Instrumentation for GW detectors

An overview

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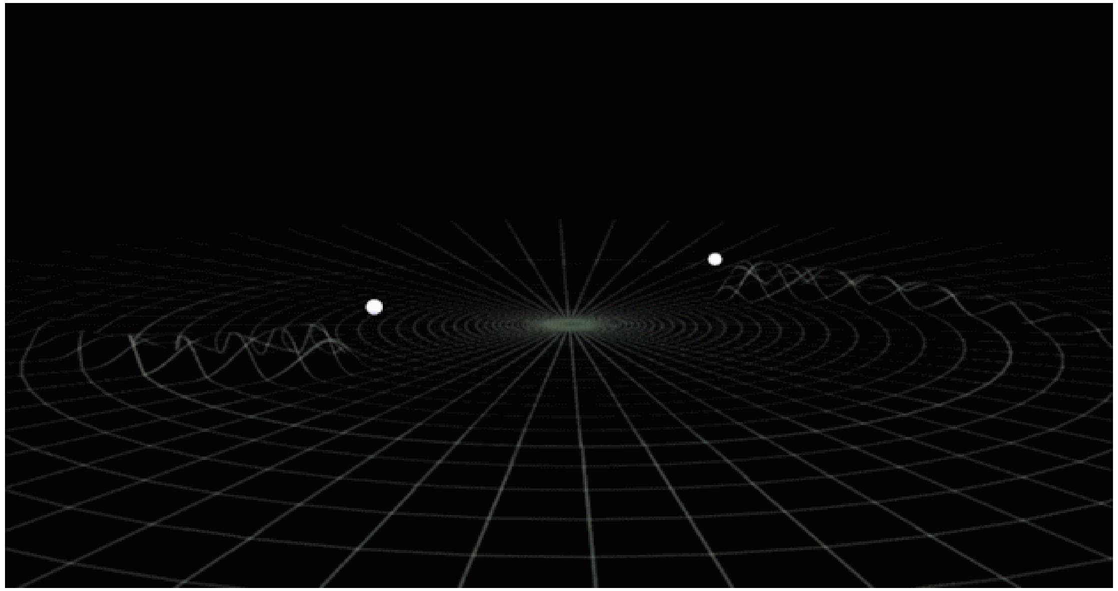
Université de Liège

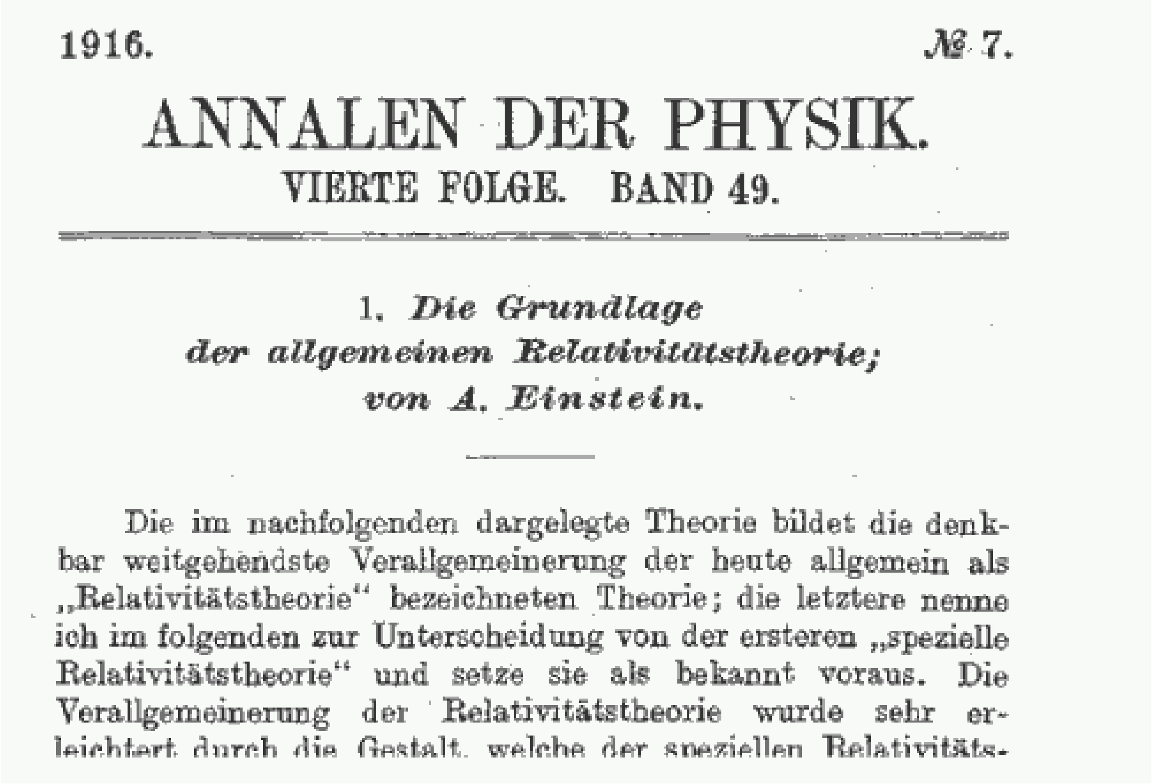
16th November 2023

Spoilers

- **What are gravitational waves?**
- **How can we detect them?**
- **How a detector works**
- **How we make it work**
  - Sensors
  - Actuators
  - The humans
  - The control room
- **The E-TEST project at ULiège**



What are GWs?



1916. № 7.

ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;*
von A. Einstein.

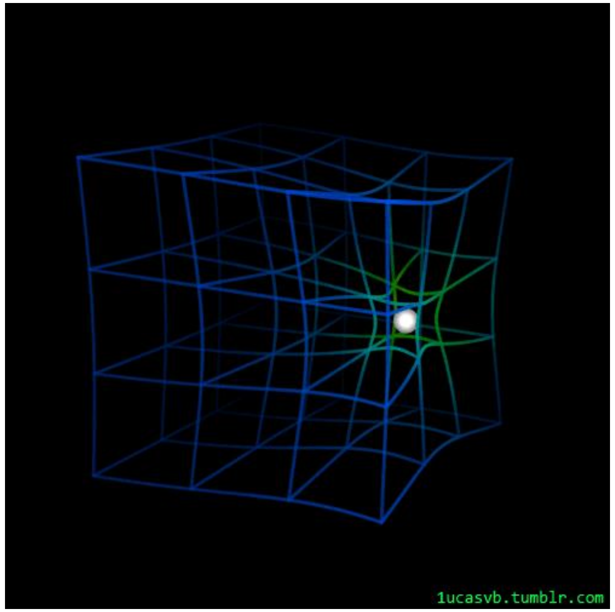
Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitäts-

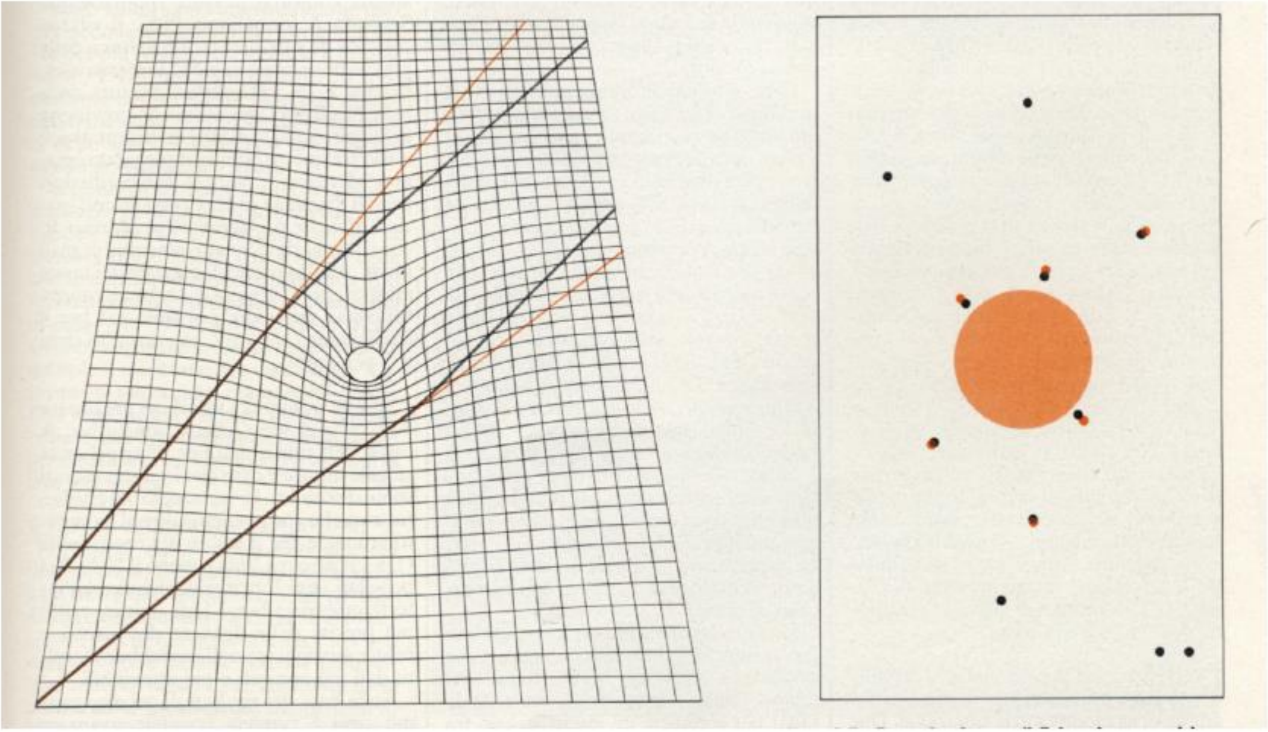
Gravitational waves are deformations of the spacetime due to *big, traumatic events in the Universe.*

Einstein theorized them in 1916, after proving that we live in a 4D universe (x,y,z,t) and that the geometrical system in which we live (the spacetime) can bend and deform.

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Gravity is *not* a force but a property of the spacetime, thanks to the possibility of deformation.

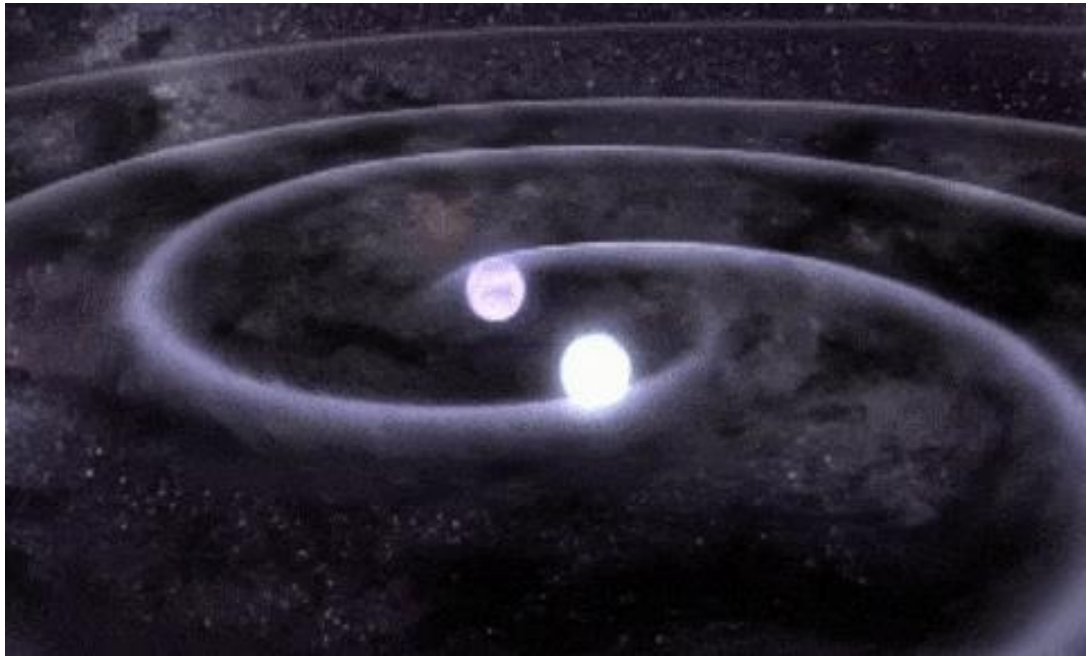


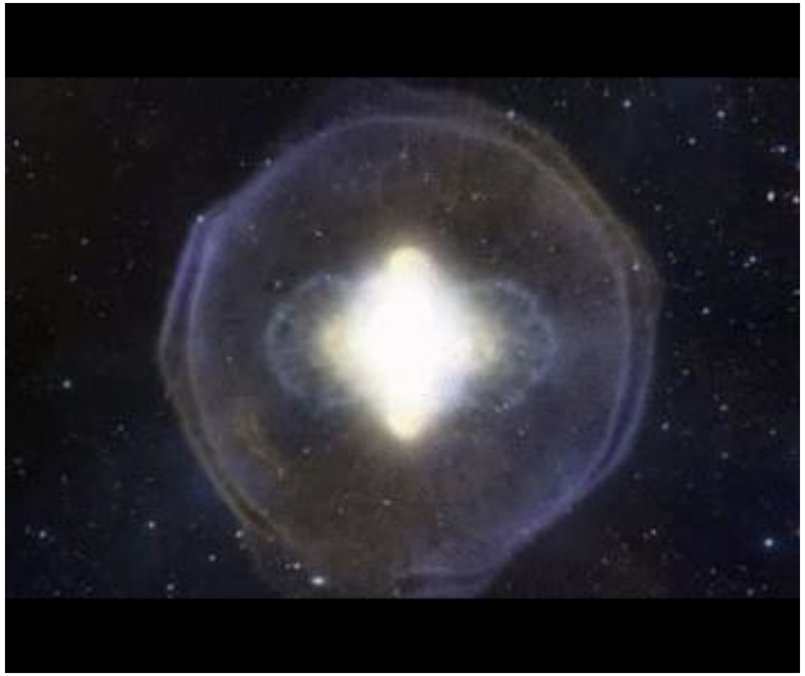


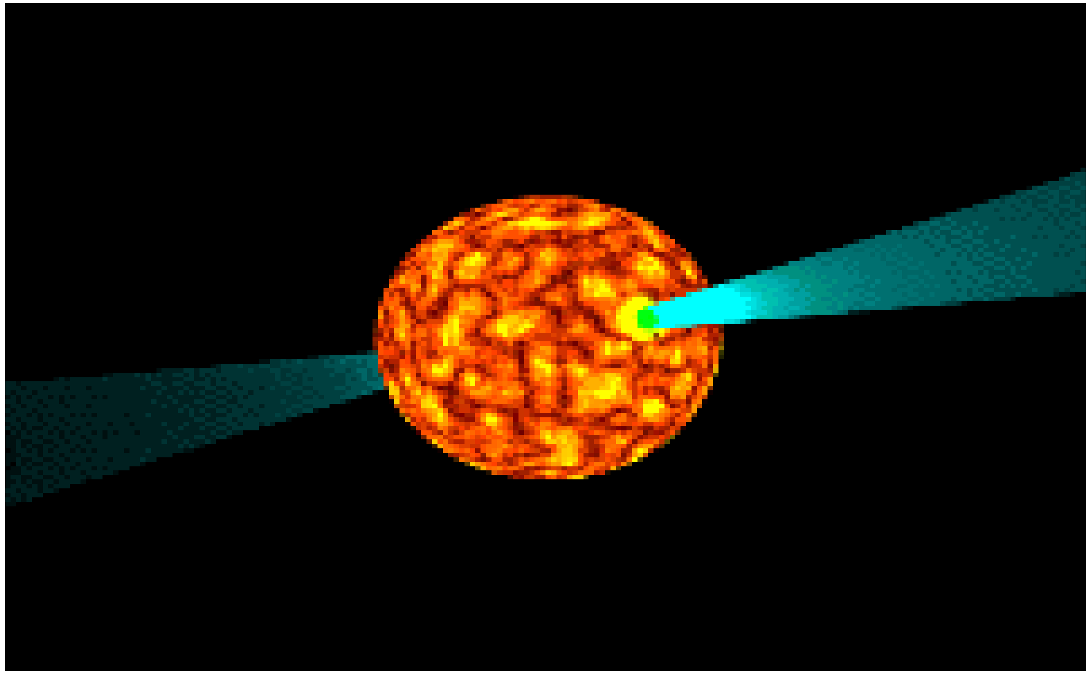
Ok, but what does that imply?

