Archimedes: how much does the vacuum weigh?

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MG17 PESCARA 7-12 JULY 2024
SEVENTEENTH MARCEL GROSSMANN MEETING

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:

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

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

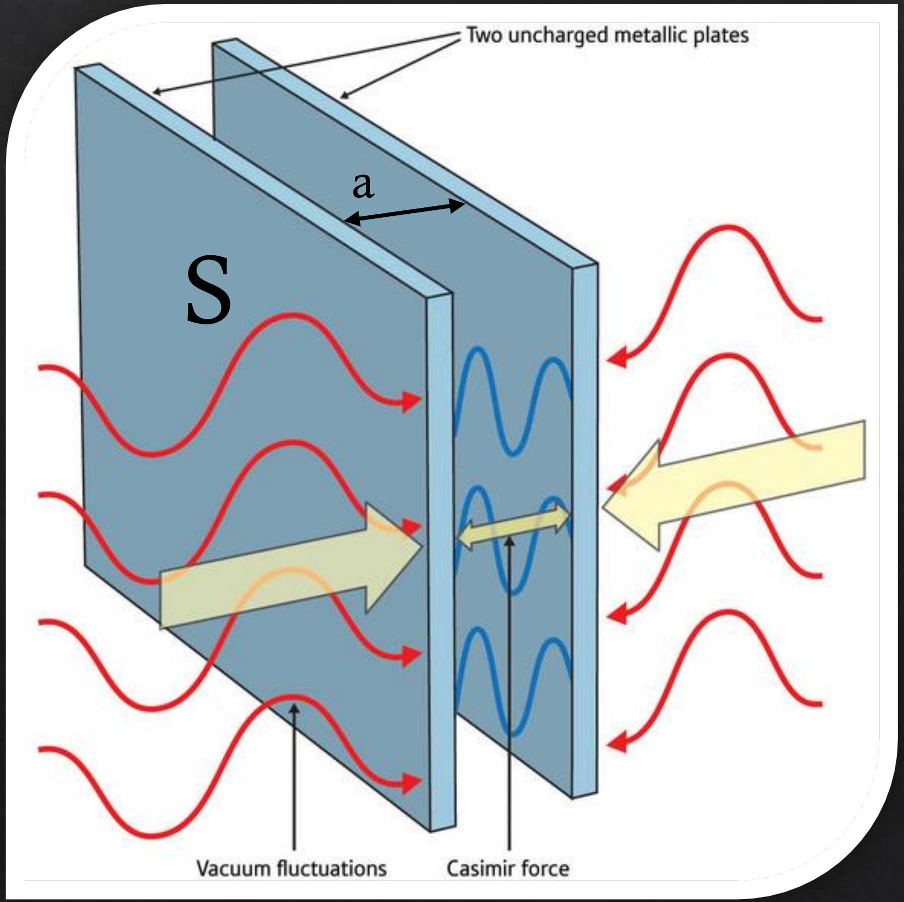
Macroscopic evidence of zero-point energy: Casimir effect

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.



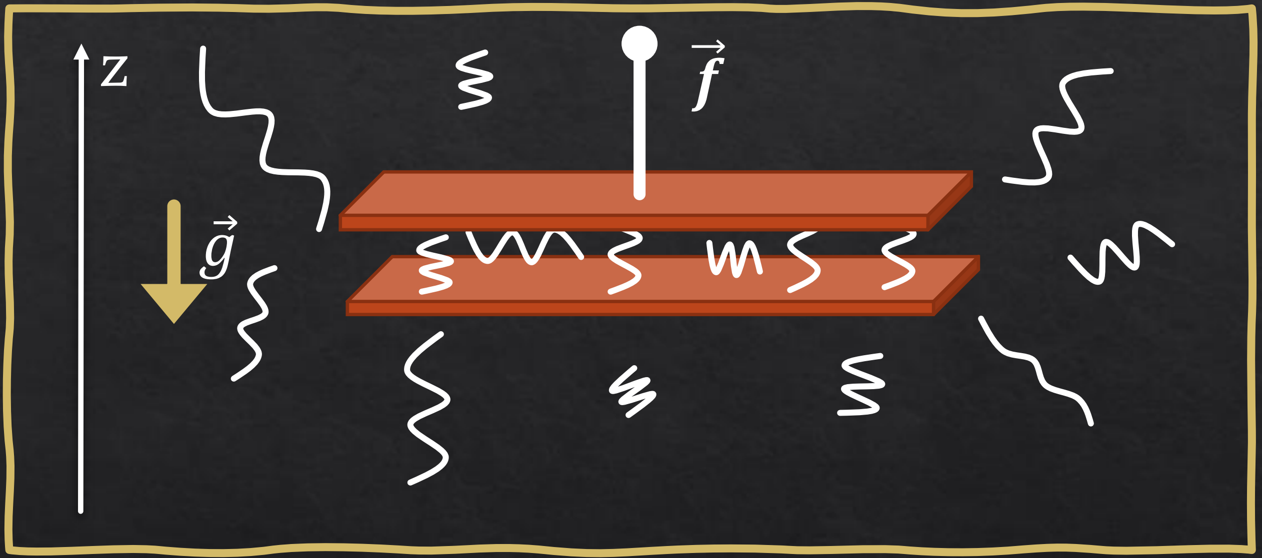
tipically a~1 μm, S~1cm^2 → $\mathcal{E}_{\mathrm{cas}}$~40 fJ, F_{cas}~10^{-7} N

Casimir cavity in the Gravitational Field

Weigh a **rigid** Casimir cavity

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

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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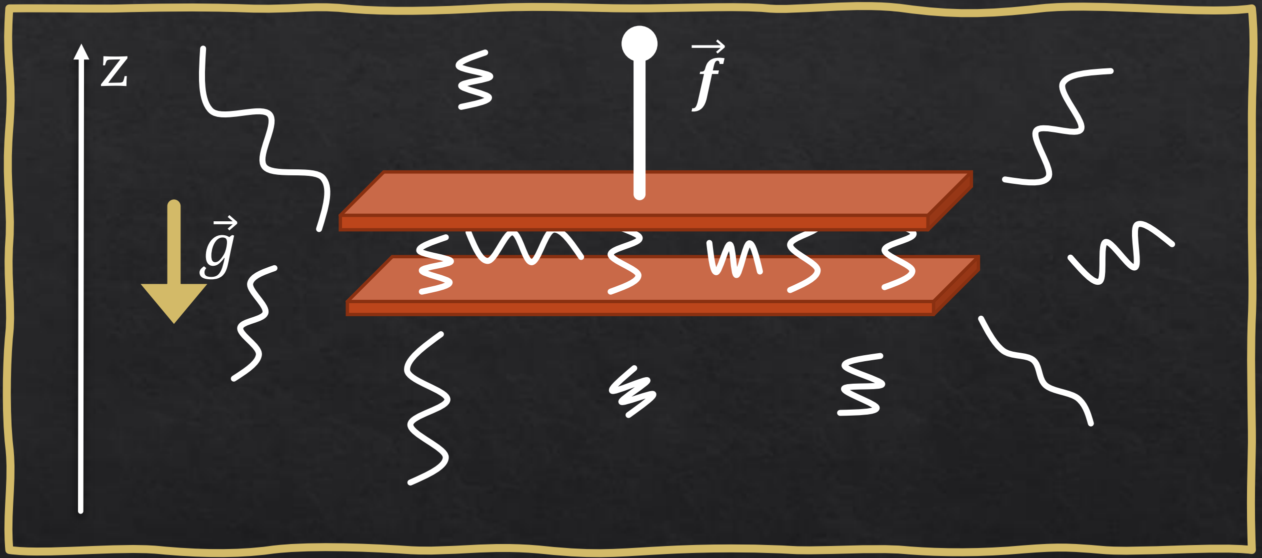


The cavity *immersed in the vacuum* is subjected to an upwards force equal to the *weight of the displaced vacuum* – **Archimedes "buoyancy of vacuum"**

[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»

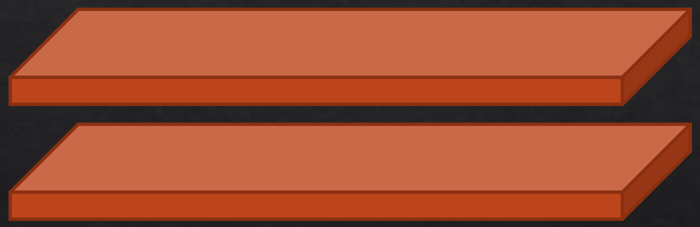
3. Suspend samples of «Casimir cavity» to the balance arm

Casimir cavity with superconductors

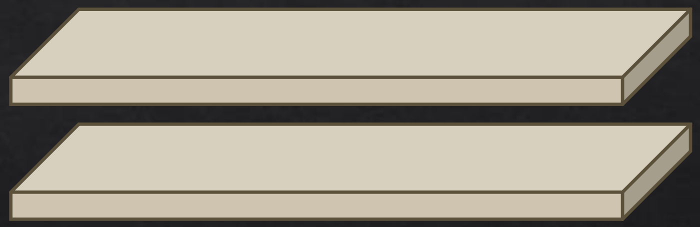
Cavities with tunable reflectivity: superconductors!

