Measuring the weight of quantum vacuum with Archimedes experiment

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Scientific motivation: Quantum Vacuum and Gravity

Archimedes and the cosmological constant problem

In QED, EM field is expressed in terms of creation and annihilation operators, and the expectation value of the EM field energy density $\mathcal{H}$ on the vacuum state is infinite:

$$\boxed{\langle 0|\mathcal{H}|0\rangle = \sum_{\lambda}\int \frac{d^3k}{4(2\pi)^3}\langle 0|[a^{(\lambda)}(k)a^{(\lambda)\dagger}(k) + a^{(\lambda)\dagger}(k)a^{(\lambda)}(k)]\,|0\rangle \to \infty}$$

Scientific motivation: Quantum Vacuum and Gravity

- In **QED** the normal-ordering of operators is introduced to re-define vacuum state as the state of zero-energy, and compute energy variations between states (although if the zero-point energy changes, it is also observable at a macroscopic level → ***Casimir effect***!)

- Differently from QFT, **General Relativity** is sensitive to the absolute value of the energy. Zero-point energy could be accounted for in Einstein's equations as a cosmological constant term:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Scientific motivation: Quantum Vacuum and Gravity

The cosmological constant problem [Weinberg, 1989]

Summing up all the zero-point EM modes up to a cut-off (Planck scale) and inserting the value of the energy density in the static Eisntein solution, takes to a disagreement of 120 orders of magnitude with respect to observations

The expected radius of the Universe was 31 Km!

"The largest discrepancy between theory and experiment in all of science"
"The worst theoretical prediction in the history of Physics"

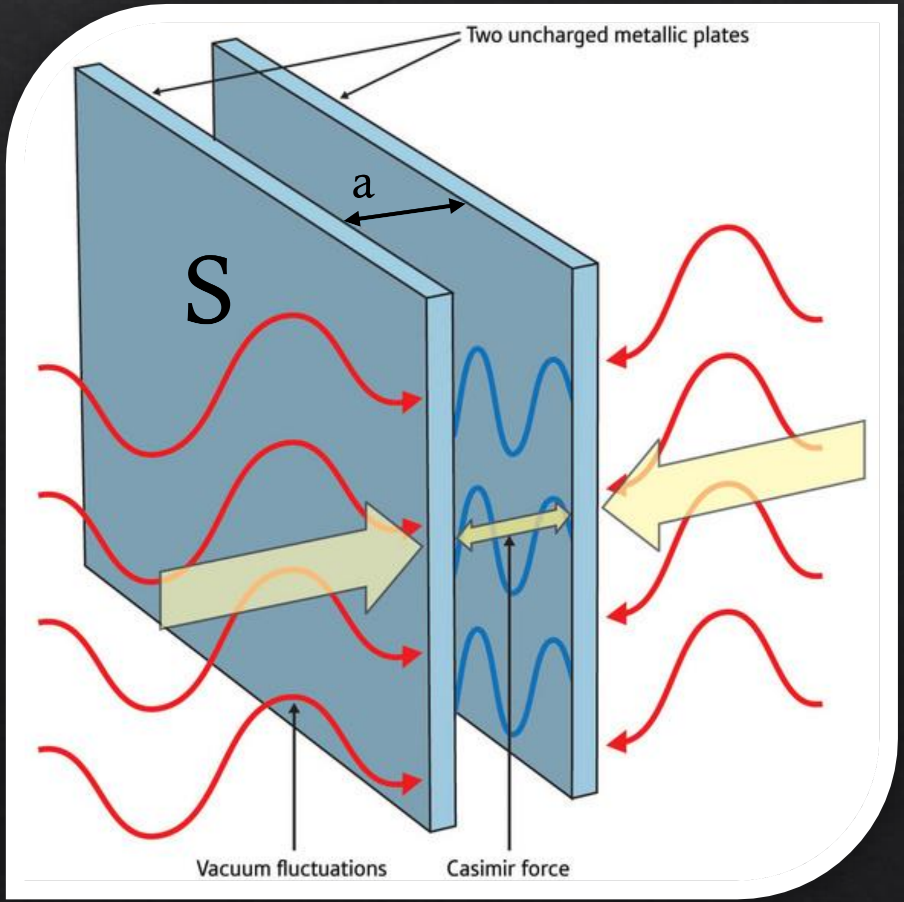
Macroscopic evidence of zero-point energy: Casimir effect

If boundary conditions for zero-point EM field change, we can't get rid of the zero-point infinite energy, not even in QFT → Casimir effect

$$E_{reflective\ plates} - E_{empty} \equiv \mathcal{E}_{\mathrm{cas}} = -\frac{\pi^2}{720}\frac{\hbar c}{a^3}S$$

The difference of zero-point energy due to the presence of the metallic plates gives rise to a negative energy

Vacuum energy inside the cavity is less when plates are reflective.



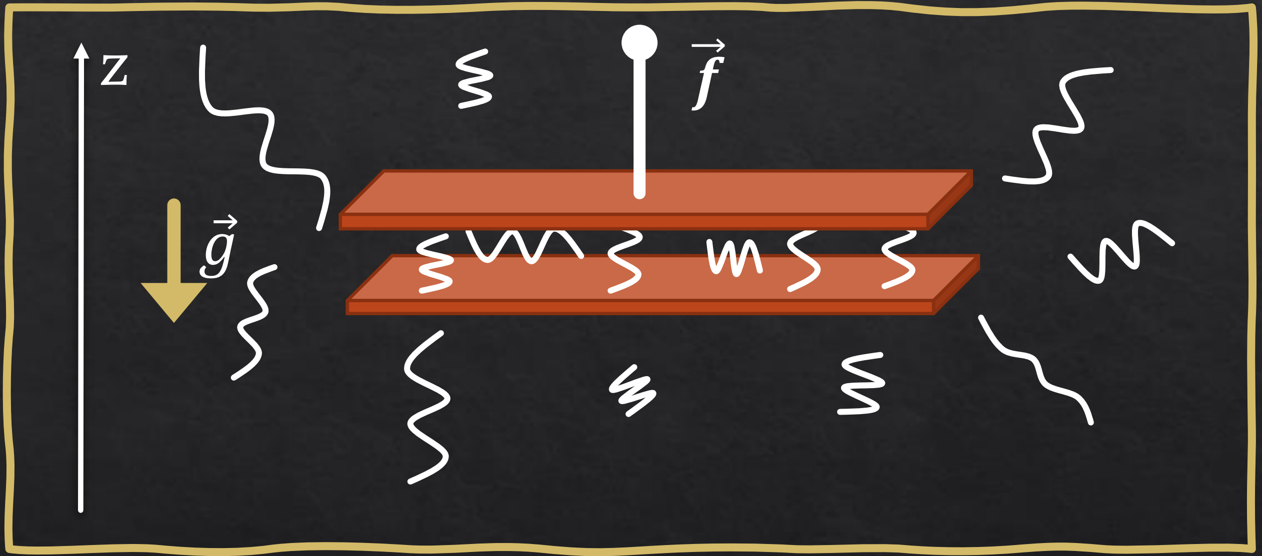
tipically a~1 μm, S~1cm² → $\mathcal{E}_{\mathrm{cas}}$~40 fJ, $F_{\mathrm{cas}}\sim 10^{-7}$ N