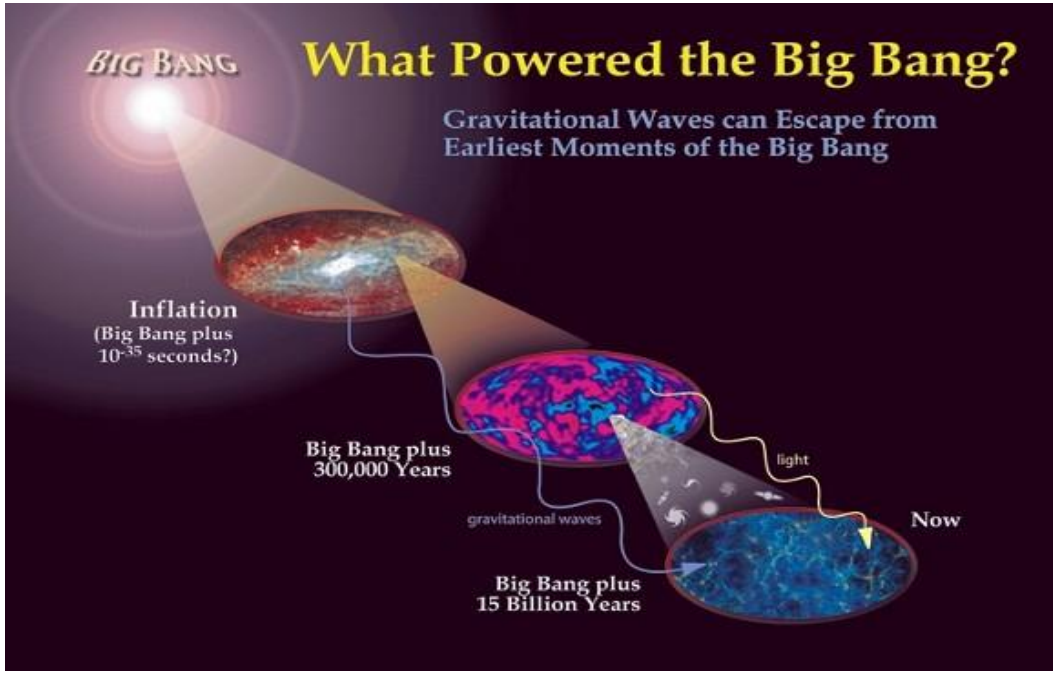
That the more massive the object, the bigger the deformation.
And what if the objects move?
And how massive is massive?
And how big is big?

What causes a GW generation?

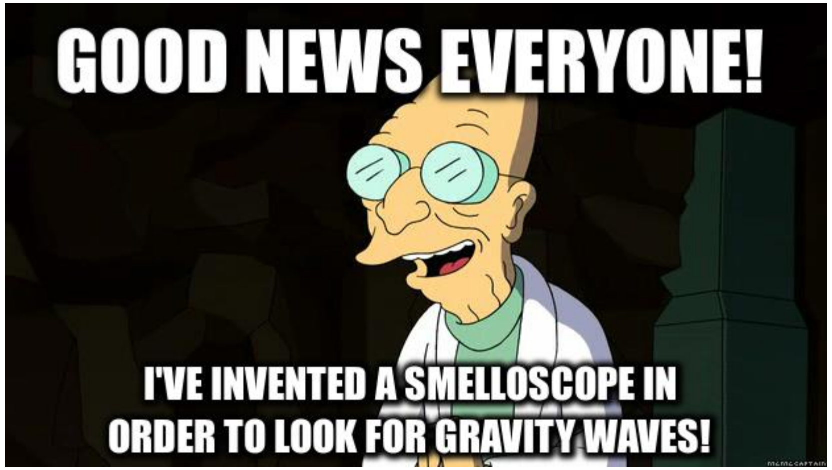







BIG BANG
What Powered the Big Bang?
Gravitational Waves can Escape from
Earliest Moments of the Big Bang
Inflation
(Big Bang plus
10^{-35} seconds?)
Big Bang plus
300,000 Years
light
gravitational waves
Now
Big Bang plus
15 Billion Years

How can we detect them?



'Listen! There they are again – echoes of the Big Bang. The beginning of creation!'

Nope.

The effect of a GW is a **deformation of lengths**.

This means that when a GW passes thru an object, this deforms in lengths (stretches and squeezes).

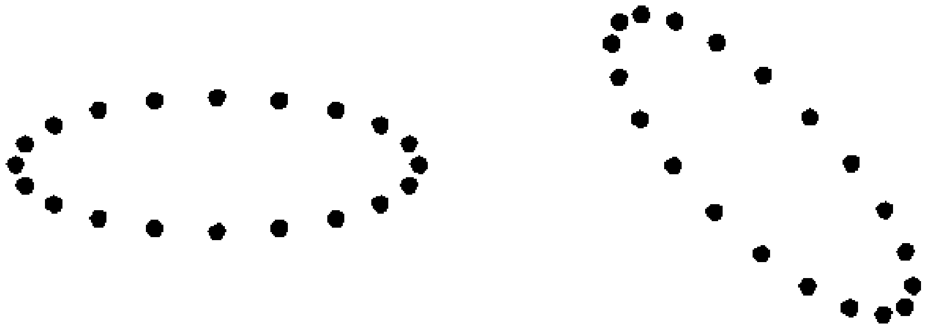
So what, we place a ruler and we measure how much the object changed? **Nope, again.**

The deformation induced by the GW passage is around 10e-18 m.

For reference, **the H atom is about 10e-12 m…**

Einstein itself did not believe they could be ever measured…

How a detector works



We cleverly opted for an *indirect measurement*:
What we need to measure is a **length *s* (in m).** And we know that ***s = v x t*.**

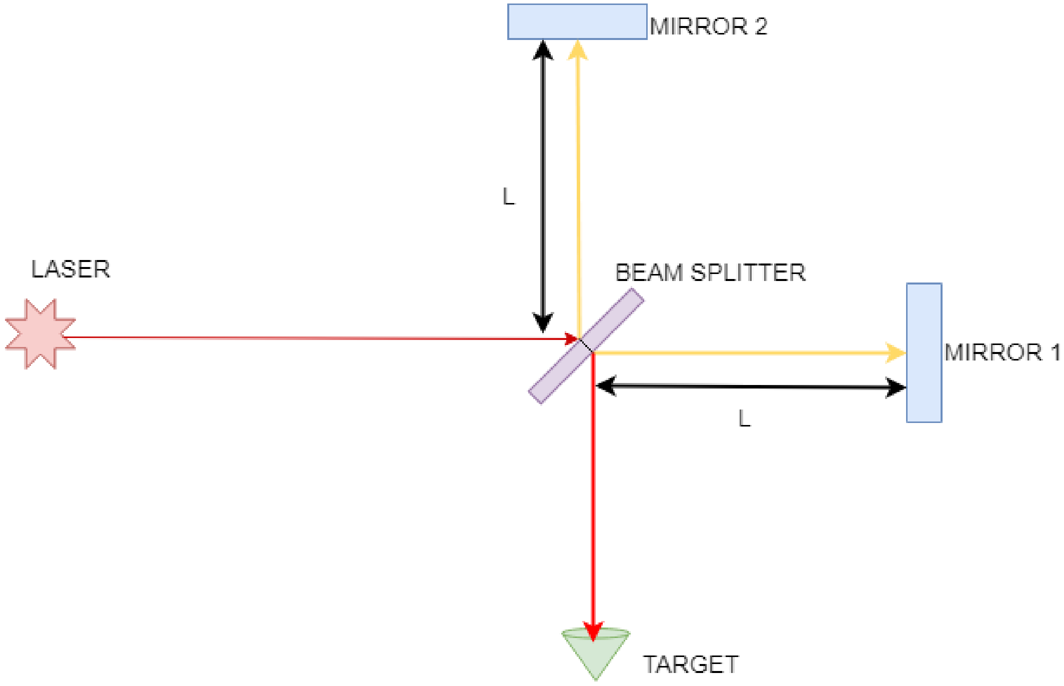
If we manage to keep ***v = const*.** and find a way to measure the **time passing during a GW event**, we could calculate *s*!

Amazing, let's do it!

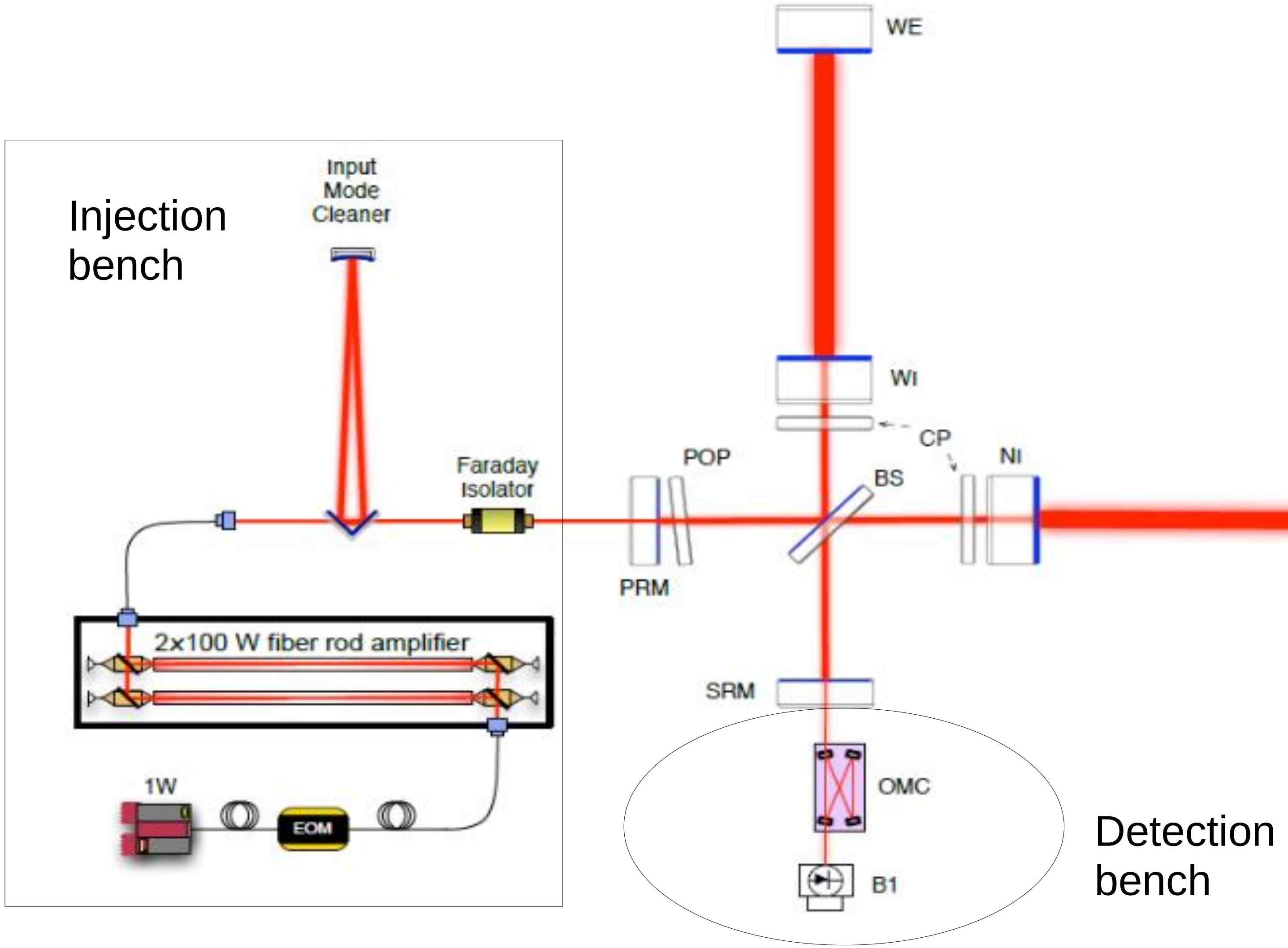
What can go at constant speed? **Light in vacuum**. Let's use that.

<u>How can we measure that it took a different time to go from here to there?</u>

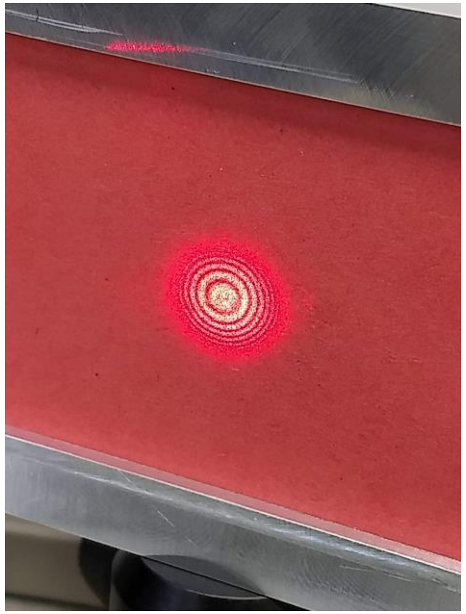
There is a nice instrument, known since end of 1800s, that can do the trick: the **Michelson Interferometer**.



Let’s complicate a bit



This is interference



We use **the deformation of the arm lengths** to look at the fringes, **moving thanks to the different travel times**. This provides a **phase shift** between beams that can be recorded.

From there, we can reconstruct the wave form and the event that generated it.

Let’s make it horror

Each piece is a *chamber*.

Inside each chamber there is instrumentation dedicated to different features of the detector.

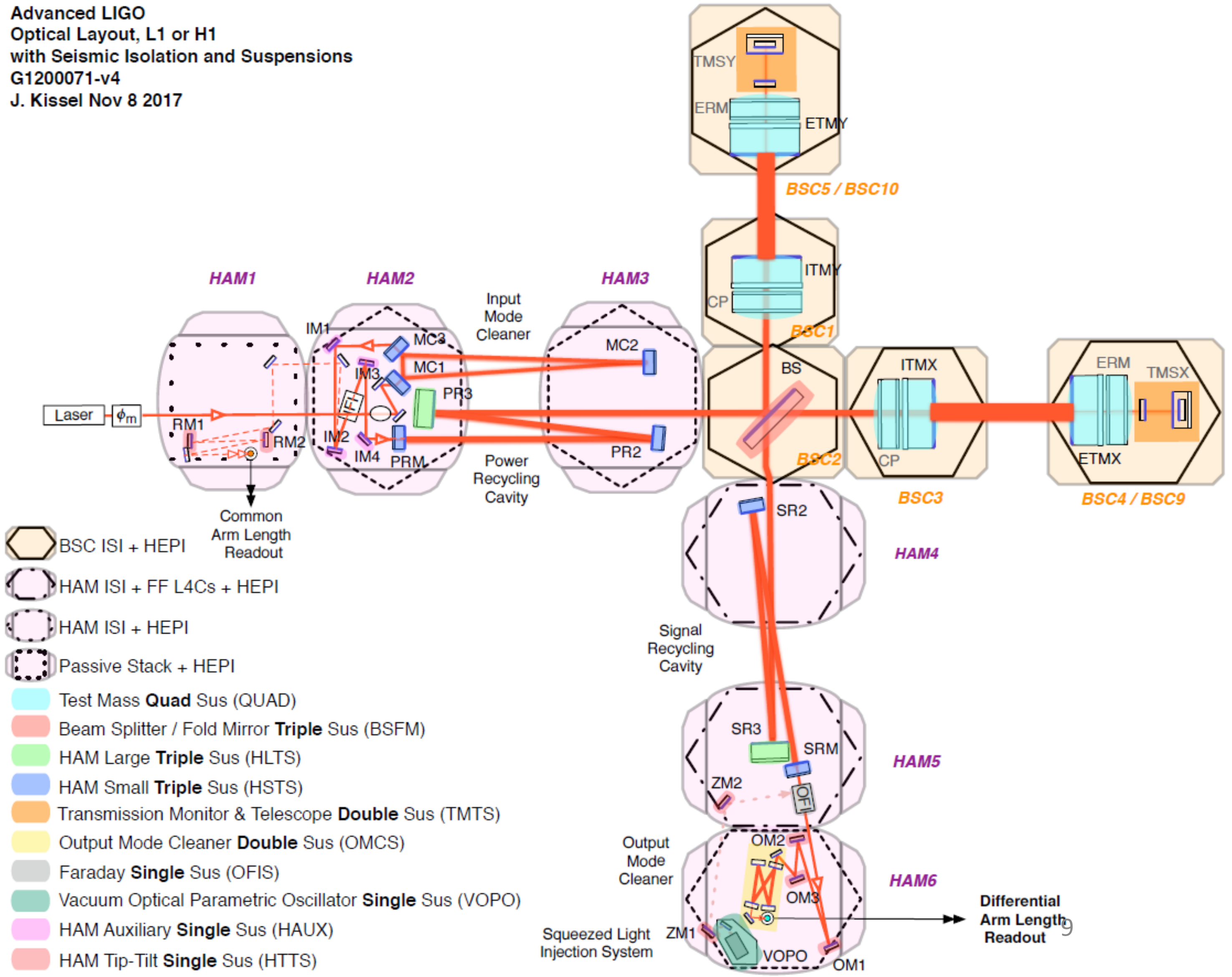
Each line of chamber is enclosed in a <u>tube for vacuum</u>.