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



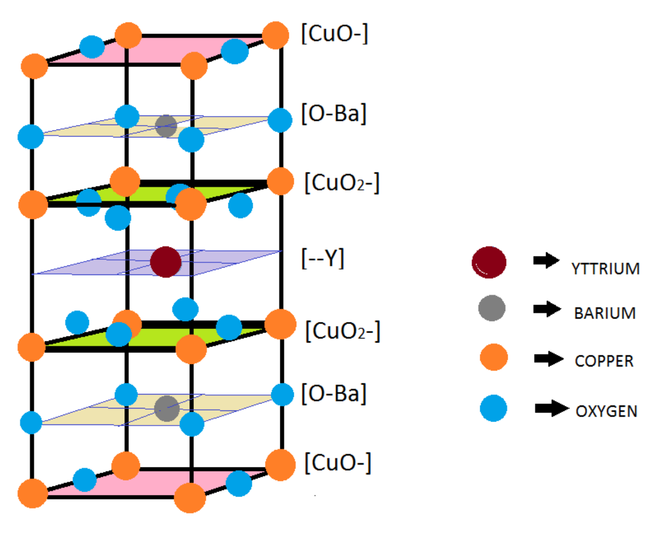
Modulating the samples temperature (and superconductivity) the “amount of vacuum” inside the cavities is modulated, and possibly the total weight

Casimir cavities with type II superconductors

High-Tc superconductors

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

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

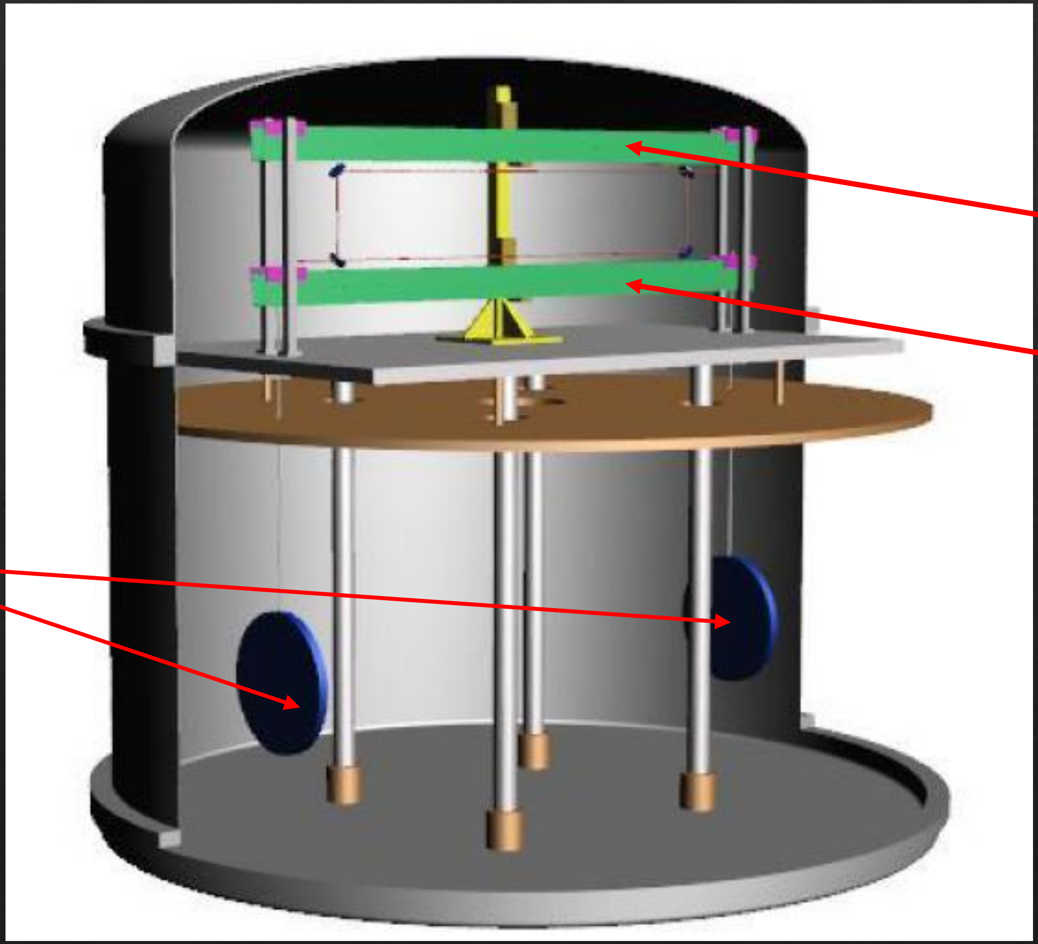


For a disk-shaped YBCO with R = 5 cm, thickness 5 mm

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

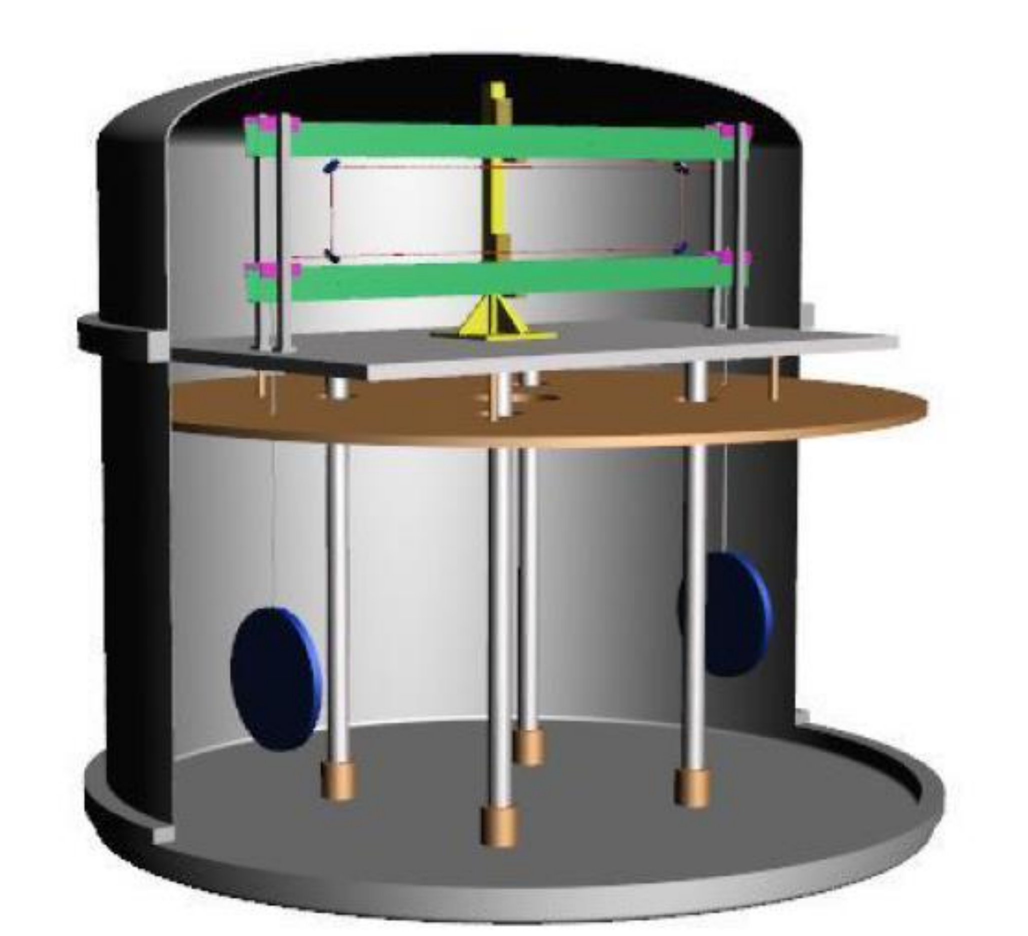
You need a very sensitive balance to detect such weight variations…

