INFN seminario tecnologico

Progetto di ricerca finanziato – grant giovani CSN5

SIPS

Suspended Interferometric Ponderomotive Squeezer

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Overview

- Squeezed states of light

- Quantum Limit: Shot Noise and Radiation Pressure
- Quantization of the EM field: coherent and squeezed states
- Generation of squeezed light: OPO and Ponderomotive

- Ponderomotive generation with a SIPS

- Research Framework
- The suspended interferometer: structure and mirror suspension
- Suspension and mirror coating thermal noise
- Interferometer equivalent noise

- Project impact

- Sensitivity improvement in IGWD (Adv Virgo, LIGO, ET)
- Scientific & Technological impact in other fields

- Project details

- Expected budget & Collaboration duties
- Expected timeline

Squeezed states of light

Squeezed states of light

Quantum Limit: Shot Noise and Radiation Pressure

Photon shot noise (SN)

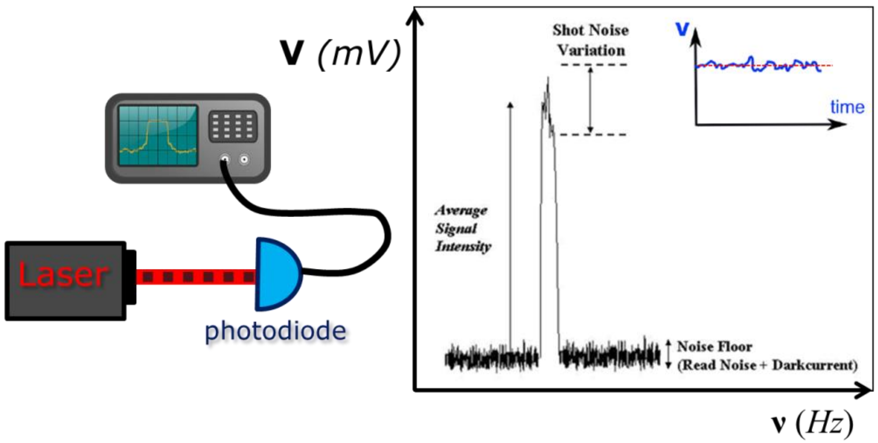
sensing noise:

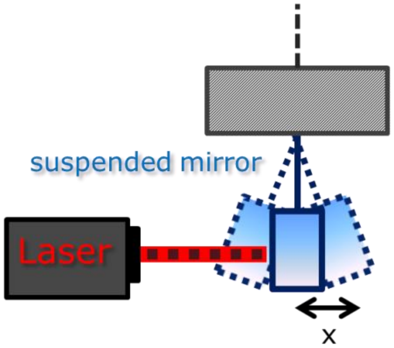
photons in a laser beam are not equally spaced in time but they follow a Poissonian distribution **photo-current time - series fluctuations**

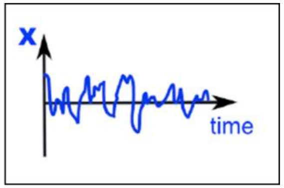
Photon Radiation Pressure (RP)

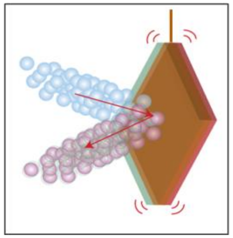
back-action noise:

photons transfer their momentum (i.e. a *radiation pressure force*) to the mirror with a temporally inhomogeneous distribution **mirror position fluctuations**









Standard Quantum Limit (SQL):

SN and RP fluctuations equal and uncorrelated

minimal uncertainty in a coherent state

Squeezed states of light

Quantization of the EM field

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

Quadrature Operators:

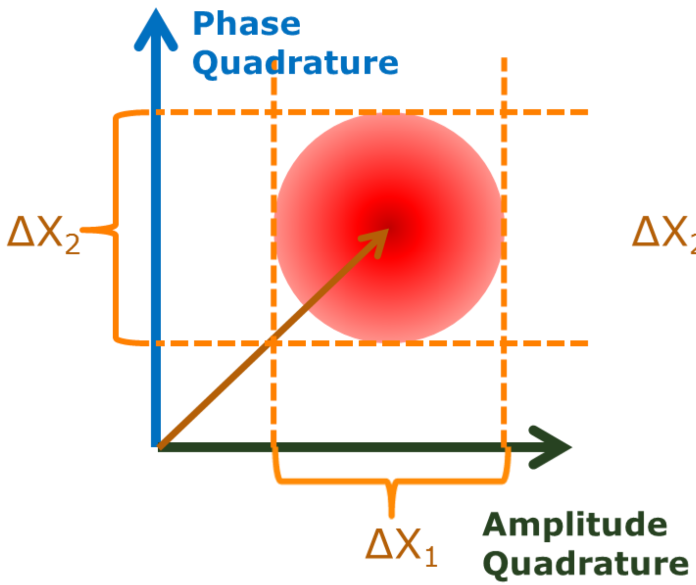
Phase: $X_2(\vec{r}) = i[a^*(\vec{r}) - a(\vec{r})]$

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

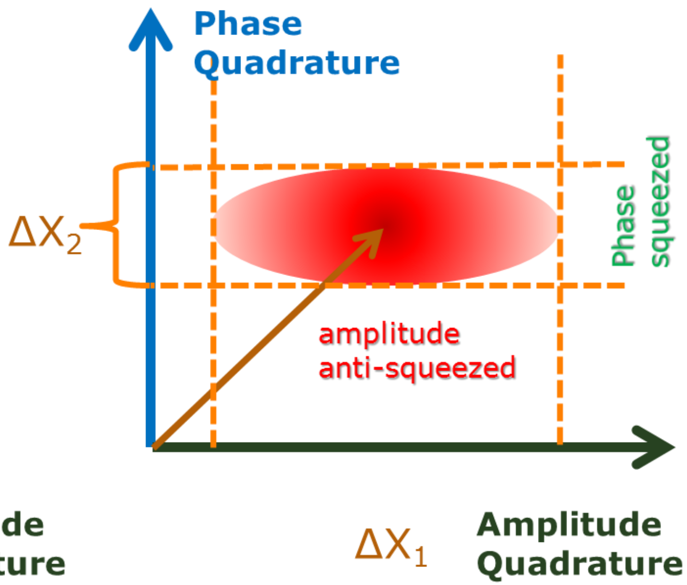
Heisenberg principle:

