Search for the ultralight B-L dark photon with the Archimedes Experiment

E. Calloni – 2025-01-10

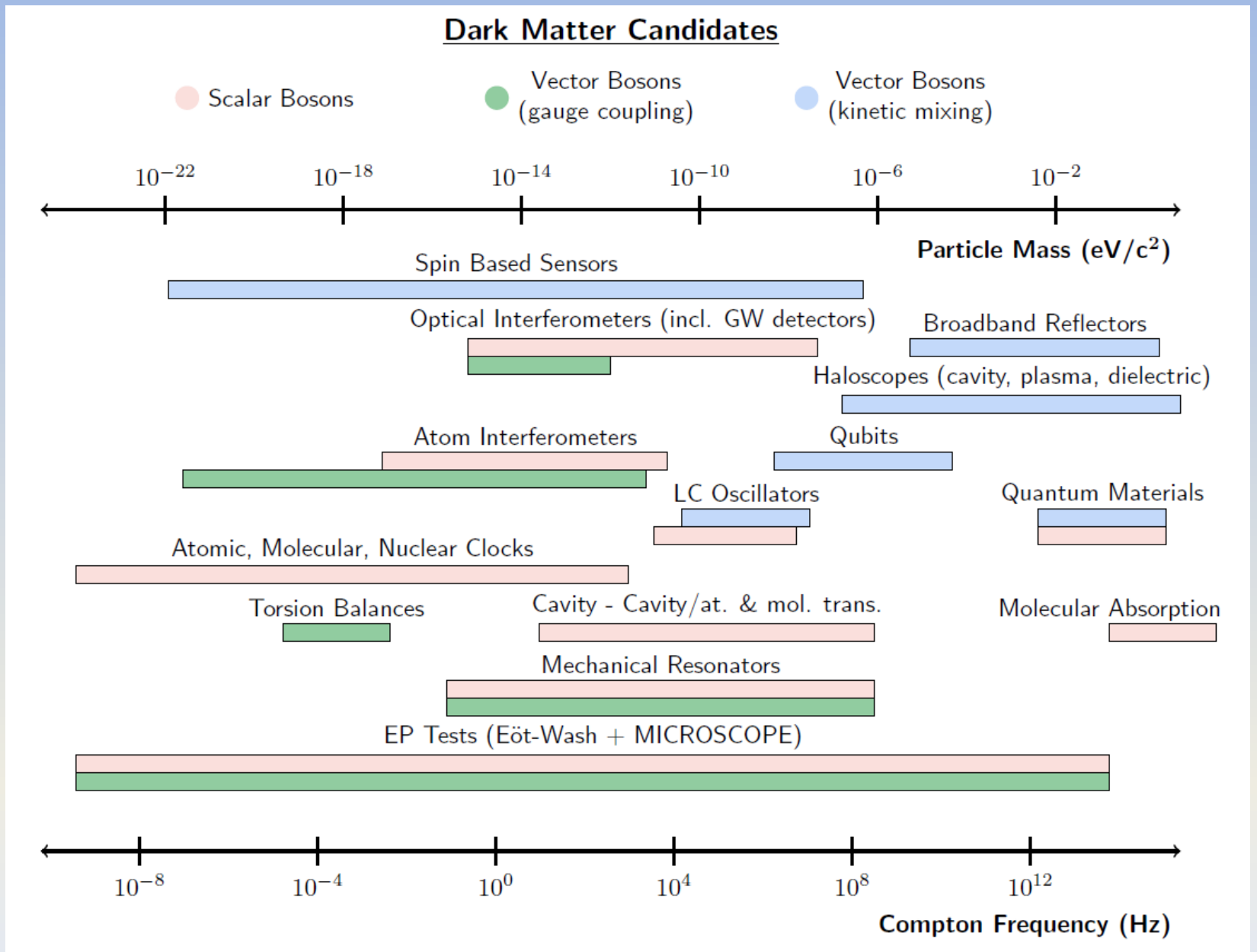
Ultralight particles and classical fields

- For some years now, the idea that dark matter could be formed by ultralight bosons has gained ground, with lower limits on the mass of the order mA $\approx 10^{-22}$ eV, given by astronomical observation

Snowmass 2021 White Paper
New Horizons: Scalar and Vector Ultralight Dark Matter

- The occupation numbers are large, so that the expected field is 'classical', superposition of waves oscillating at frequency f0 = mAc^2/h, width $\Delta f = \frac{1}{2}\left(\frac{v_0}{c}\right)^2 f_0 \approx 2.94 \times 10^{-7} f_0$ and coherence times of the order of Tcoh ≈ 10^6 Tosc (v0 = 220 km/s is the speed at which the DM orbits the galaxy)

Search Methods



We focus on dark-photon

We focus on the massive vector field coupled with B or B − L current J_D, whose Lagrangian is given by

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\nu A_\nu - \epsilon_D e J_D^\nu A_\nu$$

where $F_\mu \equiv \partial_\mu A - \partial A_\mu$ is the field strength, m_A is the mass of the vector field, and ε_D is the gauge coupling constant normalized to the electromagnetic coupling constant e.

$$\vec{A}(t,\vec{x}) = \frac{\sqrt{2\rho_{\rm DM}}}{m_A}\vec{e}_A \cos\left(m_A t - \vec{k}\cdot\vec{x} + \delta_\tau(t)\right)$$

($\hbar$ = c = 1) - where $\vec{e}_A$ is the unit vector parallel to $\vec{A}$, $\rho_{DM} \simeq 0.3$ GeV/cm^3 is the local dark matter density, and k = m_Av with v $\simeq 10^{-3}$ being the local velocity of dark matter. Note that A_0 is negligibly smaller than A_i, and hence can be ignored.

Force on a mass m

$$\boldsymbol{F}(t,\boldsymbol{x}) = \epsilon e q_D \frac{\partial \boldsymbol{A}}{\partial t} = A_0 \epsilon e q_D m_A \boldsymbol{e} cos(m_A t - \boldsymbol{k}\boldsymbol{x} + \phi(t))$$

