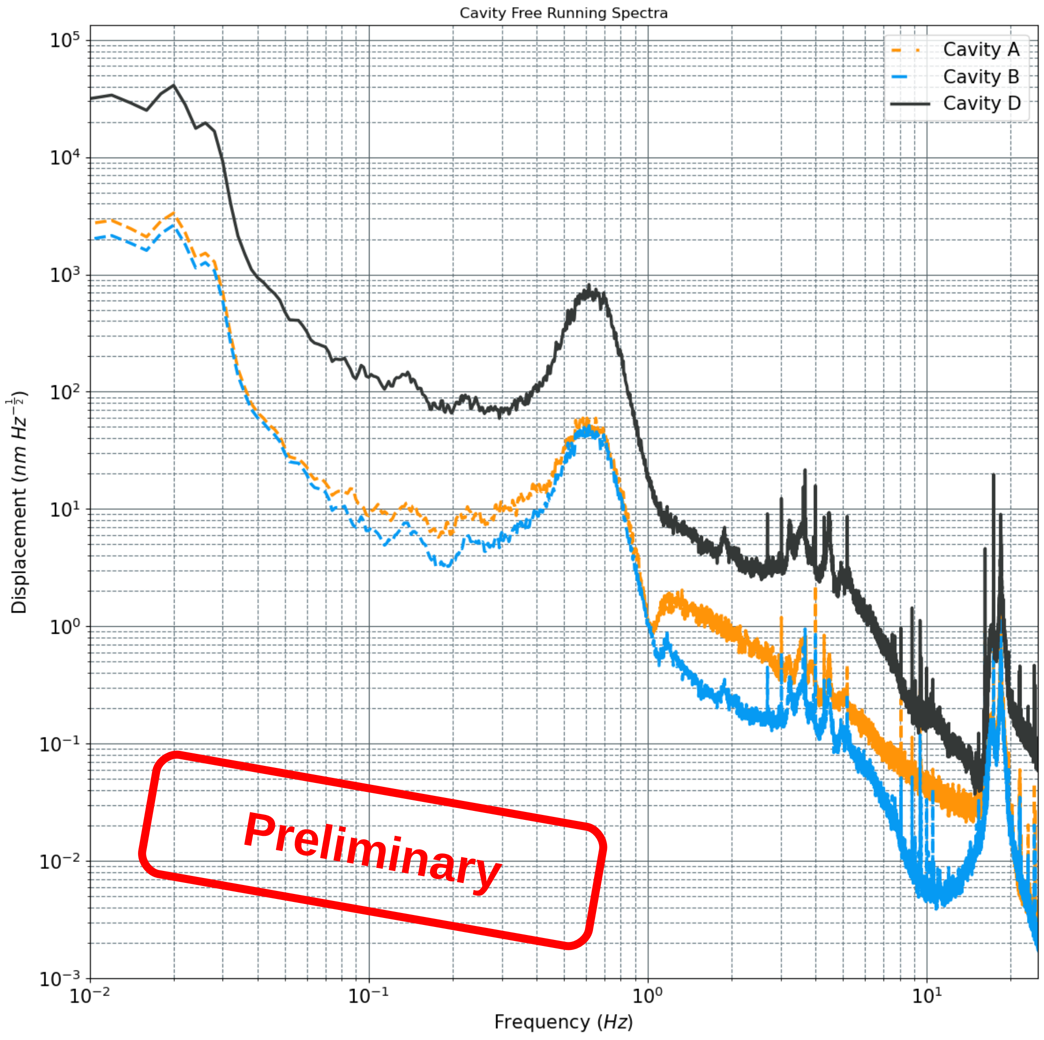


← Residual motion of

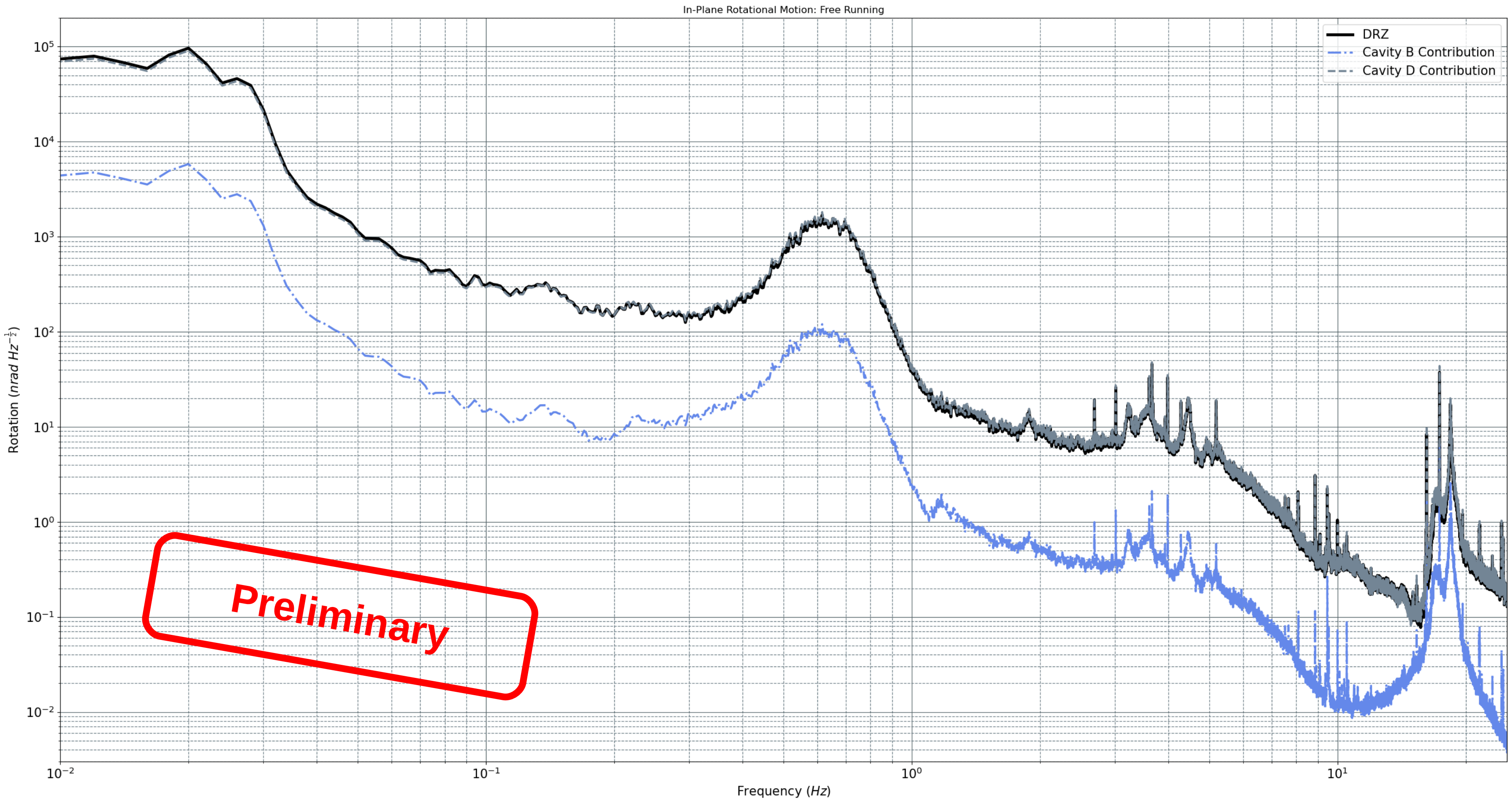
3 cavities.

Free Running → motion of these cavities.

Still investigating why cavity D is much higher ($\approx {}^{70}/_{5}$).



Current Interferometric Performance



Unfortunately dominated by the discrepancy between cavities B, and D.

- Mostly cavity D motion.

Utilising the ideal, 3 cavity, diagonalisation.

