Status of the POLIS project

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on behalf of POLIS collaboration°

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ET EINSTEIN TELESCOPE 6th Einstein Telescope Symposium

19-20 November 2014 *Lyon*

POnderomotive LIgth Squeezing

POLIS

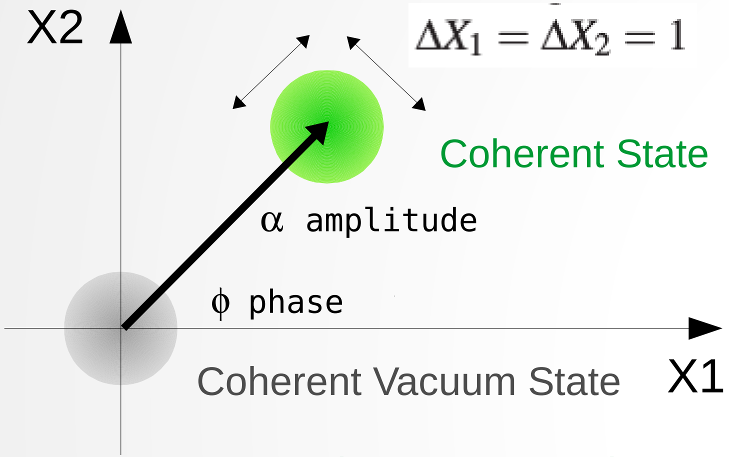
Project to build a completely suspended interferometer to generate

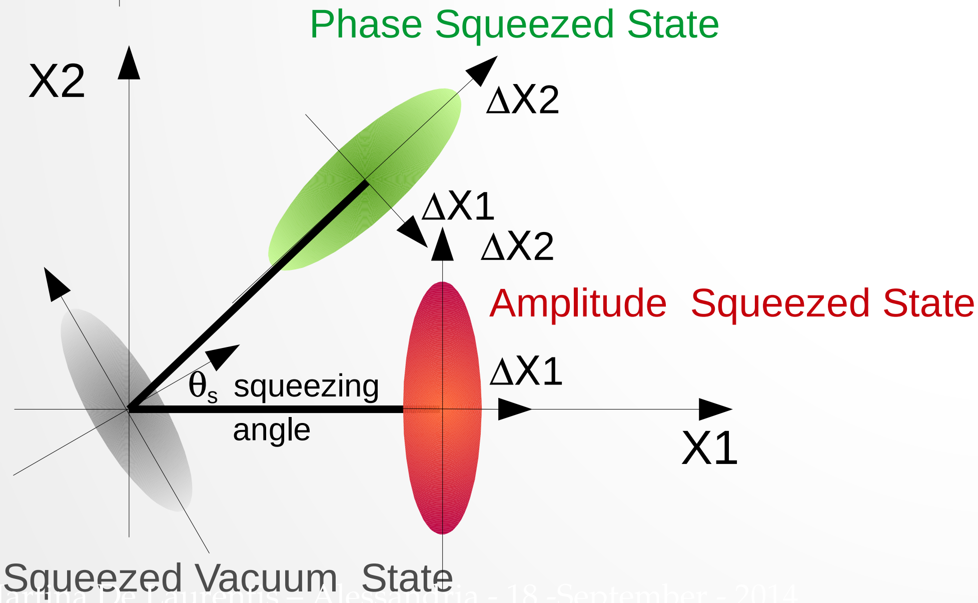
Ponderomotive Squeezed Light

It involves several groups mainly in the Virgo collaboration

Squeezed State of Light

Minimum Uncertainty States $\Delta X_1 \Delta X_2 = 1$





A bright beam (α>0) has
the same fluctuations of the vacuum

Light as '*sensitive*' element

its intrinsic quantum fluctuations
determines the final sensitivity

We cannot violate the uncertainty principle
but
we can squeeze the quantum fluctuations on
one quadrature at the expenses of the other
and 'use' that quadrature
as sensitive element

Squeezed States

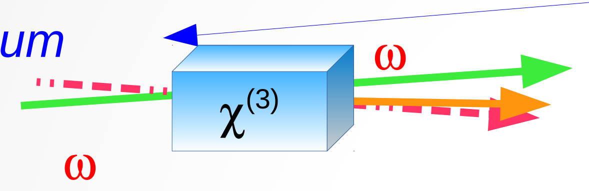
Generation of Squeezed Light

Squeezed states → ***quadrature fluctuations correlated***

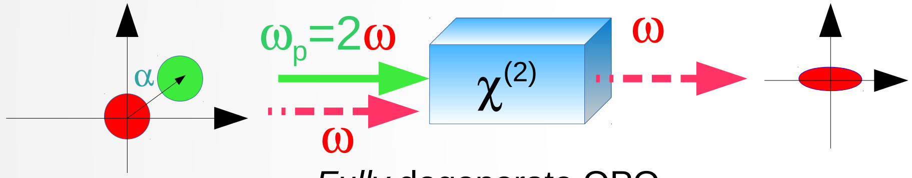
- **Non linear process in dielectric medium:** →

the 3th and 2th order nonlinear susceptibilities induces the correlation between the phase and amplitude fluctuations