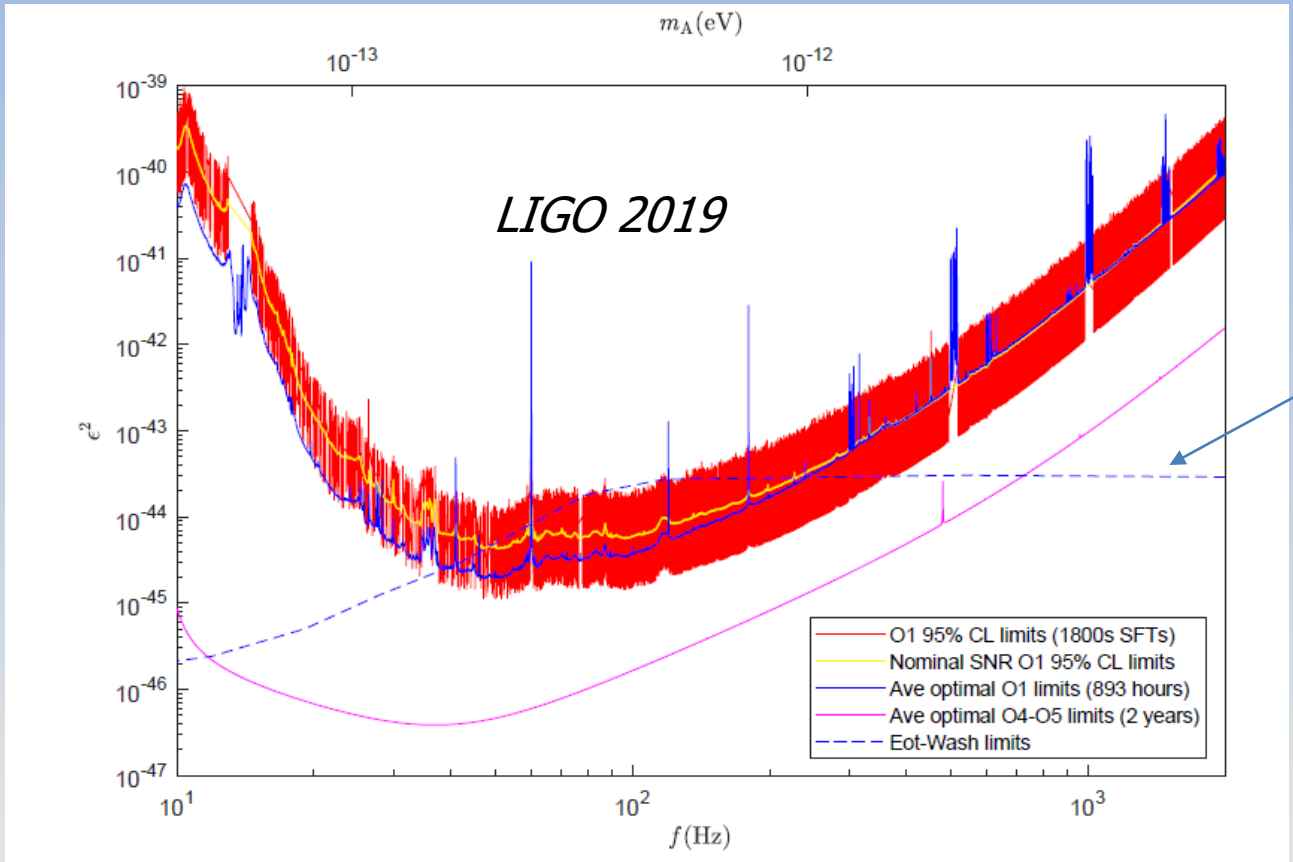
$$A_0 = \frac{\sqrt{2\rho_{DM}}}{m_A}$$

Here is q_D the B (or B-L) total charge, which is equal to the number of the barions (or neutrons) of the mass m. The amplitude of the field A_0 is related to the dark photon energy density ρ_{DM} by: $A_0 = \text{sqrt}(2\rho_{DM})/m_A$. Substituting and performing the mean over the direction of polarization and using SI units, the standard deviation of the force along the X axis is

$$\sqrt{< \boldsymbol{F_x}^2 >} = \frac{1}{\sqrt{3}} \frac{\epsilon e q_D}{\sqrt{\epsilon_0}} \sqrt{\rho_{DM}}$$

q_D is the number of barions contained in the mass m in case of B boson
q_D is the number of neutrons contained in the mass m in case of B-L boson

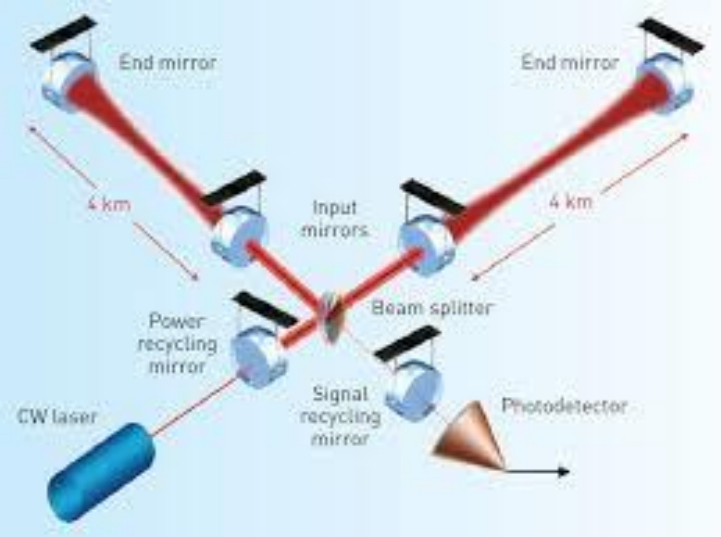
The first astrophysical search based on the force



Coupling limits of LIGO-O1 and projections O4-O5

- *Notice the limit placed by Eot-Wash (no hypothesis «static measurement»)*
- *Ligo limit under the hypothesis that the whole dark matter is B bosons*

LIGO/Virgo Equal material masses: signal is due to time delay

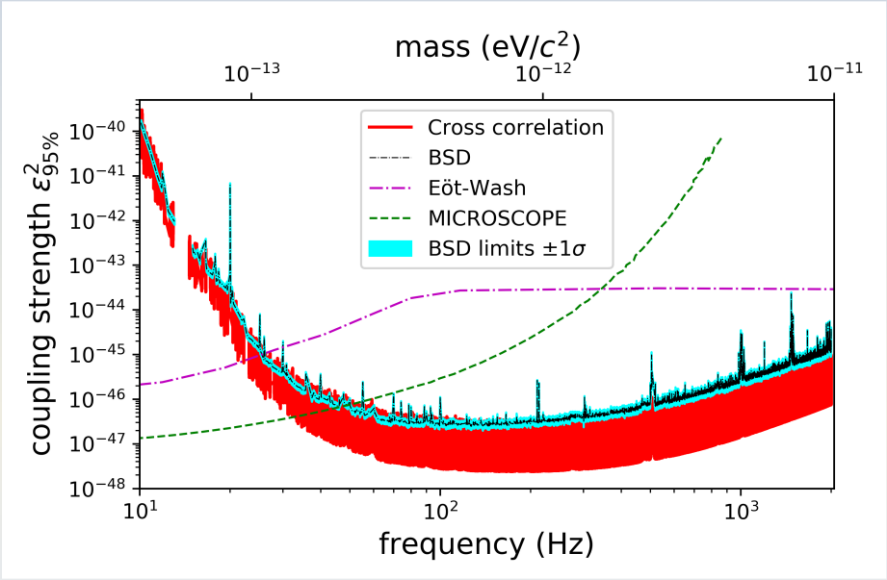


$$f_0 = \frac{m_A c^2}{2\pi\hbar}.$$

Oscillation frequency of the field

$$\sqrt{\langle h_D^2 \rangle} = C \frac{q}{M} \frac{v_0}{2\pi c^2} \sqrt{\frac{2\rho_{\rm DM}}{\epsilon_0}} \frac{e\epsilon}{f_0}$$

v0 is 220 km/s is the velocity at which dark matter orbits the center of our galaxy, i.e. the virial velocity



Improved LIGO/Virgo 2021

Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run

LIGO Scientific and KAGRA and Virgo Collaborations • R. Abbott (LIGO Lab., Caltech) et al. (May 27, 2021)

Published in: *Phys.Rev.D* 105 (2022) 6, 063030, *Phys.Rev.D* 109 (2024) 8, 089902 (erratum) • e-Print: 2105.13085 [astro-ph.CO]

Ultralight vector dark matter search using data from the KAGRA O3GK run

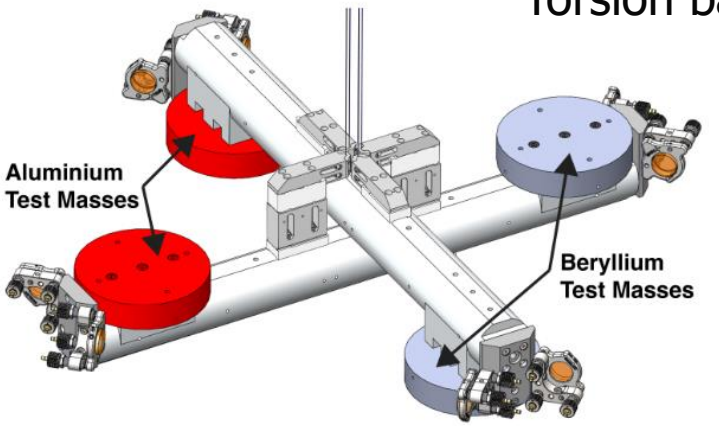
KAGRA and LIGO Scientific and VIRGO Collaborations • A.G. Abac (Hannover, Max Planck Inst. Grav.) et al. (Mar 5, 2024)

Published in: *Phys.Rev.D* 110 (2024) 4, 042001 • e-Print: 2403.03004 [astro-ph.CO]

pdf DOI cite claim reference search 12 citations

Lower mass regime

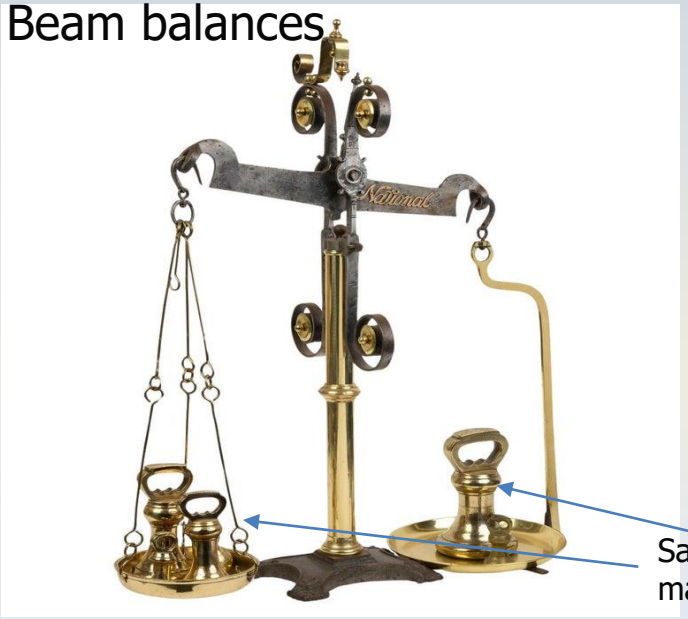
Torsion bars



Torsion pendulums and balances are particularly suited to the search for the B-L photon at lower boson masses

$$\sqrt{< \boldsymbol{F_x}^2 >} = \frac{1}{\sqrt{3}} \frac{\epsilon e q_D}{\sqrt{\epsilon_0}} \sqrt{\rho_{DM}}$$