Each tube is **3 or 4 km long**.

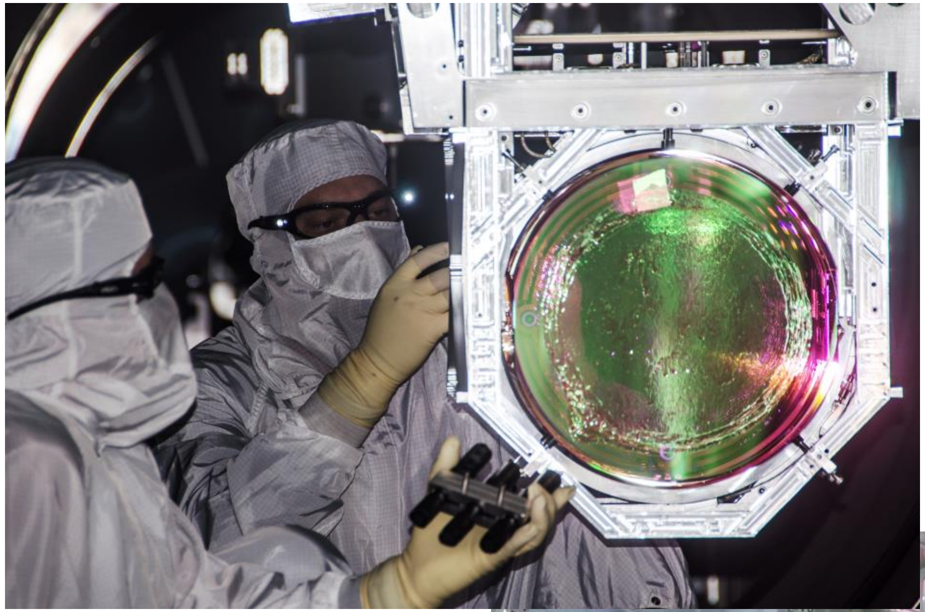
$$\Delta\phi_{gw} = \frac{4\pi h L}{\lambda}$$

This is why…

Where **h ≈ 10e-21** is the **amount** that distances are stretched or compressed by a passing GW, relative to the original length.

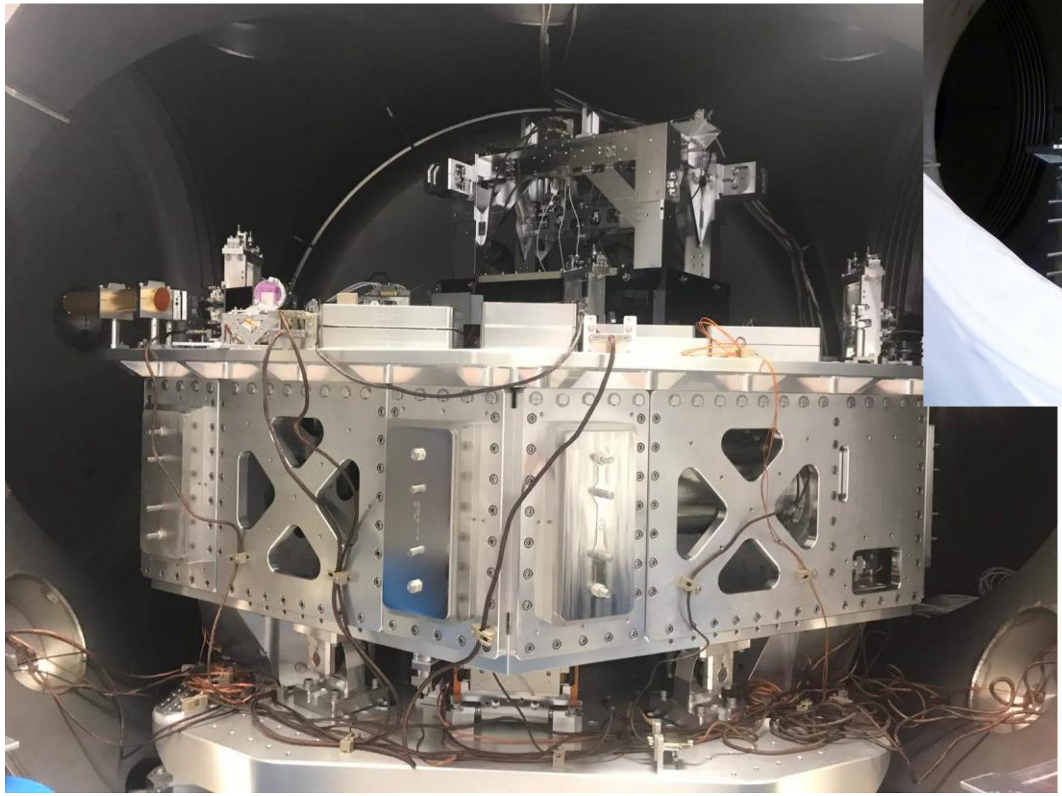


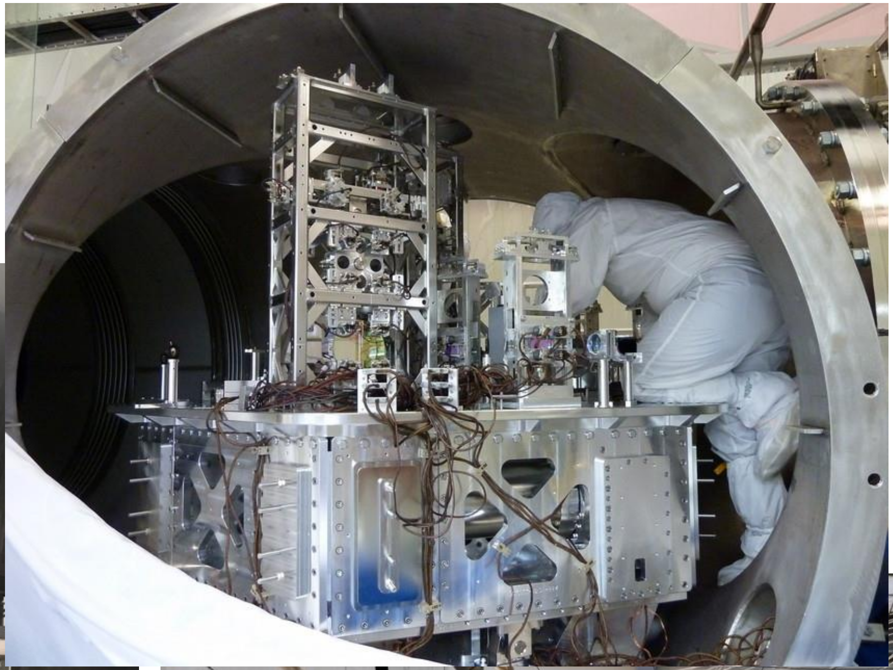
How it looks like in pics

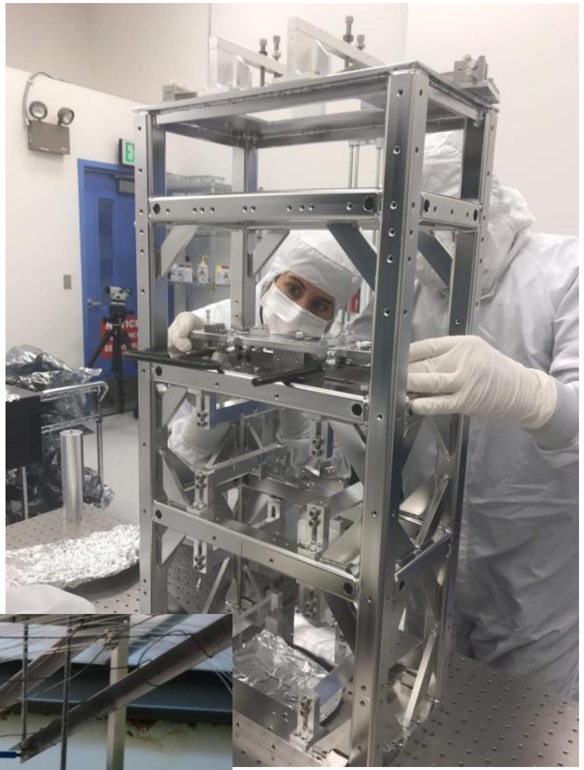


Credits: LIGO and Virgo collaboration

And inside…







Credits: LIGO and Virgo collaboration
University of Western Australia

How we make it work

Interferometers are incredibly challenging instruments to drive and this requires the *contribution of people with the most variety of competences.*

This is because they need to drive **sensors and actuators**, possibly without breaking anything and without getting in conflict with other parts of the instrument working at the same time.

How many sensors/actuators are involved? Hard to guess, since every sub-group is expert of their own section of the instrument…

Sensors

There are several conditions to monitor in an interferometer:

- seismic motion and vibrations
- temperature and thermal effects
- laser performance and stability (power, modes, temperature, pressure)
- quantum effects
- gravity effects
- optical deformations

I will focus here on the section about seismic sensors.
Happy to give contacts if interested in other sections

Seismic isolation

Seismic noise is one of the most important affecting the detector.
This is because the smallest vibration can provide **fringe moving and spoil a measurement**.

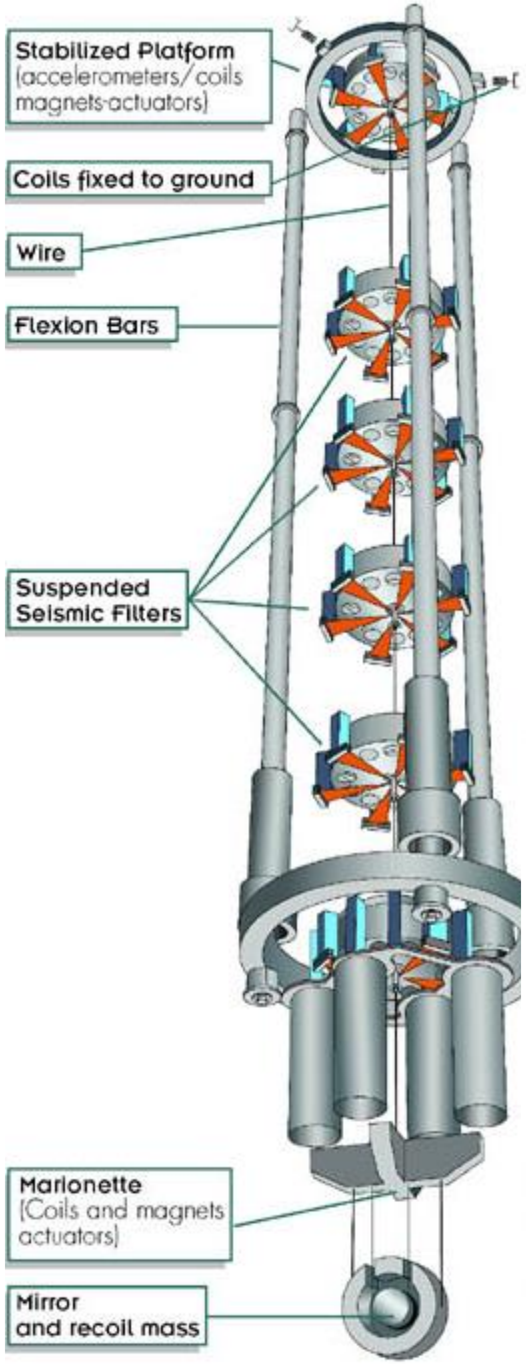
This is done in *passive and active ways.*

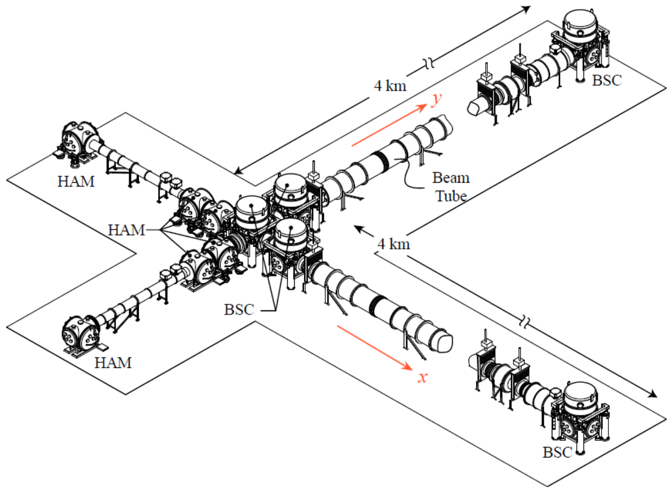
Virgo detector opted for a fully passive way, using a multi-level pendulum.

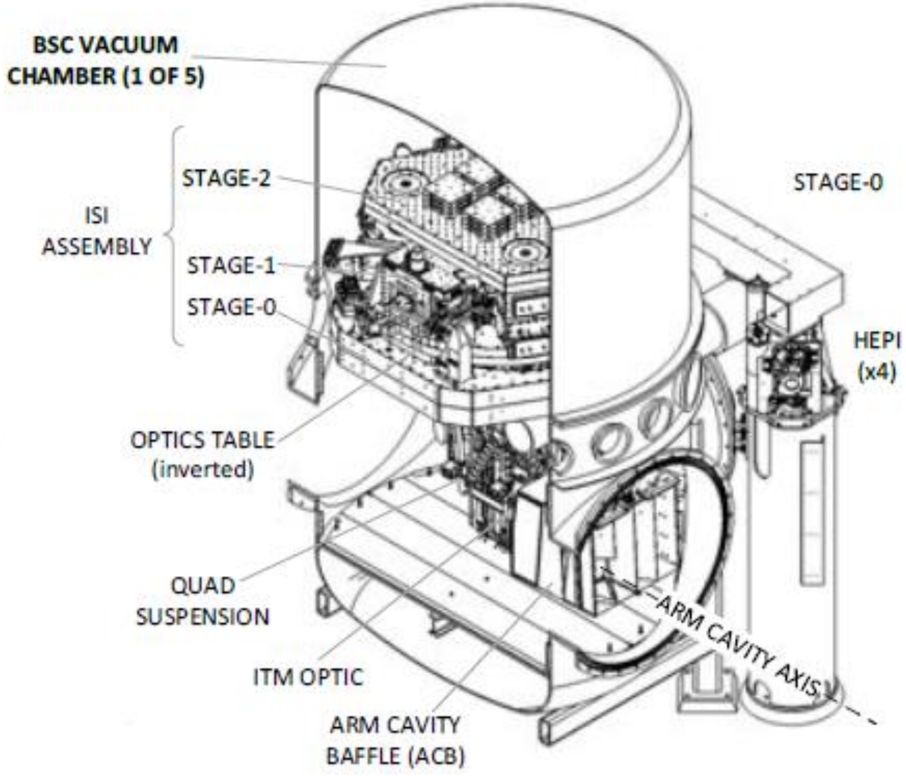
LIGO opted for active and passive ways, using a small pendulum and an active platform.