Archimedes beam-balance



Archimedes beam-balance

- High-Tc multilayered superconductor (YBCO-GdBCO-BSSCO) 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

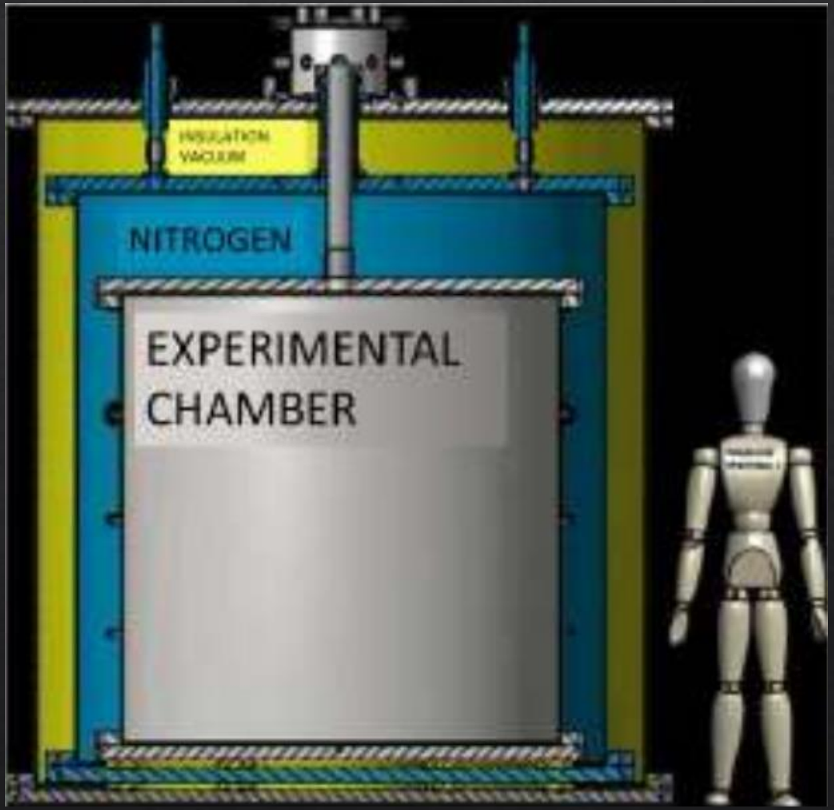


Expected modulation force:
$F = 4 * 10^{-16} N$

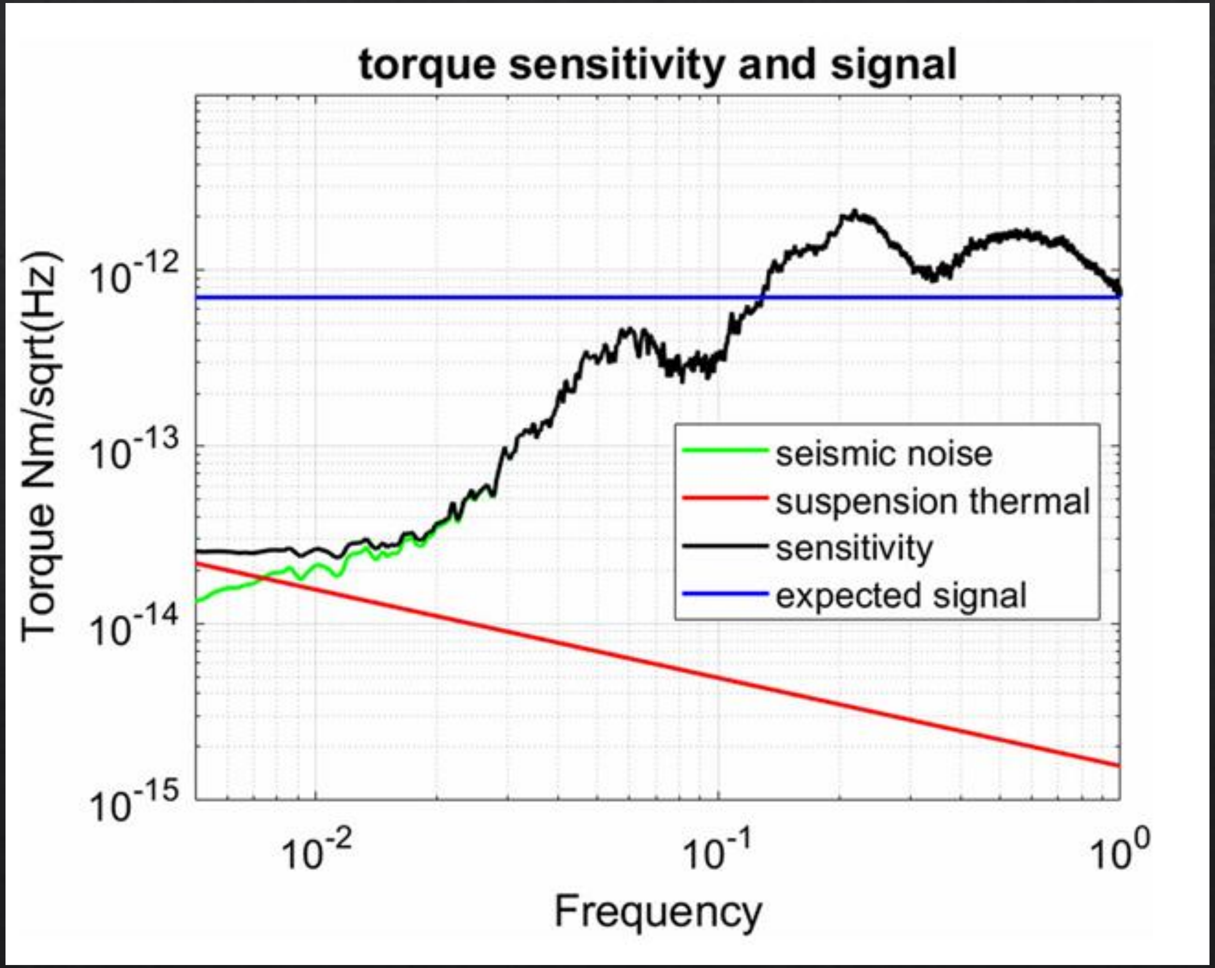
Archimedes beam-balance

The whole experiment will be cooled down at 90K to stay close to samples' 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 detectors



Expected torque sensitivity (1.4 m arm)



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

Total arm-length: 1.4 m

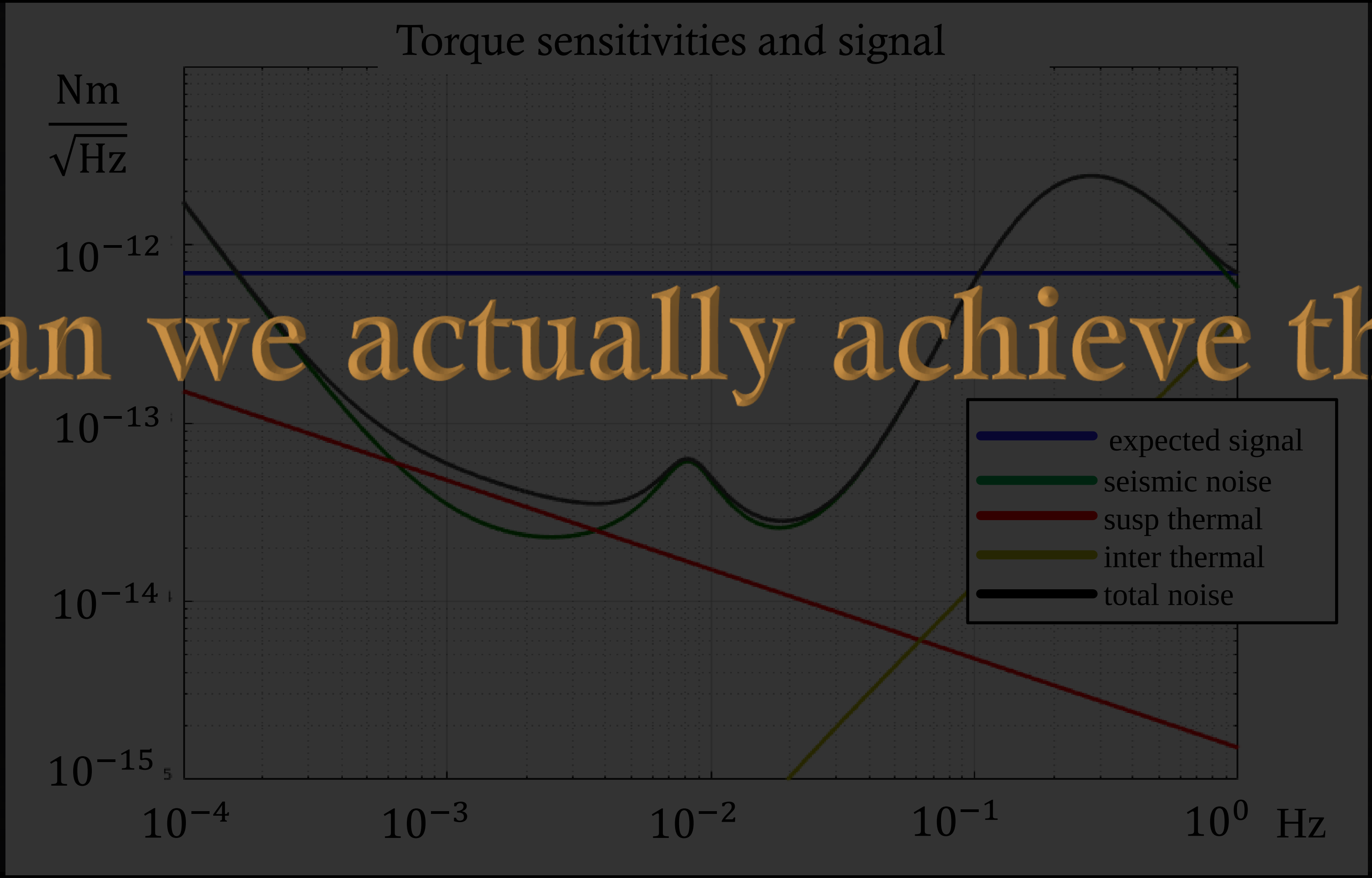
$$|\vec{\tau}| = \left|\vec{F}\right| \cdot 0.7\ \mathrm{m}$$
$$\simeq 3.5 \cdot 10^{-16}\ \mathrm{Nm}$$