Casimir cavity in the Gravitational Field

Weigh a **rigid** Casimir cavity

$$\vec{f} = \frac{|\mathbf{E_C}|}{\mathbf{c^2}}\,\mathbf{g}\,\hat{\mathbf{z}}$$

The total force is directed **upward** and it is equal to the weight of the vacuum modes that are removed from the cavity



The force that keeps an extended body suspended in a gravitational field depends on its internal energy $\rightarrow \vec{f}$ depends on the vacuum energy inside the Casimir cavity

[G.Bimonte, E. Calloni, G. Esposito, L. Rosa - Phys. Rev D 76:025008 (2007)]

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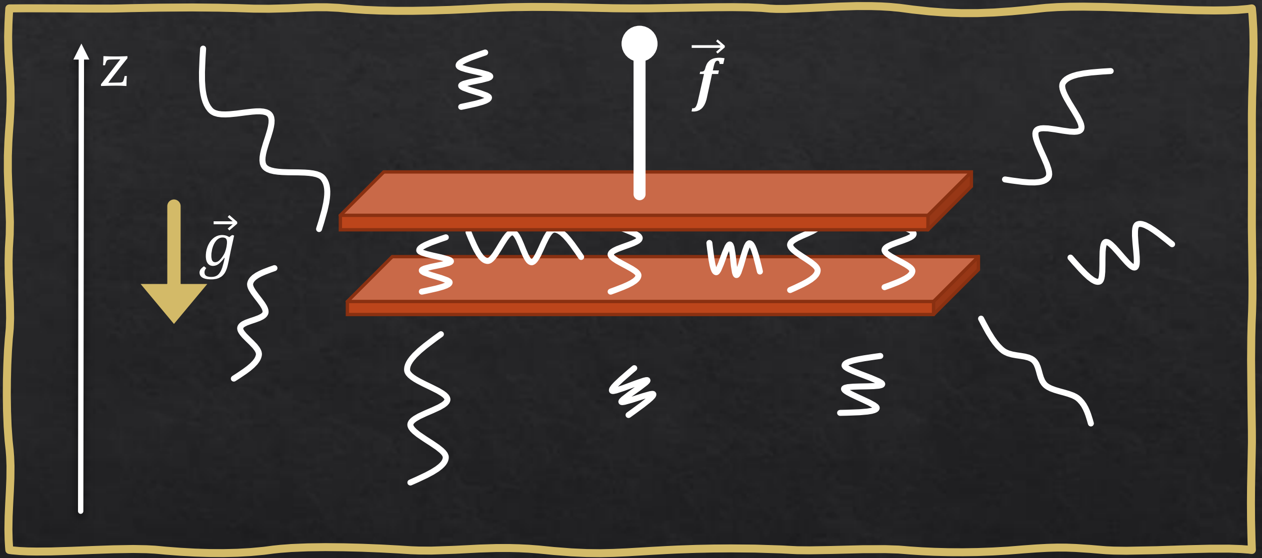


The cavity *immersed in the vacuum* is subjected to an upwards force equal to the *weight of the displaced vacuum* – **Archimedes "buoyancy of vacuum"**

[G.Bimonte, E. Calloni, G. Esposito, L. Rosa - Phys. Rev D 76:025008 (2007)]

How to measure it?

1. Modulate the reflectivity of the Casimir plates to modulate vacuum modes inside it. In this way, a possible weight variation can be detected at the modulation frequency

2. Build a very sensitive balance to «weigh the vacuum»

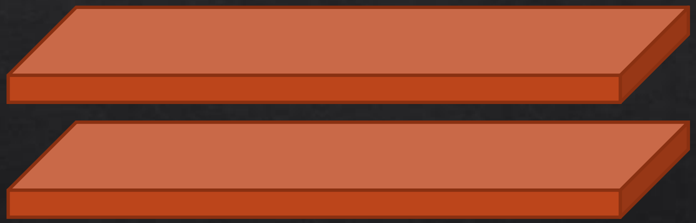
3. Suspend samples of «Casimir cavity» to the balance arm

Casimir cavity with superconductors

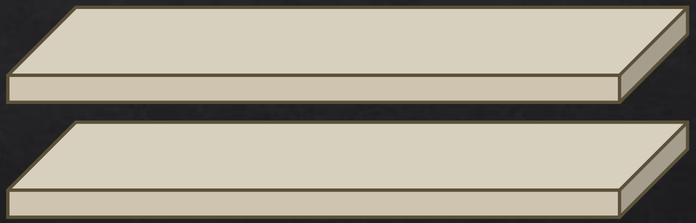
Cavities with tunable reflectivity: superconductors!

Reflectivity can be changed by switching into superconductive phase

Plates at **superconductive** state: Casimir cavity, "less" zero-point EM modes because of boundary conditions



Plates at **normal** state: transparent cavity, all EM modes allowed



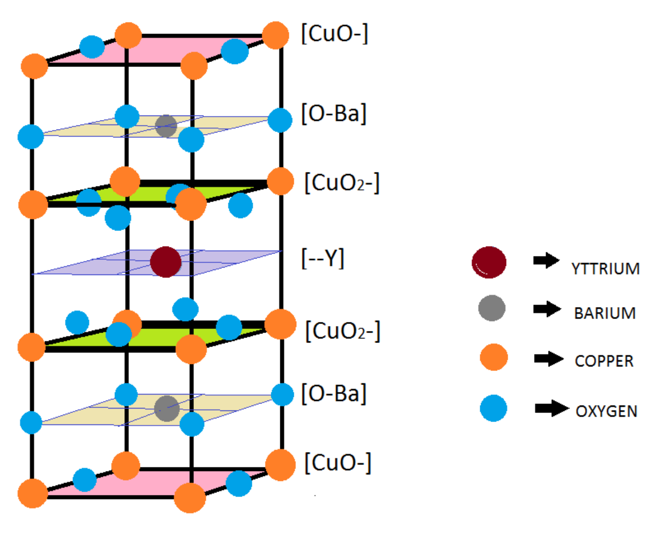
Modulating the samples temperature (and superconductivity) the "amount of vacuum" inside the cavities is modulated, and possibly the total weight

Casimir cavities with type II superconductors

High-Tc superconductors

Some crystals (i.e. YBCO) are natural multilayered Casimir cavities

for YBCO: $T_c \simeq 92$ K, $\frac{\Delta\mathcal{E}_{\text{cas}}}{\mathcal{E}_{\text{cas}}} \simeq 10^{-4}$

