Ponderomotive squeezing of light: overcoming the Standard Quantum Limit in the detection band of interferometric gravitational wave detectors

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Overview

- Squeezed states of light

- Quantization of the EM field;
- Graphical representation;
- Squeezed vs. Coherent states;
- Historical point of view;

- Squeezed light in interferometric GW detectors

- AdVirgo & ET LF sensitivity curves;
- Motivation & concept;
- GW effect on a coherent state;
- GW effect on a phase-squeezed state;
- Frequency-dependent squeezing;
- Experimental sensitivity enhancement;

- Squeezed light: OPO-based & Ponderomotive

- OPO vs. Ponderomotive;
- OPO-based squeezing;
- Ponderomotive squeezing;

- The POLIS experiment

- **Po**nderomotive **Li**ght **S**queezer;
- Optical parameters;
- Setup sketch;
- Homodyne detection;
- The suspended double-bench;
- Suspended mini payloads;
- Suspension thermal noise;
- Mirror coating thermal noise;
- Interferometer equivalent noise;

- Conclusions

Squeezed states of light

Squeezed state of light

Quantization of the EM field

Electric field **E** in the position **r** at time **t**:

Polarization **p**

$$\vec{E}(\vec{r},t) = E_0\left[a(\vec{r})e^{-i\omega t} - a(\vec{r})^* e^{i\omega t}\right]\vec{p}(\vec{r})$$

Complex amplitude **a**
(function of phase φ):

Angular frequency ω

$$a(\vec{r}) = a_0(\vec{r})e^{-i\varphi(\vec{r})}$$

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

$$\begin{cases} X_2(\vec{r}) = X^-(\vec{r}) = i[a^*(\vec{r}) - a(\vec{r})] \\ X_1(\vec{r}) = X^+(\vec{r}) = a^*(\vec{r}) + a(\vec{r}) \end{cases}$$

X_2 → **Phase quadrature**

X_1 → **Amplitude quadrature**

Quantization of the EM Field :

$$\boxed{\hat{X}^+ = \frac{1}{2i}(\hat{a}^+ + \hat{a}) \qquad \hat{X}^- = \frac{1}{2i}(\hat{a} - \hat{a}^+)}$$

Heisenberg principle:

$$\boxed{\langle(\Delta\hat{X}^+)^2\rangle\langle(\Delta\hat{X}^-)^2\rangle \geq \frac{1}{16}}$$

Squeezed state of light

Quantization of the EM field

Coherent states can be written in terms of the eigenstate of the annihilation operator $\hat{a}$: $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$ and of number states $|n\rangle$

→ $\hat{E}$ has a sinusoidally oscillating expectation value (classical-like behaviour)

$$\boxed{|\alpha\rangle = \exp(-\frac{1}{2}|\alpha|^2)\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}|n\rangle}$$

$|\alpha| \propto$ field amplitude

n photon number

$$n = \langle\alpha|\,\hat{n}\,|\alpha\rangle = |\alpha|^2$$

$\hat{n}^2$ gives the photon number fluctuations:

$$\begin{aligned}\langle\alpha|\,\hat{n}^2\,|\alpha\rangle &= \langle\alpha|\,\hat{a}^\dagger\hat{a}\hat{a}^\dagger\hat{a}\,|\alpha\rangle \\ &= |\alpha|^4 + |\alpha|^2 = n^2 + n\end{aligned}$$

$$\Delta^2 n = \langle\hat{n}^2\rangle - \langle\hat{n}\rangle^2 = n$$

typical for a ***Poissonian*** *process*

$$P_n = |\langle n|\alpha\rangle|^2 = e^{-n}\frac{\overline{n}^n}{n!}$$

Squeezed state of light

Quantization of the EM field

A squeezed state is generated by the squeezing operator $\hat{S}$:

$$\hat{S}(\xi) = \exp\left(\frac{1}{2}(\xi^* \hat{a}\hat{a} - \xi \hat{a}^\dagger \hat{a}^\dagger)\right) \; ; \; \xi = re^{i\phi}$$

$0 \le r \le \infty$ squeezing parameter

$0 \le \phi \le 2\pi$ quadrature angle

When $\hat{S}$ acts on a state $|\varphi\rangle$ we obtain the squeezed state:

$$\boxed{|s\rangle = \hat{S}\,|\psi\rangle}$$

taking $\varphi = 0$ and calculating the variances of $\hat{X}^+$,$\hat{X}^-$ we find:

$$\Delta^2 \hat{X}_1 = e^{-2r}$$ squeezed

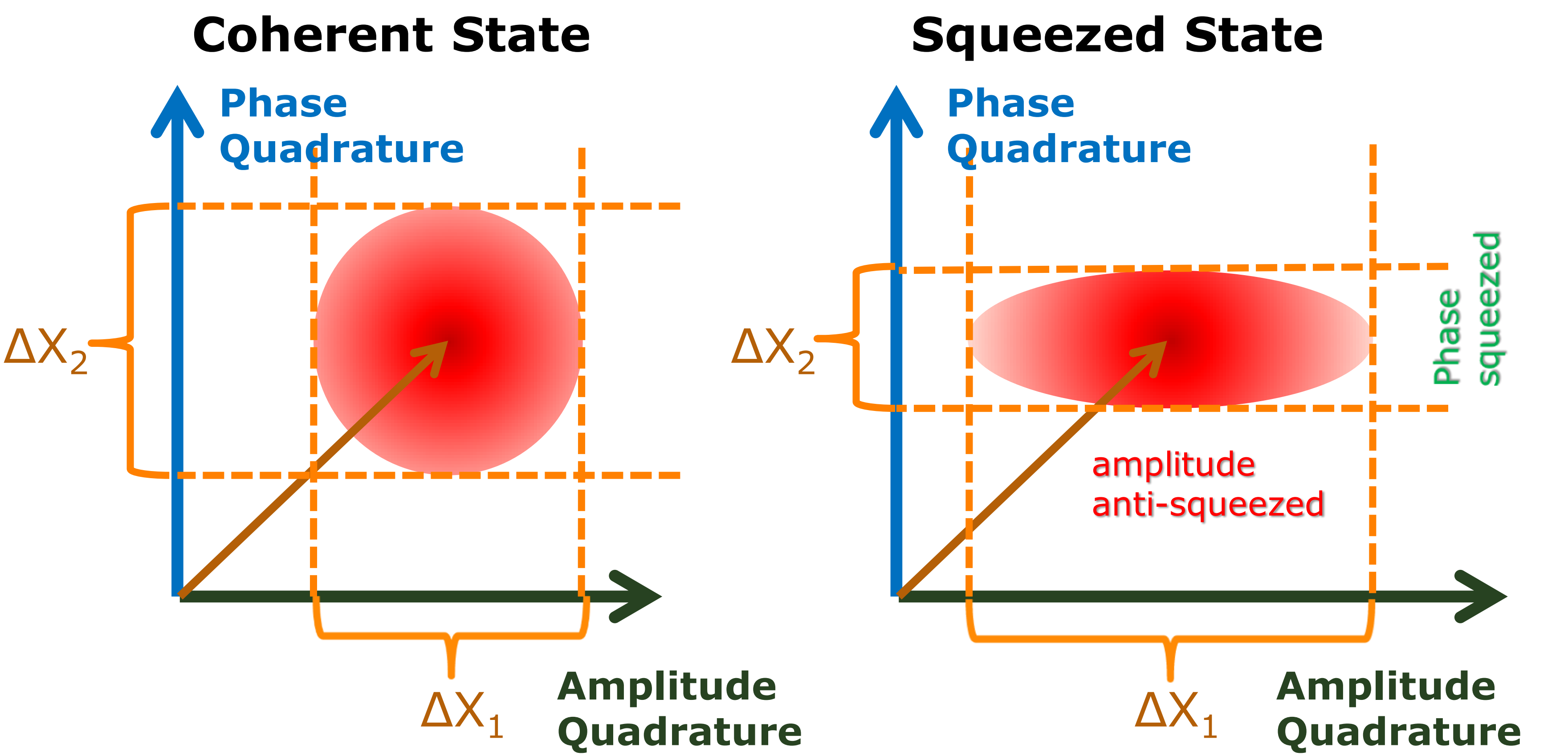
$$\Delta^2 \hat{X}_2 = e^{2r}$$ anti-squeezed

A rotation by π gives the opposite condition: $\hat{X}^-$ squeezed and $\hat{X}^+$ anti-squeezed.

Finally, the displacement operator $\hat{D}$ generates the displacement in the phase-amplitude plan:

$$|\alpha, \xi\rangle = \hat{D}(\alpha)\hat{S}(\xi)\,|0\rangle$$

Squeezed state of light
Graphical representation

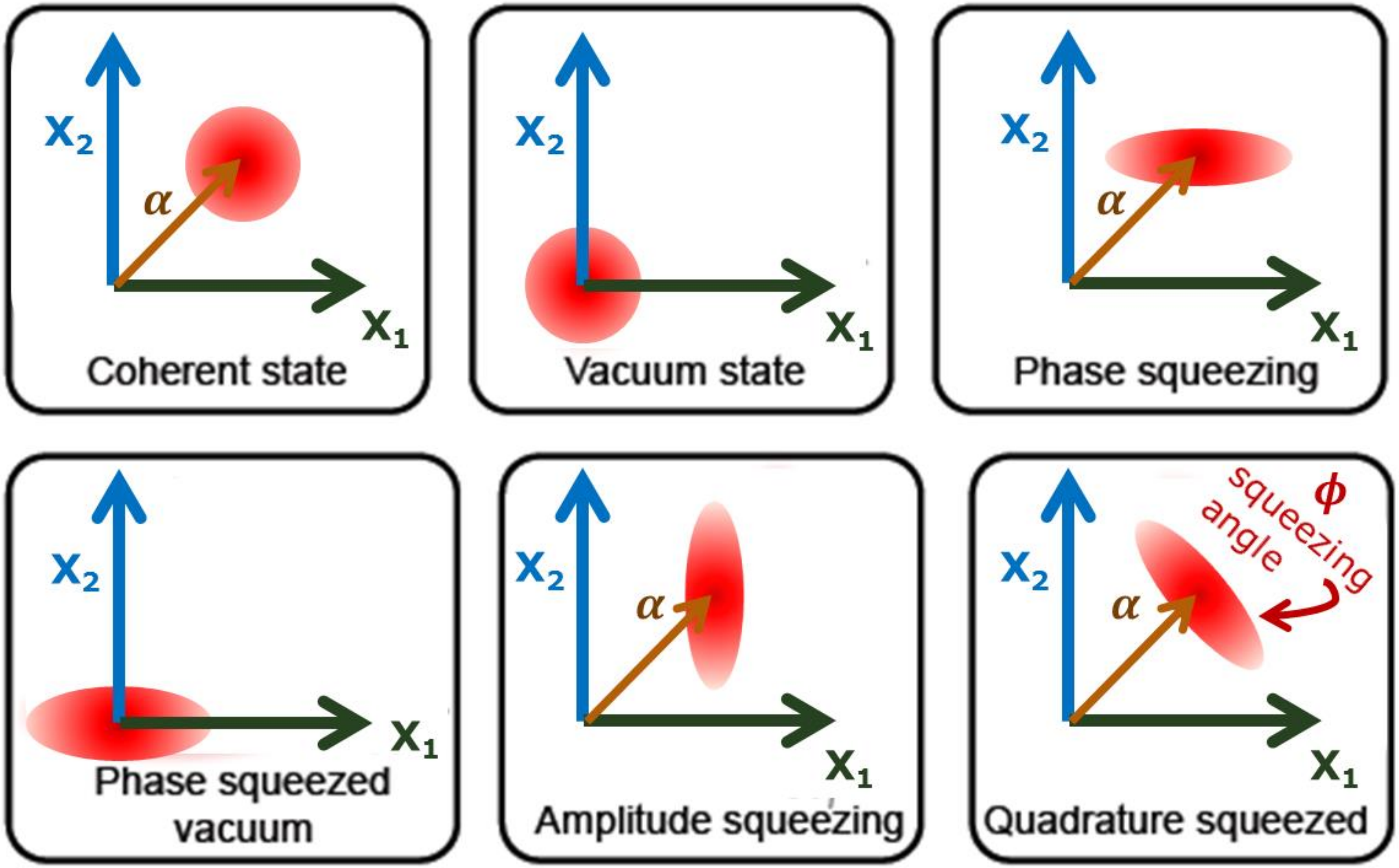


$\Delta\hat{X}_1\Delta\hat{X}_2 \geq 1$ **Heisenberg uncertainty principle ↔ <u>minimal area</u> of the *ball***

Squeezed state of light

Graphical representation

$\Delta X_1 \Delta X_2 \geq 1 \leftrightarrow$ Heisenberg minimal uncertainty



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

Squeezed state of light

squeezed vs coherent states

Using light as probe (e.g. interferometer)

Minimal uncertainty shows up in a coherent state as the **Standard Quantum Limit** (**SQL**):

In this case uncorrelated **Shot noise** and **radiation pressure**-induced fluctuations (due to the *Poissonian* distribution of photons in a light beam) introduce an intrinsic limitation on the accuracy in the position measurement of a free mass using coherent light.

Squeezed state of light

squeezed vs coherent states

Using light as probe (e.g. interferometer)

A bright laser beam ($\alpha>0$) has the same fluctuation of the vacuum state

Its intrinsic quantum fluctuations determines the detector sensitivity

We can't violate the Heisenberg uncertainty but…

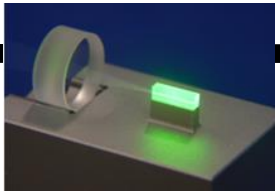
We can **squeeze** the *uncertainty* on one quadrature and *use* that quadrature as *sensing element*

overcoming the standard quantum limit of coherent light!

squeezed states ↔ **correlation** between two quadratures (i.e. *phase* and *amplitude*)

Squeezed state of light
historical point of view


Schrödinger Vs. Heisenberg



Non-linear Crystals

1927

Concept and first theory of coherent states and minimum uncertainty;

1970

- Re-discovery of definition of **squeezed states**: increasing interest for their applications to optical communications and sensor noise reduction and for the theory of *Standard Quantum Limit;*
- From **80s** the experimental generation of squeezed states begins using non-linear crystals at high frequencies; application to **GWD** is proposed..

2000

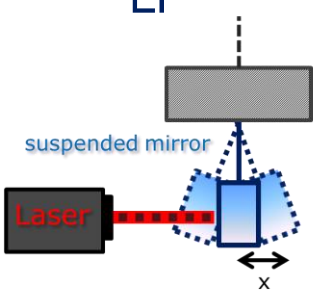
- Low frequency squeezed light generation begins with OPOs;
- Effective application to **Gravitational Wave Detectors** to overcome the Standard Quantum Limit (GEO600, LIGO, Advanced Virgo+);
- Experimental studies on the *ponderomotive technique* to generate squeezed light and on *optical springs*.

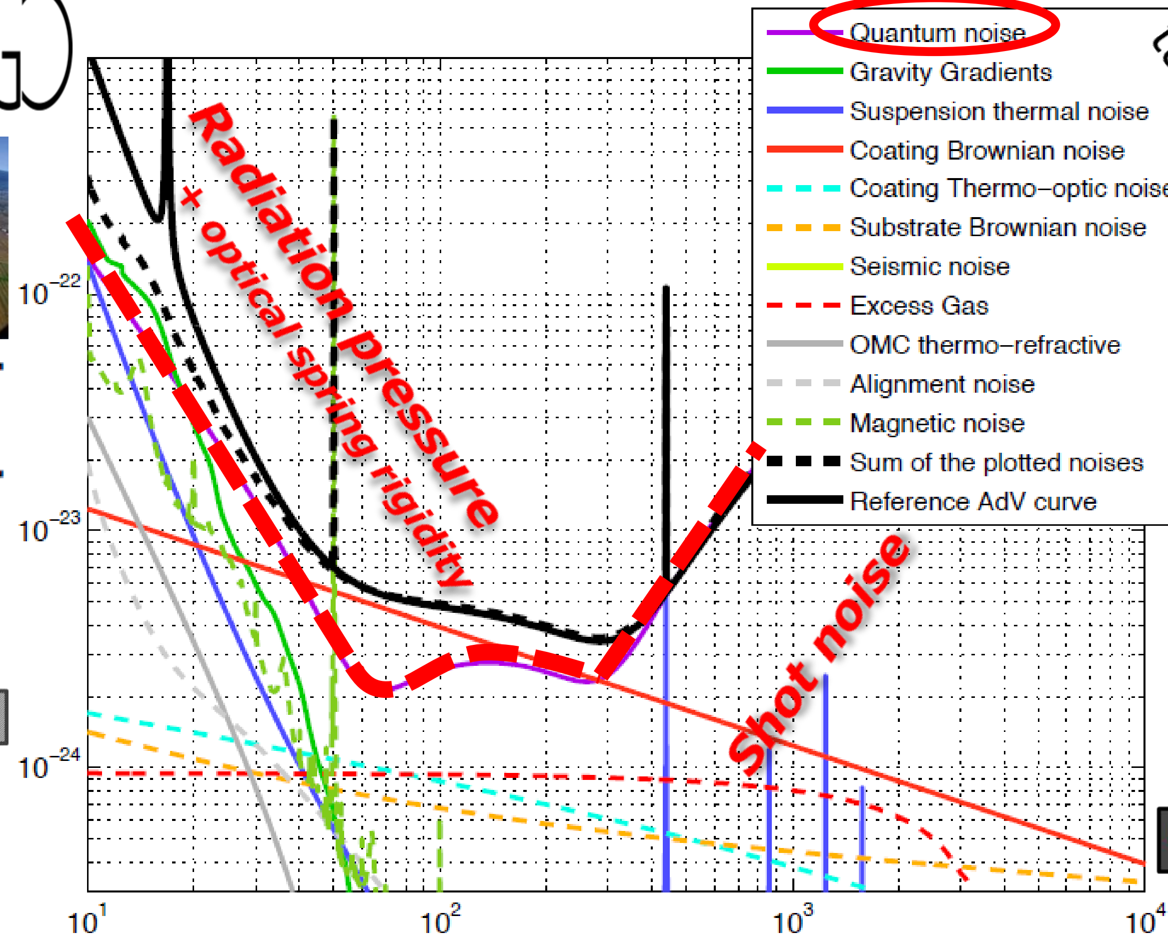
Squeezed light in Interferometric Gravitational Wave detectors

