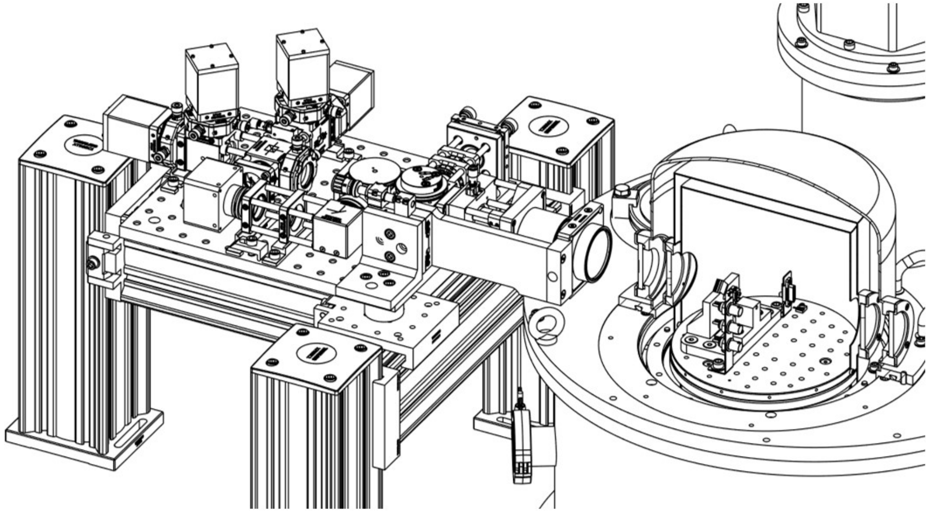
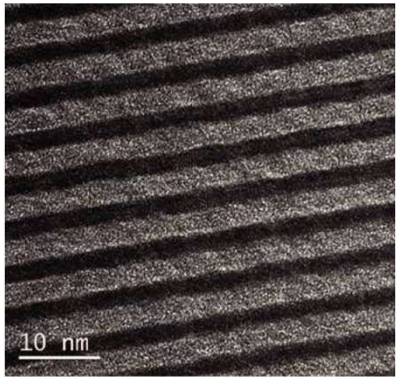
High-Resolution Microcantilever-Based Loss Angle Measurements for Quarter Wavelength and Nanolayered Coating Research





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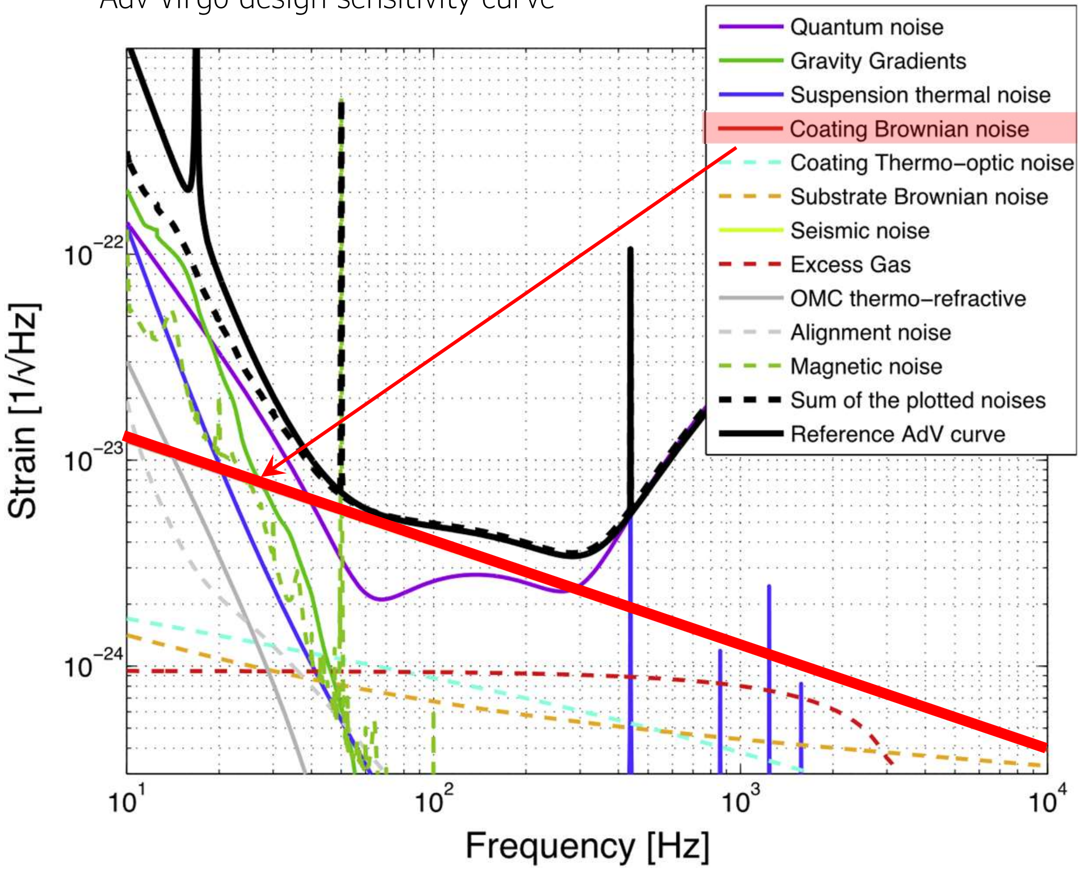
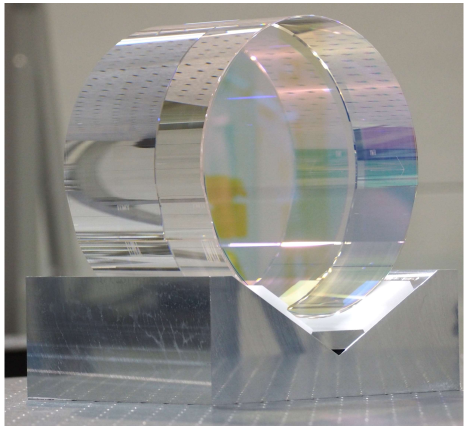
Coating thermal noise is a big problem for GWD

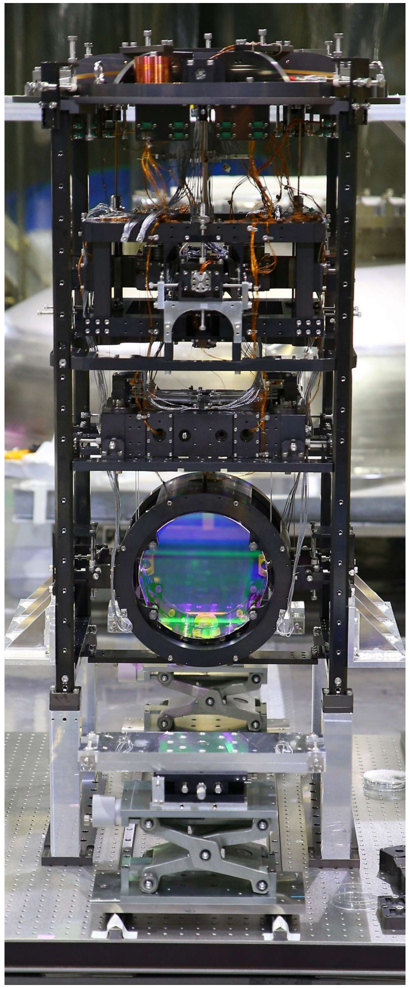
Adv Virgo design sensitivity curve



Acernese & al, *Class. Quantum Grav.* 32 (2015) *024001*
https://gwcenter.icrr.u-tokyo.ac.jp/en/kagra-gallery



A sapphire mirror for KAGRA. 22cm diameter, 15cm thick and 23kg weight



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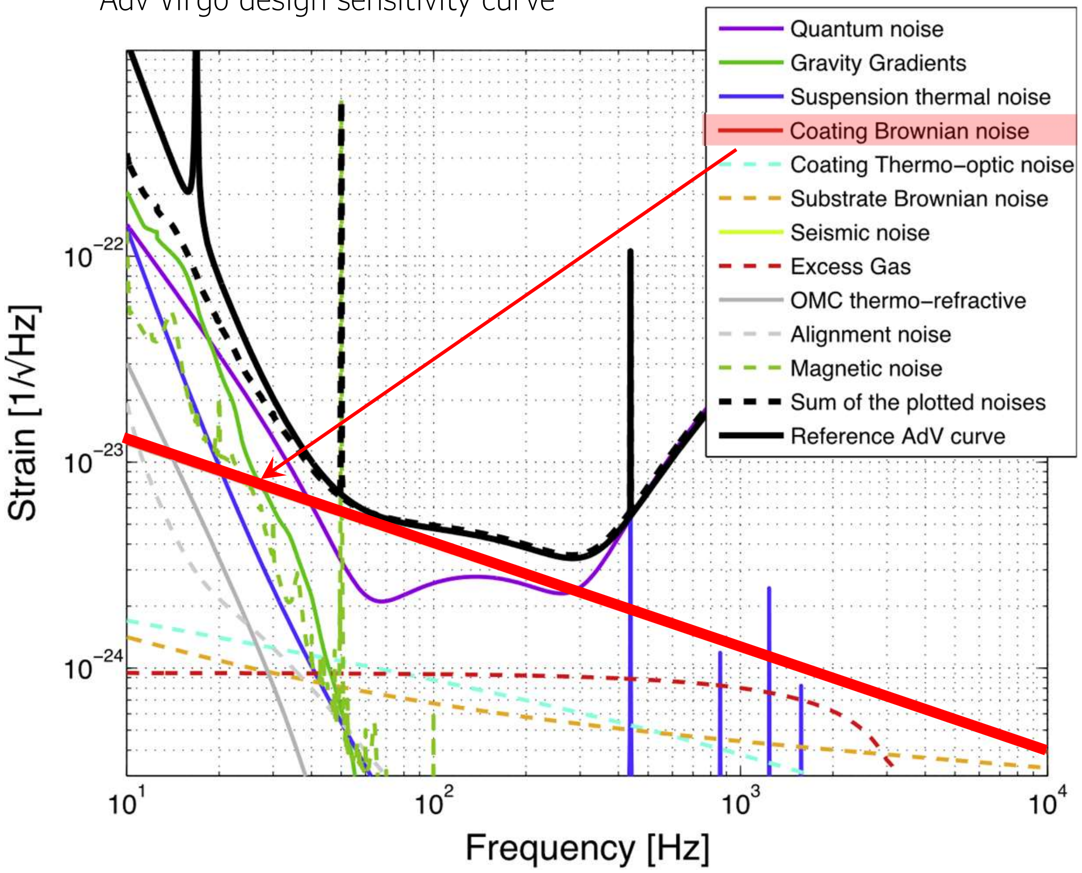
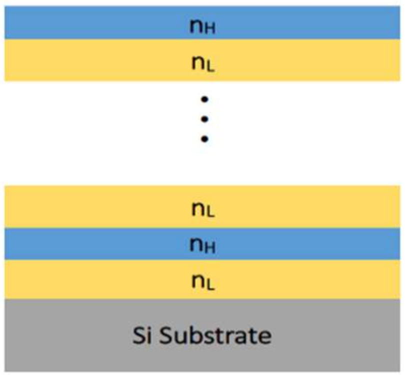


Coating Brownian noise power spectral density (PSD)

$$S_{\mathrm{CB}j} = \frac{2k_B T \phi'_j d_j}{\pi^2 w_m^2 f}\left[\frac{(1+\sigma'_j)(1-2\sigma'_j)}{Y'_j(1-\sigma'_j)} + \frac{Y'_j(1+\sigma)^2(1-2\sigma)^2}{Y^2(1-\sigma_j'^2)}\right]$$

QW HR stack



$\Phi_{substrate} \approx 10^{-8}$
$\Phi_{SiO_2} = 2{,}3\,.\,10^{-5}$
$\Phi_{Ti:Ta_2O_5} = 2{,}4\,.\,10^{-4}$
$\Phi_{coating} = 2{,}3\,.\,10^{-4}$

(at 300 K)

Acernese & al, *Class. Quantum Grav.* 32 (2015) *024001*
Class.Quant.Grav. 19 (2002) 897-918

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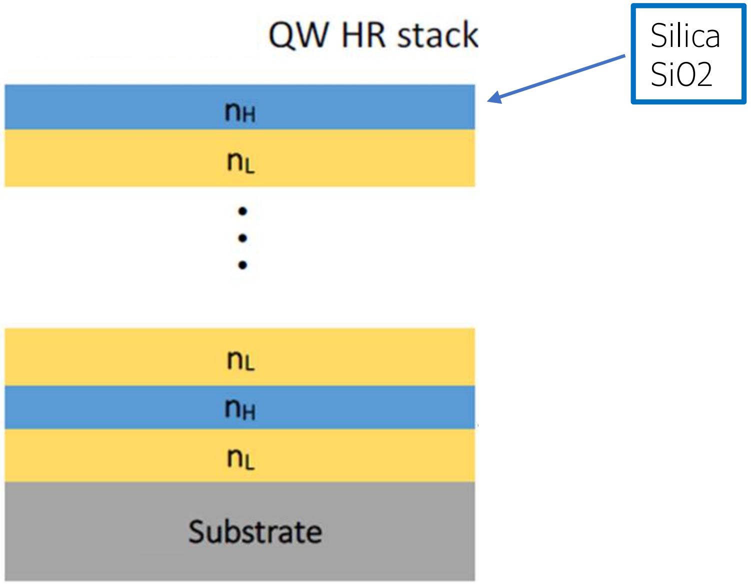
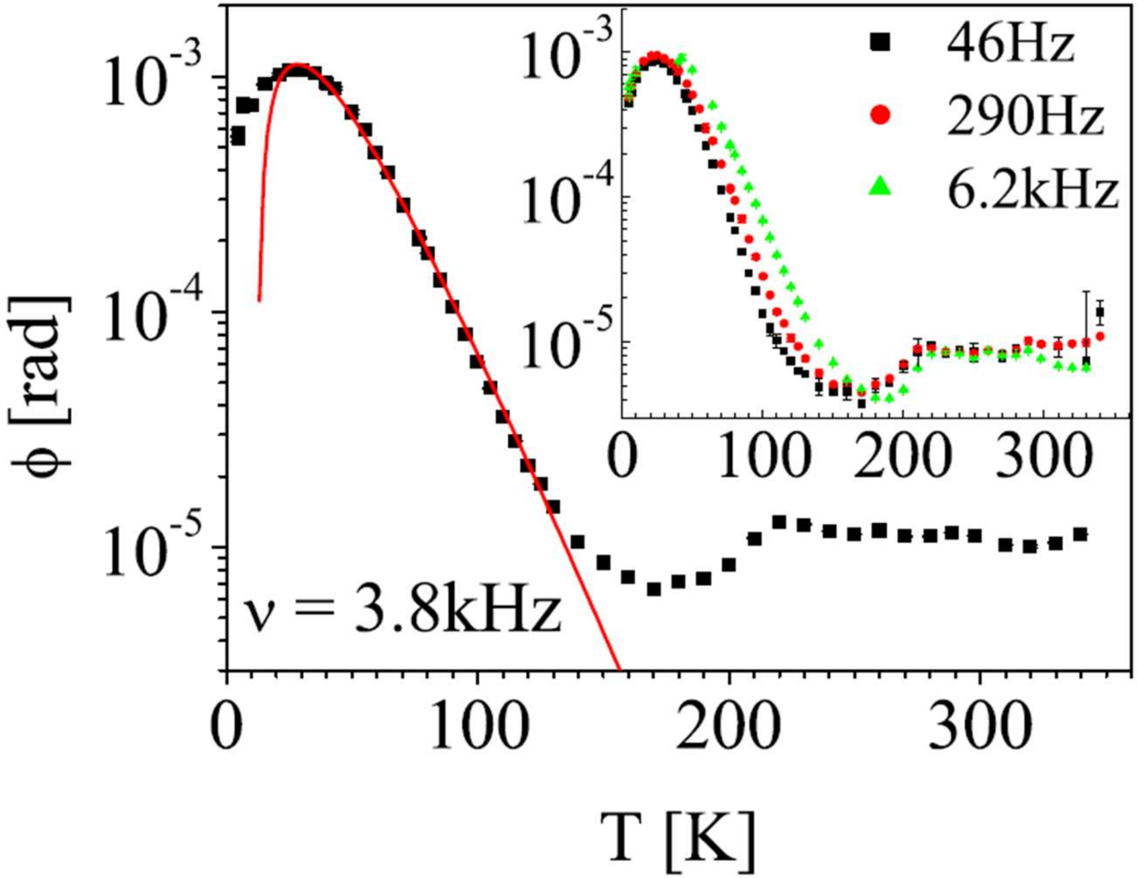
Cryocooling the mirrors is not trivial

The best found optical coating materials for room temperature operation unfortunately display a low temperature peak (cryopeak) in their loss angle





