The Archimedes Experiment, results on the thermal modulation system

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on behalf of the Archimedes collaboration

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TAUP VIENNA 2023

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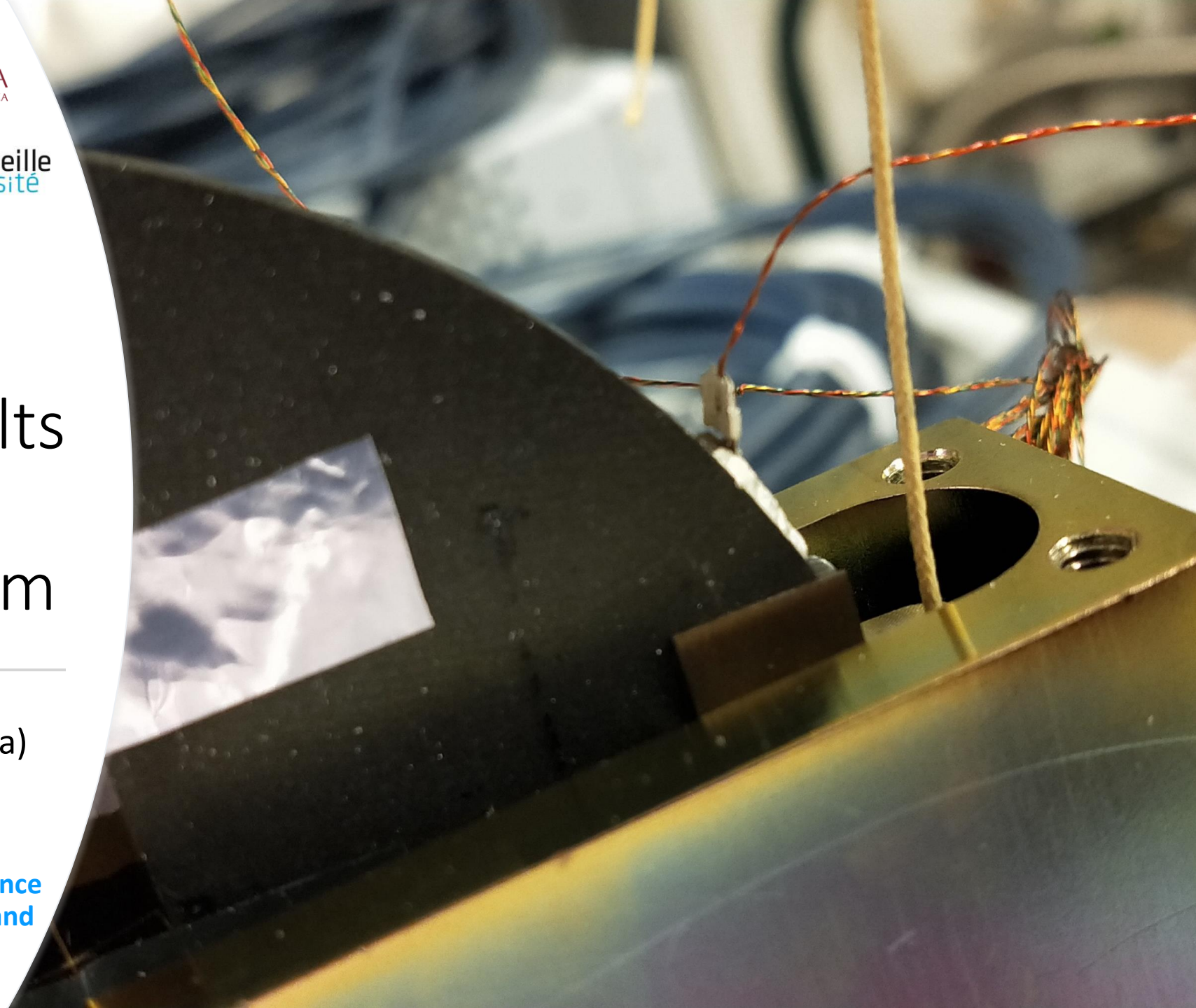
28 August – 01 September 2023, Vienna (Austria)



ARCHIMEDES

The Archimedes experiment at the Sar-Grav Laboratory

The aim of the Archimedes experiment is the evaluation of the interactions between vacuum energy and gravity. The vacuum energy will be weighted by a very precise balance measuring the arm tilts by the mean of interferometric readout. The e

Domenico D'Urso (Universita e INFN, Perugia (IT)), Davide Rozza (University of Sassari and INFN-LNS)
30 August 2023 16:15

Einstein Telescope site characterization in Sardinia

Due to its unique geophysical features and to the low population density of the area, Sos Enattos is a promising candidate site to host the Einstein Telescope (ET), the third-generation Gravitational Wave Observatory. The characterization o

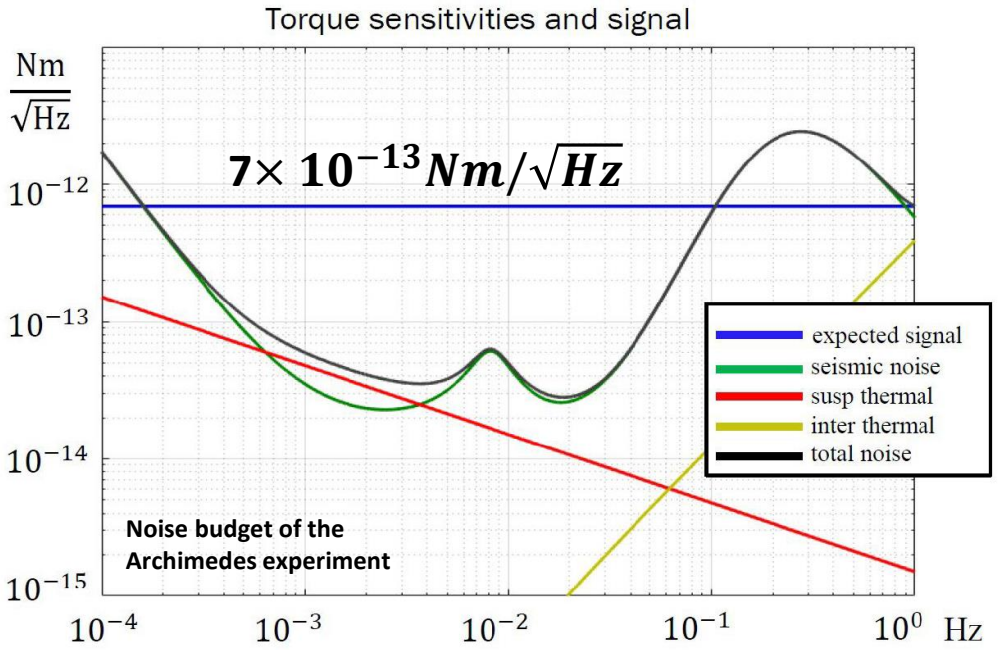
Luca Naticchioni (INFN Roma)
31 August 2023 14:00

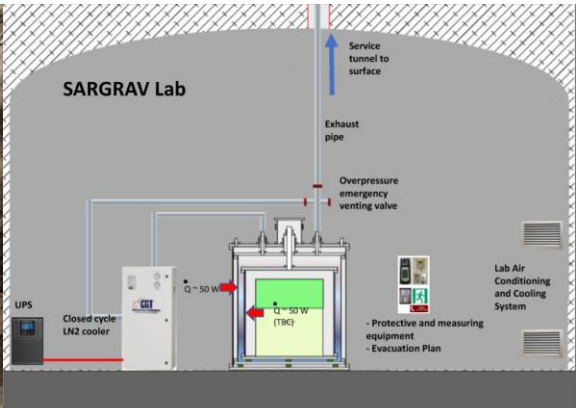
Archimedes is an INFN-funded fundamental physics experiment that searches for small weight variations induced by quantum vacuum fluctuations.

It is the first experiment to be installed in the **Sar-Grav laboratory**, in the area of the disused Sos Enattos mine near Lula (Nu, **Sardinia**). The SarGrav laboratory has both surface and underground facility, and is **dedicated to the research on gravitational waves, gravitational physics and geophysics**.

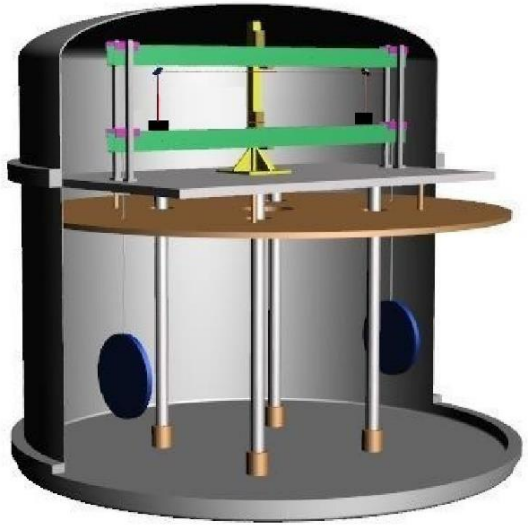
Archimedes will work in the frequency range from 5 mHz to 10 mHz and the signal will be limited by seismic and thermal noise.

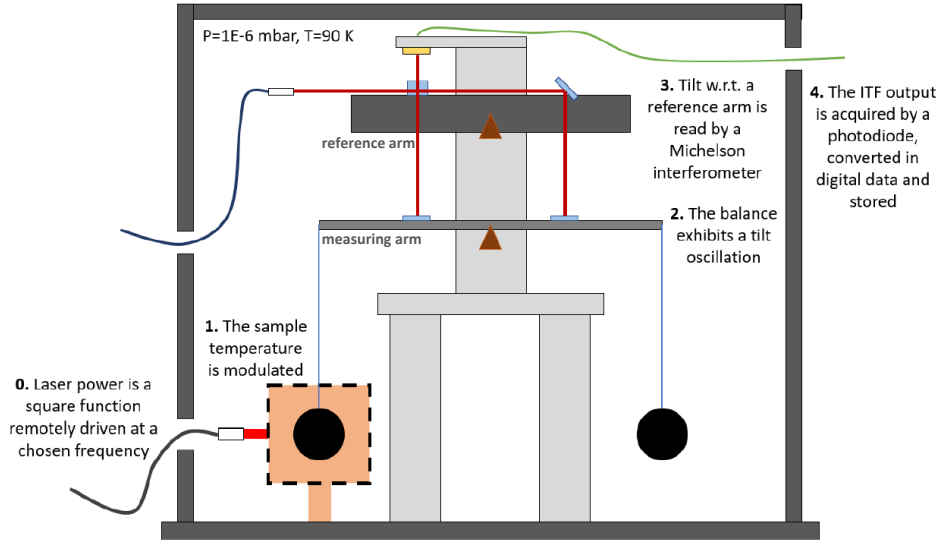
Thanks to the unique geological properties of Sardinia and the low population density, **Sos Enattos area** is an excellent site to host experiments that require **very low seismic noise levels**. Working at **cryogenic temperatures** (cryostat) reduces the **thermal noise**.