- *Kerr medium*

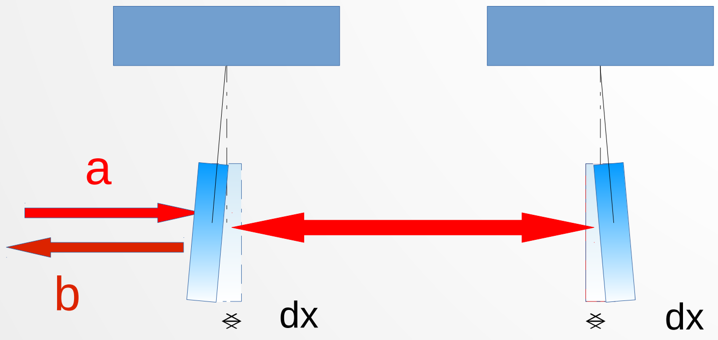


- *Optical Parametric Oscillator (OPO) below threshold*



Fully degenerate OPO
(polarizations and frequencies degeneracy)

- **Empty cavity with suspended mirrors:** ***Ponderomotive Squeezing***



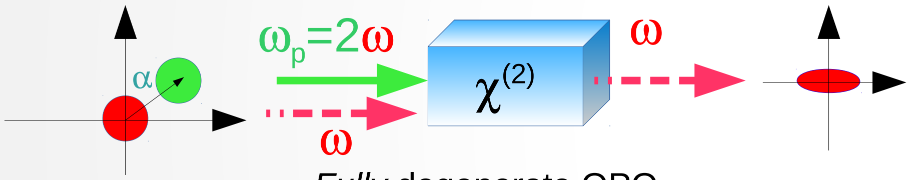
the **radiation pressure on the mirror** that is free to oscillate ***induces a coupling*** **between its position and the intensity of the light beam**

Correlation between
the **phase and amplitude quadrature** of the output state

Generation of Squeezed Light

Squeezed states → ***quadrature fluctuations correlated***

- Optical Parametric Oscillator (OPO)



Fully degenerate OPO
(polarizations and frequencies degeneracy)

At present the OPOs result to be the more efficient light squeezing generator

- *higher squeezing reached (12.7 dB)*
  (Eberle -Phys. Rev. Lett., 104:251102, 2010)
- *Squeezing at lower frequency (10 Hz)*
  (Vahlbruch,New Journal of Physics 9 (2007) 371,
  Chua, Opt. Lett., 36:4680, 2011)
- *Tested long time operation*
  LIGO - Nature Photonics 7.8 (2013), pp. 613–619
  GEO600 -

What is interesting in ponderomotive squeezing?

- **Squeezing generation in MOEMS (Micro-Opto-Electro-Mechanical Systems) → Communication and integrated sensors; on chip devices**

  OPO integration in the well consolidate silicon technology (mixed technology with KTP and LiNb on Si) is more expensive and does not allow the same integration factor

- **Macroscopic opto-mechanical objects and their quantum mechanical behavior** → Theoretical interest

- **Low frequencies and frequency independent squeezing**

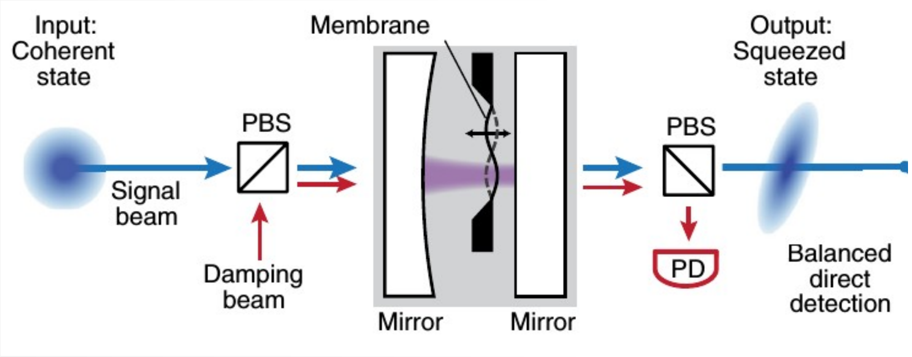
  PS is a completely suspended system → we expect that could be, at *regime*, less vulnerable to seismic noise

  In long period operation OPO squeezer seems *experimentally* frequency limited due to losses mechanism in the medium (photo-thermal fluctuations) even if progress in material engineering and dedicate mechanical design promises to overcome these limits

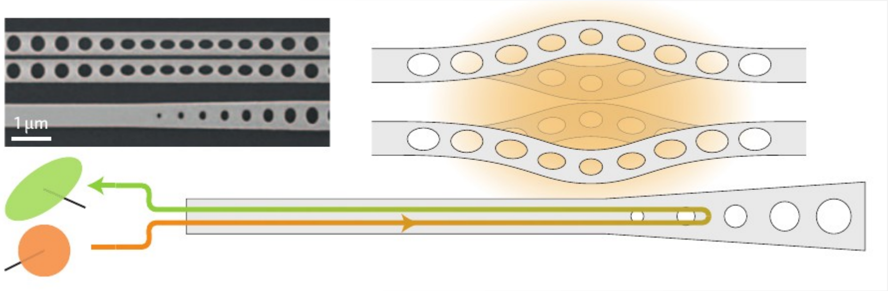
Ponderomotive Squeezing

- At present only a generation of a bright squeezed light in MOMS*

**MOMS Micro-Opto-Mechanical-System*



T. P. Purdy et al. Physical Review X 3, 031012 - 2013



Safavi-Naeini, A. H. et al. Nature 500, 185-189 (2013)

