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

Laura Giacoppo

9th International Conference on New Frontiers in Physics (ICNFP 2020)

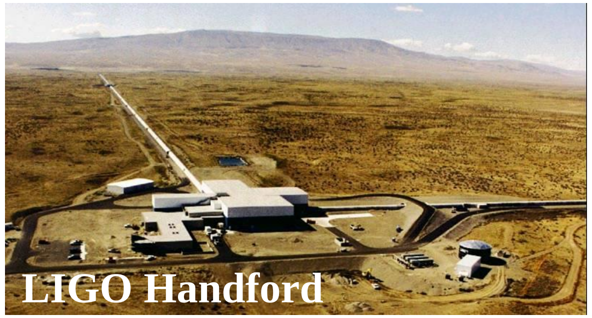
***Crete,** 5 September 2020*

OUTLINE

1. Quantum noise in Gravitational Wave interferometers
2. Squeezing as a technique to overcome it
3. Ponderomotive Squeezing technique
4. SIPS suspended ITF for ponderomotive squeezing: design and status
5. SIPS as a test bench for the EPR squeezing
6. Conclusions and perspectives

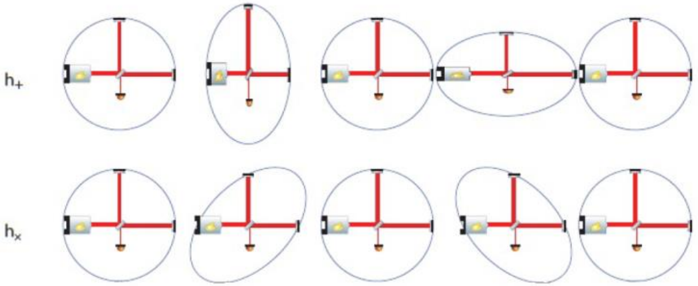
1. Quantum noise in Gravitational Wave interferometers

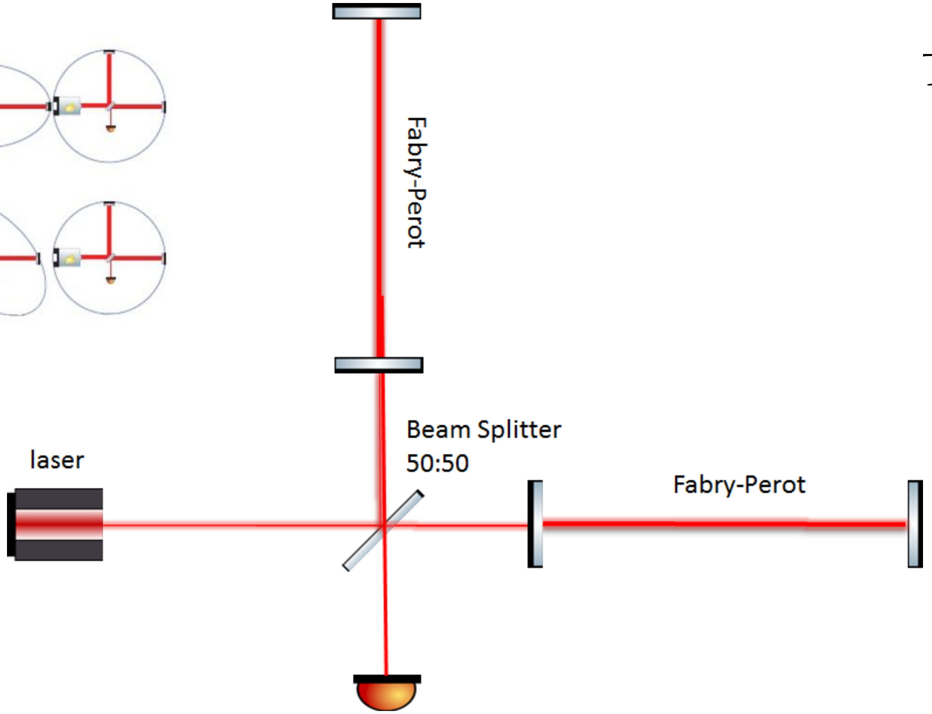

VIRGO


LIGO Handford


LIGO Livingston

Michelson ITF with Fabry-Pérot (FP) cavities





The phase difference is measured

$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta L \approx \frac{4\pi}{\lambda} h_0 L \frac{2\mathcal{F}}{\pi}$$

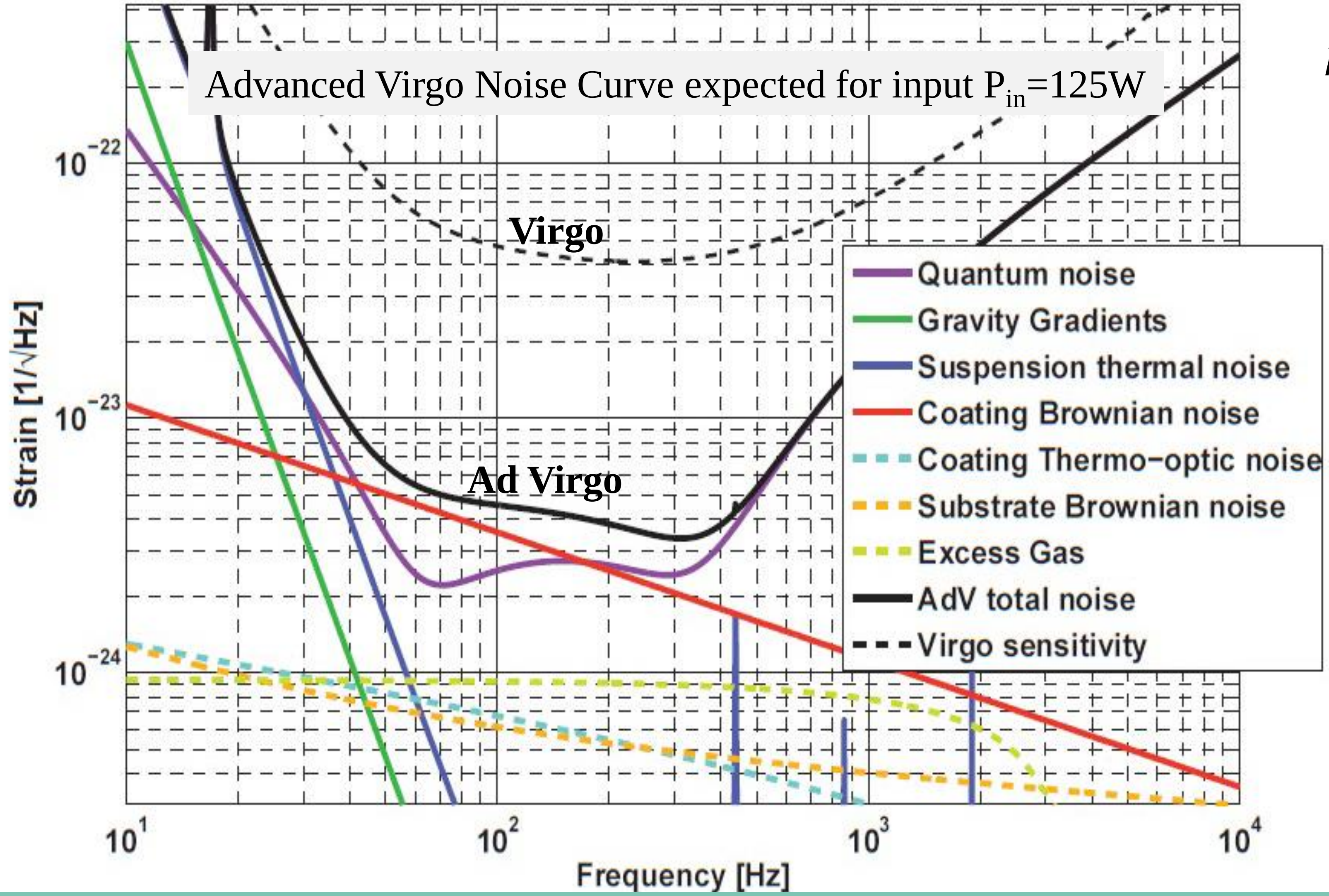
GW signal

Arm-Length

FP *finesse*

1. Quantum noise in Gravitational Wave interferometers

QUANTUM NOISE (**SHOT NOISE** & **RADIATION PRESSURE NOISE**) constitutes an intrinsic limit in the position measurements of a free mass using coherent light:



Advanced Virgo Noise Curve expected for input P_{in}=125W

$$h_{quantum}(\nu) = \sqrt{h^2_{shot}(\upsilon) + h^2_{RP}(\upsilon)}$$

Shot noise **(sensing noise)**: Power fluctuation due to statistical fluctuation in number of incident photons on the photodiode (above 200 Hz)

Radiation pressure noise **(back-action noise)**: a stochastic force originated by the fluctuation of the number of photons hitting the mirror (low frequency)

↓

SQUEEZING

2. Squeezing as a technique to overcome it

Quantization of Electromagnetic field: $\hat{E}_x(z,t) = E_0 \sin(kz)(\hat{X}\cos\omega t + \hat{Y}\sin\omega t)$