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

Spectral torque signal:

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

Expected torque sensitivity (1.4 m arm)



Can we actually achieve this sensitivity?

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

Total arm-length: 1.4 m

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

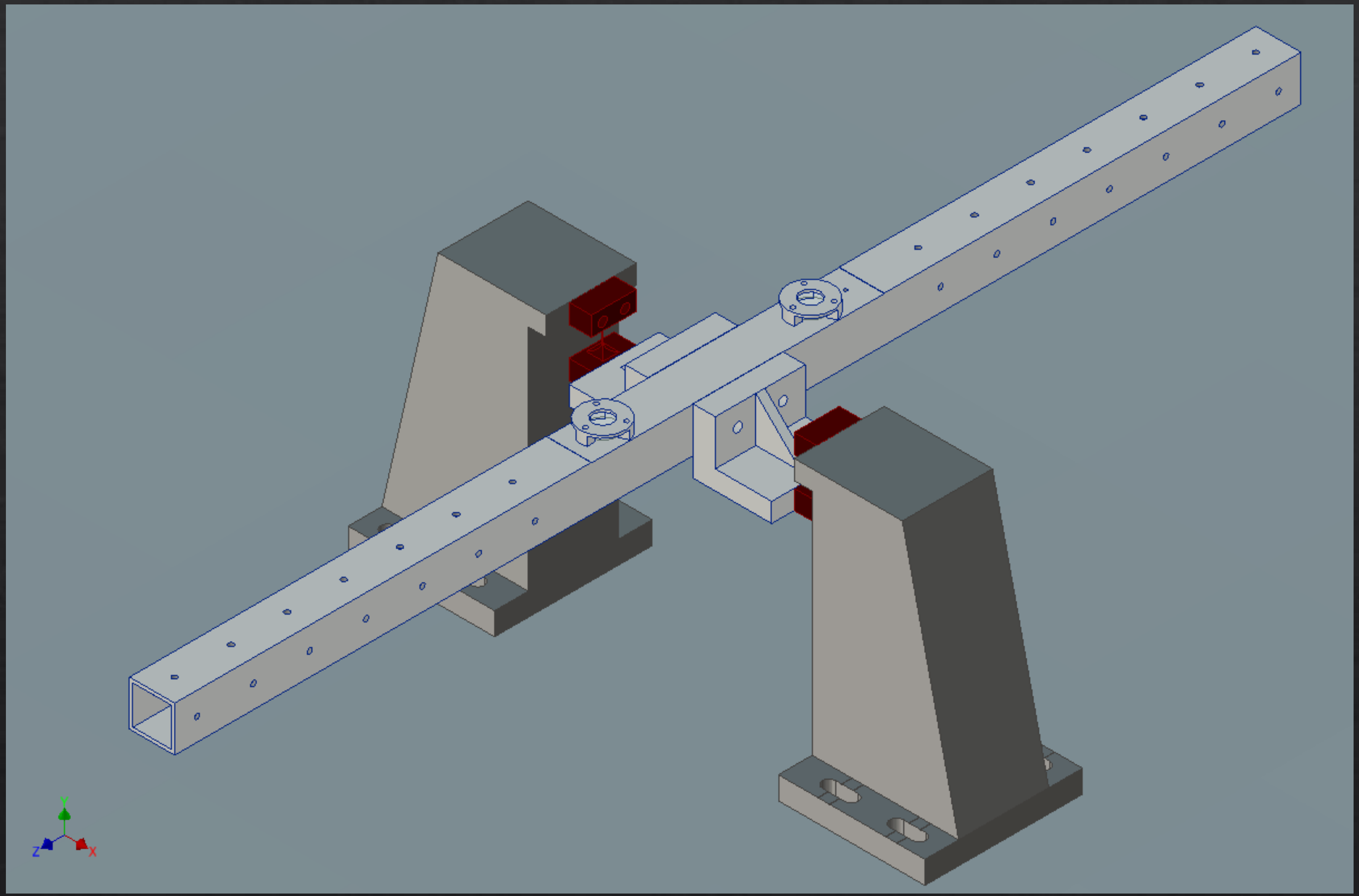
Integration time: 10^6 s (~ two weeks)

Spectral torque signal:

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

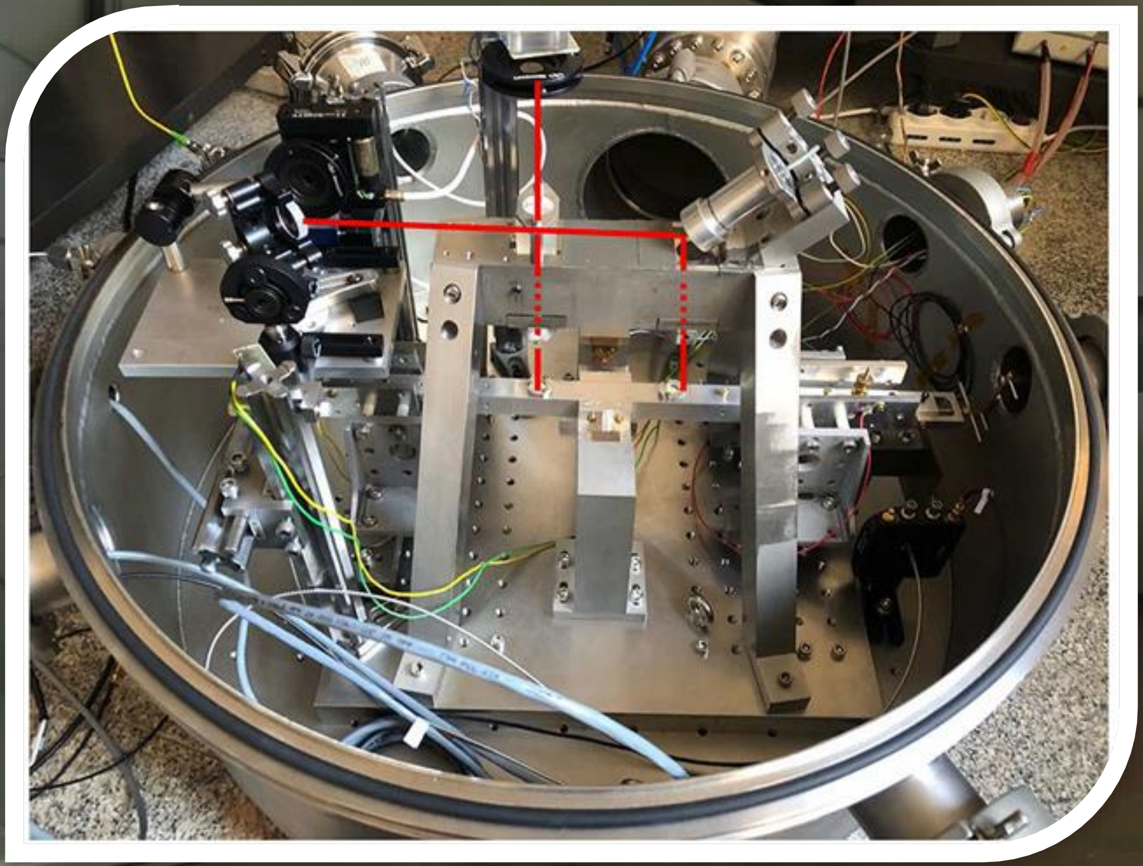
The balance prototype

- 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** ($< 10\ \mu m$) to minimize couplings with ground motion
- Interferometric read-out to sense the arm position wrt the ground