EPL, 80 (2007) 50008

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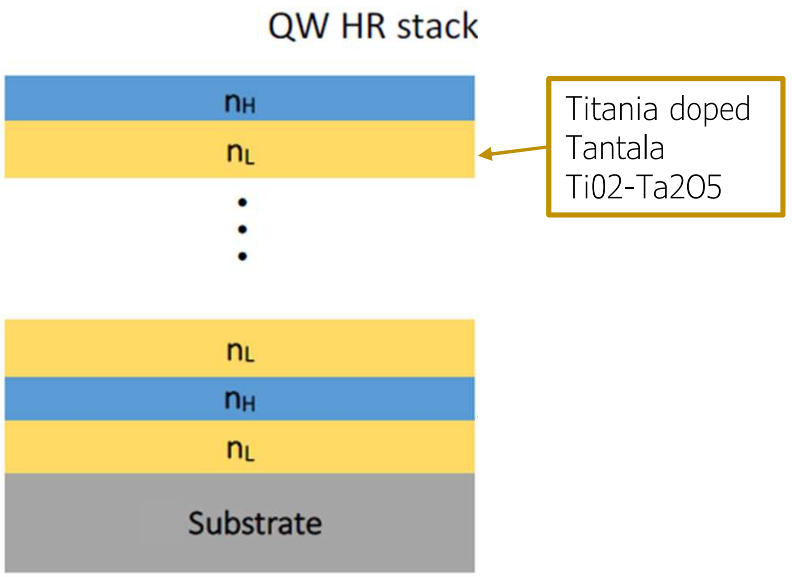
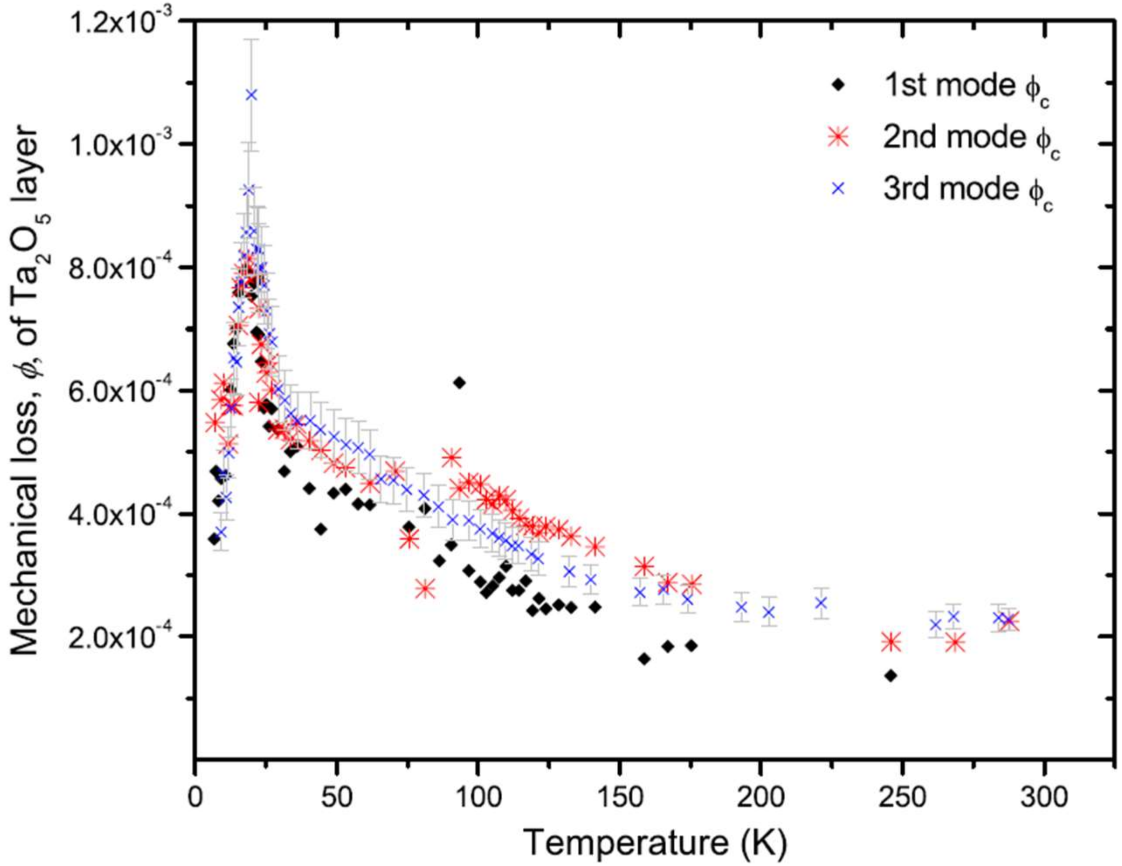


Titania doped Tantala Ti02-Ta2O5



Class. Quantum Grav. 25 (2008) 055005

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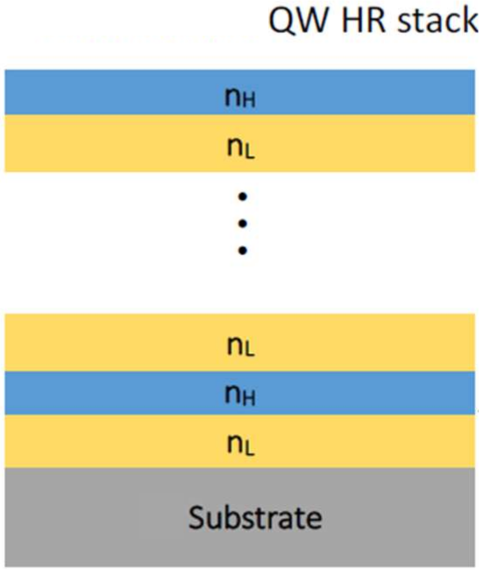
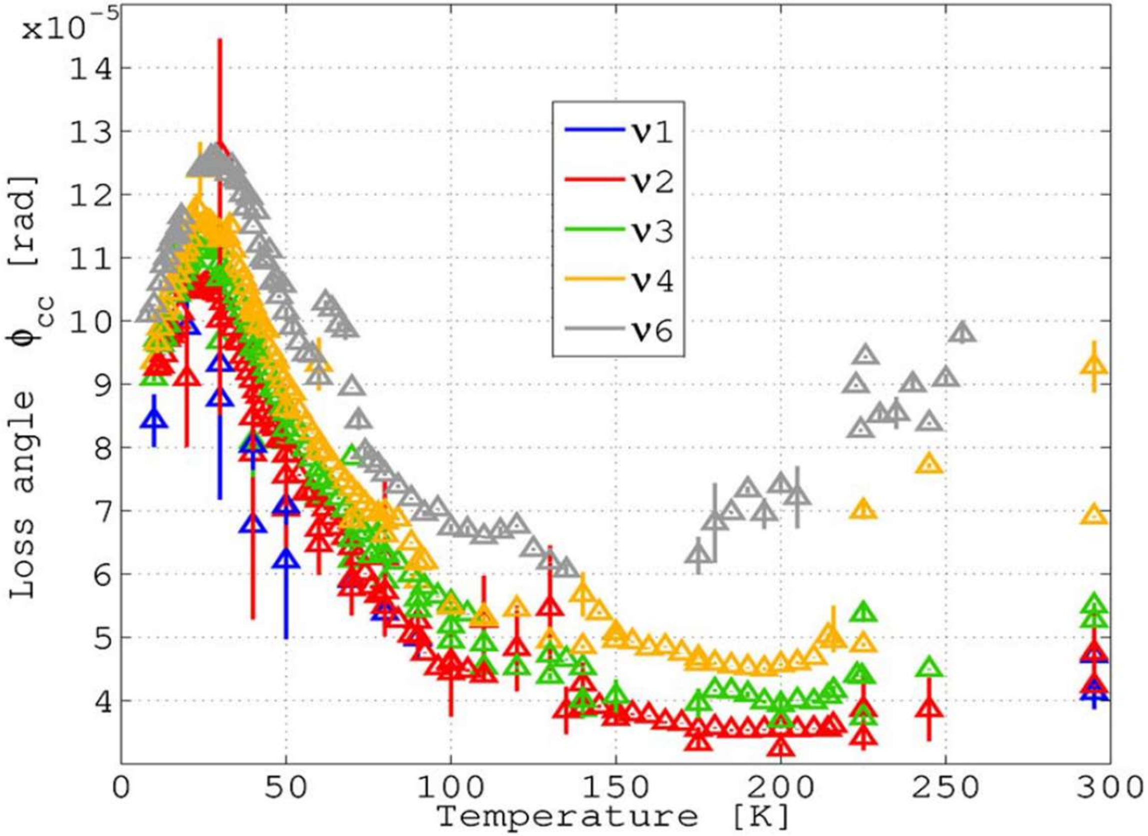


LIGO multilayer (optimized)



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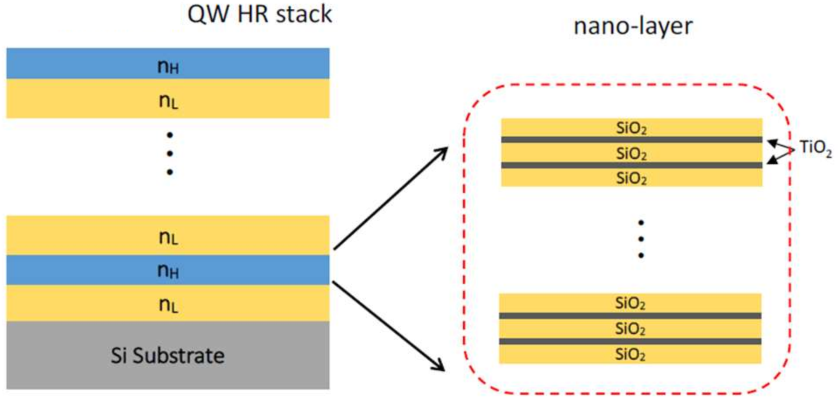
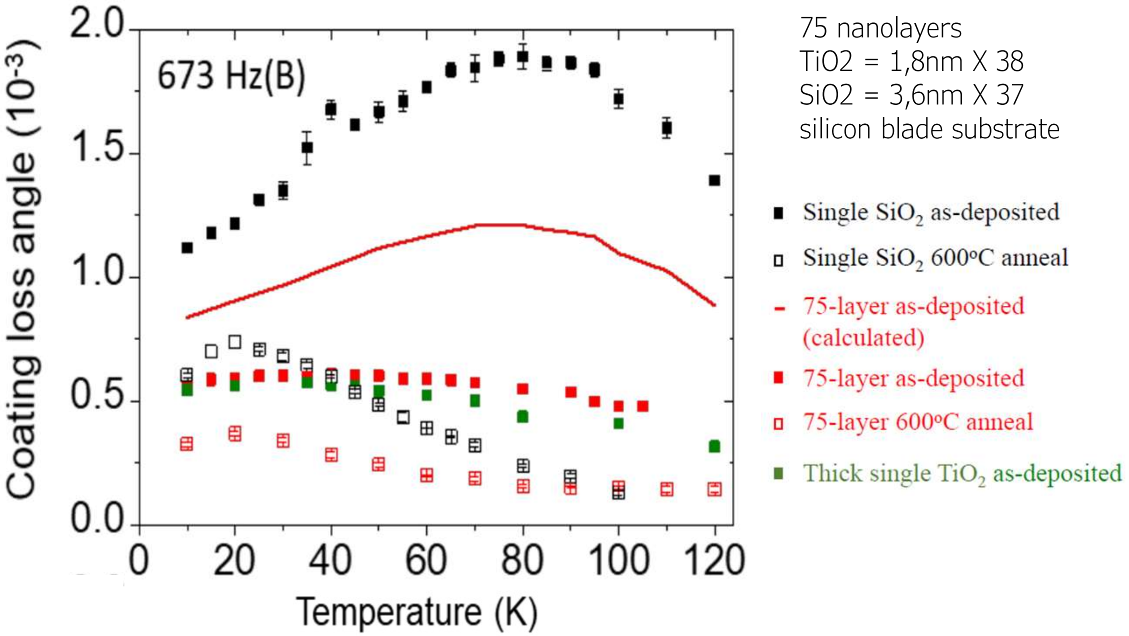
Nanolayering

The idea: replace the conventional quarter wavelength (QW) layer in a Bragg High Reflectivity (HR) stack by a nanolayered sub-stack
Wide-range tuning of the effective refractive index and the effective Young's modulus
Two importants low-thickness effect observed on silica/titania nanolayered stacks:

- titania can be annealed to higher temperatures without crystallization
- the loss angle cryopeak of silica is strongly suppressed



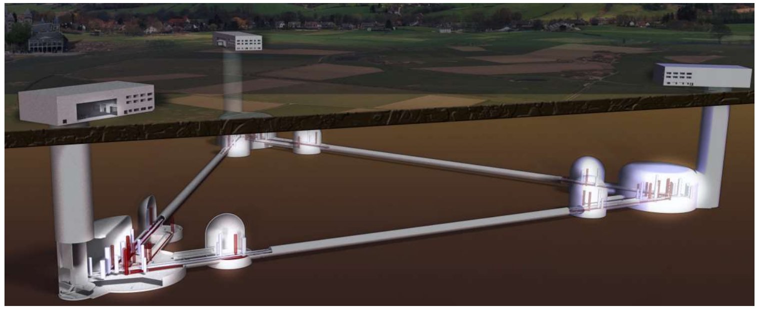


75 nanolayers
TiO2 = 1,8nm X 38
SiO2 = 3,6nm X 37
silicon blade substrate

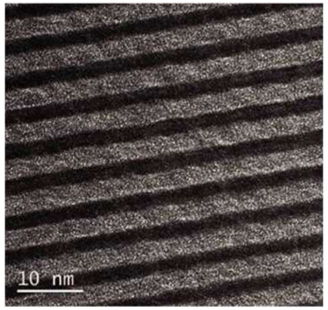
LIGO-G1900356-V3
LIGO-P1900090

We need a new measurement paradigm

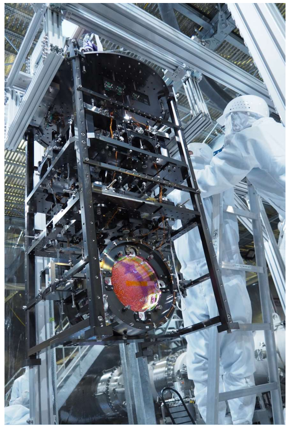
In summary, nanolayering appears as a very promising technology for room temperature and cryogenic gravitational wave detector, like the ET project or KAGRA.



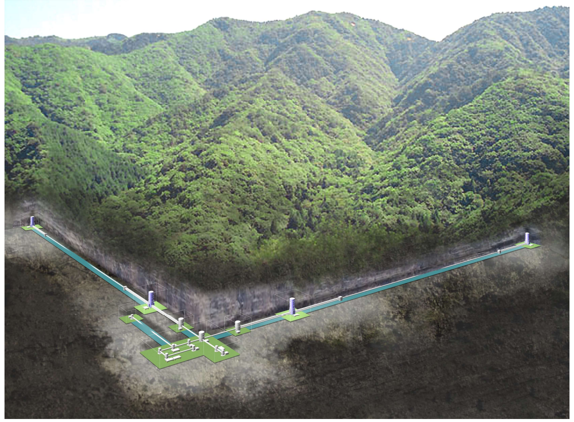
The Einstein Telescope (ET) project



TEM of the SiO2-TiO2 nanolayers



One of Kagra Saphire mirror
in a cryogenic suspension



Bird's eye view of the KAGRA GWD

But we still need to better understand nanolayering:

- as an exemple it is not completely clear if the cryo loss peak suppression effect is also present in titania
- an hypothesis for the cryo peak suppression is the suppression of two-level systems (TLS) corresponding to atom chains longer than the film thickness. This hypothesis should be verified.
- we generally need more data, possibly with different materials

To do all of that, we need a loss angle measurement method that can resolve a single nanolayer

http://www.et-gw.eu/
https://gwcenter.icrr.u-tokyo.ac.jp/en/kagra-gallery

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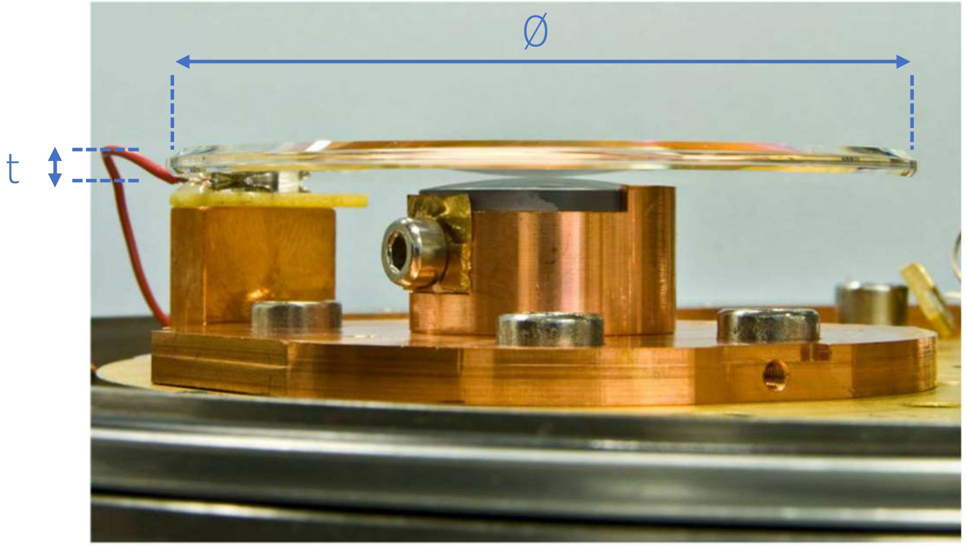
Measuring coating loss angle: think about the substrate first

In coating research, the substrate is a part of your instrument.



A GeNS system, where a silica wafer is suspended on a silicon lens.

In **GeNS** (Gentle Nodal Suspension), the substrate is a thin disc or wafer suspended on a point-like contact.

The disc is typically Ø = 76 mm and t = 0,5 mm to 1 mm

The mechanical dissipation is obtained from a ring-down experiment.

This is the most common loss angle measurement method in the GWD community. Low spurious losses from the suspension means good reproducibility.

However, this same suspension makes it hard to do cryogenic measurements, because it make the sample cooling and temperature monitoring difficult. Also, they are still open metrological issues with this concept (temperature, edge, curvature, thermoelastic...).