Squeezed light in IGWDs

Advanced Virgo* sensitivity curve

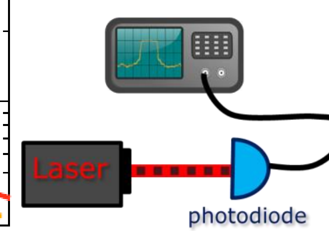
RP
LF





*see F. Travasso's talk about GWD

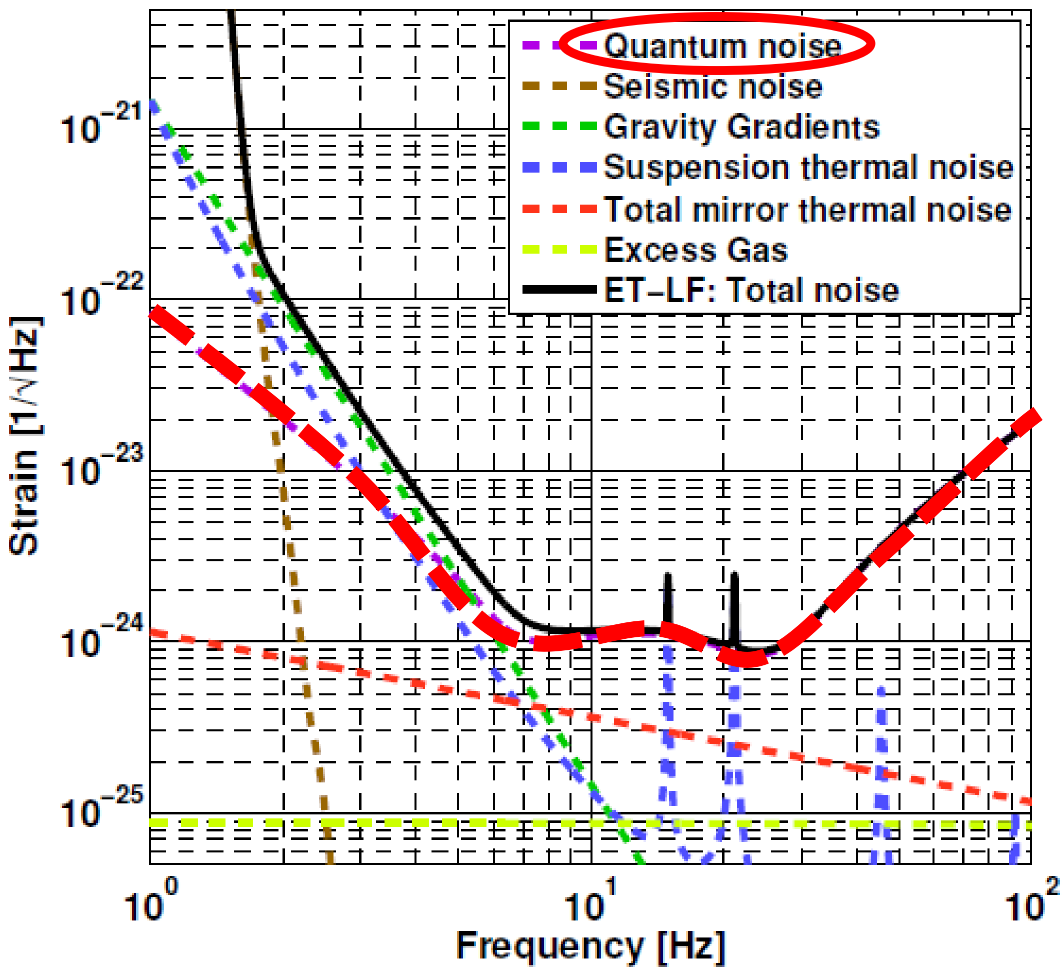
SN
HF

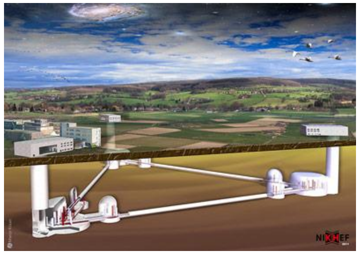


Squeezed light in IGWDs

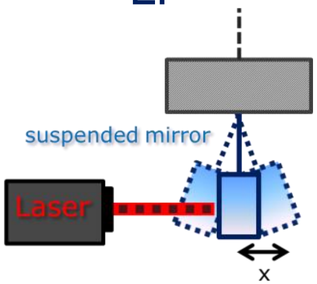
Einstein Telescope* LF sensitivity curve

*see F. Travasso's talk about GWD

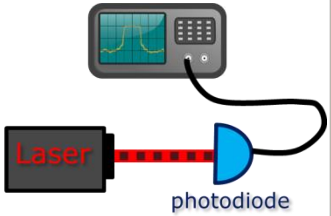




RP
LF



SN
HF

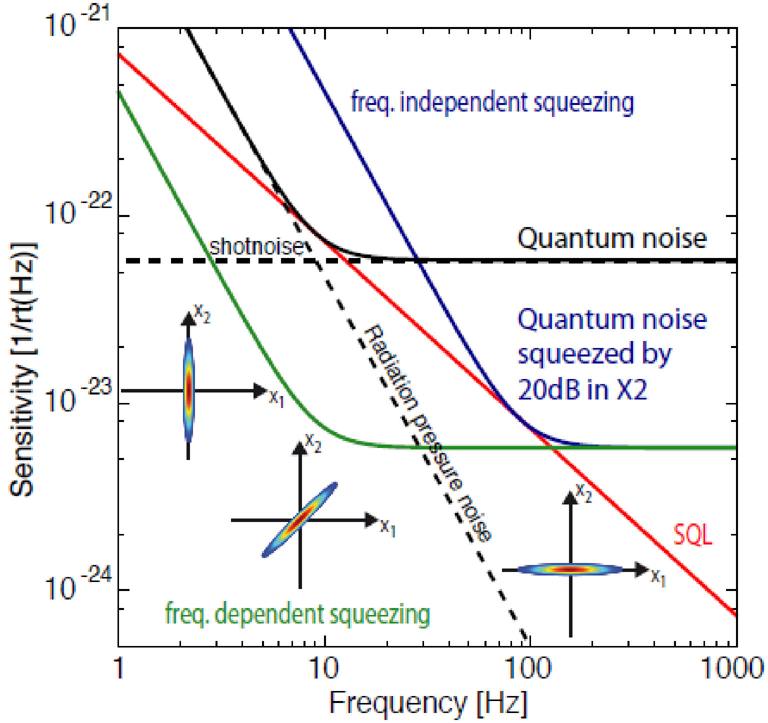


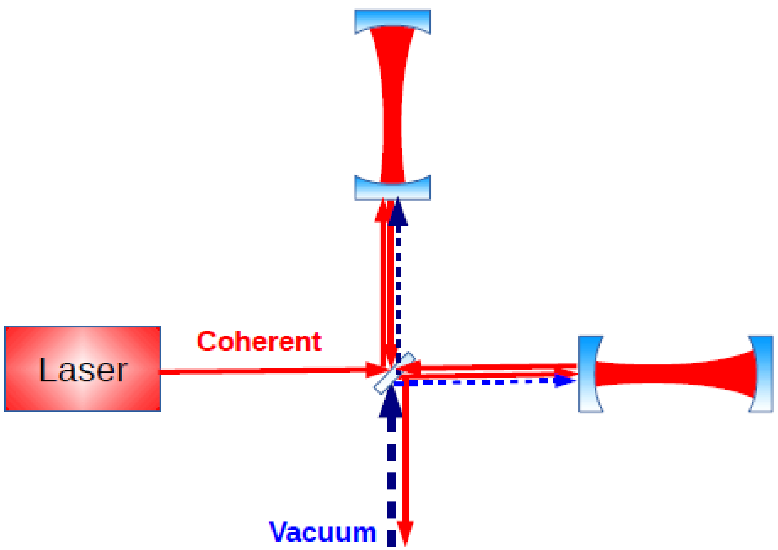
Squeezed light in IGWDs

motivation & concept

Motivation: push the sensitivity of GWID 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





C.M. Caves, *Phys. Rev. D 23*, 1981

Squeezed light in IGWDs
motivation & concept

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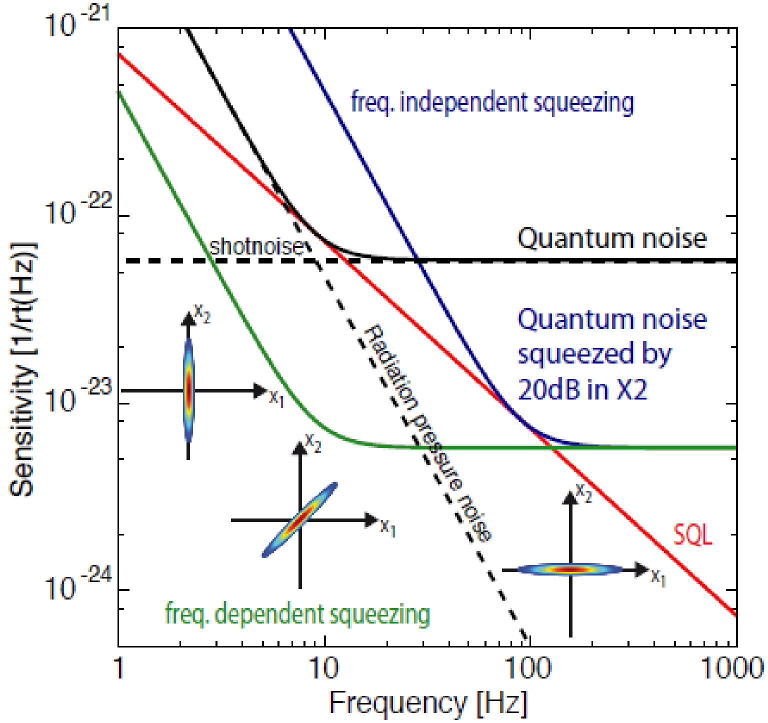
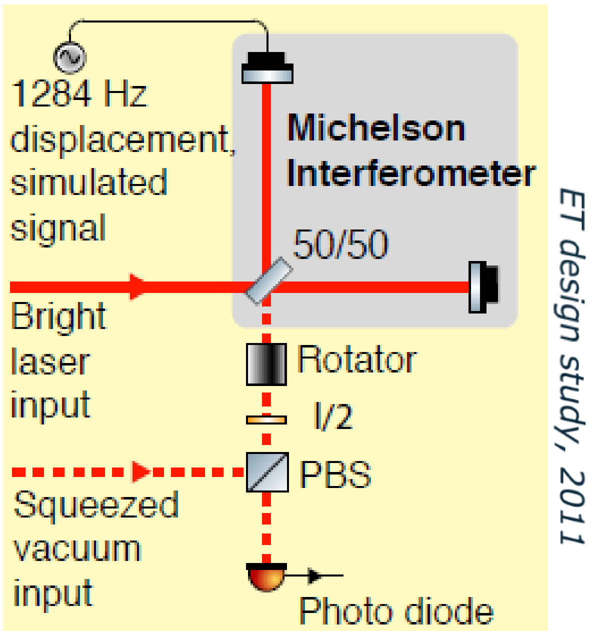
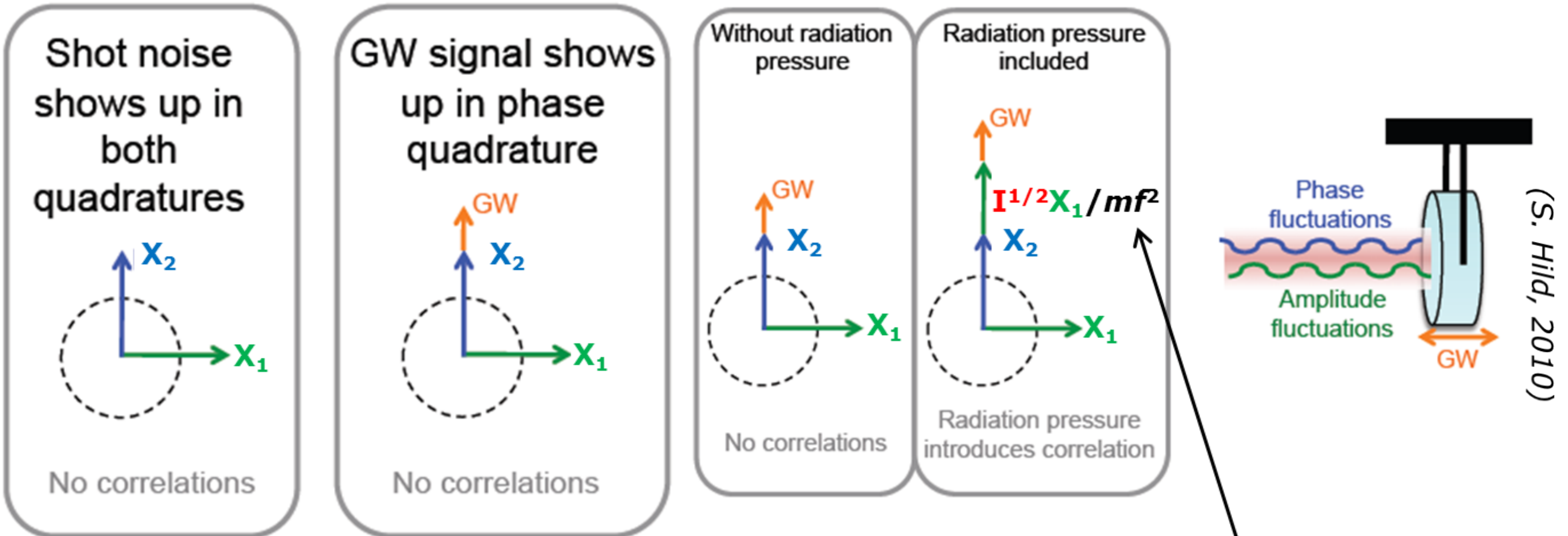




C.M. Caves, *Phys. Rev. D 23*, 1981

Squeezed light in IGWDs

GW effect on a coherent state



Cavity tuned around its resonant frequency:
GW signal in phase quadrature

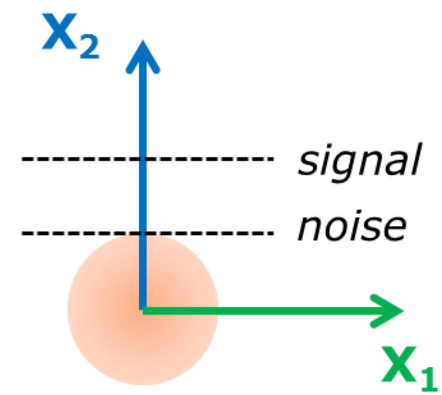
Amplitude fluctuations act on the suspended mirror:
mirror motion produces fluctuations in phase quadrature
(correlated to those in amplitude) that depend on mirror mass *m* and f^2

Squeezed light in IGWDs

GW effect on a coherent state

Fluctuations in the two quadratures are correlated:

Shot noise ↔ sensing noise ↔ phase fluctuation
RP noise ↔ displacement noise ↔ amplitude fluctuation



Amplitude fluctuations

Radiation Pressure

RP fluctuations

Mirror position fluctuations

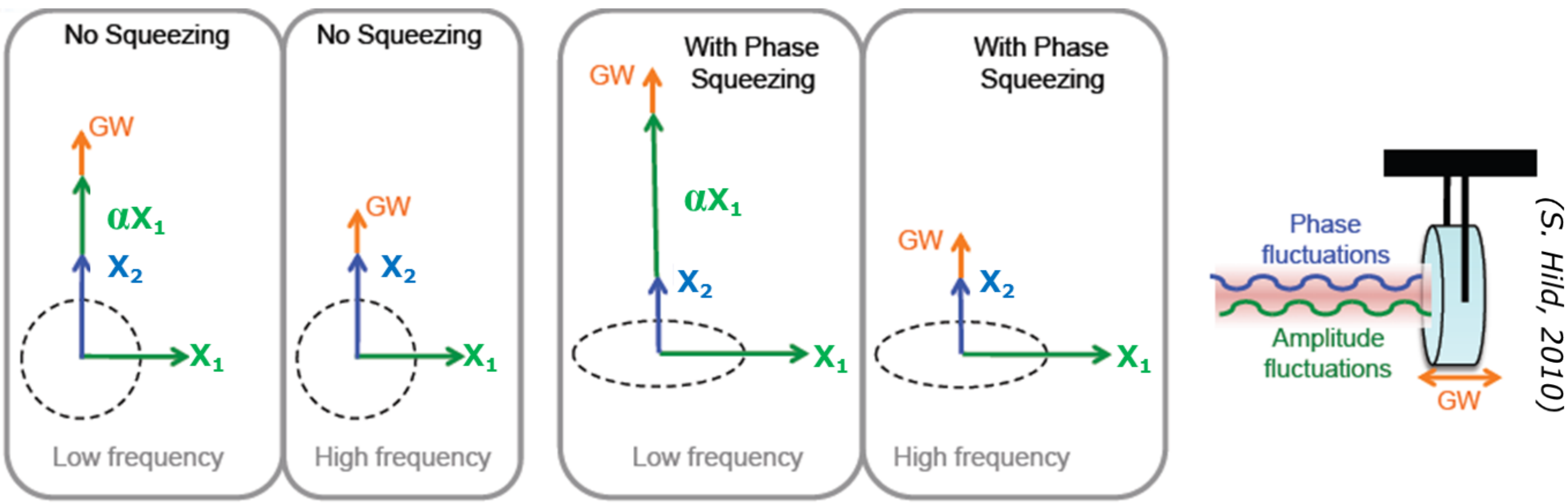
Optical path fluctuations

Phase fluctuations

GW signal shows up in this quadrature!

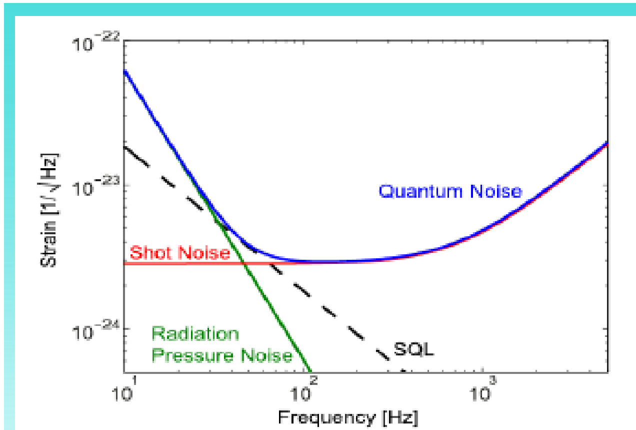
Squeezed light in IGWDs

GW effect on a phase-squeezed state



GOOD for HIGH FREQUENCY sensitivity but BAD for LOW FREQUENCY
somehow equivalent to radiation power increase.
Pure phase squeezing is not enough to beat the SQL in the GWID detection bandwidth!
→ <u>frequency-dependent with squeeze angle is a better choice</u>

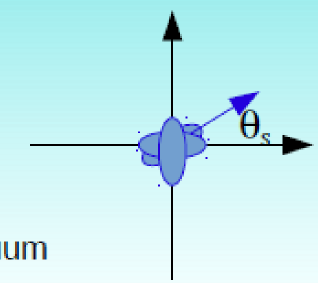
Squeezed light in IGWDs
Frequency-dependent squeezing



Es.: Michelson with Fabry-Perot in arms and homodyne detector

- Shot Noise (SN) related to the input vacuum field phase quadrature;
- Radiation-Pressure Noise (RPN) related to the input Amplitude quadrature

- High frequencies (SN dominated) → Phase squeezed vacuum ($\theta_s = \pi/2$)
- Low frequencies (RPN dominated) → Amplitude squeezed vacuum ($\theta_s = 0$)

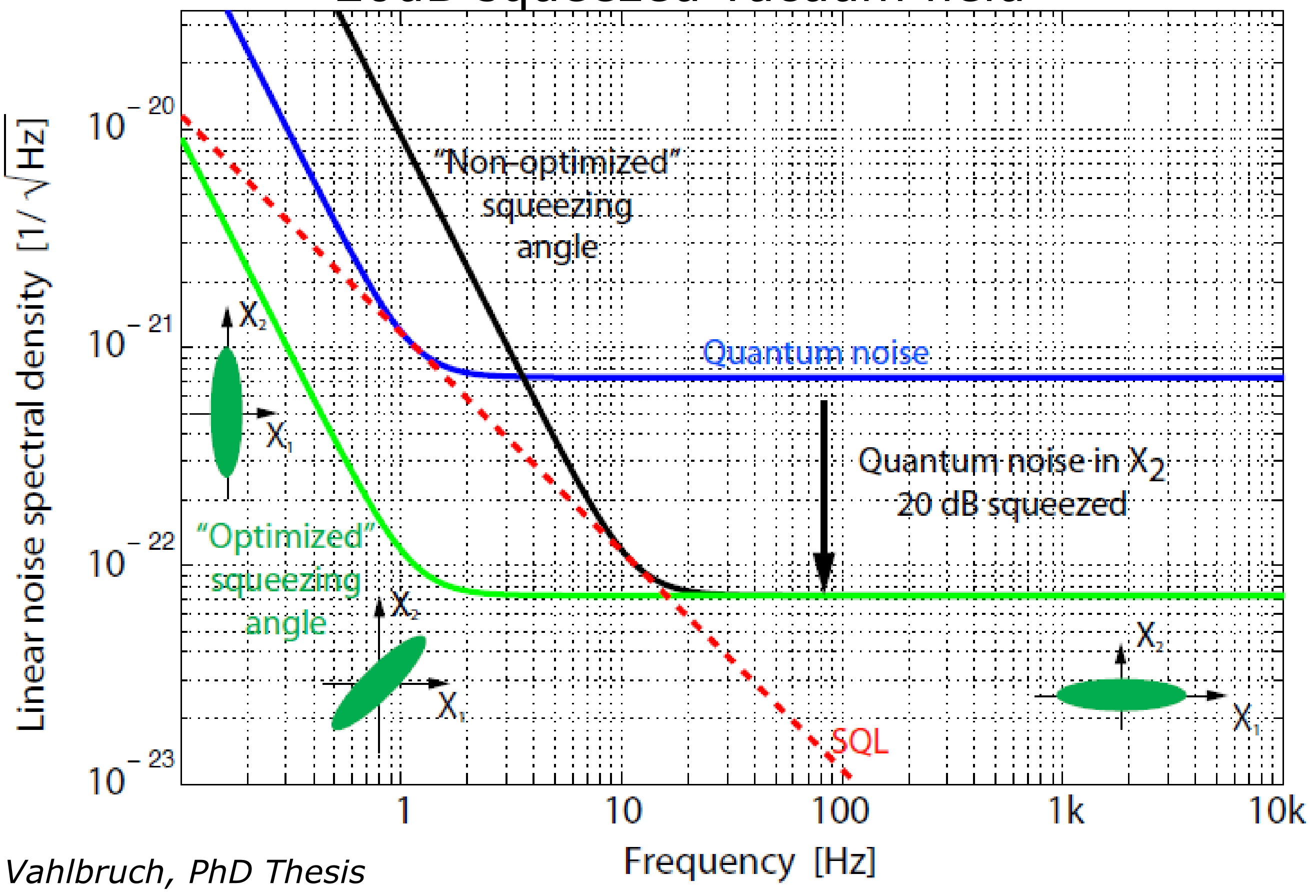


IGW detectors require a frequency-dependent squeezing quadrature:
squeezing angle $\theta_s = \theta_s(\Omega)$, with Ω = detection frequency

