Small scale Suspended Interferometer for Ponderomotive Squeezing (SIPS) as test bench for EPR squeezer integration in Advanced Virgo

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OUTLINE

1. Quantum noise in GW detectors
2. Ponderomotive squeezing
3. SIPS interferometer
4. Status of SISP construction
5. Integration with EPR squeezer
6. Conclusions and perspectives

1. Quantum Noise in GW detectors

Quantum Noise

is the uncorrelated sum of: $h_{quantum}(\nu) = \sqrt{h^2_{shot}(\nu) + h^2_{RP}(\nu)}.$

Shot Noise (SN)

sensing noise

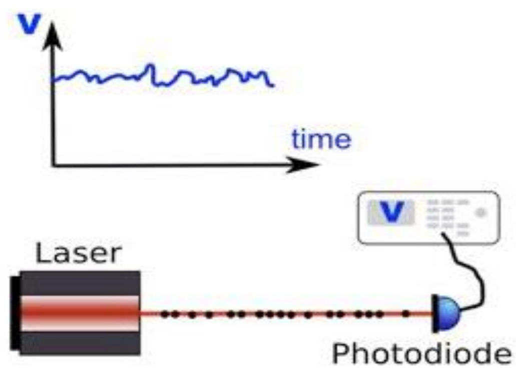
Photons arriving on the photo-detector follow a Poisson distribution in time, inducing **photo-current fluctuations**

Radiation Pressure Noise (RPN)

back-action noise

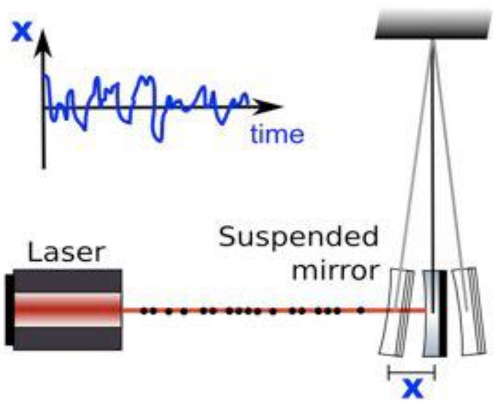
Photons impinging on the suspended mirror transfer their momentum (RP force) and due to electrical fields fluctuations inside the cavity they induce **mirror position fluctuations**

Phase Noise



$$X_{shot}(\omega) = \frac{1}{8\mathcal{F}}\sqrt{\frac{2h\lambda c}{P_{las}}}.$$

Amplitude Noise

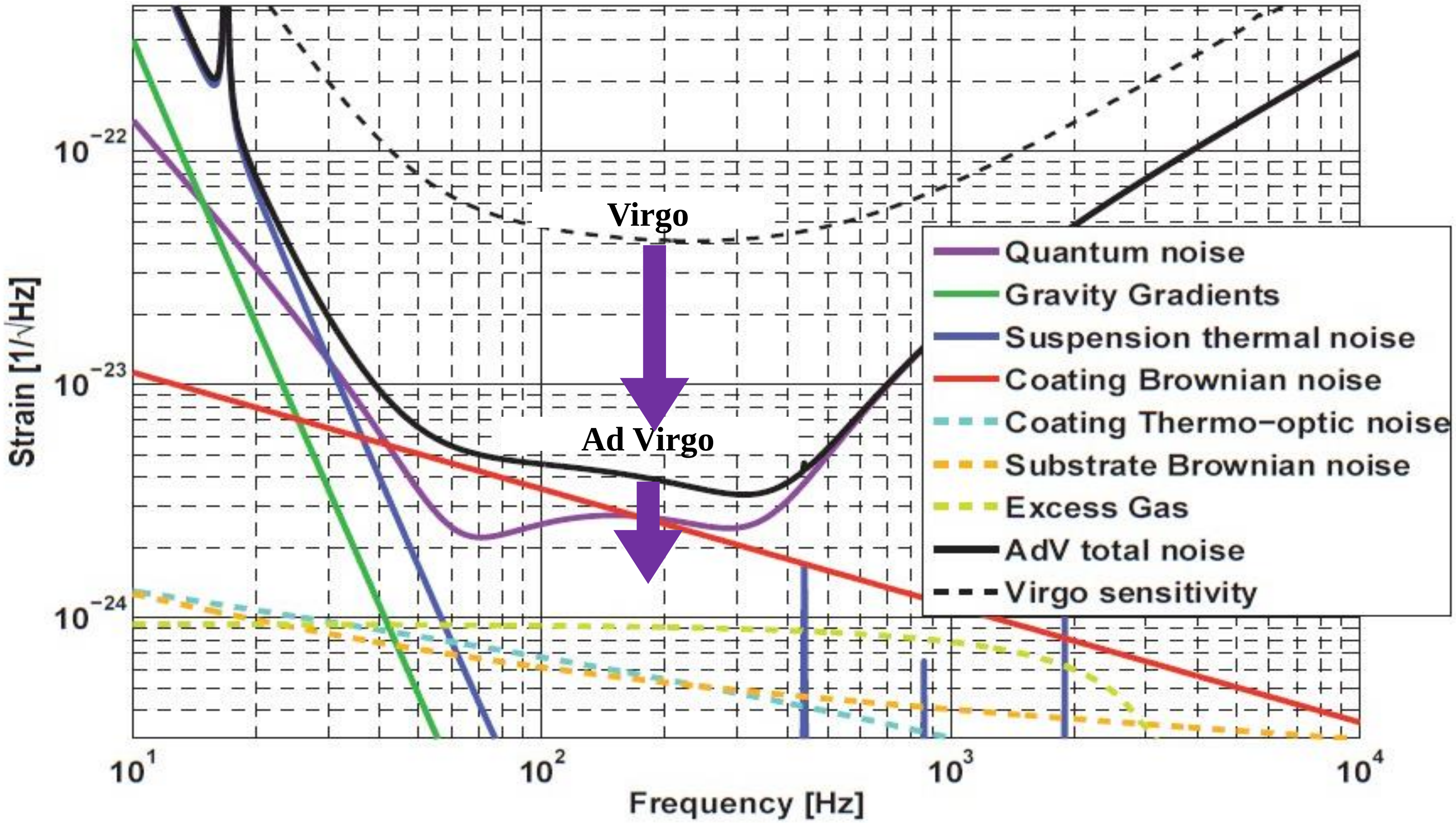


$$X_{RP}(\omega) = 2\frac{\mathcal{F}}{m\omega^2}\sqrt{\frac{8h}{(2\pi)^2}\frac{P_{las}}{\lambda c}}$$

1. Quantum Noise in GW detectors

Quantum Noise (**SN** & **RPN**) constitutes the Standard Quantum Limit (SQL): an intrinsic limit in the position measurements of a free mass using coherent light

Advanced Virgo Noise Curve expected for input Pin=125W



Advanced Virgo TDR (2012)

1. Quantum Noise in GW detectors

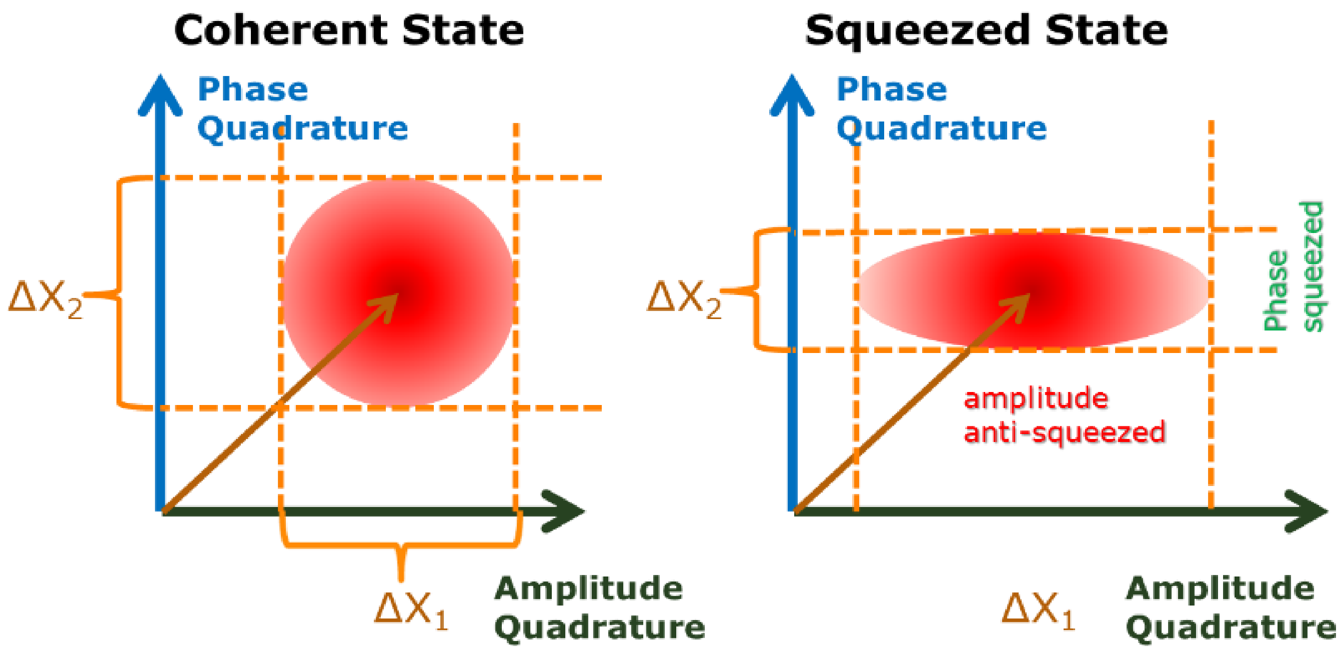
Quantized electromagnetic field:

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

X_1 = Amplitude Quadrature → $\Delta X_1 = X_{RP}$ Radiation Pressure Noise

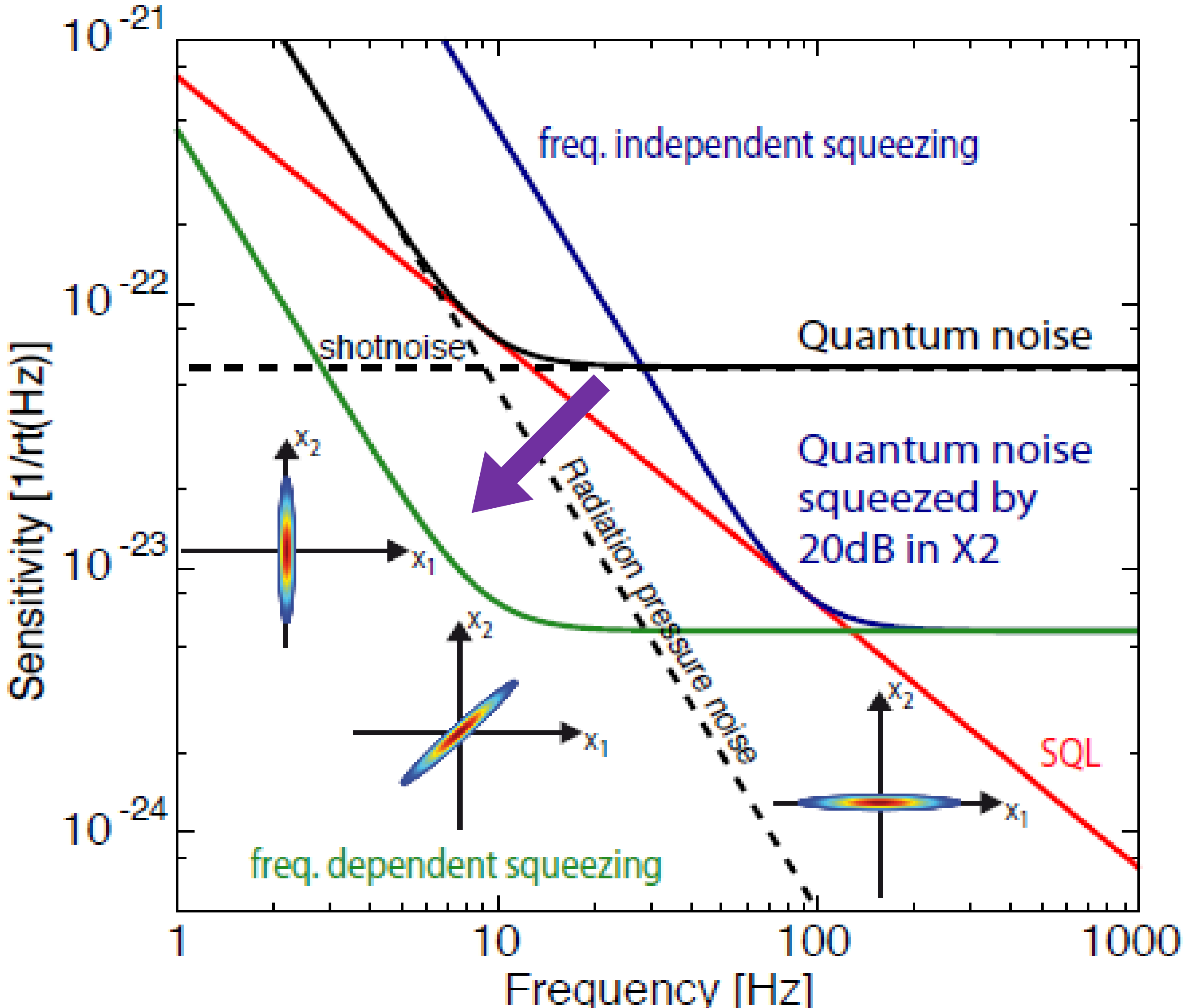
X_2= Phase Quadrature → $\Delta X_2 = X_{shot}$ Shot Noise

ΔX_1, ΔX_2 related by the **Heisenberg Principle**: $\langle(\Delta\hat{X}_1)^2\rangle\langle(\Delta\hat{X}_2)^2\rangle \geq \frac{1}{16}$



1. Quantum Noise in GW detectors

Injecting Squeezed State at the dark port of a GW detector reduces Quantum Noise

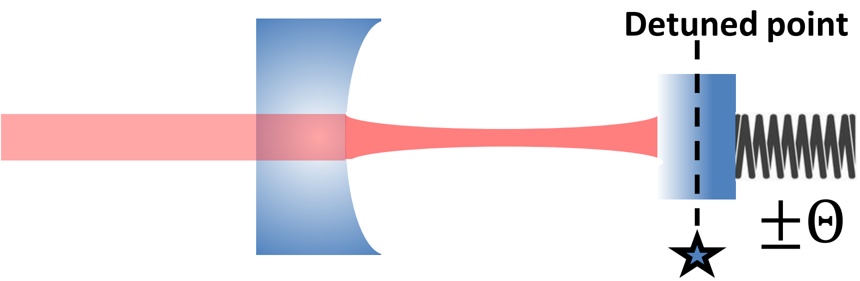


Credits H.Vahlbruch, (2008)

Frequency Dependent Squeezing (FDS) increases sensitivity in all frequency spectrum without the need of a high laser power

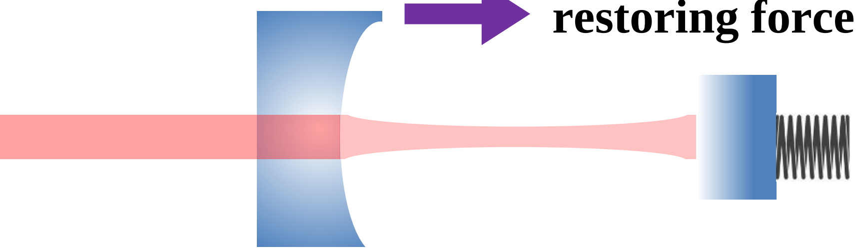
Opto-Mechanical coupling in a detuned cavity

Optical spring



cavity longer, detuning increases, power decreases

restoring force



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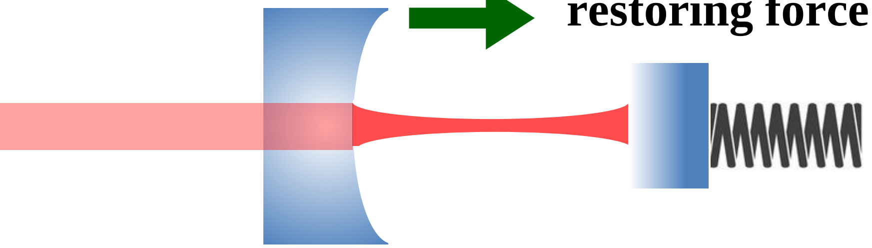
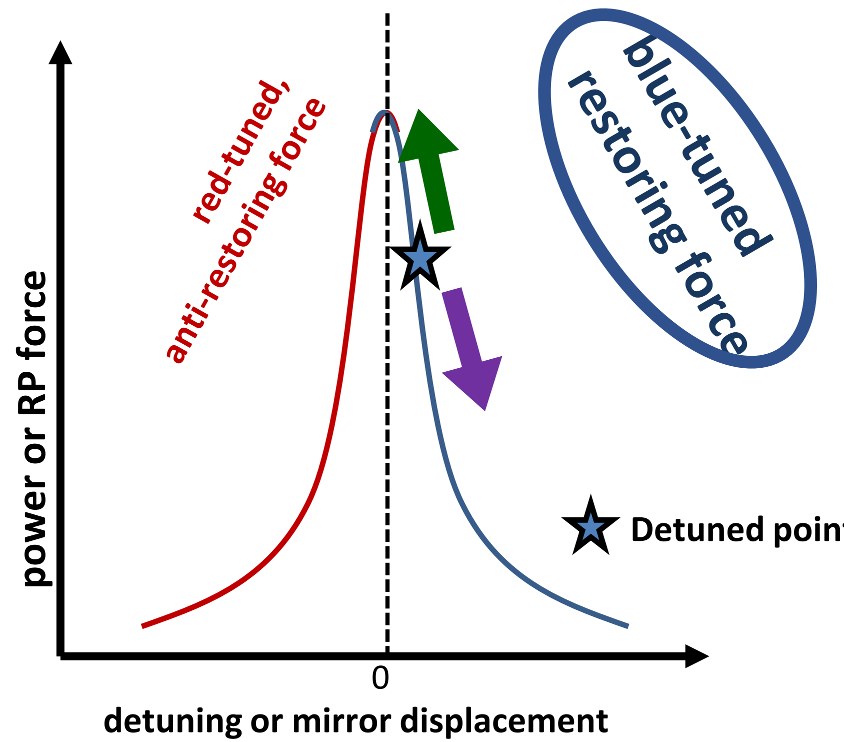


±Θ Optical Spring Frequency

$$F \cong kx - \gamma\dot{x} \qquad F \cong -kx + \gamma\dot{x}$$



γ: (anti)damping term ↔ spring instability

2. Ponderomotive Squeezing

In an optical cavity with suspended mirrors

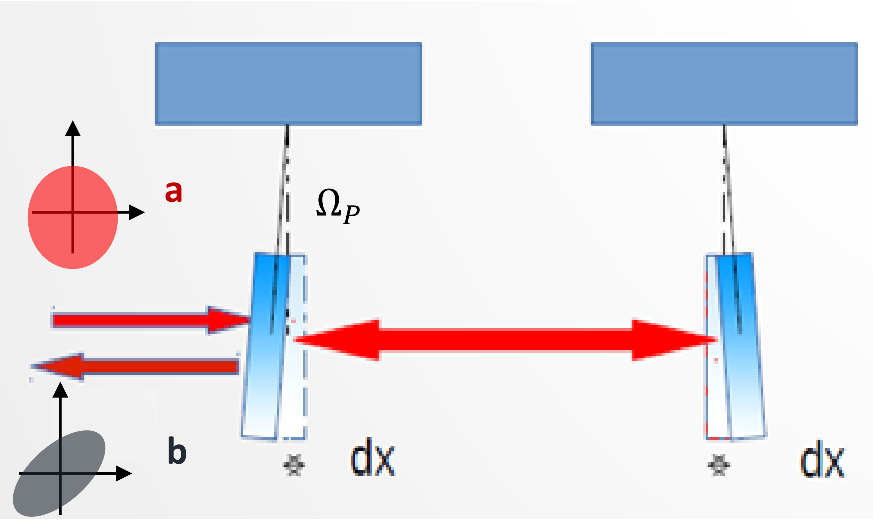
Amplitude fluctuations **of the field inside the cavity induces motion of the suspended mirror**

