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THE ARCHIMEDES EXPERIMENT: CAN QUANTUM VACUUM FEEL GRAVITY?

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on behalf of Archimedes collaboration

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PREAMBLE: INTERDISCIPLINARITY IN ARCHIMEDES

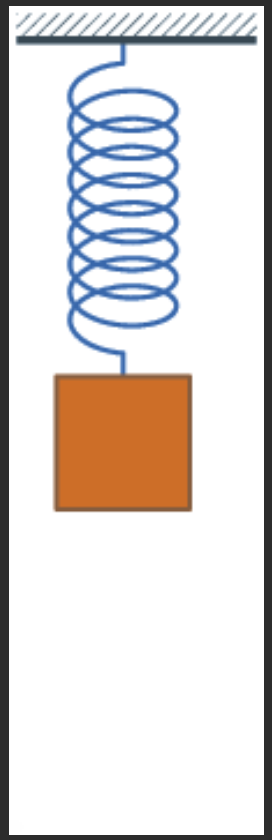
In the very spirit of ICNFP 2024,
ARCHIMEDES is a truly interdisciplinary experiment:

- Scientific motivations involve GR and QFT;
- The expected signal is produced through Superconductivity and Thermodynamics;
- The signal detection is based in high precision opto-mechanics.

And finally, there are some spin-off implication related to DM search and Geophysics.

- Gravity
- Quantum Field Theory
- Superconductivity
- Cryogenics
- Precision Mechanics
- Optics
- Electronics
- Dark Matter search
- Geophysics

SCIENTIFIC MOTIVATION: COUPLING BETWEEN GRAVITY AND VACUUM



$$\vec{P} = m\vec{g}$$

In Newtonian Mechanics $m \propto N_{\text{atoms}}$ (internal energy U not coupled with gravity)

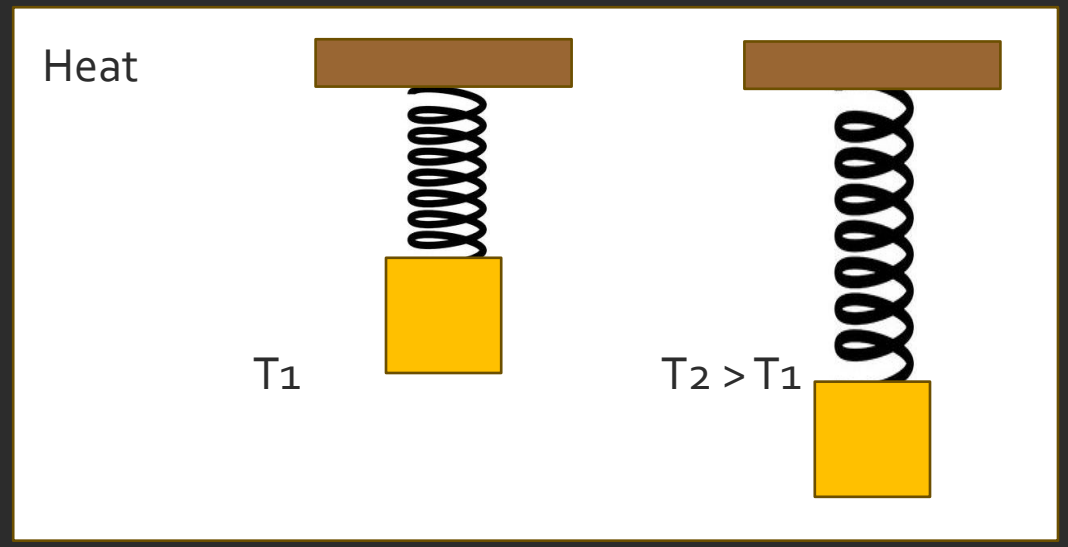
In General Relativity $U = m_U c^2$

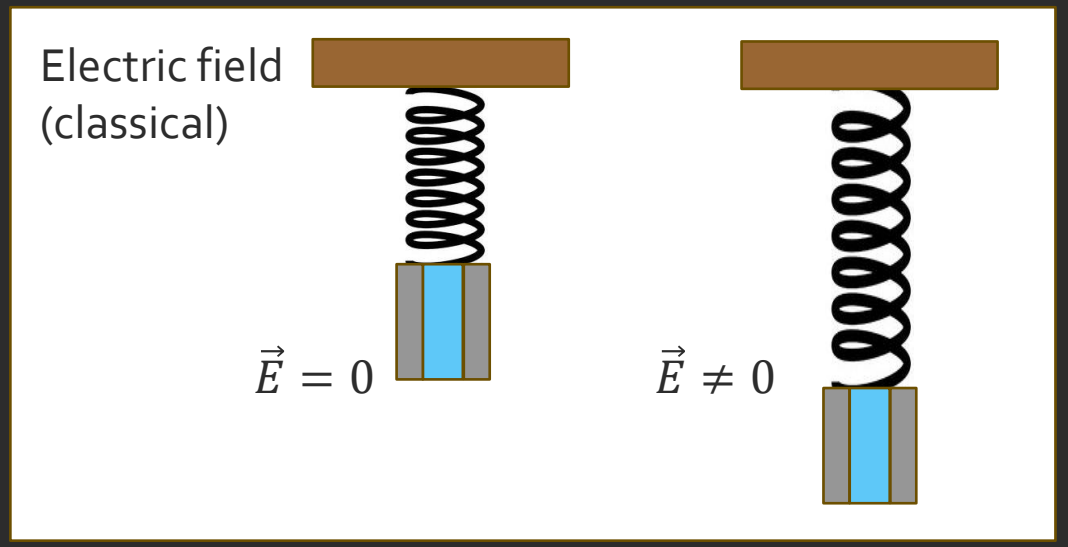
Thus, the weight depends also by its internal energy

$$m \simeq m_{\text{atoms}} + \frac{U}{c^2} \not\propto N_{\text{atoms}}$$

In general, the weight should also depend by the whole stress-energy tensor of the body, but energy is the dominant contribution.

SCIENTIFIC MOTIVATION: THE WEIGHT OF QUANTUM ENERGY





The problem with quantum fields: vacuum state energy tends to infinity.

$$\rho_{em}^{(\mathrm{vac})} \simeq \int_0^{\frac{2\pi}{l_P}} \frac{d\vec{k}}{(2\pi)^3} \sum_{s=1}^{2} \frac{1}{2} \hbar \omega_{\vec{k}} \simeq 10^{108}\ \mathrm{J/m^3}$$

Any object should be tremendously heavier than it is!