- Equal combination of geometrically opposite cavities.
- Cavity B + Cavity D.

Requires the *free running* error signal time series.

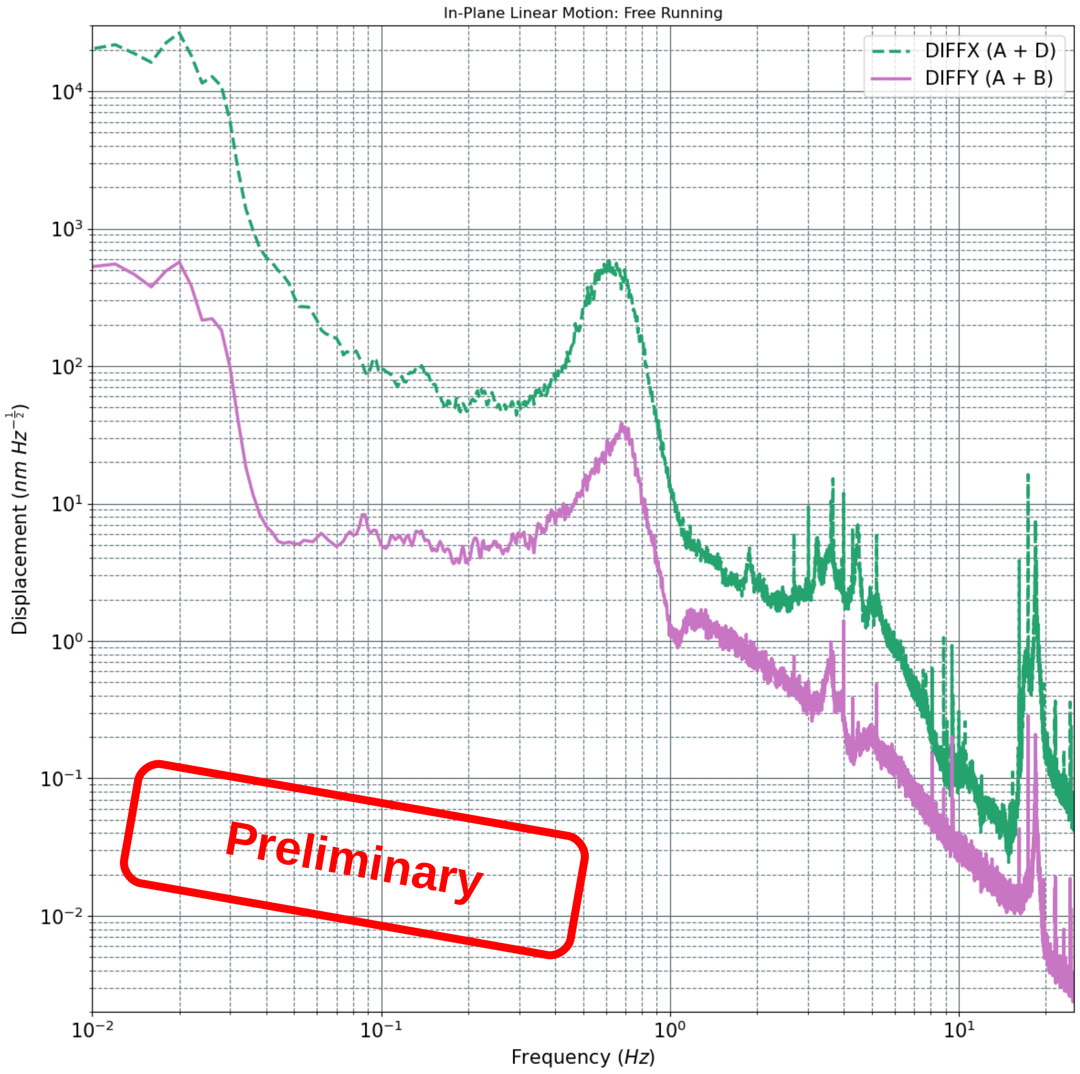
DIFFX and DIFFY

Again using idealised diagonalisation matrix.