The balance prototype

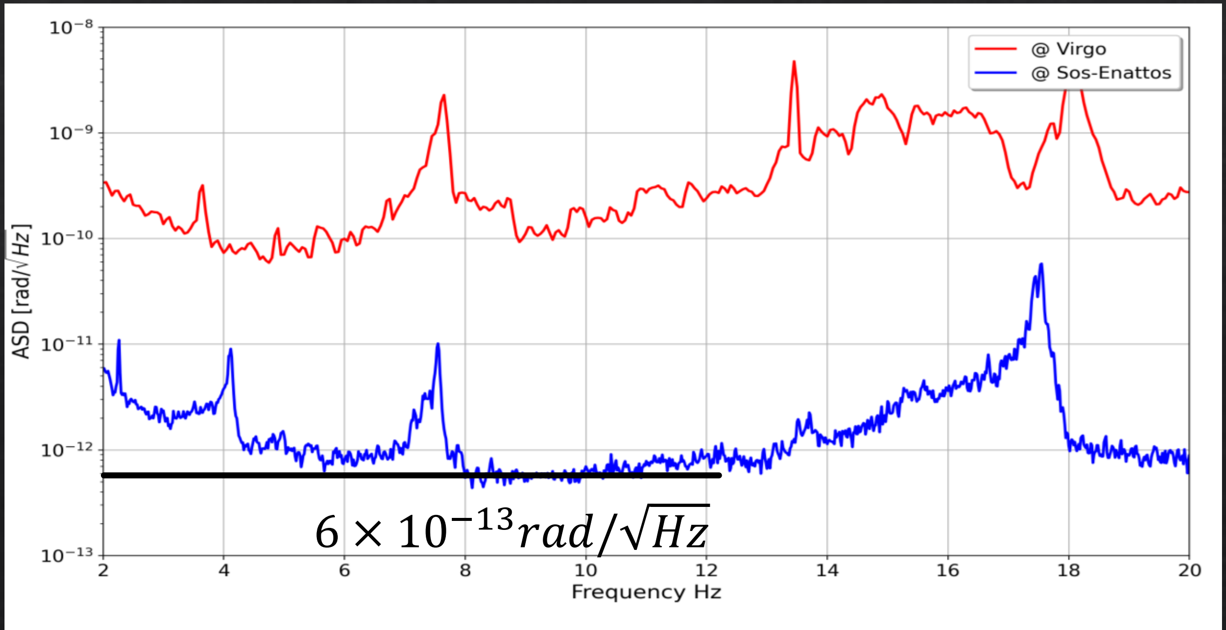
Installed at the **Sar-Grav** surface laboratories in Lula (NU) – Sos-Enattos mine



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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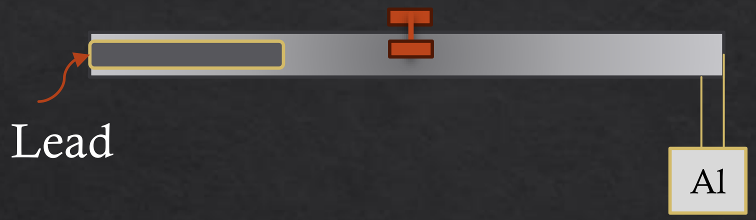
Current sensitivity in torque (prototype)

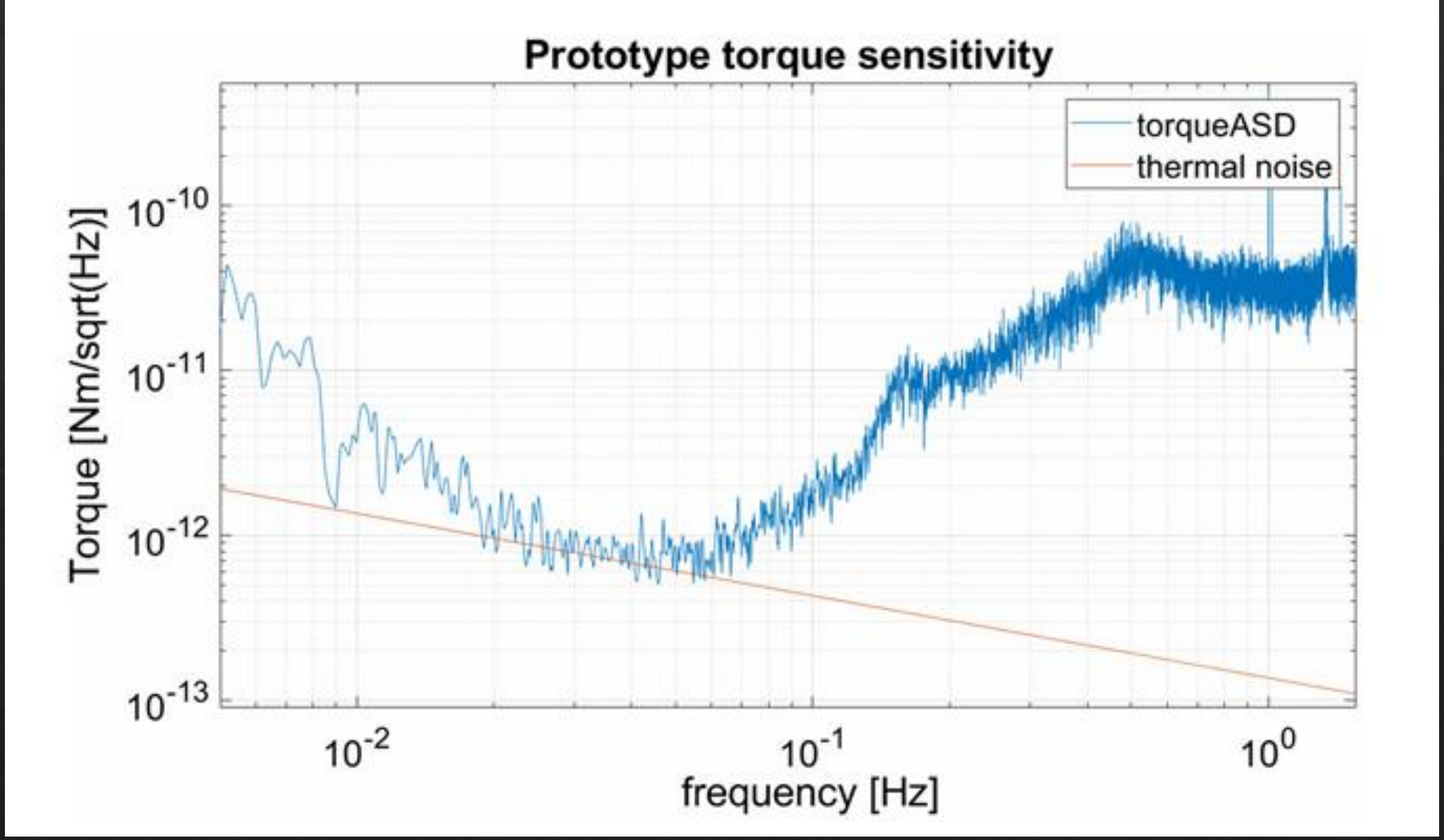


Suspended aluminum sample (right)
Lead counterweight (left)

Torque sensitivity achieved with the prototype reaches

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

A factor 10 of improvement in the sensitivity would be enough to perform the measurement



