GRAFIQO

GRAvitational Force In Quantum Optomechanics

Starting date January 1 2023; 6 years

Objectives: explore the territory between quantum physics and gravity. More specifically

1. **Measurement of the smallest gravitational force (masses ~ 10 mg)**

2. **Measurement of this small force when these masses are in a quantum state (limited only by quantum fluctuations)**

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Unità INFN partecipanti: **Trento, Firenze, Perugia**

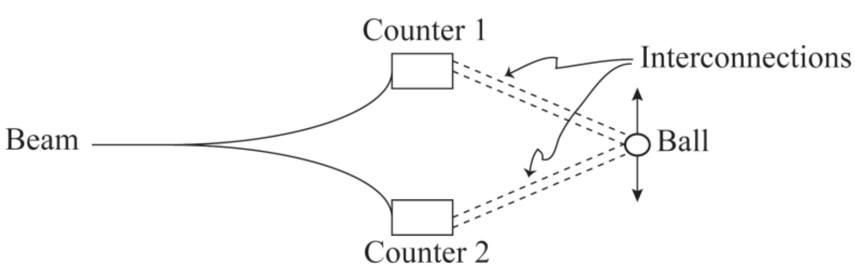
Responsabili locali: **Enrico Serra (TN) , David Vitali (PG)**

PHYSICS & MOTIVATION

Are we sure that gravity must be quantized ?

We can answer even without any clue on quantum gravity (i.e. in a model-independent way)

R. Feynman, in Chapel Hill Conference Proceedings (1957)



- Put a source of a gravitational field in a quantum superposition of two separated locations
- Verify its quantum nature by detecting entanglement on a degree of freedom of the source-probe mass system

PRL 119, 240402 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

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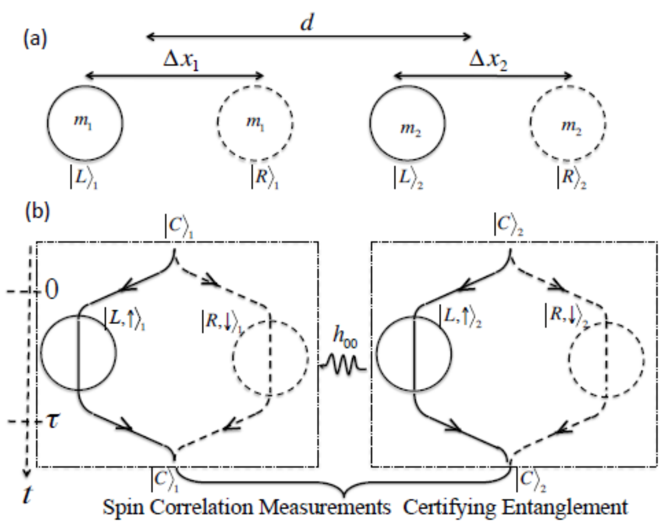
(Received 6 September 2017; published 13 December 2017)

PRL 119, 240401 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

Spin Entanglement Witness for Quantum Gravity

Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4] Mauro Paternostro,[5] Andrew A. Geraci,[6] Peter F. Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]

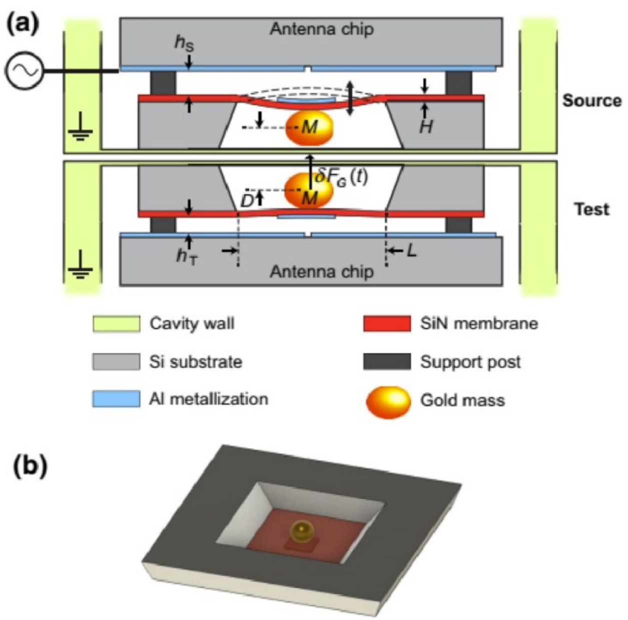


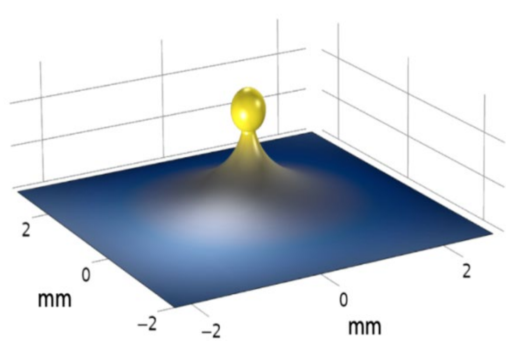
These proposals are too hard in view of current technology

one needs to keep large enough masses isolated from noise and decoherence for a long enough time t

$$\varphi_g \approx \frac{\Delta E_{grav} t}{\hbar} \approx G \frac{m_s m_p}{\hbar d} t$$

We target a fundamental intermediate step: accurate measurement of the gravitational force between objects in a quantum state, i.e., with quantum-limited position-momentum fluctuations

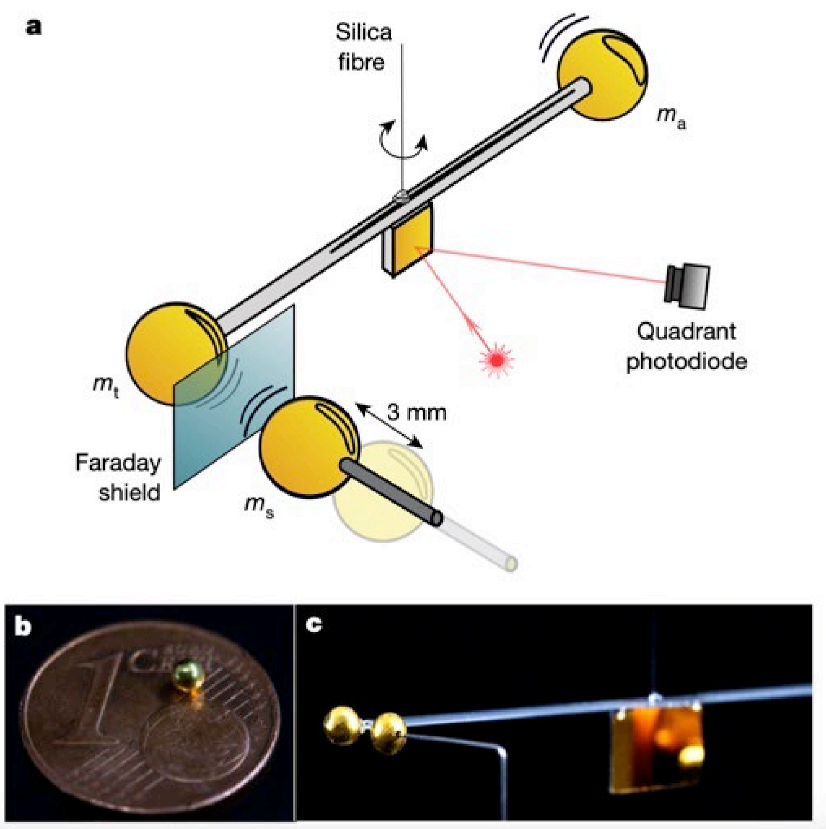




For example:
Masses are operated and measured by coupling to microwave cavities in a dilution cryostat at 10 mK (M. Sillanpää , Phys. Rev. Applied **15**, 034004 (2021)