Beam balances



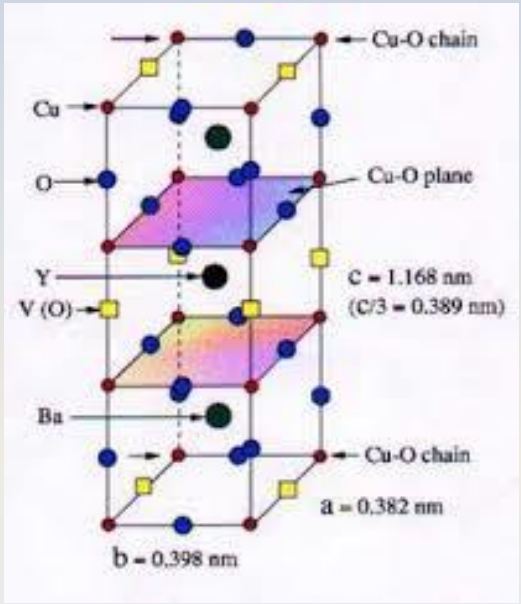
If the two masses of the balances are made of different materials, with different number of neutrons Δq_D, a net torque arises

$$\Delta q_D = \frac{M}{mb}\left[(1 - Z_{Pb}/A_{Pb}) - (1 - Z_{Al}/A_{Al})\right] = 0.0863\frac{M}{mb}$$

Samples made of different materials

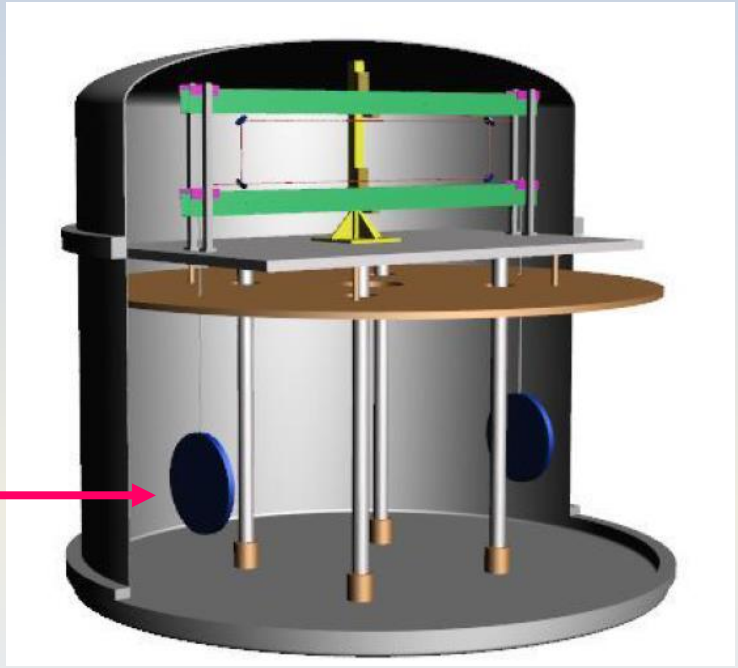
The Archimedes Experiment

- Devoted to measure the discussed interaction of vacuum energy with gravity – The Cosmological Constant Problem
- Measurement method: a cryogenic balance measures the weight variation of a superconductive stratified sample when the vacuum energy contained in the sample changes due to the variation of reflectivity of the planes, at the transition



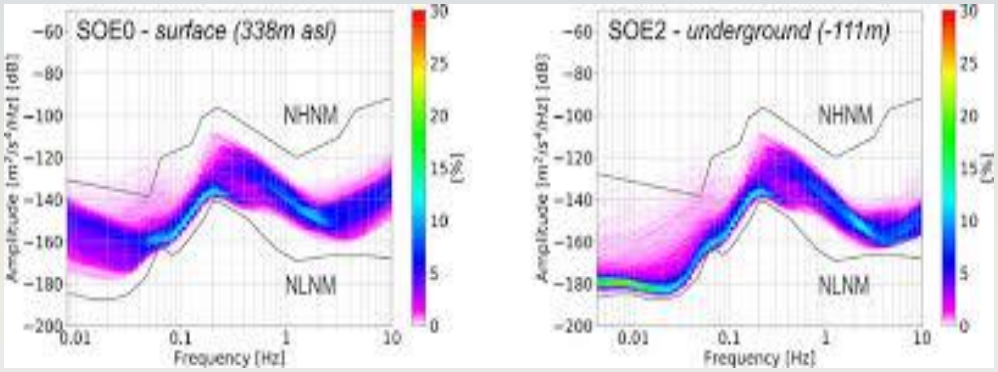
Casimir Energy Variation

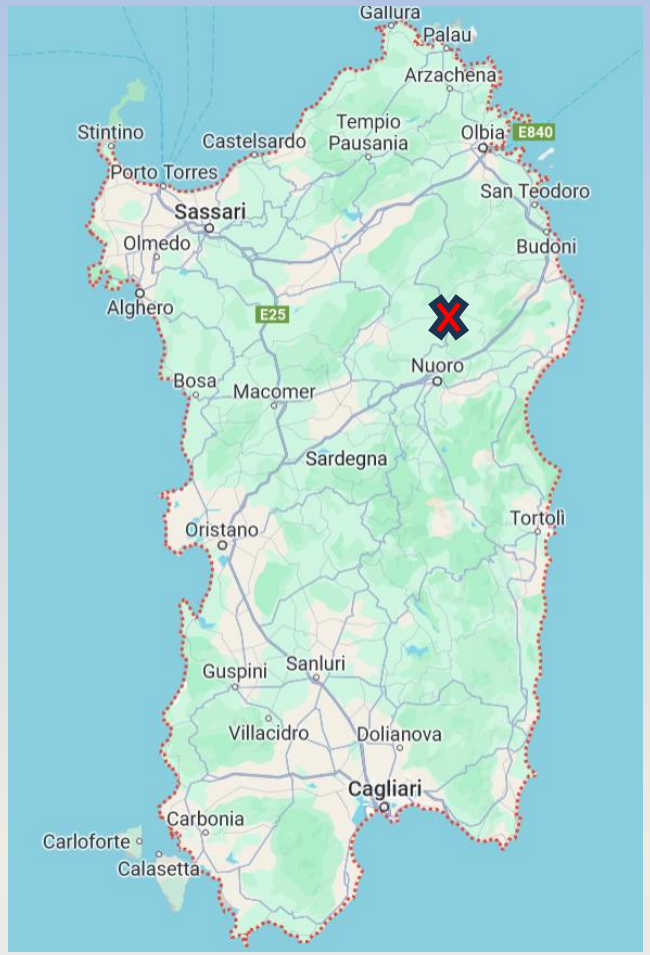
$$\Delta\eta_E = \frac{\Delta E_C}{E_C} \approx 10^{-4}$$



