COSMIC WISPERS CA21106

The Archimedes experiment

D. D'Urso on behalf of the Archimedes Collaboration

Summary

- Scientific motivations
- Experimental strategy
- The apparatus
- The Archimedes Prototype
- The environmental noise and the SarGrav laboratory
- Status of the activities: the prototype and the balance

Scientific motivations

- Since the birth of Quantum Mechanics the question rised if the zero-point energy gravitates
- Summing up all the zero-point EM modes up to a cut-off (Planck scale) and inserting the value of the energy density in the static Einstein solution takes to a disagreement of many orders of magnitude with respect to observations:
  - In QED the expectation value of the EM field energy density H on the vacuum state is infinite:

$$\langle 0|\mathcal{H}|0\rangle = \sum_{\lambda}\int \frac{d^3k}{4(2\pi)^3}\langle 0|[a^{(\lambda)}(k)a^{(\lambda)\dagger}(k) + a^{(\lambda)\dagger}(k)a^{(\lambda)}(k)]\,|0\rangle \to \infty$$

  - GR is sensitive to the absolute value of the energy. Zero-point energy could be accounted for in Einstein's equations as a cosmological constant term:

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

Cosmological Constant Problem: disagreement between observations and predictions of QFT of 120 orders of magnitude.

Does vacuum fluctuations gravitate or not?

Rev.Mod.Phys. 61 (1989) 1-23)

Macroscopic evidence: the Casimir effect

- The Casimir effect 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
- A Casimir cavity selects specific modes satisfying boundary conditions

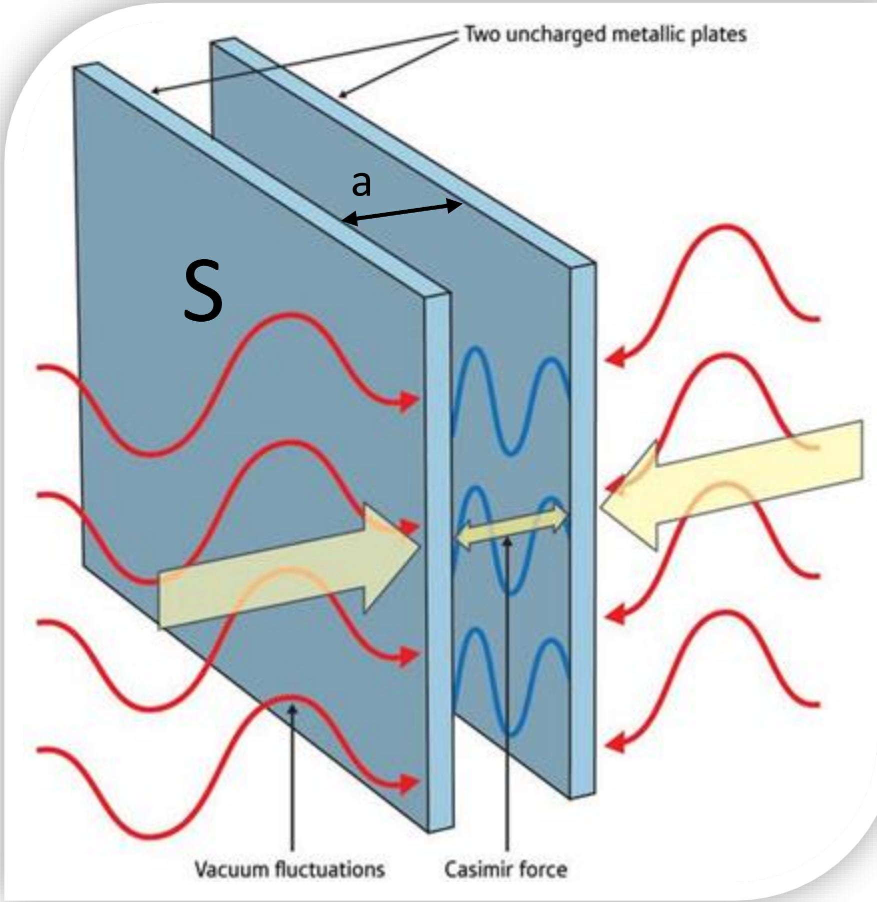
- If boundary conditions for zero-point EM field change, we can't get rid of the zero-point infinite energy, not even in QFT -> Casimir effect

$$E_c = E_{reflective\ plates} - E_{empty} \equiv \mathcal{E}_{\mathrm{cas}} = -\frac{\pi^2}{720}\frac{\hbar c}{a^3} S$$

- The difference of zero-point energy due to the presence of the metallic plates gives rise to a negative energy

tipically $a \sim 1\ \mu\mathrm{m}$, $S \sim 1\mathrm{cm}^2 \longrightarrow \mathcal{E}_{\mathrm{cas}} \sim 40\ \mathrm{fJ}$, $F_{\mathrm{cas}} \sim 10^{-7}\ \mathrm{N}$

Vacuum energy inside the cavity is less when plates are reflective.



The Experimental Strategy

Experimental strategy

- Realize a ”large” Casimir cavity

- Modulate the reflectivity of the Casimir plates to modulate vacuum modes inside it. In this way, a possible weight variation can be detected at the modulation frequency, e.g. by performing a superconducting transition of the plates, modulating the temperature of superconductive material

- Build a very sensitive balance to «weigh the vacuum»

- Suspend samples of «Casimir cavity» to the balance arm

- Find a “quiet” site!

Casimir cavities with type II superconductors

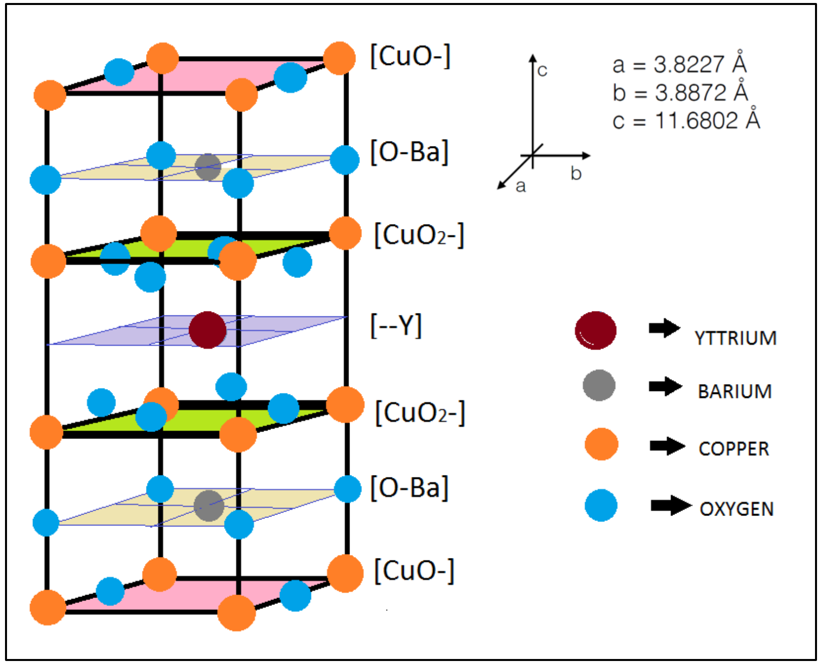
- Some crystals (i.e. YBCO, GdBCO) are natural multi-layered Casimir cavities

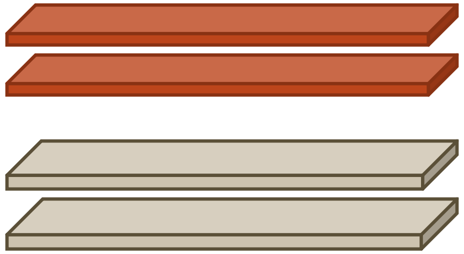
$$\text{for YBCO: } T_c \simeq 92\text{ K},\quad \frac{\Delta\mathcal{E}_{\text{cas}}}{\mathcal{E}_{\text{cas}}} \simeq 10^{-4}$$

- Modulating the samples temperature (and superconductivity) the “amount of vacuum” inside the cavities is modulated, and possibly the total weight => The variation of Casimir energy could be detectable

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

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





Plates at **superconductive** state: Casimir cavity, “less” zero-point EM modes because of boundary conditions

Plates at **normal** state: transparent cavity, all EM modes allowed

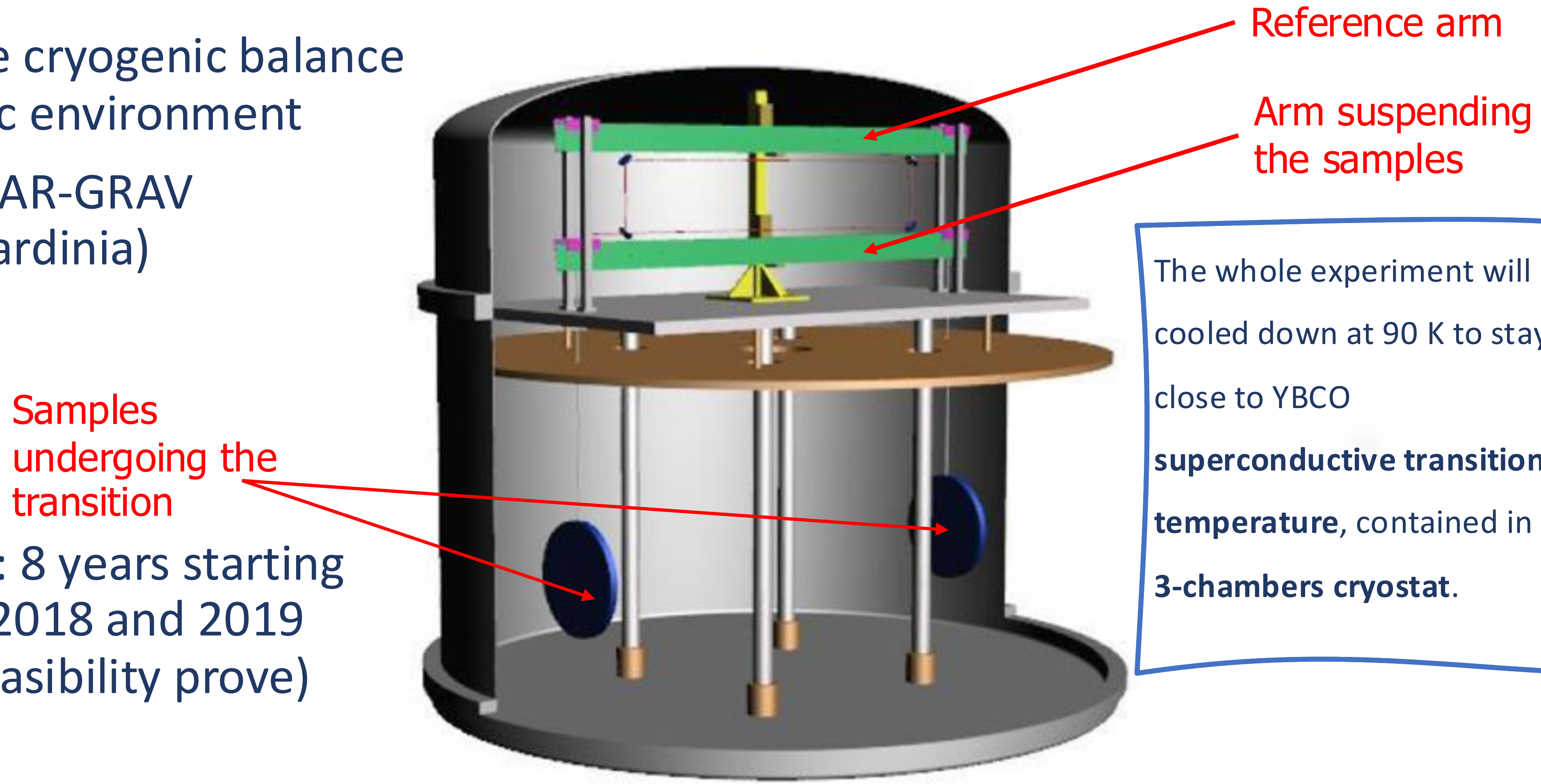
The Apparatus

The apparatus scheme

➢ Extremely sensitive cryogenic balance in very quiet seismic environment

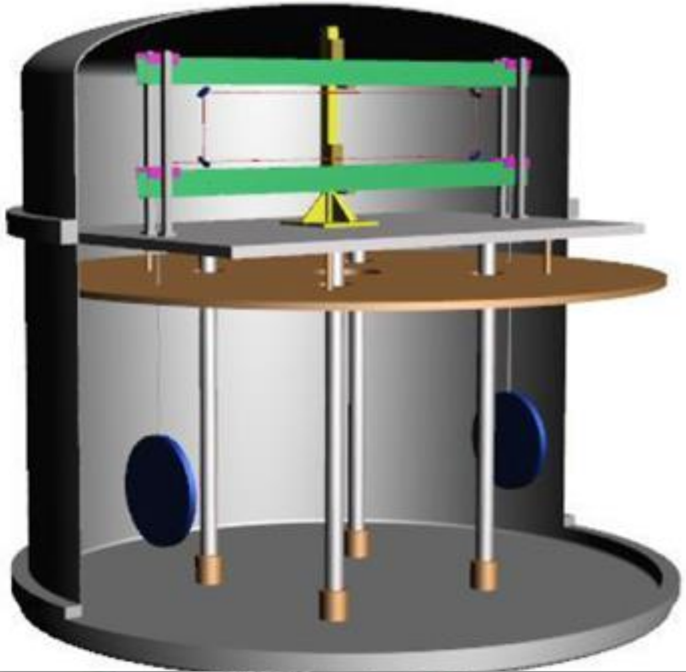
(Sos Enattos mine – SAR-GRAV laboratory – LULA - Sardinia)

➢ Updated Timescale: 8 years starting from 2020 - (after 2018 and 2019 being devoted to feasibility prove)



The whole experiment will be cooled down at 90 K to stay close to YBCO **superconductive transition temperature**, contained in a **3-chambers cryostat**.

