Weighing quantum vacuum with Archimedes experiment

A. Allocca (UNINA, INFN-NA) and L. Errico (UNINA, INFN-NA) on the behalf of the Archimedes collaboration

ABSTRACT

The interaction between gravity and energy terms coming from Quantum Field Theory is still nowadays a 100-year open problem in Fundamental Physics.

Descriptions of ground states as states with an infinite (but not entirely accessible) energy are unsustainable in General Relativity, where absolute energy has physical consequences. One possible opportunity to investigate this interaction comes from high-Tc cuprates, whose lattice reproduces Casimir cavities at nanoscale. Archimedes experiment will measure the weight variation of such material sample while modulating the internal ground state energy via Casimir effect, trying to establish if virtual photons are coupled with gravity.

The cosmological constant problem

In QED the vacuum state has infinite energy. This is acceptable in Particle Physics, where only energy variations are observable, but not in General Relativity, where the absolute value of the energy counts.
In Pauli's calculus, if the vacuum energy is taken into accounf, the radius of the Universe comes to be only 31 Km! This problem is known as the **cosmological constant problem** [Weinberg, 1989]

Vacuum energy should affect Einstein equations as well as if it was a cosmological constant (and viceversa).

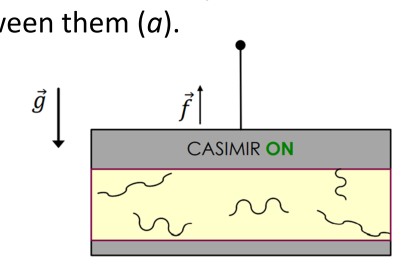
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad T_{\mu\nu}^{vac} = \rho_{vac} g_{\mu\nu}$$

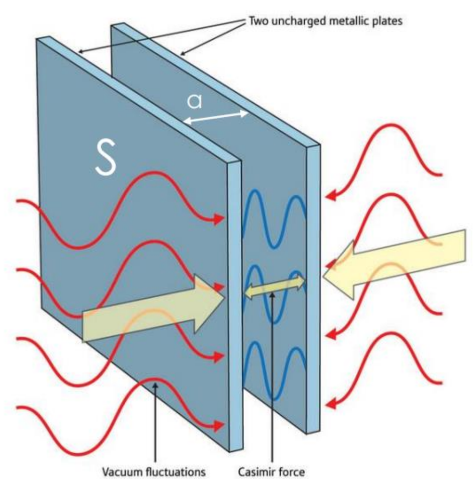
The Casimir energy

Casimir effect (1948) is considered as one of the most direct proofs of the existence of vacuum fluctuations. Given two metallic plates, the Casimir effect is derived considering the zero-point EM energy contained in the cavity volume, when boundary conditions are imposed to the electromagnetic field:

$$E_{reflective} - E_{transparent} \equiv -\frac{\pi^2}{720}\frac{\hbar c}{a^3} S$$

The difference of zero-point energy due to the presence of the metallic plates gives rise to a negative energy, which is proportional to the plates' surface (S) and inversely proportional to the cube of the distance between them (a).





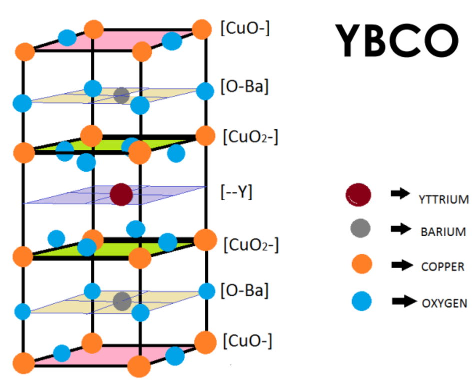
If vacuum and gravity are coupled, Casimir effect could modulate this coupling.

The force that keeps an extended body suspended in a gravitational field depends on its internal energy [1,2,3]. → $\vec{f}$ depends on the vacuum energy inside the Casimir cavity and represents the cavity weight in the GR framework

$$\vec{f} = \frac{E_{casimir}}{c^2}\vec{g}$$

[1] Bimonte, G. et al., Relativistic mechanics in Casimir apparatuses in a weak gravitational field, (2007)
[2] Calloni, E. et al, Towards weighing the condensation energy to ascertain the Archimedes force of vacuum. Phys. Rev. D2014,90, 022002.
[3] Avino, S., et al, A. Progress in a Vacuum Weight Search Experiment. Physics2020,2, 1–13.

How to measure it?



In order to have the highest Casimir energy stored in the sample it's necessary to use:
1) Casimir cavities with *a* (the distance between metallic plates) as small as possible
2) A material sample containing as many Casimir cavities as possible.

Furthermore, it's necessary to use *tunable* Casimir cavities, whose Casimir effect can be modulated without disassembling the cavities (the experiment would be not feasible otherwise).

Such requirements are fulfilled by **superconductive layered crystals**, whose lattice is a natural overlaying of nanoscopic Casimir cavities (thus, with the densest concentration of cavities) and Casimir effect is tuned together with the superconductive transition.

