Elements of Cryogenics in GW detectors

E. Majorana

PhD International School on Technologies in Gravitational Waves Detection

Erice – EMFCSC - 20–27 May 2026

GW detectors VS cryogenics

1. Historical background
2. Current scientific targets
3. The main purpose is reducing thermal noise: basic concepts and a sample essay the thermoelastic effect
4. Cryogenics spin-offs on actual interferometers (thermal lensing)
5. What we have (e.g. KAGRA) and the feasibility of techn. porting to ET
6. Some basic thermodynamics considerations
7. A viable project
8. A glance at R&Ds

Surf/interact on 75 slides + not used !!

GW detector insights

Resonant Bars @ Low Temperature

Experimental Gravitation. Proceedings of a school, Varenna, Italy, 17-19 July 1972. B. Bertotti, Ed. Academic Press, New York, 1974. Proceedings of the International School of Physics "Enrico Fermi," Course 56.

The scientific motivation

These measurements require techniques of extreme sensitivity, low noise and great mechanical and electrical stability.
Two types of advantages emerge from cooling at very low temperature, one based on macroscopic quantum effect, namely superconductivity and superfluidity, and the other based on the general reduction of the *k T* thermal noise, thermal expansion, thermal electromotive force, creep, etc...

The Use of Low-Temperature Technology in Gravitational Experiments.

W. M. FAIRBANK
Stanford University - Stanford, Cal.

1. – Introduction.

One of the challenging problems of experimental gravitational physics is the very small size of the gravitational effects one wishes to measure. For example, the force of gravity of the entire Earth on an electron or positron is equal to the electrical force on it due to a single elementary charge situated at a distance of 5 meters from the electron or positron. The rotation with respect to the fixed stars of the axis of a perfect gyroscope in a polar Earth orbit when oriented perpendicular to the Earth's axes is predicted to be only 0.05 seconds of arc per year. The amplitude of vibration of a 5 ton aluminum bar 10 feet long excited by a spherically symmetric gravity wave emitted at the center of our Galaxy with energy, mc^2, of one solar mass 10^{54} erg, is predicted to be 10^{-14} cm. Furthermore, some gravitational experiments of great interest, such as a test of the equivalence principle, involve a search for minute deviations from null. A test of the equivalence principle at the level of weak interactions requires a check on the differences between gravitational and inertial mass to 1 part in 10^{14}.

These measurements require techniques of extreme sensitivity, low noise and great mechanical and electrical stability.

Two types of advantages emerge from cooling to very low temperatures: one based on macroscopic quantum effects, namely superconductivity, and superfluidity, and the other based on the general reduction of kT thermal noise, thermal expansion, thermal e.m.f., creep, etc.

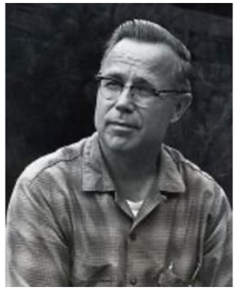
2. – Macroscopic quantum phenomena.

Several properties of superconductors are useful in measurements on gravity, but I want to begin by pointing out in particular the importance of macroscopic quantization. In 1948 LONDON [1] put forward his profound conjecture

280

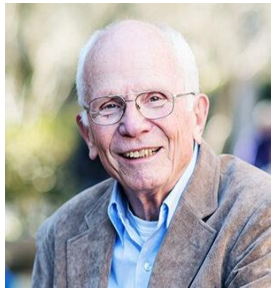
Principle motivations (and disclaimers) ~100 y of debates

Cryogenics in physics: Fairbank's theorem and Hamilton lemma



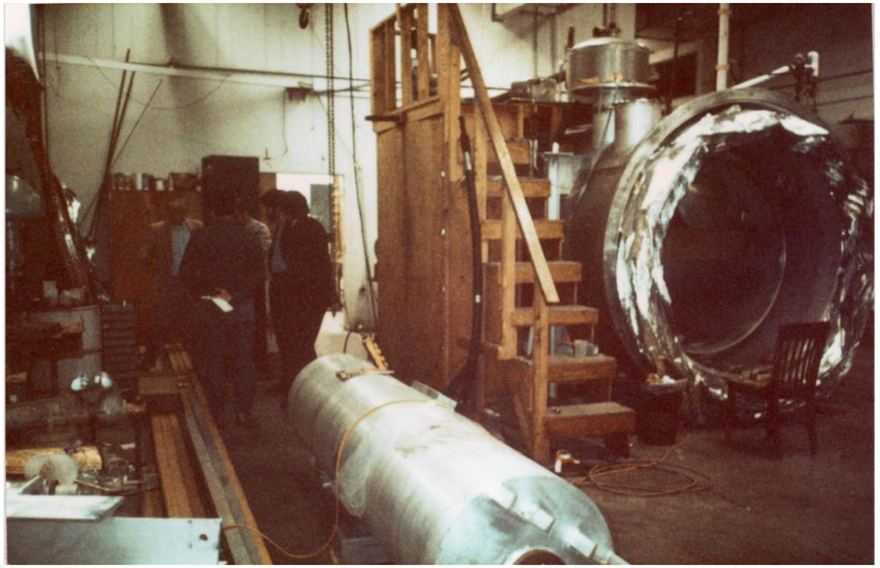
"Any experiment is better, if it is done at low temperature"

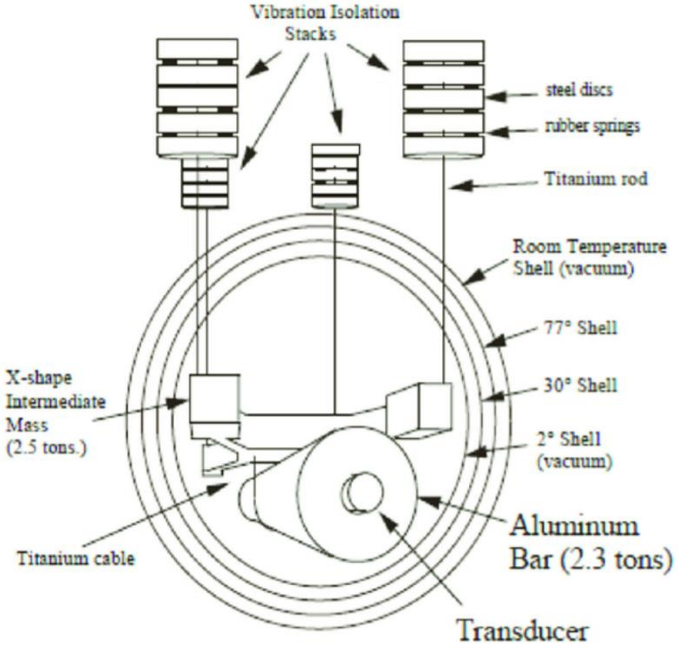
W. M. Fairbank

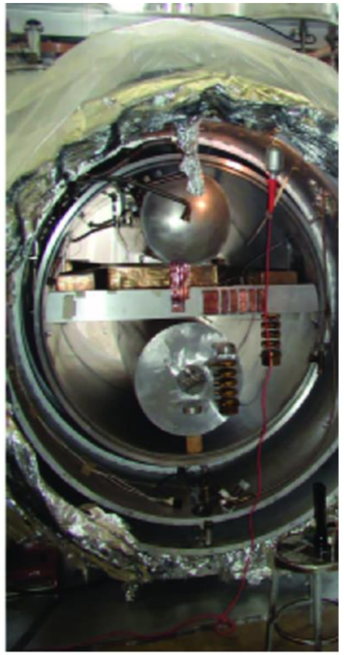


"Any experiment will be harder, if it is done at low temperature"

W. Hamilton







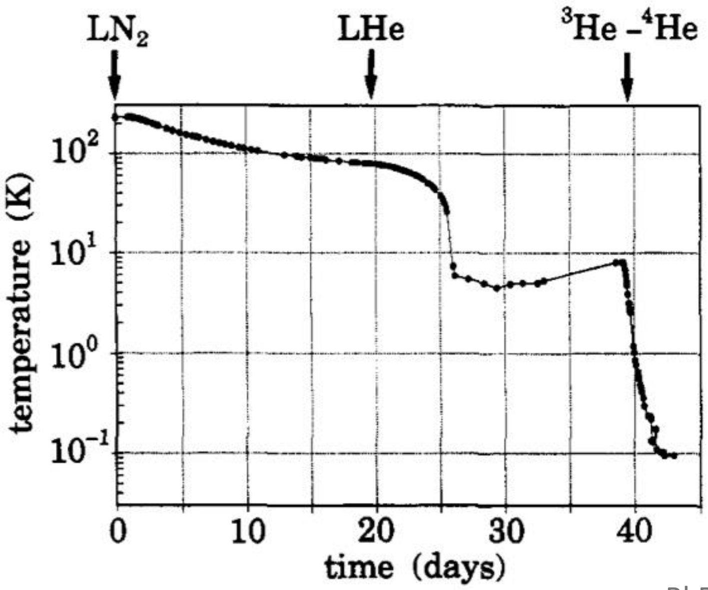
The GW massive detector achieving the lowest temperature

Don’t be afraid of cooling down large masses

P. Astone, M. Bassan, P. Bonifazi, F. Bronzini, P. Carelli, M.G. castellano, G. Cavallari, E. Coccia, C. Cosmelli, V Fafone, S. Frasca, E. Majorana, I. Modena, G. V. Pallottino, G. Pizzella, P. Rapagnani, F. Ricci, M. Visco: "

First cooling below 0.1 K of the new gravitational wave antenna of the Rome group

Europhys. Lett., 16 (3), pp. 231-235 (1991)

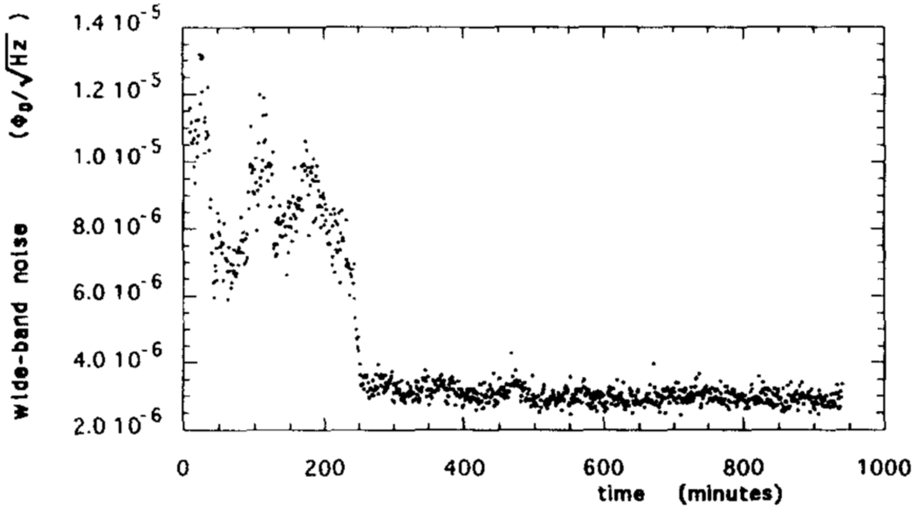


T= 95 mK - M=2300 kg

NAUTILUS - INFN

The GW massive detector and achieving superfluid quite operation

- **Cooling down with cryogenic liquids**: He II shield at 2K using superfluid (→"vibration free") He. This technique is nowadays a standard at CERN



Mean Noise innovation measured in terms of fractions of magnetic quantum flux (SQUID)

ϕ_o = *h/(2c) =2x10* $^{-15}$ *Web*

He II two fluids model (Landau)

$\vec{v}_{nor} + \vec{v}_{super} = \vec{0}$

Low temperature naturally yields interesting devices

Proceedings of the X Italian Conference on General Relativity and Gravitational Physics Bardonecchia (TO, Italy), Sept. 1–5, 1992

Developmentof a Back Action Evading Transducing Scheme for Cryogenic Gravitational Wave Antennas

Ettore MAJORANA[1,3], Piero RAPAGNANI[1,2] and Fulvio RICCI[1,2]

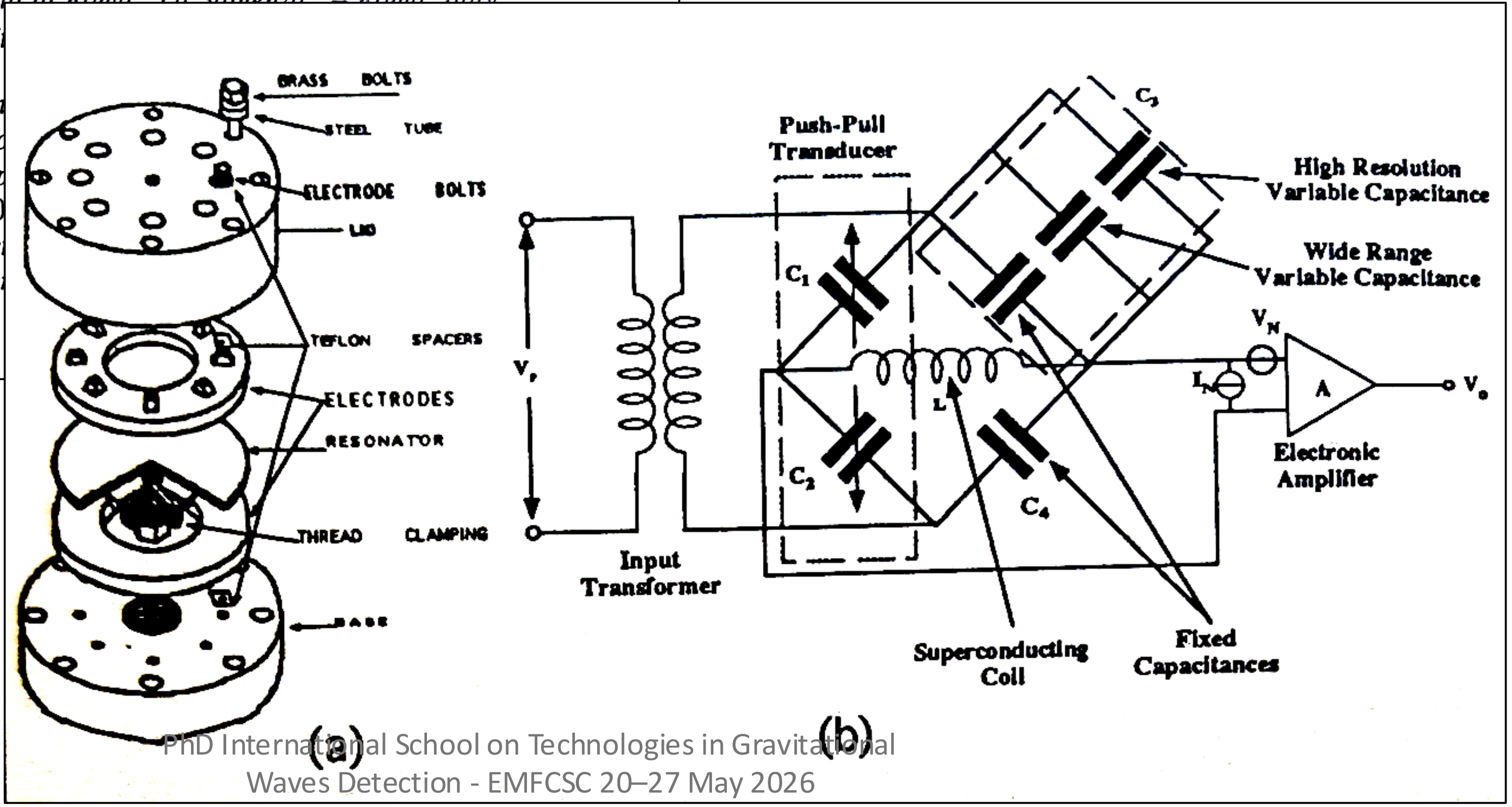
[1]*Istituto Nazionale di Fisica Nucleare – P.le A. Moro 2 00185 Roma, Italy*
[2]*Dipartimento di Fisica, Università di Roma "La Sapienza" – Roma, Italy*
[3]*Dipartimento di Fisica, Universi*

Summary: We present the design
wave antennas (g.w.a.) suitable fo
results of some tests at low temp
mechanical merit factor (2.8 · 10
ppm and an electrical quality fac
the system is in satisfactory agree