Squeezed light in IGWDs

Frequency-dependent squeezing

Improvement of sensitivity on Michelson Interferometer injecting 20dB squeezed vacuum field

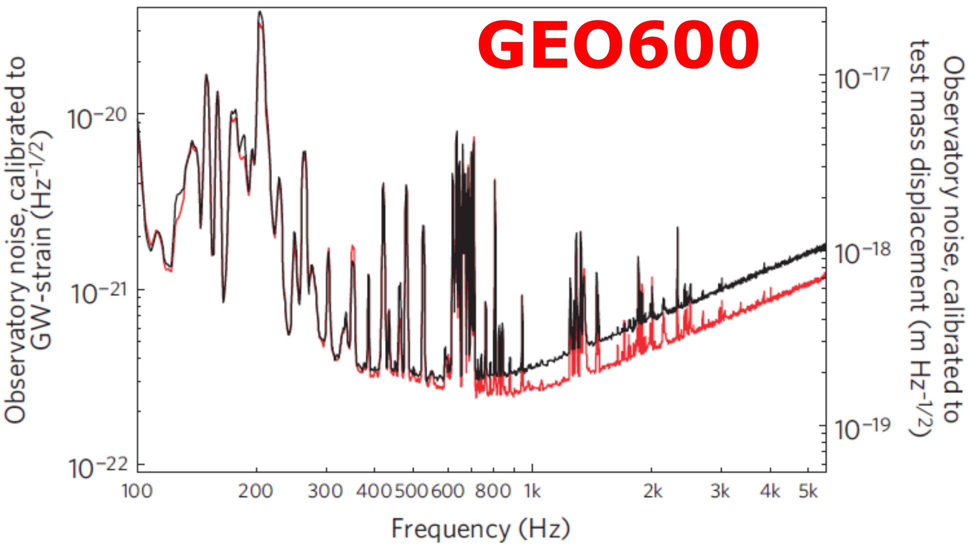


frequency-dependent

from H. Vahlbruch, PhD Thesis

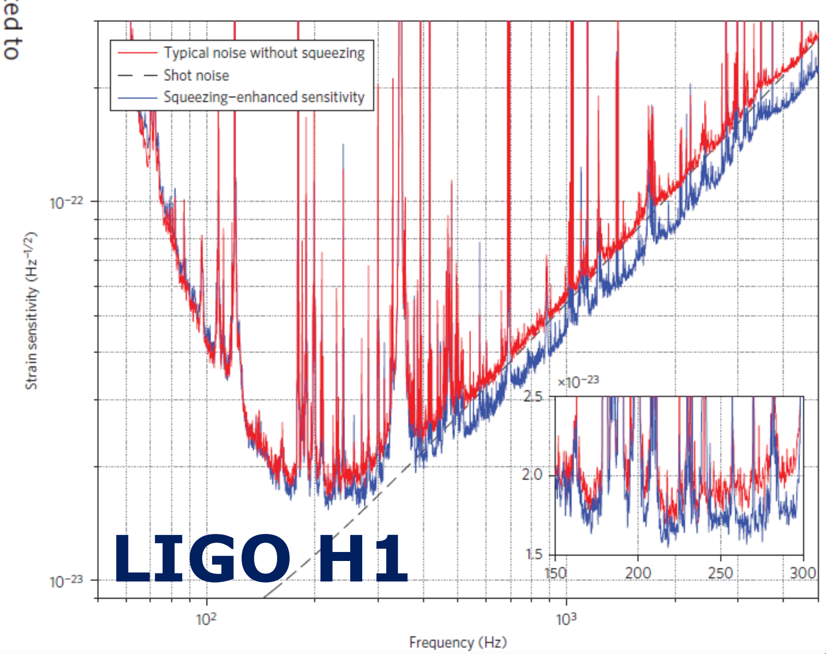
Squeezed light in IGWDs

Experimental sensitivity enhancement



broadband noise reduction of up to 3.5 *dB* in the shot-noise-limited frequency band
LSC, Nature Phisics 7.12 (2011), pp. 962-965

up to 2.15 *dB* in the shot-noise-limited frequency band
J. Aasi et al., Nature Photonics 7.8 (2013), pp. 613-619



Squeezed light production: OPO-based and ponderomotive techniques

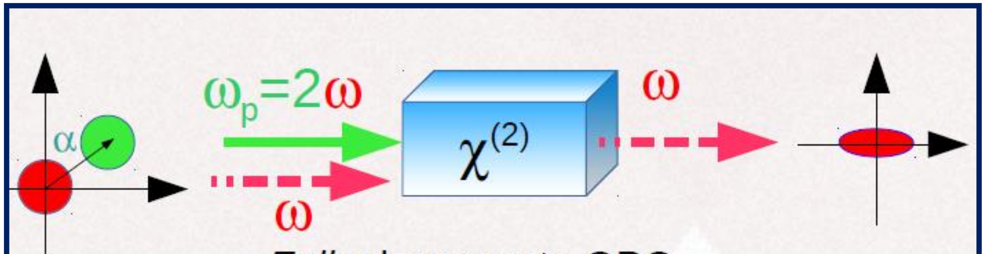
Squeezed light production

OPO vs ponderomotive

Non-linear processes in dielectric medium

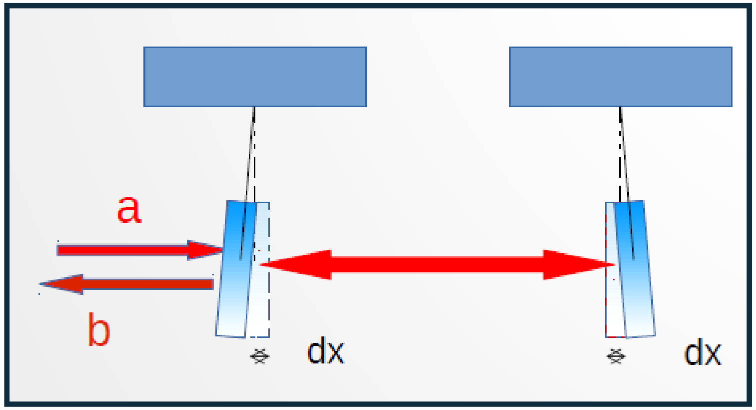
- **Kerr medium**
- Optical Parameter Oscillator (**OPO**)

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



Fully degenerate OPO
(polarizations and frequencies degeneracy)

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 light production

OPO-based squeezing

historical point of view

Year	Group	Mag.	Freq.	Cavity	λ [nm]	Material
1986	Wu *et al.* [90]	3 dB	1.8 MHz	Linear	532 & 1064	MgO:LN
1992	Polzik *et al.* [91]	6.0 dB	1.4 MHz	Bow-Tie	856	KNB
1992	Ou *et al.* [92]	3.6 dB	1.1 MHz	Bow-Tie	540 & 1080	KTP
1996	Schneider *et al.* [93]	4.3 dB	5 MHz	Hemilithic	1064	MgO:LN
1998	Schneider *et al.* [94]	6.5 dB	6.5 MHz	Hemilithic	1064	MgO:LN
1999	Lam *et al.* [95]	7.1 dB	3 MHz	Monolithic	1064	MgO:LN
2002	Bowen *et al.* [62]	2.5 dB	220 kHz	Hemilithic	1064	MgO:LN
2004	McKenzie *et al.* [63]	2.0 dB	500 Hz	Hemilithic	1064	MgO:LN
2006	Suzuki *et al.* [96]	7 dB	1 MHz	Bow-Tie	860	PPKTP
2007	Takeno *et al.* [97]	9 dB	1 MHz	Bow-Tie	860	PPKTP
2007	Goda *et al.* [60]	7.4 dB	2 kHz	Linear	1064	PPKTP
2007	Vahlbruch *et al.* [98]	10 dB	5 MHz	Monolithic	1064	MgO:LN
2010	Mehmet *et al.* [99]	11.5 dB	5 MHz	Monolithic	1064	MgO:LN
2010	Eberle *et al.* [86]	12.7 dB	5 MHz	Monolithic	1064	PPKTP
2011	Khalaidovski *et al.* [100]	9.5 dB	3 kHz	Hemilithic	1064	PPKTP
2011	Mehmet *et al.* [101]	12 dB	60 kHz	Hemilithic	1550	PPKTP
2011	Chua *et al.* [102]	8.6 dB	10 Hz	Bow-Tie	1064 & 532	PPKTP
2012	Stefszky *et al.* [87]	10 dB	10 Hz	Bow-Tie	1064 & 532	PPKTP

6 dB ~ factor 2

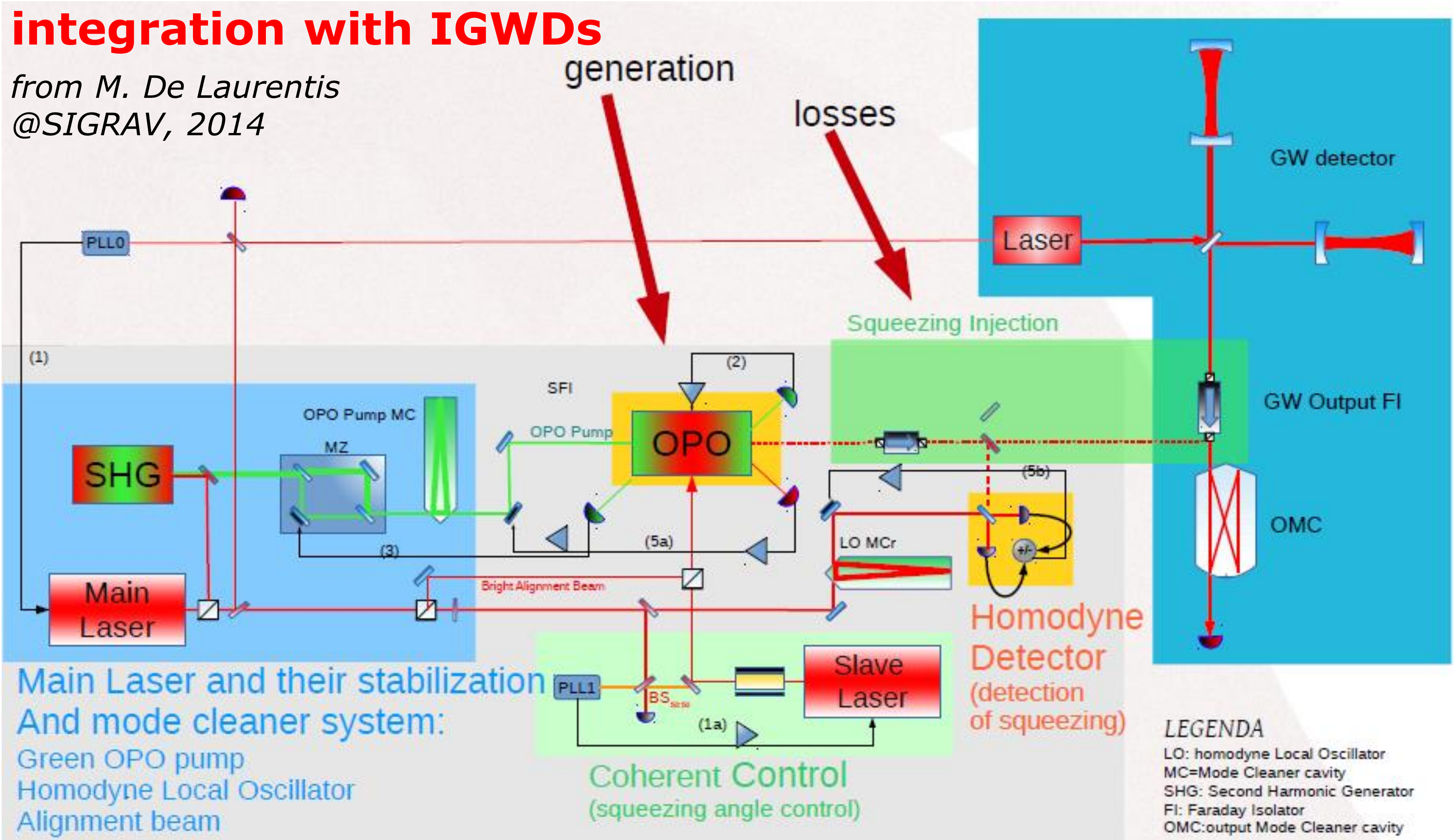
from M.S. Stefszky, PhD thesis, 2012

Squeezed light production

OPO-based squeezing

integration with IGWDs

from M. De Laurentis @SIGRAV, 2014

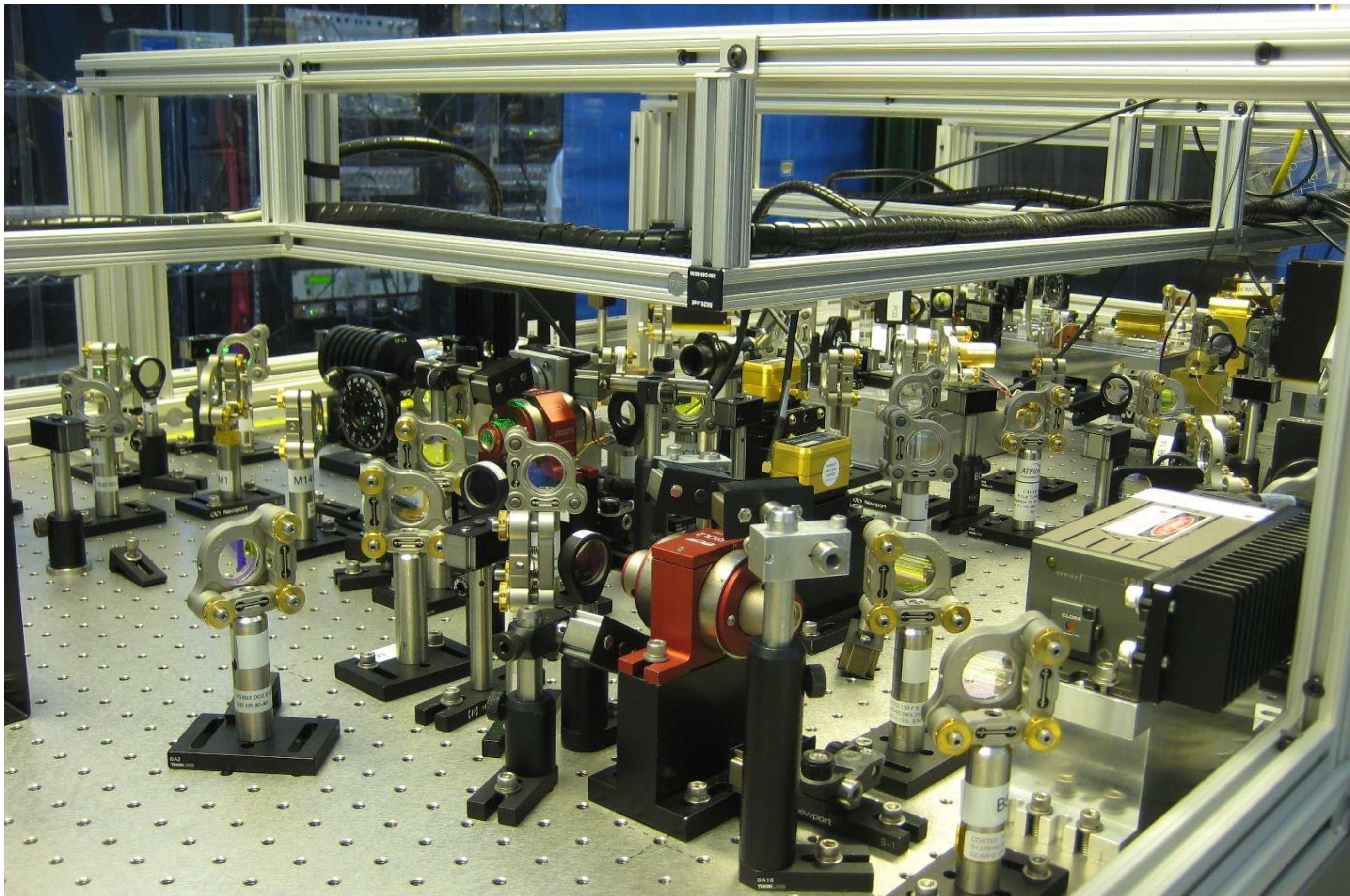


Squeezed light production

OPO-based squeezing

integration with IGWDs

Advanced LIGO squeezer



Squeezed light production

OPO-based squeezing

PROS:

- Long experience over two decades;
- Already integrated in IGWDs like GEO600 and LIGO, demonstrated the sensitivity improvement;
- Integration in micro-opto-electro-mechanical systems (MOEMS) for communication and integrated sensors on chip devices (but yet *expensive*);

CONS:

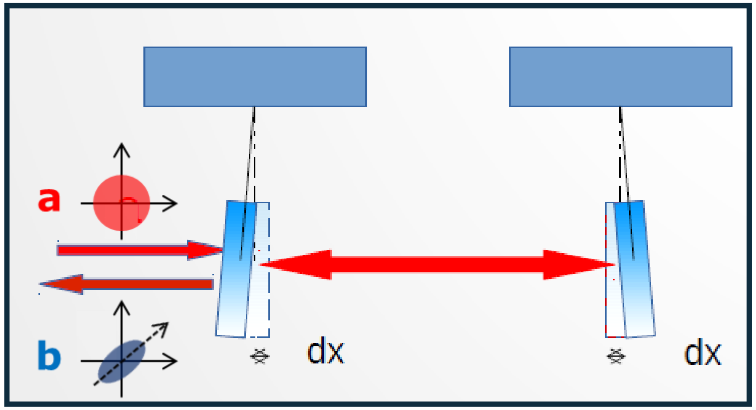
- Frequency limitation due to losses mechanisms in the medium (e.g. phototermal fluctuations);
- Stability issue, especially in the low frequency band (where we expect many interesting GW signals).

Squeezed light production

Ponderomotive squeezing

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.

