The Weight of Vacuum

INFN Istituto Nazionale di Fisica Nucleare
Università degli Studi di Napoli Federico II
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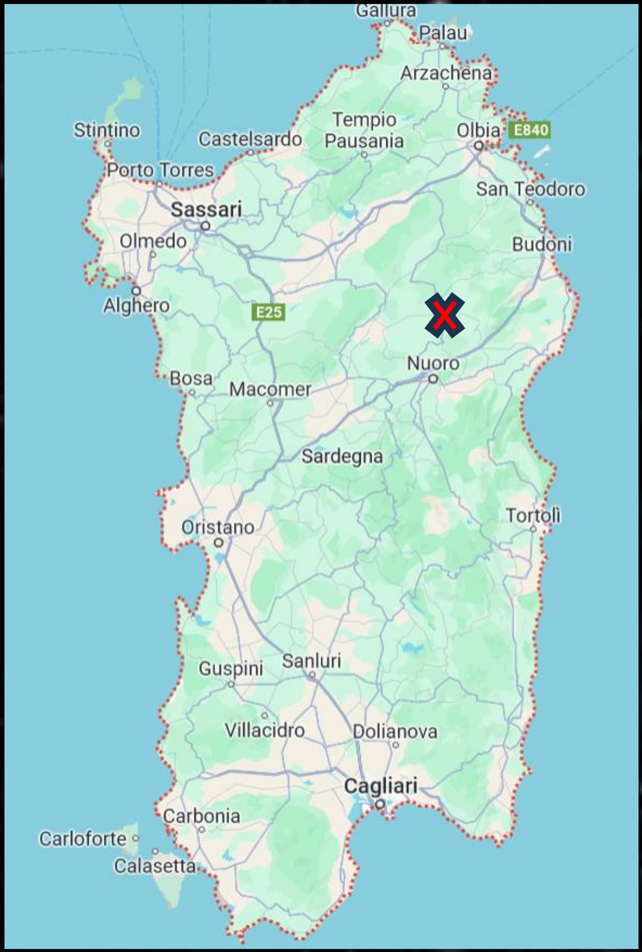
Università di Cagliari
Sapienza Università di Roma
EGO European Gravitational Observatory
Università degli Studi di Milano Bicocca
Aix Marseille Université
INO-CNR Istituto Nazionale di Ottica



E. Calloni – 2025-06-23

Archimedes: an interdisplinary experiment

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 Motivations

Since the birth of Quantum Mechanics the question rised if the zero-point energy gravitates (Nerst, Pauli…) –The first attempt of by Pauli

$$\sum \frac{1}{2}\hbar\omega \rightarrow \infty$$

Pauli inserted a cut-off on the minimal length (electron classical radius) and inserted the value of the energy density in the static Eisntein solution

The expected radius of the Universe was: 31 Km!

Cosmological constant problem: "why the universe exhibits a vacuum energy density much smaller than the one resulting from application of quantum mechanics and equivalence principle?" (Weinberg **Rev.Mod.Phys. 61 (1989) 1-23**)

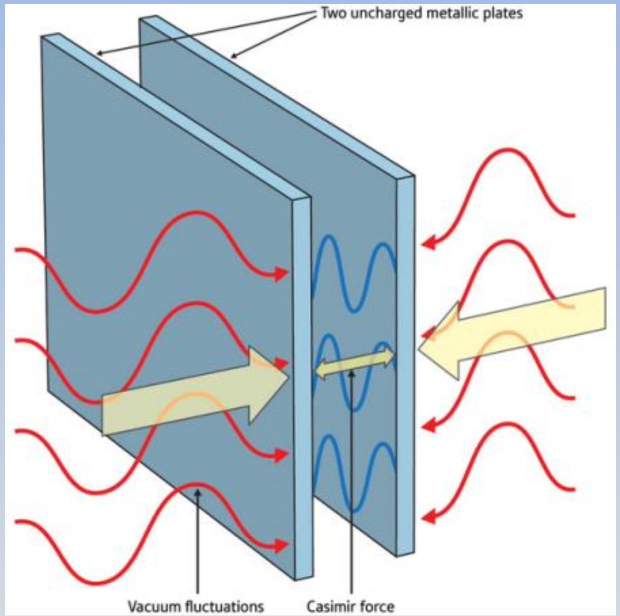
Main question still open with no experimental answer

Does vacuum fluctuations gravitate or not?

Does vacuum pressure exhibits the red-shift ?

The reality of macroscopic vacuum fluctuation.

The Casimir effect It is derived considering the zero point e.m. energy contained in a Casimir cavity, i.e. in the volume defined by two perfectly reflecting parallel plates



$$E = \sum \frac{1}{2}\hbar\omega$$

If the plates are perfectly reflecting the modes that can oscillate must have discrete wavenumbers on vertical axes $k_z = n\pi/a$ while all values are allowed for k_x e k_y

$$E = \frac{hcL^2}{2} \sum_{n=-\infty}^{n=\infty} \int \frac{d^2k}{(2\pi)^2} \sqrt{k^2 + \left(\frac{n\pi}{a}\right)^2} \longrightarrow \infty$$

The regularization is made by determing the Casimir Energy as the <u>change</u> in energy when the plates are at distance "a" with respect to the plates having a→infinity

$$E_{reg} = E(a) - E(\infty)$$

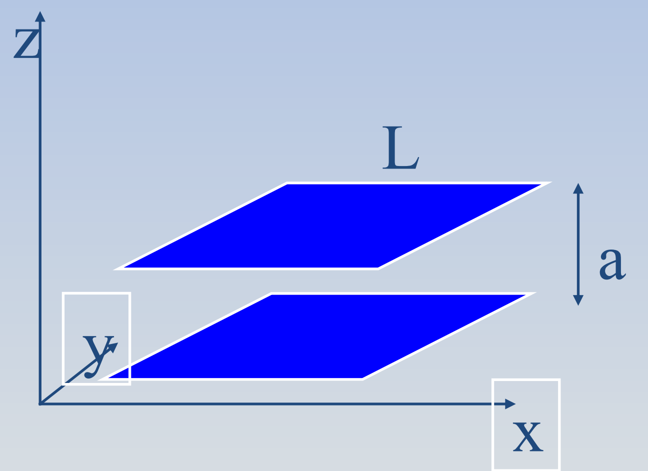
- **Casimir Energy** $E_{reg} = -\frac{\pi^2 L^2 hc}{720 a^3}$

- **Casimir Pressure** $P_C = \frac{1}{L^2}\frac{\partial U}{\partial a} = -\frac{\pi^2 hc}{240 a^4}$ $= 1.3 \times 10^{-3}\ N/m^2 (1\mu m/a^{4})$

First prediction: Casimir 1948
First measure (force): Sparnay 1956
First measure (force) in the original flat-flat configuration: Carugno: 2002
Presently tested (force) with an accuracy of 0.5% (Mohideen: 2005)
(No problems in QFT in flat space-time)

Weighing the vacuum

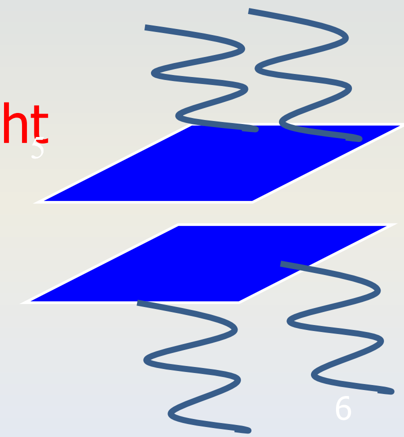
The idea is to weigh a **rigid** Casimir cavity when the vacuum energy is modulated by changing the reflectivity of the plates. The forces along z are



$$f_\nu = -\frac{1}{\sqrt{-\det g}}\frac{\partial}{\partial x^\mu}\left(\sqrt{-\det g}\, T_\nu^{\ \mu}\right) + \frac{1}{2}\frac{\partial g_{\rho\sigma}}{\partial x^\nu} T^{\rho\sigma},$$

$$\vec{F}_{tot} = \frac{|E_C|}{c^2} g\ \hat{z}$$

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



IN ANALOGY WITH ARCHIMEDES FORCE

ELSEVIER

20 May 2002

Physics Letters A 297 (2002) 328–333

PHYSICS LETTERS A

www.elsevier.com/locate/pla

Vacuum fluctuation force on a rigid Casimir cavity in a gravitational field

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Received 24 September 2001; received in revised form 4 April 2002; accepted 5 April 2002

PHYSICAL REVIEW D **74,** 085011 (2006)

Energy-momentum tensor for a Casimir apparatus in a weak gravitational field

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(Received 6 June 2006; published 10 October 2006)

PHYSICAL REVIEW D **76,** 025008 (2007)

Relativistic mechanics of Casimir apparatuses in a weak gravitational field

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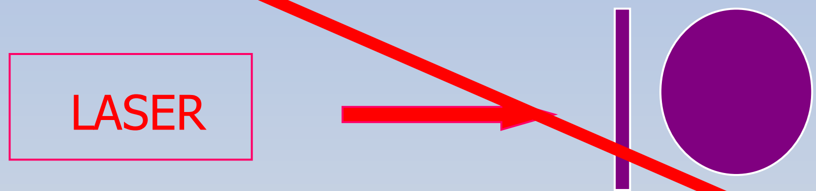
(Received 7 March 2007; published 6 July 2007)

Experimental problem: <u>modulate</u> Casimir energy without exchanging too much energy with the system (to not destroy the possibility of measurement and control) and measure it.



The energy E sent to the film is about 5x10^(5) J
The variation of casimir energy ΔE_{cas} is about 2.5x10^(-19) J

The efficiency is $\varepsilon = \Delta E_{cas}/E$ = 10^(-14)

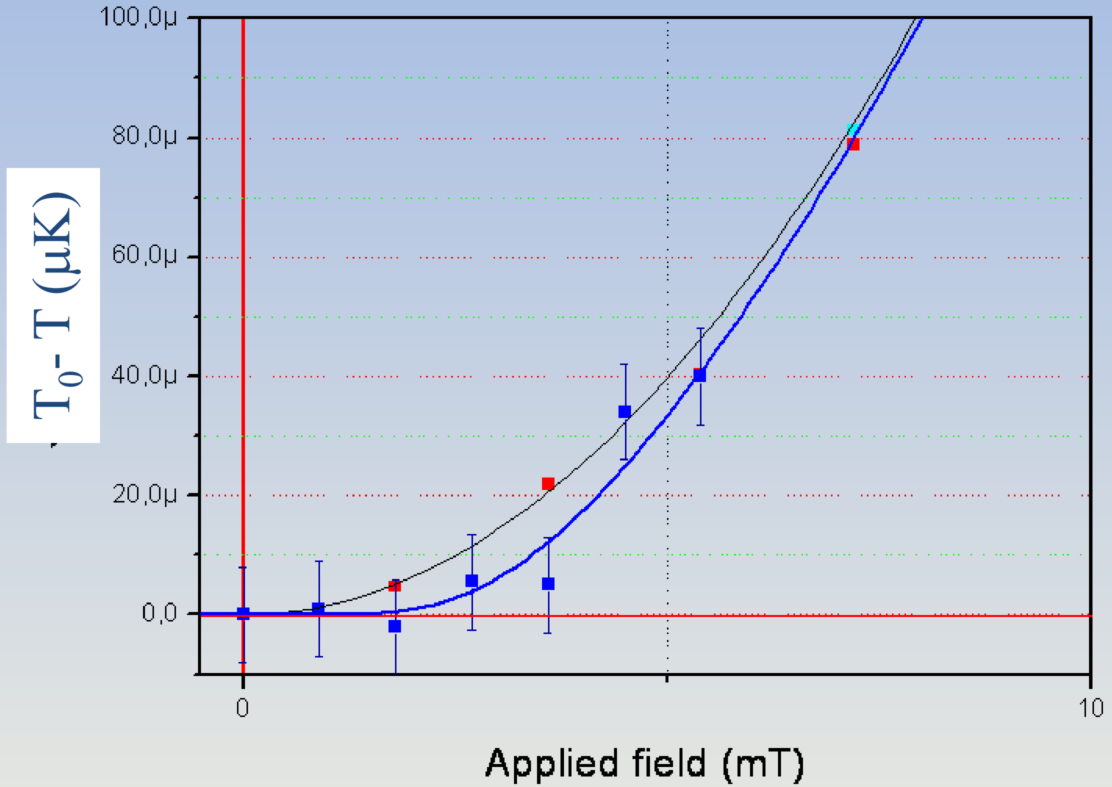
Modulation of Casimir energy with superconductors (type I)

Use of superconductors

- The 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 of the same order, or even dominates, the total transition energy

$$\frac{V}{2\mu_0}\left(\frac{B_{c\|}^{\mathrm{cav}}(T)}{\rho}\right)^2 = \mathcal{E}_{\mathrm{cond}}(T) + \Delta E_{\mathrm{cas}}(T)$$

Results and references on energy modulation – Aladin Experiment



The data are 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)

Use of Stratified high Tc superconductors

IOP Publishing Journal of Physics A: Mathematical and Theoretical

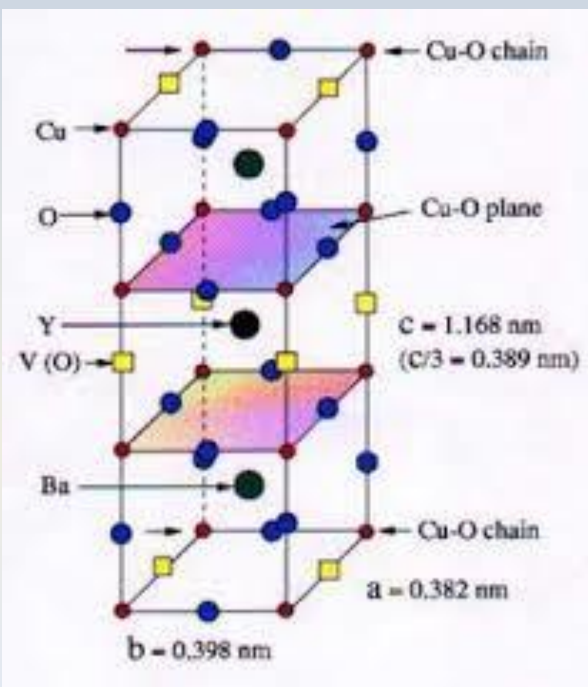
J. Phys. A: Math. Theor. **41** (2008) 164038 (5pp) doi:10.1088/1751-8113/41/16/164038