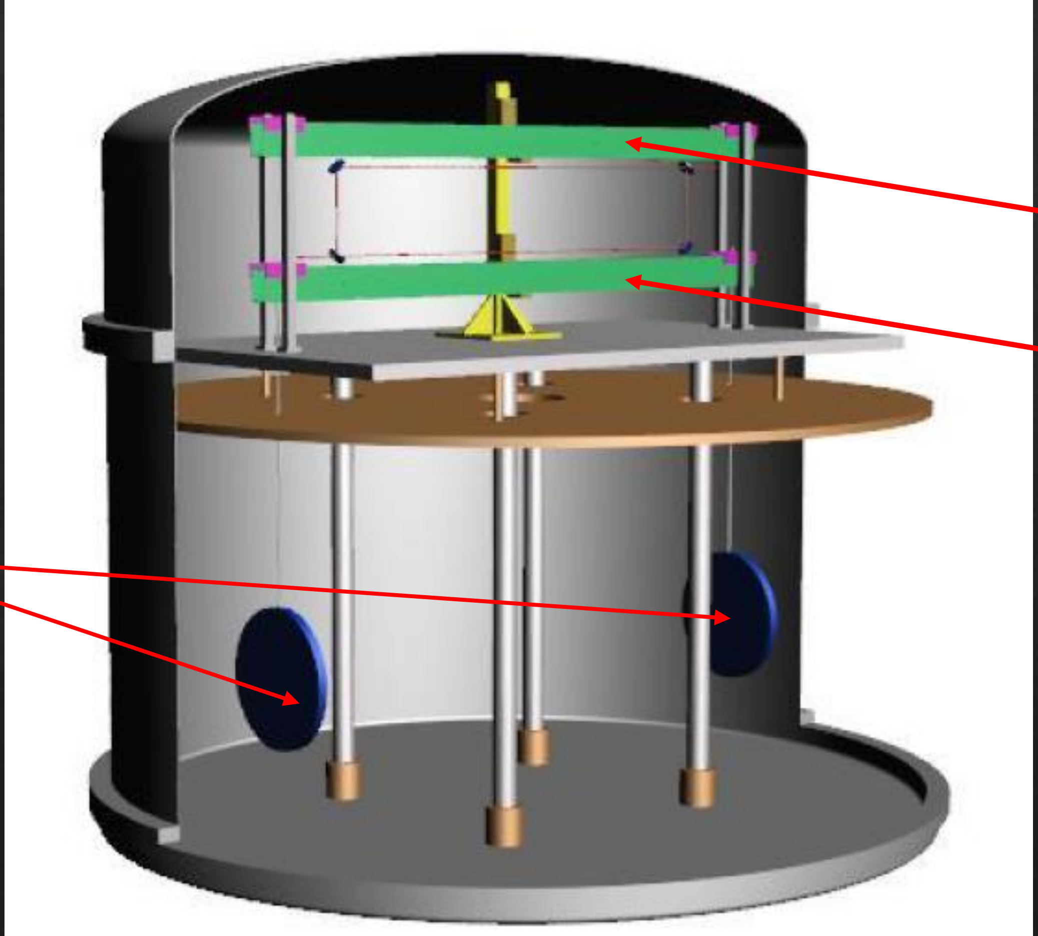


For a disk-shaped YBCO with R = 5 cm, thickness 5 mm

$$\boxed{|\vec{F}| \simeq 5 \cdot 10^{-16}\ \text{N}}$$

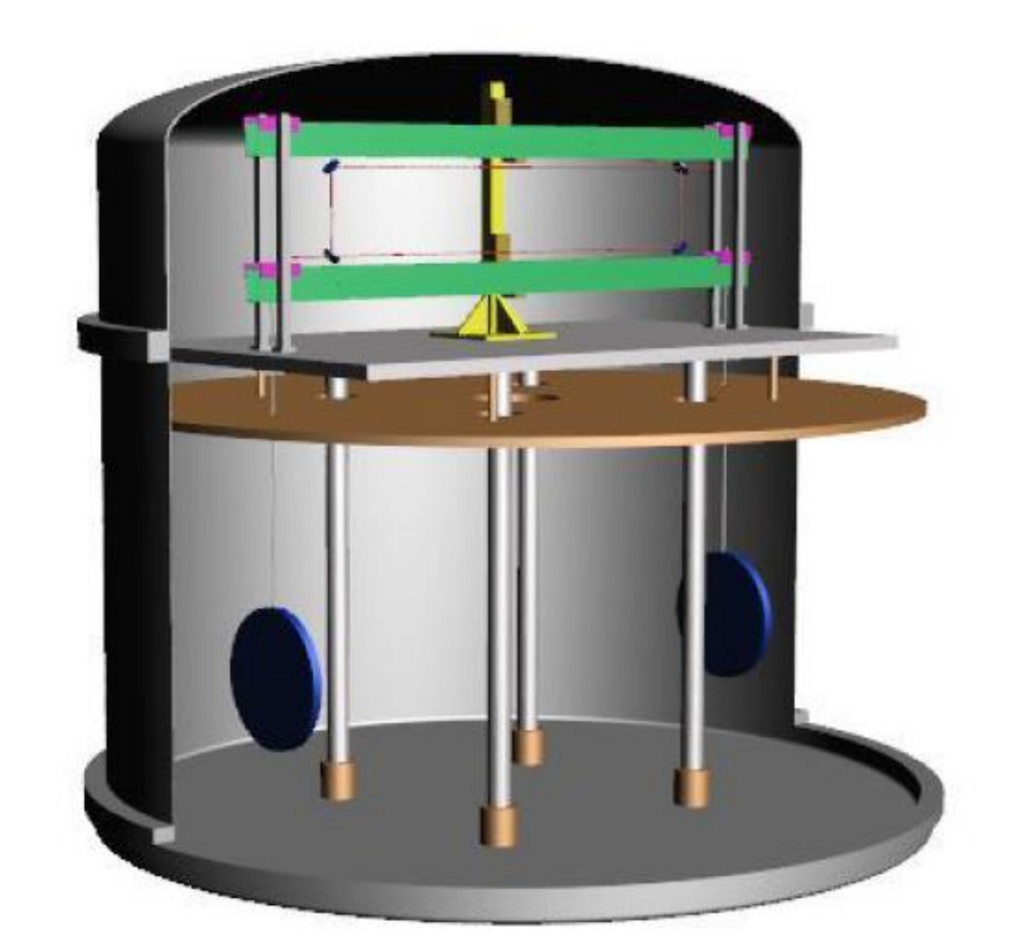
You need a very sensitive balance to detect such weight variations…

Archimedes beam-balance



Archimedes beam-balance

- High-Tc multilayered superconductor (YBCO) as natural Casimir cavities
- Relative tilt of the arms for coherent noise subtraction
- Interferometric read-out
- Feedback control at low frequencies
- High vacuum (10^{-6} mbar) and cryogenic (T~ 92 K) measurements
- Modulation via thermal actuators
- Low seismic noise site