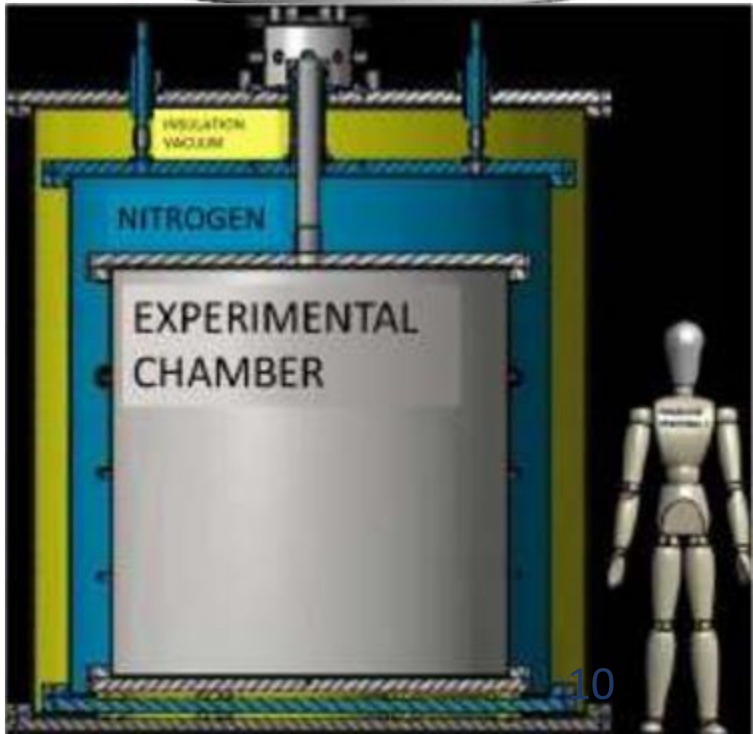
The apparatus scheme



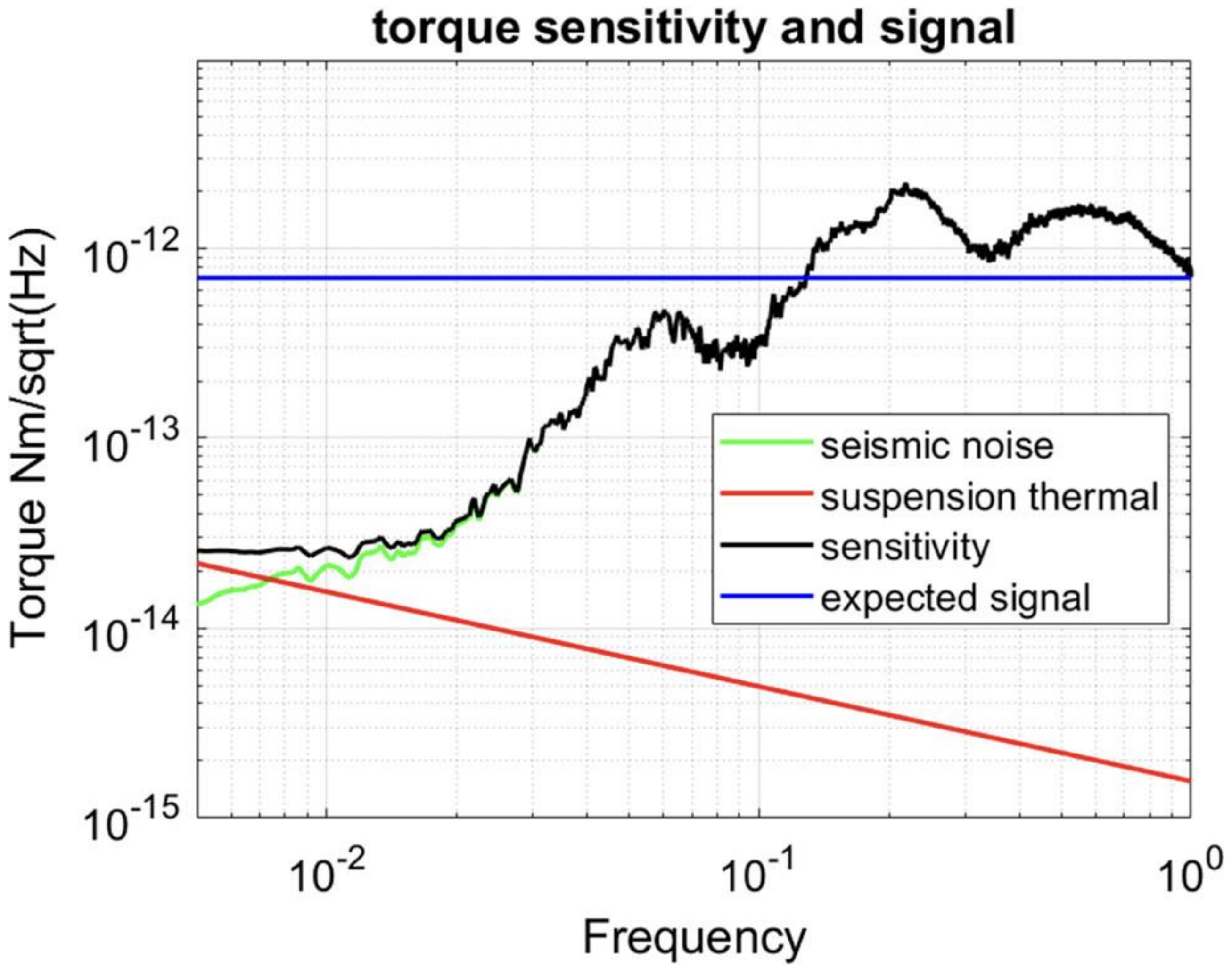
- High-T_c multilayered superconductive as natural Casimir cavities
- Relative tilt arms for coherent noise subtraction
- Interferometric readout
- Feedback control at low frequencies
- Vacuum (10^{-6} mbar) and cryogenic (T~90° K) measurements
- Modulation via thermal actuators
- Low seismic noise site

One of the biggest opto-mechanical cryogenic experiments in Europe!

The same technology will be exploited for 3rd generation GW detector like the Einstein Telescope



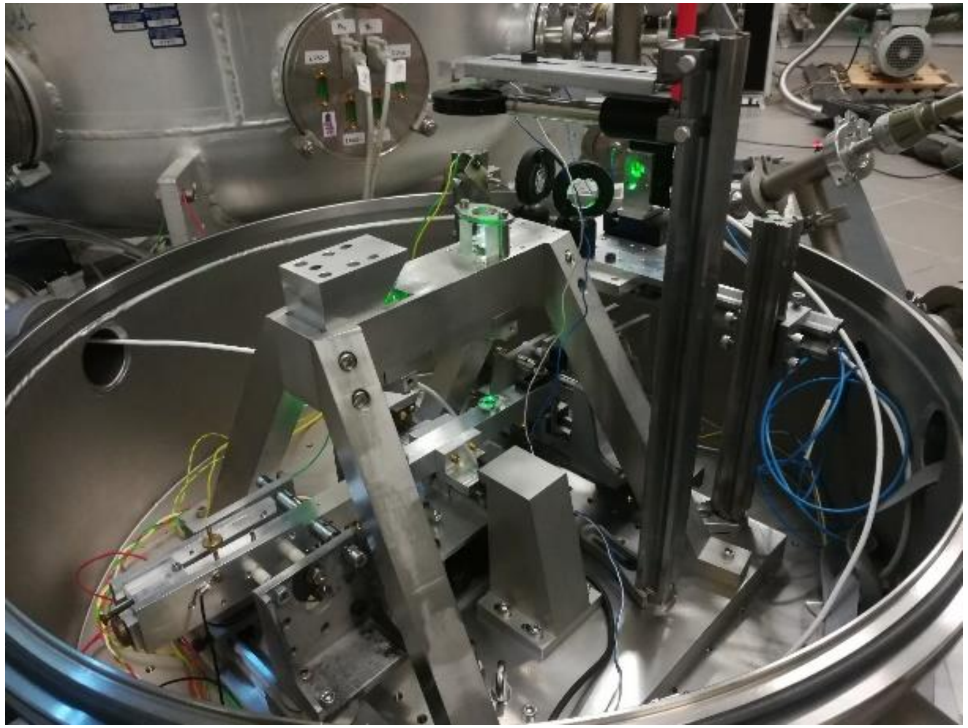
Archimedes Balance: Design Sensitivity



The Archimedes Prototype

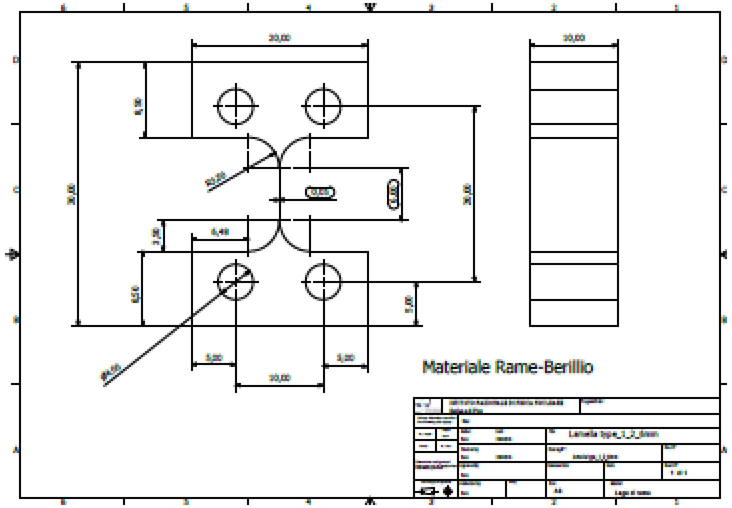
The Balance prototype

- ❑ Arm suspended with soft joints
- ❑ Interferometric Read-Out
- ❑ Freed-back with electrostatic actuators to have a very long term stability