Studies at ULiege for hybrid options ongoing…

Credits: LIGO and Virgo collaboration

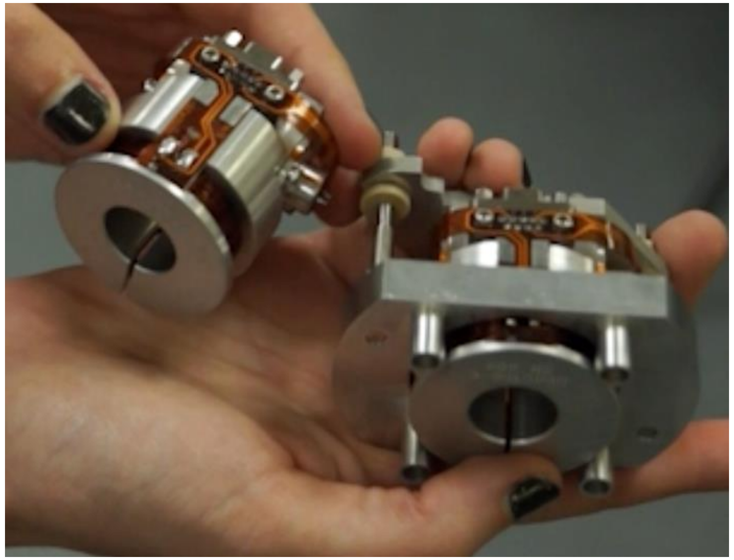




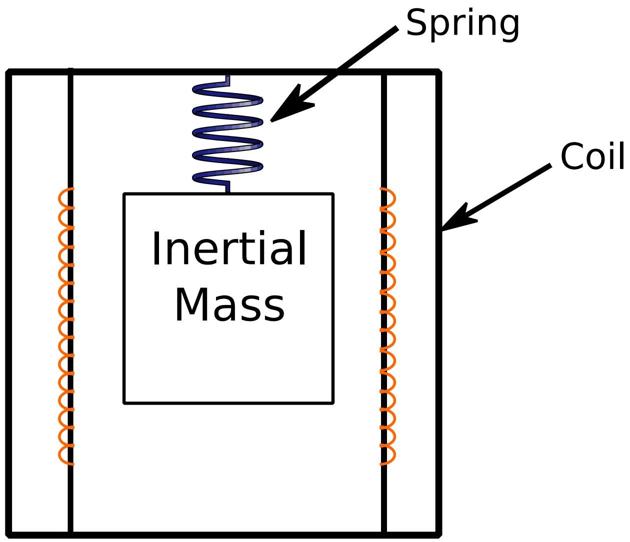


Credits: LIGO and Virgo collaboration

Displacement sensors

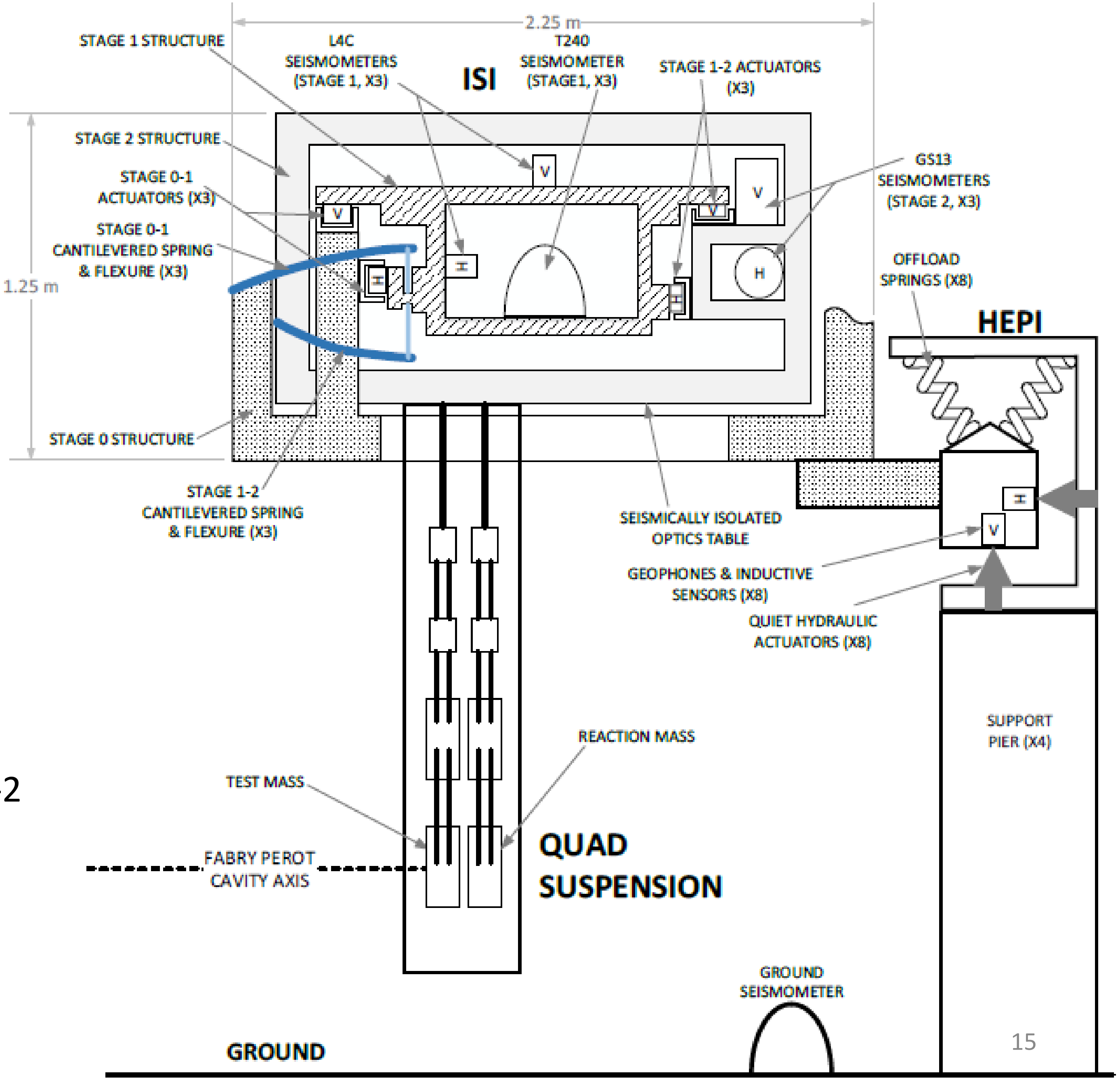


Inertial sensors



Examples include

- Geotech GS-13
- Streckeisen STS-2
- Sercel L-4C
- Trilium T240

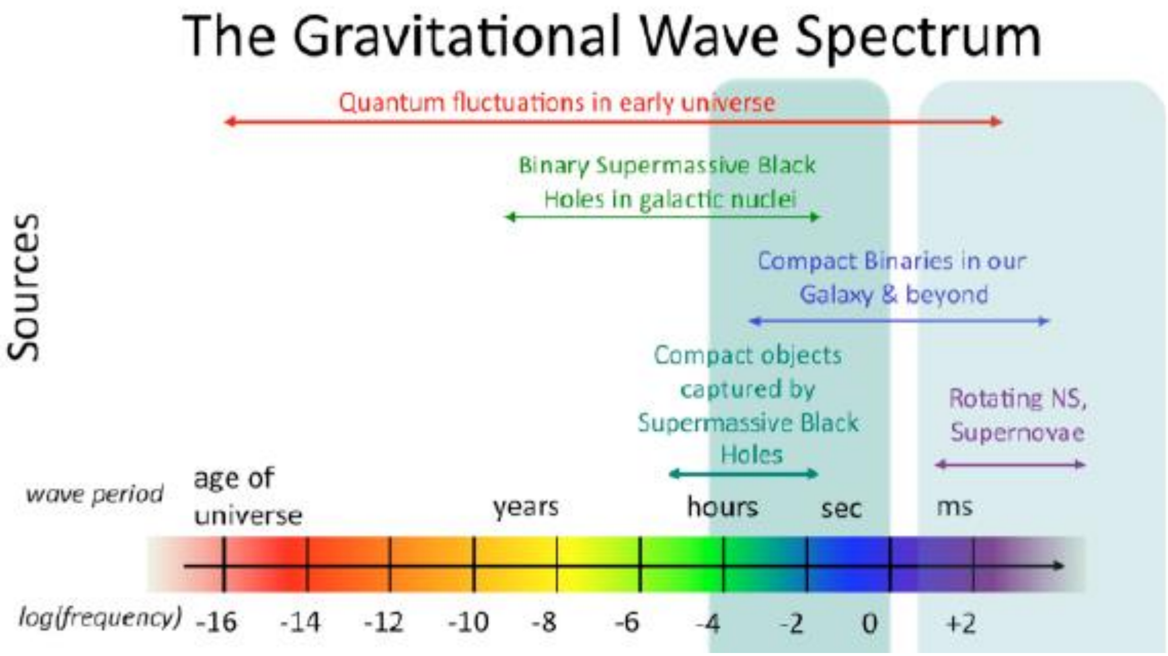


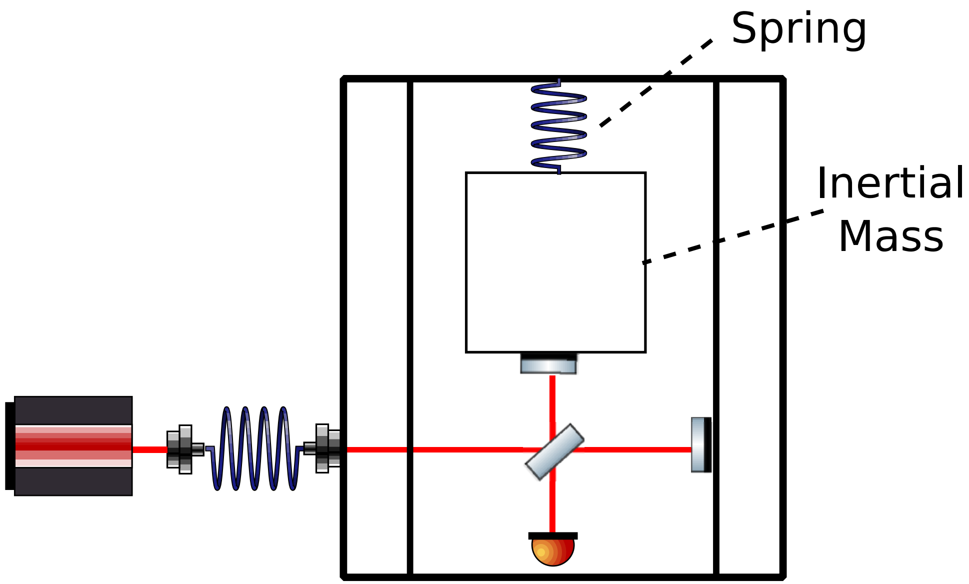
A lot of new science and engineering to improve the inertial sensors below 1 Hz!

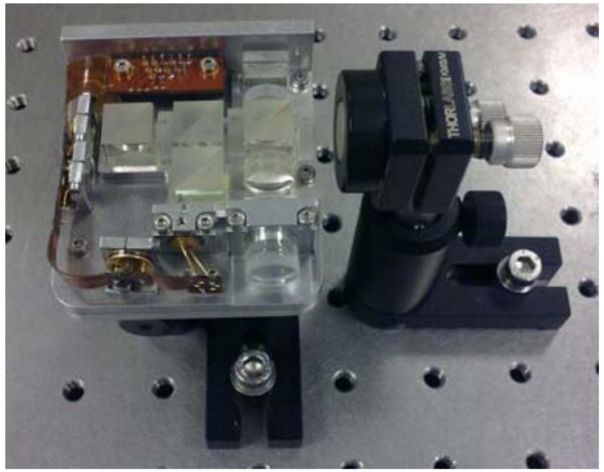
The technology chosen is *compact interferometry*.

This idea is under development in many research labs and it provides sensitivity down to 10mHz and 100 Hz.

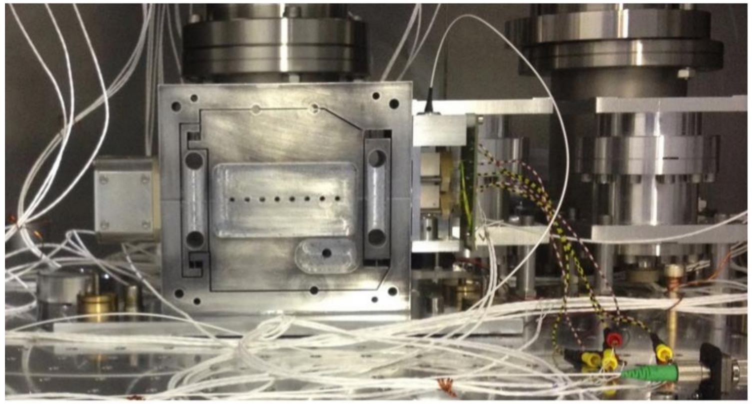
We are interested in those frequencies because **the detectors are blind there**, where instead they could detect several interesting objects



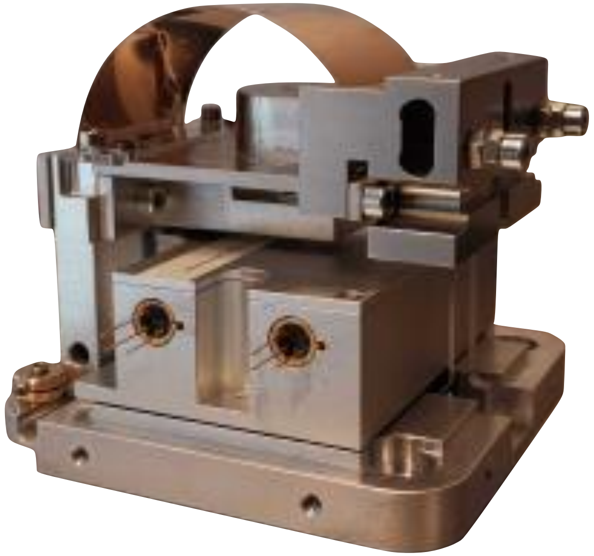




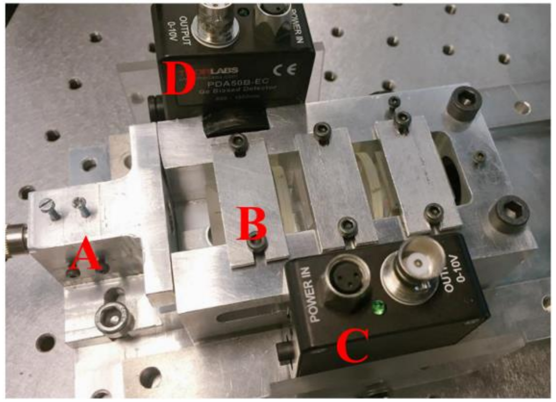
Aston (2011)



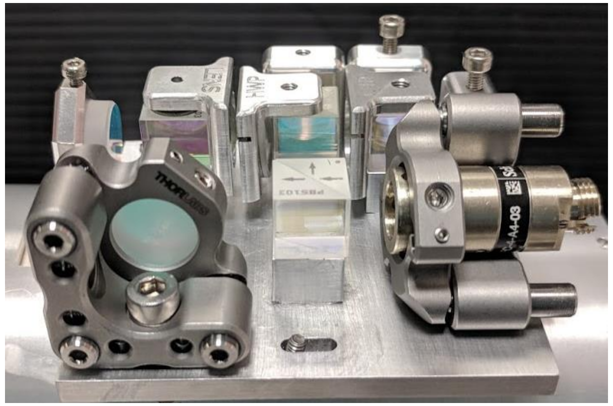
Van Heijningen (2018)



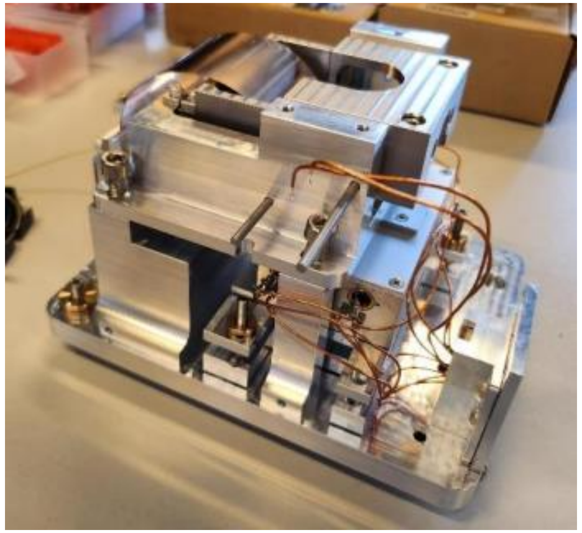
Amorosi, Amez-Droz – Uliege 2023

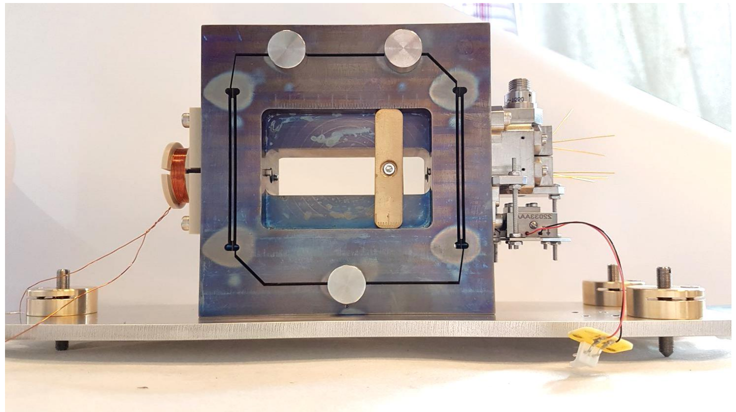


Ding (2018)