On the Casimir effect in the high-T_c cuprates

Achim Kempf

Departments of Applied Mathematics and Physics, University of Waterloo, ON N2L 3G1, Canada

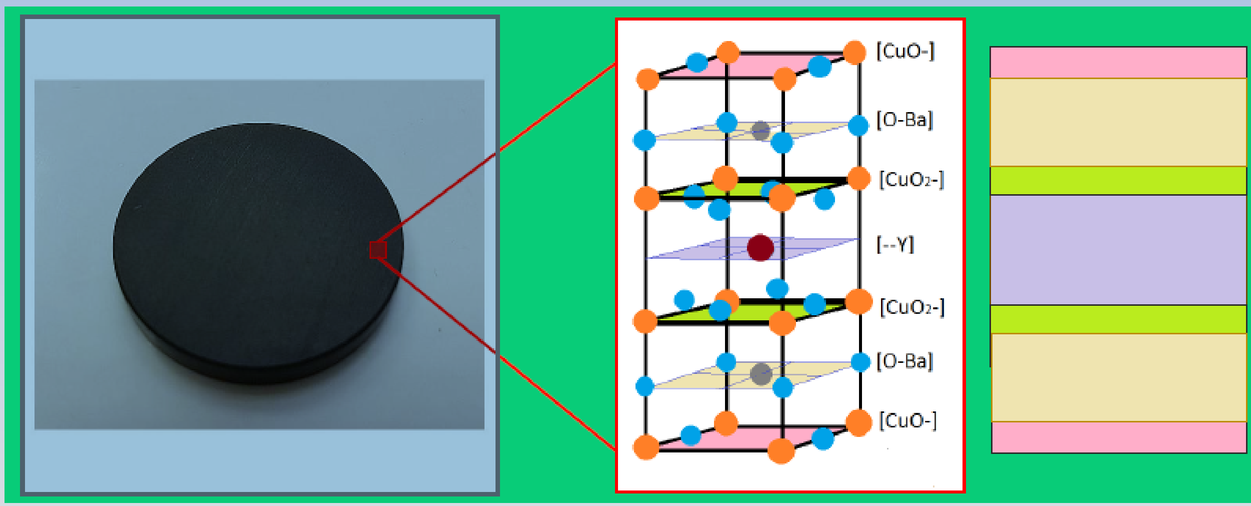
In normal state the plane (that will become superconducting) is a very poor conductor → good variation of Casimir energy at the transition



$$\Delta\eta_E = \frac{\Delta E_C}{E_C} \approx 10^{-4}$$

The variation of casimir energy can be a significative fraction of the whole energy condensation

Experiment method : weighing the condensation energy of Type II superconductors and modulate the transition to modulate the weight



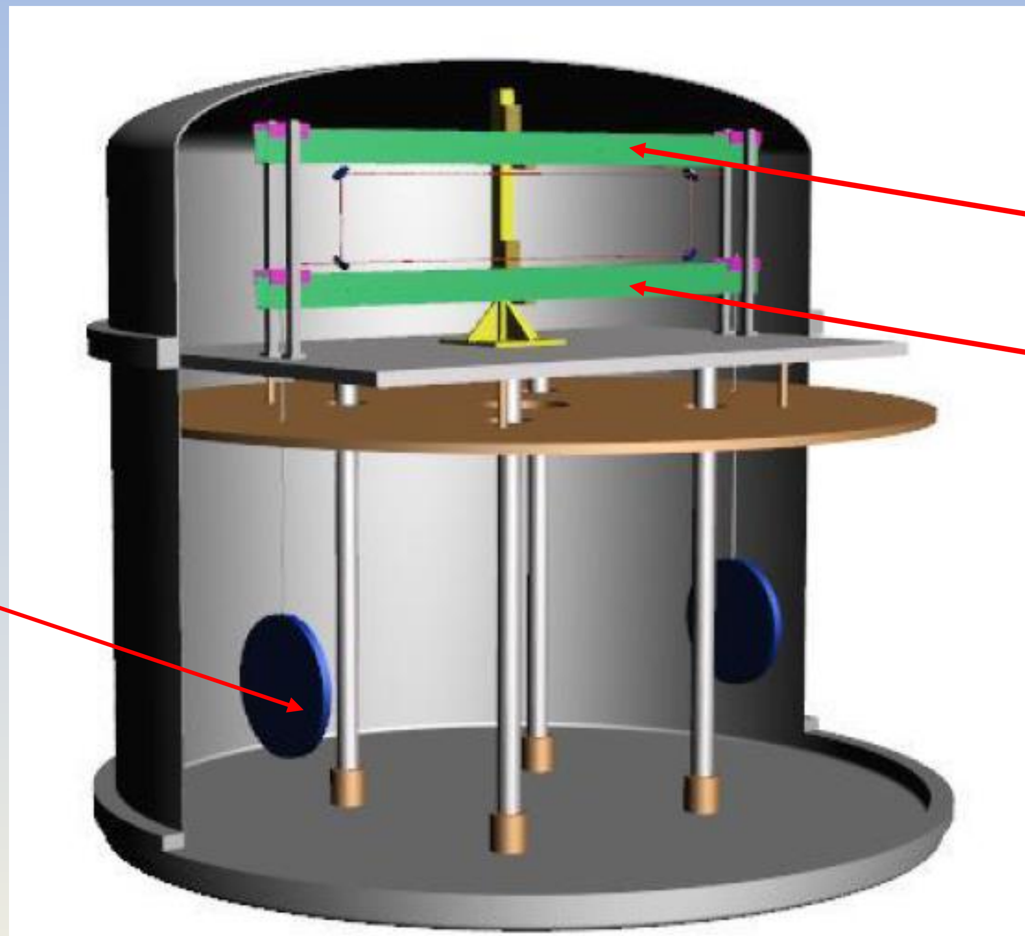
Millions of «Casimir cavities»

Macroscopic "crystals"

Expected weight modulation

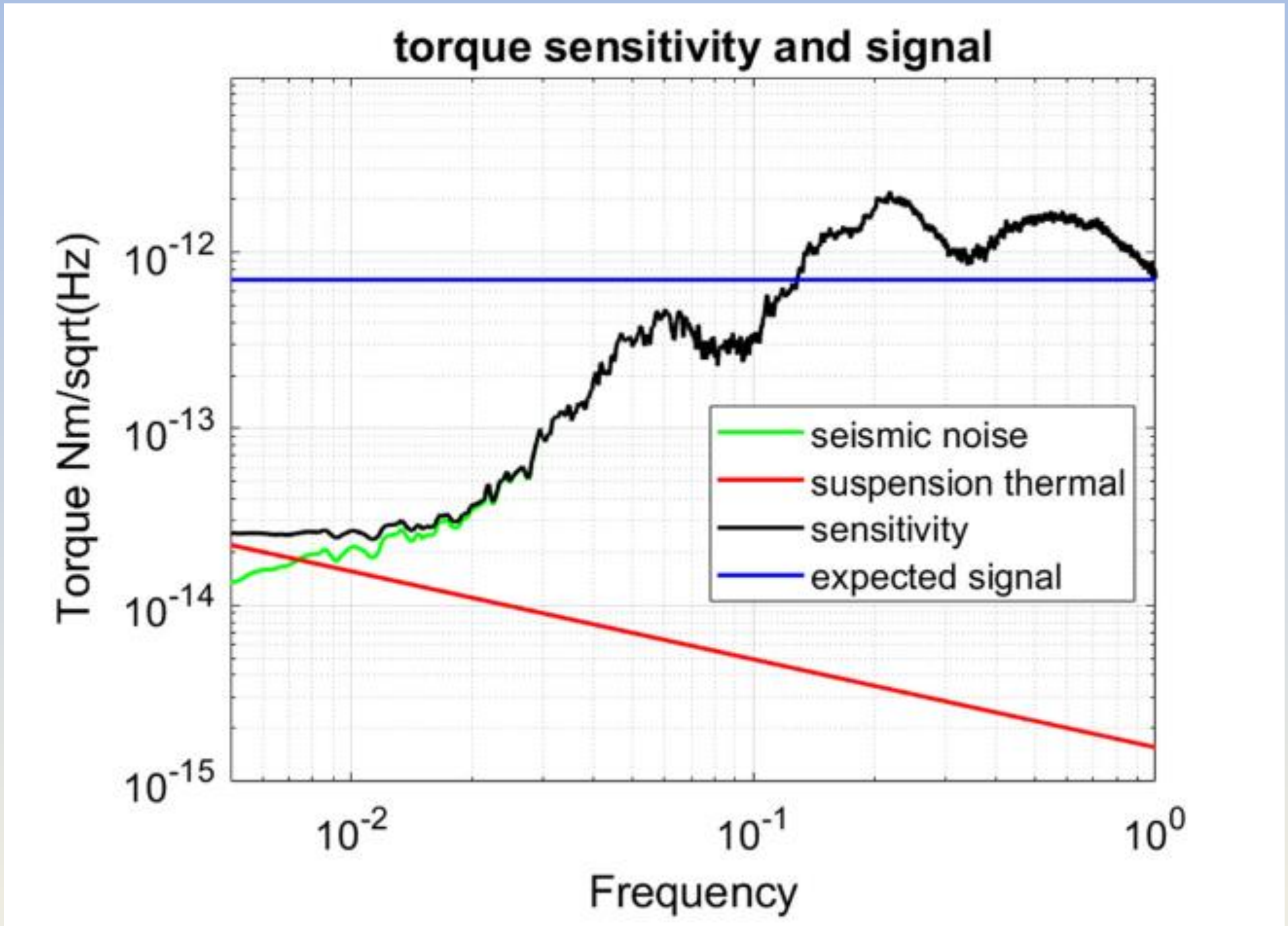
$F = 5*10^{-16}$ N

Measurement scheme



Use a beam-balance → modulate the force by modulating the temperature of the superconductor so that it makes transitions bewteen Normal and superconducting state - Expected modulation of force $F = 5*10^{-16}$ N

Expected sensitivity



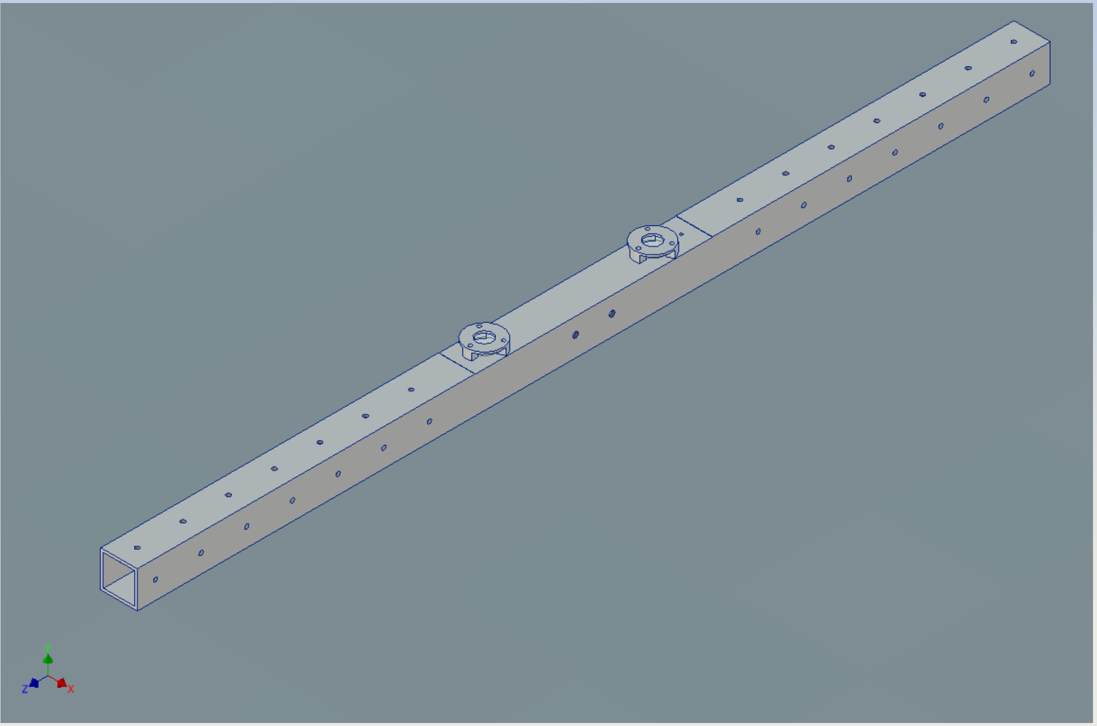
Sensitivity and signal in one-month integration time