BALANCE

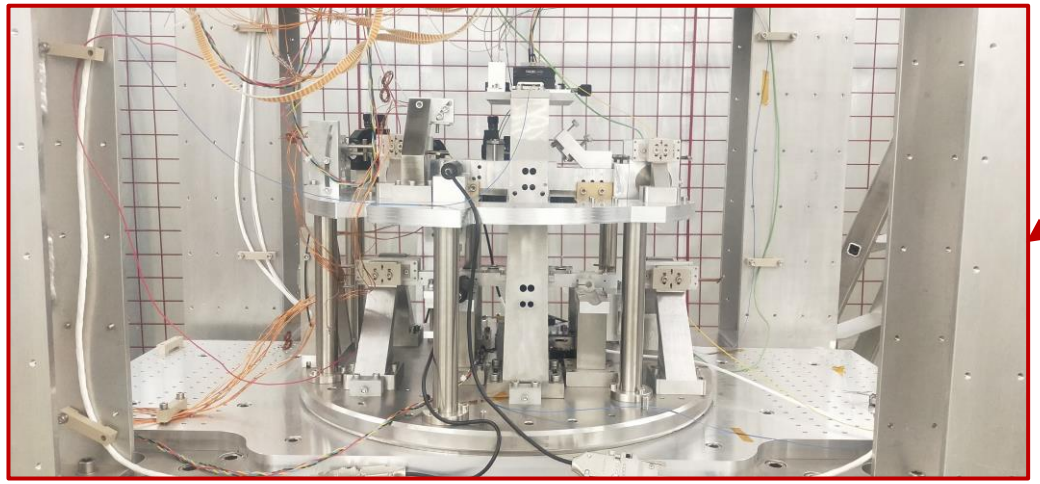




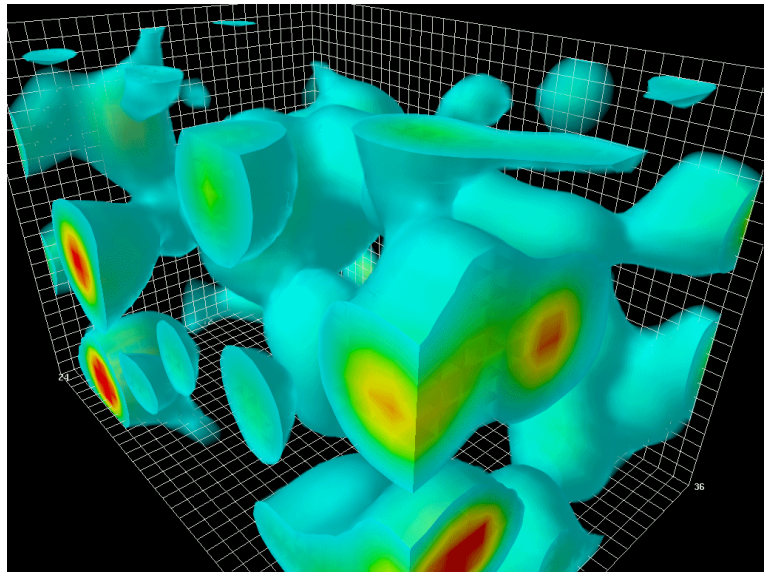
courtesy of Dr Luciano Errico

Suspending two equal superconducting discs at the ends of a balance arm at rest in a gravitational field and modulating the Casimir energy only in one superconductor, the **variation in weight** may be measured using a **very high sensitivity cryogenic balance based on laser interferometry**.

The **modulation of the temperature** of only one **superconducting sample** will produce a **periodic signal of tilt of the measuring arm** with respect to the reference arm taken into account, so that the ground tilt can be subtracted.
This torque signal will be read using a Michelson interferometer.



HOW TO WEIGH THE VACUUM?



Weigh the vacuum energy stored in a rigid Casimir cavity formed by parallel conductive plates.

The Casimir effect is one of the **macroscopic** manifestations of vacuum fluctuations.

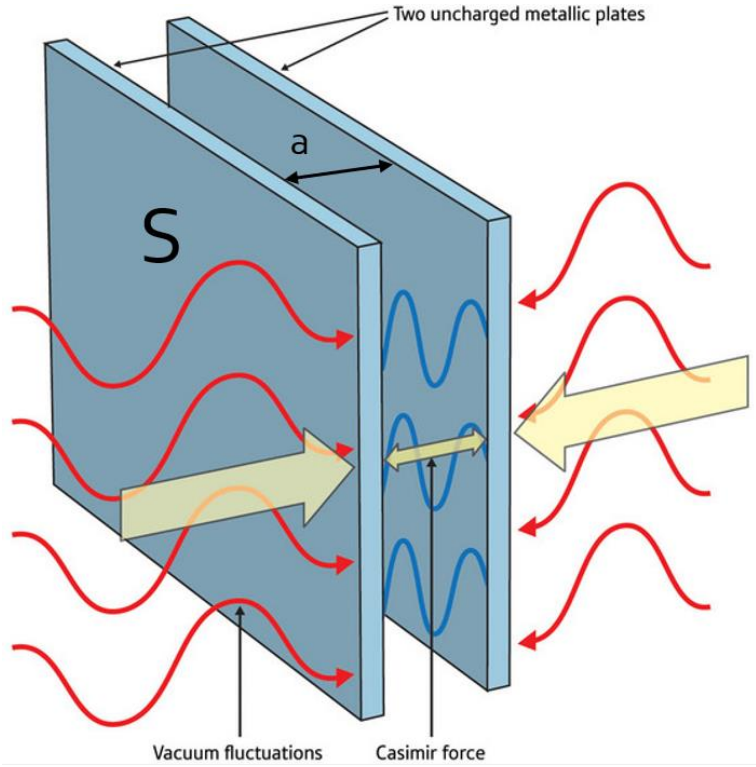
Only some modes can resonate inside the Casimir cavity:
the ones which do not satisfy specific boundary conditions are expelled
and the total vacuum energy changes.

If the vacuum energy interacts with gravity,
a force directed upwards acts on the cavity and
is equal to the weight of the modes expelled from the cavity
(analogous to the **Archimedes force**) [*]:

$$\vec{F} = \frac{E_C}{c^2}\vec{g}$$

$$E_C = \mathrm{E(a)} - \mathrm{E}(\infty) = -\frac{\pi^2 \hbar c}{720 a^3} S$$

The force depends on the vacuum energy inside the Casimir cavity.



[*] G. Bimonte, E. Calloni, G. Esposito, L. Rosa – Physical Review D 76, 025008 (2007) – DOI: 10.1103/PhysRevD.76.025008

STRATEGY

The idea is to modulate the vacuum energy of a rigid Casimir cavity by changing the reflectivity of the plates with time.

A possible way to modulate the reflectivity is by performing a **superconducting transition of the plates**.

The variation of Casimir energy is relevant in case of **type II high Tc layered superconductors** (like **YBCO** and **GdBCO**), which behave as natural **multi-layer Casimir cavities**.

A transition from normal to superconducting state and vice versa can be induced by the **modulation of the temperature** of a superconductor.

Archimedes will measure the **variation of the Casimir energy** within this superconductor/multi-layer cavity [*]:

$$\vec{F}_s = \frac{\Delta E_C}{c^2}\vec{g}$$

For a superconducting disc with diameter 100 mm and thickness 5 mm, **the expected force on this object is approximately $5.0 \cdot 10^{-16}$ N (ΔE_C ~ 4.6 J).**

modulation of the vacuum energy contained in a Casimir cavity

↑

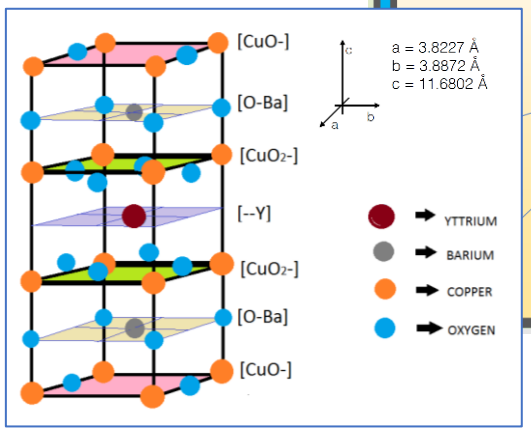
modulation of the reflectivity of the plates with time

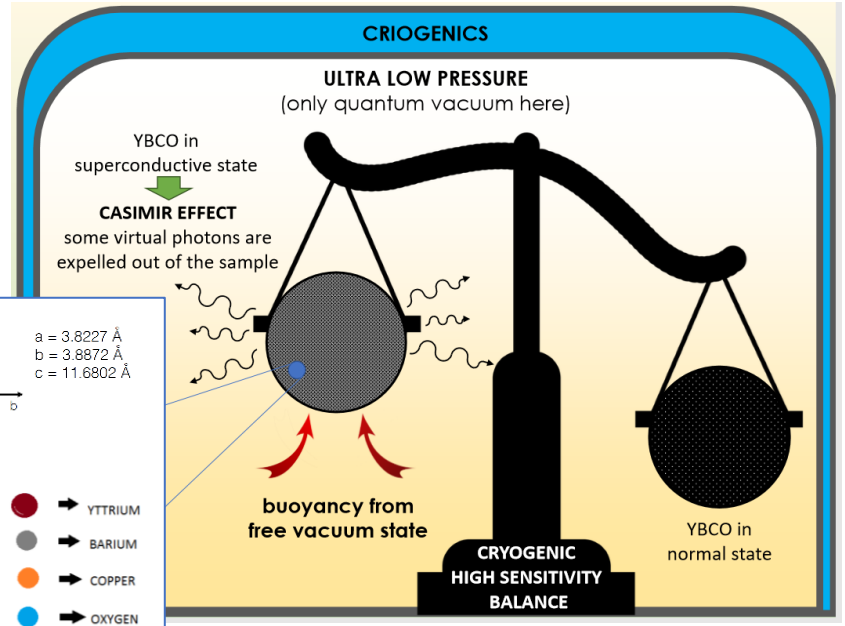
↑

superconducting transition of the plates

↑

thermal modulation around T_c of a superconducting sample





courtesy of Dr Luciano Errico

[*] E. Calloni et al. – Physical Review D 90, 022002 (2014) – DOI: 10.1103/PhysRevD.90.022002