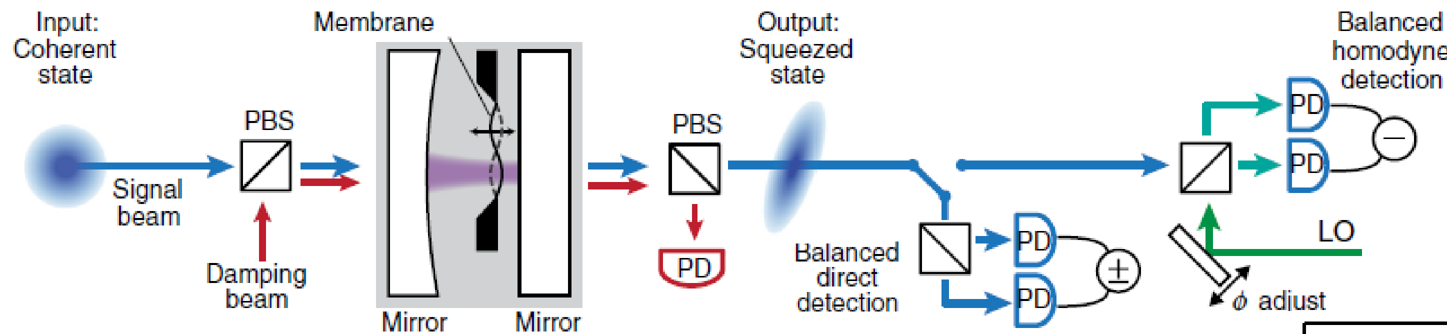


Radiation pressure on the suspended mirror induces a *coupling* between its *position* and the *intensity of light beam* → *correlation* between *phase* and *amplitude* quadrature of the output state

Squeezed light production

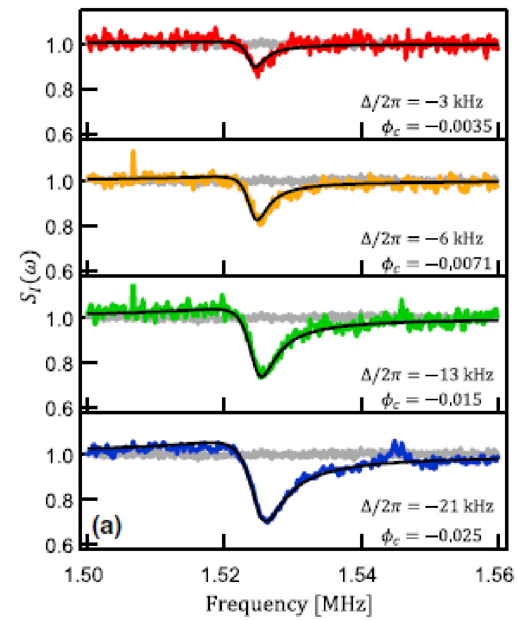
Ponderomotive squeezing

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*)*



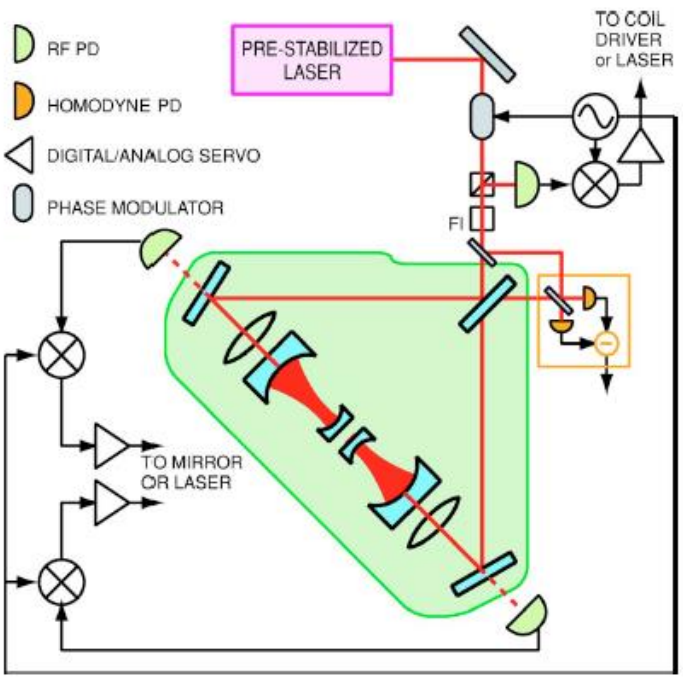
BUT

- Not a so high gain;
- ω » IGWD frequency band
- bright beams instead of squeezed vacuum (that is what we want to inject in a IGWD!)

Squeezed light production
Ponderomotive squeezing

First proposal of a suspended *macroscopic* interferometer as frequency-independent squeezer below 1kHz:

Corbitt et al., *Phys. Rev. A 73*, 2006



Target: 5dB

Squeezed light production
Ponderomotive squeezing

PROS:
- Large squeezing values without using high laser powers and/or very high cavity finesse
- Feasible integration in IGWD
- Stability at low frequencies: good for IGWD

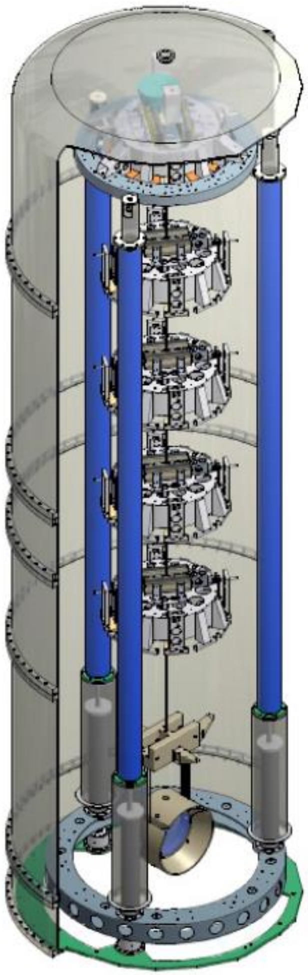
CONS:
- Suspension of very small mirrors in order to observe the RP
- High suppression of **seismic** and **thermo-elastic** noises

Robust seismic filter: *e.g. the multistage **Superattenuator** of Virgo*

Monolithic suspension: *e.g. the SiO_2 fibers in Virgo and LIGO*

Squeezed light production

Ponderomotive squeezing



Robust 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*:
SiO2 fibers welded to mirrors as in Virgo and LIGO: low thermoelastic losses respect to metallic wires

**see F. Travasso's talk*

Squeezed light production

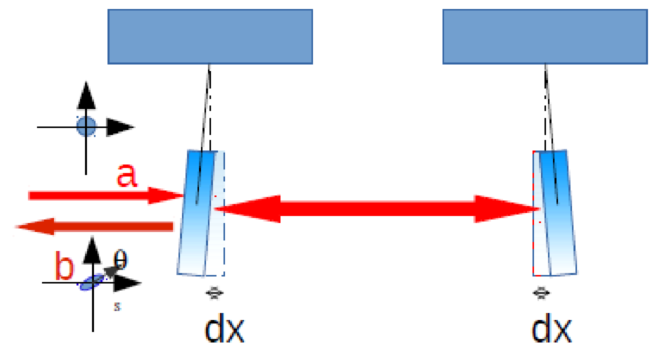
Ponderomotive squeezing

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



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

from M. De Laurentis @SIGRAV, 2014

Squeezed light production

Ponderomotive squeezing

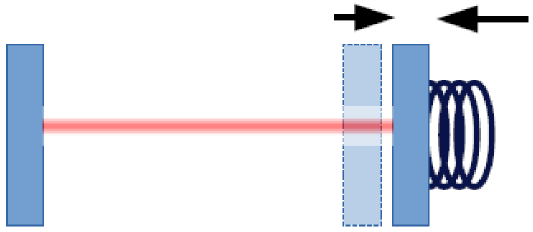
Frequency independent with **optical spring**

Detuned Cavity *(Optical Spring)*

detuning increases (cavity becomes longer)

the intra-cavity power decreases

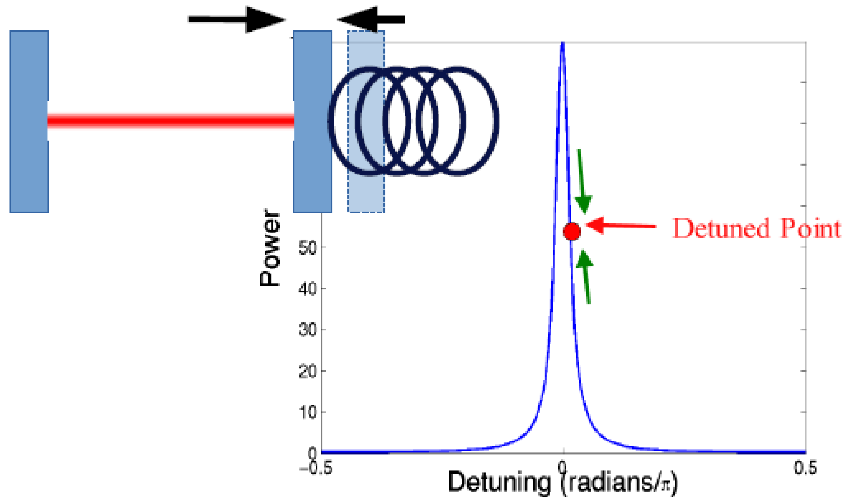
mirror is pushed back to the detuned point



detuning decreases (cavity shorter)

power in the cavity increases

and the mirror is pushed back



from M. De Laurentis @SIGRAV, 2014

Squeezed light production

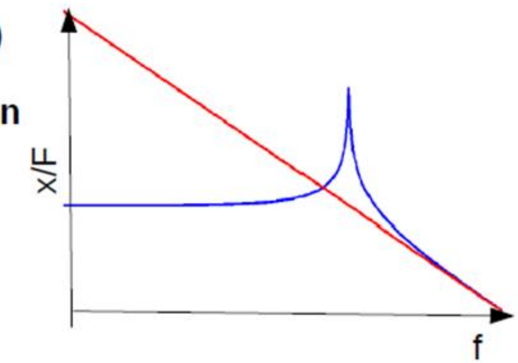
Ponderomotive squeezing

Frequency independent with **optical spring**

Optical Spring → ***modification of the cavity dynamics***

If the *pendulum frequency* can be neglected (Ωp << Ω, |Θ|)

the mechanical resonance of the mirror is completely given by the *optical spring characteristic frequency* ±Θ



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

Detuning normalized to the cavity linewidth

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

constant

1) frequency independent squeezing

2) The ***Optical Spring resonance*** gives the ***frequency independent squeezing band***

from M. De Laurentis @SIGRAV, 2014

Squeezed light production

Ponderomotive squeezing

Opto-mechanical parameters

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

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

Fixed the ξ and Θ

key parameters are: Input power, Cavity Finesse, Cavity detuning, Suspended mirrors mass

Parameters value optimization

to have

A large enough squeezing factor and an **useful frequency band**

from M. De Laurentis @SIGRAV, 2014

The POLIS experiment

The POLIS experiment

POnderomotive LIght Squeezer

we are currently setting up an OPO-based squeezer for Advanced Virgo similar to that of GEO600…

but meanwhile we are also exploring the ponderomotive technique:

The study and construction of the suspended interferometer **POLIS** was founded by a PRIN project (PPPS), involving the collaboration of 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

The POLIS experiment

Optical Parameters

cavity detuning, squeezing factor and band

Cavity detuning: ***trade-off between squeezing value/band***

High level *increases band*

Low level increases squeezing

We fix: δ=0.3 => ξ=18 dB and Θ=2π kHz

By considering the losses, this will assures more than 10 dB of potential injected squeezing in the interferometer

It covers the GWD band

from M. De Laurentis @SIGRAV, 2014

The POLIS experiment

Optical Parameters

cavity Finesse

enters directly in the reachable squeezing coupling with the cavity losses

Large values

- Large Optical spring frequency;
- Reduce effective intracavity losses;

Low values

Reduce optical spring instability;
Higher circulating power could damage mirrors

losses of 10 ppm, if we impose that **squeezing not degraded by more than 60%**
(to reach the anyway remarkable experimental value of 12 dB of squeezing)

$\Rightarrow$ **F≤ 30 000**

from M. De Laurentis @SIGRAV, 2014

The POLIS experiment

Optical Parameters

Input power

Large value
- Large Optical spring frequency

Low values
- Use of available lasers;
- No problem with mirrors damage threshold

Fixed the detuning, the finesse and the desired optical spring stiffness, we can derive the value for the input power. **With high finesse we can relax the input power**

P=2.5 W

N.B.: The most important constraint on the power circulating in the cavity: for powers higher than 0.2 MW the thermal effects start to degrade the behavior of the cavity, For beam waist of mm size, so a circulating power of 0.1 MW will be our conservative constraint.

from M. De Laurentis @SIGRAV, 2014

The POLIS experiment

Optical Parameters

Suspended mirror mass

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

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

We choose a relatively high mass value since we can take advantage of a significant seismic attenuation, suspending our interferometer from the Virgo **SAFE Superattenuator**

$$\boxed{\mathbf{m = 10}\boldsymbol{g}}$$

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

Higher mass value relaxes the sensitivity requirements

The POLIS experiment

Optical Parameters

Cavity parameters

Constrain for the cavity length: internale SAFE diameter **L = 440 mm**

Negative stability factor in the cavities with low suspended masses reduce the angular instability **gi = −0.76**

Available Radii of Rurvature of the commercial substrates **RoC = RoCE = 250 mm**

This value of the RoC assures the maximum spot size on the mirrors with the available commercial radii **wi = 0.447 mm**

(large w => reduce thermal deformation of the coating)

N.B.: Other commercial values: RoCI = RoCE = 300 mm → are wi = 0.383 mm
RoC = 200 mm → unstable cavity

Gouy phase = 2.43 rad = 0.773493π

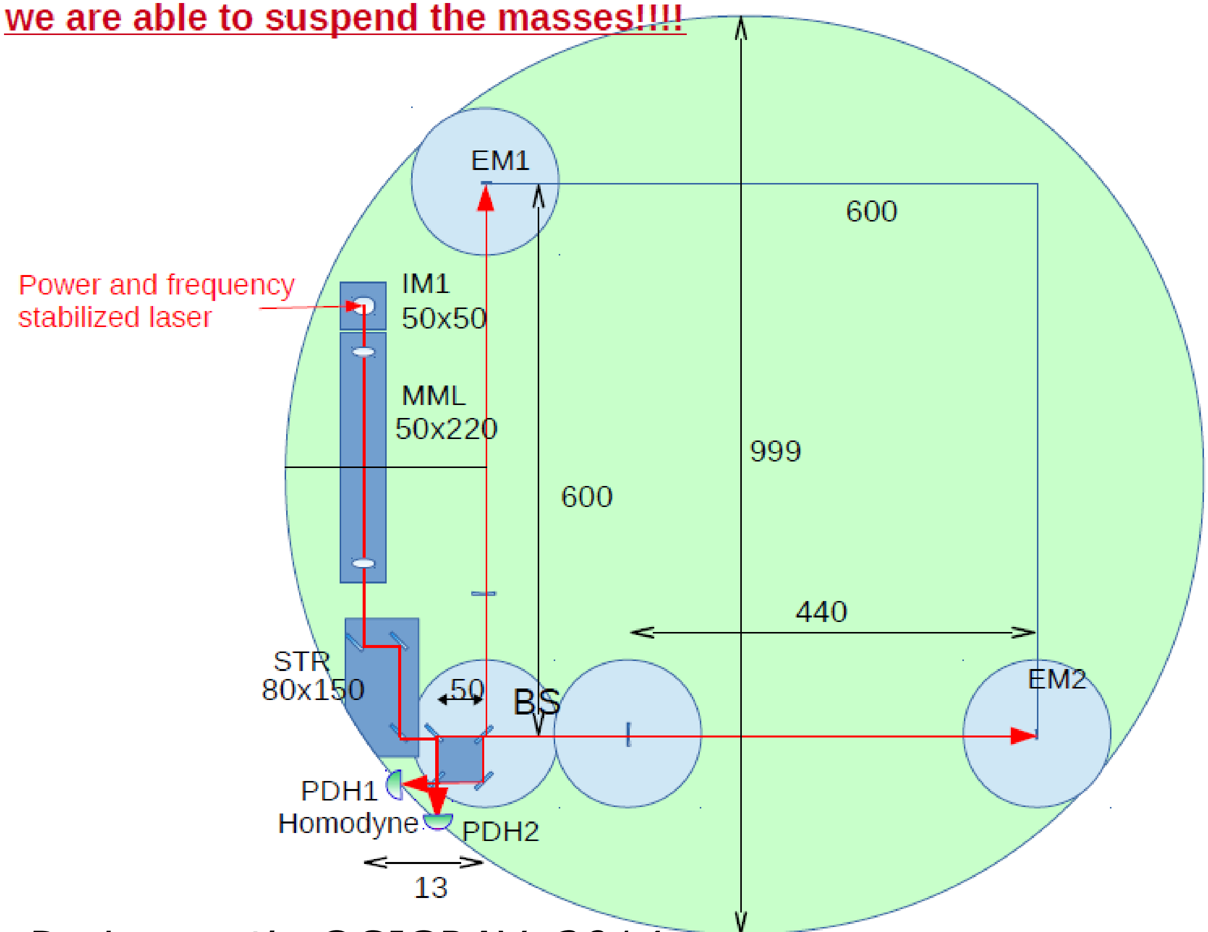
well stable cavity, avoiding the couplings with thermal deformation or imperfections, mis-match problems and the higher order mode resonance

from M. De Laurentis @SIGRAV, 2014

The POLIS experiment

Setup sketch

Configuration simpler than the OPO squeezer set-up **IF**
we are able to suspend the masses!!!!



LEGENDA
IM1: input mirror
Is the mirror that brings the Beam from the top on this stage
MML: Mode Matching Lens
STR: Beam Steering Mirrors
To alline the interferometers
BS:*Beam Splitter*
EMi: *End Mirror*
IMi:*Input Mirror*

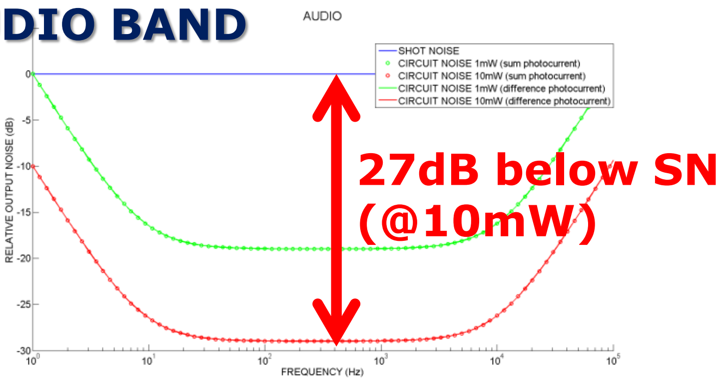
from M. De Laurentis @SIGRAV, 2014

The POLIS experiment

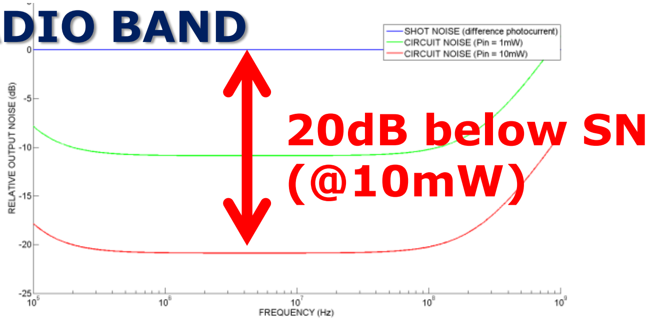
Homodyne detector

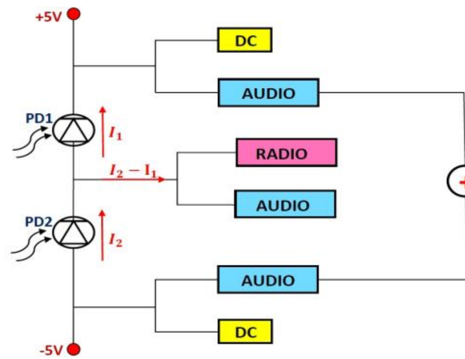
Low-noise balanced homodyne detector electronics has been already designed and built by INFN-Roma for the *OPO-based squeezer* of Advanced Virgo. We can rely on the same electronics for the Homodyne block of **POLIS**.