Review of Scientific Instruments 80, 053904 (2009)
GWADW2021 talk by F. Piergiovanni

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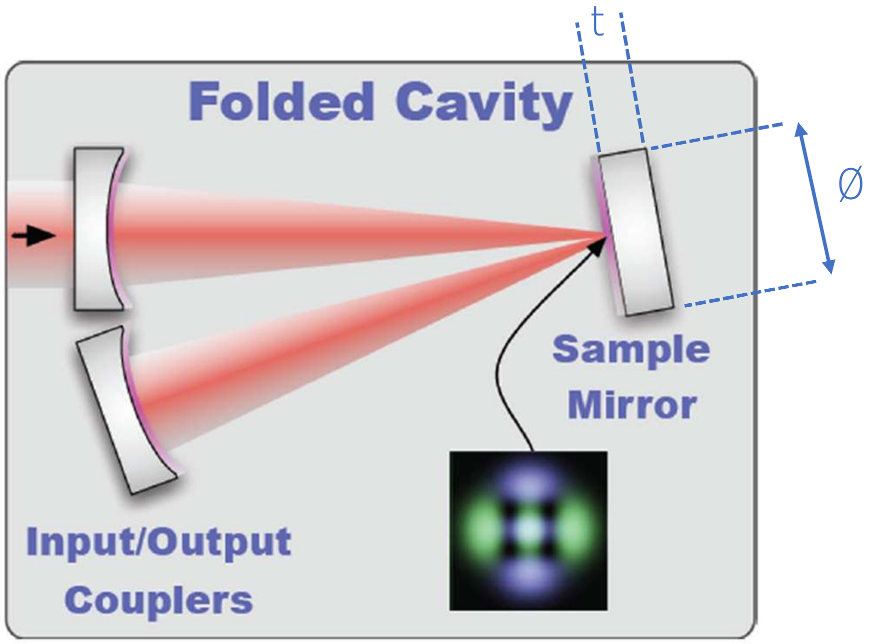

The folded Fabry-Pérot cavity of the MIT TNI

In the MIT TNI (Coating Thermal Noise Interferometer) the substrate is the typical witness sample used during coating deposition.

This typically consist in a thick disc with dimensions Ø =25 mm and t = 10 mm.

The sample thermal noise is measured directly by making it the end mirror of a folded Fabry-Pérot cavity

However the SNR strongly depends of the cavity finesse, which make the measurements possible only on high reflectivity coatings.

There are still discrepancies between ring-down measurement and thermal noise measurement.
We believe that direct thermal noise measurement is the way to go.

Physical Review D 95, 022001 (2017)

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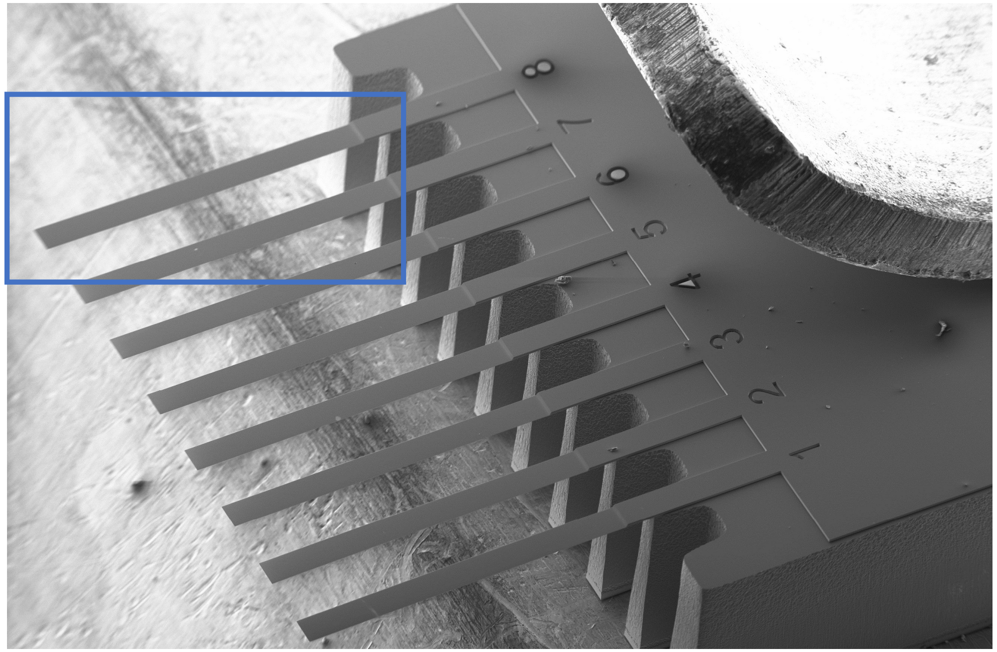


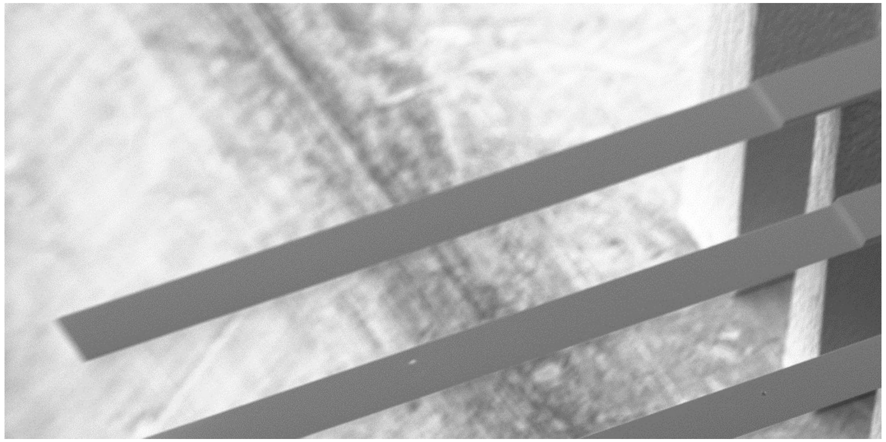
A typical µcantilever sample observed with a SEM.
These µcantilevers have a length of 1mm

In the **QPDI** concept, the substrate is a microcantilever.

A sample consists in a silicon chip where an array of µcantilevers are anchored (no clamping !). The entire sample is made from a single crystal of silicon.

Commercially available and well known. Coming from the field of micro/nanotechnology. Used as sensor/resonator in a variety of very high resolution experiments.

Cryo friendly = easy to cool down and to monitor temperature



http://www.micromotive.de/Octosensis_e.php

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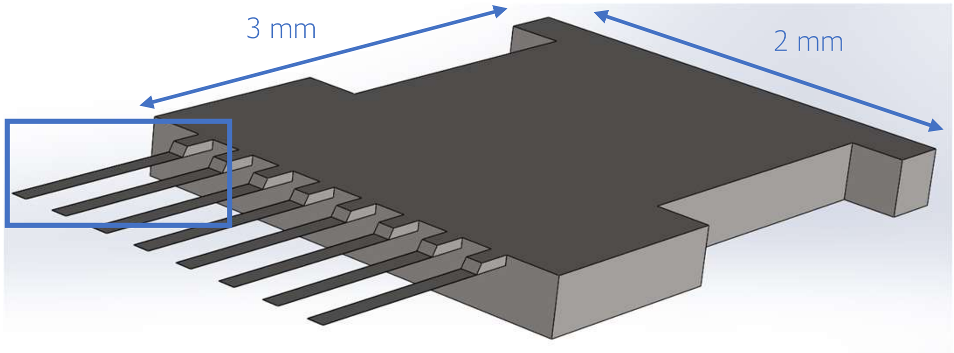
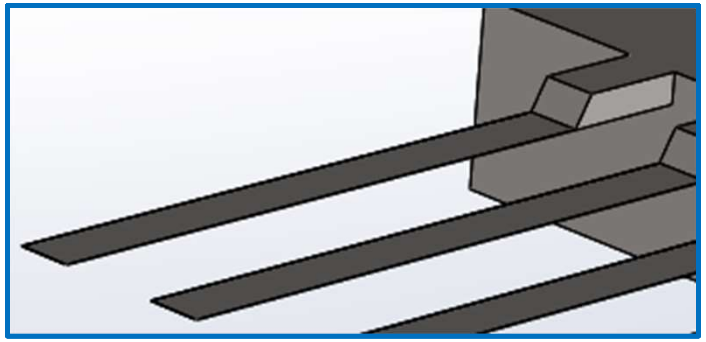


3D rendering of a μcantilever sample



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The typical dimensions of a μcantilever are:
- length 500 μm to 1000 μm
- width 90 μm
- thickness 1 μm to 5 μm (red blood cell thickness = 2μm)

This give them a very low stiffness, with two important consequences:
- They display a good amount of Brownian motion/thermal noise induced displacement. Direct thermal noise measurement is routinely performed.

$$\langle z^2 \rangle = \frac{k_b T}{K}$$ where K is the μcantilever stiffness

- For the same coating thickness, they display a substantially larger dilution factor.

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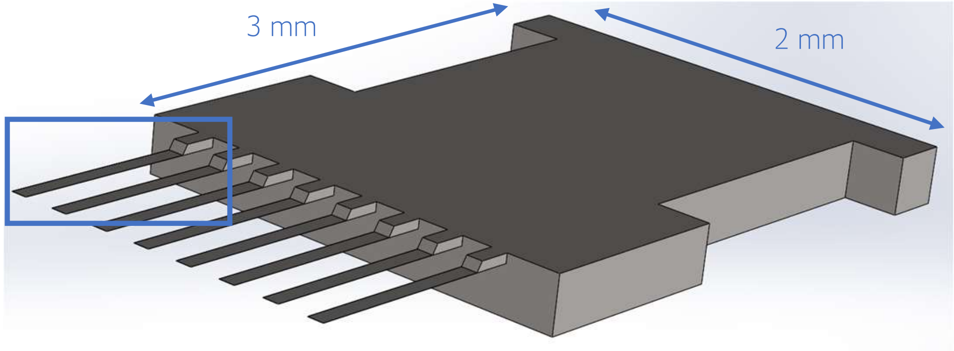

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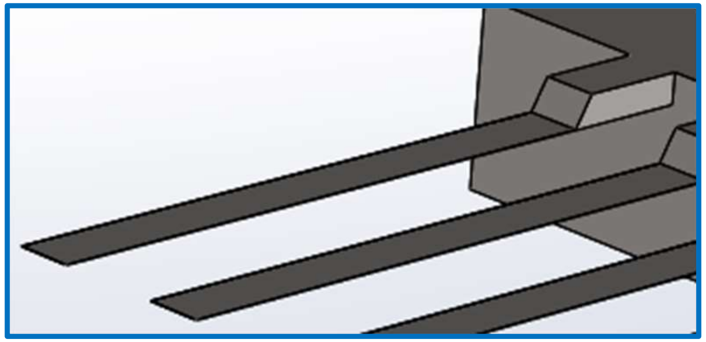

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Here $\sqrt{\langle z^2 \rangle}$ is typically 0,1 nm RMS. We need a high resolution displacement measurement system

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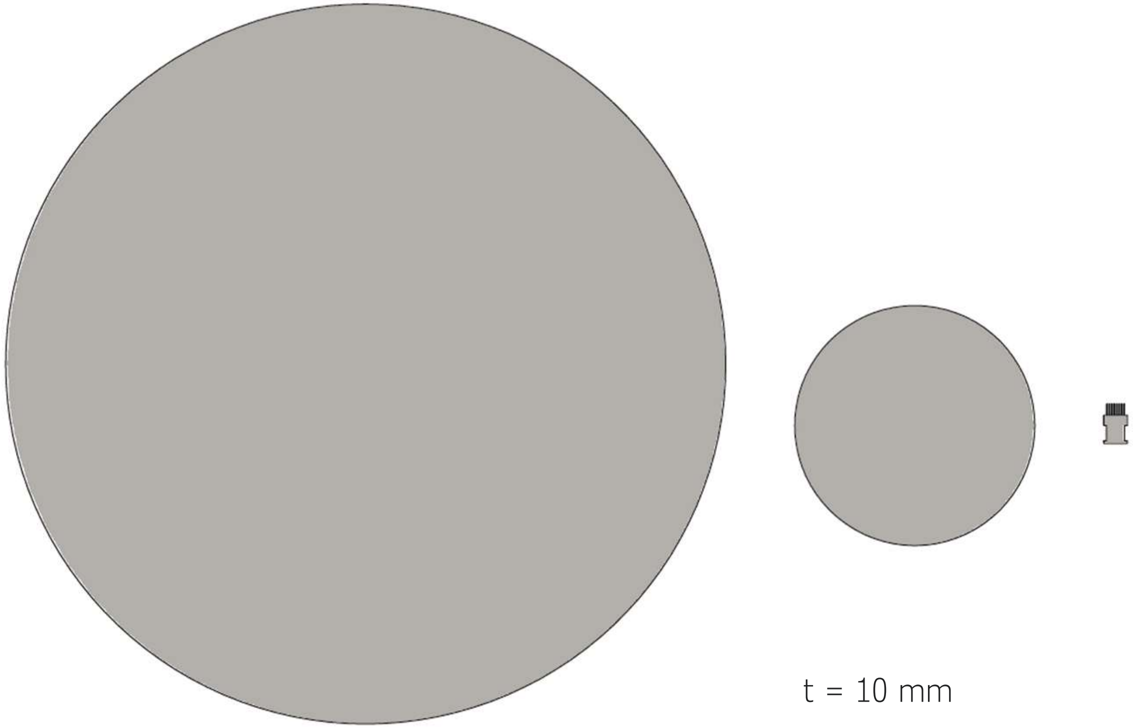
Substrate comparison



size comparison between a wafer, a witness and a µcantilever sample

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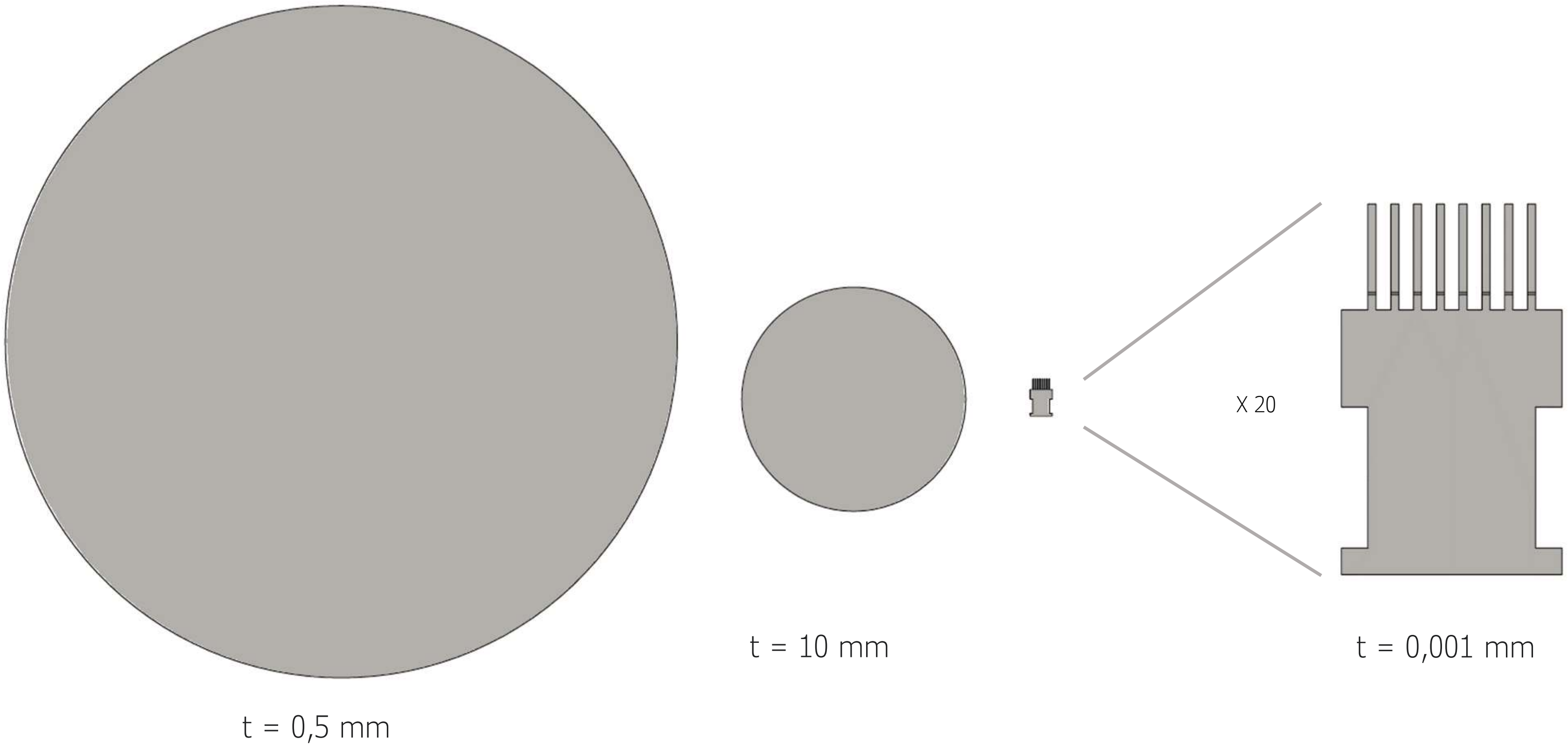