Quadrature Operators

$\hat{X}$ Phase quadrature → ΔX Shot Noise

$\hat{Y}$ Amplitude quadrature → ΔY Radiation Pressure Noise

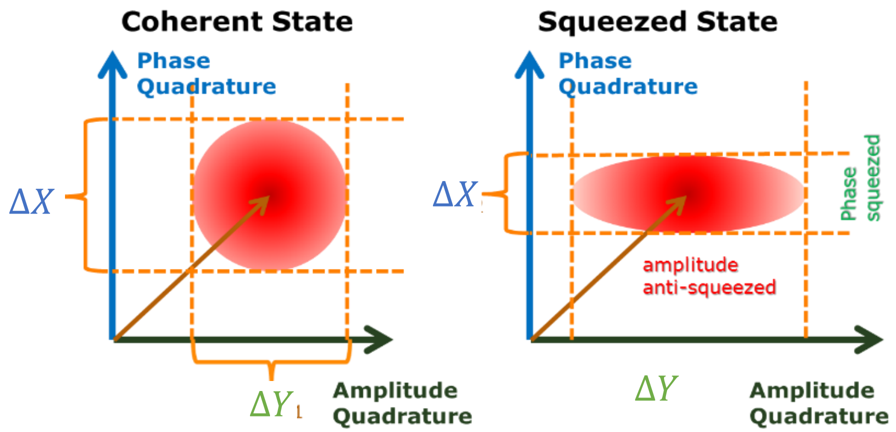
Shot Noise and RPN uncorrelated

↓

Heisenberg Uncertainty Principle

$$(\Delta X)^2(\Delta Y)^2 \geq \frac{1}{16}$$

Representation in phase-space

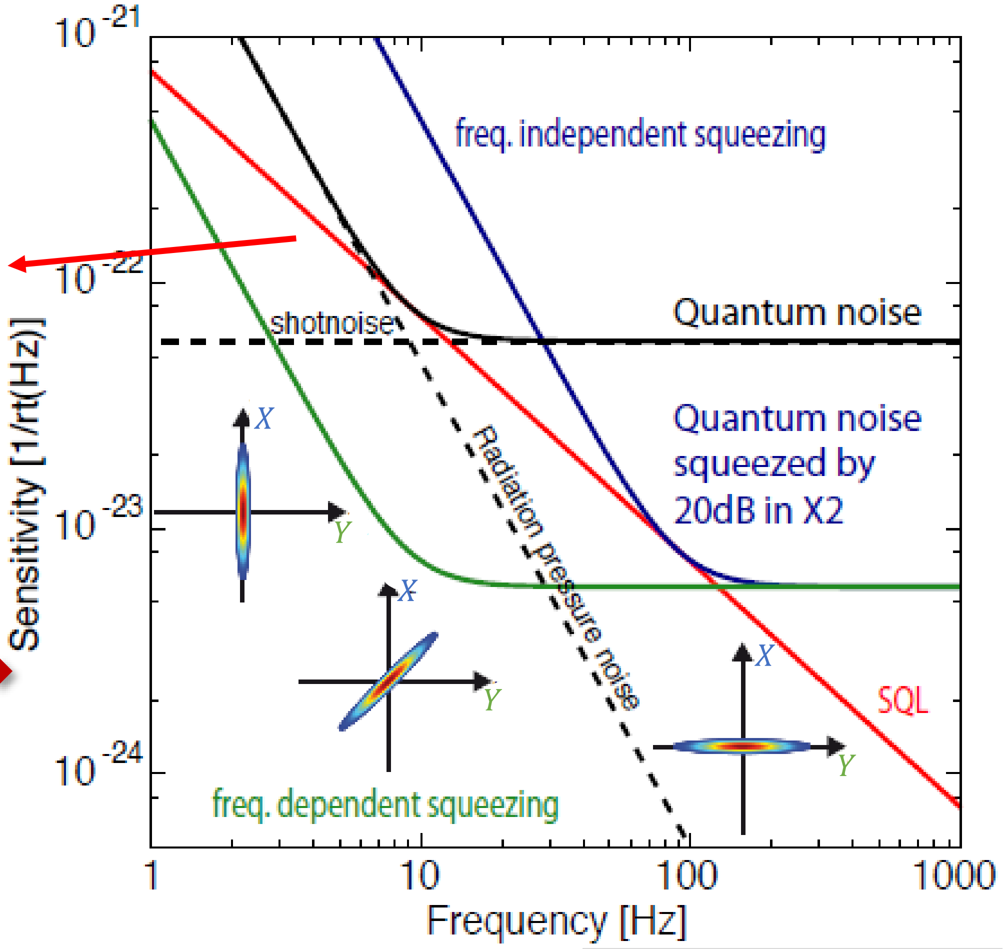


Standard Quantum Limit:

$$\tilde{h}_{SQL} = \sqrt{\frac{4\hbar}{M\Omega^2 L^2}}$$

↓

Frequency Dependent Squeezing (FDS) →

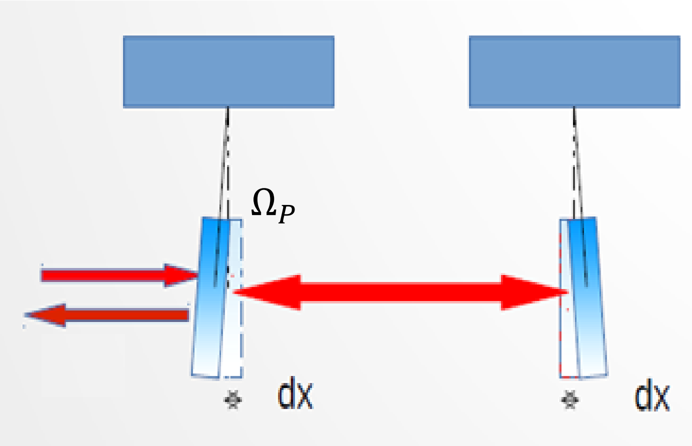


Credits H.Vahlbruch, (2008)

3. Ponderomotive Squeezing technique

Ponderomotive:
Empty cavity with suspended mirror acting as an ***'optical spring'***

Radiation Pressure (RP) due to the laser power inside the cavity impinging on the suspended mirror induces a coupling between its position and the intensity of light beam



Amplitude fluctuations (ΔY) of the field inside the cavity induces suspended mirror motion

↓

Displacement of mirror produces a phase shift (ΔX) in the reflected light, that is proportional to amplitude fluctuations (ΔY)

↓

coupling between phase and amplitude quadrature fluctuations

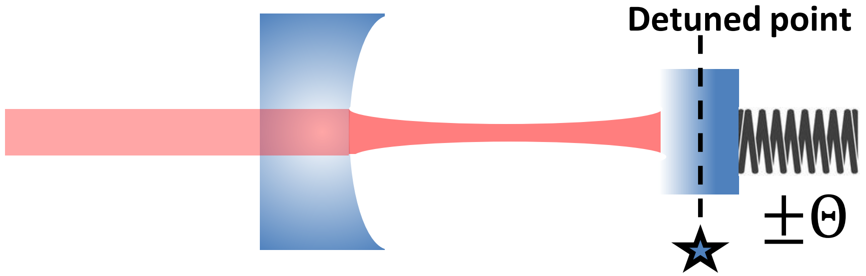
↓

PONDEROMOTIVE SQUEEZING

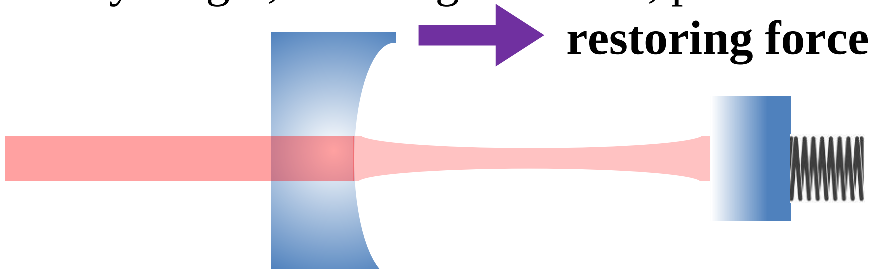
3. Ponderomotive Squeezing technique

Opto-Mechanical coupling in a detuned cavity

Optical Spring

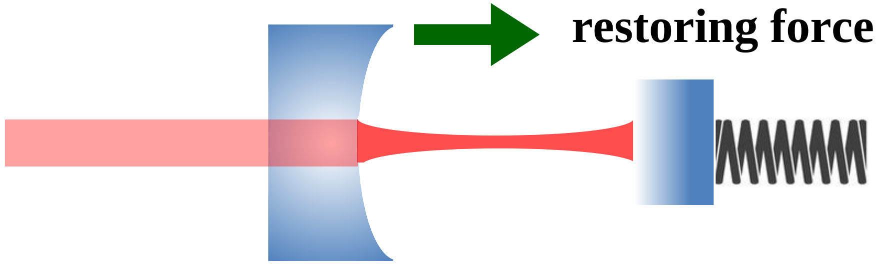


cavity longer, detuning increases, power decreases



restoring force

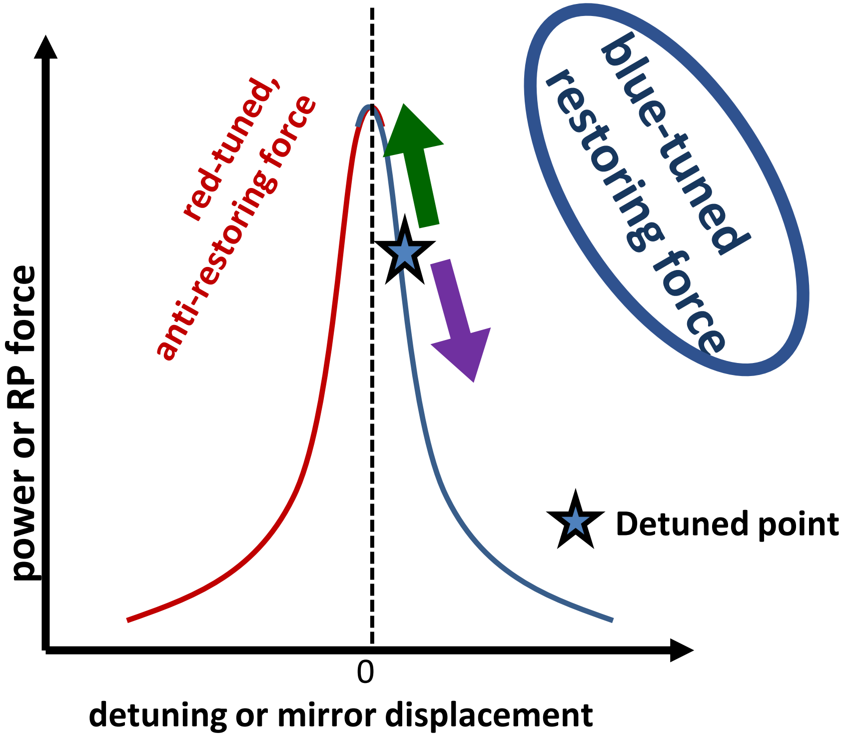
cavity shorter, detuning decreases, power increases