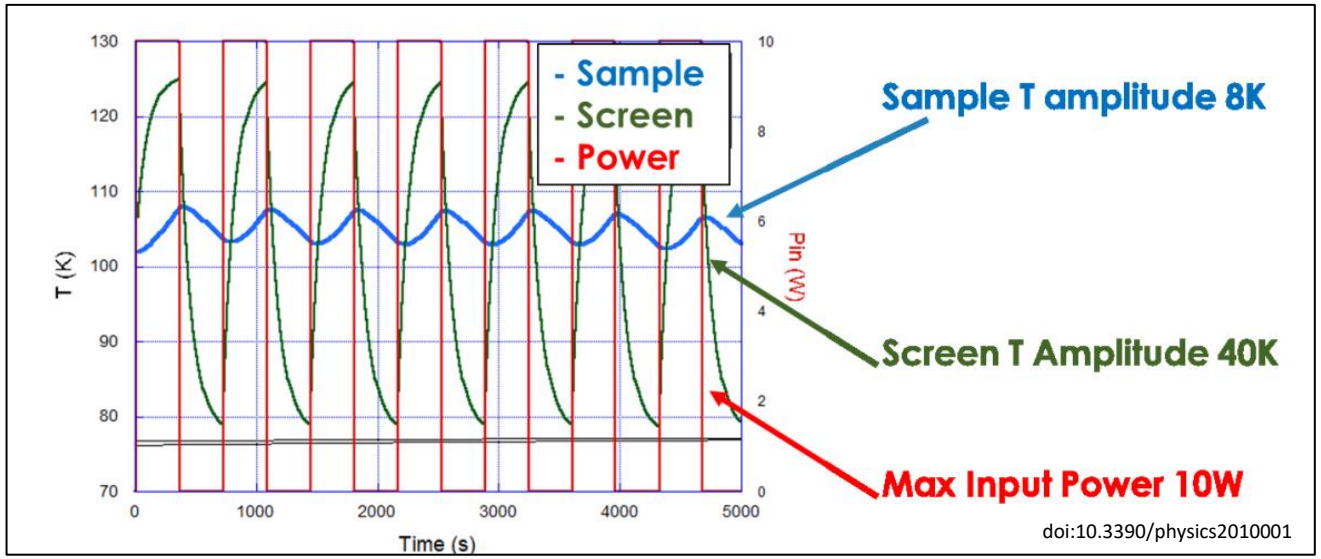
THERMAL MODULATION

The thermal modulation must be done by radiative exchange between sample and screen which surrounds it.

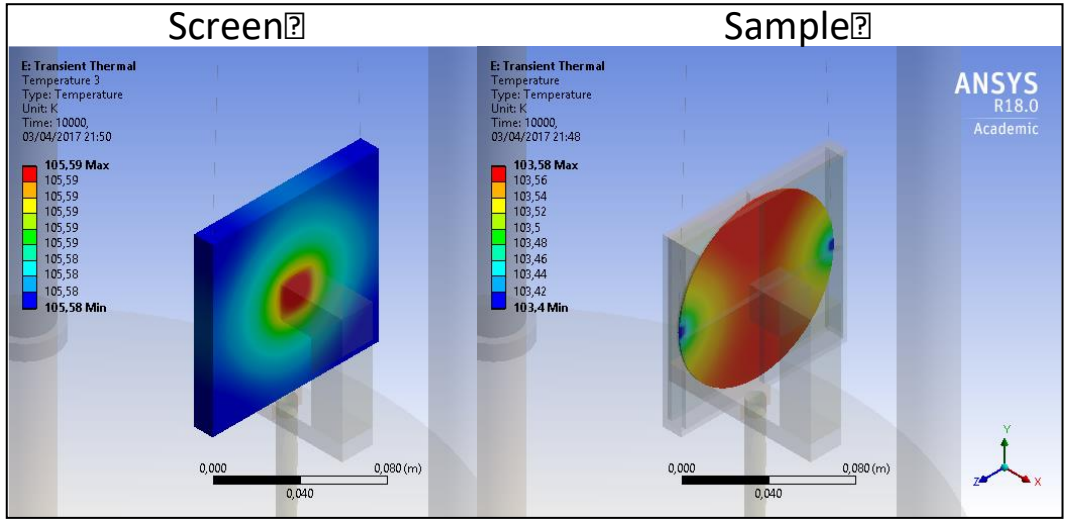
Modulation frequency and its amplitude around T_c depend on the thermal properties of the materials.

A finite element study is important for the geometry definition and the material choice.

Example simulation of the temperature modulation



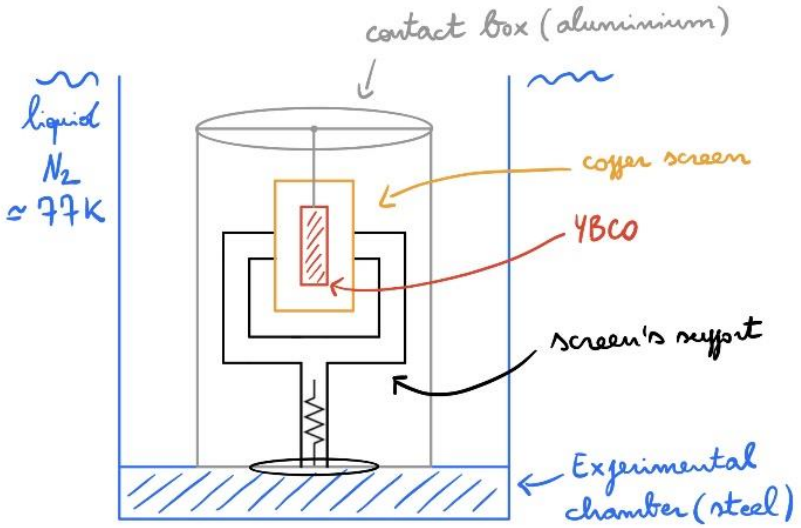
doi:10.3390/physics2010001

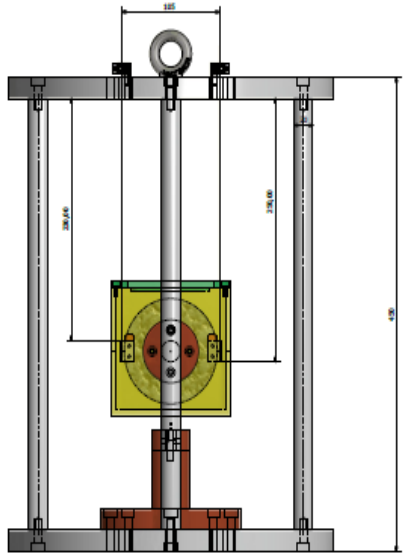


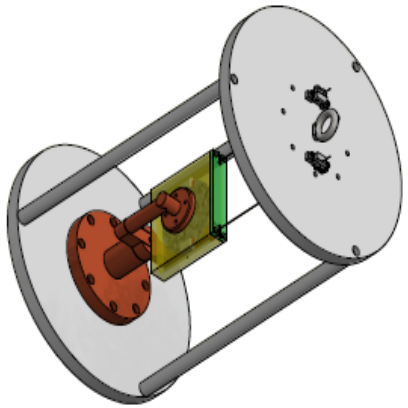
courtesy of Dr Paola Puppo

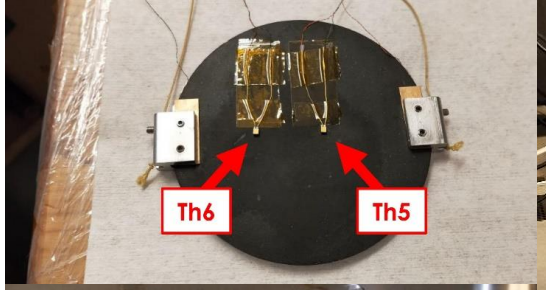
The time constants are different because of the different mechanisms of heat exchange:
- in the screen the conductivity dominates;
- in the sample only the radiative mechanism is present.

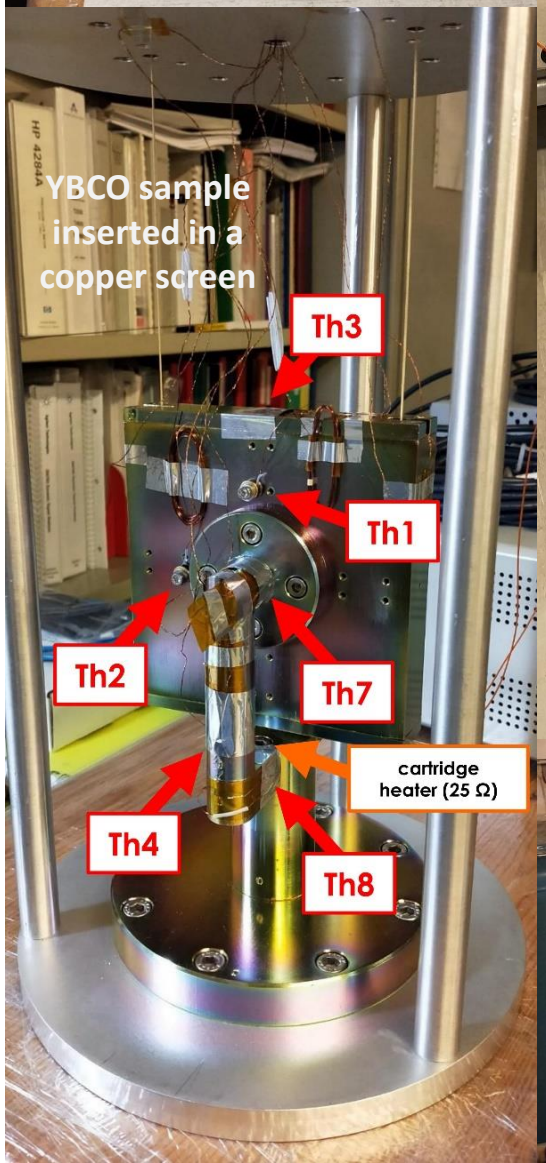
After the sample has reached T_c, its temperature will be modulated by switching on and off a heater connected to the screen at a frequency of approximately 10 mHz and an amplitude of max 3 K around T_c.


contact box (aluminium)
liquid
N_2
≃ 77K
copper screen
YBCO
screen's support
Experimental
chamber (steel)