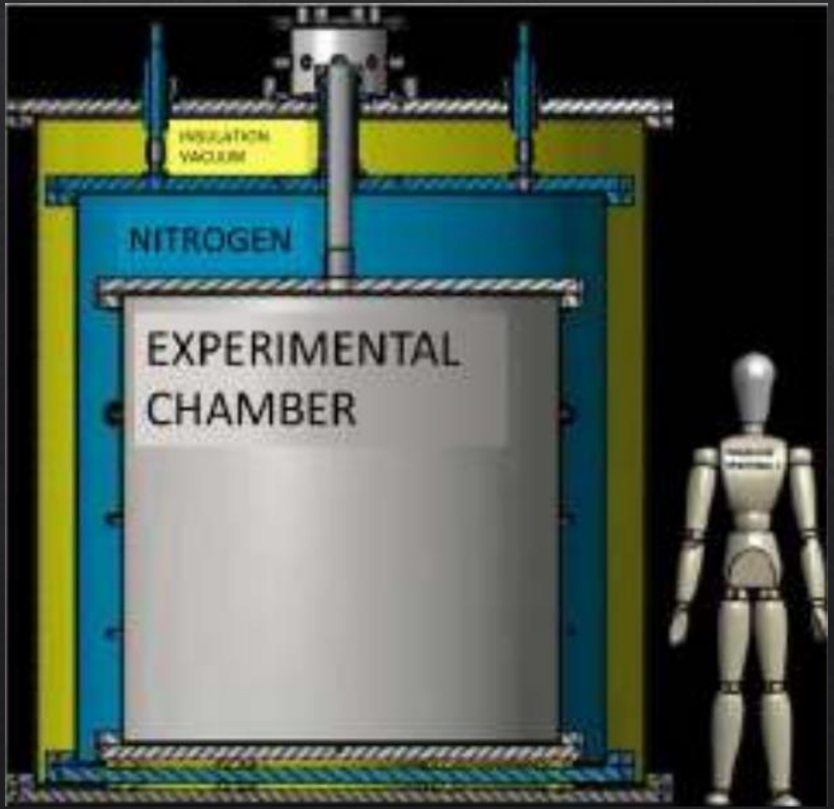


Expected modulation force:
$F = 4 * 10^{-16} N$

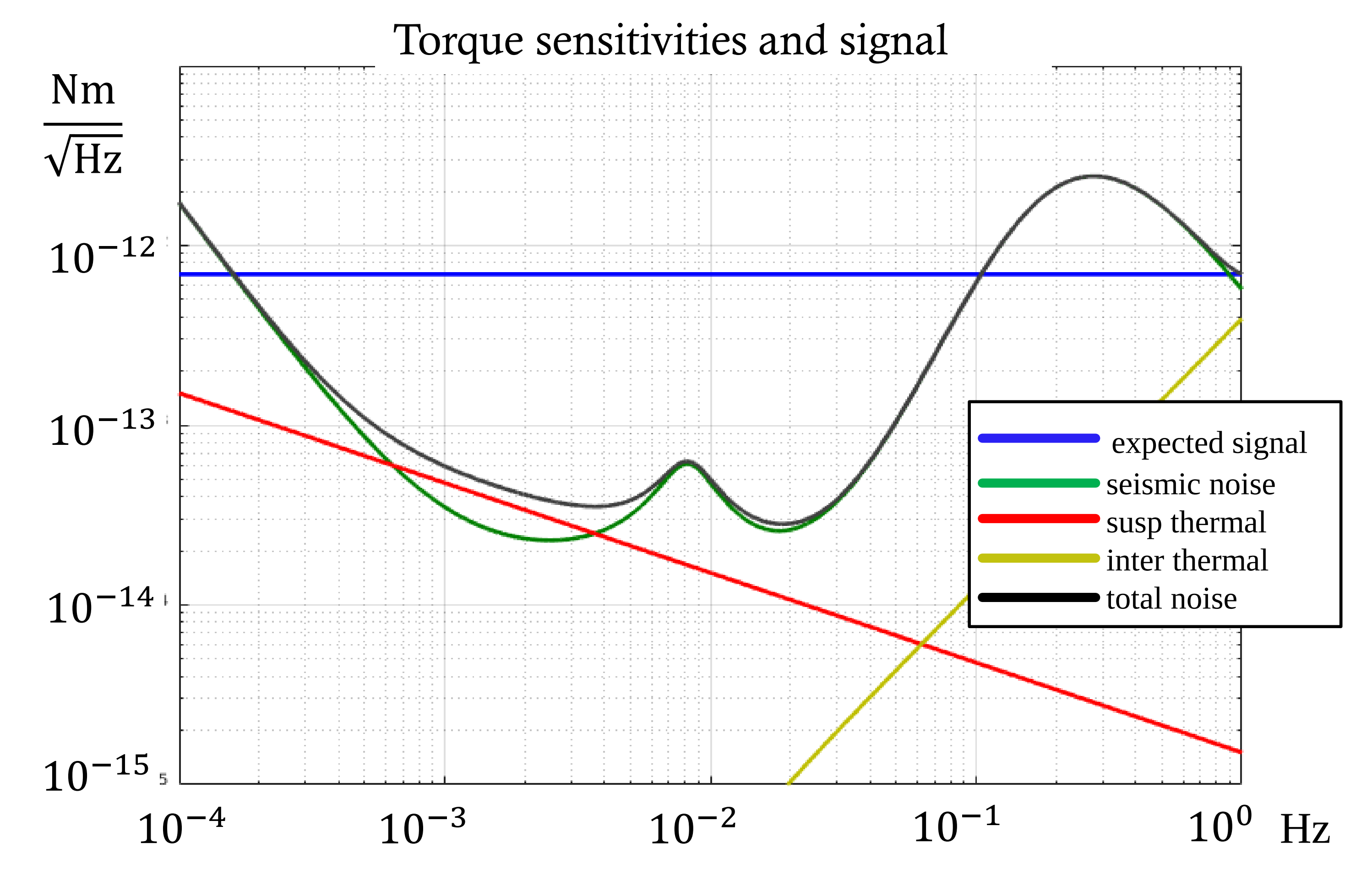
Archimedes beam-balance

The whole experiment will be cooled down at 90K to stay close to YBCO superconductive transition temperature, so it will be contained in 3-chambers cryostat.

→ One of the biggest opto-mechanical cryogenic experiments in Europe! The same technology will be exploited for 3rd generation GW detector, Einstein Telescope



Expected torque sensitivity (1.4 m arm)



$$|\vec{F}| \simeq 5 \cdot 10^{-16}\ \mathrm{N}$$

Total arm-length: 1.4 m

$$|\vec{\tau}| = |\vec{F}| \cdot 0.7\ \mathrm{m}$$
$$\simeq 3.5 \cdot 10^{-16}\ \mathrm{Nm}$$