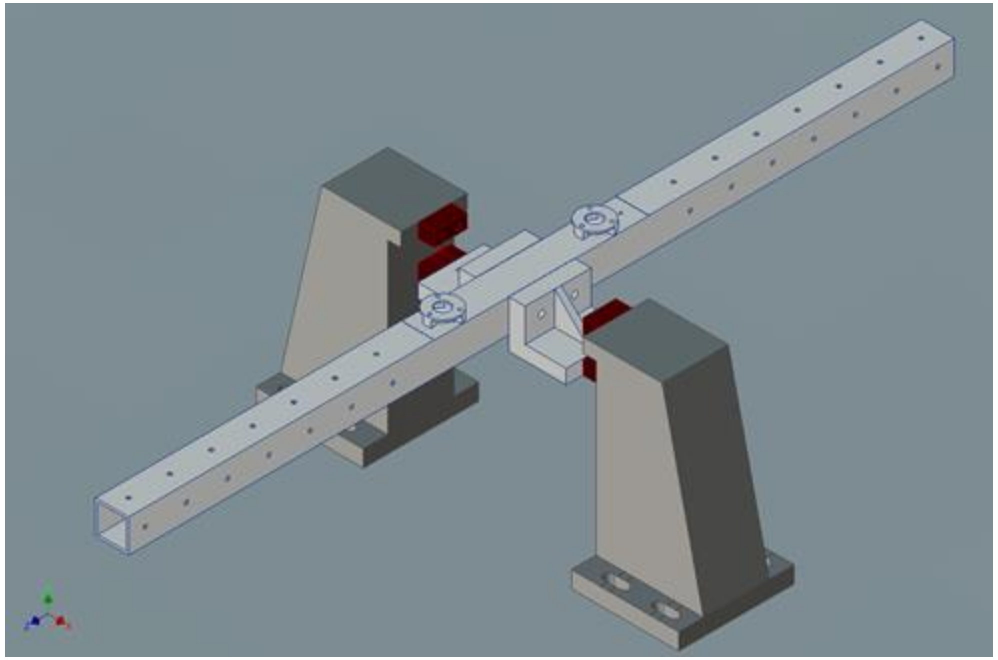


Laser light green to facilitate alignemnts

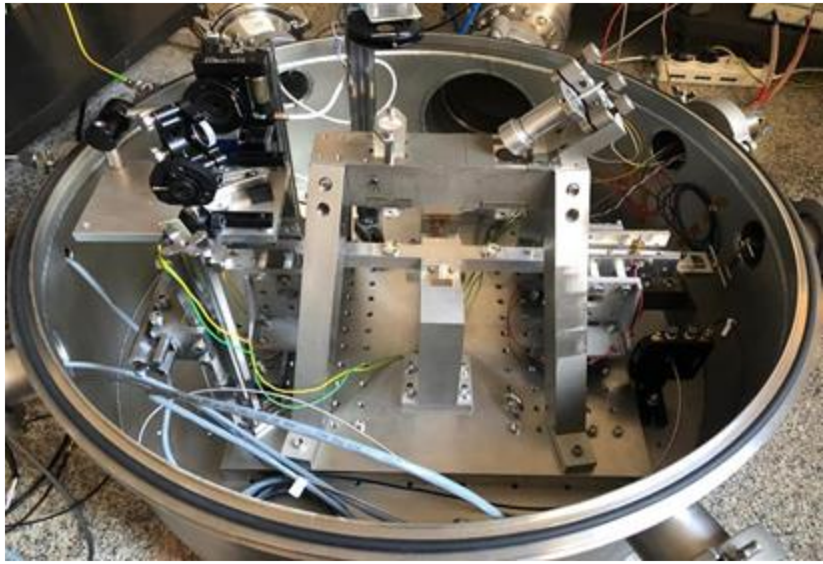
Much work on the Joints



The balance prototype

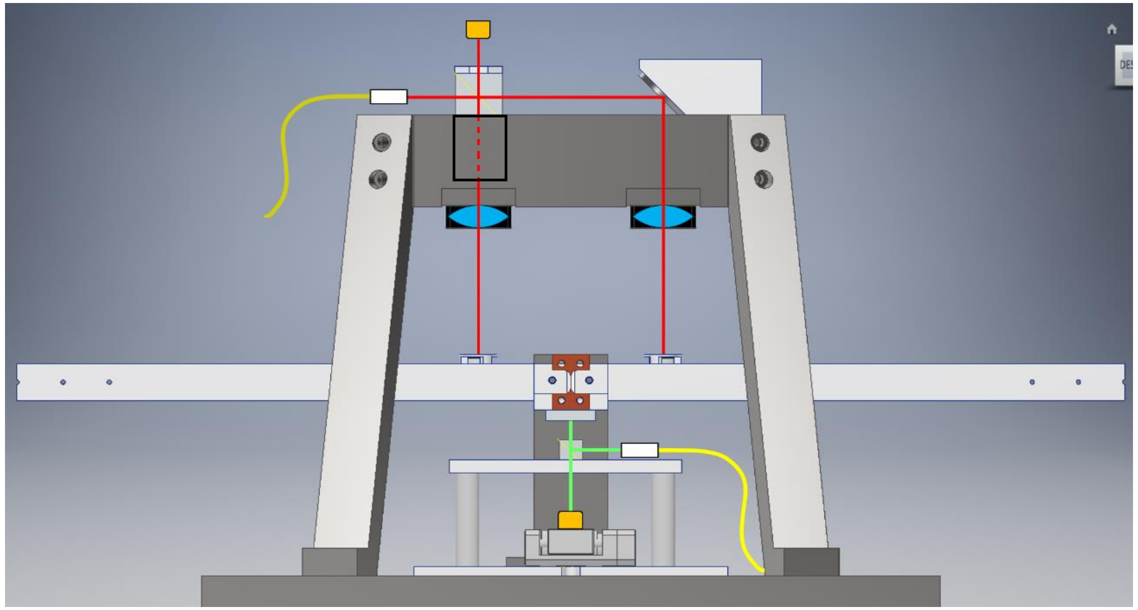


- 50 cm long arm with low momentum of inertia
- suspended through thin flexible joints (Cu-Be, 100 µm x 500 µm), similar to LIGO tiltmeters (Venkateswara et al. 2014)
- Balance center of mass positioned as close as possible to bending point (~10 µm) to minimize the coupling with ground motion



- Resonance frequency ~20-30 mHz
- Installed at the Sar-Grav surface laboratories in Lula (NU) – Sos-Enattos mine

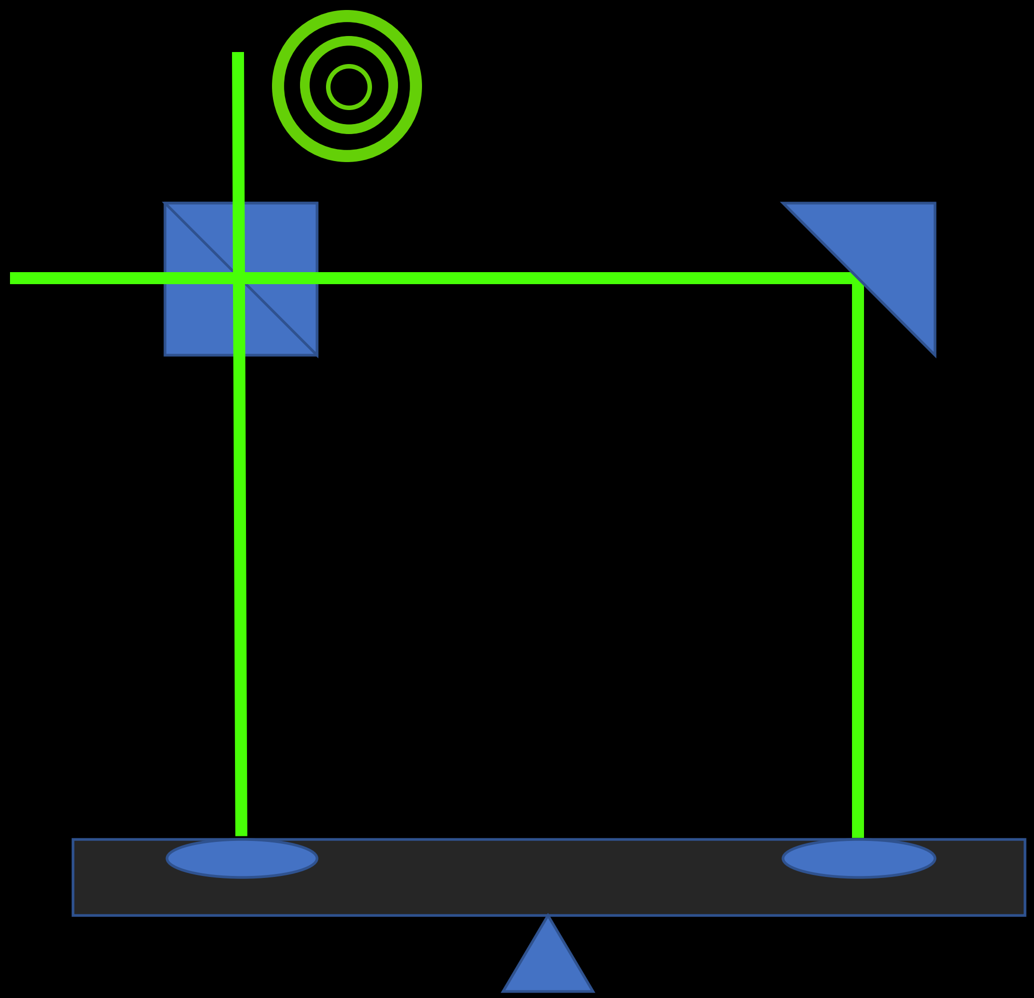
Optical Read-Out

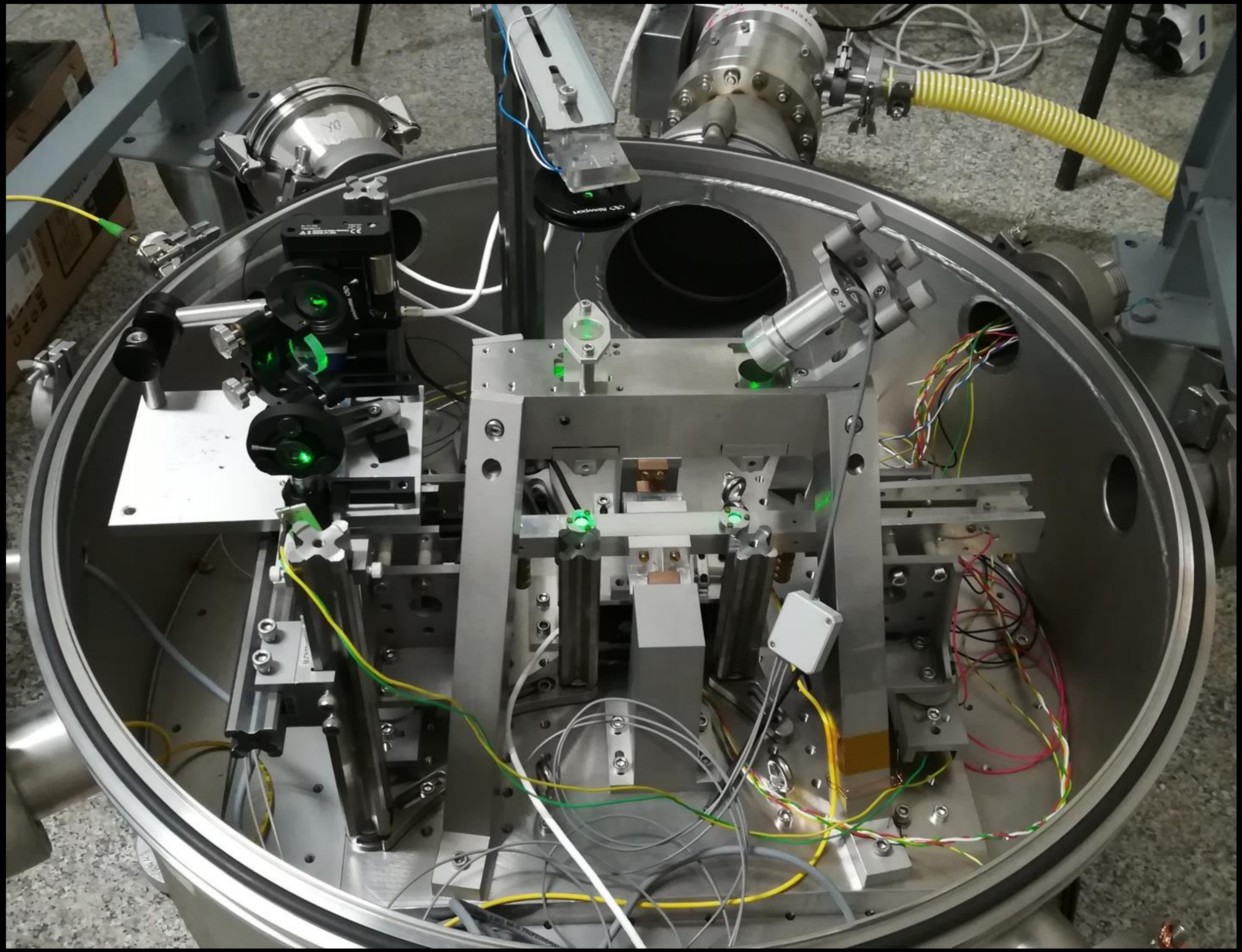


Tilts w.r.t. the ground are read finely with a **Michelson interferometer**

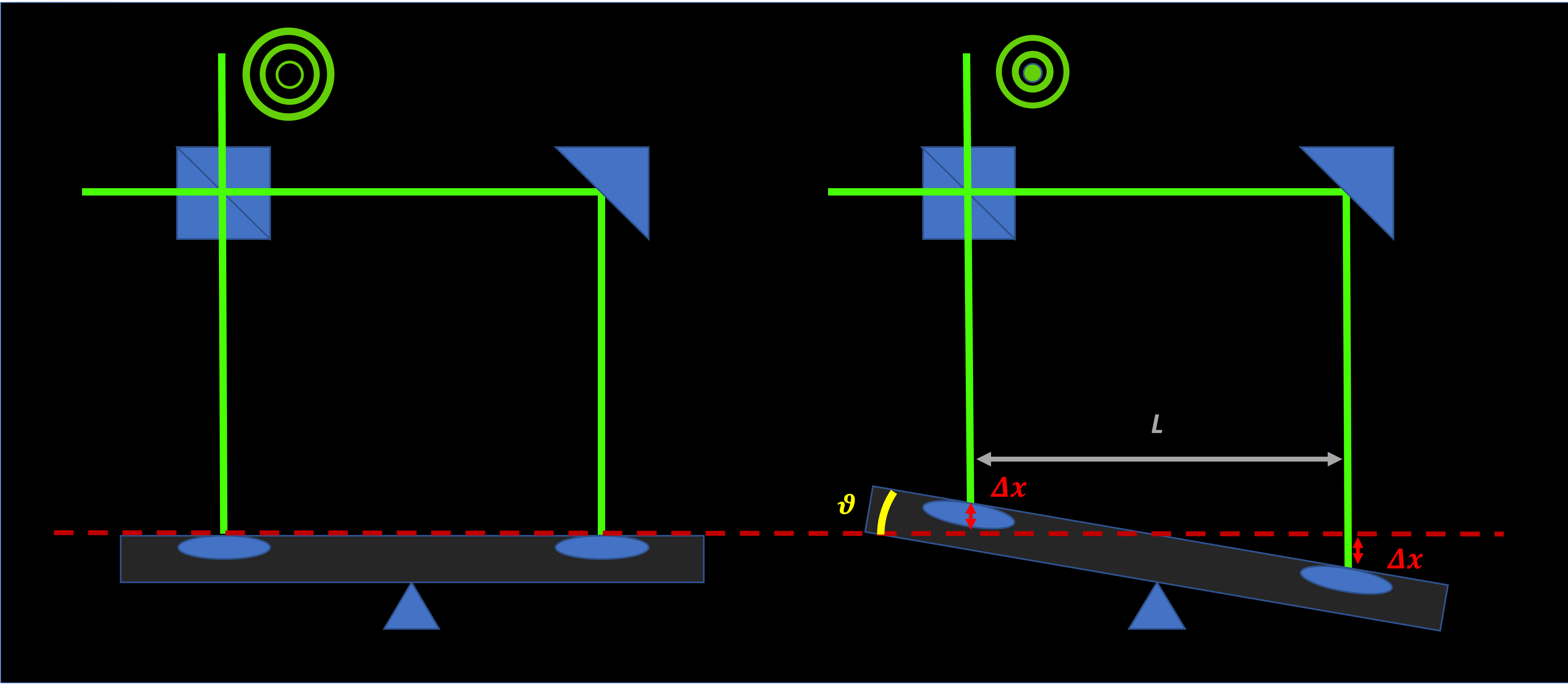
Optical lever only as coarse positioning sensor