restoring force

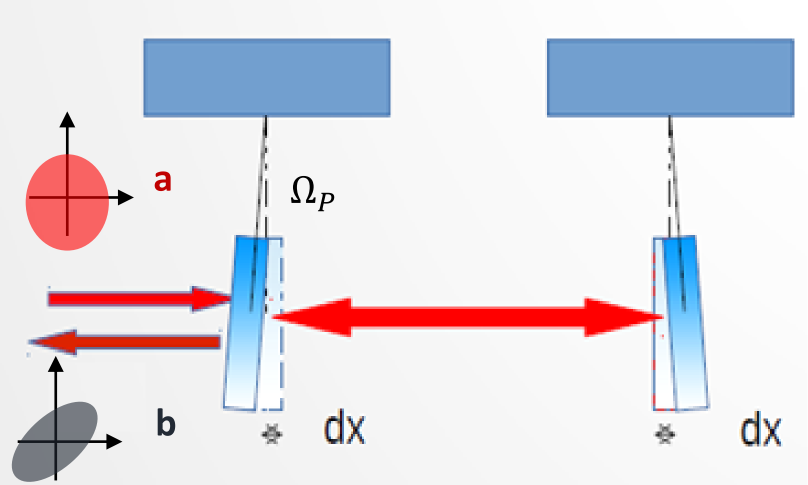
±Θ Optical Spring Frequency

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



γ: (anti)damping term ↔ spring instability

3. Ponderomotive Squeezing technique



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

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

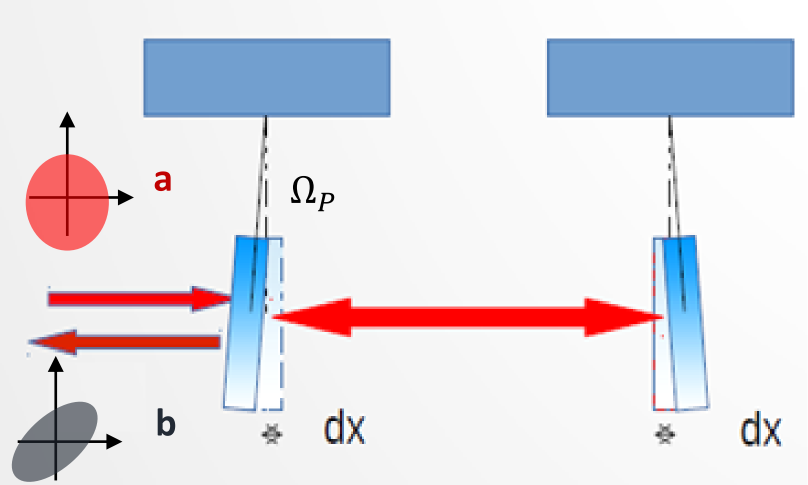
If the mirror mechanical resonance Ω_P is such that
$\Omega_P \ll \Omega, |\Theta|$
Ω_P depends only on the ***optical spring resonance frequency*** $\pm\Theta$

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

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

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

3. Ponderomotive Squeezing technique



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ponderomotive squeezing factor (freq.-dependent)

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

Corbitt, et al. 2006

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

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

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

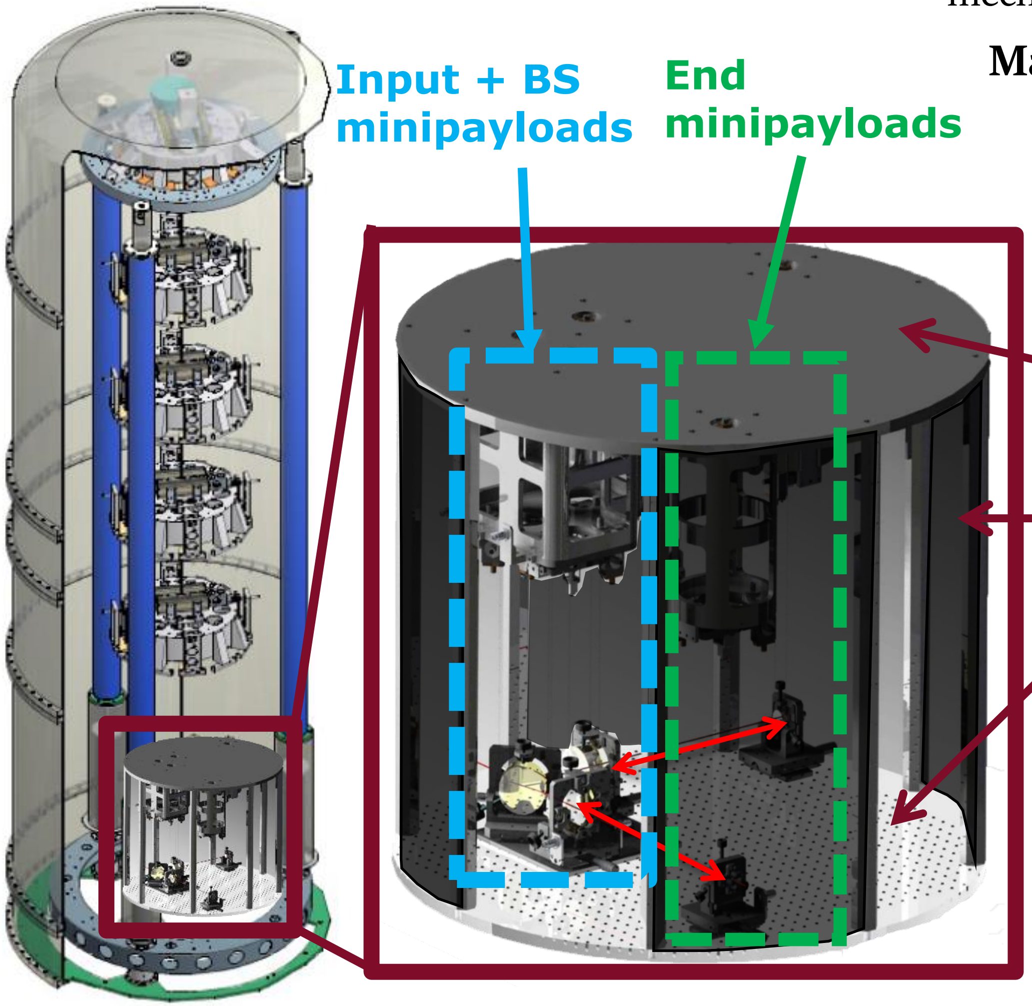
Real parameters must be chosen to ensure a **large squeezing factor** and a **suitable squeezing band**, taking into account the mechanical feasibility

4. SIPS suspended ITF for ponderomotive squeezing: design and status

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**)

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

Material: anticorodal (Al-alloy)



Height: 800 mm
Diameter: 960 mm
Weight: ~ 150 kg

Upper plate (auxiliary bench)

Cylindrical baffles

Main optical bench

Michelson ITF with two Fabry-Pérot cavities finesse=23000, L=35cm

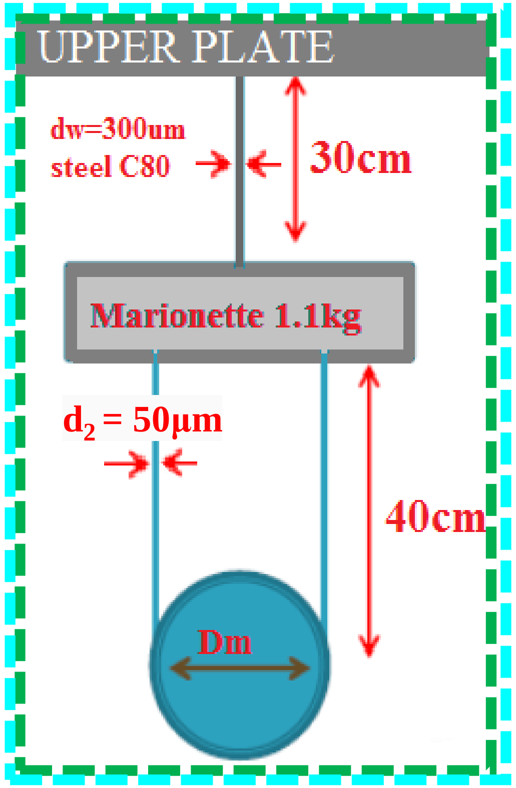
Control: magnet-coil actuators on mirror marionette