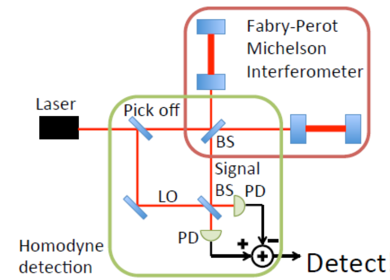
AUDIO BAND

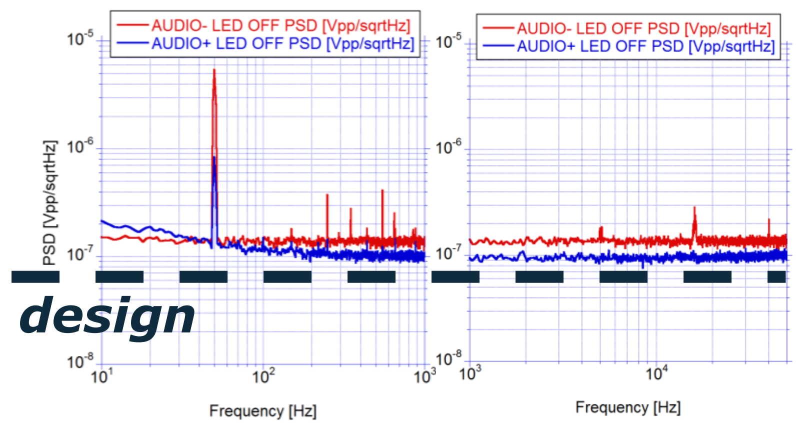


RADIO BAND









The POLIS experiment

Homodyne detector

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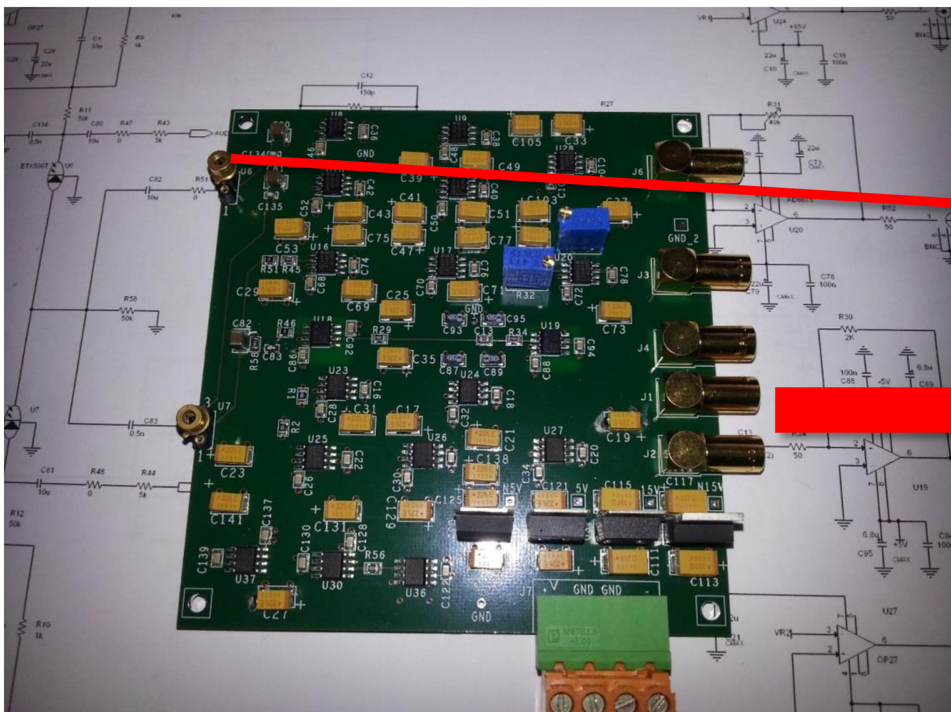
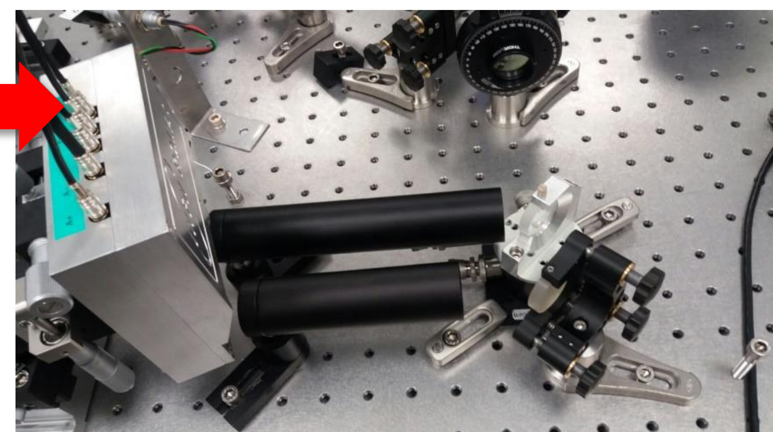


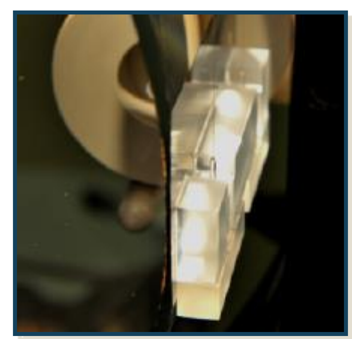


The POLIS experiment

The suspended double-bench

Motivation for a suspended squeezer bench:

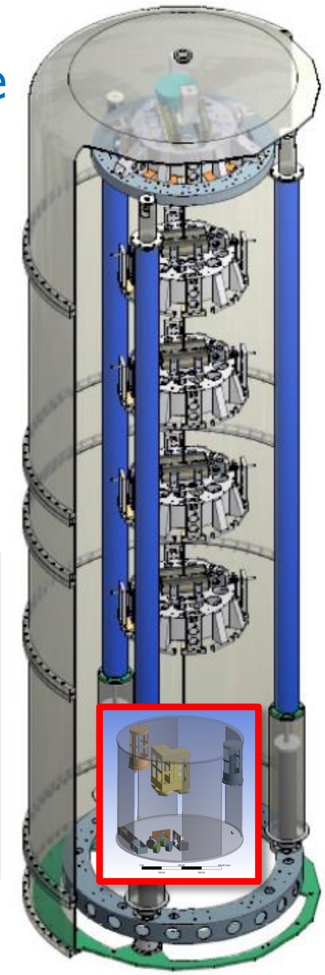
Taking advantage of the seismic isolation given by the suspension of SAFE (Super Attenuator Facility at EGO), reaching an higher sensitivity in the low frequency band.



<u>End mirrors of the cavities can have relatively higher masses compared to that of other ponderomotive squeezing experiments.</u>

Advantages:

- easier construction & assembly (e.g. Virgo-like monolithic suspension);
- easier sensing & position control;
- lower thermal noise;
- commercial size mirrors can be used (e.g. 1'', 10 *g*)



The POLIS experiment
The suspended double-bench

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

Height: 800 *mm*
Diameter: 960 *mm* (allowing two cavities 440*mm*-long)
Weight: ~ *150 kg*

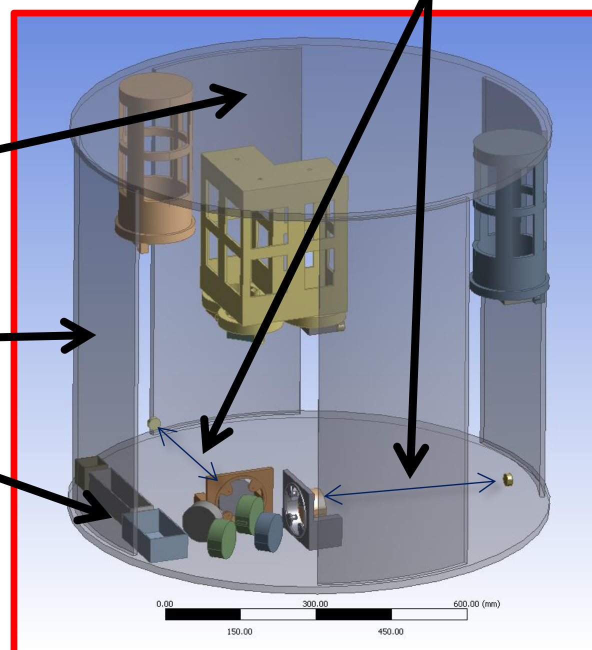
Material: anticorodal (Al-alloy)

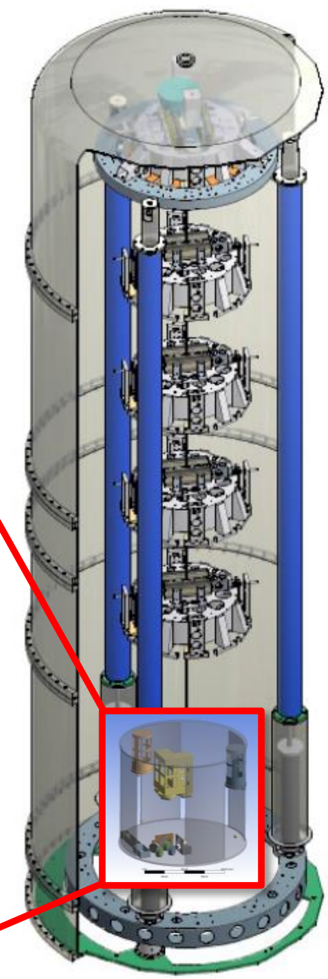
Upper plate (auxiliary bench)

Cylindrical baffles

Main optical bench

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

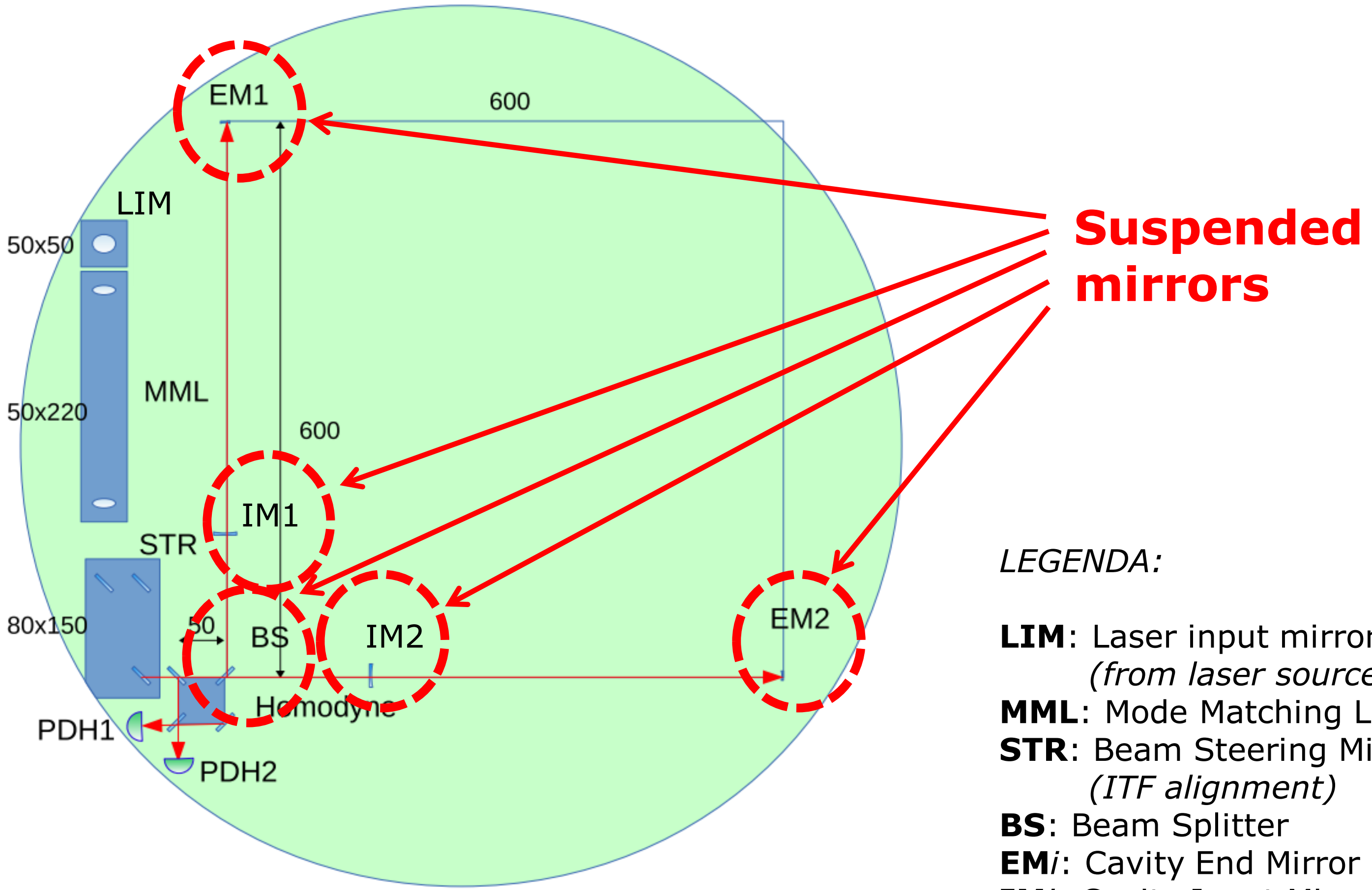




The POLIS experiment

The suspended double-bench

Lower bench layout *(main opt bench)*

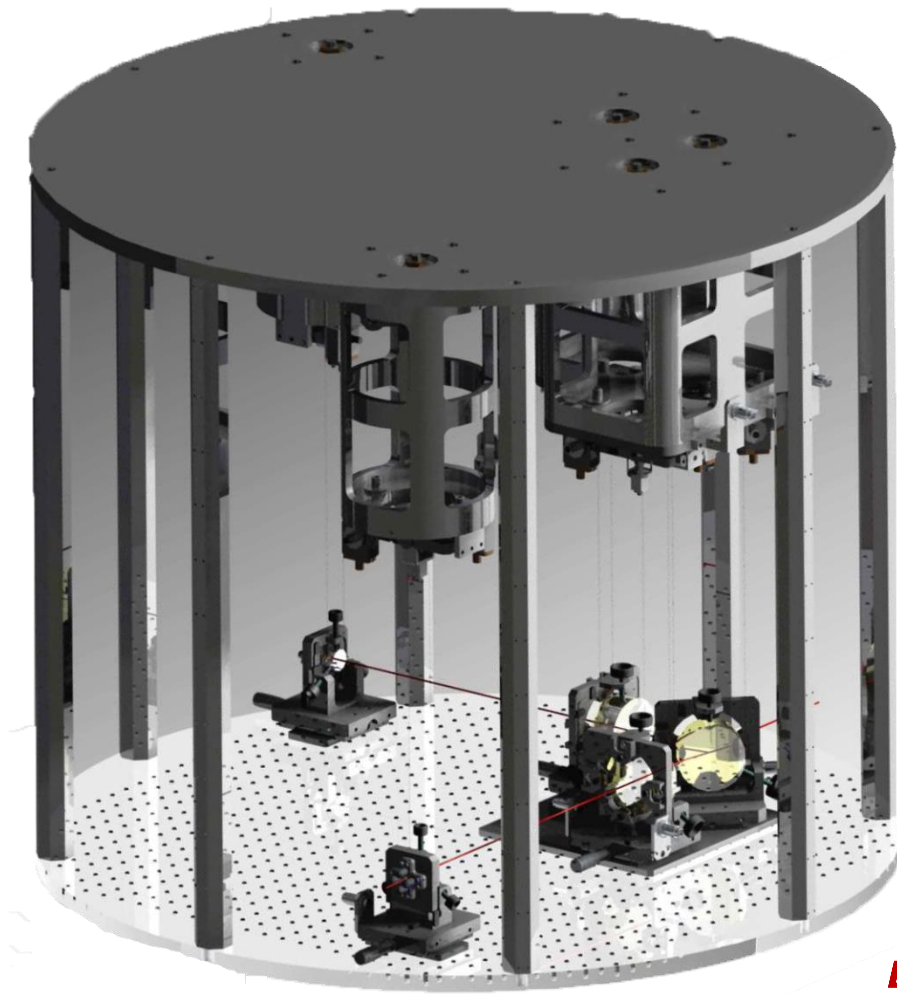


LEGENDA:

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

The POLIS experiment

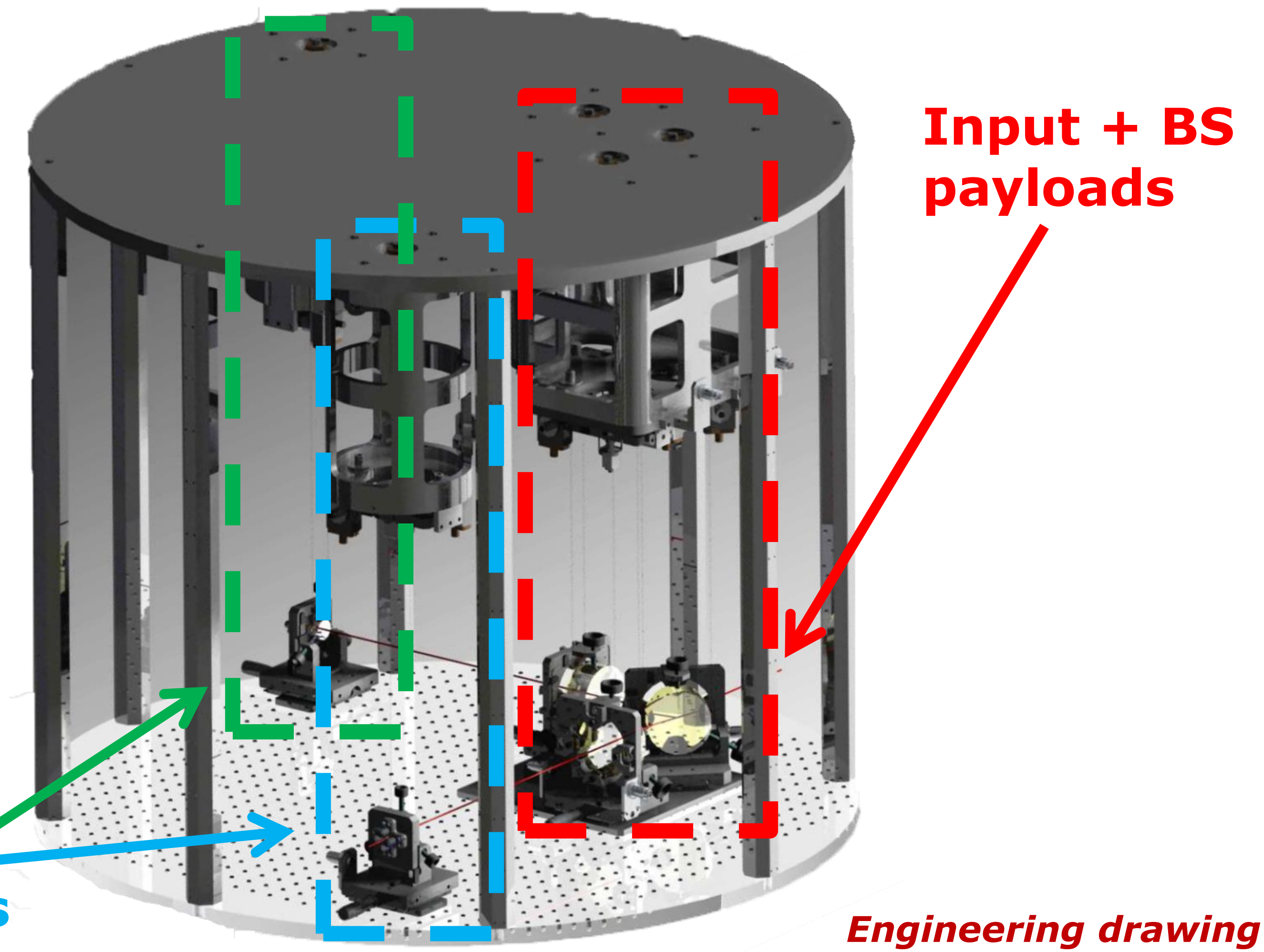
The suspended double-bench



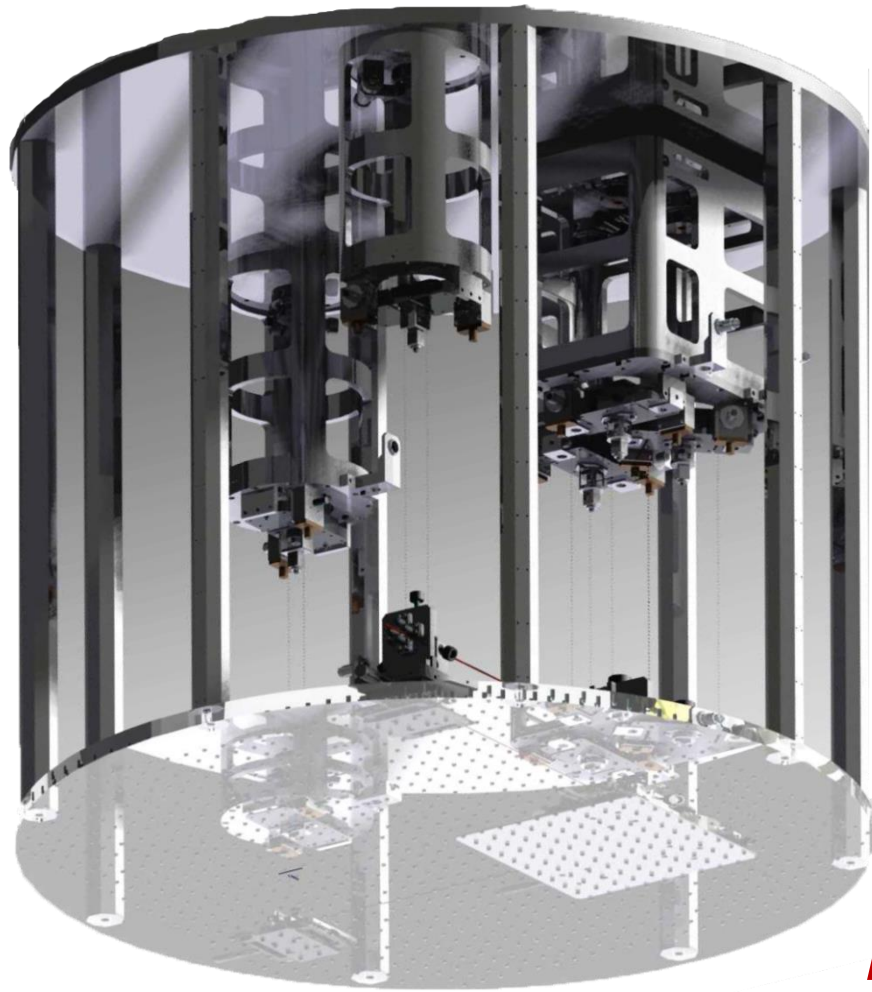
Engineering drawing

The POLIS experiment

The suspended double-bench



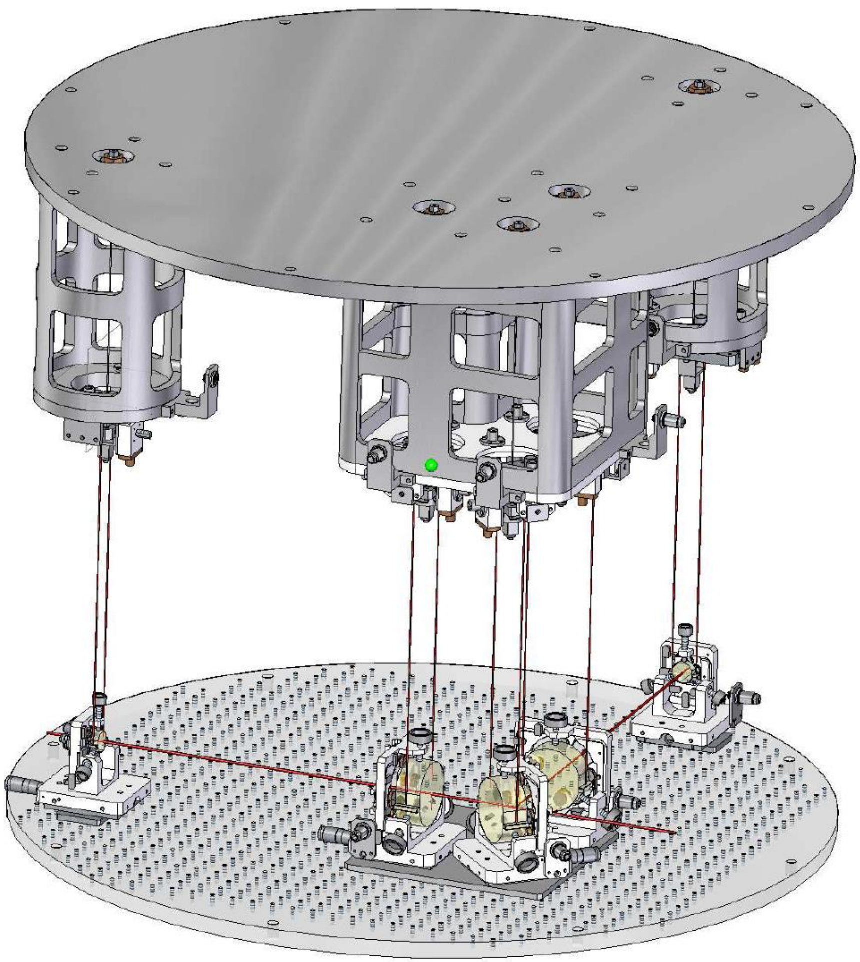
The POLIS experiment
The suspended double-bench



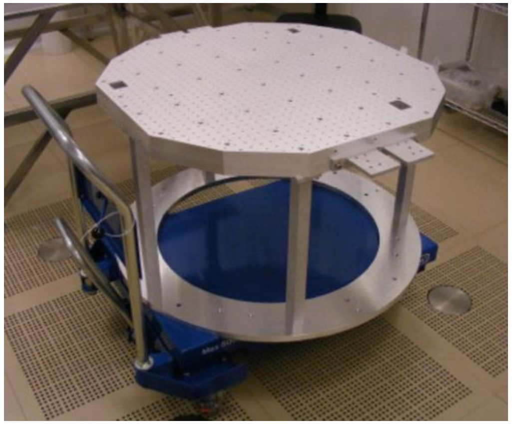
Engineering drawing

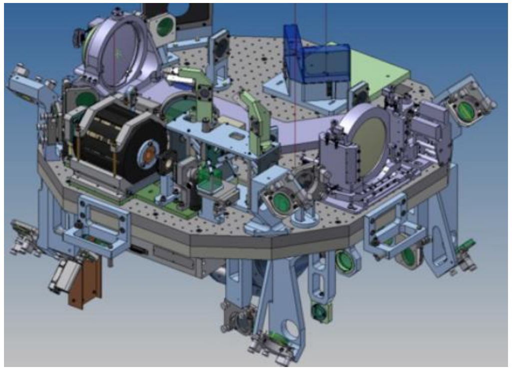
The POLIS experiment

The suspended double-bench



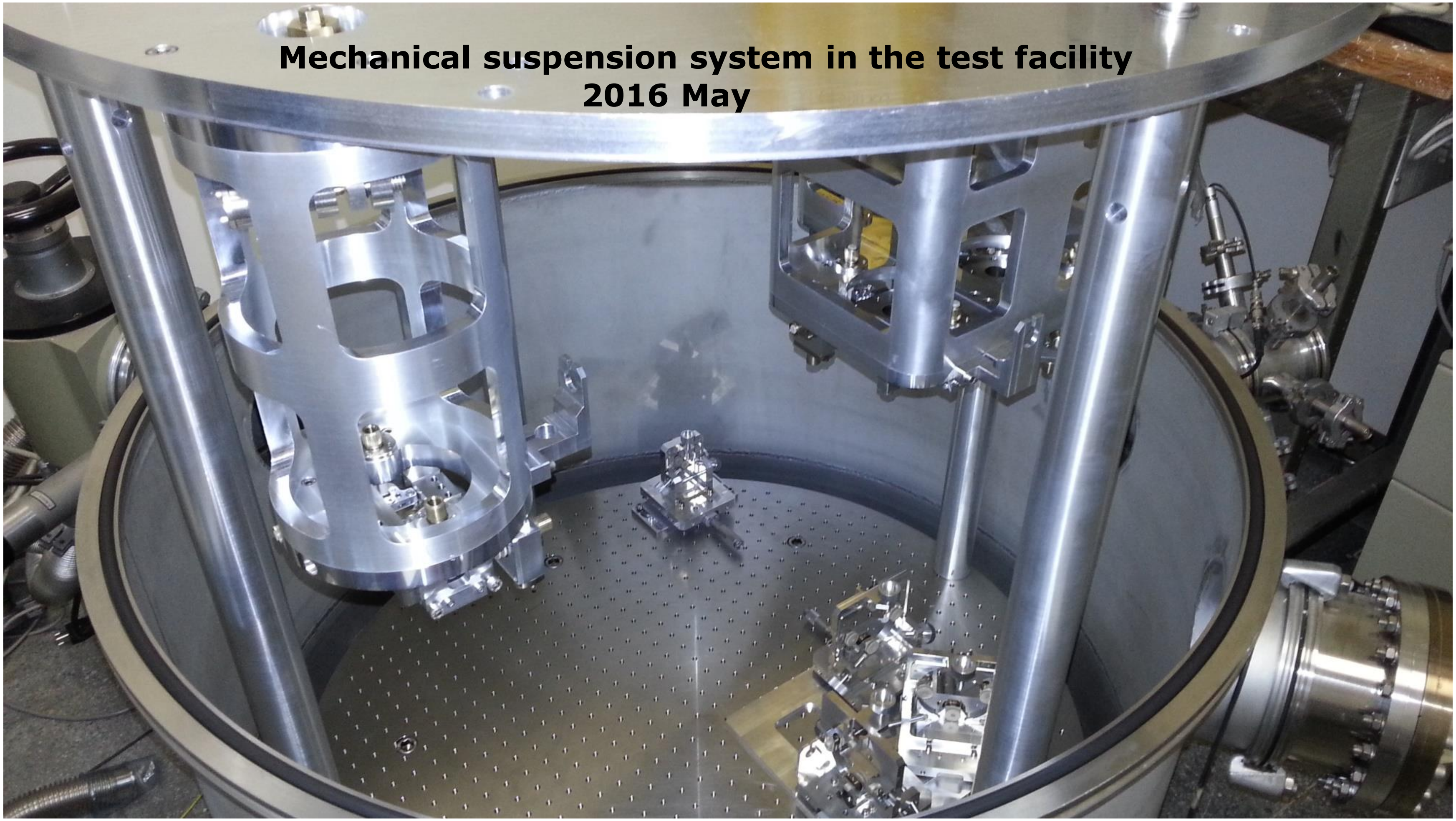
The definitive design of the lower bench will be based on the octagon shape like AdV injection





AdV suspended injection bench

The POLIS experiment
The suspended double-bench

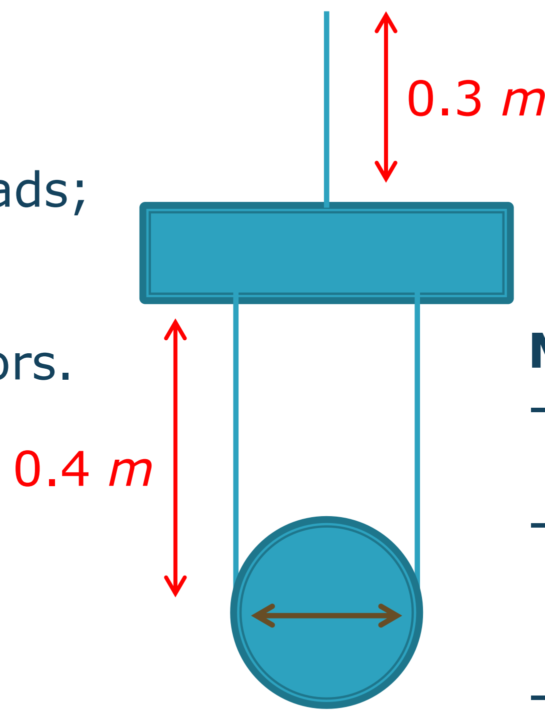


The POLIS experiment
Suspended mini-payloads

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.

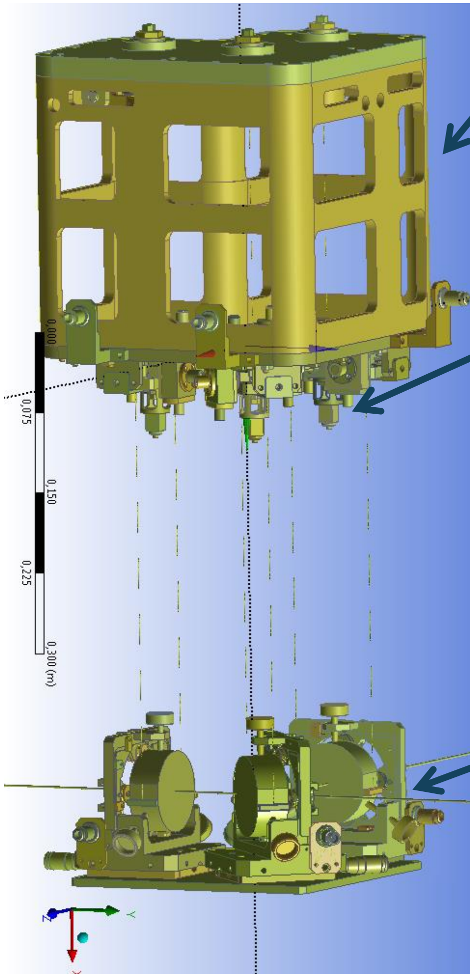


Mirrors:
- 0.3 *kg*, 3″ (BS & Input), 10^{-2} *kg*, 1″ (End);
- two fused silica fibers, $\Phi_{IN,BS} = 300\ \mu m$, $\Phi_{END} = 50\ \mu m$;
- magnet-coil actuators.

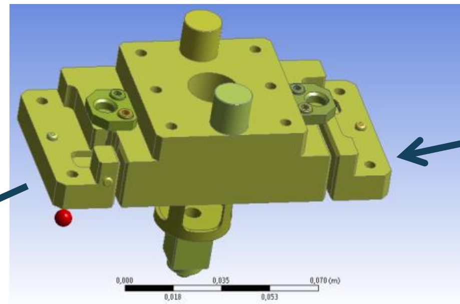
The POLIS experiment

Suspended mini-payloads

Beam Splitter and Input

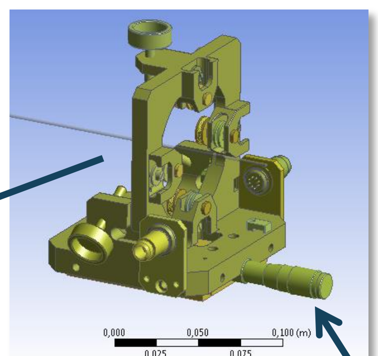


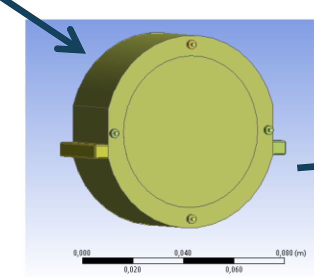
cage + coil holder Anticorodal Al, ~ 6 *kg*