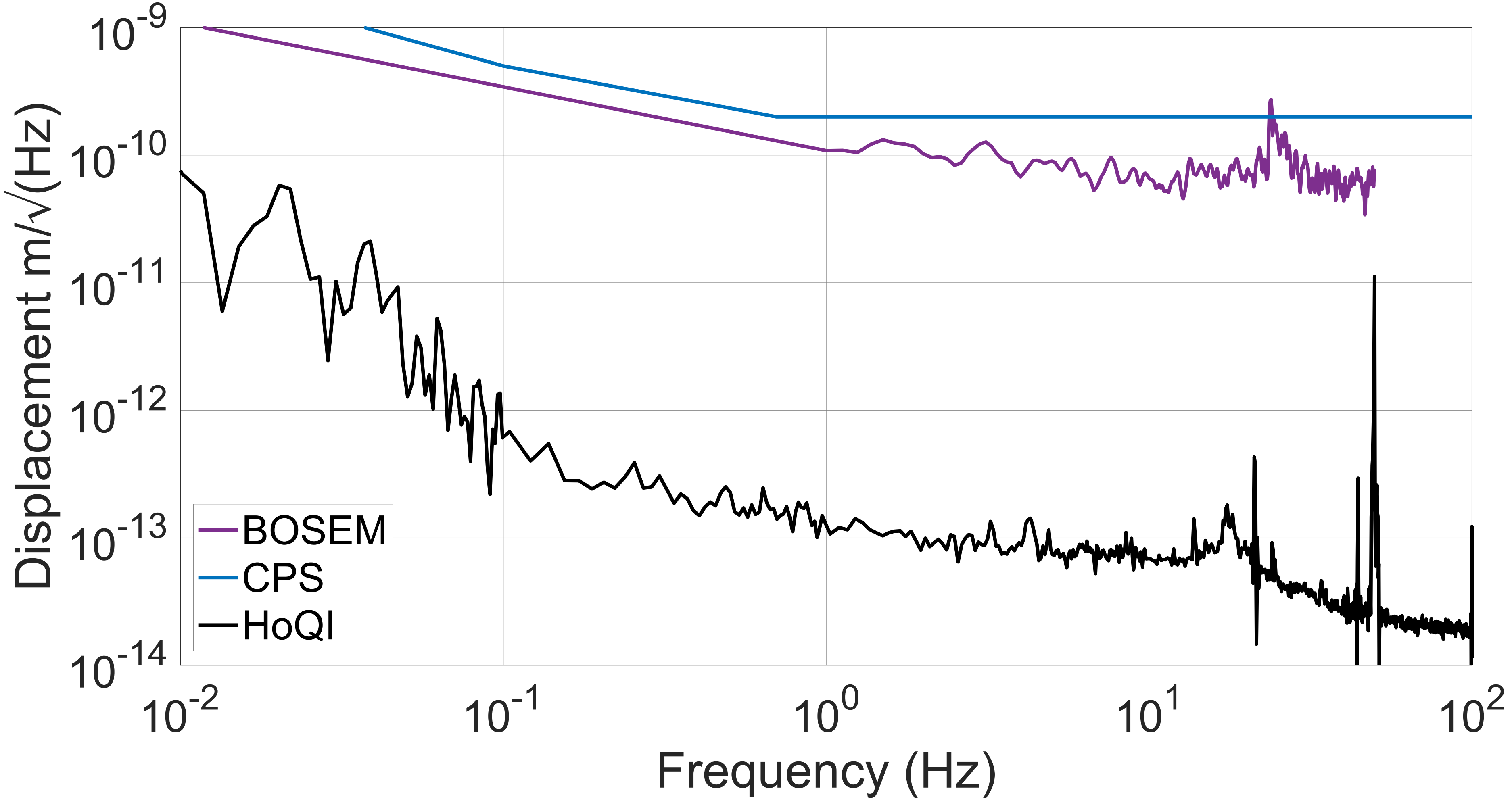
Cooper (2018) - HoQI





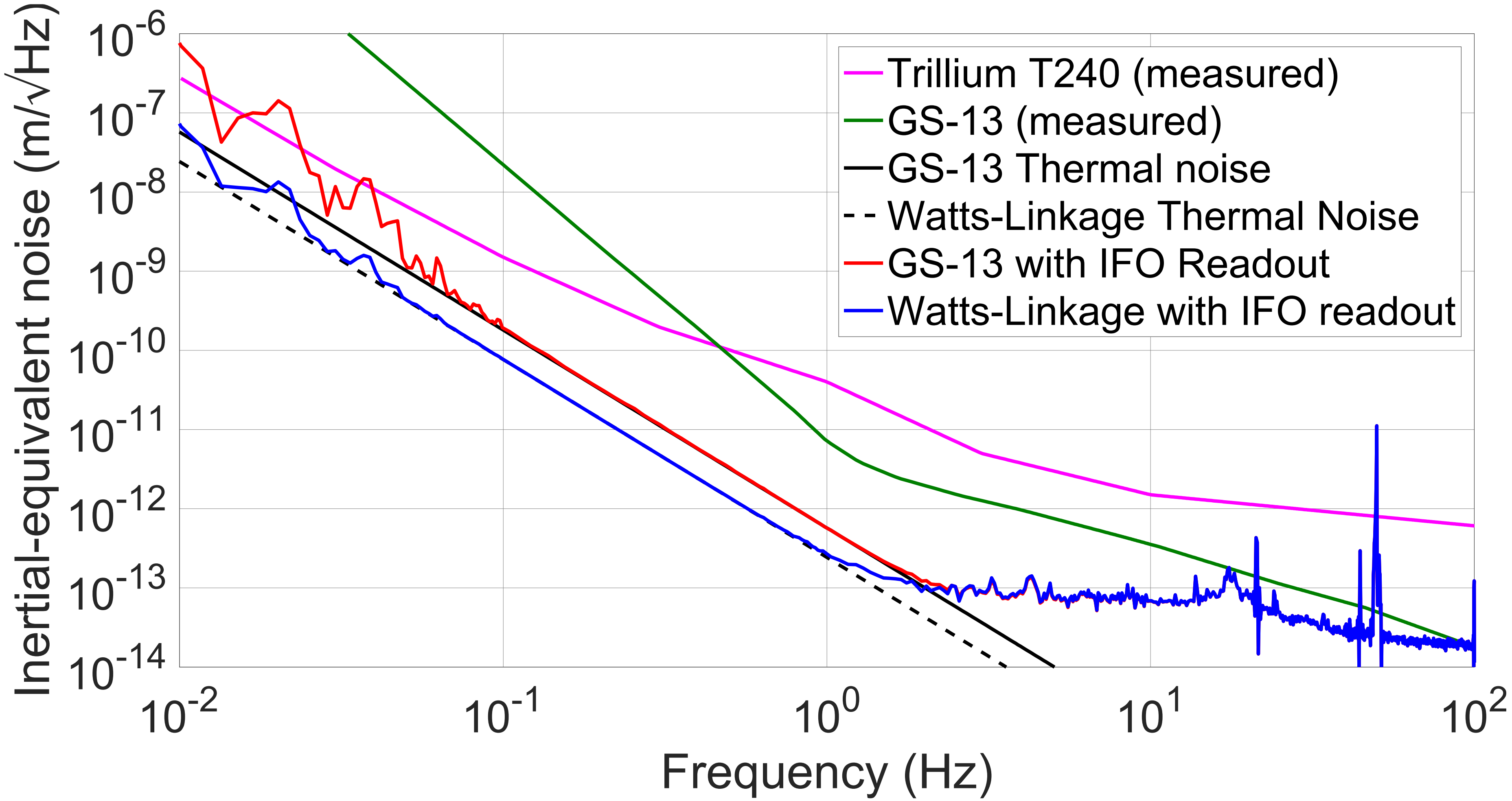
Zeoli – Uliege 2023

This is an example of better performance of interferometric sensing (HoQI) applied to displacement sensors, compared to nominal sensors.
Study from University of Birmingham (UK).



Credit: Dr. Sam Cooper

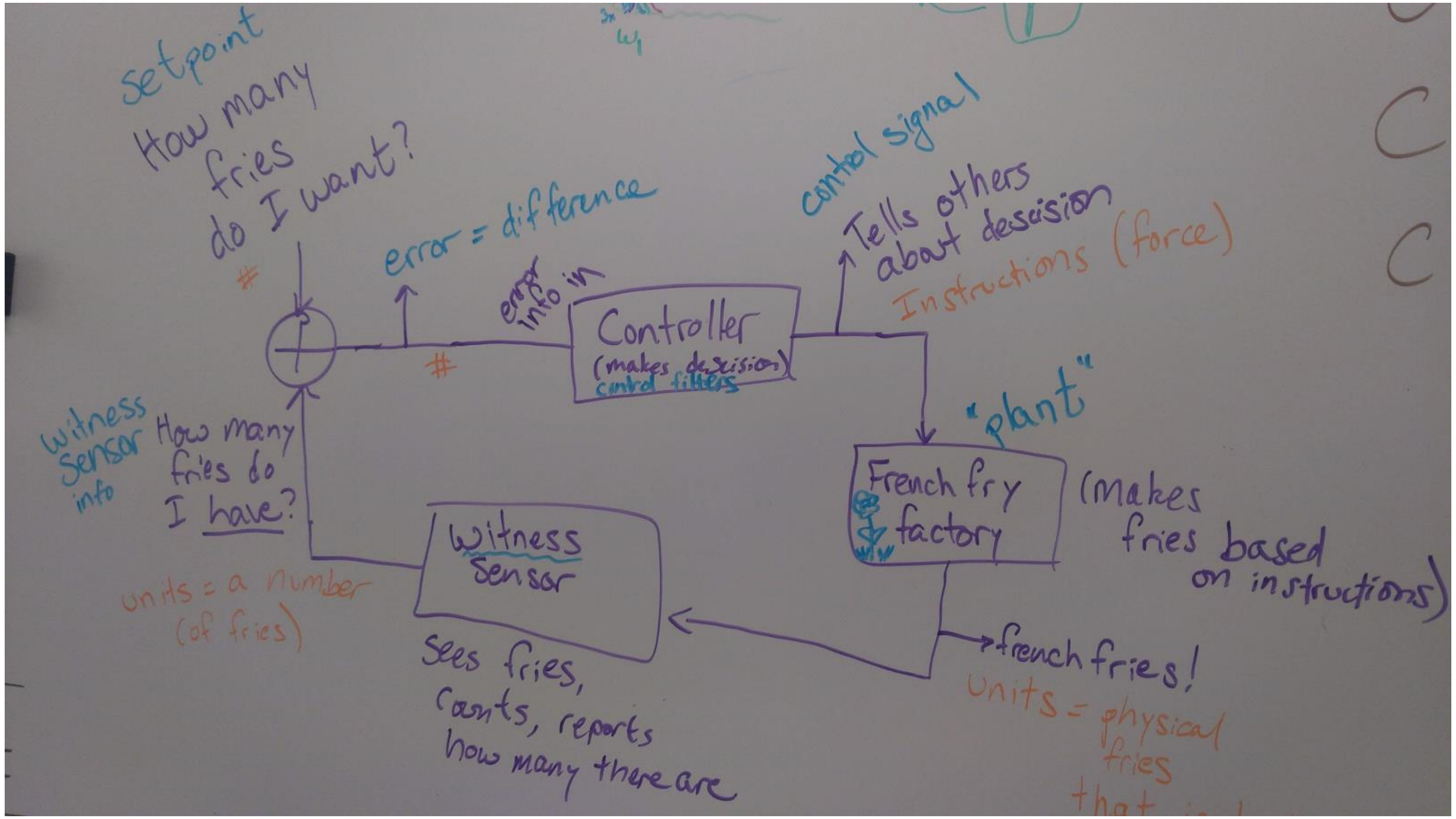
This is an example of better performance of interferometric sensing applied to inertial sensors, compared to nominal sensors.
Study from University of Birmingham (UK).



Credit: Dr. Sam Cooper

Actuators

The majority of the sensors is pared to a control loop for **noise suppression.**

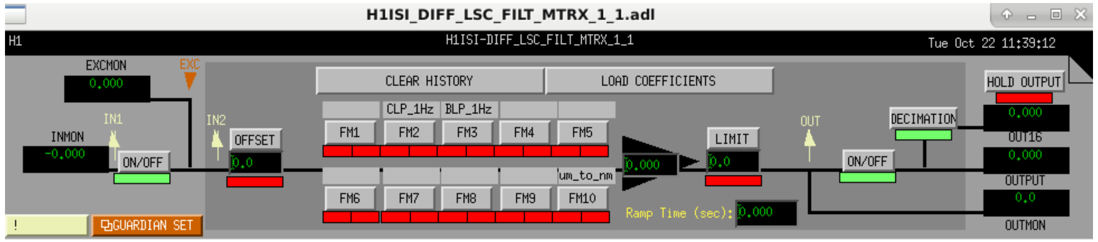


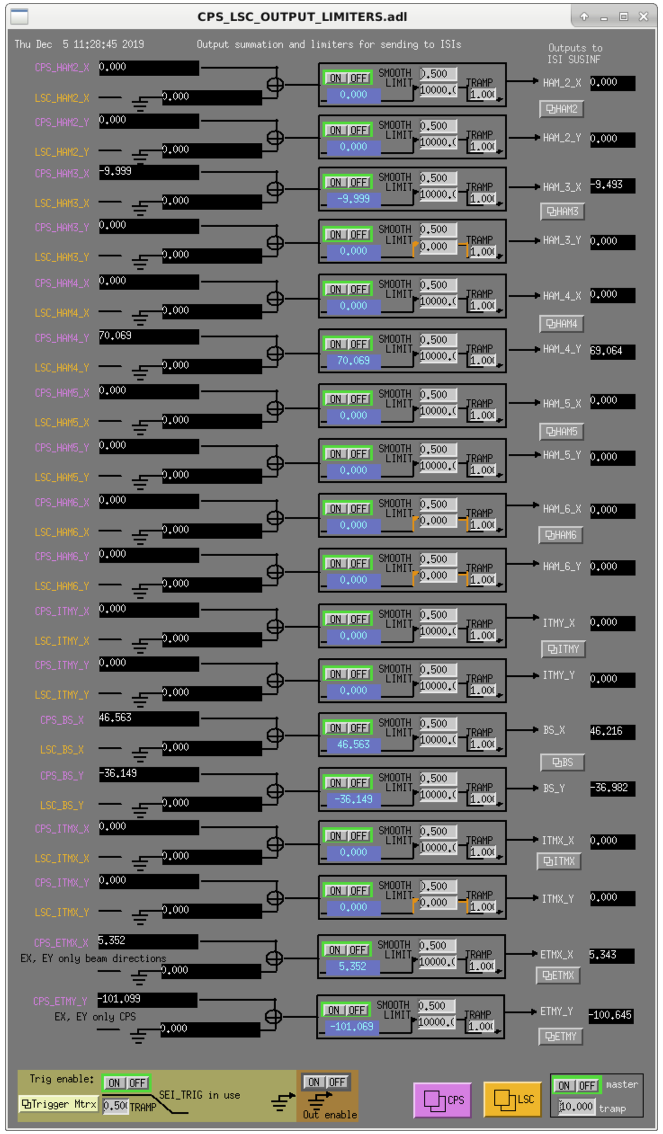
Actuators receive info from the sensors and **apply corrections** in case it is needed.

