The SIPS experiment

a Suspended Interferometer for Ponderomotive Squeezing

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for the SIPS/POLIS team

Outline

- **1. Quantum noise & Ponderomotive squeezing**
- **2. Experiment design**
- **3. Experimental setup of SIPS**
- **4. Perspectives & conclusions**

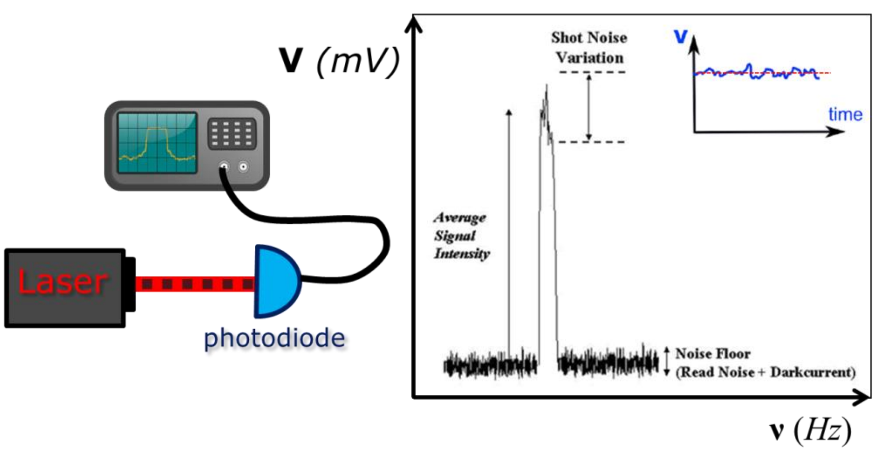
Quantum Limit: Shot Noise and Radiation Pressure Noise

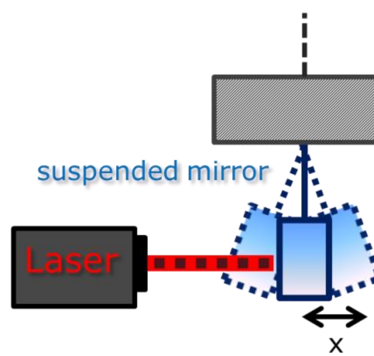
Photon shot noise (SN)

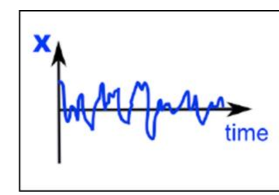
sensing noise:
photons in a laser beam are not equally spaced in time but they follow a Poissonian distribution **photo-current time - series fluctuations**

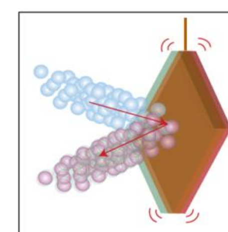
Photon Radiation Pressure noise (RPN)

back-action noise:
photons transfer their momentum (i.e. a *radiation pressure force*) to a suspended mirror with a temporally inhomogeneous distribution **mirror position fluctuations**









Quantization of the EM field in an optical cavity

$$\vec{E}(\vec{r},t) = E_0[X_1 \cos(\omega t) - X_2 \sin(\omega t)]\vec{p}(\vec{r})$$

Quadrature Operators:

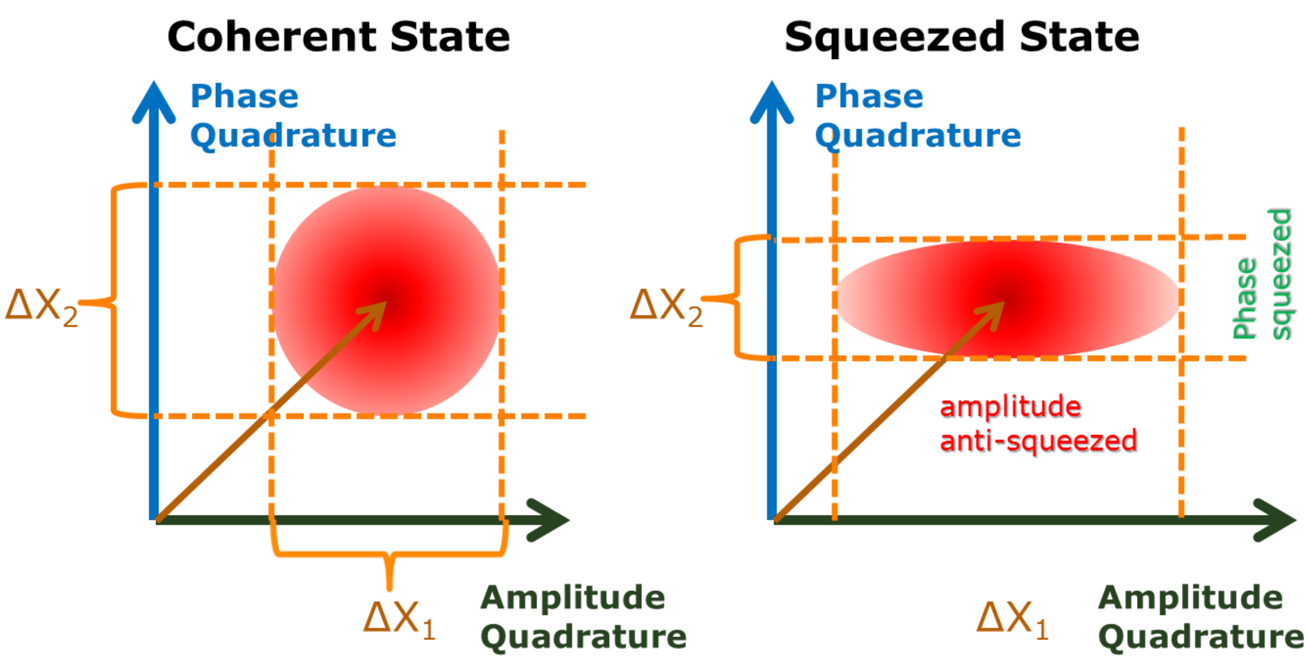
Phase: $X_2(\vec{r}) = i[a^*(\vec{r}) - a(\vec{r})]$

Amplitude: $X_1(\vec{r}) = a^*(\vec{r}) + a(\vec{r})$

… by defining $\hat{a}$, $\hat{a}^+$ …

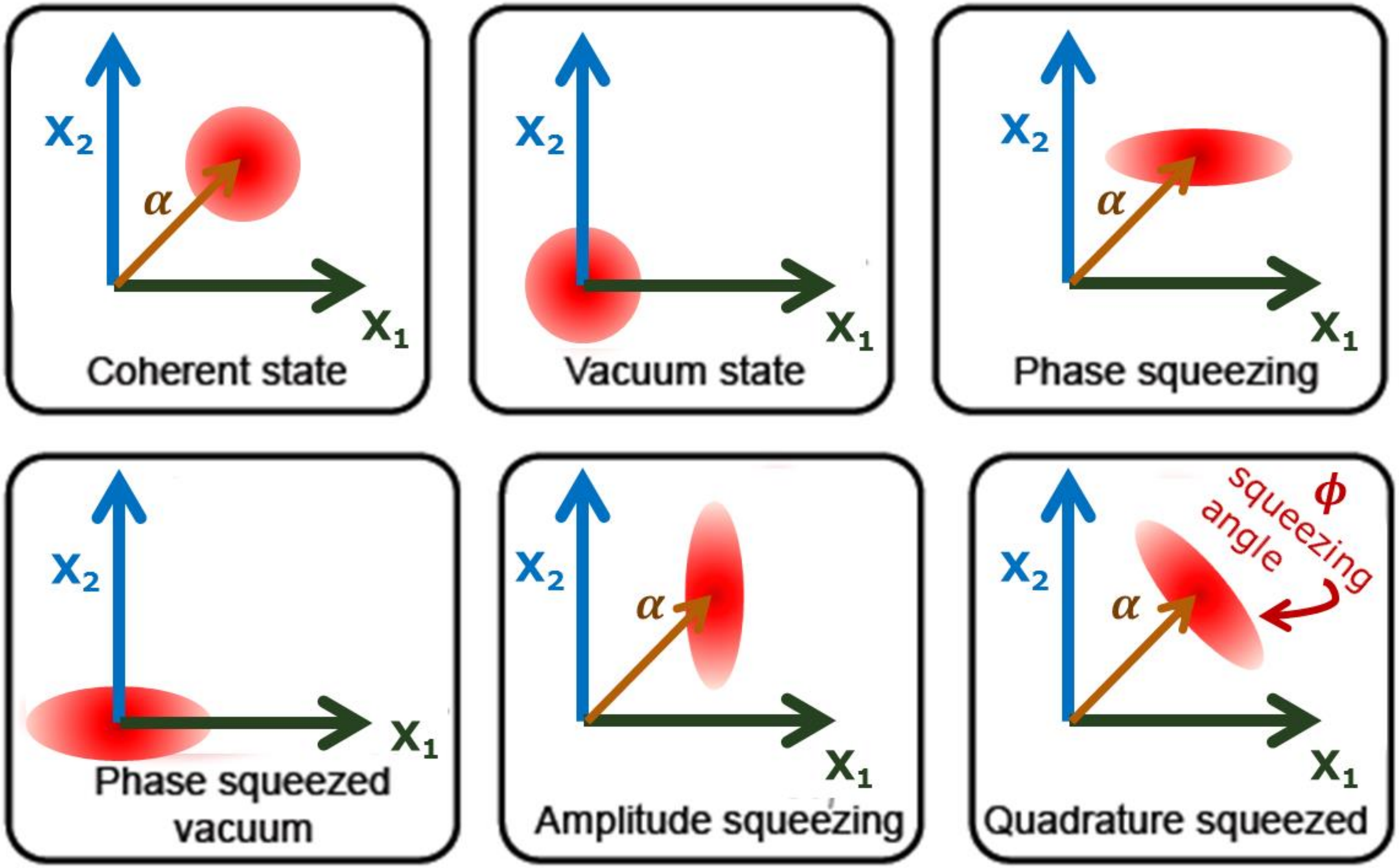
$$\langle(\Delta\hat{X}_1)^2\rangle\langle(\Delta\hat{X}_2)^2\rangle \geq \frac{1}{16}$$

Heisenberg uncertainty principle



Squeezed states of light

$$\langle(\Delta\hat{X}_1)^2\rangle\langle(\Delta\hat{X}_2)^2\rangle \geq \frac{1}{16} \leftrightarrow$$ Heisenberg minimal uncertainty



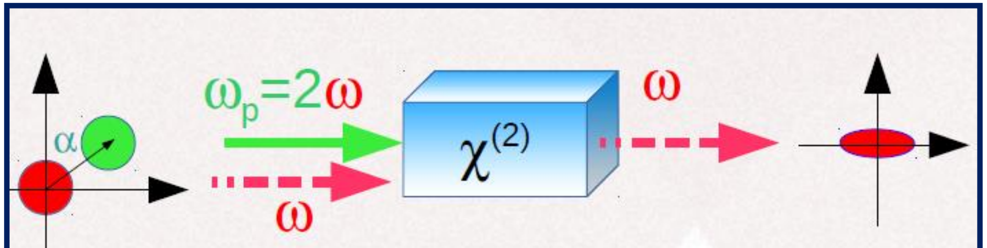
Quadrature picture: X1=amplitude, X2=phase, ϕ=rotation, α=displacement

Application to GW detectors: Martina De Laurentis' talk!