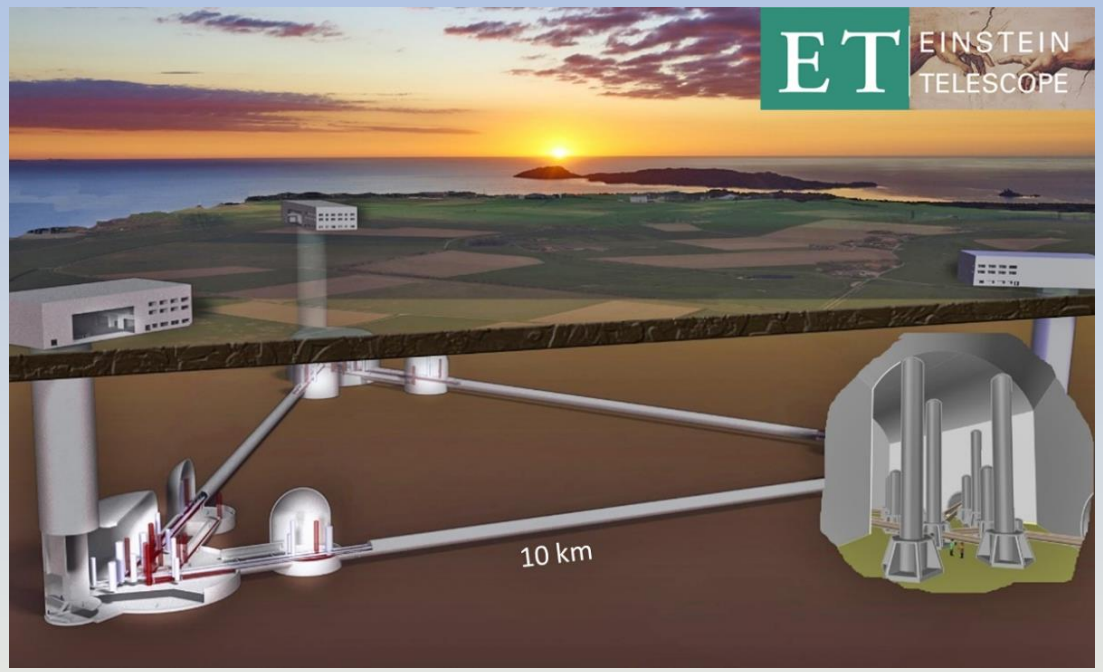
See the talk by P. Puppo

Located in Sardinia to have low seismic and anthropic noise





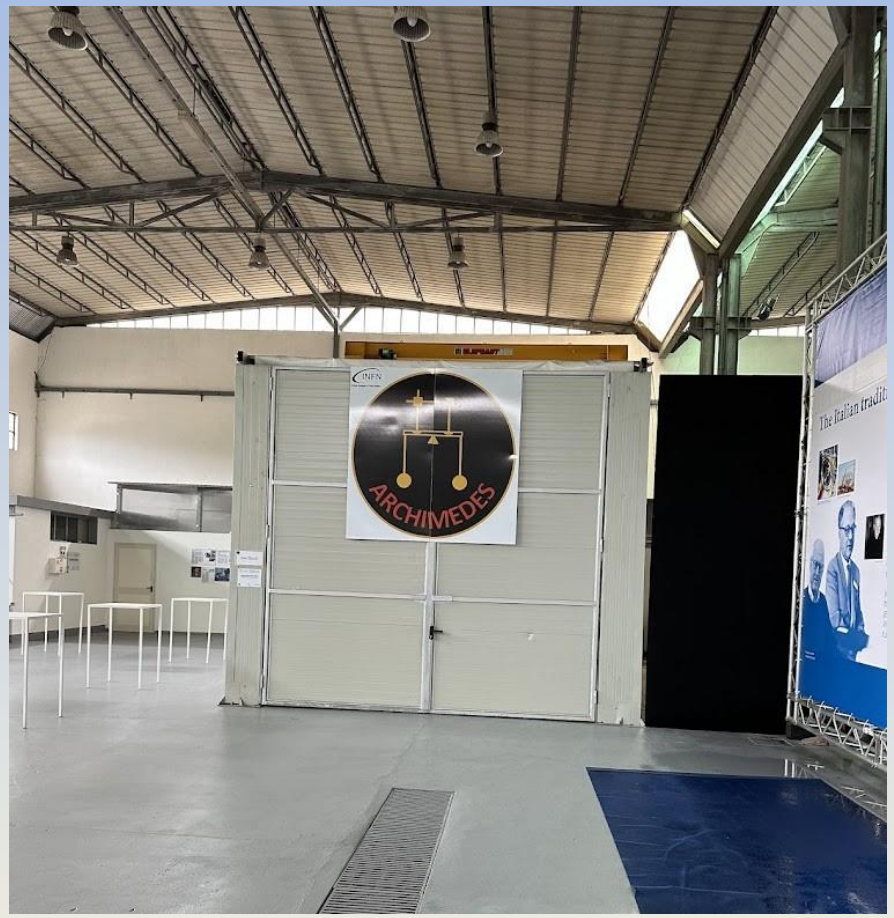
The same site - sos Enattos - candidate to host ET



The present lab

Beckestein hall (in this hall the prototype is located)

The control room



The front view of Planck hall (in this hall the Archimedes balance is located)

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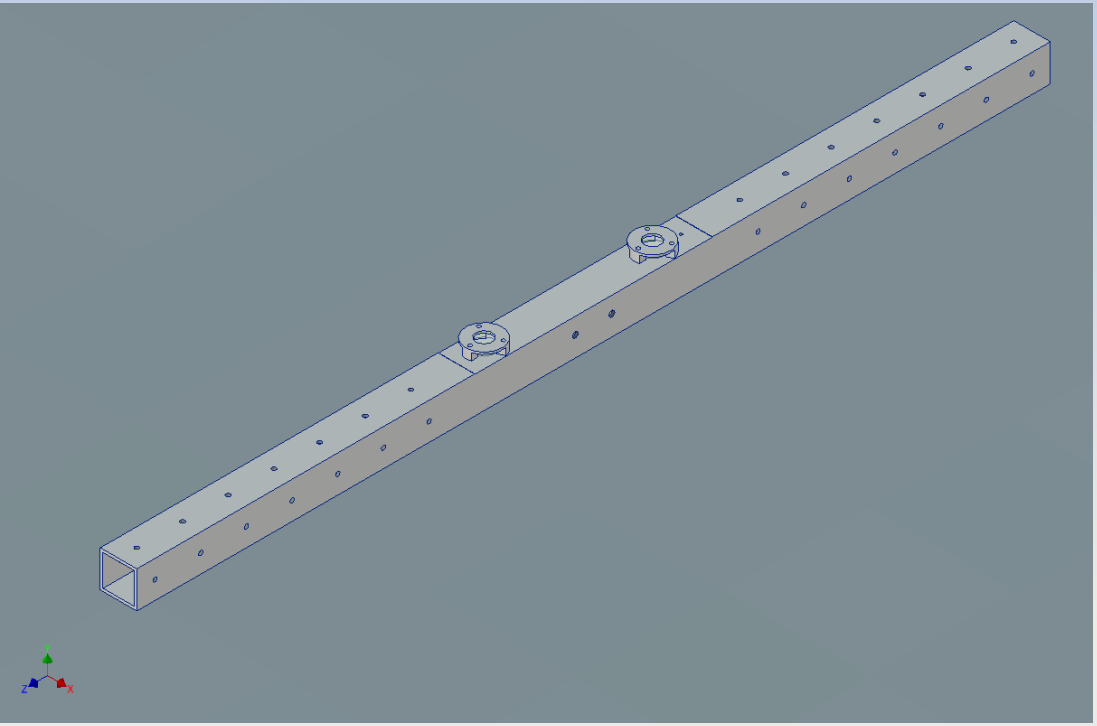
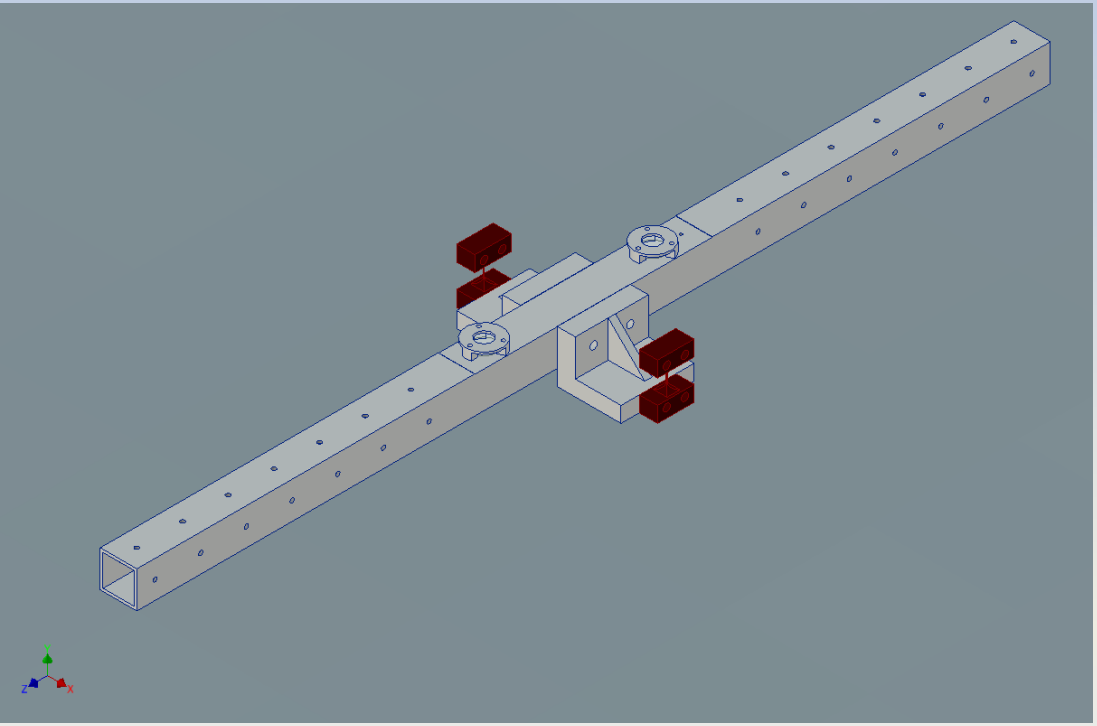
Balance prototype: Mechanics