SCIENTIFIC MOTIVATION: FROM LOCAL TO COSMOLOGICAL IMPLICATIONS

Such amount of vacuum energy should be able to produce a gravitational field by itself.

Vacuum is everywhere; thus, it should affect spacetime geometry on cosmological scale.

$$G_{\mu\nu} + \Lambda_{\text{eff}}\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\Lambda_{\text{eff}} = \Lambda - 8\pi \frac{G}{c^4} \rho^{(\text{vac})}$$

or equivalently $\rho_{\text{eff}} = \rho^{(\text{vac})} - \frac{c^4}{8\pi G}\Lambda$

- *Pauli's calculus: R_{Universe} is only 31 Km!*
- From cosmological expansion measurements: $|\rho_{\text{eff}}| \leq 10^{-10}\ \text{J/m}^3$

The cosmological constant problem [Weinberg, 1989]

SCIENTIFIC MOTIVATION: WEIGHT EFFECT PROBES A «STRONG» COUPLING

Some known evidence of EM-Gravity coupling:

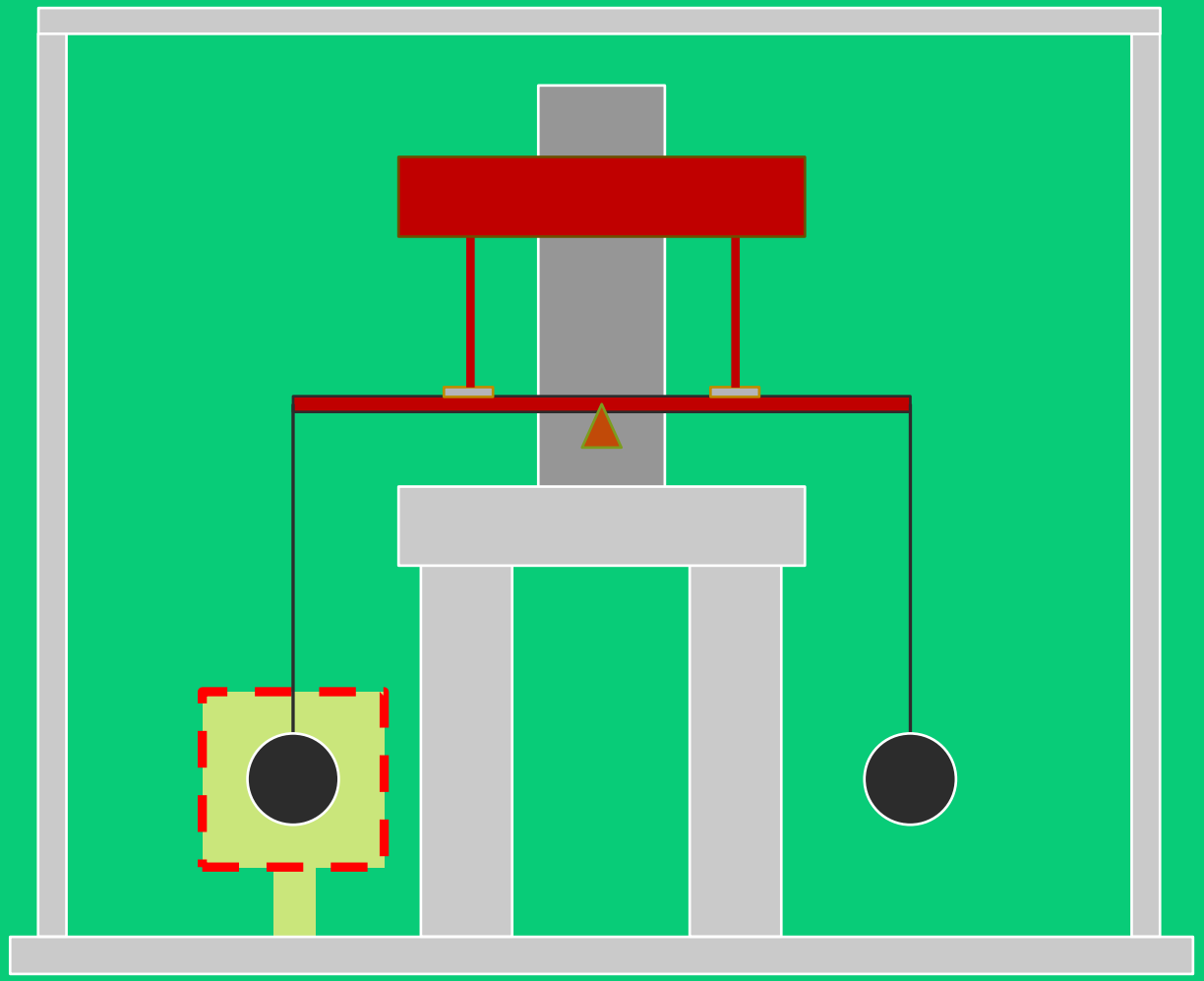
- Gravitational lensing
- Gravitational redshift
- Unruh effect (not observed)
- Ehrenfest-Tolman effect (not observed)

In these phenomena spacetime geometry acts only as a *background* in which a certain kinematics occurs

Vacuum contribution on the weight of massive bodies is a dynamical effect, where the nature of the field is taken into account in the generalized dynamic equation:

$$F^{\mu} = m\, a^{\mu}, \qquad \text{where} \qquad m = m_{\text{atoms}} + U_{\text{vacuum}}/c^2$$

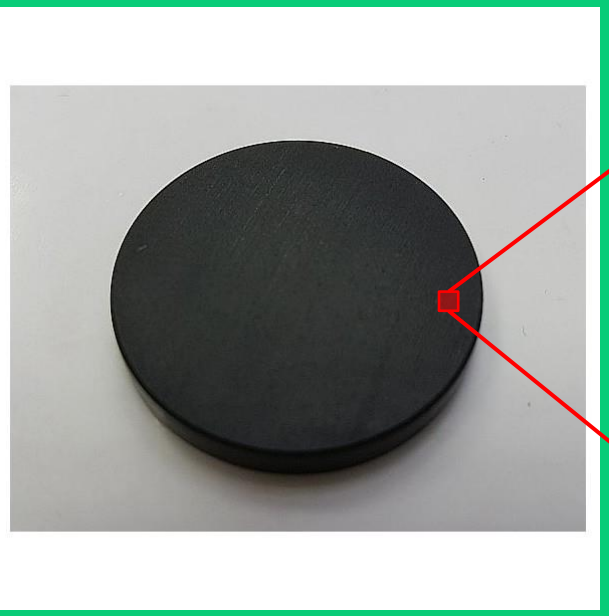
ARCHIMEDES' STRATEGY: HOW VACUUM WEIGHT CAN BE MEASURED?