The displacement of mirror produces a ***phase shift*** **in the reflected light**

The produced ***phase shift*** **is proportional to the** ***amplitude fluctuations***

↓

coupling between ***phase*** **and** ***amplitude*** **quadrature fluctuations**



2. Ponderomotive Squeezing

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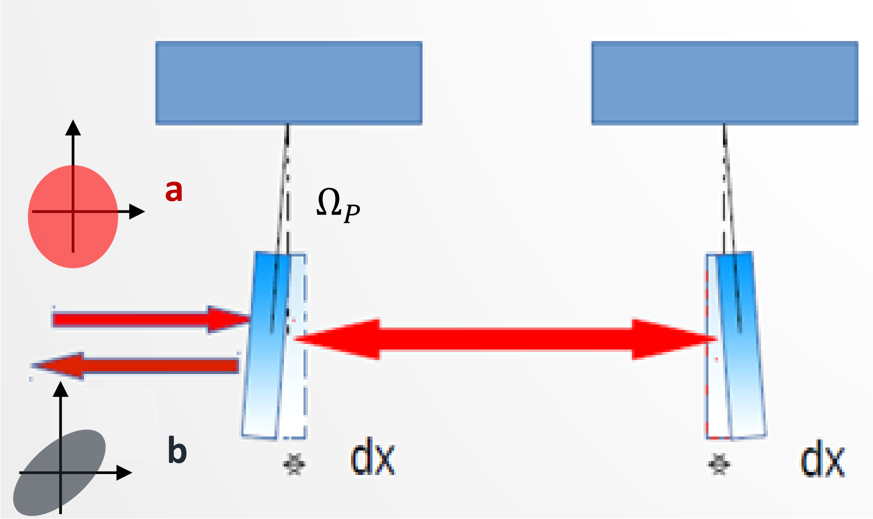
↓

coupling between *phase* and *amplitude* quadrature fluctuations

↓

PONDEROMOTIVE SQUEEZING

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



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

coupling factor (frequency-dependent)

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

ponderomotive squeezing factor (freq.-dependent)

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

Corbitt, et al. 2006

2. Ponderomotive Squeezing

If the mirror mechanical resonance Ω_P is such that $\Omega_P \ll \Omega, |\Theta|$
Ω_P depends only on the ***optical spring frequency*** $\pm\Theta$

$$\begin{cases} \Omega \gg |\Theta| & \text{Output not squeezed} \\ \Omega \approx |\Theta| & \text{Frequency Dependent Squeezing} \\ \Omega \ll |\Theta| & \text{Frequency Independent Squeezing} \end{cases}$$

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

$$\mathcal{K} = \frac{1}{\bar{\delta}_\gamma}$$

ponderomotive squeezing factor

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

The *optical spring frequency* $|\Theta|$ depends on:
input power W, cavity finesse $\mathcal{F}$ ***, detuning factor*** δ_γ ***mirror mass M***

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

Corbitt, et al. 2006

Once $|\Theta|$ has been fixed, we design the suspension system to have
$\Omega_P \ll |\Theta|$

Real parameters must be chosen to ensure a **large squeezing factor** and a **suitable squeezing band**, taking into account the mechanical feasibility

3. SIPS interferometer

from 2014

POLIS

Preliminary R&D on a low frequency ponderomotive squeezer in the past years (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

Mechanical design and realization (Roma1)
Optical design (Napoli, Roma2)
Main laser (Urbino, Napoli)
Optical benches (Pisa)

from 2017

SIPS

The experimental setup was then funded in the past 2 years (2017-2018) by **INFN** – CSN5 under the name of SIPS and the collaboration of

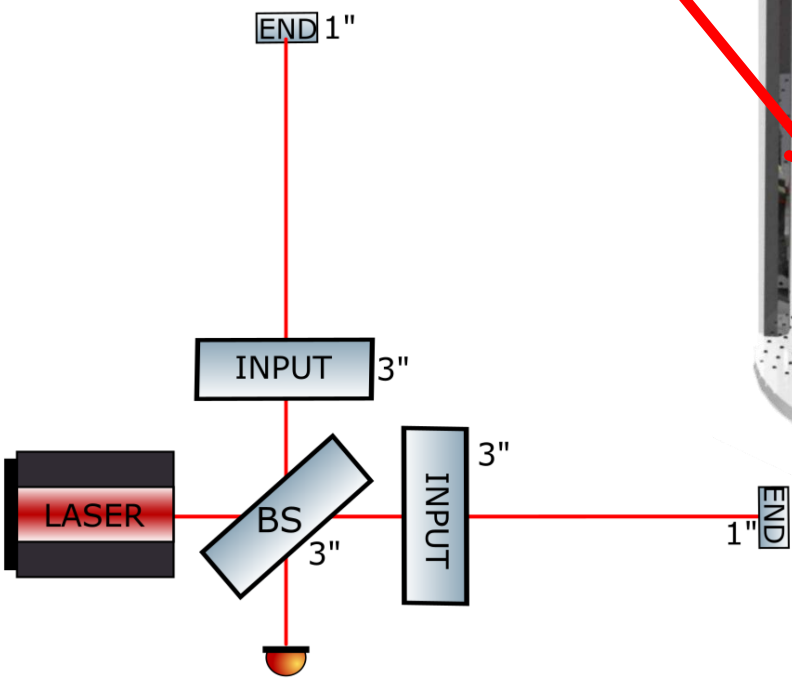
Mechanical design and realization (Roma1)
Monolithic Suspension (Perugia)
Optical benches (Pisa)

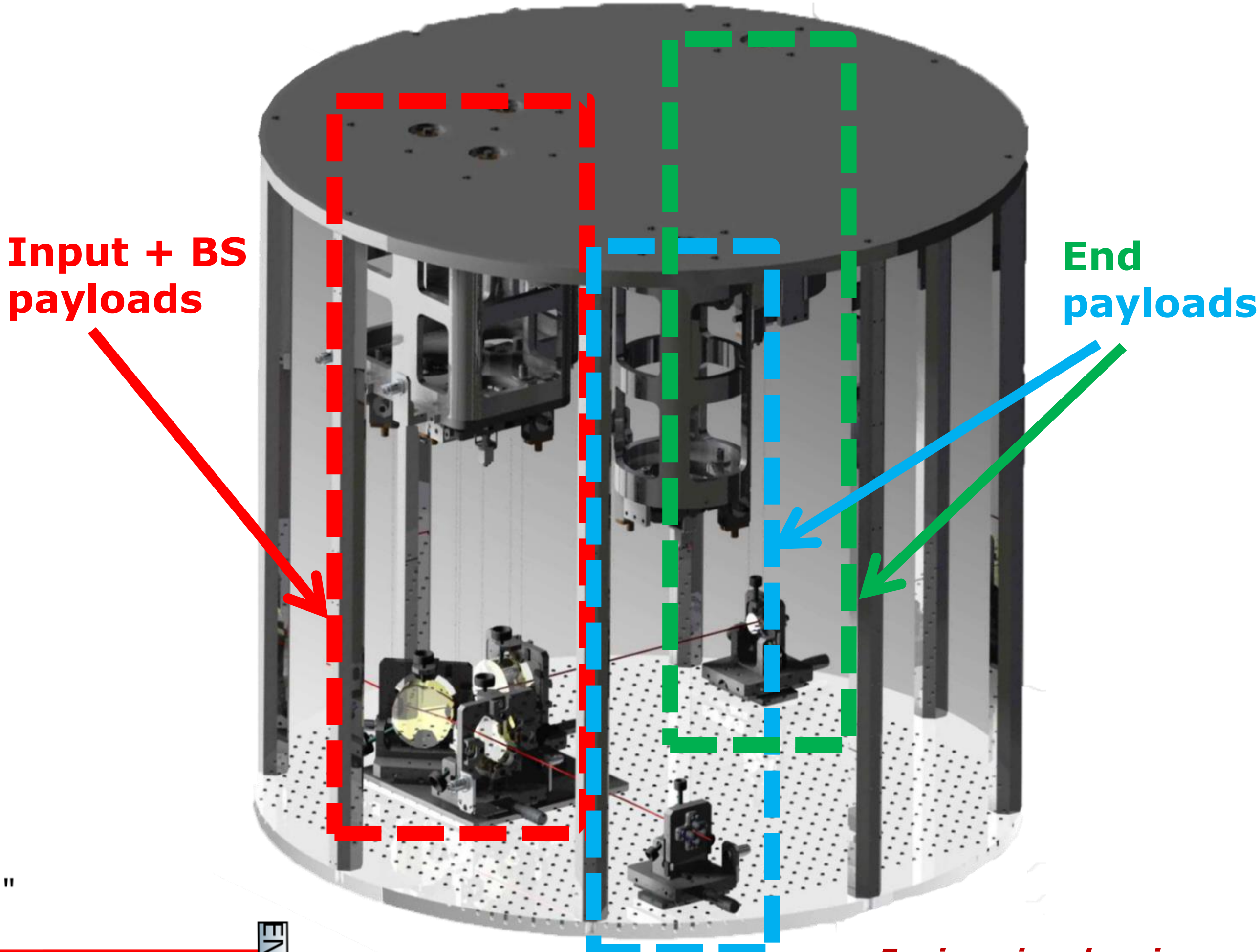
SIPS as test bench for EPR squeezing

Since end 2017 collaboration with EPR squeezing group of INFN and Virgo

3. SIPS interferometer

Small scale Suspended Interferometer for Ponderomotive Squeezing





Engineering drawing

3. SIPS interferometer

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**)

