Weighing the vacuum with the Archimedes Experiment

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on behalf of the Archimedes collaboration

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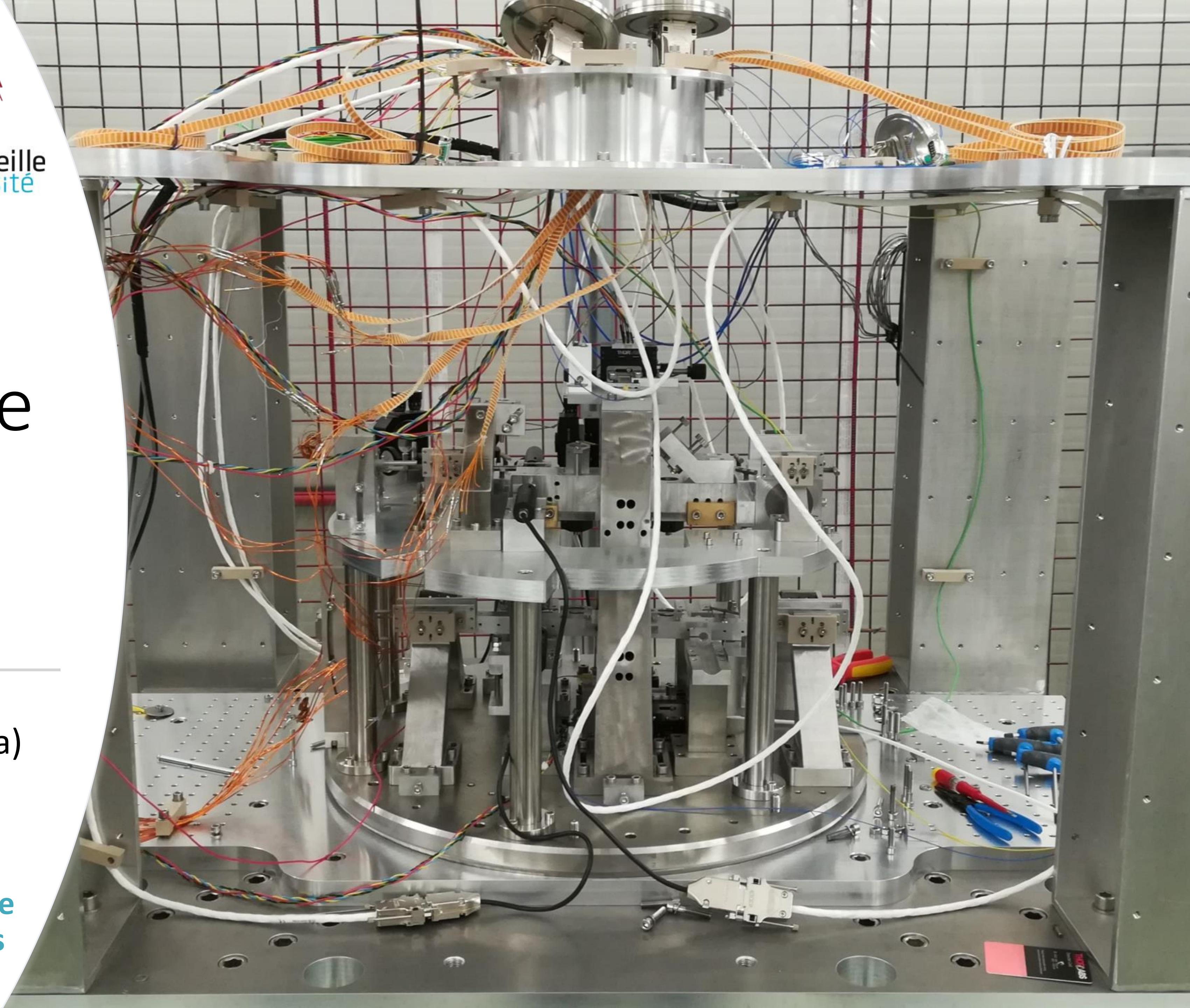
XII International Conference on New Frontiers in Physics

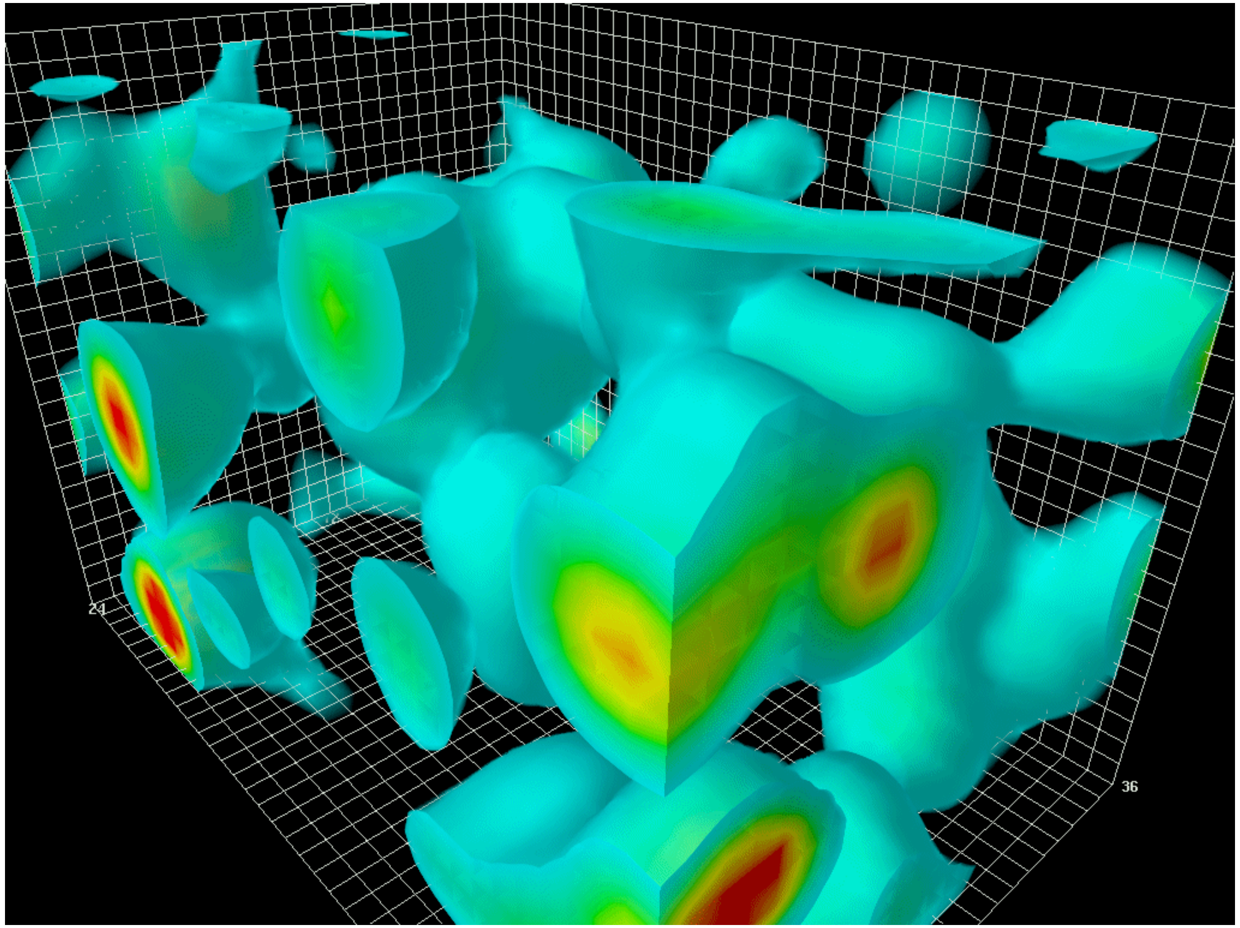
10-23 July 2023, Crete (Greece)



THE WEIGHT OF THE VACUUM

- Do vacuum fluctuations interact with gravity?
- Does vacuum weigh?
- Do virtual photons gravitate?
- Can the interaction between vacuum fluctuations and gravity be measured?

- Vacuum weight and Cosmological Constant problem.



The general expectation is that vacuum energy gravitates.

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.

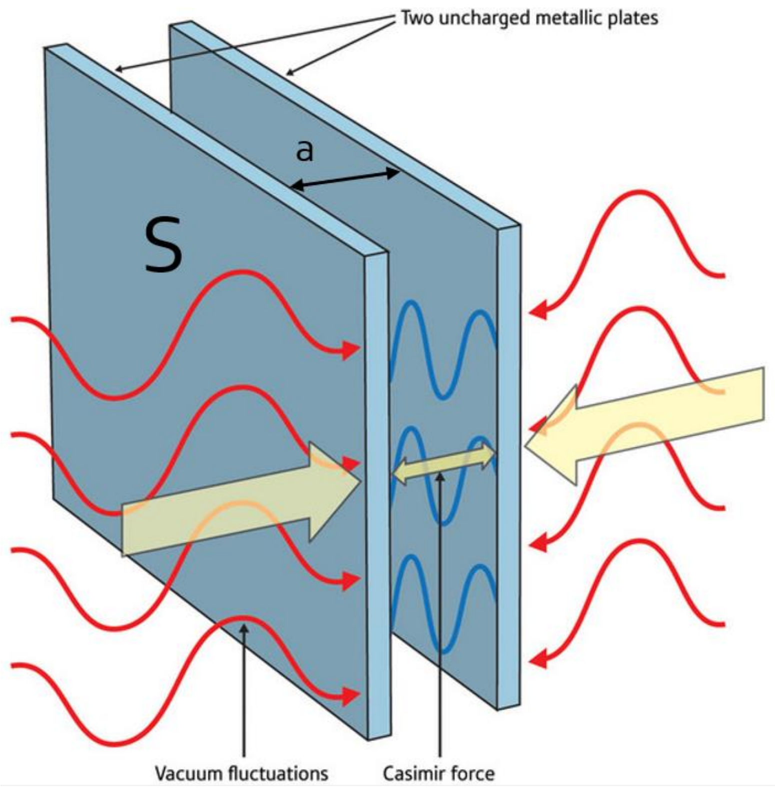
Only some modes can resonate inside the Casimir cavity:
the ones which do not satisfy specific boundary conditions are expelled
and the total vacuum energy changes.

