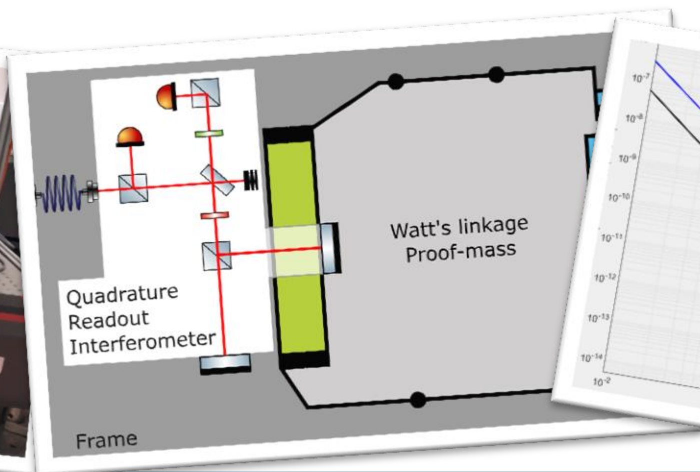
UNIVERSITY OF BIRMINGHAM

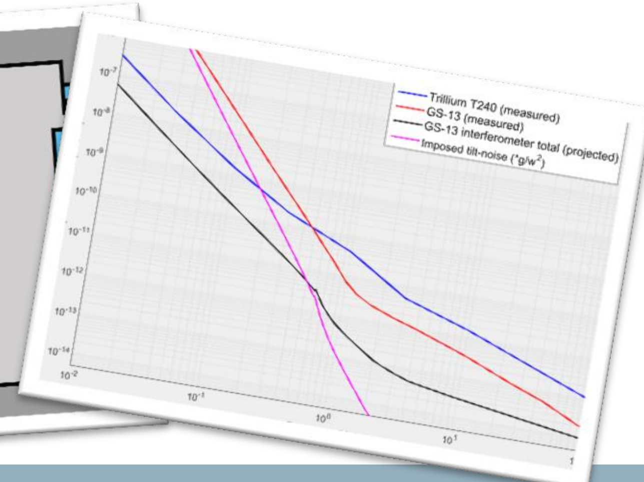
Low-frequency Sensors, 10mHz to 10Hz

A quick summary of some current projects and design considerations

Conor Mow-Lowry

Including substantial work by **Sam Cooper**





Motivation

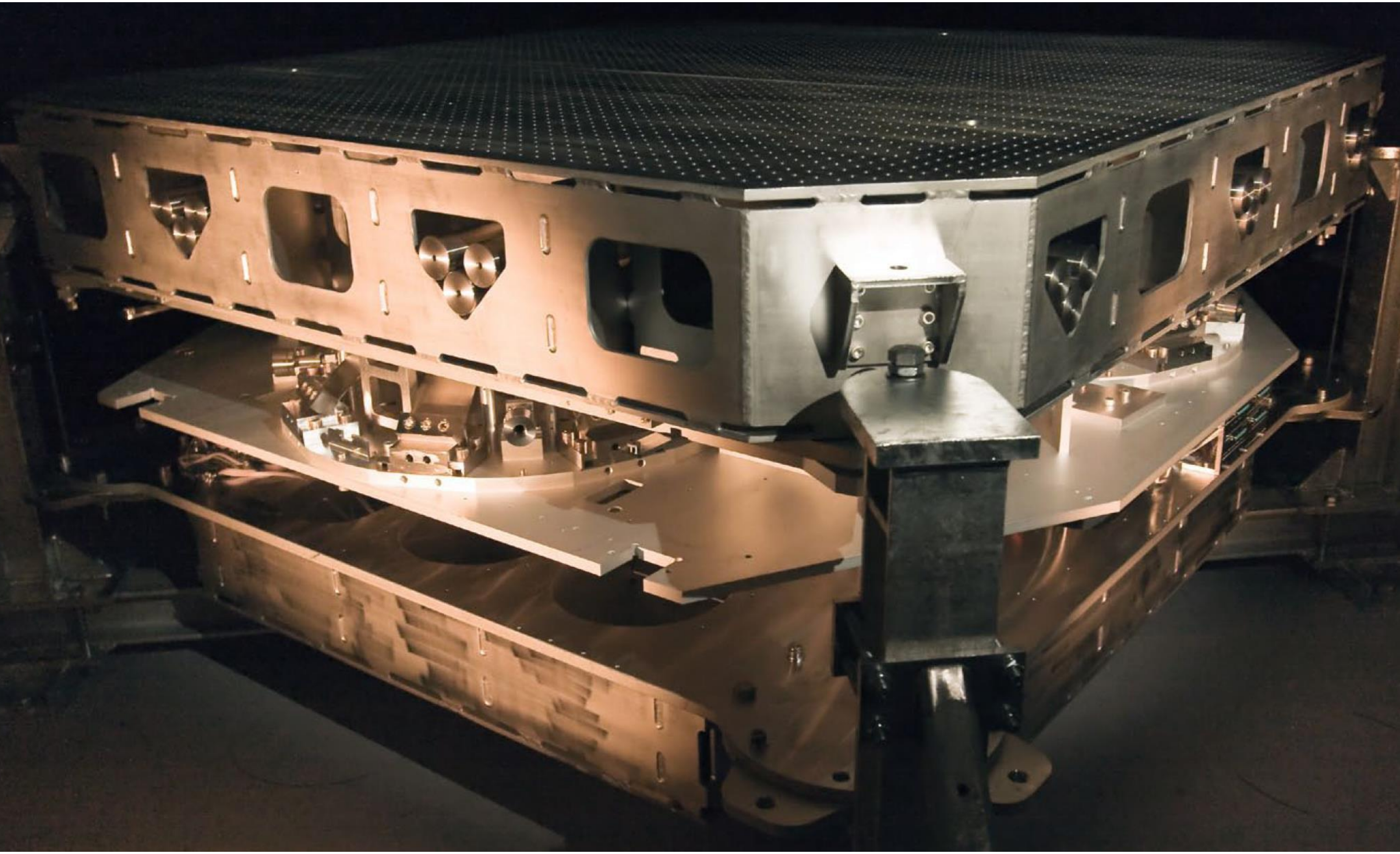
Inertial sensors: Lock acquisition and duty cycle.

Position sensors: Improved suspension damping, reduced 10Hz+ noise injection, simpler global controls.

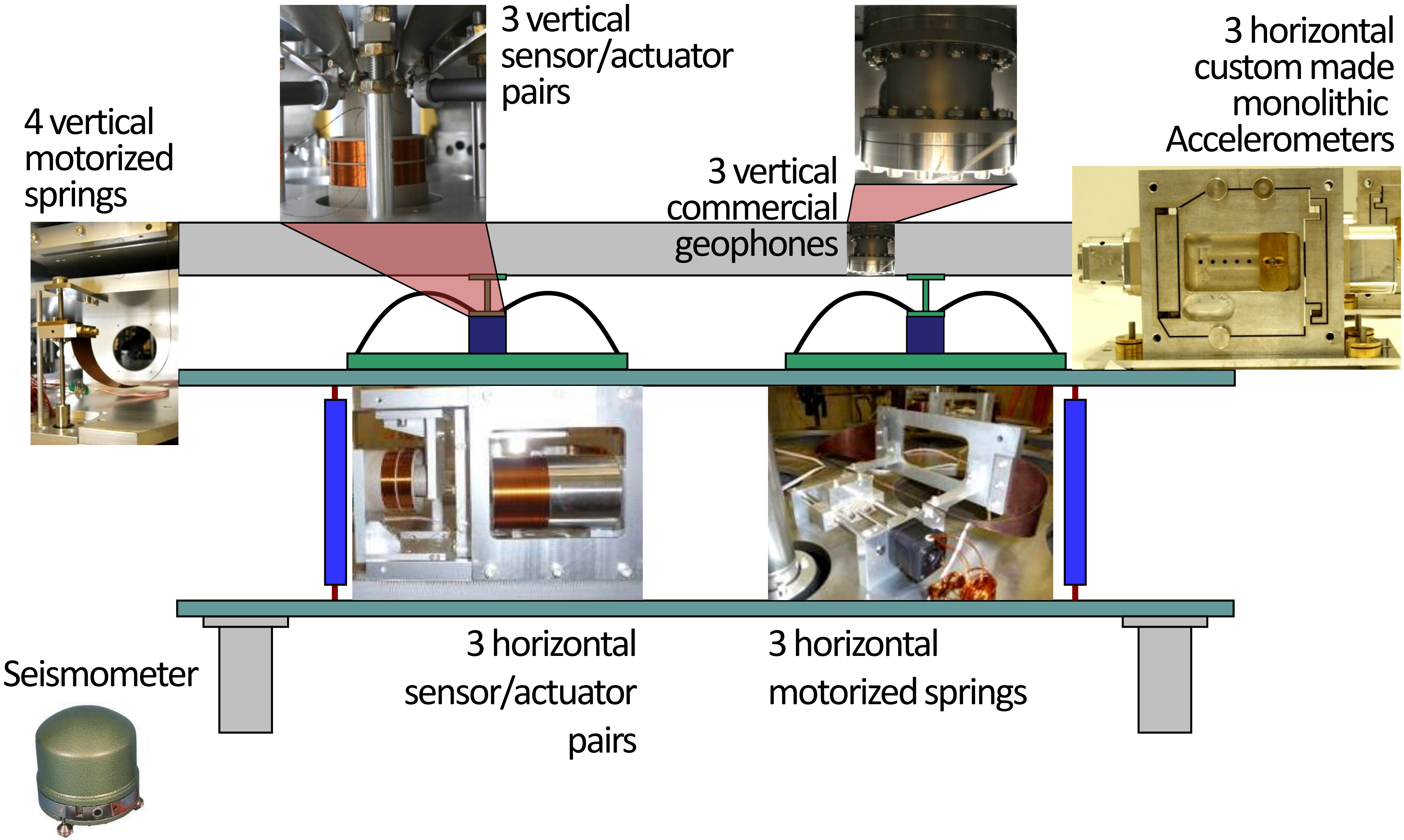
Low-frequency GW experiments such as TOBAs or Atom interferometers need (way) more low-f isolation.

Geophysics? Space-based accelerometers?

My personal inspiration



Sensor blending with noisy sensors



A. Wanner *et al.*, Class. Quantum Grav. **29**, 245007 (2012)

Design considerations with inertial sensors

- ‘Ideal’ sensors are limited by suspension thermal noise: roughly white in force noise ($1/f^{2\text{-ish}}$ in inertial-equivalent displacement). More bending material = more noise.

- *g* is large. Vertical sensors need to be strong, which needs lots of material. Hard to get low resonant frequencies.

- White readout noise becomes $1/f^2$ below resonance.

- Horizontal sensors couple tilt like g/w^2, but low-loss anti-springs make good low-f sensors.