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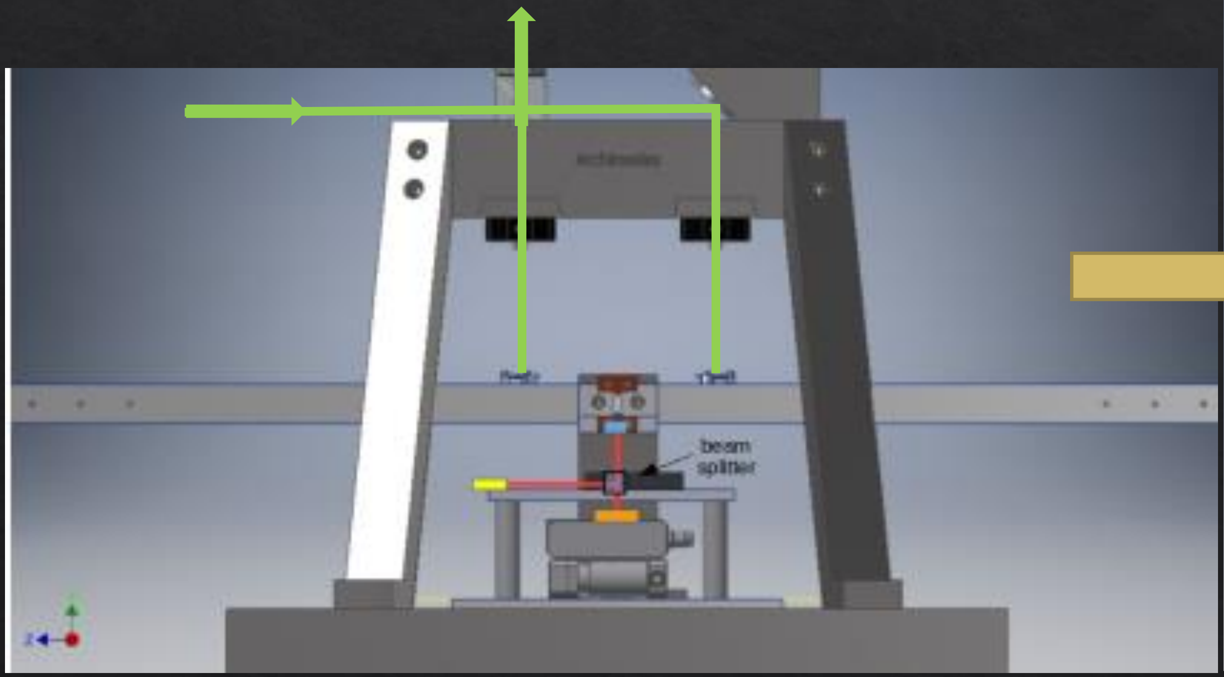
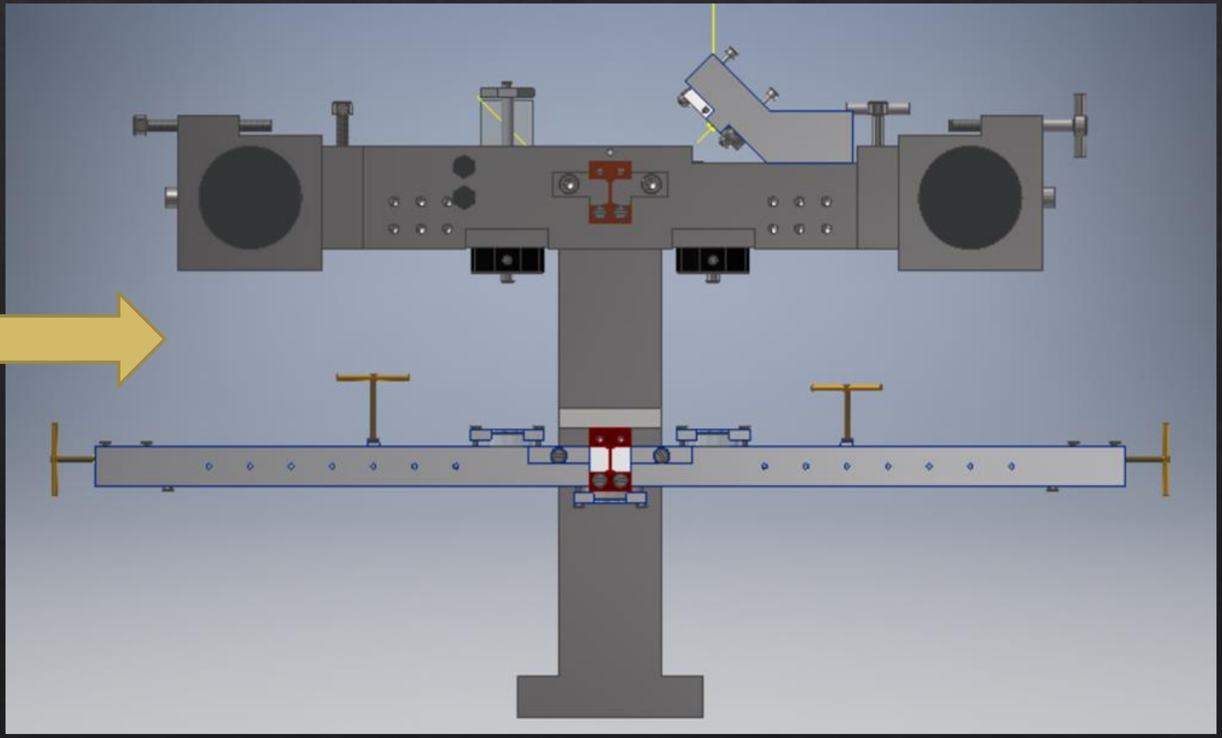
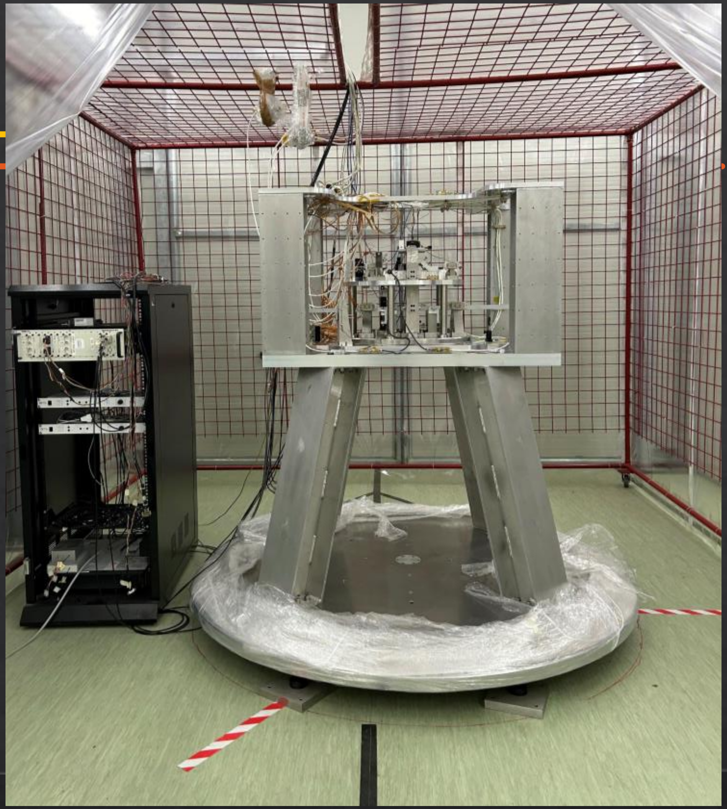
Archimedes final balance

Prototype



Final balance (short arm)