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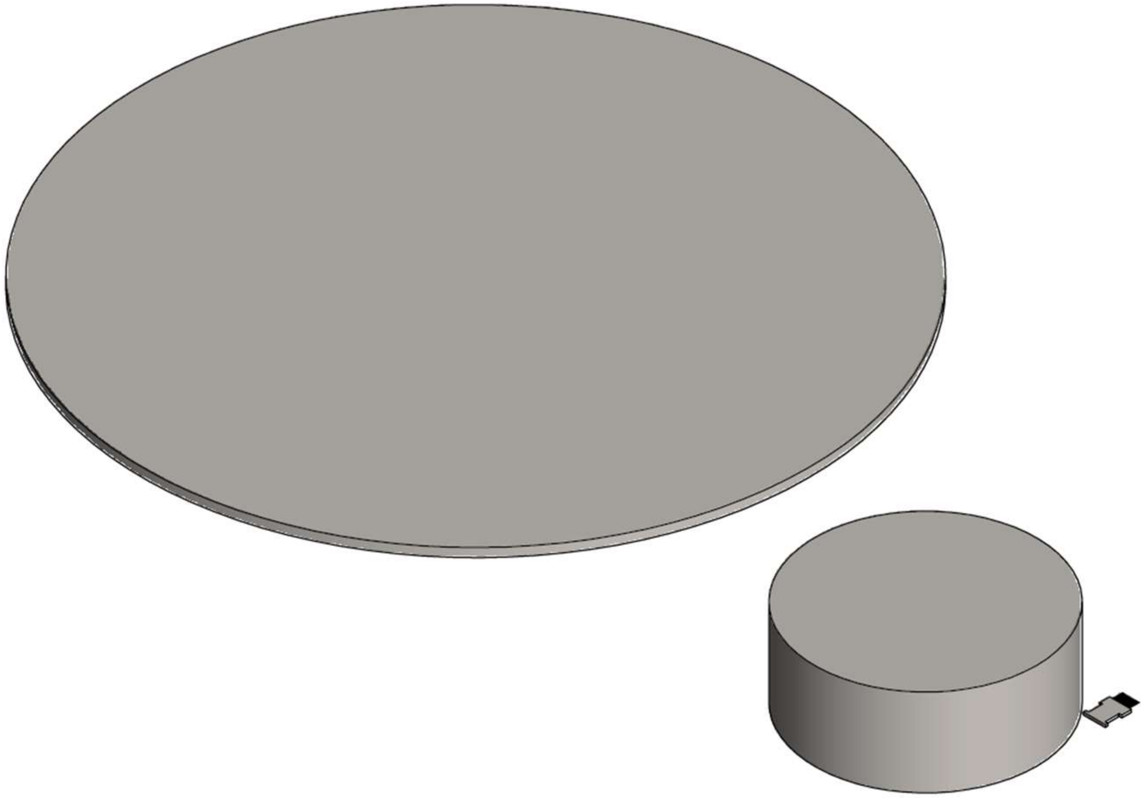

size comparison between a wafer, a witness and a µcantilever sample

Substrate comparison

For GeNS and the MIT TNI, the dilution factor values are only orders of magnitude. For µcantilevers the values are computed from Phys. Rev. D 89, 092004 using t=1µm, Ys=169Gpa (silicon 110) and Yc = 100GPa (~midpoint between Silica and Tantala).

	GeNS (wafer)	**MIT TNI (thick disc)**	**QPDI (µcantilevers)**
dilution factor for a single QW layer (thickness 150 nm)	0,01	< 0,01	0,23
dilution factor for a nanolayer thickness of 1 nm	0,0001?	0,0001?	0,002
direct thermal noise measurement	No	Yes	Yes
cryo friendly	No	?	Yes

Using µcantilevers, measuring the loss angle of a single nanolayer will be challenging, but doable. Using other method, it is reasonable to assume that a single nanolayer cannot be resolved.

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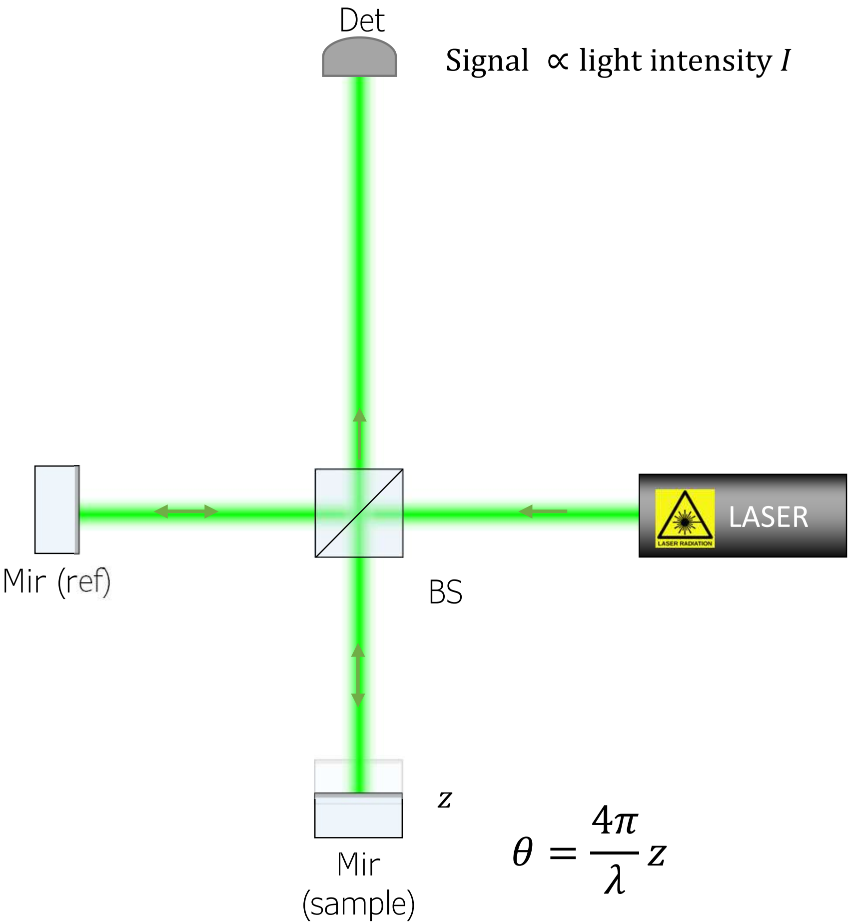
The Quadrature Phase Differential Interferometer QPDI

Start with a classic laser Michelson Interferometer: we have 4 unknows

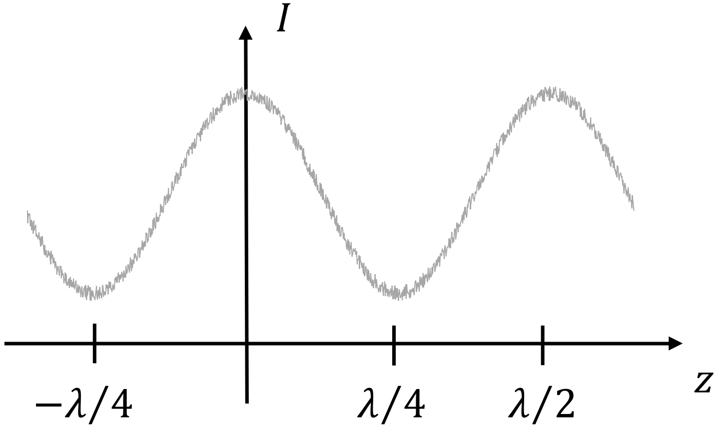


$$\theta = \frac{4\pi}{\lambda} z$$

real signal: $I = k(A + B\cos\theta)$

A and B amplitude, $B \leq A$
k laser intensity noise
z displacement
λ laser wavelength
θ spatial phase

nonlinear response
direction indetermination
laser noise



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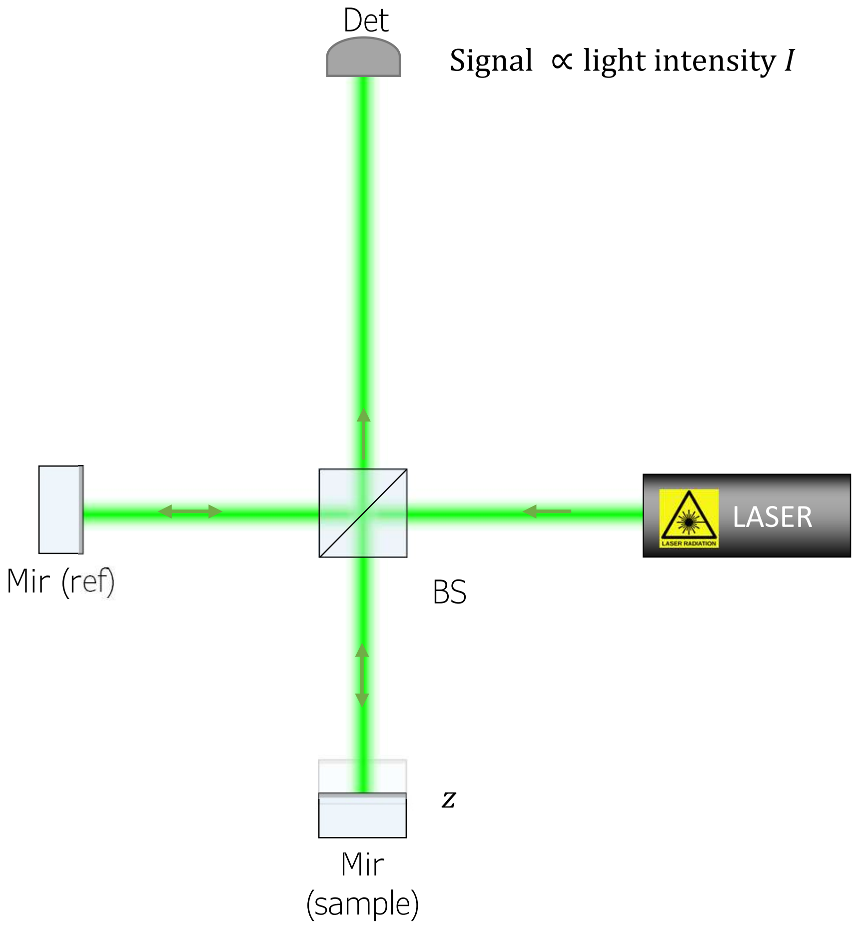
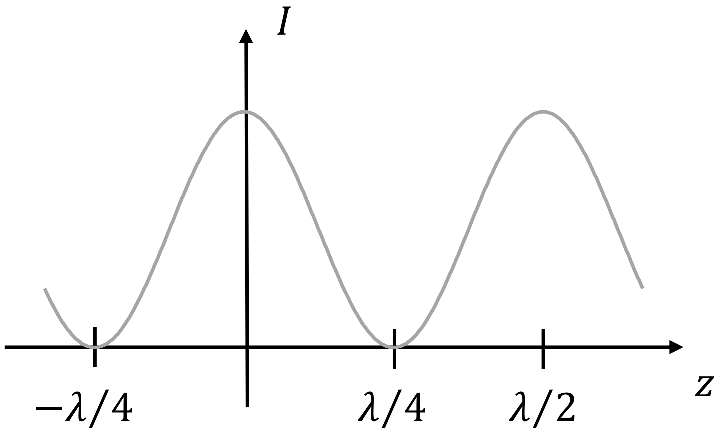


Signal $\propto$ light intensity I

ideal signal: $I \propto 1 + \cos\theta$



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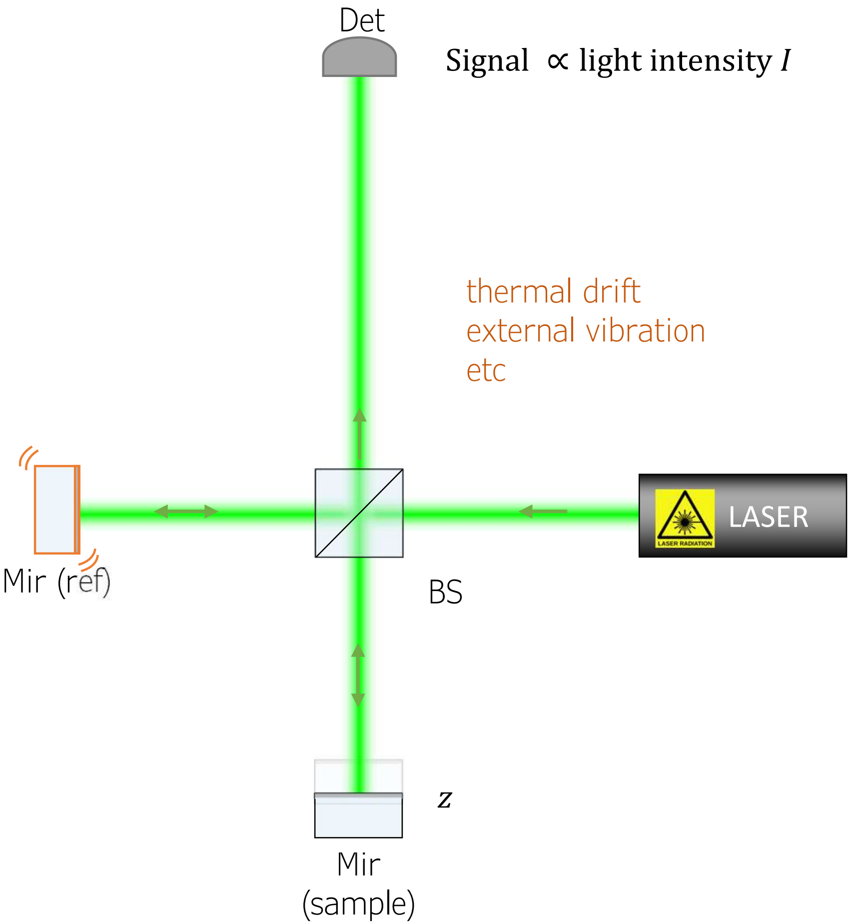
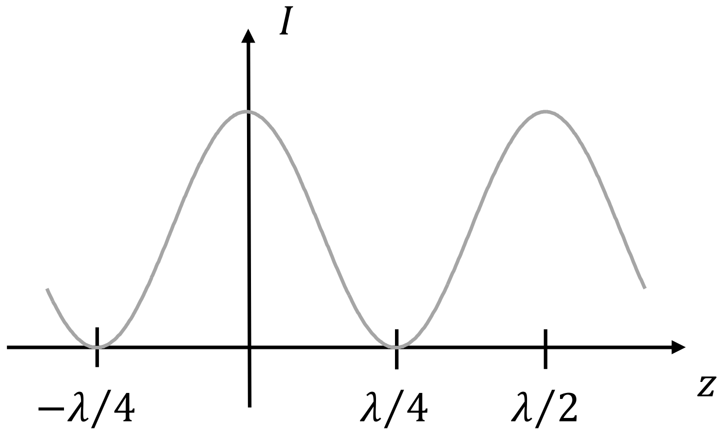


Signal $\propto$ light intensity I

thermal drift
external vibration
etc

ideal signal: $I \propto 1 + \cos\theta$



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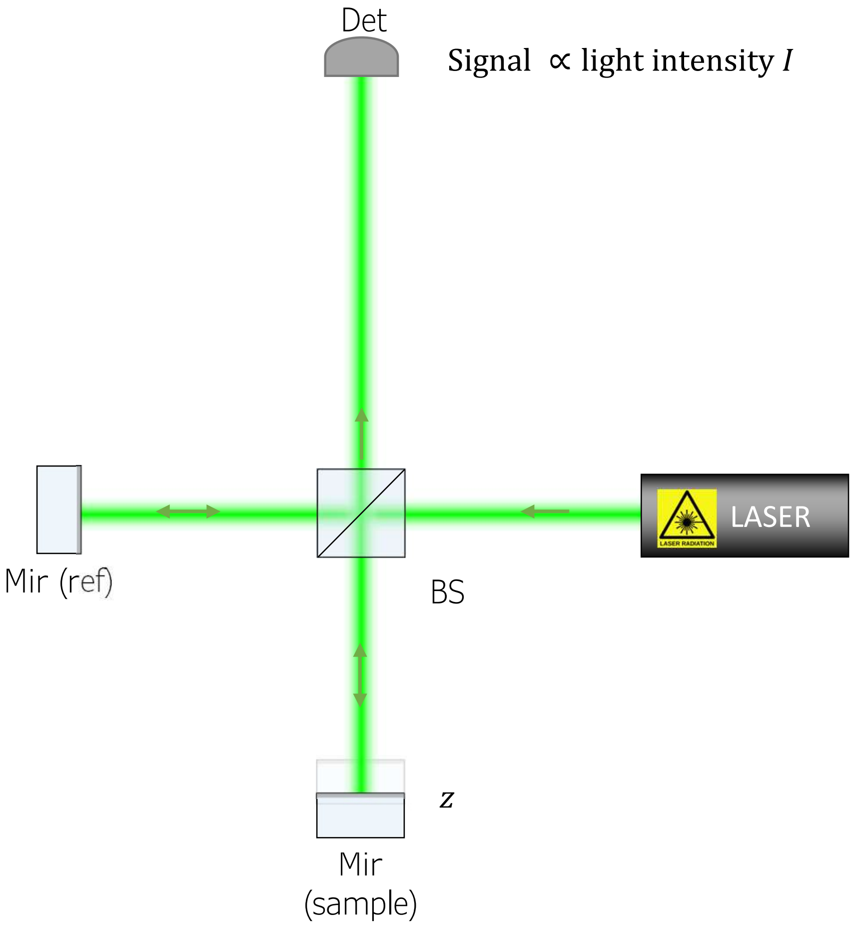