DoF design considerations

DoF	Type	f_0 (Hz)	Design considerations
Z	Mass-spring	~1	Thermal noise, low-f readout noise ($1/f^2$), very low cross-coupling
Z	Anti-Spring	~0.2	Huge thermal noise
X,Y	Pendulum	1	Readout noise ($1/f^2$), tilt-coupling ($1/f^2$)
X,Y	Watt's linkage	~0.1	Tilt-coupling ($1/f^2$), low thermal noise
RX,RY	Differential-Z	~1	Small signal, large common mode, huge low-f readout noise (effectively $1/f^4$)
RX,RY	BRS	~0.01	Small signal, Mechanical tuning and drift/control, low-f readout (effectively $1/f^2$)
RZ	Torsion balance	~0.001	Tiny signal, large RMS rotation
RZ	Differential-X,Y	~0.1	Tiny signal, tilt-rejection

Some randomly sampled work in the LSC

Tilt-coupling is seeing quite some attention,

- Tilt-free seismometry (Dooley)
- BRS for tilt-correction (Venkateswara)
- Differential-Z for closed-loop (Mow-Lowry)

Interferometric readout

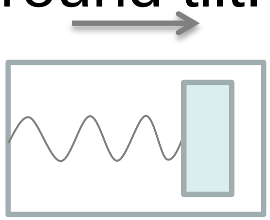
- Watt’s linkage with Michelson (van Heijningen)
- EUCLID-type readout (Mow-Lowry)

Thermal noise via exotic springs (not discussed here)

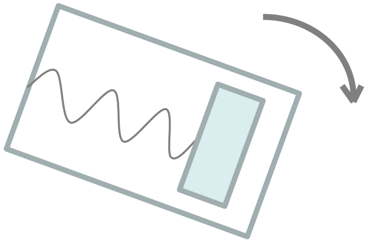
Most remaining slides are courtesy of Kate, Krishna, and Joris.

Tilt versus Horizontal displacement

- Conventional seismometers and tiltmeters cannot differentiate between horizontal displacement and ground tilt.



$\delta x \propto a_x$



$\delta x \propto g\theta$

Tilt response to horizontal displacement response for <u>all</u> seismometers = $-g/\omega^2$

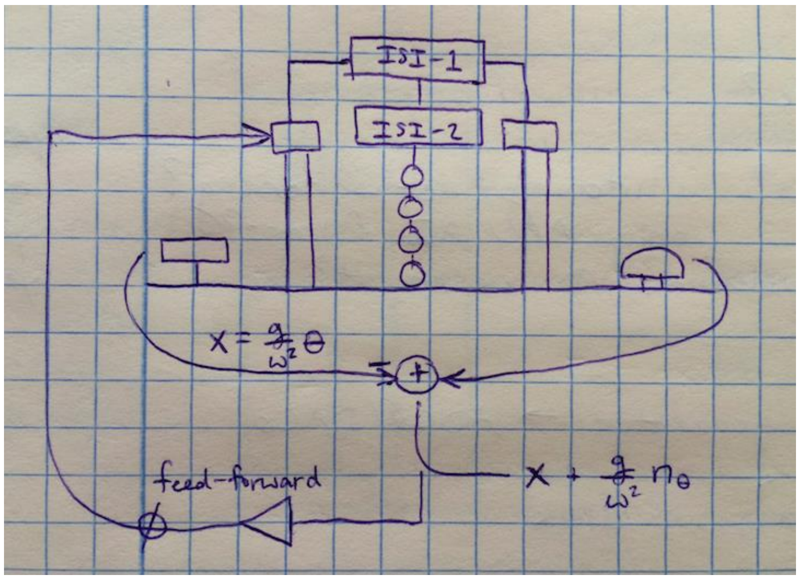
$\Rightarrow$ Tilt is confused with horizontal motion at low frequencies (below ~ 0.1 Hz).

<u>Solution</u>: Inertial rotation sensors, Tilt-free seismometers or ring-laser gyroscopes…

Source: Krishna Venkateswara

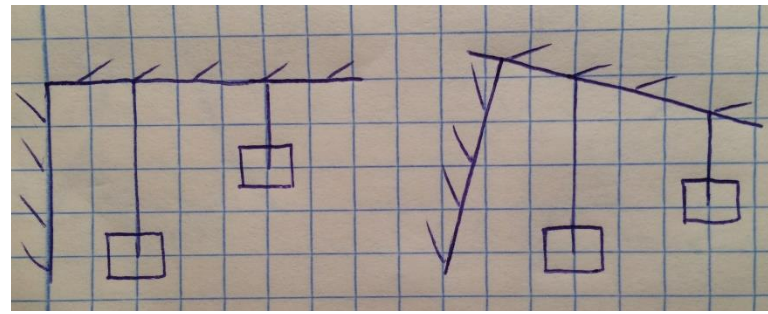
Two different approaches

Measuring tilt



Independently measure ground tilt and subtract it.