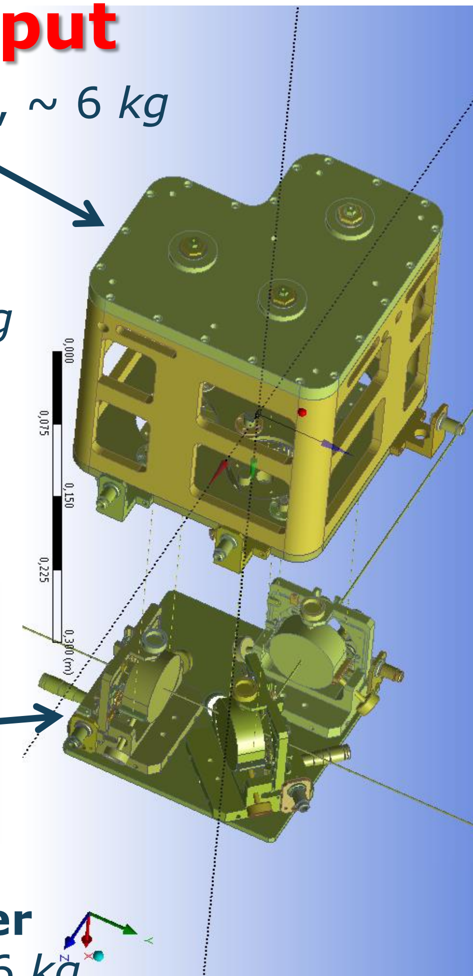


Marionette
Steel, 1.1 *kg*

Mirror Fused Silica, 0.3 *kg*





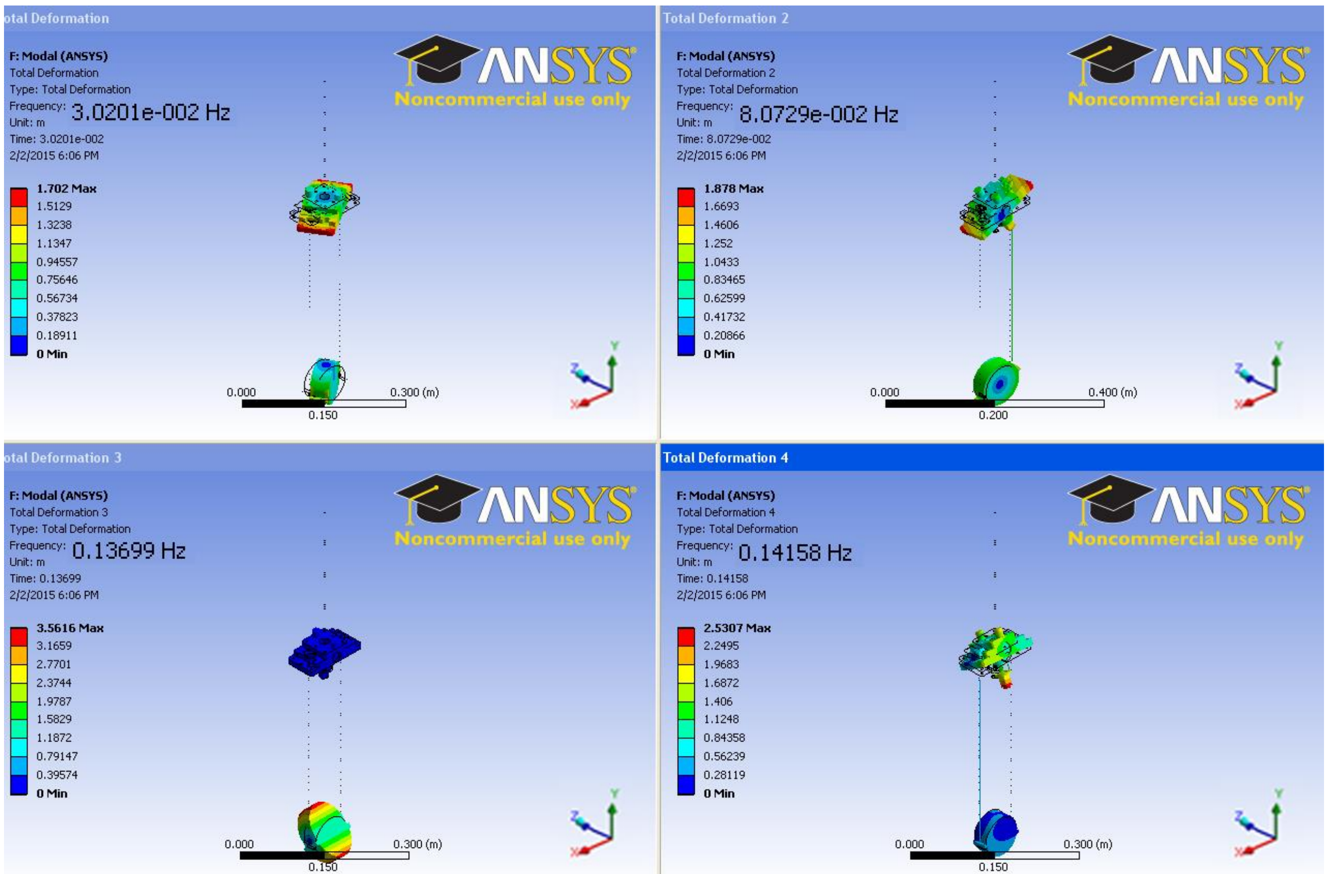


Mirror coil holder
Anticorodal Al, 1.6 *kg*

The POLIS experiment

Suspended mini-payloads

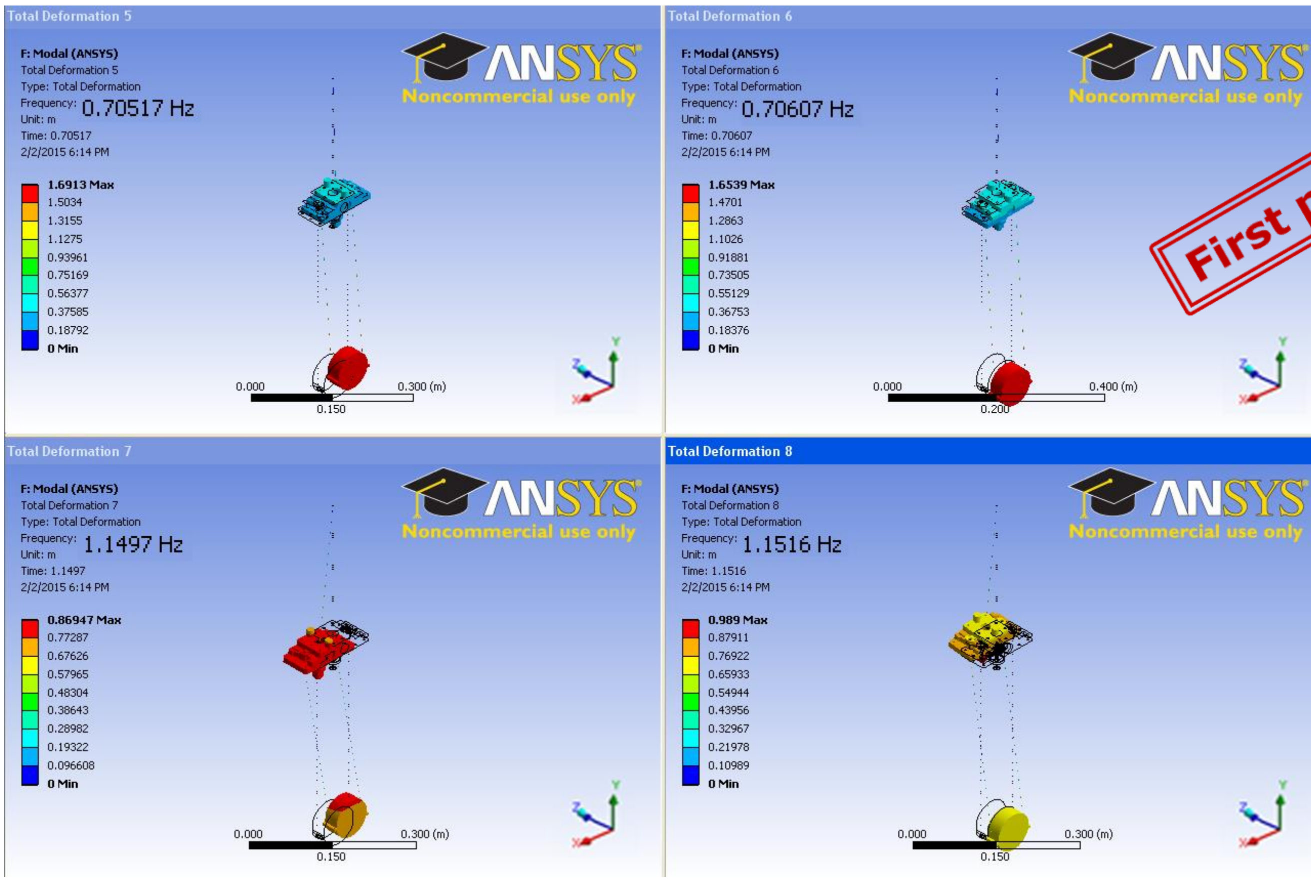
Input Payload vibration modes



The POLIS experiment

Suspended mini-payloads

Input Payload vibration modes

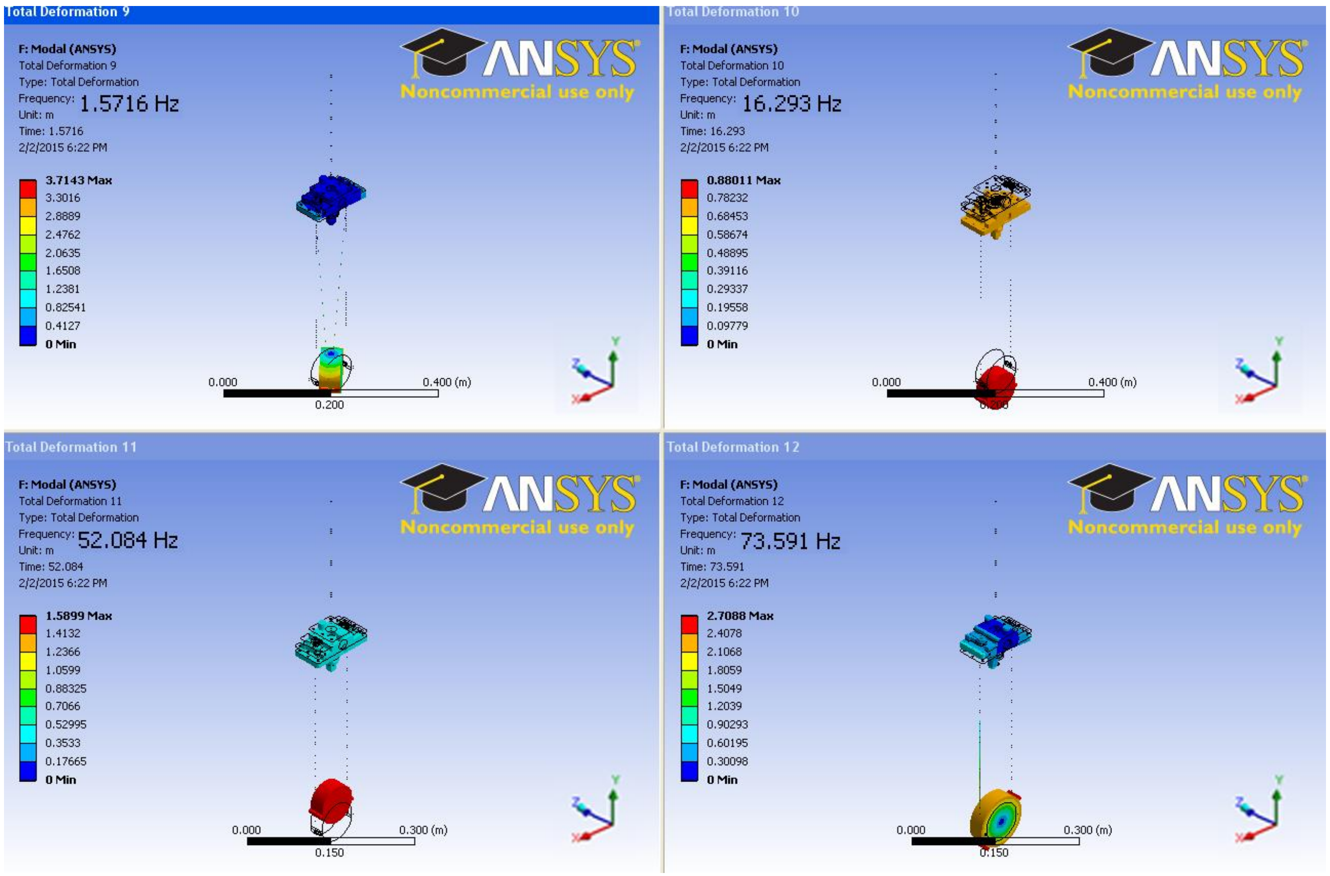


First pendulum

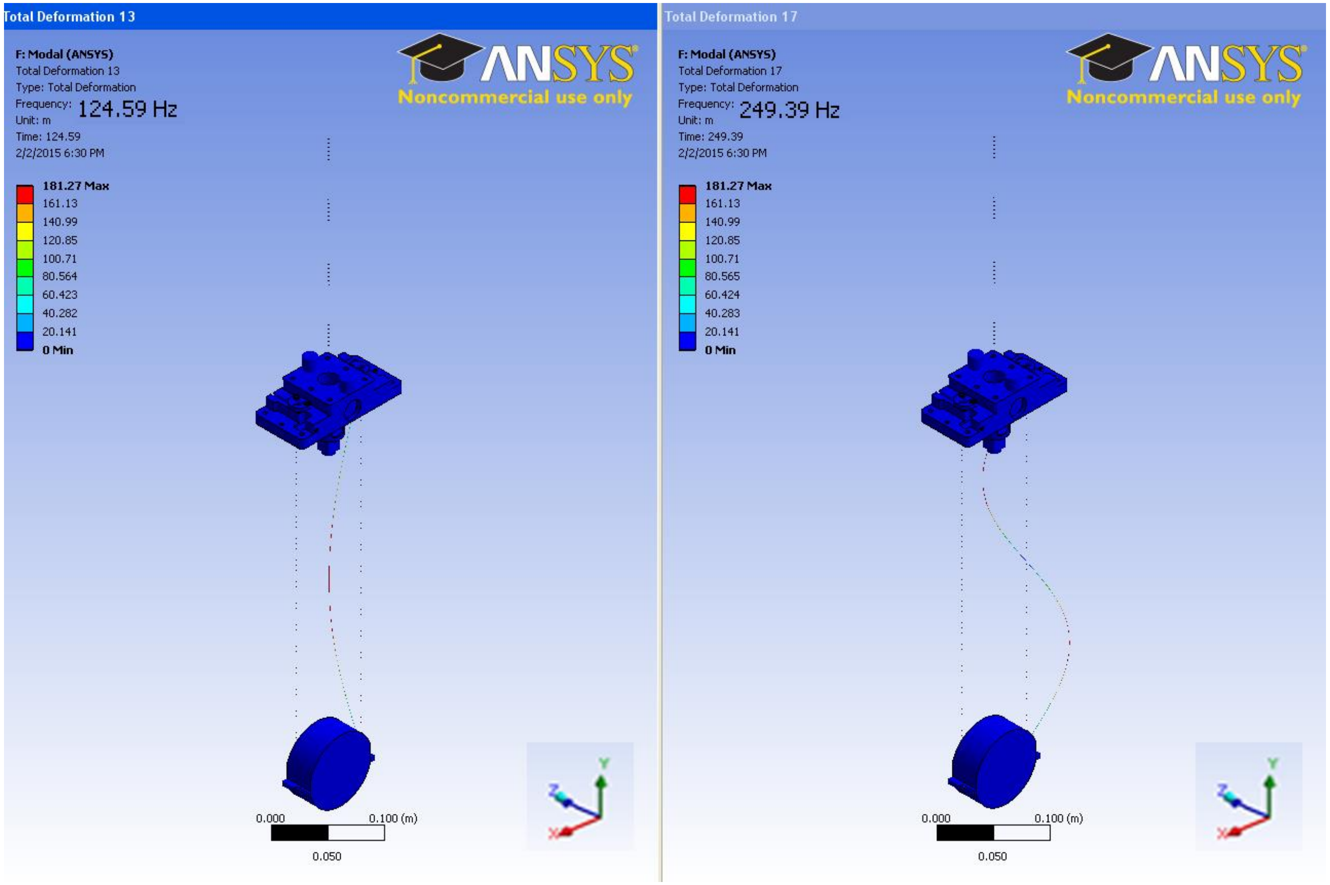
The POLIS experiment

Suspended mini-payloads

Input Payload vibration modes

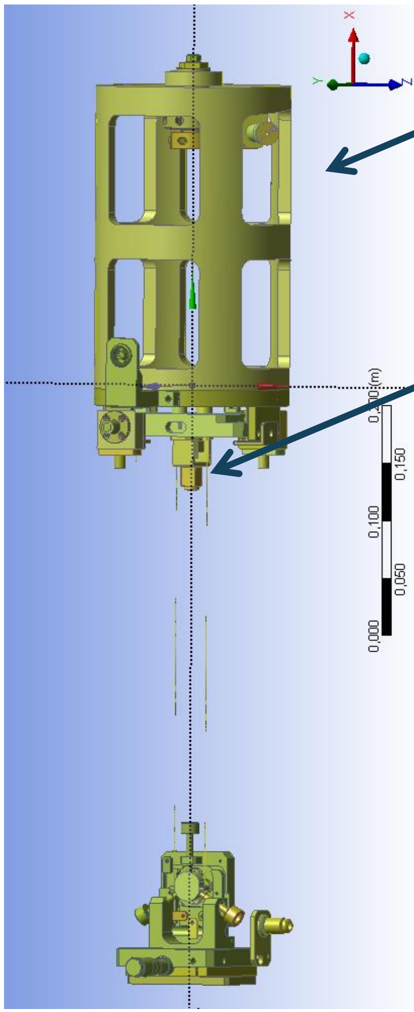


The POLIS experiment
Suspended mini-payloads



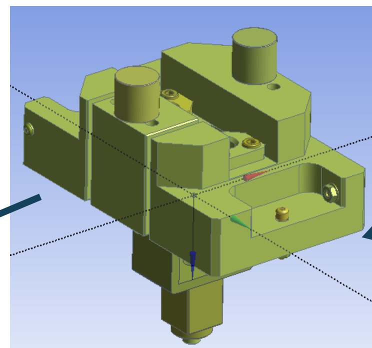
The POLIS experiment

Suspended mini-payloads

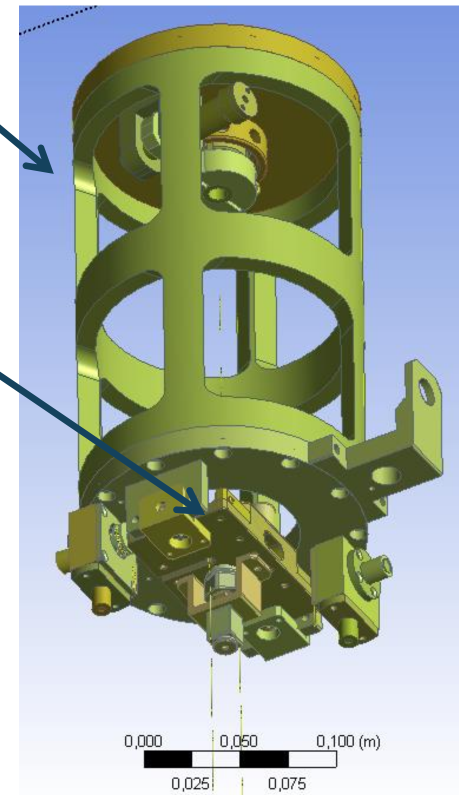


End Payload

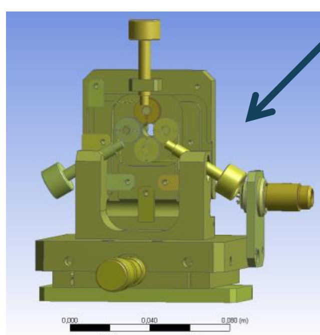
cage + **coil holder** Anticorodal Al, ~ 2.3 *kg*