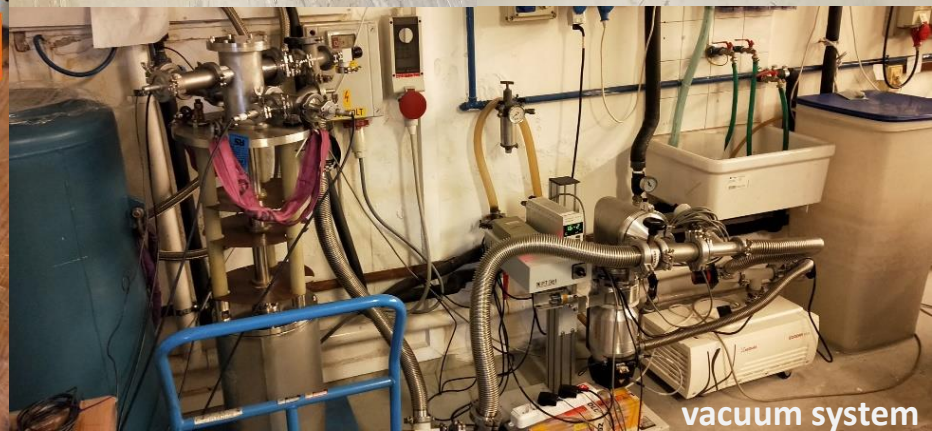



Th6
Th5


YBCO sample
inserted in a
copper screen
Th3
Th1
Th2
Th7
cartridge
heater (25 Ω)
Th4
Th8


experimental
chamber


liquid
nitrogen
cryostat


vacuum system

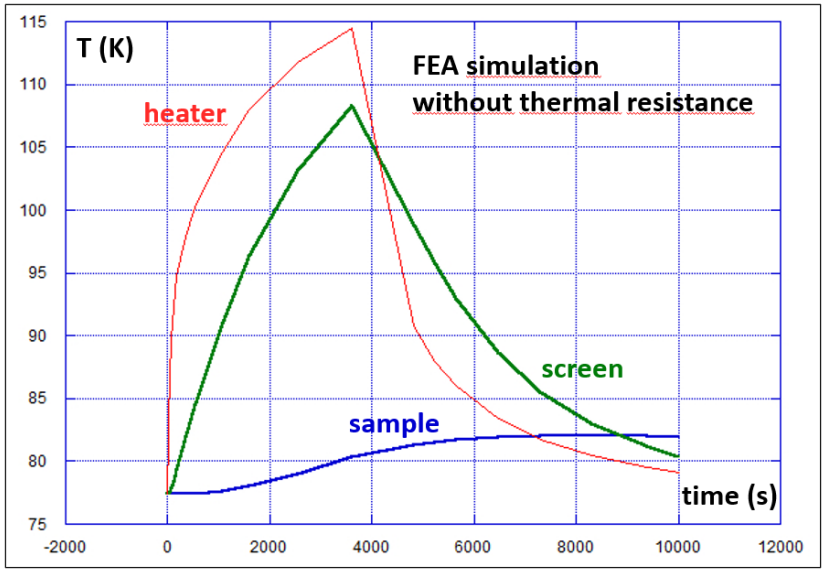
Procedure

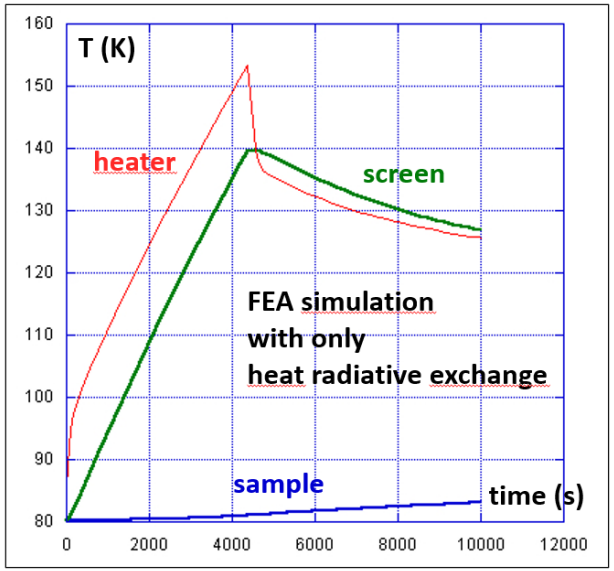
1. creating vacuum (P ~ 10^{-5} mbar);
2. cooling down the system to the liquid nitrogen temperature;
3. heating the screen using a resistance (40 W);
4. turning the resistance off.

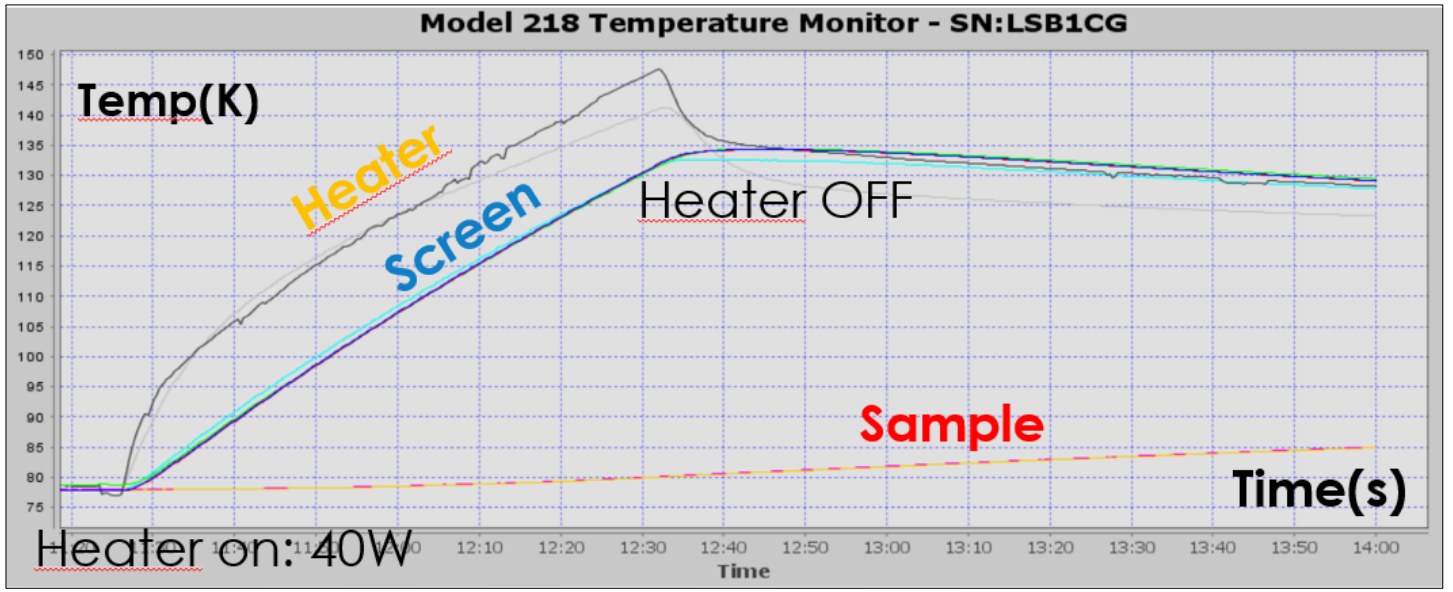
What happens

1. The heat flows to the screen through the conductive copper support increasing its temperature.
2. The sample temperature increases through the radiative heat transfer with the screen.
3. The heating times are very different.
4. Once the resistance is turned off, the temperature of the screen should decrease to 77 K through the thermal conduction, but this does not happen!
5. The temperature of the sample cannot be modulated at around 10 mHz as required .

courtesy of Dr Paola Puppo

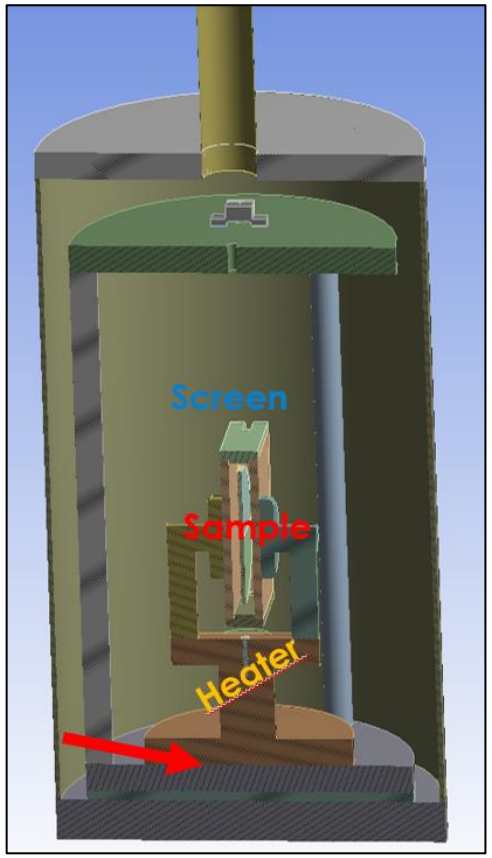




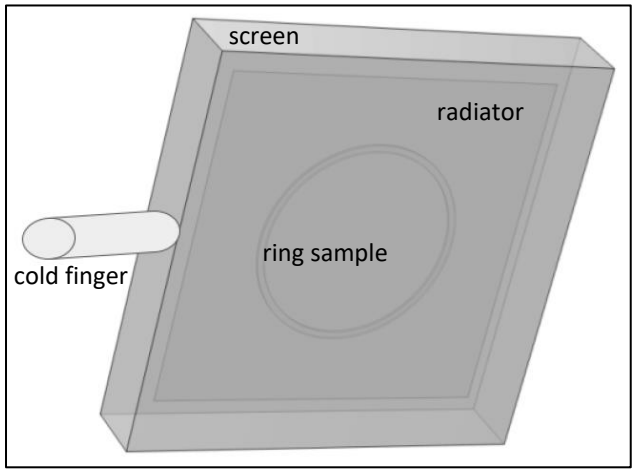


Why happens

- high thermal resistance between the support of the screen and the base of the experimental chamber (red arrow);
- low efficiency of radiation heat transfer between screen and sample due to the disc geometry of sample.