Talk given by Ettore MAJORANA

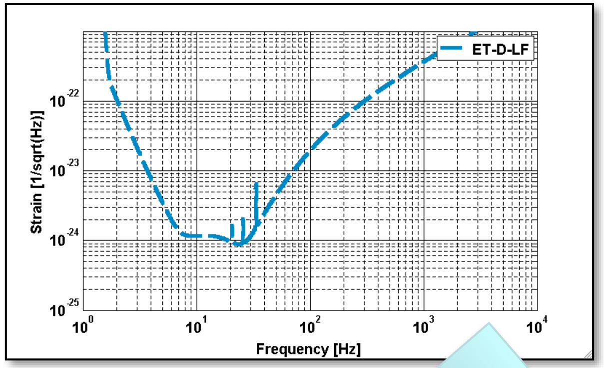
Cryogenics experience at the dep. of Physics of Sapienza started in the 80ies with resonant bar antennas

- ➔ Then LCGT (now KAGRA)
- ➔ ET design 2007-2010
- ➔ Strongly Rekindled by ET, after 2015 (GW discovery)

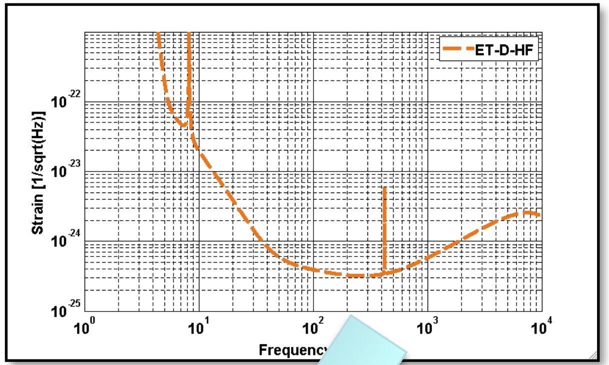


2 - Current scientific targets

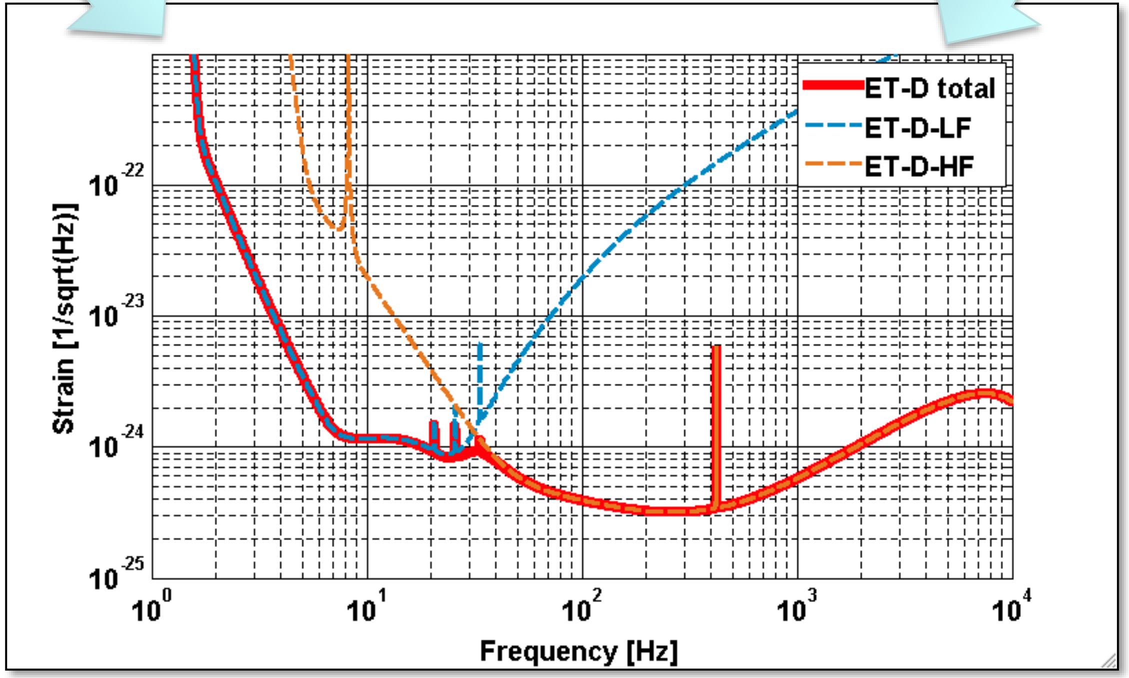
The too-short blanket: “hybrid detector” concept



DIVIDE TECHNOLOGIES



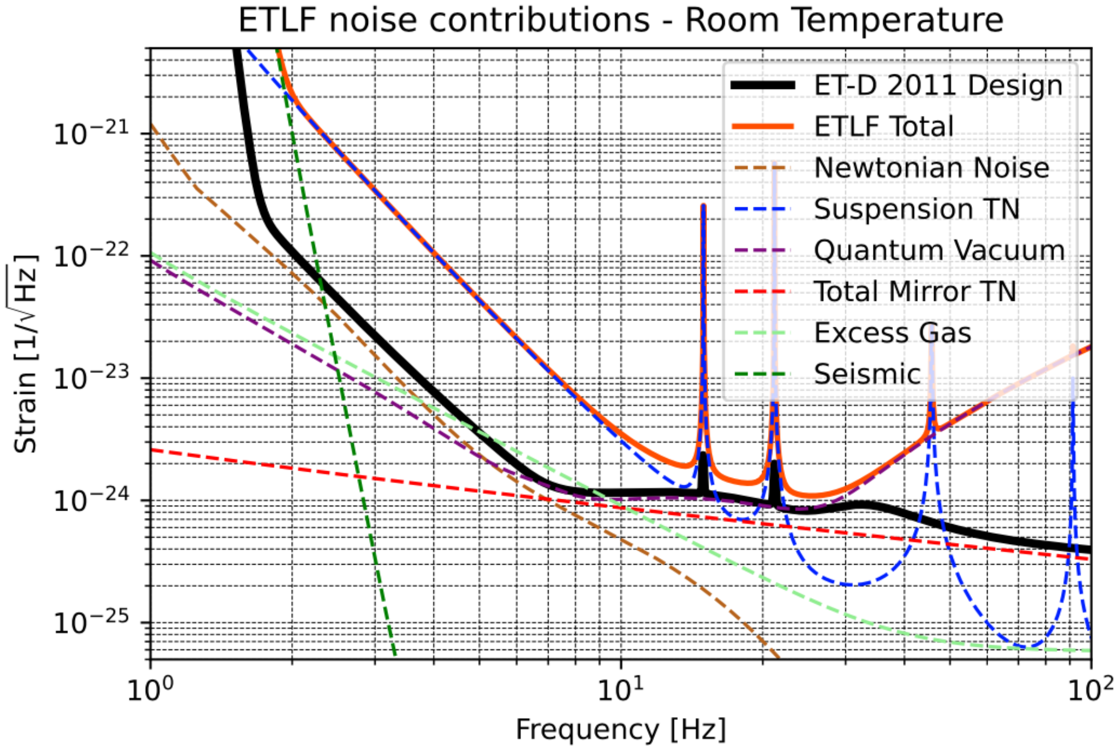
AND COMPOSE MULTIFOLD



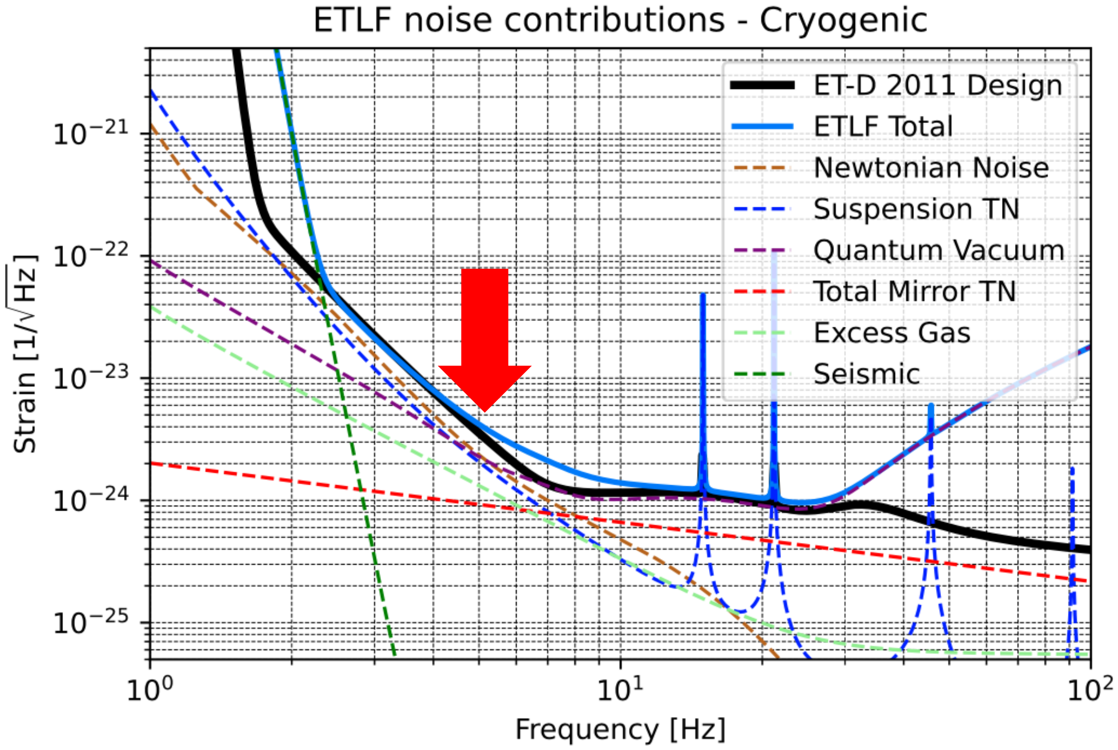
The strong motivation to implement cryogenics in ET

Cryogenics contributes to a significant increase of sensitivity at in the low frequency range

Room-Temperature ET-LF



Cryogenic ET-LF



Why do we want to cool down our GW detectors?

- **Low Frequency band (3-10Hz) is crucial** for BNS localization and for pushing the detection range towards the primordial universe.

- If we don't cool down the detector, we are not able to improve the sensitivity in the LF band.
  - De-scoping of a 3G *observatory* like ET
  - No-sense to spend ~G€ to go underground…

- OK, let's assume we succeed to cool down the detector and make it work, what about the control noises at LF?
  - Low Temperature can help also here! Low noise sensors & actuation (but R&D is required!)

Not only BBHs, BNS

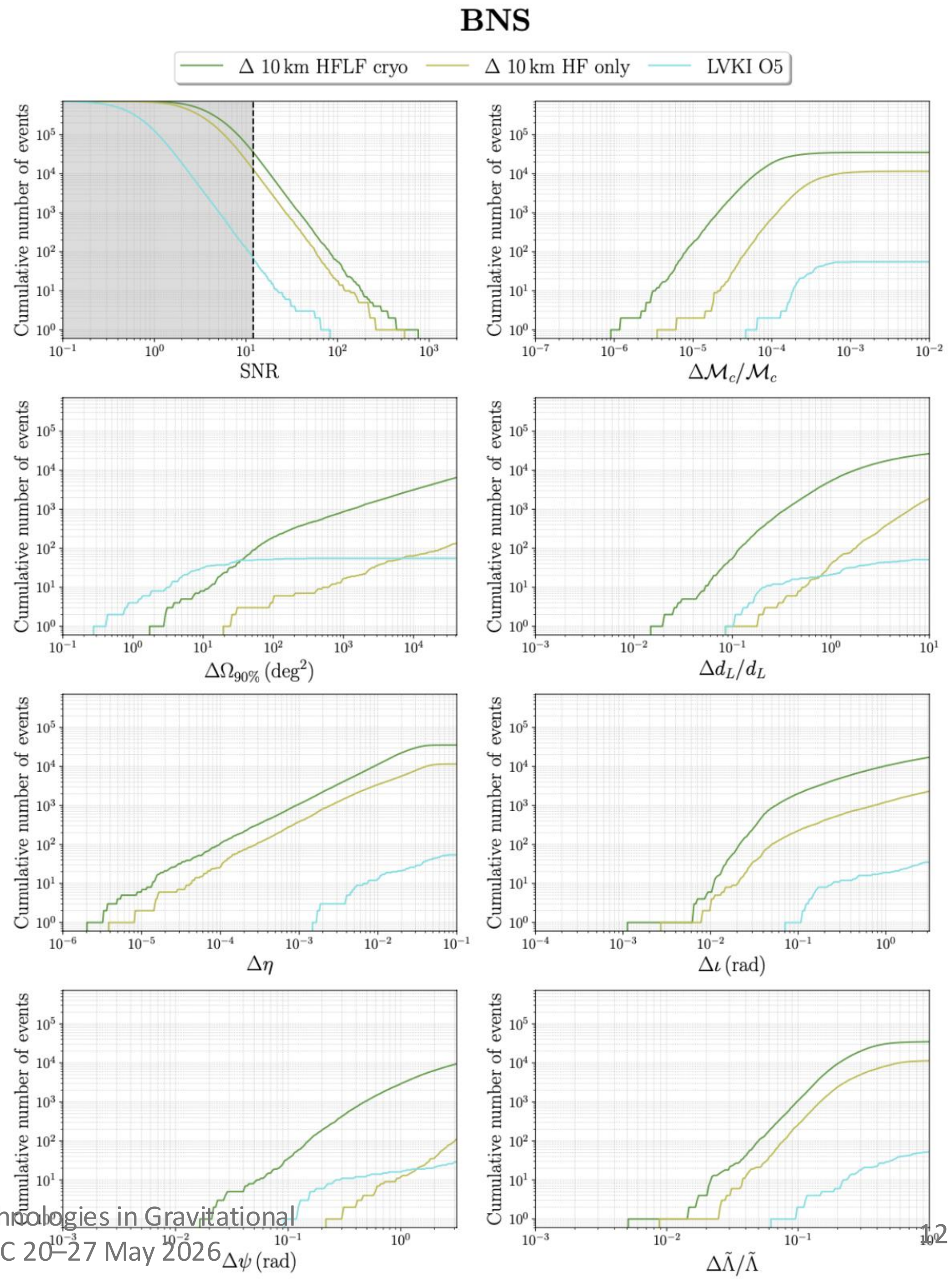
Missing Low Frequency sensitivity in ET (seismic isolation, cryogenics, low noise electronics …), to save money, to hurry up, or simply because hardware developments are too slow

➔**strongly affects BNS detection**. E.g. GW170817 would stay about 1 day in hybrid ET BW before the merge, just ~10 minutes without the LF section of the detector.