Interferometric Read-Out





Interferometric Read-Out



The environmental noise and the SarGrav laboratory

THE SAR-GRAV LABORATORY

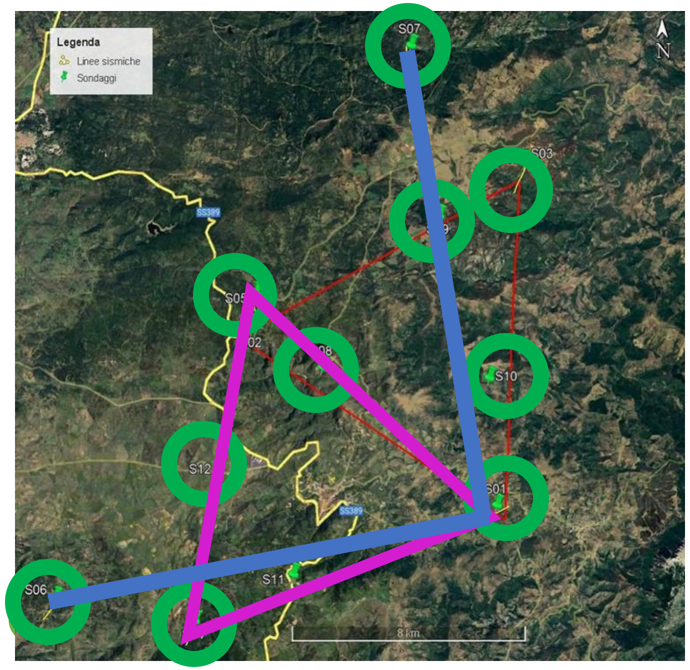
The **Sar-Grav Laboratory is funded with 3.5 M€** by the **Regione Autonoma della Sardegna** (RAS)

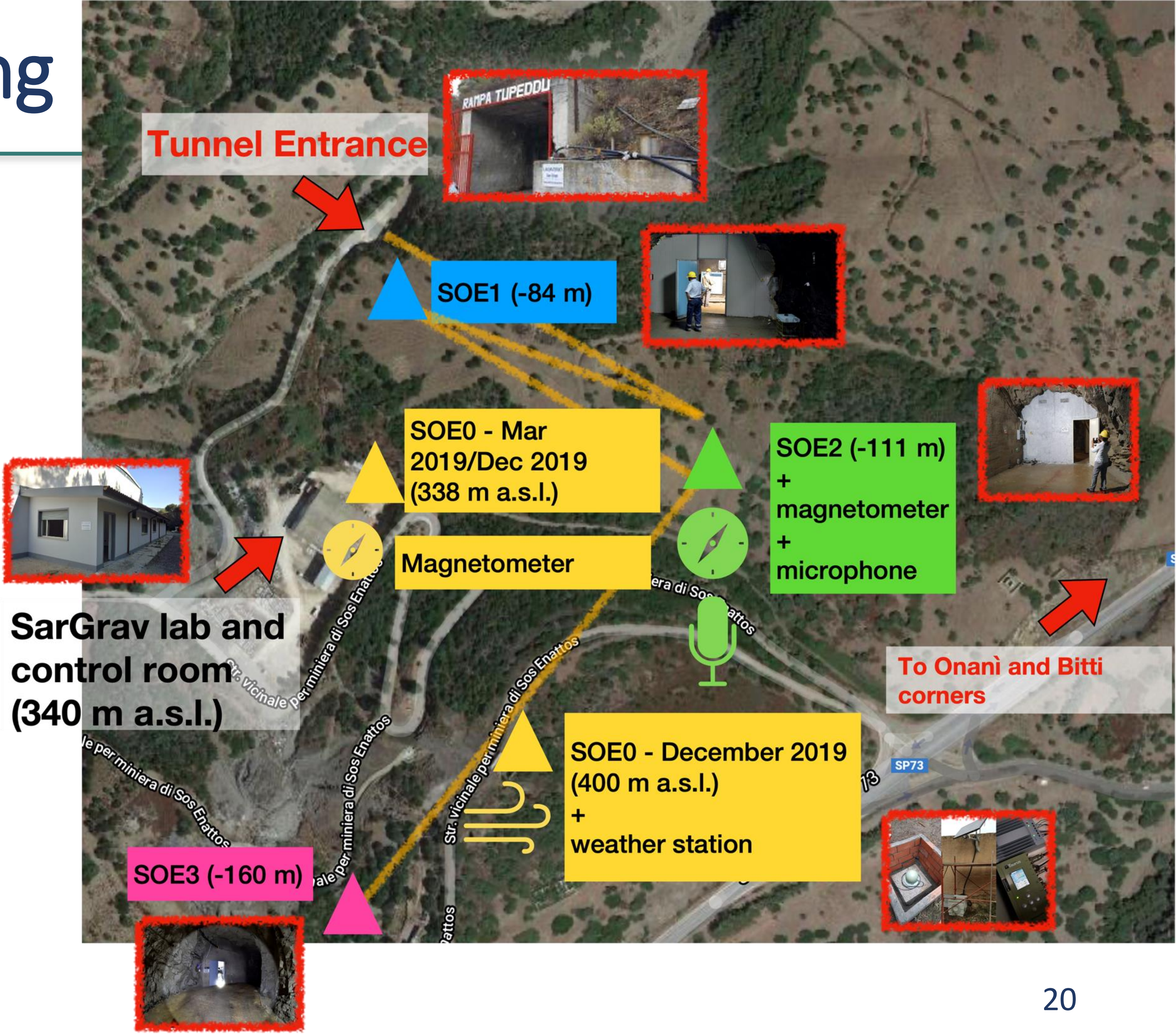
It is located in **Sardinia** (Italy) close to **Lula** (Nuoro) in the area of the **Sos Enattos mine candidate to host Einstein Telescope (ET)**

(Sos Enattos: former mine with underground access guaranteed through tunnels and shaft)

The **laboratory**, **a seed of ET**, aims to host underground experiments, cryogenic payloads, low frequency and cryogenic sensor development that need low seismic and anthropogenic noise

Site Monitoring



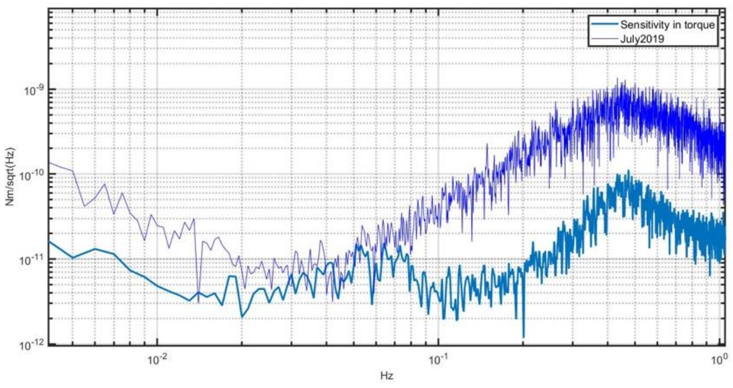


Status of activities: the prototype

Realized during 2018/19 – used for a while as a tiltmeter in Virgo in the run O3 and since 2020 used in Sos Enattos for sensitivity studies to help construction and commissioning of the Final Balance

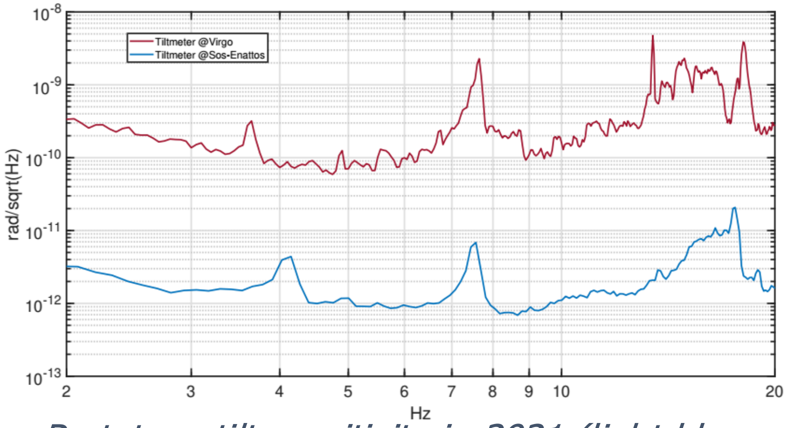
Main achievements

Best balance in the 10-50 mHz frequency region



Prototype torque sensitivity in 2021 (light blue) with respect to 2019 (blue)

Best tiltmeter in the 2-20 Hz frequency region



Prototype tilt sensitivity in 2021 (light blue – sos enattos) with respect to 2019 (red – Virgo site)

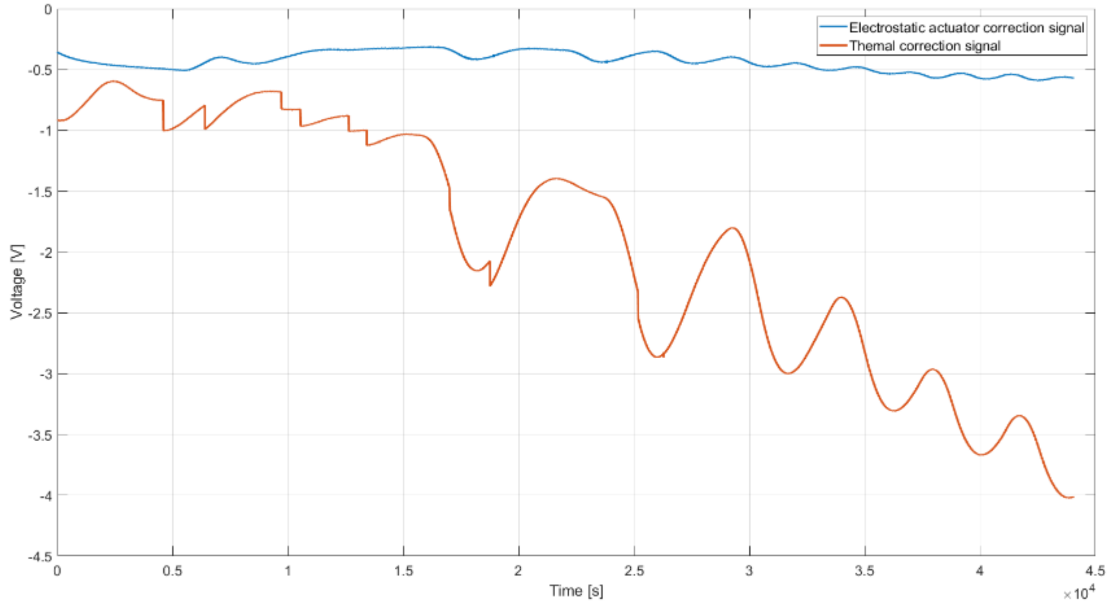
Status of the activities: the prototype and the balance

Status of activities: the prototype

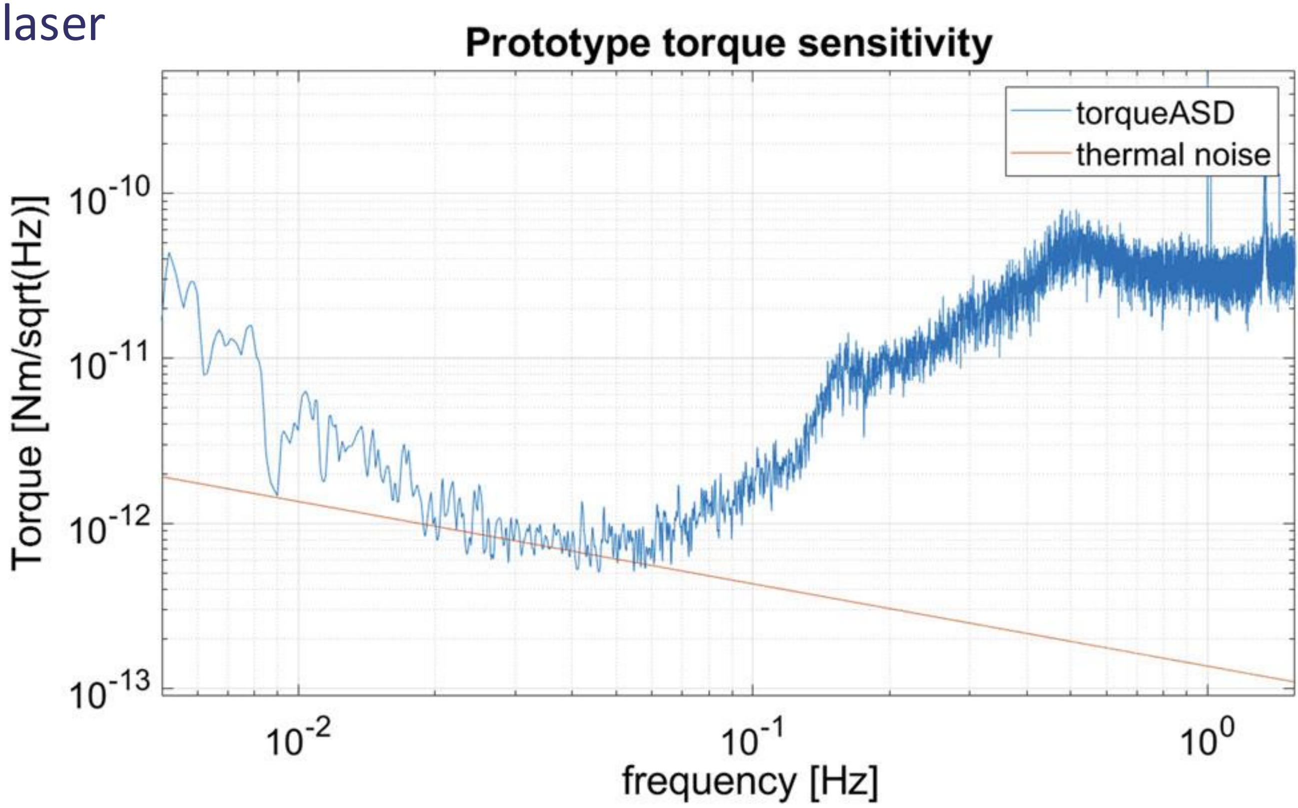
- Thermal compensation of dritfs
- Calibration on a suspended sample with high power laser