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***):

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

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

[G.Bimonte, E. Calloni, G. Esposito, L. Rosa - Phys. Rev D 76:025008 (2007)]



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

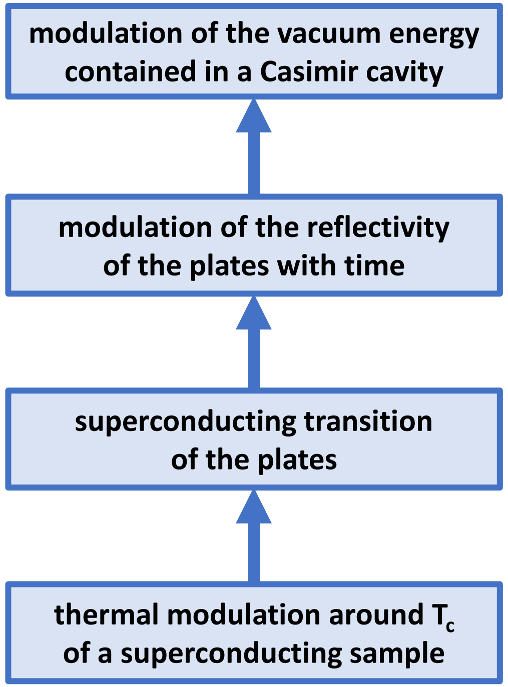
STRATEGY

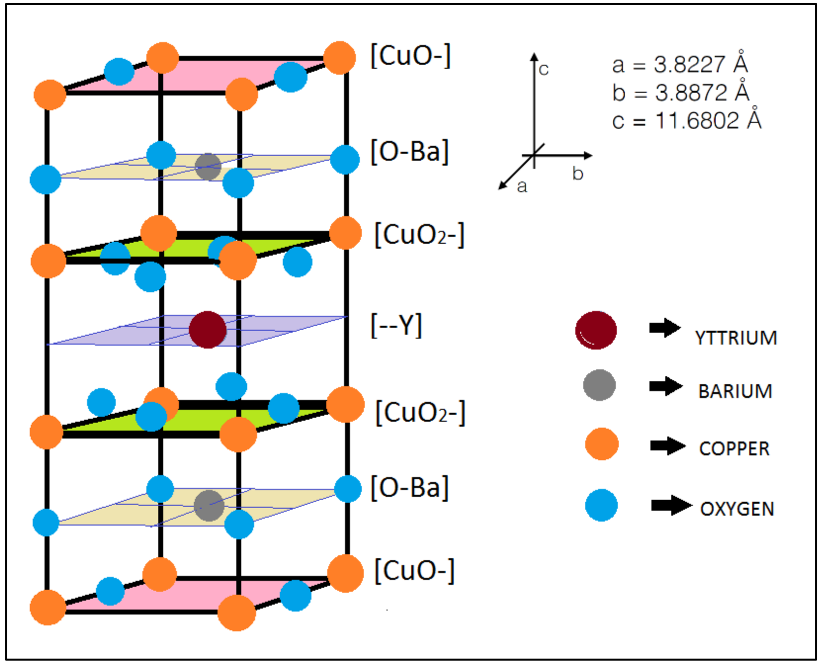
The idea is to modulate the vacuum energy of a rigid Casimir cavity by changing the reflectivity of the plates with time.

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

18 September 2021
Inauguration of the Archimedes Experiment.

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

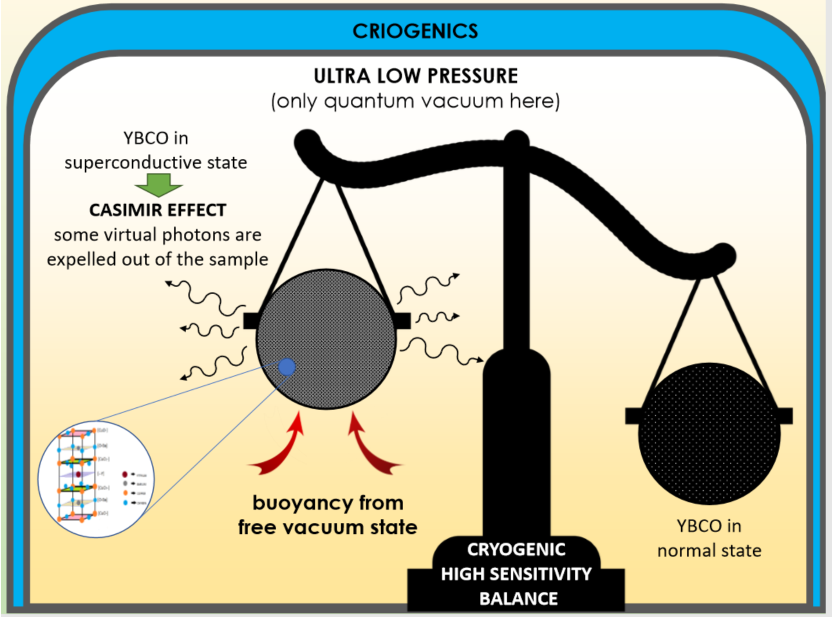
Suspending two equal superconducting discs at the ends of a balance arm at rest in a gravitational field
and modulating the Casimir energy only in one superconductor,
the expected change of weight is measured with a suitably designed high sensitivity cryogenic beam balance.

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 $5 \cdot 10^{-16}$ N.**

courtesy of Dr Luciano Errico



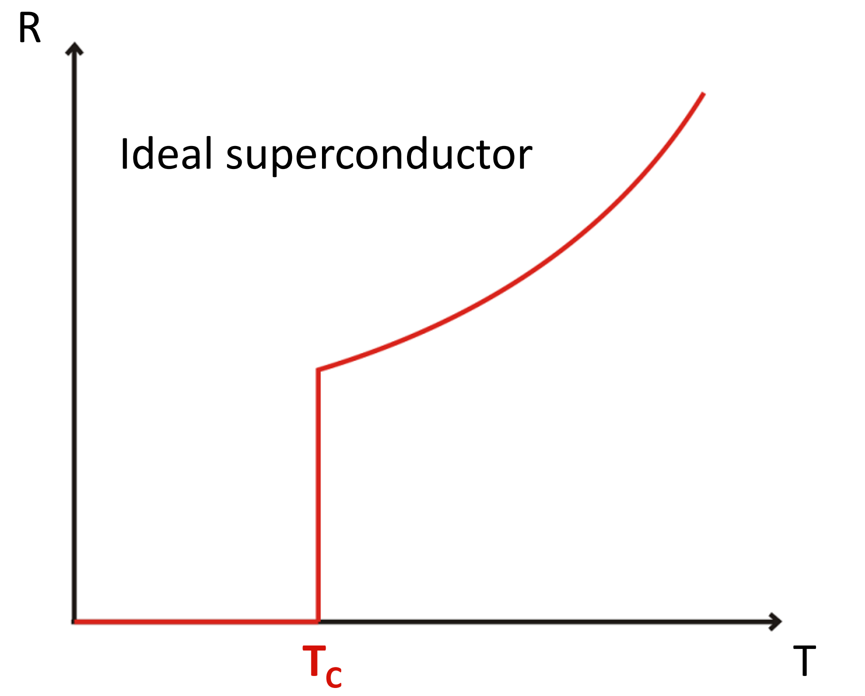
SAMPLES

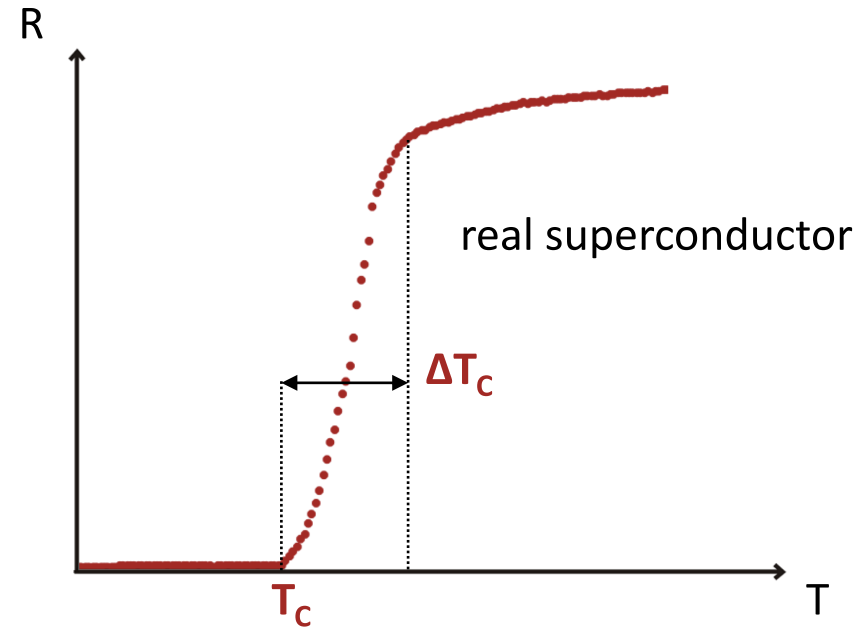
Requirements:

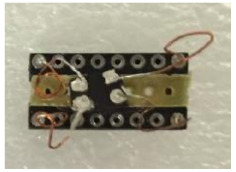
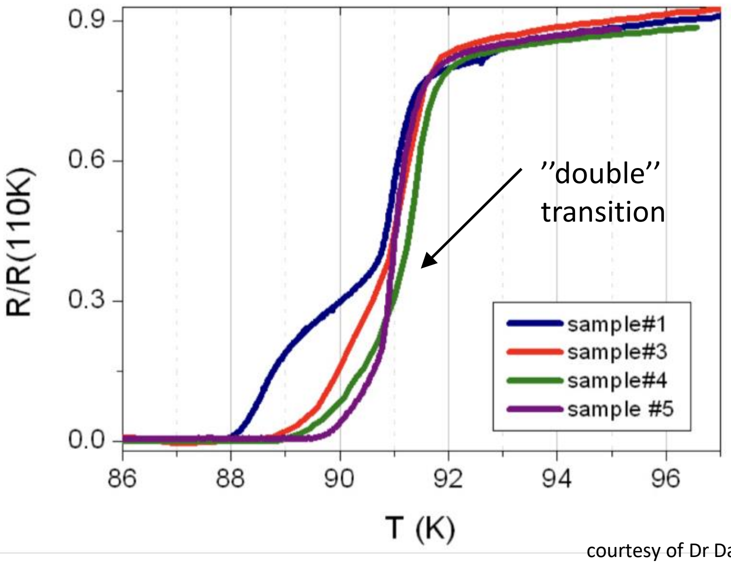
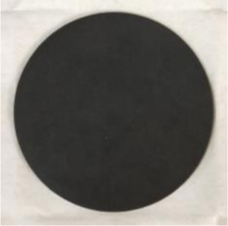
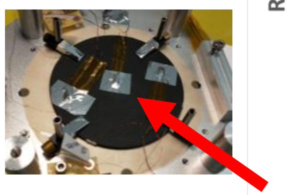
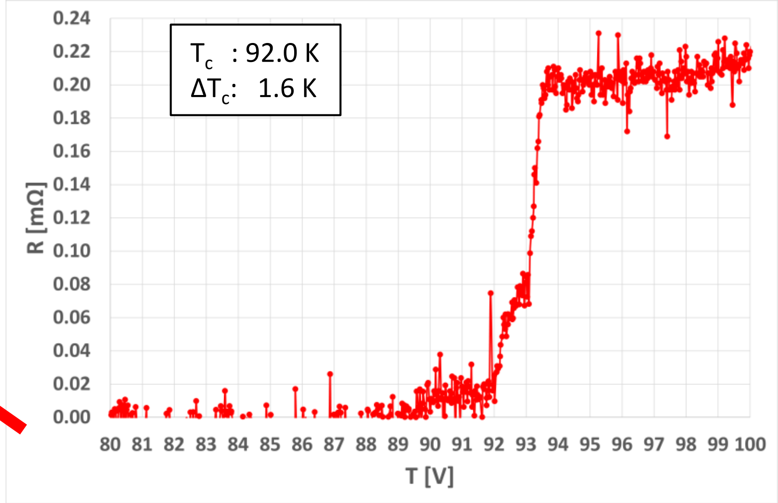
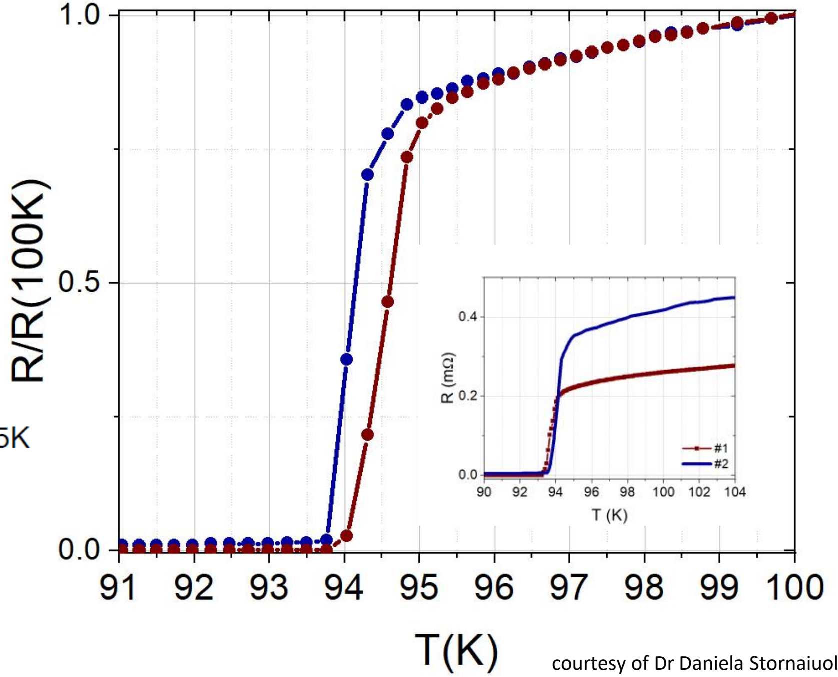
- **T_C > 80 K and $\Delta T_C \leq 2$ K**
- **Large mass > 200 g → samples with a 10 cm diameter**