courtesy of Dr Paola Puppo



courtesy of Dr Luca D'Onofrio

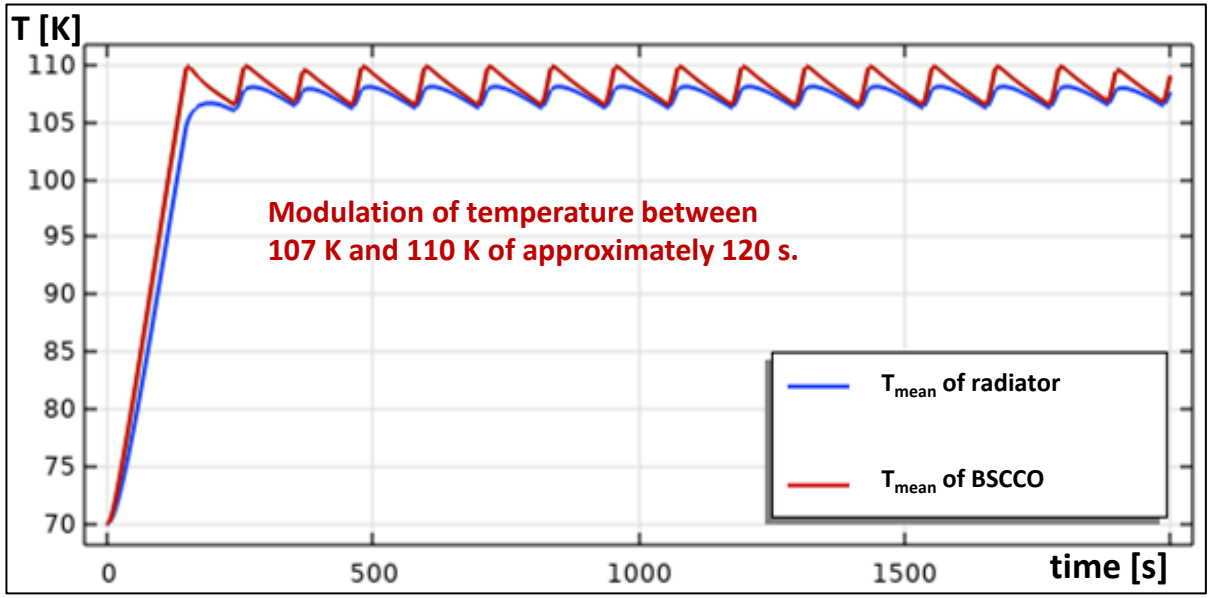
BSCCO ring sample	**Graphite radiator**	**Screen**	**Laser**
R_{in} = 92 mm	400x400 mm	500x100 mm	P = 10 W
R_{out} = 100 mm	thickness = 0.1 mm	thickness = 0.1 mm	
V = $20 \cdot 10^3$ mm^3			

What's next?

Upgrade of the Thermal Modulation System

- improving the heat exchange between the system and the liquid nitrogen bath;
- changing the shape of the sample, from disc to ring;
- introducing a sample + radiator system to facilitate a faster heat exchange with the screen;
- continuing to investigate alternative solutions.

courtesy of Dr Luca D'Onofrio



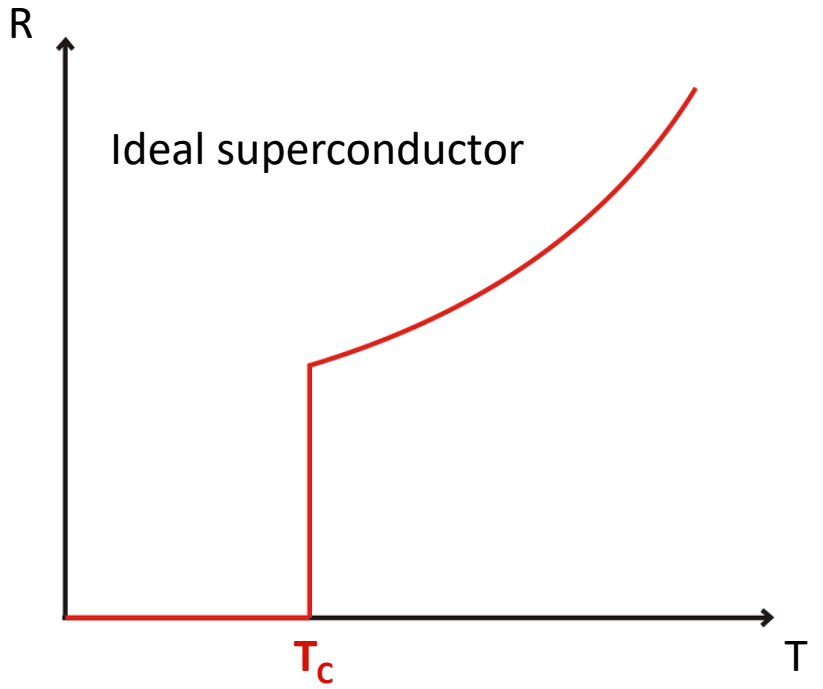
SAMPLES

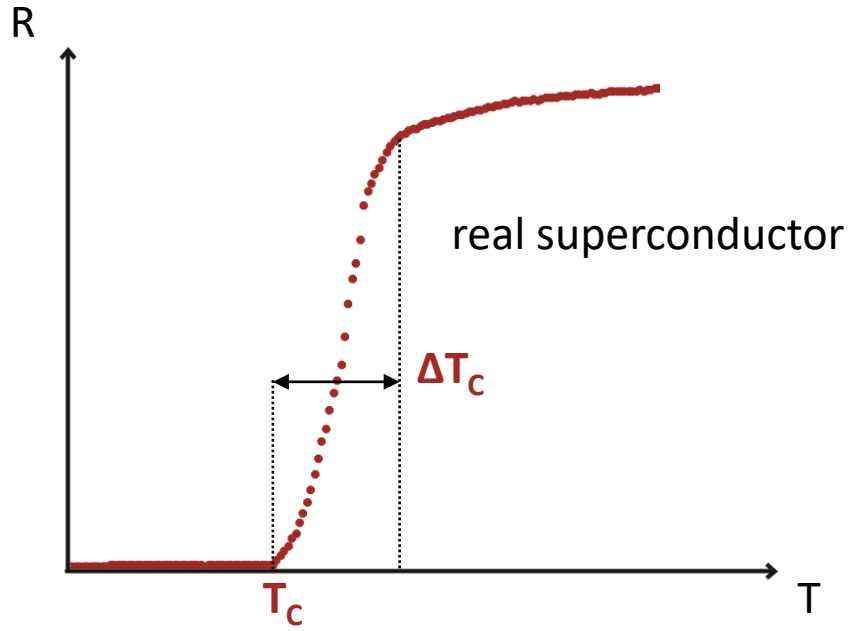
Requirements:

- **T_C > 80 K and $\Delta T_C \leq$ 2 K**
- **Large mass > 200 g → samples with a 10 cm diameter**

From the **electrical resistance as a function of temperature plot** it is possible to obtain information on the first requirement.

Also, these plots will let us understand the quality of a sample and if a certain degree of dis-uniformity exits in it.



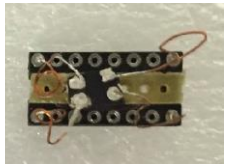


FRAGMENTS OF A DISC

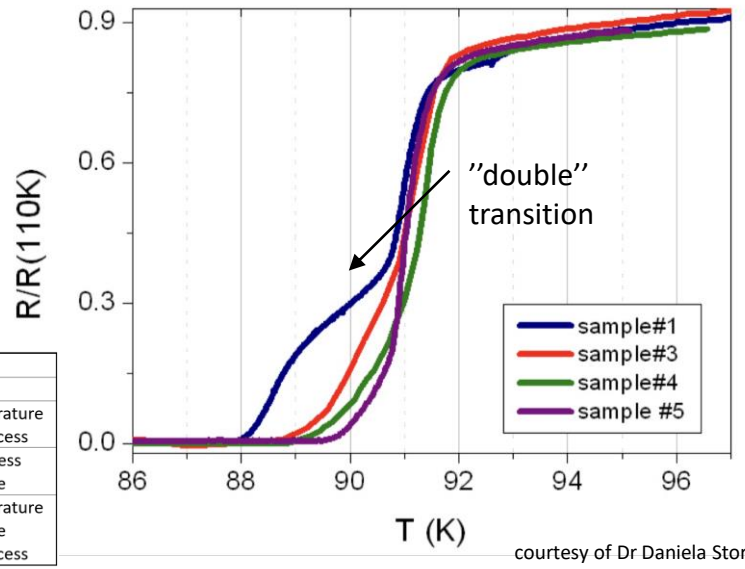
ENTIRE DISC

Sintered YBCO

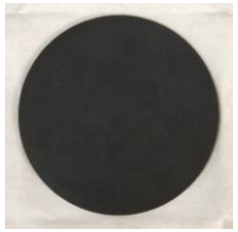
Sintered YBCO discs were prepared in different sintering conditions (temperature, oxidation) in order to maximise T_C and reduce ΔT_C (CAN Superconductors).

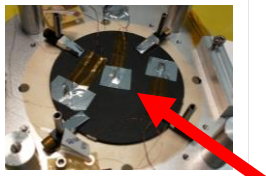


	T_c (K)	ΔT_c (K)	notes
sample#1	88.0	3.5	
sample#3	88.5	3.0	higher sintering temperature + extra oxidation process
sample#4	89.0	2.5	extra oxidation process + isostatic pressure
sample#5	89.5	2.0	higher sintering temperature + isostatic pressure + extra oxidation process

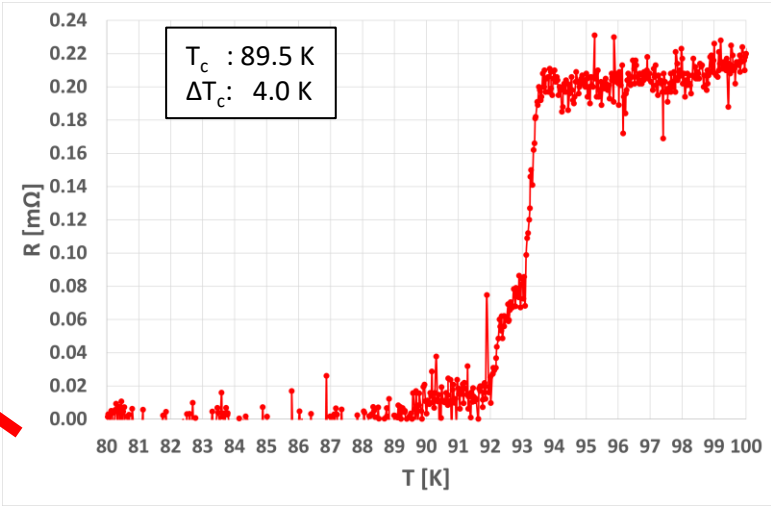


courtesy of Dr Daniela Stornaiuolo



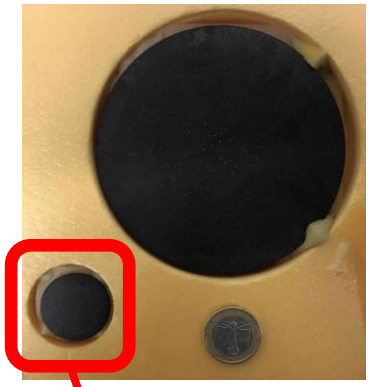


diameter: 100mm
thickness: 3 mm
mass: ~ 124 g
(like sample#3)