Squeezing generation: OPO vs Ponderomotive

- **Kerr medium**
- Optical Parameter Oscillator (**OPO**)

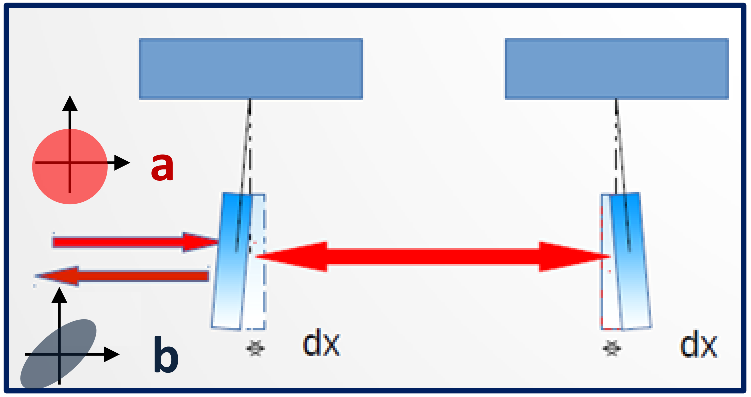
3rd and **2nd** susceptibilities induces *correlations* between *phase* and *amplitude* fluctuations



Fully degenerate OPO
(polarizations and frequencies degeneracy)

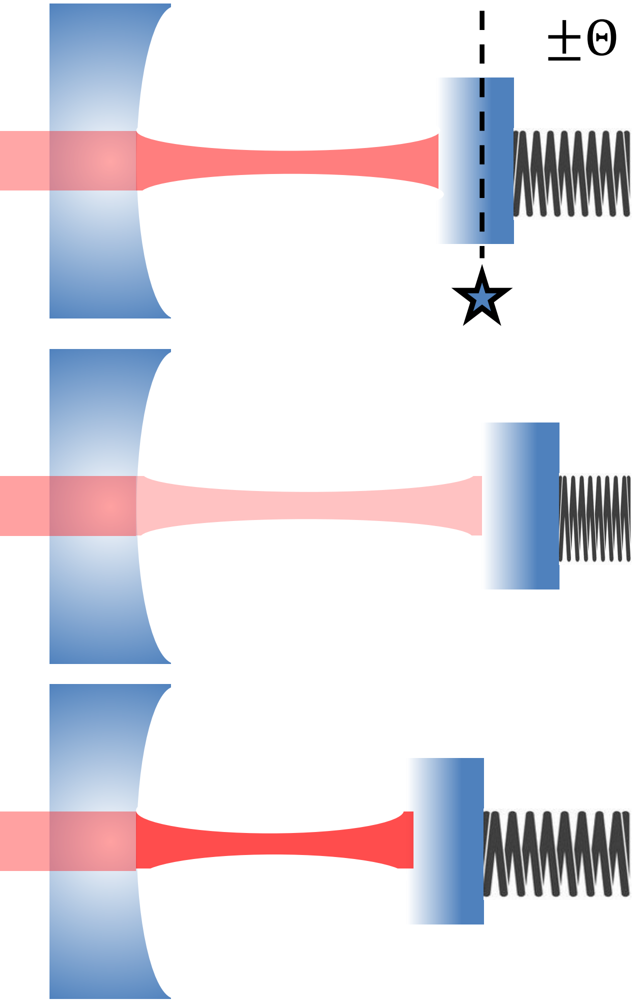
Frequency limitations due to losses mechanisms in the medium (phototermal fluctuations) and stability issues at low frequencies...

Empty cavity with suspended mirrors (ponderomotive)



Radiation Pressure (RP) on the suspended mirror induces a *coupling* between its *position* and the *intensity of light beam* → *correlation* between *phase* and *amplitude* quadrature of the output state

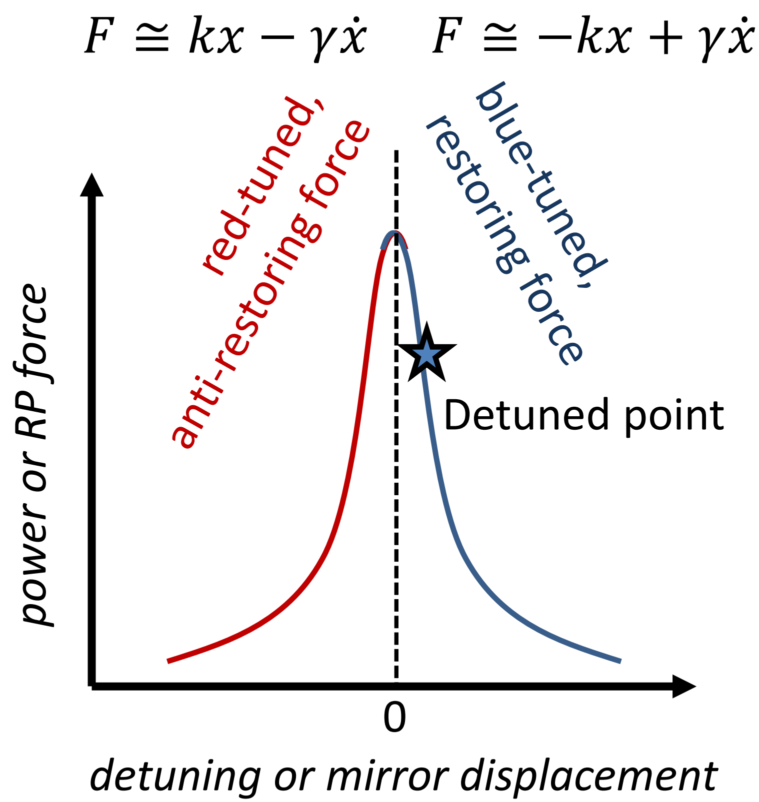
Opto-Mechanical coupling in a detuned cavity



Optical spring

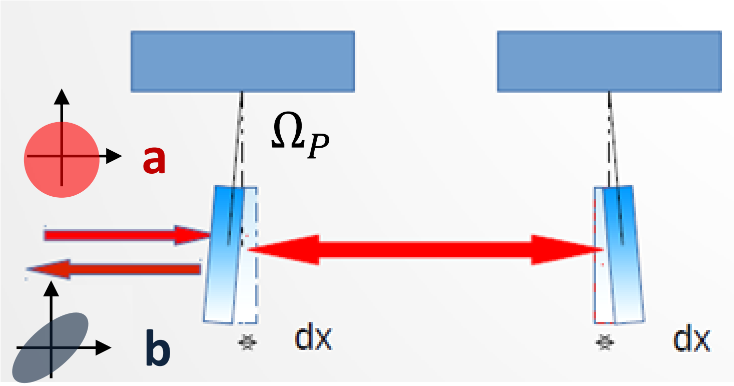
cavity becomes longer
→ detuning increases
→ power decreases
→ restoring force

cavity becomes shorter
→ detuning decreases
→ power increases
→ restoring force



**γ: (anti)damping term ↔ spring instability*

Ponderomotive squeezing in a cavity with suspended mirrors



Gravity + RP acting on the mirrors → optical spring

$$\begin{pmatrix} b_A \\ b_P \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -2\mathcal{K}(\Omega) & 1 \end{pmatrix} \begin{pmatrix} a_A \\ a_P \end{pmatrix}$$

coupling factor (frequency-dependent):

$$\mathcal{K}(\Omega) = \left(\frac{1}{1 - \left(\Omega^2 - \Omega_p^2\right)/\Theta^2} \right) \frac{1}{\delta_\gamma}$$

Intensity (amplitude) **fluctuations** inside the cavity cause suspended mirror motion

↓

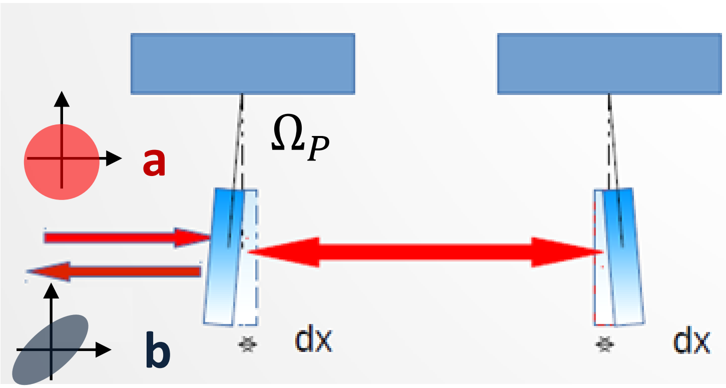
Displacement of mirrors produces a phase shift in the reflected light

↓

Phase shift proportional to intensity fluctuations → *coupling between phase and amplitude quadrature fluctuations* → **squeezing**

Pros: broadband and high value squeezing (>10dB), audio frequency (10Hz-10kHz), room temperature

Ponderomotive squeezing in a cavity with suspended mirrors



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ponderomotive **squeezing factor**:

$$\xi_{min}(\Omega) = \frac{1}{|\mathcal{K}(\Omega)| + \sqrt{1 - \mathcal{K}(\Omega)^2}}$$

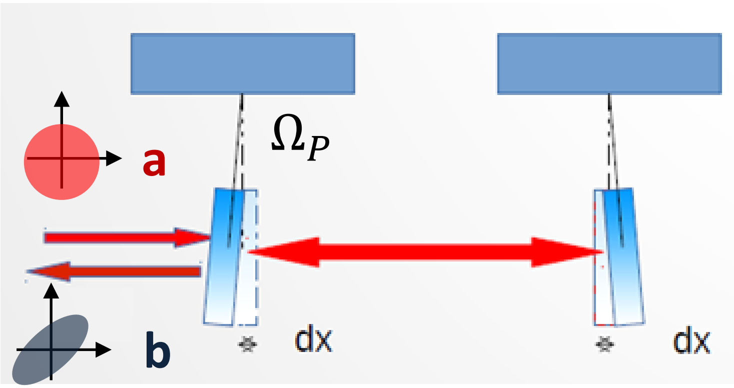
When $\Omega_P \ll \Omega, |\Theta|$ the mirror mechanical resonance depends only on the optical spring resonant frequency $\pm\Theta$

$$\begin{cases} \Omega \gg |\Theta| & \rightarrow \text{Output not squeezed} \\ \Omega \approx |\Theta| & \rightarrow \text{Frequency-dependent squeezing} \\ \Omega \ll |\Theta| & \rightarrow \text{Frequency-independent squeezing} \end{cases}$$

constant coupling, squeezing band given by $|\Theta|$

$$\mathcal{K} = \frac{1}{\bar{\delta}_\gamma} \qquad \xi_{min}(\Omega << |\Theta|) = \frac{|\bar{\delta}_\gamma|}{1 + \sqrt{1 + \bar{\delta}_\gamma^2}}$$

Ponderomotive squeezing in a cavity with suspended mirrors



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coupling factor (frequency-dependent):

$$\mathcal{K}(\Omega) = \left(\frac{1}{1 - \left(\Omega^2 - \Omega_p^2\right) / \Theta^2} \right) \frac{1}{\bar{\delta}_\gamma}$$

The *optical spring frequency* $|\Theta|$ depends on: ***input power, cavity finesse, detuning factor, mirror mass***

$$\Theta^2 \equiv \frac{K_{opt}}{M} = -\frac{4\omega_0 \bar{W}}{\gamma M L c} \frac{\bar{\delta}_\gamma}{1 + \bar{\delta}_\gamma{}^2} = -\frac{4\omega_0 \bar{I}_0 \bar{\delta}_\gamma}{M c^2} \left(\frac{2\mathcal{F}}{\pi} \frac{1}{1 + \bar{\delta}_\gamma^2} \right)^2$$

Once these parameters (and then $|\Theta|$) are fixed, we design the system in order to have $\Omega_P \ll |\Theta|$ by choosing an appropriate **pendulum length**

*Real parameters must be chosen ensuring a **large squeezing factor** and a **suitable squeezing band**, tanking into account the mechanical feasibility*

Parameters choice for SIPS

Cavity detuning: $\boldsymbol{\delta = 0.3 \rightarrow \xi = 18\, dB\, , \Theta = 2\pi\, kHz}$
(large values increase the band; low values increase the squeezing factor)

Squeezing factor and band

Cavity finesse: $\boldsymbol{\mathcal{F} \leq 3 \cdot 10^4}$
(large values increase Θ and reduce intracavity losses; low values increase the optical spring stability)

Input power: $\boldsymbol{I_0 = 2.5\, W} \rightarrow 0.1MW$ circulating power
(large values increase Θ but above 0.2MW thermal effects lead to degradation of the cavity behaviour)

Optical spring

The other parameters depends on trade-off with other experimental constraints: seismic noise pre-insulator, optical bench dimension ($\varnothing < 1m$) …

Cavity length: $\boldsymbol{l = 350\, mm}$
Mirror RoC: $\boldsymbol{RoC = 250\, mm}$

Cavity stability

Parameters choice for SIPS

Suspended mirror mass

High values:
- easy to suspend
- easy to sense and actuate (feedback control)

Low values:
- Large optical spring resonance (frequency-independent band)

Given a suitable seismic pre-insulation we can choose a relatively high mass value:

$$10g \leq m \leq 300g$$

A standard 25.4 mm mirror in fused silica with a 6.35 mm thickness has a mass of about 7.8 g, while with a 10 mm of thickness it can reach a mass of 11.1 g.