The experiment

What is needed

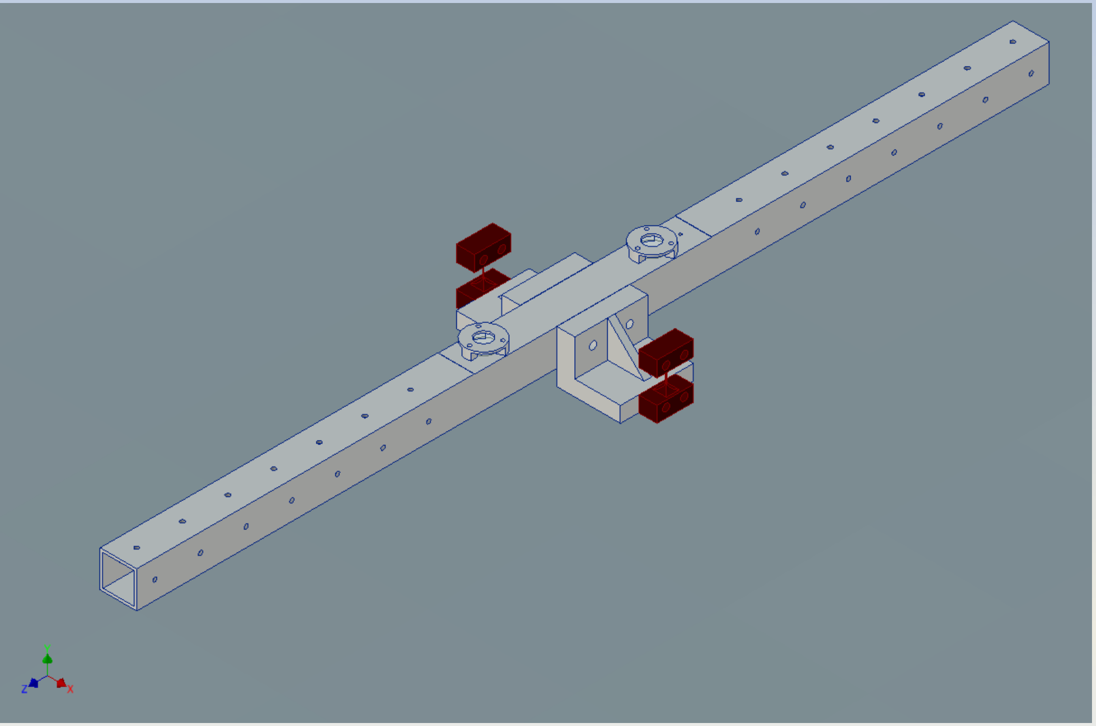
- ❑ An extremely sensitive cryogenic balance
- ❑ A suitable modulation technique & sample choice
- ❑ A very low seismic noise site

Balance prototype



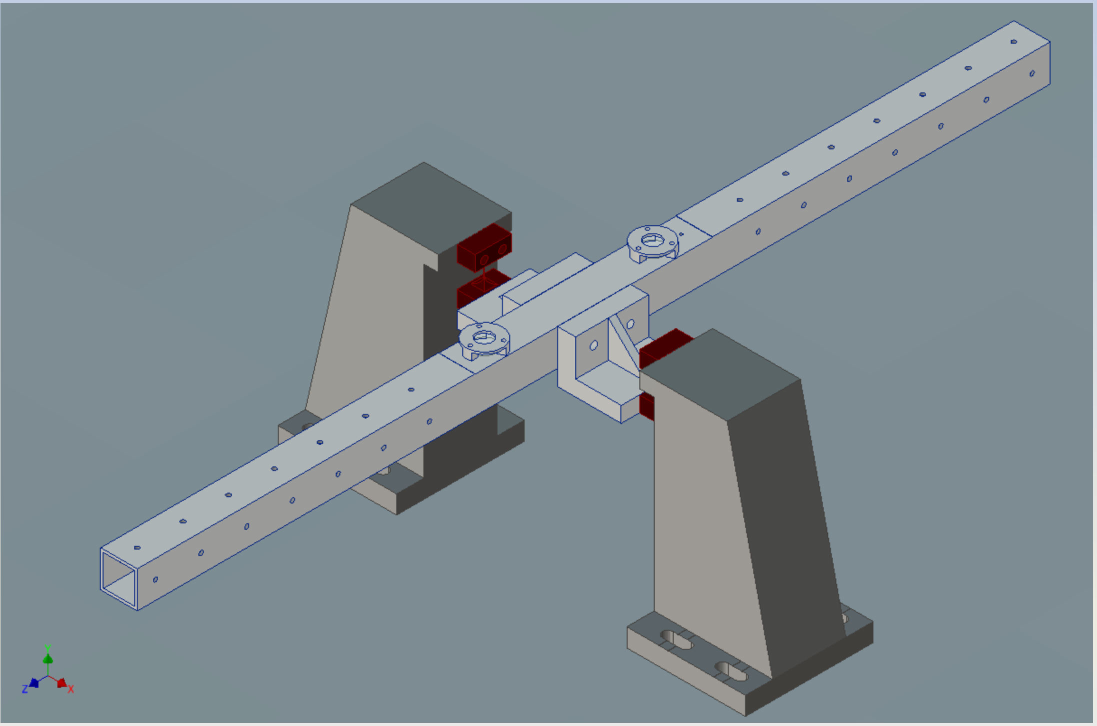
- 50 cm long arm with low momentum of inertia

Balance prototype



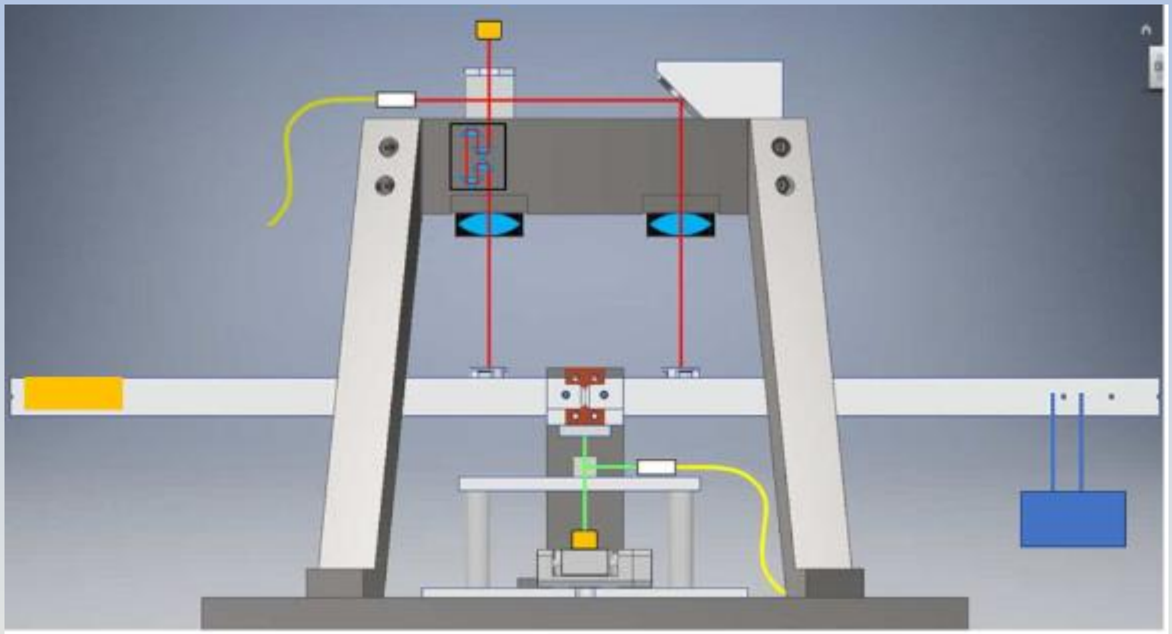
- 50 cm long arm with low momentum of inertia
- Suspended through **thin flexible joints** (Cu-Be, 100 µm x 500 µm), very similar in design to LIGO tiltmeters (Venkateswara et al., 2014)

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** ($\approx 10\ \mu m$)

Optical Read-Out



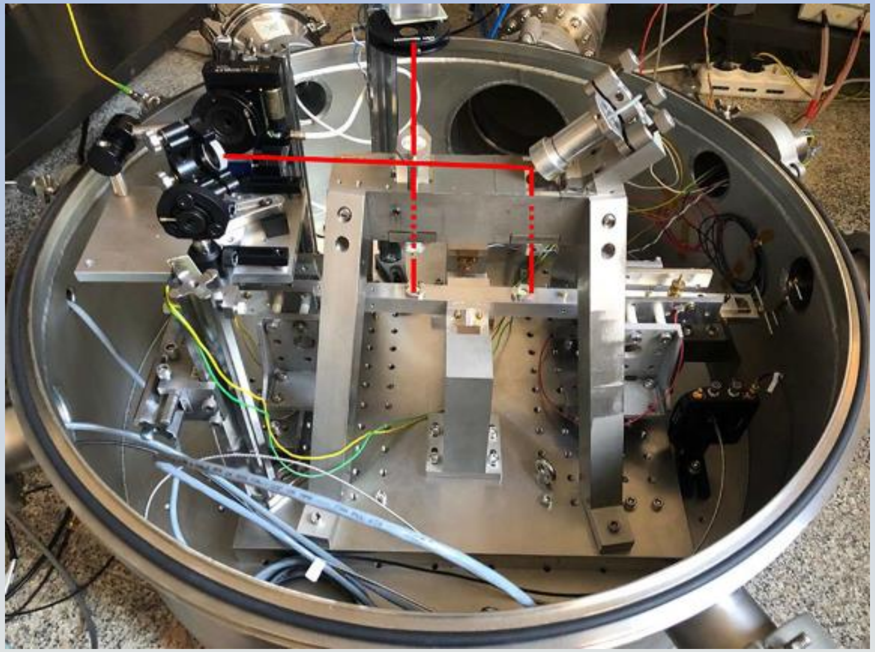
The interferometer is kept in the working point with a feed-back system

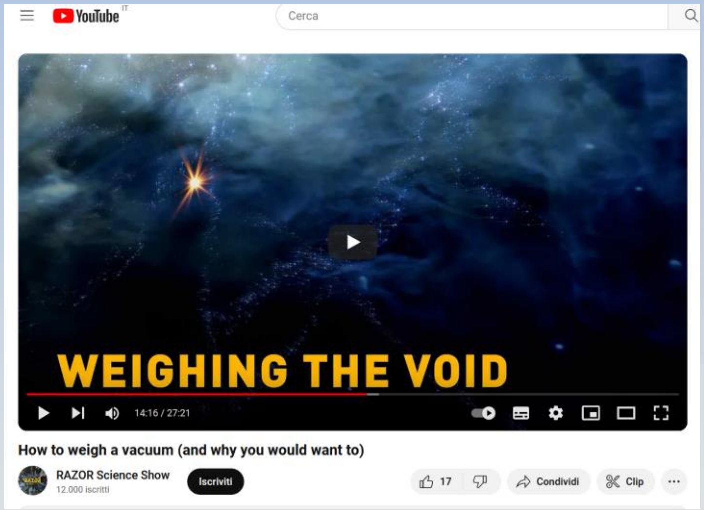
Tilts w.r.t. the ground are read finely with a **Michelson interferometer**

Optical lever only as coarse positioning sensor

The Balance prototype

[How to weigh a vacuum (and why you would want to) (youtube.com)](https://youtu.be/oWDZBUeBQzk)