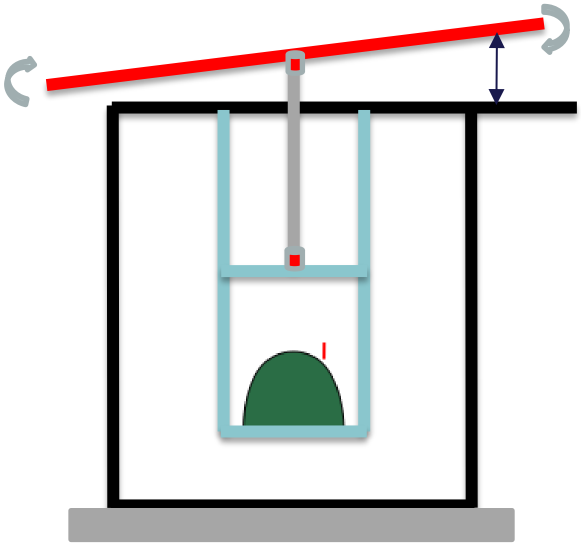
Filtering tilt

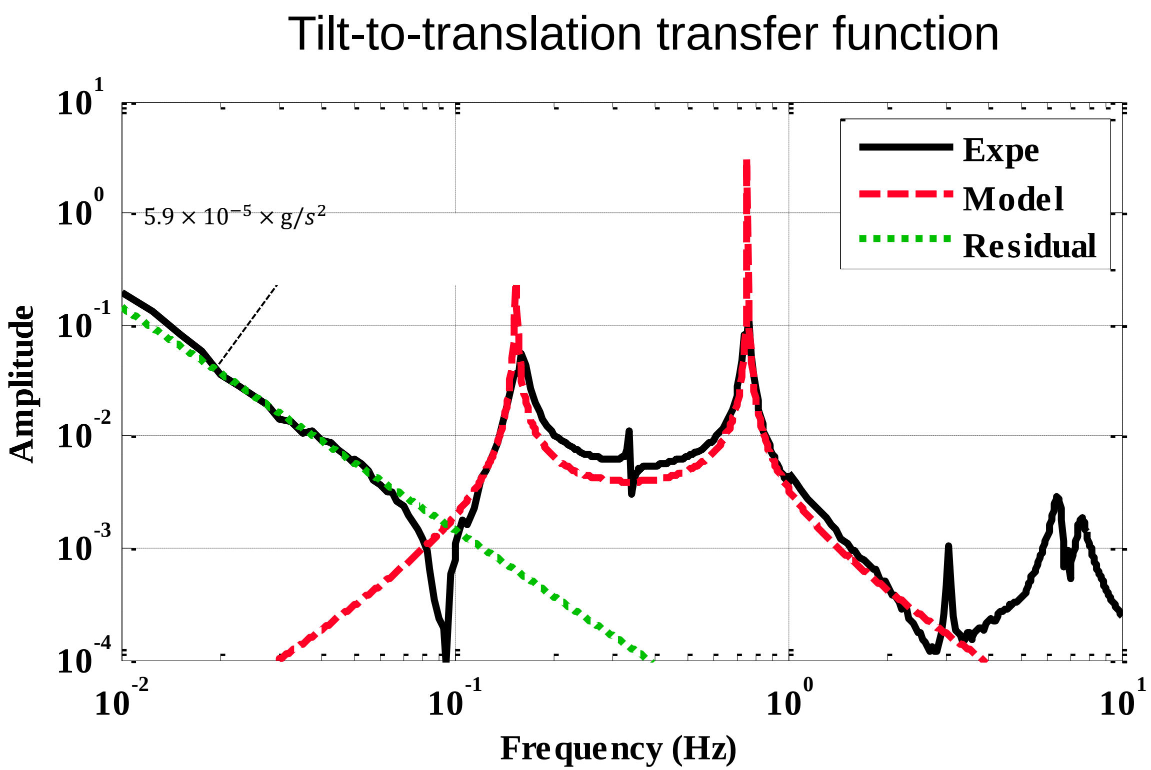


Mechanically filter tilt from reaching the seismometer in the first place

Source: Kate Dooley

Example results: tilt-filtering demonstration

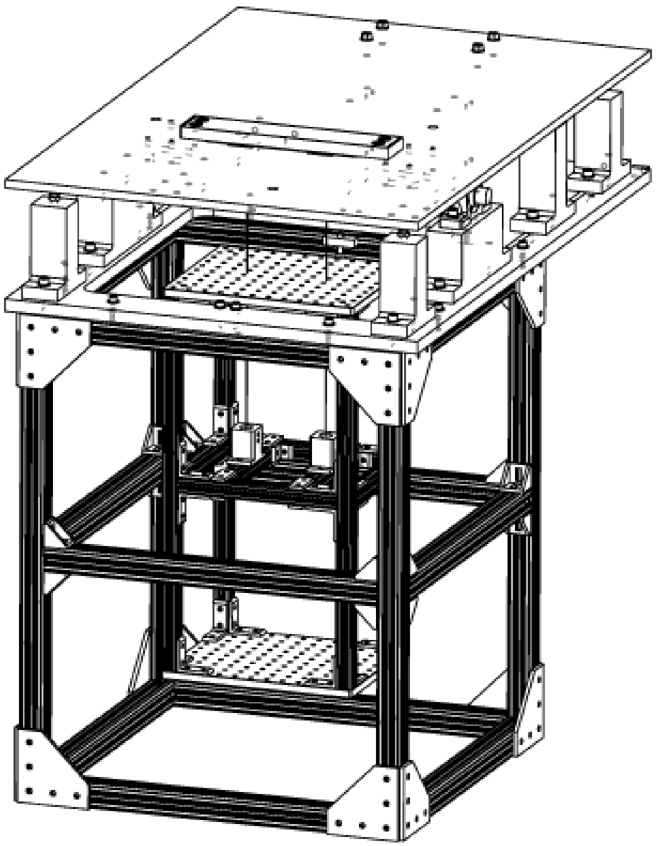




Matichard et al. P1400061

Source: Kate Dooley

Outlook and message

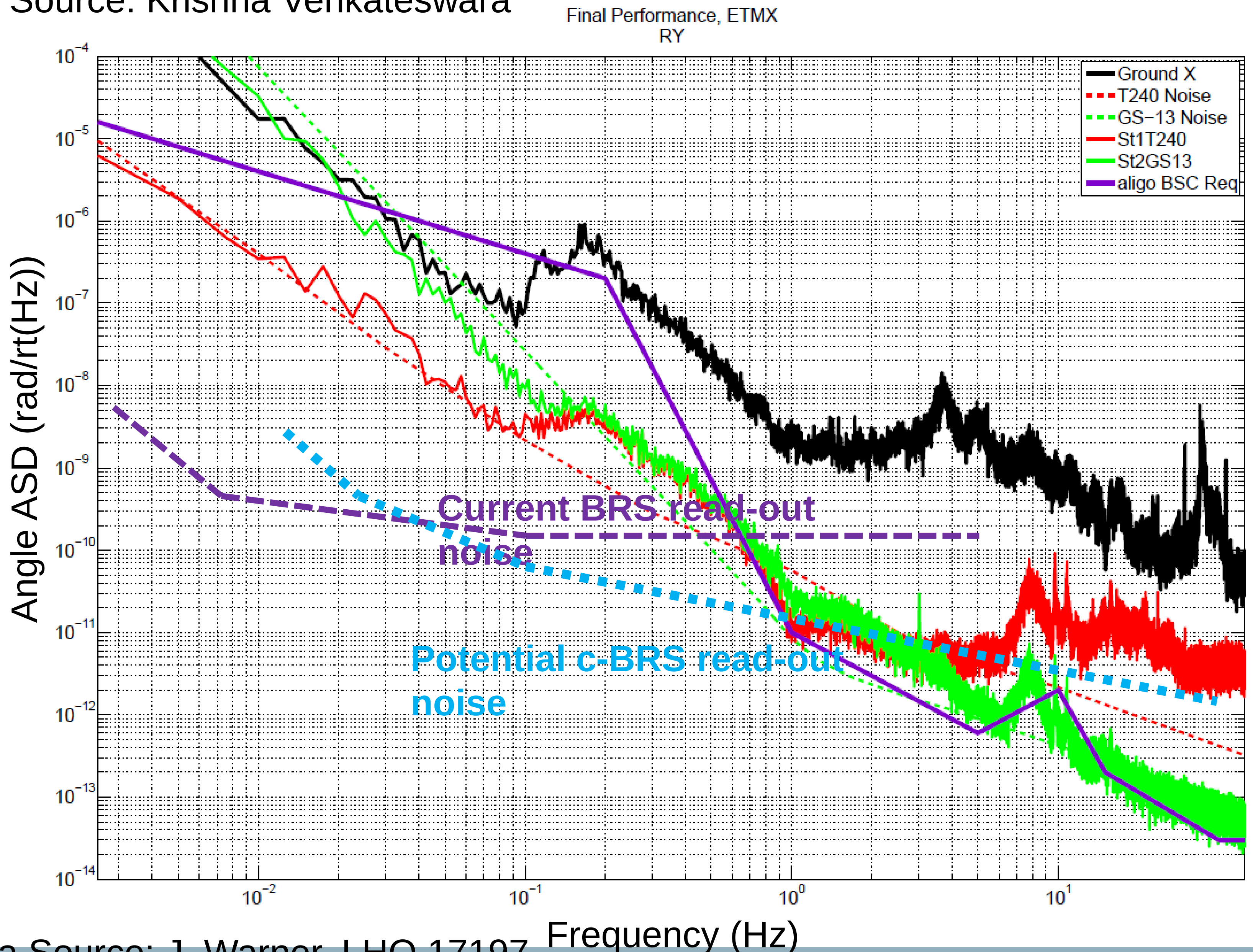


- Build prototype suspension and measure transfer functions using commercial seismometer
- Conduct huddle test
- Build and test custom seismometer (inverted pendulum with Michelson readout)

Source: Kate Dooley

Sensitivity comparison

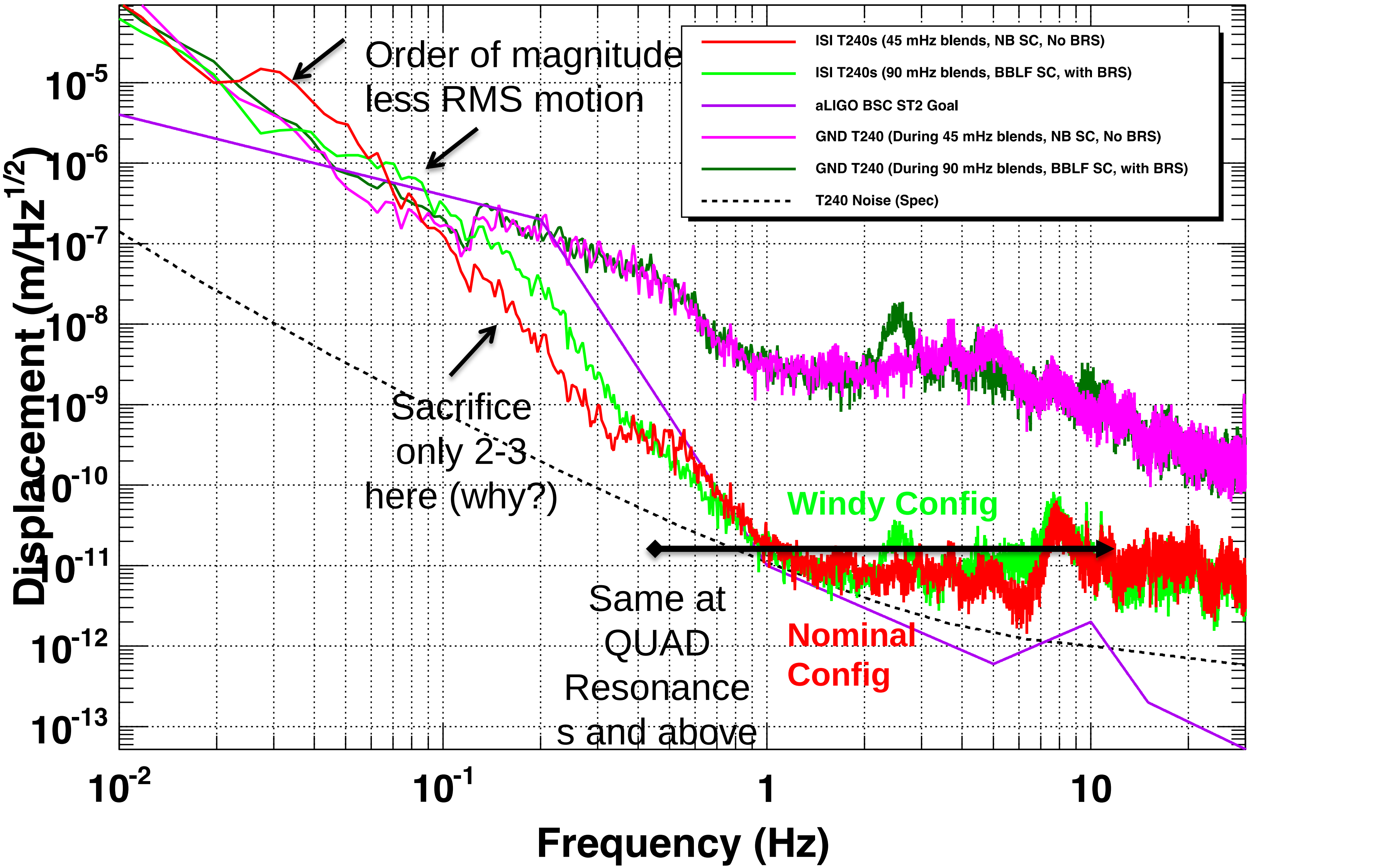
Source: Krishna Venkateswara



Extra Source: J. Warner, LHO 17197

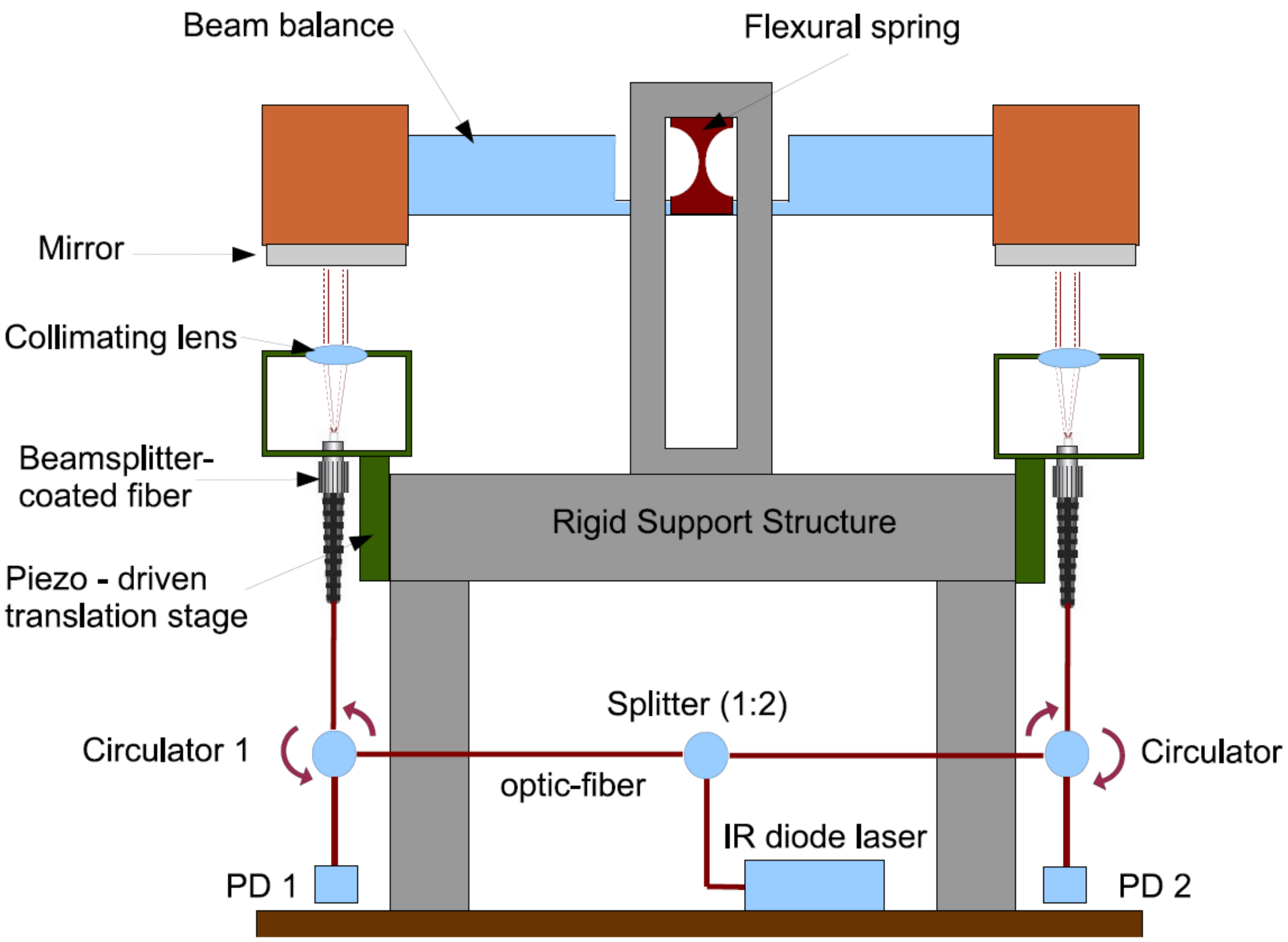
Improving ISI performance with BRS

(LHO aLOG 17729)



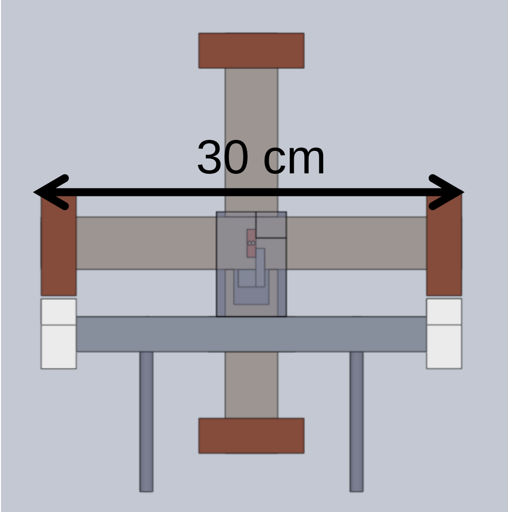
Source: J. Kissel, G1500475 2nd order source: Krishna Venkateswara