Modulation in temperature (around T_C) → Modulation of $E_{Casimir}$

Among the superconductive layered crystals, **high-T_C cuprates** (as YBCO, in the picture) should produce the most intense weight variation (the physical signal to measure) due to Casimir energy variation, since at the end of superconductive transition

$$\Delta E_{cond} \approx \Delta E_{Casimir} \qquad \text{and} \qquad \frac{\Delta E_{Casimir}}{E_{Casimir}} \simeq 10^{-4}$$

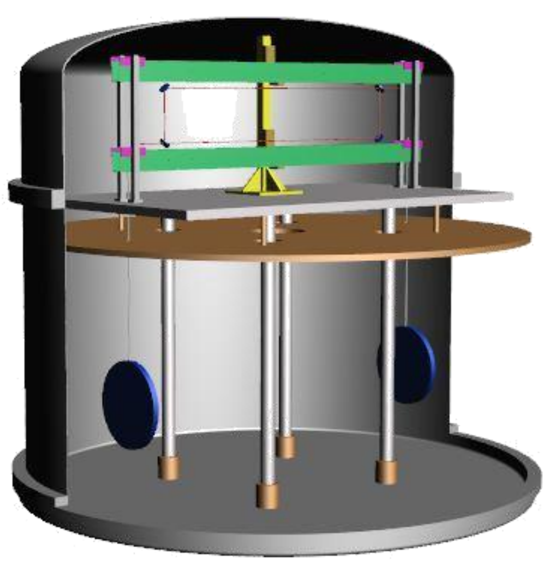
$$(\Delta E_{cond} + \Delta E_{Casimir} = \Delta E_{tot})$$

(for other crystals, relative Casimir energy variation is orders of magnitude smaller).

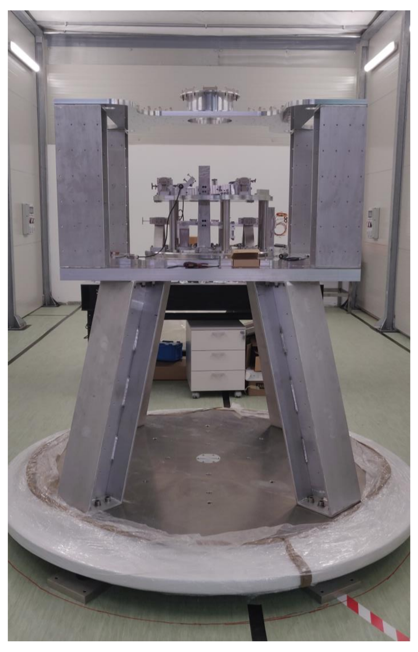
The Archimedes experiment

The experiment consists into measuring the weight variation of a YBCO sample while its vacuum energy (i.e. the number of virtual photons stored inside the Casimir cavities composing it) is changed through a thermal modulation.

The experimental setup to perform this procedure has many challenging features:
- **Seismically suitable environment:** the entire experiment has to be placed in a seismically quiet environment, since seismic noise can severely affect the sensitivity of the balance measuring weight variation;
- **Cryogenic system for human-size loads:** the entire apparatus (YBCO sample, thermal modulators and the balance measuring weight variation) has to be kept at $T \simeq T_c^{YBCO} \simeq 90\ K$, since no heat-intrusion has to occur during the normal/superconductive transition (see poster [4] for more details);
- **High-precision opto-mechanic devices:** the expected weight variation is so weak that no commercial scale has the sensitivity to detect it. Archimedes experiment requires the use of a specifically designed beam-balance, whose tilts are monitored by an interferometric readout.



3D schematic of the final Archimedes setup



Picture of the final setup installed at Sos-Enattos

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

$$|\vec{F}| = \left|\frac{\Delta U_{Casimir} \cdot V}{c^2}\vec{g}\right| \simeq 5 \cdot 10^{-16} N$$

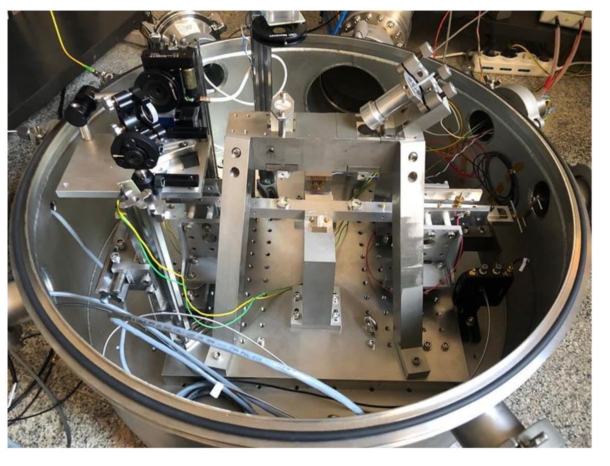
Integration time: 106 s (~ two weeks)