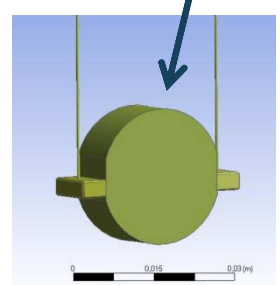
Marionette
Steel, 1.1 *kg*



Mirror coil holder
Anticorodal Al, 1.7 *kg*



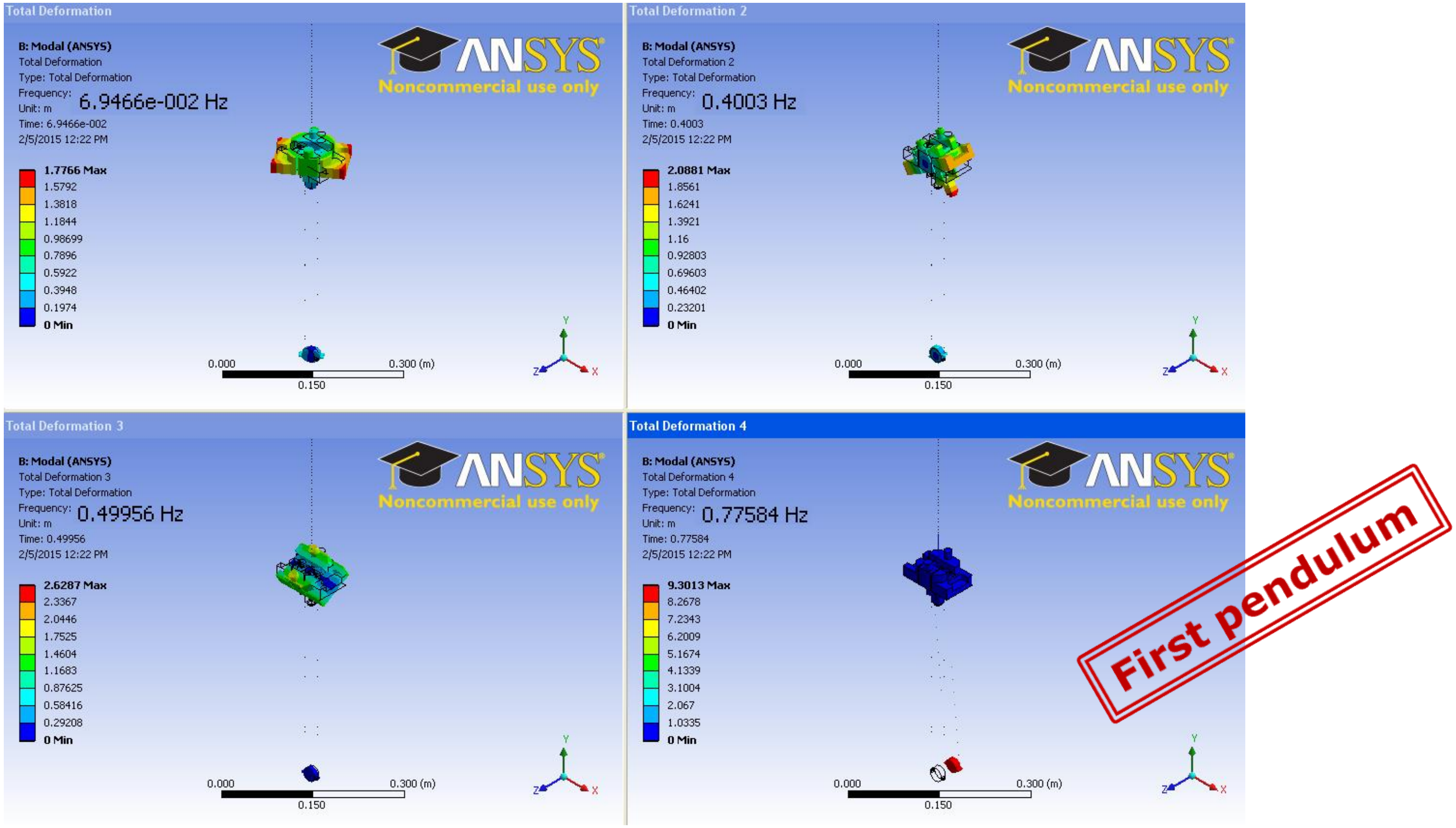
Mirror
Fused Silica,
10^{-2} *kg*



The POLIS experiment

Suspended mini-payloads

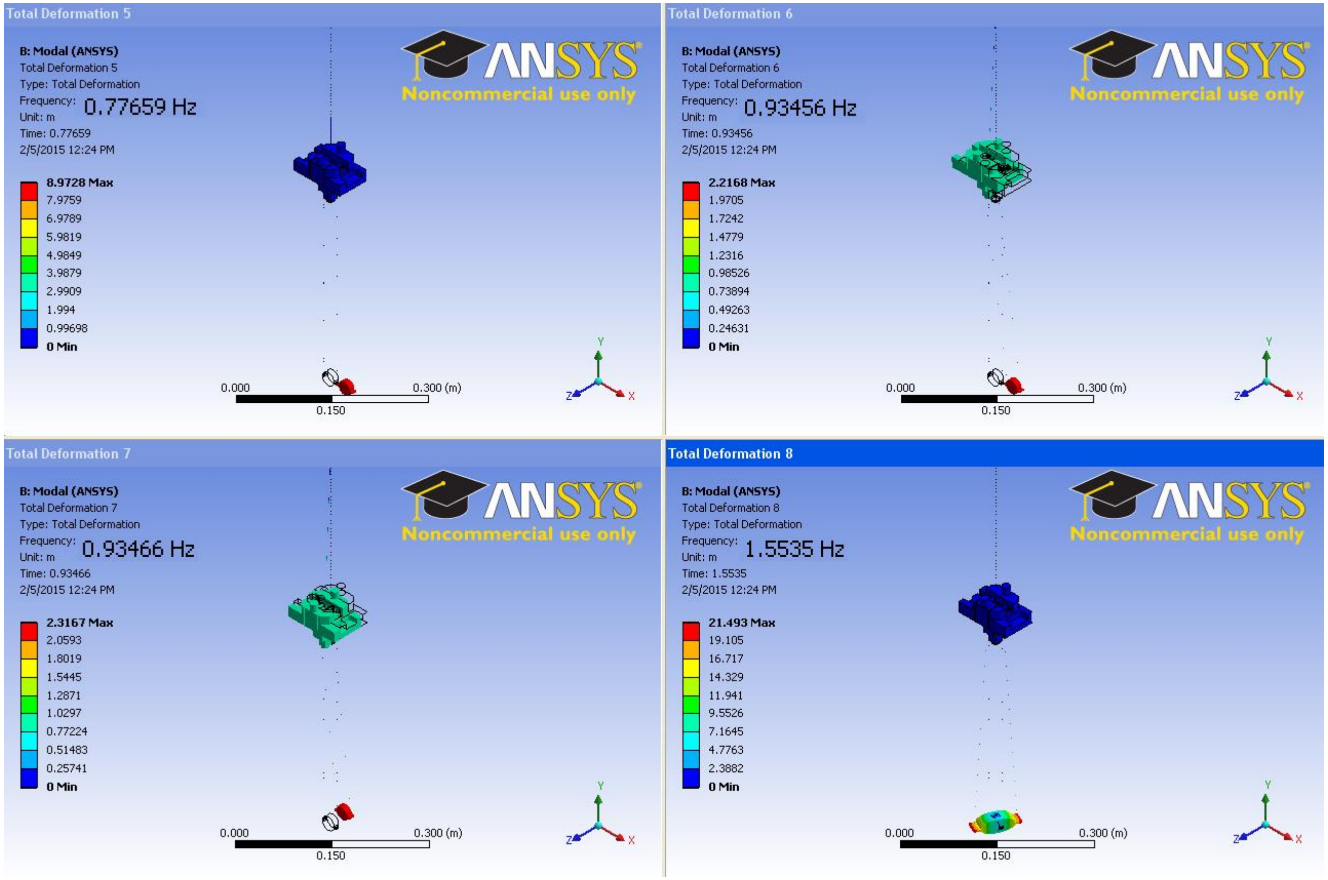
End Payload vibration modes



The POLIS experiment

Suspended mini-payloads

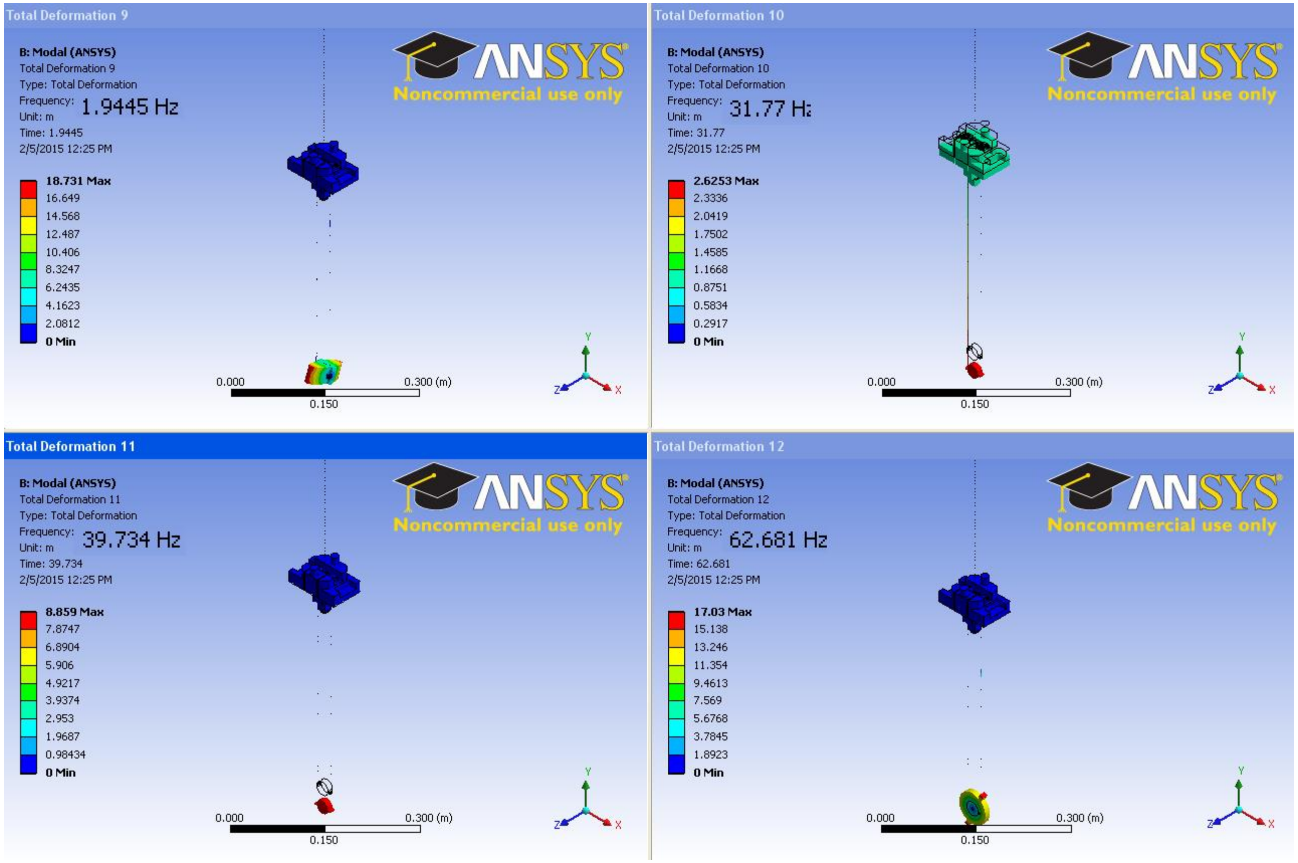
End Payload vibration modes



The POLIS experiment

Suspended mini-payloads

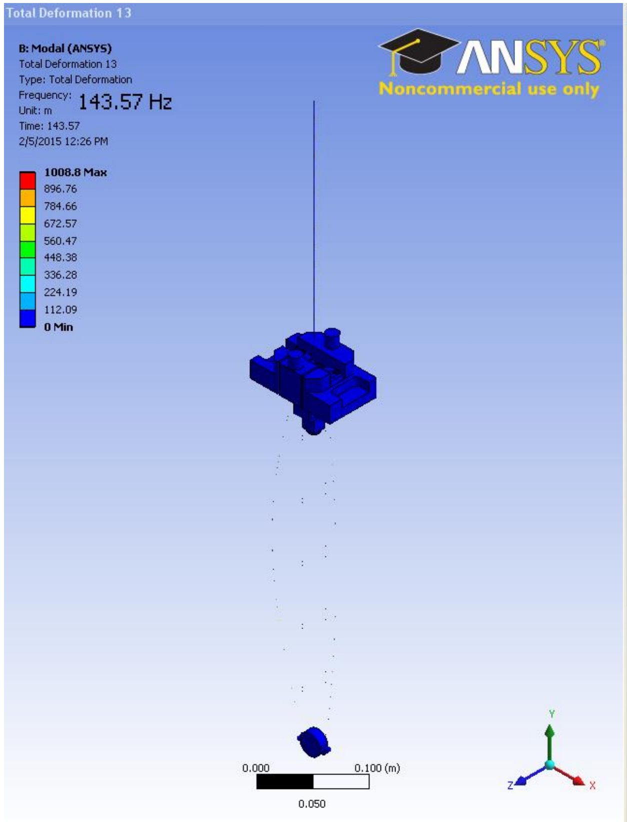
End Payload vibration modes

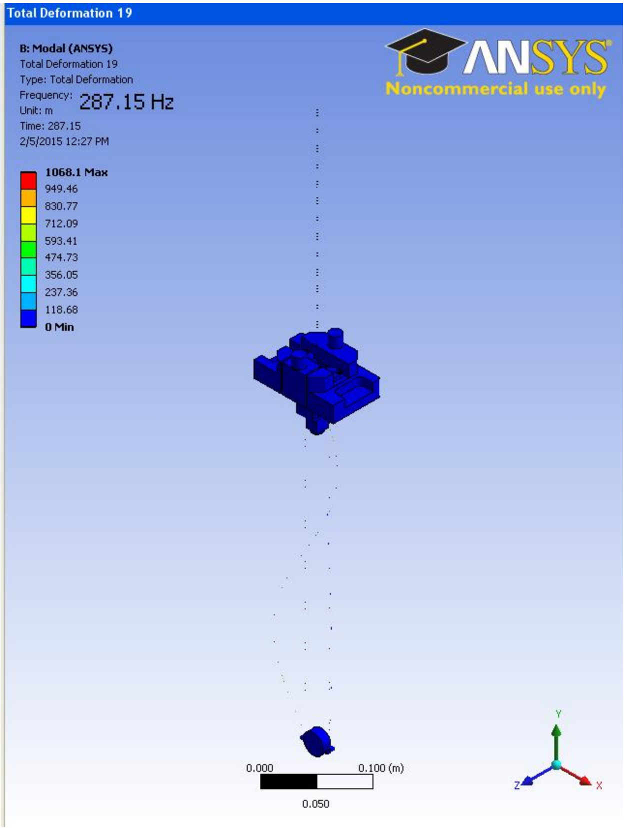


The POLIS experiment

Suspended mini-payloads

End Payload violin modes





The POLIS experiment

Suspended mini-payloads

Summary of the mechanical resonances

Mode	INPUT frequency (Hz)	END frequency (Hz)
Theta y (MA)	5.7×10^{-2}	6.9×10^{-2}
Theta z (MA)	8×10^{-2}	40×10^{-2}
Theta x (MA)	0.14	0.49
Theta x (MI)	0.14	1.94
Pendulum z (MI)	0.71	0.77
Pendulum x (MI)	0.71	0.77
Pendulum x (MA)	1.15	0.93
Pendulum z (MA)	1.15	0.93
Theta y (MI)	1.57	1.55
Y (MA)	16.3	31.7
Y (MI)	52.1	39.7
Theta z (MI)	73.6	62.7
First violin (MI)	124.6	143.6
Second violin (MI)	249.4	287.1

The POLIS experiment

Suspension thermal noise

From the Fluctuation-Dissipation Theorem:

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

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:

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

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

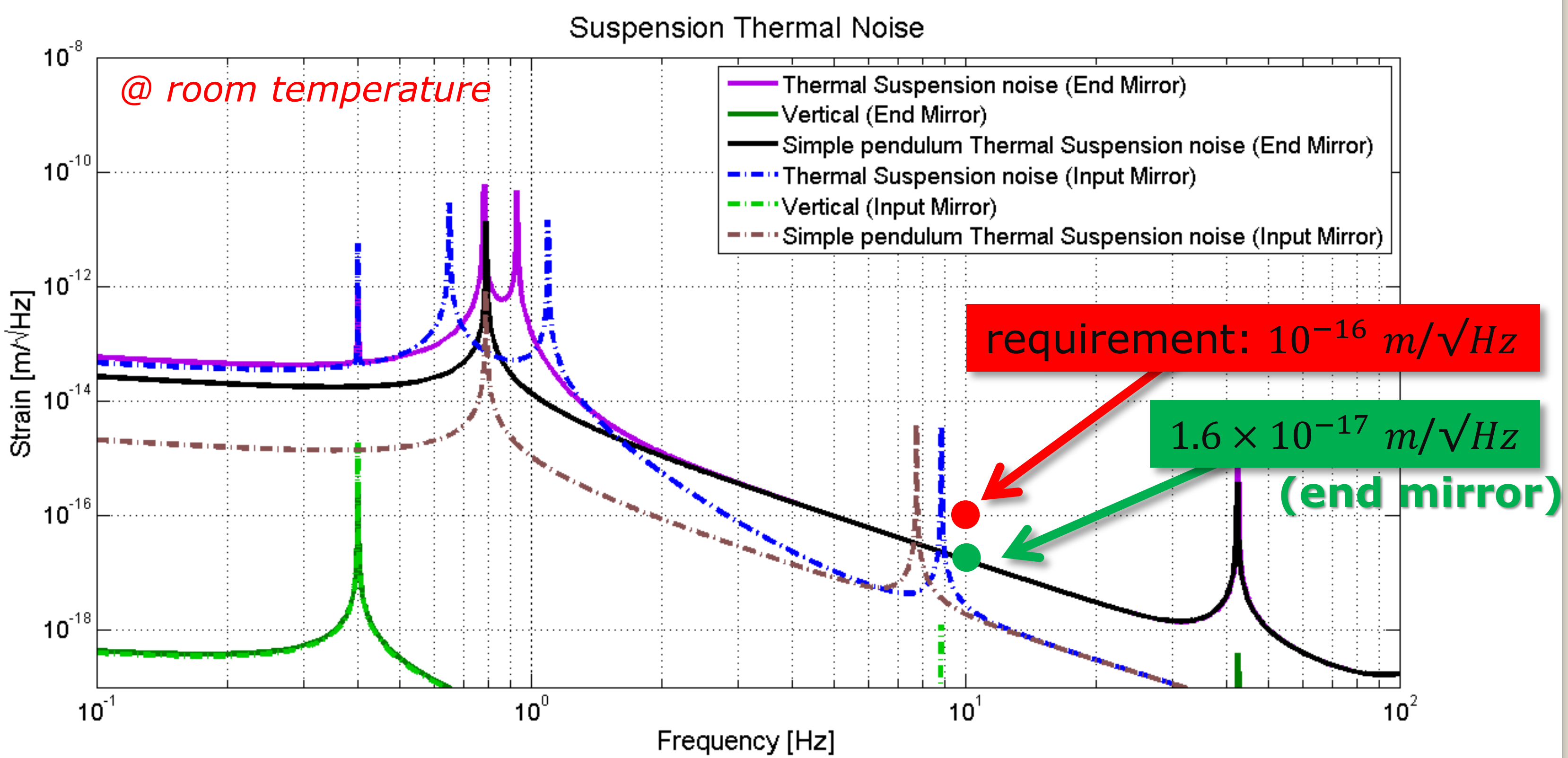
suspension wires:

Parameter	C85 steel (*Marionette*)	Fused silica (*Mirror*)
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)

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

The POLIS experiment

Suspension thermal noise



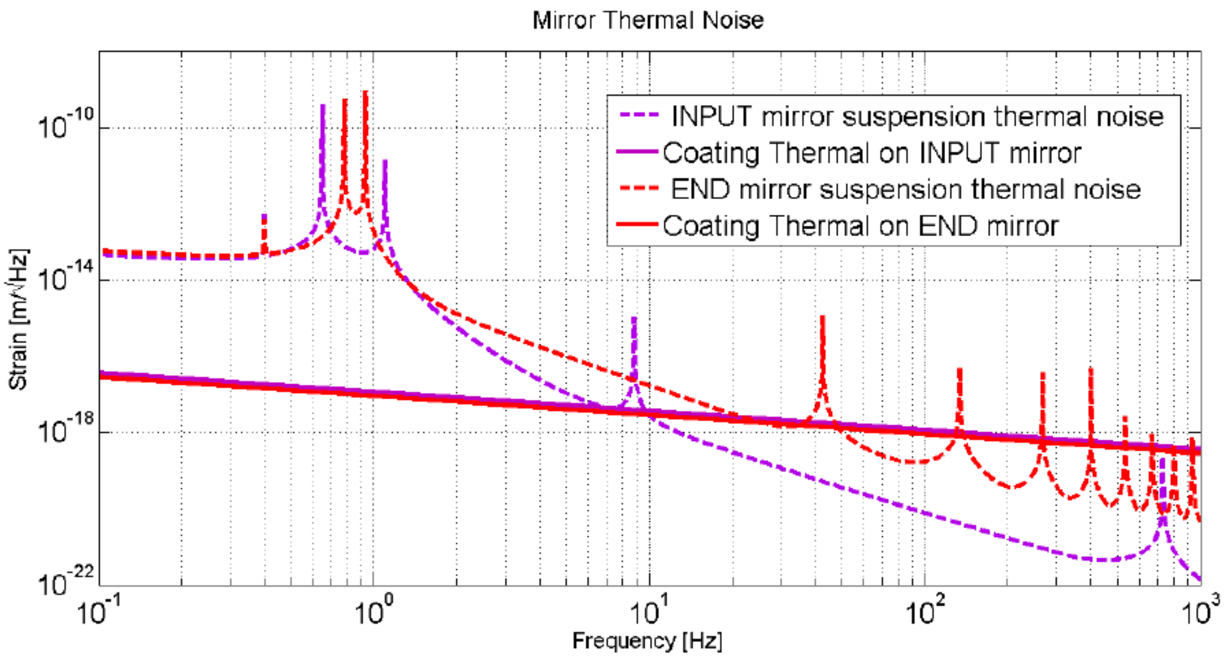
Calculated for a double pendulum, considering the previous parameters, using a MatLab-based code

The POLIS experiment
Mirror coating thermal noise

Calculated using the *Levin* approach*:

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

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**

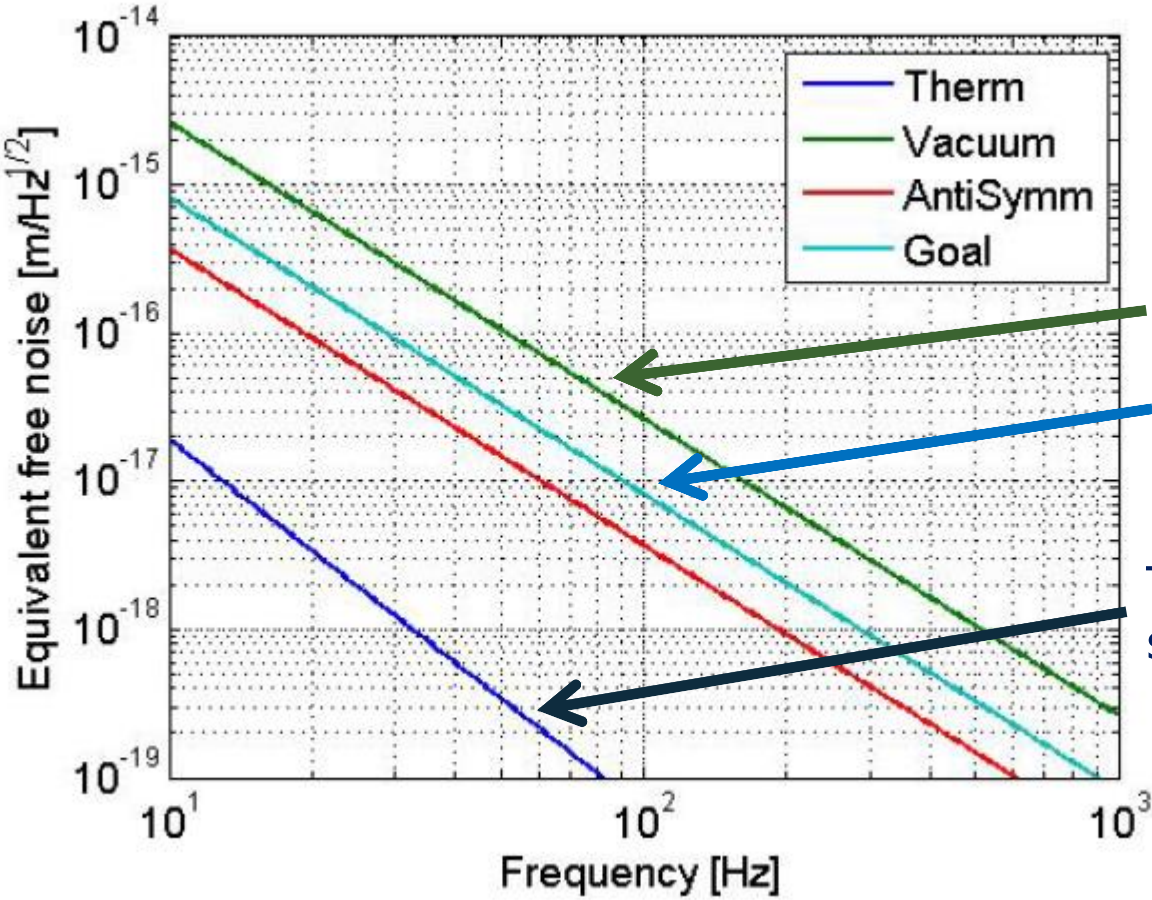
Parameter	value
ρ_{eff}	$4085.8\ kg/m^3$
Y_{eff}	$99.6\ GPa$
ν_{eff}	0.204
ϕ_{coat}	1.48×10^{-4}

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

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

The POLIS experiment

Interferometer equivalent noise



Unsqueezed vacuum

Conservative (realistic) target: 7dB of squeezing

Thermal noise from suspensions and coatings

Conclusions

- Squeezed states of light can be used to overcome the SQL;
- Squeezed light has already proved to enhance the sensitivity of a quantum-limited detector, like interferometric GW detectors;
- Phase-squeezing and frequency-dependent squeezing will be a standard choice for the next upgrades of the current GW interferometers and for third generation GW observatories;
- Ponderomotive squeezing is a promising alternative to OPO-based squeezers;
- Exploiting the seismic insulation provided by the Virgo SA we are setting up the ponderomotive squeezer POLIS, designed to work in the low-frequency band (<1*kHz*);
- POLIS FEM studies and thermal noise evaluations have been shown;
- The mechanical parts of POLIS have been already assembled and are currently under test (local control and feedback actuation) in a dedicated facility. Next steps: monolithic suspension of the small cavity mirrors, installation of the optical elements and input laser, integration in the SAFE Superattenuator @ EGO-Virgo.

Thank you for your attention!

Virgo
INFN Napoli group

E. Calloni, M. De Laurentis

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