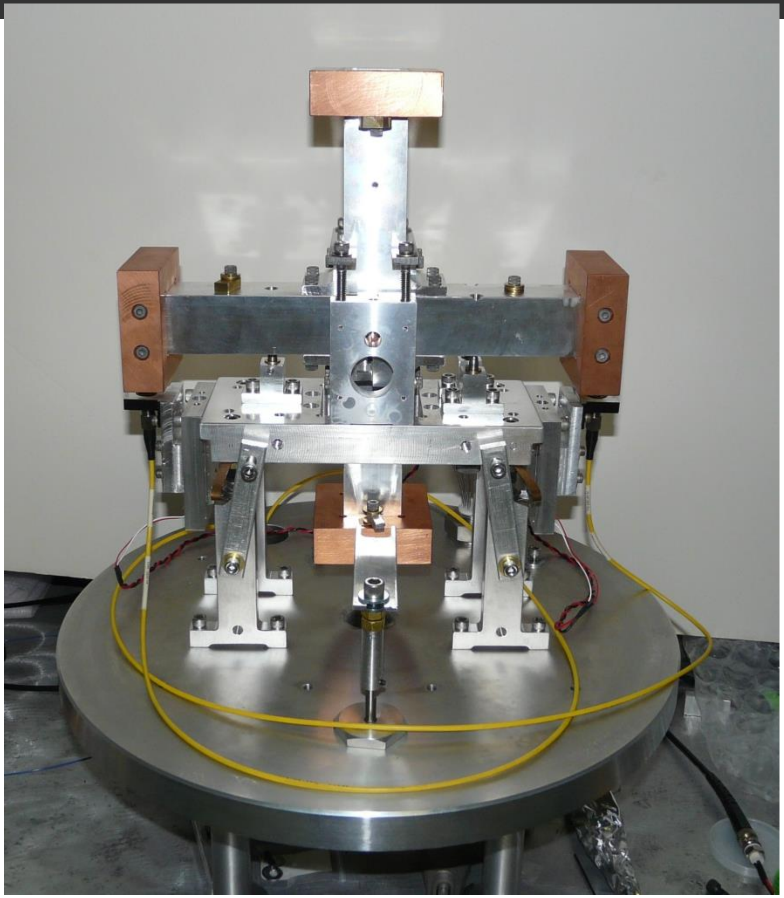
Schematic



Source: Krishna Venkateswara

Compact-BRS





New features

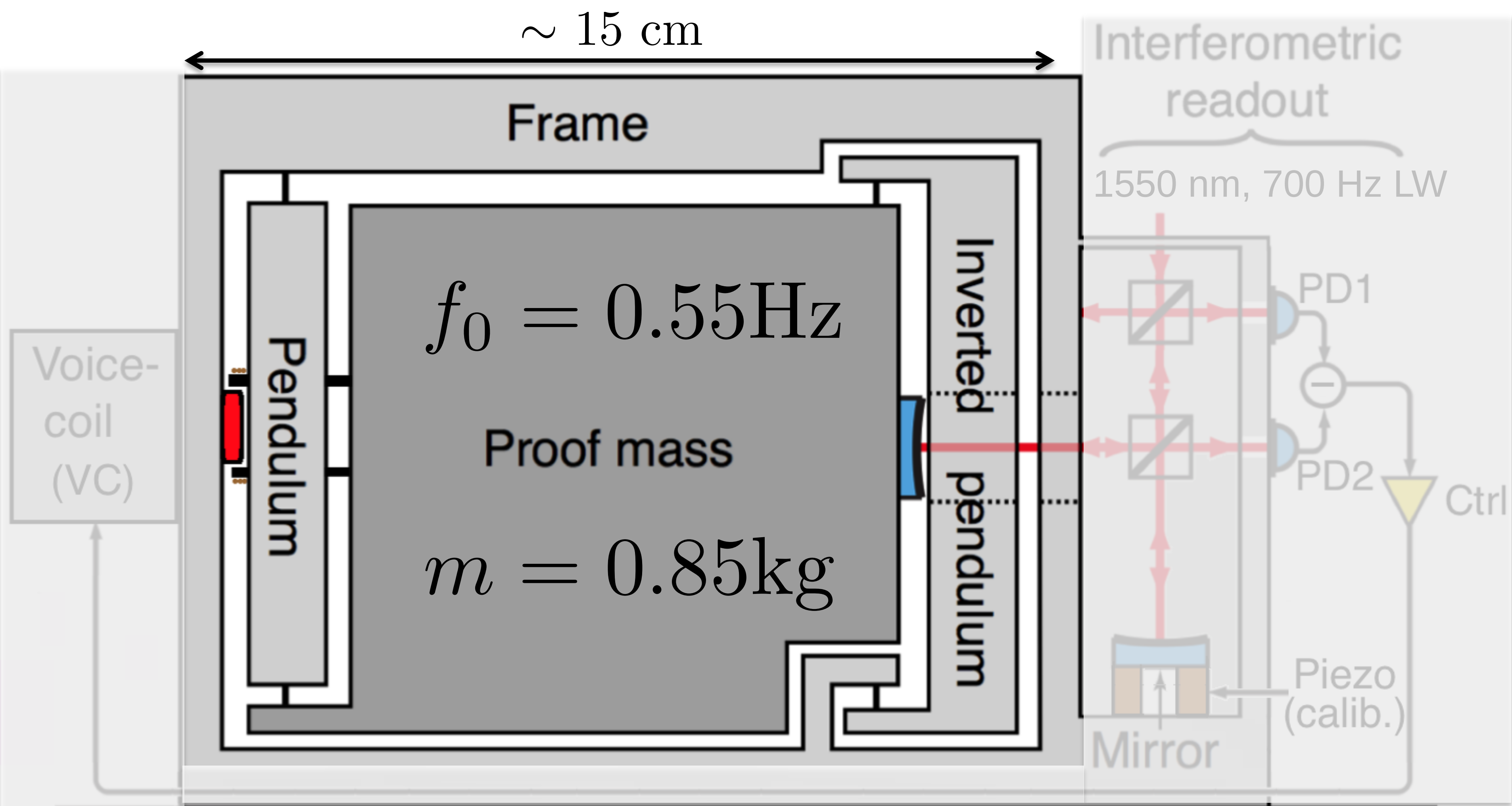
1. Cross Shape (~0 quadrupole moment) ensures first order insensitivity to gravity gradient noise.
2. New compact interferometric readout with ~10X better sensitivity.
3. Kinematic seat for transportation/repositioning (?)

Source: Krishna Venkateswara

Inertial Sensors with Interferometers

- Non-contact, low-noise readout
- Michelson or Fabry-Perot
  - Extreme sensitivity
  - Small dynamic range (closed loop required)
  - Lots of experience in the field
- Homodyne phasemeters (e.g. EUCLID)
  - Huge dynamic range (~cm range, ~cm/second speed)
  - (Potentially) High sensitivity (10^{-14}m/rt(Hz))
  - No actuators required (magnets, wires, cables)
  - Excellent calibration (fixed to the optical wavelength)