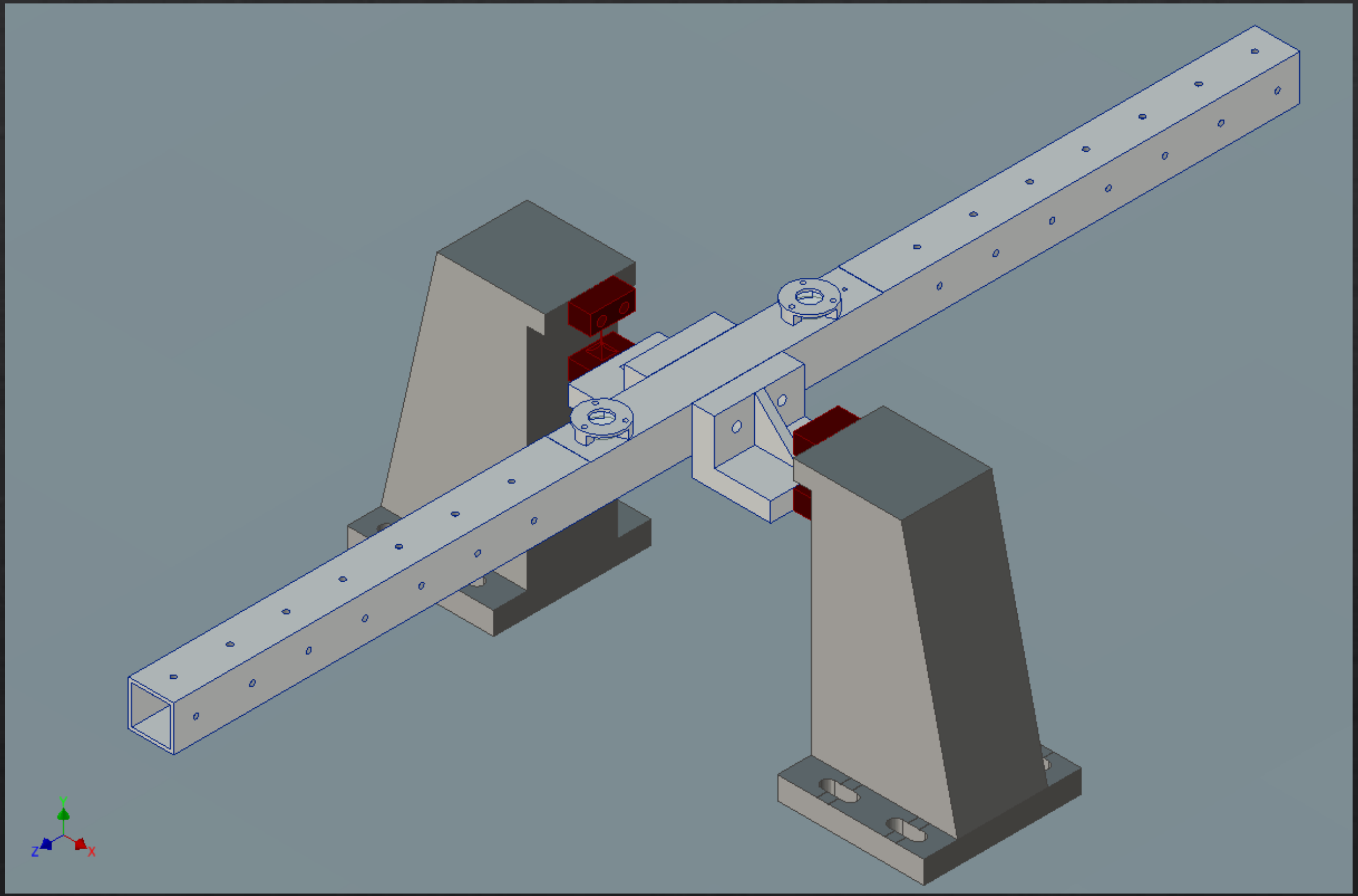
Integration time: 10^6 s (~ two weeks)

Spectral torque signal:

$$\tau_s = 3.5 \cdot 10^{-13}\ \frac{\mathrm{Nm}}{\sqrt{\mathrm{Hz}}}$$

The balance prototype

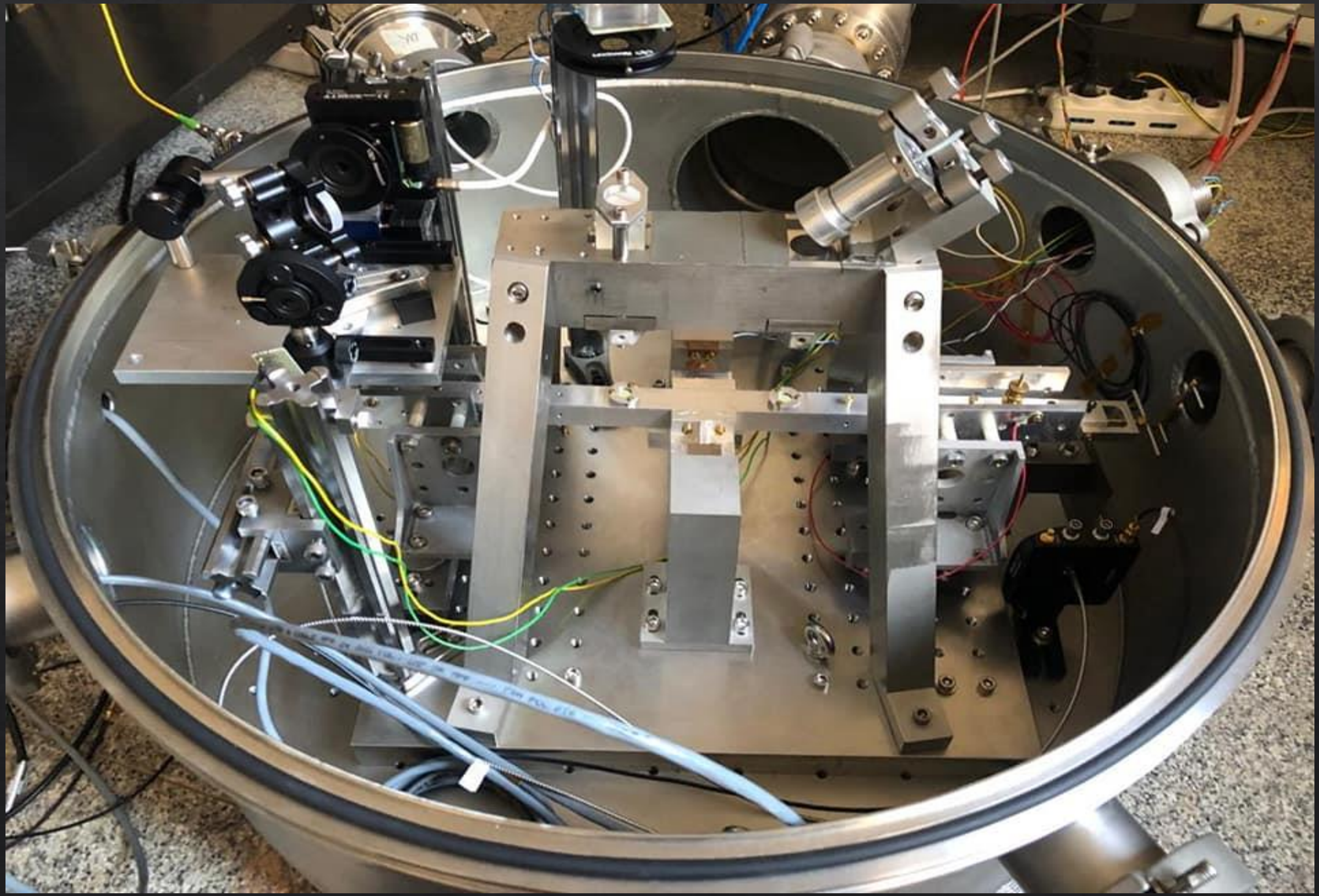
- 50 cm long arm with low momentum of inertia
- Suspended through **thin flexible joints** (Cu-Be, 100 µm x 500 µm), very similar in design to LIGO tiltmeters (Venkateswara et al., 2014)
- The balance **center of mass** is positioned **as close as possible to the bending point** ($\approx 10\ \mu m$) to minimize couplings with ground motion
- Depending on the center of mass positioning, its **resonance frequency** is around **20-30 mHz**