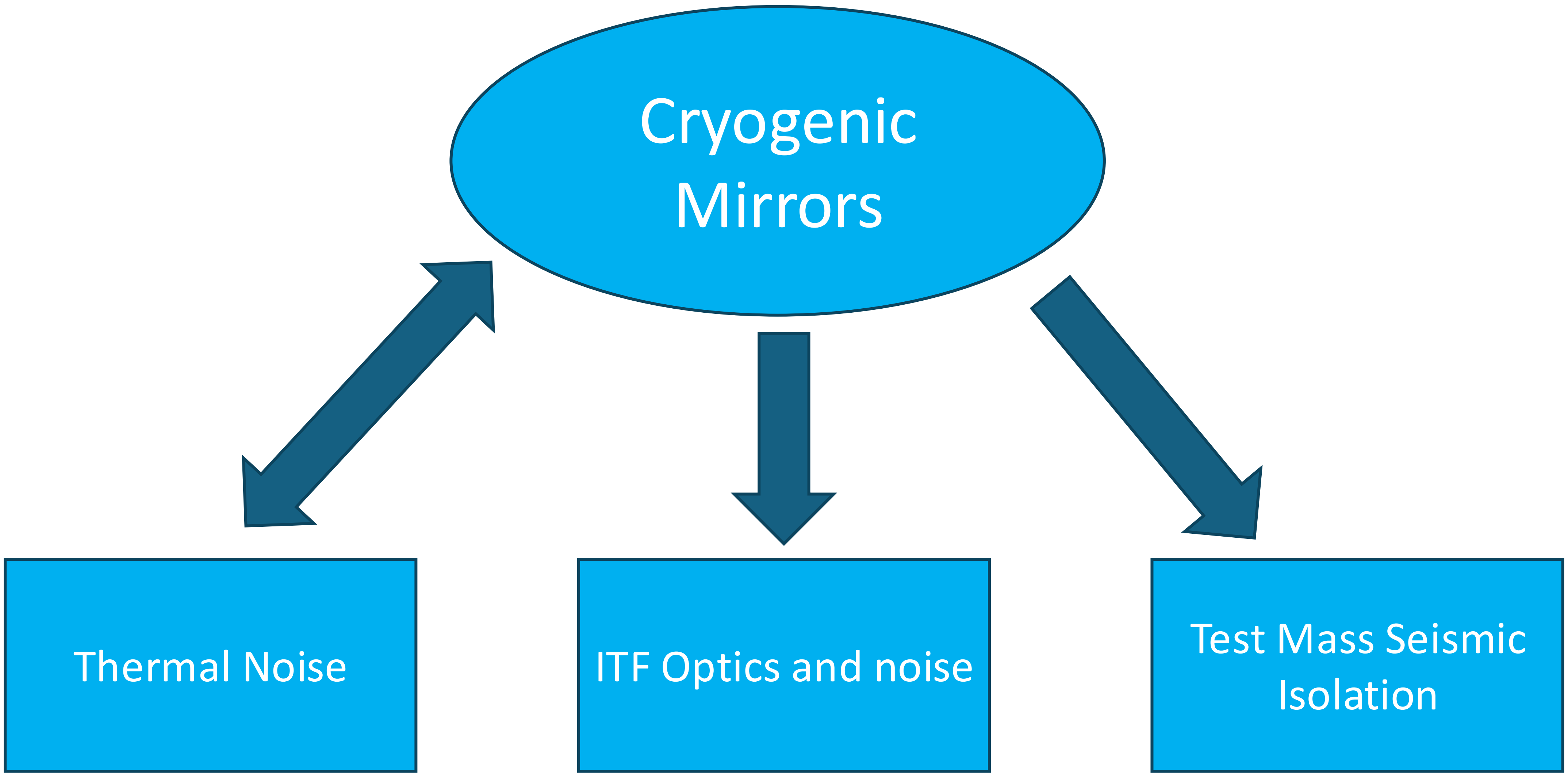
All the cases have been studied and in particular:

- W/WO LowFreq implementations

❖ localization loosing **Δ10km VS 2L-15km 45deg**
❖ event rates VS z



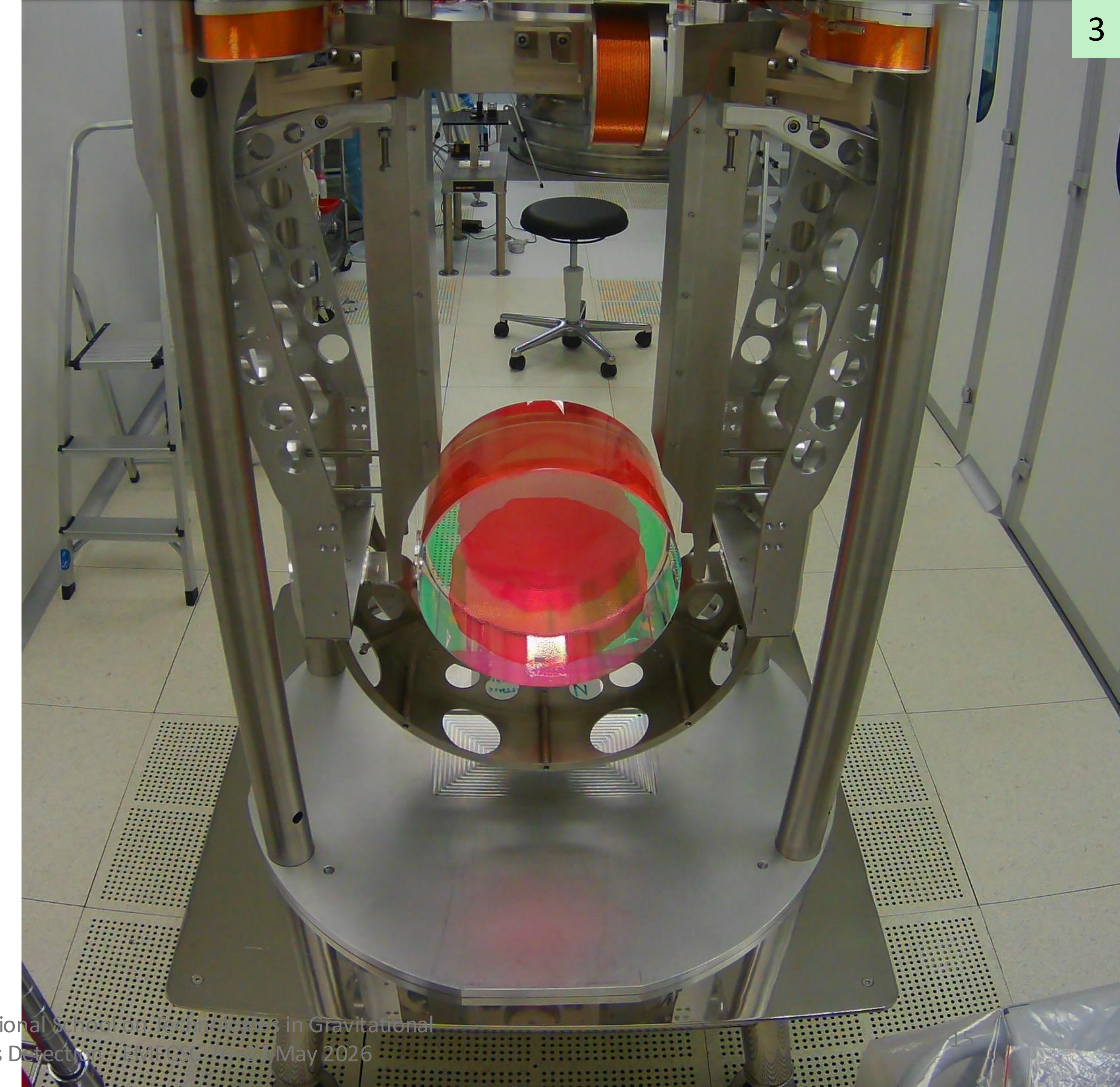
3 - The main purpose is reducing thermal noise: basic concepts and a sample essay the thermoelastic effect


Cryogenic Mirrors
Thermal Noise
ITF Optics and noise
Test Mass Seismic Isolation

The so-called Test-Masses **are** mirrors, even at toom temperature it is not easy

Very accurate and sophisticated control must be used to let them be the elements of a laser interferometer

- most of the experimental aspects of ET require R&D
- A factor 20 in sensitivity is not for free !
- Soft ! The range of angular and pendulum modes of the payload is 0.02 - 1 Hz



The source of Fabry-Perot mirror reflection fluctuation: thermal noise

• The test masses are a part of a large, ground-based, digitally controlled, opto-mechanical system.

• The coordinate x of such a mechanical chain is probed by the ITF at the mirror level and can be considered in quasi-inertial state from 10 Hz.

• Each test-mass is not physically point-like and then, at thermal equilibrium the mirror surface as probed by the interferometer optics fluctuates due to thermal impulse fluctuation into its body and through the whole mechanical chain. According to the Fluctuation Dissipation Theorem (FDT):

$$SF_{xx} = 4kT \cdot \Re\{Z_{xx}\} \quad [N^2/Hz] \qquad SX_{xx} = \frac{4kT}{\omega^2} \cdot \Re\{Z^{-1}{}_{xx}\} \quad [m/\sqrt{Hz}]$$

Z is the mechanical impedance of the system, to be known (or measured) as a function of frequency in order to be inverted.

- **Callen H.B., Greene F., *On a Theorem of Irreversible Thermodynamics I-II*, *Phys. Rev.* 86-88, (1952) (fundamental).**
- Majorana E., Ogawa Y., *Mechanical thermal noise in coupled oscillators*, *PLA* 233 ,1997 (didactical essay).
- **Levin Y., *Internal thermal noise in the LIGO test masses: A direct approach PRD 57, 2, 1998 (revolutionary operative)***
- *P. Ruggi et al., Mechanical simulation tool based on impedance matrices, PRD, (2025) (ultimately deep and general)*

The source of Fabry-Perot mirror reflection fluctuation: thermal noise

$$F(t) = m\ddot{x} + \int_{-\infty}^{t} k(t-s)x(s)ds$$

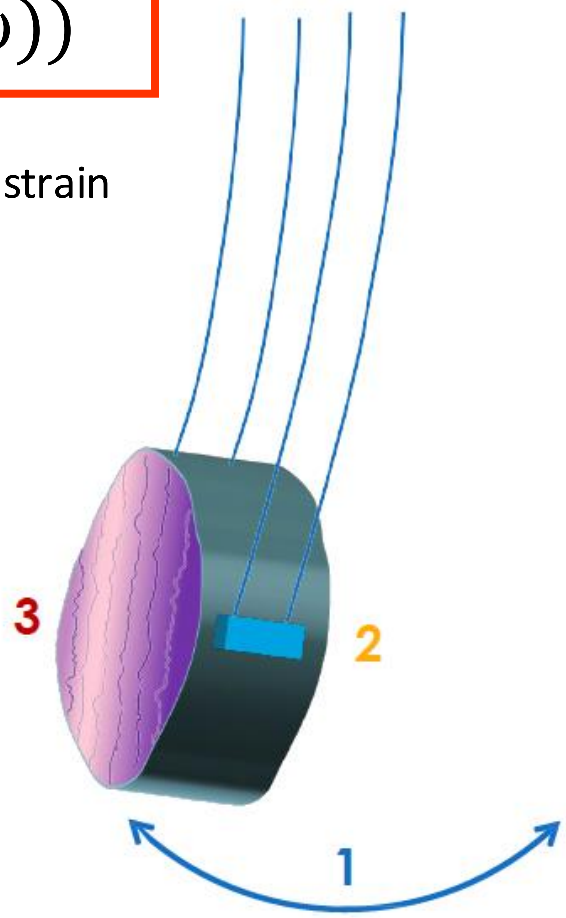
$$k(\omega) = k(1 + i\,\Phi(\omega))$$

Phenomenological model that accounts for phase lag between strss and strain
P. R. Saulson, Phys. Rev. D 42, 2437 (1990).

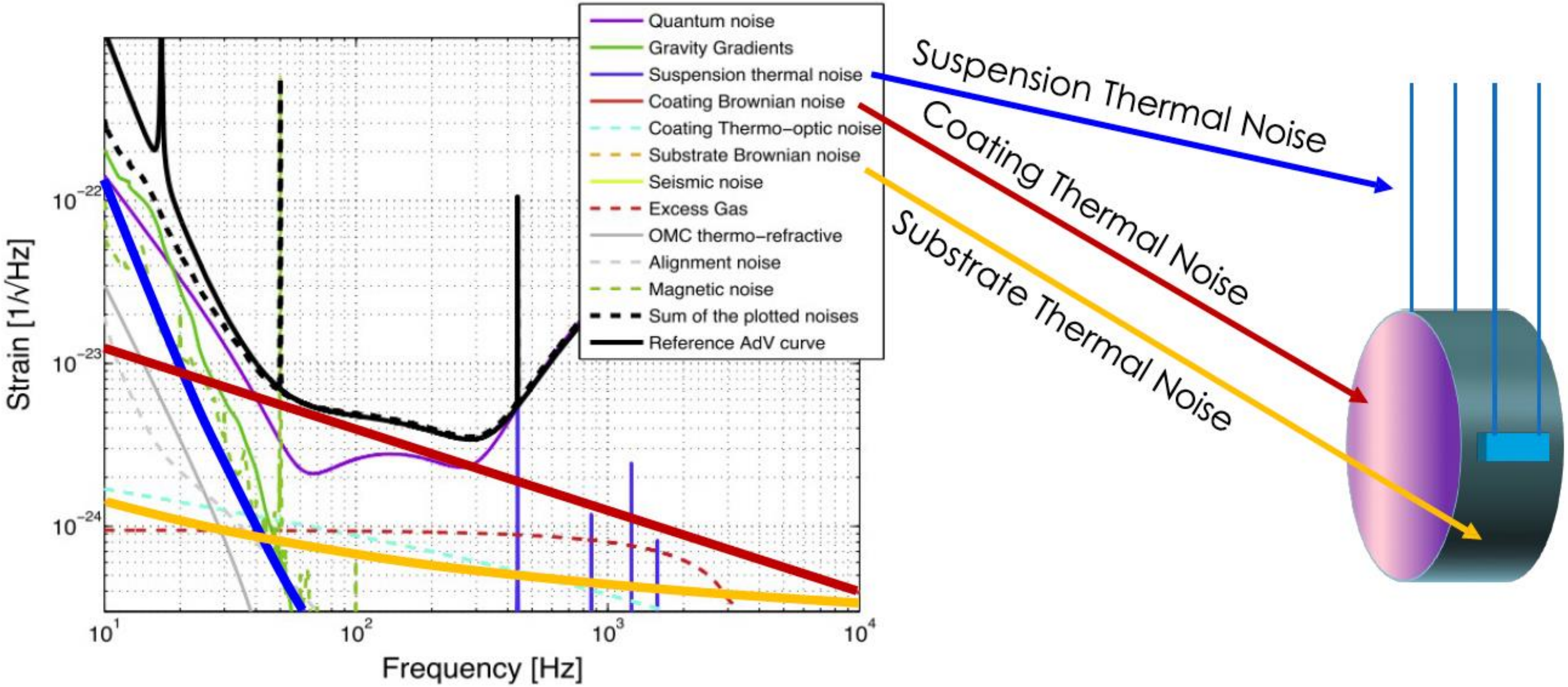
1. Rigid body motion of the mirror:
SUSPENSION NOISE

2. Deformation of the mirror substrate:
SUBSTRATE NOISE

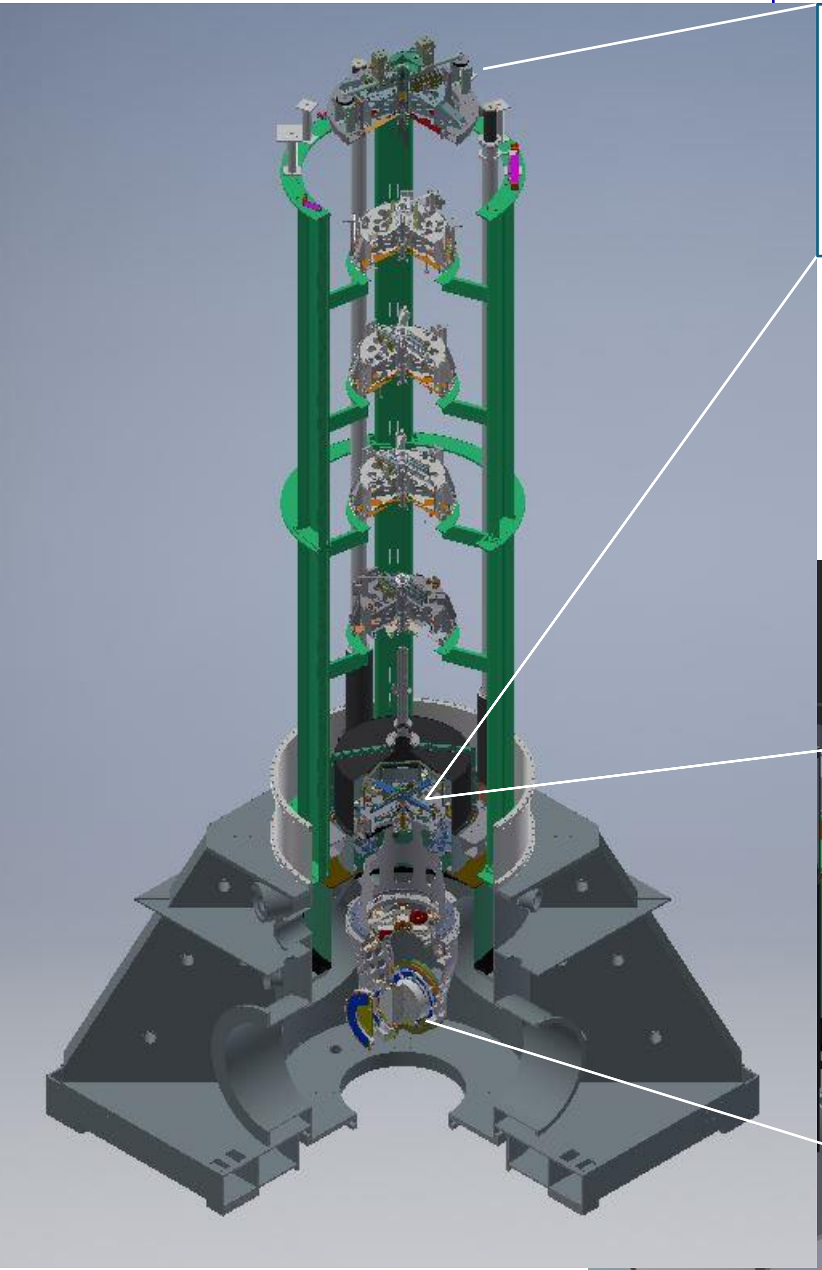
3. mechanical or optical fluctuation inside the Bragg mirror (several layers overlapped)
COATING NOISE