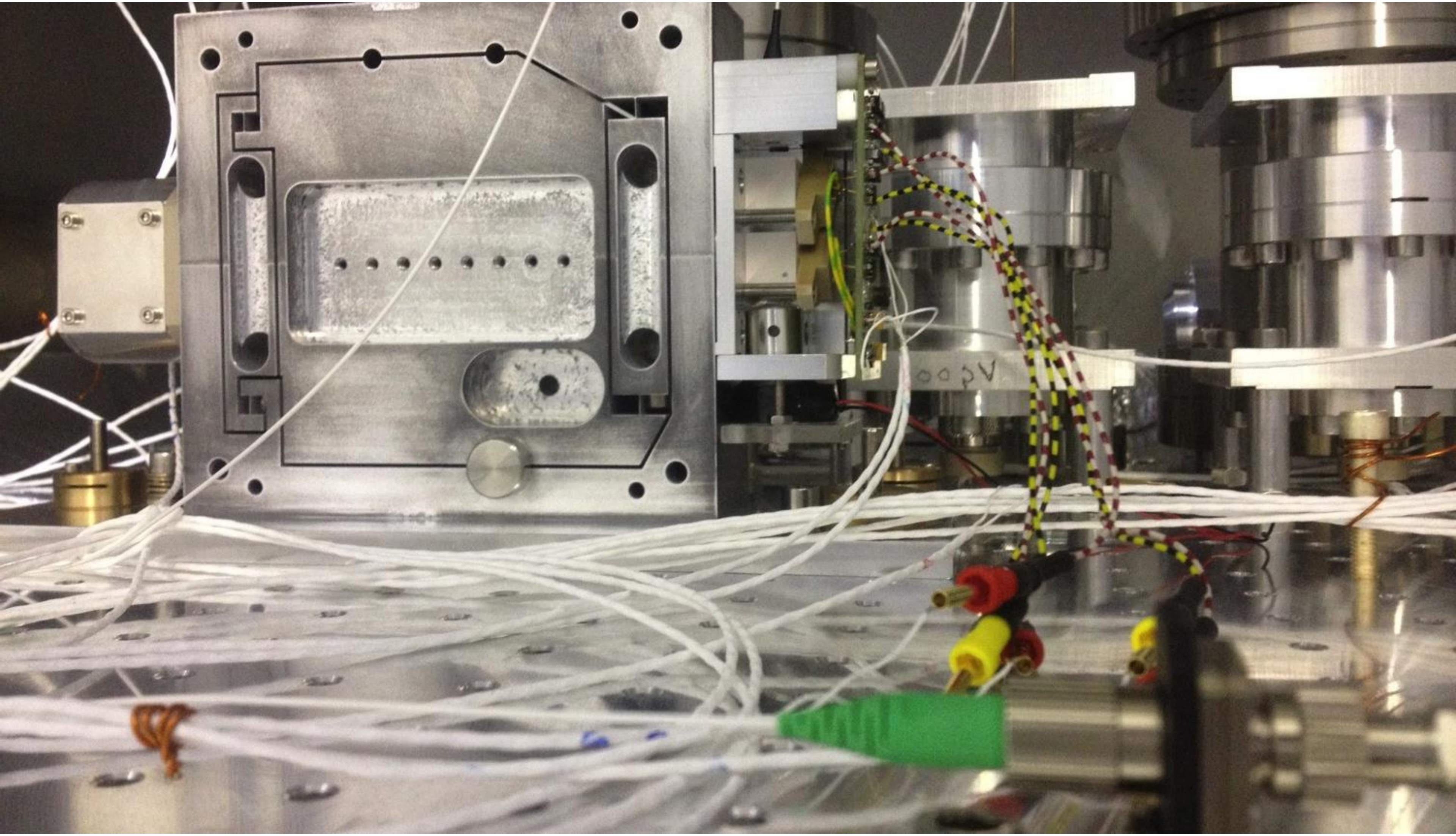
Nikhef interferometric Watt's linkage



A. Bertolini et al., NIM A, 556, pp 616-623 (2006)

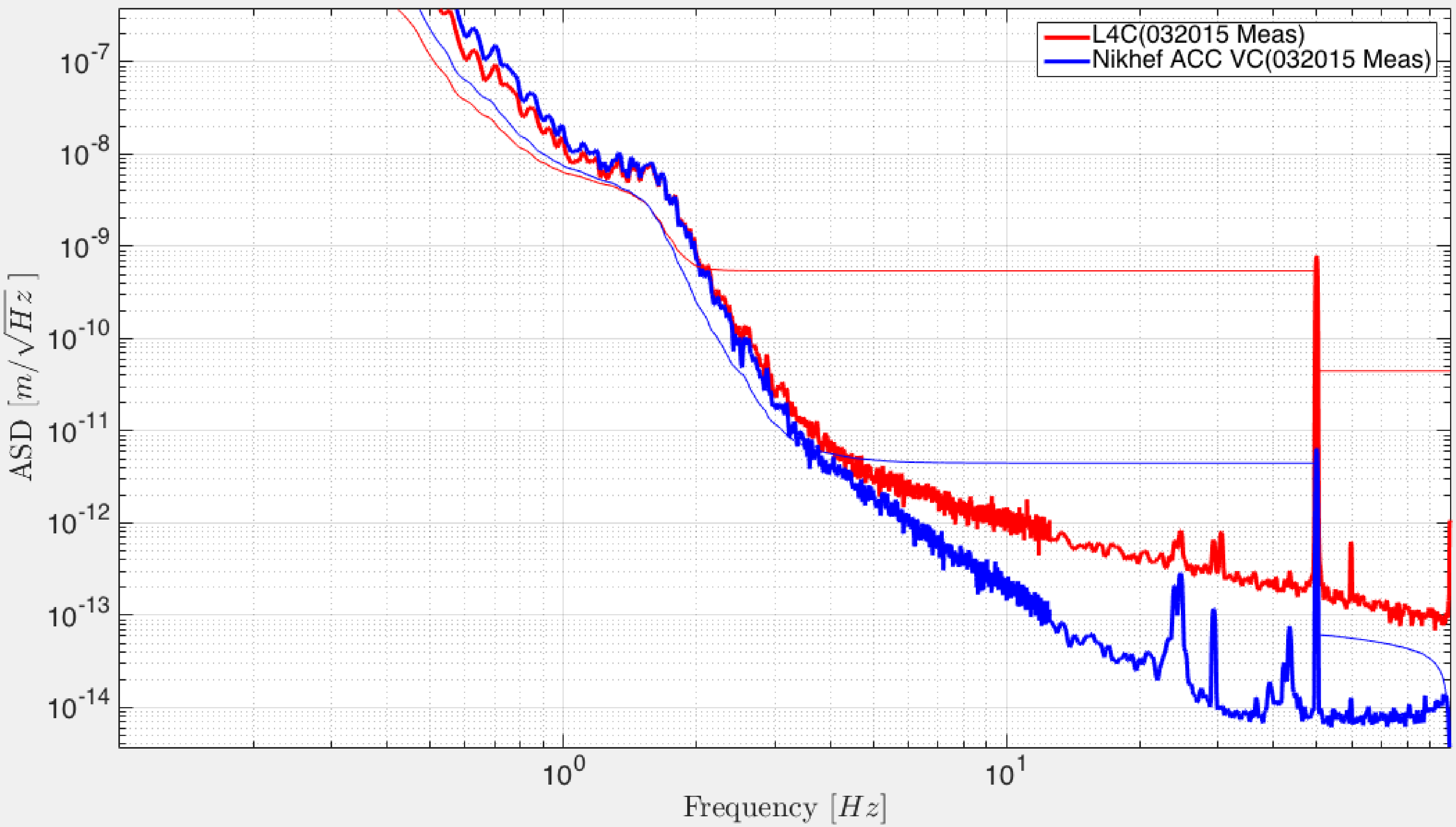
M.B. Gray et al., Opt.Quant.Electron., 31, pp 571-582 (1999)