Can be suspended with a monolithic Virgo-like technique (→thermal noise reduction)

Higher mass value relaxes the sensitivity requirements

R&D and experiment setup

The POLIS legacy

Preliminary R&D on a low frequency ponderomotive squeezer in the past years (under the acronym POLIS, funded by a PRIN of the Italian MIUR), involving many research institutions:

Università di Roma Sapienza & INFN-Roma, Università di Napoli Federico II & INFN-Napoli, Università di Roma Tor Vergata & INFN-Roma2, Università di Pisa & INFN-Pisa, INFN-Genova, INFN-Perugia, Università del Sannio, Università di Firenze & INFN-Firenze, Università di Salerno, Università di Trento & INFN-Padova-Trento & Fondazione B.Kessler, Università di Camerino, Università di Urbino, CNR

→ Design and realization of the mechanics for a **suspended interferometer** (Roma1); **Main laser** (Urbino, Napoli); **optical design** (Napoli, Roma2), **optical benches** (Pisa)…

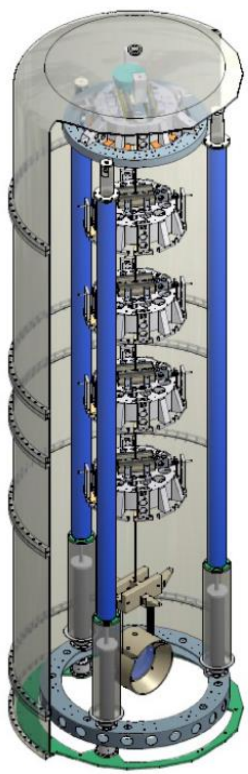
SIPS

The experimental setup was then funded in the last 2 years (2017-2018) by **INFN** – CSN5

R&D and experiment setup

Seismic and **thermal noises** are the main limitations to exploit the RP with a 10-100g-scale mirrors

Solutions: well-known technologies in GW detectors



Efficient seismic filter:
Superattenuator of Virgo inverted pendulum + a chain of pendula, passive+active damping. Provides a seismic attenuation of -180*dB* at 10Hz

Monolithic suspension:
SiO_2 fibers welded to mirrors as in Virgo and LIGO GW detectors: low thermoelastic losses with respect to metallic wires

VIRGO

R&D and experiment setup

Bench Requirements: must be compliant with the allowed size and weight in order to be suspended at the **SAFE** (Super Attenuator Facility at **EGO-Virgo**):

Height: 800 *mm*
Diameter: 960 *mm* (allowing two cavities 350*mm*-long)
Weight: ~ *150 kg*

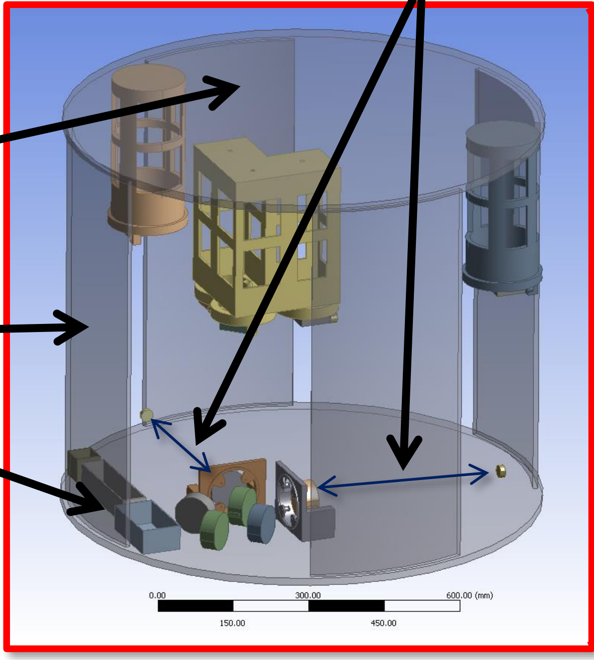
Material: anticorodal (Al-alloy)

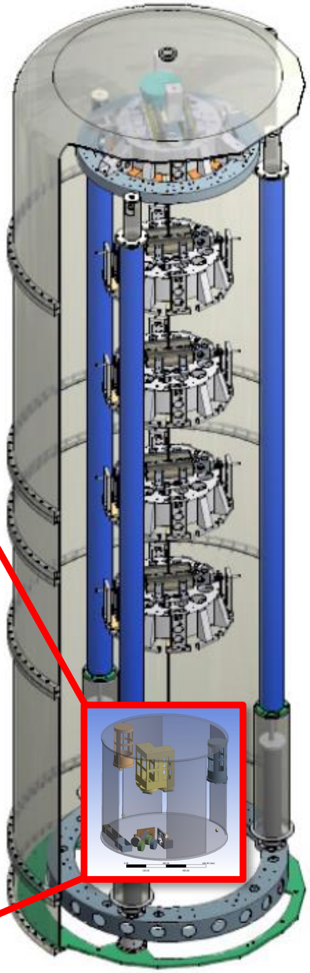
Upper plate
(auxiliary bench)

Cylindrical baffles

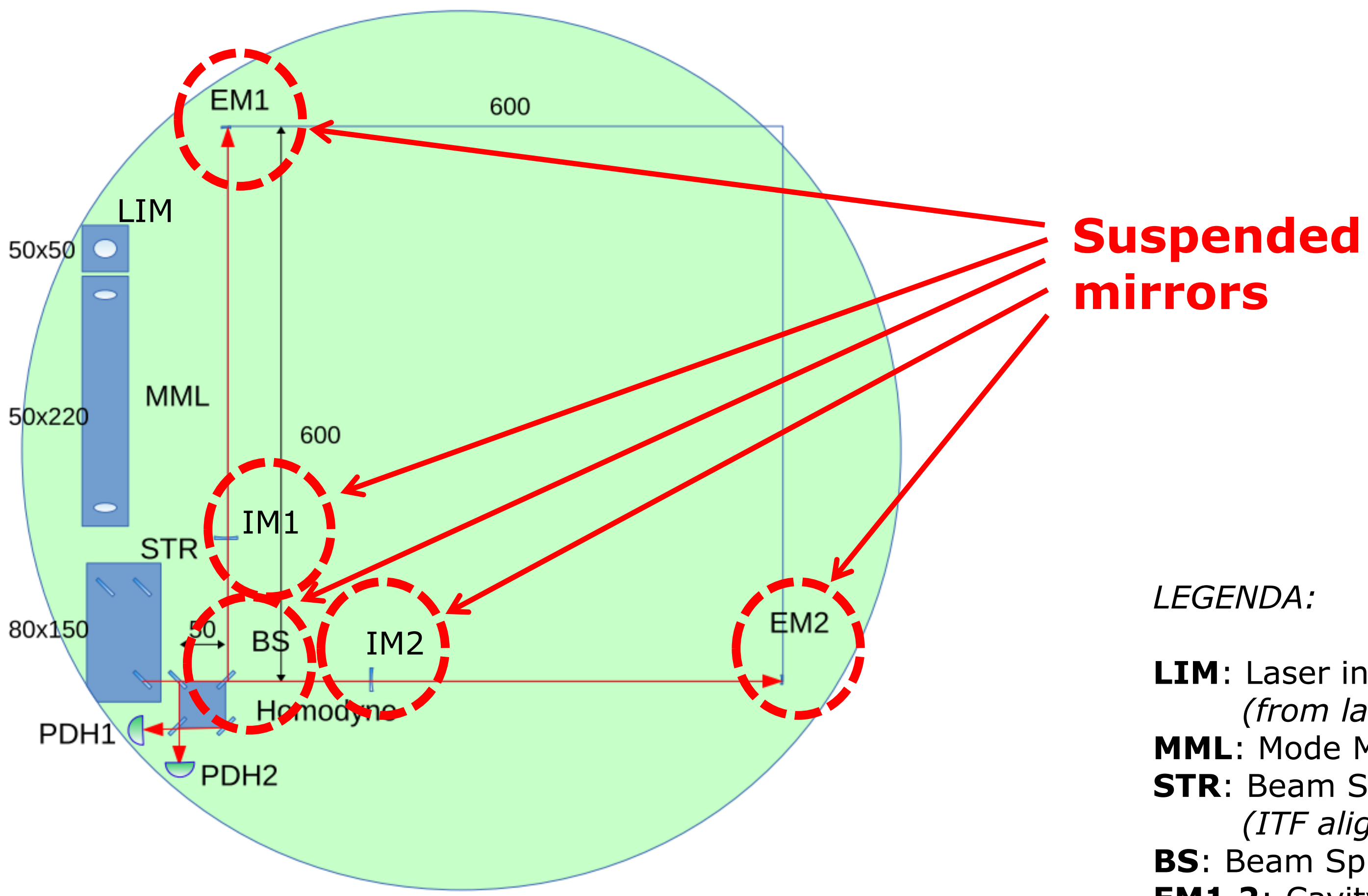
Main optical bench

The structure must combine <u>high stiffness</u> (to push up the mechanical mode frequencies) and <u>low mass</u> (< SA limit).





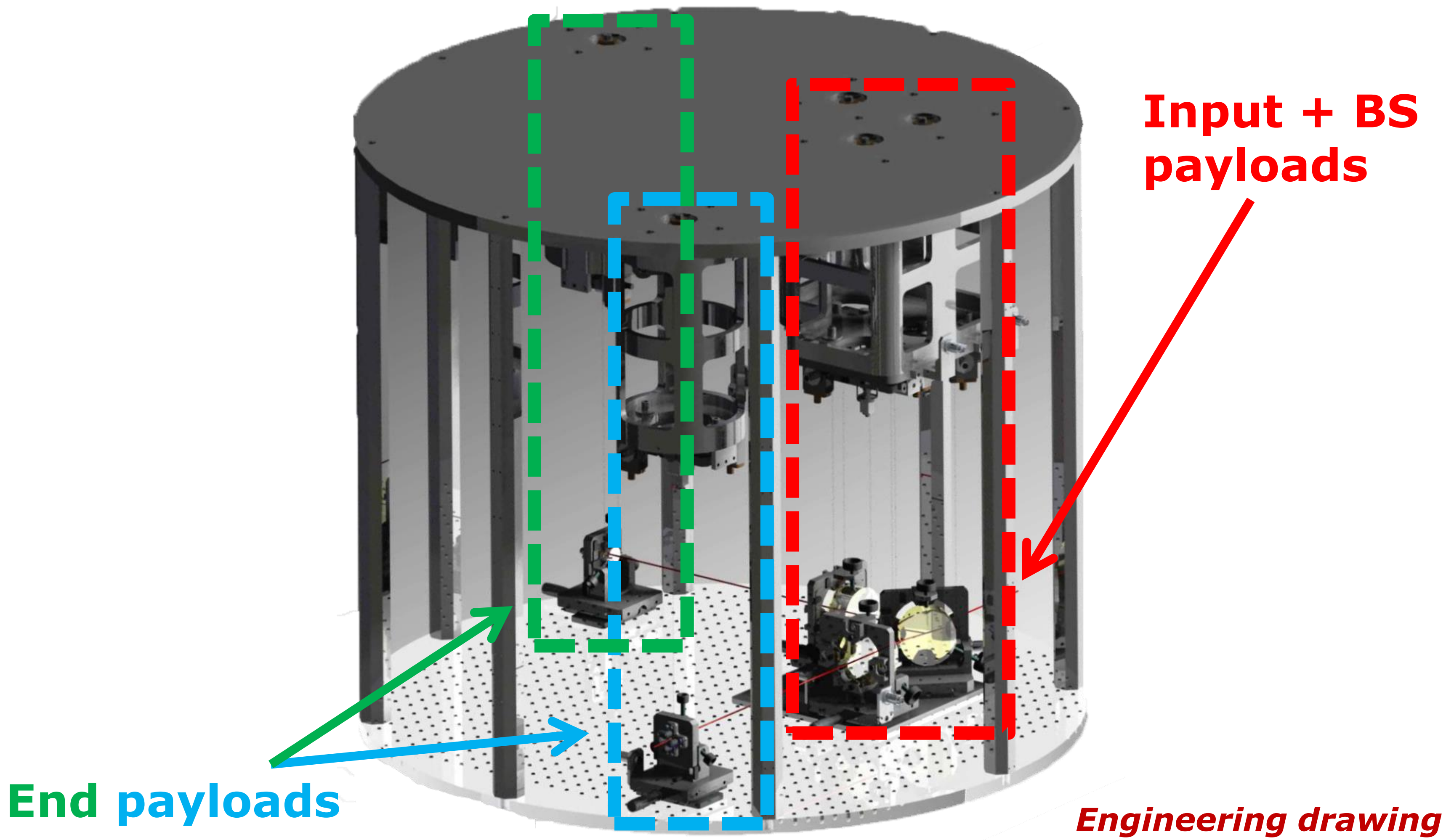
Optical Bench



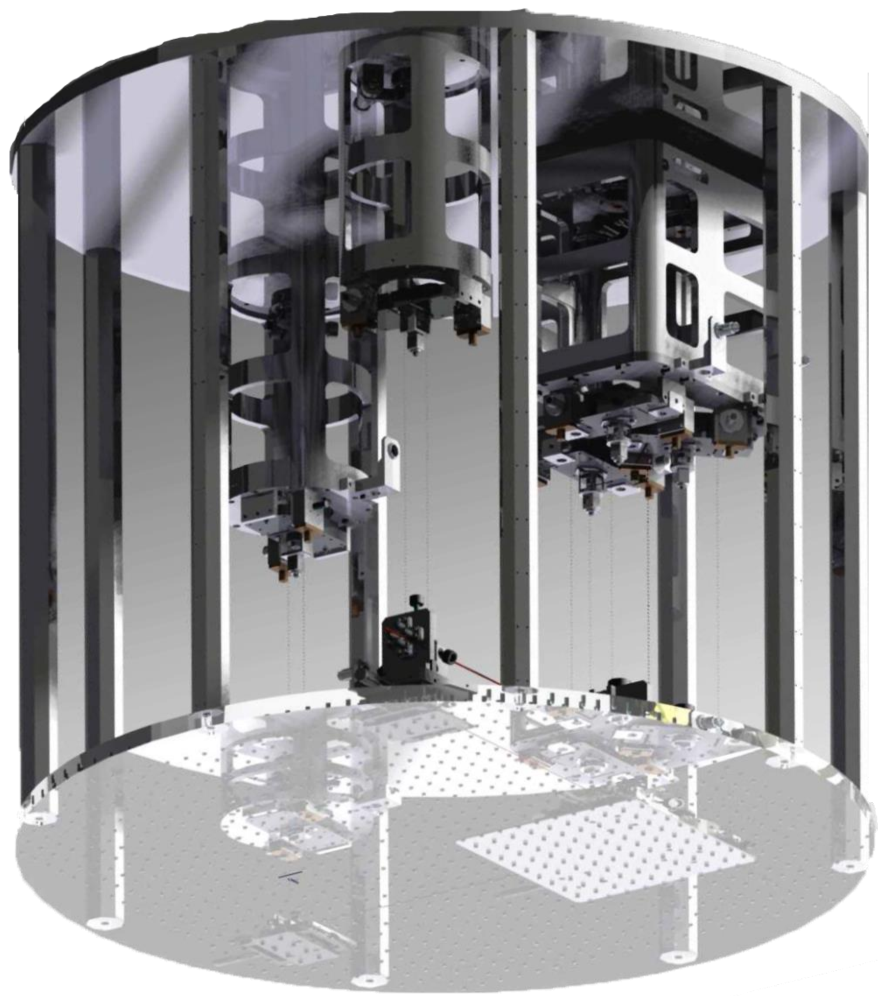
LEGENDA:

LIM: Laser input mirror *(from laser source)*
MML: Mode Matching Lens
STR: Beam Steering Mirrors *(ITF alignment)*
BS: Beam Splitter
EM1,2: Cavity End Mirror
IM1,2: Cavity Input Mirror

Suspended Bench



Suspended Bench

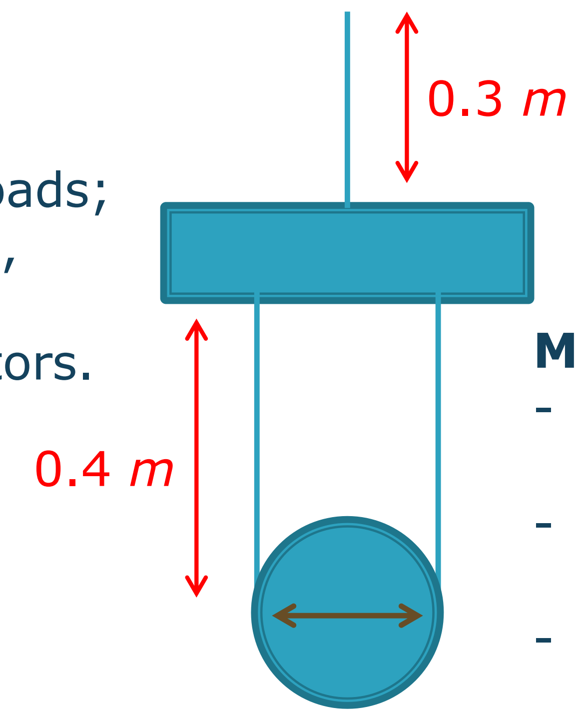


Mirror suspension (mini-payloads)

Requirements: the fundamental constraint is that the suspension thermal noise of the lighter (end) mirror must be below $\sim 10^{-16}\, m/\sqrt{Hz}$ at $10\, Hz$; if not squeezing would be undetectable.

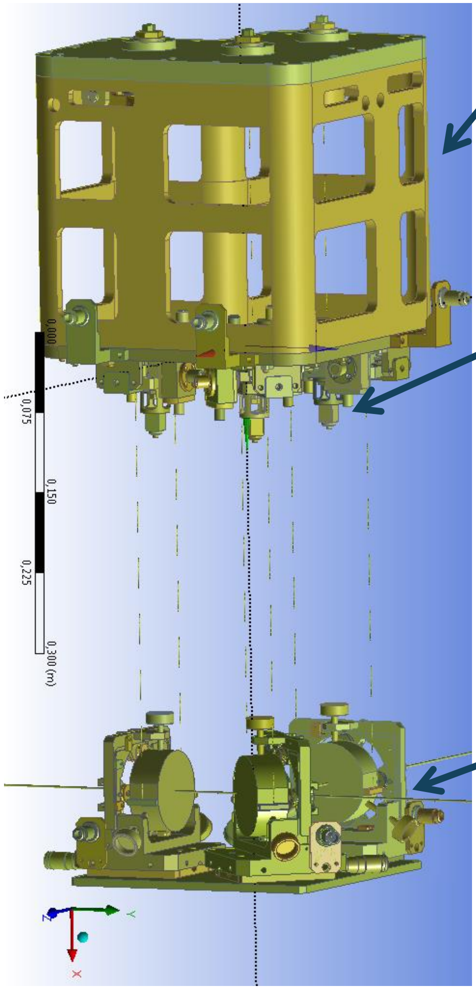
Payload Design: double pendulum suspension (monolithic suspension of the mirrors).

Marionette:
- 1.1 *kg* for all payloads;
- one steel C80 wire, $\Phi_w = 300\ \mu m$;
- magnet-coil actuators.



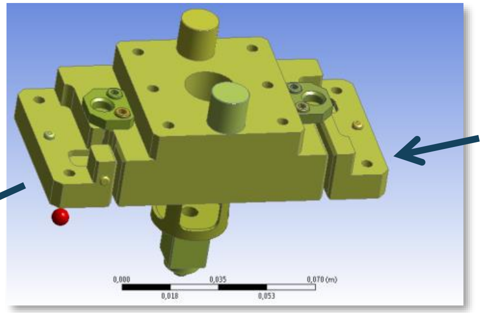
Mirrors:
- 300 *g*, 3″ (BS & Input), 10 *g*, 1″ (End);
- two fused silica fibers, $\Phi_{fibers} = 50\ \mu m$,
- magnet-coil actuators.

Mirror suspension (mini-payloads)



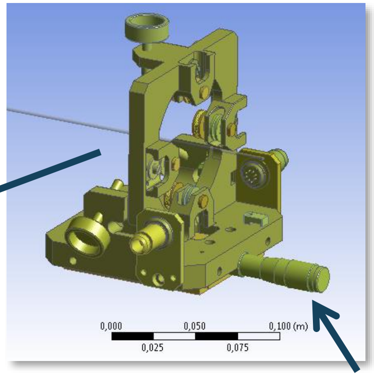
Beam Splitter and Input

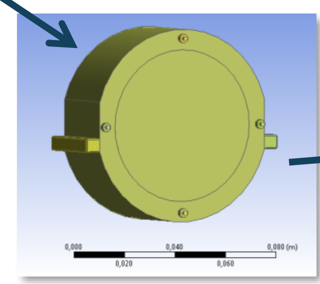
cage + coil holder Anticorodal Al, ~ 6 *kg*

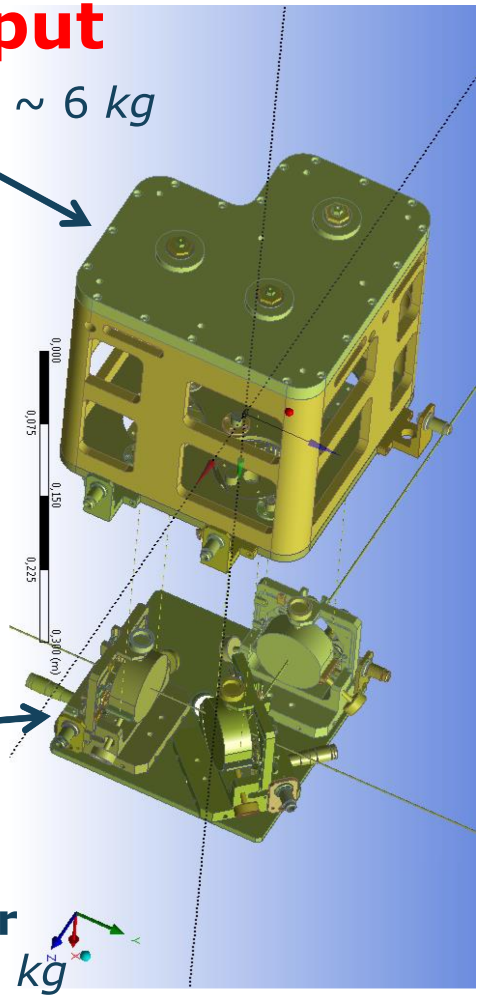


Marionette
Steel, 1.1 *kg*

Mirror Fused Silica, 0.3 *kg*



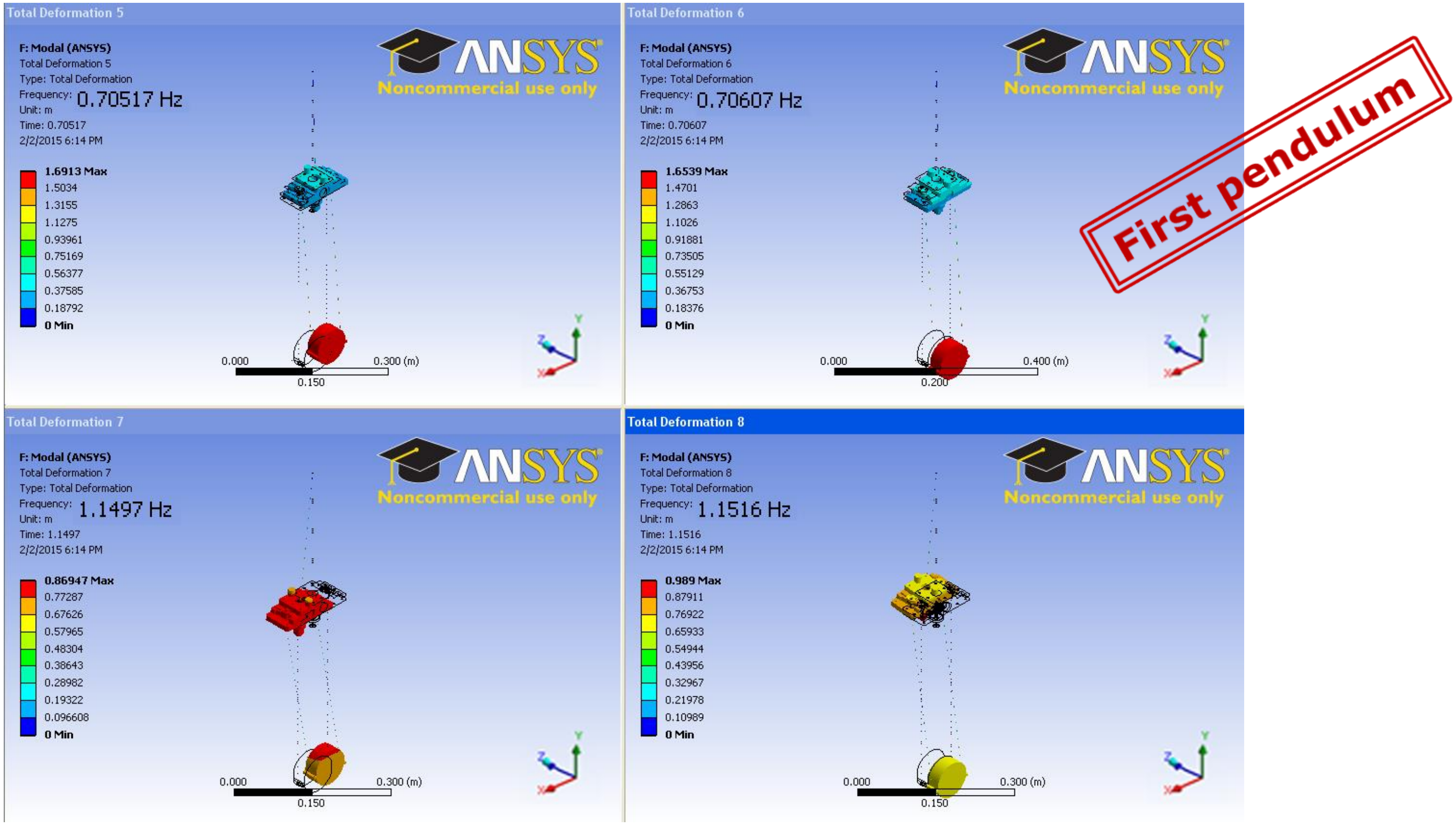




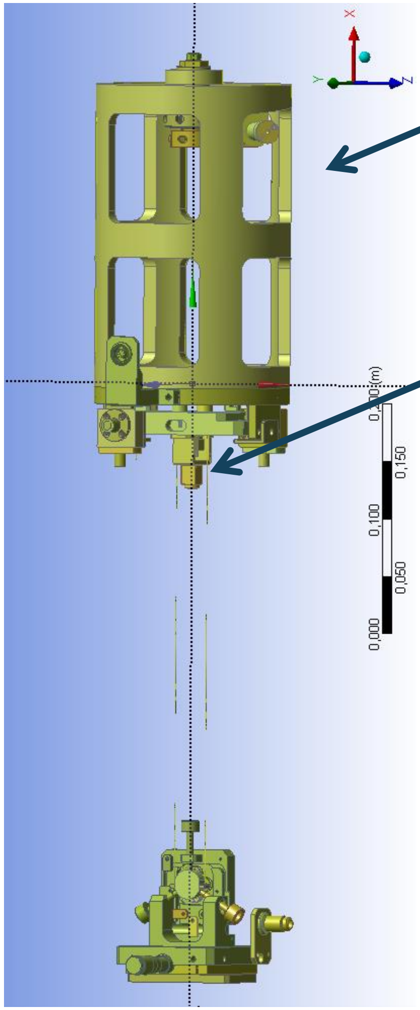
Mirror coil holder
Anticorodal Al, 1.6 *kg*