Scientific state-of-the-art

A recent experiment that revealed the gravitational force in case of **sub-100 mg masses (in the classical regime)**



Torsional pendulum
(interaction between two gold spheres)

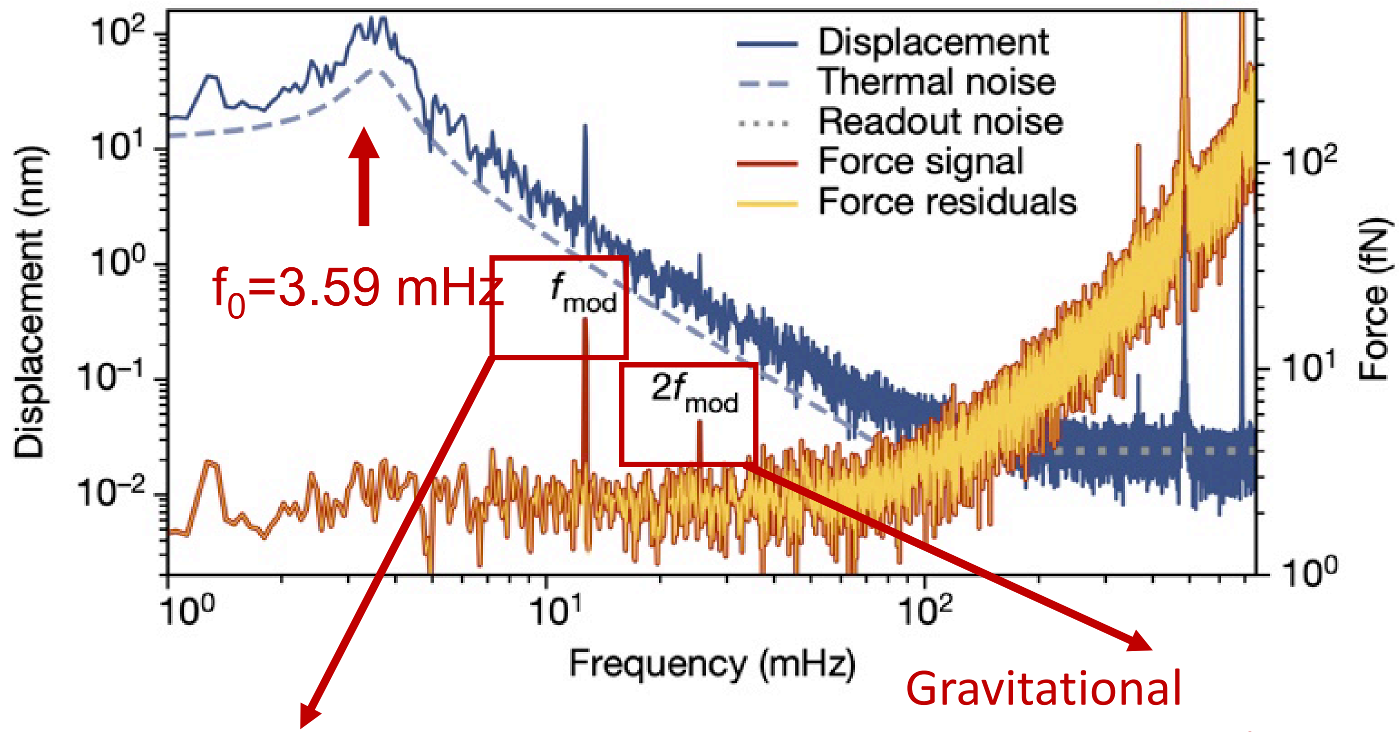
Test mass (mg)	**90.7**
Source mass (mg)	**92.1**
Quality factor	**4.9**
Resonance frequency (Hz)	**3.59×10^{-3}**
Modulation frequency (Hz)	**12.3×10^{-3}**
Temperature (K)	**300**
Vacuum (Pa)	**6×10^{-7}**

Aspelmeyer Group in Vienna
Nature 591, 225–228 (2021)

Quasi-resonant measurement of a modulated gravitational force

$$F_{\mathrm{mod}} = \frac{\partial F_g}{\partial x} A_{\mathrm{mod}} \qquad F_g \approx G \frac{m_s m_p}{x^2}$$

II-Experiment with sub-100 mg masses



Peak due to gravitational coupling (12.7 mHz)

Gravitational non linearities (24.5 mHz)

- Long integration time (~ 13.5h)
- Insulation stage for seismic noise

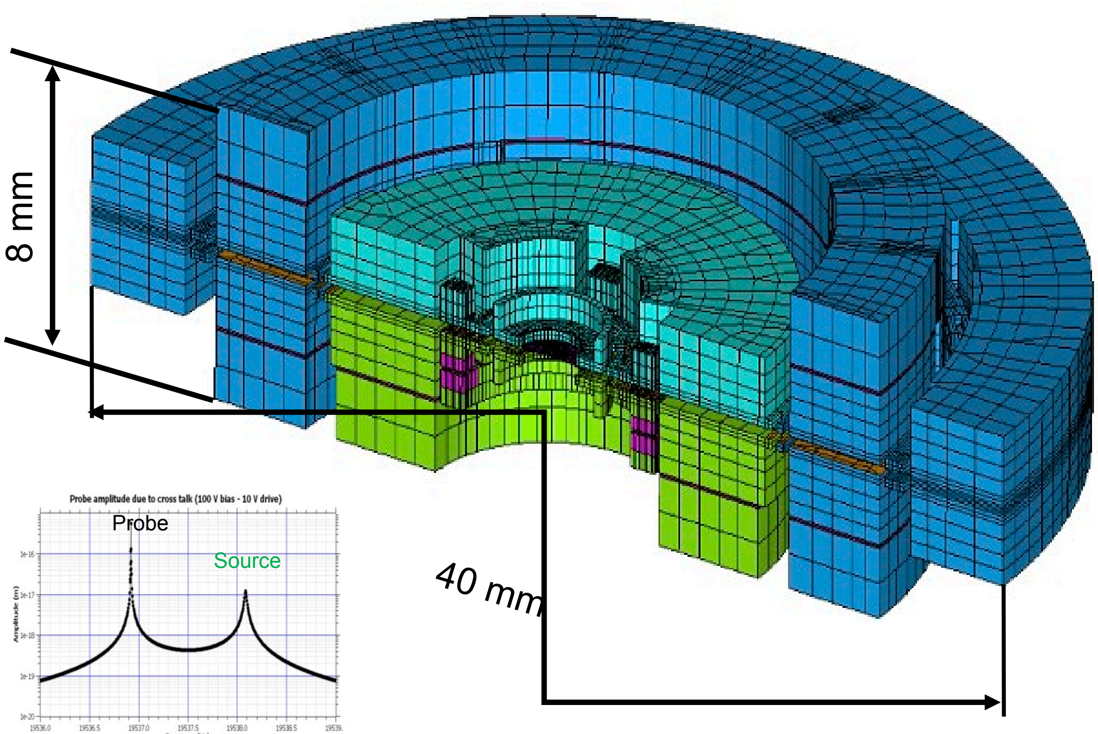
Possible improvements:

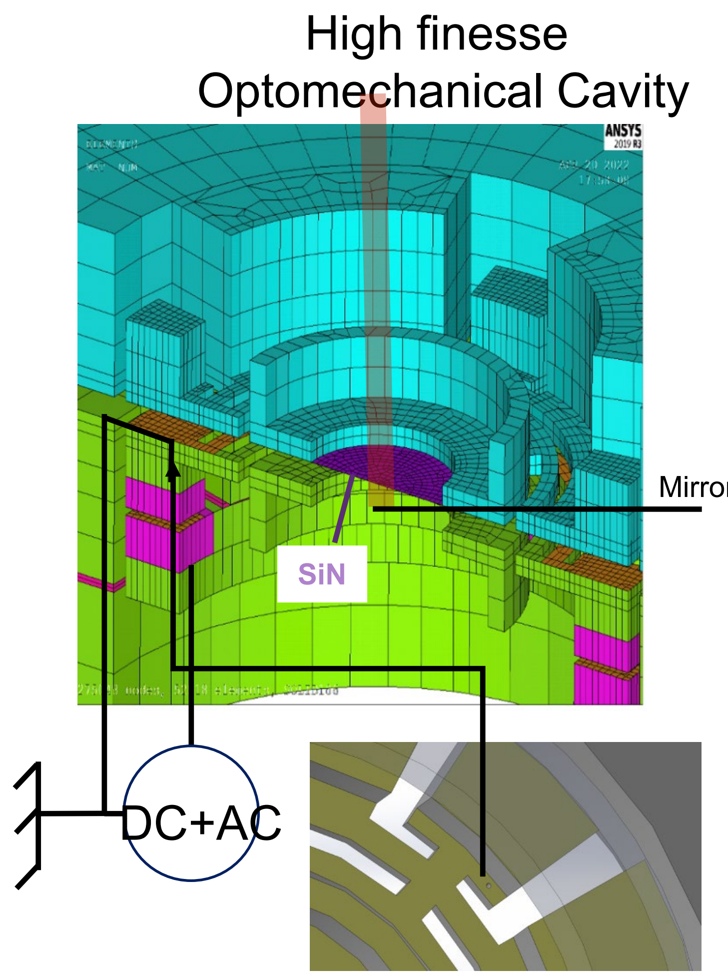
- High Q resonators
- Higher modulation frequency
- Ultracryogenic environment

GRAFIQO proposal

Resonant measurement of the **gravitational force between two mass Silicon "disk" resonators**; the probe mass is optically read via radiation pressure on a SiN membrane (purple)

		Source	*Probe*
massa sensibile (mg)	m_g		14.9 [a]
massa efficace (mg)	m_{eff}		37 [b]
fattore di qualità	Q	1×10^6 [c]	50×10^6 [d]
frequenza di risonanza (kHz)	$\Omega/2\pi$	20	20
temperatura (K)	T		0.02





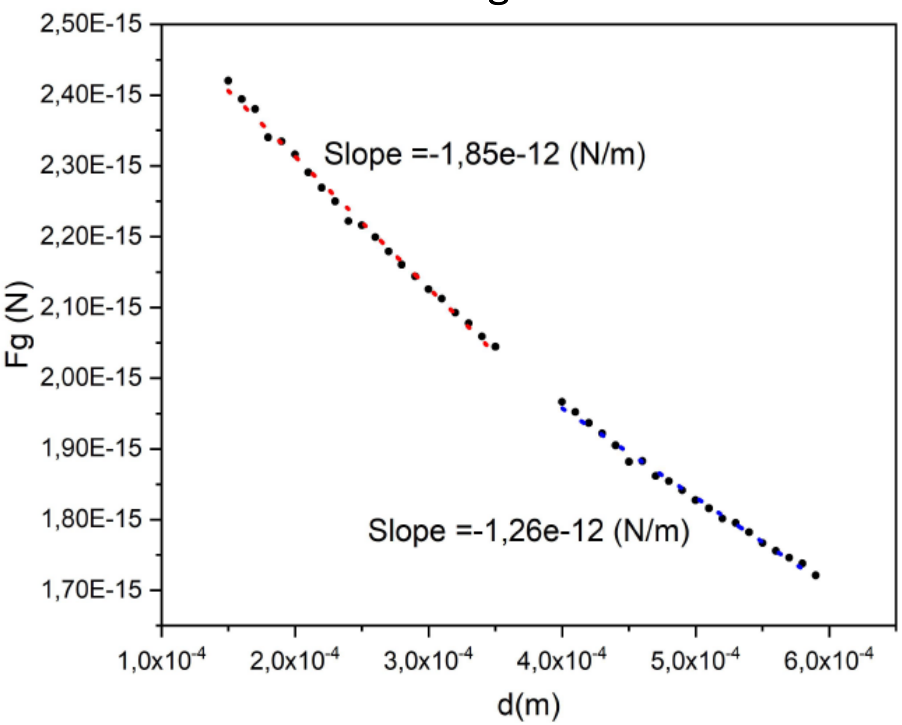
Metalized
Through Silicon Vias - TSVs
(VERTICAL INTER-CONNECTIONS)

GRAFIQO proposal II

	Source	Probe
Test mass (mg)	37	14,9
Quality factor	1×10^6	50×10^6
Resonance frequency (kHz)	20	20
Temperature (mK)	20	20

Source amplitude oscillation of 1 micron with 100 V bias and 10 V AC drive

FEM-evaluated gravitational force



$\Rightarrow$The gravitational force is $F_g = 1.8 \times 10^{-18}$ N (for source amplitude A = 1 micron)