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

Coherent State

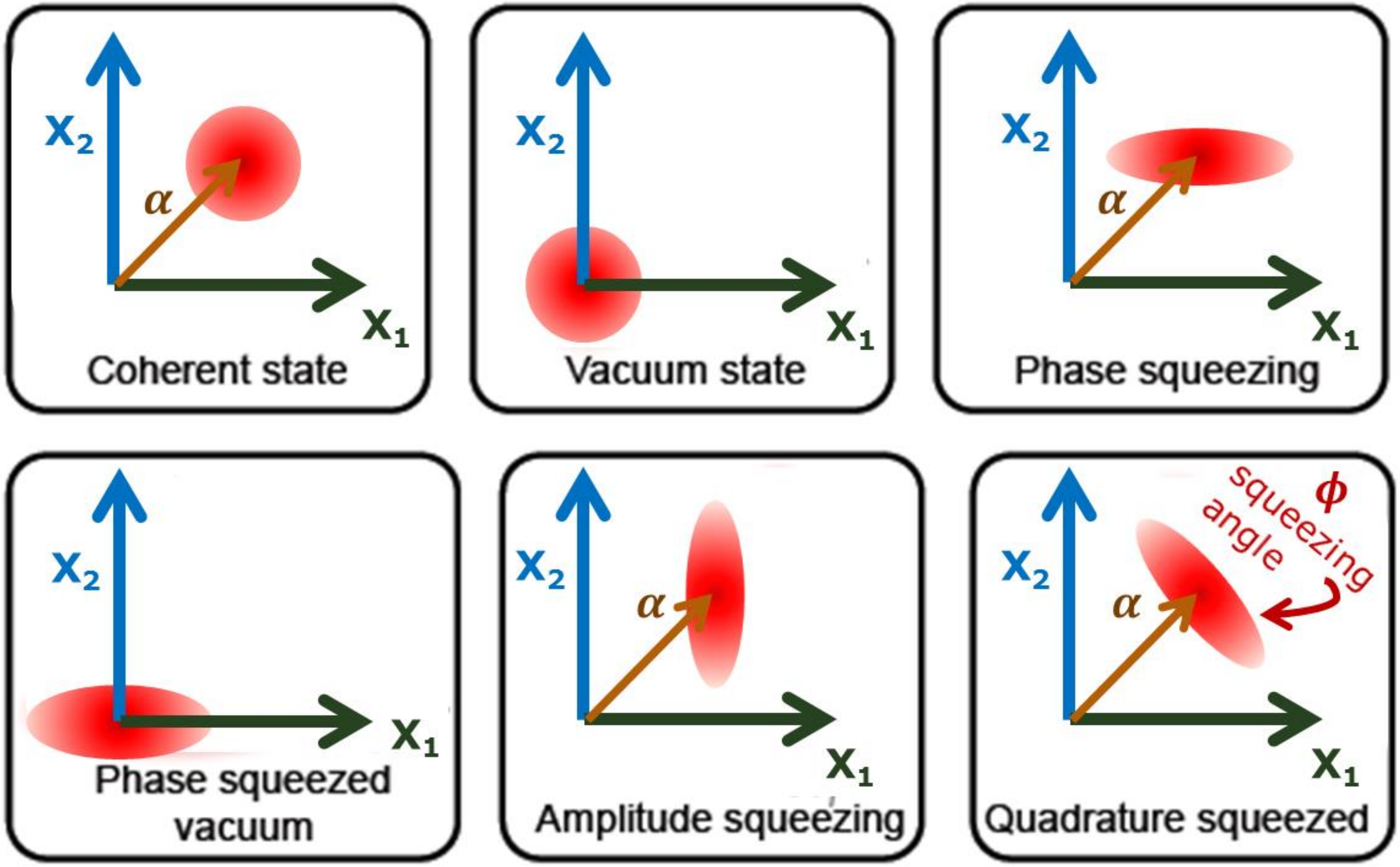


Squeezed State



Squeezed states of light

Quantization of the EM field



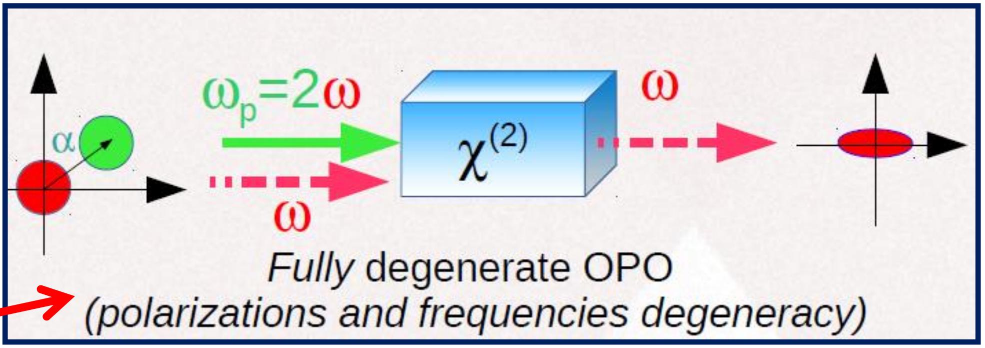
Squeezed states of light

Generation of squeezed light: OPO & ponderomotive

Non-linear processes in dielectric medium

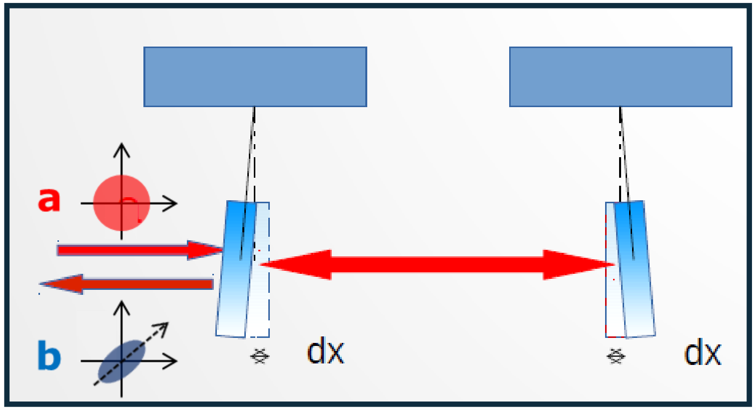
- **Kerr medium**
- Optical Parameter Oscillator (**OPO**)

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



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 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

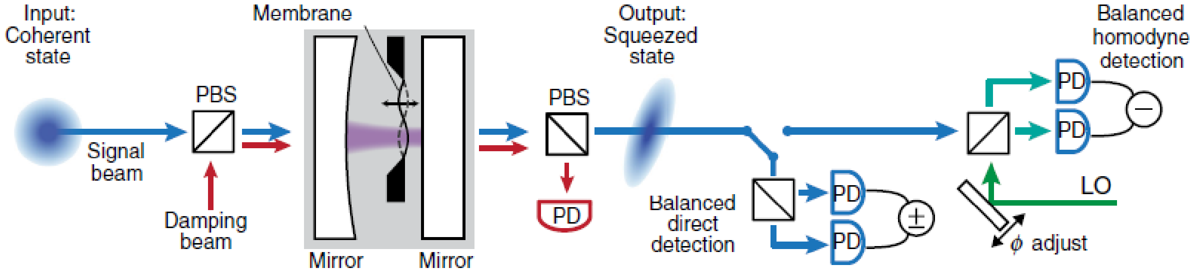
Squeezed states of light

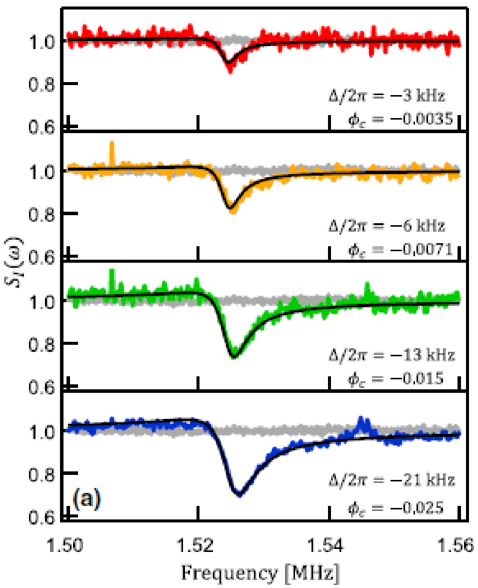
Generation of squeezed light: OPO & ponderomotive

Rising interest in the ponderomotive technique:

- Application to MOEMS: cheaper than OPO integration, better integration factor;
- Study of coupling between macroscopic opto-mechanic objects and their quantum behavior (theoretical and practical interest);
- Application to IGWD: low frequency performances and stability.

So far realized only in micro-opto-mechanical systems (MOMS):





1.7*dB* below shot noise @ 1.54*MHz*
(T.P. Purdy et al, Phys. Rev. X 3, 031012 2013*)*

BUT
- Not a so high gain;
- ω » IGWD frequency band
- bright beams instead of squeezed vacuum

Squeezed states of light

Generation of squeezed light: OPO & ponderomotive

Use of
radiation pressure as the squeezing mechanism

Intensity fluctuations of laser field creates test mass motion

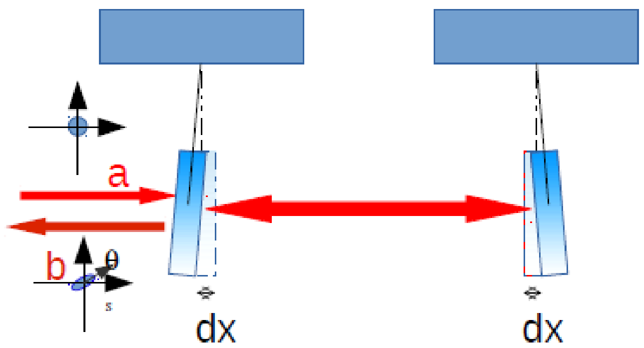
↓

Test mass motion creates phase shift of reflected light

↓

Phase shift is proportional to intensity fluctuations

RP + gravity: *Optical Spring*



This frequency-dependent shift couples the *phase quadrature* with the *amplitude quadrature* and generates the squeezing

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

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

Coupling Factor Frequency Dependent → **Frequency Dependent Squeezing**

Credit to M. De Laurentis, 2014

Ponderomotive generation with SIPS

Suspended Interferometric Ponderomotive Squeezer

Ponderomotive generation (SIPS)

Research framework

Preliminary R&D on a low frequency ponderomotive squeezer in the last few years (under the acronyms PPPS and POLIS), involving many 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

PPPS/POLIS legacy:

Design and realization of a **suspended interferometer** (Roma1); **Main laser** (Urbino, Napoli) and **R&D on laser stabilization** (Roma2); **optical benches** (Pisa)…

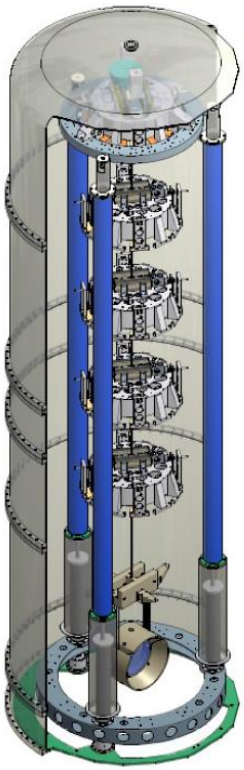
R&D and integration of crucial parts (optics, monolithic suspension, local control…) still to do in order to convert the suspended interferometer in an effective ponderomotive squeezer!