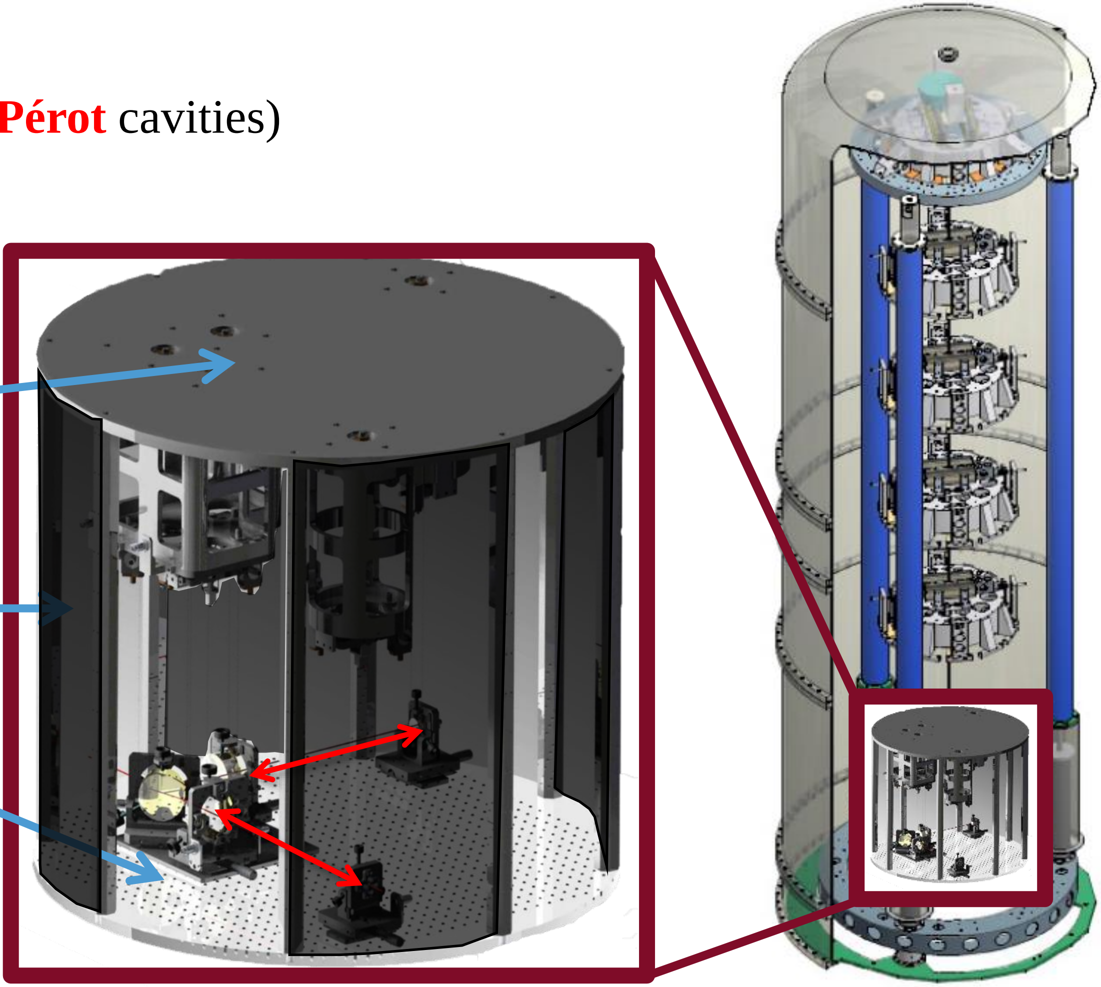
Height: 800 mm
Diameter: 960 mm (two **Fabry-Pérot** cavities)
Weight: ~ 150 kg

Material: anticorodal (Al-alloy)

Upper plate
(auxiliary bench)

Cylindrical baffles

Main optical bench



The structure must combine **high stiffness** (to push up the mechanical mode frequencies) and **low mass** (< SAFE limit)

3. SIPS interferometer

Parameters Choice

Squeezing factor and band

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)*

Optical spring

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

For other parameters: trade-off with experimental constraints such us allowed space in SAFE, suspension system

Cavity length: L = 350 mm
Mirror RoC: RoC = 250 mm

Cavity stability

Suspended mirror mass

High values	**Low values**
easy to suspend	High optical spring resonance
easy to sense and actuate	not easy to suspend

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

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

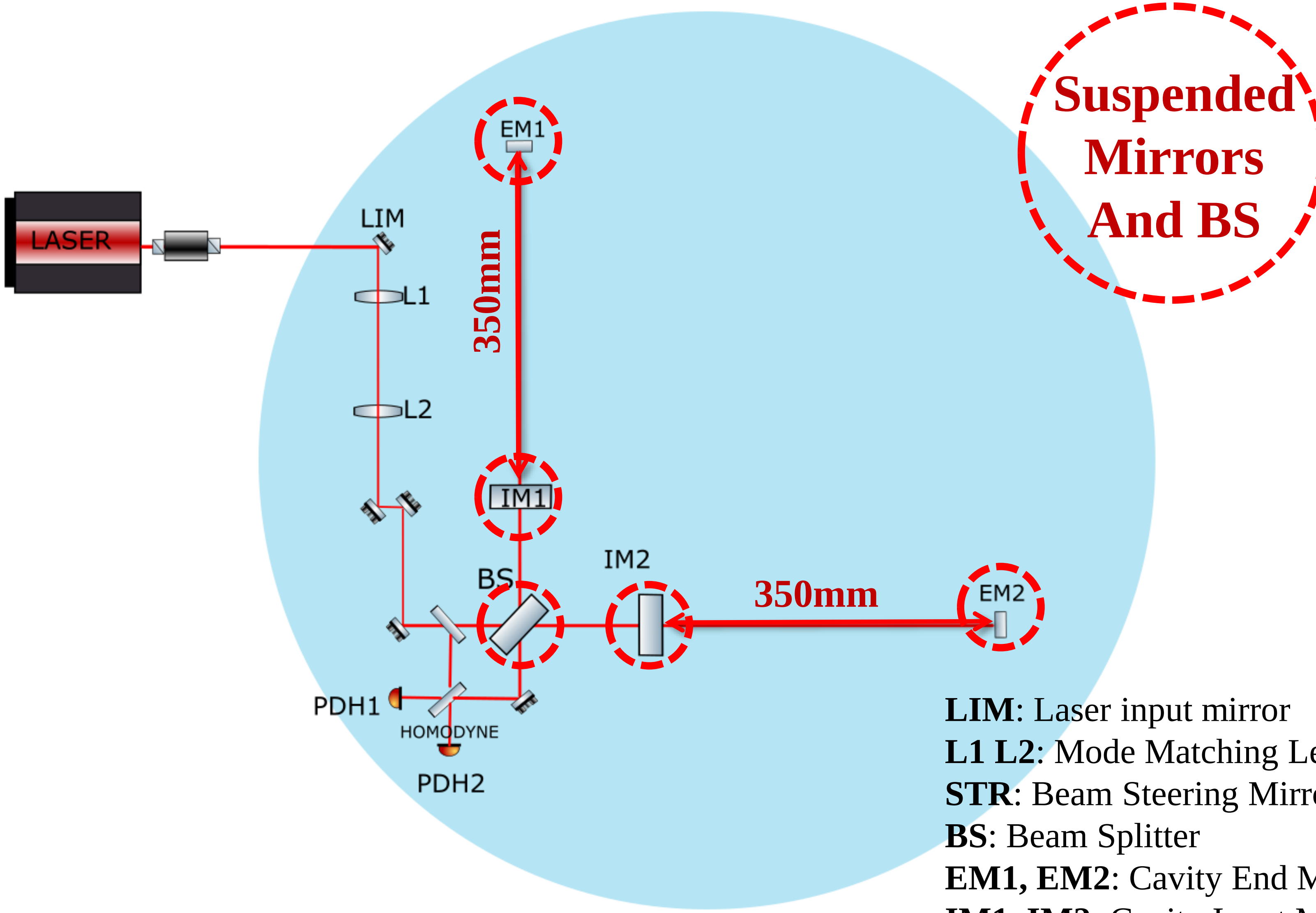
1 inch fused silica mirror, 10mm thick: mass of ~10g

3 inch fused silica mirror, 30mm thick: mass of 300g

They can be suspended with a monolithic Virgo-like technique for thermal noise reduction

Higher mass value relaxes the sensitivity requirements

Main Optical Bench Design



LIM: Laser input mirror
L1 L2: Mode Matching Lenses
STR: Beam Steering Mirrors
BS: Beam Splitter
EM1, EM2: Cavity End Mirror
IM1, IM2: Cavity Input Mirror

3. SIPS interferometer

Requirements: suspension thermal noise of the lighter end-mirror must be below $X_{ThNS} \leq 10^{-16}\, m/\sqrt{Hz}$ at 10 Hz: if not squeezing would be undetectable.

Suspension Thermal Noise

The total thermal noise of the suspensions is:

$$X_{ThNS}(\omega) = \sqrt{X^2_{thpend}(\omega) + X^2_{vio}(\omega)}$$

$$X_{thpend}(\omega) = \sqrt{\frac{4\, k_B\, T}{m\, \omega}} \sqrt{\frac{\omega_p^2\, \phi_p(\omega)}{\left(\left(\omega_p^2 - \omega^2\right)^2 + \left(\omega_p^2\, \phi_p(\omega)\right)^2\right)}}$$

The overall ϕ_p pendulum loss angle is mainly given by the thermoelastic ϕ_{te} and surface ϕ_e **loss angles**

$$\phi_p(\omega) = D_{ilF}\left(\phi_{SiO2} + \phi_e + \phi_{te}(\omega)\right)$$

Mirror Thermal Noise

Levin's approach, FE analysis with ANSYS

$$X_{Levin}(\omega) = \sqrt{\frac{8\, k_B\, T}{\omega\, F_0^2} U_{mirr} \phi_{tot}}$$