DIFFX is dominated by cavity D motion.

DIFFY shows good cancellation.

- Less common motion at ≈ 20 Hz.
- Only 1 of the roll modes is clearly visible – somewhat expected.
- Less intrusion of DRZ.



Pathway to Improvements

Resolve the excess noise in cavity D.

Optimise the diagonalisation of differential modes.

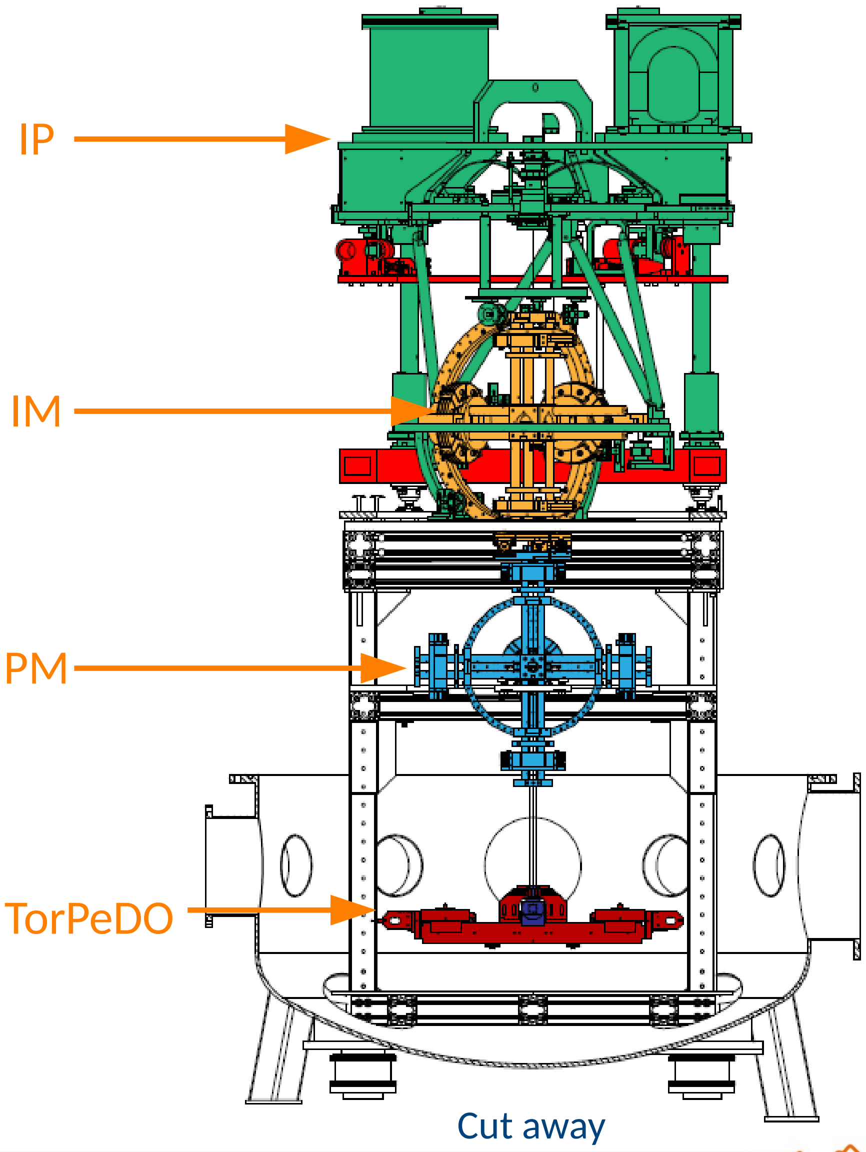
We have collected all of the data for the *differential actuation projection*.

- Yet to be analysed.
- Big MIMO (12× inputs, 3× outputs) system.

Move back to a mechanical locking.

- Reduce re-injected local sensor noise.
- Allow cavity C to be locked too.

Overview of the Seismic Isolation Chain



Consists of:

0: Inverted pendulum stage (IP) – Innoseis/Nikhef/ Virgo MultiSAS.