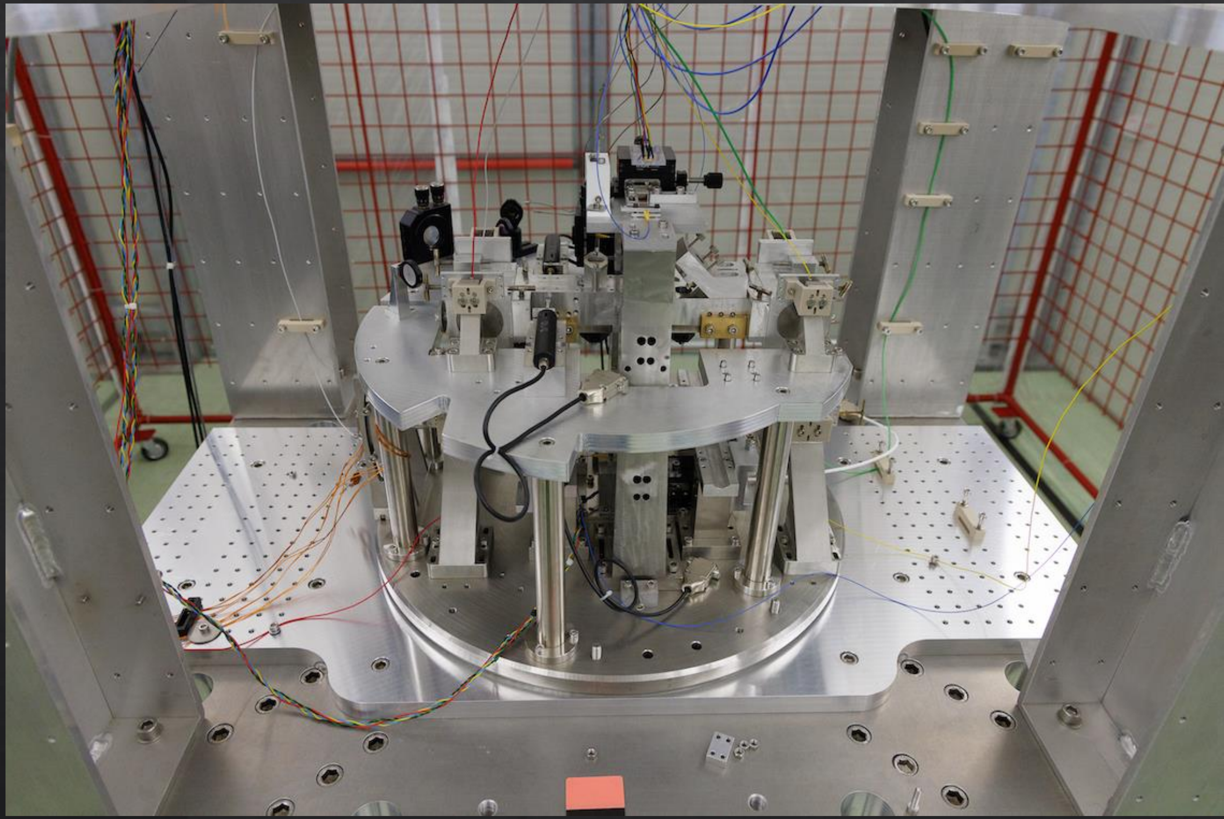




Archimedes final balance

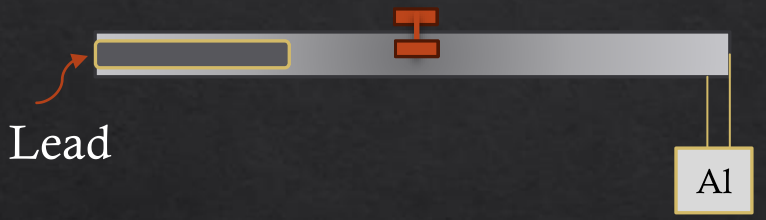
Archimedes final balance

- The final balance construction has been completed (during this week) at the Sos-Enattos site: test samples suspended for the first room temperature measurements
- Inner shield of the cryostat is already in place, the other two chambers will be delivered in few months
- Superconductive samples tests ongoing on YBCO, GdBCO and BSSCO
- Commissioning already ongoing; the balance will operate at room temperature for 2024/2025
- **Setup in cryogeny by 2026 and first data taking**



Dark Photon search

Archimedes setup can also explore other aspects of fundamental physics



Prototype equipped with weight and counterweight of different materials, to check what limits could be reached by this balance in the direct search of dark matter in the form of ultralight dark photon B-L

Direct search: the background of dark photon is expected to generate time-dependent force on bodies, which in principle can be detected at the dark photon field frequency

$$f = m_A c^2 / h$$

→ Dark photon direct search – coupling constant upper limits:

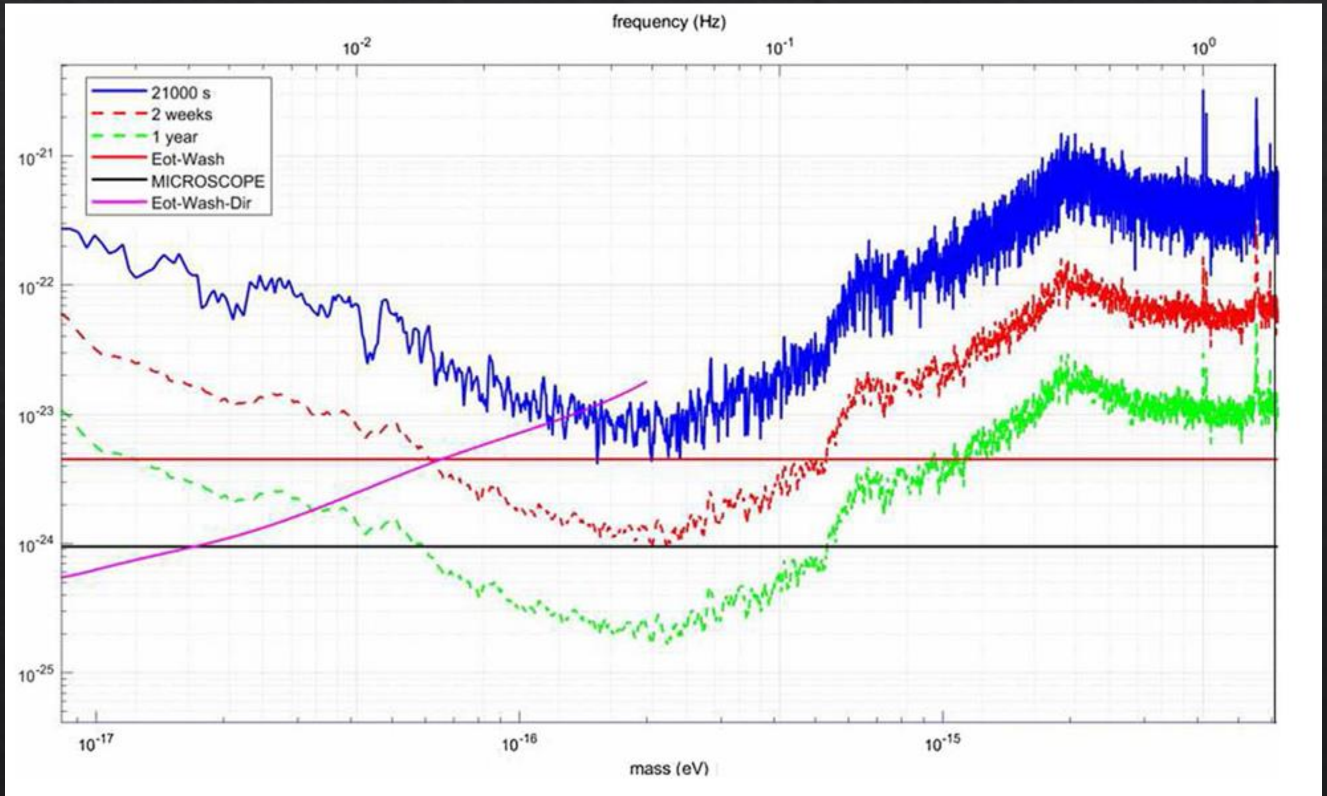
- **LIGO – Virgo** in mass range $10^{-14} eV - 10^{-11} eV$
- **Archimedes** in mass range $10^{-15} eV - 10^{-16} eV$

(under the hypothesis that the whole dark matter mass is due to this particle)

https://www.epj.org/epjplus-news/2736-epjplus-highlight-beam-balance-designs-could-elucidate-the-origins-of-dark-energy

Dark Photon search

Limits on dark photon B-L coupling constant



$$\mathcal{L} \equiv -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu$$

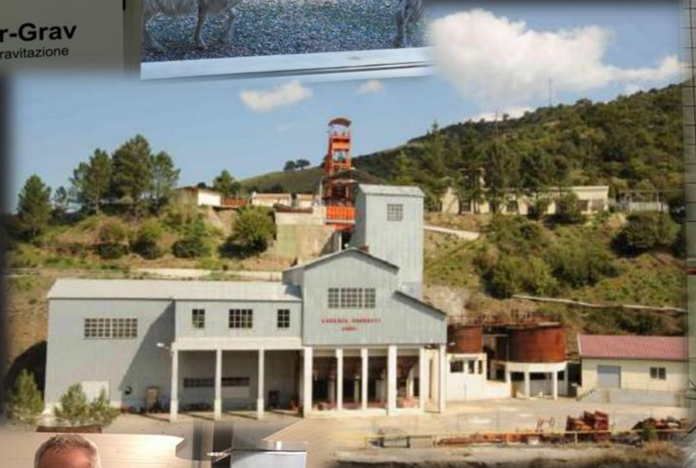
Constraints on the dark photon couplings reached through equivalence principle tests (Eot-Wash and MICROSCOPE)