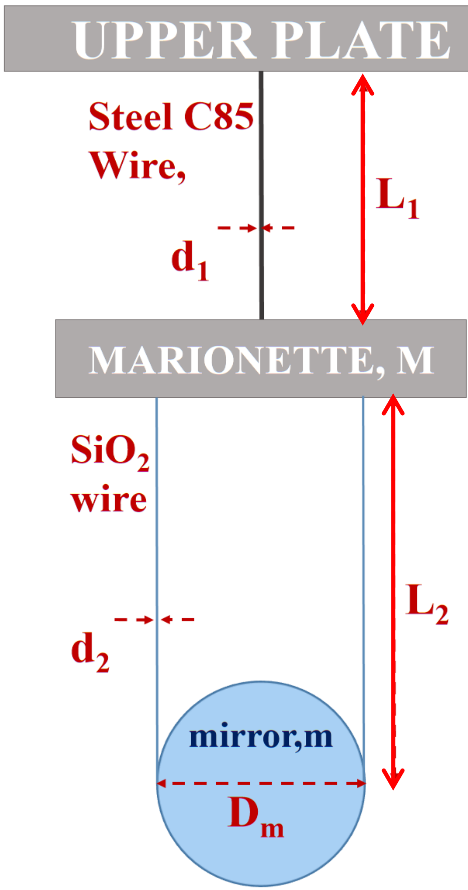
U_{mirr} = total strain energy
ϕ_{tot} = Sum of all dissipative contributions calculated *(AdV like coating + 315nm thick Silicate Bonding)*

impinging Gaussian pressure $P = \frac{2\, F_0}{\pi w^2} e^{-\frac{2\, r^2}{w^2}}$

w = beam waist on mirror
r = coord. on mirr surface
F_0 = 1 integrated force

Monolithic suspension system of the main optics: Minipayload

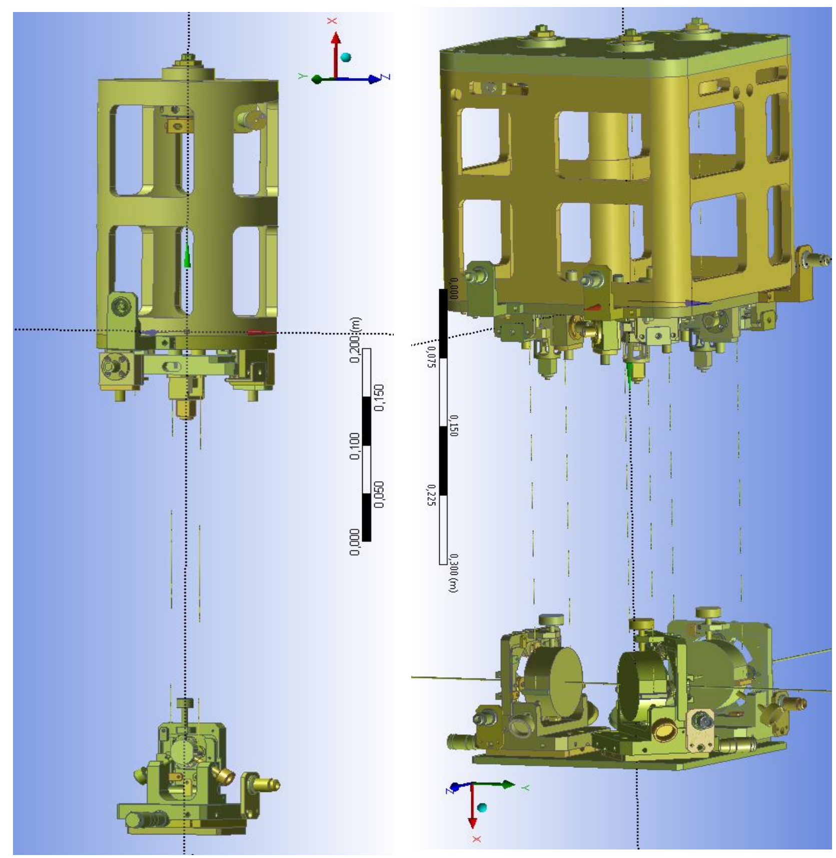
Double Pendulum System with Monolithic Suspension of the main optics



Marionette for all payloads:
Mass M=**1.1kg**
Suspended by one steel C85 wire, **d_1=300µm, L_1=30cm**
Control: magnet-coil actuators

Mirrors:
Input: diameter **3”**, mass **300g**
BS: diameter **3”**, mass **300g**
End: diameter **1”**, mass **10 g**
Suspended by two fused silica fibers: **d_2 = 50µm, L_2=40cm**
Control: magnet-coil actuators.

END **BS + 2 INPUT**



4. Status of SIPS

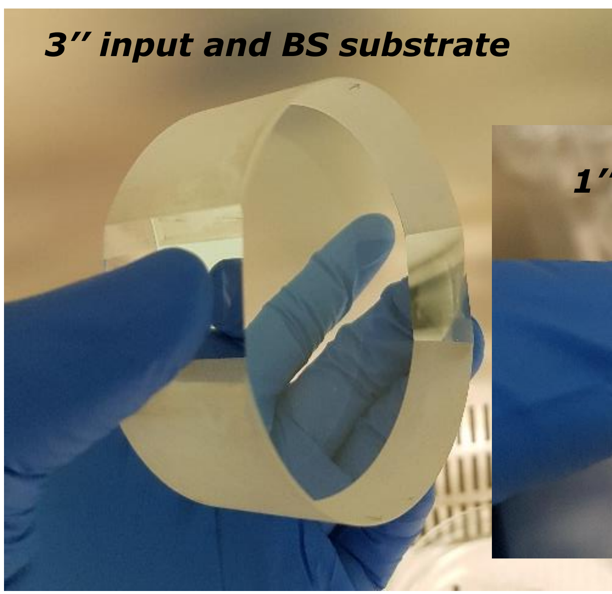
Main Optics

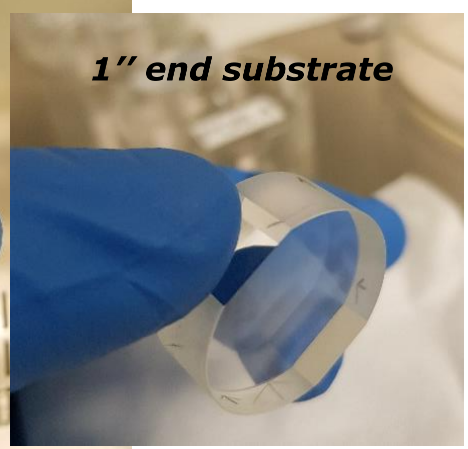
Substrates of SUPRASIL:

- Input mirrors: 3”, 30mm, RoC 250mm, 300g
- Beam Splitter 3”, 30mm, 300g
- End mirros: 1”, 10mm, RoC 250, 10g

Coatings:

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



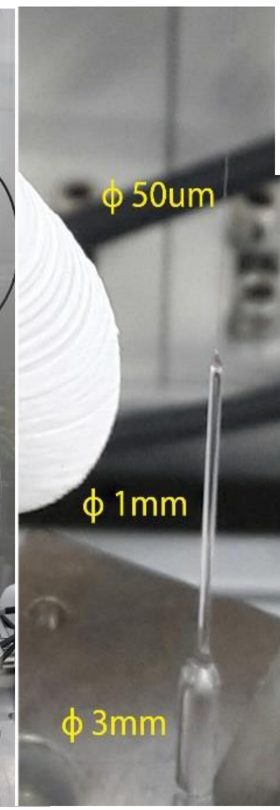


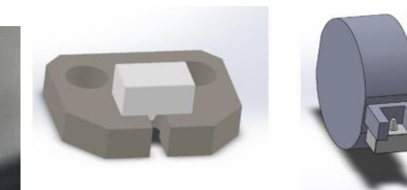
Monolithic Suspension

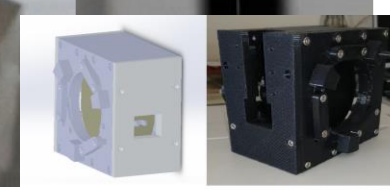
CO_2 Laser Machine @EGO

50µm diameter fused silica fibers

Ears-Anchors system:

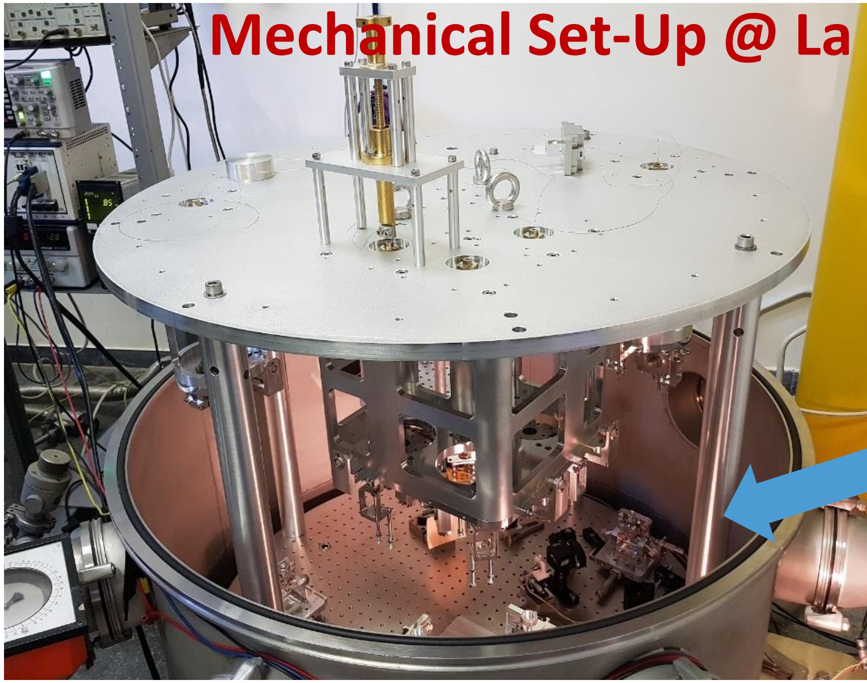


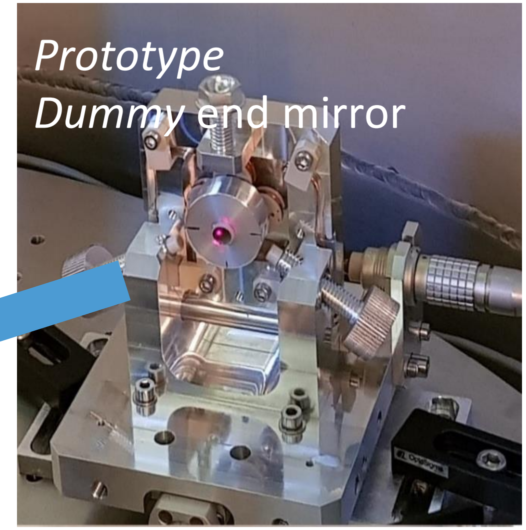




4. Status of SIPS

Mechanical Set-Up @ La Sapienza & INFN Roma1

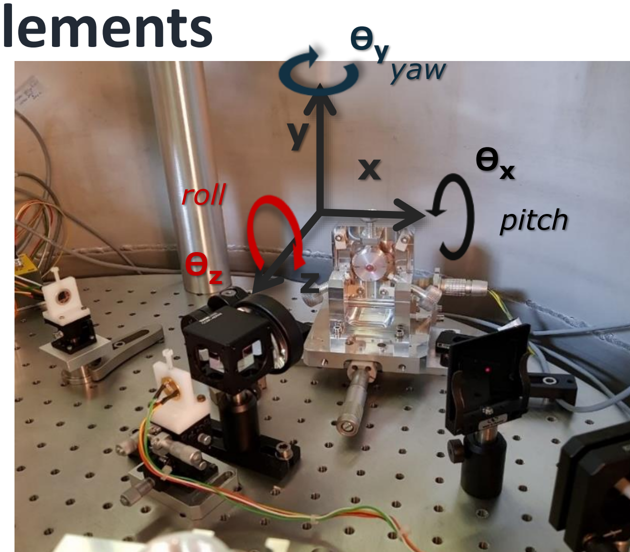




Local control of suspended elements

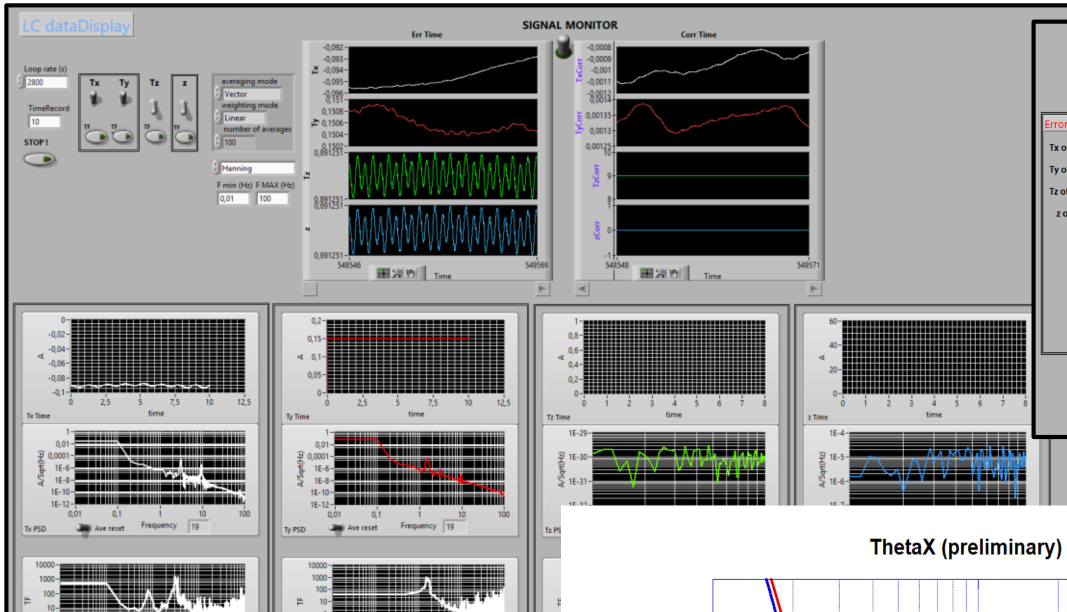
- Optical levers setup for mirror and marionette (5 SLED + QPDs)
- 4 Coil-magnet actuator for each mirror and marionette

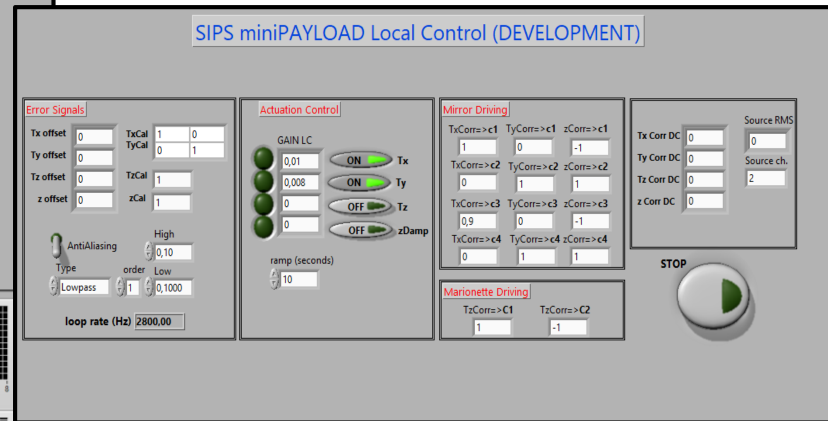
Controlled DOF:
Mirror: z, θx, θy
Marionette: θz, θy