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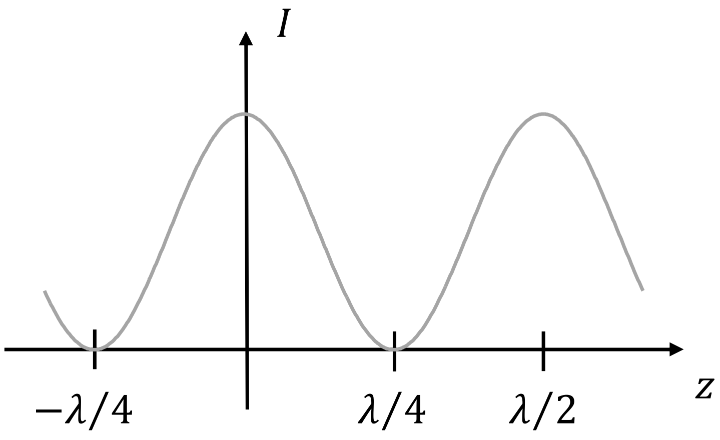

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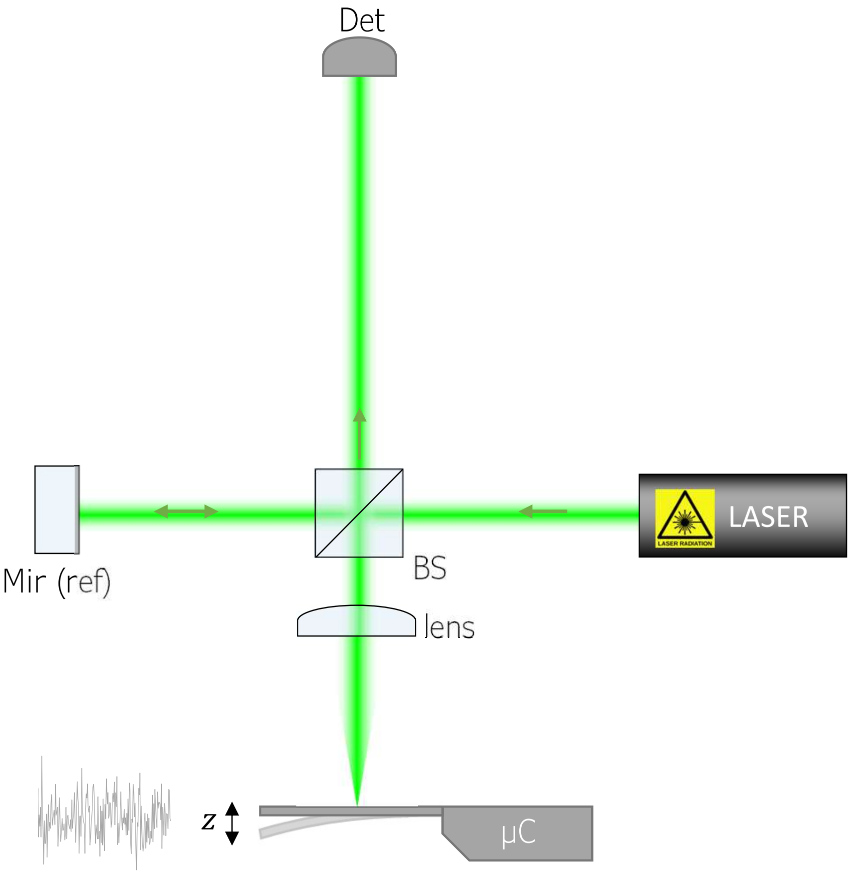

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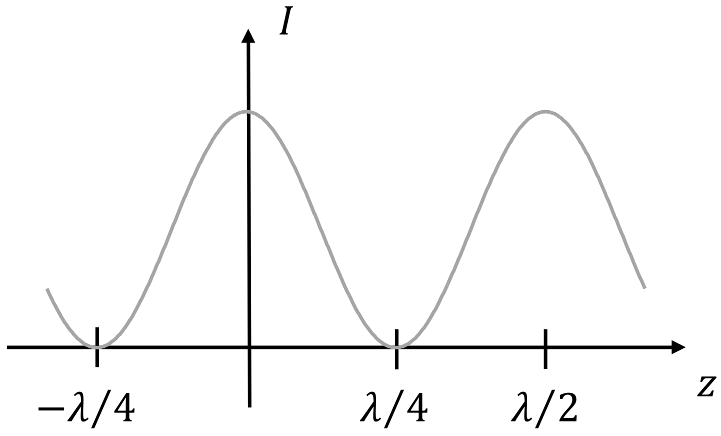

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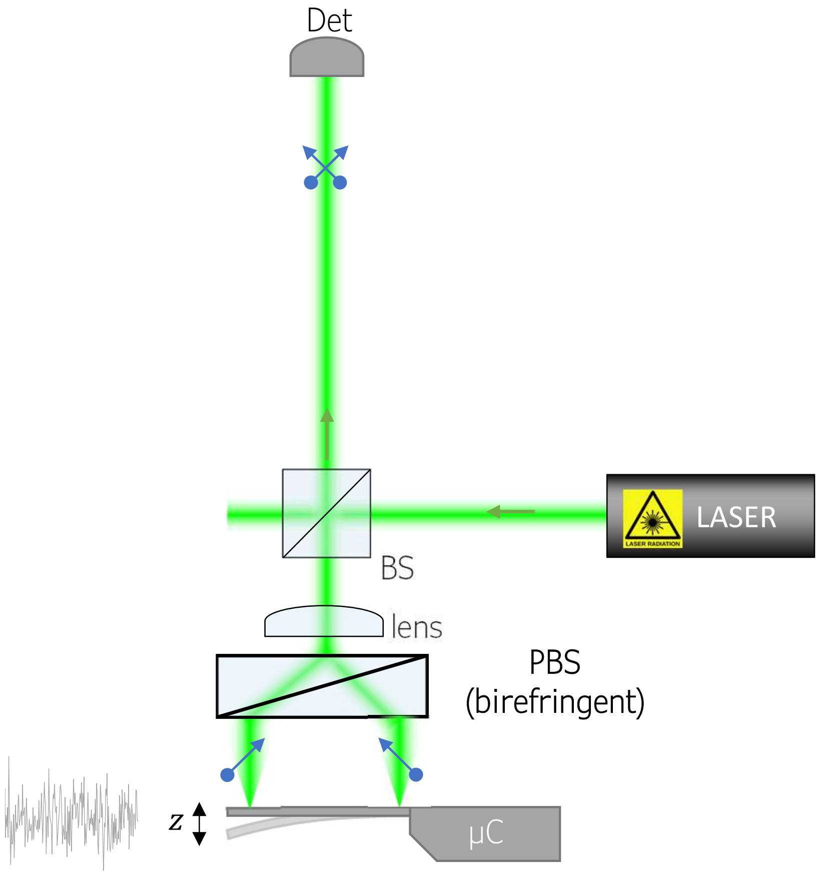

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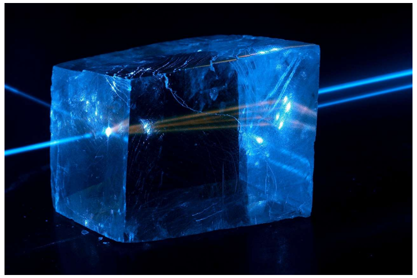

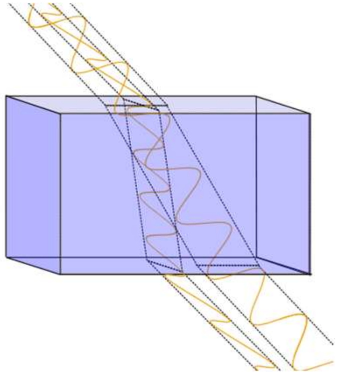

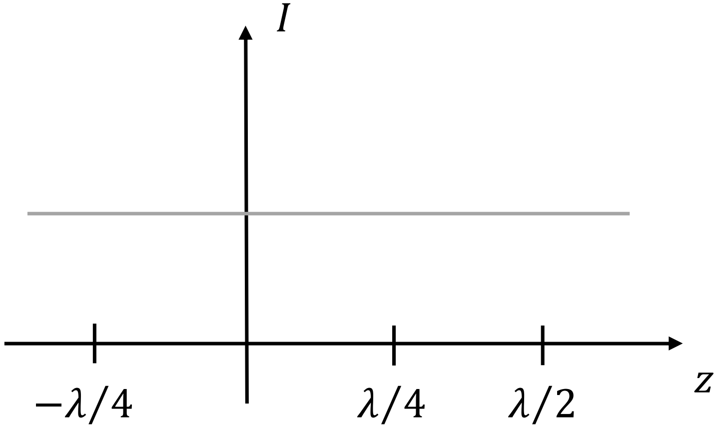

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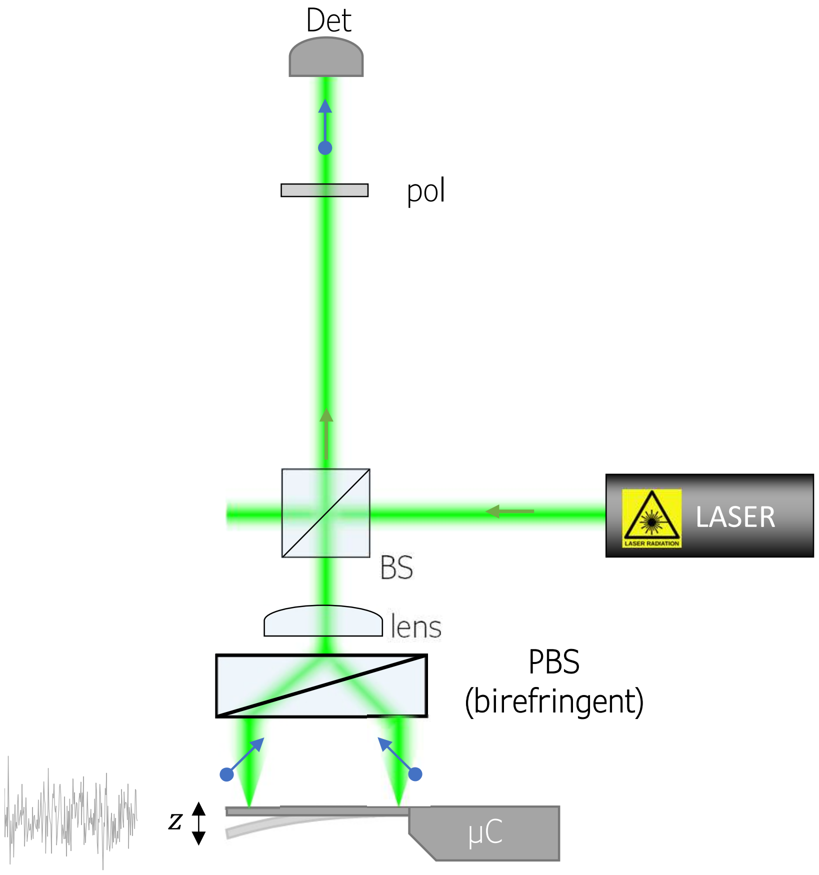

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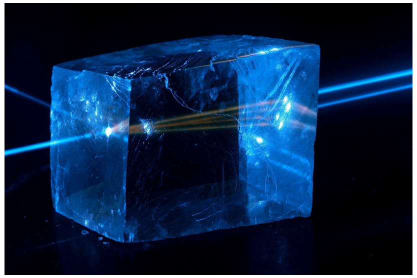

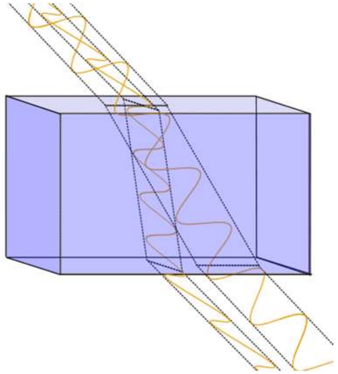

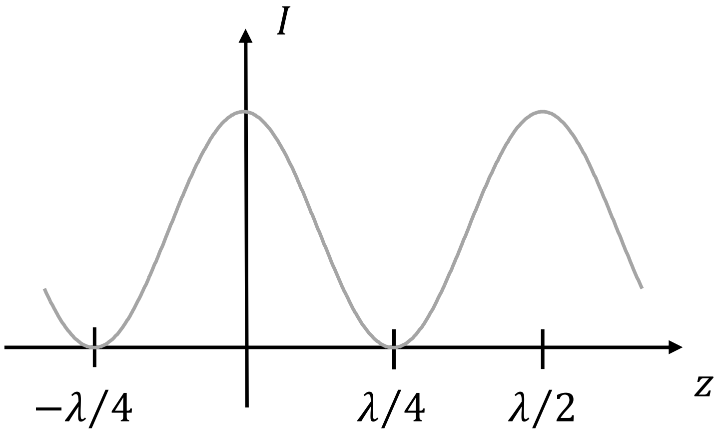

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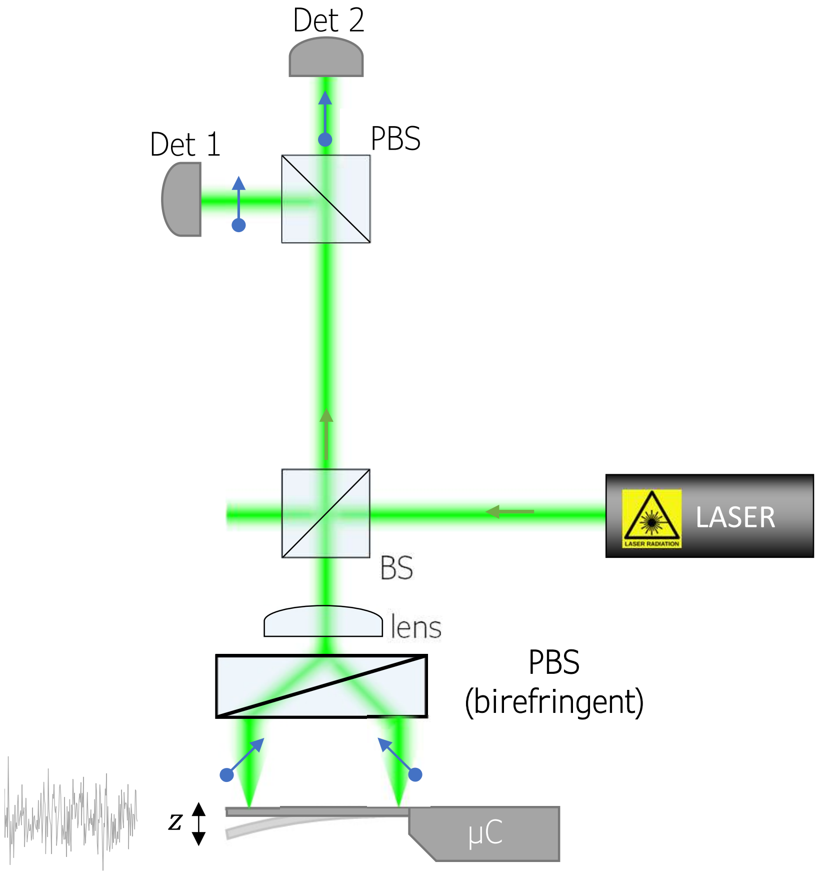
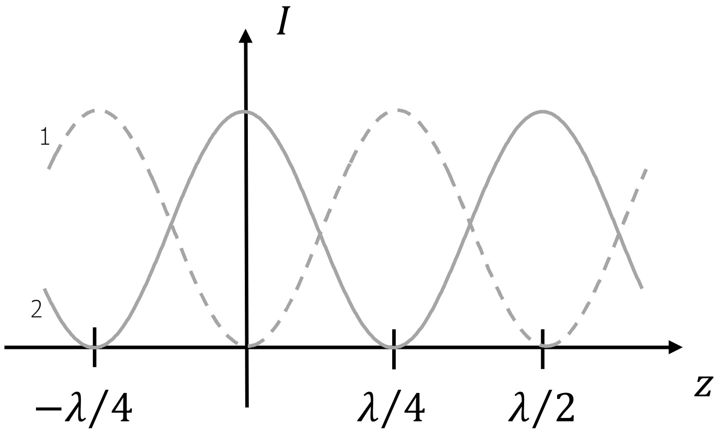
The Quadrature Phase Differential Interferometer QPDI

Start with a classic laser Michelson Interferometer: we have 4 unknows



ideal signal: $I_1 \propto 1 + \cos\theta$

$I_2 \propto 1 - \cos\theta$



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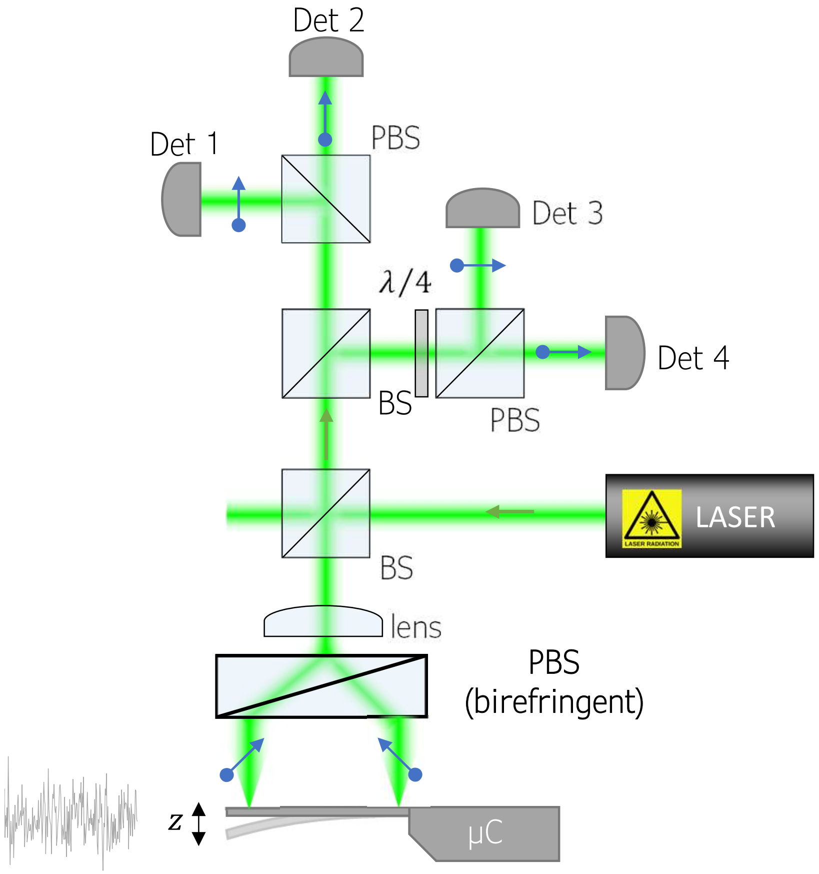