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.





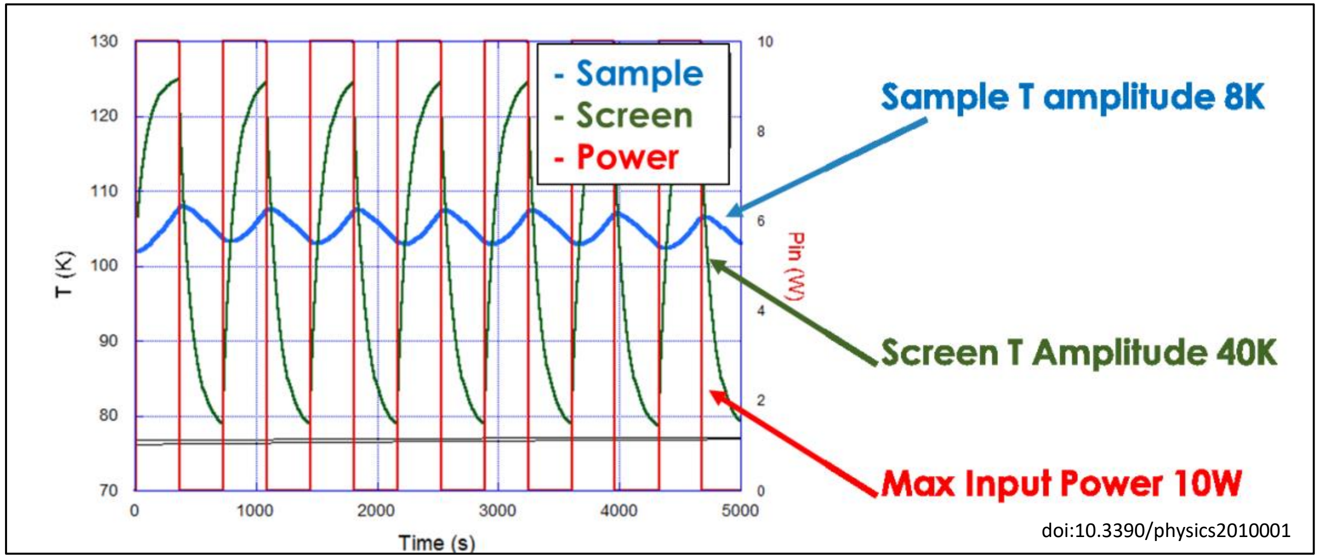
	FRAGMENTS OF A DISC	ENTIRE DISC
Sintered YBCO Sintered YBCO discs were prepared in different sintering conditions (temperature, oxidation) in order to maximise T_C and reduce ΔT_C (CAN Superconductors).	   courtesy of Dr Daniela Stornaiuolo	   diameter: 100mm thickness: 3 mm mass: ~ 124 g
crystalline GdBCO/Ag Single-domain melt-textured bulk pieces (CAN Superconductors).	 Tc=93.5K ΔT=1K  courtesy of Dr Daniela Stornaiuolo	 *work in progress*  diameter: 100mm thickness: 4 mm mass: ~ 213 g

THERMAL MODULATION

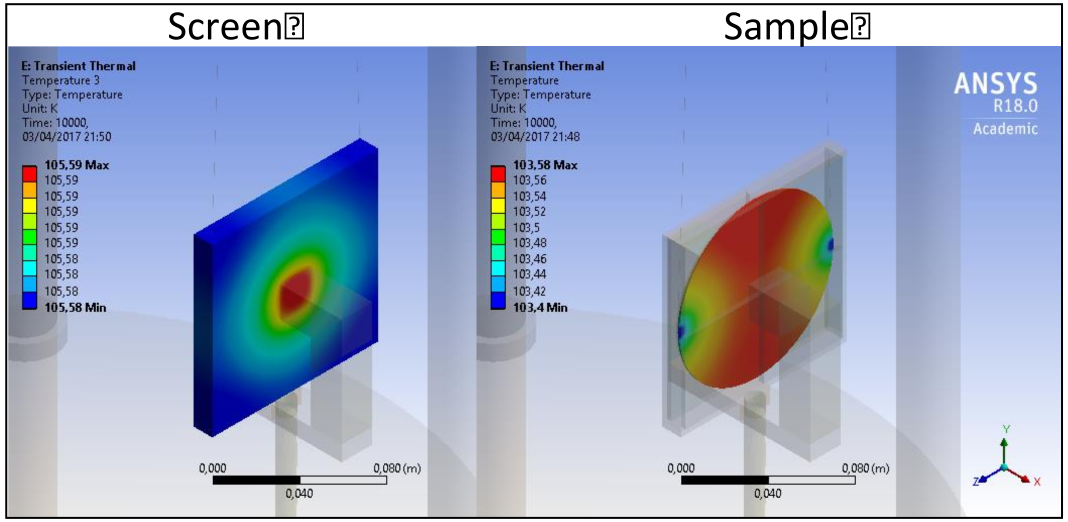
The thermal modulation must be done by radiative exchange between sample and screen which surrounds it.

Frequency modulation 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.



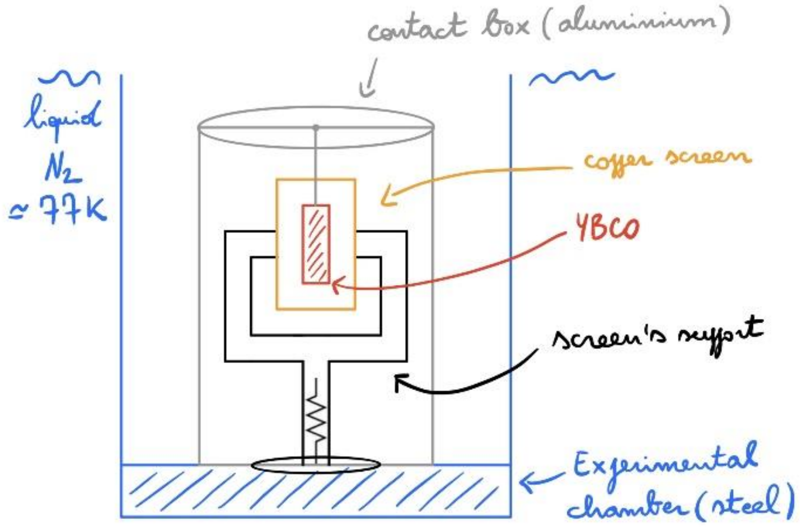
doi:10.3390/physics2010001

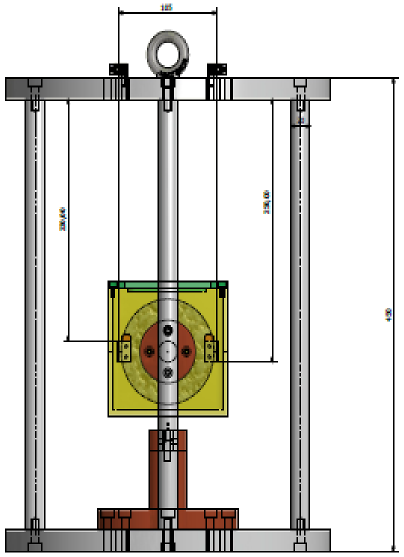


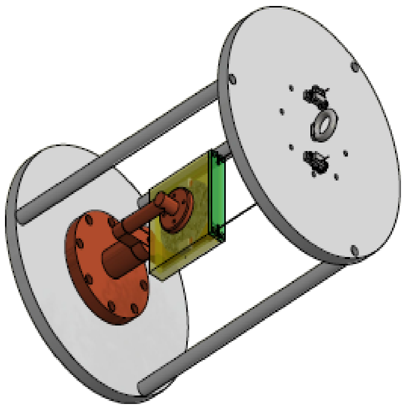
courtesy of Dr Paola Puppo

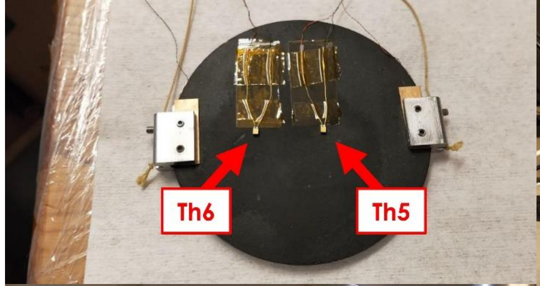
The time constants are different because of the different mechanisms of heat exchange:
- in the screen the conductivity dominates;
- in the sample only the radiative mechanism is present.