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

Input and BS:
Dm=3'', 300g
End:
Dm=1'', 10 g

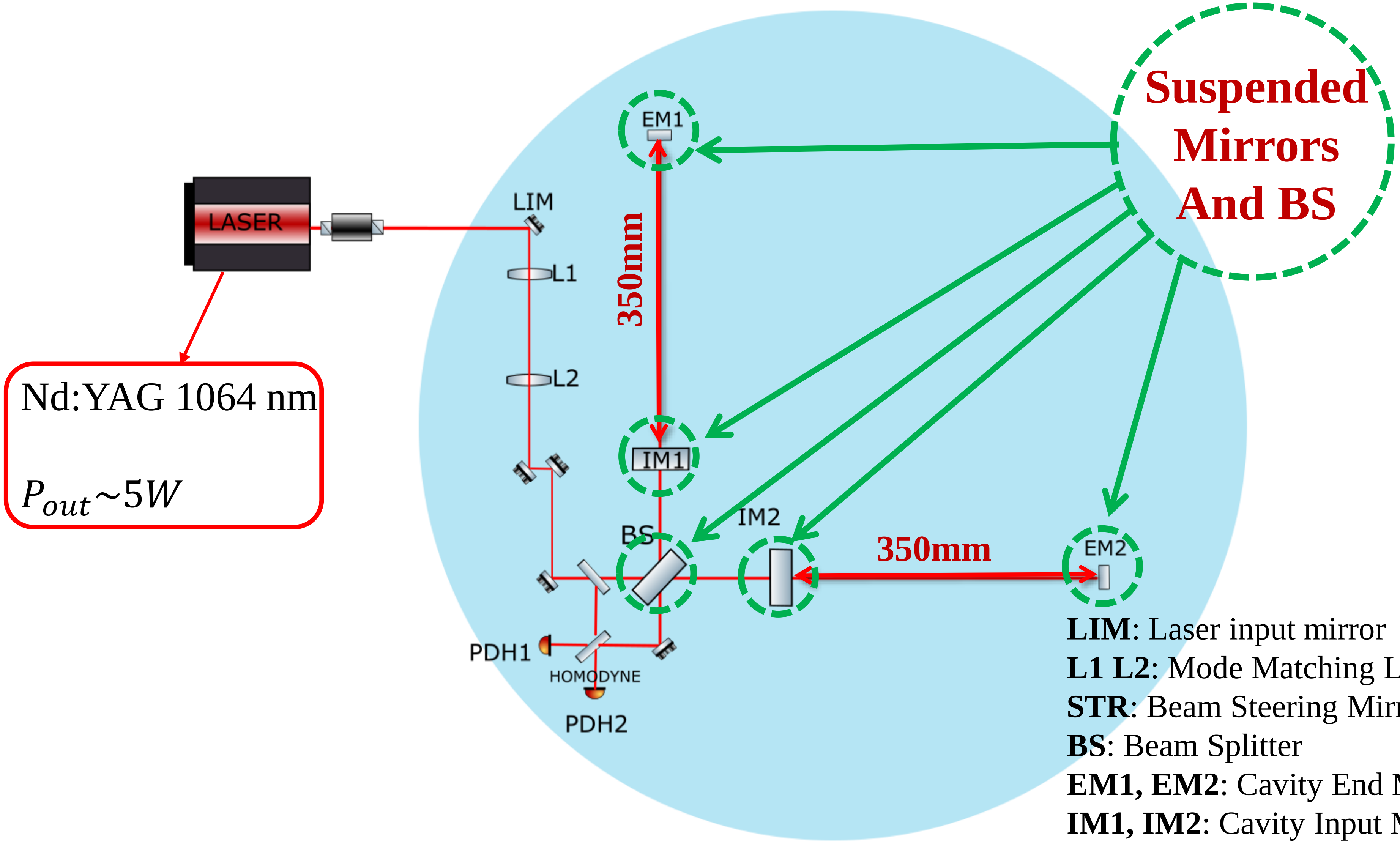
They can be suspended with a monolithic Virgo-like technique for thermal noise reduction

Minipayload:
Monolithic suspension system of the main optics
(2 fused silica fibers of 50μm)



4. SIPS suspended ITF for ponderomotive squeezing: design and status

Main Optical Bench Design



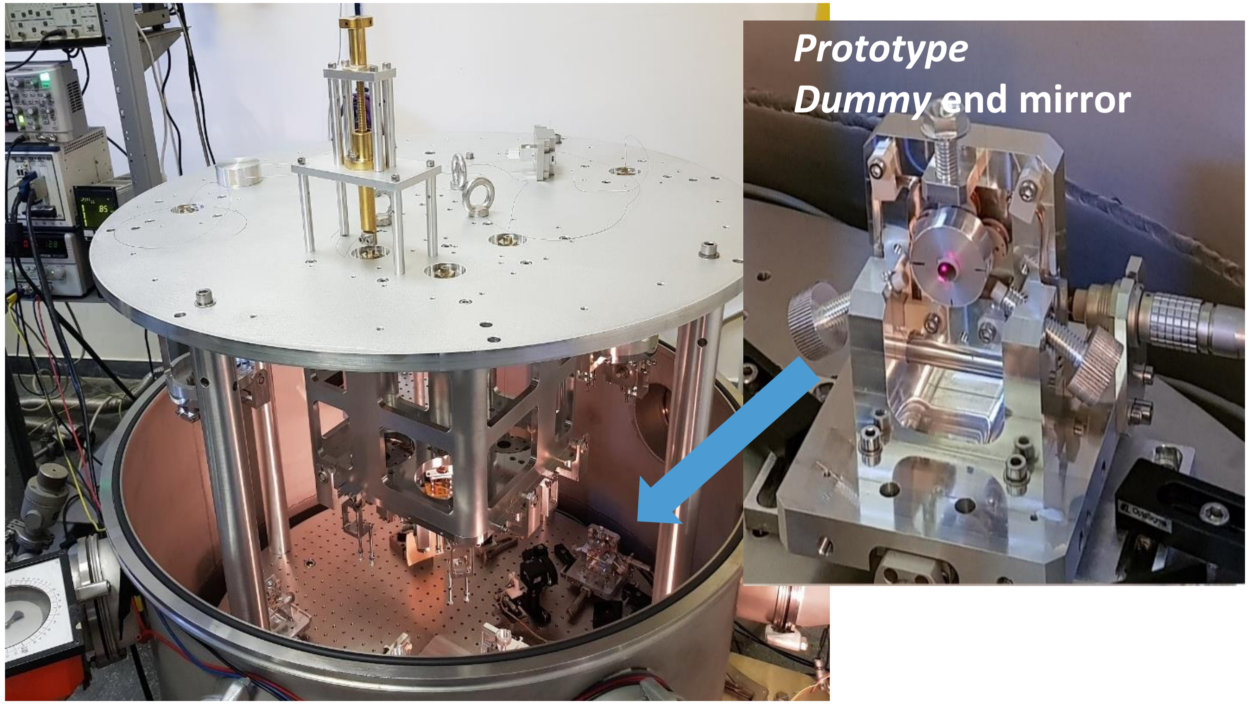
Nd:YAG 1064 nm

P_{out}~$5W$

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

4. SIPS suspended ITF for ponderomotive squeezing: design and status

Mechanical Set-Up @ La Sapienza & INFN Roma1

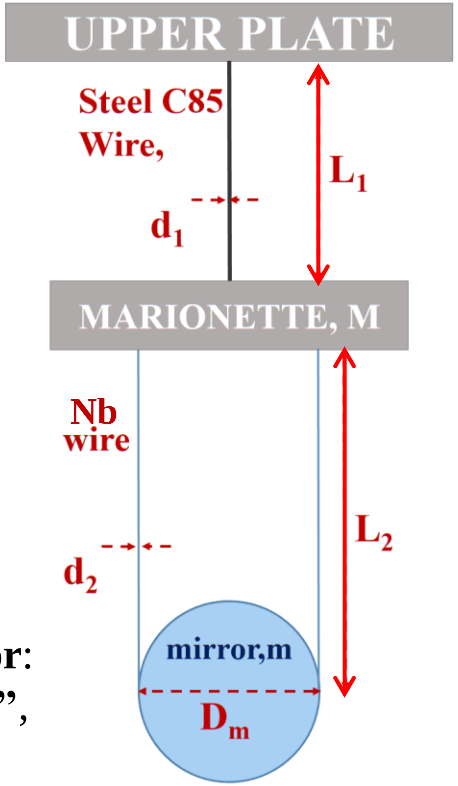


d_1=300µm
L_1=30cm

M=**1.1kg**

d_2 = 50µm
L_2=40cm

End mirror:
diameter **1”**,
mass **10 g**



4. SIPS suspended ITF for ponderomotive squeezing: design and status

Main Optics

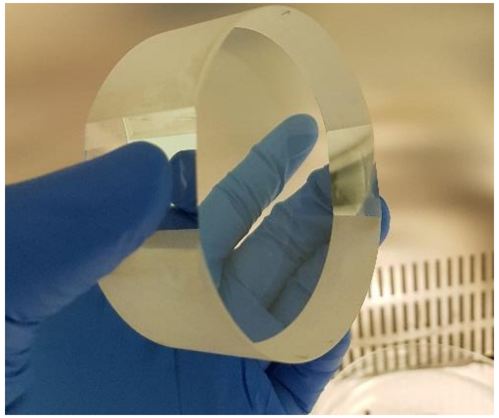
Substrates of SUPRASIL:

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

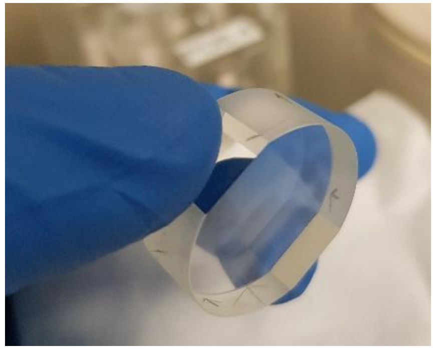
Coatings (done by LMA):

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

3” Input Mirror substrate



1” End Mirror substrate



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)*

Cavity finesse: $\boldsymbol{\mathcal{F} \simeq 23000}$

(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

Cavity stability

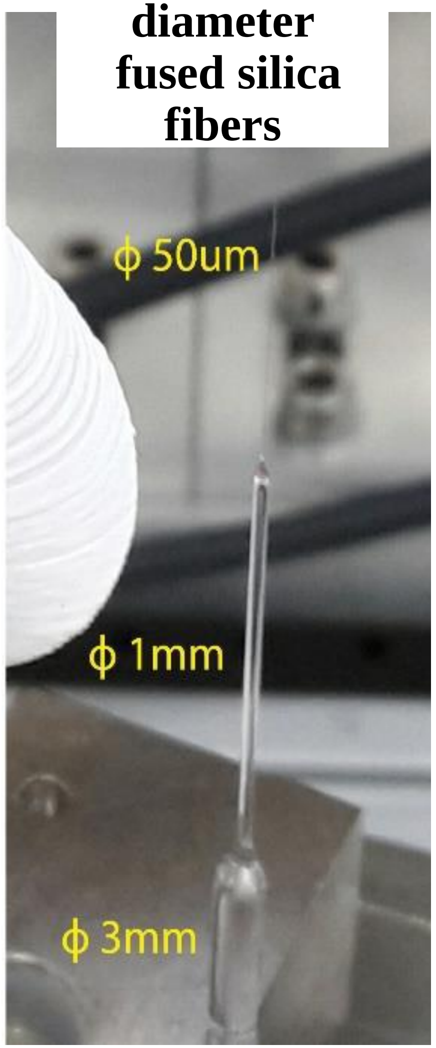
Cavity length: $\mathbf{L = 350\ mm}$
Mirror RoC: $\mathbf{RoC = 250\ mm}$