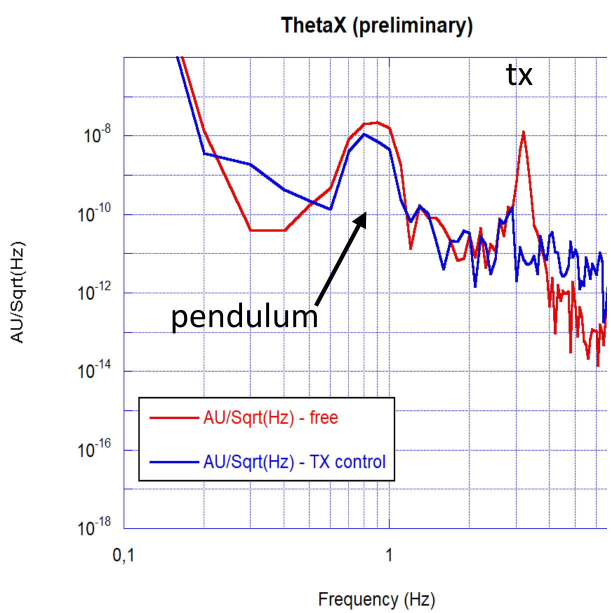
4. Status of SIPS

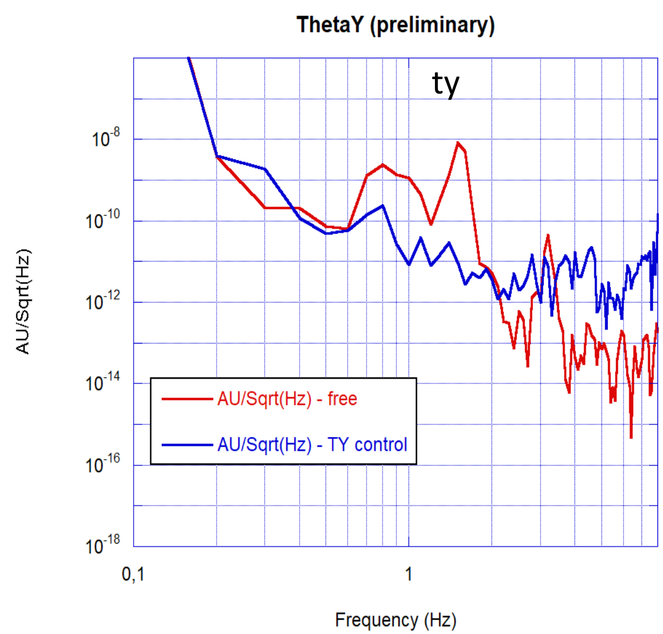
Local control of suspended elements





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

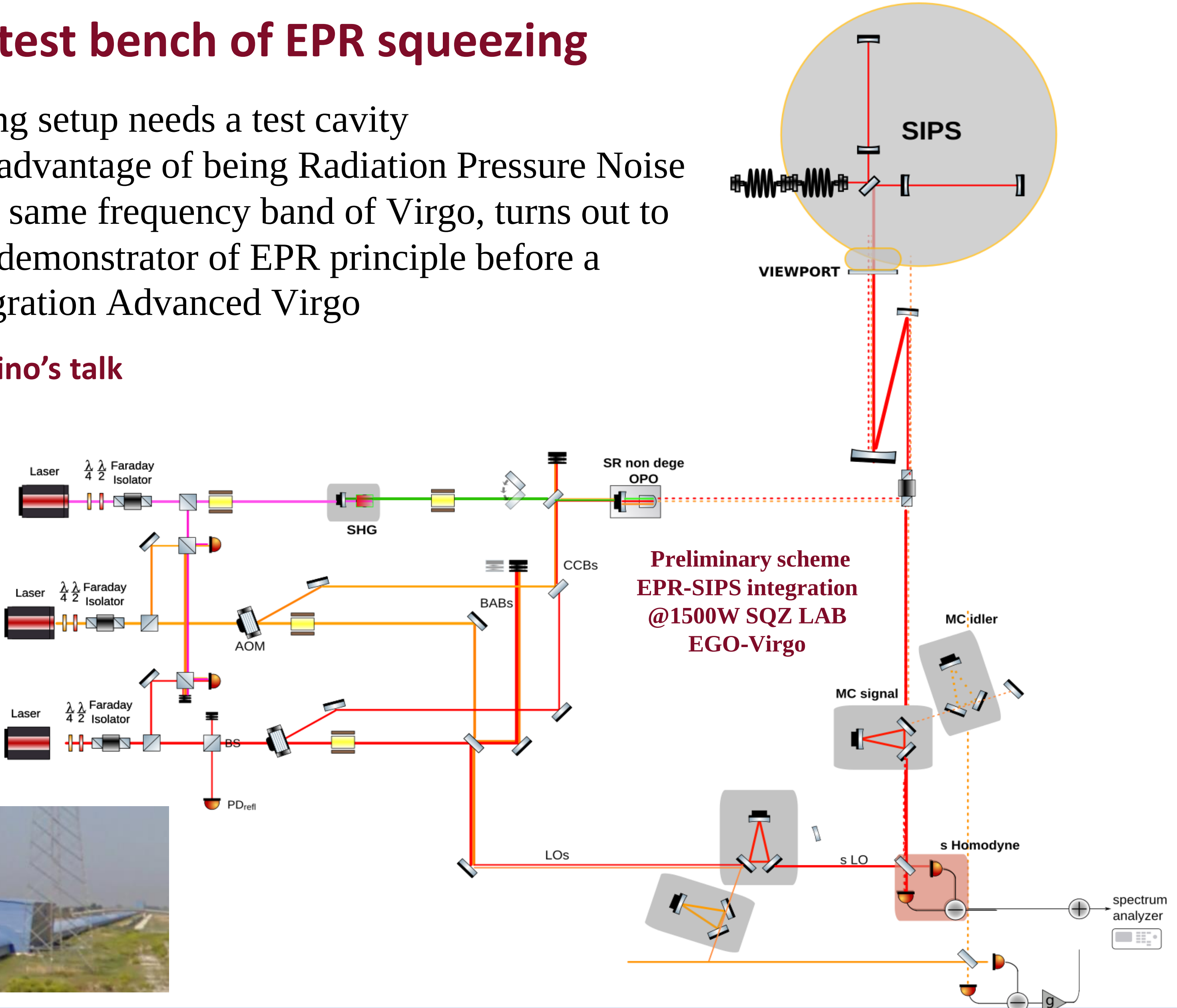




SIPS as test bench of EPR squeezing

EPR squeezing setup needs a test cavity SIPS, taking advantage of being Radiation Pressure Noise limited in the same frequency band of Virgo, turns out to be a suitable demonstrator of EPR principle before a possible integration Advanced Virgo

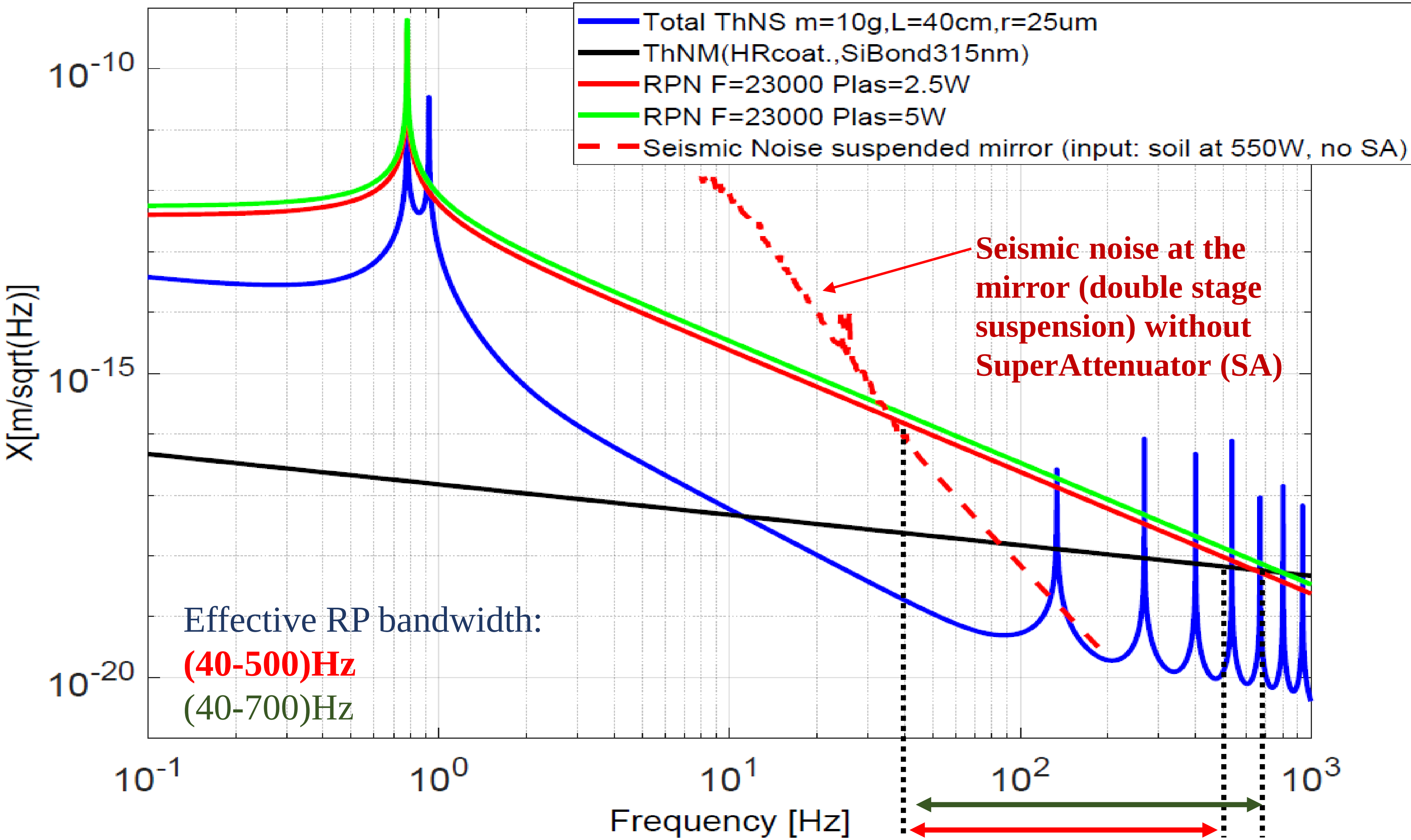
See Valeria Sequino's talk



5. Integration with EPR squeezer

SIPS as test bench of EPR squeezing

RPN vs thermal noise + seismic noise



5. Conclusions

- SIPS is an experiment with the target of **squeezing** generation through **ponderomotive** technique in the frequency band of ground-based GW detectors
- A suitable seismic and thermal noise reduction allowed to design a tabletop interferometer with **macroscopic** mirrors opto-mechanically coupled by radiation pressure
- It constitutes an interesting alternative to OPO-based squeezers

Perspectives

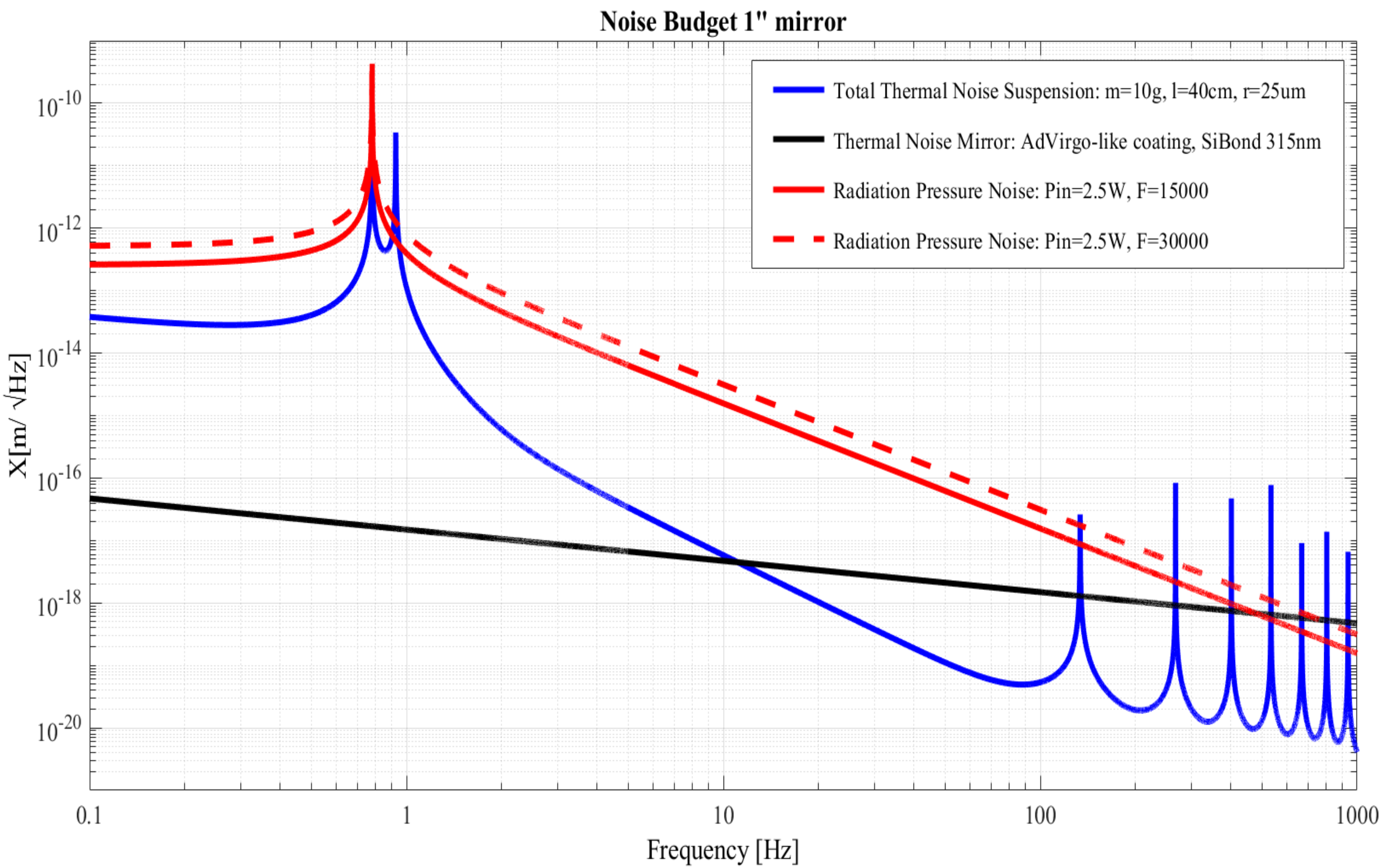
- Local control of main suspended optics with coil-magnet system has been successfully tested on the mechanical prototype, and global control system is under development
- The production of the 50µm thin silica fibers is feasible with the laser machine at EGO, Virgo and the monolithic suspension structure is under development at INFN Perugia
- On the short term, SIPS will be used as demonstrator of EPR squeezing principle before a possible integration Advanced Virgo