- **largest squeezing measured:**

1.7 dB below the shot-noise level @ **1.54 MHz**

POnderomotive **LI**ght **S**queezing
POLIS project

Project to realize a completely suspended low frequency independent ponderomotive squeezer in the low frequency range

moving from the pioneers' work made in the LIGO laboratory at the MIT

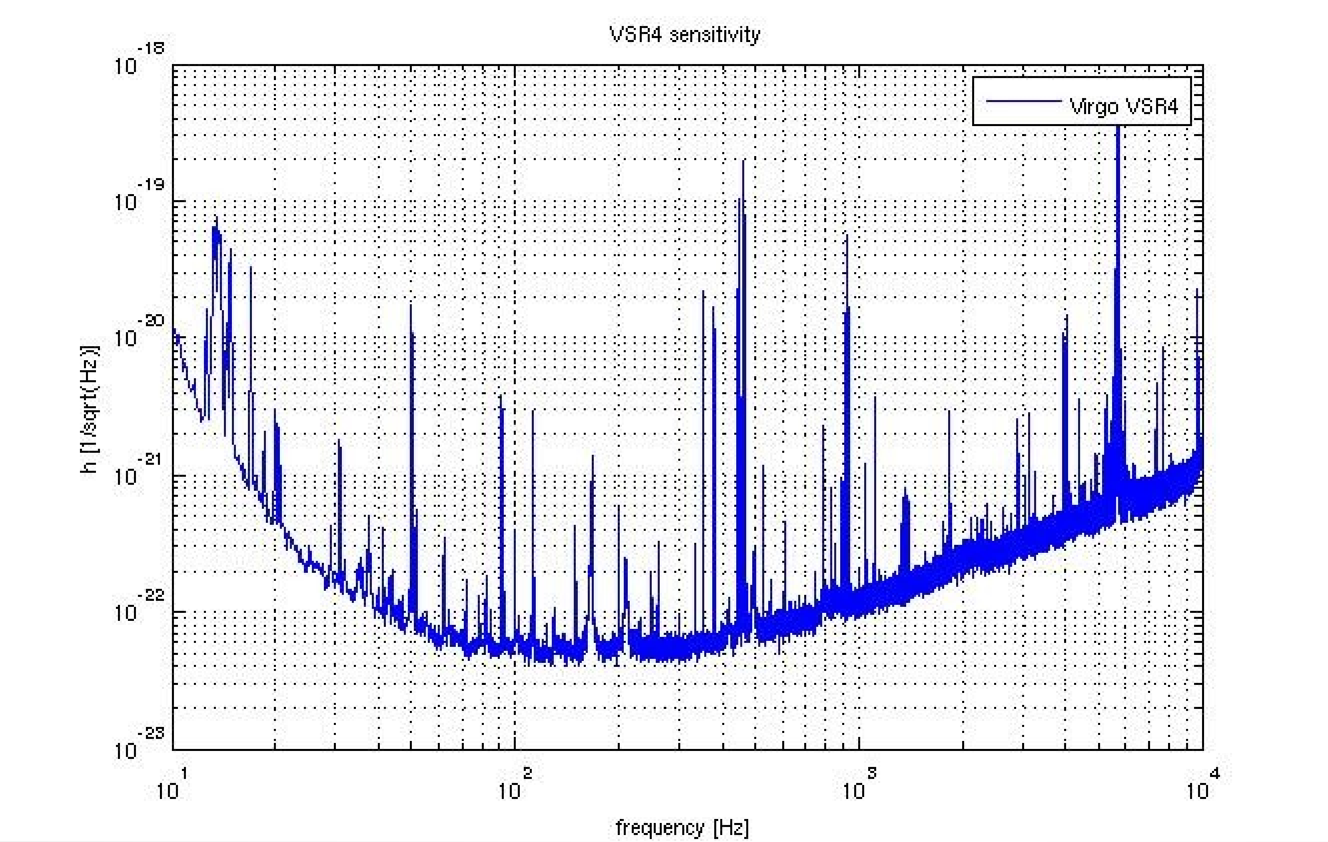
[*Corbitt et al.* Phys. Rev. A 73 (2 Feb. 2006), p. 023801]

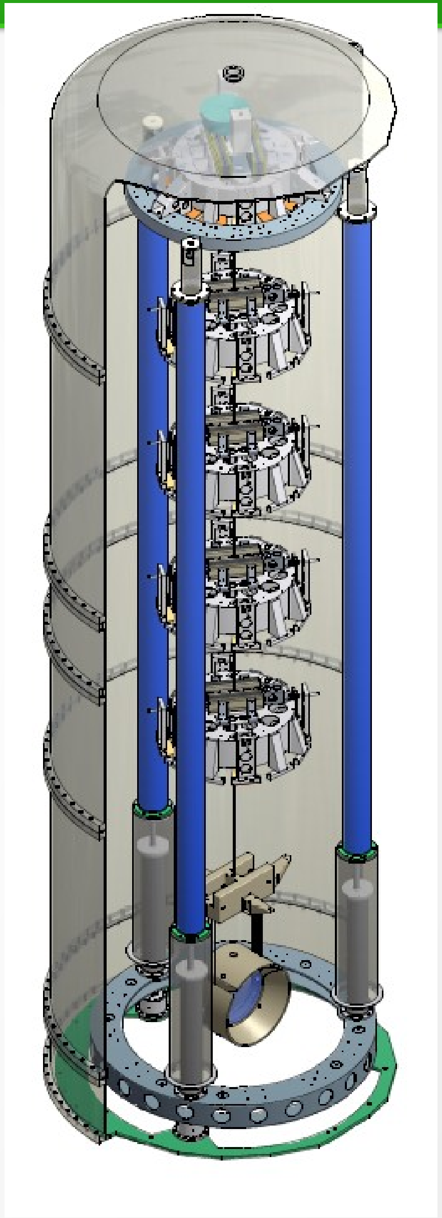
and

taking the advantage of the available Virgo Super Attenuator Facility at EGO, SAFE