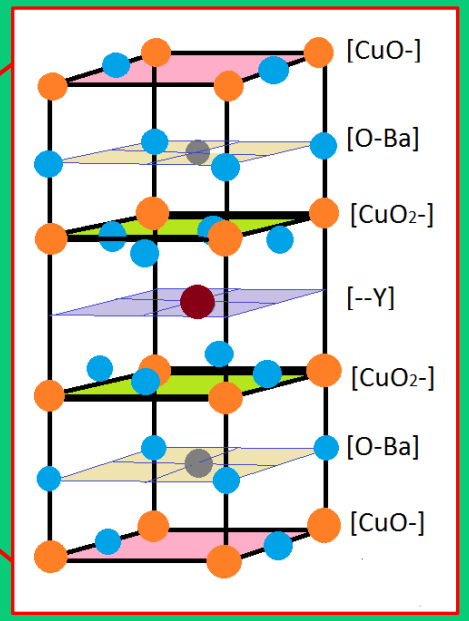


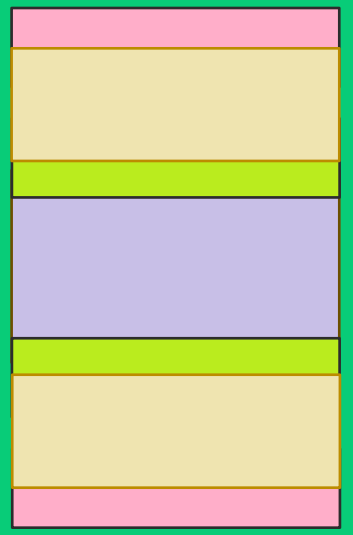
Archimedes' wishlist:

- A massive sample full of variable vacuum energy
- A non-invasive physical process for varying vacuum energy in the sample
- A «weight detector» (commonly, a beam balance) with a high enough sensitivity to detect weight variations
- A tilt read-out able to detect beam balance oscillations
- A seismic noise and a thermal noise smaller than the weight signal.

ARCHIMEDES' STRATEGY: CUPRATE SUPERCONDUCTORS AS SAMPLES







Cuprate crystals are stacked Casimir cavities, whose plates are made by metallic atomic planes.

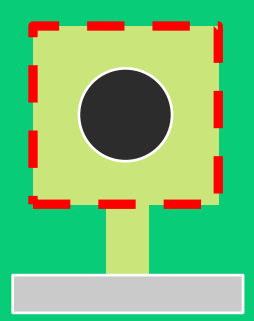
$$\mathcal{E}_{Casimir} = -\frac{\pi^2}{720}\frac{\hbar c}{a^3}S$$

For a~1 μm, S~1cm² ⟶ $\mathcal{E}_{Cas}$~**40 fJ**

The reflectivity of such planes (the «efficiency» of Casimir cavities) depends by the conductive state of the sample.

ARCHIMEDES' STRATEGY: VARYING VACUUM ENERGY WITH TEMPERATURE

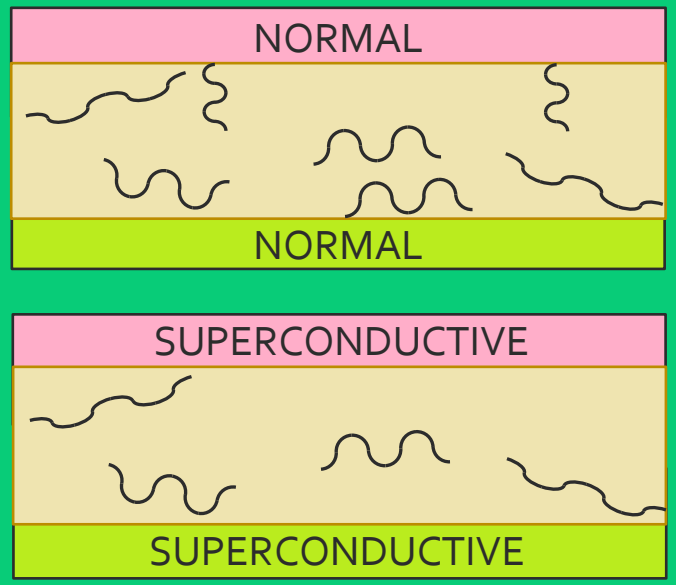
Modulation in temperature (around T_c)