$\boxed{\textbf{Spectral torque signal:} \quad \tau_s = 3.5 \cdot 10^{-13}\ \mathrm{Nm}/\sqrt{Hz}}$

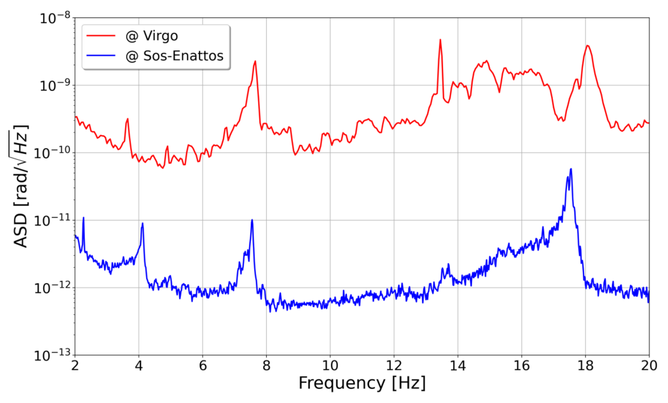
- The final balance has been installed in the SarGrav surface laboratories, at the Sos-Enattos site. Thanks to the low seismic and anthropic noise of the site, environmental disturbances are significantly reduced.
- The final beam-balance will be composed by a measurement arm 1.4m long and a reference arm, which will measure and subtract the ground tilt from the main signal.
- The whole experiment will be cooled in a cryostat composed by three independent shields.
- In the final configuration, it is foreseen to bring the experiment underground, to further reduce seismic contributions.

[4] V. Mangano «Thermal modulation of YBCO samples through radiation heat transfer for the Archimedes experiment»

The balance prototype at SarGrav and first tilt measurements



Picture of the balance prototype installed at Sos-Enattos



Comparison between tilt measurement at Virgo (red) and Sos-Enattos (blue) [3].

The balance prototype is currently installed in the SarGrav surface laboratories, at the Sos-Enattos site.

When the balance has no samples hanged to its hands, it behaves as a rotational sensor, which is a **tiltmeter**.

As described in poster [5], the prototype arm is 50 cm long and is suspended through two thin suspensions. The momentum of inertia and the suspension restoring force are kept as low as possible for the balance to have a very high torque-to-tilt transfer function. To satisfy these conditions, the arm is hollow and made of Aluminum, which keeps its weight low; moreover, the suspensions section is made as thin as possible, and two flexible joints of Cu-Be 0.5 mm × 0.1 mm are used for this purpose. If the balance center of mass is kept within 10 µm from the suspension point, its resonance frequency results to be around 25 mHz.

A coarse and a fine readout systems are used to sense the arm position. The first consists of an optical lever, while the finer positioning is provided by a Michelson interferometer with unequal arms. Common noise reduction is however guaranteed by arm length equalization through an optical delay line and input power subtraction.

To keep the prototype arm in its working point, two electrostatic actuators are used at each end of the arm. The interferometer output signal is fed to a control system which suppresses the low frequency motion, leaving the arm free to oscillate at frequencies higher than 1 Hz. In this configuration, the first measurement of the tilt in the Newtonian Noise frequency band was performed at the Sos-Enattos site, showing that the angular noise level is at least two orders of magnitude lower than the Virgo site, where the prototype was previously installed [6,7].

[5] L. Pesenti and D. Rozza, "The Archimedes' prototype at Sar-Grav laboratory"
[6] Calloni, Enrico.; Archimedes Collaboration.; Virgo Collaboration. High-bandwidth beam balance for vacuum-weight experiment and Newtonian noise subtraction. Eur. Phys. J. Plus10362021,136, 335.
[7] Allocca, A.; et al; Archimedes Collaboration. Picoradiant tiltmeter and direct ground tilt measurements at the Sos Enattos site. Eur. Phys. J. Plus2021,136, 1069.

Torque sensitivity at low frequency

To detect the signal, a thermal modulation will be performed to increase the samples temperature from $T < T_c^{YBCO}$ (where YBCO behaves as a "string" of Casimir cavities) to a higher value, so to bring the YBCO to the normal state. This modulation will be performed at few tens of mHz, to allow the system thermalization at each modulation. As highlighted above, we expect a torque signal of about $3.5 \times 10^{-13} Nm/\sqrt{Hz}$ for an integration time of two weeks.

The first measurement of torque at low frequency has been performed with the balance prototype and is shown in the figure. Accounting for the loop gain, around 10 mHz the torque sensitivity has been measured to be around $5 \times 10^{-12} Nm/\sqrt{Hz}$.
This value is about one order of magnitude above the signal that we aim to measure. However, this preliminary result is encouraging, as many improvements will be implemented in the final setup. Indeed, a further reduction of the seismic noise will be performed thanks to the reference arm. Furthermore, the balance resonance frequency will be further lowered, and more performing suspensions will be used, which will allow to decrease the signal glitchness in the frequency band of interest.