Thank You
for
Your Attention

Extra slides

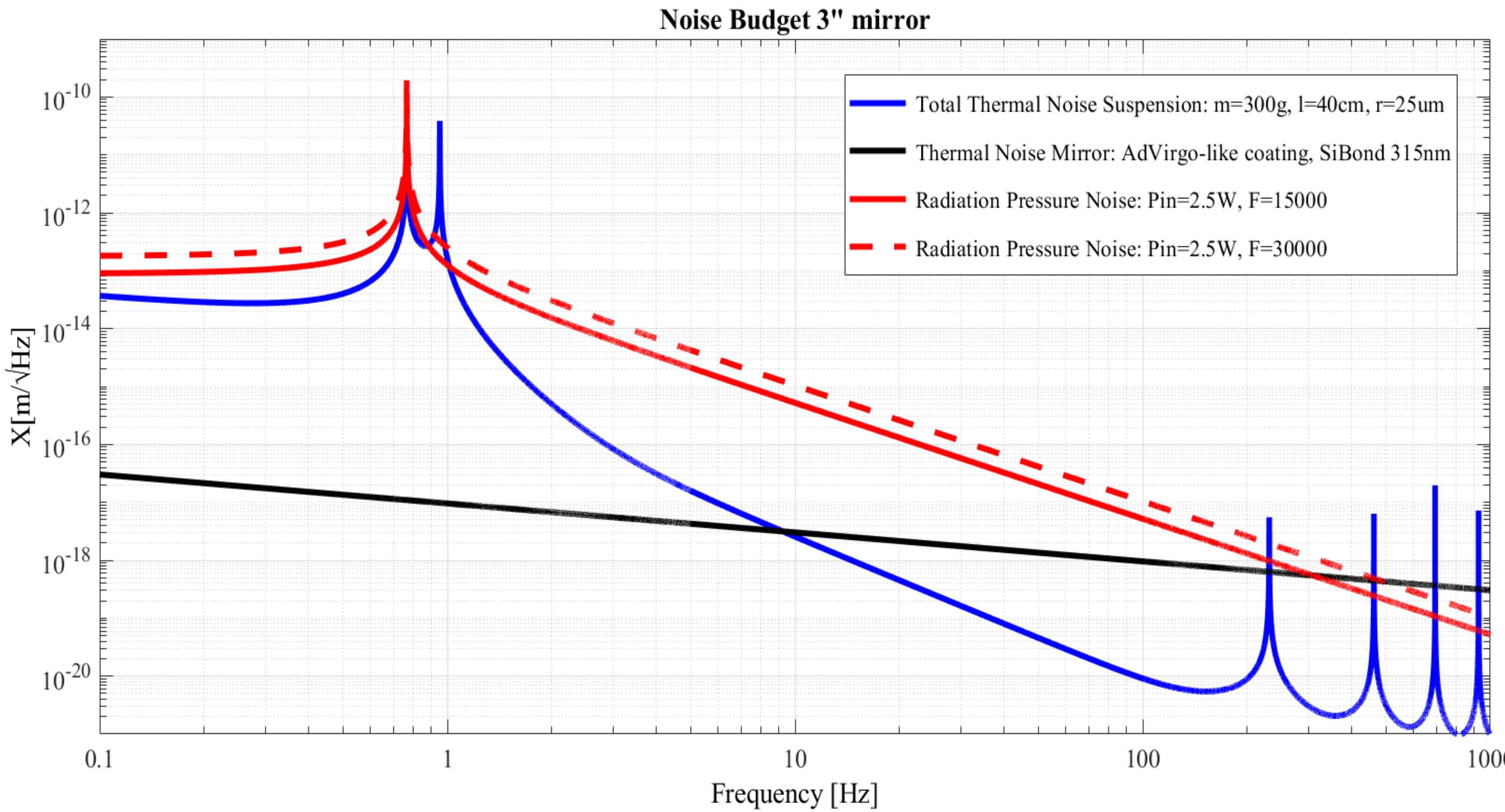
SIPS: Sensitivity

1″ mirror, 10g

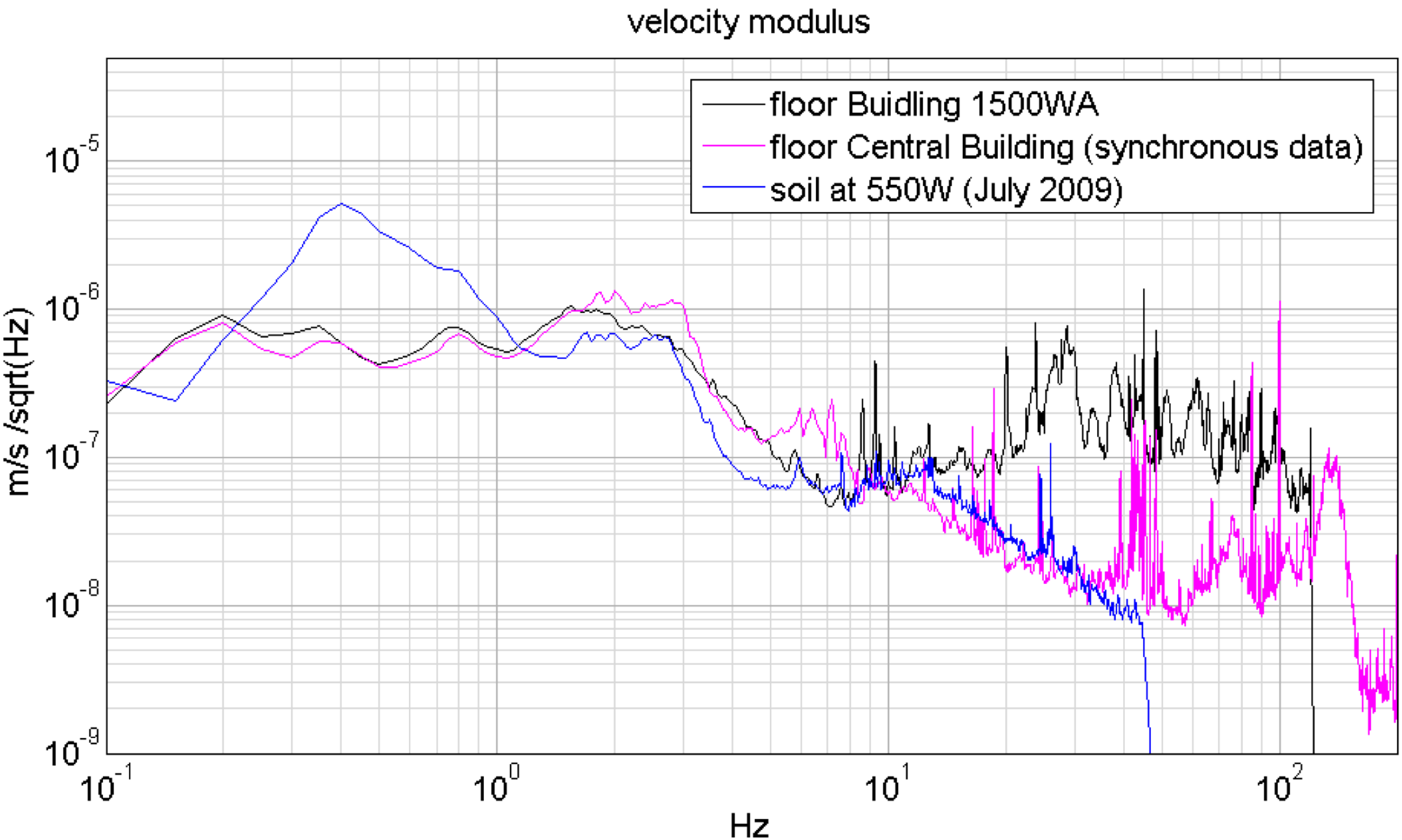


SIPS: Sensitivity

3'' mirror, 300g



SIPS: seismic noise at Virgo site



SAFE or ACTIVE FILTERS on SIPS vacuum chamber

Thermal Noise

Requirements: suspension thermal noise of the lighter end-mirror must be below $X_{ThNS} \leq 10^{-16}\, m/\sqrt{Hz}$ at $10\ Hz$: if not squeezing would be undetectable.

From the **Fluctuation-Dissipation Theorem**:

Suspension Thermal Noise

The total thermal noise of the suspensions is:

$$X_{ThNS}(\omega) = \sqrt{X_{thpend}^2(\omega) + X_{vio}^2(\omega)}$$

$$X_{thpend}(\omega) = \sqrt{\frac{4\,k_B\,T}{m\,\omega}}\sqrt{\frac{\omega_p^2\,\phi_p(\omega)}{\left((\omega_p^2 - \omega^2)^2 + \left(\omega_p^2\,\phi_p(\omega)\right)^2\right)}}$$

$$X_{vio}(\omega) = \sqrt{\frac{4k_BT}{\omega}D}\sqrt{\sum_n \frac{1}{n}\frac{\omega_n^2\Phi_n}{(\omega_n^2 - \omega^2)^2 + (\omega_n^2\Phi_n)^2}}$$

The overall ϕ_p pendulum loss angle is mainly given by the thermoelastic ϕ_{te} and surface ϕ_e **loss angles**

$$\phi_p(\omega) = D_{ilF}\left(\phi_{SiO2} + \phi_e + \phi_{te}(\omega)\right)$$

Mirror Thermal Noise

Calculated with Levin's approach and FE analysis (FEA) with ANSYS software

$$X_{Levin}(\omega) = \sqrt{\frac{8\,k_B\,T}{\omega\,F_0^2}U_{mirr}\phi_{tot}}$$

U_{mirr} = total strain energy

ϕ_{tot} = Sum of all dissipative contributions calculated with FEA *(AdV like coating + 315nm thick Silicate Bonding)*

impinging pressure $P = \frac{2\,F_0}{\pi w^2}e^{-\frac{2\,r^2}{w^2}}$

w = 254,3μm beam waist on end mirror

r = coord. on mirr surface

F_0 = 1 integrated force