$T_1 > T_c$

$T_2 < T_c$

Modulation of $\mathcal{E}_{cas}$



$\mathcal{E}_{Cas}$

$\mathcal{E}_{Cas} - |\Delta\mathcal{E}_{Cas}|$

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

For a disk-shape YBCO with V ≃ 40 cm³

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

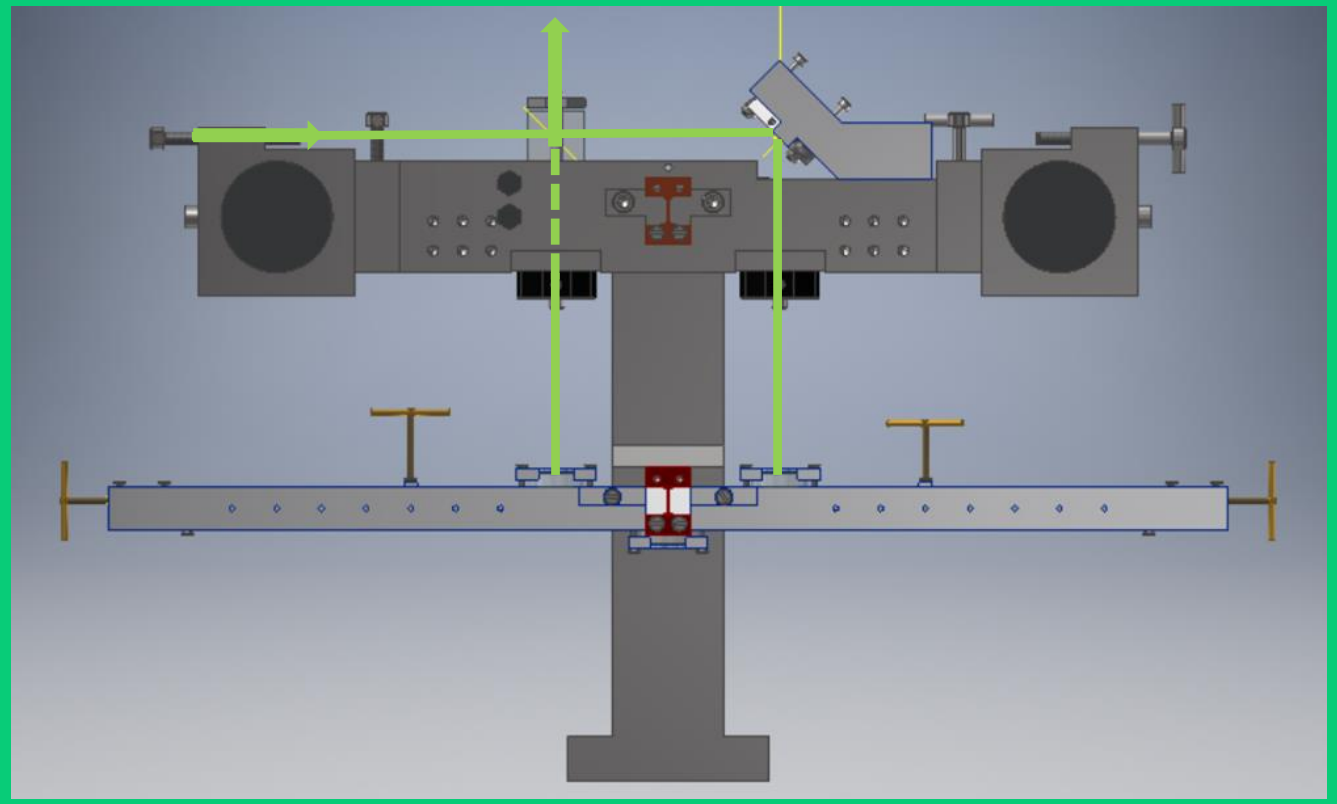
ARCHIMEDES' STRATEGY: A WORLD RECORD SENSITIVITY BEAM BALANCE

Remote fine tuning of CM position:

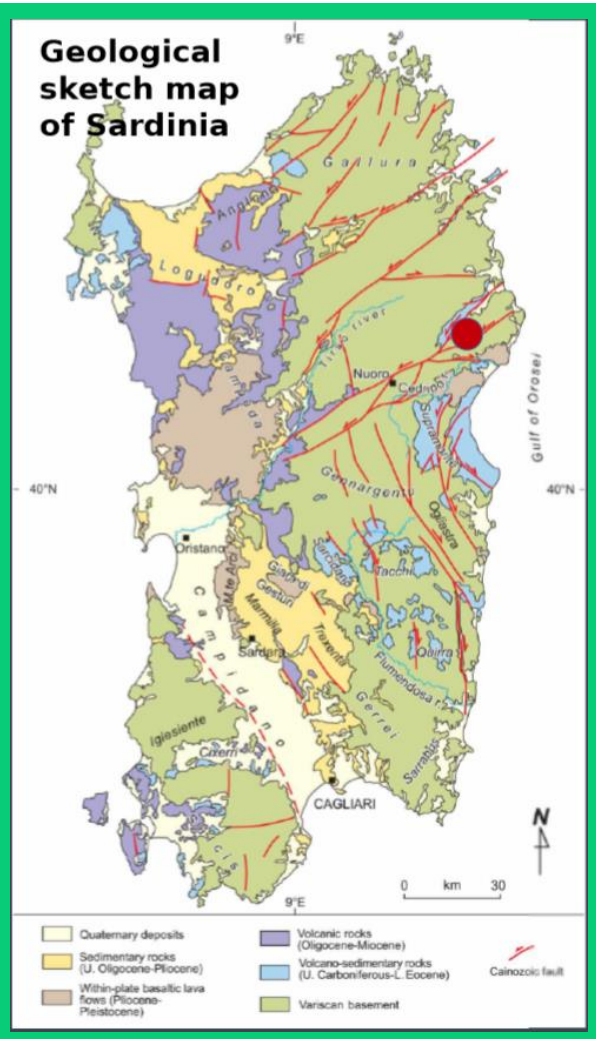
- to place CM within 10 μm from the center of rotations and reduce shift-to-tilt coupling
- to tune the resonant frequency of the arms below 10 mHz
  (lower than weight signal frequency)

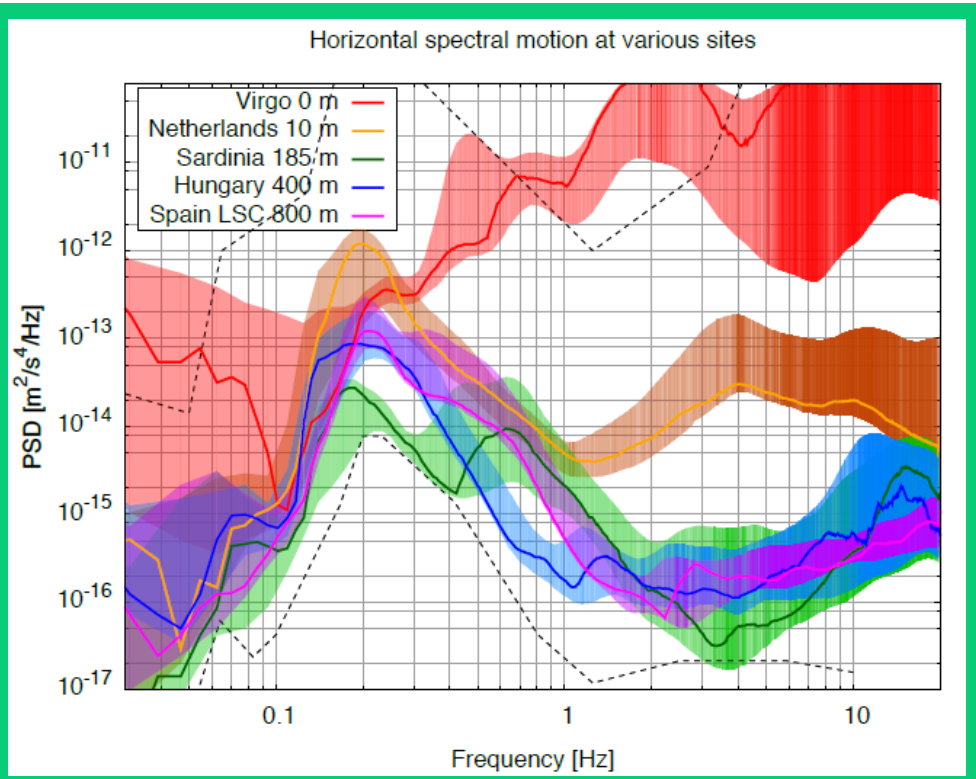
Optical read-outs:

- 2 optical levers to monitor arms' tilt relative to the ground
- 1 interferometer integrated in the arms to monitor arms' relative tilt
  (common noise rejection)



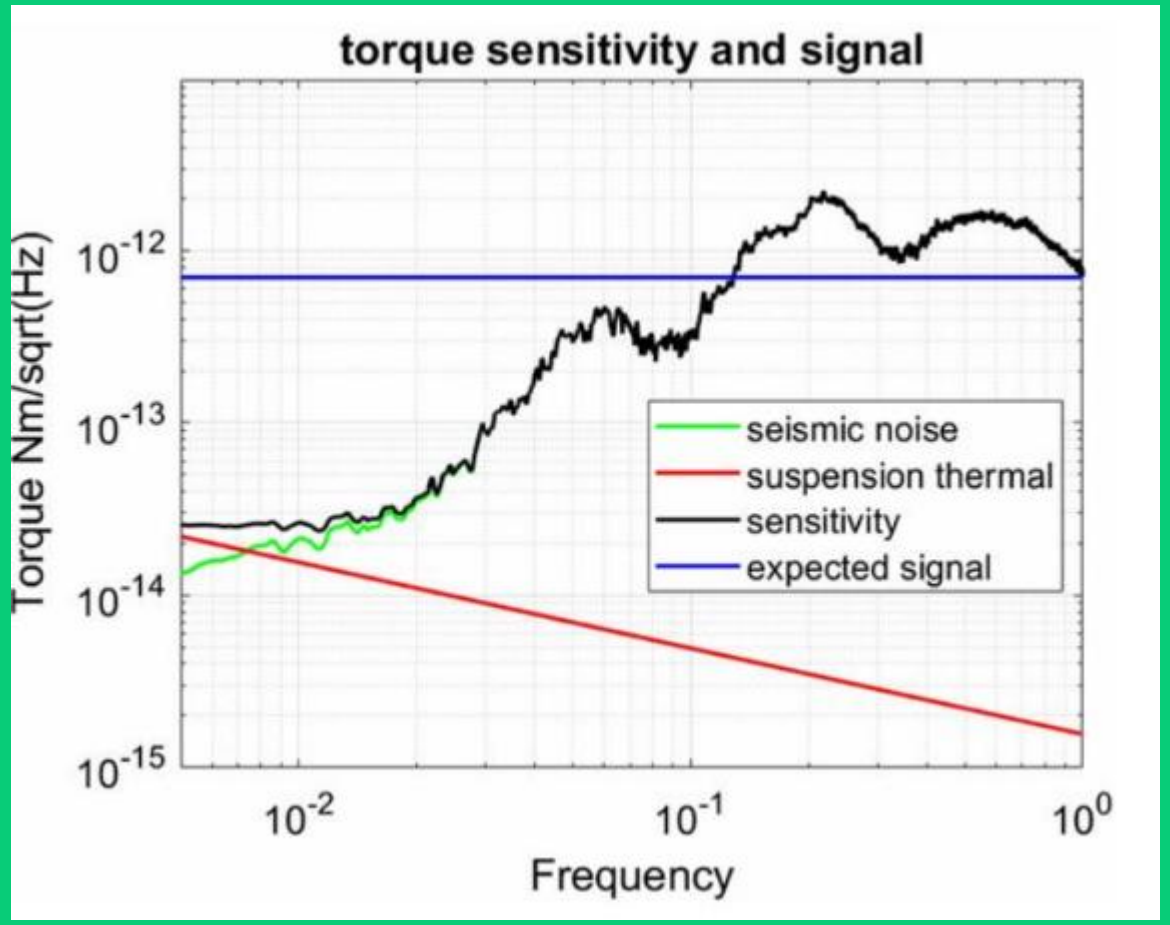
ARCHIMEDES' STRATEGY: *IXNO'YΣΣA*, THE QUIETEST EUROPEAN SITE





Italian candidate to host **Einstein Telescope** – 3rd generation GW detector

ARCHIMEDES' STRATEGY: EXPECTED NOISE BUDGET



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

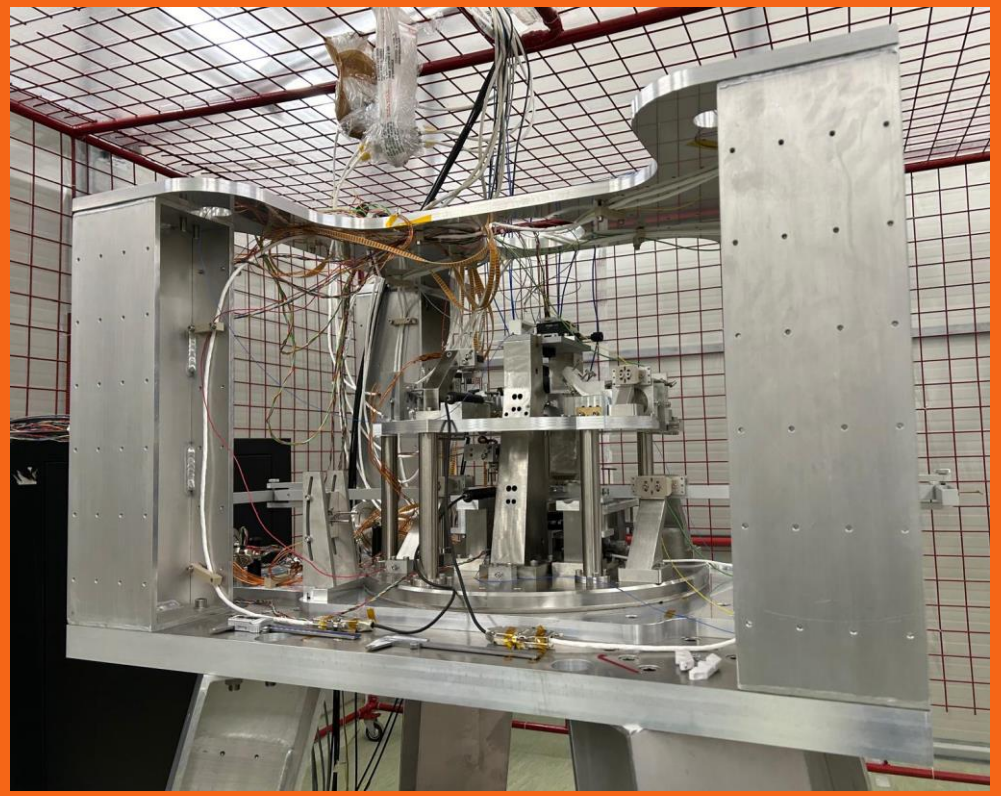
$$|\vec{\tau}| = \left|\vec{F}\right| \cdot 0.7\, m \simeq 3.5 \cdot 10^{-16}\, N \cdot m$$