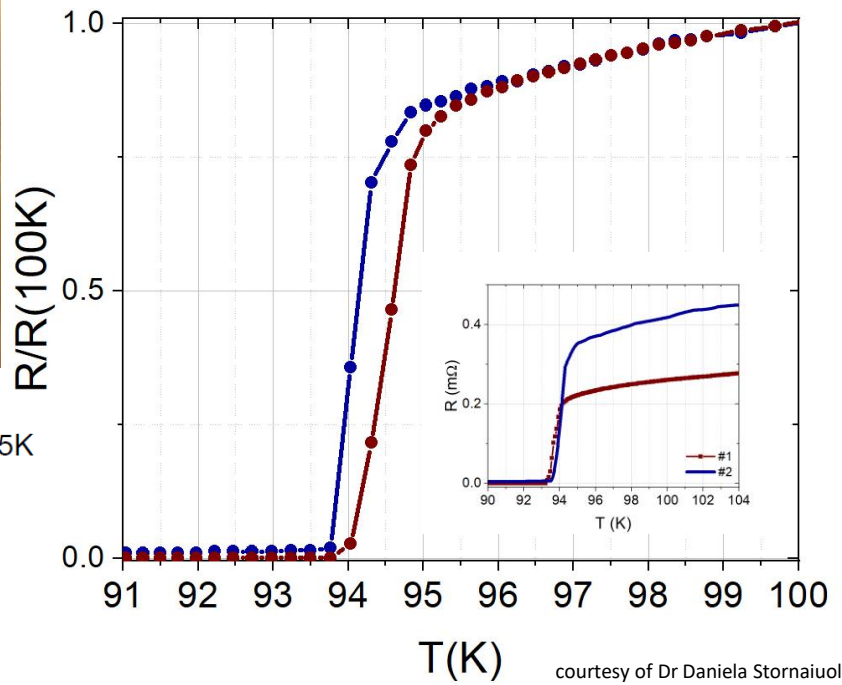
crystalline GdBCO/Ag

Single-domain melt-textured bulk pieces (CAN Superconductors).



Tc=93.5K

ΔT=1K



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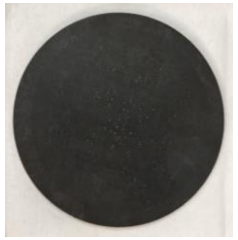

diameter: 100mm
thickness: 4 mm
mass: ~ 213 g

work in progress

CONCLUSIONS

- ✓ **Archimedes** is an experiment conceived to shed light on the discussed **interaction between the gravitational field and the vacuum fluctuations**.
- ✓ The **measurement** must be performed **using an extremely sensitive balance** (D'Urso's talk) and **modulating the temperature of superconductors at very low frequencies (about tens of mHz) and with amplitude of a few K**. The experiment will work at **cryogenic temperature** and in a **seismically quiet site** (Naticchioni's talk).
- ✓ An **upgraded thermal modulation system** is currently under construction. The goal is to **remove any thermal resistance** and **improve the thermal modulation of the sample**.
- ✓ The results of the simulations support the **mechanically isolated system, composed of a ring sample (GdBCO or BSCCO) in thermal contact with a radiator, that exchanges heat only with its thermal bath whose temperature is modulated by the screen that surrounded this system**.

SOME REFERENCES

Eur. Phys. J. Plus (2022) 137:826
https://doi.org/10.1140/epjp/s13360-022-03025-7

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Casimir energy for N superconducting cavities: a model for the YBCO (GdBCO) sample to be used in the Archimedes experiment

PHYSICAL REVIEW B **106**, 134502 (2022)

doi: 10.1103/PhysRevB.106.134502

Quantum zero point electromagnetic energy difference between the superconducting and the normal phase in a high-T_c superconducting metal bulk sample

PHYSICAL REVIEW D **90,** 022002 (2014) doi: 10.1103/PhysRevD.90.022002

Towards weighing the condensation energy to ascertain the Archimedes force of vacuum

Eur. Phys. J. Plus (2021) 136:511
https://doi.org/10.1140/epjp/s13360-021-01450-8

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency

SCIENTIFIC AMERICAN

COVID Health Mind & Brain Environment Technology Space & Physics Video Podcasts Opinion

https://www.scientificamerican.com/article/how-much-does-nothing-weigh/

PARTICLE PHYSICS

How Much Does 'Nothing' Weigh?

The Archimedes experiment will weigh the void of empty space to help solve a big cosmic puzzle

By Manon Bischoff on May 1, 2023

physics

MDPI

Physics 2020, 2, 1–13; doi:10.3390/physics2010001

Article

Progress in a Vacuum Weight Search Experiment

The Archimedes Experiment

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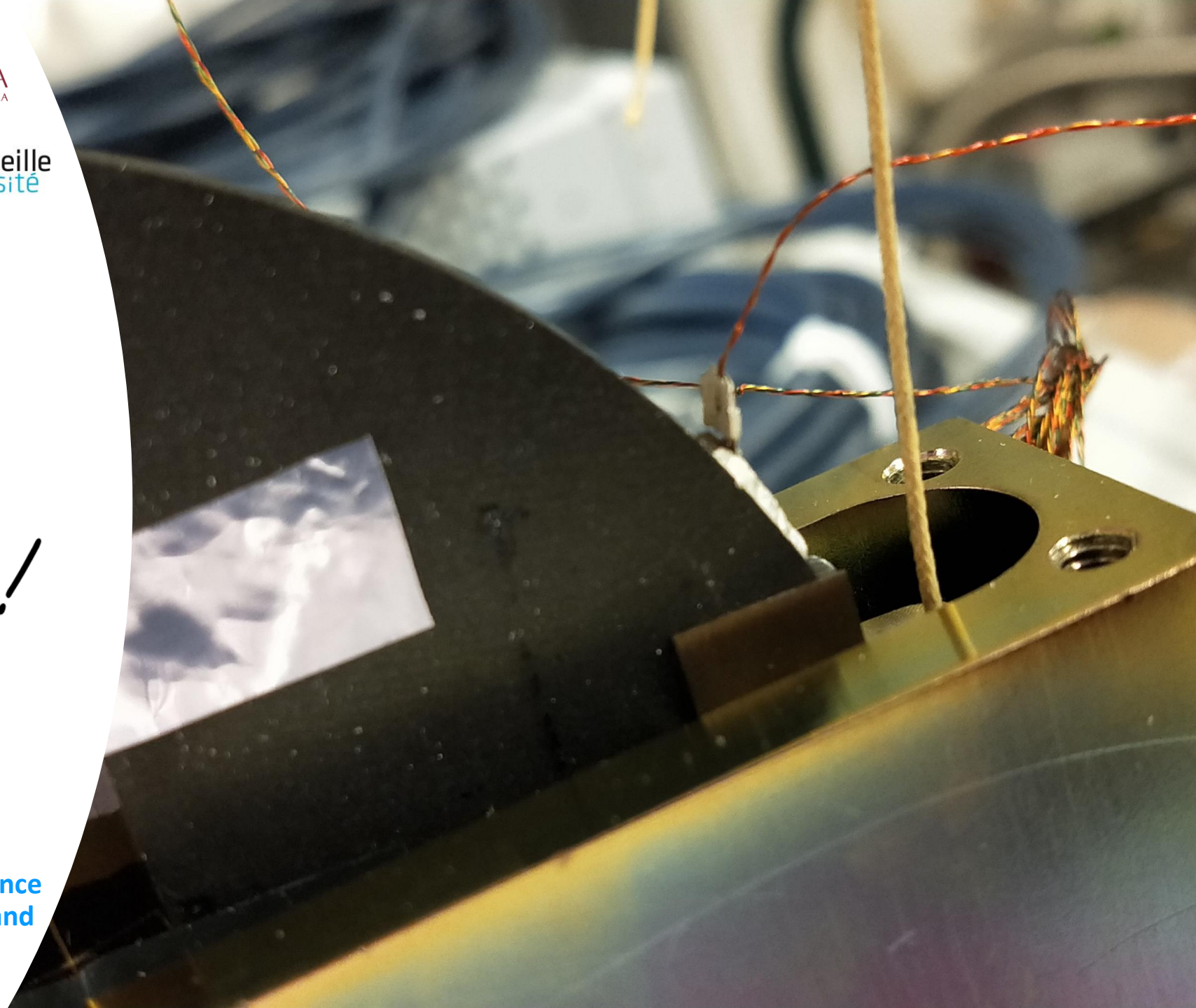
Thank you

for your attention!



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28 August – 01 September 2023, Vienna (Austria)

EXTRA SLIDES

The candidate sites for the ET are:

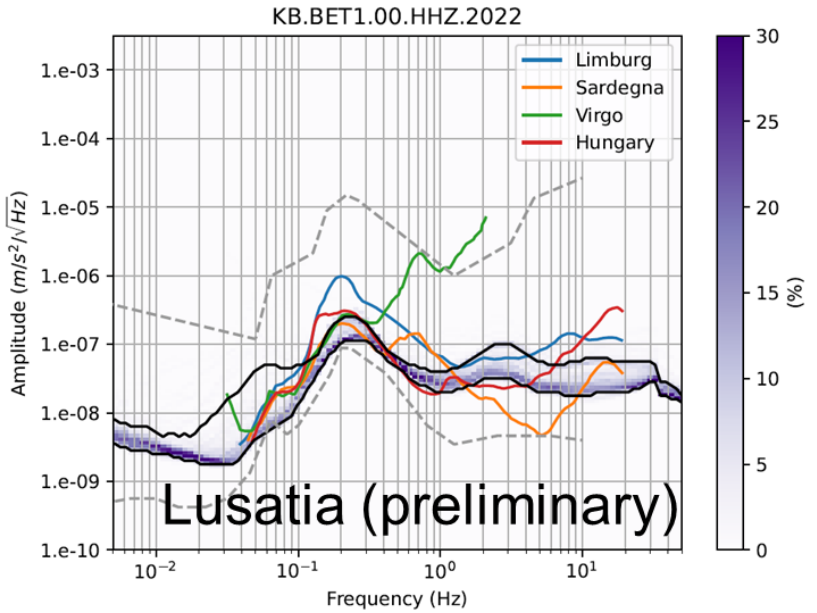
- Sos Enattos in Sardinia;
- Euregio Meuse-Rhine (EMR),