Lessons learned towards final balance

a) The role of thermal stability of the balance
b) No major problem injecting high power laser under vacuum
c) Needed of careful mitigation of diffused light

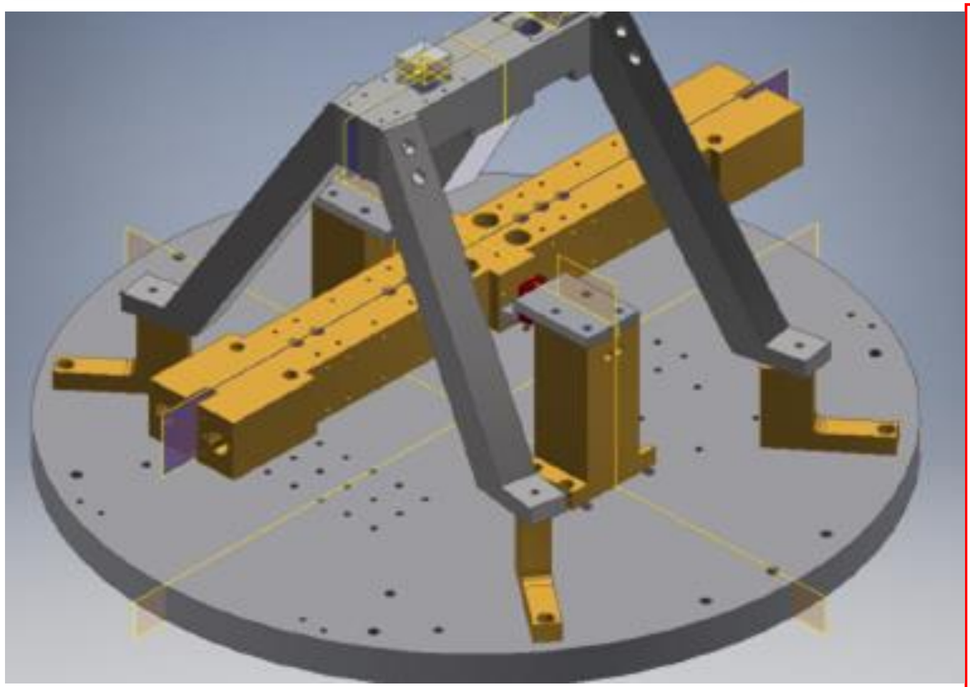


Thermal compensation (red) allows to maintain low value of electrostatic correction signal (blue)



Torque sensitivity

Prototype: applications



Prototype at Virgo in O3 Run

- Tiltmeter: a new one installed in Virgo for the run O4
- Tiltmeter: a second one is also under construction for Sos Enattos to be possibly installed underground
- Tiltmeter: remarkable interest by INGV and hopefully a collaboration with **FABER**

Bulik T et al: *Study of correlations between seismic data and Virgo's gravitational-wave detector data* ***Class.Quant.Grav.*** **39 (2022) 9, 095009**

Archimedes and Virgo collaborations*: High-bandwidth beam-balance for vacuum weigth experiment and Newtonian Noise subtraction* ***Eur.Phys.J.Plus*** 136 (2021) 3, 335

Annalisa Allocca et al: *Picoradiant tiltmeter and direct ground tilt measurements at the Sos Enattos site* ***Eur.Phys.J.Plus 136 (2021) 10, 1069***

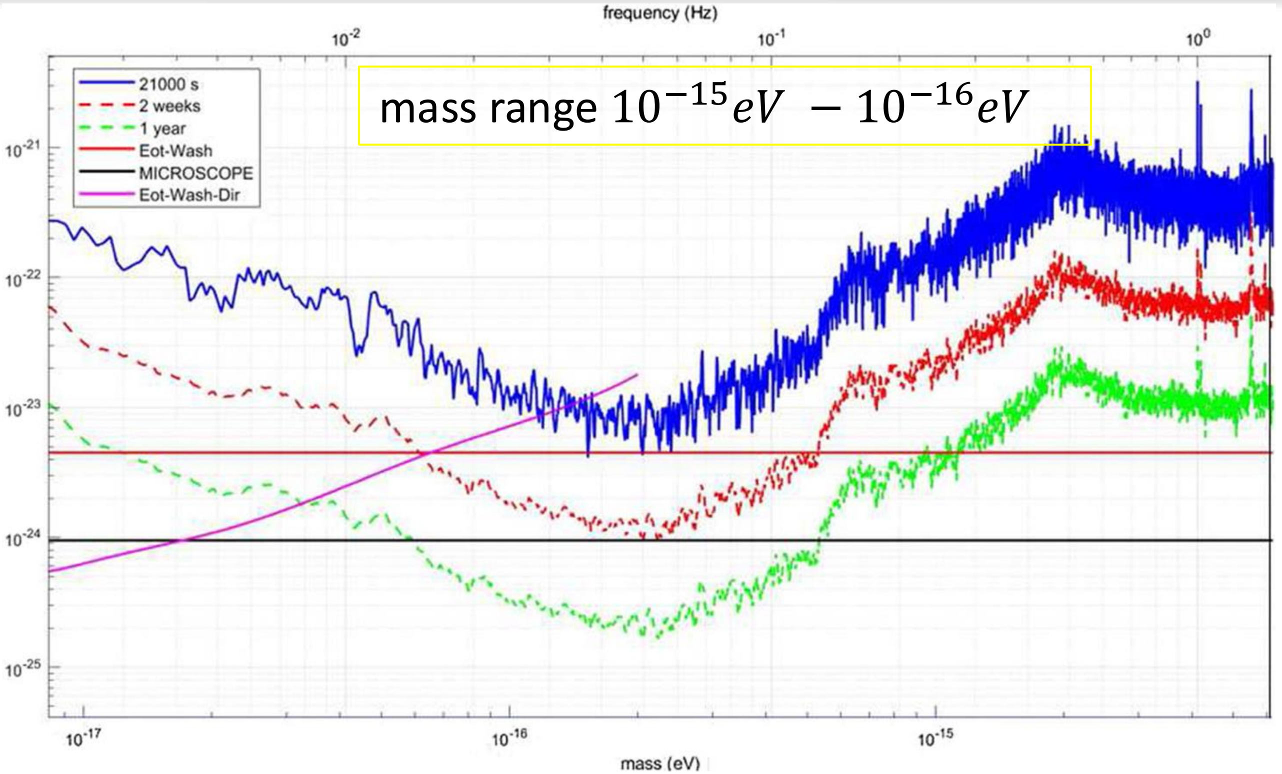
Ayatri Singha et al: *Characterization of the seismic field at Virgo and improved estimates of Newtonian-noise suppression by recesses* ***Class.Quant.Grav. 38 (2021) 24, 245007***

Prototype: Dark Matter search

Virgo/LIGO collaboration set constraints on the coupling constant of the Dark Photon in the low mass range

(R. Abbott et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration) Phys. Rev. D 105, 063030)

$$\sqrt{\langle \Delta L^2 \rangle} = C \frac{\hbar^2 \epsilon |k| L}{m_A^2 c^4} \frac{eq}{M\sqrt{\varepsilon_0}} \sqrt{2\rho_{\mathrm{DM}}}.$$

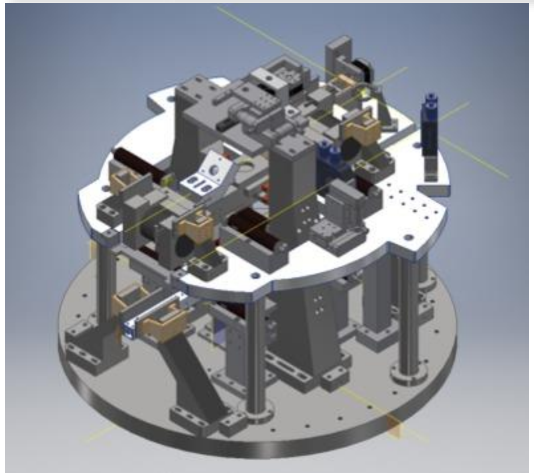


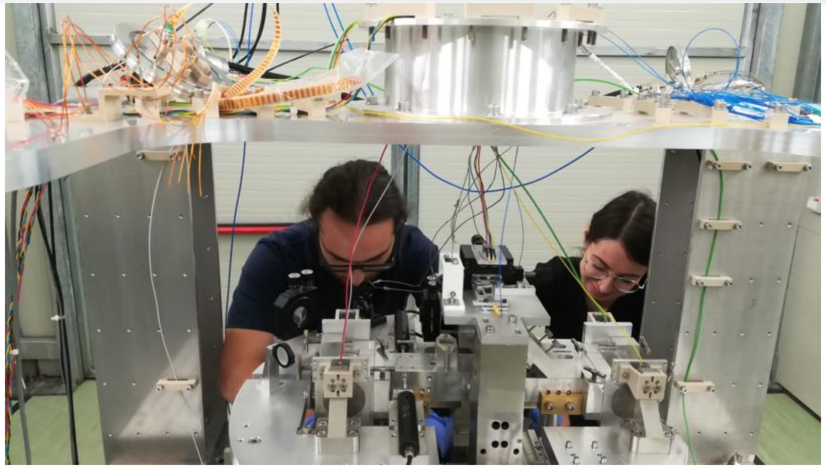
Archimedes prototype may be used used to add constraints in Dark Photon search in low mass regime of $m_a = 10^{-14}$ eV, using weight and counterweight of different materials (Pb vs Al)

Measurements are on going and preliminary results are very much encouraging

([Allocca, A., Avino, S., Calloni, E. et al. Thermal noise-limited beam balance as prototype of the Archimedes vacuum weight experiment and B-L dark photon search.](https://doi.org/10.1140/epjp/s13360-024-04920-x) *Eur. Phys. J. Plus* **139**, 158 (2024). https://doi.org/10.1140/epjp/s13360-024-04920-x)

Status of activities: the Balance



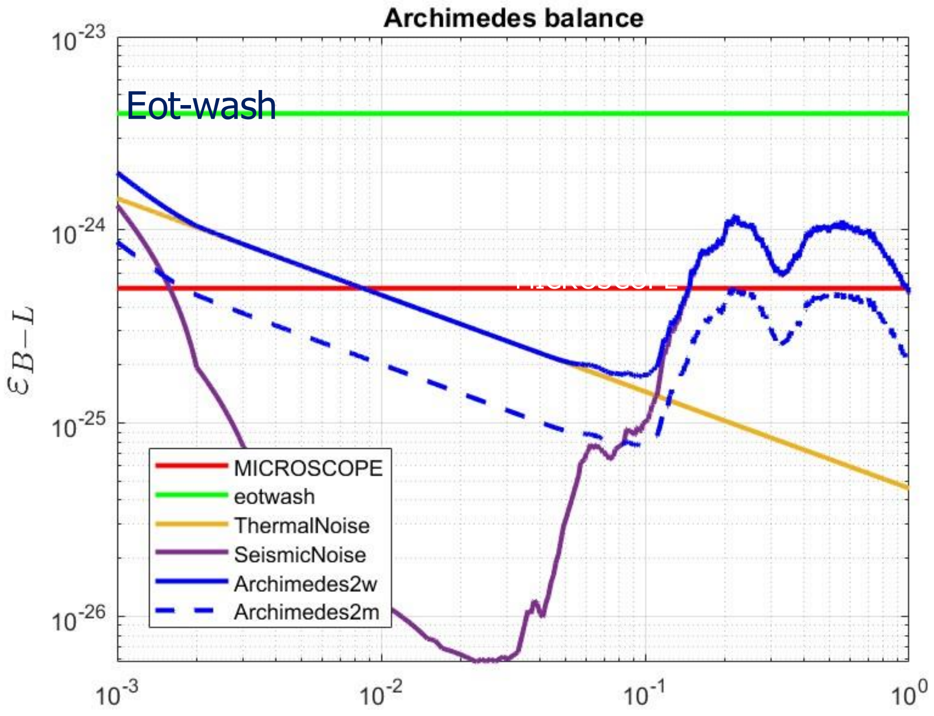


- Mechanics – completed[(1)]
- Electrical cabling and vacuum feedthroughs – completed
- Optical components and cabling and vacuum feedthroughs – 3 optical feedthroughs being machined in EGO
- Temporary Acquisition and Control system – ready and cabled
- Vacuum system – on site
- The first run at room temperature and in vacuum on going.