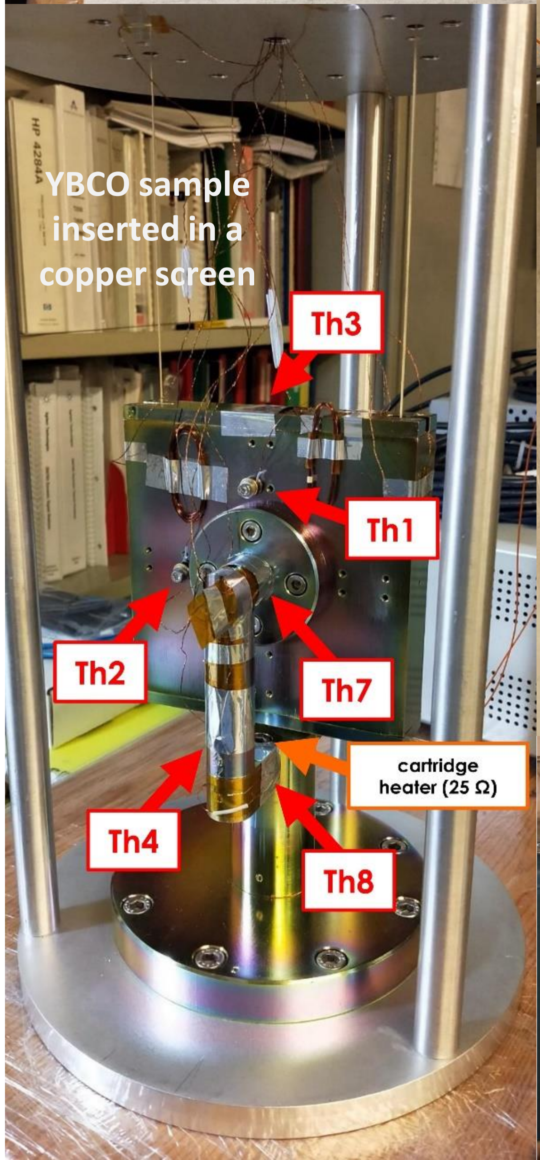
After the sample has reached T_c, its temperature will be modulated by switching on and off a heater connected to the screen at a frequency of approximately 10 mHz and an amplitude of max 3 K around T_c.


contact box (aluminium)
liquid
N2
≈ 77K
copper screen
YBCO
screen's support
Experimental
chamber (steel)



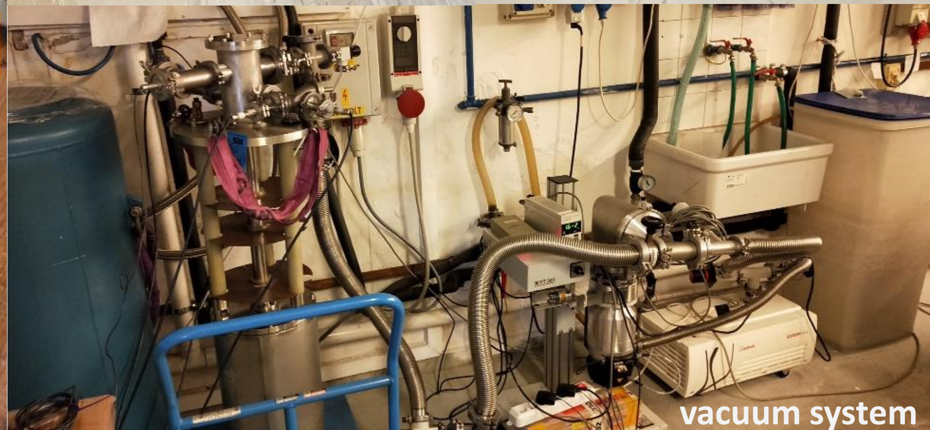


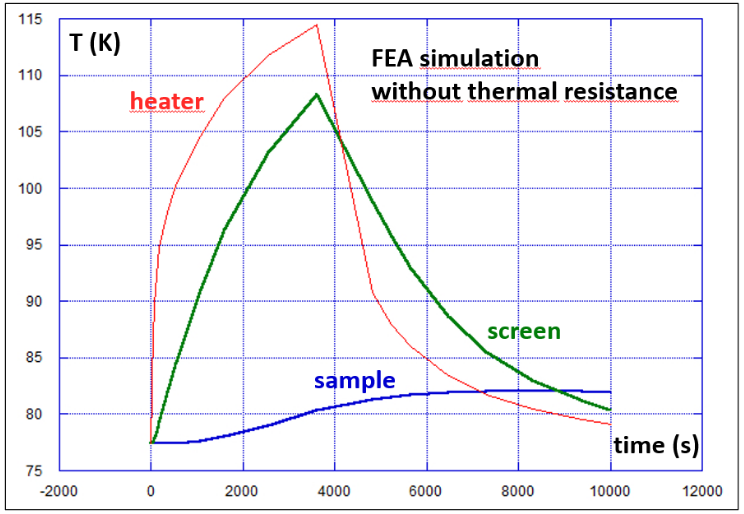

Th6
Th5

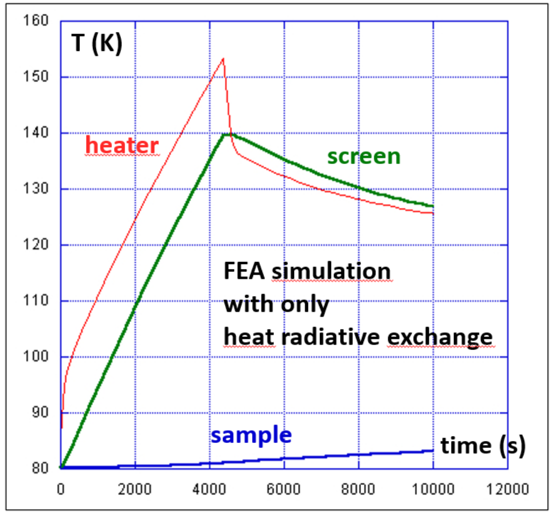

YBCO sample
inserted in a
copper screen
Th3
Th1
Th2
Th7
cartridge
heater (25 Ω)
Th4
Th8


experimental
chamber

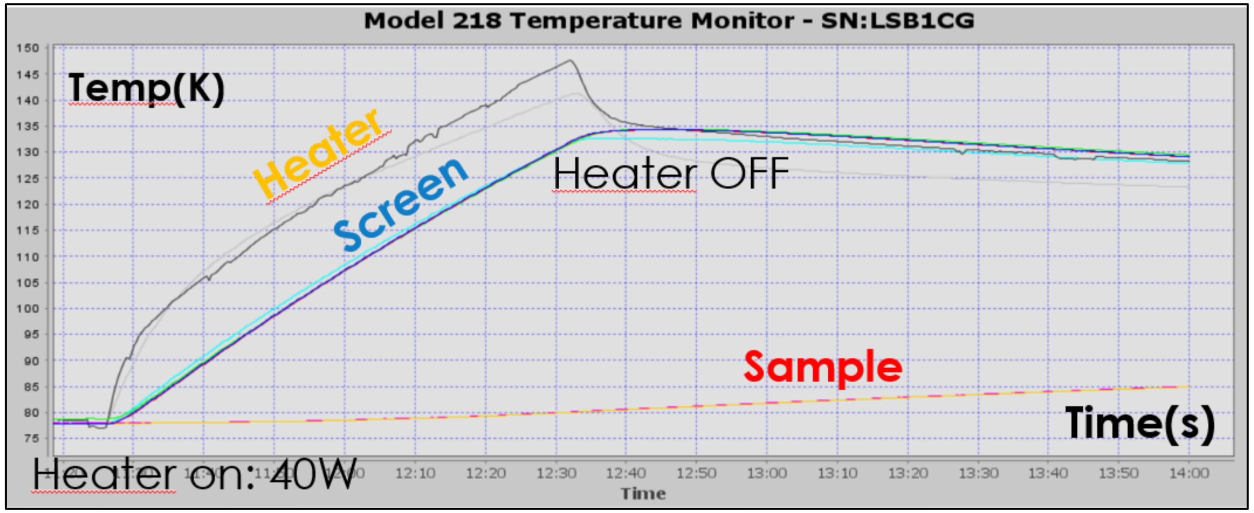

liquid
nitrogen
cryostat


vacuum system





courtesy of Dr Paola Puppo



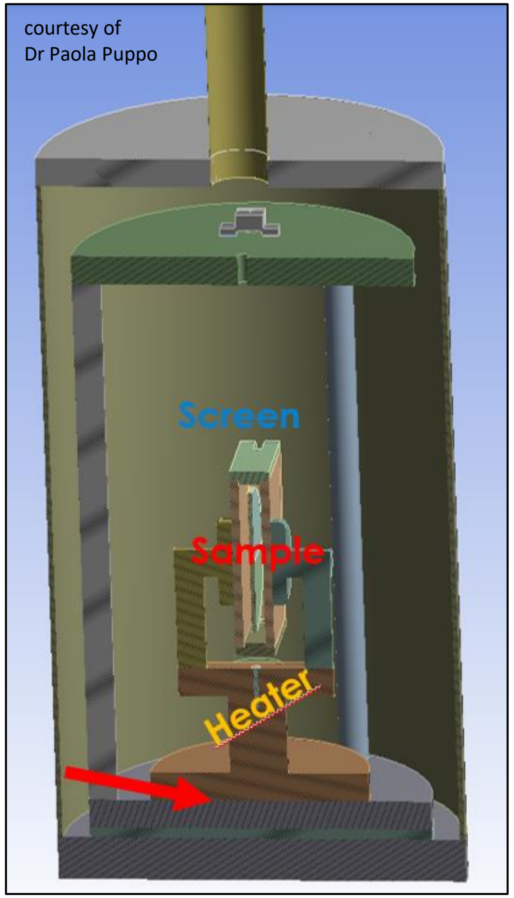
Procedure:

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

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 neat 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:
since this does not happen, it means there is a high thermal resistance (red arrow) and the dominant mechanism is the radiation heat transfer.

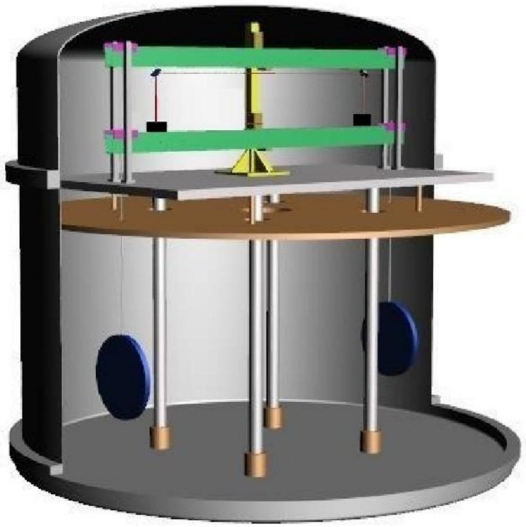
What's next?
Improving the thermal contact between the system and the experimental chamber.

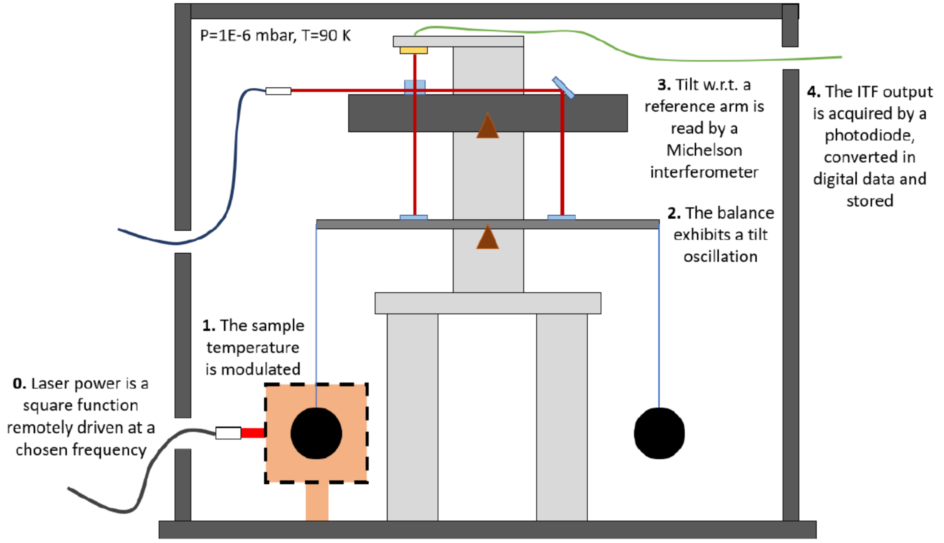


BALANCE

The variation in weight is measured using a **very high sensitivity cryogenic balance based on laser interferometry**.