1: Intermediate mass (IM) sphere.

2: Penultimate mass (PM) sphere.

3: TorPeDO sensor.

Attenuate low frequency seismic motion.

- Reach the suspension thermal noise limit.

For more details see G2100477.

- Presented at March 2021 LVK meeting.

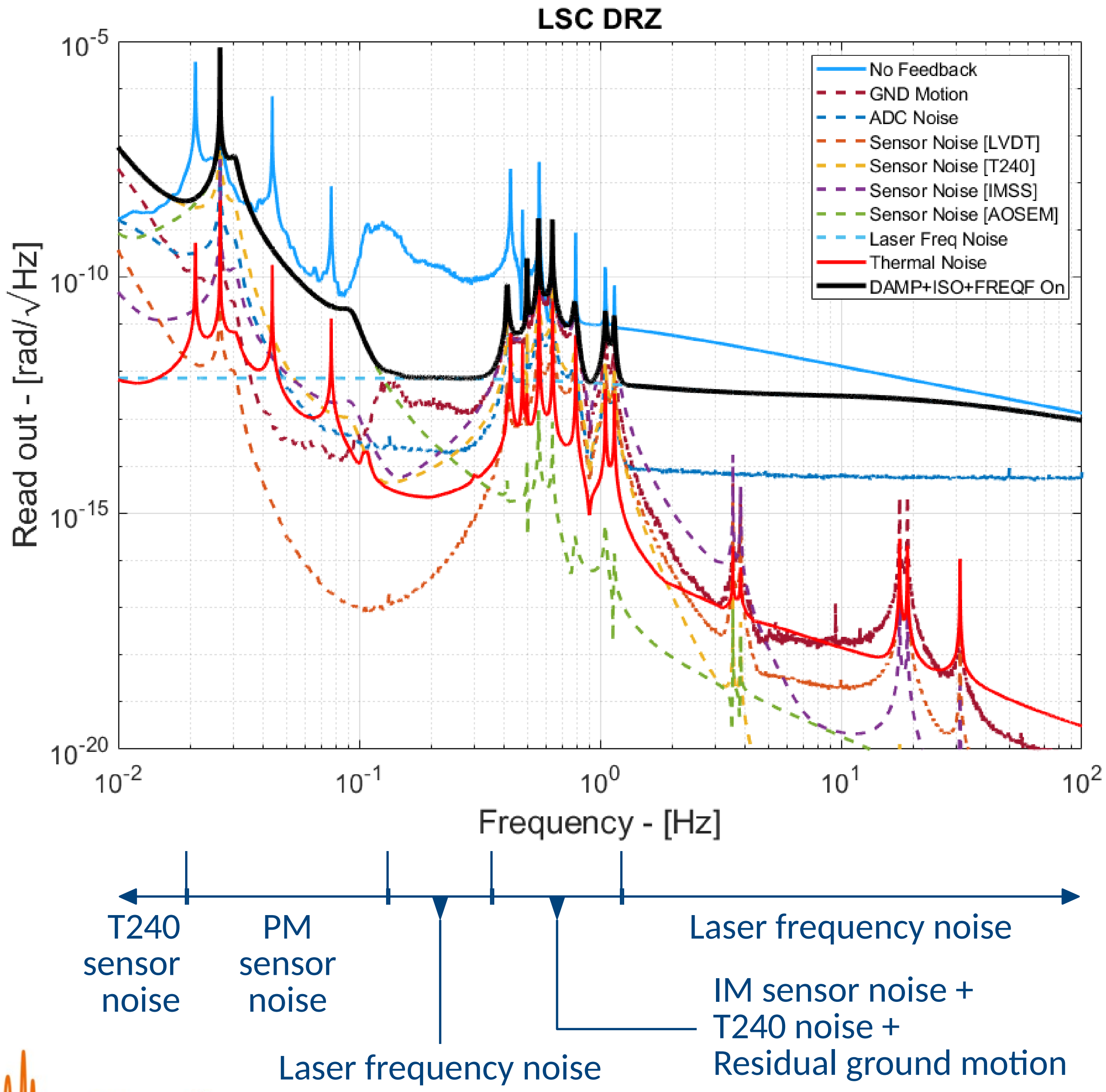
Initial Performance

Installation into vacuum enclosure in Q3 2021.