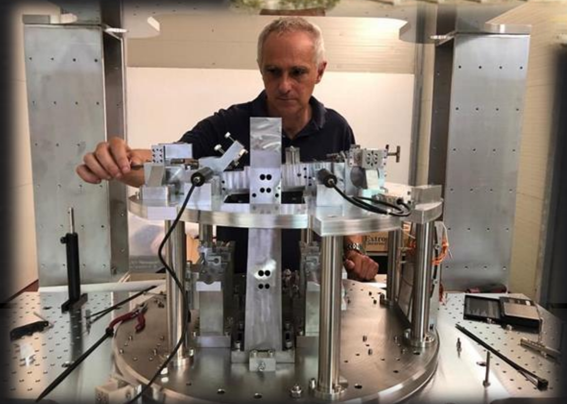
Calloni, E. *et al. Eur. Phys. J. Plus* **139**, 158 (2024)

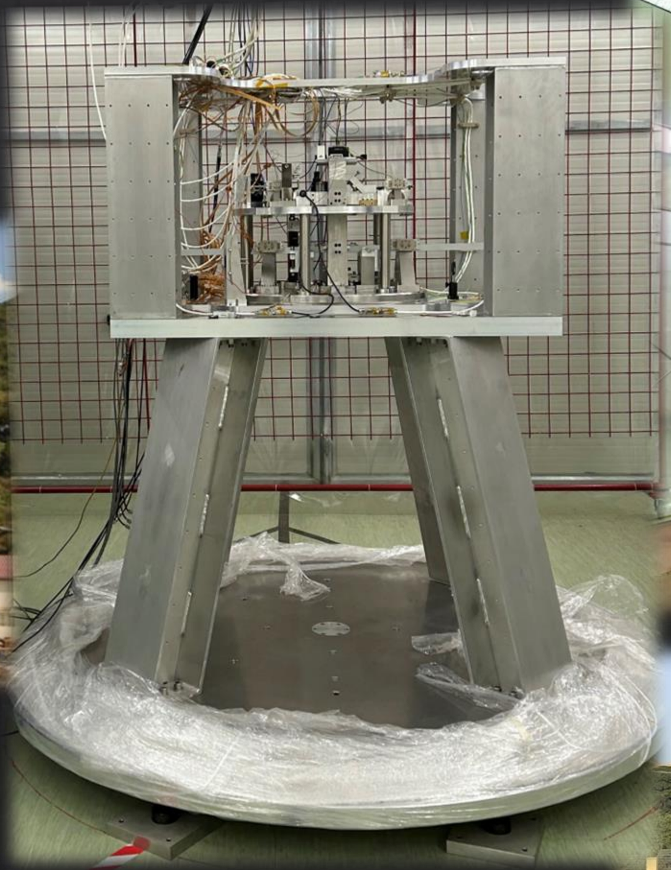
Conclusions

- Archimedes aims at measuring the interaction between zero point energy of EM field and gravitational field using a very sensitive, suitably designed and realized beam balance
- The experiment is installed in one of the quitest place in Europe, the Sos-Enattos mine in Sardinia (Italy), and will start taking calibration data by the end of this year, while the first vacuum weight measurements are foreseen to be acquired by the end of 2026
- Meanwhile, Archimedes is already giving exciting physical results:
  - Most sensitive tiltmeter in the frequency band of interest for GW detectors
  - Possible use of this setup also for other fundamental physics measurements (dark photon search, …)

Thanks for your attention!







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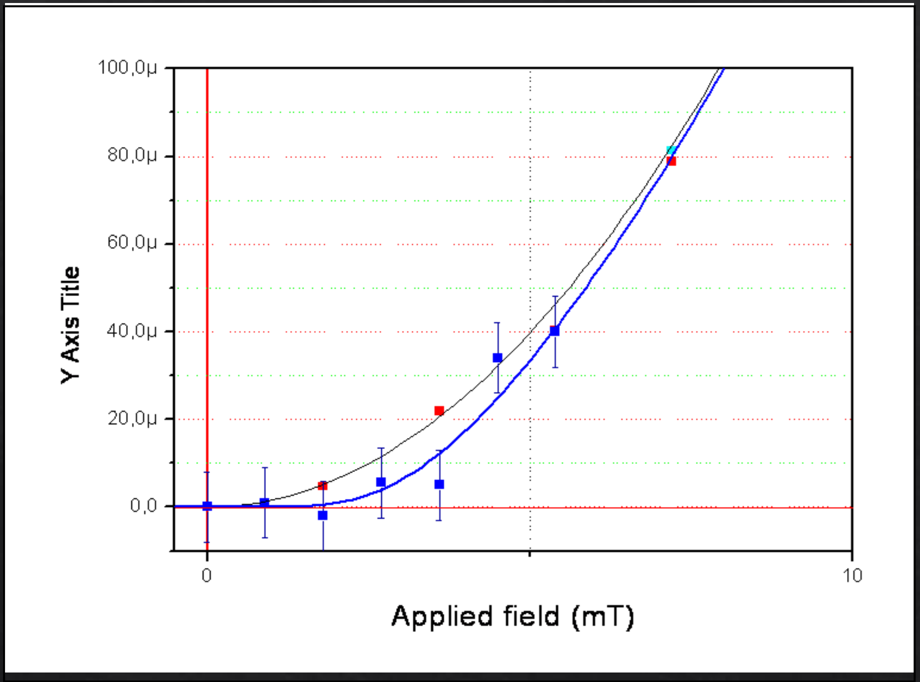
- A. Allocca, E. Calloni, L. Errico *et al*, Eur. Phys. J. Plus (2021) **136**: 1069
- A. Allocca *et al*, *Eur. Phys. J. Plus* **137**, 826 (2022)
- Calloni, E. *et al. Eur. Phys. J. Plus* **139**, 158 (2024)

Extra slides

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

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

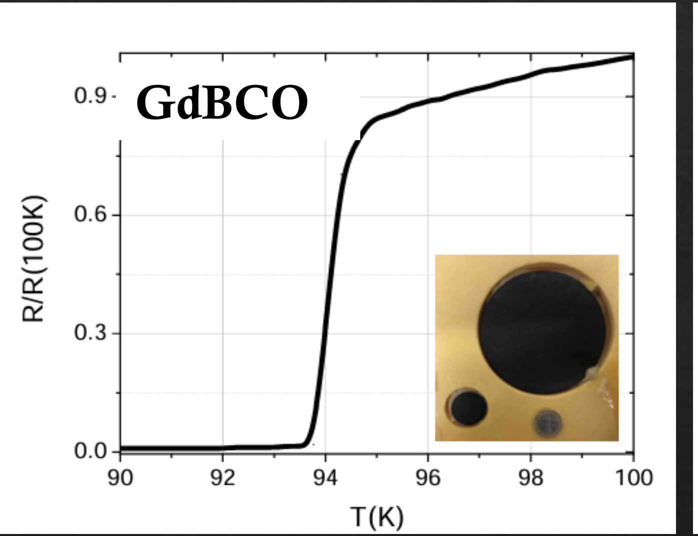
Data compatible with the theory and the region of energy of different behaviour is the expected one

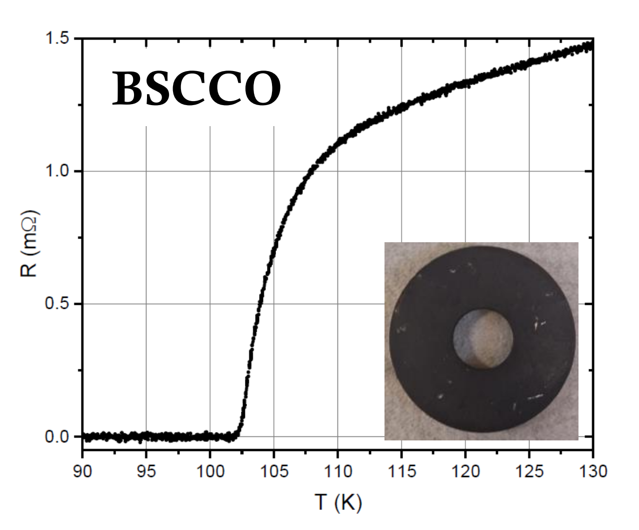
G. Bimonte et Al. - J. Phys. A: Math. Theor. **41** 164023 (2008)
A. Allocca et Al. Jour. Of. Supercond. And Novel Magnetism. **25**, 2557-2565 (2012)

Casimir cavities with type II superconductors

High-Tc superconductors

New tests with other kind of cuprates (with higher Tc)





Higher Tc makes thermal modulation easier

«Oven» to perform the transition