$\Rightarrow$ probe displacement = 1.7×10^{-16} m

Thermal fluctuation peak at 20 mK

$S_{xx} = 3 \times 10^{-14}$ m/√Hz

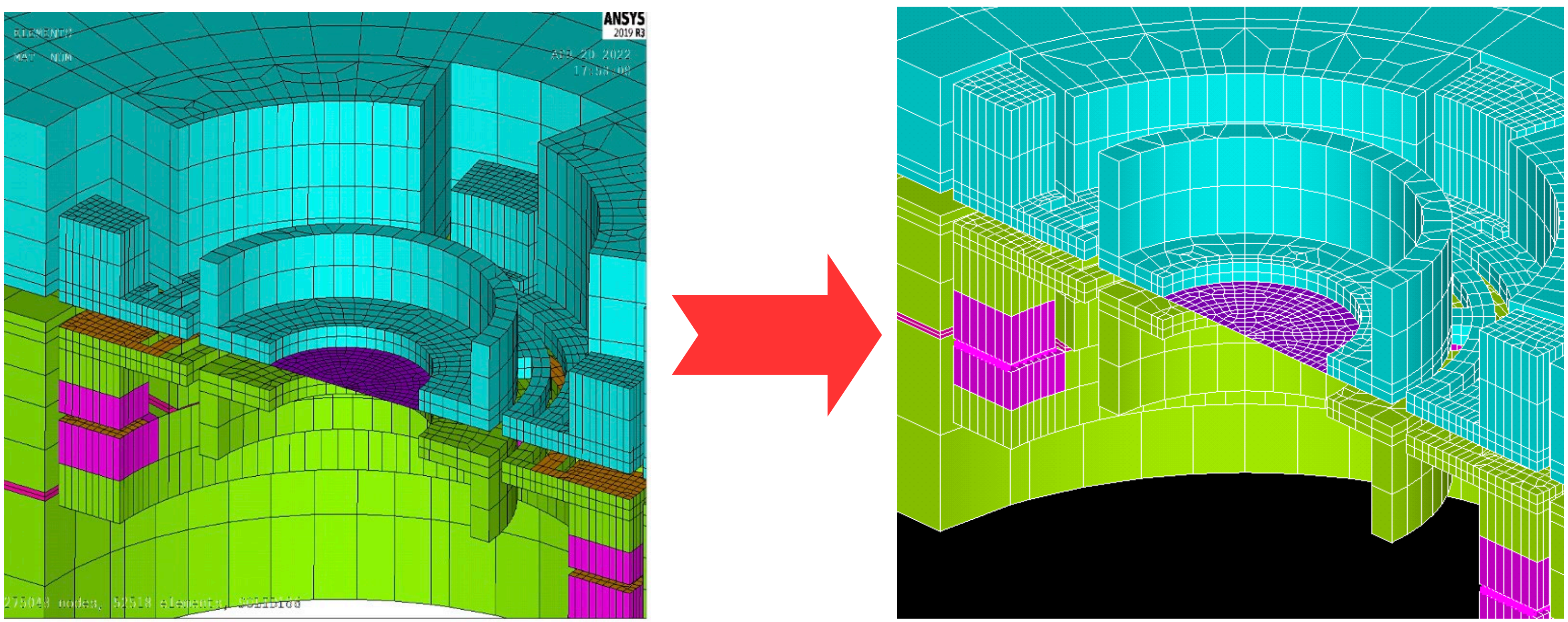
Integration time to get a unit SNR is 10^4 s

(may be smaller for larger A and shorter distance)

Improved source-probe design (2023)

Dopo le verifiche con il possibile produttore degli oscillatori in silicio, abbiamo fatto un primo giro di modifiche delle strutture per soddisfare I vincoli posti dai macchinari utilizzati.

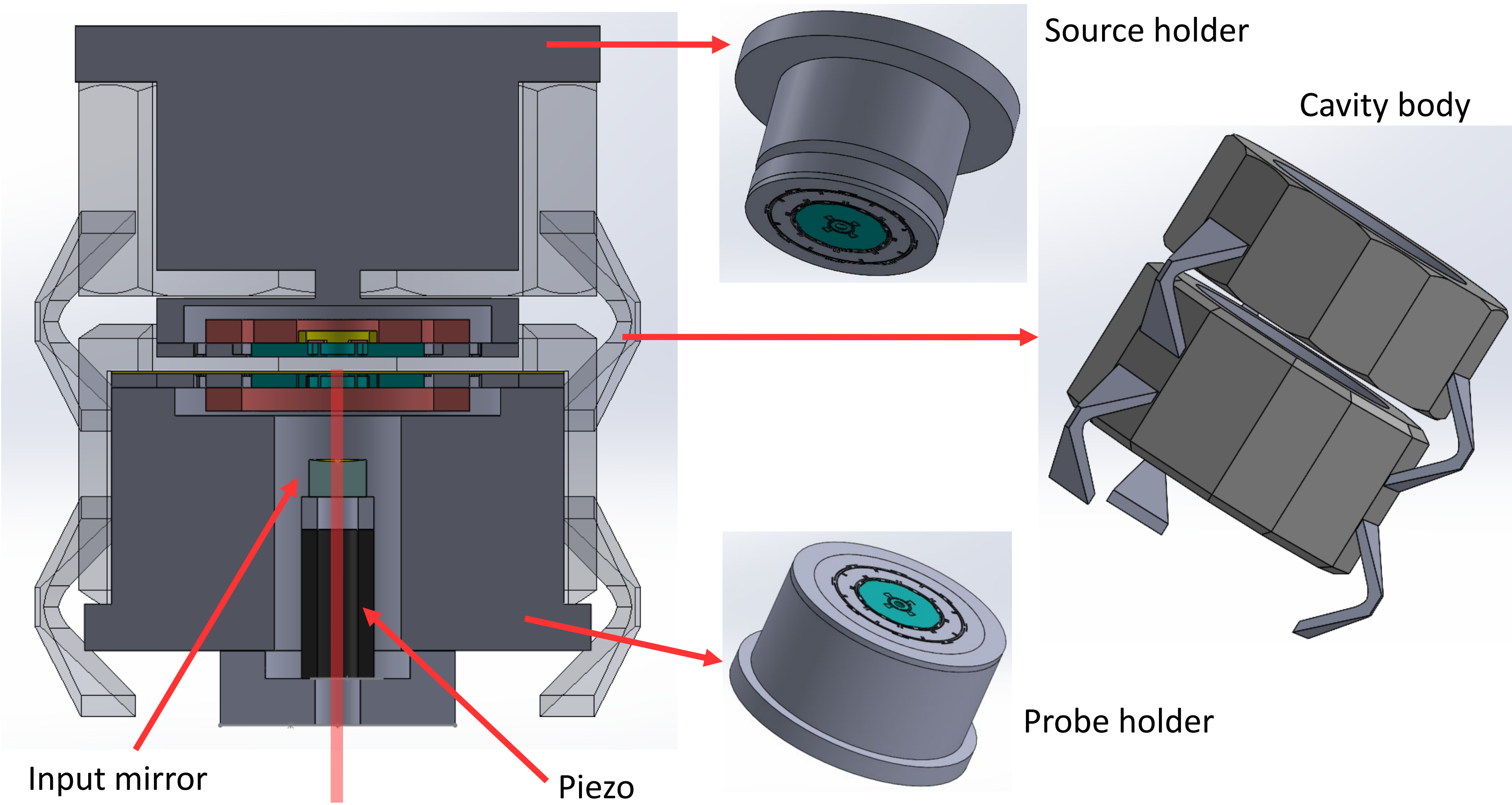
- Ridotto lo spessore complessivo da 2000 a 1500 micron e evitati scavi RIE con doppia profondità.
- Ripetute tutte le simulazioni FEM e verificato che il disegno attuale conserva le prestazioni e gli aspetti critici della proposta originale



Cavity design I (2023)

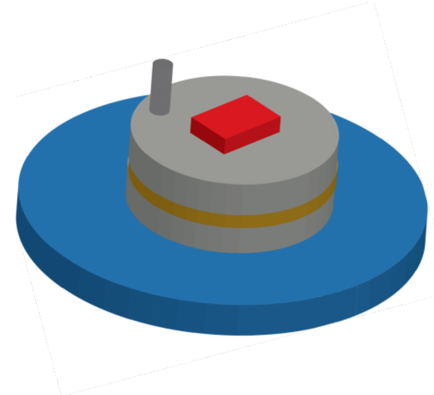
Lavoro preliminare necessario per definire le misure dei device e iniziare la produzione