Interferometer testing



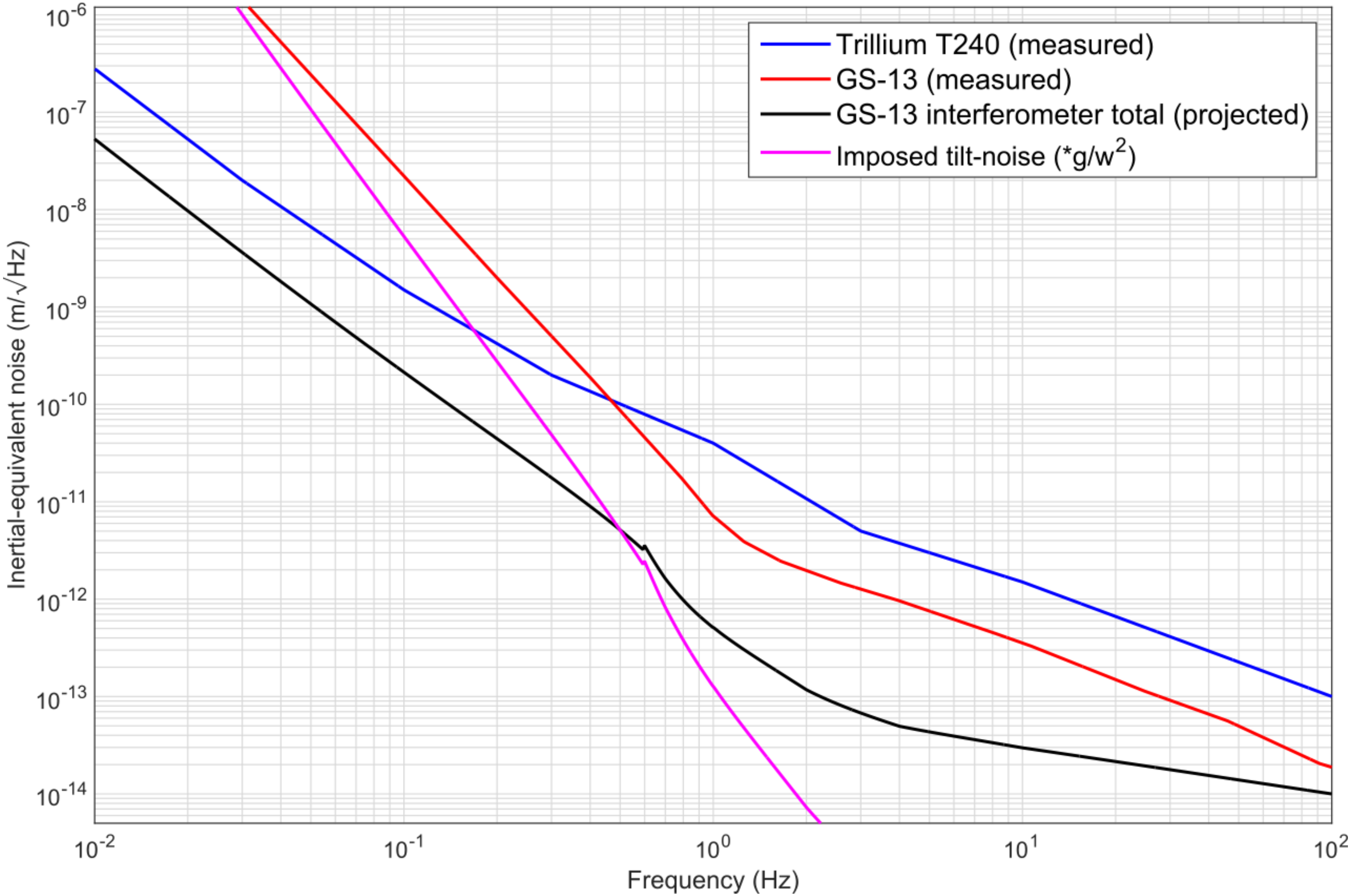
Source: Joris van Heijningen

Spectra on undamped Multi-SAS bench

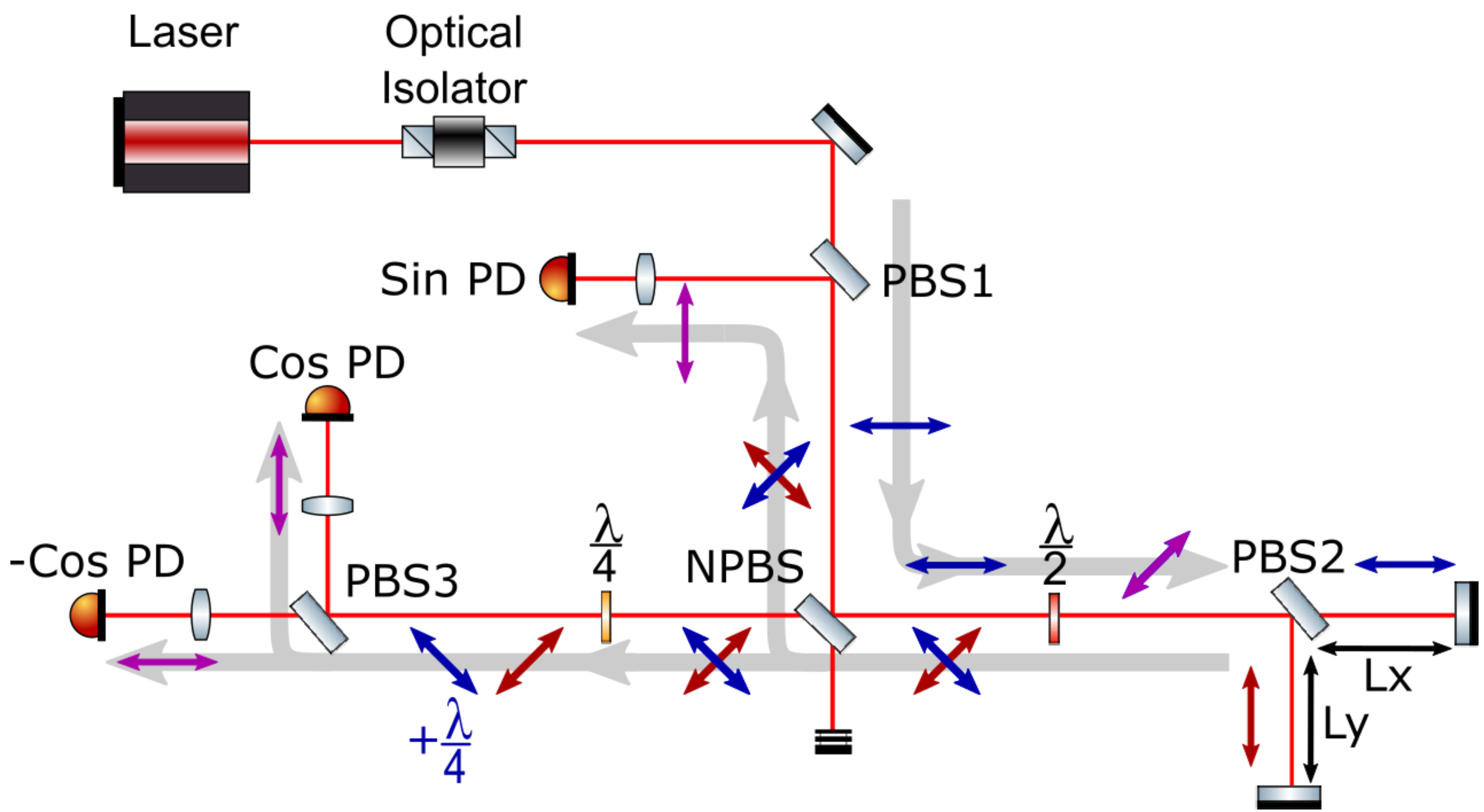


Source: Joris van Heijningen

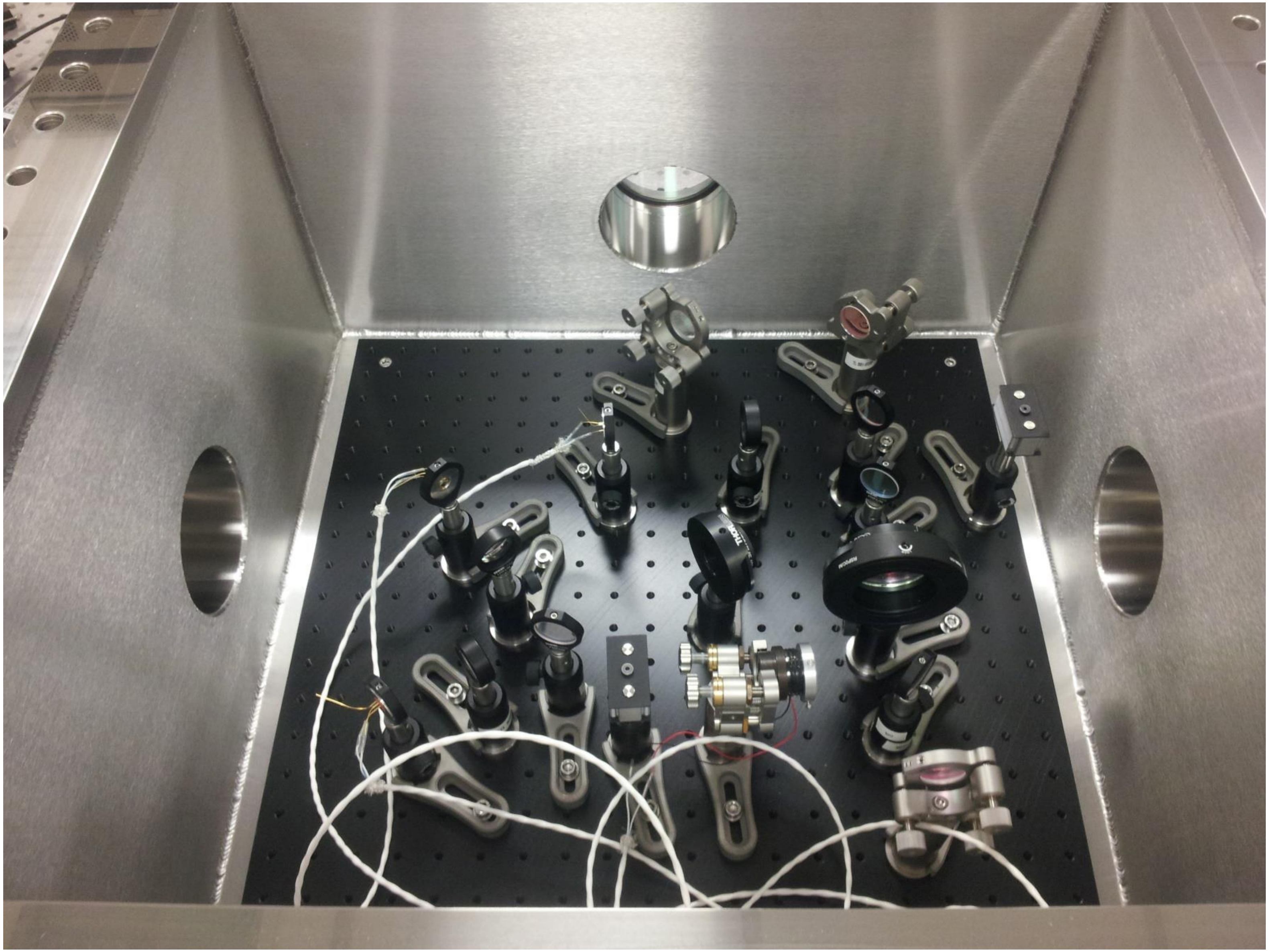
Design aim for GS-13 readout



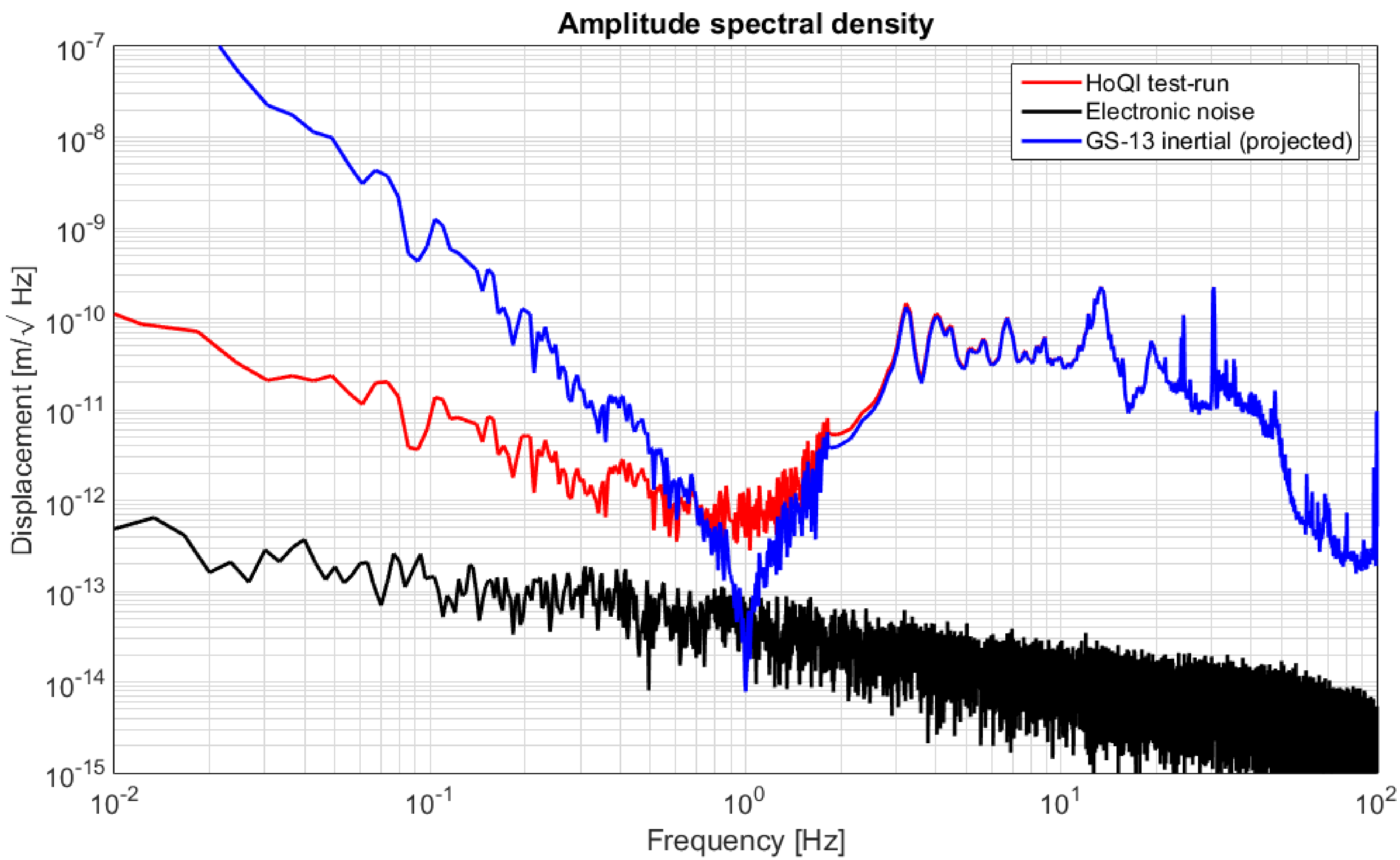
Homodyne Quadrature Interferometer



Homodyne Quadrature Interferometer



HoQI trial measurement (in vacuum)