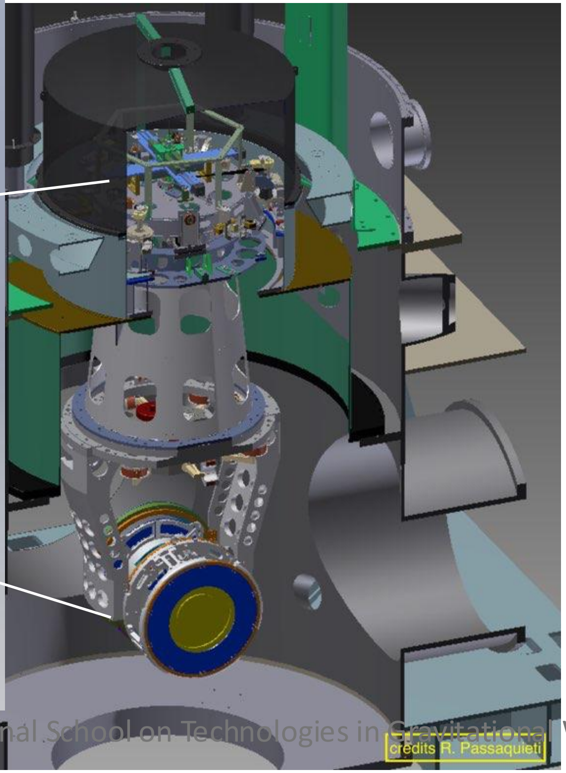
The source of Fabry-Perot mirror reflection fluctuation: thermal noise

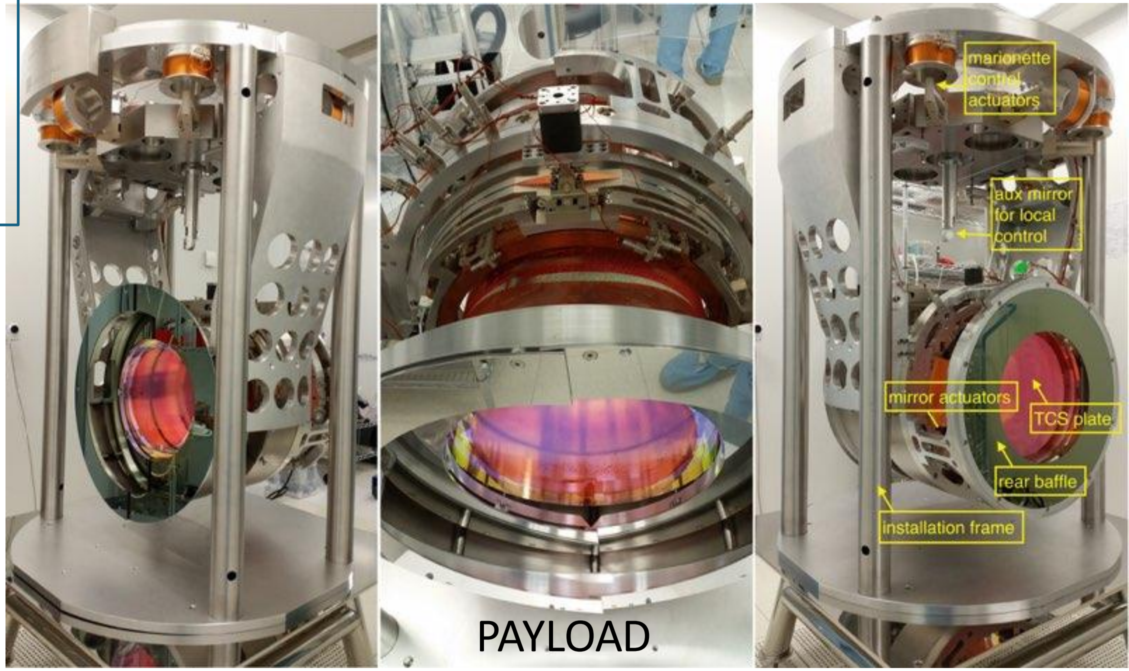


At room temperature



Example: in AdV the are 5 stages (horizontal and vertical) above tha payload contructed 25 years ago ~OK also for ET



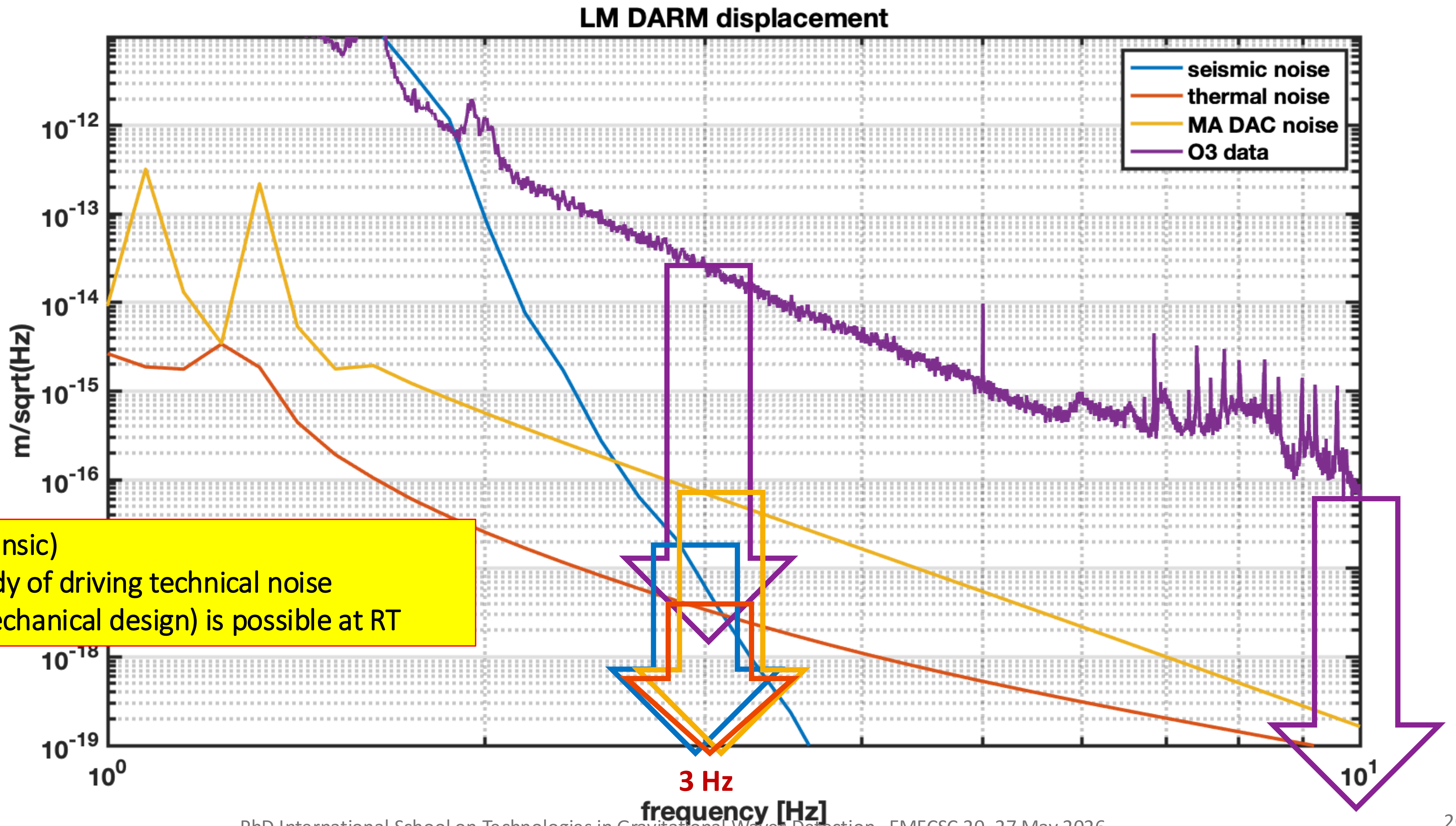


The payload (mirror + steering stages) is deployed through the bottom flange

The last mechanical filter is prolonged downwards, is in the same vacuum environment of the payload and surrounds it: it is the mirror "actuation cage".

The mirror dynamics is determined JUST by the controlled seismic isolation system and resonant beams

ET from Room Temperature prospective



A) TN (intrinsic)
B) The study of driving technical noise (electromechanical design) is possible at RT

Cryogenics: temperature and thermal noise

Which is the most appropriate temperature to operate cryogenics?

Two main benefits considering cryogenic <u>MATERIALS</u> VS <u>TEMPERATURE</u>

- Mirror thermal noise must be small enough (smaller thermal noise).
- Thermal lens must be enough small (smaller shot noise).

Cryogenics: temperature and thermal noise

Thermal noise basics: amplitude of thermal noise (off resonance) is proportional to:

$$x^2(\omega) = \frac{4k_BT}{\omega}\frac{k\phi(\omega)}{\left[(k-m\omega^2)^2 + k^2\phi(\omega)^2\right]}$$

$$\phi(\omega)_{viscous} = \frac{b}{k}\omega$$

$$\phi(\omega)_{structural} = const = \frac{1}{Q}$$

$(T/Q)^{1/2}$

Notice that in general Q = Q(T), the mechanical quality factor depends on temperature

- Specific investigations can be carried out, to define the best cryogenic region
- Also, the suspension mechanical design strongly matters, concerning the suspension thermal noise and its capability to isolate the test-mass once connected to the cryogenic system, for N point-like masses, it reads:

$$\langle X_{\mathrm{th}_i}(\omega)^2\rangle = \frac{4k_BT}{\omega^2}\mathrm{Re}\{(\mathbf{Z}_N(\omega)^{-1})_{ii}\}$$

- Test-Mass High_Q_AND_Low_T IS NOT ENOUGH FOR THE WIDE-BAND DETECTORS !!!

Levin's Formula for TN

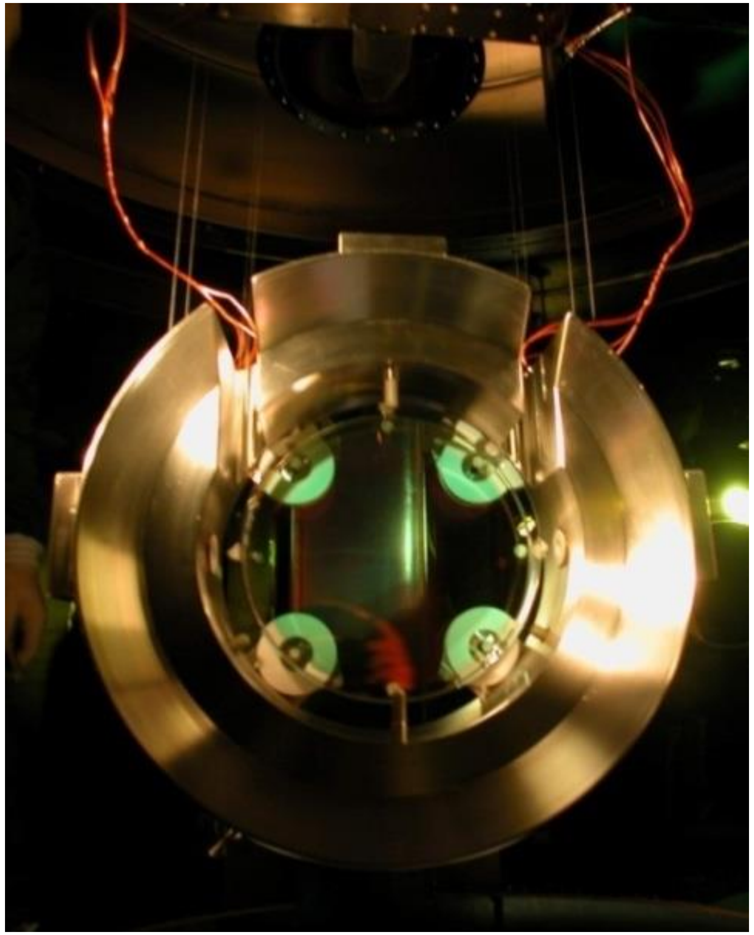
- Energy Equipartition on all the modes
- Only the modes coupled to the TEM matter

$$X^2_{therm} = \frac{4k_bT}{\omega}\sum_i \frac{\omega_i^2\varphi_i}{M_i}\frac{1}{\left((\omega_i^2-\omega^2)^2+(\omega_i^2\varphi_i)^2\right)}$$

$$\frac{1}{2}M_i\omega_i^2X^2 = E_i$$

M_i equivalent mass associated to the i-mode

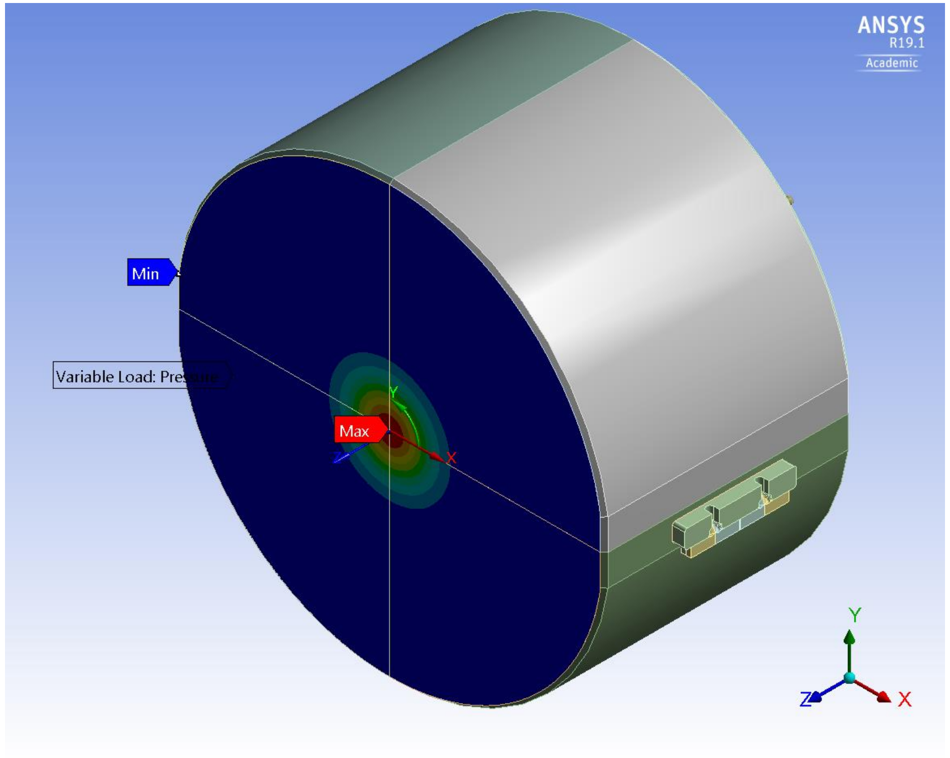
$$\varphi_i = \varphi_{str} + \varphi_{coat}$$



Levin's Formula for TN

every mechanical component may potentially couple to the beam

$$S_X^{FEM}(\omega) = \frac{4\,k_bT}{\omega\,F_o^2}\,2\,\left(\phi_{wires}E_{wires}(\omega) + \phi_{layers}E_{layers}(\omega) + \phi_{Mario}E_{Mario}(\omega) + \phi_{\substack{Silica\\parts}}E_{\substack{Silica\\parts}}(\omega) + \phi_{\substack{Mario\\Cable}}\,E_{\substack{Mario\\Cable}}(\omega)\,\ldots\right)$$



Strain energies $E_i(\omega)$ from the FEM applying a unitary gaussian force on the suspended mirror face.