to control the main noises source in the low frequencies range

SAFE **Super Attenuator Facility at EGO**

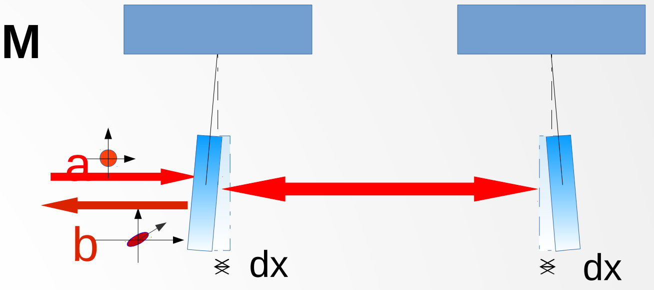




resonance frequency of the first stage =40 mHz

Frequency independent Ponderomotive Squeezing

USE OF RADIATION PRESSURE AS SQUEEZING MECHANISM



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

Laser Intensity fluctuations ⟷ test mass motion

Phase shiftproportional to intensity fluctuations

↓

(**FREQUENCY DEPENDENT SHIFT**)

↓

Coupling between *phase quadrature and amplitude quadrature*

↓

Squeezing ξ(Ω)

OPTICAL SPRING FOR FREQUENCY INDEPENDENT SQUEEZING

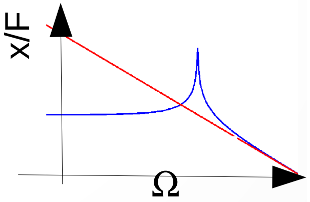
Optical Spring modifies the cavity dynamics

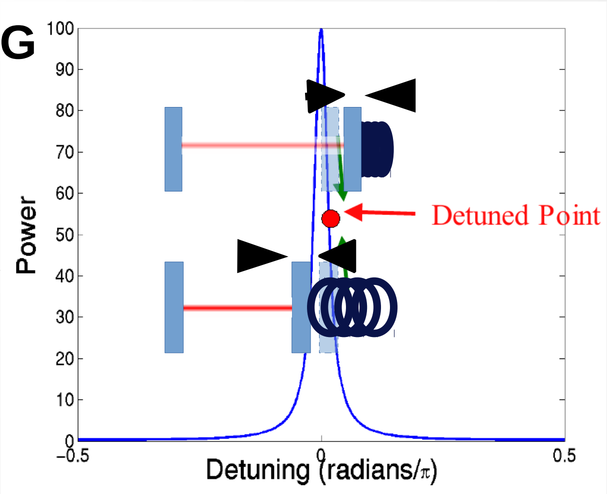
ξ(Ω) ⟶ ξ constant for **Ω** << **Θ**

optical spring characteristic frequency

↓

gives the *frequency independent squeezing band*





PS Optomechanical Parameters

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

squeezing factor

Optical stifness

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

Optical spring resonance

Fixed the ξ and Θ
key parameters are:

Input power I_o, Cavity Finesse $\mathcal{F}$, Cavity detuning δ_γ, Suspended mirrors mass M

⇕

Parameters value optimization
to have

A large enough squeezing factor and the desired **frequency band**

POnderomotive LIght Squeezing
POLIS project

Ponderomotive Squeezing:

large squeezing values without use high laser power and/or very high cavity finesse requires very small suspended mirrors mass

↓

very critical point is the mass suspension

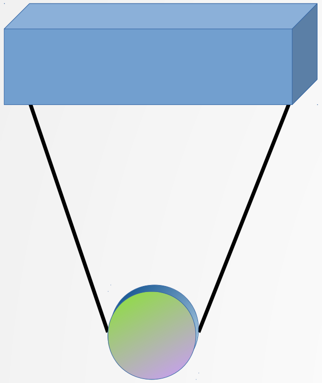
A relative large mass allows us to use the available
well consolidate technologies
to control the low frequency noise

↓

higher chance of success of the project

POLIS Optical Parameters

Suspended Mirrors Mass



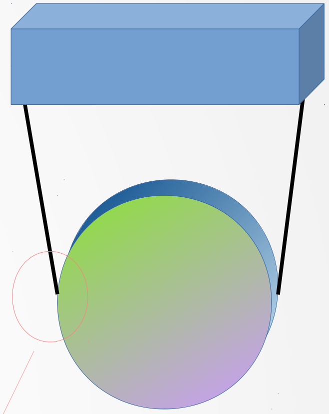
Low value of mass

- Large optical Spring resonance

(*frequency independent squeezing Band)*

High value of mass

- ease of construction;
- ease to sense and actuate motion;
- use commercial size