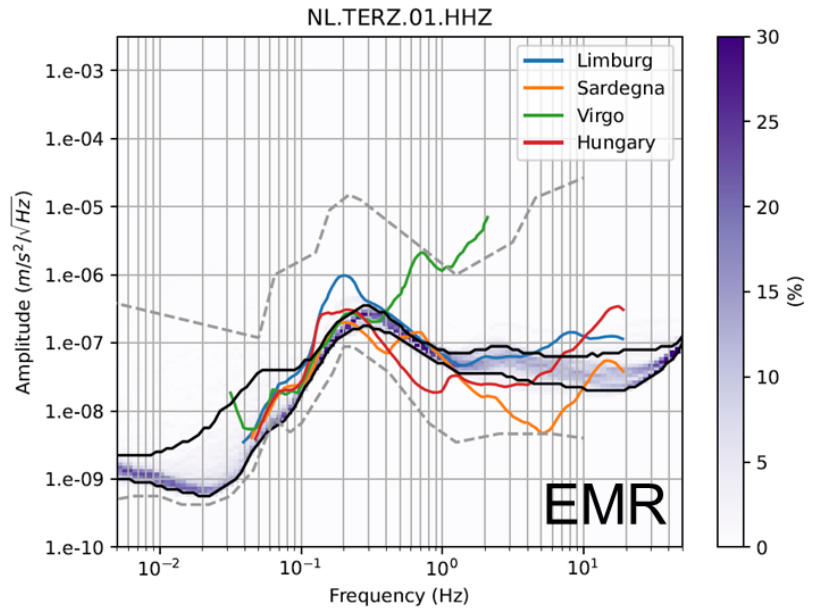
border region between Belgium,

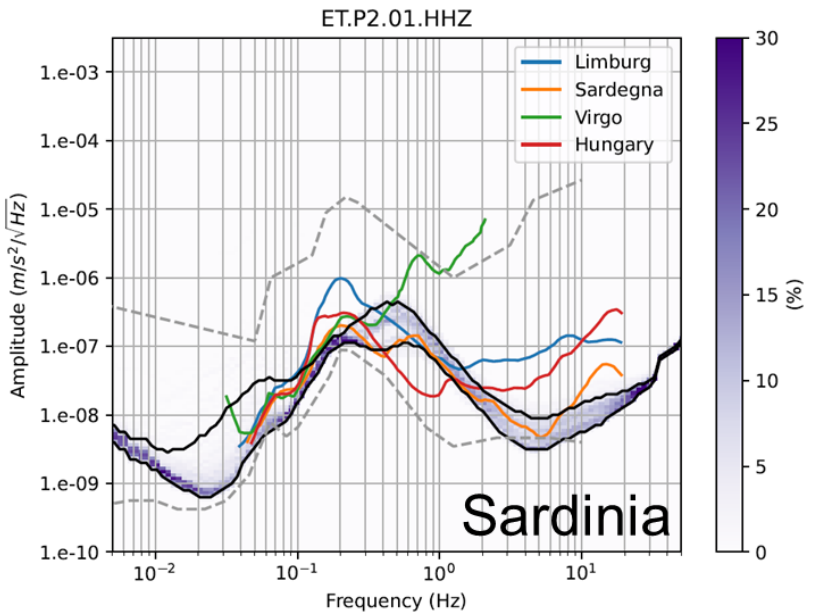
the Netherlands and Germany;

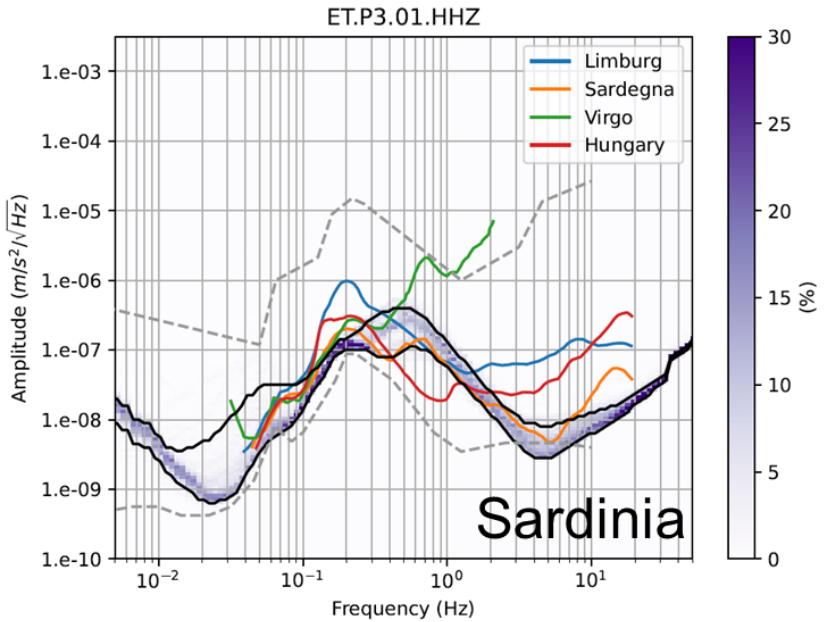
- Lusatia in Saxony.

In the low frequency range of ET (from 2 Hz to 10 Hz),
Sos Enattos area is among the quietest sites in the world.









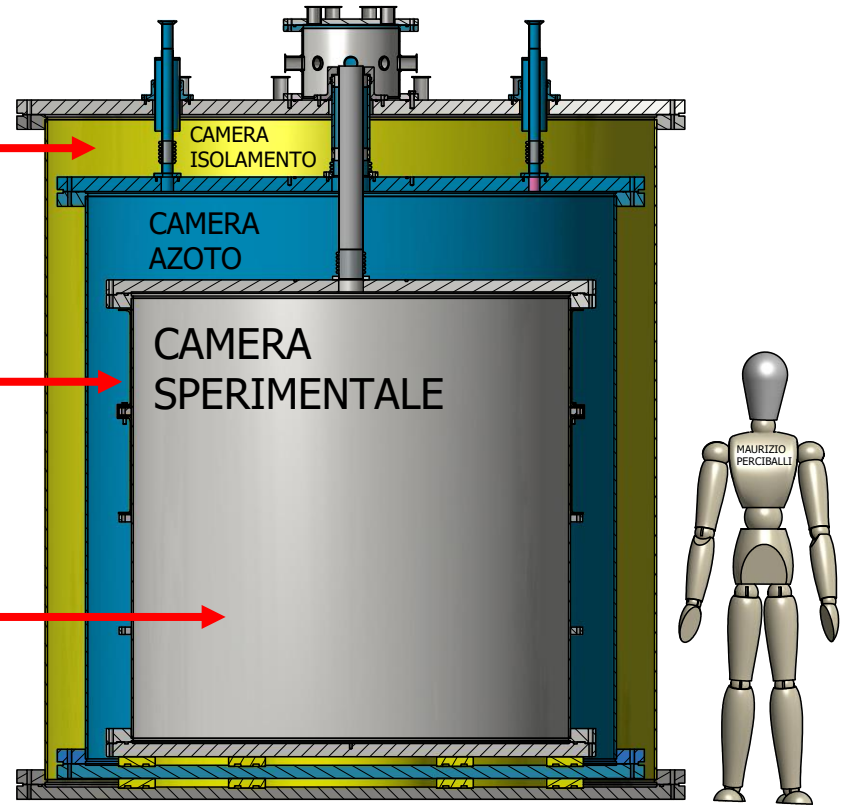
courtesy of Dr Luca Naticchioni

CRYOSTAT

Vacuum/Insulation Chamber
company: ???
material: steel
height , diameter: 3240 mm , 2730 mm
mass: 8100 kg

Nitrogen Chamber
company: Fantini Sud S.p.A. (Italy)
material: steel
height , diameter: 2003 mm , 2400 mm
mass: 6100 kg

Experimental Chamber
company: L.M.P. Amicuzi (Italy)
material: steel
height , diameter: 1780 mm , 2000 mm
mass: 3500 kg



The cryostat consists of three chambers.

The **Experimental Chamber**, that will hosts the balance, will be completely submerged in liquid Nitrogen inside the **Nitrogen Chamber**.

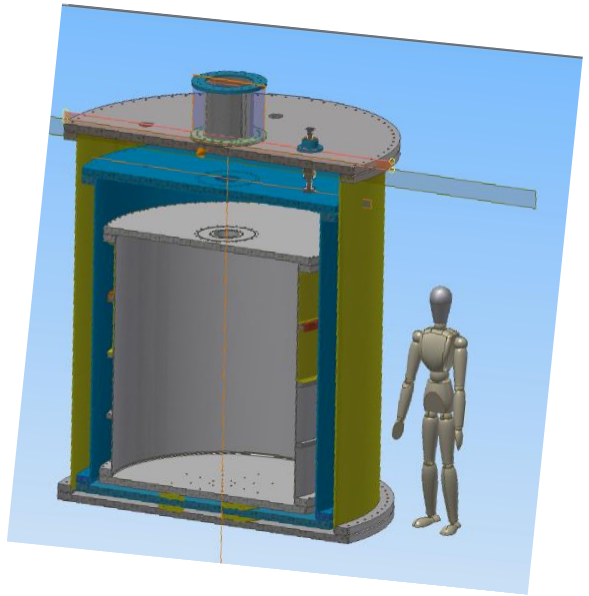
The volume of liquid Nitrogen in the tank is approximately 4000 l.

An Aluminium screen around the Experimental Chamber ensures good thermal uniformity even with low liquid Nitrogen level.

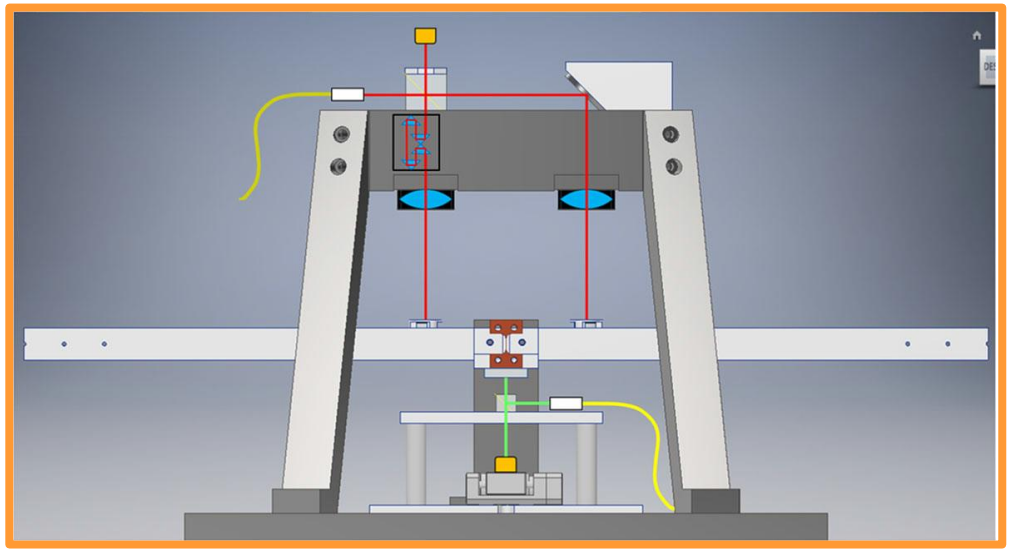
Given a thermal input of about $2W/m^2$, the evaporation time of liquid Nitrogen is estimated to be about 5 months.