Ponderomotive generation (SIPS)

Suspended bench

Requirements:

- Suspension of very small mirrors in order to observe the **RP**
- High suppression of **seismic** and **thermo-elastic** noises



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 IGWD: low thermoelastic losses respect to metallic wires

Ponderomotive generation (SIPS)

Suspended bench

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 440*mm*-long)
Weight: ~ *150 kg*

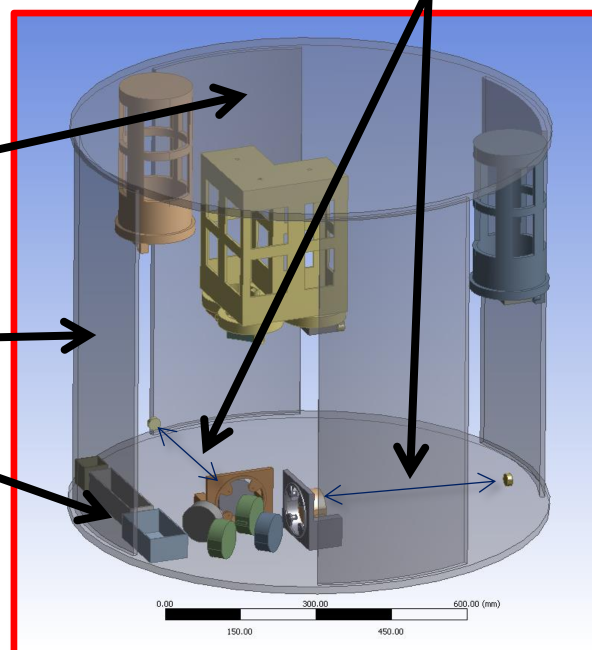
Material: anticorodal (Al-alloy)

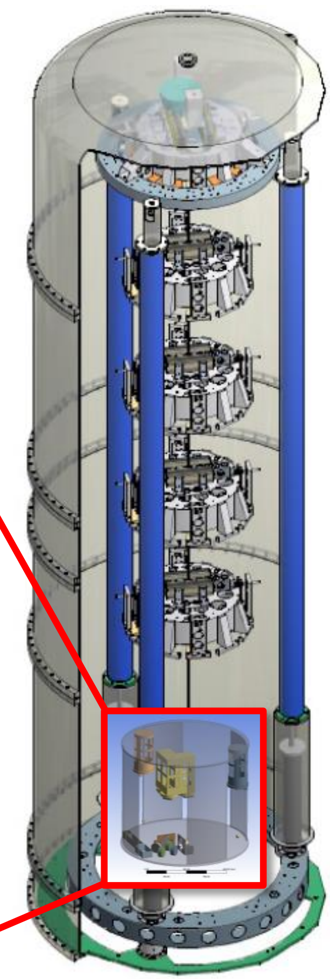
Upper plate (auxiliary bench)

Cylindrical baffles

Main optical bench

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

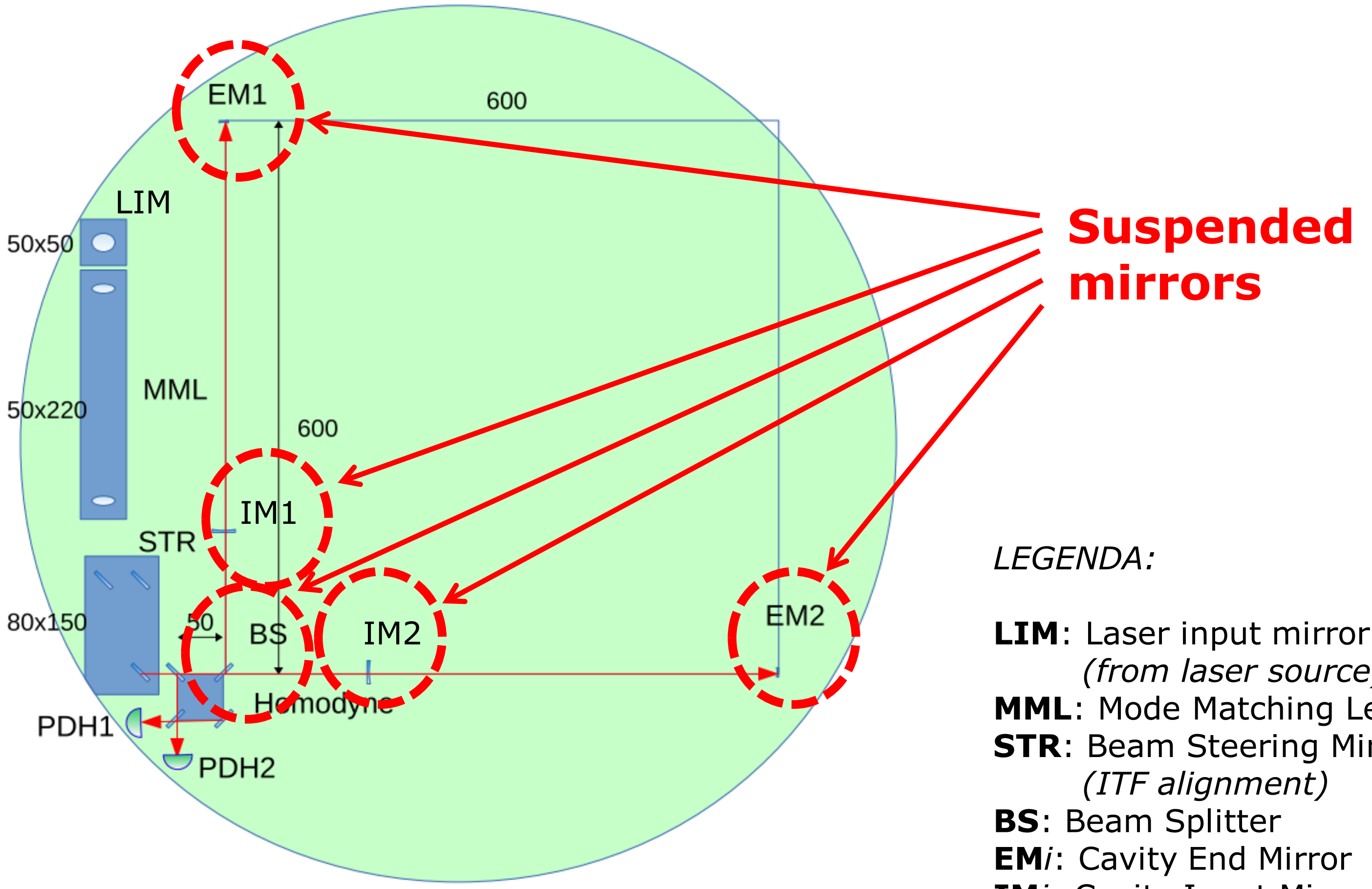




Ponderomotive generation (SIPS)

Suspended bench

Lower bench layout *(main opt bench)*

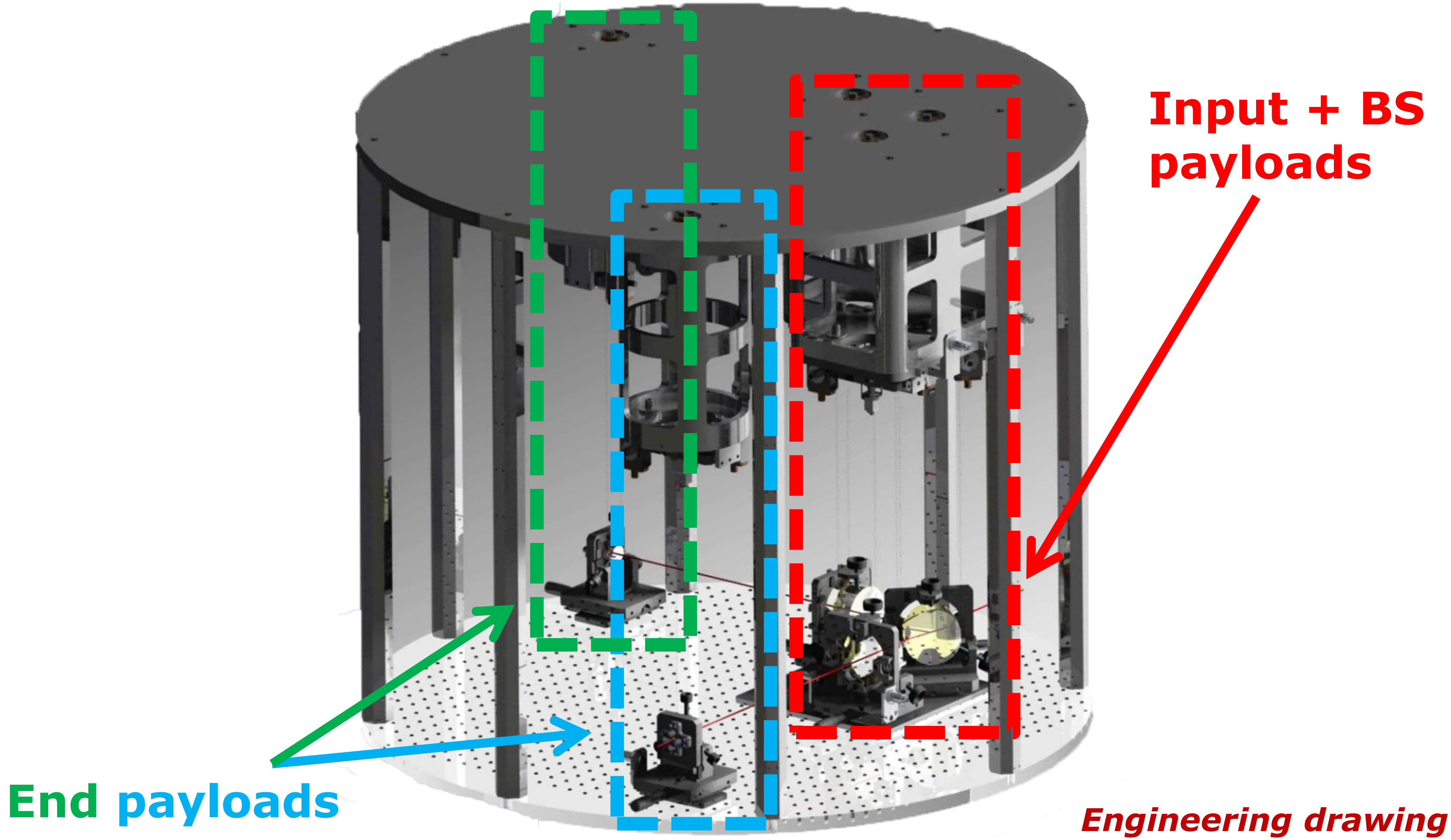


LEGENDA:

LIM: Laser input mirror *(from laser source)*
MML: Mode Matching Lens
STR: Beam Steering Mirrors *(ITF alignment)*
BS: Beam Splitter
EM*i*: Cavity End Mirror
IM*i*: Cavity Input Mirror

Ponderomotive generation (SIPS)

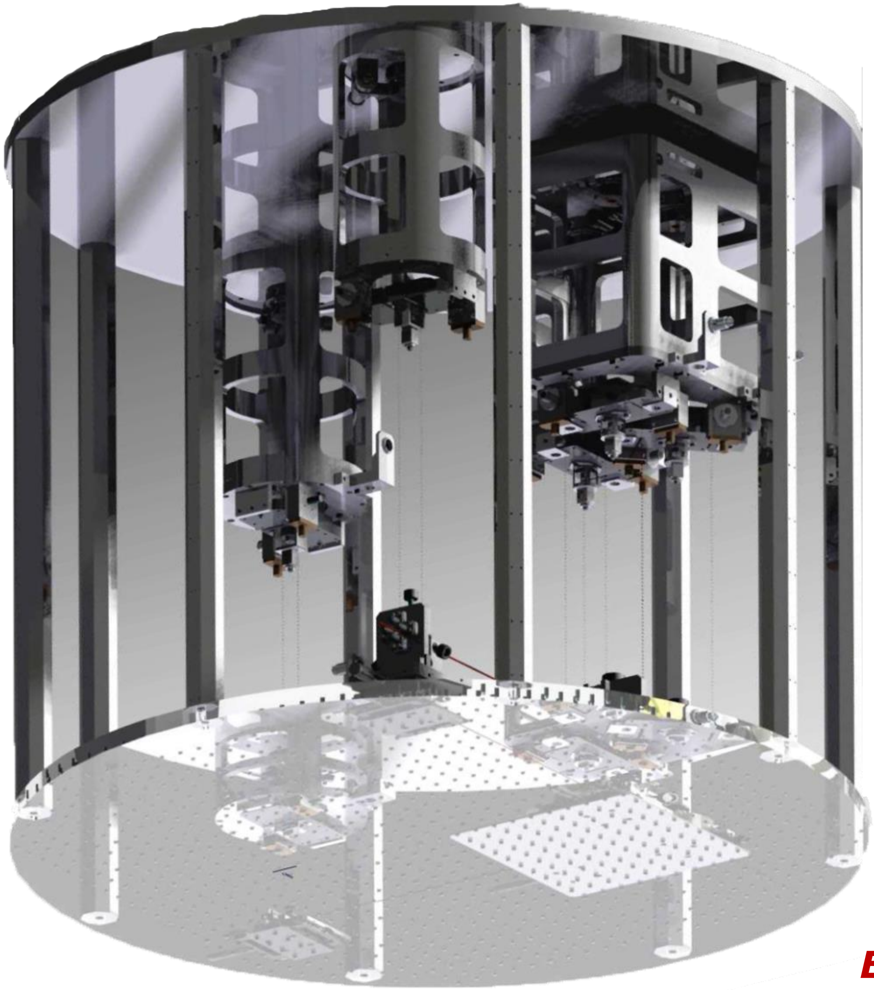
Suspended bench



Engineering drawing

Ponderomotive generation (SIPS)

Suspended bench



Engineering drawing

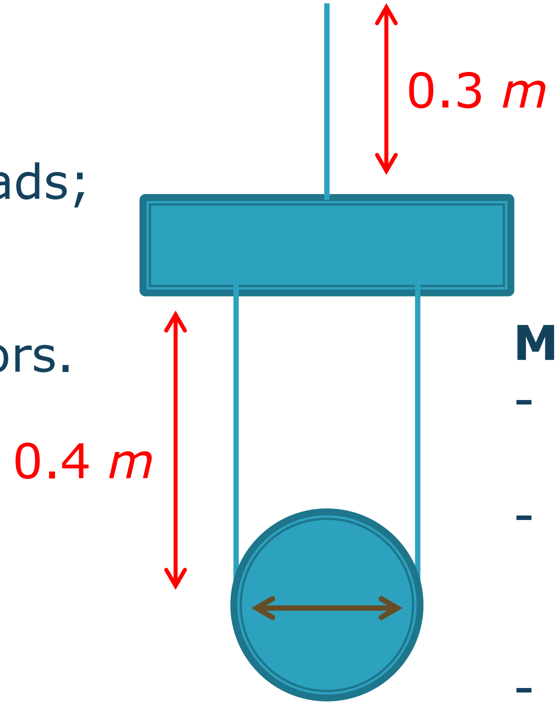
Ponderomotive generation (SIPS)

Mini-payloads

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

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.

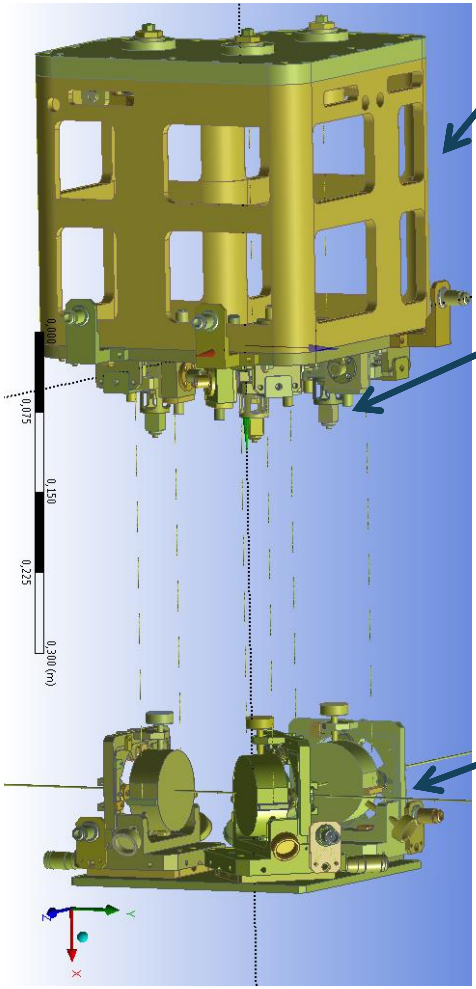


Mirrors:
- 0.3 *kg*, 3″ (BS & Input), 10^{-2} *kg*, 1″ (End);
- two fused silica fibers, $\Phi_{IN,BS} = 50\text{-}300\ \mu m$, $\Phi_{END} = 10\text{-}50\ \mu m$;
- magnet-coil actuators.

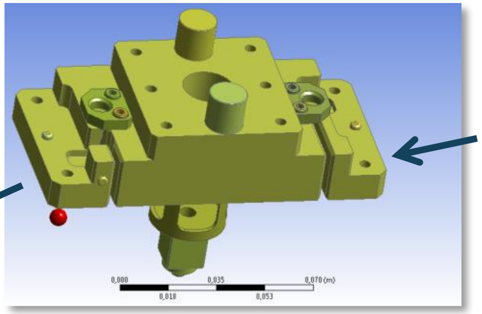
Ponderomotive generation (SIPS)

Mini-payloads

Beam Splitter and Input

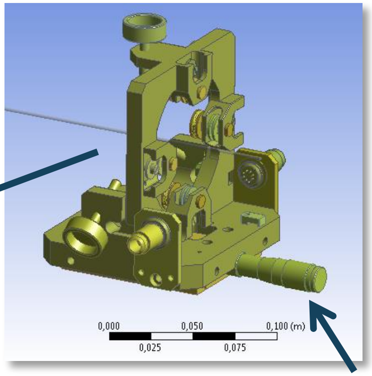


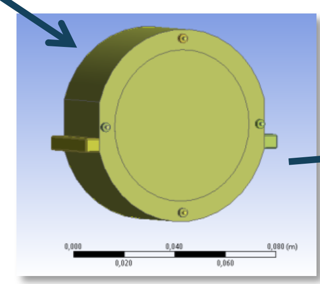
cage + **coil holder** Anticorodal Al, ~ 6 *kg*