4. SIPS suspended ITF for ponderomotive squeezing: design and status

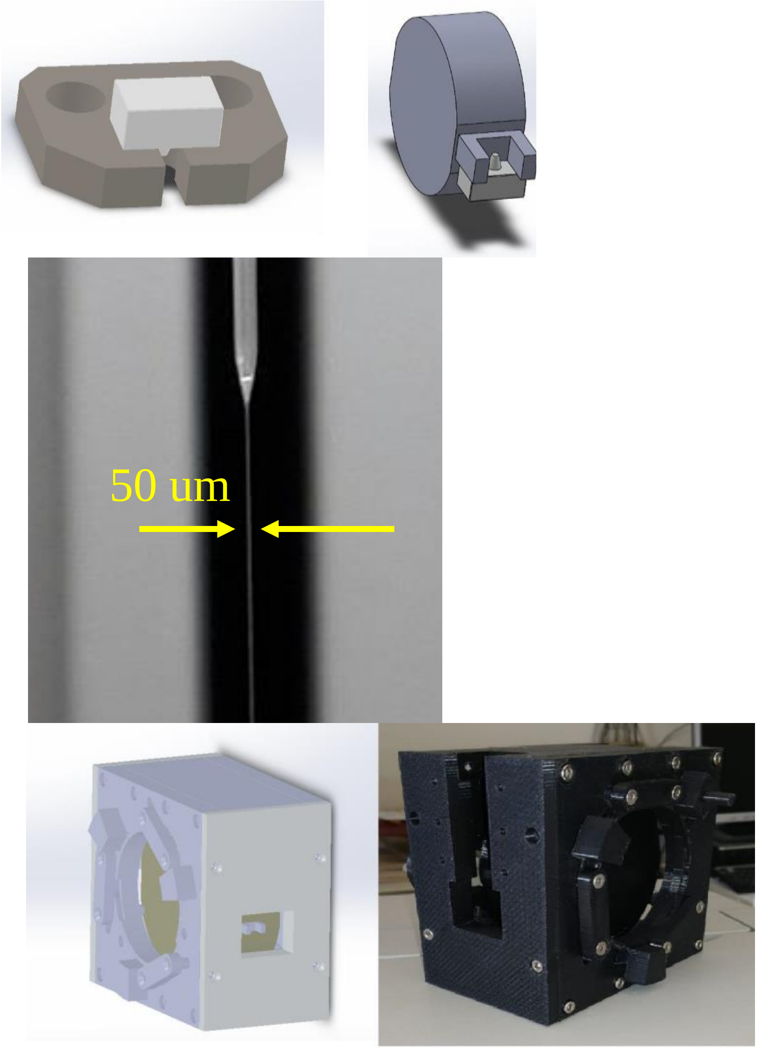
Monolithic Suspensions

CO_2 Laser Machine @EGO

50µm diameter fused silica fibers



Ears-Anchors system:



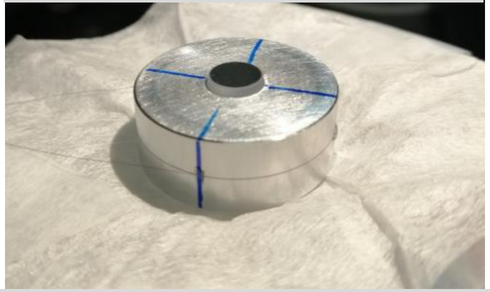
4. SIPS suspended ITF for ponderomotive squeezing: design and status

Test of local control of suspended elements:

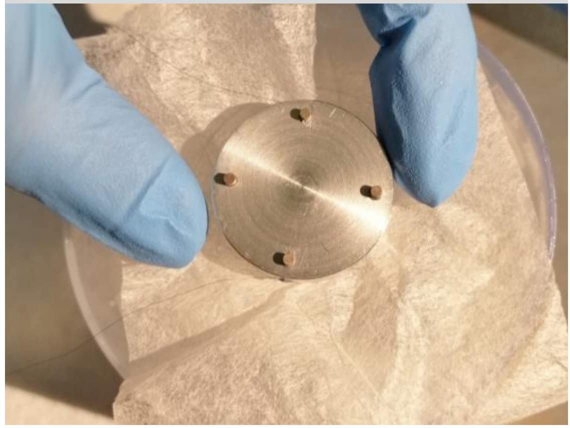
Coils behind mirror and **magnets** glued on the mirror