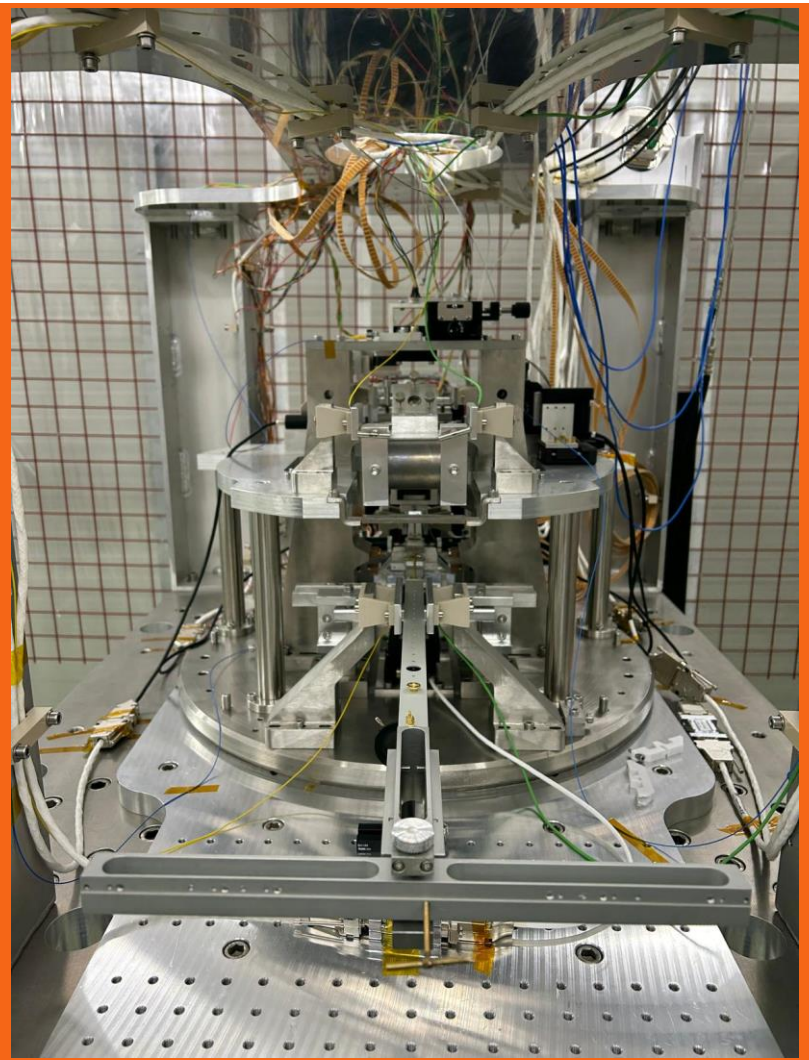
Integration time: $10^6\ s$ (~ 2 weeks)

Spectral Torque Signal:

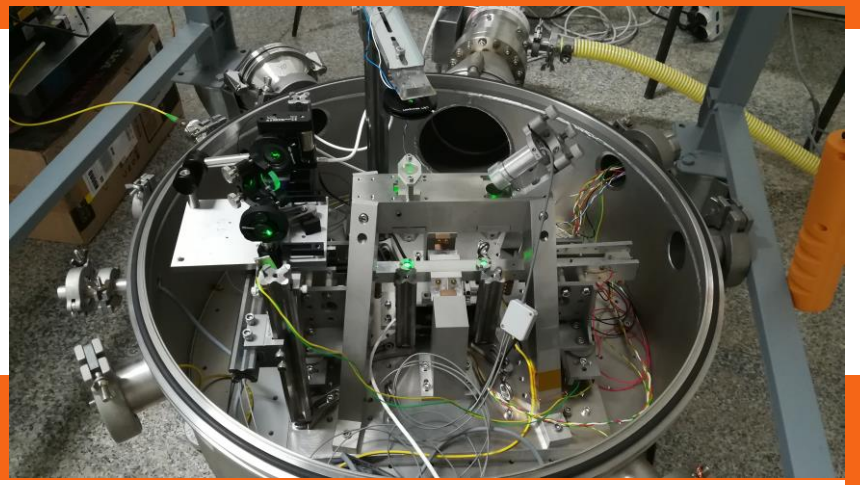
$$\tau_s = 3.5 \cdot 10^{-13}\ \frac{N \cdot m}{\sqrt{Hz}}$$