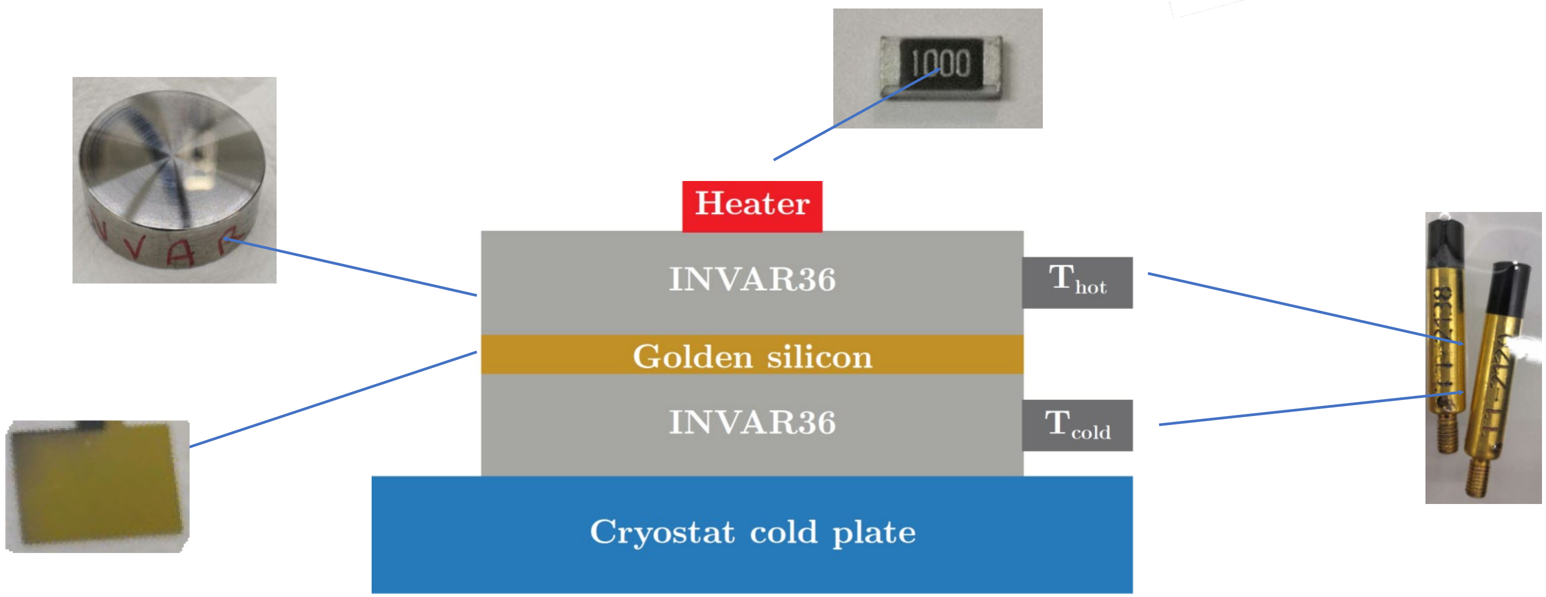
- Disegnata una prima versione di cavità da validare a livello di configurazione ottica e termica.
- Misure di conducibilità su contatti metallo/silicio a Camerino.



Thermal Conductivity Measurement

1. **Design of the system for the measurement of the thermal conductivity of Si-elements with golden coating:** measurement needed for estimating the thermal gradient and inferring the effective oscillators temperature.





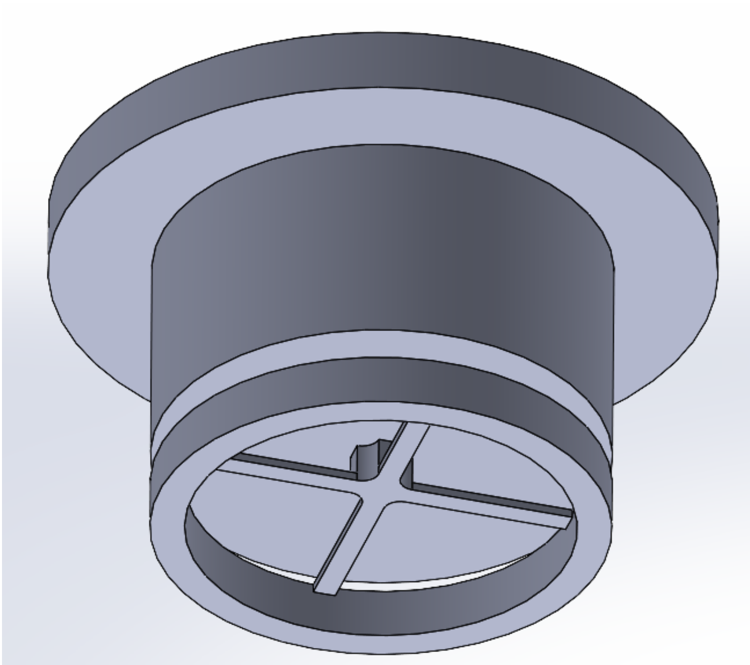
2. System assembled and ready for test.

Cavity design III (2023)

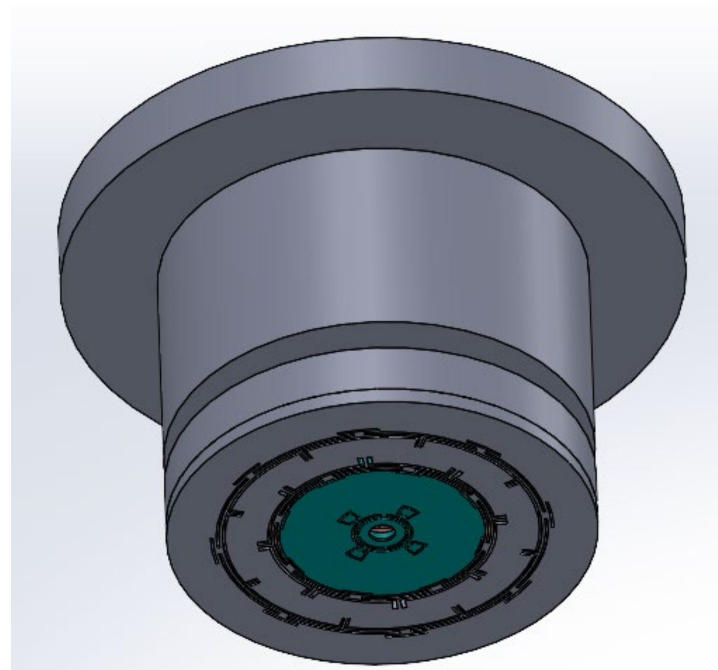
La struttura della cavità permette di ottenere **la reiezione meccanica necessaria** per l'esperimento grazie ad un filtro meccanico aggiunto nel supporto del source.

Questo disegno preliminare permette di migliorare la reiezione di un fattore 100 (obiettivo CDR). Stiamo lavorando per migliorare di un ulteriore fattore 10 di sicurezza.

NB: il supporto del source deve soddisfare requisiti meno stringenti per la termalizzazione, dato che l'oscillazione di drive è molto maggiore del suo termico. Questo permette maggiore flessibilità di design.