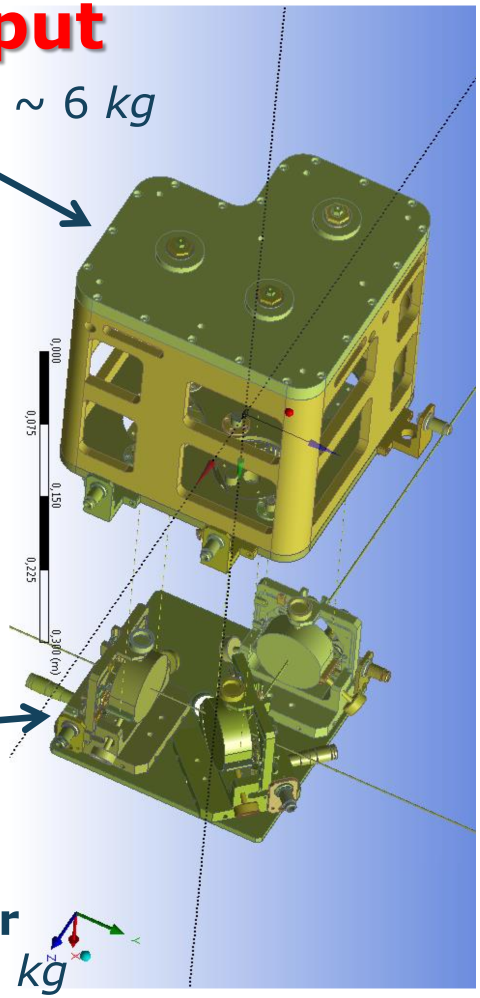


Marionette
Steel, 1.1 *kg*

Mirror Fused Silica, 0.3 *kg*







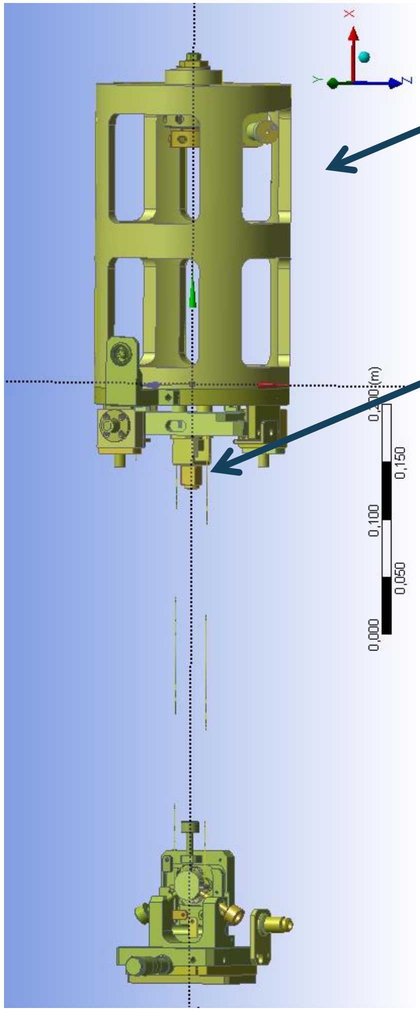
Mirror coil holder
Anticorodal Al, 1.6 *kg*

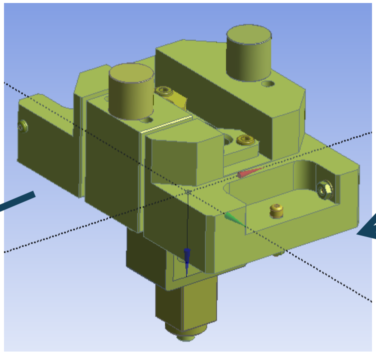
Ponderomotive generation (SIPS)

Mini-payloads

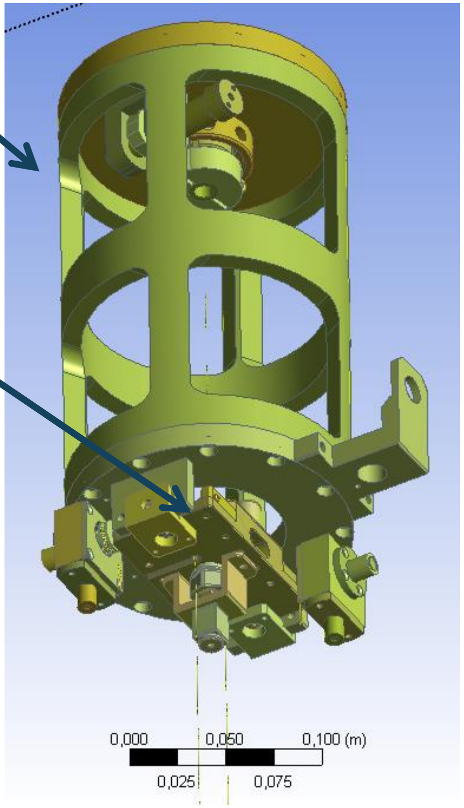
End Payload

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



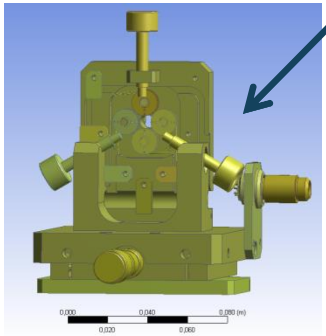


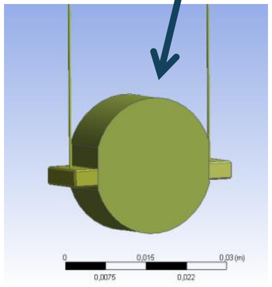
Marionette
Steel, 1.1 *kg*



Mirror coil holder
Anticorodal Al, 1.7 *kg*

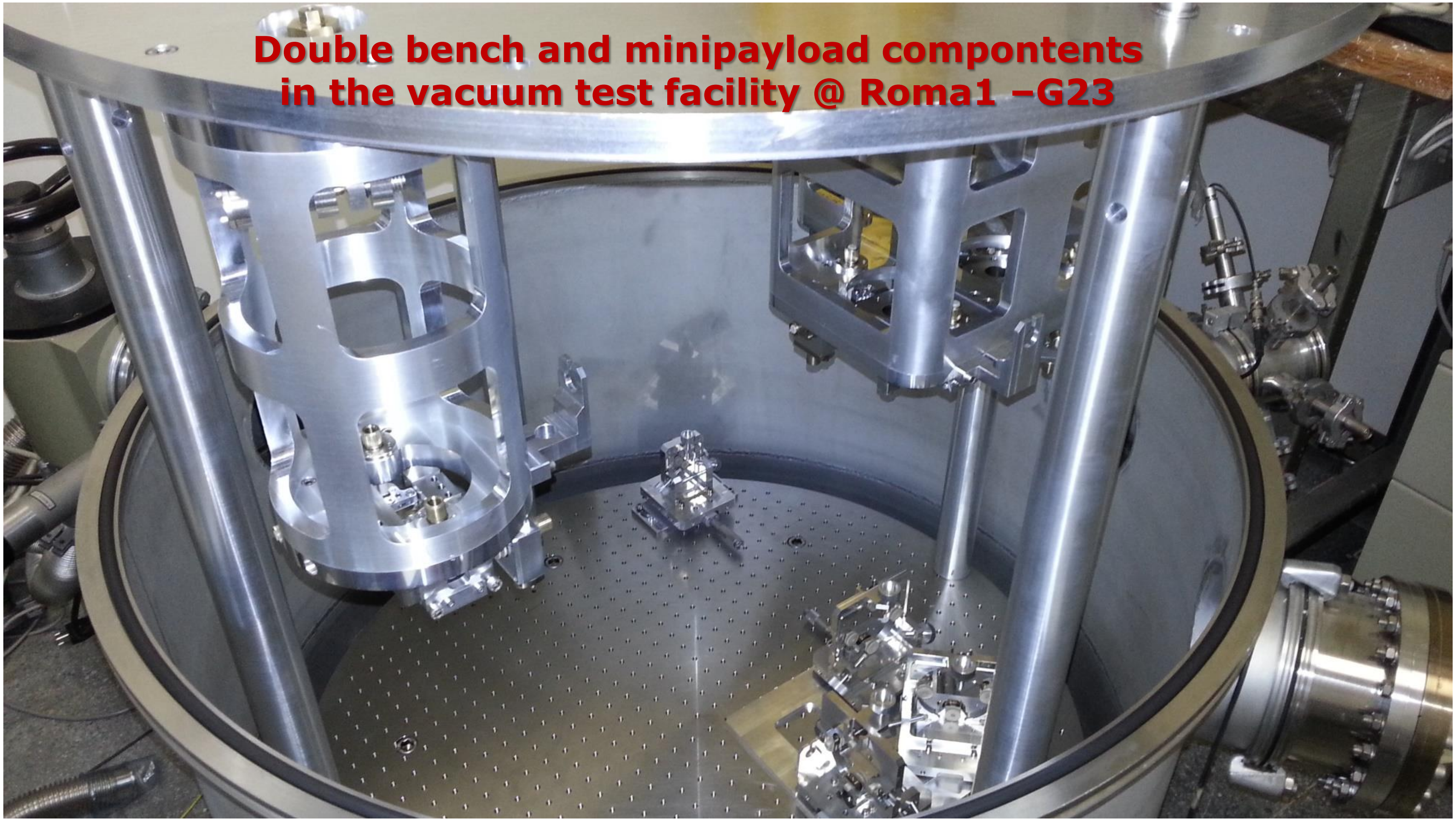
Mirror
Fused Silica, 10^{-2} *kg*





Ponderomotive generation (SIPS)