The **modulation of the temperature** of only one 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.





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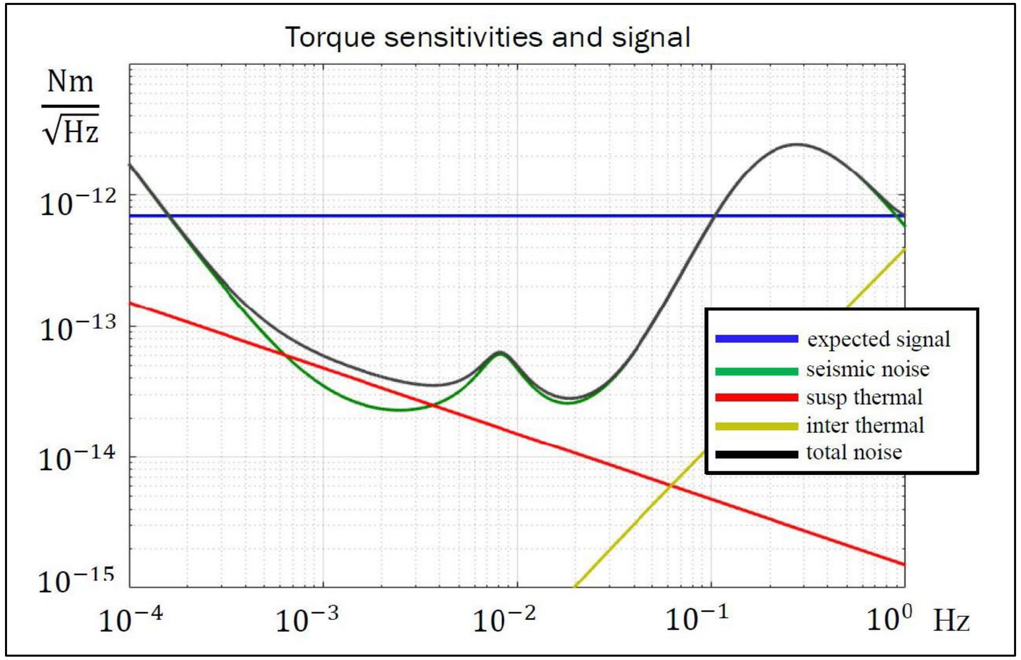
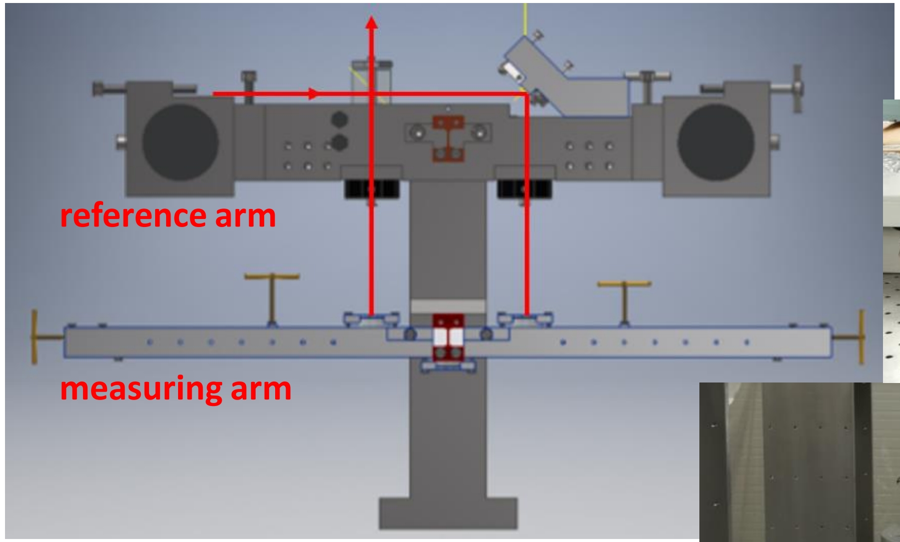
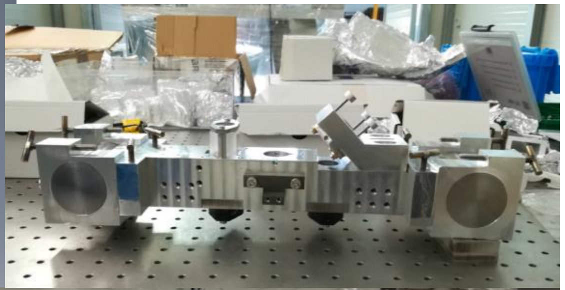
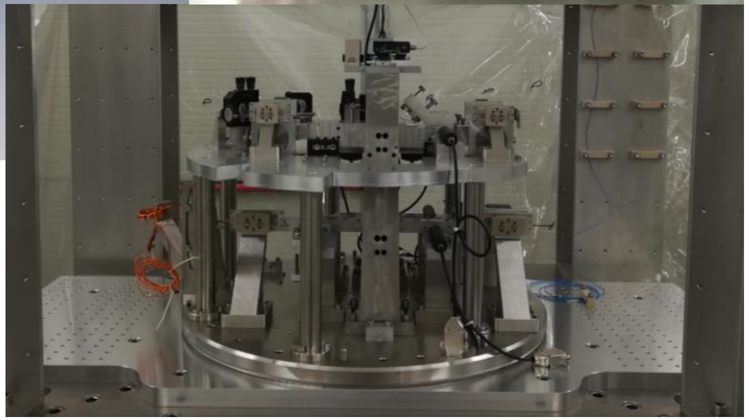




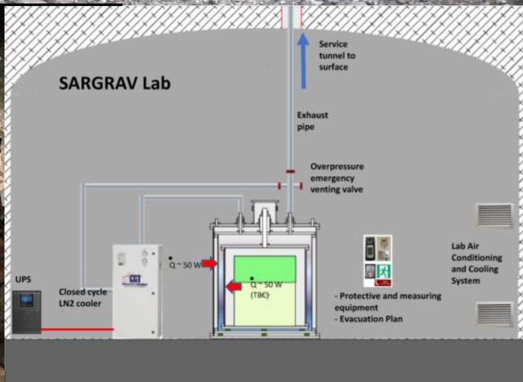




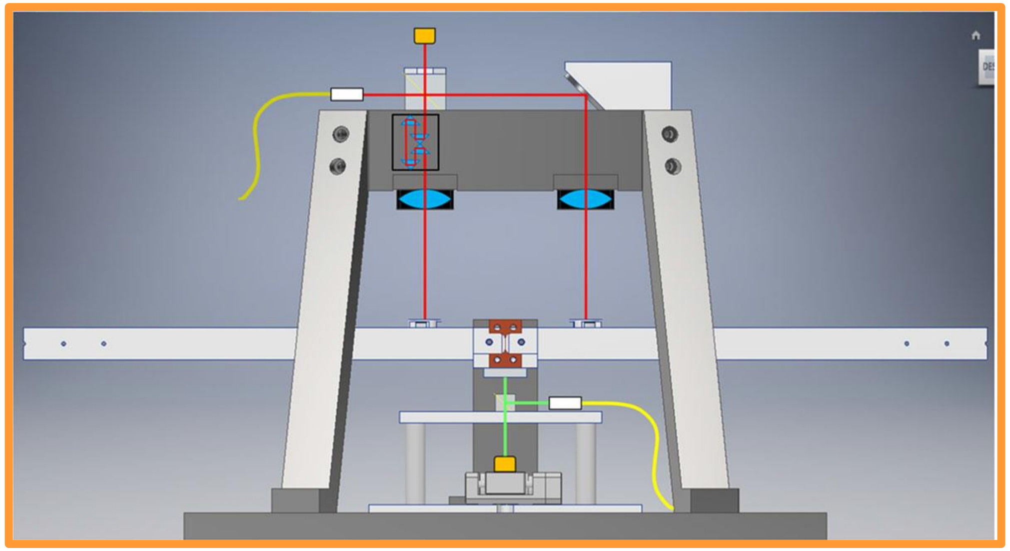
Noise budget of the Archimedes experiment
Archimedes experiment will work at a frequency in the region **5 mHz – 10 mHz** and the signal will be limited by thermal and seismic noise.

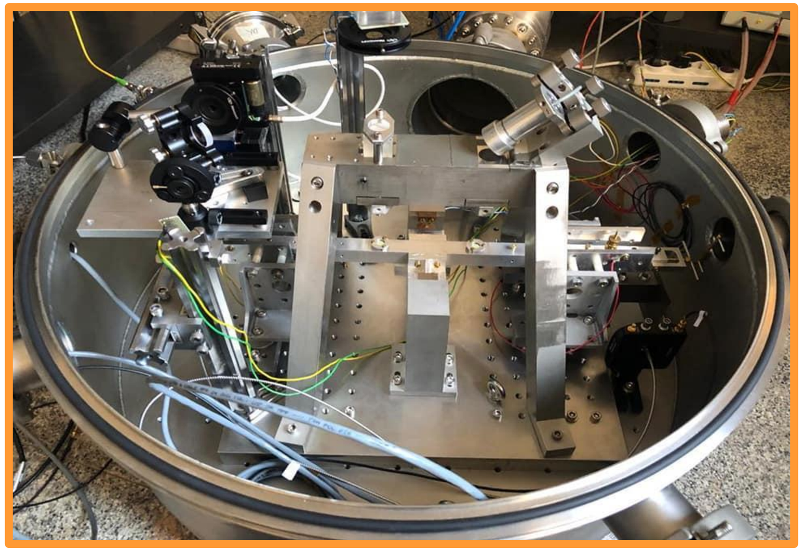
Archimedes is the first experiment to be installed in the Sar-Grav laboratory, in the area of the disused Sos Enattos mine near Lula (Nu, Sardinia).

Thanks to the very low seismic noise level due to the unique geological properties of Sardinia and the low population density, Sos Enattos area is also an excellent candidate site to host the third generation GW detector Einstein Telescope.