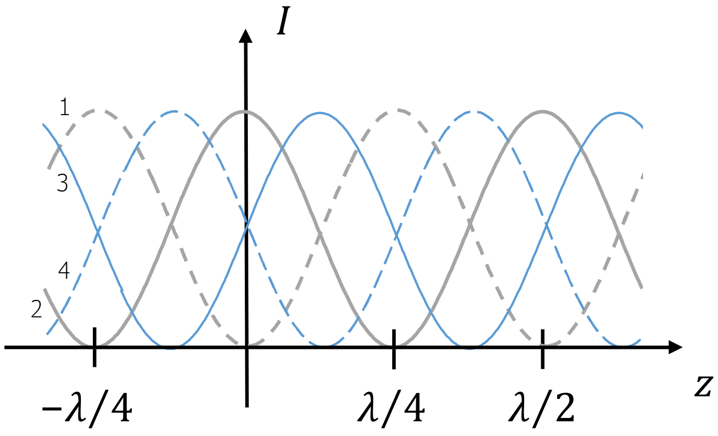
ideal signal: $I_1 \propto 1 + \cos\theta$

$$I_2 \propto 1 - \cos\theta$$

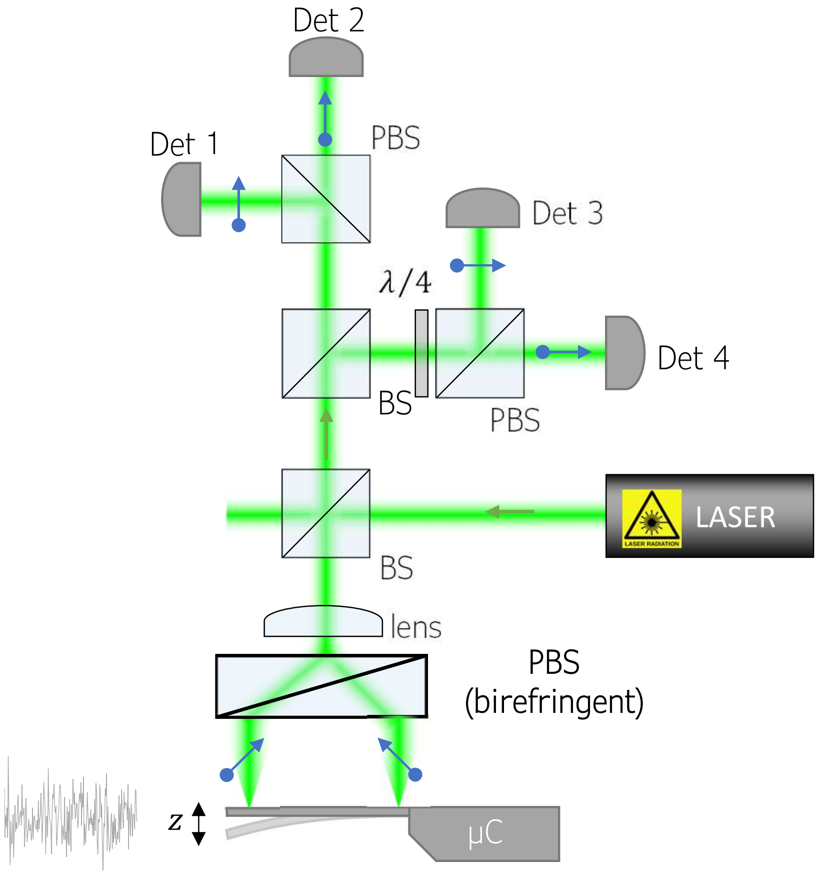
$$I_3 \propto 1 + \sin\theta$$

$$I_4 \propto 1 - \sin\theta$$

Using polarization interference
we create 4 signals in quadrature



The Quadrature Phase Differential Interferometer QPDI



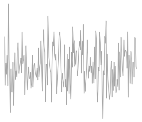
ideal signal:

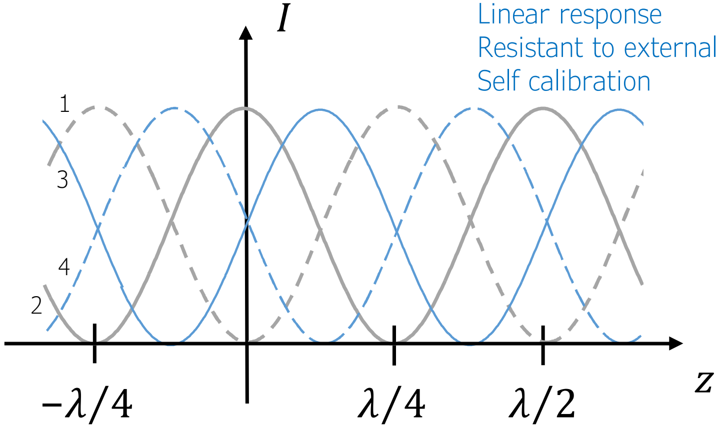
$$C_x = \frac{I_1 - I_2}{I_1 + I_2} = \cos\theta$$

(eliminate k laser intensity noise)

$$C_y = \frac{I_3 - I_2}{I_3 + I_2} = \sin\theta$$

$$\theta = \tan^{-1}\frac{C_y}{C_x} \qquad z = \frac{\lambda}{4\pi}\theta \Rightarrow$$





Linear response
Resistant to external disturbance
Self calibration

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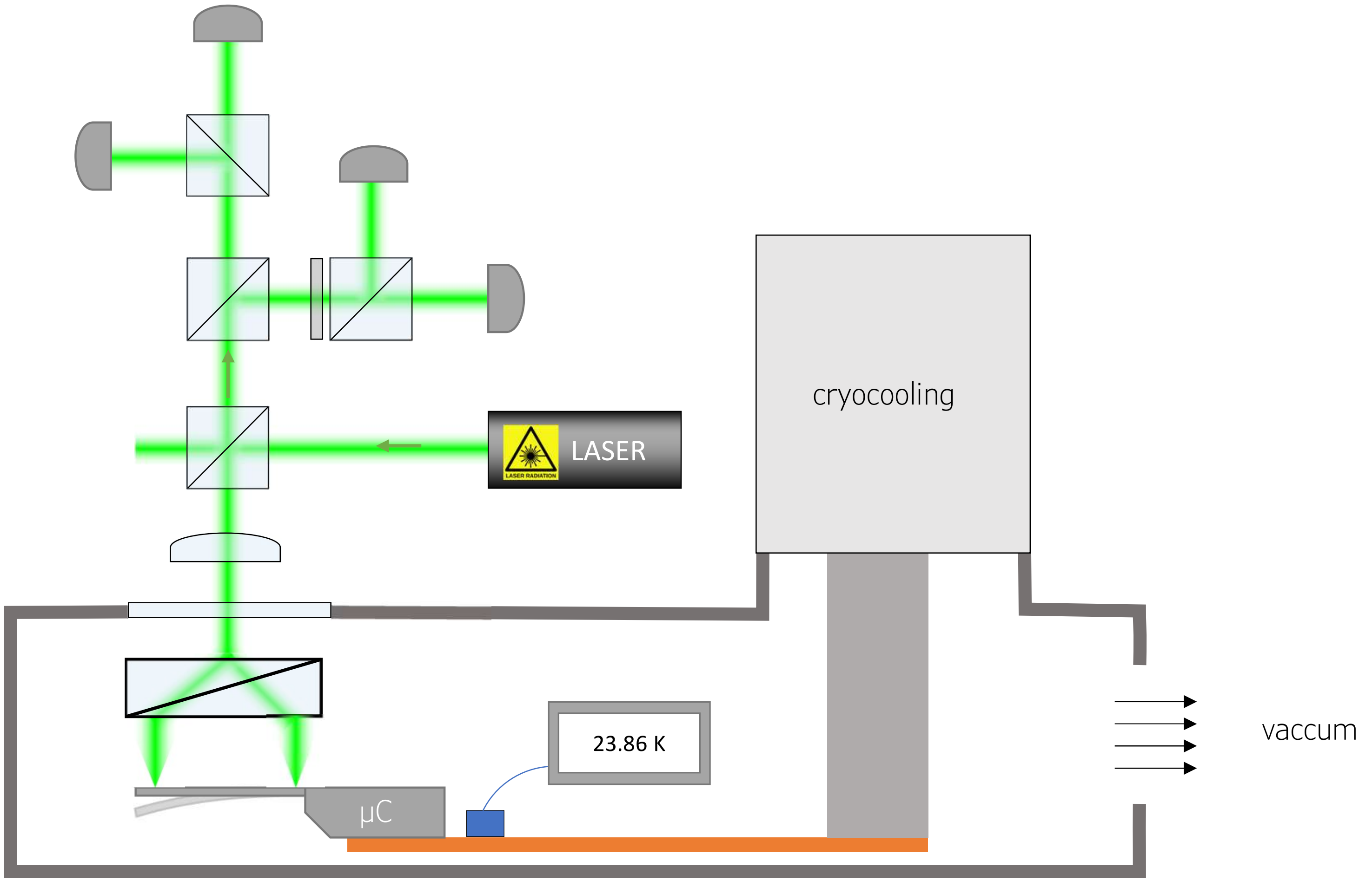
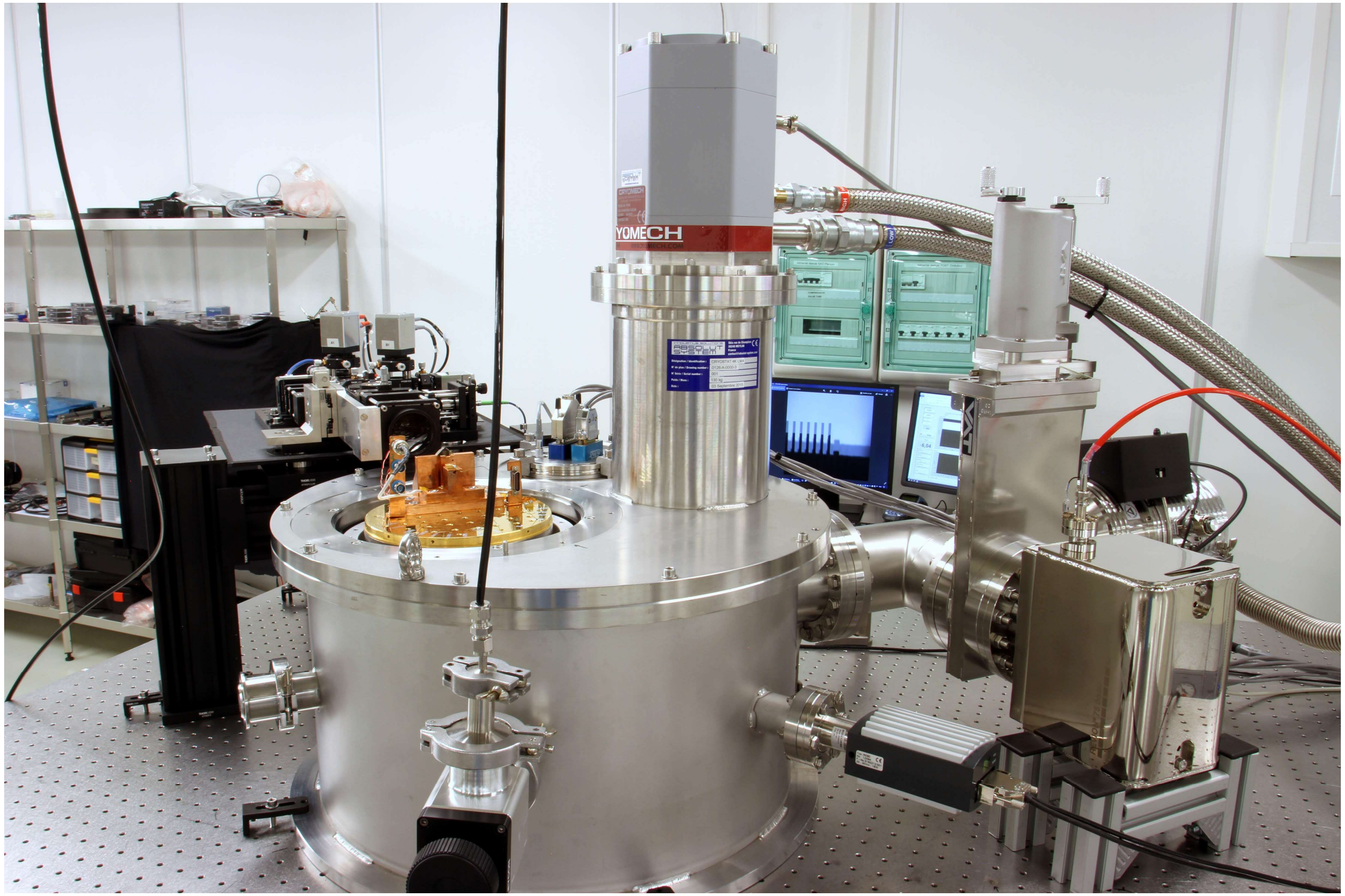
The Quadrature Phase Differential Interferometer QPDI

Start with a classic laser Michelson Interferometer: we have 4 unknows



The CryoQPDI at LMA



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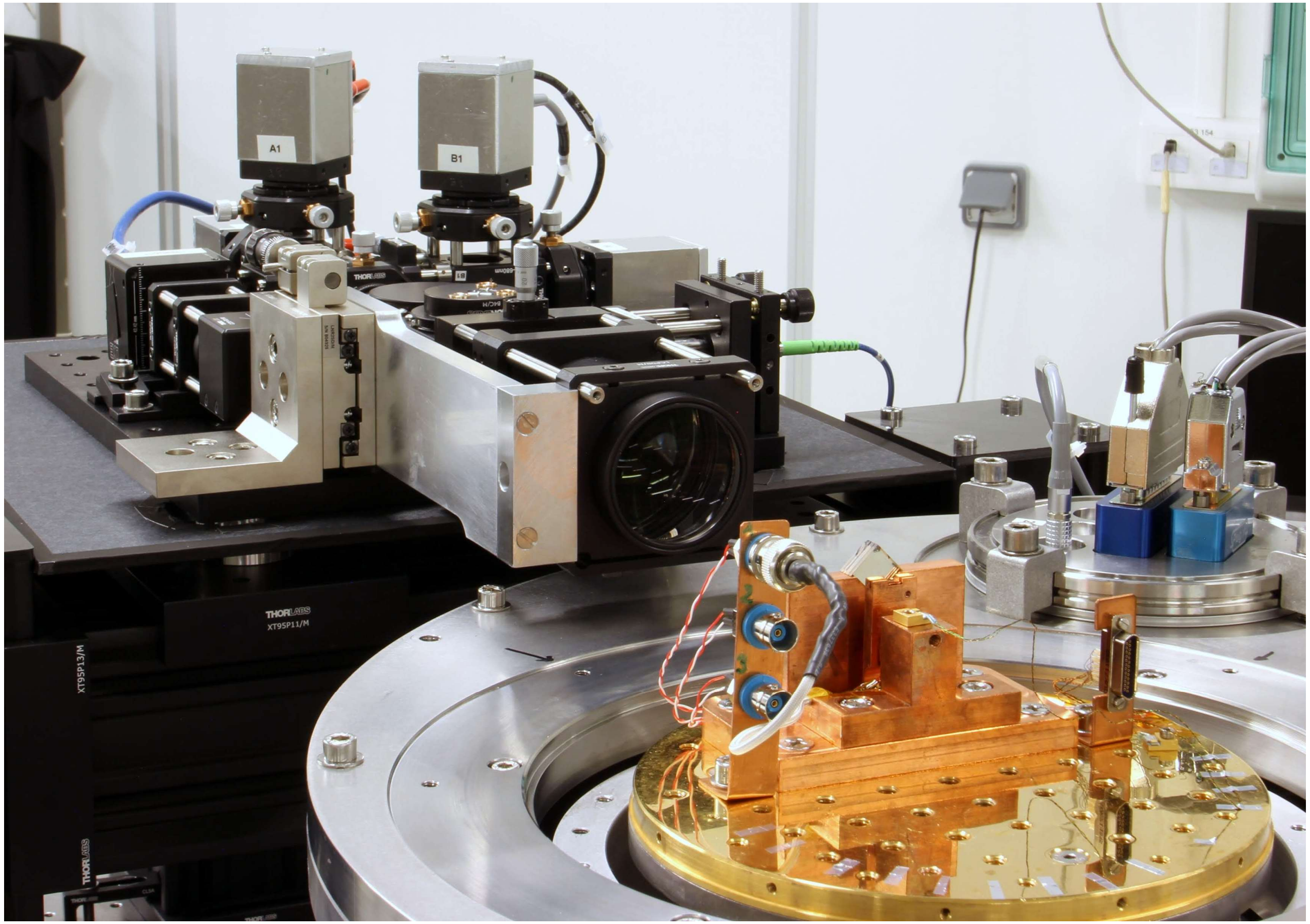
The CryoQPDI at LMA