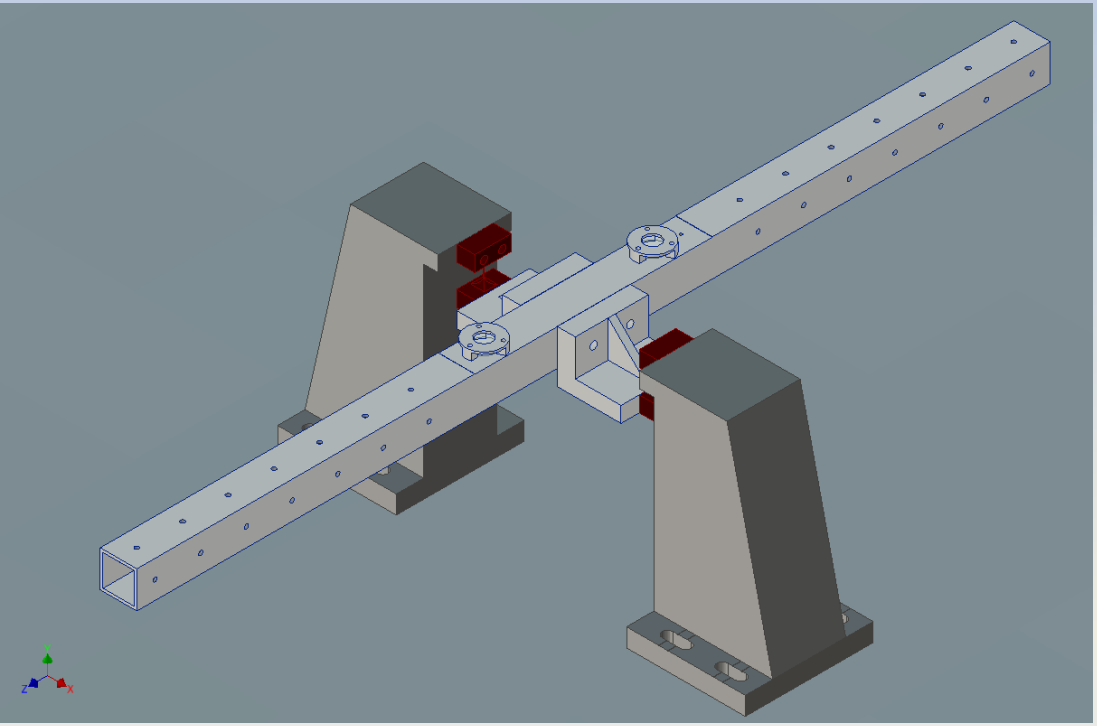
- 50 cm long arm with low momentum of inertia

Balance prototype: Mechanics



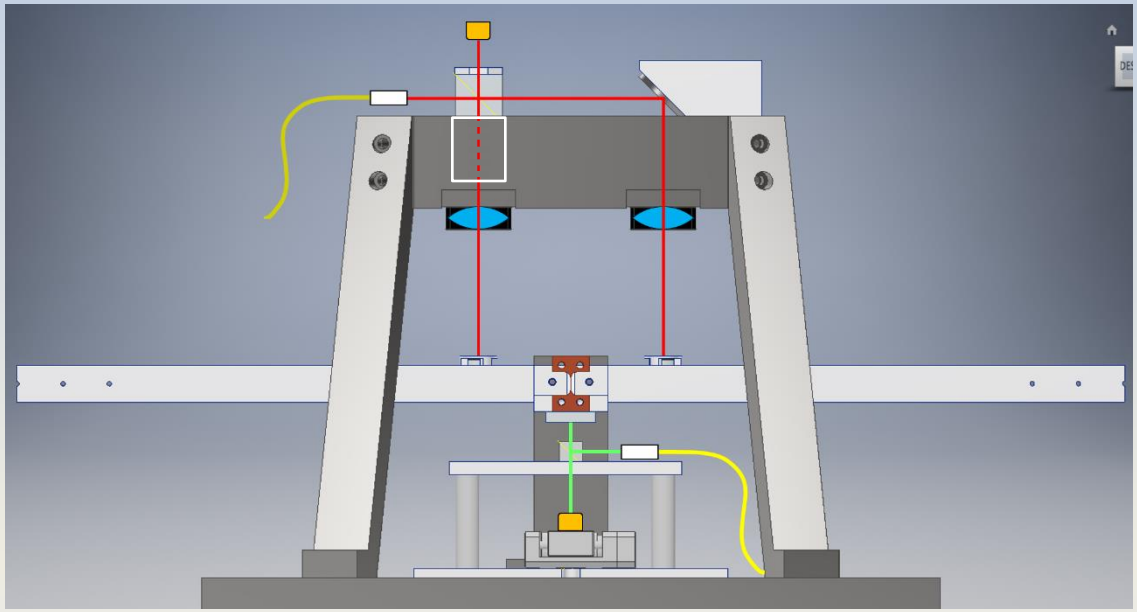
- Measurement arm very light to lower the moment of inerzia
- Suspended with **thin flexible joints** (Cu-Be, 100 μm x 100 μm)

Balance prototype: Mechanics



- 50 cm long arm with low momentum of inertia
- Suspended through **thin flexible joints** (Cu-Be, 100 μm x 100 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

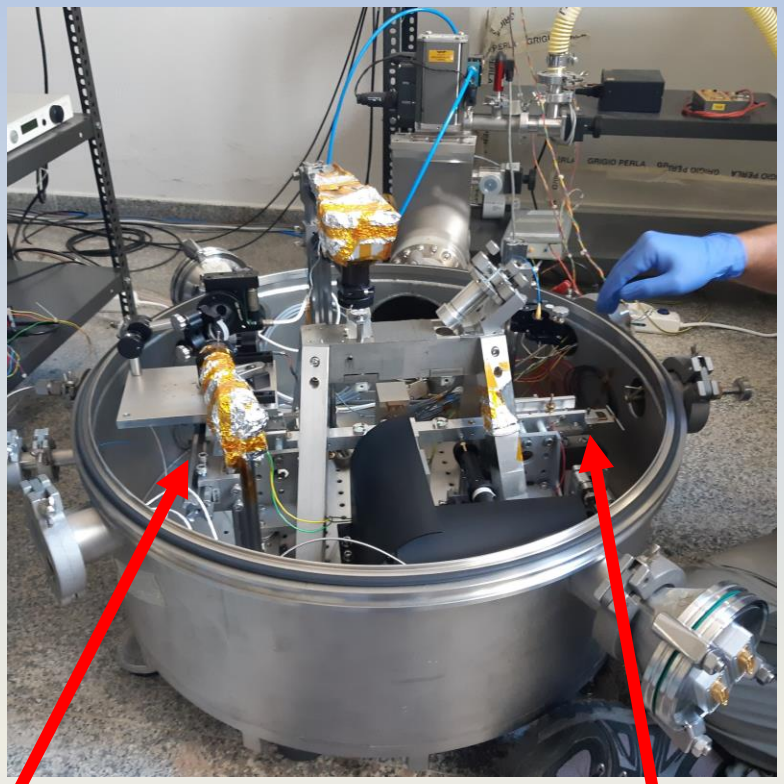


The tilt is read with a **Michelson interferometer**

The green ligth is an auxiliary optical lever used for initial alignment and high range control

The balance prototype

- Arm Suspended to ultra-thin joints
- Interferometric read-out
- Feed-back controlled with electrostatic and temperature actuators