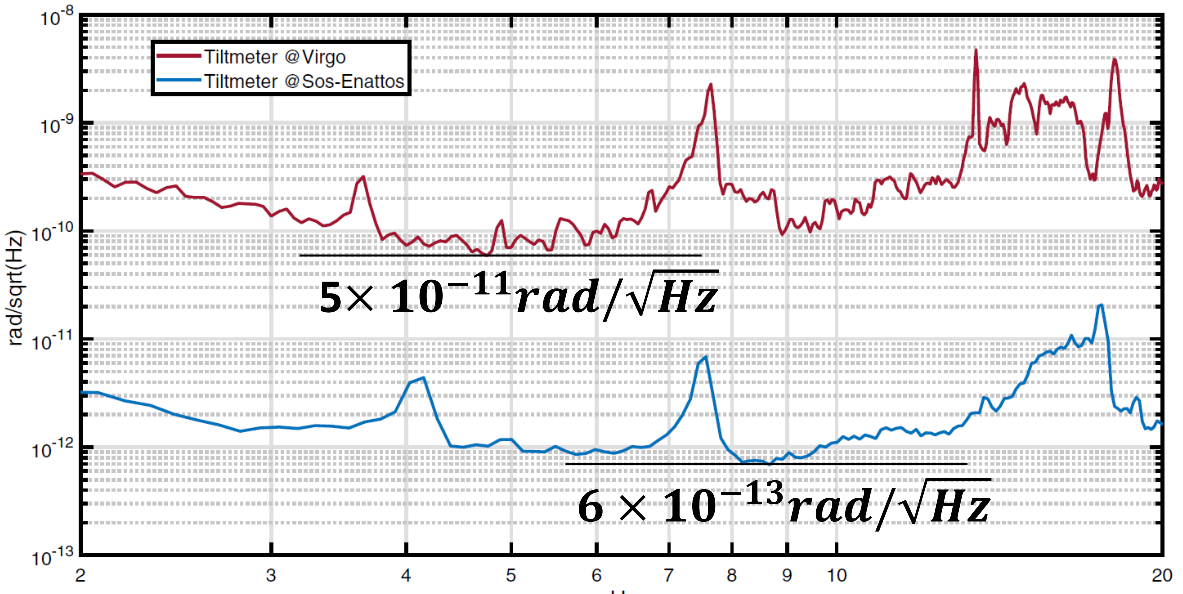


A **prototype of balance** was built to test every component and find the best optic-mechanical configuration for the final balance.



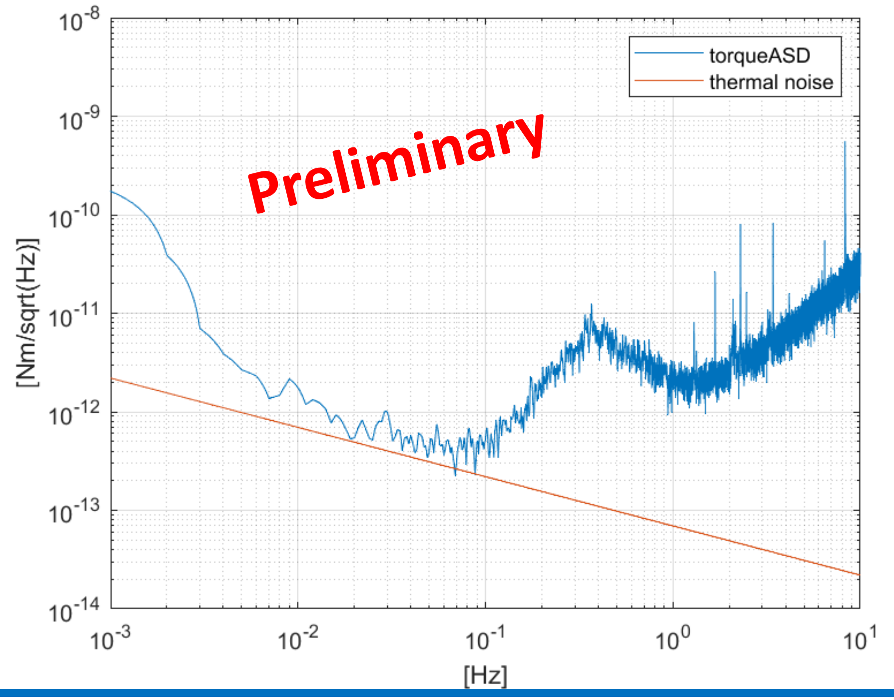


Tilt measurement comparison between Virgo gravitational wave interferometer (Cascina, Pisa) and Sos Enattos (Sardinia) sites.
Most sensitive tiltmeter in the world in the frequency band from 2 Hz to 20 Hz.



https://doi.org/10.1140/epjp/s13360-021-01993-w

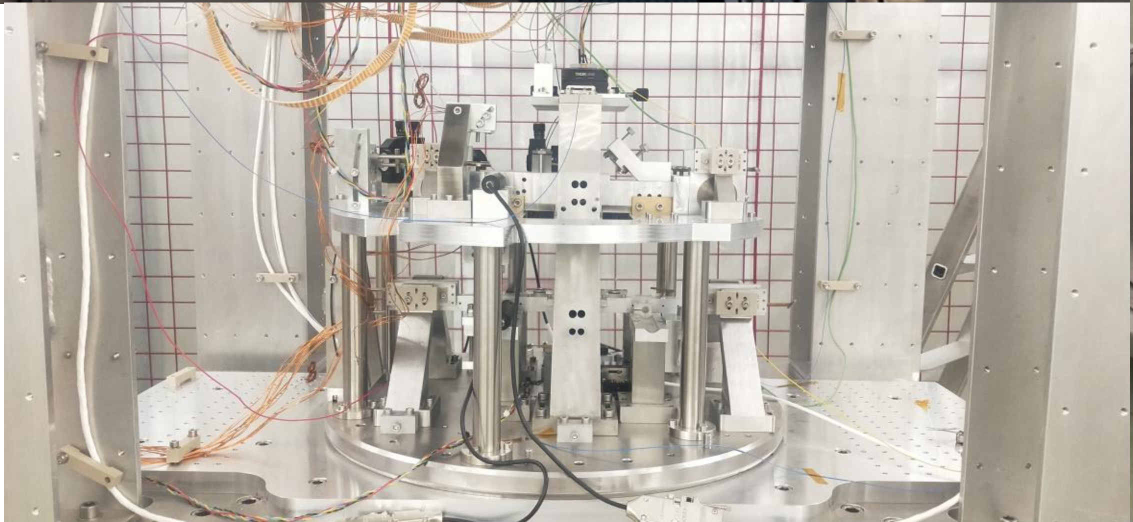
Prototype sensitivity in torque is limited by thermal noise.



18-19 July 2023

The balance is almost completed.
Then, the Experimental Chamber will be positioned above it and lowered.

The first run of measurments at room temperature and in vacuum will start soon.



CRYOSTAT

The cryostat consists of three chambers.

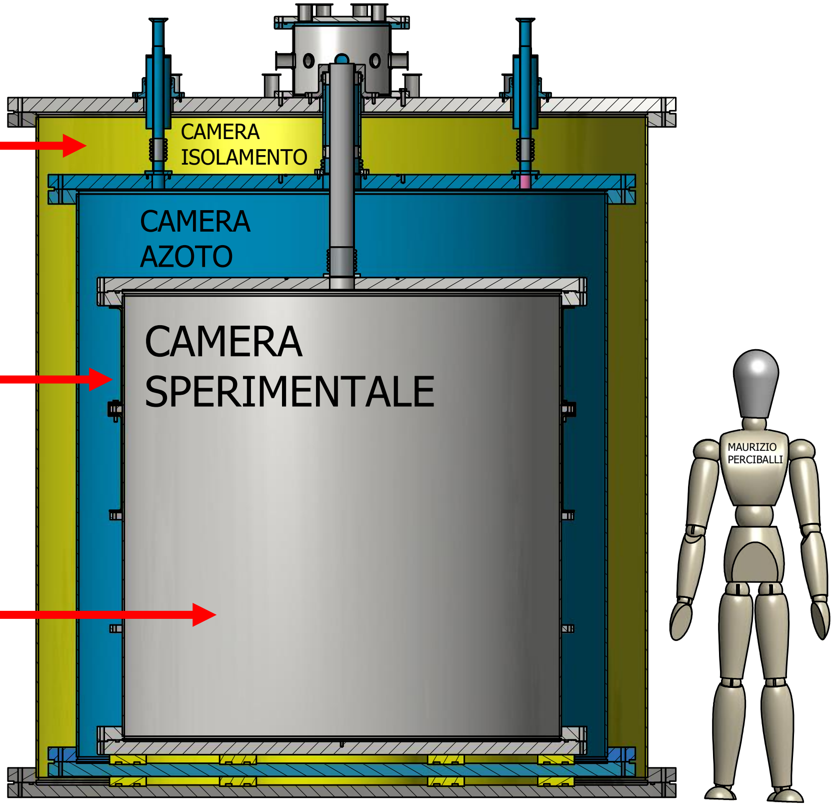
The **Experimental Chamber**, that will hosts the balance, will be completely submerged in liquid Nitrogen inside the **Nitrogen Chamber**.

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

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

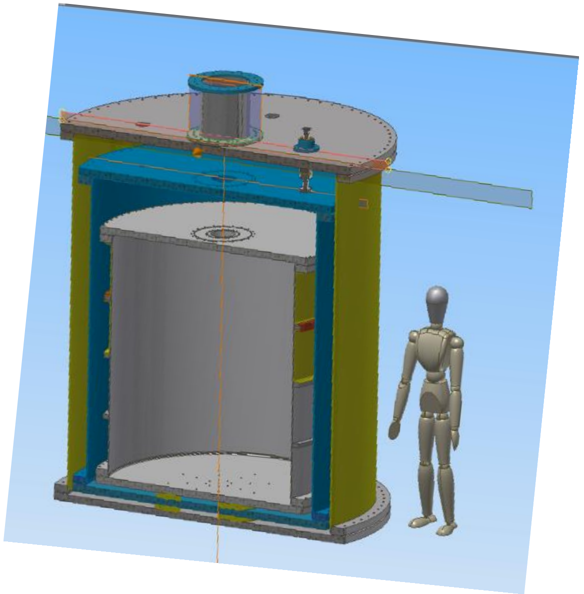
Experimental Chamber
company: L.M.P. Amicuzi (Italy)
material: steel
height , diameter: 1780 mm , 2000 mm
mass: 3500 kg



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

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

In the **Insulation Chamber** a vacuum (~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.

June 2020

Experimental Chamber
Ready for tests.

July 2020

Experimental Chamber
Vacuum and cryogenic tests: no leaks have been detected at a sensitivity level **better than ~8×10^{-10} mbar l/s**.

October 2020

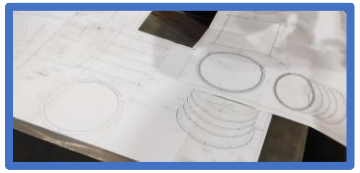
Experimental Chamber
Arrival in Sardinia.

April 2023

Nitrogen Chamber
Ready for tests.

June 2023

Nitrogen Chamber
Vacuum and cryogenic tests: no leaks have been detected at a sensitivity level **better than ~3×10^{-10} mbar l/s**.



2023

Vacuum Chamber
Call for tender is launched.

CONCLUSIONS

- ✓ **Archimedes** is an experiment conceived to shed light on the discussed **interaction between the gravitational field and the vacuum fluctuations**.
- ✓ **YBCO and GdBCO superconducting samples** tests are in progress.
- ✓ A new test **thermal modulation system** is currently under construction and new tests will start in the next months.
- ✓ The **balance** will start soon working at room temperature and in vacuum. The first cryogenic measurements are expected by 2024.
- ✓ **Prototype**: best sensitivity in the world for a tiltmeter in the region 2 Hz – 20 Hz and first balance limited by thermal noise (to our knowledge).
- ✓ Inner chamber of the **cryostat** is already at Sos Enattos, the middle one has been built and tested, and the call for tender was made for the outer one.
- ✓ Thanks to its extreme sensitivity, Archimedes will develop a detailed profile of the environmental and anthropogenic disturbance of the area of Sos Enattos, contributing to verify the suitability of the site to host **Einstein Telescope**.