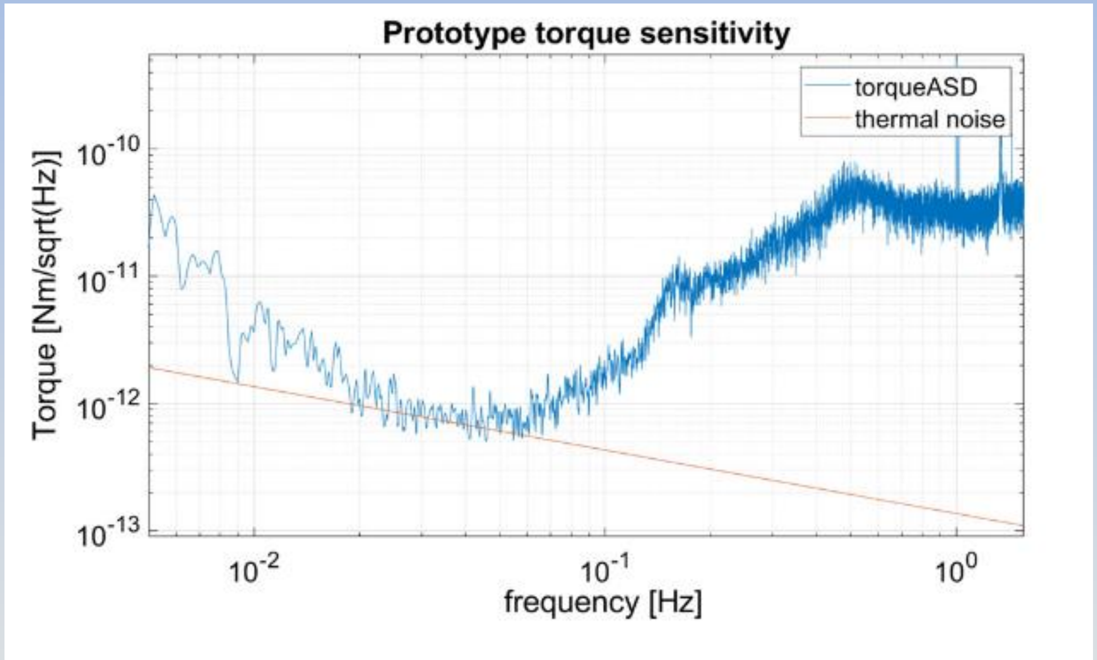




Laser light path in red

https://youtu.be/oWDZBUeBQzk
14.56

Prototype results



Best sensiitivity of the balance Prototype – compatible with thermal noise limit

The prototype balance with thermal patches

Lessons Learned

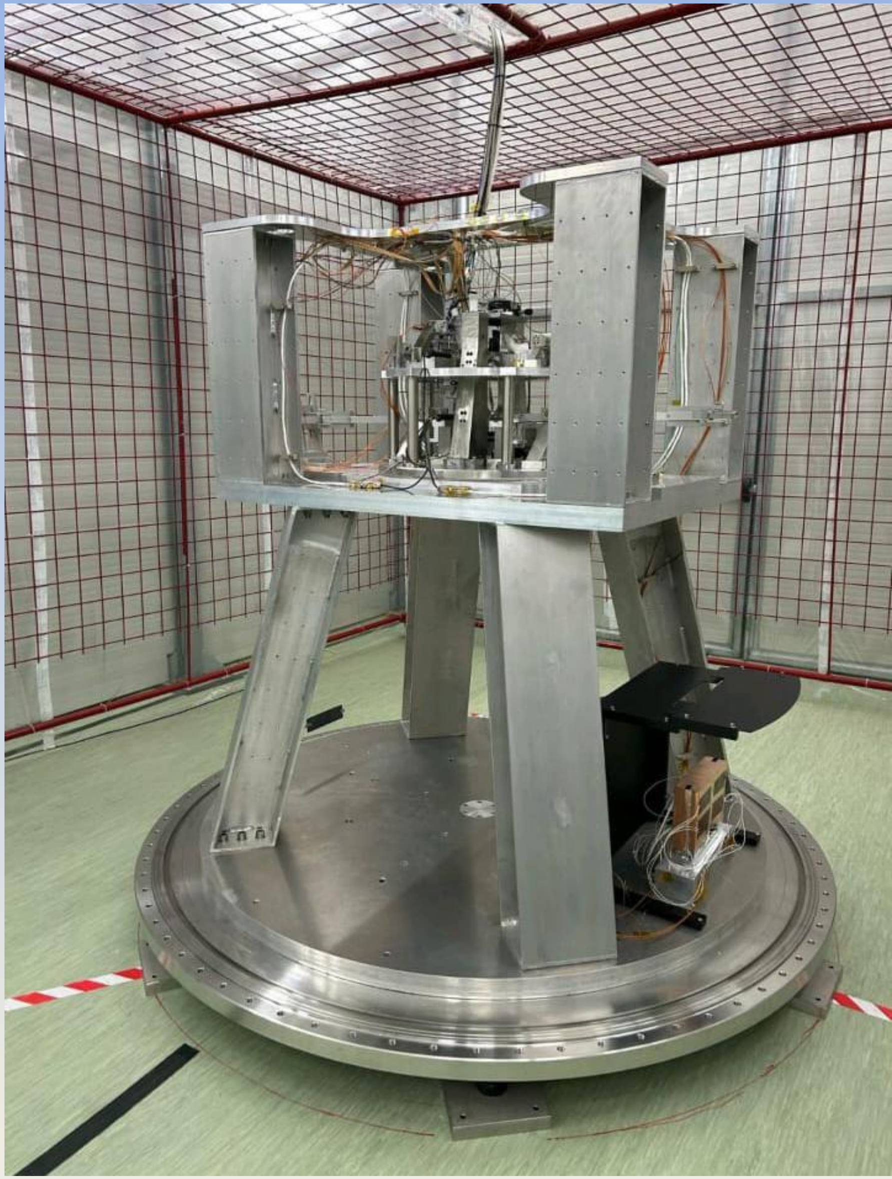
1) Verification of efficiency of optical read-out and control systems
2) Importance of low environmental noises (pumps, air conditioning, seismic noise)
3) Importance of environmetal temperature stability

The final apparatus: cryostat

The cryostat has been completed and tested by the end of July. It is now ready to be sent to the site. Presently we are considering where to have it sent. Indeed timescale requires that we start the cryogenic activities in the temporary building, so for the moment the cryostat is hosted in the factory.

The final balance and the start of the commissioning

Search for spurius electromagnetic signals

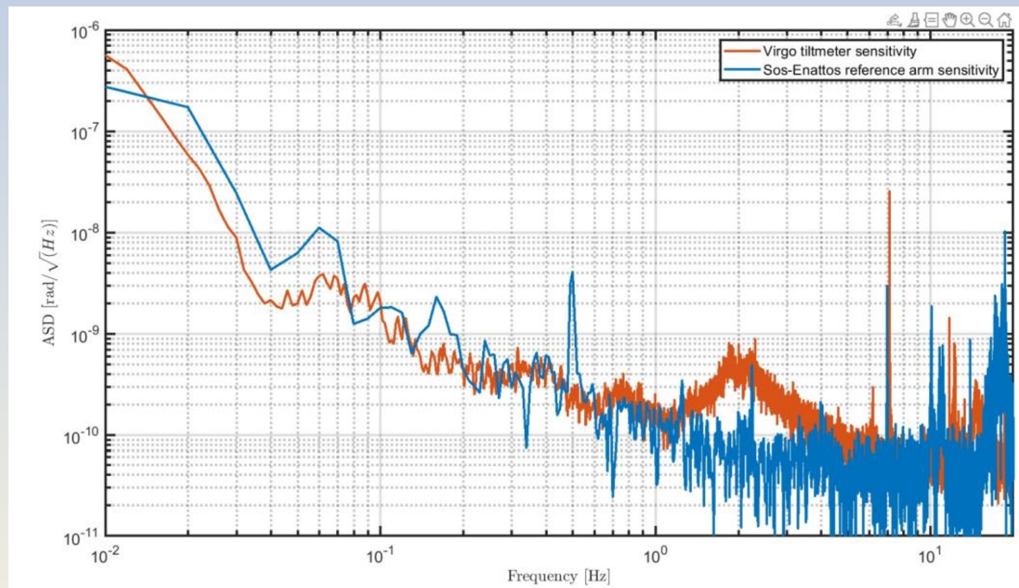


The balance suspending two different test samples – one sample is inside the owen

The very first data of the balance under vacuum

- The lock is acquired and is stable with the reference arm suspended (not obvius because the reference arm is optically more complex with respect to measurmenent arm)
- All connections tested – no major noise problems
- Accident….re-opened last week – new closure expected for mid July

Experimental «accident» : the T of the measurement arm «jumped» over the fork



Good noise of the reference – equal or better than in Virgo – but just a hint, because it is affected by the noise of the measurement arm with the T touching the fork

Casimir Energy Modulation

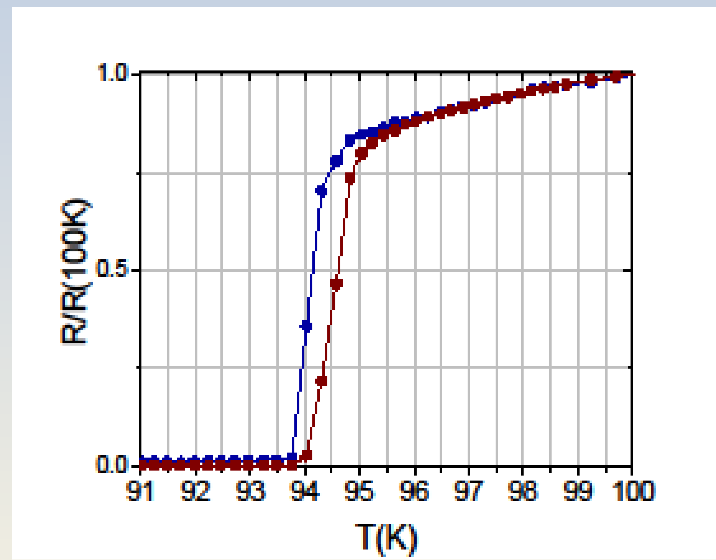
The method is to have the sample in a thermal bath, modulate «slowly» the temperature of the bath so that the sample makes a reversible transformation from normal to superconductor and viceversa

INFN Istituto Nazionale di Fisica Nucleare

Supercondutor choice: GdBCO

- GdBCO: **single crystal** already realized in discs of 10 cm diameter and tests on 15 cm diameter - acquired 1) a 10 cm disc and 2) several smaller discs.
- BSCCO: pressed powder (polycristalline) realized in discs/rings 10 cm diameter – acquired several small samples tested with negative results – pressed powder not suitable for the experiment

GdBCO sample

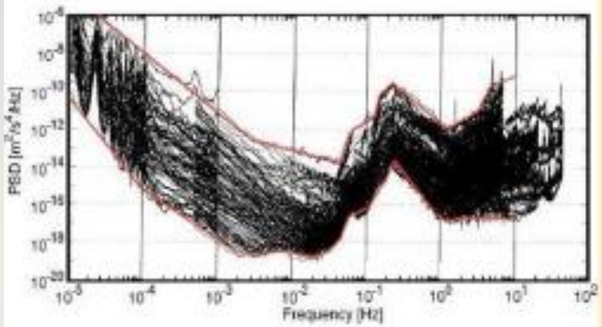


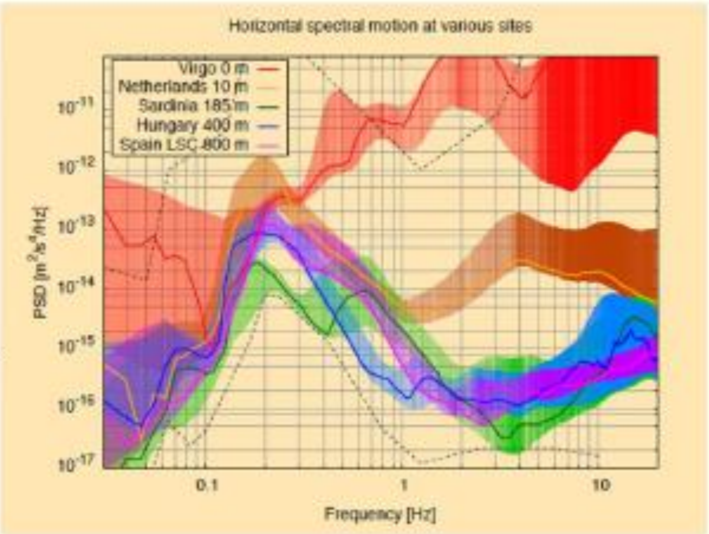
GdBCO: transitions of two pieces of the same sample $\Delta Tc = 0.5$ K

Need of a quiet site!
Low seismic – No antropic noise

Sindaco	Mario Calia (lista civica) dall'11-6-2012
Territorio	
Coordinate	40°28′N 9°29′E
Altitudine	521 m s.l.m.
Superficie	148,72 km²
Abitanti	1 407[1] (31-7-2016)
Densità	9,46 ab./km²
Comuni confinanti	Bitti, Dorgali, Galtellì, Irgoli, Loculi, Lodè, Onani, Orune, Siniscola