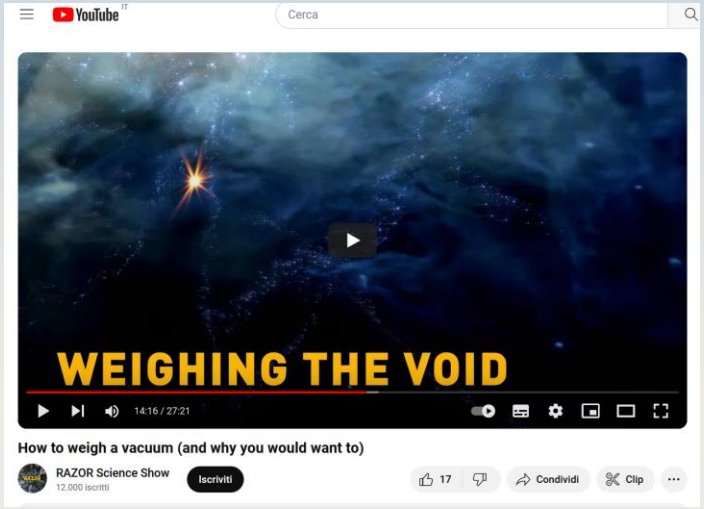


Brass (now Pb)

aluminum

Laser light green to facilitate alignemnts

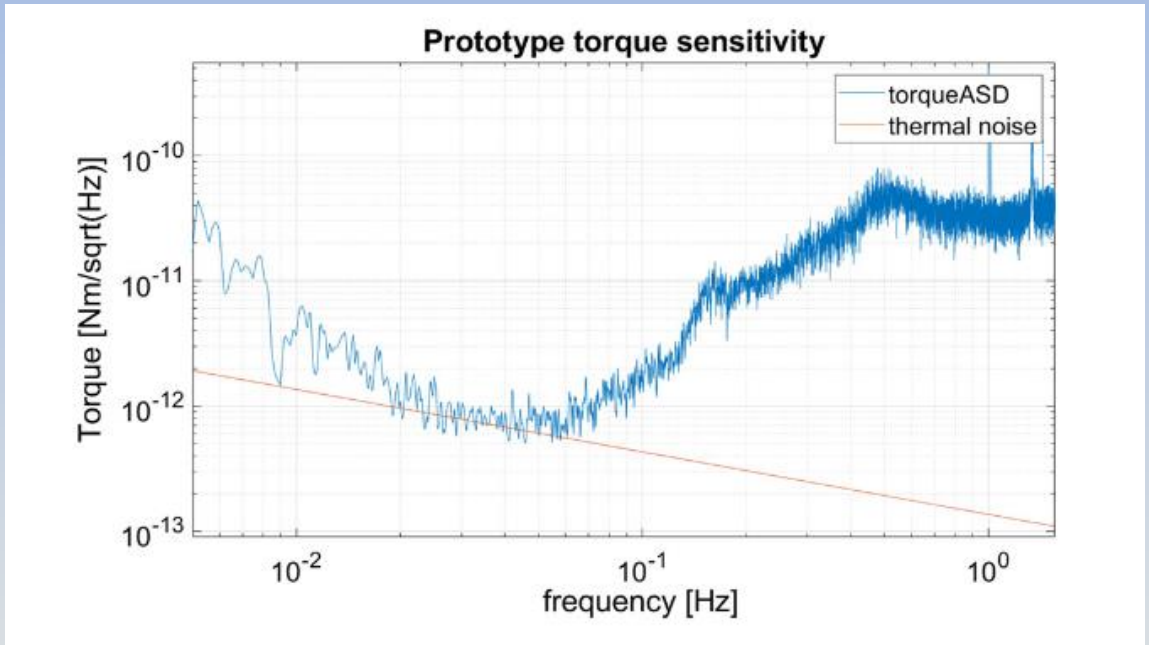
[How to weigh a vacuum (and why you would want to) (youtube.com)]



https://youtu.be/oWDZBUeBQzk

14.56 – GCNT

Prototype balance sensitivity results



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

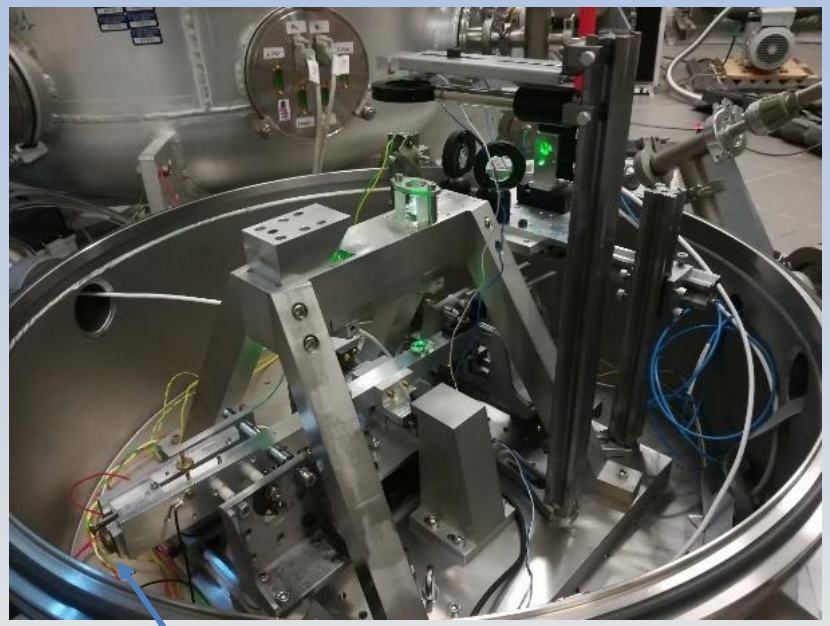
The prototype balance with thermal patches

Lessons Learned

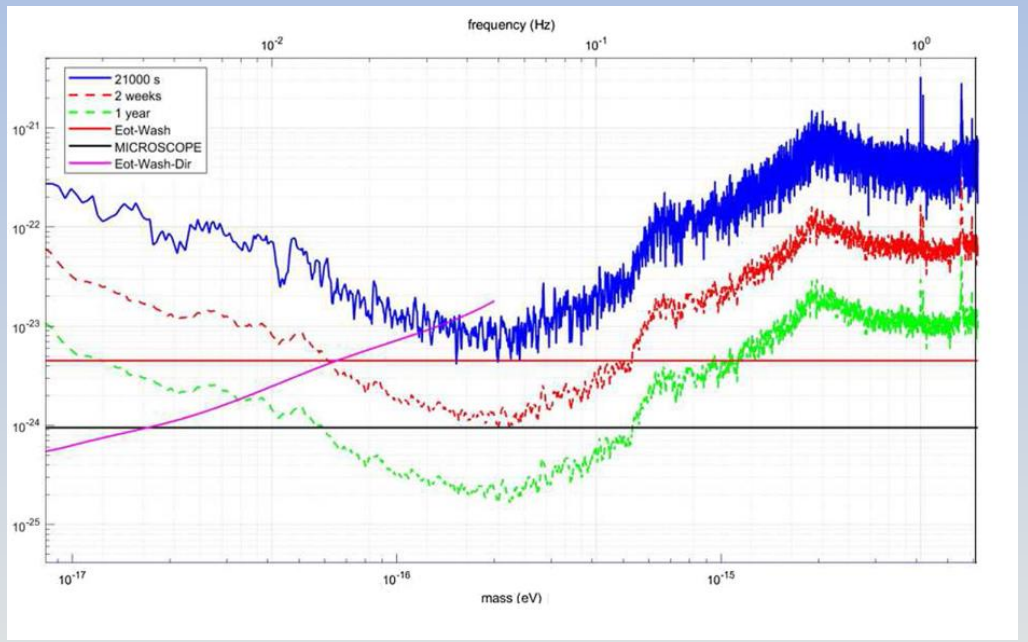
1) Verification of efficiency of optical read-out and control systems
2) Importance of low environmental noises (pumps, air conditioning, seismic noise)
3) Importance of environmetal temperature stability

B-L dark photon search results

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



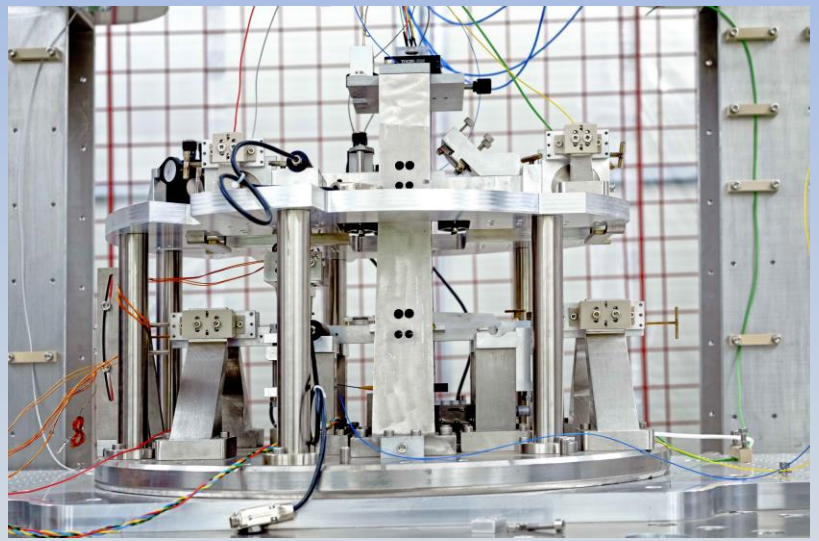
Position of the counterweight



Present constraints on B-L dark photon with 1 night integration time with Aluminum suspended sample and lead counterweight (blue) , and expected limits with 10 nigths (dashed red) and 100 nights (dashed green)