SOME REFERENCES

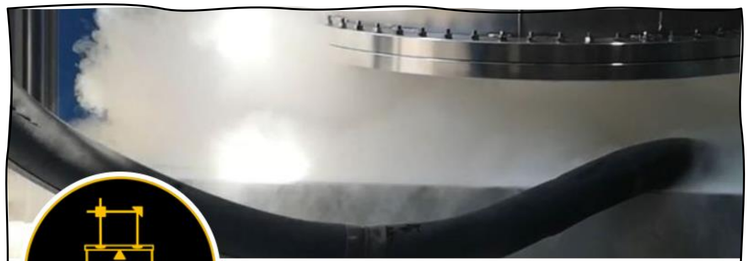
Eur. Phys. J. Plus (2022) 137:826
https://doi.org/10.1140/epjp/s13360-022-03025-7

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Check for updates

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



The Archimedes Experiment

ARCHIMEDES

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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

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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

Eur. Phys. J. Plus (2021) 136:1069
https://doi.org/10.1140/epjp/s13360-021-01993-w

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

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Picoradiant tiltmeter and direct ground tilt measurements at the Sos Enattos site

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

THE EUROPEAN PHYSICAL JOURNAL PLUS

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

physics

MDPI

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

Article

Progress in a Vacuum Weight Search Experiment

Eur. Phys. J. Plus (2021) 136:335
https://doi.org/10.1140/epjp/s13360-021-01214-4

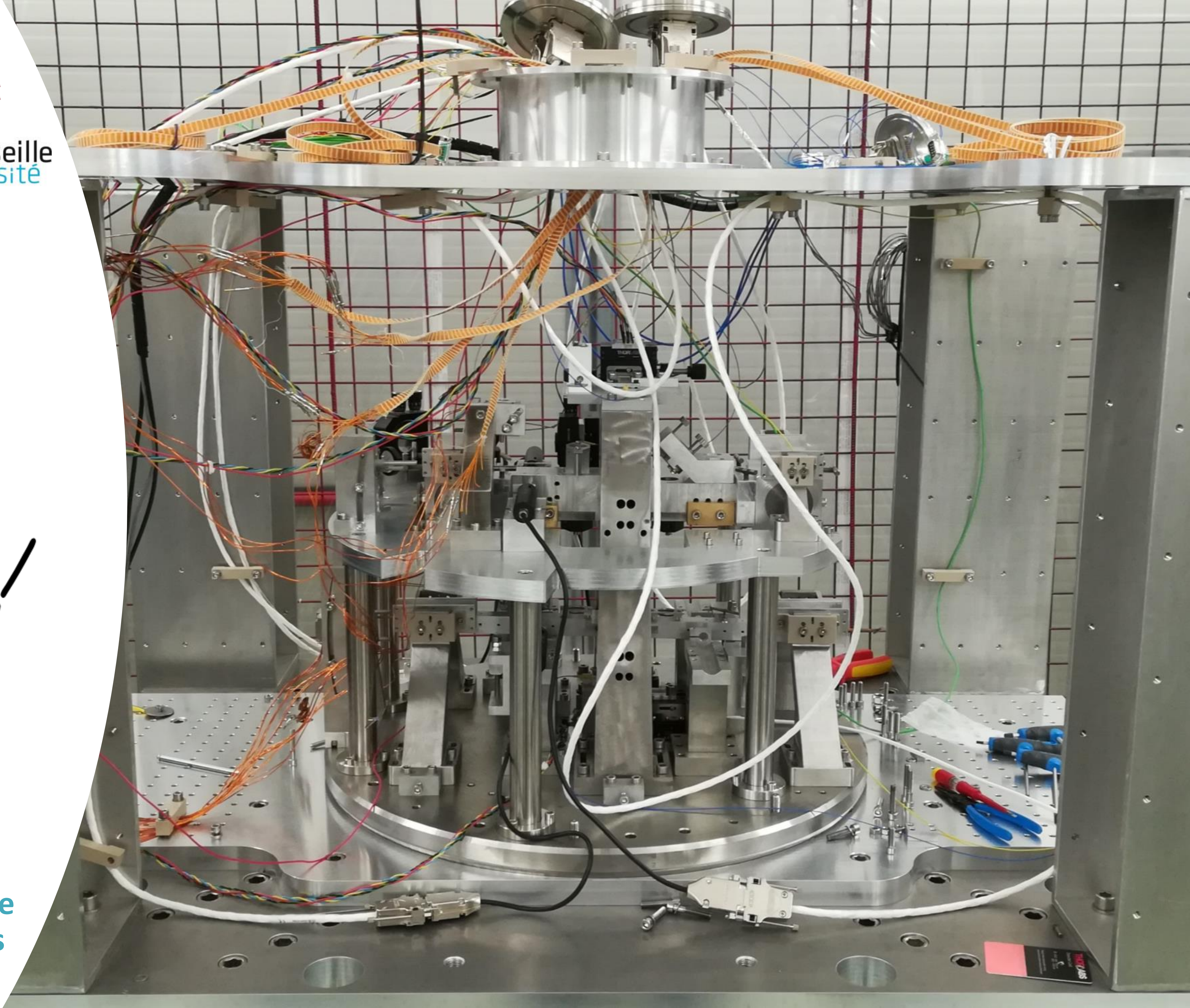
THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Check for updates

High-bandwidth beam balance for vacuum-weight experiment and Newtonian noise subtraction

Thank you for your attention!



XII International Conference on New Frontiers in Physics

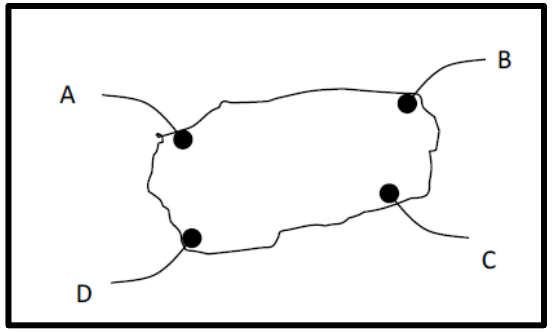
10-23 July 2023, Crete (Greece)

EXTRA SLIDES

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

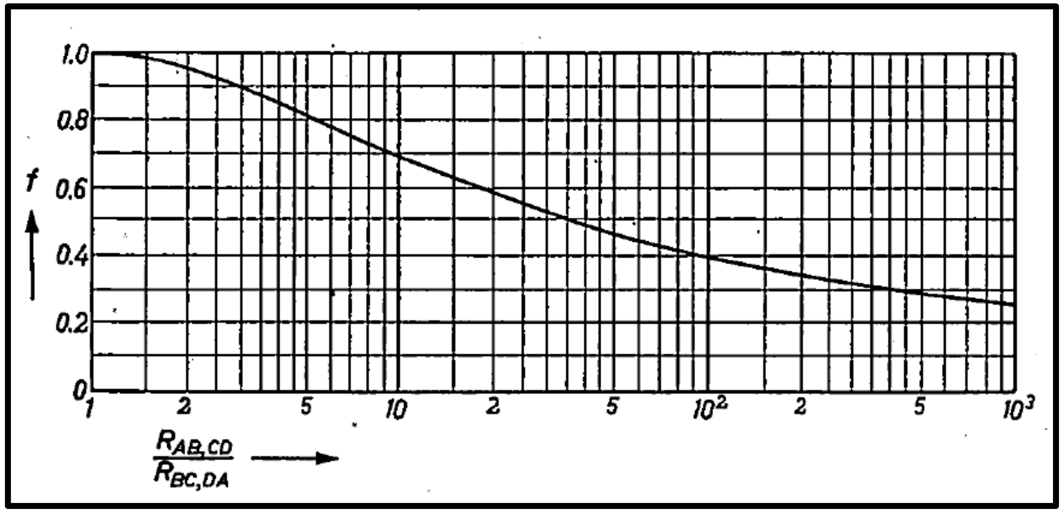
- the sample is two-dimensional (surface area >> thickness), solid (no holes) and homogeneous in thickness;
- the contacts are sufficiently small and placed at the circumference of a sample.

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:
$R_{AD,BC} = V_{BC} / I_{AD}$.



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

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}

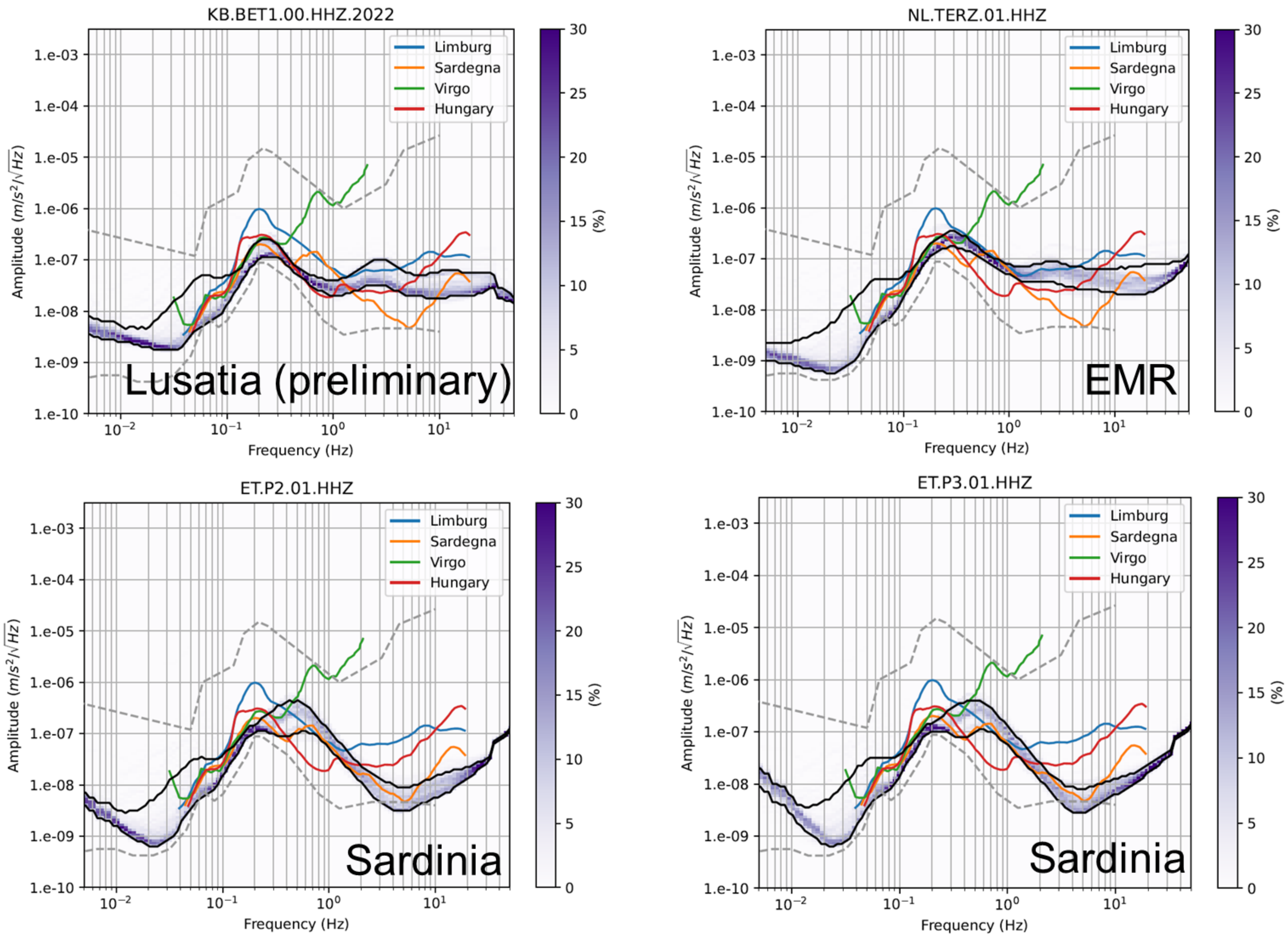


[*] van der Pauw, 'A method of measuring specific resistivity and Hall effect of discs of arbitrary shape', Philips Research Reports 13 1-9 1958.