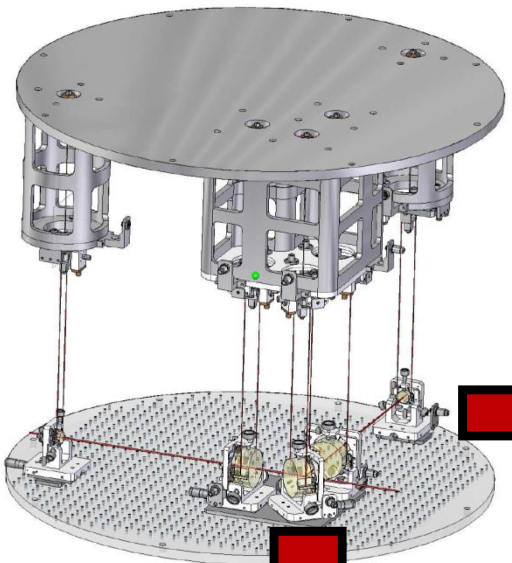
Current state of the mechanic structure

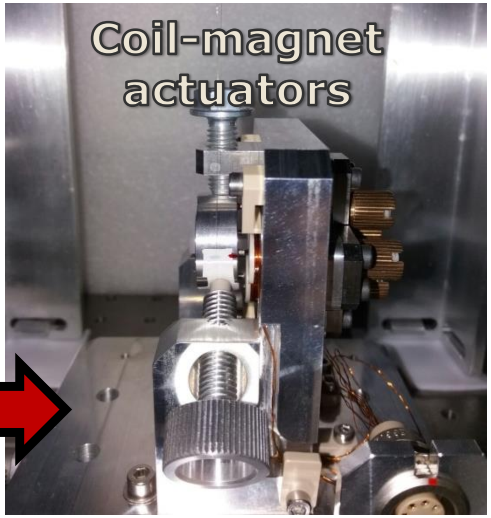


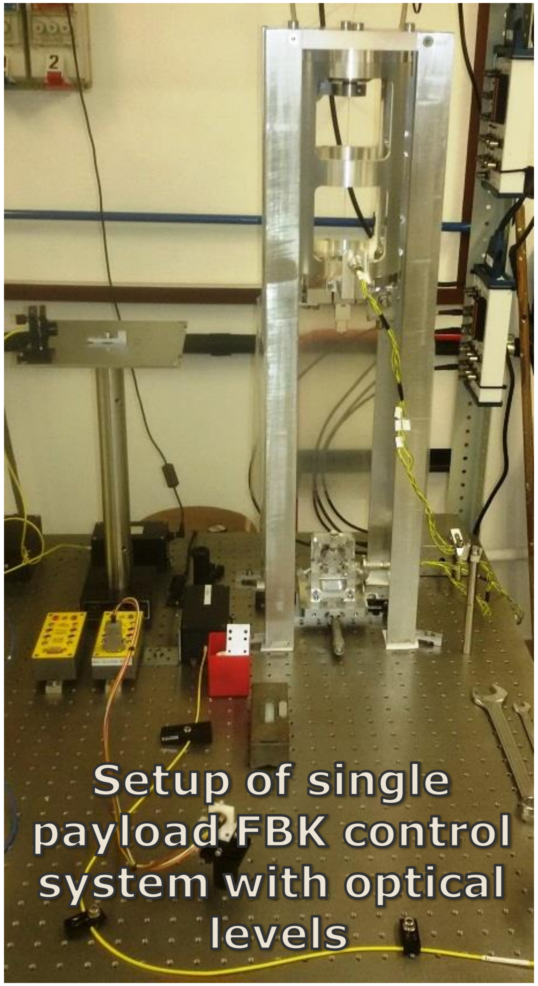
Double bench and minipayload compontents in the vacuum test facility @ Roma1 –G23

Ponderomotive generation (SIPS)

Activity in progress before project start







Ponderomotive generation (SIPS)

Suspension thermal noise

From the Fluctuation-Dissipation Theorem:

Suspension thermal noise

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

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

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

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:

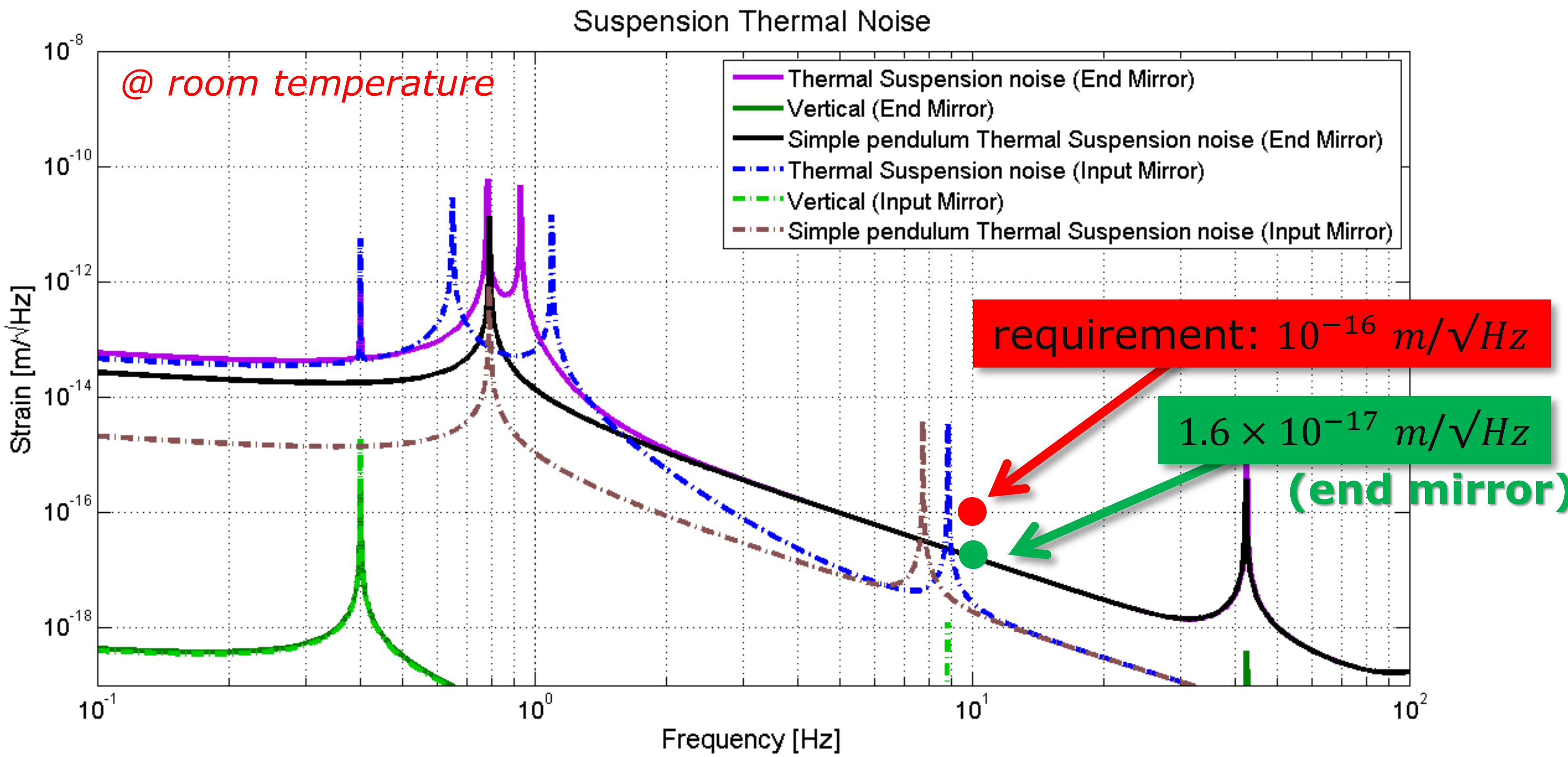
Marionette *Mirror*

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}	1.5×10^{-4} (Input) 2.5×10^{-5} (End)

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

Ponderomotive generation (SIPS)

Suspension thermal noise



Calculation based on Fluctuation-Dissipation Theorem for a double pendulum and FEM simulation, considering the project parameters, using a MatLab-based code