Ready to go under vacuum

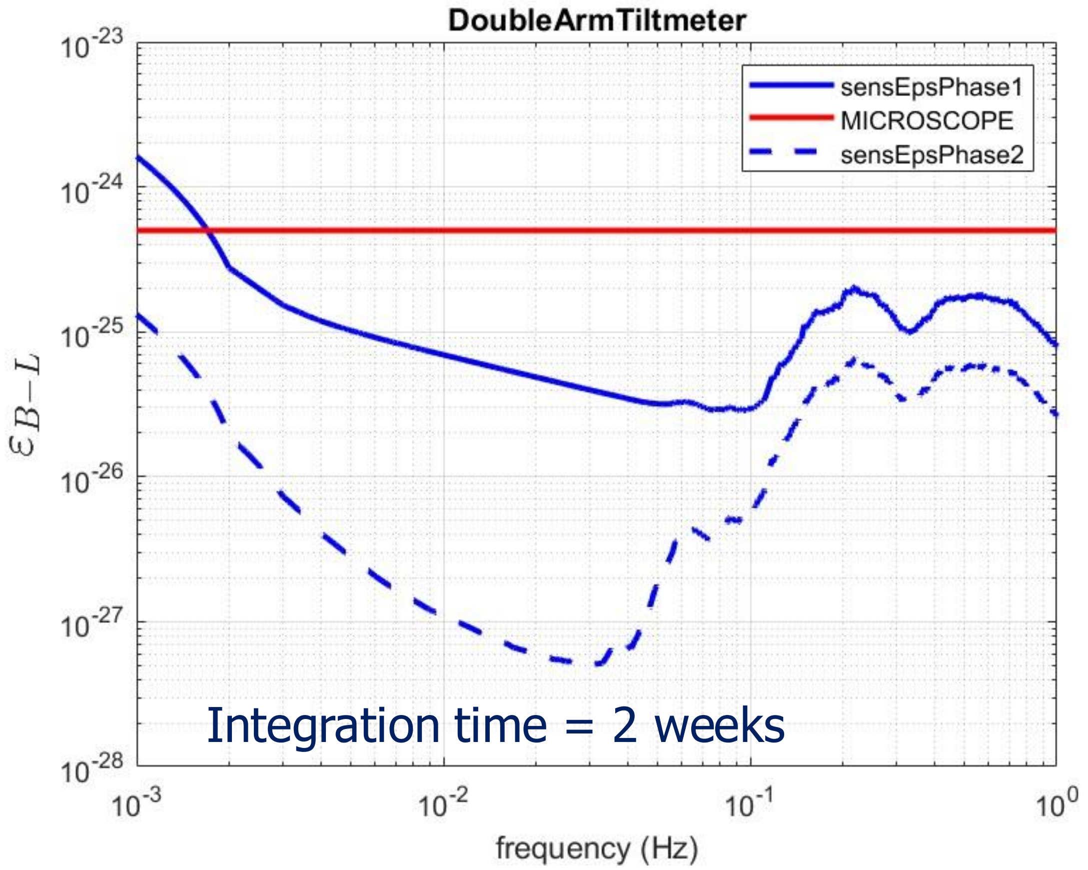
(1) Samples are not suspended yet

Expected sensitivity with Archimedes balance



Resonance Frequency = 6 mHz
Quality factor = 300
Integration time = 2 weeks (blue)
Integration time = 2 months (--blue)

A similar (simpler) balance could be designed for dark photon search



Armlength = 2 m
Sample mass = 5kg
No Suspended masses
Joints' material = fused silica

ET SUN-Lab

- Realization of a Research Center in the Sos Enattos former-mine to host (10M from RAS + 10M from INFN-INAF-INGV)
  - research activities of interest for INFN, INAF and INGV
    - ✓ the **Earth Telescope**
  - dissemination and outreach activities
  - training activities

Thanks for the attention

Some References

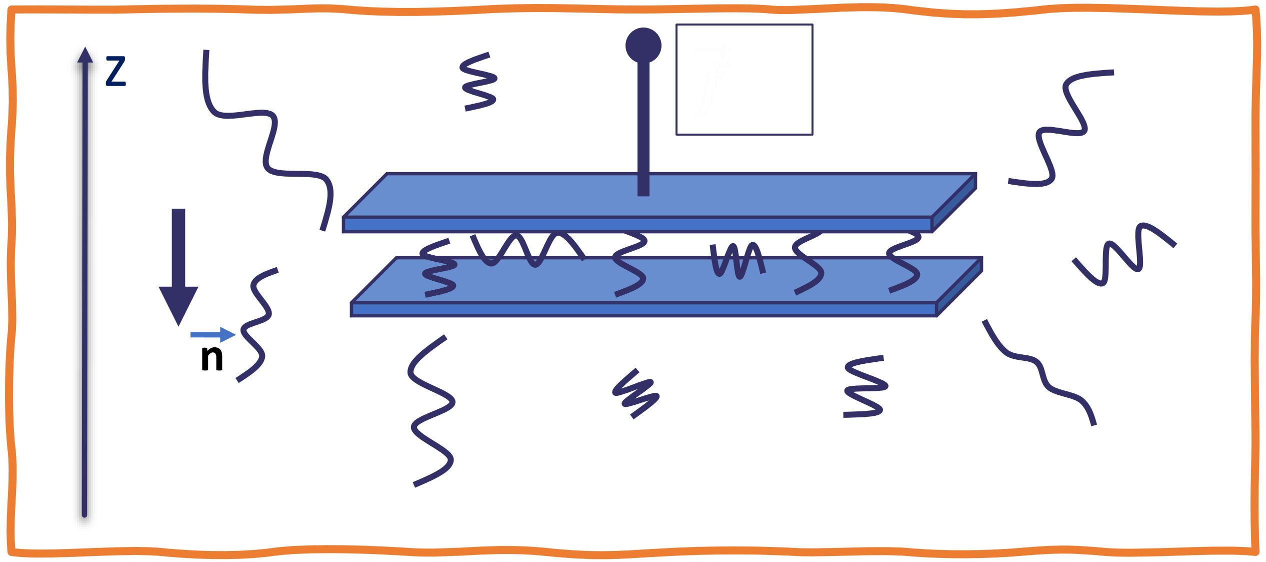
- Relativistic mechanics of Casimir apparatuses in a weak gravitational field - Phys. Rev D 76:025008 (2007)
- Casimir Energy for two and three superconducting coupled cavities: Numerical Calculations – Eur. Phys. J. Plus 132 (2017) 11, 478
- Variation of Casimir Energy from a Superconducting Transition - Nucl.Phys.B 726 (2005) 441-463
- Toward Measuring variations of Casimir Energy by a Superconducting Cavity - Phys. Rev. Lett 94 (2005) 180402
- High-bandwidth beam balance for vacuum-weight experiment and Newtonian noise subtraction - Eur. Phys. J. Plus136, 335 (2021)
- Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency - Eur. Phys. J. Plus 136, 511 (2021).
- Picoradiant tiltmeter and direct ground tilt measurements at the Sos Enattos site - Eur. Phys. J. Plus 136, 1069 (2021).
- Quantum zero point electromagnetic energy difference between the superconducting and the normal phase in a high-Tcsuperconducting metal bulk sample - Phys.Rev.B 106 (2022) 13, 134502
- Casimir energy for N superconducting cavities: a model for the YBCO (GdBCO) sample to be used in the Archimedes experiment - Eur. Phys. J. Plus 137, 826 (2022)

Backup slides

Casimir cavity in the Gravitational Field

$$\vec{f} = \frac{|E_C|}{c^2} g\,\hat{z}$$

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



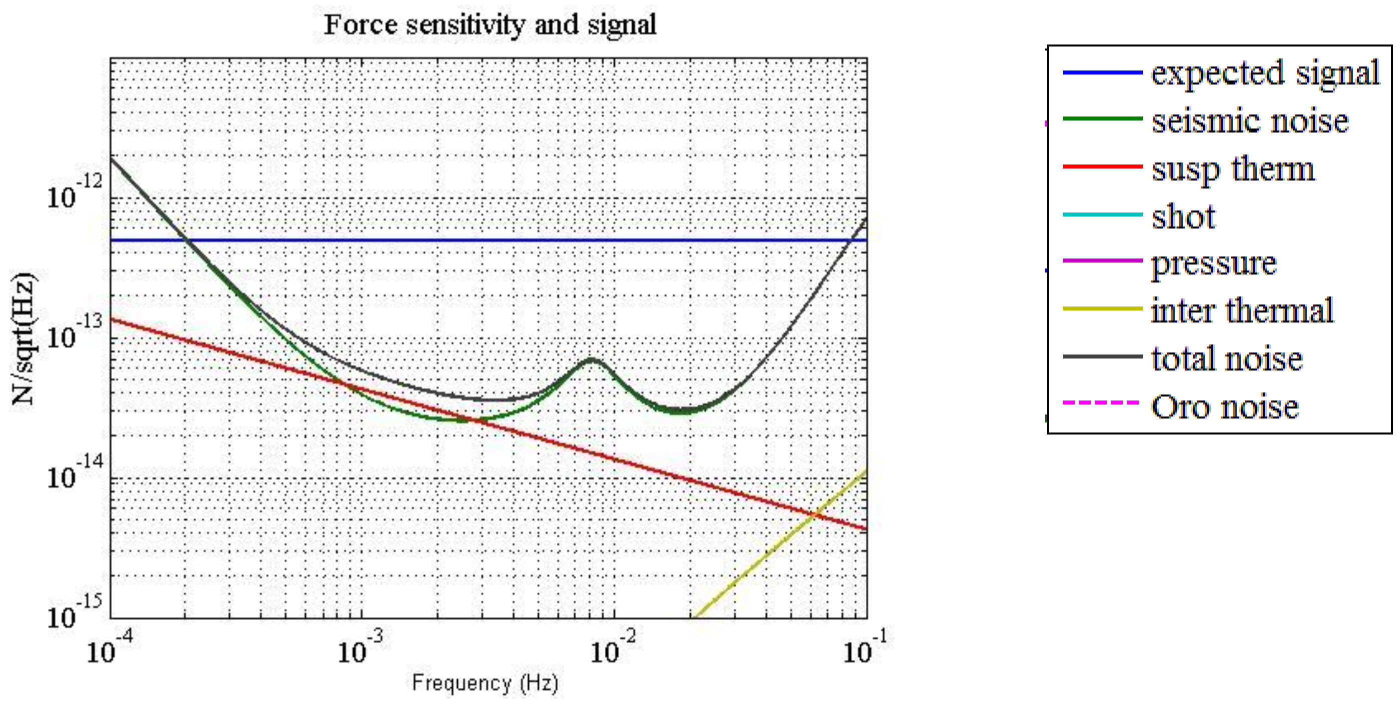
The force that keeps an extended body suspended in a gravitational field depends on its internal energy -> $\boldsymbol{f}$ depends on the vacuum energy inside the cavity

The cavity immersed in the vacuum is subjected to an upwards force equal to the weight of the displaced vacuum – Archimedes "buoyancy of vacuum"

<u>For a single Casimir cavity with $S \approx 1\,dm^2$ and $a \approx 1\,\mu m$, the signal force intensity would be $|\vec{F}| \simeq 4 \cdot 10^{-28} N$</u>

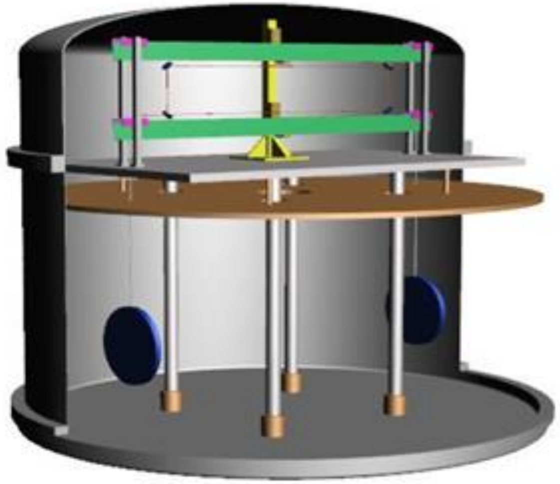
[G.Bimonte, E. Calloni, G. Esposito, L. Rosa - Phys. Rev D 76:025008 (2007)]

- Thanks to these feasibility studies we proposed the final experiment and the INFN decided to fund it starting from Jan 2018
- The project sensitivity as limited by fundamental noises

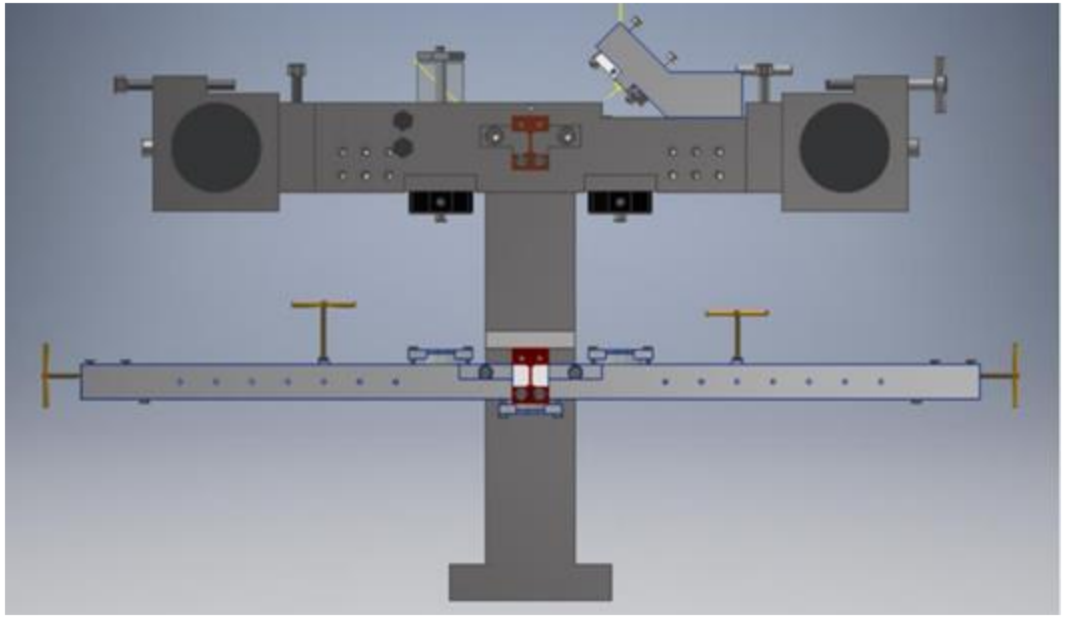


Signal (in blue the level of the signal to be intended at a single frequency). Sensitivity is for 1 months of integration time (10^6 s) Limited by : <u>thermal noise and seismic noise</u>

DECOUPLING FROM THE GROUND TILT



- The measurement arm can be sensitive to the **ground tilt**: therefore we use an additional reference arm as a **tiltmeter**, to subtract the common seismic noise