Use of **SAFE** → **High sensitivity in the low frequency** range thanks to better seismic isolation → **we can choose slightly higher mass:** $\mathbf{M=10\ g}$

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: It can be suspended with the available technology in Virgo

We expect no particular problem with the suspension fibre welding

Moreover, macroscopic mass reduces the thermal noise

POLIS 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: $\delta=0.3$ => $\xi=18$ dB and **$\Theta=2\pi$ kHz**

By considering the losses, this assures more than 10 dB of potential squeezing delivered by the interferometer

It covers the GWD band
(but is not vacuum squeezed)

POLIS Optical Parameters:

cavity *Finesse*

enters directly in the reachable squeezing coupling with the cavity losses

Large values

- Large Optical spring frequency;
- Reduce effective intra-cavity losses;

Low values

Reduce optical spring instability;
Reduced intra-cavity circulating power

losses of 10 ppm, if we impose that **squeezing is not degraded by more than 60%** of the theoretical goal

$\mathcal{F} \leq$ **30 000**

Recently cavities with Finesse as high as 0.5 10^6 has been realized with commercial, low cost mirrors [*F Della Valle et al.* New Journal of Physics 15.5 (2013), p. 053026]

POLIS 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 and a 10 g mass we can relax the input power

$$\mathbf{P_{in}=2.5\ W}$$

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.

POLIS status: cavity parameters

Constrain for the cavity length: inner SAFE diameter

L = 440 mm

Negative stability factors, g_i, in the cavities with low suspended masses reduce the angular instability

$g_i = -0.76$

Available Radii of Rurvature of the commercial substrates

$RoC_{INPUT} = RoC_{End} = 250$ mm

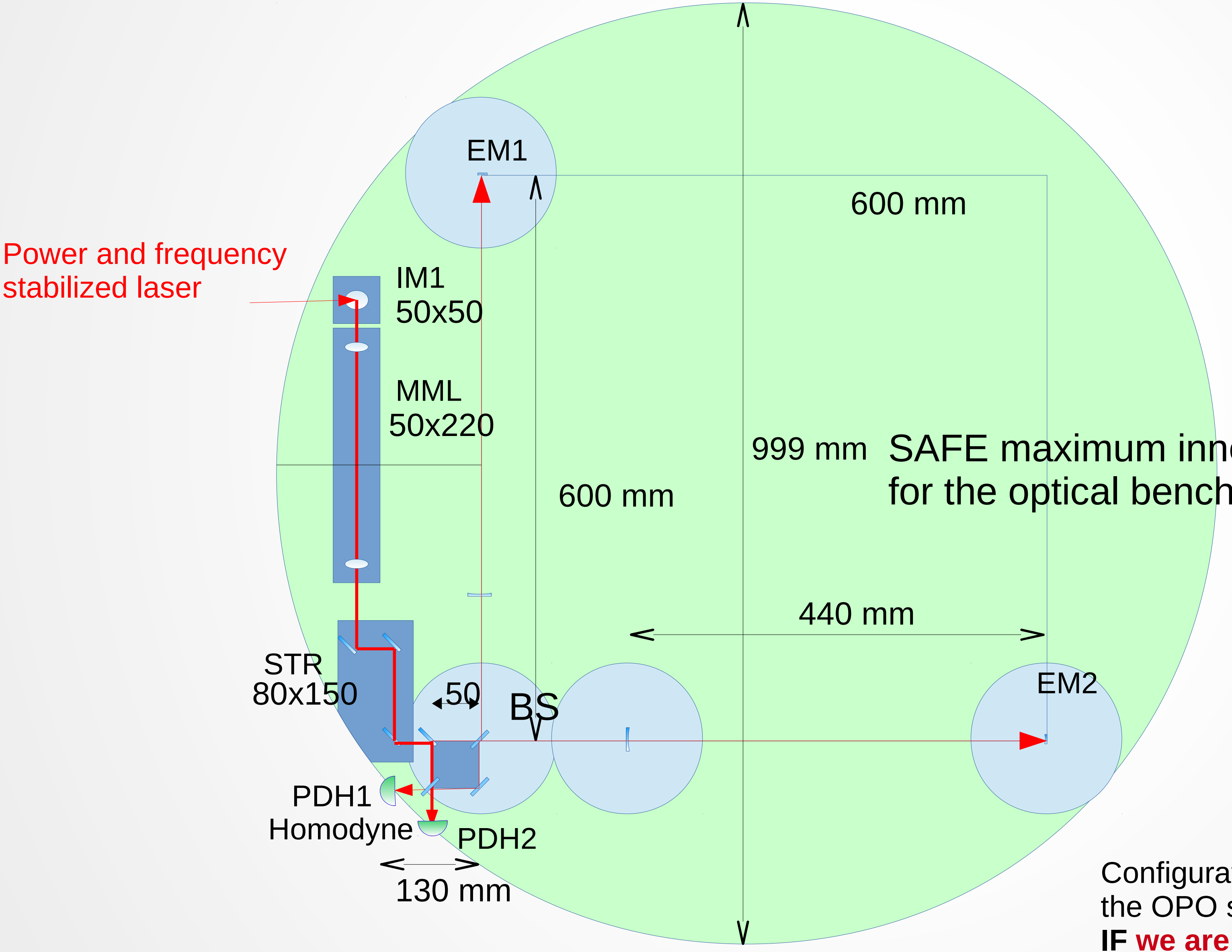
This value of the RoC assures the maximum spot size, w_i, on the mirrors with the available commercial radii
(large spot => reduces thermal deformation of the coating)