Coils-magnets also on the marionette

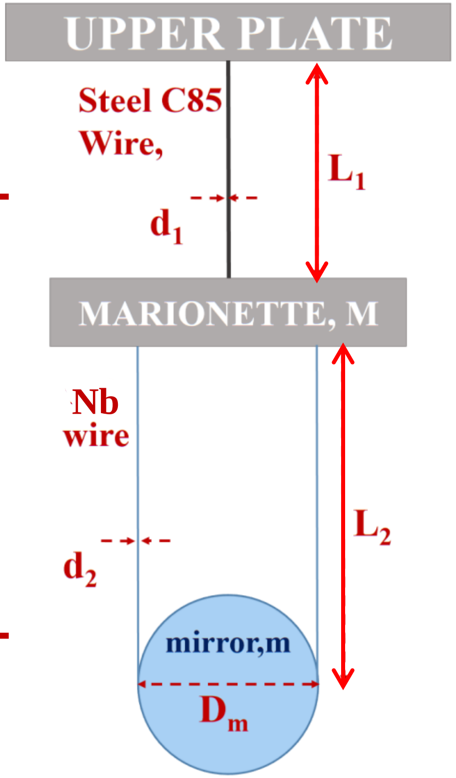
Front side



Back side with magnets



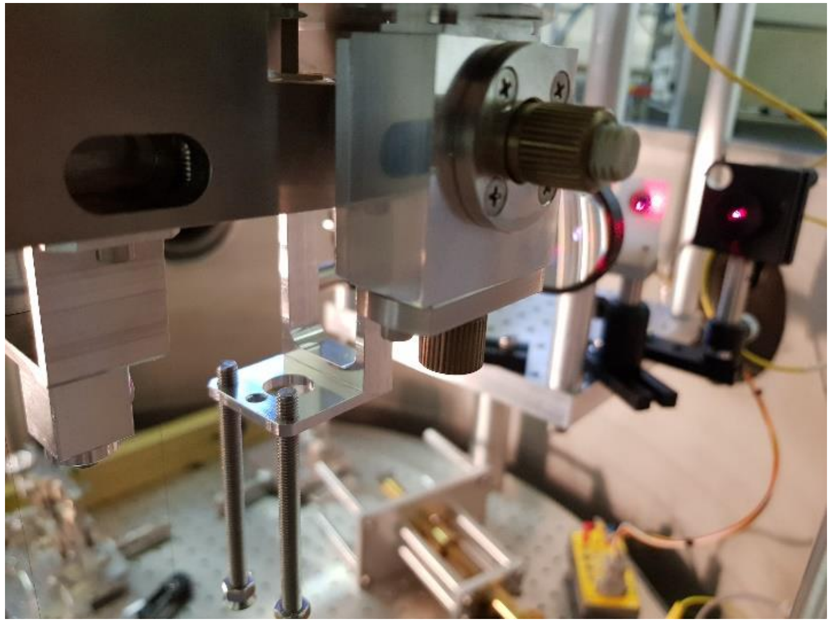
Dummy end mirror suspension

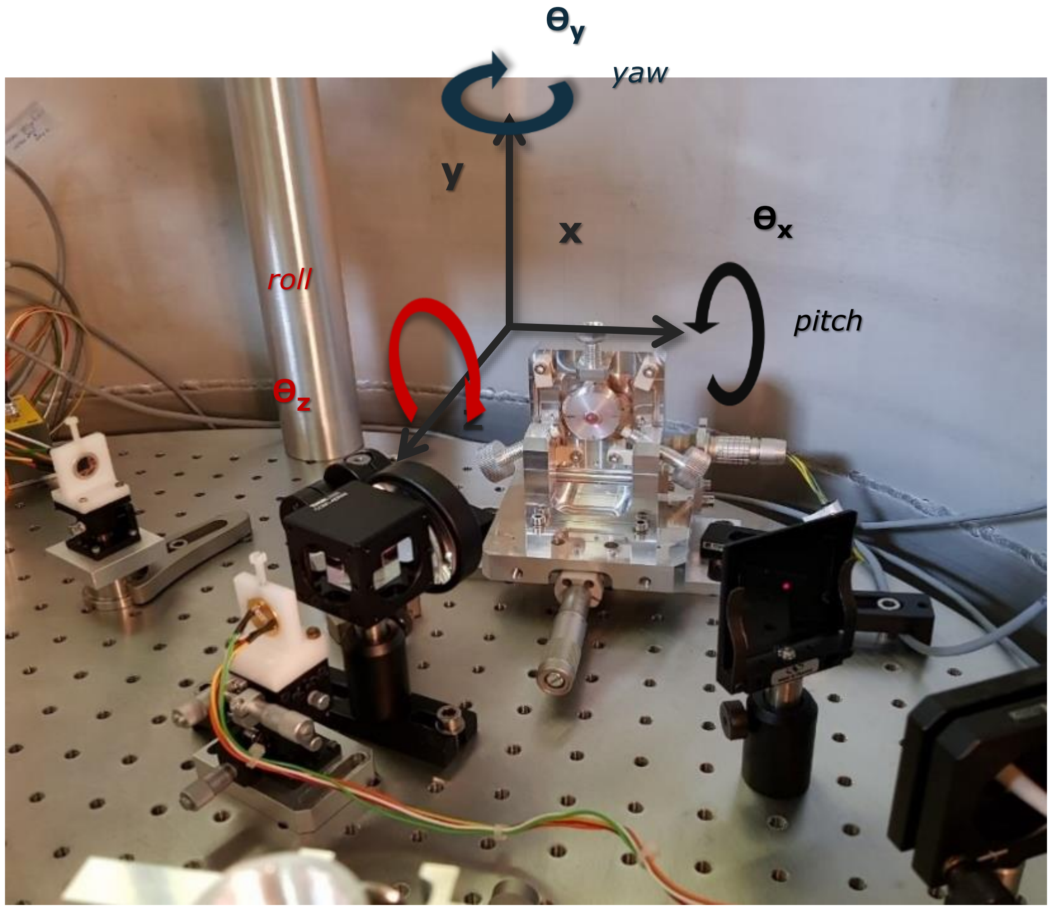


4. SIPS suspended ITF for ponderomotive squeezing: design and status

Local control of suspended elements with dummy mirrors

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

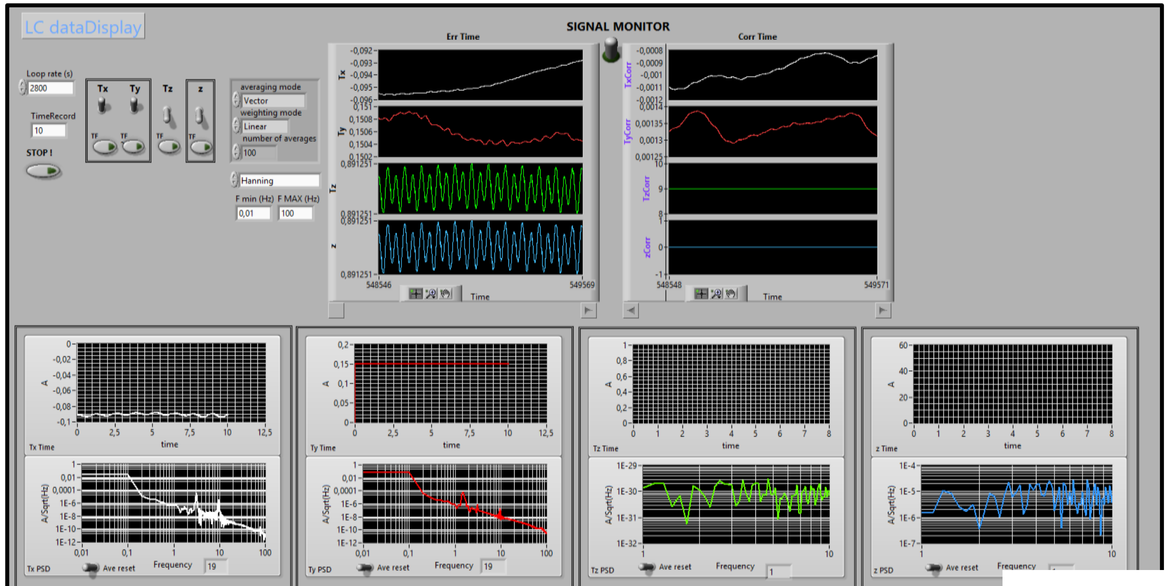




Controlled DOF:
Mirror: z, θx, θy
Marionette: θz, θy

4. SIPS suspended ITF for ponderomotive squeezing: design and status

Local control of suspended elements



Loop rate (s) 2800

TimeRecord 10

STOP !

averaging mode Vector

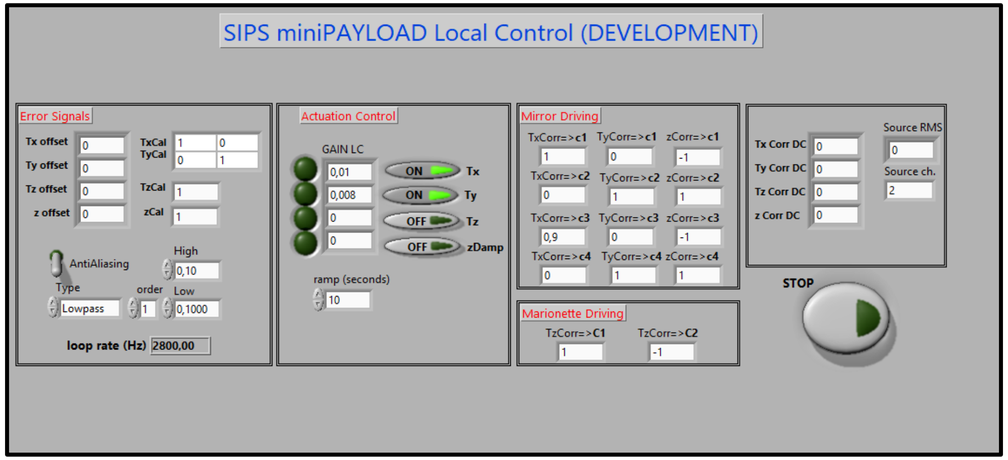
weighting mode Linear

number of averages 100

Hanning

F min (Hz) 0,01

F MAX (Hz) 100



SIPS miniPAYLOAD Local Control (DEVELOPMENT)

Error Signals

Tx offset 0

Ty offset 0

Tz offset 0

z offset 0

TxCal TyCal 1 0 / 0 1

TzCal 1

zCal 1

AntiAliasing

Type Lowpass

order 1

High 0,10

Low 0,1000

loop rate (Hz) 2800,00

Actuation Control

GAIN LC

GAIN LC		
0,01	ON	Tx
0,008	ON	Ty
0	OFF	Tz
0	OFF	zDamp

ramp (seconds) 10

Mirror Driving

TxCorr=>c1	TyCorr=>c1	zCorr=>c1
1	0	-1
TxCorr=>c2	TyCorr=>c2	zCorr=>c2
0	1	1
TxCorr=>c3	TyCorr=>c3	zCorr=>c3
0,9	0	-1
TxCorr=>c4	TyCorr=>c4	zCorr=>c4
0	1	1