STATE OF THE ART: ARCHIMEDES' BALANCE



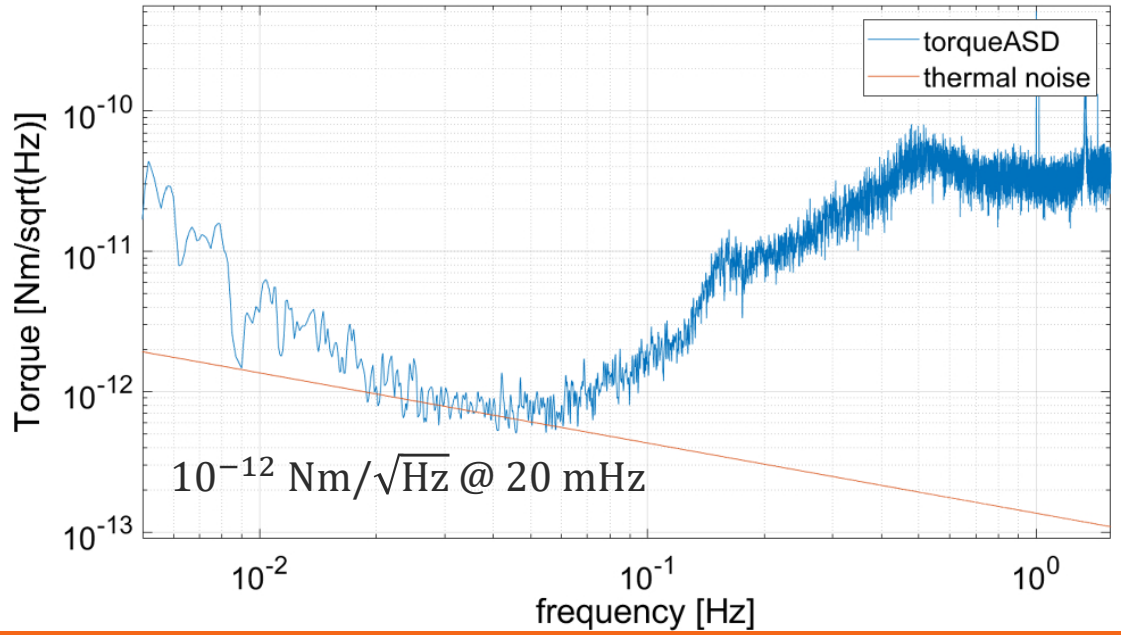


STATE OF THE ART: ARCHIMEDES' PROTOTYPE



Torque sensitivity

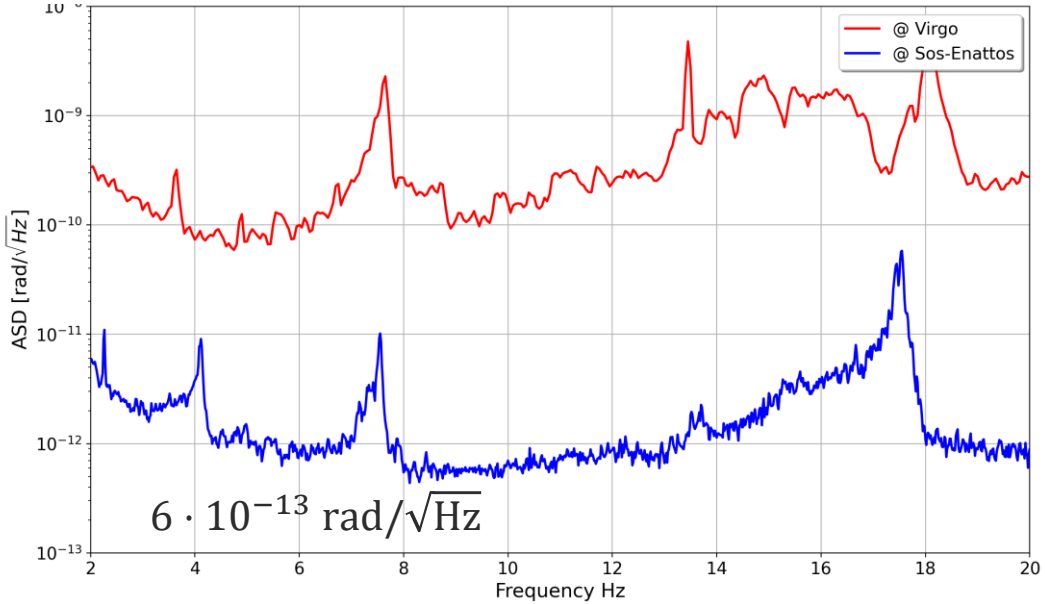
«only» a factor 10 far
from the sensitivity needed for the measurement



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

Tilt sensitivity

world most sensitive tiltmeter in the frequency band 2-20 Hz (interesting for noise subtraction in GW detectors).



A. Allocca, E. Calloni, L. Errico et al, Eur. Phys. J. Plus (2021) 136: 1069

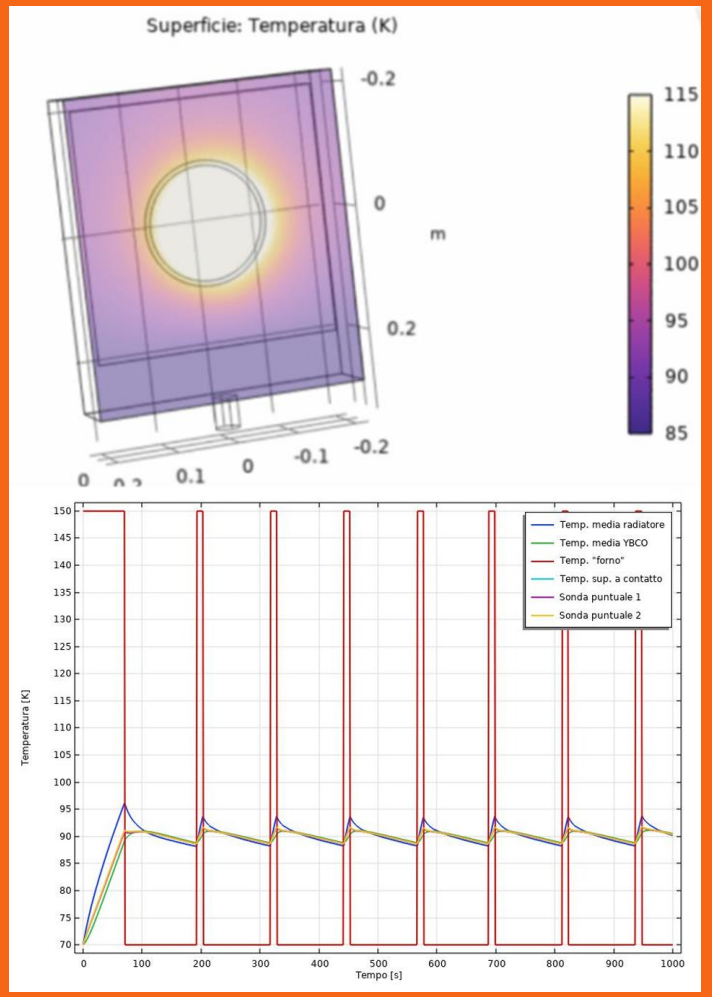
STATE OF THE ART: THERMAL MODULATION

COMSOL heat transfer simulations have shown that a radiative element in contact with the sample is necessary to perform a heating-cooling cycle in around 100 s.

First tests will be performed with a 0.1 mm graphite sheet radiator.

The «oven» prototype has been realized and tested with a heating pad. In the final experiment it will be warmed up with a laser beam.