$w_i = 0.447$ mm

Gouy phase = 2.43 rad = 0.773493 π

well stable cavity:
avoiding the couplings with thermal deformations
or imperfections, mis-match problems and the higher order modes resonance

POLIS set-up sketch



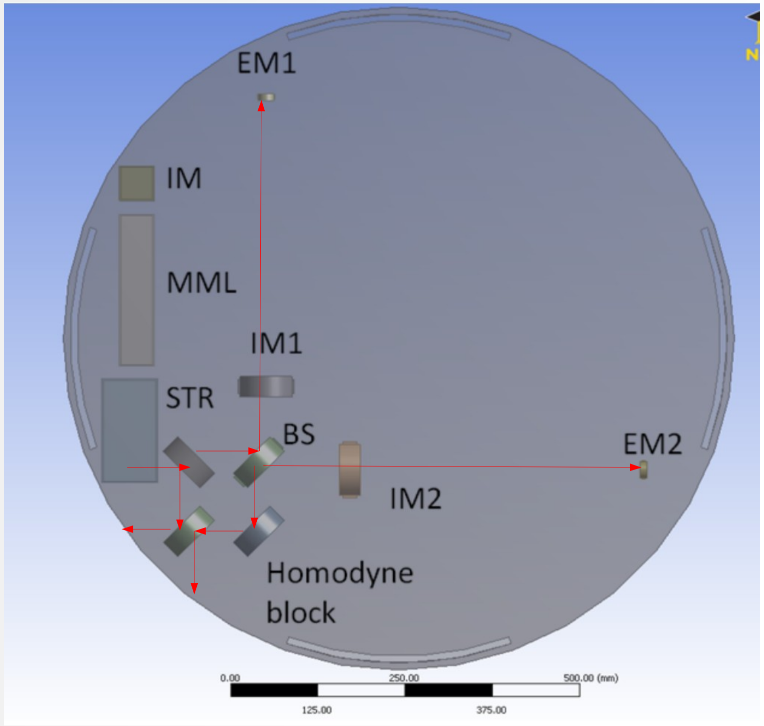
SAFE maximum inner diameter for the optical bench