Marionette Driving

TzCorr=>C1 1

TzCorr=>C2 -1

Tx Corr DC 0

Ty Corr DC 0

Tz Corr DC 0

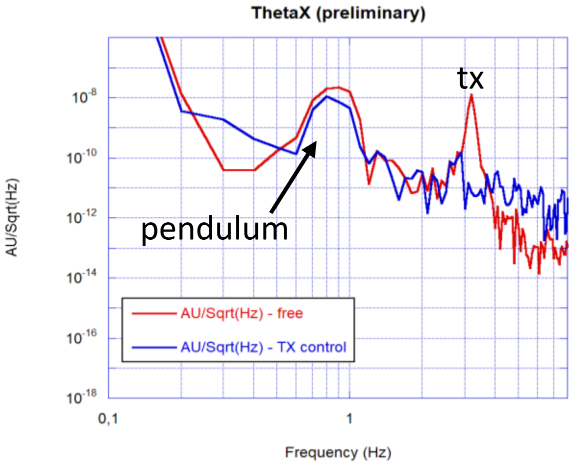
z Corr DC 0

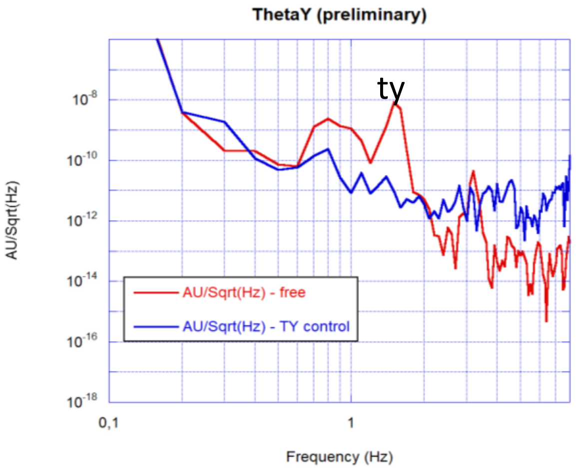
Source RMS 0

Source ch. 2

STOP

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

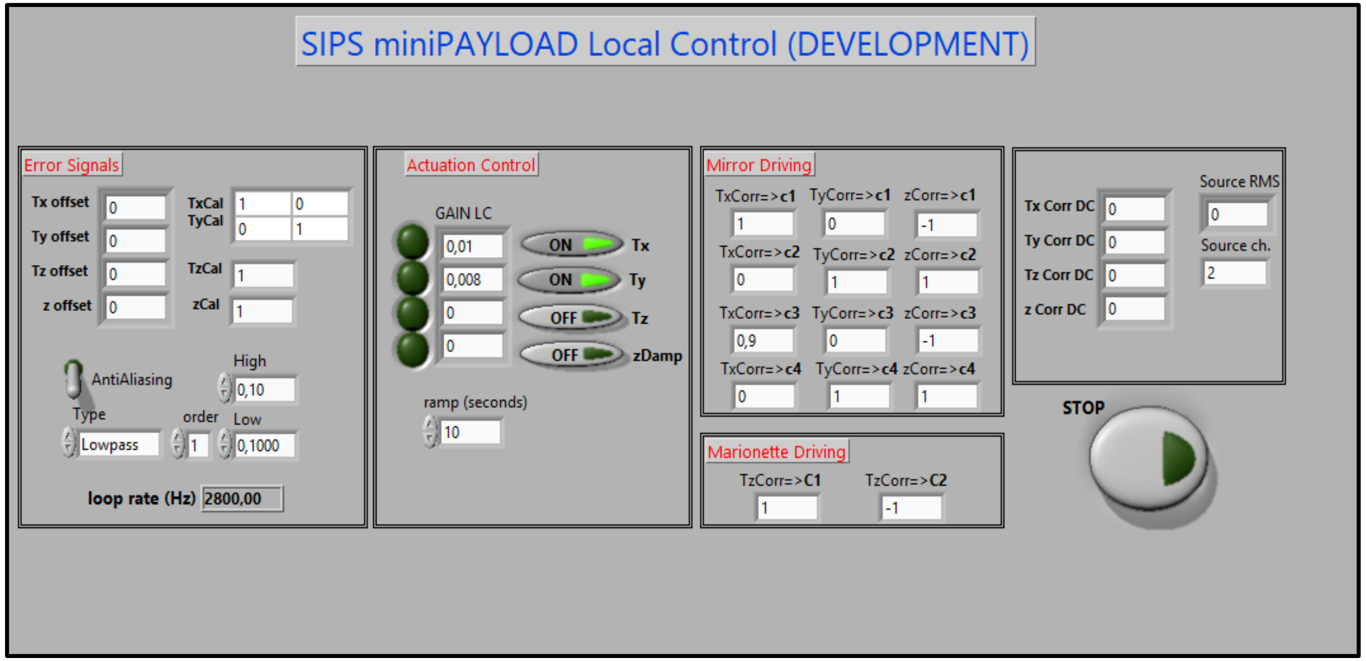




4. SIPS suspended ITF for ponderomotive squeezing: design and status

What’s next

- Starting point



SIPS miniPAYLOAD Local Control (DEVELOPMENT)

Error Signals

Tx offset 0
Ty offset 0
Tz offset 0
z offset 0

TxCal TyCal		
	1	0
	0	1

TzCal 1
zCal 1

AntiAliasing
Type Lowpass
order 1
High 0,10
Low 0,1000

loop rate (Hz) 2800,00

Actuation Control

GAIN LC		
0,01	ON	Tx
0,008	ON	Ty
0	OFF	Tz
0	OFF	zDamp

ramp (seconds) 10

Mirror Driving

TxCorr=>c1	TyCorr=>c1	zCorr=>c1
1	0	-1

TxCorr=>c2	TyCorr=>c2	zCorr=>c2
0	1	1

TxCorr=>c3	TyCorr=>c3	zCorr=>c3
0,9	0	-1

TxCorr=>c4	TyCorr=>c4	zCorr=>c4
0	1	1

Marionette Driving

TzCorr=>C1	TzCorr=>C2
1	-1

Tx Corr DC 0
Ty Corr DC 0
Tz Corr DC 0
z Corr DC 0

Source RMS 0
Source ch. 2

- Optimize Labview code for local control on one mini-payload system for end mirror and marionette.
- Implementation and test on all mini-payloads

4. SIPS suspended ITF for ponderomotive squeezing: design and status

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

Suspension Thermal Noise

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

Pendulum Thermal Noise

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

Violin Thermal Noise

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

$k_B = 1.38 \cdot 10^{-23}\ J/K$ *Boltzmann const.;*
$T =$ *temperature*

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)

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

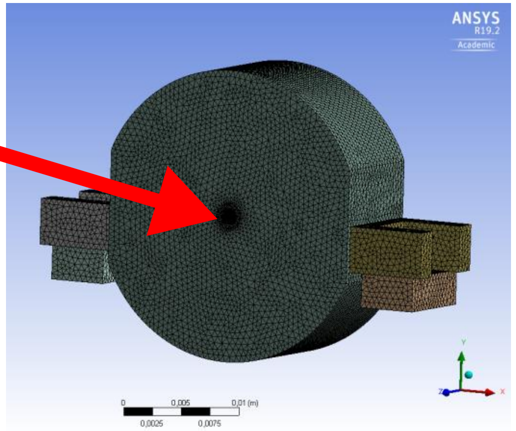
U_{mirr} = total mirror strain energy
ϕ_{tot}= Sum of all dissipative contributions
(AdV like coating + 315nm thick Silicate Bonding)

$U_{mirr}\phi_{tot}$ calculated with FE analysis with ANSYS software

impinging Gaussian pressure

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

w = 254,3μm beam waist on mirror
r = coord. on mirr surface
F_0 = 1 integrated force



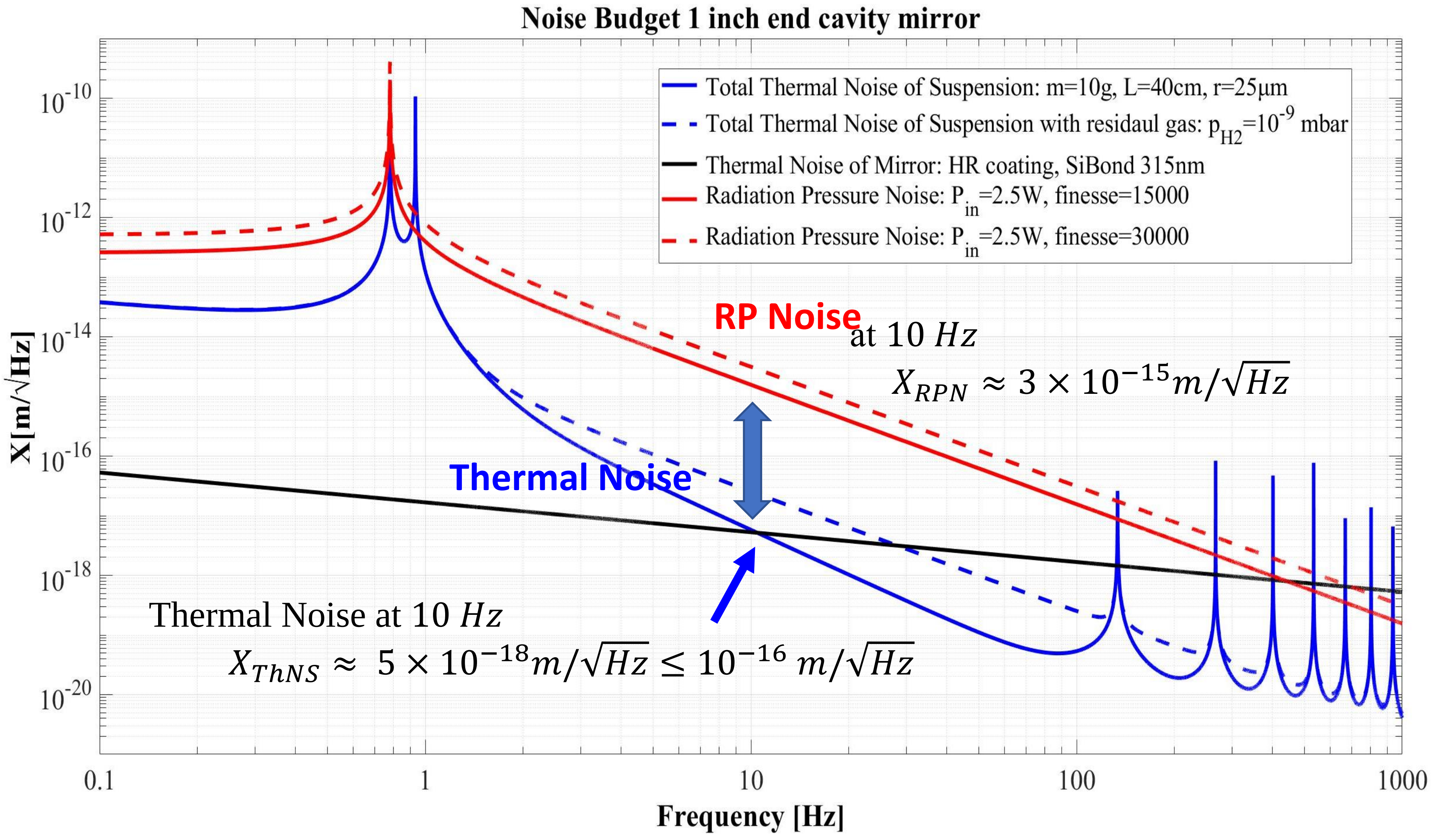
The overall loss angle:

$$\phi_{tot} = \phi_{Bulk} + \frac{U_{coatHR}}{U_{tot}}\phi_{HRmat} + \frac{U_{coatLR}}{U_{tot}}\phi_{LRmat} + \frac{U_{SiBond}}{U_{tot}t}\phi_{SiBond}$$