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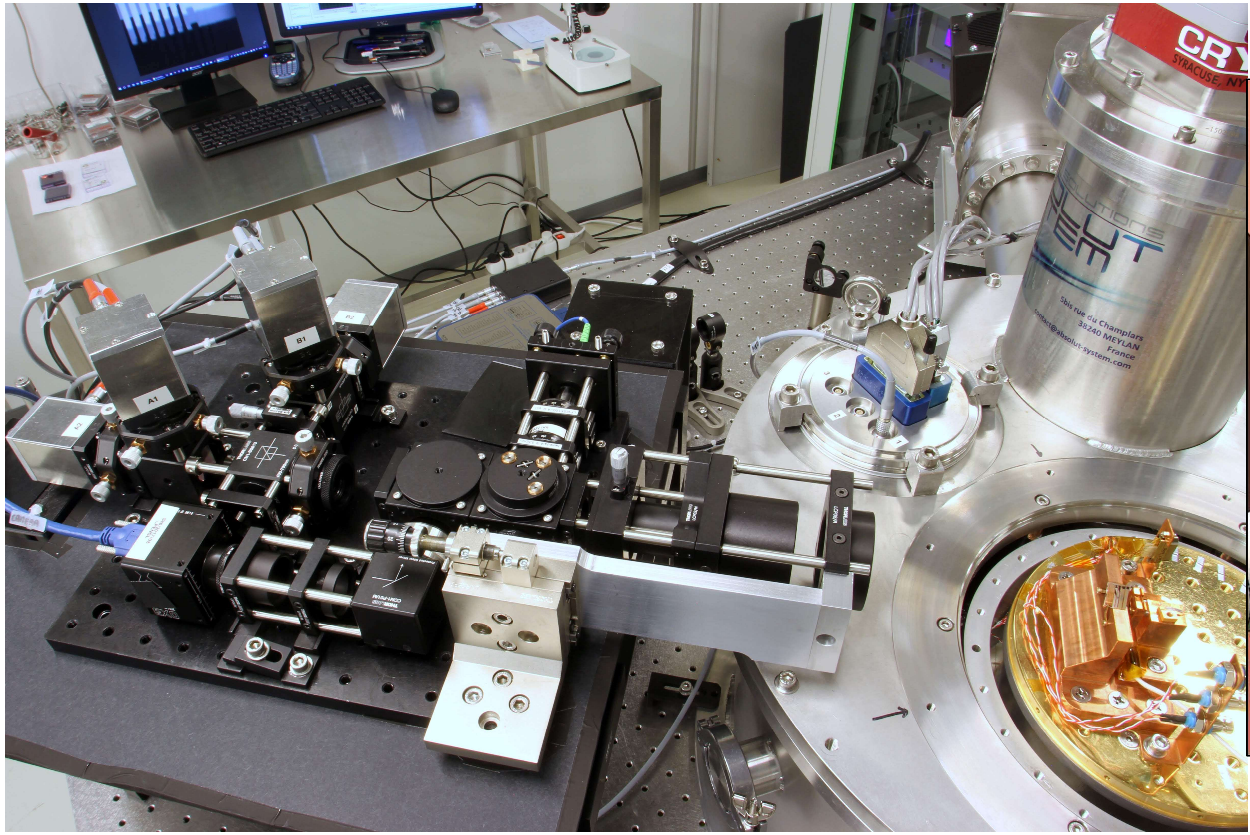
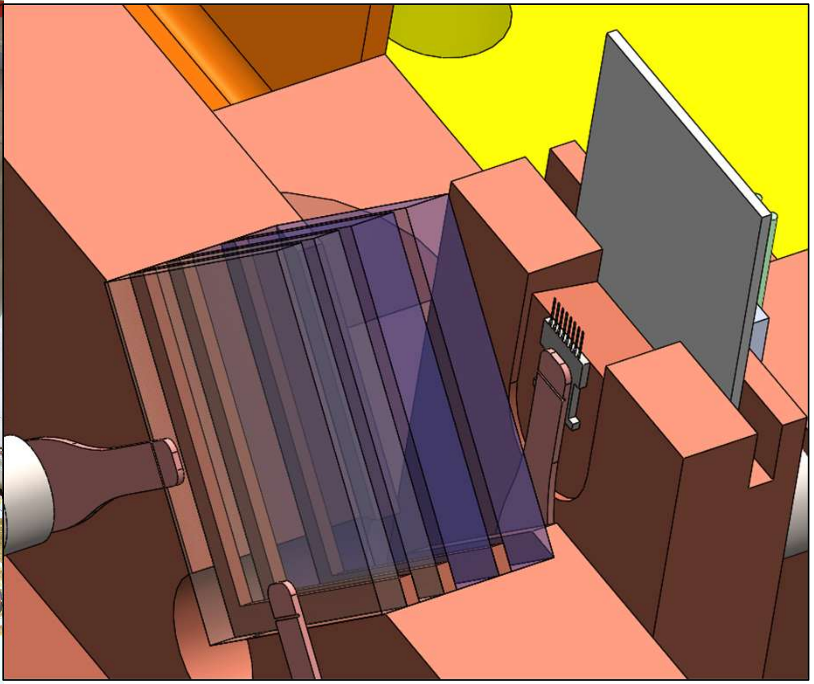
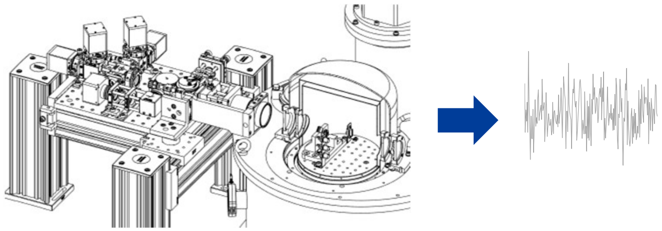
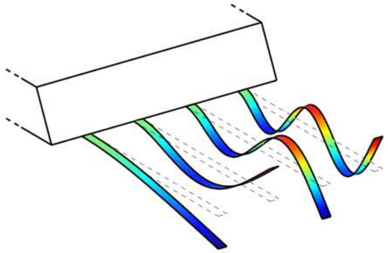
The CryoQPDI at LMA



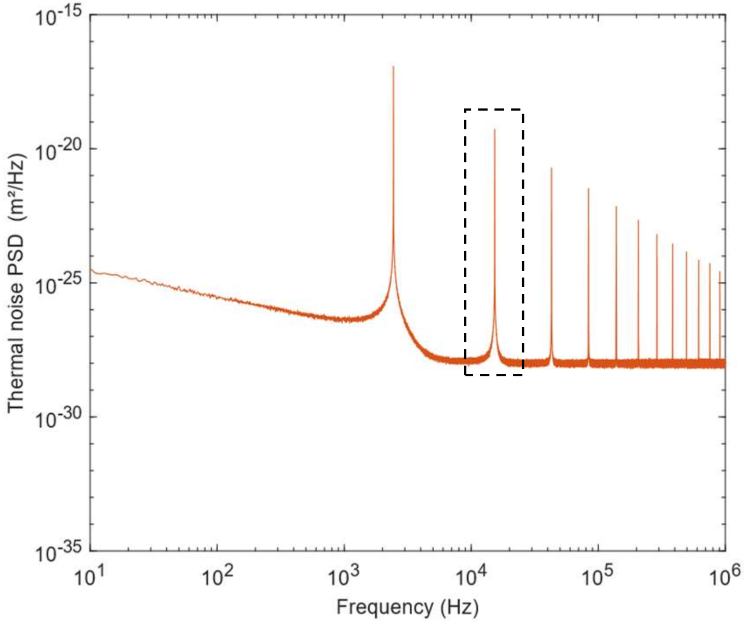


Data analysis: direct thermal noise measurement

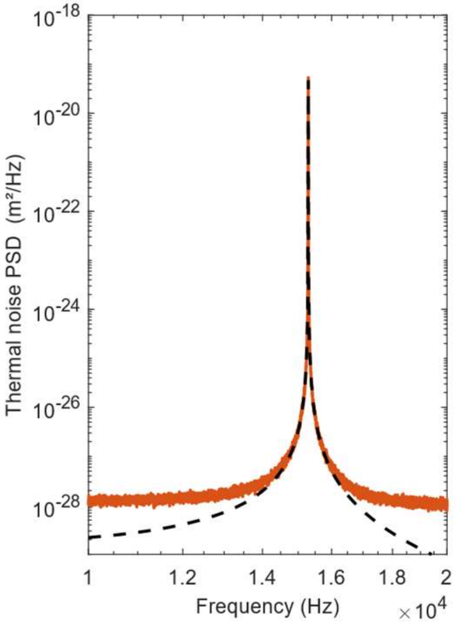




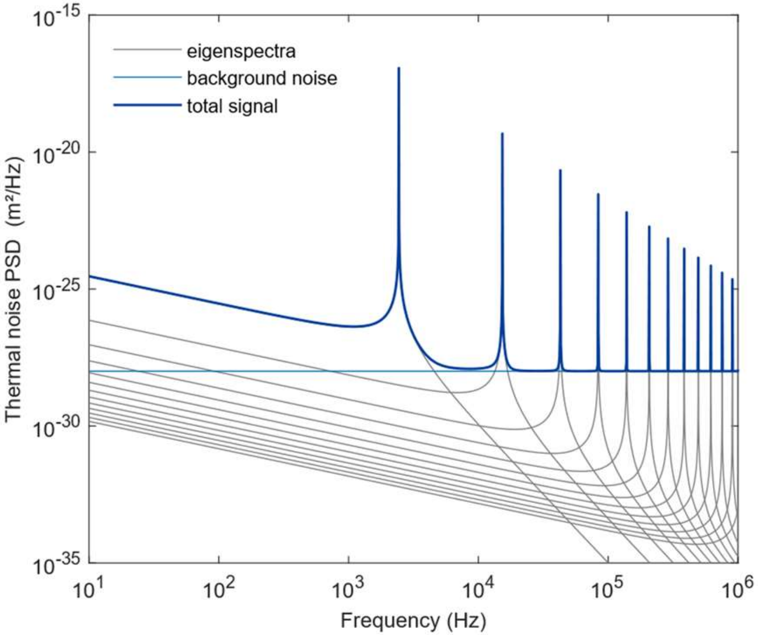
$|TF(z(t))|^2)$



Curve fit



Elasticity + FDT



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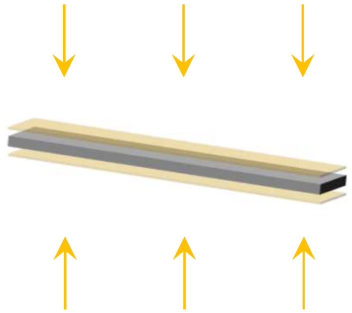
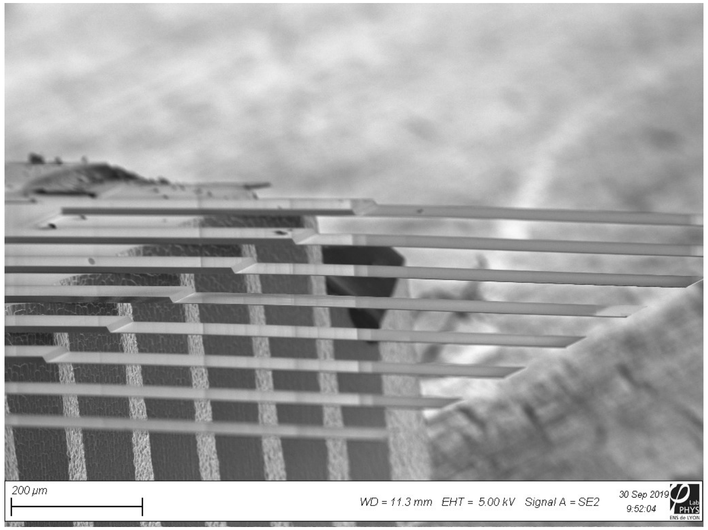
Proof of concept: measurement of a tantala monolayer

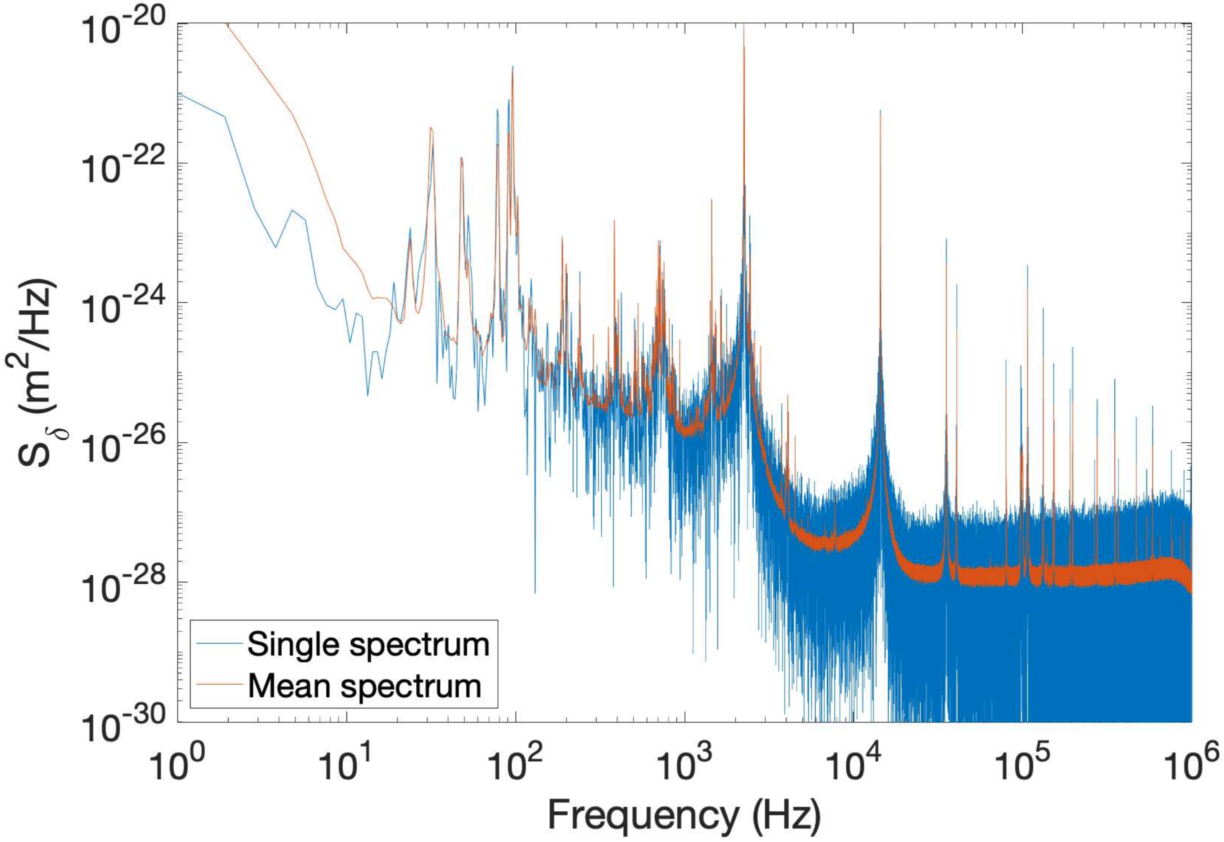


Si µcantilevers
741 µm X 90 µm X 0,94 µm

Undoped tantala coating
150 nm on both side
Deposited by IBS – LMA Spector
Dilution factor = 0.5

Measured after annealing





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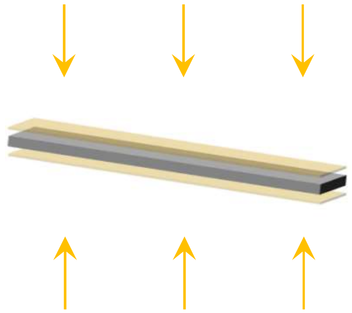

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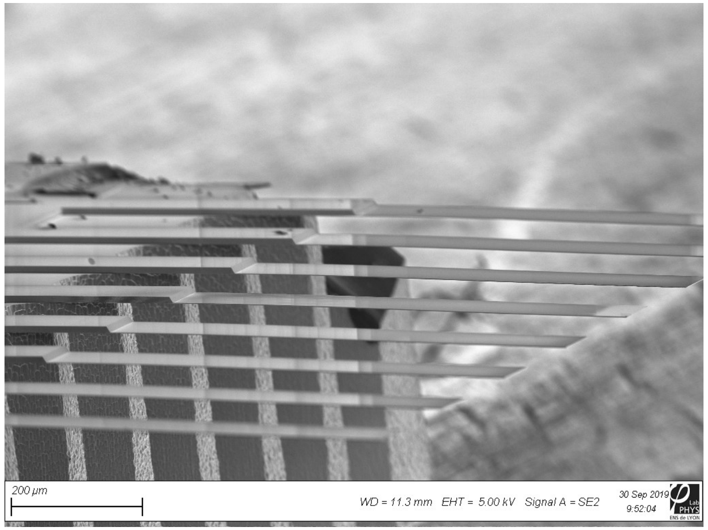