Mirror suspension (mini-payloads)

Input Payload vibration modes

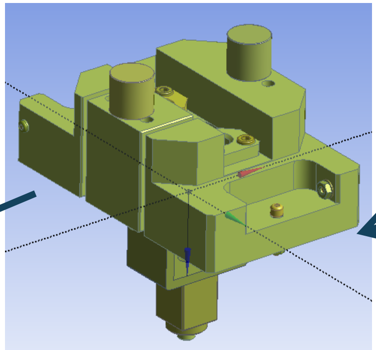


Mirror suspension (mini-payloads)

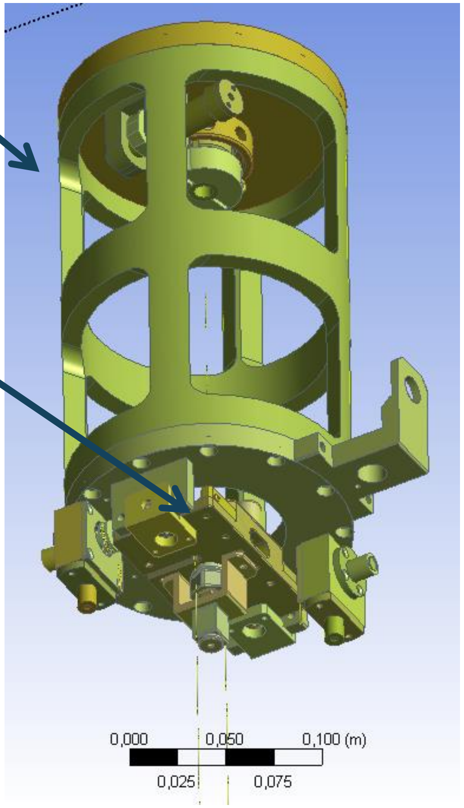


End Payload

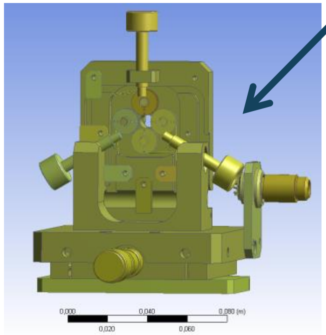
cage + coil holder Anticorodal Al, ~ 2.3 *kg*



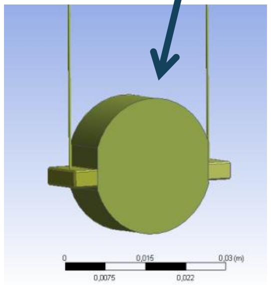
Marionette
Steel, 1.1 *kg*



Mirror coil holder
Anticorodal Al, 1.7 *kg*

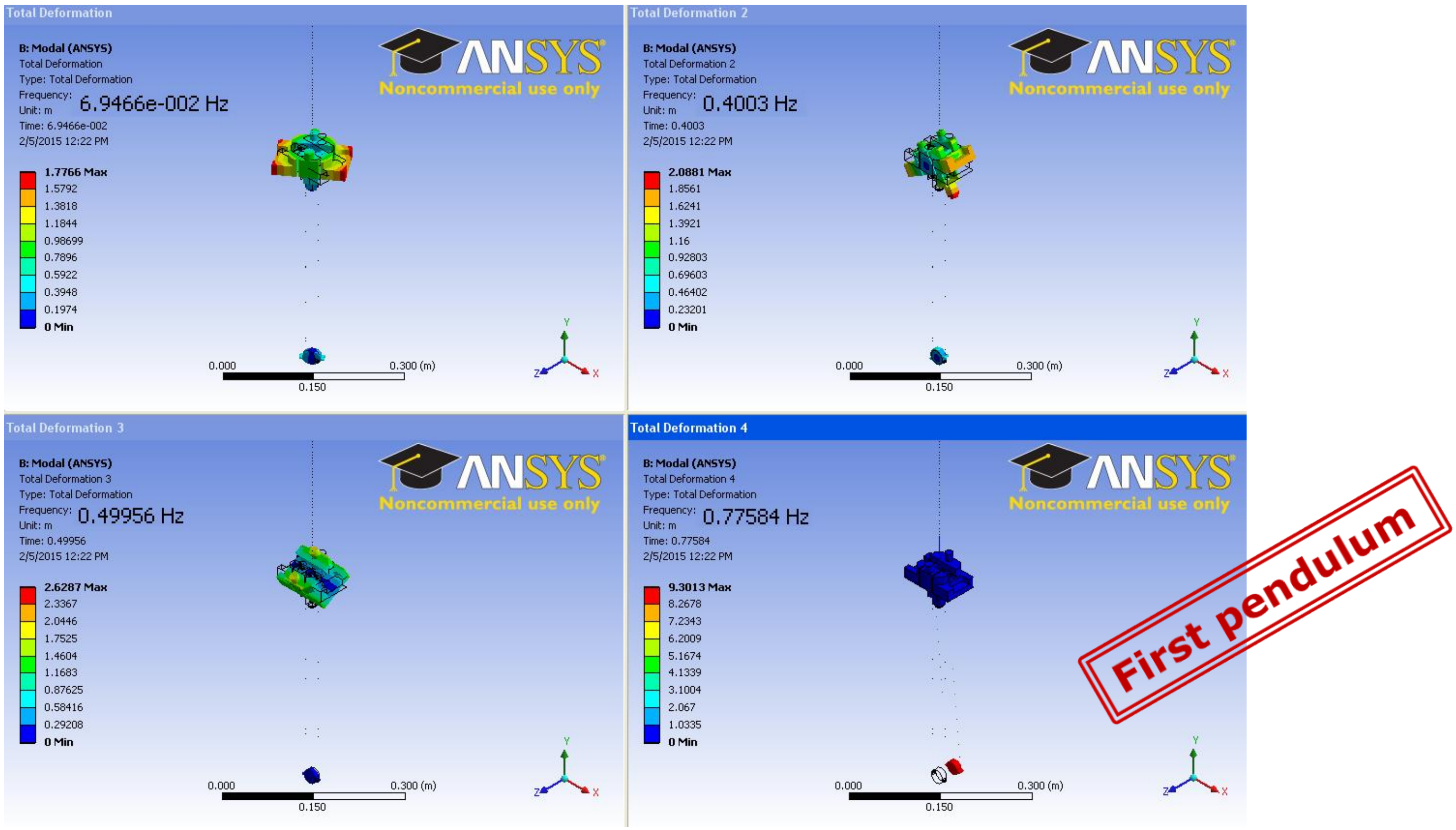


Mirror
Fused Silica,
10^{-2} *kg*

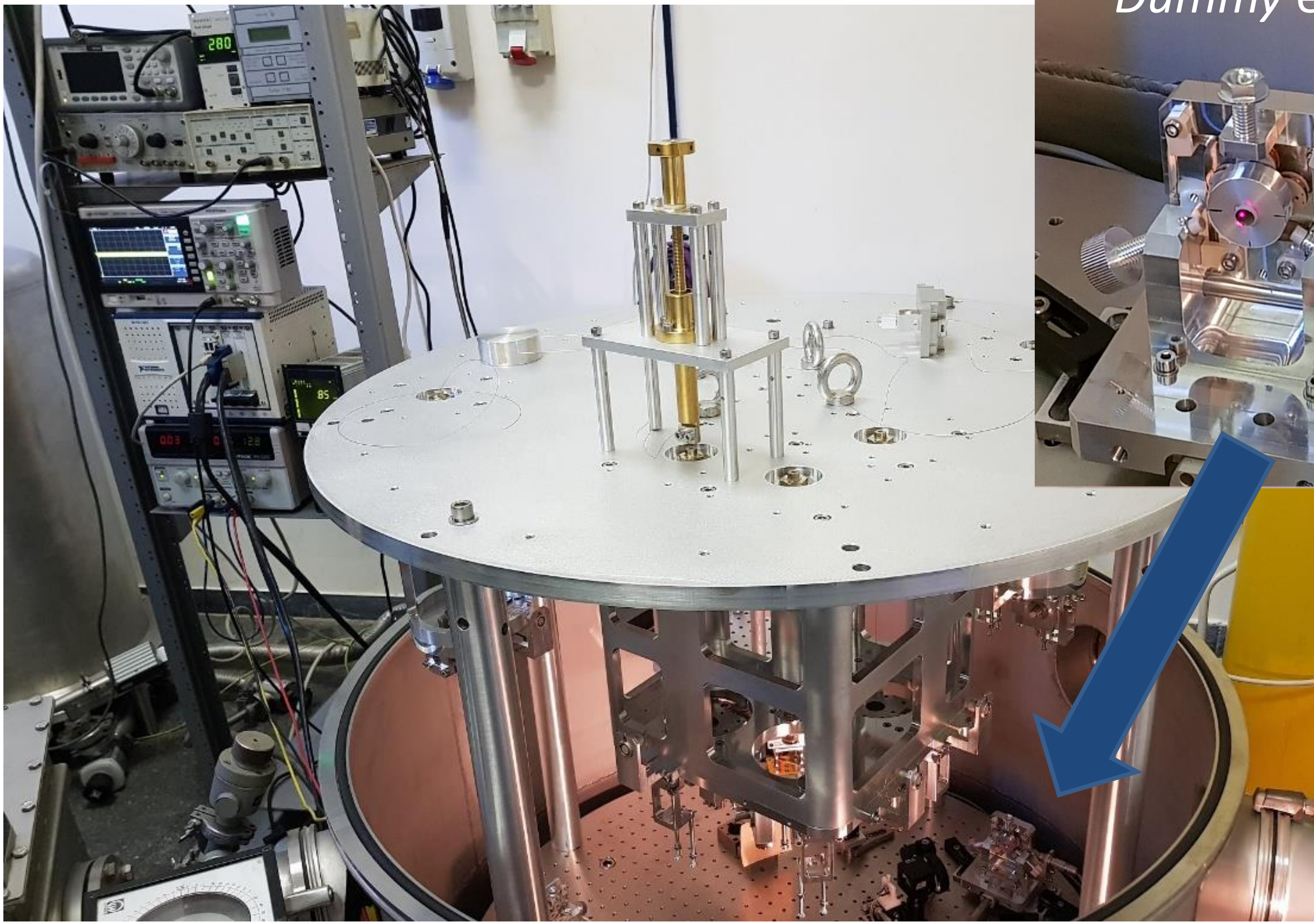


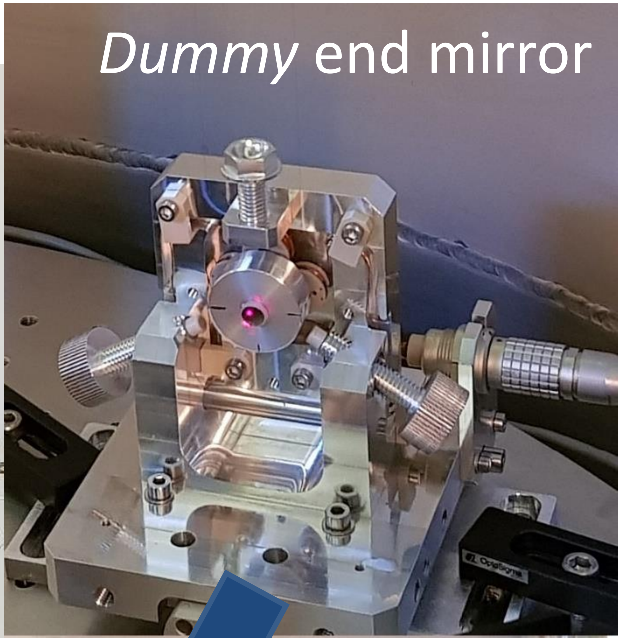
Mirror suspension (mini-payloads)