- The interferometric read out is

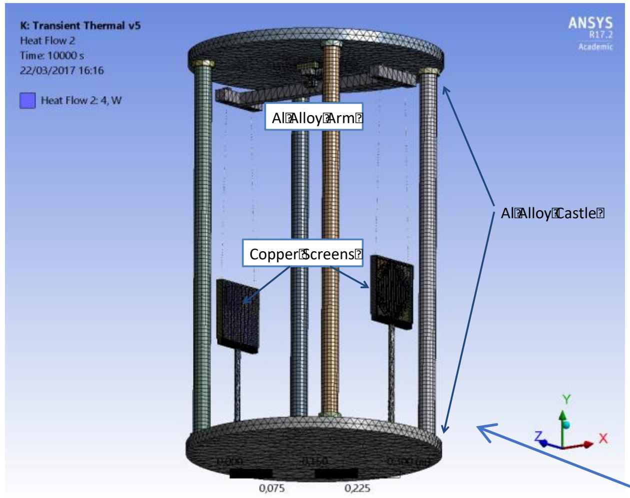
  referred to this arm, not to the ground

  → Relative tilt of the arms for coherent

  noise subtraction

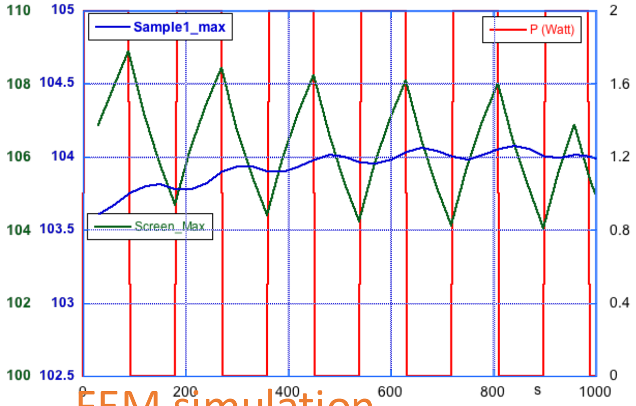
Temperature modulation

Temperature modulation is obtained by exposing the sample to a surrounding environment whose temperature is modulated



2’ diam, 5 mm thick subtrate for YBCO

Case with only radiative heat exchange



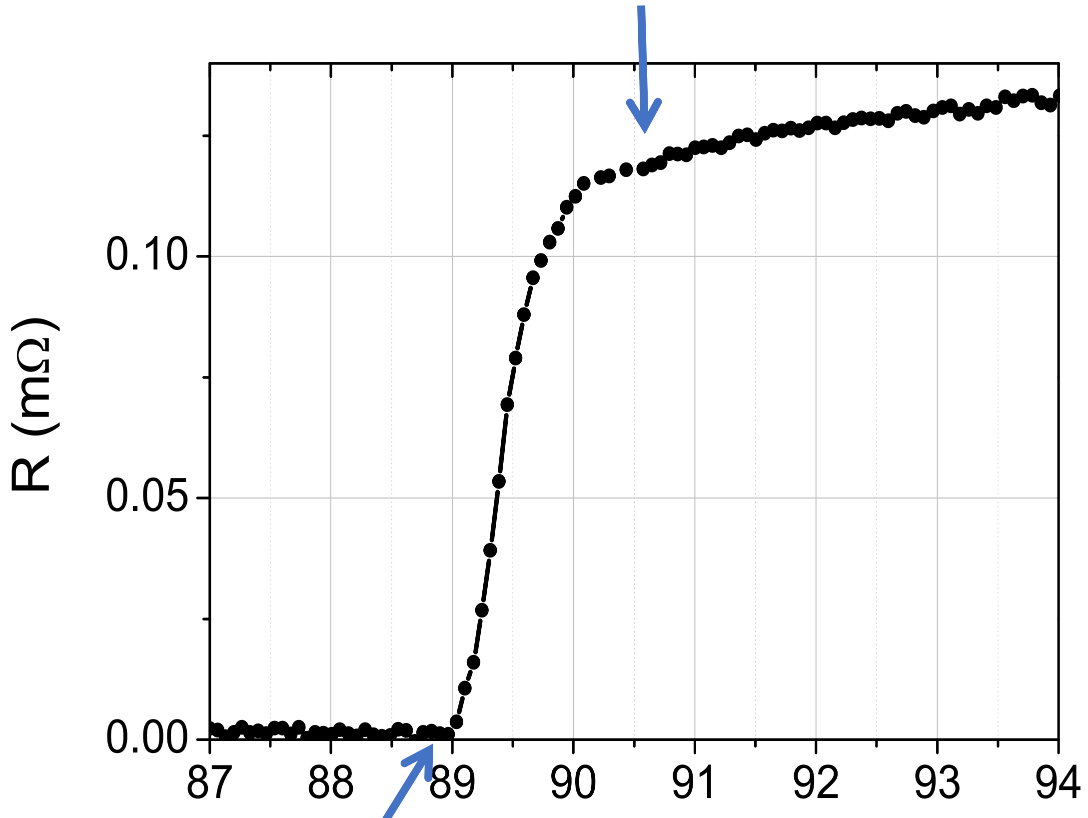
FEM simulation

Under test 1mm thick YBCO samples

Choice of the sample

single-domain melt-textured YBCO bulk samples
Dimensions: 40 x 40 x 2.5mm
Density: 6 g/cm3
Weight: 25 gr
The samples were tested using a 4 probe technique in a variable temperature insert. A thermometer was glued on the samples surface in order to obtain an accurate reading of the temperature.

onset of the superconductive transition T_{onset}

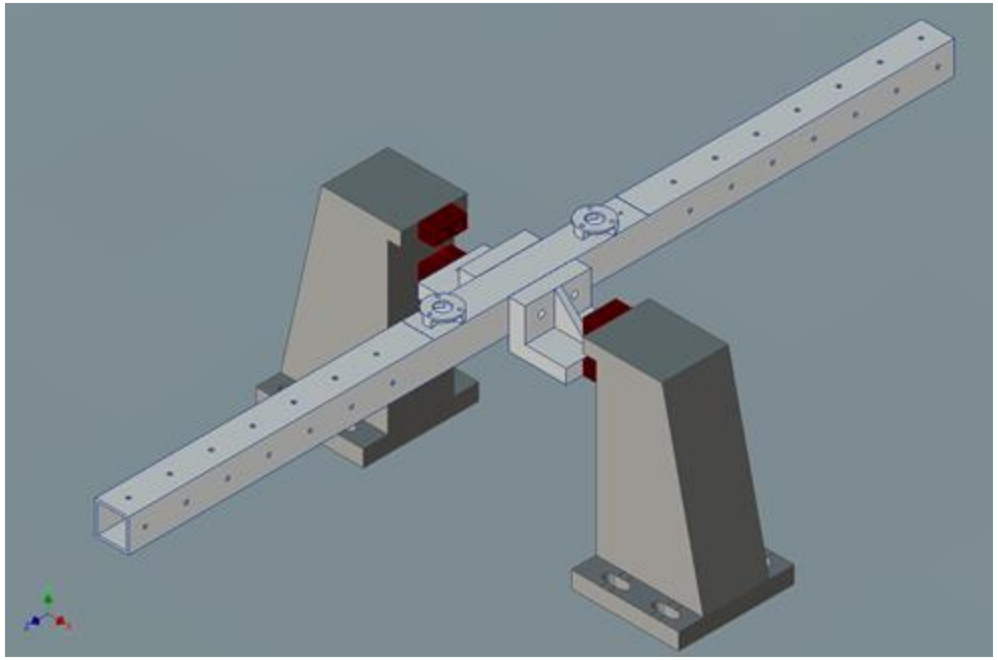


T (K)

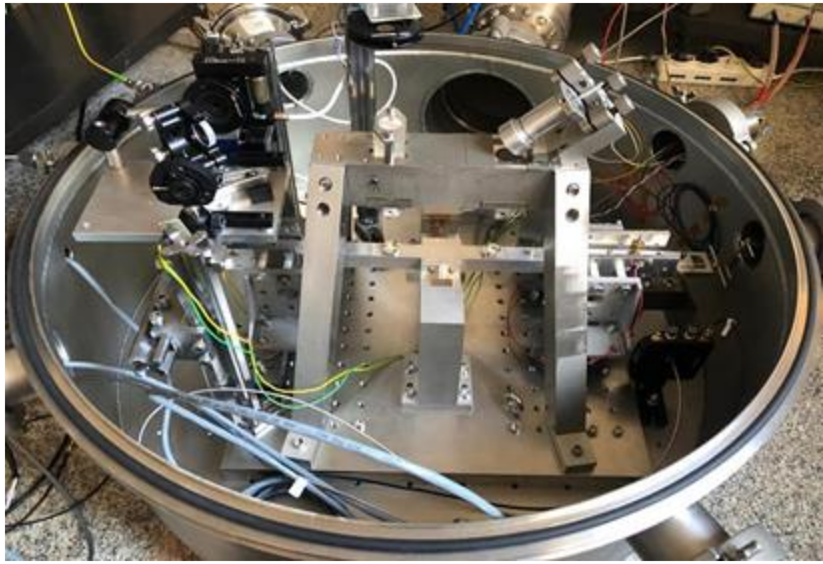
Zero resistance state T_{c0}

T_{onset}=90K
T_{c0}=89K
DT=1K

The balance prototype



- 50 cm long arm with low momentum of inertia
- suspended through thin flexible joints (Cu-Be, 100 µm x 500 µm), similar to LIGO tiltmeters (Venkateswara et al. 2014)
- Balance center of mass positioned as close as possible to bending point (~10 µm) to minimize the coupling with ground motion



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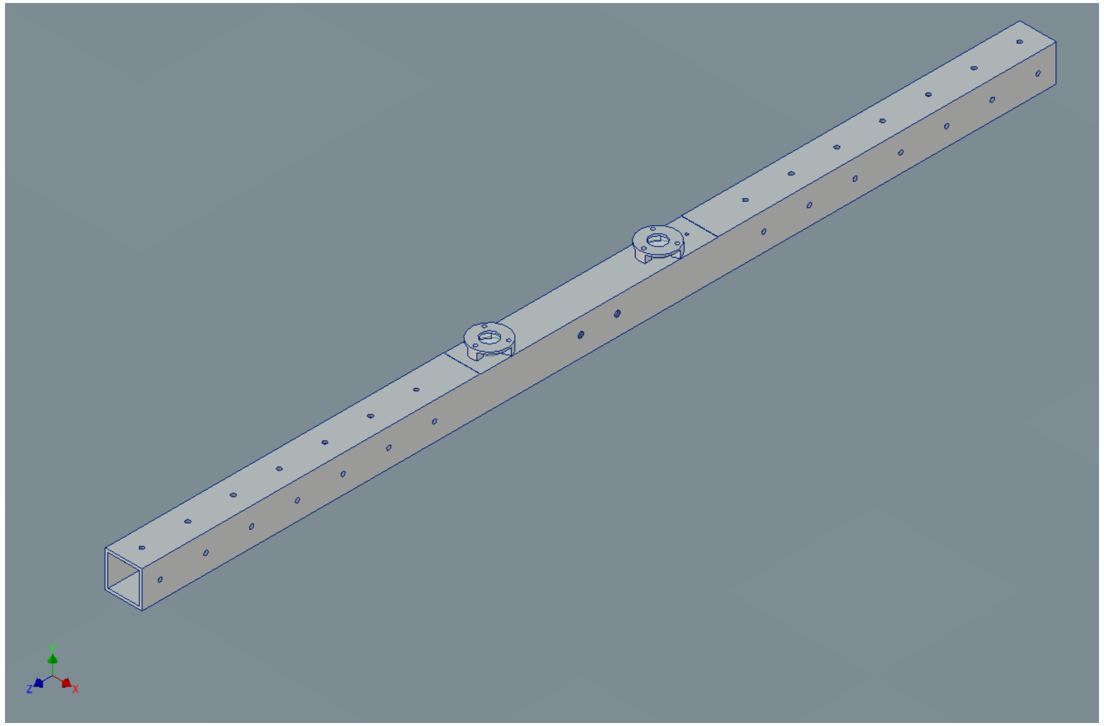
- Installed at the Sar-Grav surface laboratories in Lula (NU) – Sos-Enattos mine

Balance prototype: Mechanics



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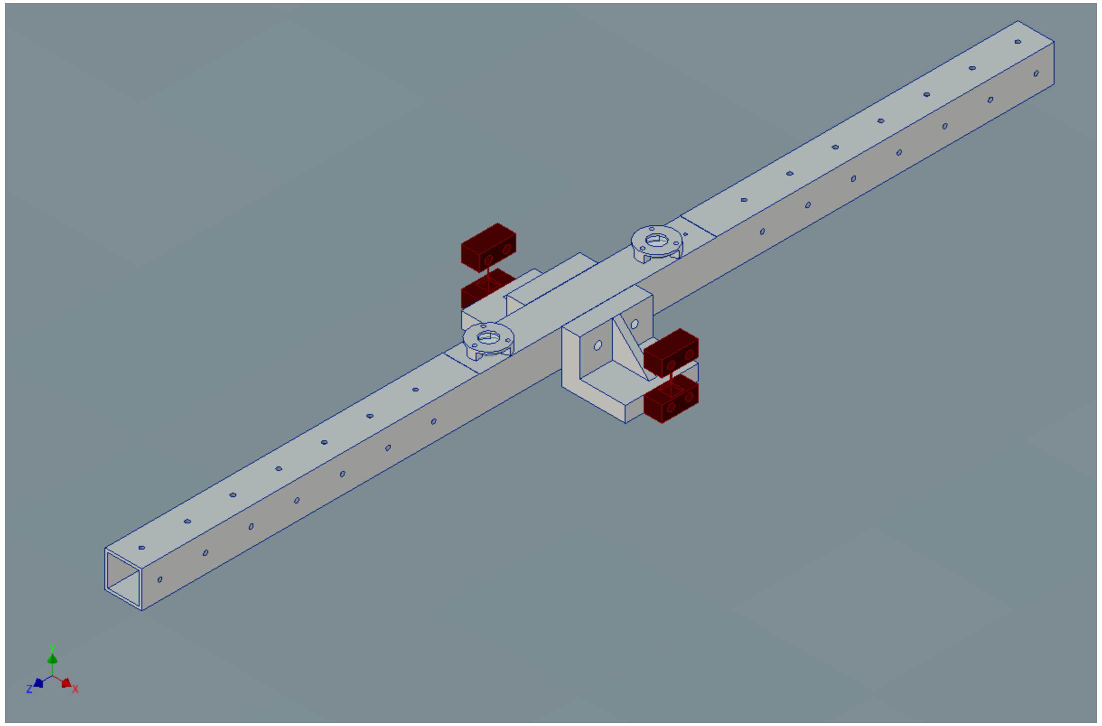