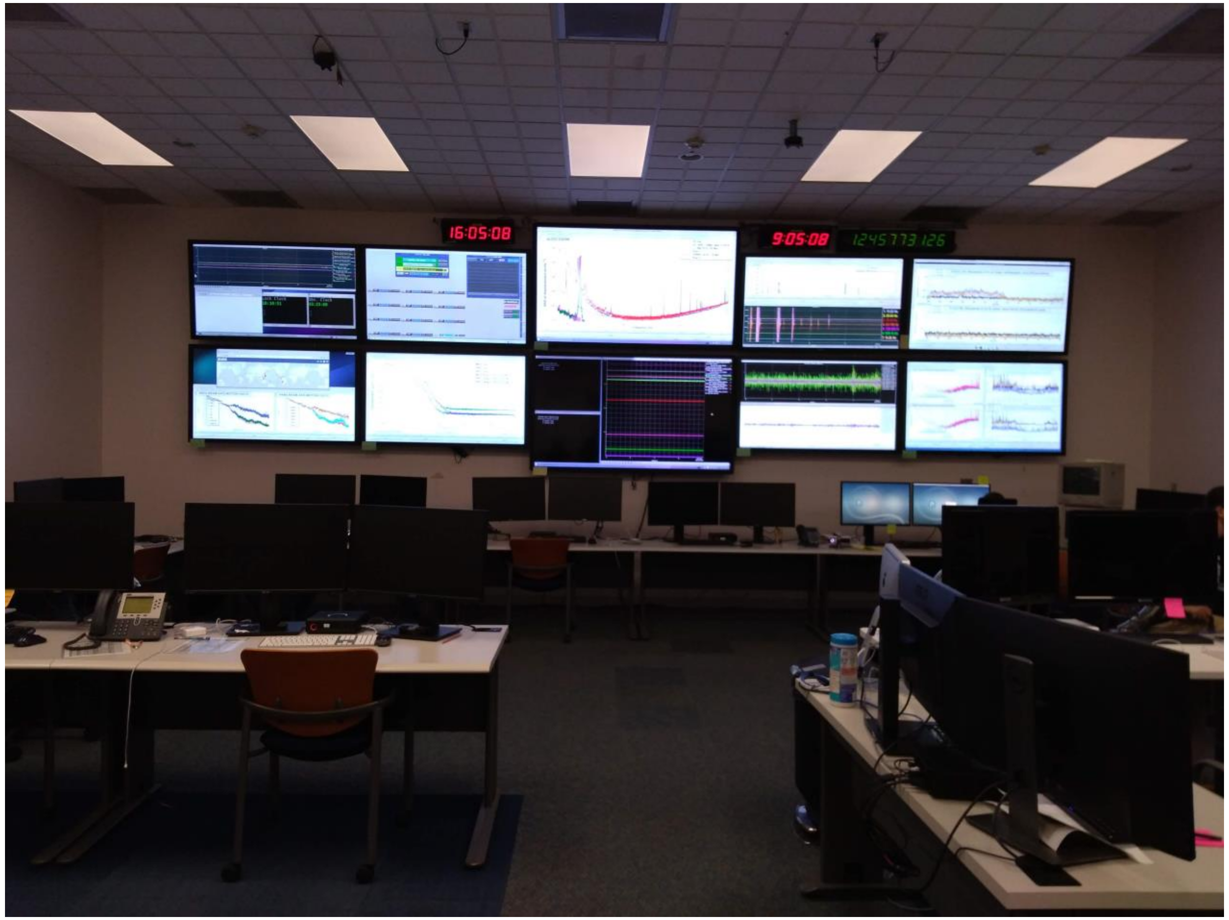
Actuators are applied where **active isolation is used.**

Credit: Dr. Jenne Driggers, LIGO Hanford

The control room



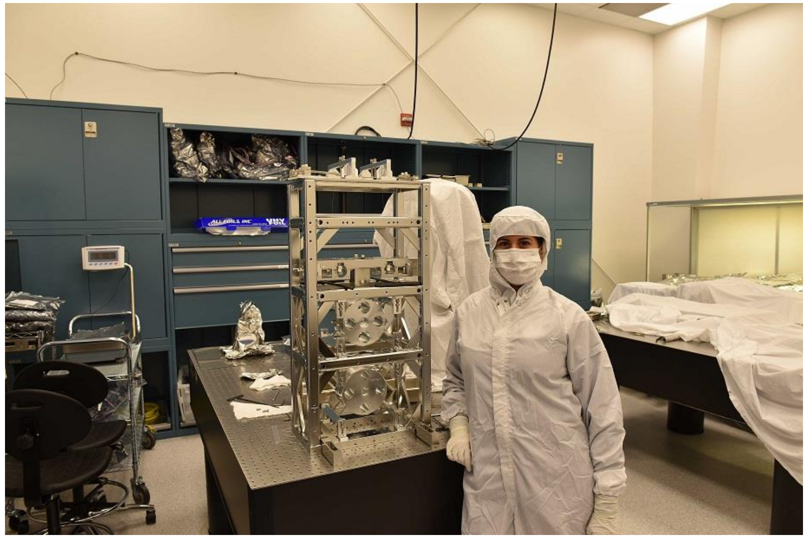




The humans

A typical interferometer is normally driven by

- Physicists
- Mechanical engineers
- Electronical engineers
- Technicians
- Server managers
- Safety managers (ah yeah, it can be dangerous)
- Researchers travelling to site from all over the world
- Fellowships students…



Me when finished to build a suspension.
Waiting for the OK for installation…

Yes, all together and in night and day shifts…

Do we really make it work?

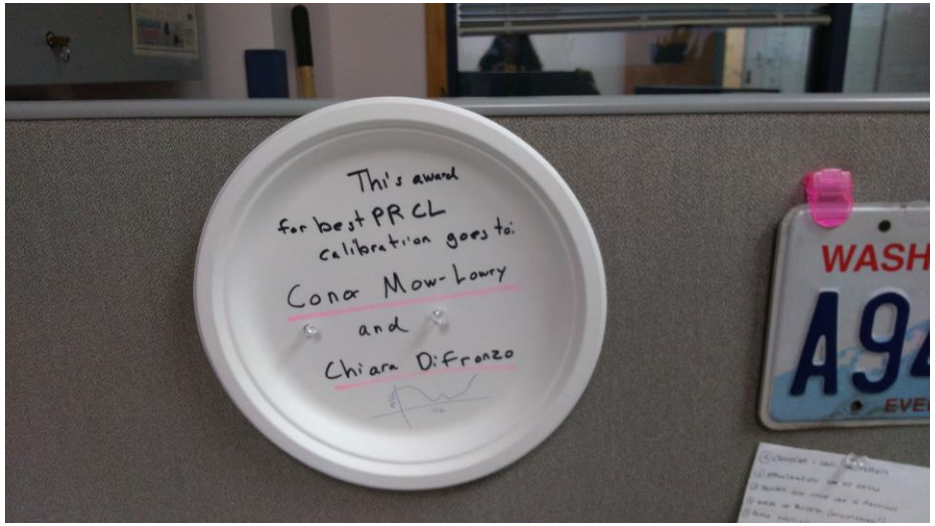
Yes, we do.

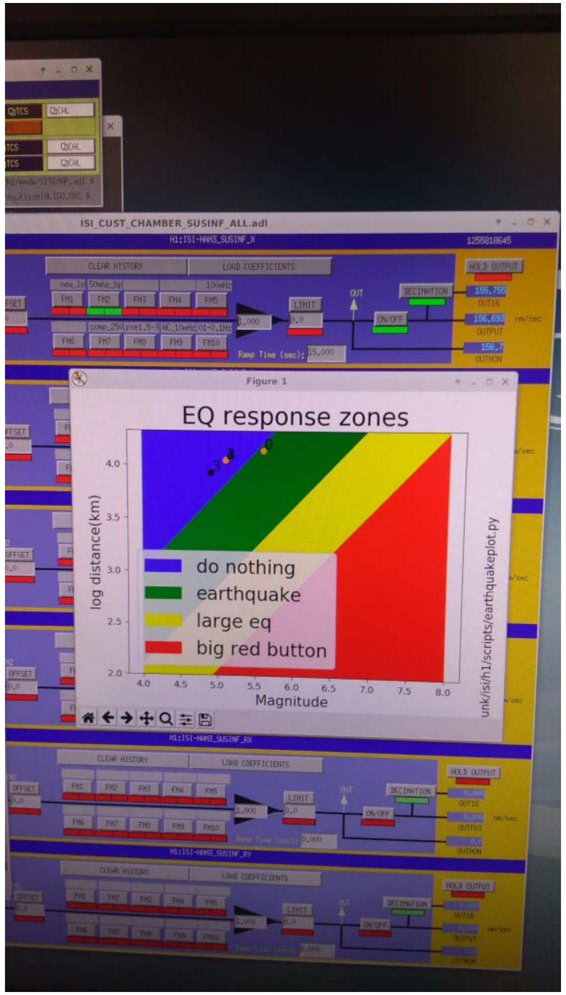
GWs were discovered in 2017 thanks to the interferometers.

Nobel prize for Physics awarded!

And also we need to consider the Idea to shut everything down…

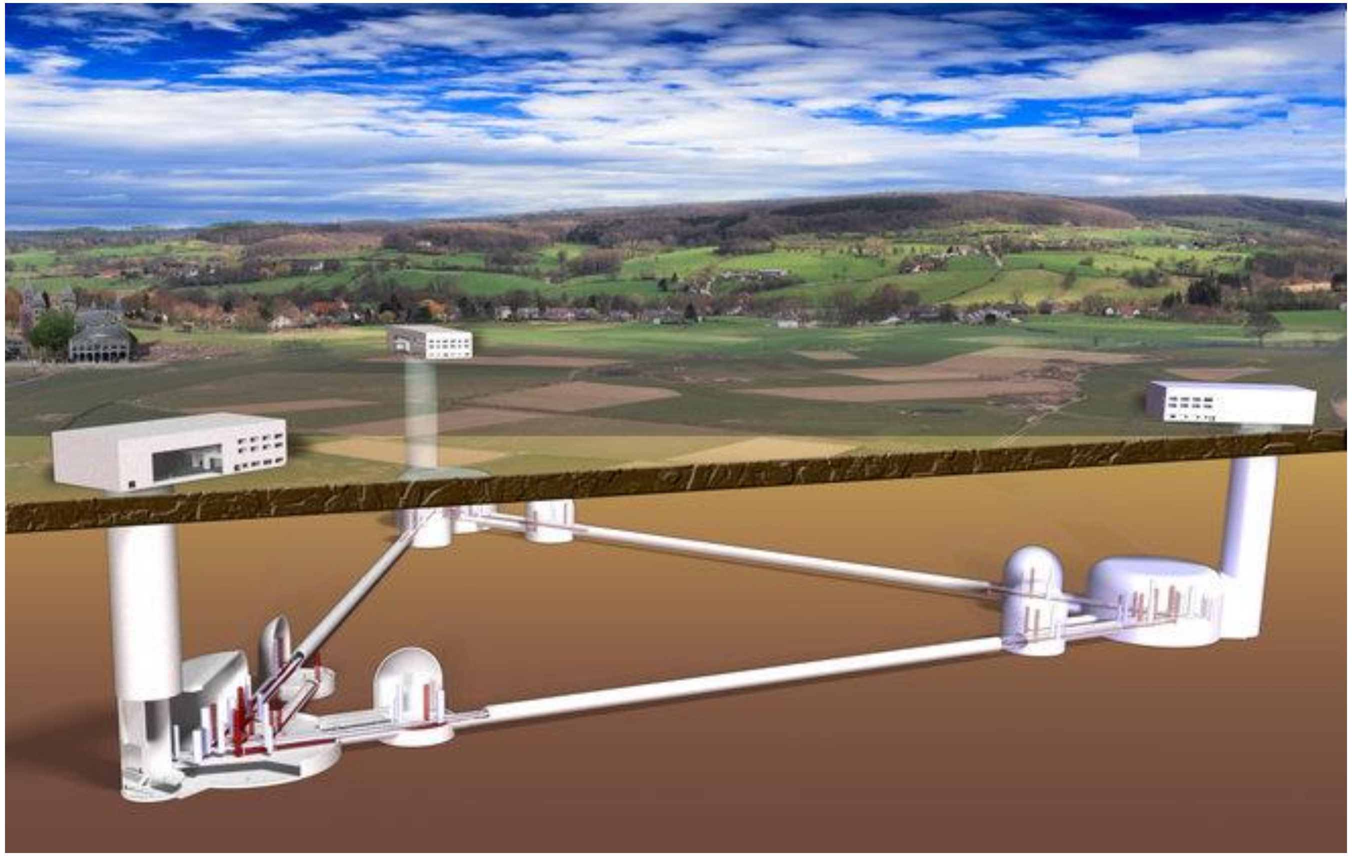
Sometimes we fail…





Shall we do better?

- 100 000 detections per year !
- Early detections
- Detection of super-massive black holes
- Multi-messenger astronomy

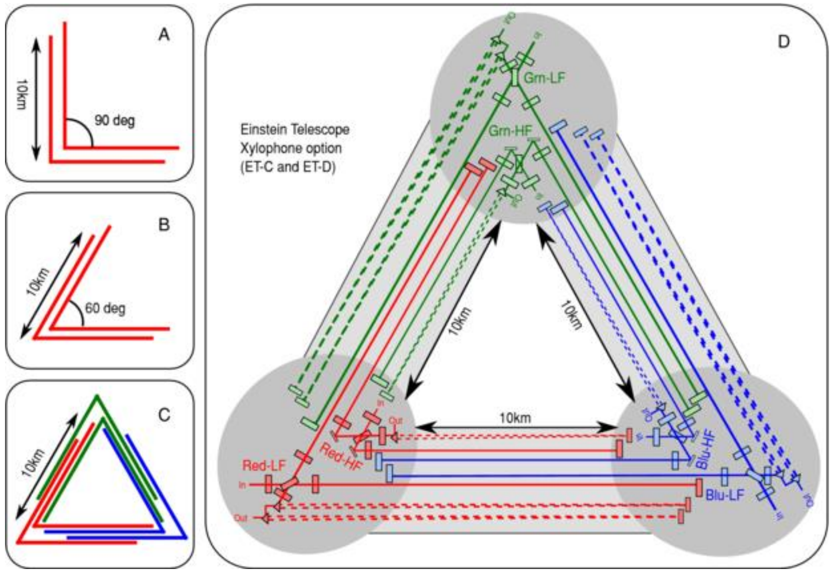


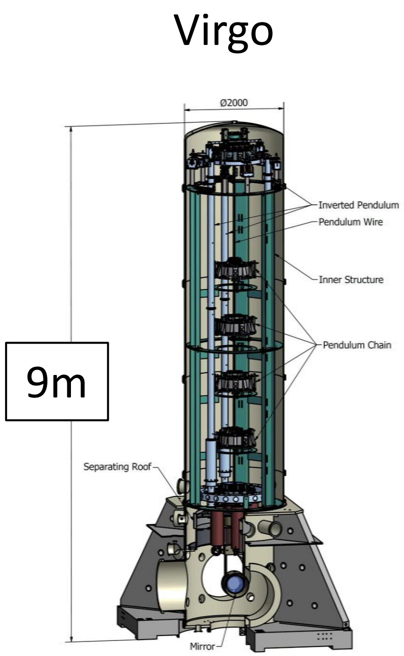
Einstein Telescope

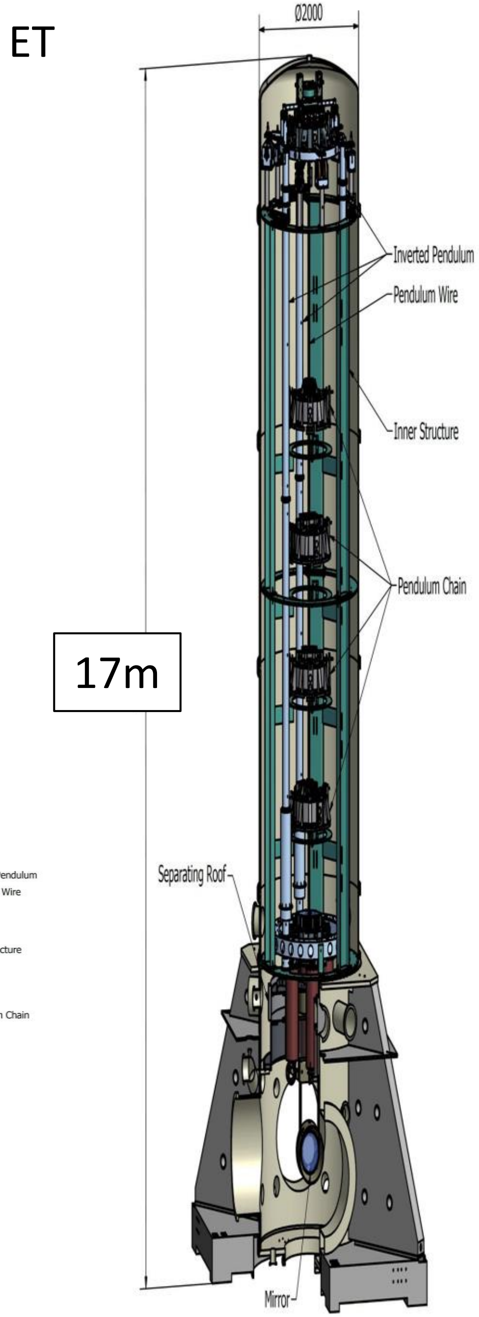
Credits: ET collaboration

Key points of ET

- 6 interferometers
- Longer arms (10 km)
- Bigger mirrors (100 Kg)
- Less thermal noise (cryo T)
- Higher pendulum (17 m)
- Reduced Newtonian noise (underground)