End Payload vibration modes



Bench Setup

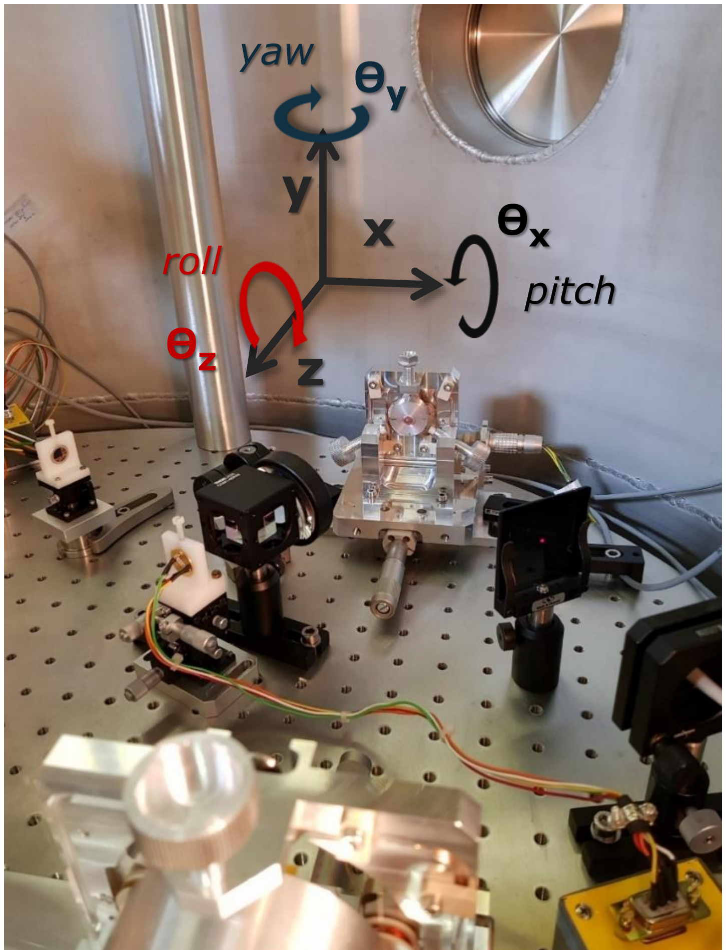




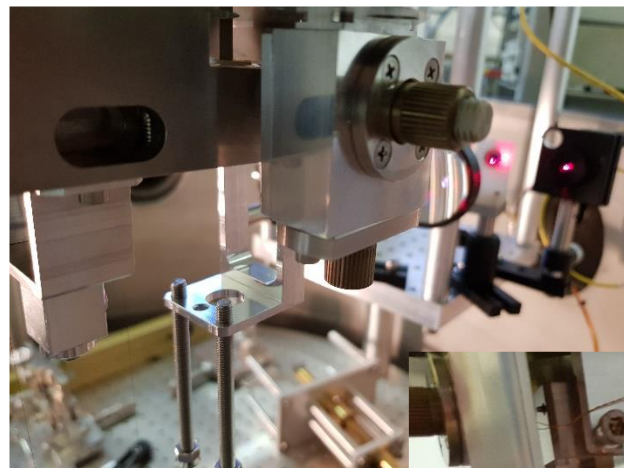
@INFN-Roma1

Bench Setup

Local control of suspended elements



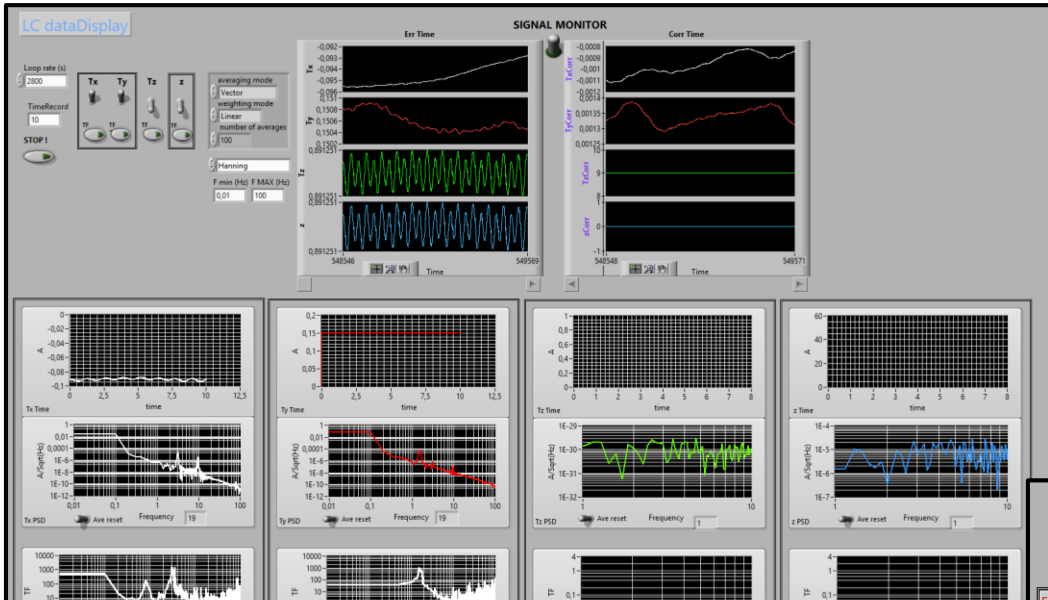
- Optical levers setup for mirror and marionette (5 SLED + QPDs)
- 4 Coil-magnet actuator for each mirror and marionette



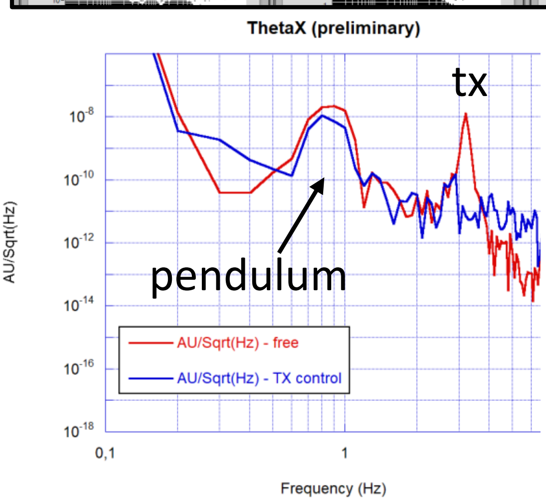
Controlled DOF:
Mirror: z, θx, θy
Marionette: θz, θy
(+z adding a PSD)

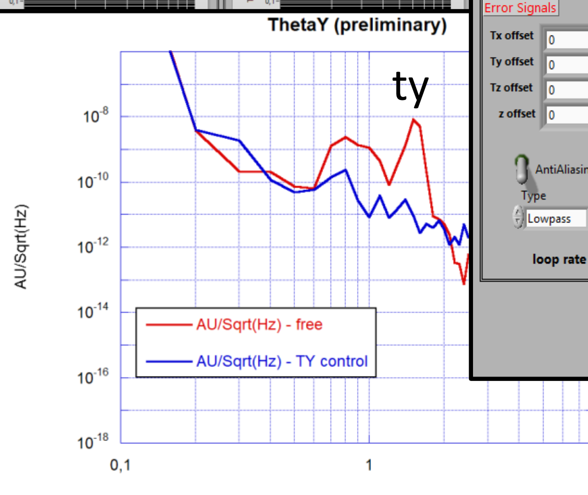
Bench Setup

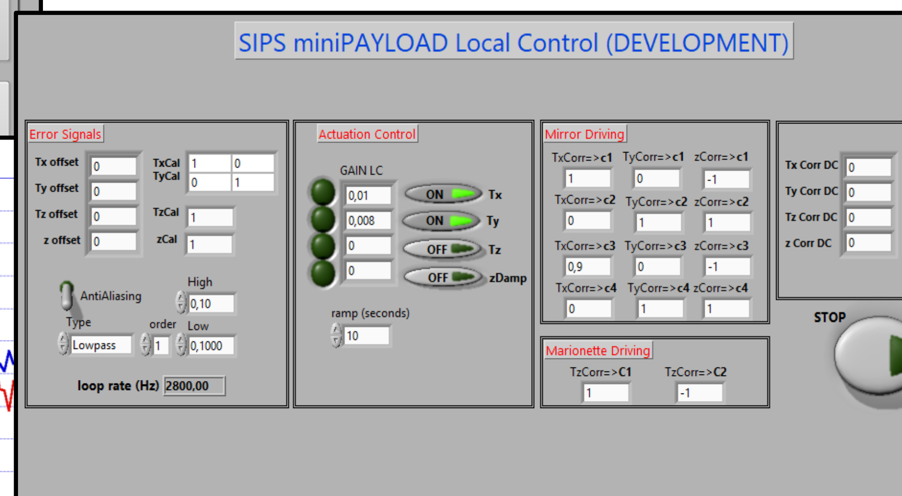
Local control of suspended elements



Local control software developed in LabView environment for monitor and real-time feedback cancellation.







Bench Setup

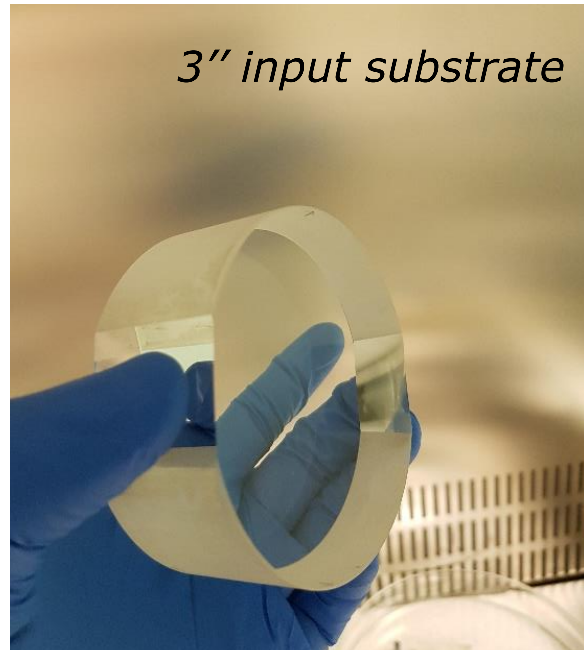
Main optics

Substrates:

- Input mirrors: 3'' diameter, 30mm thickness, 250mm RoC, 300g, *Suprasil*
- Beasplitter 3'' diameter, 30mm thickness, 300g, *Suprasil*
- End mirrros: 1'' diameter, 10mm thickness, 250mm RoC, 10g, *Suprasil*

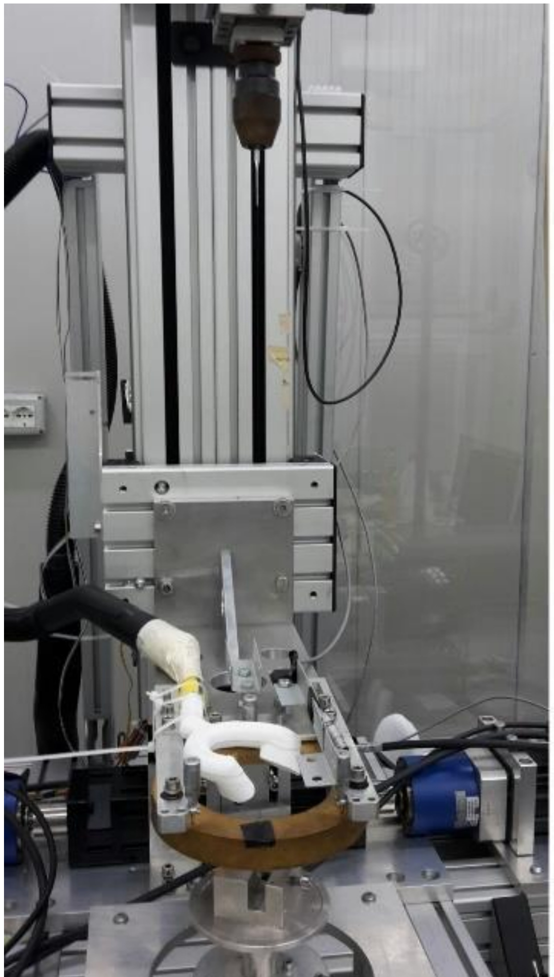
Coatings:

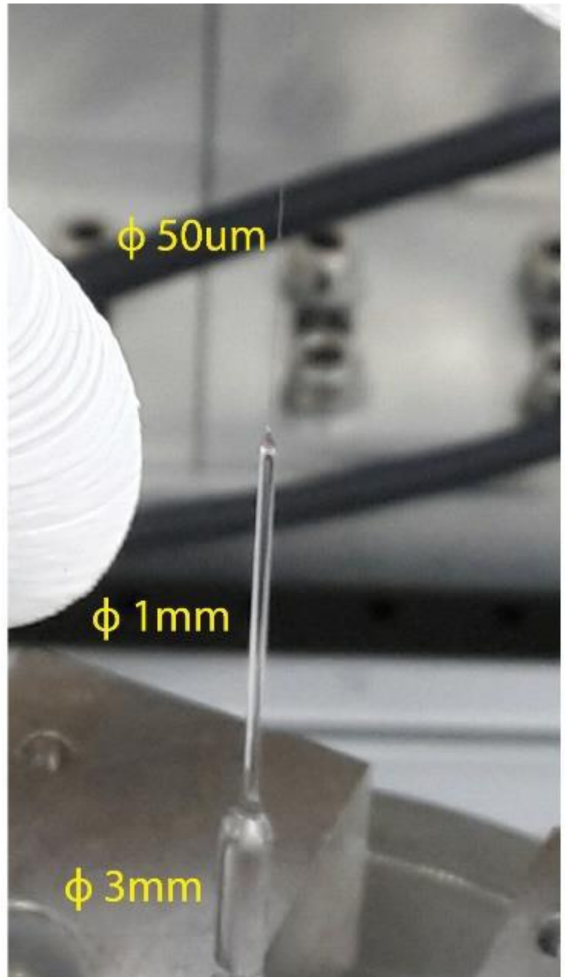
- *input: T=260ppm @0°*
- *End: T=1ppm @0°*
- *BS: 50%±0.05% @45°*

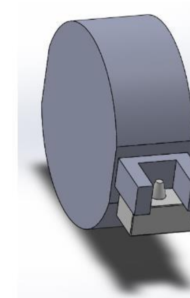


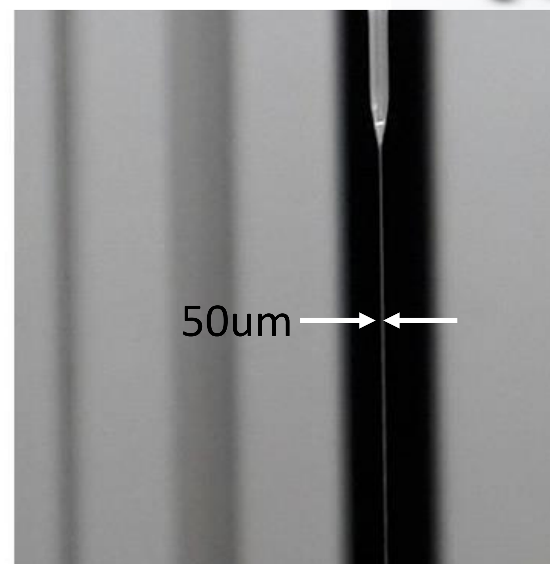
Bench Setup

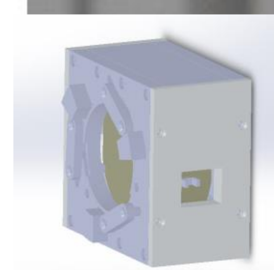
Monolithic suspension of mirrors

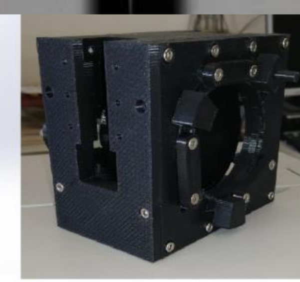




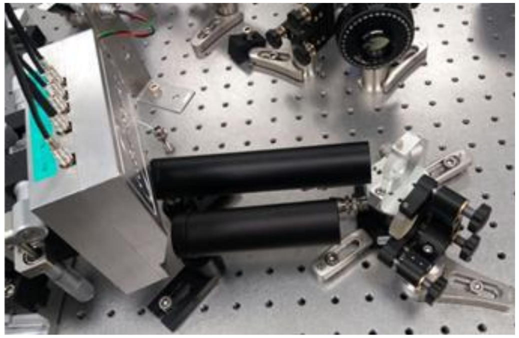






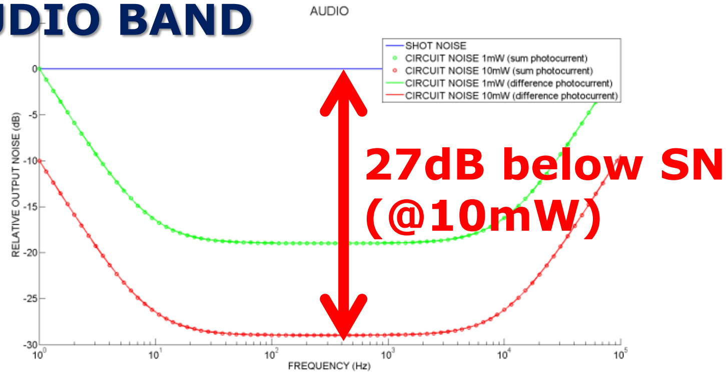


Bench Setup

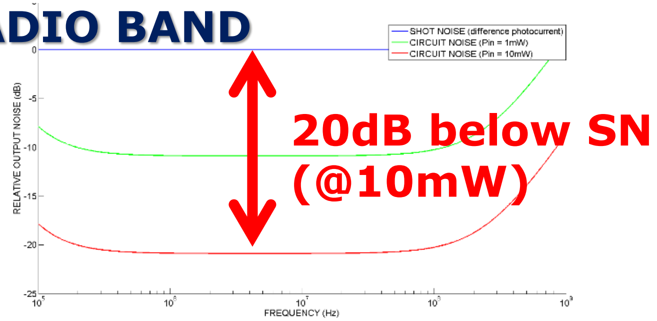


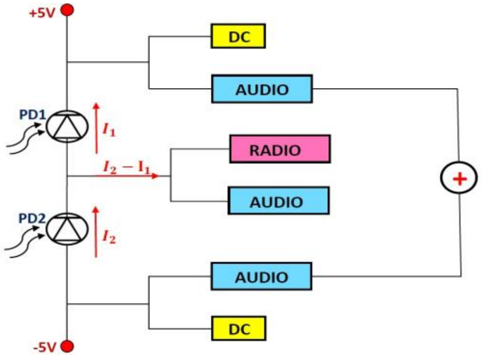
Homodyne detection

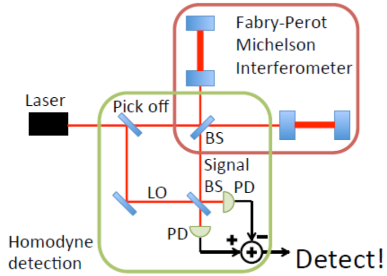
AUDIO BAND

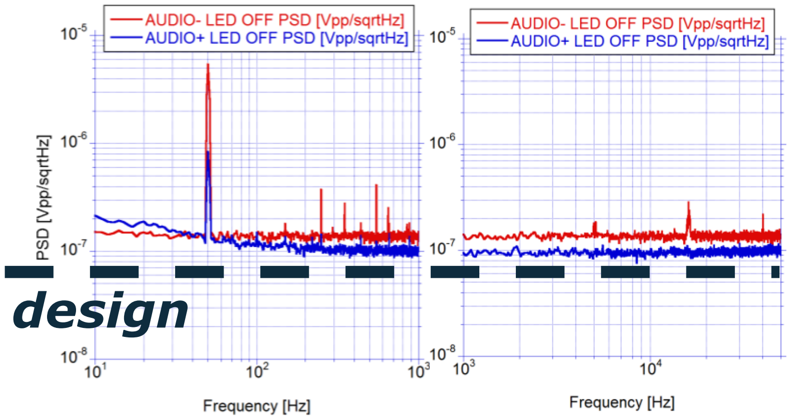


RADIO BAND









Sensitivity

From the **Fluctuation-Dissipation Theorem**:

$$S_X^{FDT}(\omega) = \frac{4k_bT}{m\omega}\frac{\omega_0^2\phi(\omega)}{(\omega^2-\omega_0^2)^2+[\omega_0^2\phi(\omega)]^2}$$

Suspension thermal noise

The overall Φ is given mainly by the Thermoelastic and Surface loss angles:

$$\phi_{te} = \Delta\frac{\omega\tau}{1+(\omega\tau)^2} \qquad \phi_s = \phi_{bulk}(1+8\frac{d_s}{d})$$

where:

$$\Delta = \frac{YT}{c\rho}\left(\alpha-\beta\frac{\sigma}{Y\pi}\right)^2$$

$$\tau = \frac{c\rho d^2}{2.16\cdot 2\pi k}$$

suspension wires:

Marionette *Mirror*

Parameter	C85 steel	Fused silica
density ρ [kg/m^3]	7.9×10^3	2.2×10^3
specific heat c [J/K/kg]	502	772
thermal conductivity k [W/K/m]	50	1.38
thermal expansion coefficient α [1/K]	1.4×10^{-7}	3.9×10^{-7}
temperature T [K]	294	294
young modulus Y [Pa]	2.1×10^{11}	7.2×10^{10}
fractional change of Y(T) β [1/K]	-	1.52×10^{-4}
wire radius r [m]	1.5×10^{-4}	2.5×10^{-5}

$\varphi_{bulk,SiO_2} = 4\times10^{-10}$; $\varphi_{bulk,C85} = 10^{-4}$; $d_{s,SiO_2} = 1.5\times10^{-2}$

coatings thermal noise

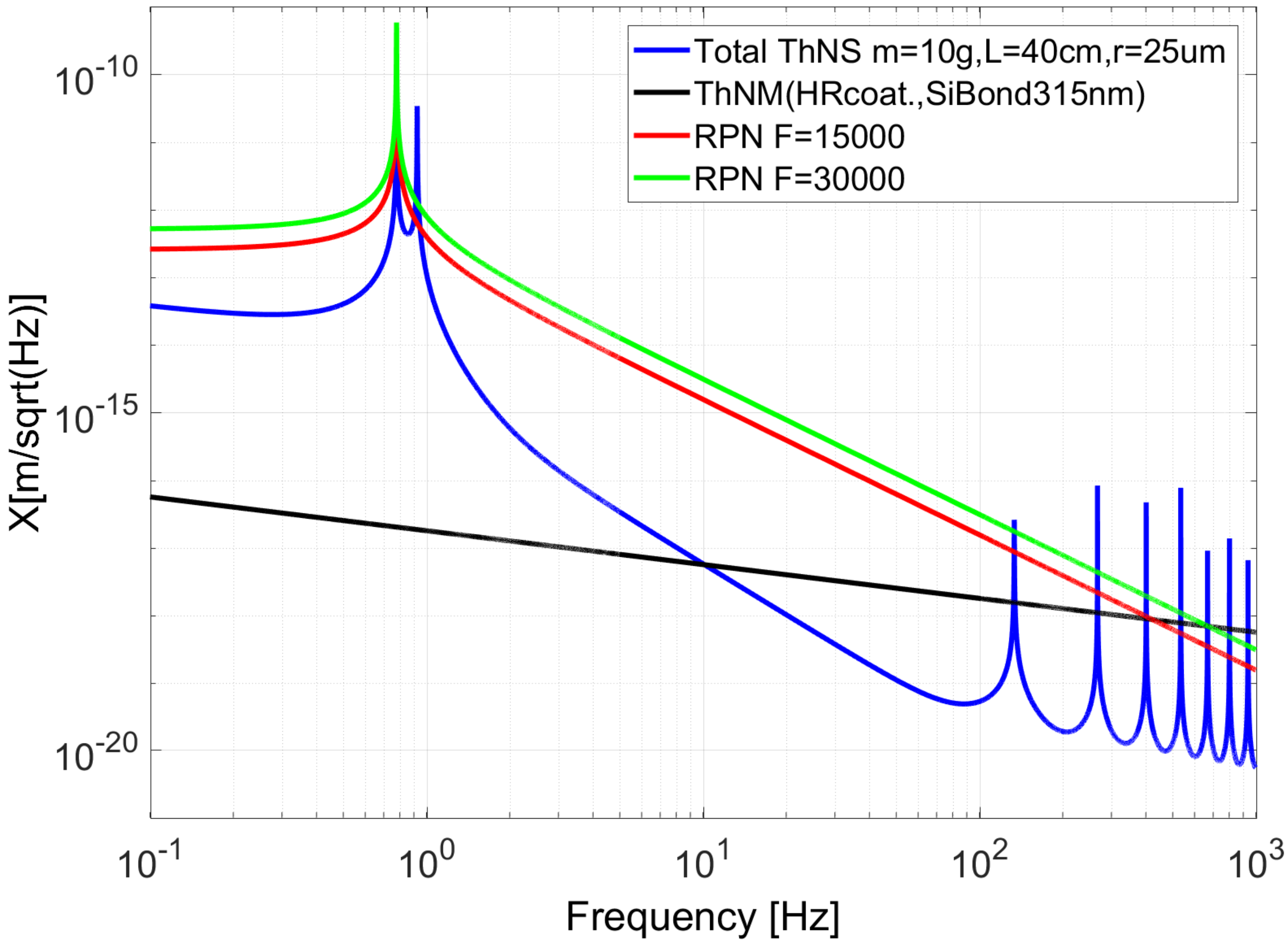
Parameter	value
ρ_{eff}	$4085.8\ kg/m^3$
Y_{eff}	$99.6\ GPa$
ν_{eff}	0.204
ϕ_{coat}	1.48×10^{-4}