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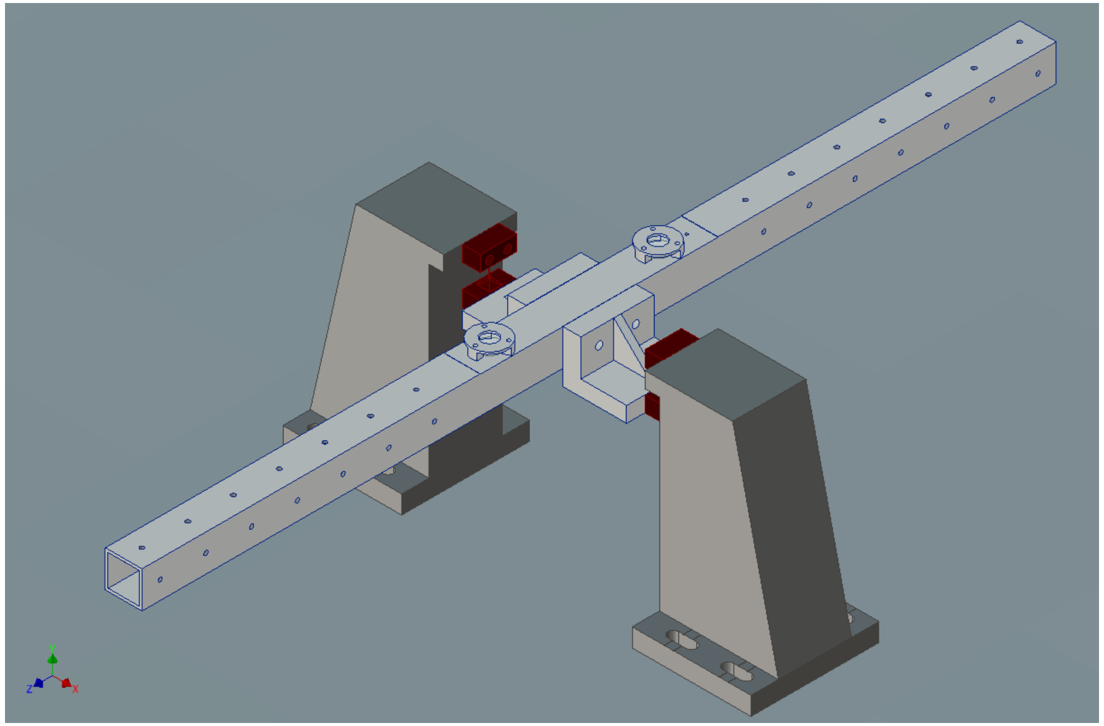
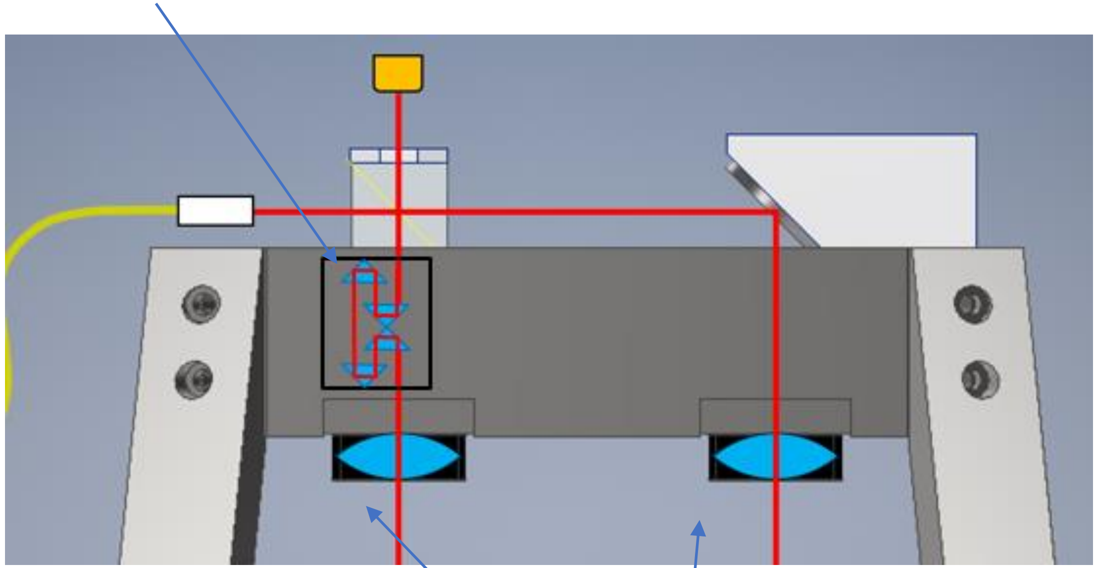


- 50 cm long arm with low momentum of inertia
- Suspended through **thin flexible joints** (Cu-Be, 100 μm x 500 μm), very similar in design to LIGO tiltmeters (Venkateswara et al., 2014)
- The balance center of mass is positioned as close as possible to the bending point (≈ 10 μm) to minimize the coupling between tilt and transverse seismic noise.

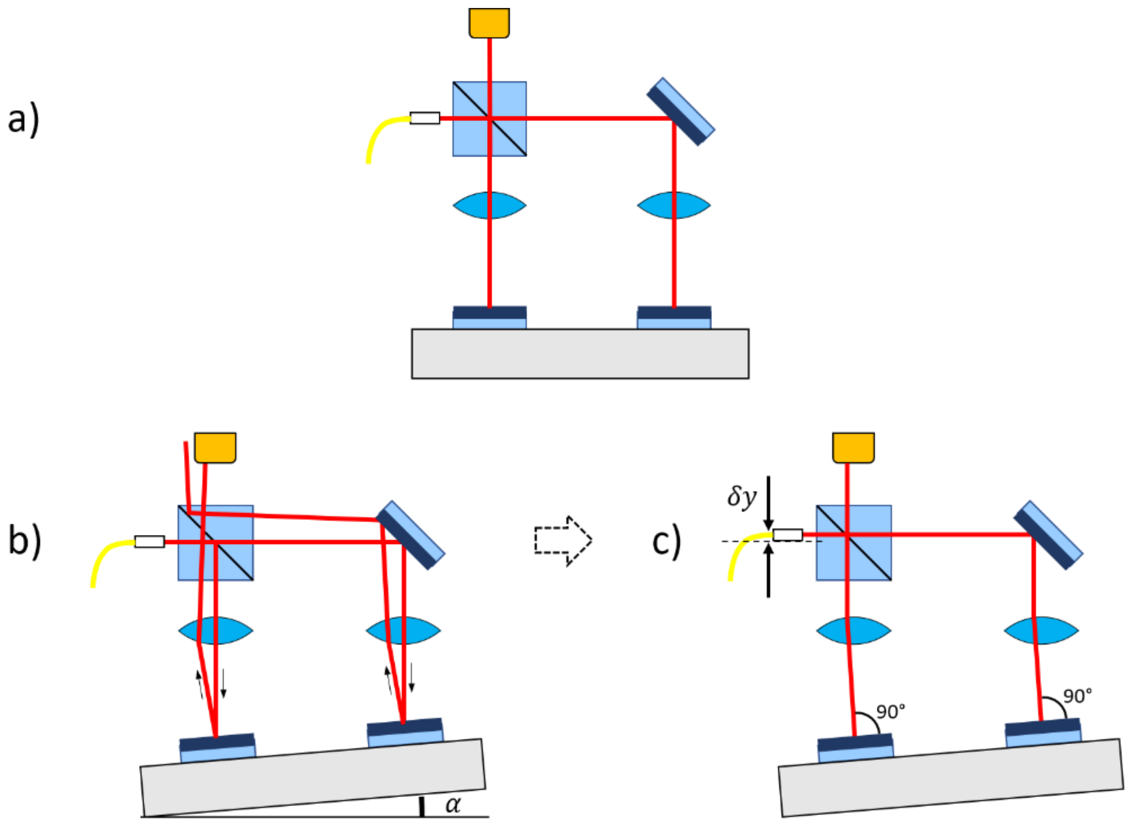
Resonance Frequency 20-30 mHz, depends on positioning of center of mass

Optical Read-Out: prisms and lenses



- Prisms are used to equalize the length f the optical path ($\Delta L \approx 2mm$) => frequency noise is highly suppressed
- Amplitude noise reduced by measuring a pick-off on the input beam and performing a signal normalization

Optical Read-Out: prisms and lenses



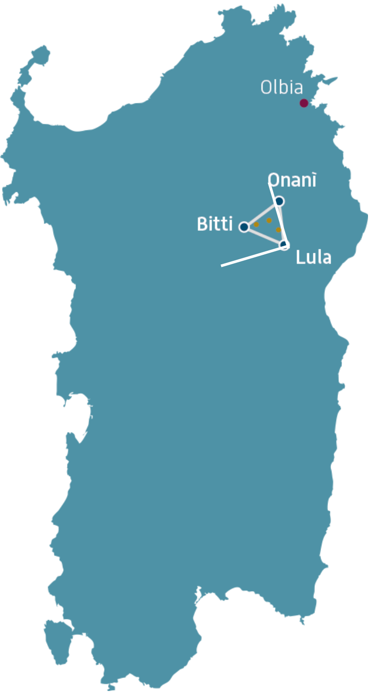
Lenses are used to maintain good alignment and contrast against static tilt.

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

b) A tilt of α would misalign the interferometer, contrast changes at second order thanks to lenses

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

Status Update of Sardinia activities



Two Geometrical Options: Δ vs 2L

Legal Framework and authorization

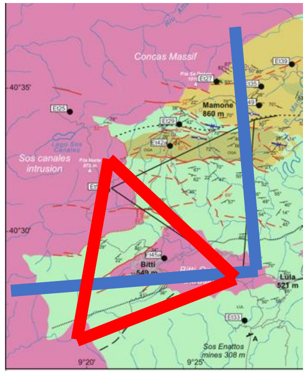
Socio-economic impact

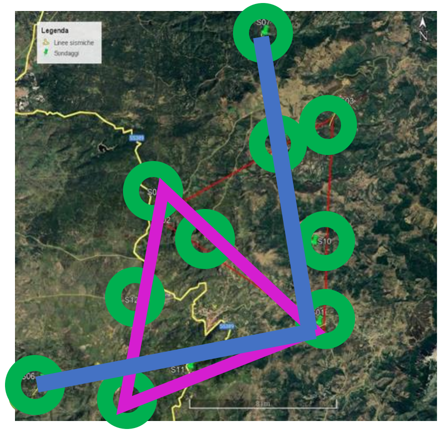
Geological studies

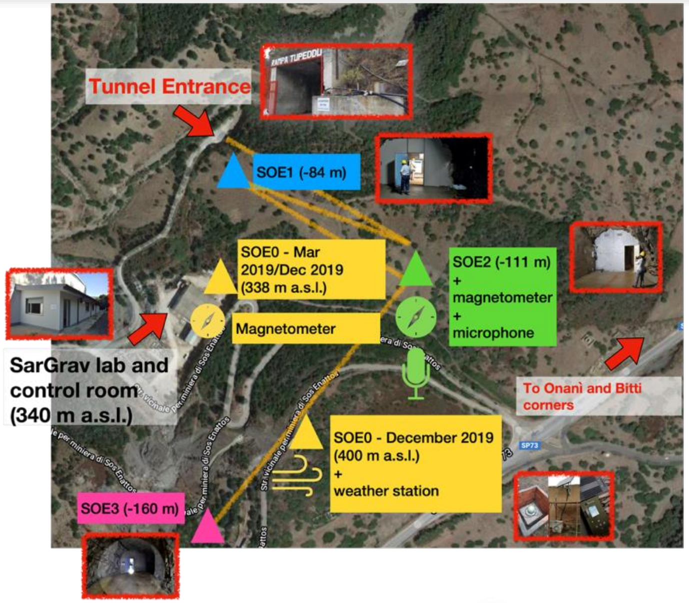
Site monitoring

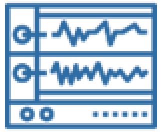
Noise impact Evaluation

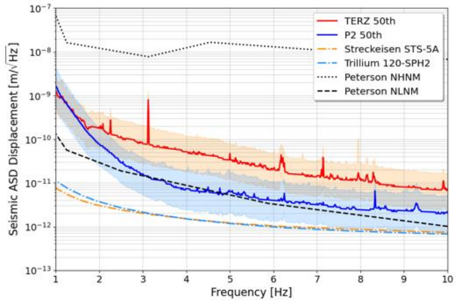
Engineering studies











From the geological and physical point of view, Sardinia is an optimal candidate to host the Einstein Telescope, either in Δ or in L (→ 2 sites) configuration!