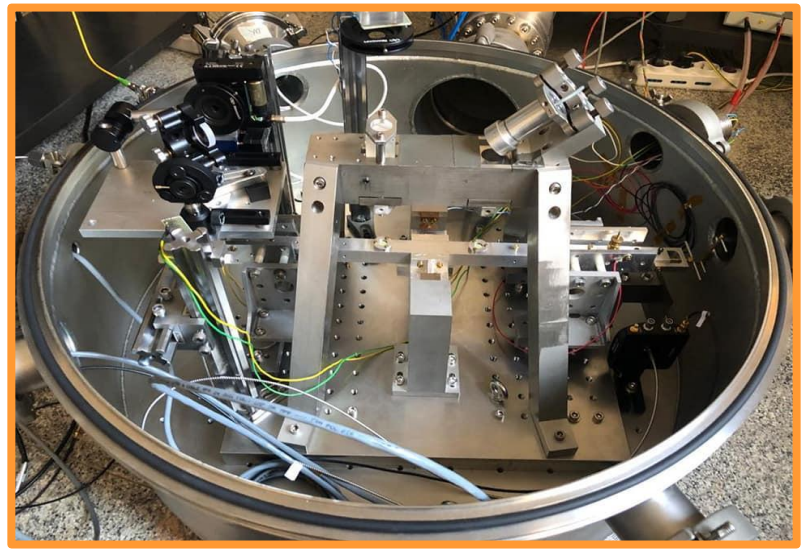
In the **Insulation Chamber** a vacuum ($\sim 10^{-6}$ mbar) will be created to isolate the system from the outside.

The Experimental Chamber can be used as a simple vacuum chamber at room temperature.

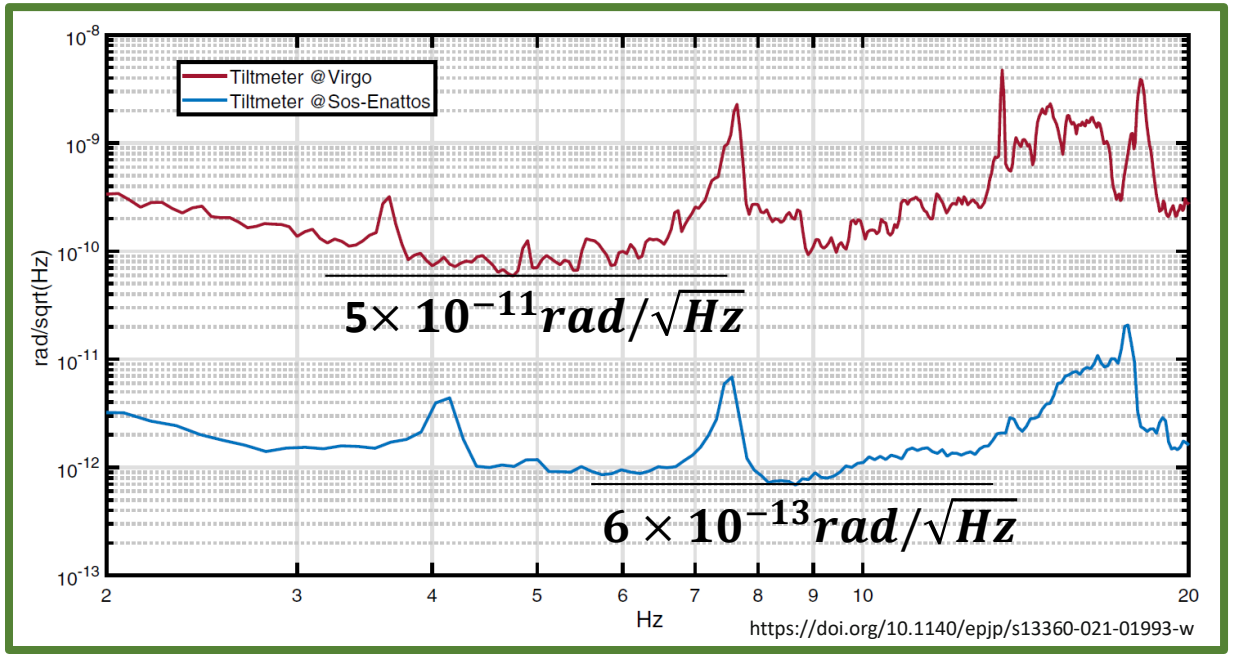


A **prototype of balance** was built to test every component and find the best optic-mechanical configuration for the final balance.

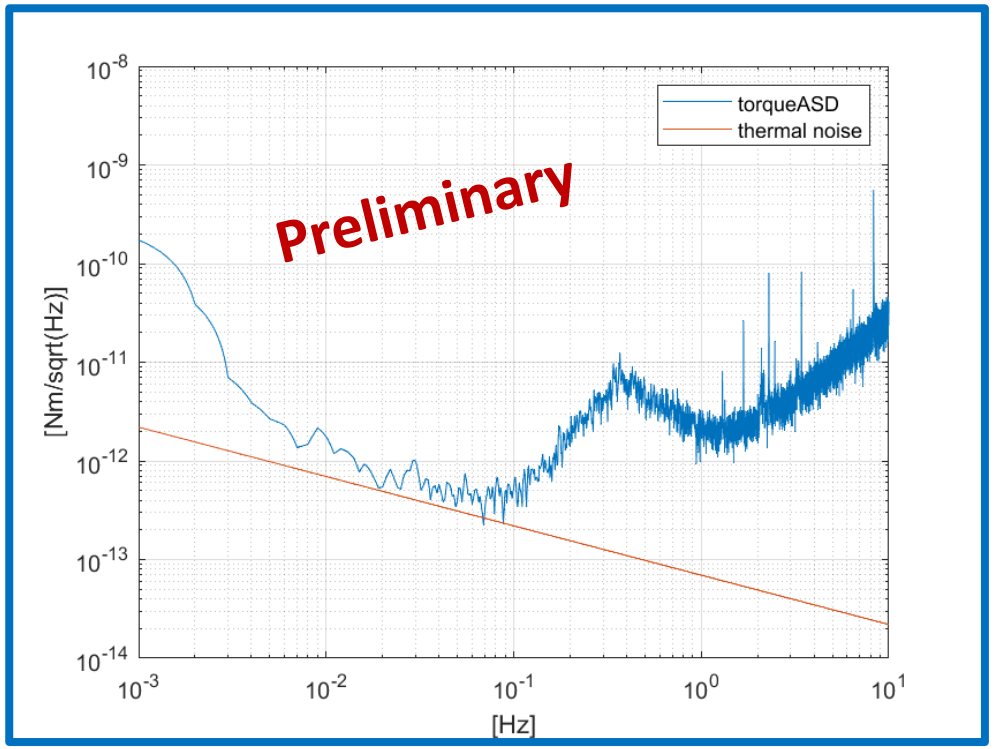




Tilt measurement comparison between Virgo gravitational wave interferometer (Cascina, Pisa) and Sos Enattos (Sardinia) sites.
Most sensitive tiltmeter in the world in the frequency band from 2 Hz to 20 Hz.

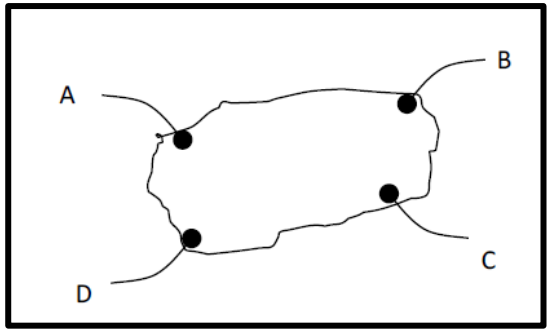


Prototype sensitivity in torque is limited by thermal noise.



The van der Pauw method* allows the average resistivity ρ of a sample of any arbitrary shape to be estimated, provided:

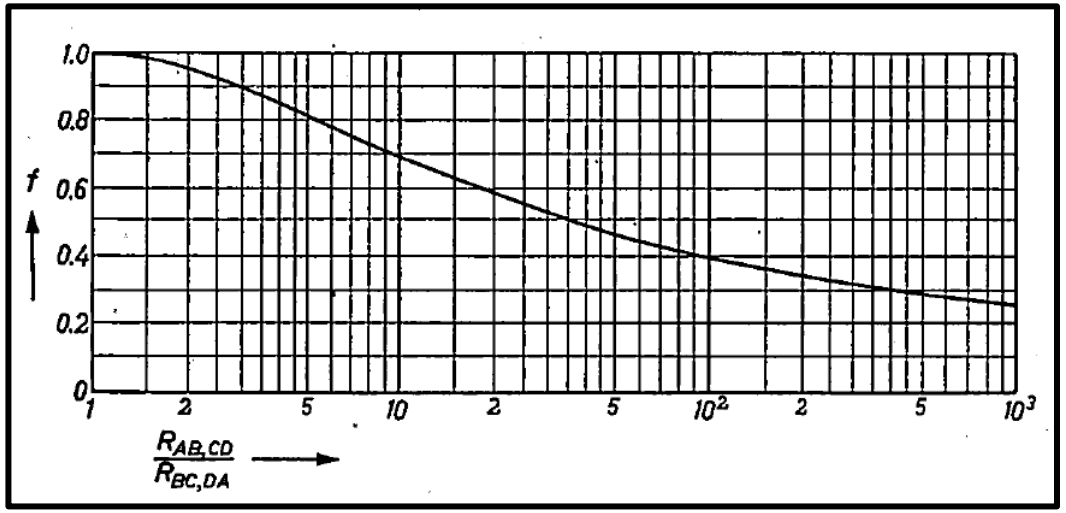
- the sample is two-dimensional (surface area >> thickness), solid (no holes) and homogeneous in thickness;
- the contacts are sufficiently small and placed at the circumference of a sample.



Four contacts are placed on the periphery of a sample (four-point technique):
a fixed current is injected through one pair of contacts (for example I_{AD}) and the voltage is measured across the other pair of contacts (for example V_{BC}).
From these two values, the corresponding resistance is obtained using Ohm's law:
$R_{AD,BC} = V_{BC} / I_{AD}$.

$$\rho = \frac{\pi t}{ln2}\left(\frac{R_{vert}+R_{horiz}}{2}\right) f\left(\frac{R_{max}}{R_{min}}\right)$$

t: thickness of sample
$R_{vert} = (R_{AD,BC}+R_{DA,CB}+R_{BC,AD}+R_{CB,DA})/4$
$R_{horiz} = (R_{AB,DC}+R_{BA,CD}+R_{DC,AB}+R_{CD,BA})/4$
R_{max} (R_{min}) : max (min) between R_{vert} and R_{horiz}



* van der Pauw, 'A method of measuring specific resistivity and Hall effect of discs of arbitrary shape', Philips Research Reports 13 1-9 1958.