SOS-Enattos Mine





Seismic
Measurements
By Virgo and
ET collaborations

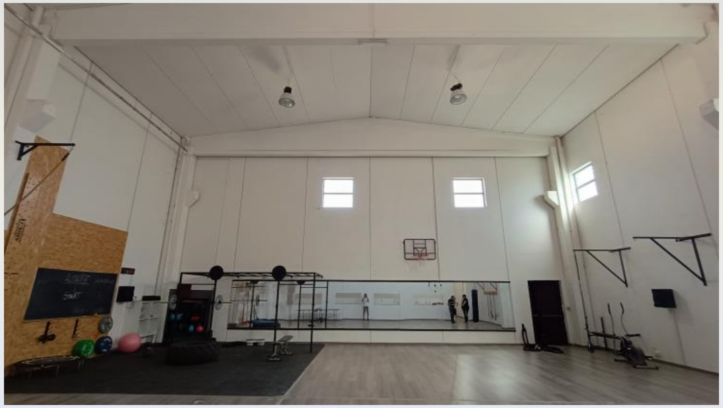
The present lab in Sos Enattos

The need of finding an alternative site

The present building

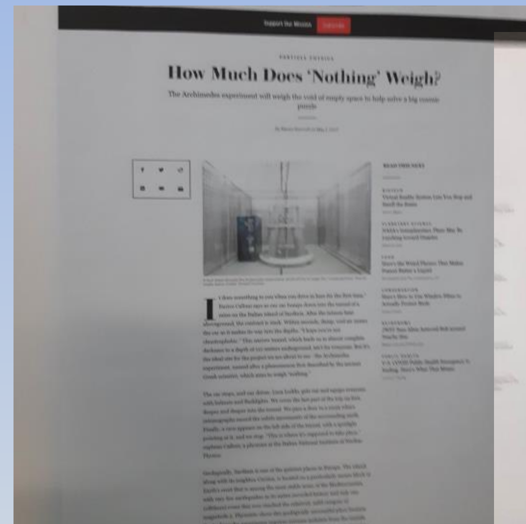
The future ET_SUnLab

Next year in a temporary building in Orosei

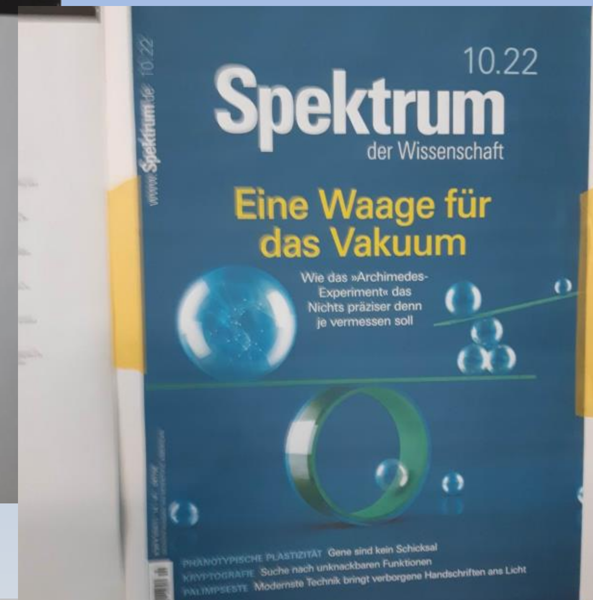


Archimedes Falls out

Make Sos Enattos a known site for Einstein Telescope



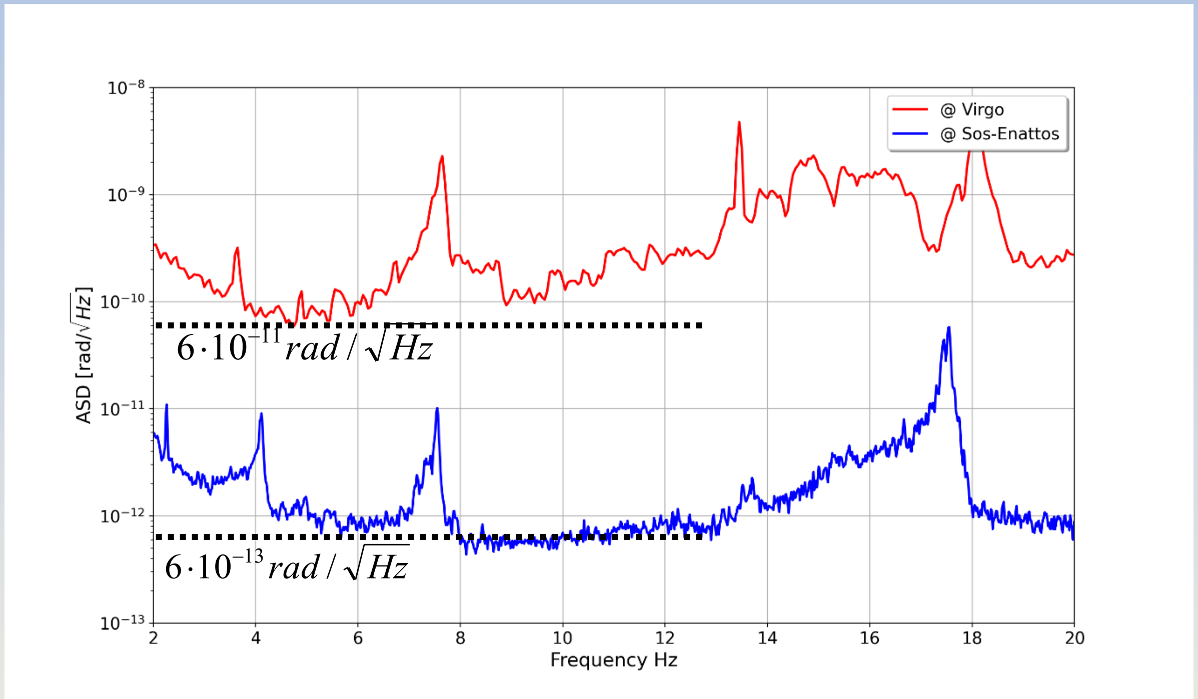
Scientific American



Le figaro

Focus

Tiltmeter – the best tiltmeter in few Hz regime



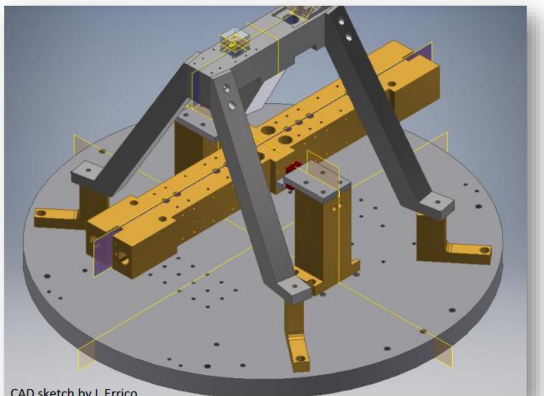
- ❑ Best sensitivity in the world for a tiltmeter in the region 2 Hz – 20 Hz

Tiltmeter installed in the Virgo GW observatory

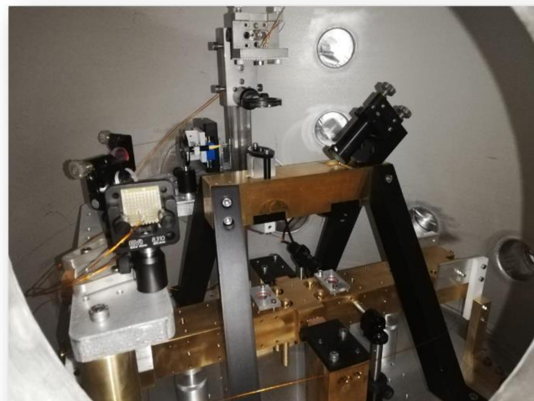
᾽Ακίνητος: the new tiltmeter

The new tiltmeter exploits the same working principles as the prototype.

Main improvement: arm with much higher momentum of inertia: 13 kg of brass, I = 0.33 kg*m^2, more than one order of magnitude bigger than the previous version, joint size: 0.1x3mm

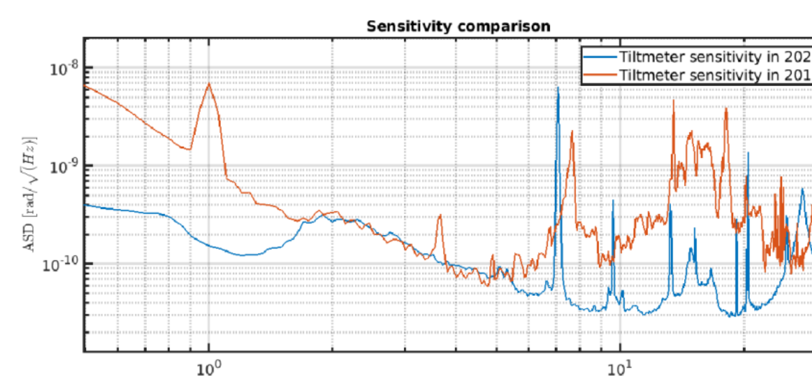


CAD sketch by L.Errico



A new tiltmeter has been realized with Virgo funds and installed in Virgo at the NE tower

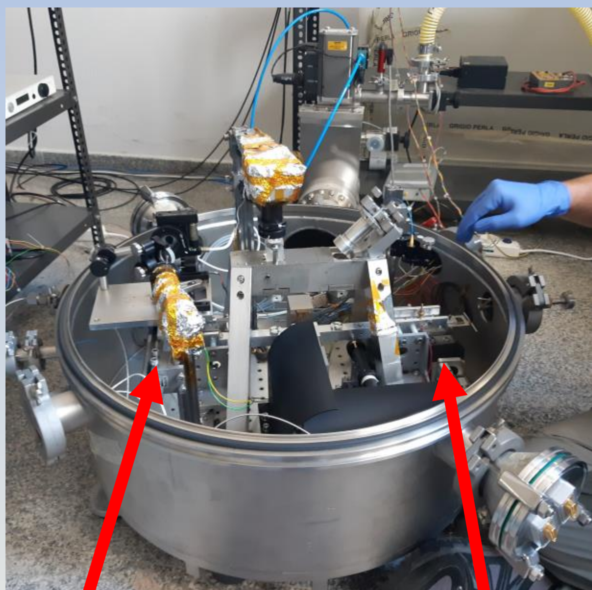
Comparison between tiltmeters sensitivity in 2019 vs 2023

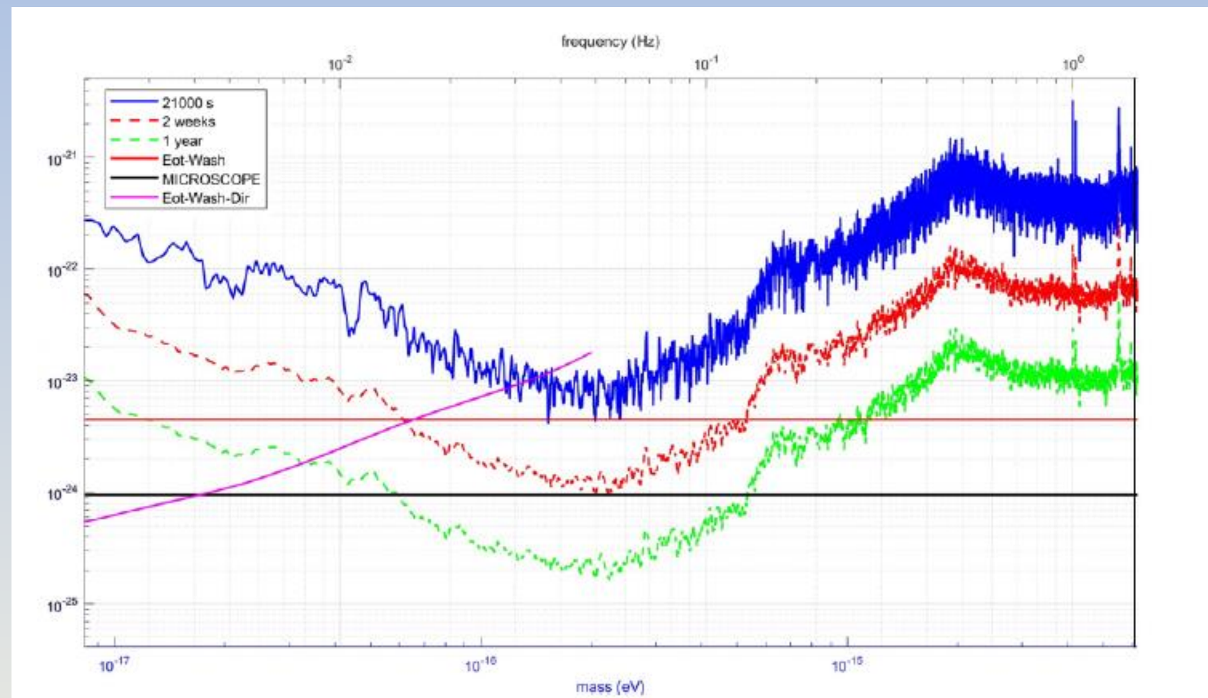


About	8 e-11 @1Hz,
	3 e-11 @10 Hz

Fall-out activites: direct search for ultralight B-L dark photon

The expected signal on the balance is a monocromatic noise at the frequency $f = mc^2/h$





1 night of measurement !

Brass (now Pb)   aluminum

Notice that the EOT-WASH and MICROSCOPE are testing the eventual existence of the dark photon as a particle but they are not testing the fact that it is a dark matter component
On the other hand the direct search can not disprove the existence of such a particle but only tests if it is the constituent of the dark matter

Conclusion

- Archimedes will run at room temperature in the next months
- Hopefully it will perform the final measurement in the next 3-4 years

Thanks

SPARES

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Physics Letters A
Volume 297, Issues 5–6, 20 May 2002, Pages 328-333

Vacuum fluctuation force on a rigid Casimir cavity in a gravitational field

E. Calloni [a b], L. Di Fiore [b], G. Esposito [b], L. Milano [a b], L. Rosa [a b]

Torre del Greco - NA

sive gravitational mass). In particular, we agree with the statement that a system with a given rest energy momentum tensor $T^{\overline{00}}$ has the inertial mass tensor $m^{ij} = T^{\overline{00}}\delta^{ij} + T^{\overline{ij}}$ [12].

Unfortunately, at present, there is not yet a direct calculation of inertial mass of a Casimir cavity in 4 dimensions; nevertheless direct calculations of inertial mass on a two-dimensional space–time [13] are in agreement with our calculation if "extended" to four dimensions. Furthermore, it is very important to note that, when considering the total force acting on the real cavity, which is an isolated system, the contribution to the force resulting from the spatial part of the energy-momentum tensor is balanced by the contribution of the mechanical energy-momentum tensor, and hence should not be considered for experimental evaluation. The resulting force is then the Newtonian force on the sum of the rest Casimir energy and rest mechanical mass: the contribution of vacuum fluctuations leads to a gravitational push on the Casimir apparatus expressed by the formula

$$\vec{F} \cong \frac{\pi^2 L^2 \hbar c}{720 a^3} \frac{g}{c^2} \vec{e}_r, \qquad (9)$$

Simulations

If the sample has the geometry of a ring and the radiating surface is increased by a thin foil then the modulation times are compatible with expectations --- **Simulations on going with Comsol and Ansys**

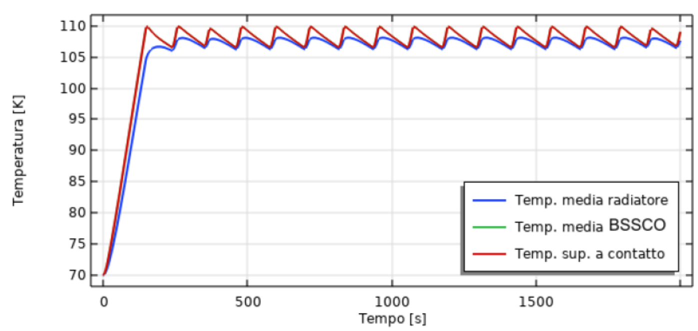


Figura 1.13: Risultati simulazione per la configurazione in Figura 1.1 e con parametri descritti nella sezione 1.2.3. La linea blu è la temperatura media del radiatore, in verde la temperatura media del campione mentre in rosso la temperatura media superficiale della corona a contatto termico.