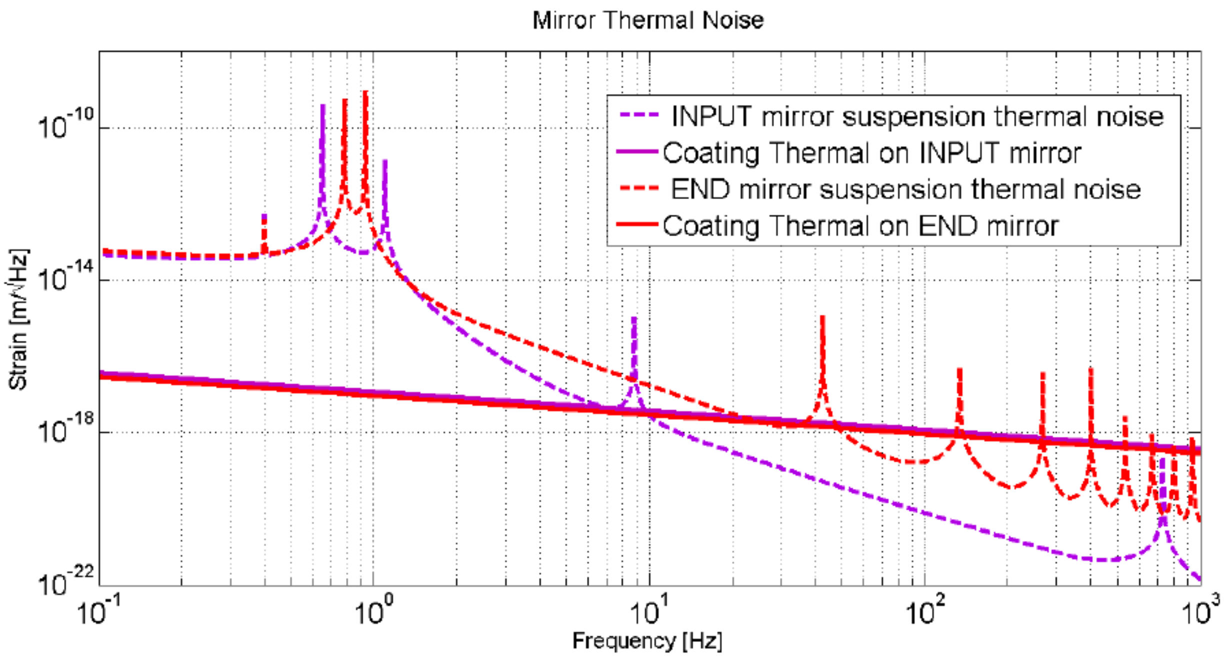
Ponderomotive generation (SIPS)

Mirror coating thermal noise

Calculated using the *Levin* approach*:

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

E_s is the strain energy stored in the dissipation zone, calculated with a harmonic response FEM simulation (F_0 is the peak value of the applied force with intensity profile of a laser Gaussian beam)



coating parameters**

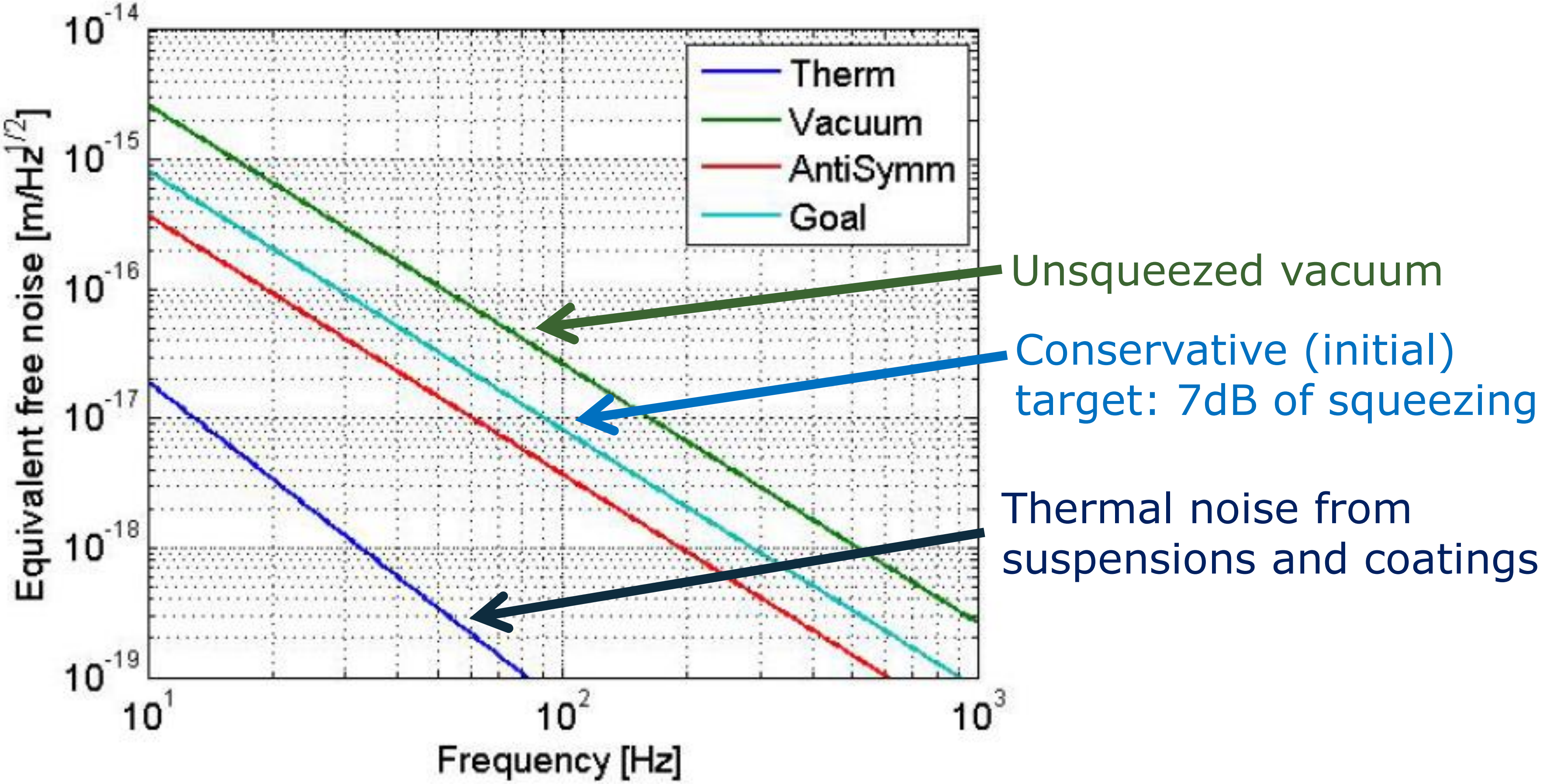
Parameter	value
ρ_{eff}	$4085.8\ kg/m^3$
Y_{eff}	$99.6\ GPa$
ν_{eff}	0.204
ϕ_{coat}	1.48×10^{-4}

* Y. Levin, *Phys. Rev. D* vol. 57, 659-663 (1998)

** G. M. Harry et al., *Class. Quantum Grav.* vol. 24, 405 (2007)

Ponderomotive generation (SIPS)