Cryogenics: temperature and thermal noise: the famous case of the thermoelastic noise

At room T we can use fused silica, at low T this is not possible.

New materials (Sapphire, Silicon) are necessary for mirror substrate and fibers to suspend mirrors. Challenge !

Let’s consider the “**thermoelastic noise**”, that is just one of the well modelled components of the TN components that affect the overall suspended test mass system.

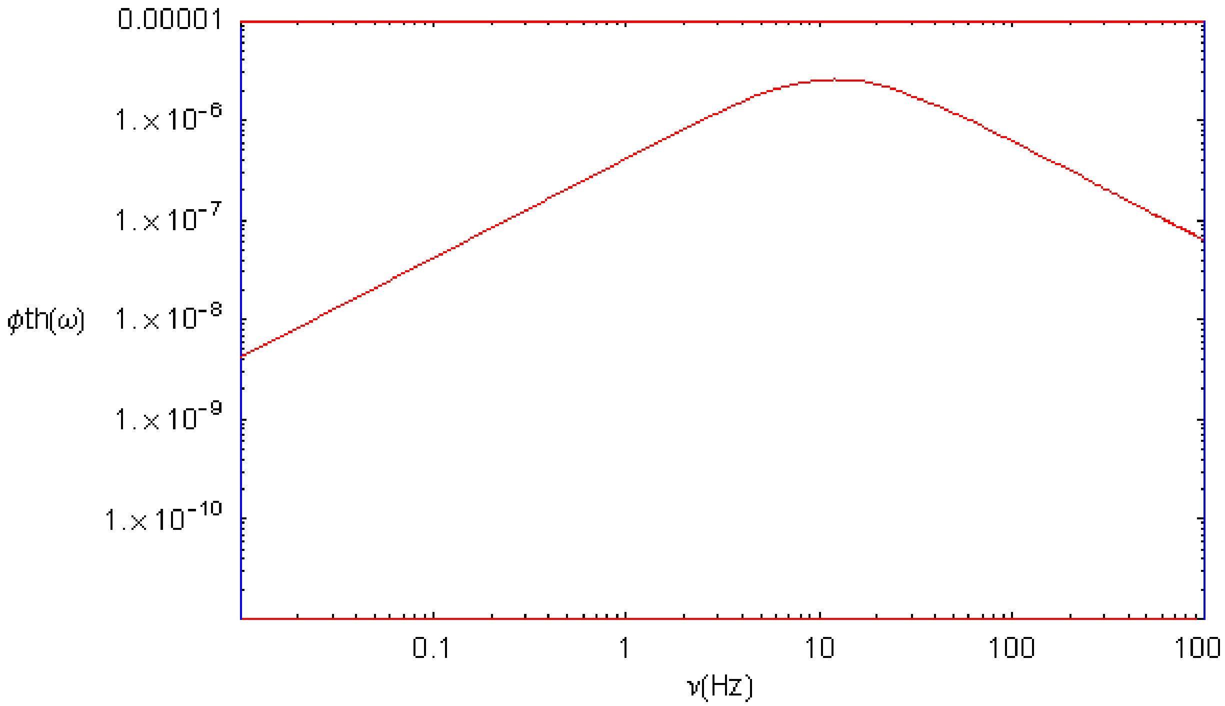
$$\varphi_s(\omega) = \varphi_{th}\ (\omega) + \varphi_{str} + \varphi_e$$

Since it strongly depends on *T*, in 2011 a dedicated study leading to ET focused on φ_{th} was done

25

The typical expression of thermal noise dissipation lag is:

$$\varphi_{th}(\omega) = \frac{Y\alpha^2 T}{\rho \quad C}\frac{\omega \quad \tau}{1 + (\omega \quad \tau)^2}$$



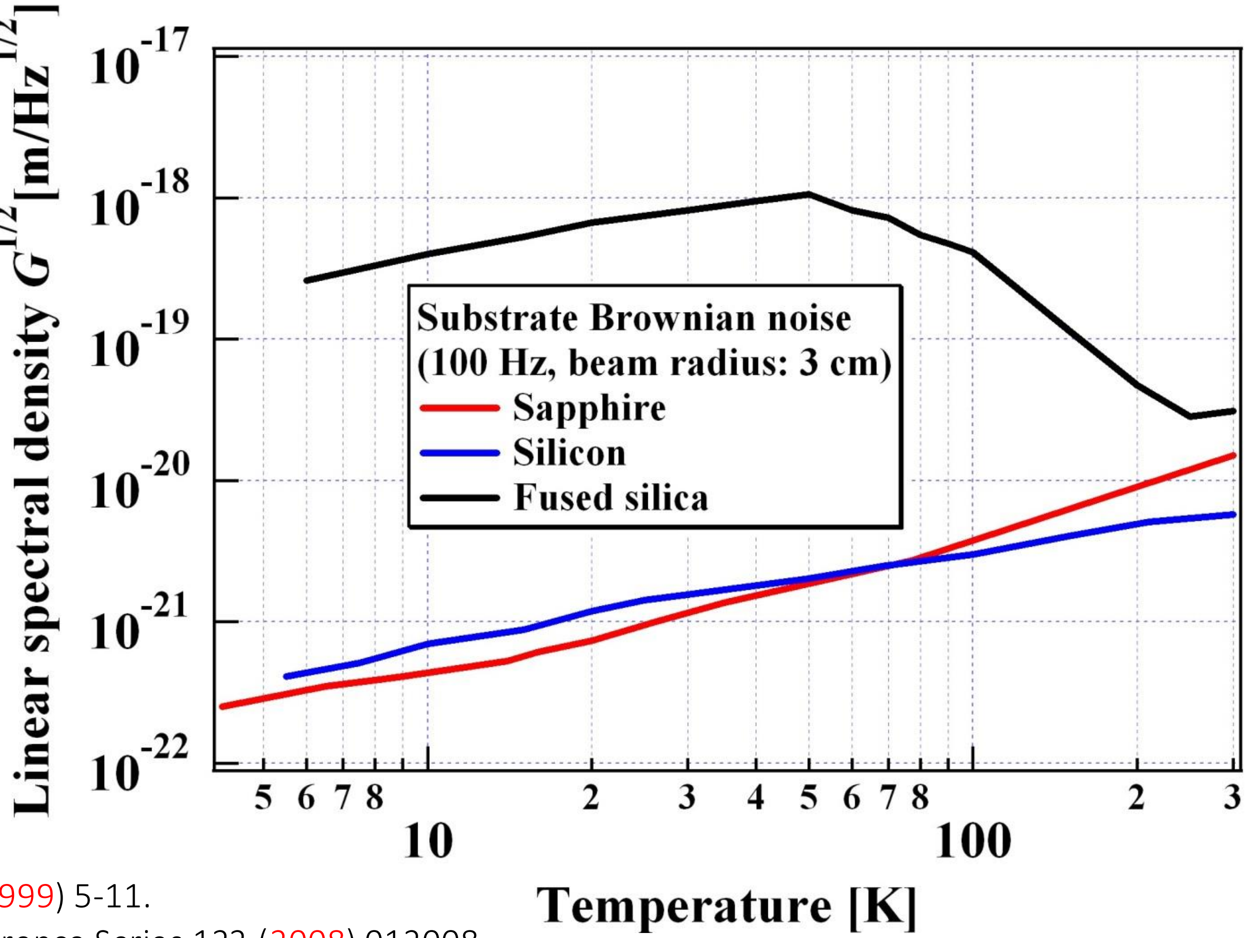
$Y =$ Young Mod.
$\alpha =$ Thermal Expansion coefficient
$\tau =$ Heat diffusion time constant (material and geometry)
$C =$ Heat capacity

For example, in case of room-T suspension, one can determine material and geometry. The same can be done adding the parameters T and $\alpha(T)$ and derive a temperature range at which φ_{th} is the lowest

Cryogenics: temperature and thermal noise

Temperature dependence of $(T/Q)^{1/2}$

$(T/Q)^{1/2}$

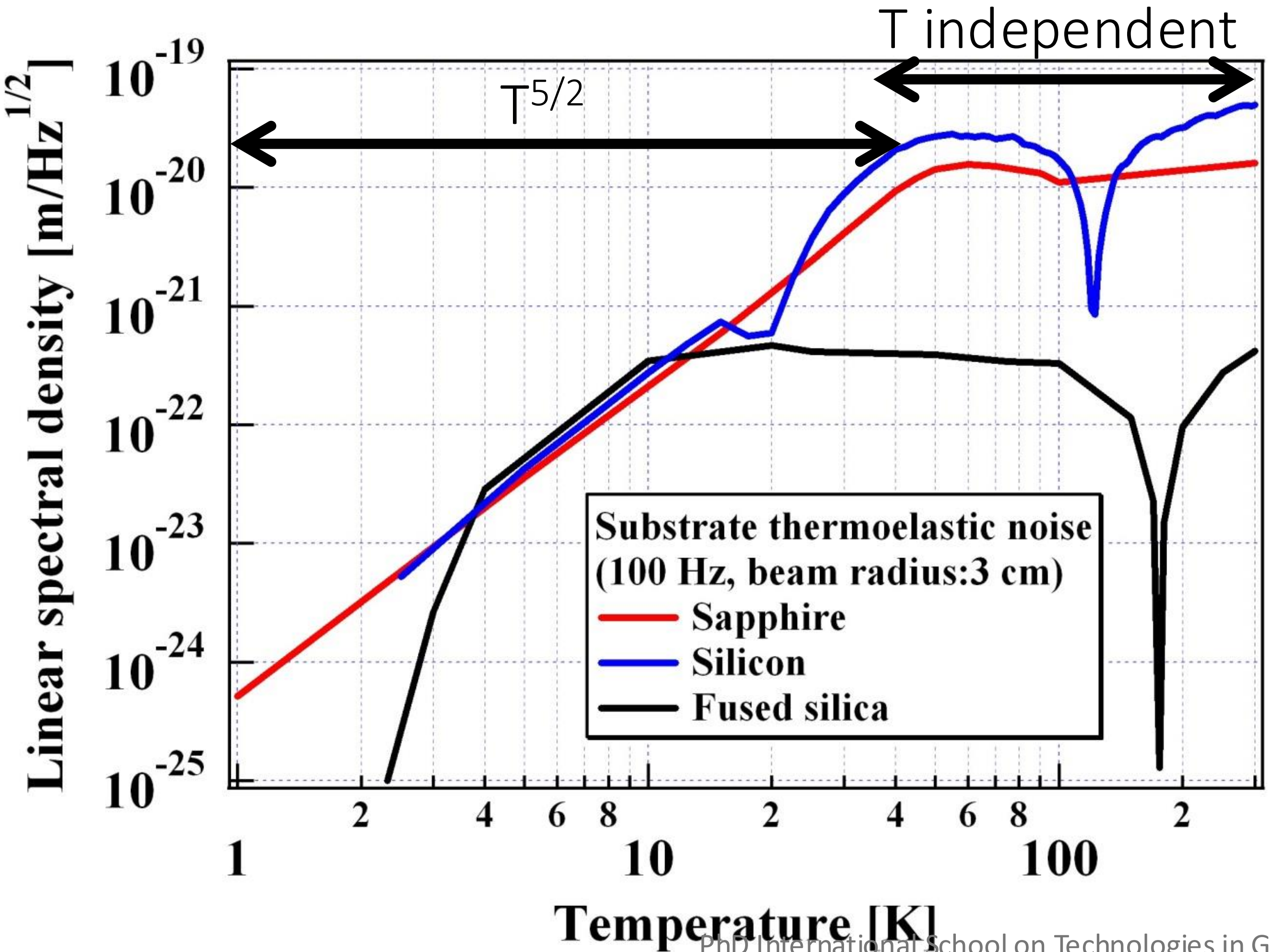


T. Uchiyama et al., Physics Letters A 261 (1999) 5-11.
R. Nawrodt et al., Journal of Physics: Conference Series 122 (2008) 012008.
C. Schwarz et al., 2009 Proceedings of ICEC22-ICMC2008.

Cryogenics: temperature and thermal noise

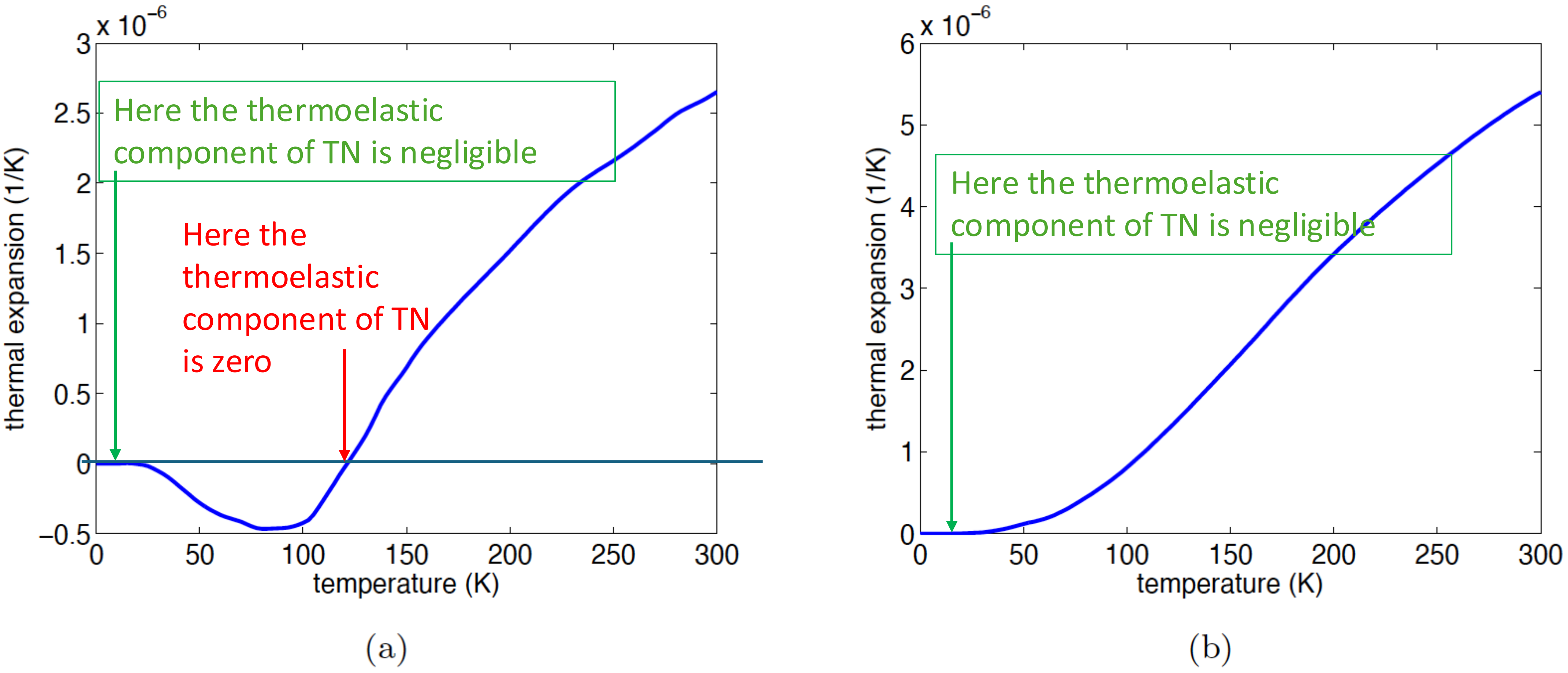
Thermal noise by thermoelastic damping (substrate)

M. Cerdonio et al., Phys. Rev. D 63 (2001) 082003.



Kenji Numata and Kazuhiro Yamamoto, "Chapter 8. Cryogenics", in "Optical Coatings and Thermal Noise in Precision Measurement" Cambridge University Press (2012).