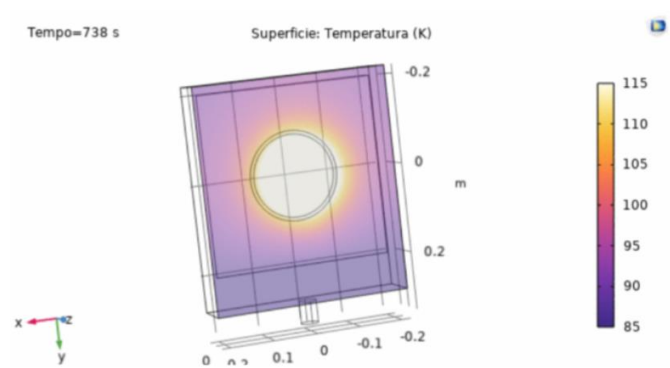
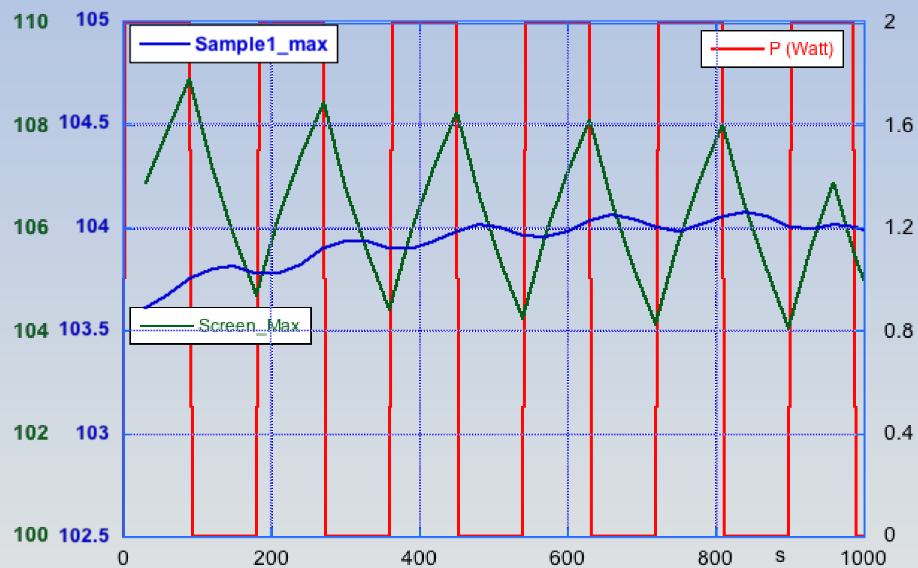


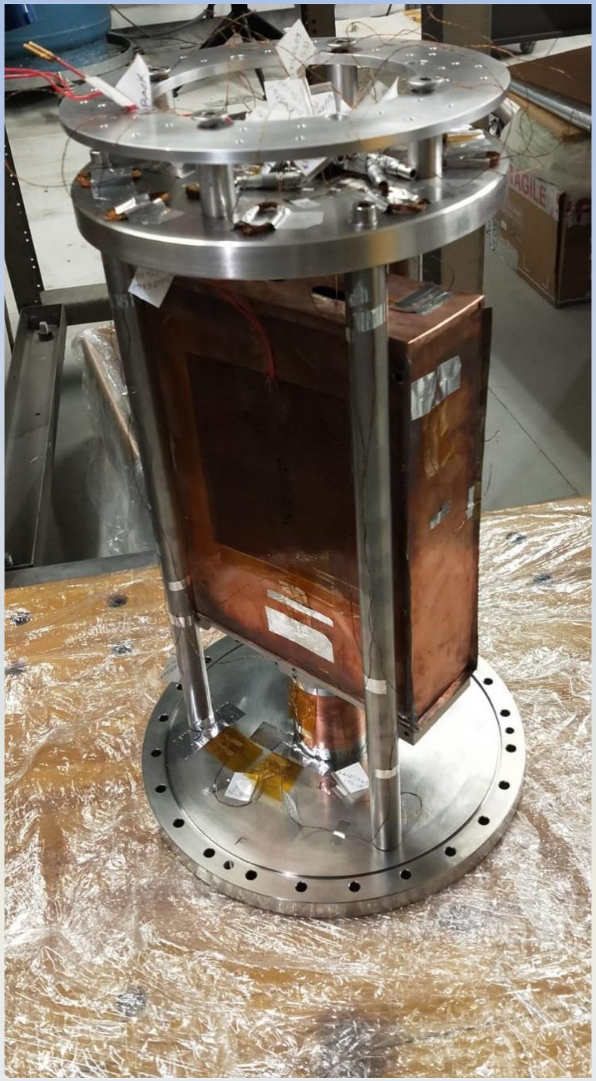
Figura 1.14: Profilo in temperatura della superficie del forno ad un certo istante di tempo $t = 738$ s corrispondente alla fase di riscaldamento. La figura mostra il profilo del fascio incidente sul forno.

BSCCO → Tc = 110 K ; Modulation Period T = 120 s; Laser Power P = 10 W;
Sample volume 20 cm^3 -- Similar for GdBCO but more critical due to Tc = 94 K

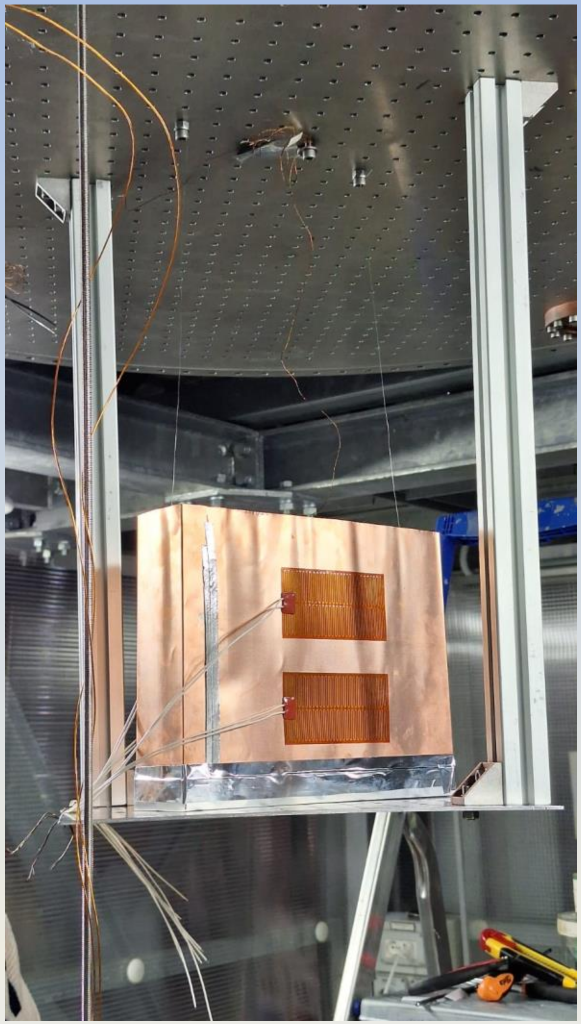
Temperature modulation: test in Rome cryogenic temperature



FEM simulation



Temperature modulation: test at **EGO** (European gravitational Observatory) at room temperature



Test of the Archimedes moduation system at room temperature

EGO *site hosting the Virgo GW detector*

Pressure red-shift

A simple summation of the lower force and upper force on the plates would bring to a somewhat unespected result:

$$F_{cas} = -L^2 \frac{\pi\hbar c}{240 a^4}$$

$$F_{\inf} + F_{\sup} = F_{cas}\left(1+\delta\phi\right) + \frac{\left|E_C\right|}{c^2} g - F_{cas} = 4\frac{\left|E_C\right|}{c^2} g$$

$$E_{cas} = -L^2 \frac{\pi\hbar c}{720 a^3}$$

The lower vacuum «photons» must exert a bigger force because the force will be red-shifted when reaching the same level of upper plate → in the experiment the sum must be done taking into account the red-shift becuase the cavity is rigid and hanged in a unique point - (**for this effect our measurement is a null measurement on pressure red-shift)**

$$\begin{cases} F_{\sup} = F_C \\ F_{\inf} = -F_C\left(1+\delta\phi\right) + \dfrac{\left|E_C\right|}{c^2} g \end{cases} \Longleftrightarrow \vec{F}_{tot} = \frac{\left|E_C\right|}{c^2} g \;\hat{z}$$

E. Calloni et.al. Phys. Letters A, 297, 328-333, (2002)
G. Bimonte, E. Calloni , G. Esposito, L. Rosa - Phys. Rev D 74, 085011 (2006)
G. Bimonte, E. Calloni et. al. Phys.Rev.D76:025008, (2007)
G. Bimonte, E. Calloni, L. Rosa, Phys.Rev.D77:044026, (2008)

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On interpretation of Tolman-Ehrenfest effect:
C. Rovelli, M. Smerlak Class. Quant. Grav. 28 (2011) 075007

Casimir Energy variation in real material

$$\Delta E^0_{\text{cas}}(a,d) = A\,\frac{\hbar}{2}\int \frac{dk_1 dk_2}{(2\pi)^2}\left\{\sum_p(\omega^{(n,TM)}_{\mathbf{k}_\perp,p}+\omega^{(n,TE)}_{\mathbf{k}_\perp,p}) - \sum_p(\omega^{(s,TM)}_{\mathbf{k}_\perp,p}+\omega^{(s,TE)}_{\mathbf{k}_\perp,p})\right\} \quad (1)$$

where $A \gg a^2$ is the area of the cavity, $\mathbf{k}_\perp = (k_1, k_2)$ denotes the two-dimensional wave vector in the xy plane, while $\omega^{(n/s,TM)}_{\mathbf{k}_\perp,p}$ $(\omega^{(n/s,TE)}_{\mathbf{k}_\perp,p})$ denote the proper frequencies of the TM (TE) modes, in the n/s states of the film, respectively.

Cauchy integral formula and renormalization

$$\left(\sum_p \omega^{(n,TM)}_{\mathbf{k}_\perp,p} - \sum_p \omega^{(s,TM)}_{\mathbf{k}_\perp,p}\right)_{\text{ren}} = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\zeta\,\left(\log\frac{\Delta^{(1)}_n(i\zeta)}{\tilde{\Delta}^{(1)}_{n\,\infty}(i\zeta)} - \log\frac{\Delta^{(1)}_s(i\zeta)}{\tilde{\Delta}^{(1)}_{s\,\infty}(i\zeta)}\right)$$

where

$$\Delta_{j\,l}^{TE} = \frac{K_j - K_l}{K_j + K_l}\,, \quad \Delta_{j\,l}^{TM} = \frac{K_j\,\epsilon_l\,(i\zeta) - K_l\,\epsilon_j\,(i\zeta)}{K_j\,\epsilon_l\,(i\zeta) + K_l\,\epsilon_j\,(i\zeta)},$$

$$K_j \quad = \sqrt{\epsilon_j\,(i\zeta) - 1 + p^2}\,, \quad I = n, s \;\; ; \;\; j\,, l = 1, 2, n, s.$$

And inserting it in (1)

$$\Delta E_{\mathrm{cas}} = A\,\frac{\hbar}{2}\int \frac{d\mathbf{k}_\perp}{(2\pi)^2}\int_{-\infty}^{\infty}\frac{d\zeta}{2\pi}\,\left(\log\frac{Q_n^{TE}}{Q_s^{TE}} + \log\frac{Q_n^{TM}}{Q_s^{TM}}\right)$$

where

$$Q_I^{TE/TM}(\zeta, p) = \frac{(1 - \Delta_{1I}^{TE/TM}\Delta_{12}^{TE/TM}e^{-2\zeta\,K_1\,L/c})^2 - (\Delta_{1I}^{TE/TM} - \Delta_{12}^{TE/TM}e^{-2\zeta\,K_1\,L/c})^2 e^{-2\zeta K_I D/c}}{1 - (\Delta_{1I}^{TE/TM})^2 e^{-2\zeta K_I\,D/c}}$$

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Ragguagli teorici

L. Rosa et al.. Casimir energy for two and three superconducting coupled cavities
Submiited to JPLP (2017)

E. Calloni et al Towards weighing the condensation energy to ascertain the Archimedes force of vacuum
Phys.Rev. D90 (2014) no.2, 022002

G. Bimonte, E. Calloni et. al. Relativistic mechanics of Casimir apparatuses in a weak gravitational field
Phys.Rev.D76:025008, (2007)

G. Bimonte, E. Calloni , G. Esposito, L. Rosa - Energy-momentum tensor for a Casimir apparatus in a weak gravitational field Phys. Rev D 74, 085011 (2006)

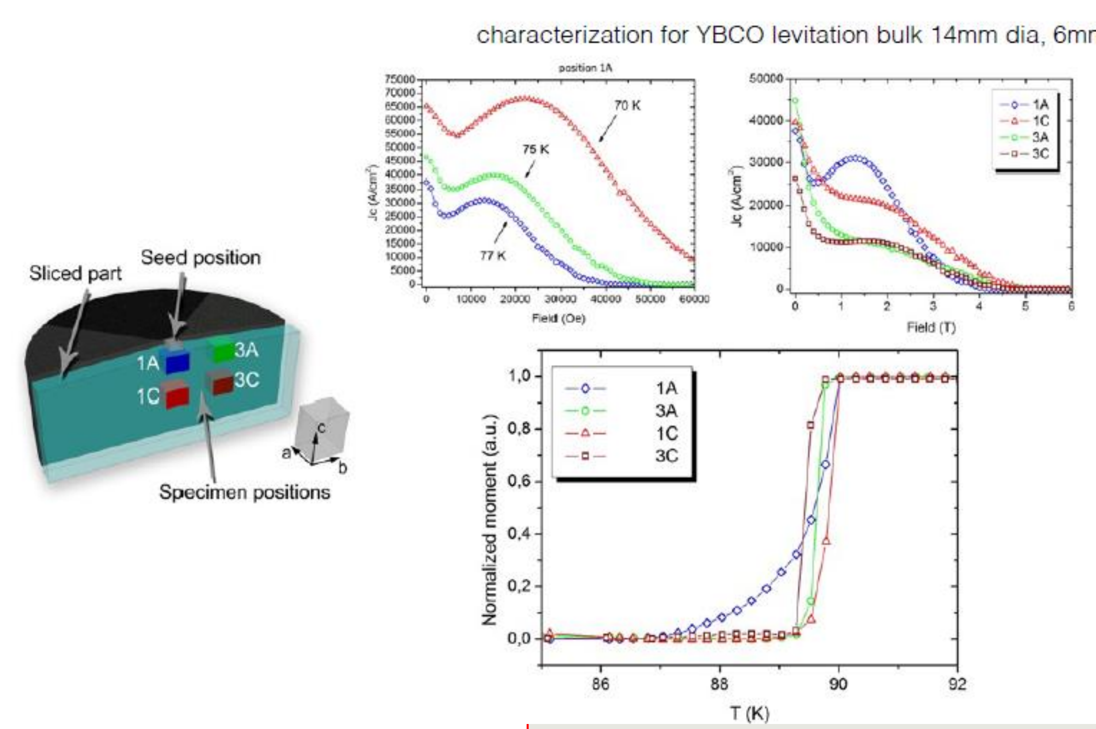
G. Bimonte, E. Calloni et al Towards measuring variations of Casimir energy by a superconducting cavity
Phys.Rev.Lett. 94 (2005) 180402

E. Calloni et.al. Vacuum fluctuation force on a rigid Casimir cavity in a gravitational field Phys. Letters A, 297, 328-333, (2002)

Da questo punto di vista, ritengo che la misura proposta da ARCHIMEDES sia di eccezionale interesse. Si tratta dell'unico esperimento di laboratorio di cui io sia a conoscenza che possa oggi dare informazioni sperimentali dirette sull'interazione fra energia di vuoto e gravità, e in particolare confermare l'esistenza di effetti fisici per i quali abbiamo oggi solo previsioni teoriche, in un contesto generale di notevole confusione teorica.