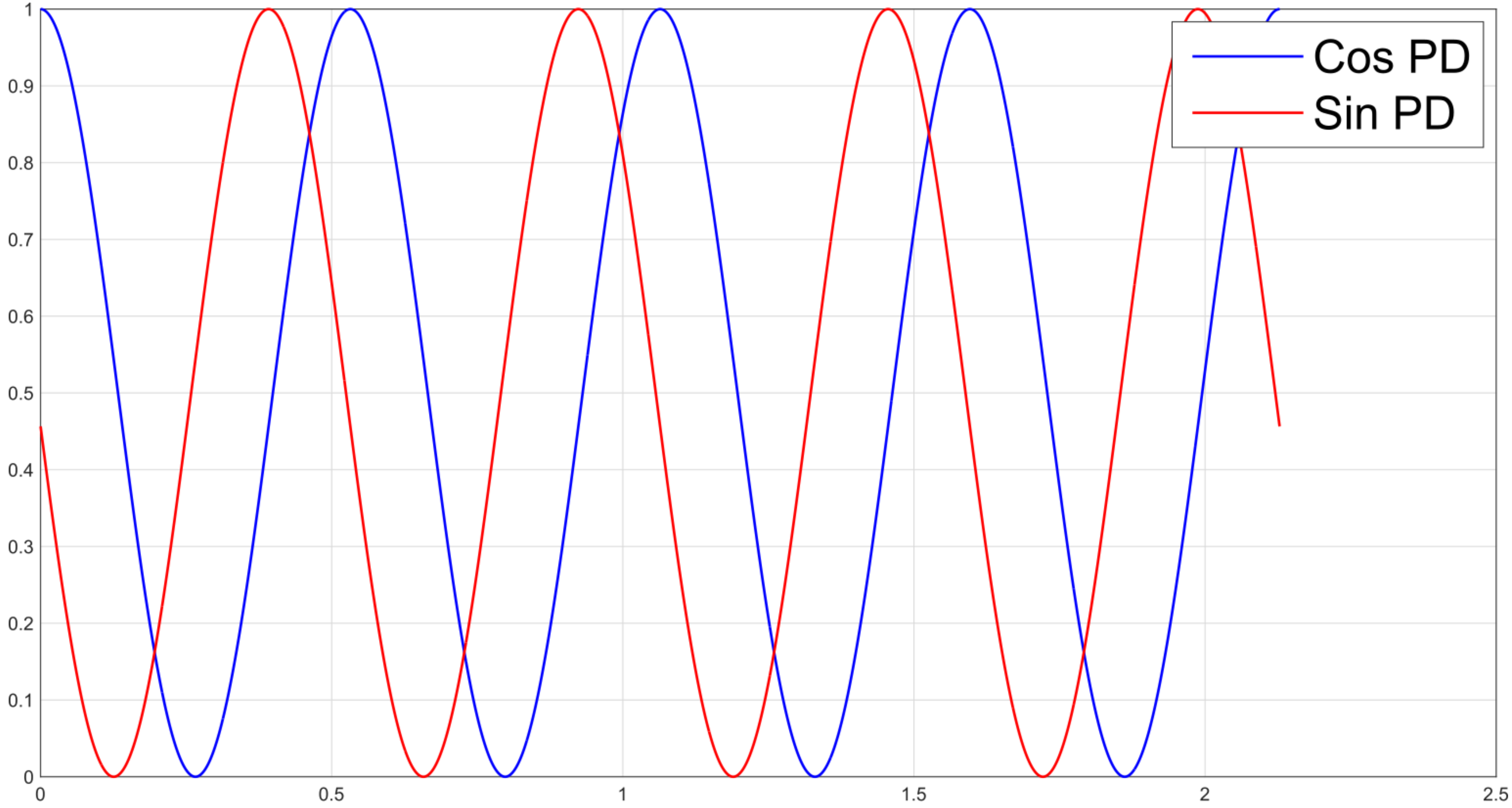


Future inertial sensor work

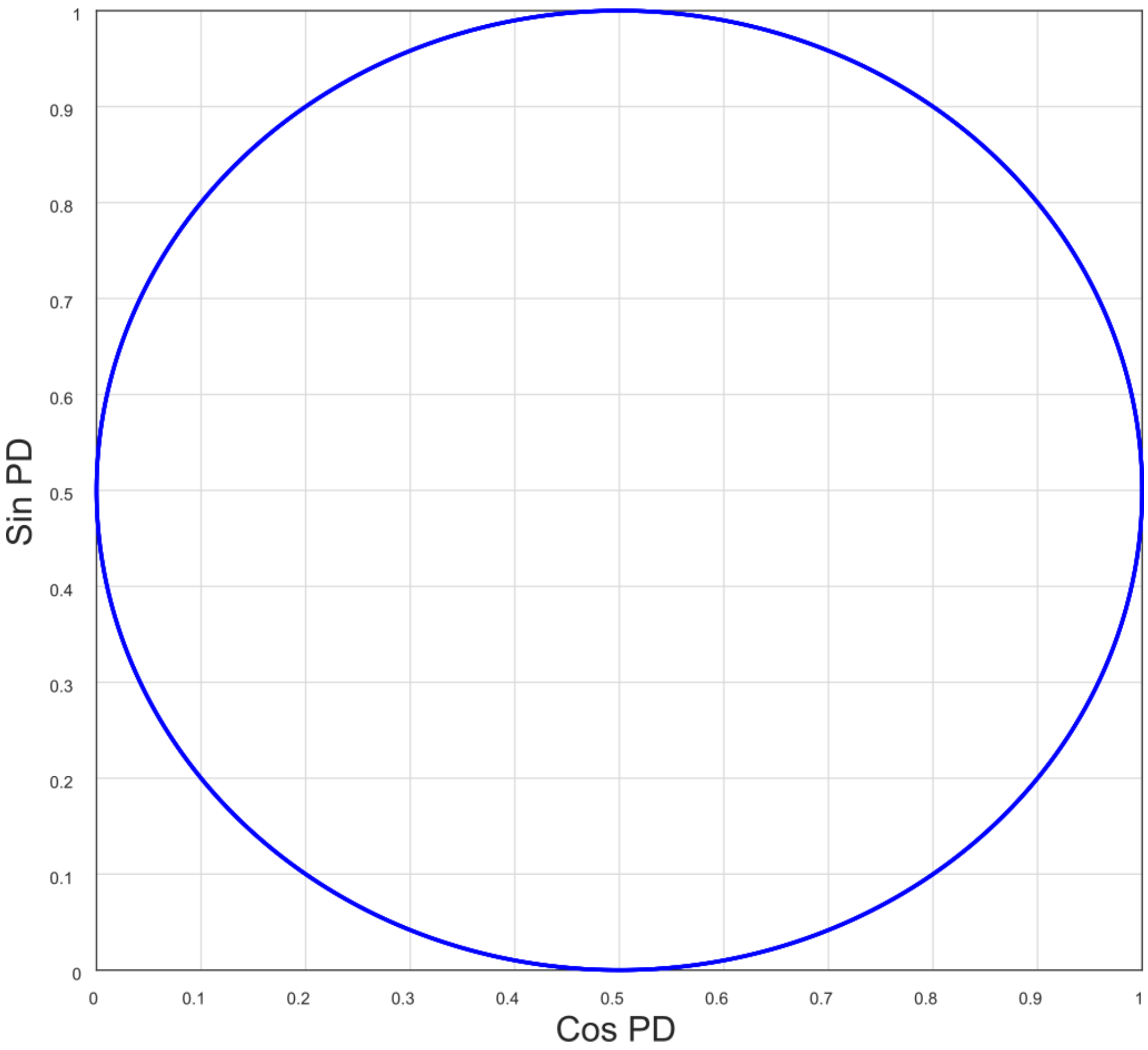
There are many topics that still need much more work here, just a few include:

- New materials,
- Spurious forces on home-made sensors,
- UHV compatibility,
- Non-mechanical devices (eg SCGs)

Homodyne Quadrature Interferometer



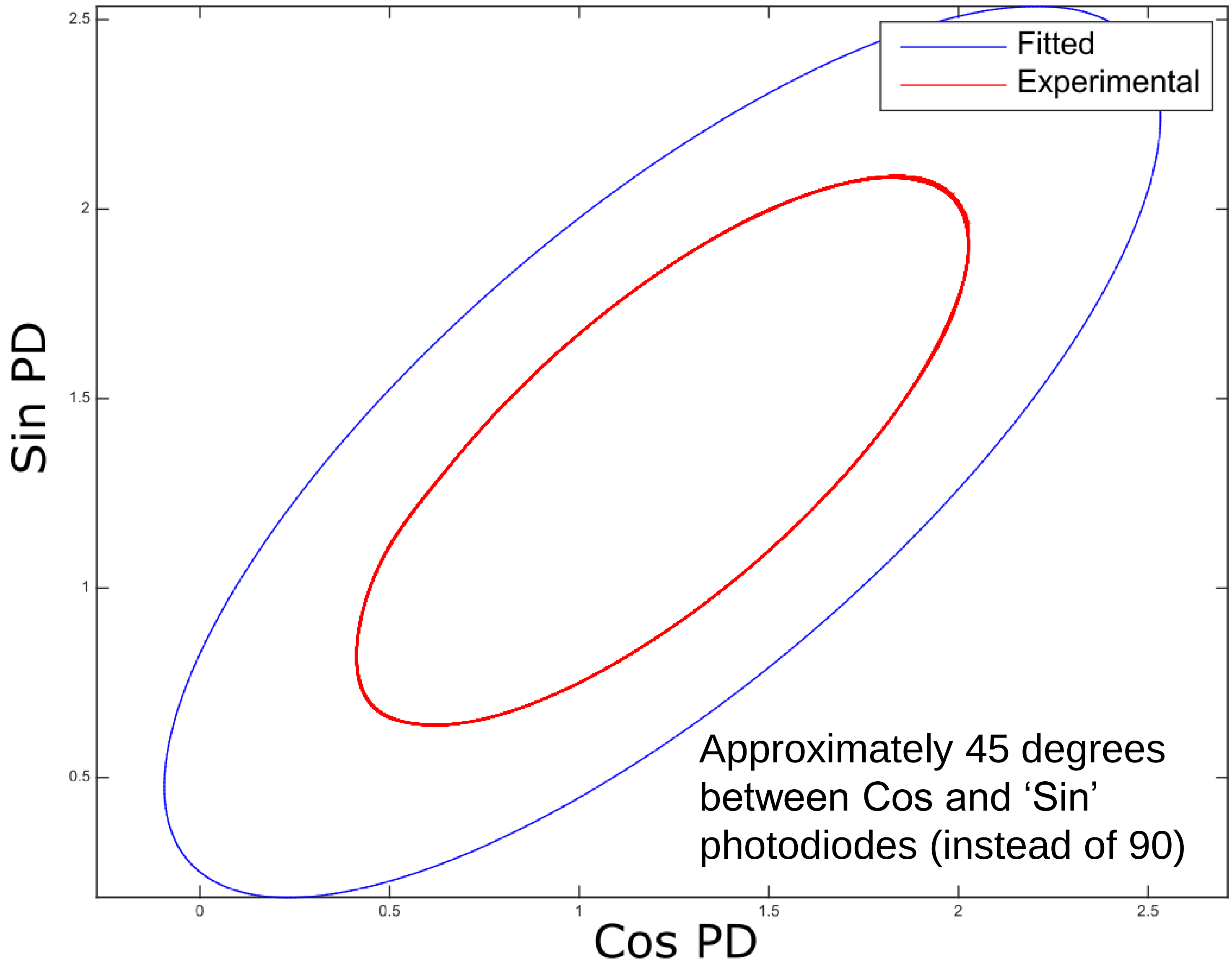
Homodyne Quadrature Interferometer



- Sin vs Cos plot creates a circle
- The centre is shifted to 0,0
- Simple arctangent (or a cordic engine) reads out the optical phase, over multiple fringes
- This repeating pattern is our Lissajous figure.

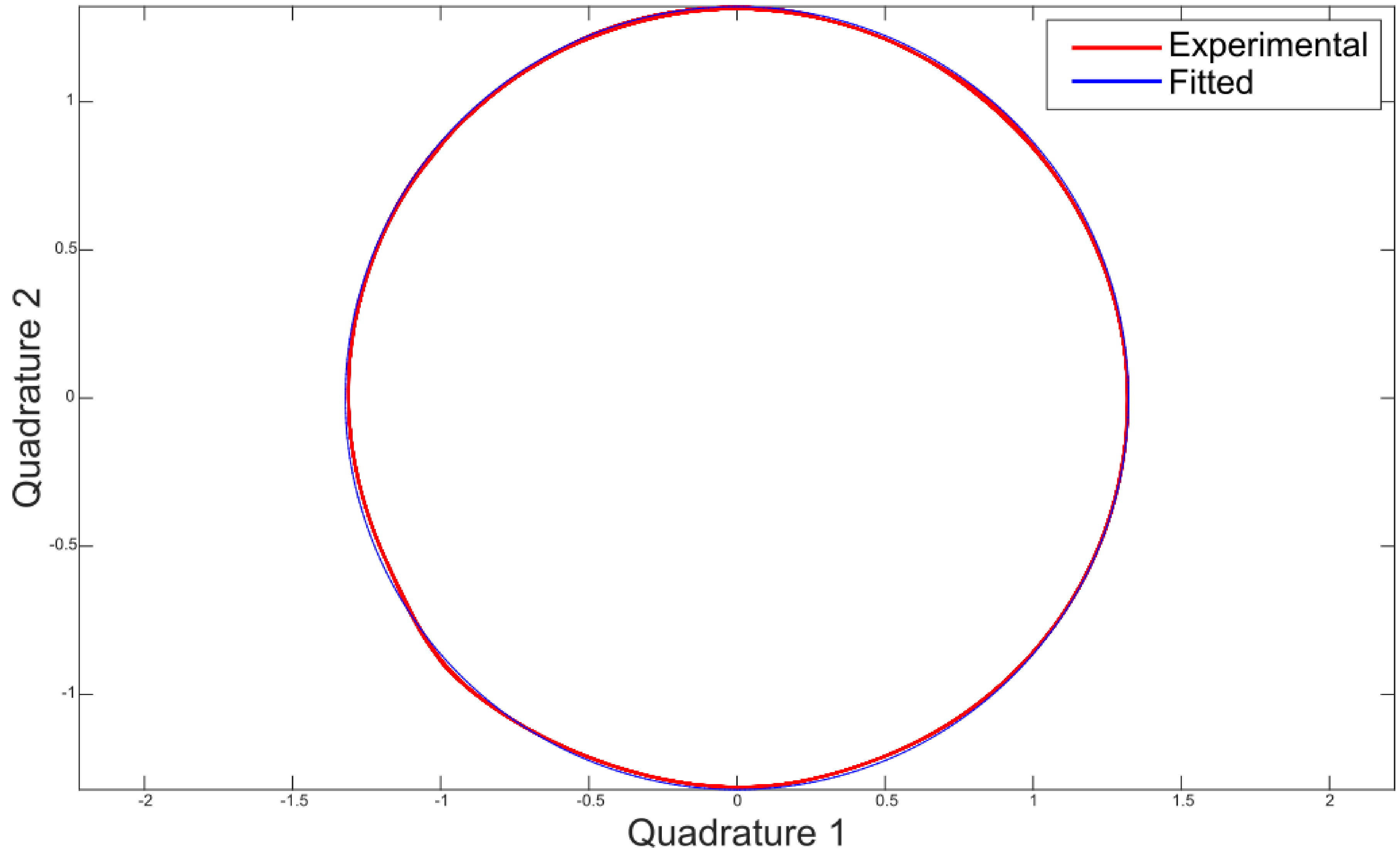
- Roughly speaking, deviations from a circle will create non-linearities in the readout.