Cryogenics: temperature and thermal noise



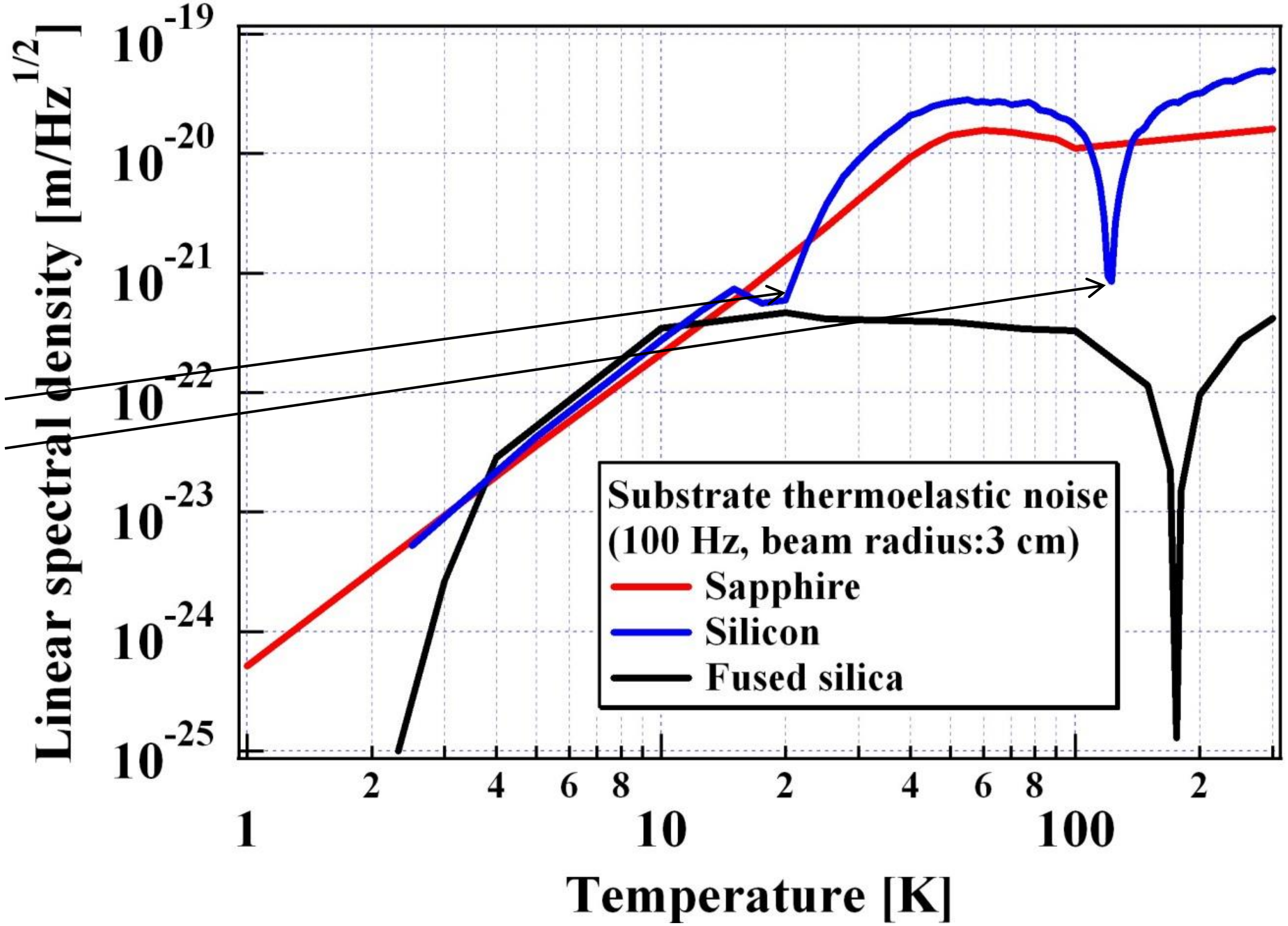
Dependence of the thermal expansion coefficient for Si (a) and Al_2O_3 (b) as a function of temperature

Cryogenics: temperature and thermal noise

Thermal noise by thermoelastic damping (substrate)

M. Cerdonio et al., Phys. Rev. D 63 (2001) 082003.

For crystalline Silicon there are specific T values where the thermal expansion is zero



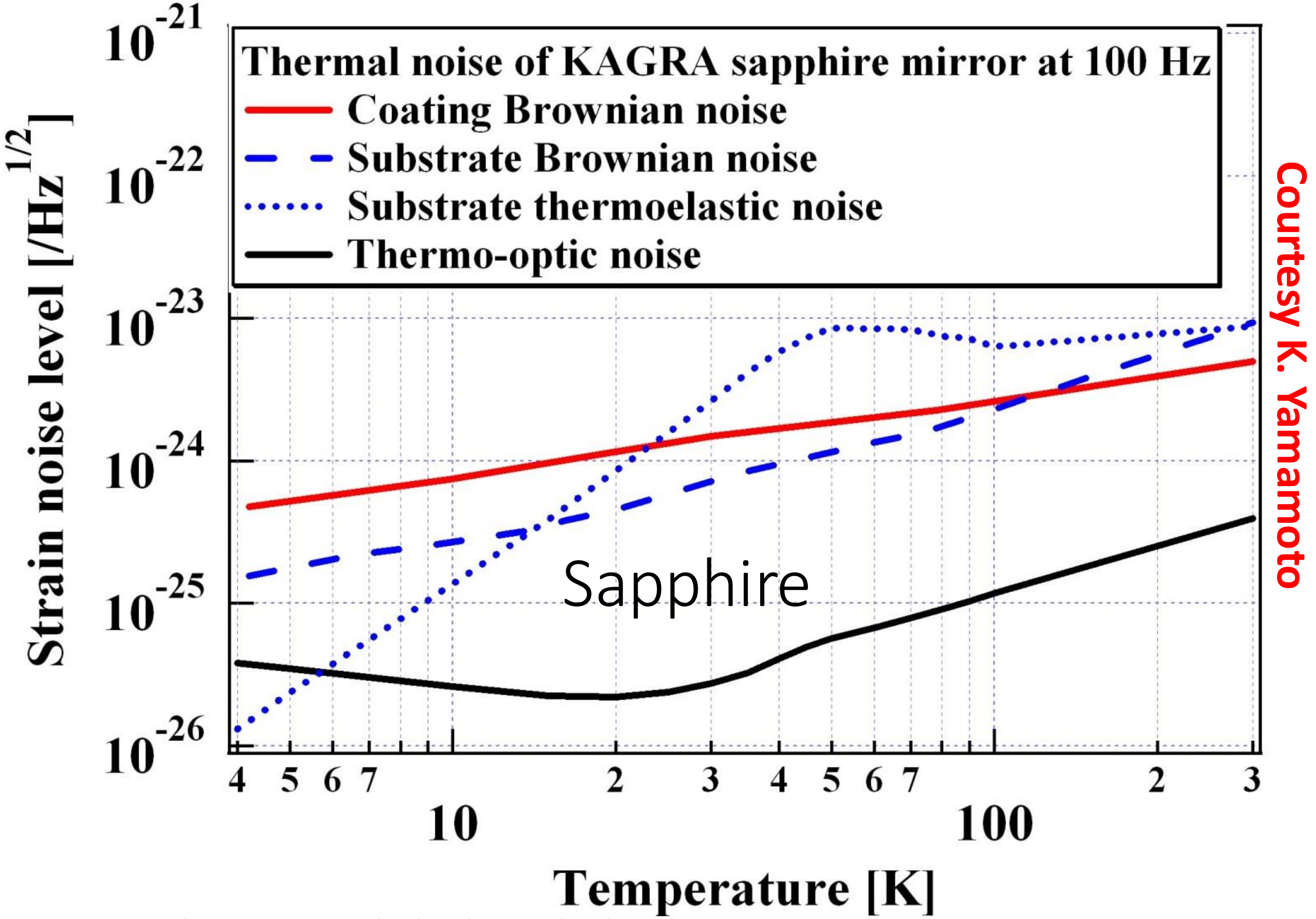
30

Cryogenics: temperature and thermal noise

Sapphire mirror:
thermoelastic noise is very low at low temperature

> 50K
Constant

<20K
Small
Enough



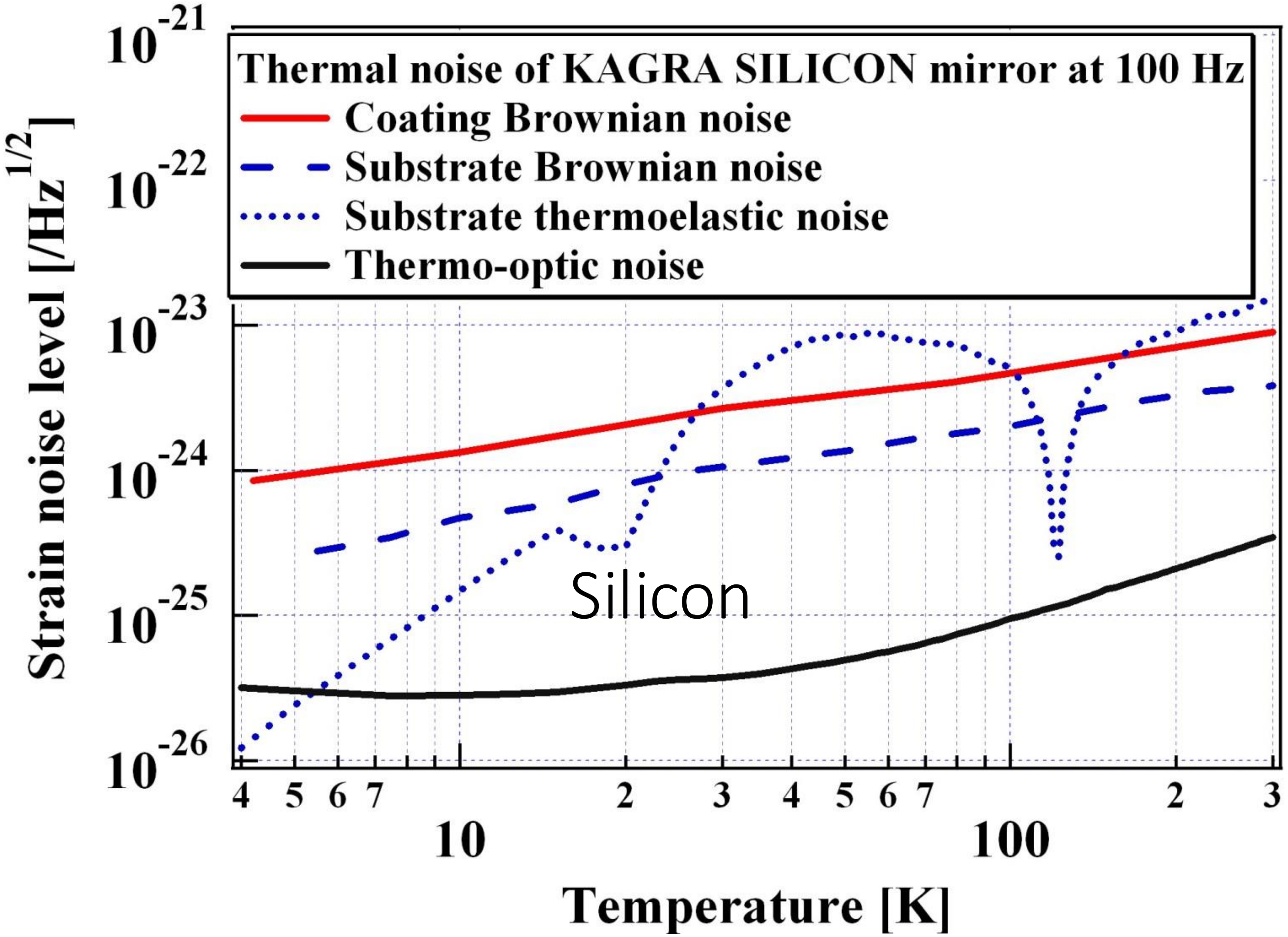
Cryogenics: temperature and thermal noise

Silicon mirror

Thermoelastic noise at low temperature is close or better than for sapphire.

At 120K
Thermoelastic noise
vanishes

BUT ! Very accurate temperature control is necessary

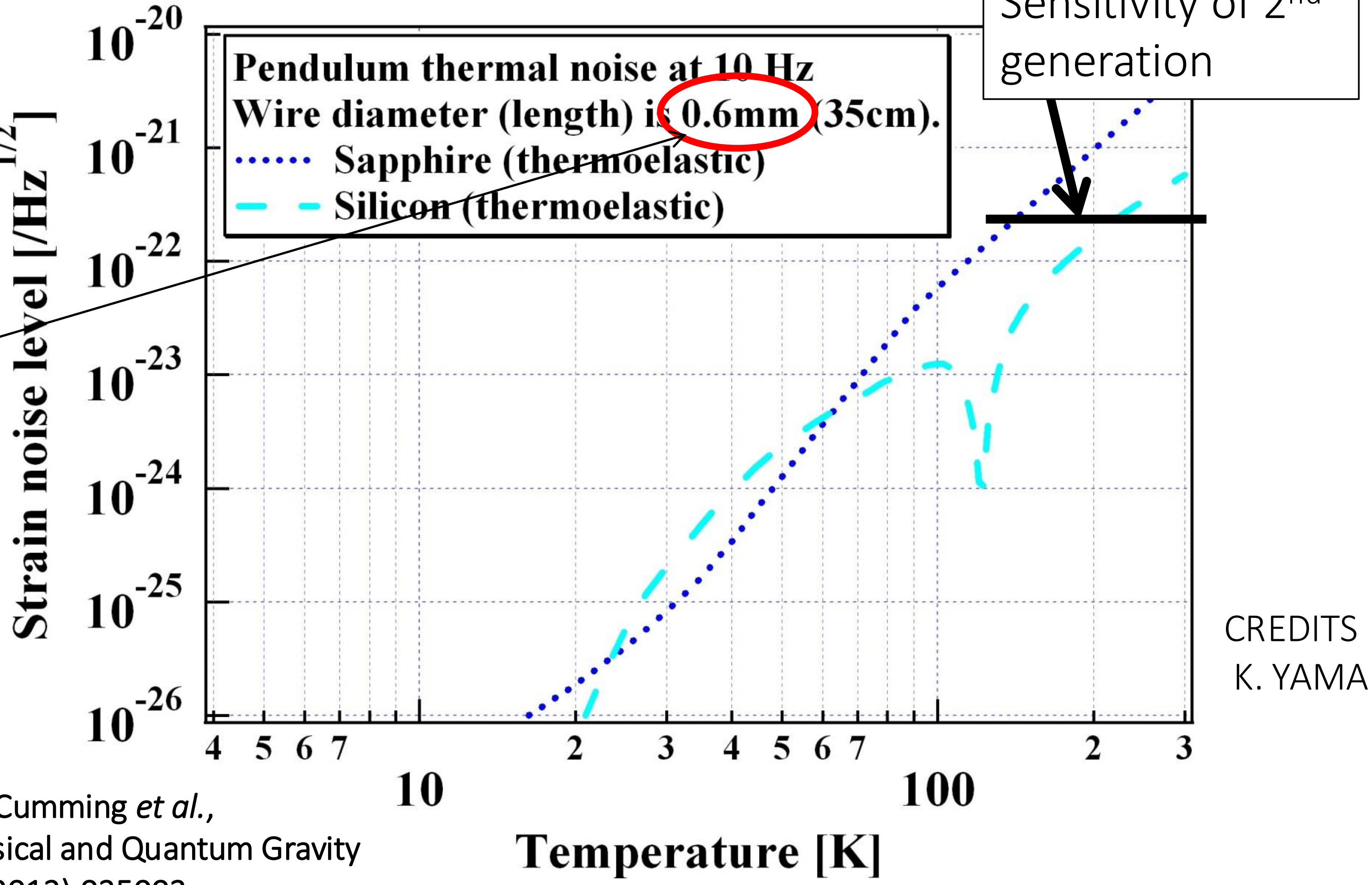


Courtesy K. Yamamoto

32

Thin VS thick fibers (needed to extract the heat) study (Thermoelastic)

- KAGRA Mirror is 23kg
- Thinnest wire (Wire strength limit)