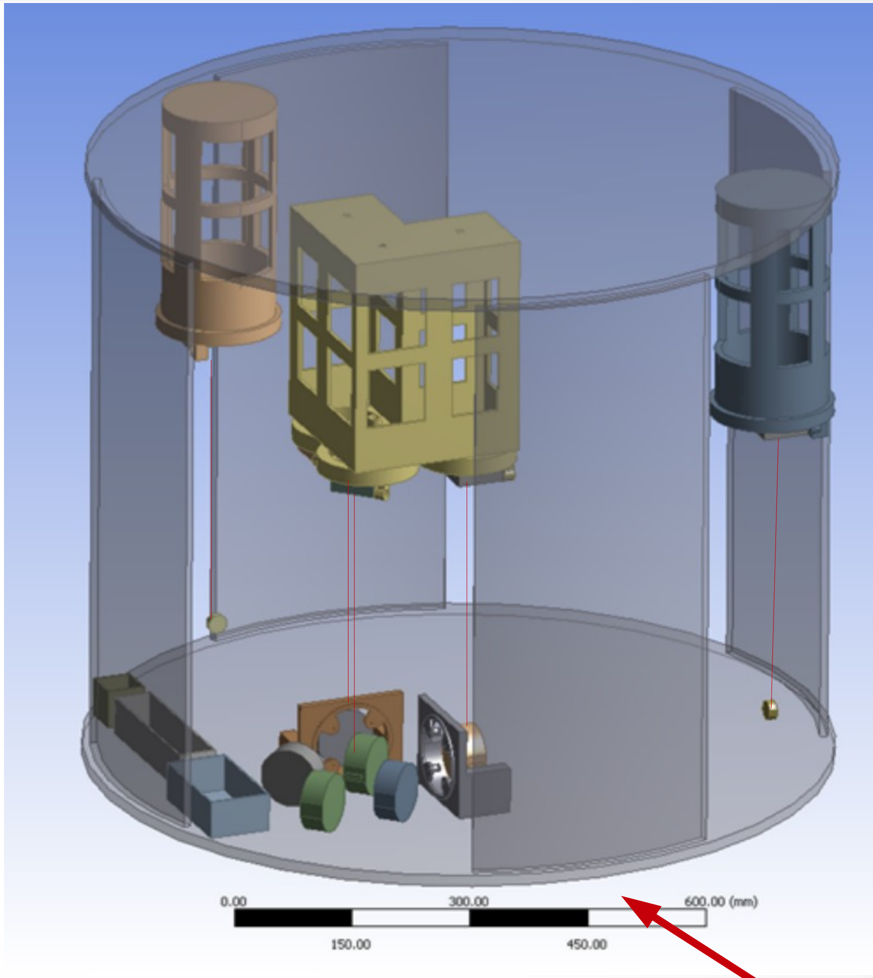
LEGENDA

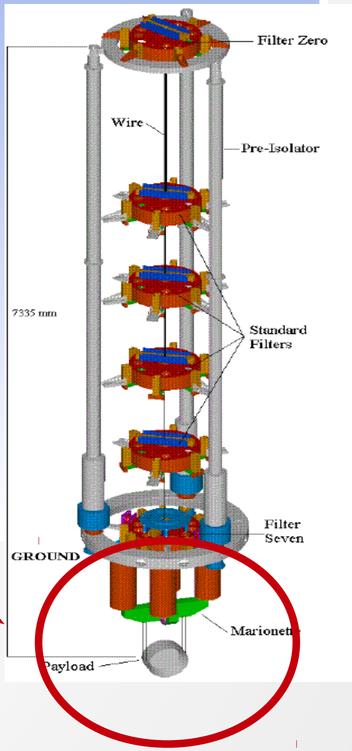
IM1: input mirror
Is the mirror that brings the Beam from the top on this stage
MML: Mode Matching Lens
STR: Beam Steering Mirrors
To alline the interferometers
BS:*Beam Splitter*
EMi: *End Mirror*
IMi:*Input Mirror*

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

POLIS design of the optical bench

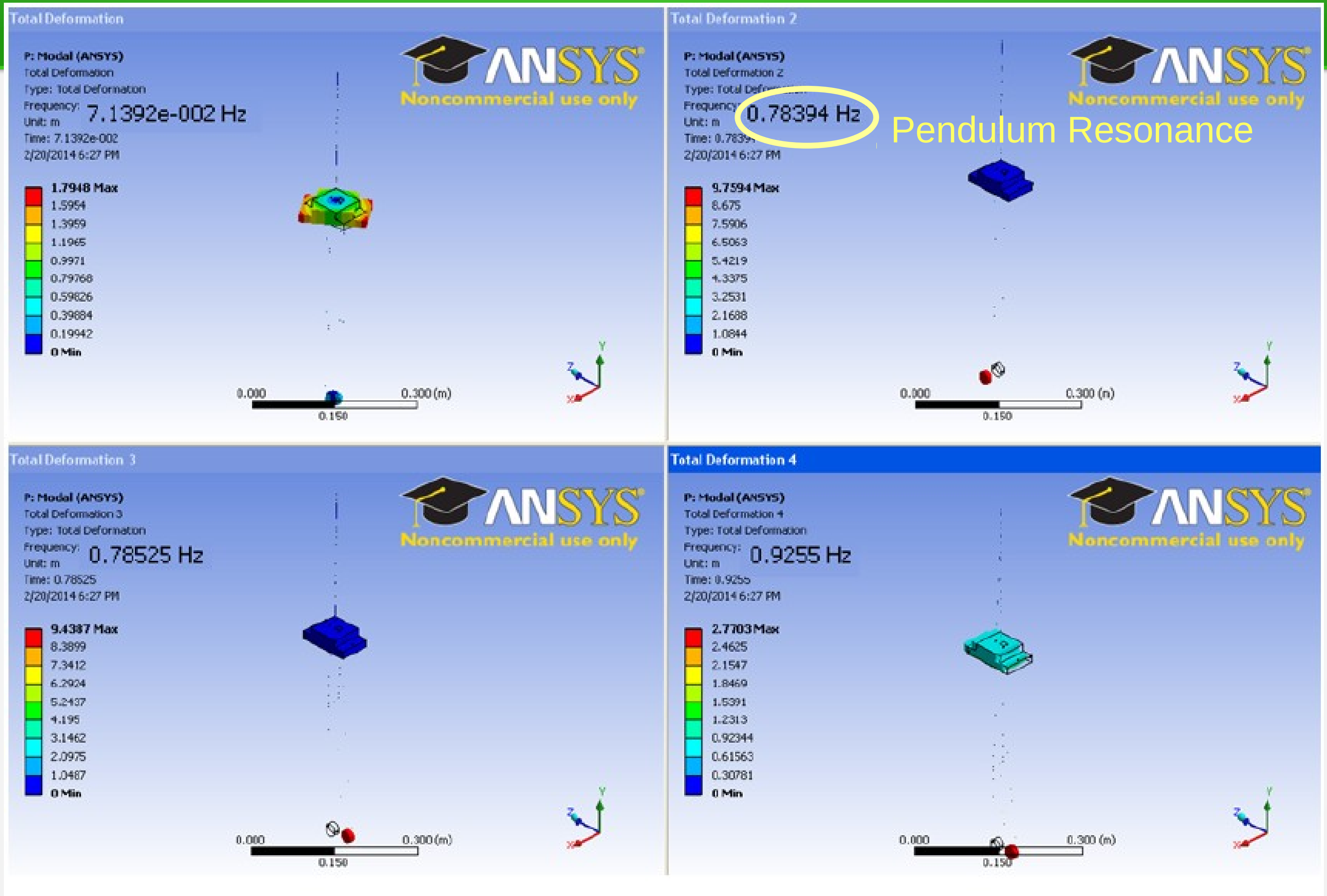






Mechanical Design by *Andrea Conte*
(Roma1 – La Sapienza)

Suspended optical bench
at the place of
the Virgo suspended mirror



Total Deformation

P: Modal (ANSYS)
Total Deformation
Type: Total Deformation
Frequency: 7.1392e-002 Hz
Unit: m
Time: 7.1392e-002
2/20/2014 6:27 PM

Total Deformation 2

P: Modal (ANSYS)
Total Deformation 2
Type: Total Defor
Frequency: 0.78394 Hz
Unit: m
Time: 0.7839
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Pendulum Resonance

Total Deformation 3

P: Modal (ANSYS)
Total Deformation 3
Type: Total Deformation
Frequency: 0.78525 Hz
Unit: m
Time: 0.78525
2/20/2014 6:27 PM

Total Deformation 4

P: Modal (ANSYS)
Total Deformation 4
Type: Total Deformation
Frequency: 0.9255 Hz
Unit: m
Time: 0.9255
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FEM simulation by *Andrea Conte (Roma1 – La Sapienza)*

Very preliminary noise estimation

Equivalent noise of the interferometer in order to reach the squeezing (blue curve), the experimental goal of 7 db (red curve), the theoretical ideal value of 17 db (green curve).