Source Holder

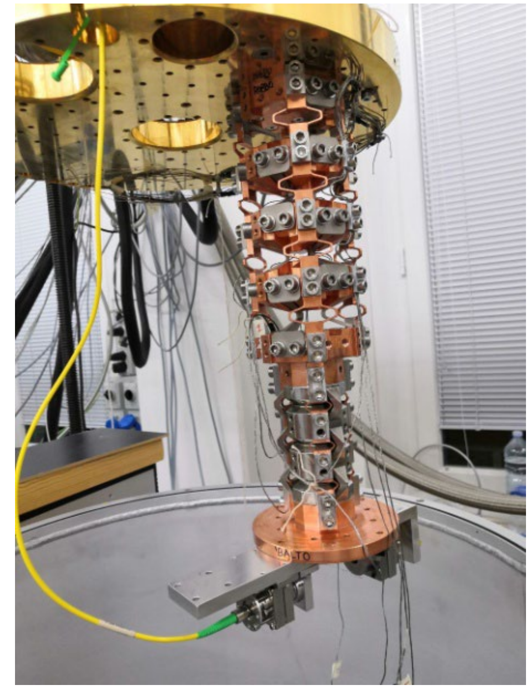


Con Source montato

Background noise

1. **Reduction of background noise floor I:** reducing **mechanical vibration and acoustic noise** with suspension system (good preliminary results)

2. **Reduction of background noise floor II:** **Laser frequency noise** below 0.01 Hz/√Hz. It can be done via active stabilization on an external cavity (ex. Auriga)



466 J. Opt. Soc. Am. B/Vol. 20, No. 3/March 2003

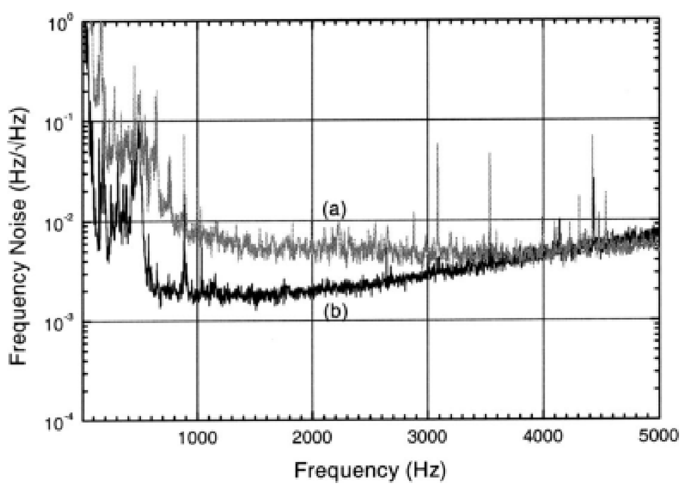
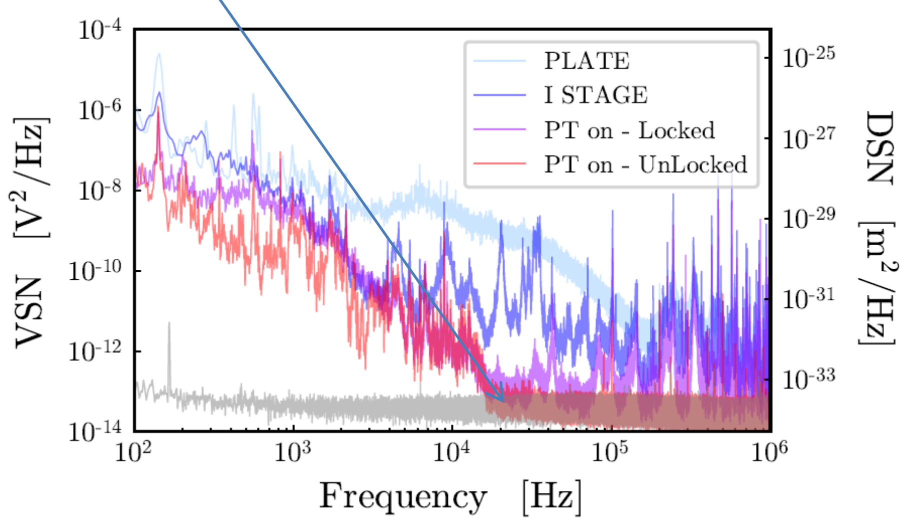
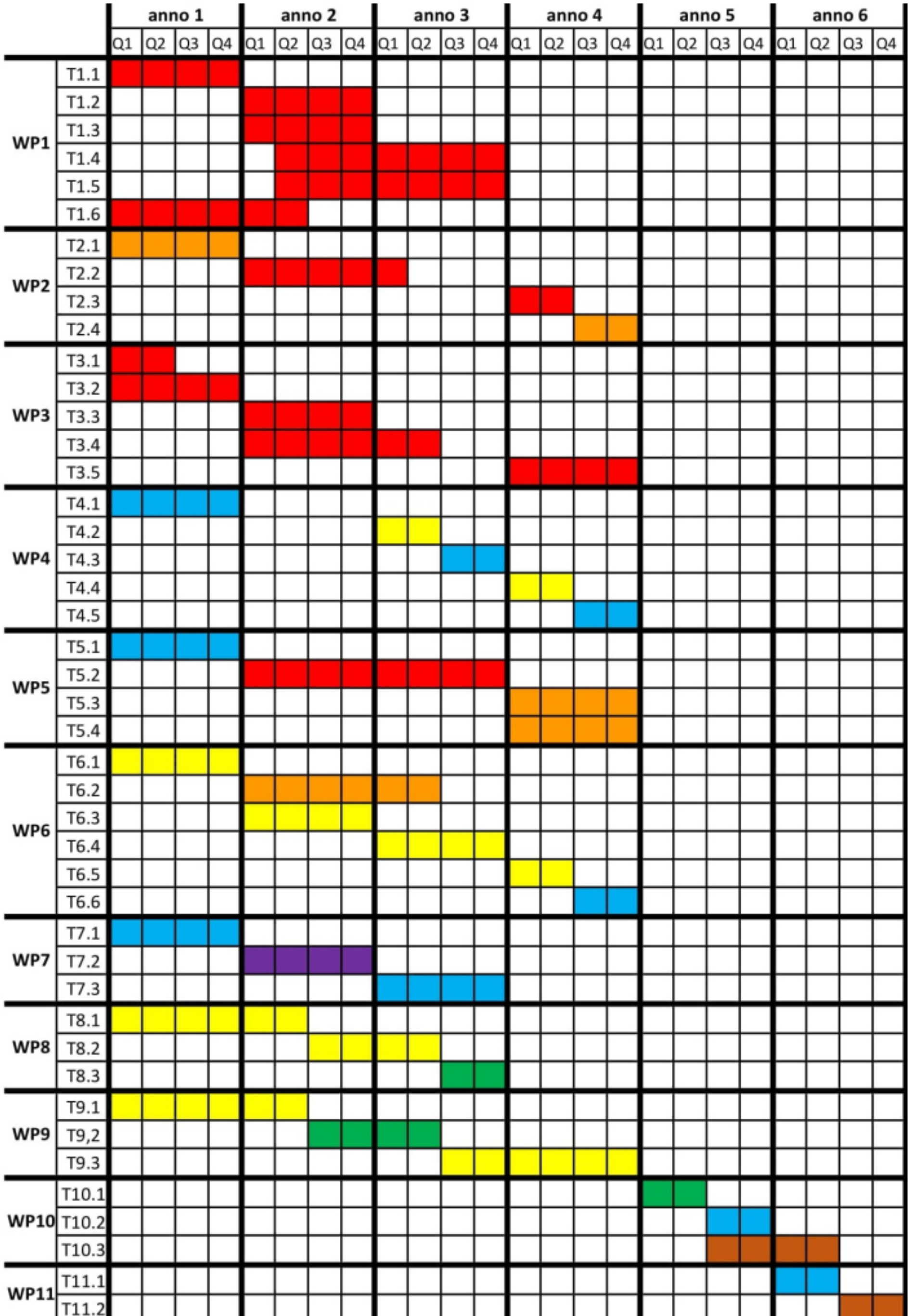


Fig. 7. (a) Frequency noise of the laser after passage through the single-mode optical fiber. (b) Lower limit to the frequency fluctuations (see text). Frequency resolution, 2 Hz.