$$S_X^{Lev}(f) = \frac{4k_BTE_s\phi_{coat}}{\pi f F_0^2}$$

Strain energy and silicate bonding contribution estimated with a FEM

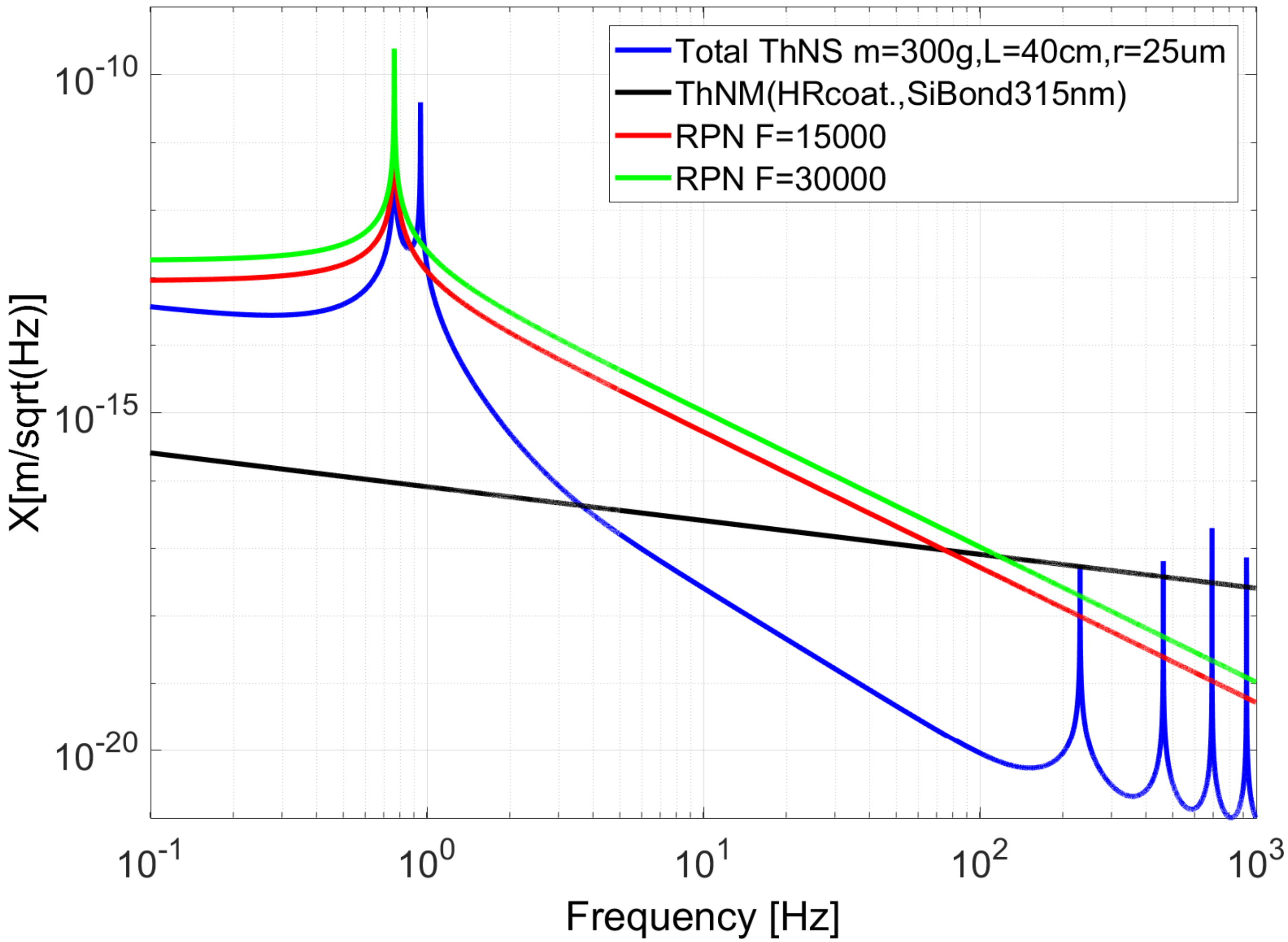
Sensitivity

1″ mirror,
10g



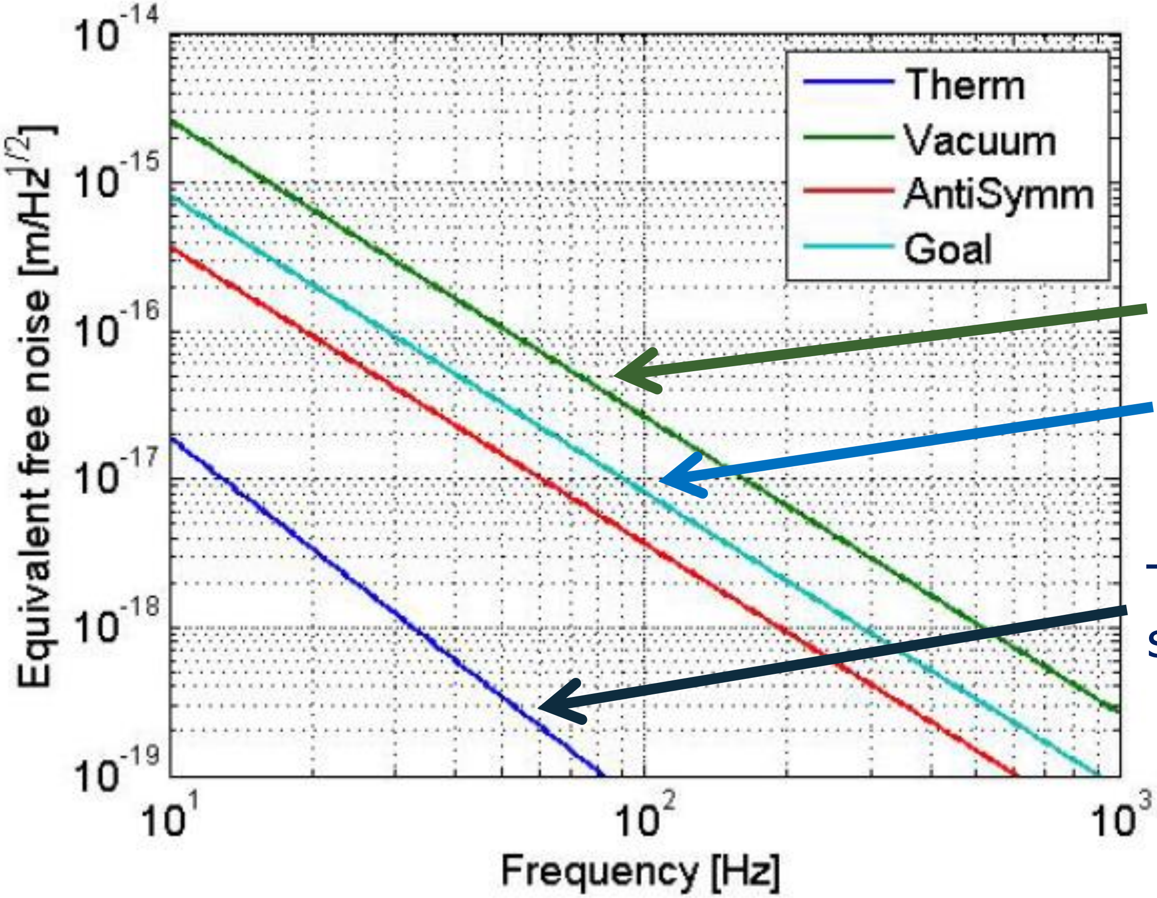
Sensitivity

3'' mirror,
300g



Sensitivity

Interferometer equivalent noise



Unsqueezed vacuum

Conservative (realistic) target: 7dB of squeezing

Thermal noise from suspensions and coatings

Next steps

Table-top Phase

- The mechanical setup is almost complete, main optics will be delivered in May 2019;
- The setup will be moved to the Squeezing Lab at EGO (Virgo);
- Main optics and monolithic suspension will be installed at EGO.

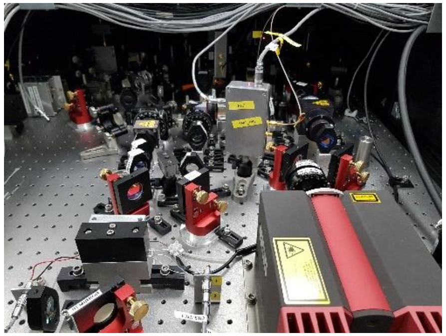
Suspension Phase

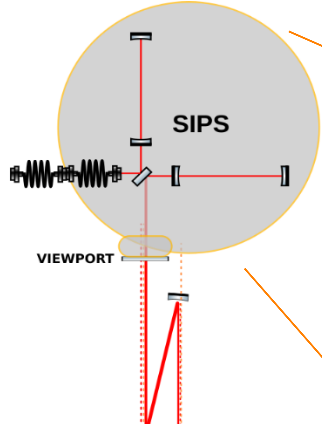
- Refit of SAFE suspension, integration study;
- Integration of SIPS in SAFE.

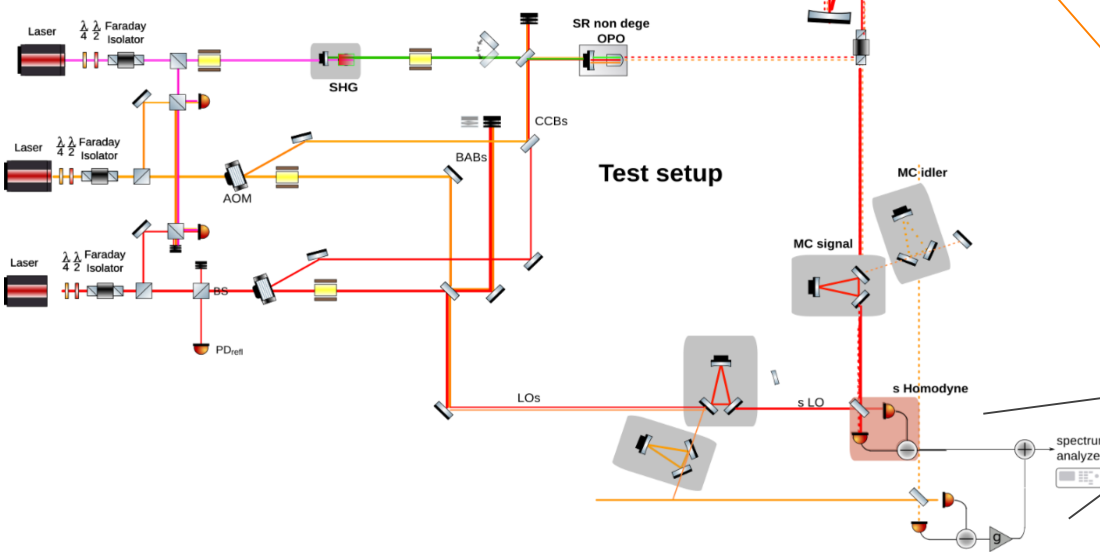
But meanwhile…

Next steps

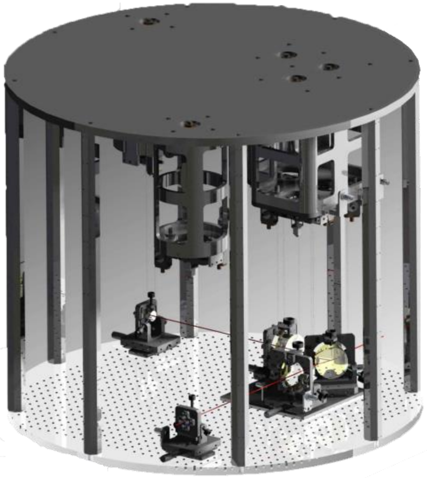
Spin-off: demonstration of EPR entanglement squeezing using SIPS cavities as a test-bed

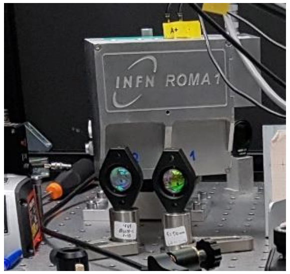






→ Valeria Sequino's talk!





Conclusions

- 1. Ponderomotive squeezing is an interesting alternative to "classic" OPO-based squeezing;

- 2. Given an adequate seismic and thermal noise reduction it is possible to design a tabletop interferometer with *macroscopic* mirrors quantum coupled by radiation pressure → *ponderomotive squeezing*;

- 3. SIPS is an experiment with the target of squeezing generation through ponderomotive technique in the *audio-band*;

- 4. The tabletop experimental setup will be used also as a testbed for EPR-entanglement squeezing generation.

Thanks for your attention!