(Credit by L. D'Onofrio, PhD)



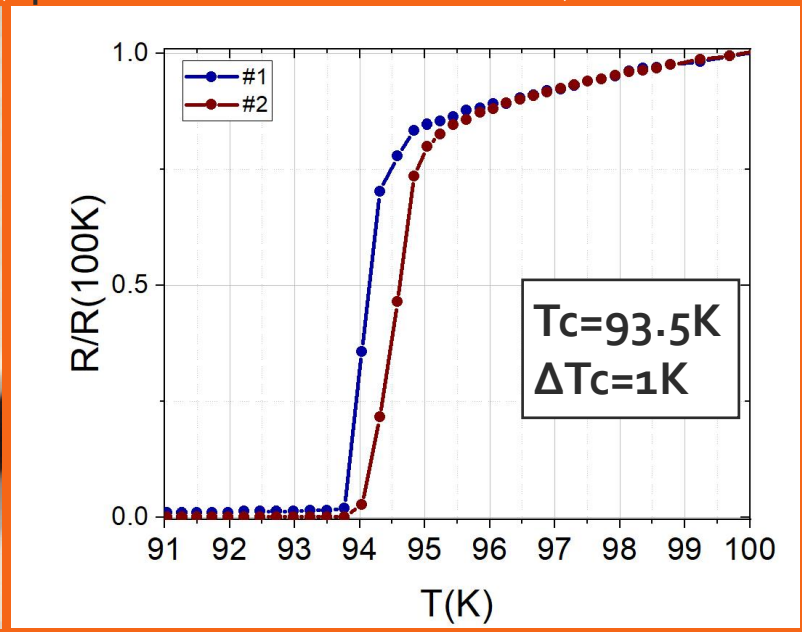
STATE OF THE ART: STUDIES ON CUPRATES (ONGOING)

THEORETICAL:

- No microscopic theory for high-T_c superconductors
- Dielectric - PlasmaSheet model, which showed a «synergy» among stacked Casimir cavities and confirmed expected Casimir energy variation (Eur. Phys. J. Plus (2022) 137: 826)
- Different approaches for TM and TE modes in bulk gave us a better comprehension of the various contribution to Casimir energy variation (Phys. Rev. B 106, 134502)

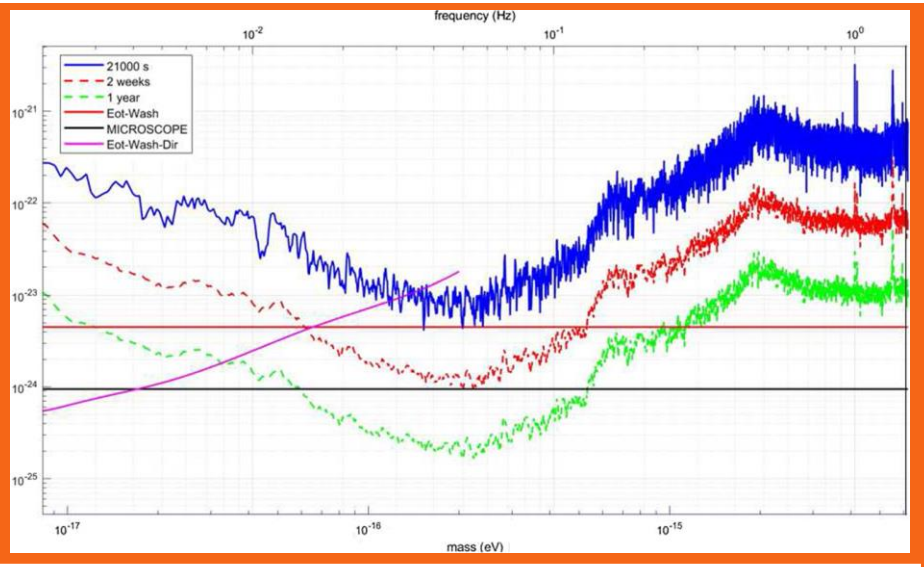
EXPERIMENTAL:

- Large samples, resistivity measurements
- Investigating the feasibility of other measurements (specific heat at transition)



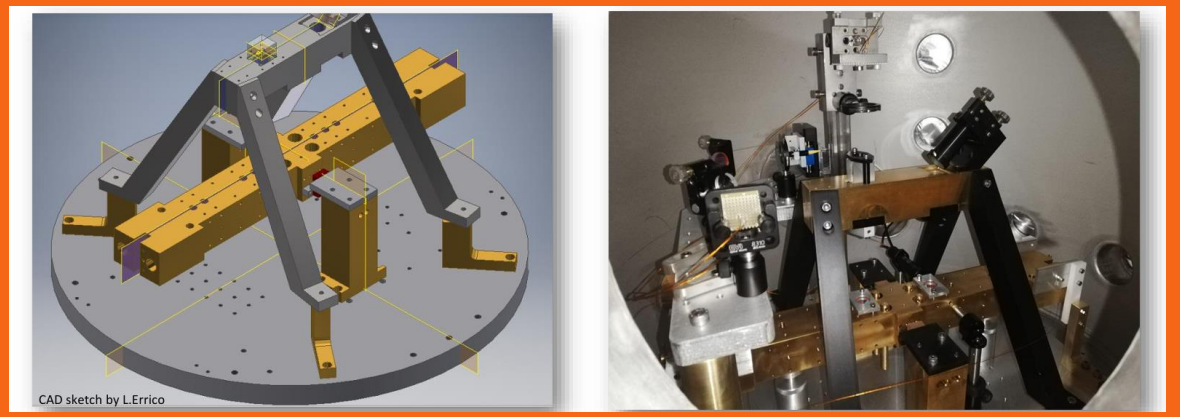
IMPACT ON OTHER FIELDS: DARK MATTER SEARCH AND TILTMETRY

Prototype equipped with counterweights made of different materials, to put upper limits in the direct search of dark matter in the form of ultralight dark photon B-L.



A suspended arm with no samples is useful to monitor tilt-ground oscillations for noise subtraction and geophysical interest.

1 operating in Virgo (Akinetos – «motionless»)
1 to-be operating in SarGrav laboratory
2 to-be operating in PLaNET (Naples, Italy)



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 quietest 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, weight of the heat, …)

THANK YOU!

BIBLIOGRAPHY

- E. Calloni. L. Di Fiore, G. Esposito, L. Milano, L. Rosa - Phys. Letters A, 297, 328-333,
- (2002)
- G. Bimonte, E Calloni, Di Fiore, G. Esposito, L. Milano, L. Rosa - CQG 21 647 (2004)
- G. Bimonte, E. Calloni , G. Esposito, L. Rosa - Phys. Rev D 74, 085011 (2006)
- G.Bimonte, E. Calloni, G. Esposito, L. Rosa - Phys. Rev D 76:025008 (2007)
- G. Bimonte, E. Calloni, L. Rosa - Phys. Rev D 77, 044026 (2008)
- A. Allocca G. Bimonte, E. Calloni, G. Esposito, U. Huebner, E. Il'ichev, L. Rosa, F. Tafuri.,
- Jour. Of. Supercond. And Novel Magnetism. 25, 2557-2565 (2012)
- E. Calloni et al., Eur. Phys. J. Plus (2021) 136:335
- 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)