TIFPA: progettazione e costruzione micro-oscillatori

Firenze: progettazione e test ottiche

Perugia (Camerino): ultra-criogenia

Ordine di grandezza della richiesta 600 k totali

2024: Totale: ~ 100 k (60 k nanofab)

PG: ~ 15 k (LN, Ottiche, Pompe vuoto) + missioni

Sez. Firenze: Responsabile nazionale e locale: Francesco Marin 2.1 FTE

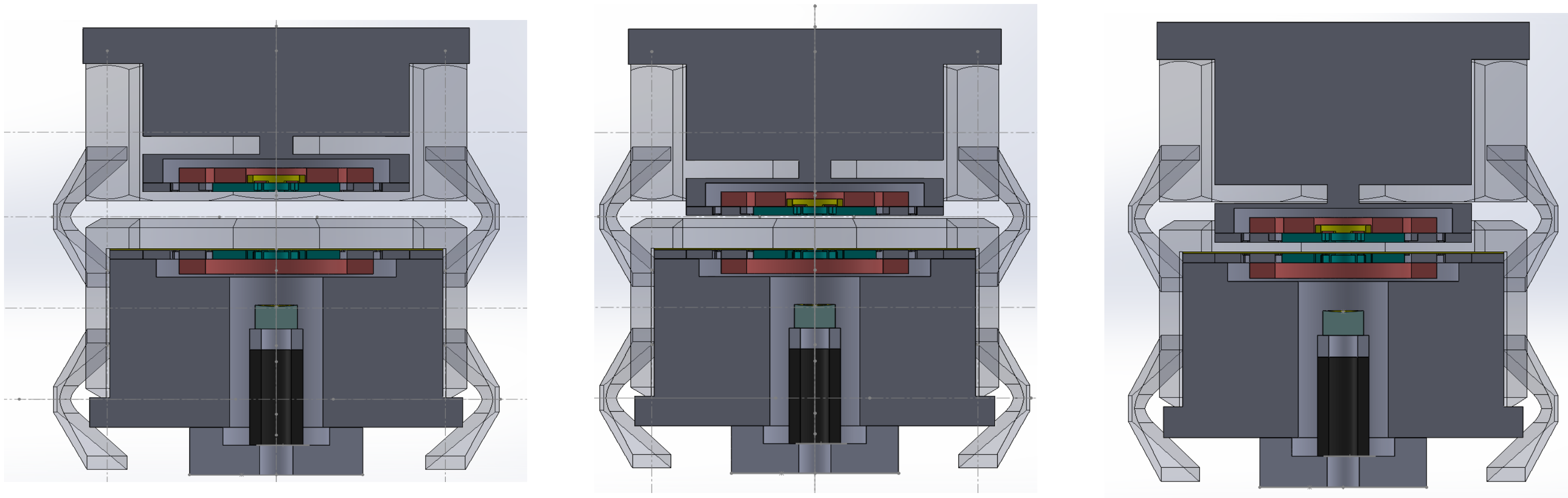
Sez. Perugia: Responsabile locale: David Vitali 5.6 FTE

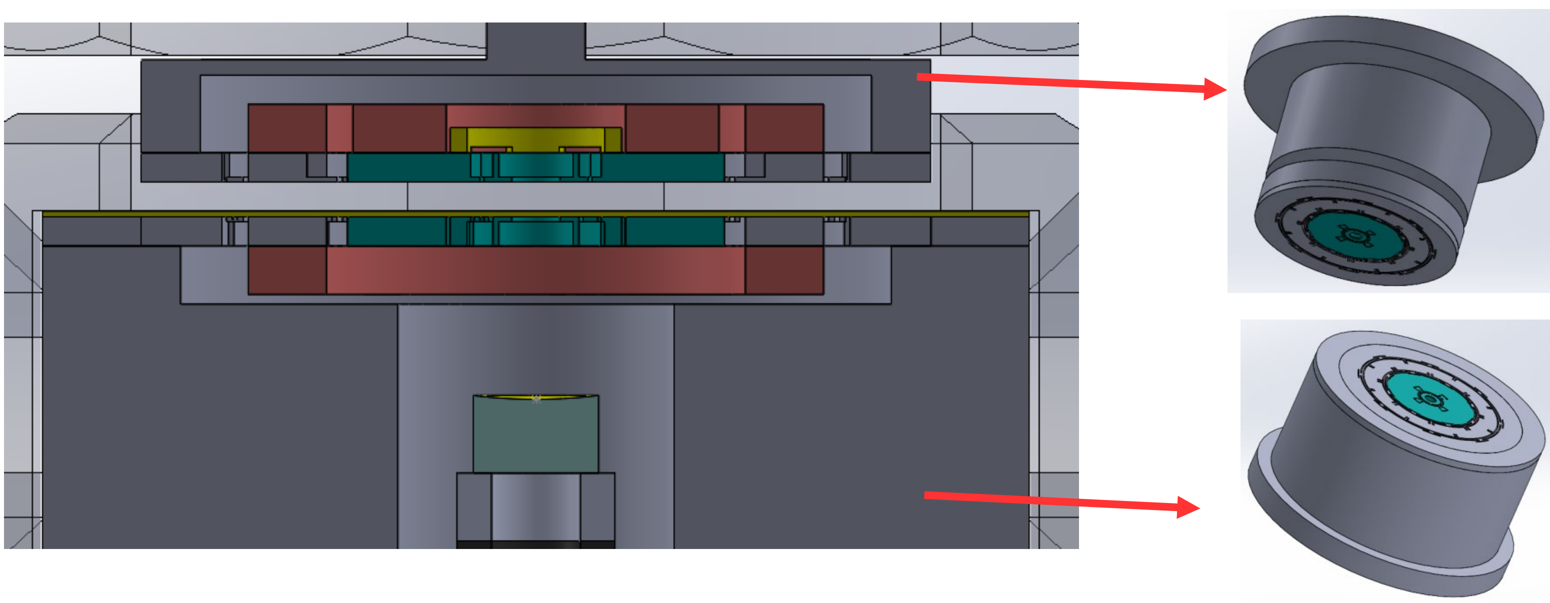
TIFPA: Responsabile locale: Enrico Serra 2 FTE

SLIDES AGGIUNTIVE

Cavity design II (2023)

La lunghezza del Source Holder definisce la distanza tra i due oscillatori (futura movimentazione?)