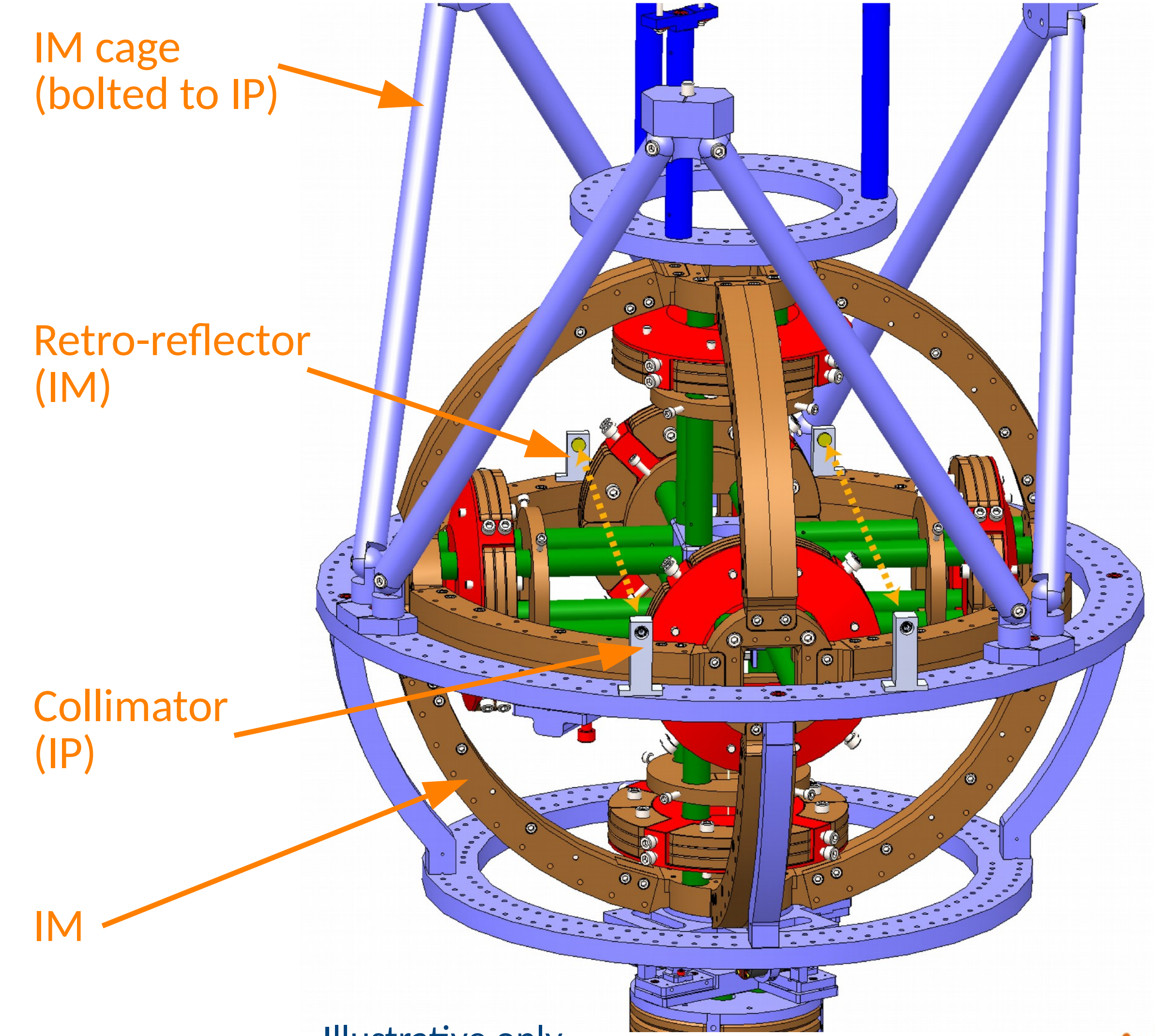
Initially commissioning with:

- LVDTs + T240s - IP.
- Shadow sensors - IM.
- AOSEMs - PM.
- BOSEMs + Oplevs – TorPeDO.