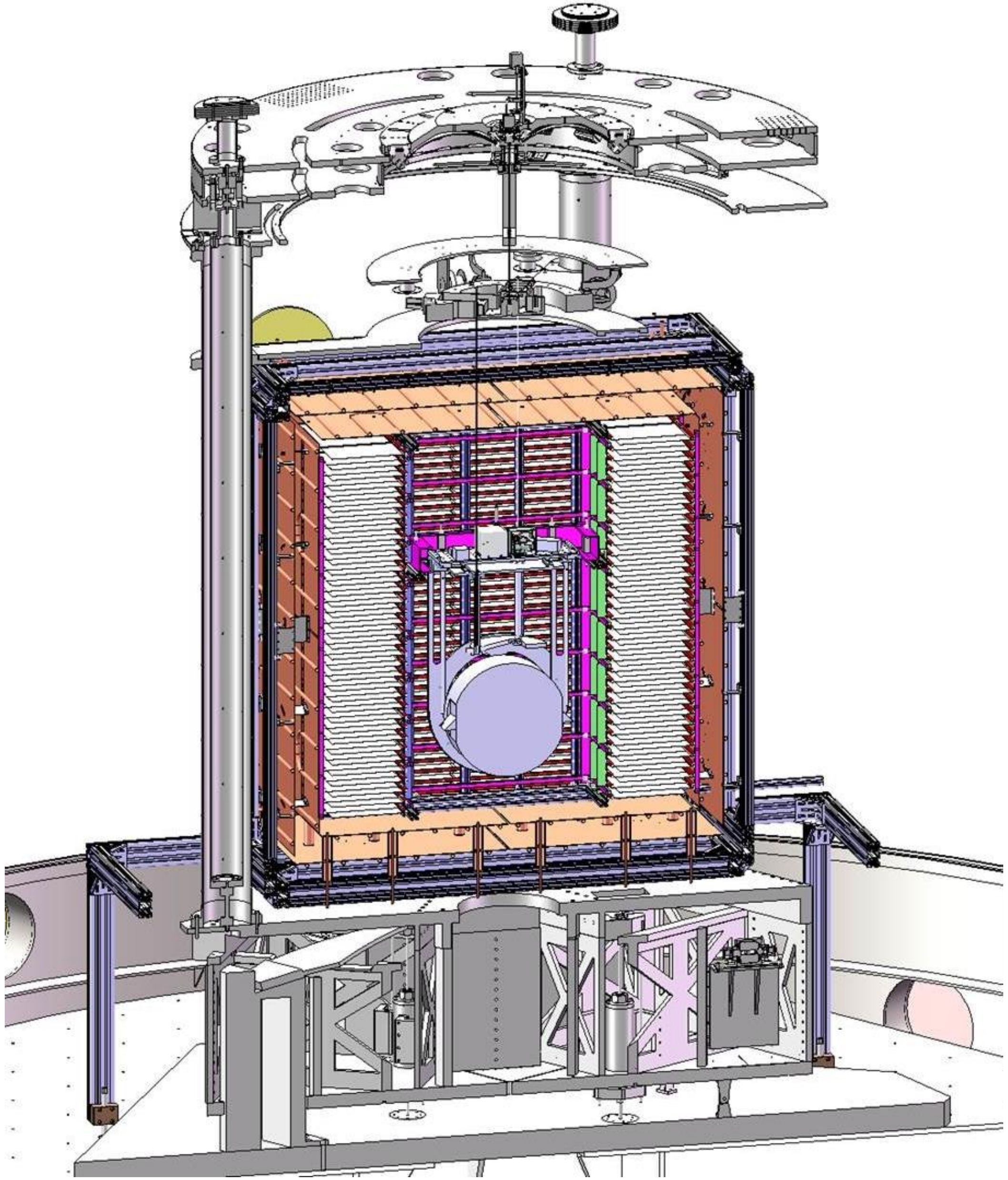
Credits: ET collaboration

The E-TEST project at ULiège

- Research at ULiege is ongoing to *improve inertial sensors* and to validate the advanced technology for new GW detectors, as Einstein Telescope (ET)
- At ULiege, the prototype E-TEST is under construction to *test the hybrid technology* mentioned before
- For more info about E-TEST in general, please visit:

https://www.etest-emr.eu/

Work in progress.
Credit: Haidar Lakkis



E-TEST objectives

- Large mirror (100 Kg)
- Cryogenic temperature (10-20 K)
- Isolated at low frequency (0.1-10 Hz)
- Compact suspension (4.5 meters)

E-TEST feasibility strategy

E-TEST is a project funded by the Interreg Euregio Meuse-Rhine and ET2SME consortium, which allow us to capitalize on existing infrastructure at Centre Spatial Liège (CSL) for the construction of the facility.

Precision Mechatronics Laboratory

CENTRE SPATIAL DE LIÈGE

RWTH AACHEN UNIVERSITY

KU LEUVEN

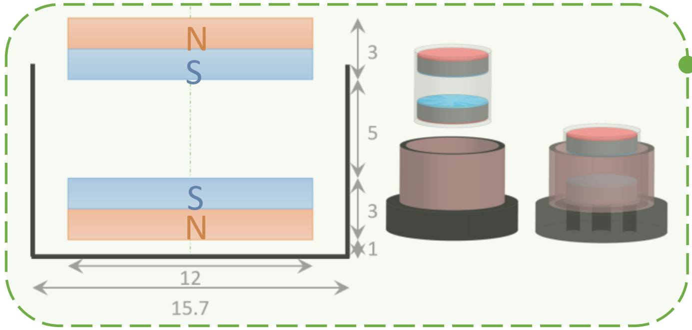
Nikhef

UCLouvain

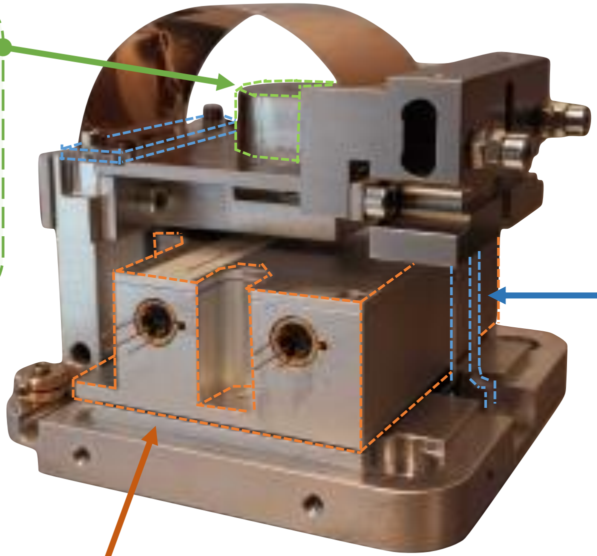
KU LEUVEN micas

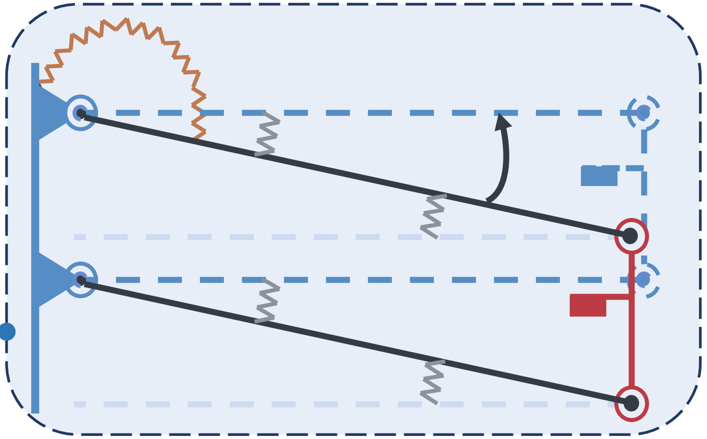
Fraunhofer ILT

Room T inertial sensor for the E-TEST project

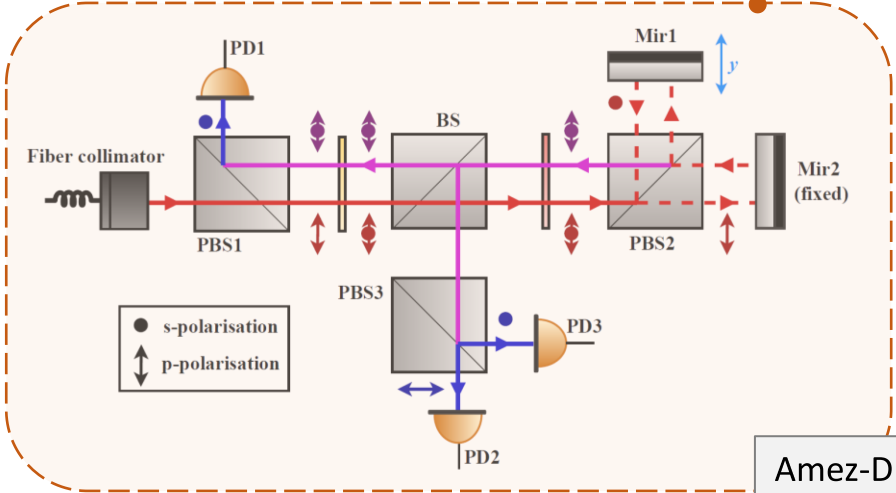


Feedback actuator:
- Moving magnet VCA.
- Self-shielded quadrupole magnet.



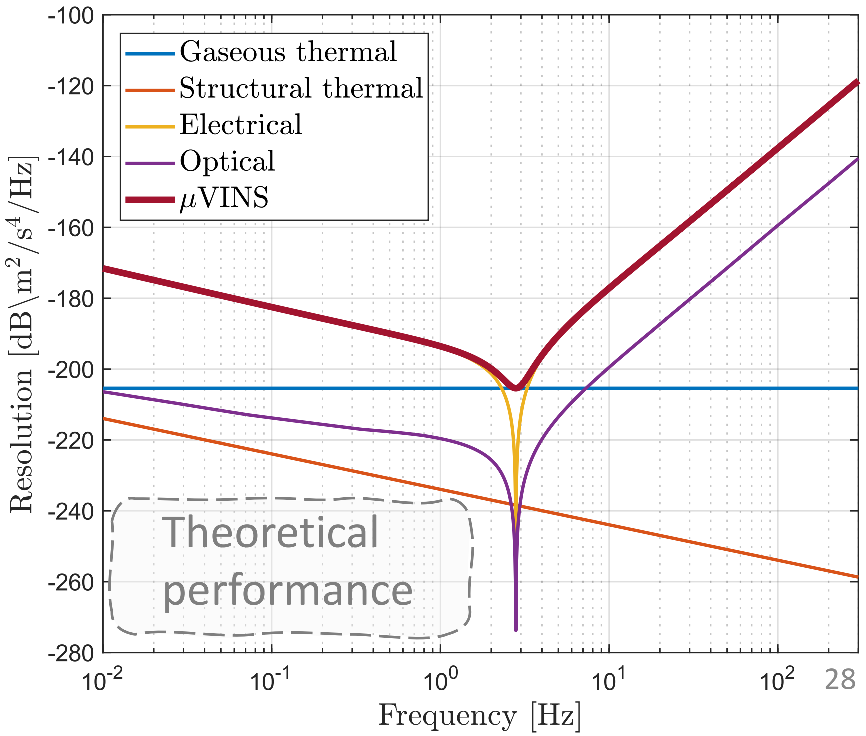


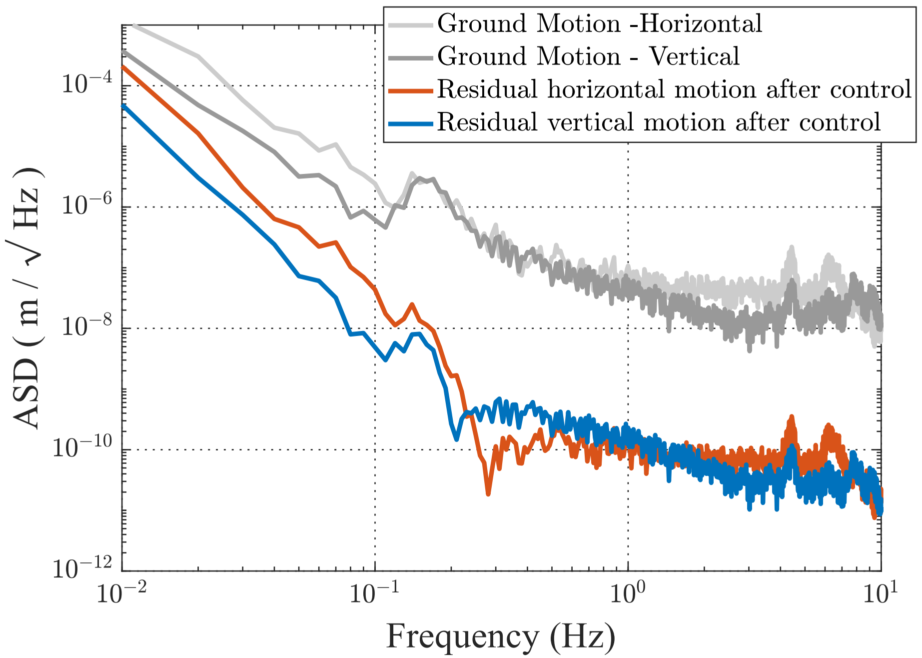
Mechanics
- Long period: $f_0 = 2$ Hz
- Low loss fused-silica flexures.
- Linear mechanical guide for the optical readout.

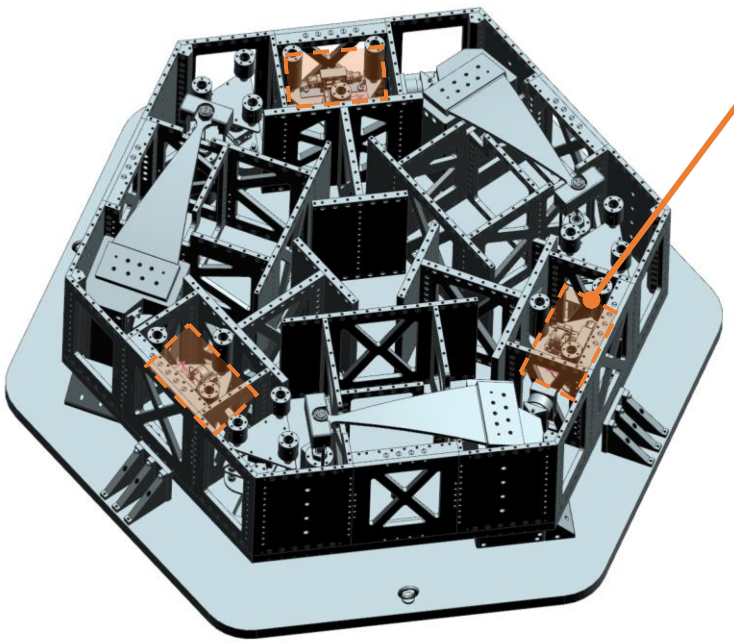


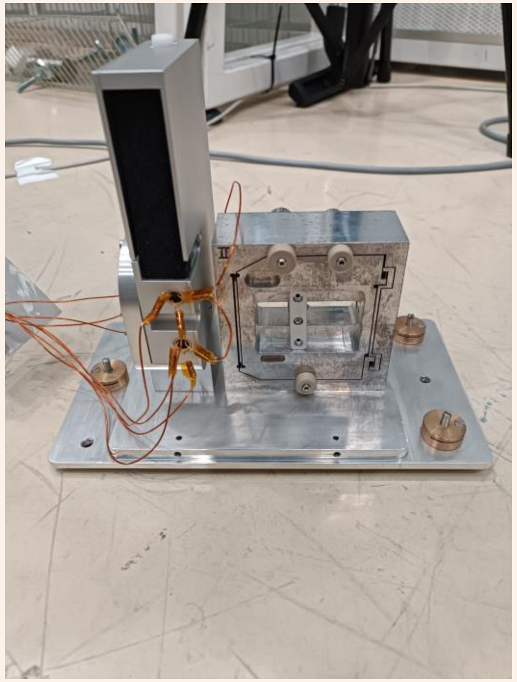
Quadrature Michelson interferometer
- High dynamic range.
- High resolution: 2×10^{-13} m/√Hz.