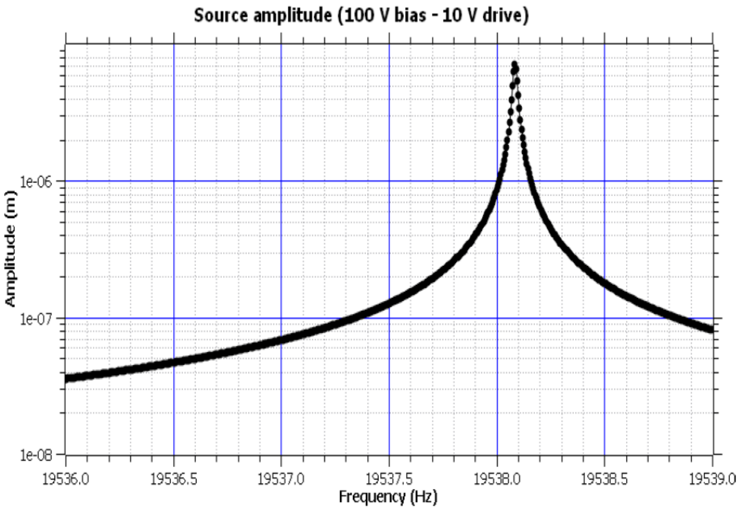


Source holder

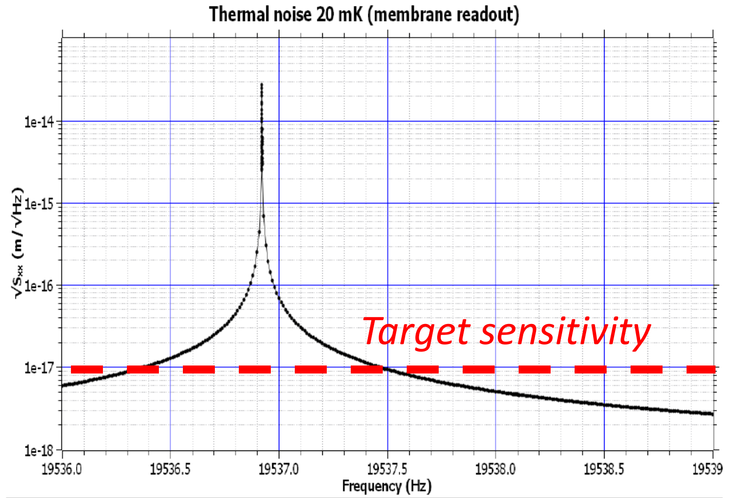
Probe holder

CRITICAL POINTS-I: Tuning

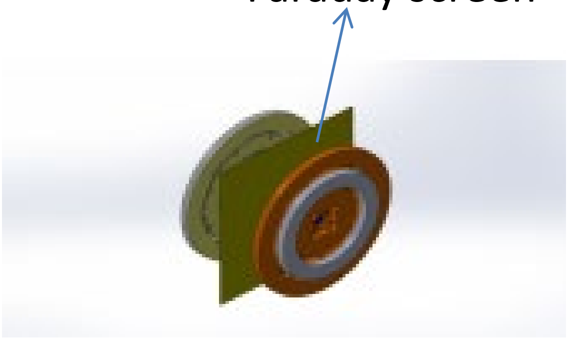
1. **Source and probe must be resonant:** suppress fabrication imperfections (order of few Hz) as much as possible. Post-production **Fine Tuning is possible** via the optical spring effect (adjusting power and cavity detuning) and/or adjusting V_{bias}



2. **Si resonator are mechanically stable** (Allan variance below 10^{-9}).
   The source drive and source resonator will be locked.

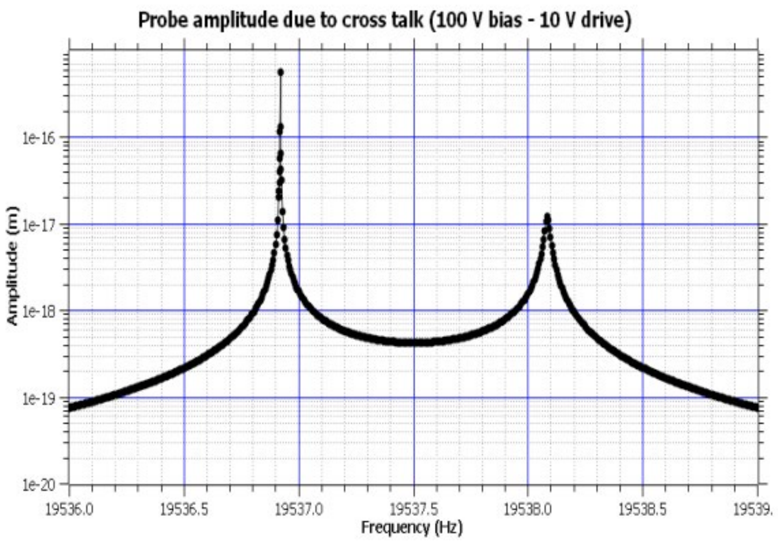


CRITICAL POINTS-II: Spurious signals



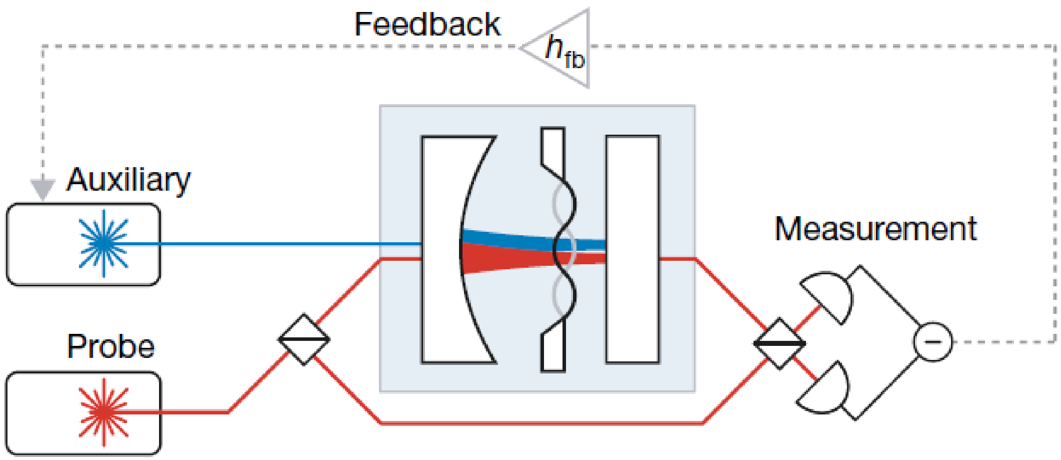
1. **Electrostatic interaction must be screened** via Faraday screen. The gravitational force is equivalent to 400 e-charges. UV discharge will also be used (on SiN membranes we have measured about 10^5 e-charges)

2. **Mechanical cross-talk must be suppressed**. We measured 10^8 rejection ratio in the worst case of fully joint resonator. A further 10^2 increase is needed, achievable with mechanical filters



Measurement in the quantum regime (final part of the project)

The only additional ingredient is to use **measurement-feedback cooling** to reach the **quantum ground state** (already demonstrated on SiN membranes), using the **homodyne readout of the optical cavity** and using an actuator (modulated radiation pressure force)



M. Rossi et al., Nature 563, 53 (2018)

The thermal peak is lowered and broadened, and the target floor sensitivity (background noise) must be improved by one order of magnitude to 10^{-18} m/√Hz