HoQI Experimental Data



Approximately 45 degrees between Cos and ‘Sin’ photodiodes (instead of 90)

HoQI Experimental Data



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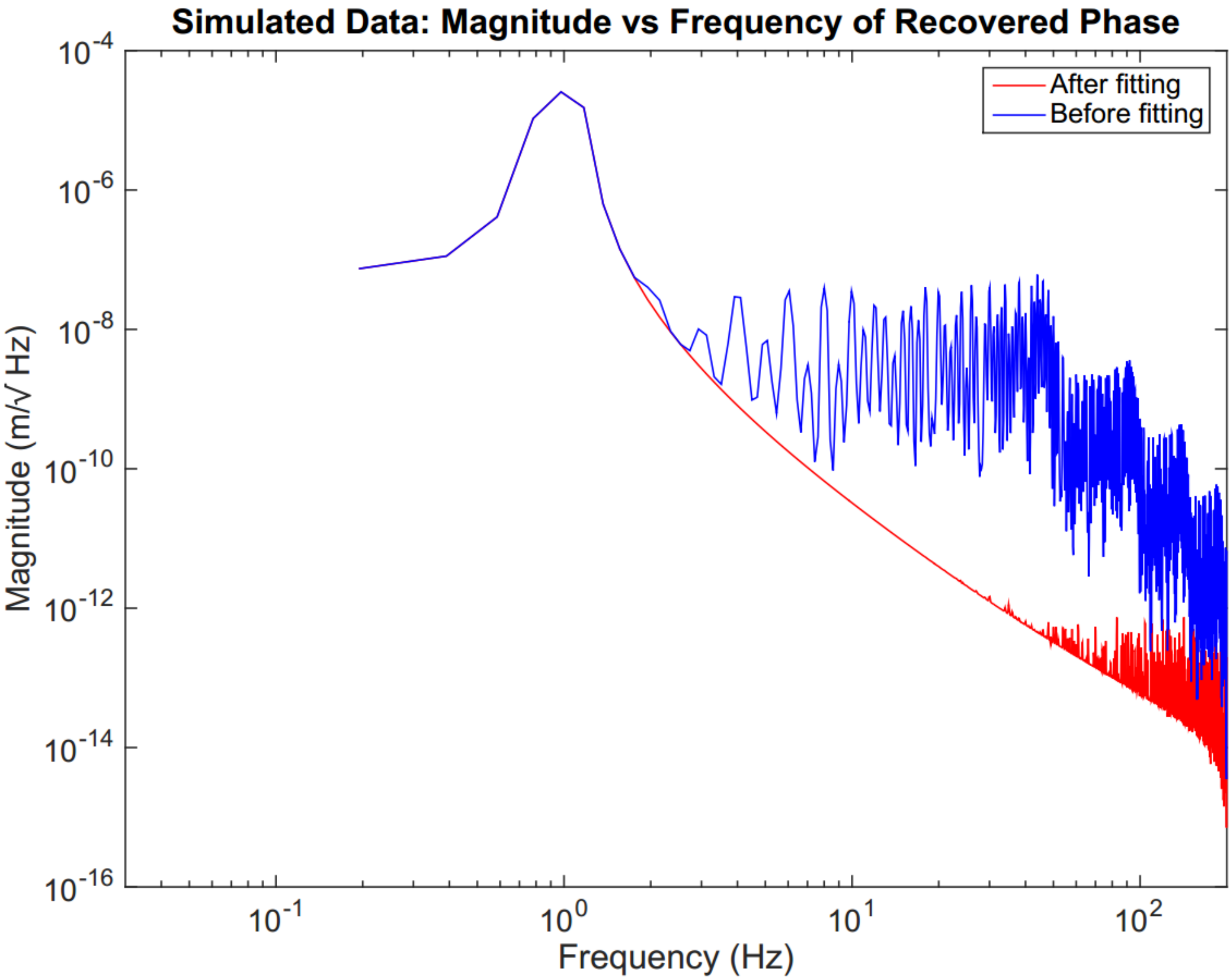
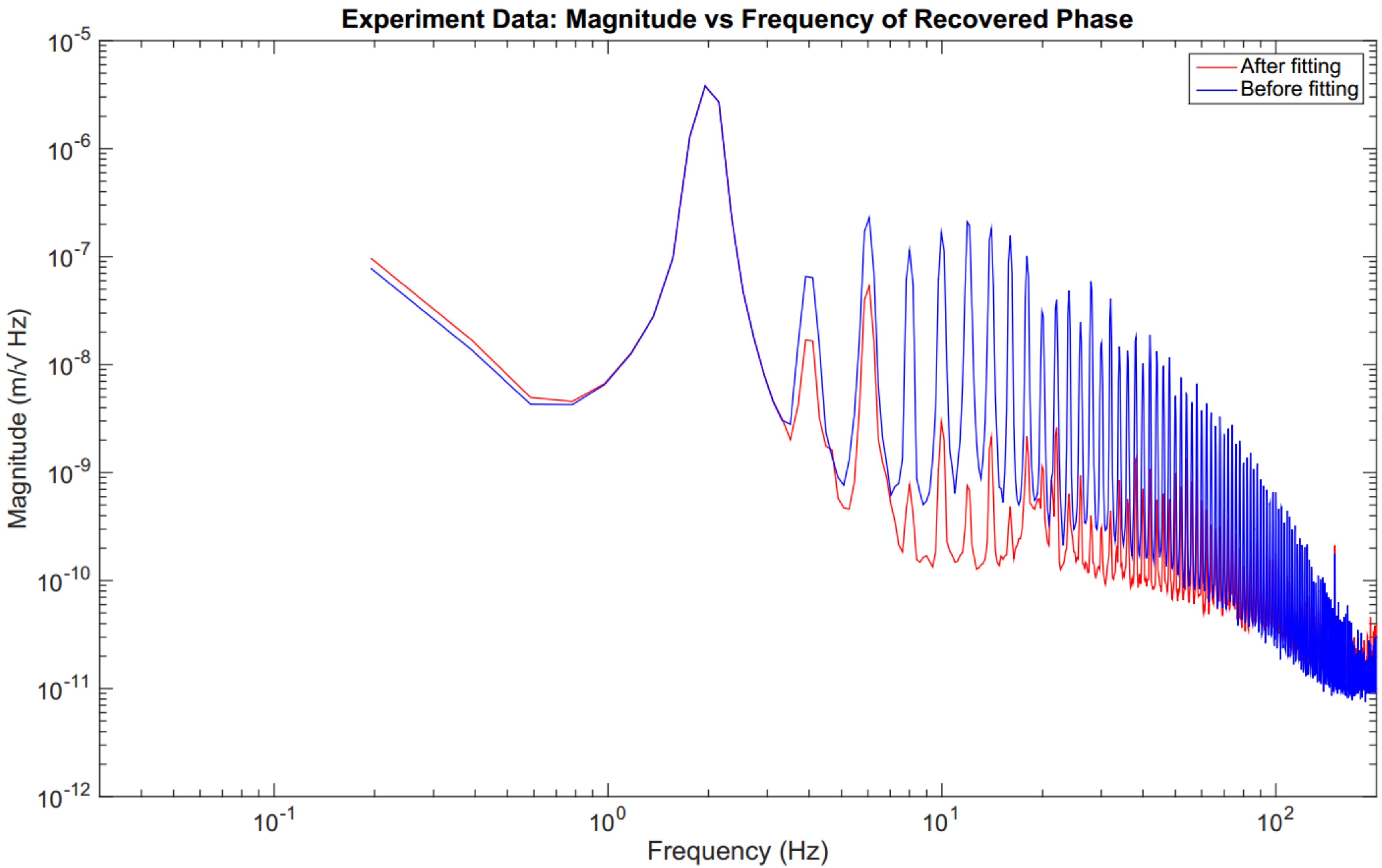
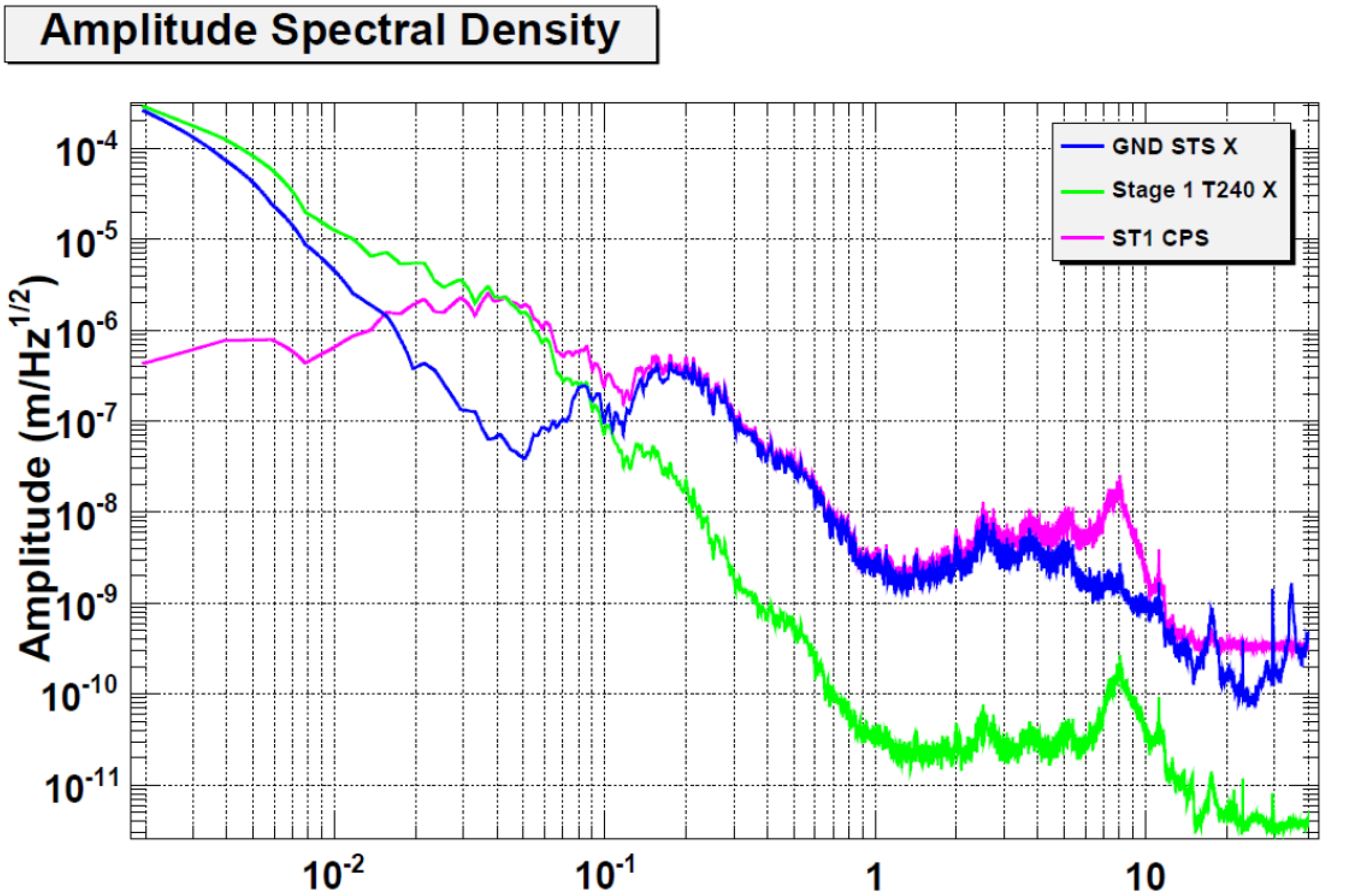


Homodyne Quadrature Interferometer



Ref: LHO 15146

Stage 1 Motion



Source: Krishna Venkateswara

T0=18/11/2014 22:00:00 Avg=10/Bin=2L BW=0.00292964