Not the ideal sensors, too noisy, but enough to make a start.



Improved Local Sensors



Illustrative only

We are developing compact sensors to operate the suspension chain:

- Fibre head + retro reflector.
- Targeting 1 pm Hz$^{-1/2}$ at 100 mHz.

Utilises digitally enhanced heterodyne interferometry.

- Time of flight measurement with phase encoding.

See related poster, G2100987, for more details.

Implementation, on isolation chain, will improve the TorPeDO's sensitivity.

Towards Detecting Newtonian Noise

Important to validate that we can detect Newtonian noise.

We have produced our own NCAL wheel.

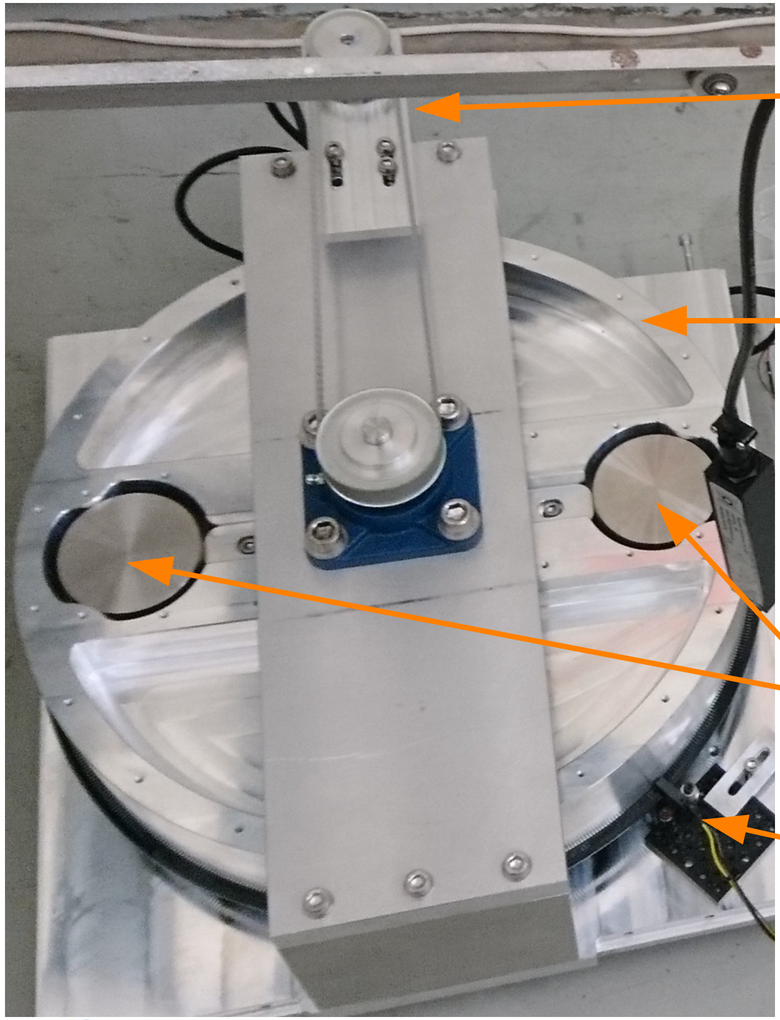
- Provide a time varying, 1 to 10 Hz, quadrupole signal.

Aluminium disk + 3 kg steel weights ×2.

- Quadrupole moment: 0.167 kg m^2.

Currently:

- Finalising commissioning.
- Calculating expected coupling.



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Full Cavity Suppression TFs