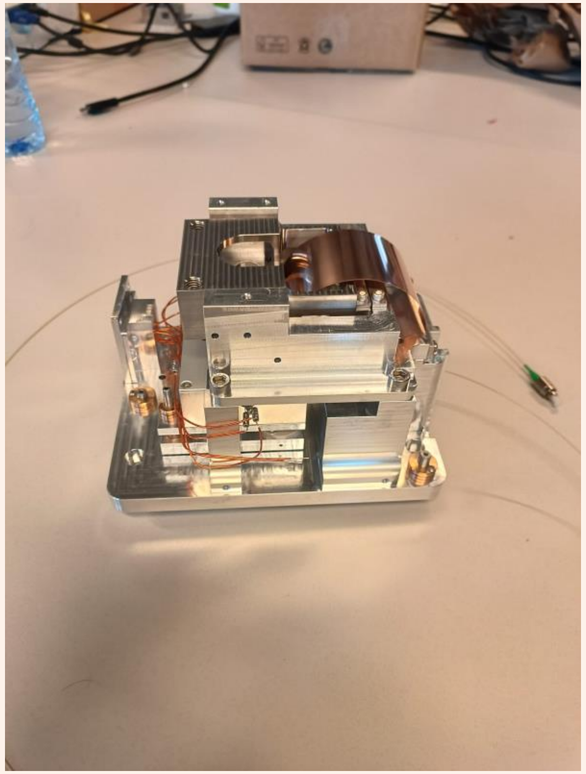
Amez-Droz L. (Loic.Amez-Droz@ulb.be)
Amorosi A. (anthony.amorosi@uliege.be)











Amez-Droz L. (Loic.Amez-Droz@ulb.be)
Amorosi A. (anthony.amorosi@uliege.be)

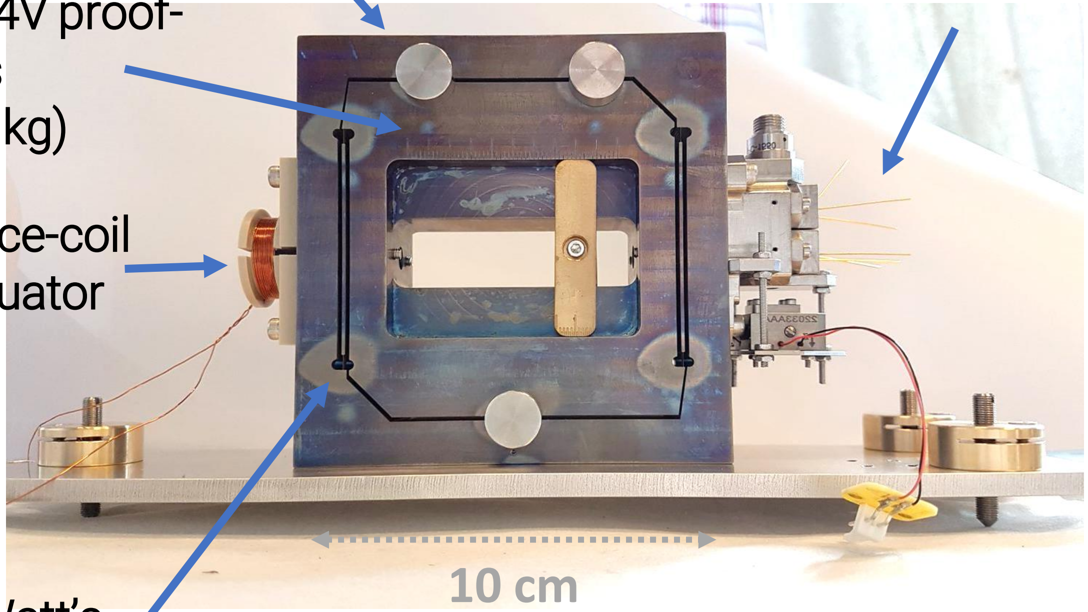
Horizontal cryogenic inertial sensor for E-TEST

Frame

Ti6Al4V proof-mass (0.68 kg)

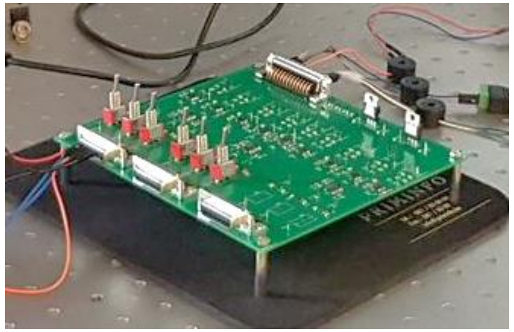
Voice-coil actuator

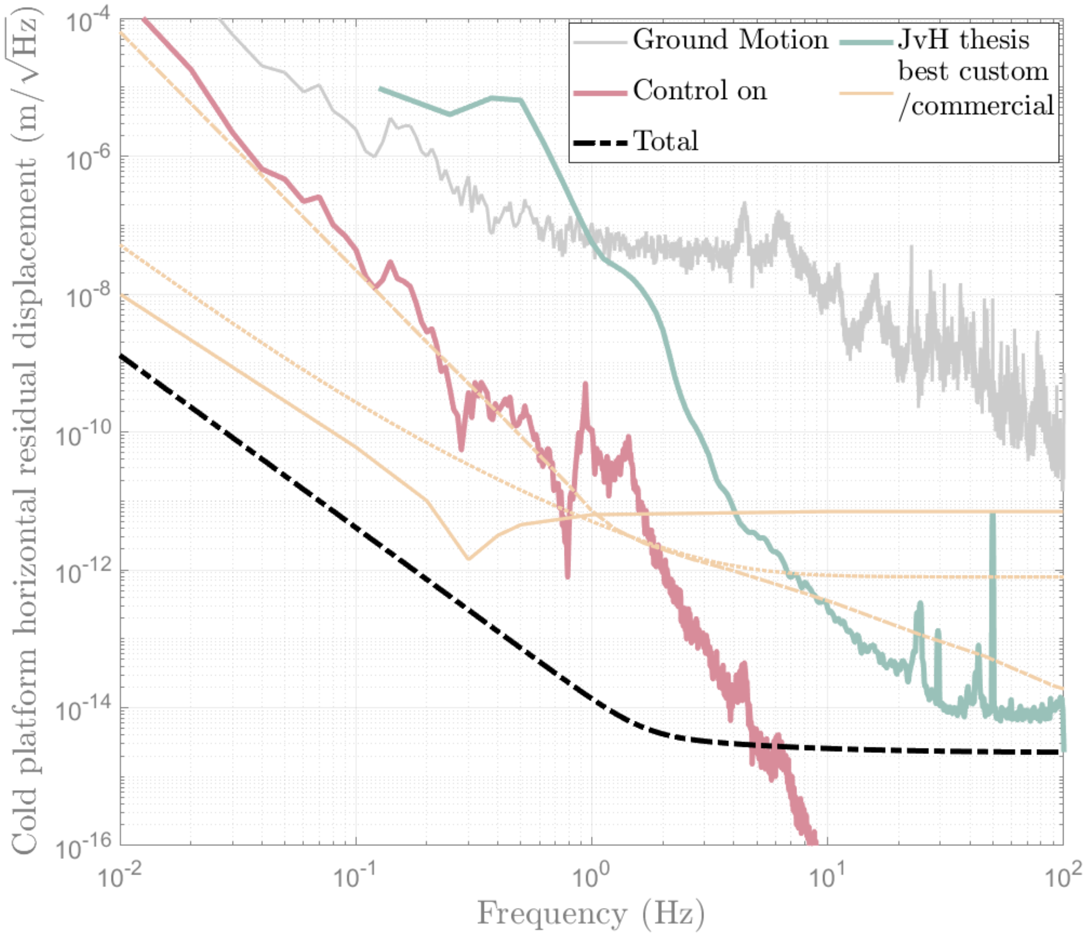
Interferometric read-out



Watt's linkage leg

Room temperature PCB with TIA, controller and current injector



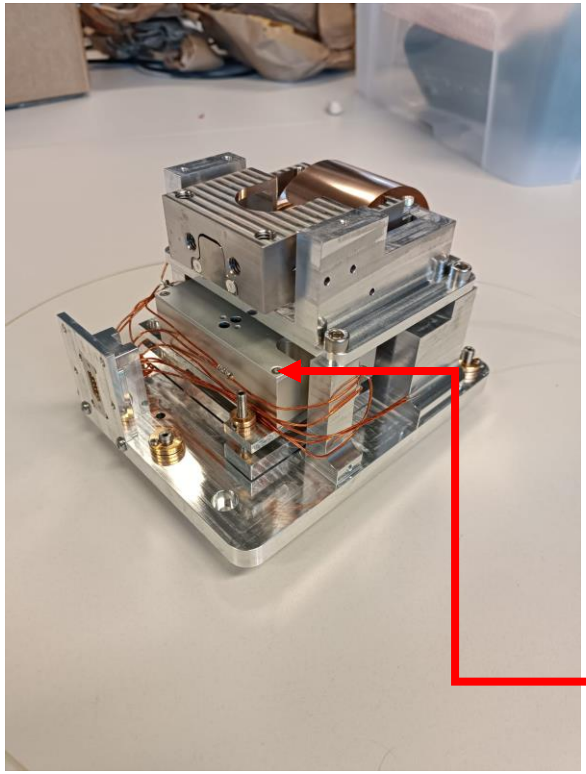


Credit: Morgane Zeoli

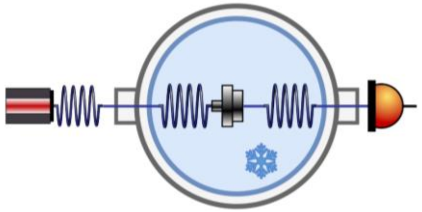
Vertical Cryogenic inertial sensor for E-TEST

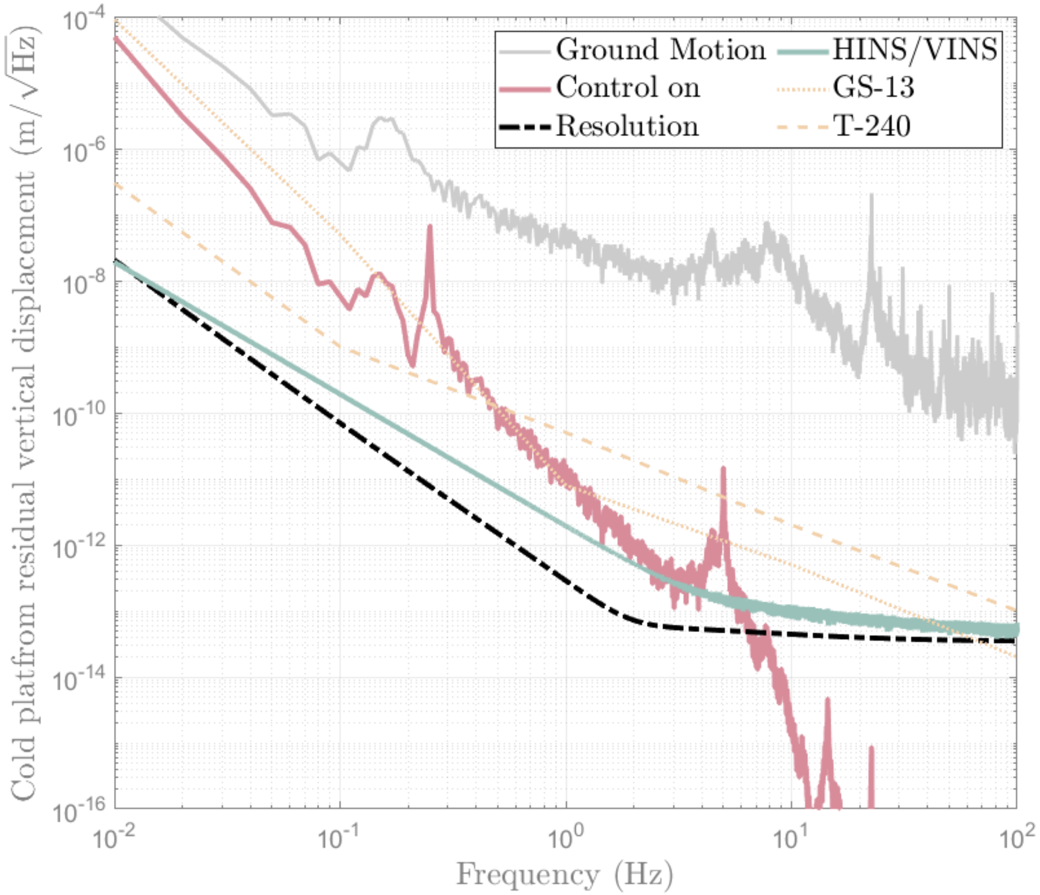
E-VINS design adapted for cryogenic working conditions

A test campaign was taken in collaboration with RWTH Aachen to select the optical elements th works the best in cryogenic conditions (collimators, photodiodes, polarization, alignment, etc). The results are used for both CSIS-V and H.



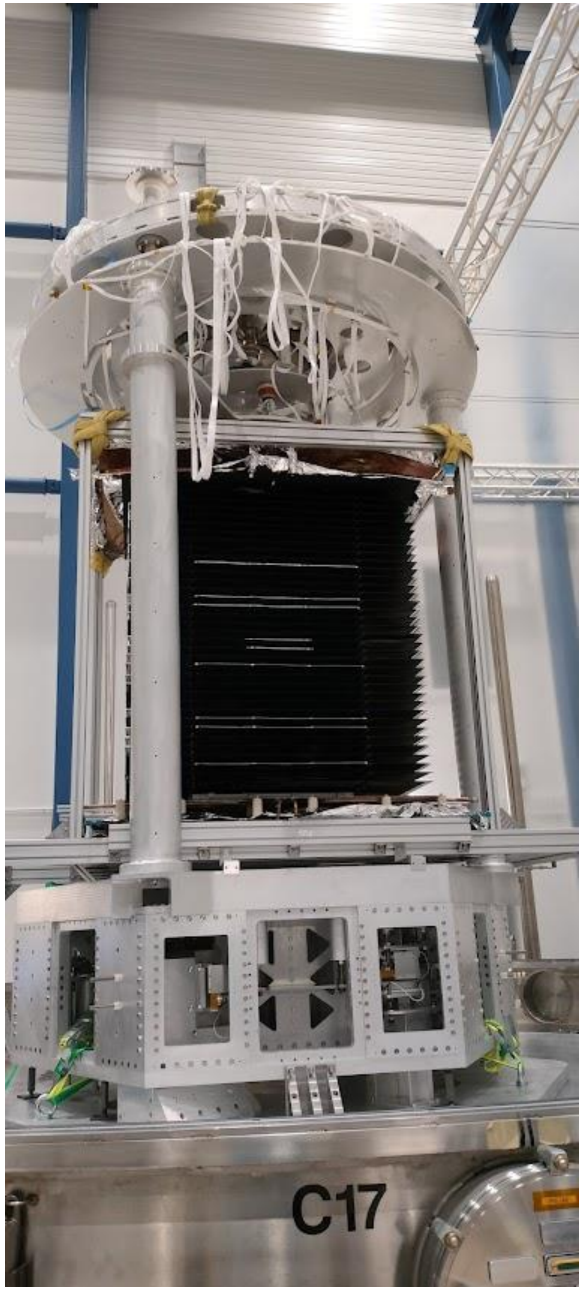
Interferometric read-out





Credit: Morgane Zeoli

Current status of E-TEST



Visiting E-TEST

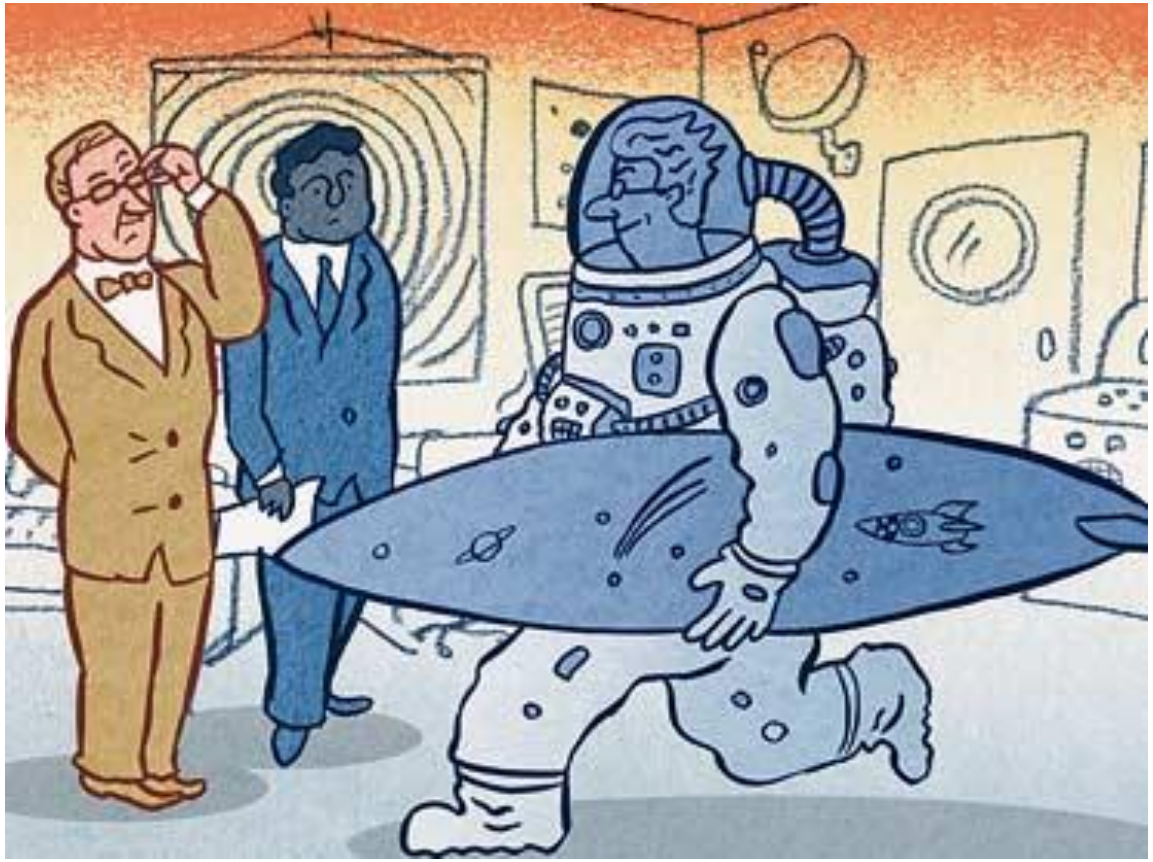
E-TEST facility is now located at the Centre Spatial de Liège and it is possible to visit.

A visit is planned for today for whoever is interested.

For other chances, please feel free to contact prof. Christophe Collette at:

Christophe.collette@uliege.be

Thanks for attending!



Useful places:

TDR

https://arxiv.org/abs/2212.10083

E-TEST Project website

https://www.etest-emr.eu/

PML website

http://www.pmlab.be/

Useful people:

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