The balance prototype

Installed at the Sar-Grav surface laboratories in Lula (NU) –

Sos-Enattos mine

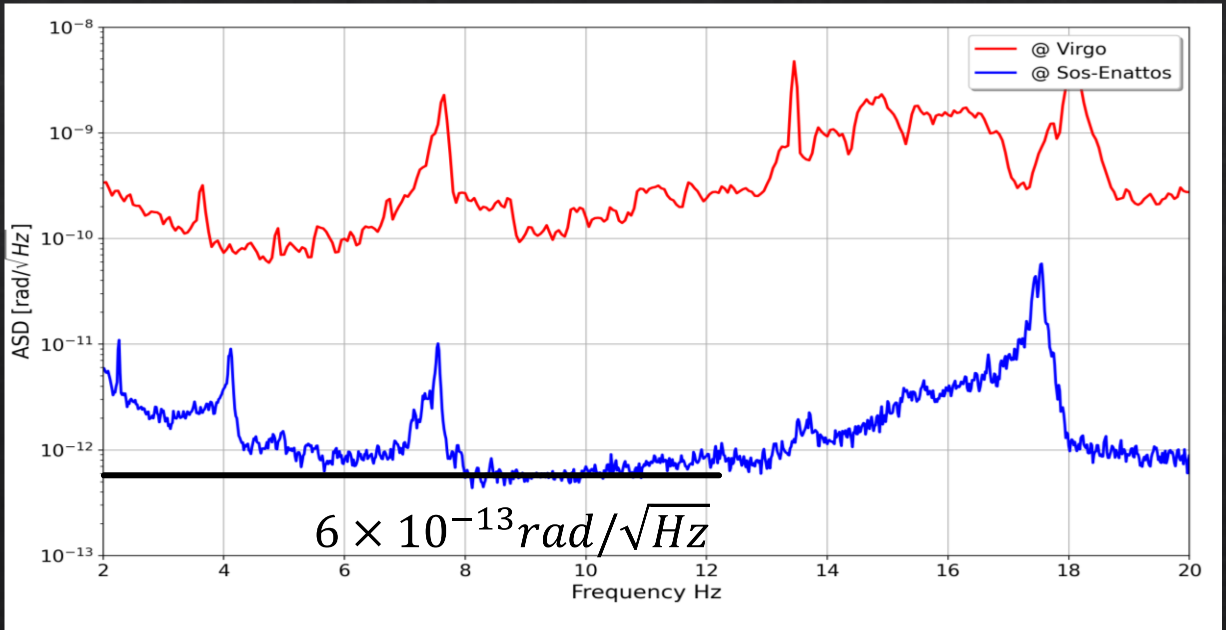


Currently under commissioning

The balance prototype

The prototype has been used as a tiltmeter (to sense the ground tilt) and has shown to be the **most sensitive tiltmeter in the world** in the frequency band 2-20 Hz (interesting band for the low frequency seismic noise subtraction for GW detectors).

Moreover, this measurement has shown how **seismically quiet** is the **Sos-Enattos site**, candidate to host the 3rd generation Gravitational Wave detector Einstein Telescope



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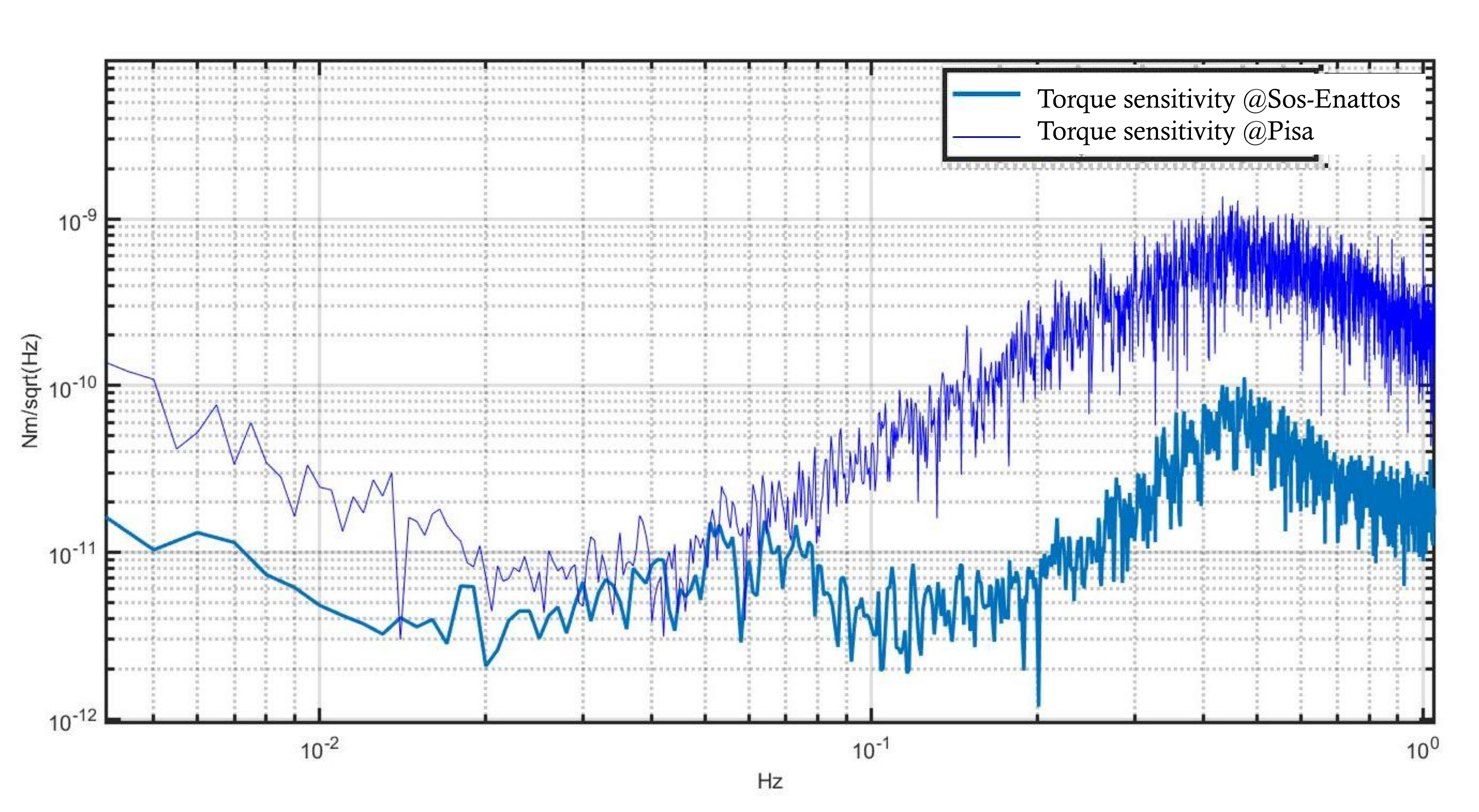
Current sensitivity in torque (prototype)