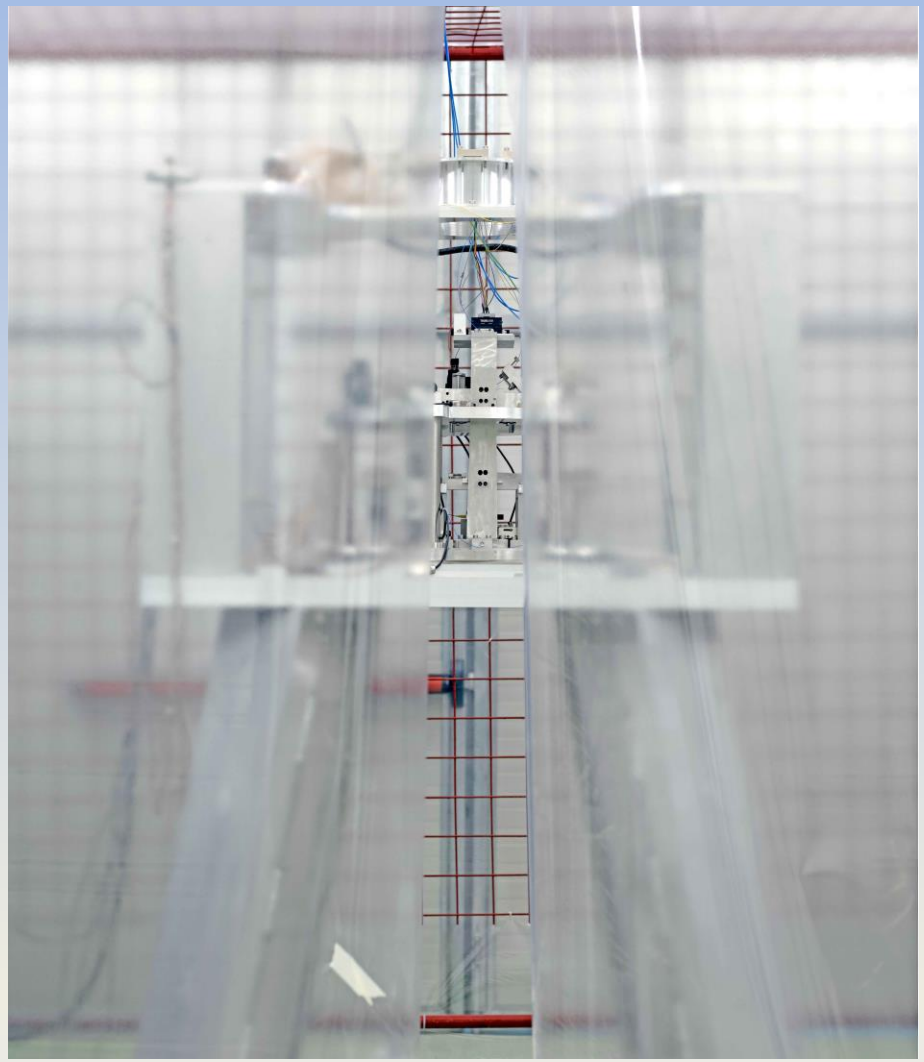
Notice that the EOT-WASH and MICROSCOPE are testing the eventual existence of the dark photon as a particle but they are not testing the fact that it is a dark matter component
On the other hand the direct search can not disprove the existence of such a particle but only tests if it is the constituent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

The Archimedes balance



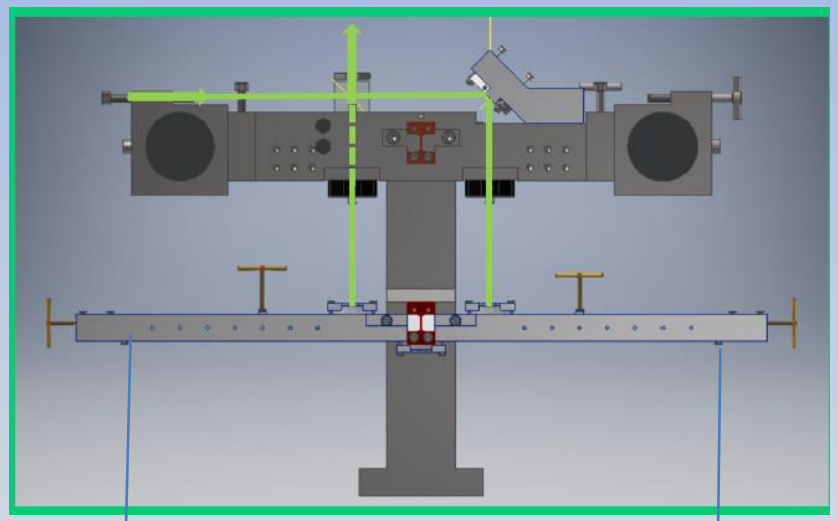
Upper stage of the balance

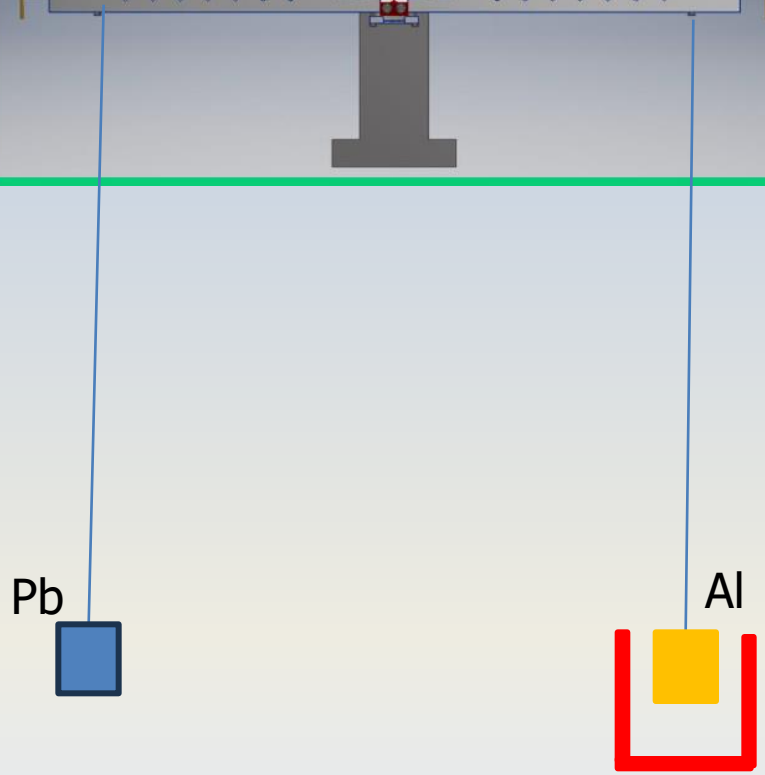
- Installed mechanics and actuation systems
- Optics and laser injection completed
- Sensors installed - wiring completed
- External control system installed
- Pre - Commissiong to start in two weeks
- Closing the chamber mid March