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.

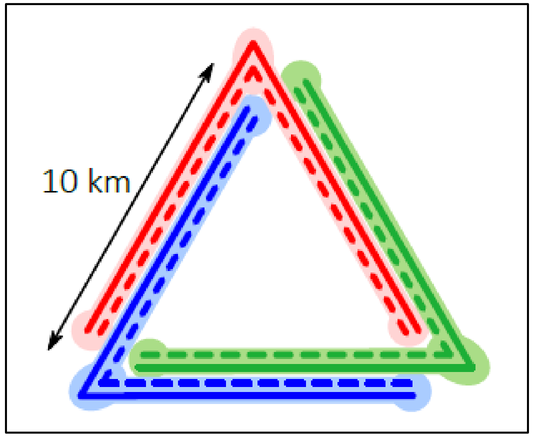
In the low frequency range of ET (from 2 Hz to 10 Hz), Sos Enattos area is among the quietest sites in the world.



courtesy of Dr Luca Naticchioni

ET will be a 3G GW underground observatory in Europe with:

- a sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band;
- wideband (possibly wider than the current detectors) accessing the frequency band below 10Hz.

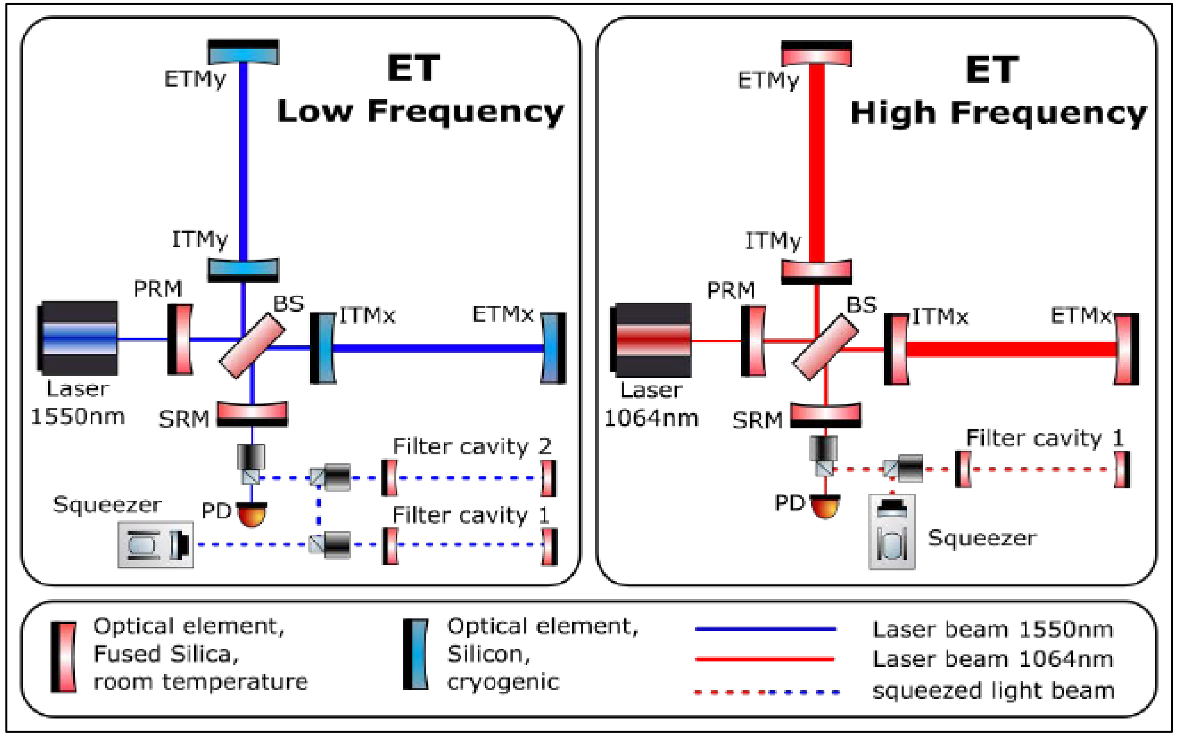


ET will consist of three nested detectors in a triangular arrangement.
Each detector will be composed of two interferometers:

- one with **low power** and **cryogenic temperatures** for detecting **low-frequency** GWs (**ET-LF**)
- one with **high power** and **high temperatures** for detecting **high-frequency** GWs (**ET-HF**).

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few

Summary of the most important parameters of the ET high and low frequency interferometers.



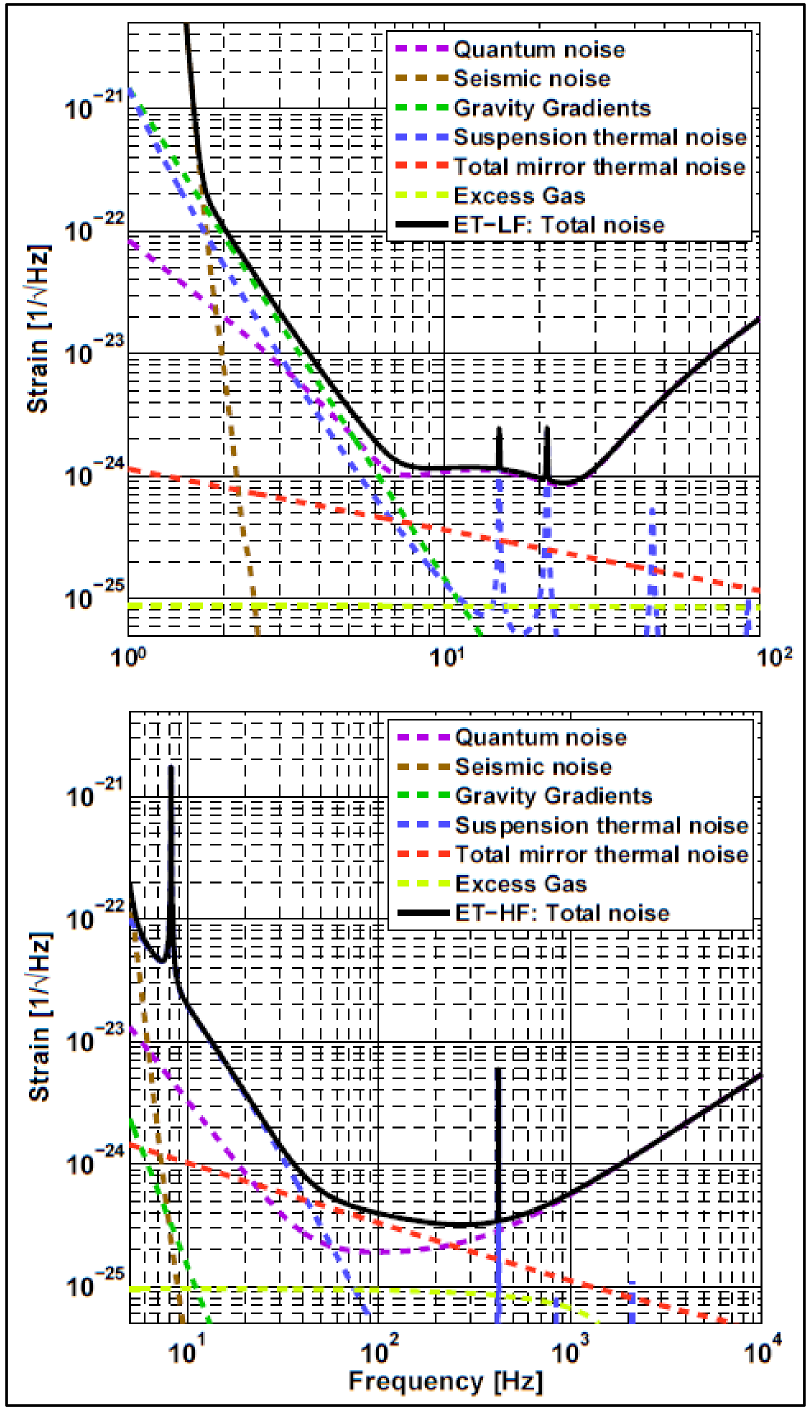
Due to the good performance of the multistage pendulum suspensions the influence of **seismic noise** can be limited to the frequency range **below 2 Hz**.

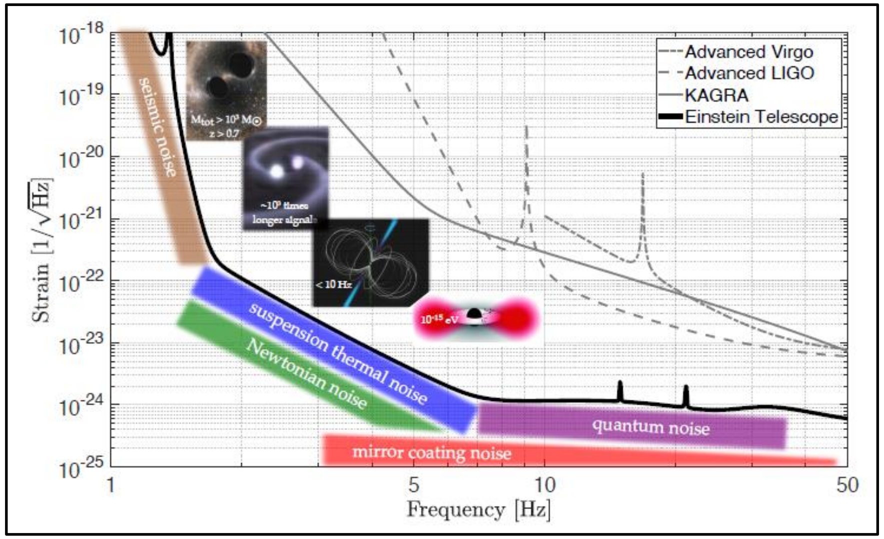
Below 7 Hz the sensitivity is limited by comparable amounts of **quantum noise, gravity gradient noise, and suspension thermal noise**.

The operation at cryogenic temperatures reduces the influence of suspension thermal noise in the frequency range **above 7 Hz** to below the **quantum noise**.

In the frequency range **from about 7 Hz to 30 Hz** the sensitivity is limited by **suspension thermal noise**, resulting from the interferometer being operated at room temperature.

From 30 Hz to 500 Hz mirror thermal noise is limiting the overall sensitivity.
At frequencies **above 500 Hz** the dominating noise source is **photon shot noise**.





https://doi.org/10.3390/galaxies10030065