Torque sensitivity achieved with the prototype reaches

$3 \times 10^{-12} Nm/\sqrt{Hz}$@ 20 mHz

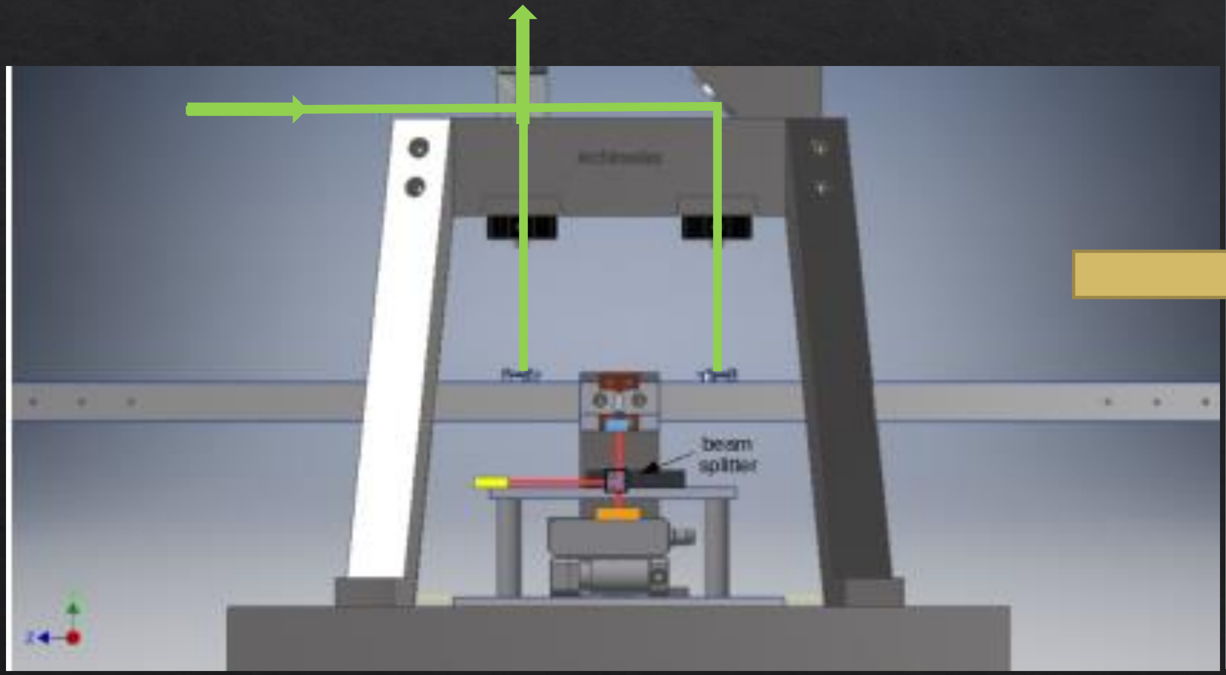
(about one order of magnitude higher than needed to perform the measurement)

This is an encouraging result; with the improvements of the final balance the target can be achieved!