An artistic picture of the balance by Vincent Fournier

Scheme and realization



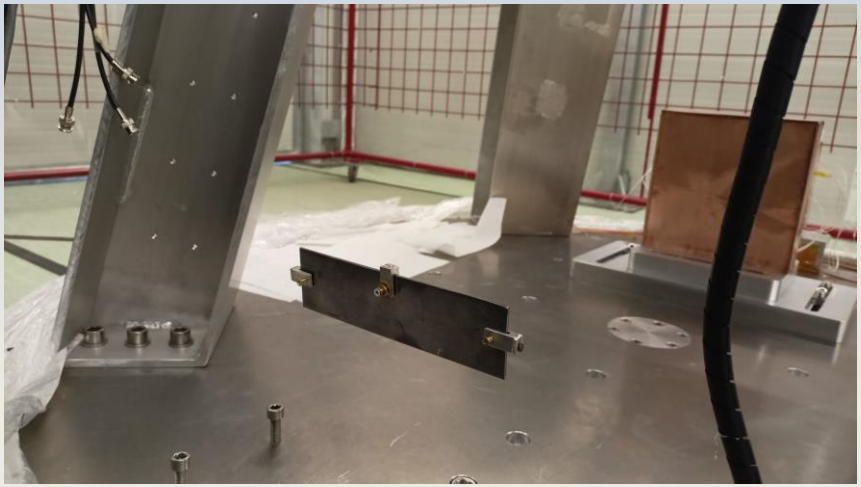


Thermal chamber

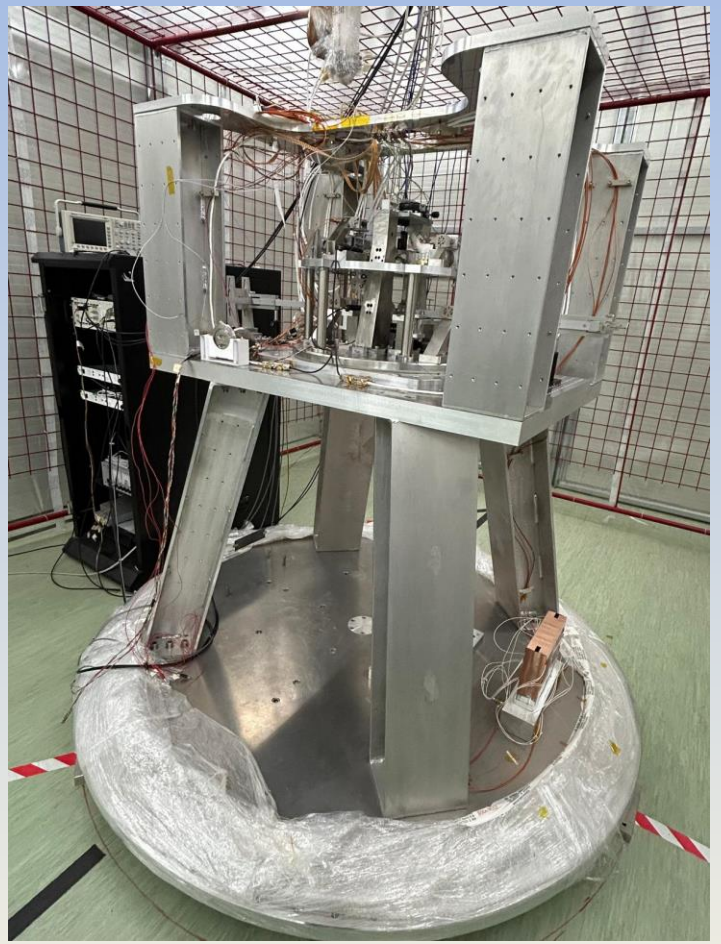
Initial mechanical tests with equal samples

The next months commissioning

- The commissiong of the next months will be performed at room temperature – the Al sample will be modulated in temperature to acquire experience
- Profiting of this time the samples have been chosen in Lead and Aluminum to perform a dark photon search

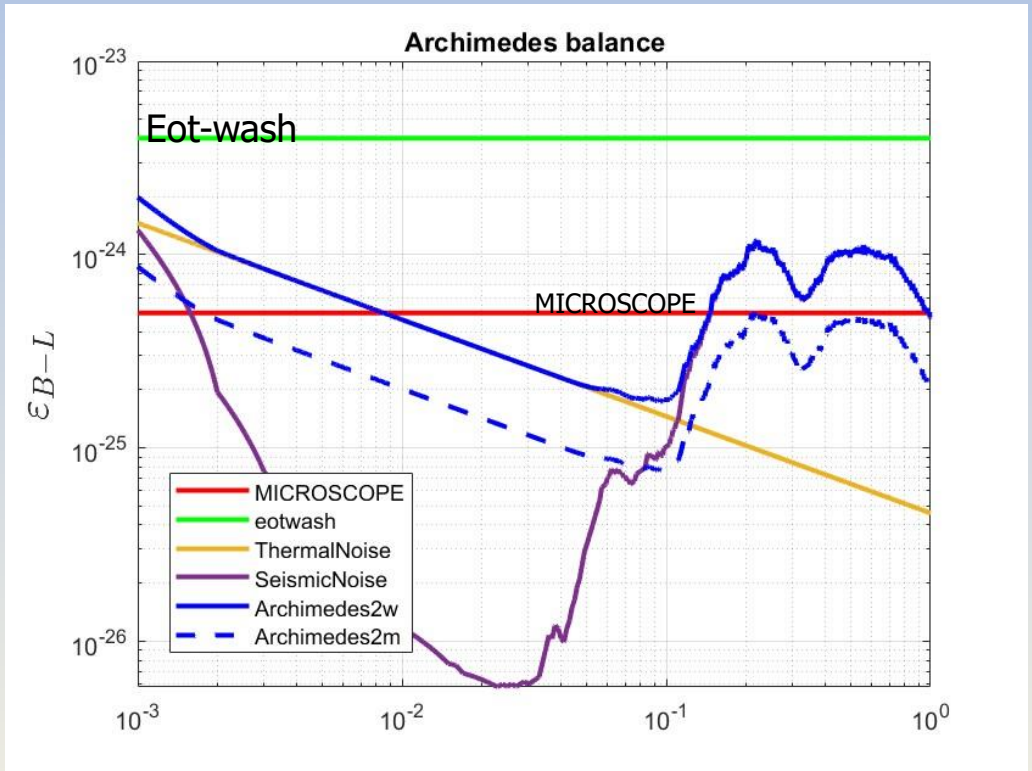


The Lead counterweight



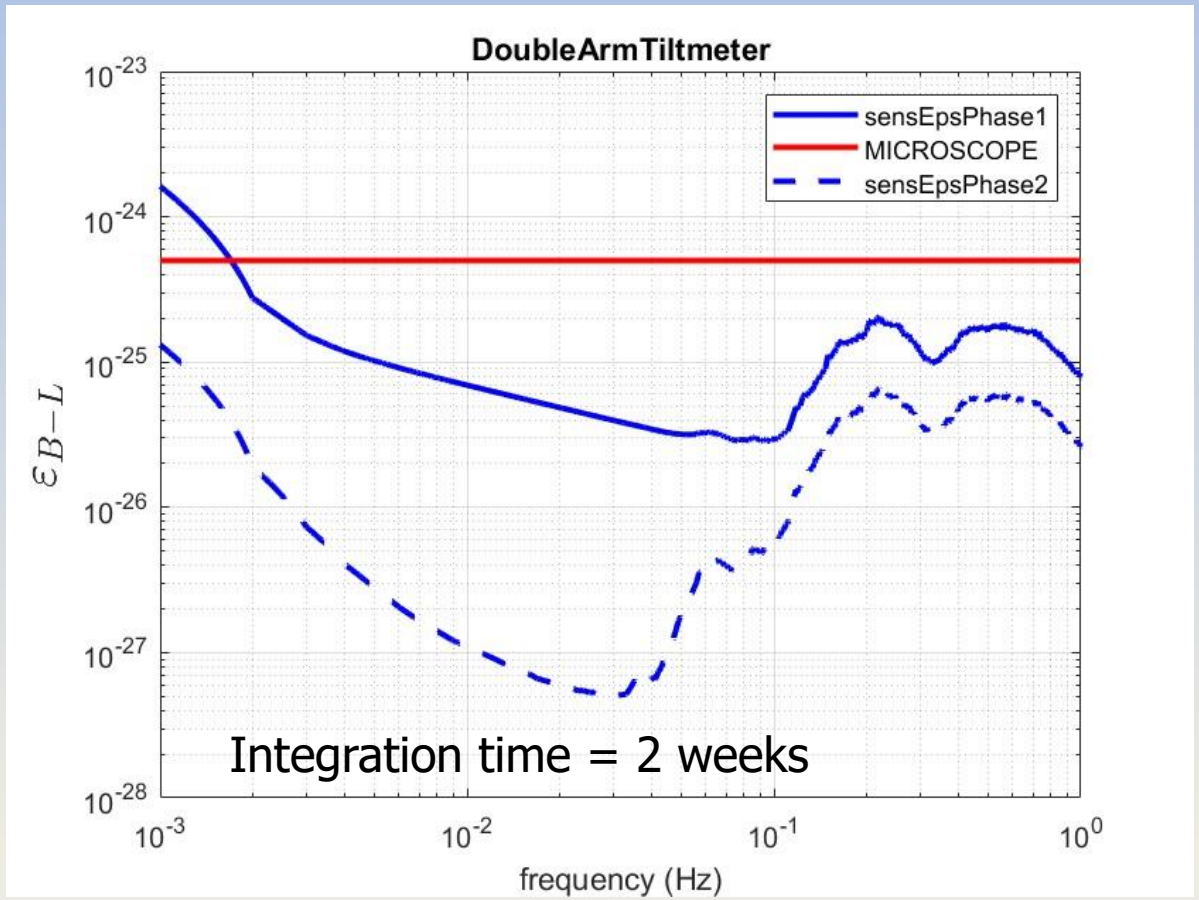
The Al sample in the thermal chamber

Expected sensitivity with present 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