4. SIPS suspended ITF for ponderomotive squeezing: design and status

Noise budget for End Mirror 1”, 10g

$$X_{RPN}(10\,Hz) \approx 600 \times X_{ThNS}(10\,Hz)$$



at 10 Hz

$$X_{RPN} \approx 3 \times 10^{-15} m/\sqrt{Hz}$$

Thermal Noise at 10 Hz

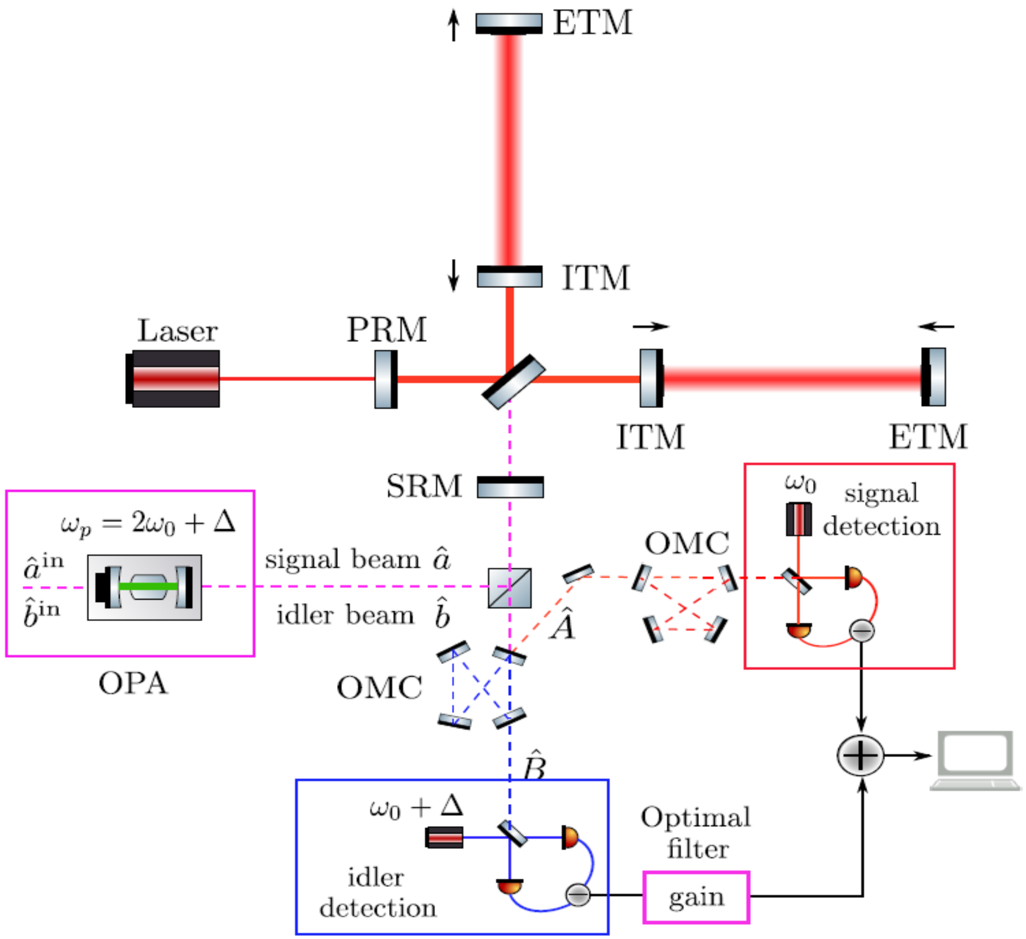
$$X_{ThNS} \approx 5 \times 10^{-18} m/\sqrt{Hz} \leq 10^{-16}\, m/\sqrt{Hz}$$

S.Di Pace et al. presented @ GRASS2019. Paper submitted to EPJD 2020 (S. Di Pace et al.)

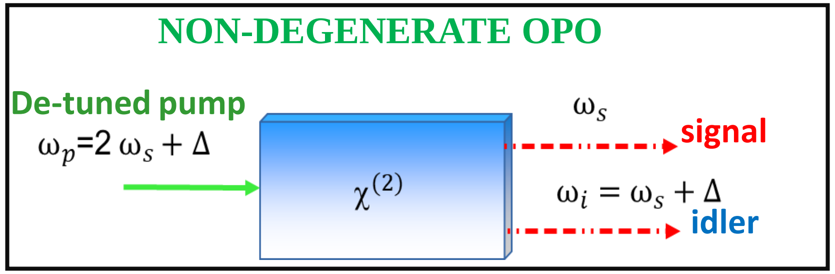
5. SIPS as a test bench for the EPR squeezing

Frequency Dependent Squeezing via quantum EPR entanglement

De-tuned pump into non degenerate OPO produces ***Signal* *and idler squeezed beams: EPR entangled***



Y. Ma et al. Nat Phys 13 no. 8, (Aug, 2017) 776–780



→ The two produced beams are EPR entangled

→ Both beams injected into the ITF dark port

ITF acts like a Filter Cavity for **idler**:

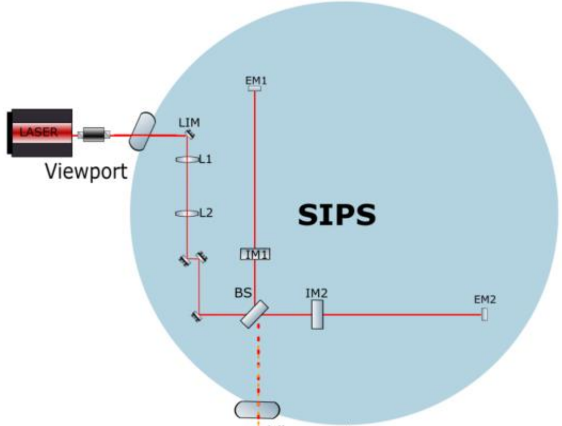
ITF is de-tuned for the **idler** ($\omega_0 + \Delta$), so ***idler*** beam experiences a ***frequency dependent squeezing***

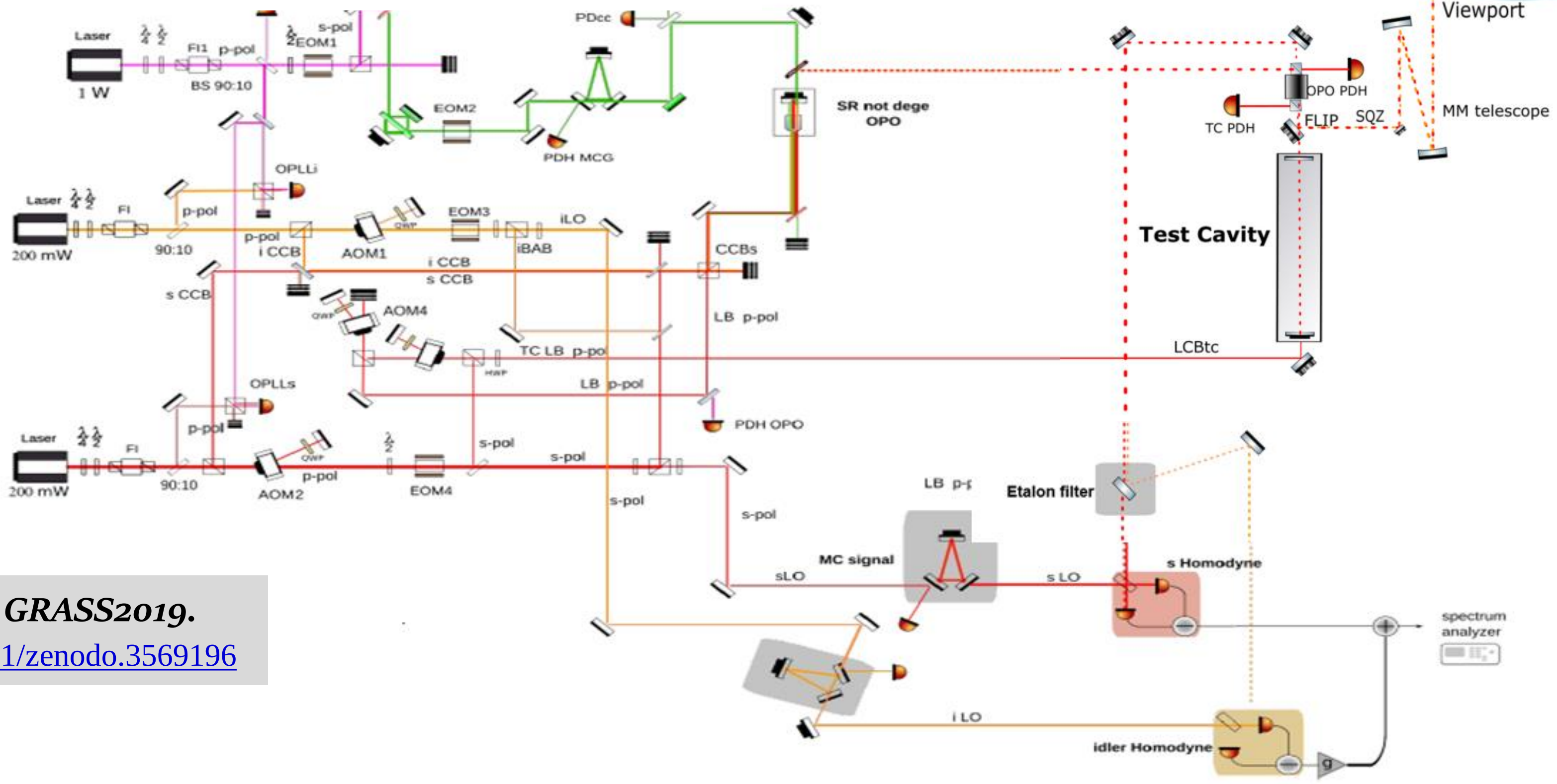
Idler* *measured on a fixed quadrature

The SIGNAL is CONDITIONALLY SQUEEZED in a FREQUENCY DEPENDENT way

5. SIPS as a test bench for the EPR squeezing

- EPR squeezing setup needs a test cavity
- SIPS small scale suspended interferometer will be RPN limited in the same frequency band of Virgo
- **SIPS interferometer turns out to be a suitable demonstrator of EPR principle before a possible integration in Advanced Virgo**
- **We expect to see quantum noise reduction below 2 kHz.**





Preliminary scheme EPR-SIPS integration @1500W SQZ LAB EGO-Virgo

S.Di Pace et al. presented @ GRASS2019. published @ https://doi.org/10.5281/zenodo.3569196

6. Conclusions and perspective

- **SIPS** has the target of **squeezing** generation through **ponderomotive** technique in the frequency band of ground-based **GW detectors**

- SIPS constitutes an interesting alternative to OPO-based squeezers

- An adequate seismic and thermal noise reduction allowed to design a tabletop ITF with **macroscopic** mirrors **opto-mechanically coupled by radiation pressure**

- **Local control** system of main suspended optics (coil-magnet system) has been successfully tested on mechanical prototype and is under upgrade, then it will be implemented in all the suspended elements. **Global control** system strategy is under development

- On the short term, SIPS will be used as demonstrator of EPR squeezing principle before a possible integration Advanced Virgo (Design of the integration must be finalized)

THANKS FOR YOUR ATTENTION