Superconduttività

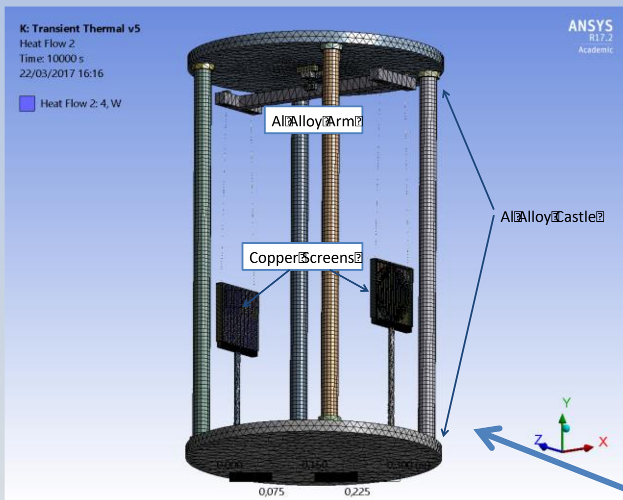
- E' stato aggiunto un WP all'esperimento ed aggiunti FTE efficaci.
- Varie ditte ri-contattate per YBCO



Inserita tra le milestone la realizzazione di un apparato per la misura di energia di transizione in dischi di grande dimensione. Questo è necessario per mantenere il controllo nel laboratorio delle caratteristiche dei materiali e perché ad una prima indagine non risulta che esista un tale apparato. Le indagini continueranno.

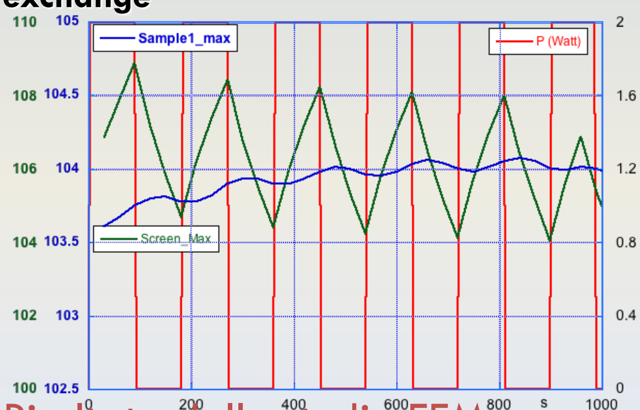
Attuazione termica (Roma)

- Modulazione della temperatura del campione superconduttore attraverso il solo scambio radiativo per non aggiungere altra energia diversa da quella legata alle fluttuazioni del vuoto

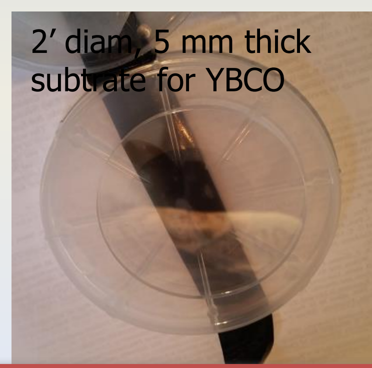


Criostato Virgo lab

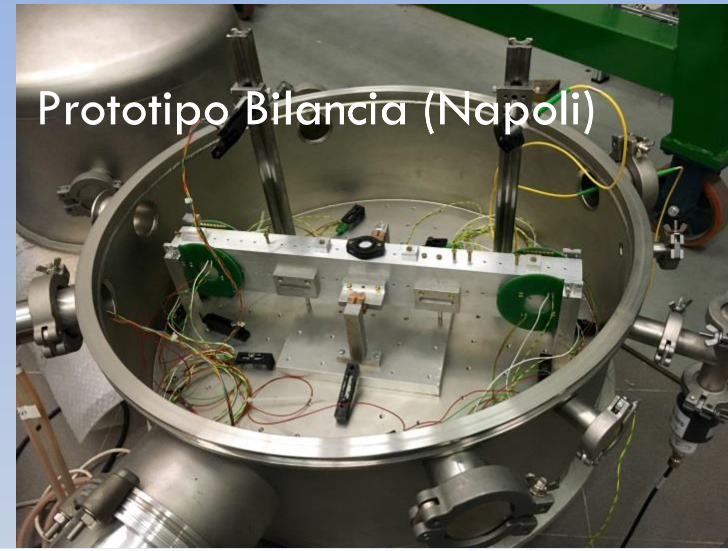
Case with only radiative heat exchange

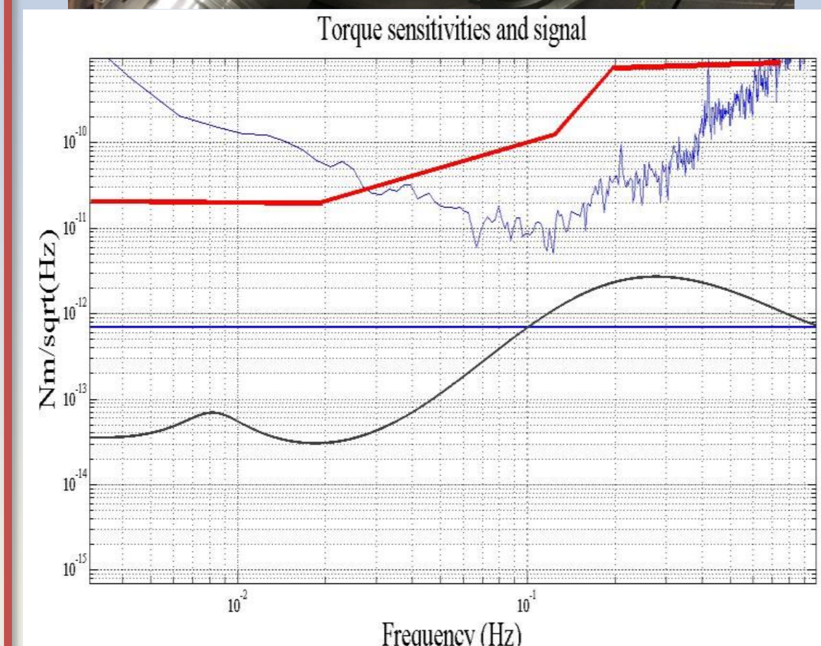


Risultato dello studio FEM



Prototipo Bilancia (Napoli)





expected signal

prototype

Wash

Archimedes noise

A side-measurement (more difficut): the weight of the entropy*T

$$\Delta U = G_n(T) + TS_n(T) - G(T,0) - TS_s(T,0)$$

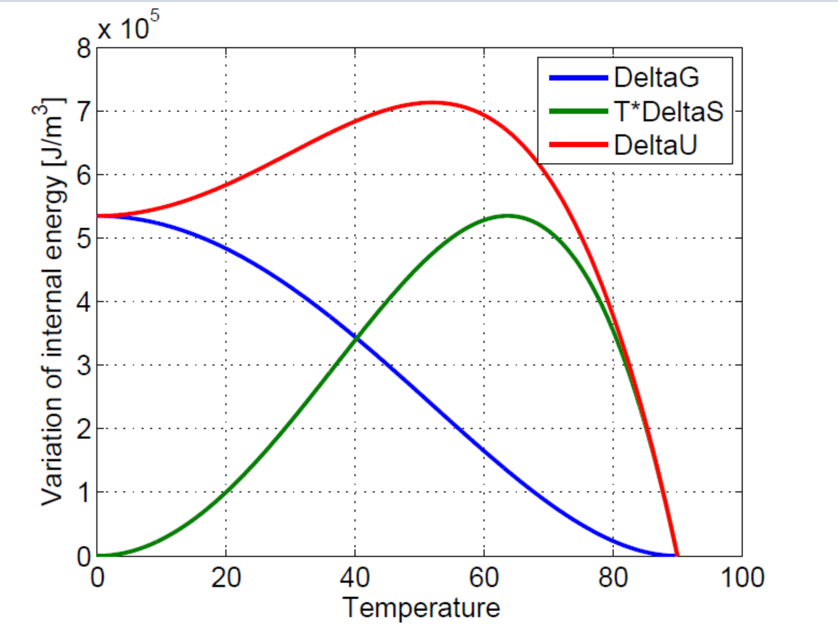
Difference in internal energy for a transition at fixed temperature

$$G_n(T) - G_s(T,0) = \frac{1}{2\mu_0} B_c(T)^2$$

$$B_c(T) = B_0 \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

$$S_n(T) - S_s(T) = 2\frac{B_0^2}{\mu_0}\left(\frac{T}{T_c^2}\right)\left[1 - (T/T_c)^2\right]$$

Difference in entropy for a transition at fixed temperature valid for BCS – approximatively for layered type II



Disregarding in this particular discussion the contribution of Casimir effect the weight of the entropy (times Temperature) can be considered as an interesting side-measurement of the final experiment. This weight is classical (no question on it) but never measured

Use of superconductors

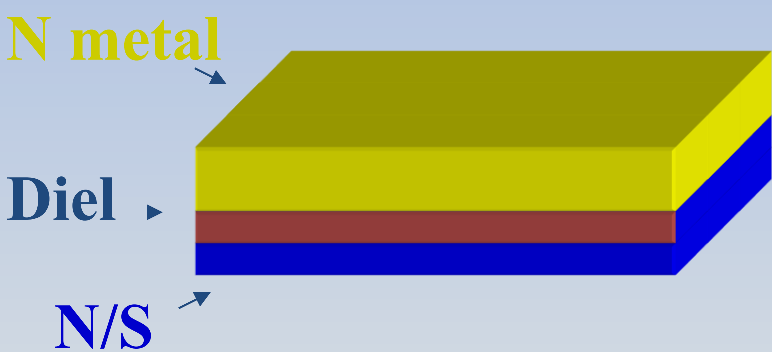
- The condensation energy is very small so it can be expected that the variation of Casimir energy at the transition for a superconductor inside a cavity can be of the same order, or even dominates, the total transition energy

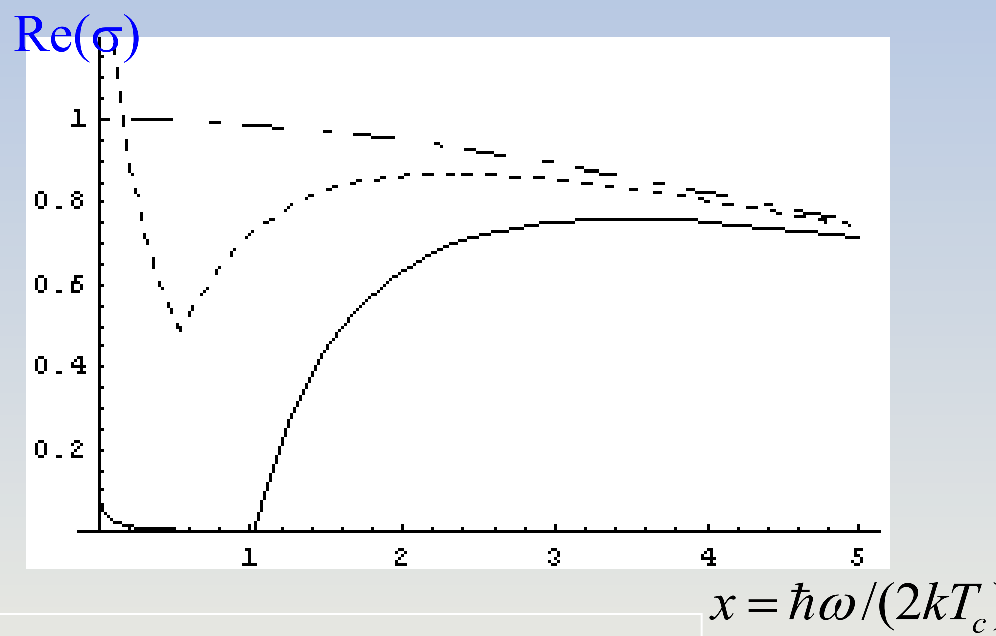
$$\frac{V}{2\mu_0}\left(\frac{B_{c\|}^{\mathrm{cav}}(T)}{\rho}\right)^2 = \mathcal{E}_{\mathrm{cond}}(T) + \Delta E_{\mathrm{cas}}(T)$$

The change in energy can be calculated following the Casimir energy calculation in case of real plates with complex conductivity σ

$$\Delta E_C = -\Delta\eta_E \frac{\hbar c \pi^2}{720}\frac{A}{L^3}$$

$\Delta\eta_E$: modulation factor with respect perfect reflectivity





$$\Delta\eta_E = \frac{\Delta E_C}{E_C} \approx \frac{kT_C}{h\nu_C} = \frac{kT_C}{hc/L} \approx 10^{-6}$$

Plot of real part of conducibility σ normalized to zero frequency Drude conducibilty σ_0 for different temperatures:

— · - T = Tc (Drude) ……… T/Tc = 0.9 ——T/Tc = 00.3

The conducibility changes only in the very low frequency region (microwave) so the modulation depth (if Tc is of the order of 1 K) is expected to be small for small T_c…

..but also the energy exchanged with the system, besides the vacuum energy, is expected to be small being linked to the condensation energy which is (roughly) proportional to T_c^2 . Better to use low T_c superconductors. If the two energy variations are comparable then it is expected that vacuum fluctuations modifies the transition

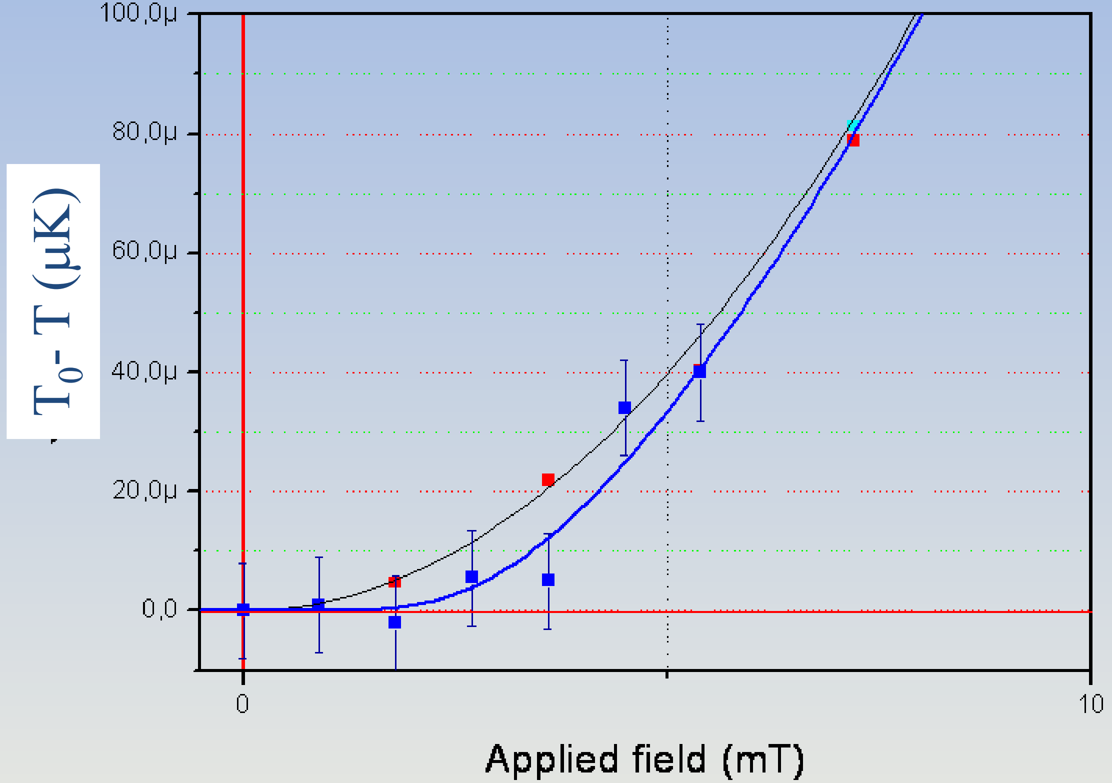
Is there a way to measure ΔF_c?

Superconductivity is destroyed by a critical magnetic field .

⬇

The proposed way to measure ΔFc consists in placing the cavity in a parallel magnetic field and measuring the critical field that destroys the superconductivity of the film.

Results and references on energy modulation – Aladin Experiment



The data are not in contrast with the theory and the region of energy of different behaviour is the expected one

2008

G. Bimonte, et Al. - Nucl.Phys. B726 (2005) 441-463

G. Bimonte et Al. - Phys.Rev.Lett. 94 (2005) 180402

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)

In the case of a thin film, of thickness $D \ll \lambda, \xi$ (with
λ the penetration depth and ξ the correlation length).

$$\rho \approx \sqrt{24}\,\frac{\lambda}{D}\left(1 + \frac{9D^2}{\pi^6 \xi^2}\right)$$

Pressure red-shift

A simple summation of the lower force and upper force on the plates would bring to a somewhat unespected result:

$$F_C = L^2 \frac{\pi\hbar c}{240 a^4}$$

$$F_{\inf} + F_{\sup} = F_C(1+\delta\phi) + \frac{|E_C|}{c^2} g - F_C = 4\frac{|E_C|}{c^2} g$$

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$$\begin{cases} F_{\sup} = F_C \\ F_{\inf} = -F_C(1+\delta\phi) + \dfrac{|E_C|}{c^2} g \end{cases} \iff \vec{F}_{tot} = \frac{|E_C|}{c^2} g \ \hat{z}$$

E. Calloni et.al. Phys. Letters A, 297, 328-333, (2002)

•G. Bimonte, E. Calloni , G. Esposito, L. Rosa - Phys. Rev D 74, 085011 (2006) *Phys.Rev.D* 74 (2006) 085011, *Phys.Rev.D* 75 (2007) 049904 (erratum),

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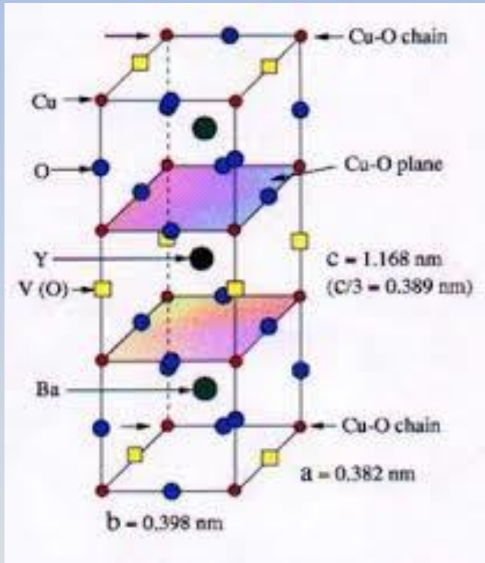
•*Phys.Rev.D* 75 (2007) 089901 (erratum), *Phys.Rev.D* 77 (2008) 109903 (erratum)

On interpretation of Tolman-Ehrenfest effect:
C. Rovelli, M. Smerlak Class. Quant. Grav. 28 (2011) 075007
Hal M. Haggard and Carlo Rovelli, arXiv:1302.0724

S. A. Fulling et al. Phys. Rev. D76:025004 (2007)
K.A. Milton et al. J. Phys. A 41:164052 (2008)

Progress on Casimir contribution to transition energy

Starting point: Kempf hypothesis: plasma sheet no dissipation – zero temperature - order of magnitude estimation



Coupled cavities and low thickness limit regime with descriptions of each layer as a very thin superconductor which undergoes conductivity variation at the transition

Coupled cavities and plasma sheet description of each layer with dissipation and actual temperature

$$\Delta\eta_E \approx 10^{-4}$$

R. Bimonte, E. Calloni et al -Towards measuring variations of Casimir energy by a superconducting cavity Phys.Rev.Lett. 94 (2005) 180402

L. Rosa et al - Casimir energy for two and three superconducting coupled cavities: Numerical calculations Eur.Phys.J.Plus 132 (2017) no.11, 478

L. Rosa et al – Casimir energy for layered superconductors (in preparation -2021)

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Theoretical issues

- Casimir effects in Layered type II superconductors
- Casimir effects in multi-layer coupled cavities
- Is plasma sheet approximation correct type II layered superconductors ?

Eur. Phys. J. Plus (2017) **132**: 478
DOI 10.1140/epjp/i2017-11750-y

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

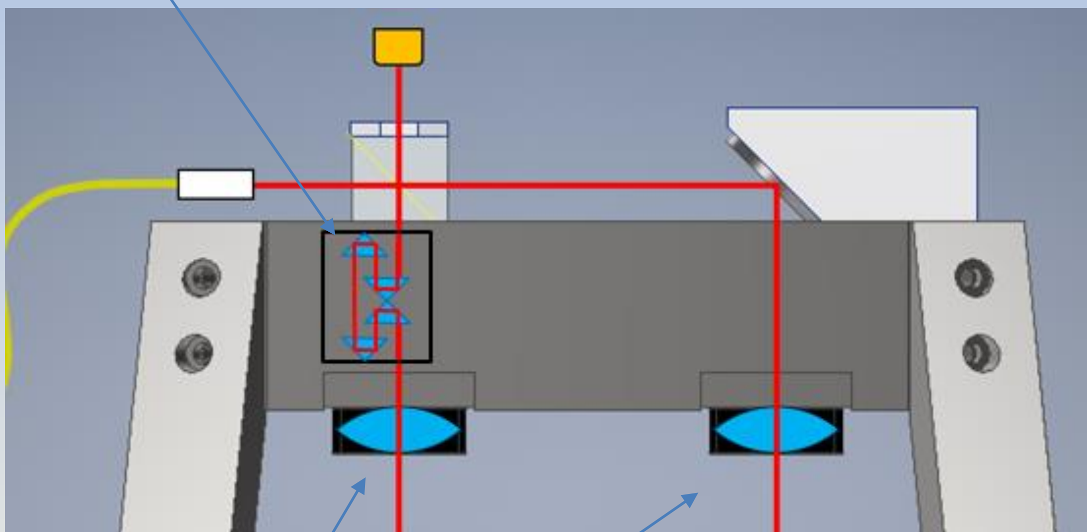
Casimir energy for two and three superconducting coupled cavities: Numerical calculations

L. Rosa[1,2,a], S. Avino[2,3], E. Calloni[1,2], S. Caprara[4,5], M. De Laurentis[1], R. De Rosa[1,2], Giampiero Esposito[2], M. Grilli[4,5], E. Majorana[6], G.P. Pepe[7], S. Petrarca[4,6], P. Puppo[6], P. Rapagnani[4,6], F. Ricci[4,6], C. Rovelli[8,9], P. Ruggi[10], N.L. Saini[4], C. Stornaiolo[2], and F. Tafuri[1]

From experimental point of view: even if the Casimir contribution would be of few percent the measurement can assess if vacuum fluctuations interacts with gravity or not

Optical Read-Out: prisms and lenses

prisms

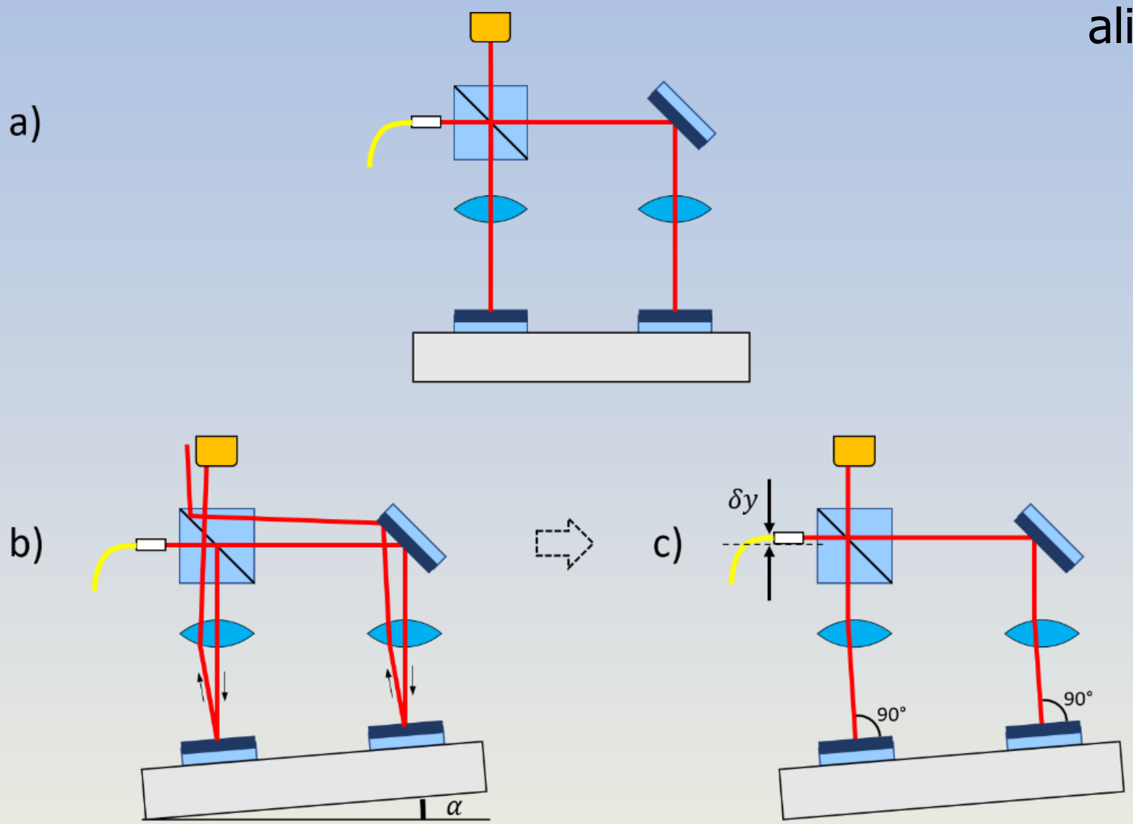


Lenses with focal lenght equal to arm distance

Prisms are used to equalize the lenght of the optical paths ($\Delta L \approx 2mm$) In this way **frequency noise is highly suppressed**.

Also amplitude noise is reduced by measuring a pick-off on the input beam and performing a signal normalization.

Optical Read-Out: prisms and lenses



Lenses are used to maintain good alignment and contrast against static tilt.

(a) The interferometer is aligned while the balance arm is horizontal

(b) An arm tilt α would misalign the interferometer, but **contrast changes at second order thanks to the lenses**

(c) Alignment can be restored by moving vertically the input laser beam by $\delta y = L_f \alpha$ (L_f lens focal length), **without moving any optics on the suspended arm**

Acquisition & Control