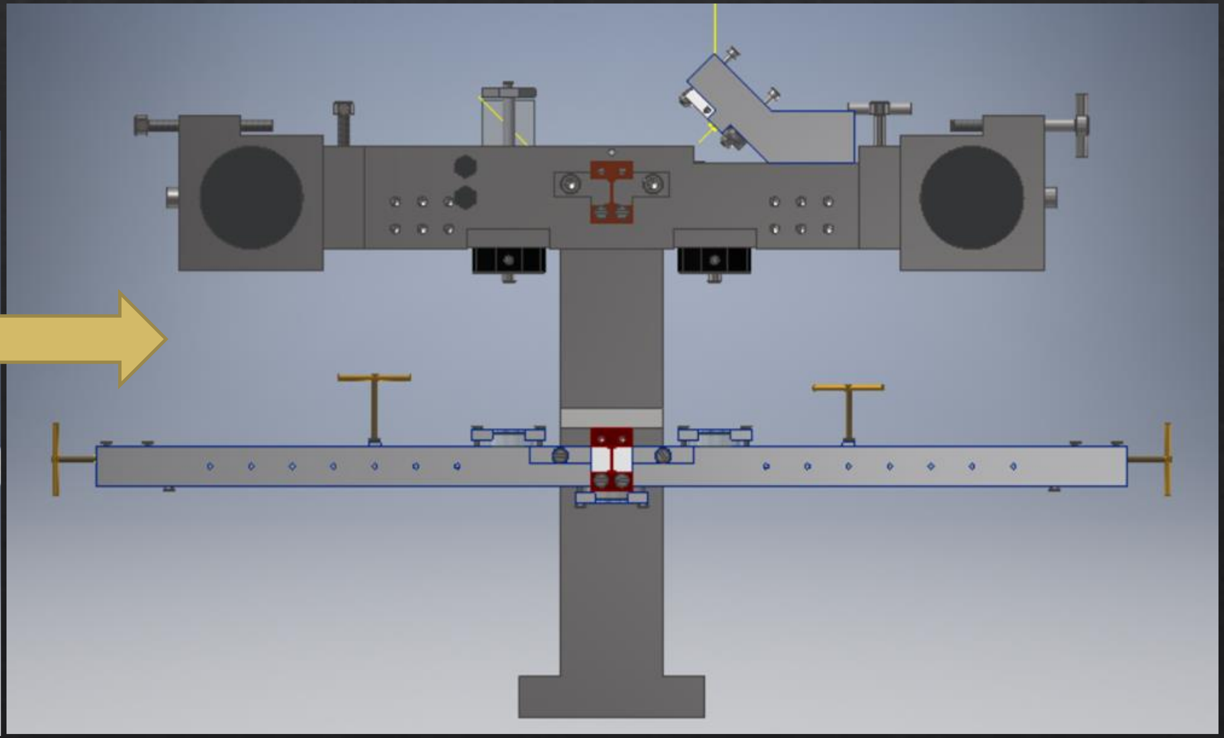


Archimedes final balance

Prototype

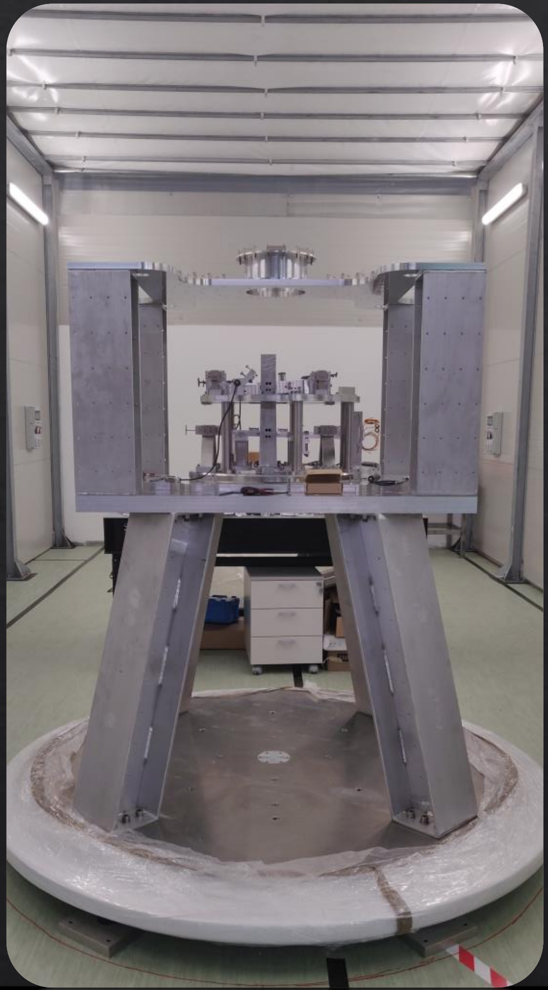


Final balance (short arm)

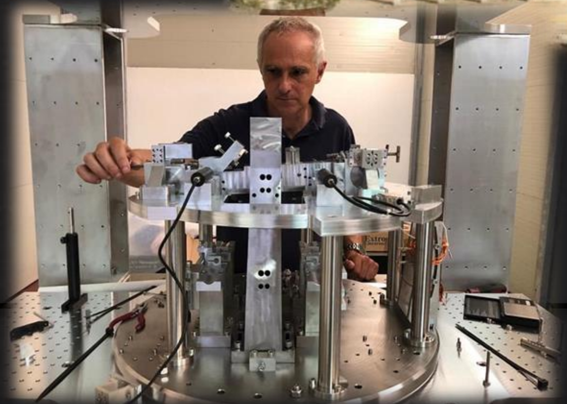


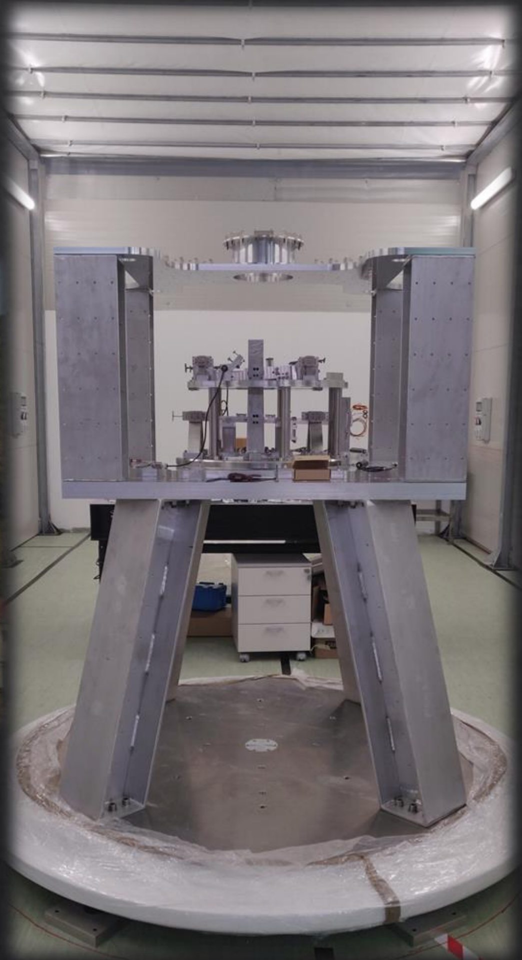
Archimedes final balance

- The final balance is currently under construction at the Sos-Enattos site: mechanics already installed, electronics setup is currently ongoing
- Inner shield of the cryostat has been delivered, the table where the balance is installed is set on the cryostat basis
- Superconductive samples tests ongoing on YBCO and GdBCO
- Commissioning will start in a few months; the balance will operate at room temperature for the whole 2023
- **Setup in cryogeny by 2024 and first data taking**



Thanks for your attention!





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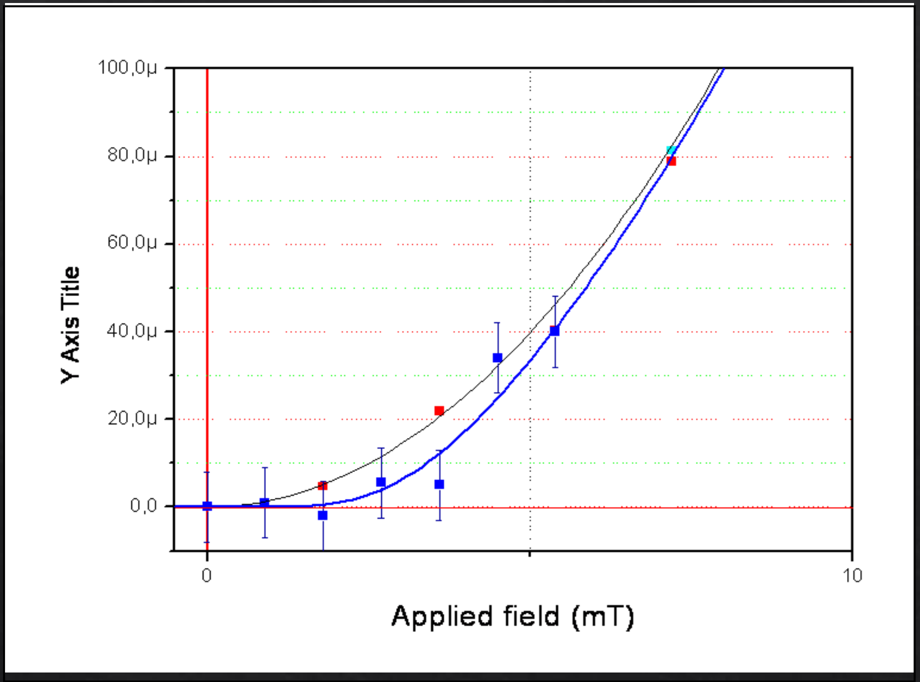
Casimir cavities with type I superconductors



Condensation energy is very small so it can be expected that the variation of Casimir energy at the transition for a superconductor inside a cavity can be comparable with the total transition energy

$$\frac{\Delta\mathcal{E}_{\mathrm{cas}}}{\mathcal{E}_{\mathrm{cas}}} \simeq 10^{-6}$$

Data compatible with the theory and the region of energy of different behaviour is the expected one

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A. Allocca et Al. Jour. Of. Supercond. And Novel Magnetism. **25**, 2557-2565 (2012)