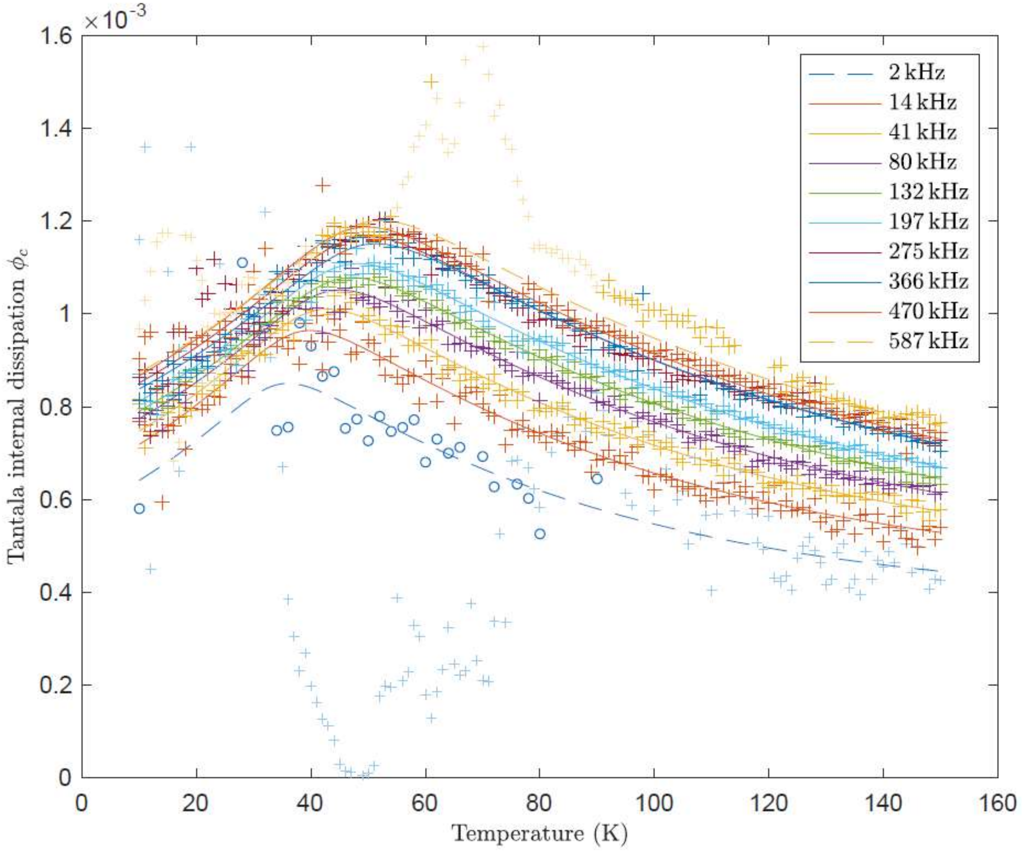

Instrumentation for thermal noise spectroscopy,
https://tel.archives-ouvertes.fr/tel-02612035

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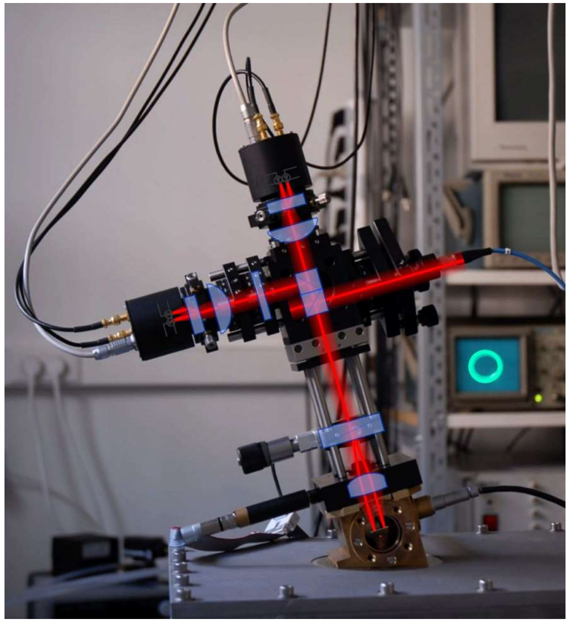
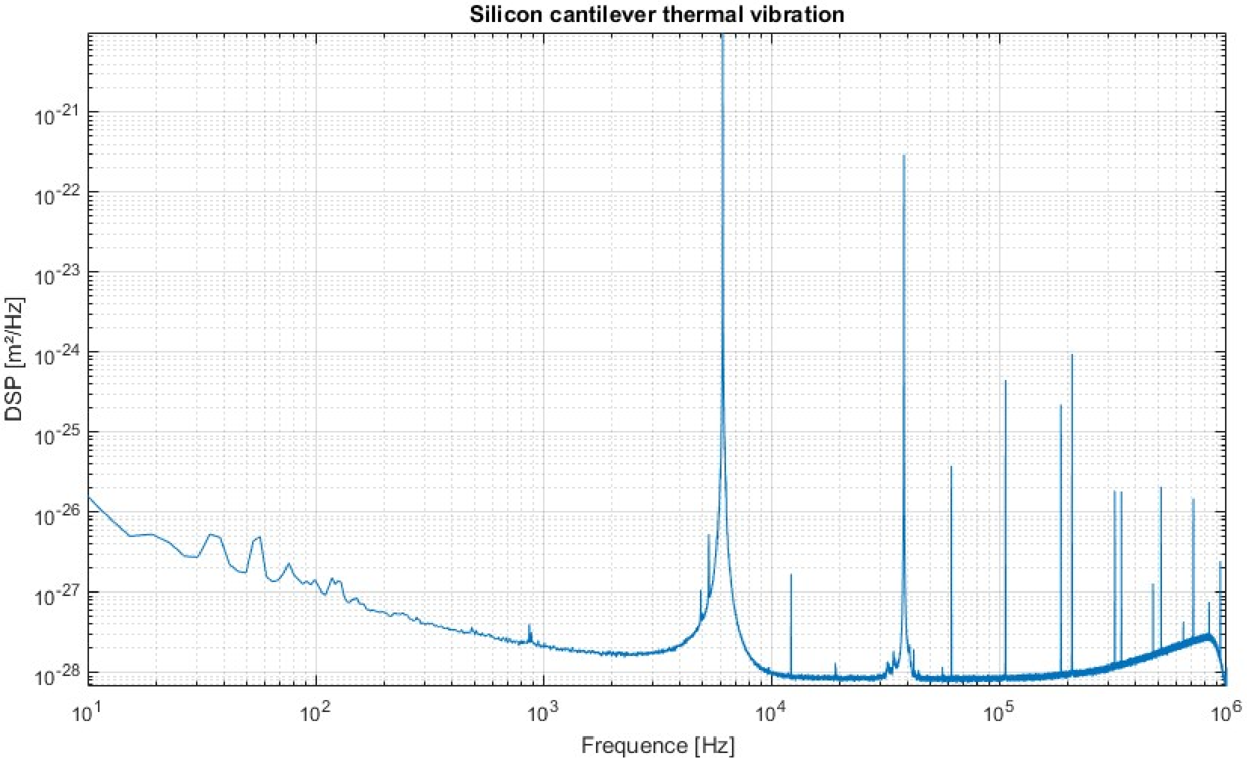
There is room for improvement



L. Bellon



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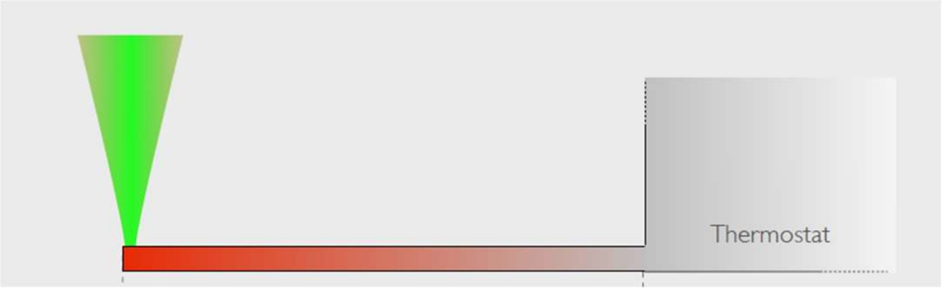
Thermal gradient in the microcantilever from laser absorption



microcantilevers

Assume that 0,25 mW is absorbed at the tip of the microcantilever.
(In reality the cantilever reflect and transmit a portion of the laser power)

$$\Delta T = R_{th} P_{laser}$$

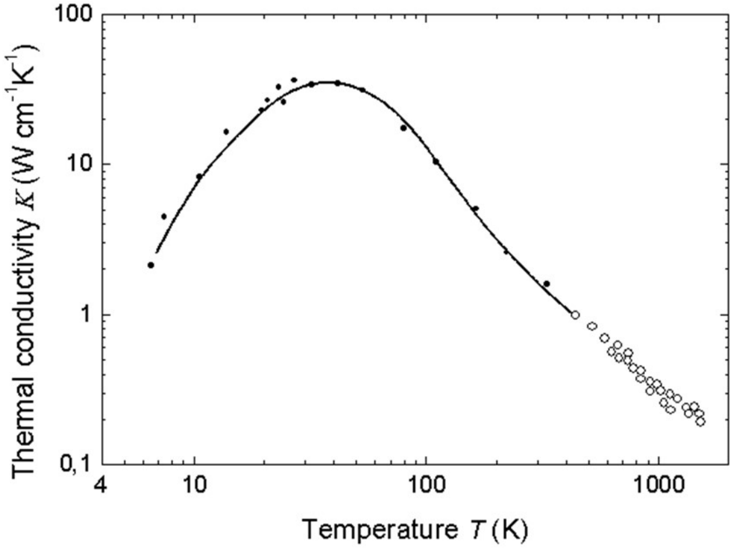
$$R_{th} = \frac{L}{K_{Si} b h}$$

L = 500 µm, b = 90 µm, h = 1 µm

$$K_{Si} \text{ @ } 300K = 1.56\, W cm^{-1} K^{-1}$$
$$\Delta T = 9K$$

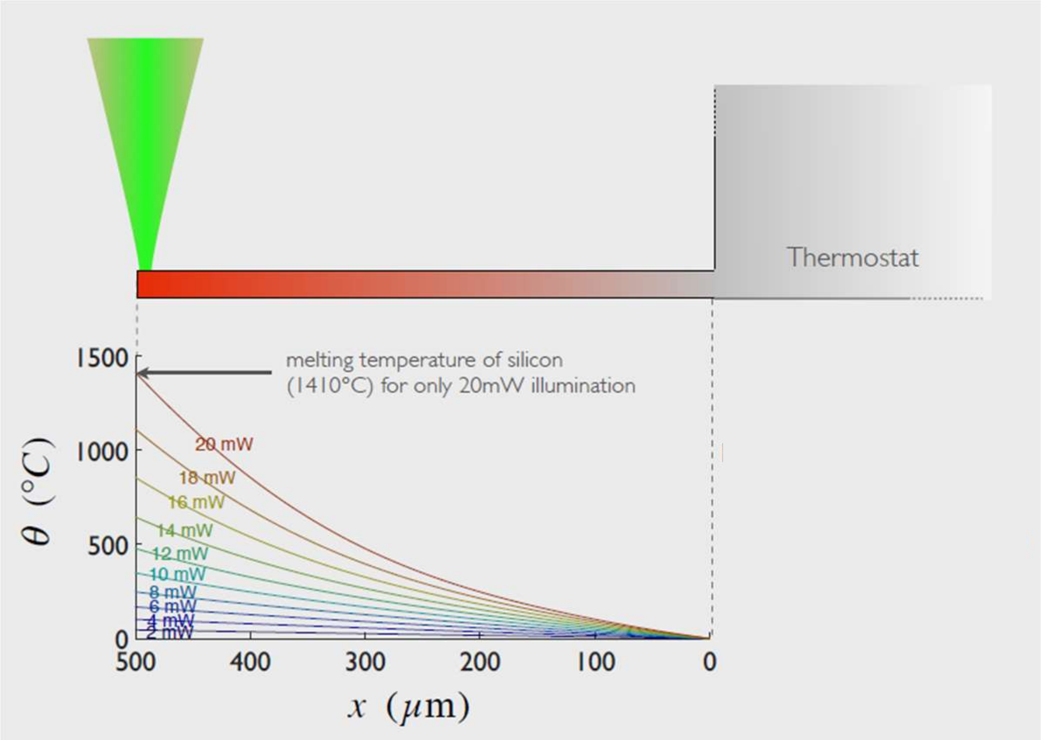
$$K_{Si} \text{ @ } 10K = 13\, W cm^{-1} K^{-1}$$
$$\Delta T = 1K$$

$$K_{Si} \text{ @ } 30K = 35\, W cm^{-1} K^{-1}$$
$$\Delta T = 0{,}4K$$



Phys. Rev. **134,** 4A (1964) A1058-A1069
For high purity silicon

Thermal gradient in the microcantilever from laser absorption



A strong thermal gradient can be generated inside the microcantilever using a modest amount of laser power.

Out of equilibrium thermodynamic.

See talk by Alex Fontana

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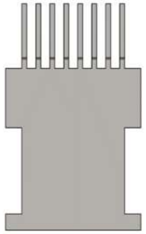
Conclusion: microcantilever and QPDI

Microcantilevers

high dilution factor

best available substrate for single nanolayers

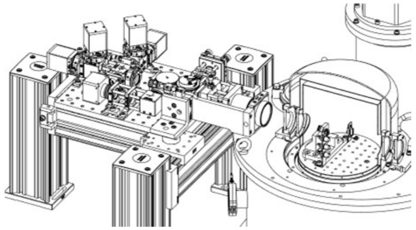
cryo friendly = easy to cool down and to monitor temperature



QPDI

high resolution, $10^{-14}\ m/\sqrt{Hz}$

best available instrument for direct thermal noise measurement on microcantilevers

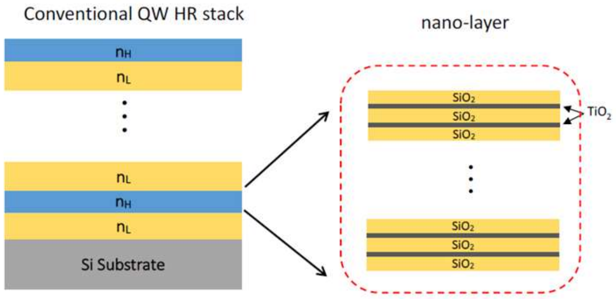


Our project

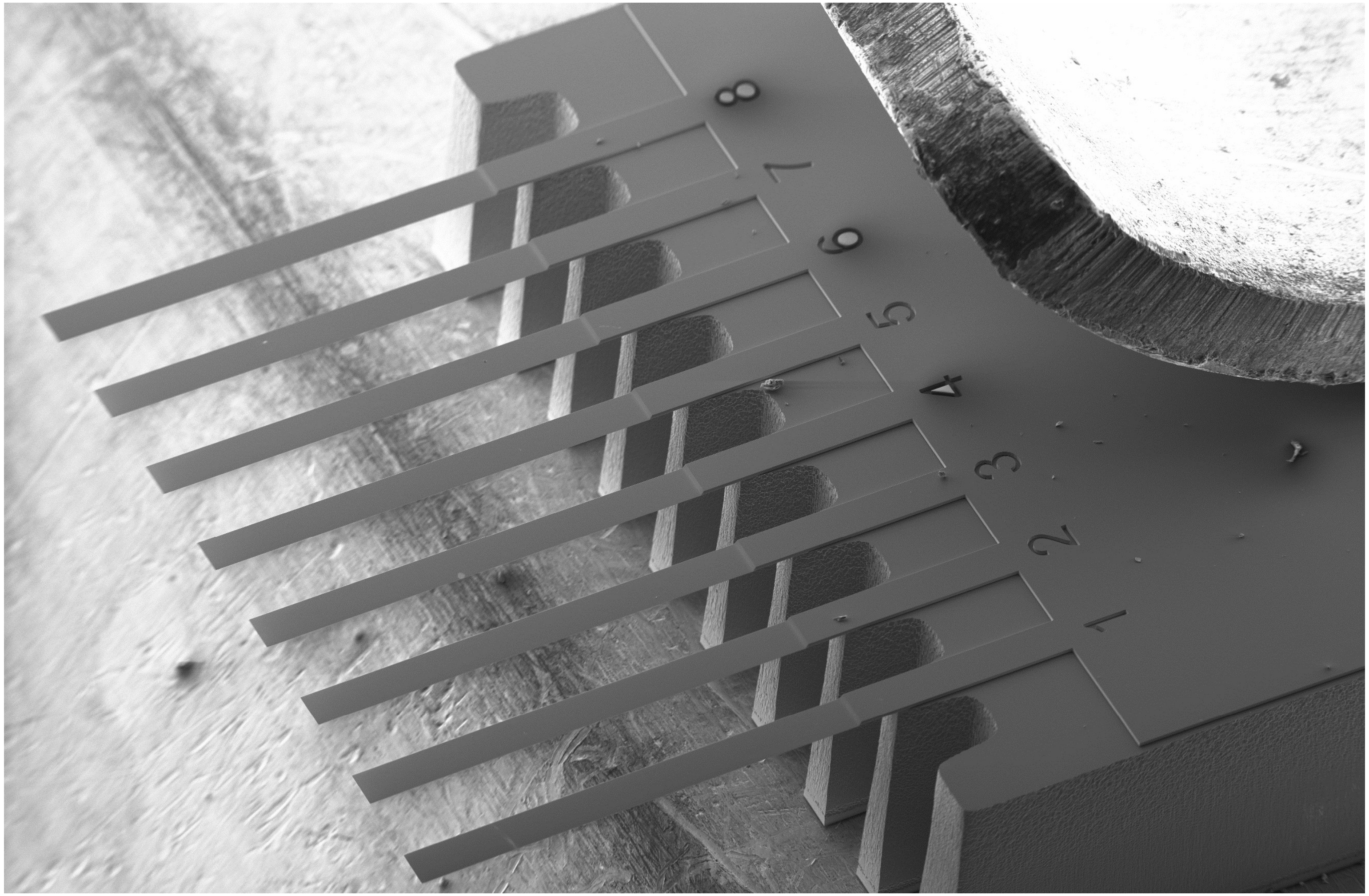
build a cryogenic QPDI to study nanolayering at low temperature

hopefully completed by mid 2022

other coatings as well



Thank you for your attention !



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