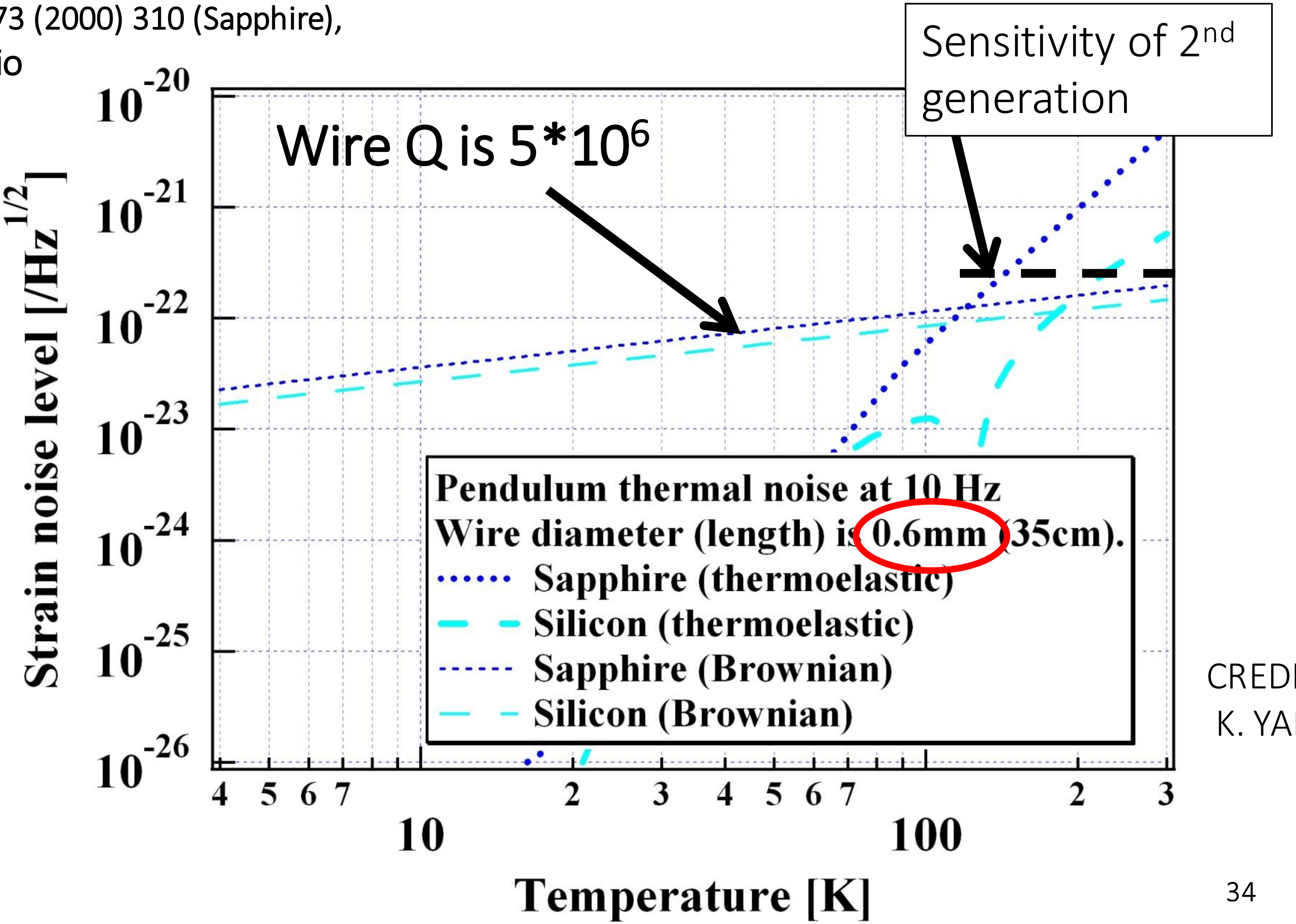
CREDITS
K. YAMAMOTO

Below 120K, thermoelastic noise does not matter.

A.V. Cumming *et al.*, Classical and Quantum Gravity 29 (2012) 035003.

Thin VS thick fibers (needed to extract the heat) study (Thermoelastic)

T. Uchiyama *et al.*, Physics Letters A 273 (2000) 310 (Sapphire), still considered as a target scenario

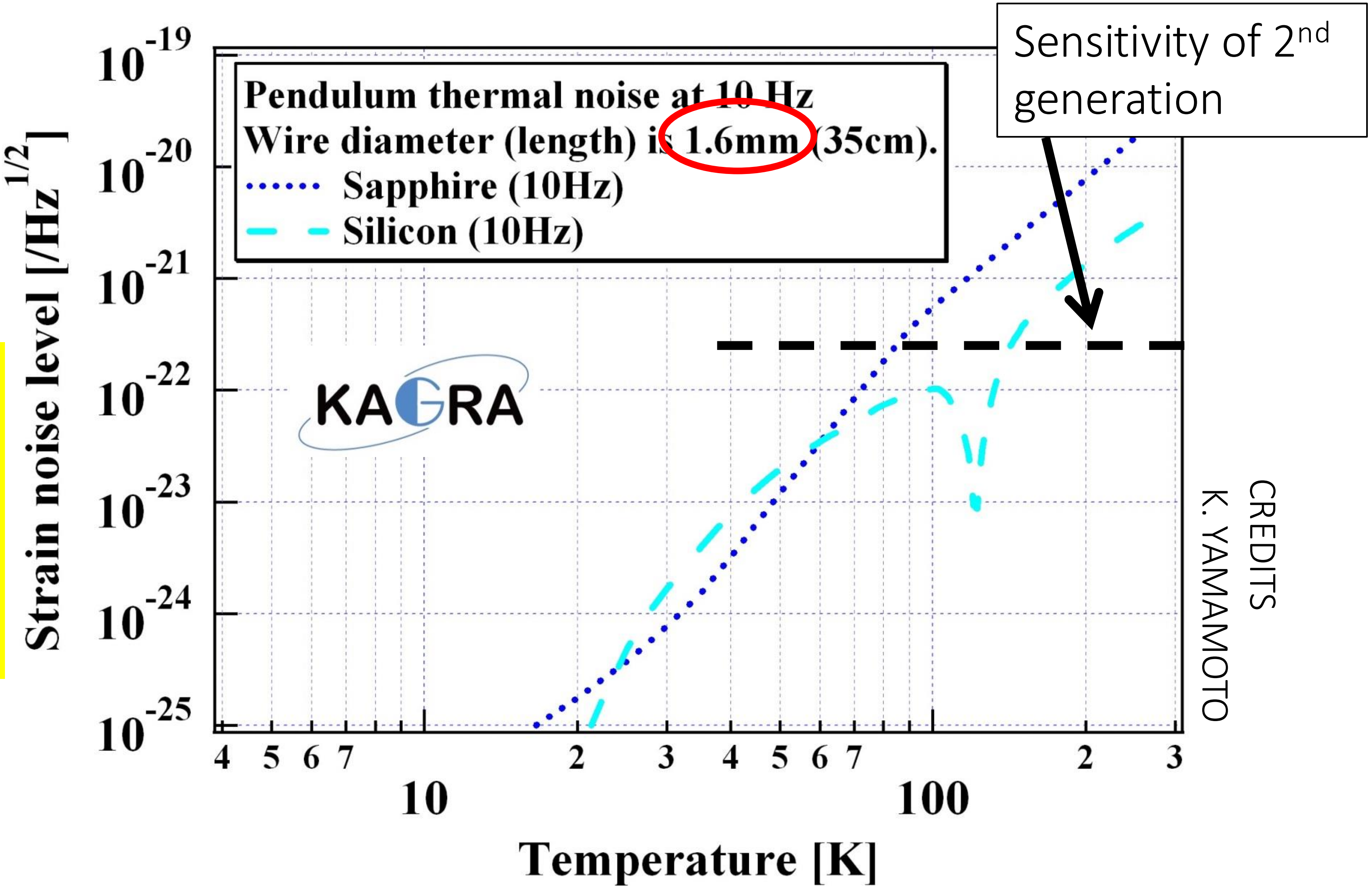


Below 120K, structure noise dominates but it does not matter.

CREDITS
K. YAMAMOTO

34

Thick fibers needed to afford thermal conductivity ! (Thermoelastic damping)



CREDITS
K. YAMAMOTO

Thermoelastic noise reduces drastically at cryogenic temperature.
Indeed Below 80K, it does not matter.

4 - Cryogenics spin-offs on actual interferometers (thermal lensing)

Cryogenics: Temperature Versus Thermal Lensing

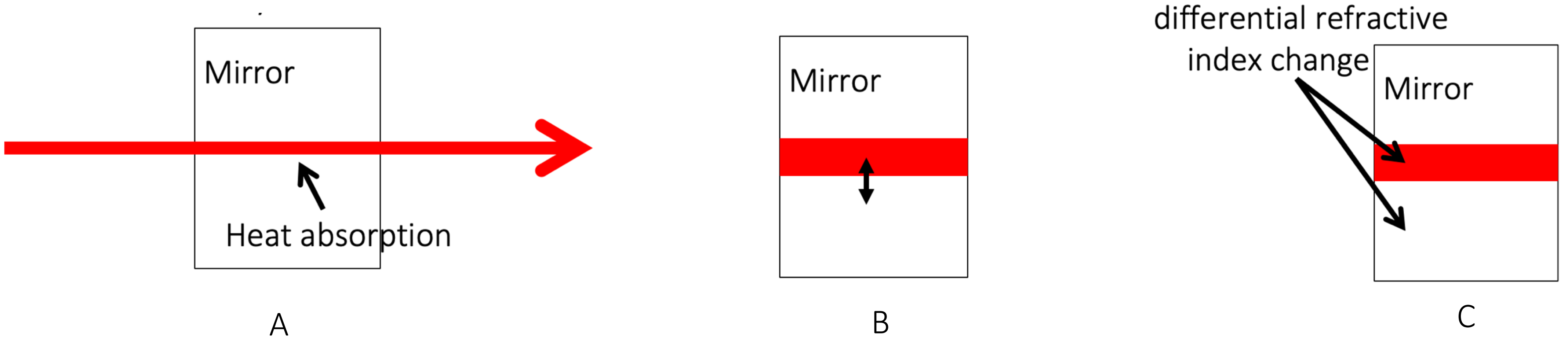
A) Light absorption in mirror

B) Temperature gradient

C) refractive index temperature dependence

➔ Wave-Front distortion

➔ Worse sensitivity



Cryogenics: Temperature and Thermal Lensing

- Advanced Virgo and LIGO: System to compensate thermal lens (compensation plate and ring heater) is one of the most relevant subsystems to operate the current (room Temperature) interferometers.

  G.M. Harry (for LSC), Classical and Quantum Gravity 27 (2010) 084006.
  - LIGO Scientific Collaboration, arXiv 1411.4547
  - ...

- 3G detector design already studied

Thermal compensation system in advanced and third generation gravitational wave interferometric detectors
- L Aiello et al 2019 J. Phys.: Conf. Ser. 1226 012019

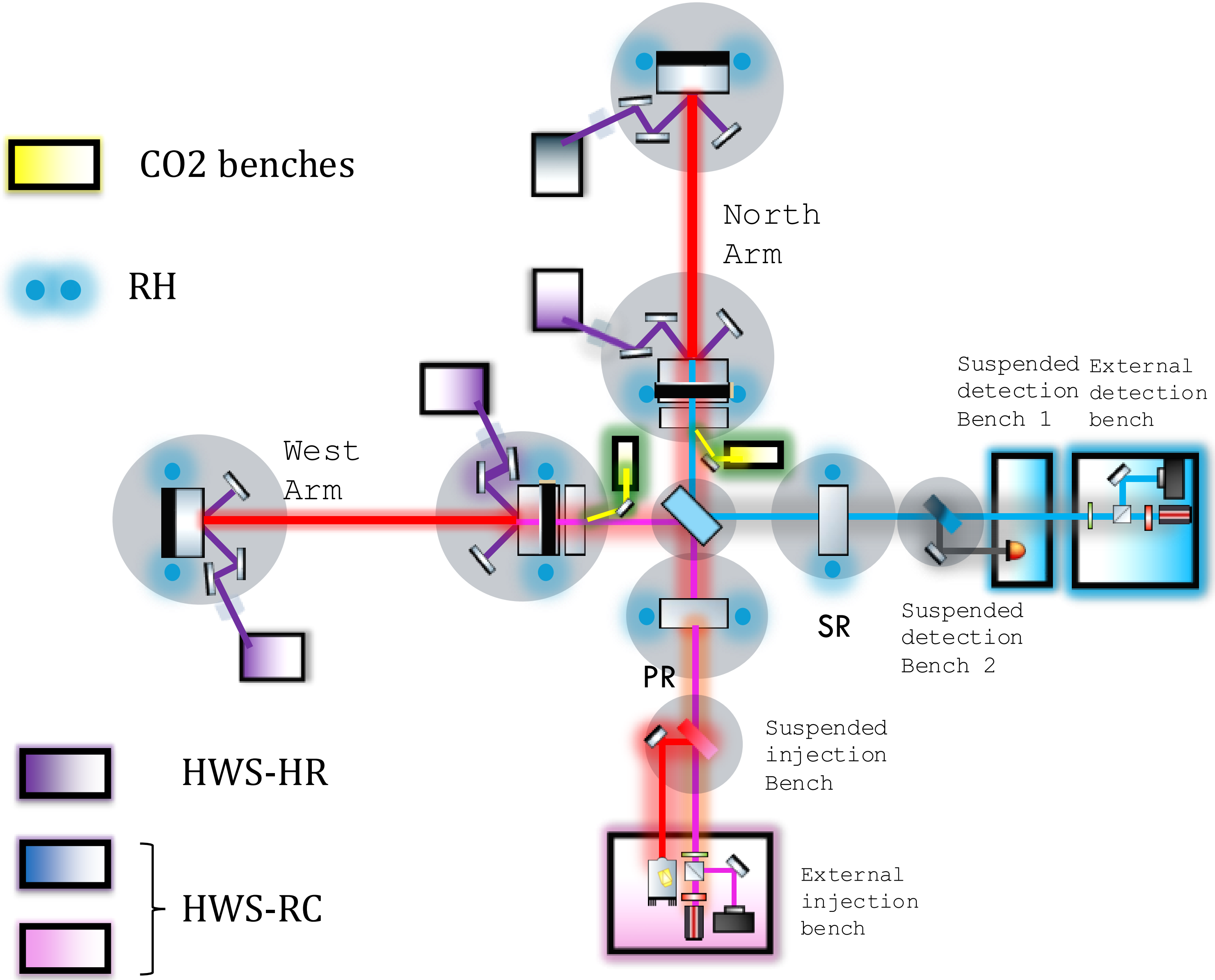
Virgo TCS, *layout*

TCS actuators :

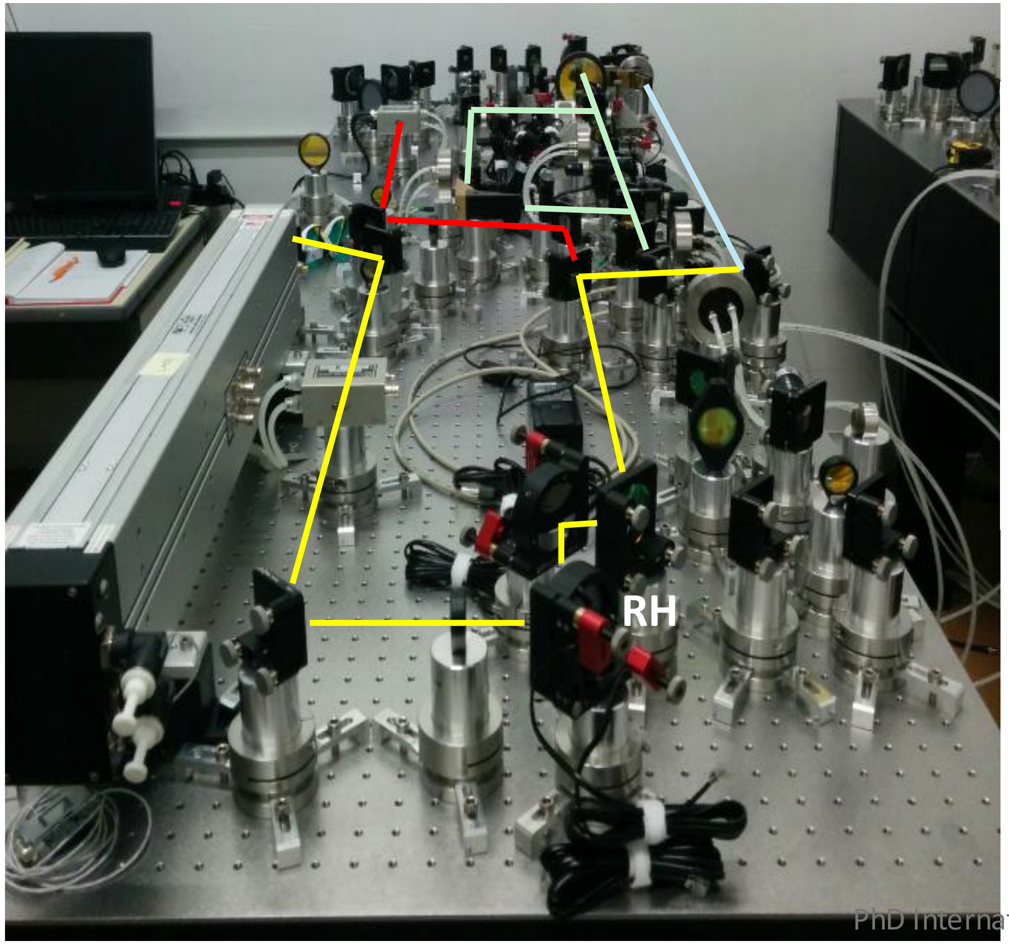
- ✓ CO_2 laser projector corrects thermal lensing
- ✓ Ring Heater (RH) acts on the thermoelastic deformation of the HR surface