Interferometer equivalent noise

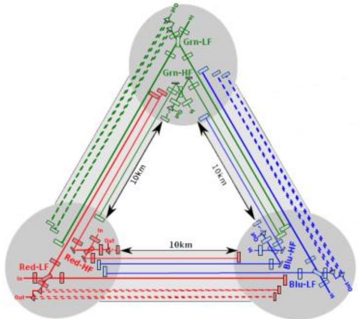


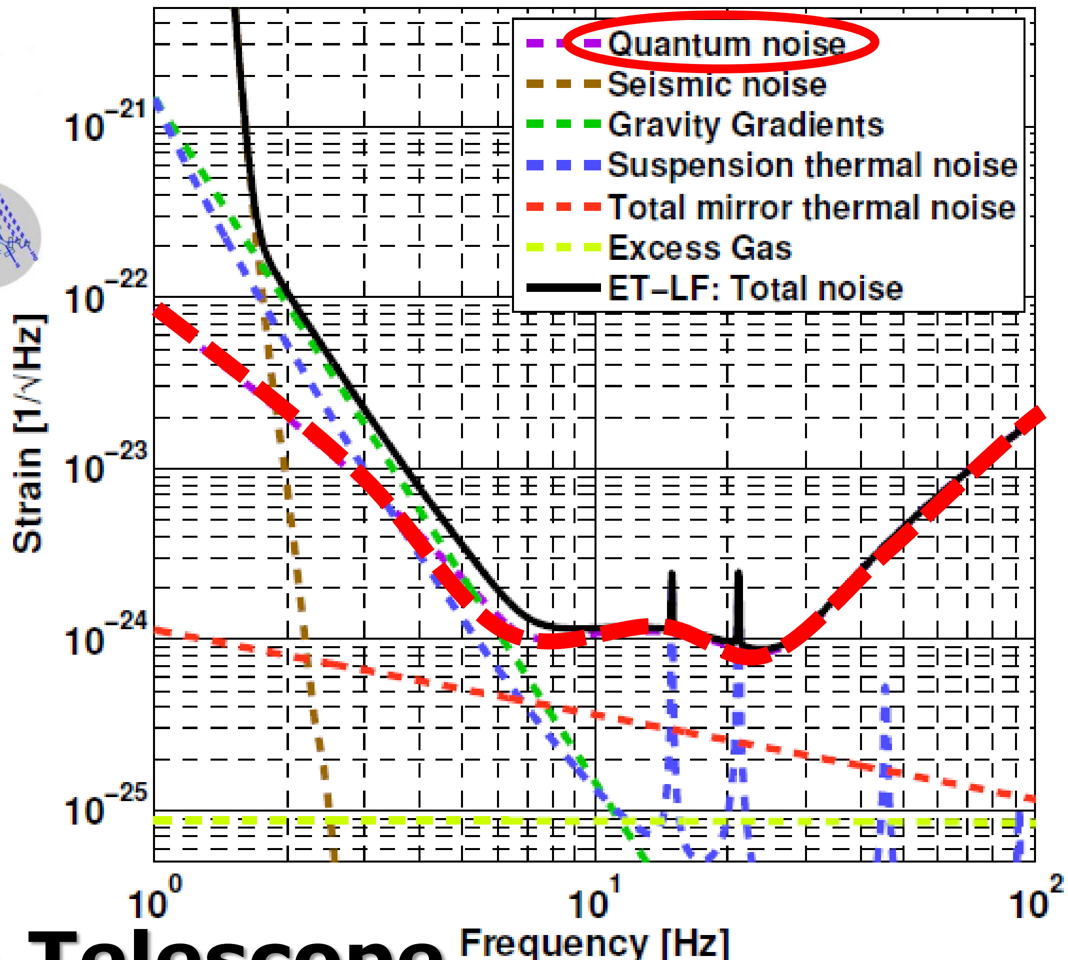
Project impact

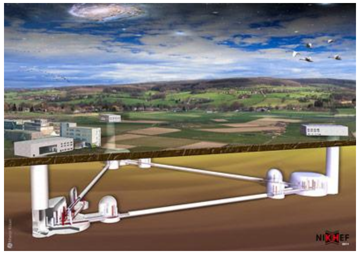
Project Impact

Improving IGWD sensitivity

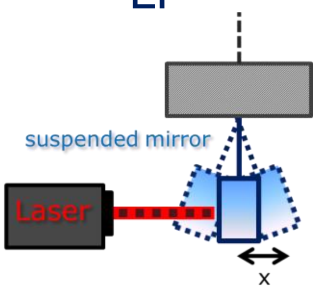
(Interferometric Gravitational Wave Detector)



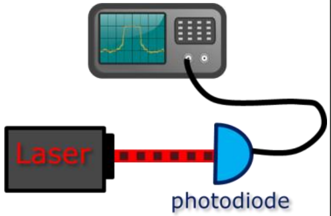




RP
LF



SN
HF

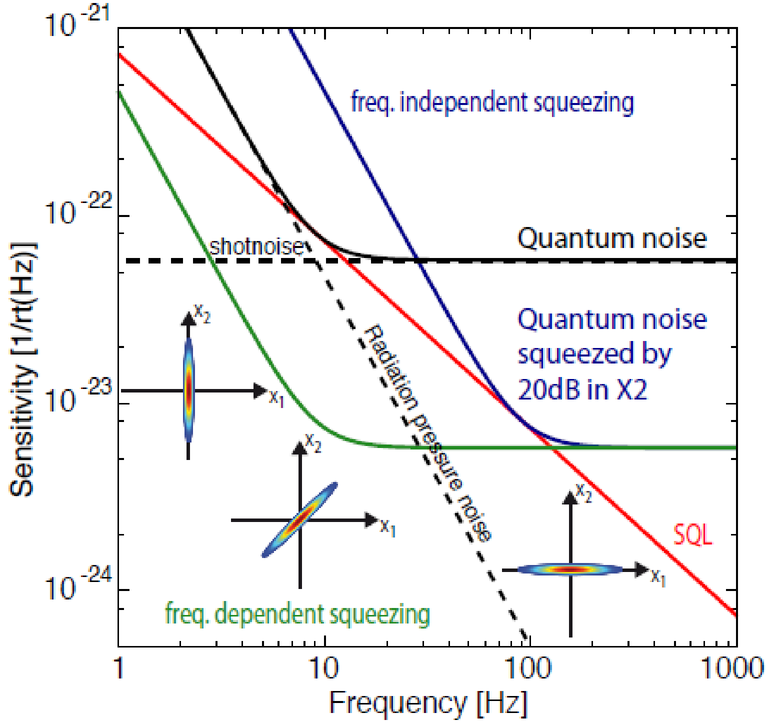


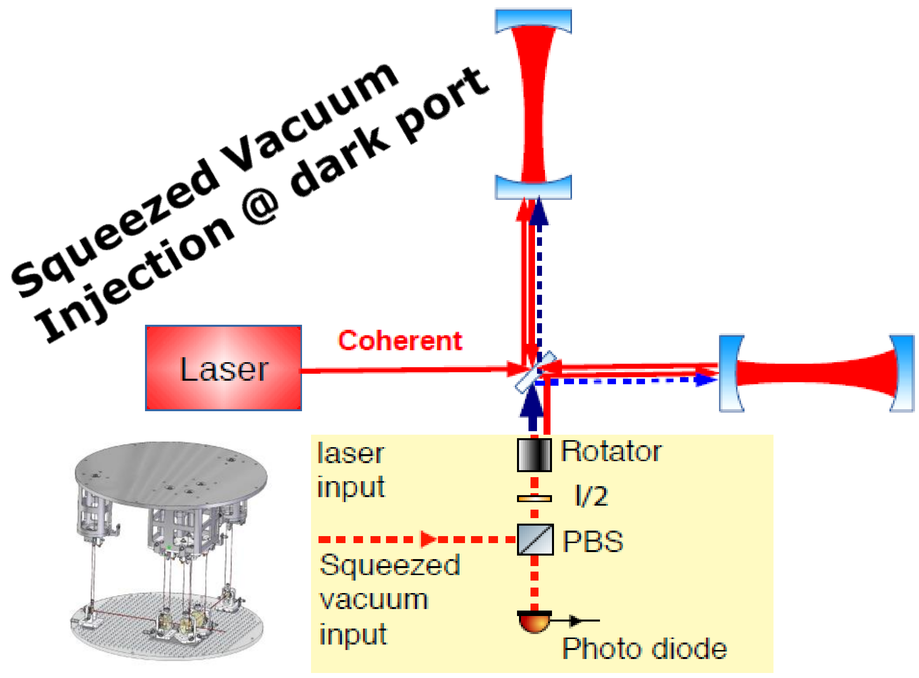
Einstein Telescope

Project Impact
Improving IGWD sensitivity

Motivation: push the sensitivity of IGWD below the SQL (radiation pressure + shot noise); reduction of the LF radiation pressure increase due to the higher circulating power in the GW interferometer's cavities.

Concept: generation and injection of squeezed fields into the dark port of the GW interferometers → Quantum entanglement → SNR reduction





Project Impact

Scientific & Technological

- Test quantum limit and entanglement at the boundary between macroscopic and microscopic scale
- Measurement of small forces down to the Heisenberg limit
- Production of SiO_2 micro-fibers (μm-scale)
- Interfaces for quantum communication and quantum computers
- Low dissipation high transparency optics
- Setup of low noise and high balanced optoelectronics
- Development of low noise DAQ, FBK and Homodyne detection electronics
- Development of simulation codes for quantum optics

Project Impact
Scientific & Technological

- Test quantum limit and entanglement at the boundary between macroscopic and microscopic scale

Quantum correlation of macroscopic mirrors

- Measurement of small forces down to the Heisenberg limit

e.g.: RP measurement to detect solar Chameleon scalar particles

- Production of SiO_2 micro-fibers (μm-scale)

Theory test + applications

- Interfaces for quantum communication and quantum computers

e.g.: Cold neutral atoms trapping using nanofiber-guided light and quantum information exchange between light and atoms

- Low dissipation high transparency optics
- Setup of low noise and high balanced optoelectronics

Telecommunication network potential applications

- Development of low noise DAQ, FBK and Homodyne detection electronics

Experimental quantum physics applications

- Development of simulation codes for quantum optics

Project details

Project Details

TOTAL BUDGET (over 2 years):

Instrumentation, Consumable, Manufacturing:	**~75 k€**
Grant:	**60 k€**

SIPS COLLABORATION:	MAIN DUTIES:
INFN-ROMA1	*Optical setup, FBK controls, Homodyne detection*
INFN-PERUGIA	*Monolithic suspension, SiO_2 microfibers, Mirrors*
INFN-PISA	*Optical bench integration, SAFE (SA) setup*

+

former POLIS institutions:

-**Univ. Urbino** (Main Laser, SiO2 microfiber production support)
-**Univ. & INFN Napoli** (Main Laser integration Optical design & support)
-**Univ. & INFN Roma2** (Laser stabilization)

EGO VIRGO :

- SAFE (SuperAttenuator)
- SiO_2 fiber production facility
- Interaction with AdV OPO squeezer team

Project Details

Expected timeline

2017 April — **2018** — **2019** — **2019 April**

SIPS end

ITF **Assembly** (*simple setup*: metal wires, test mirrors)

HQ optics integration

Feedback local **control setup**

Feedback global **control setup**

Optical design and **laser injection setup**

SiO_2 **fibers production** and **monolithic suspension**

Homodyne detector

In-vacuum tests

ITF **commissioning**

Auxilary bench for opt. lev.

Preparation and tuning of **SAFE**

Squeezed light production *(frequency independent <1kHz)*

Integration in SAFE

Assembly of the suspended double Optical Bench final configuration

From 2019:

Optimization and test of filtering techniques *(frequency dependent squeezing 10Hz < f < 1kHz)*

Study for **the integration in IGWD** *(e.g. in Adv Virgo and ET)*

Thank you for your attention!