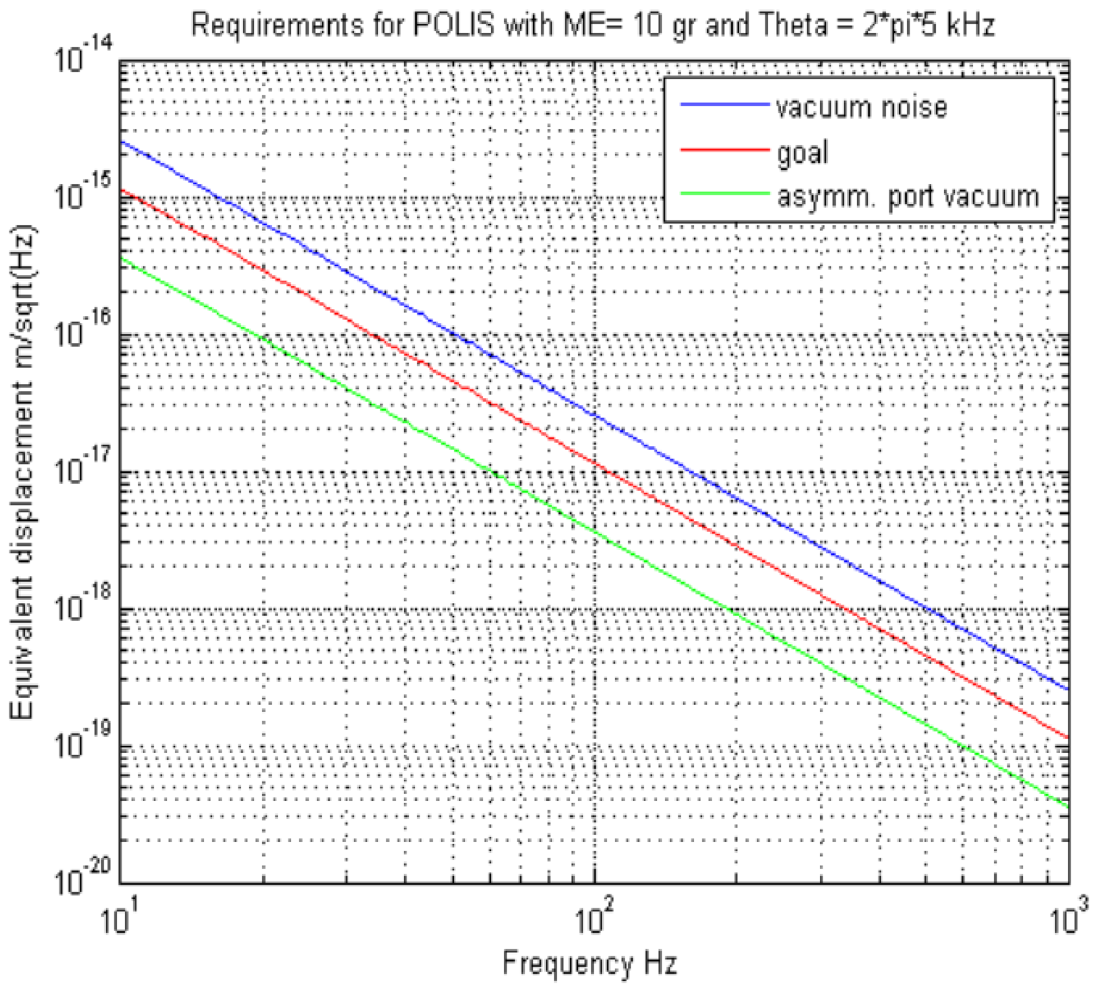
In order to have chance to observe the squeezing we must have a sensitivity of 8 *10^{-14} m/sqrt(Hz) @10Hz

(Work in progress)

Estimated spectral density of Mirror thermal motion associated to pendulum mode: the thermal noise has been evaluated @10Hz

$$\sqrt{S_z^{FDT}(10Hz)_{END}} = 6.0\cdot 10^{-17}\frac{m}{\sqrt{Hz}}$$

$$\sqrt{S_z^{FDT}(10Hz)_{INPUT}} = 1.7\cdot 10^{-17}\frac{m}{\sqrt{Hz}}$$



POLIS next steps

- **Detailed study (simulation) of the expected sensitivity (expected noise extimation → THERMAL)**
- **Build the mechanical system (marionette and suspended bench)**
- **Test the Virgo monolithic suspensions on the 1 inch/10 g mirrors**
- **Provide the mirrors for the high finesse suspended cavity (super polished substrates, coating...)**

Thank you!