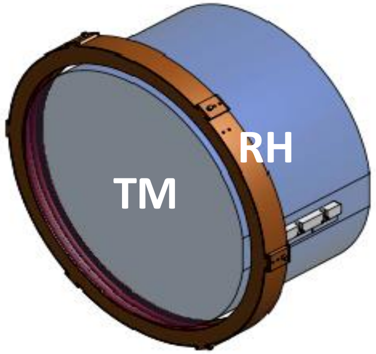
TCS sensing :

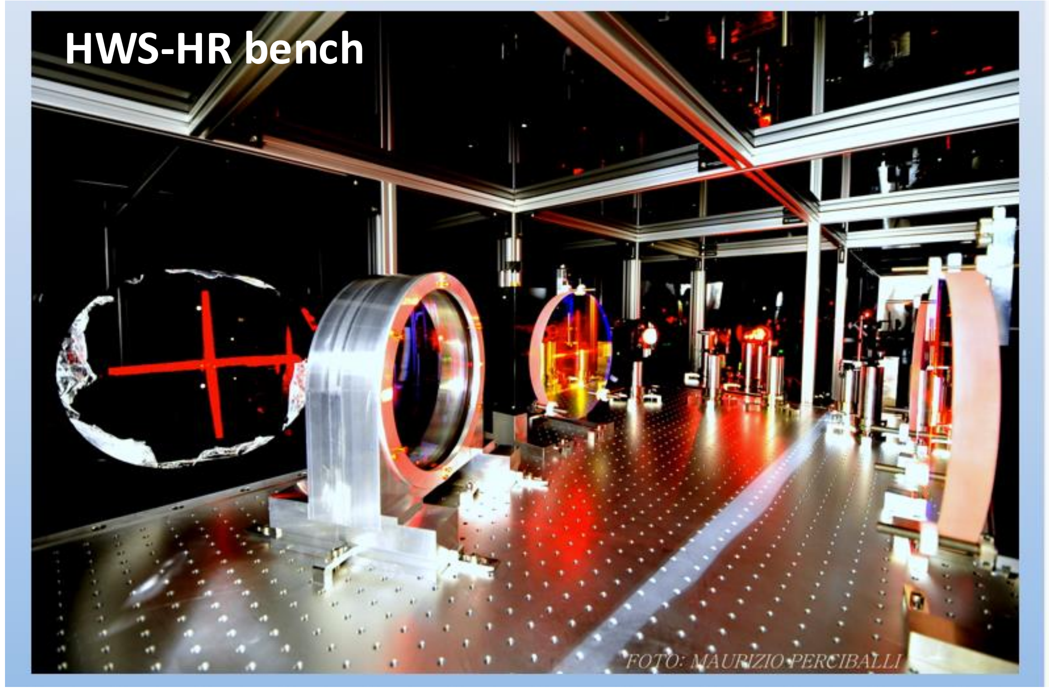
- ✓ Wavefront sensors (HWSs) in the recycling cavity to measure thermal lensing (HWS-RC)
- ✓ HWSs probing each TM surface to measure the thermoelastic effect (HWS-HR)

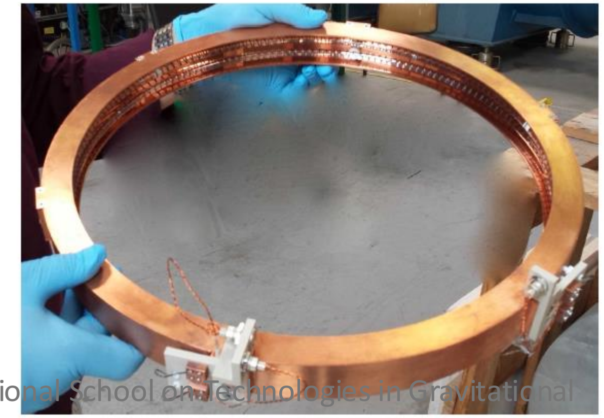


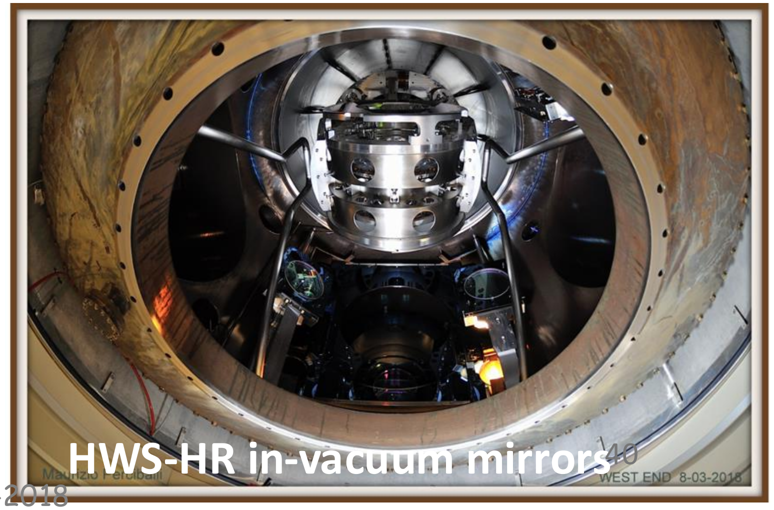
TCS, AdV Thermal Compensation System





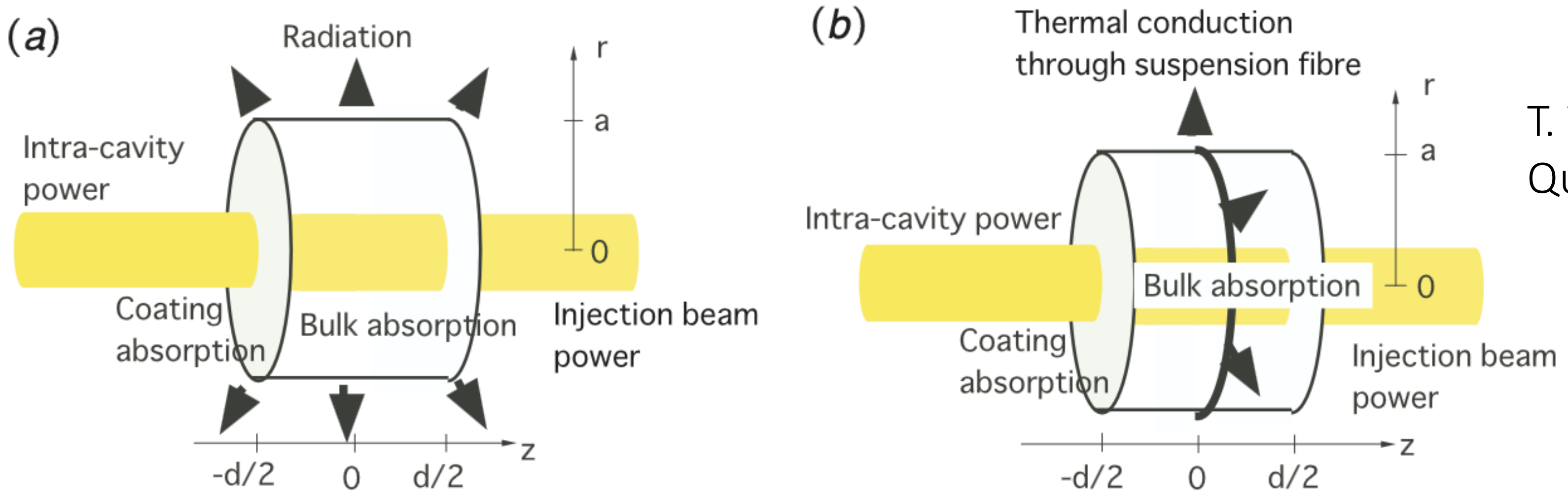






Cryogenics: Temperature and Thermal Lensing

Thermal lensing in Sapphire VS Silica below 20 K



T. Tomaru et al., Classical and Quantum Gravity 19 (2002) 2045

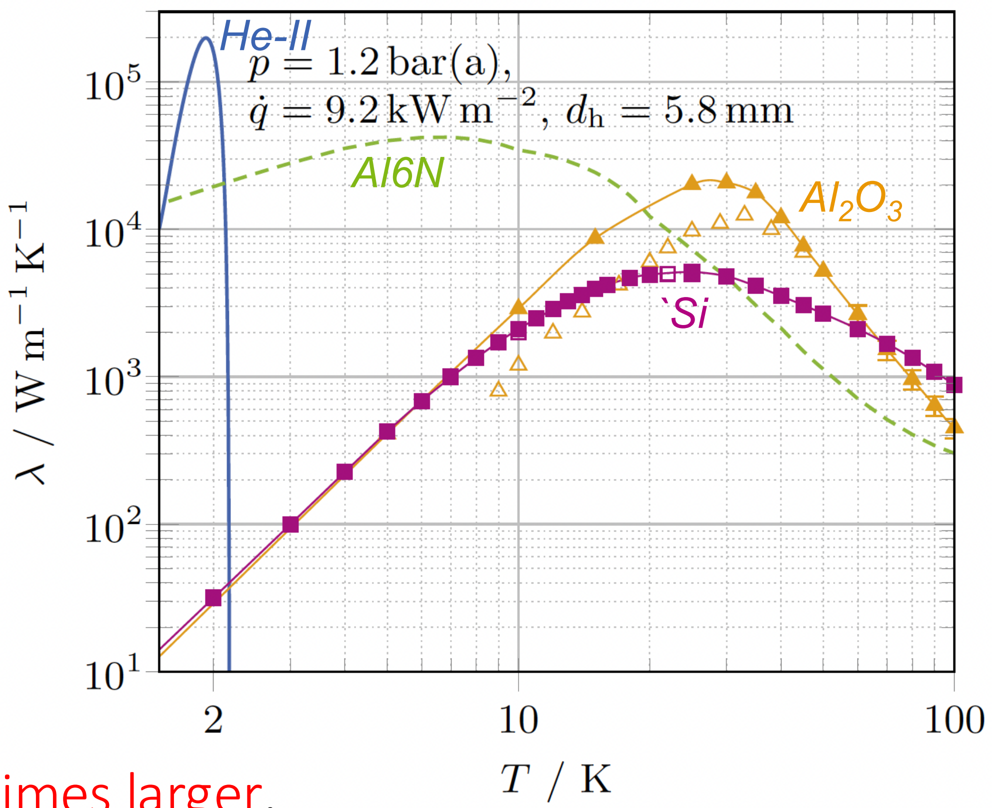
- Al_2O_3 Temperature coefficient of refractive index (β) is at least 100 times smaller
- Al_2O_3 Thermal conductivity (κ) of sapphire at 20 K is 10000 times larger than that of fused silica at 300 K
- Magnitude of thermal lensing: β / κ ➔ > 10^6 times smaller than that for fused silica

Cryogenics: Temperature and Thermal Lensing

Thermal lensing in Silicon

If T≈15-20 K, thermal lensing of Si can be predicted to be x2 that for Al_2O_3

In the case of T≈120 K, less effective (careful investigation is still needed).



- Temperature coefficient of refractive index (β) is comparable to that of fused silica at 300 K.
- Thermal conductivity (κ) of silicon at 120 K is 1000 times larger.
- Magnitude of thermal lensing:

β / κ ➔ > 10^3 times than that for fused silica

Cryogenics: Temperature and Thermal Lensing

Thermal lens in cooled sapphire and silicon is extremely smaller than at room temperature fused silica.

In principle @20K NO THERMAL COMPENSATION SYSTEM as in Virgo or LIGO

J. Degallaix Chap. 14 Cryogenic interferometers in "Advanced Gravitational Wave Detectors" Cambridge University Press 2012

Silicon at 120 K ➔ Small but not so much. Details must be checked carefully.

20K ➔ Very small. No compensation system is necessary at least for Sapphire. In view of very large power in cavities the bottleneck is indeed the heat to be extracted but not merely the the lensing.

ET Pathfinder will test "mild cryogenics" (much cheaper) using small Silicon mirrors at 120K, the rush towards large Silicon masses and 1550 nm wavelength started mainly upon TN reasoning

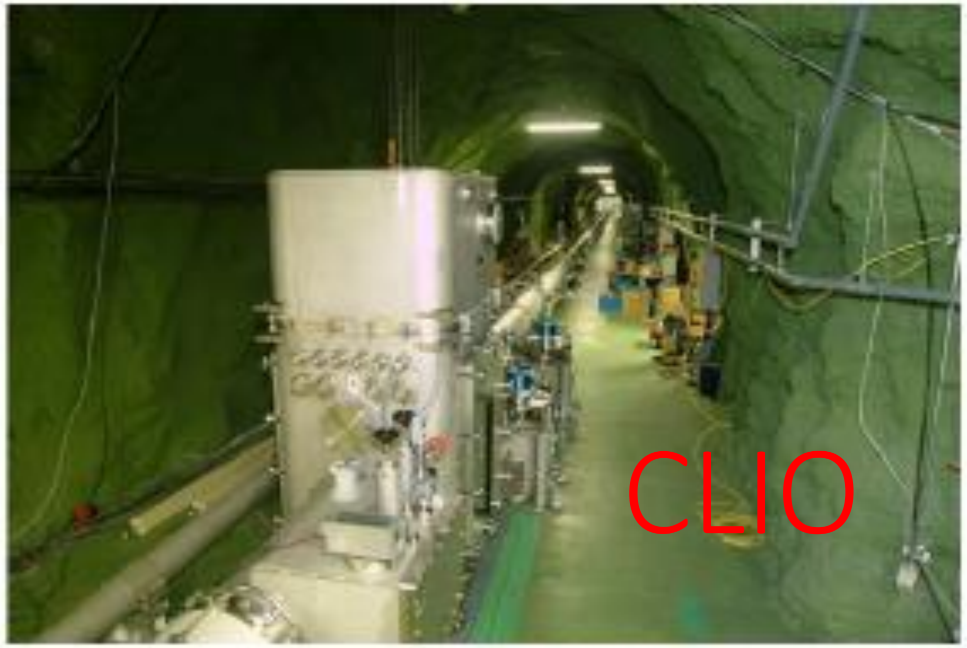
5 - What we have (a glance at KAGRA) and the feasibility of technology porting to ET

Cryogenics: Introduction, TM materials

List of cryogenic interferometric gravitational wave detectors constructed

CLIO (Japan, Sapphire, 100m)

KAGRA (Japan, Sapphire, 3km)



- T. Uchiyama et al., PRL 108 (2012) 141101.

Cryogenics: Introduction, TM materials

List of cryogenic interferometric gravitational wave detectors constructed

CLIO (Japan, Sapphire, 100m)

KAGRA (Japan, Sapphire, 3km)

Future plans, planned

Voyager (U.S.A., Silicon, 4km, LIGO facility)

Einstein Telescope (Europe, Silicon, 10km)

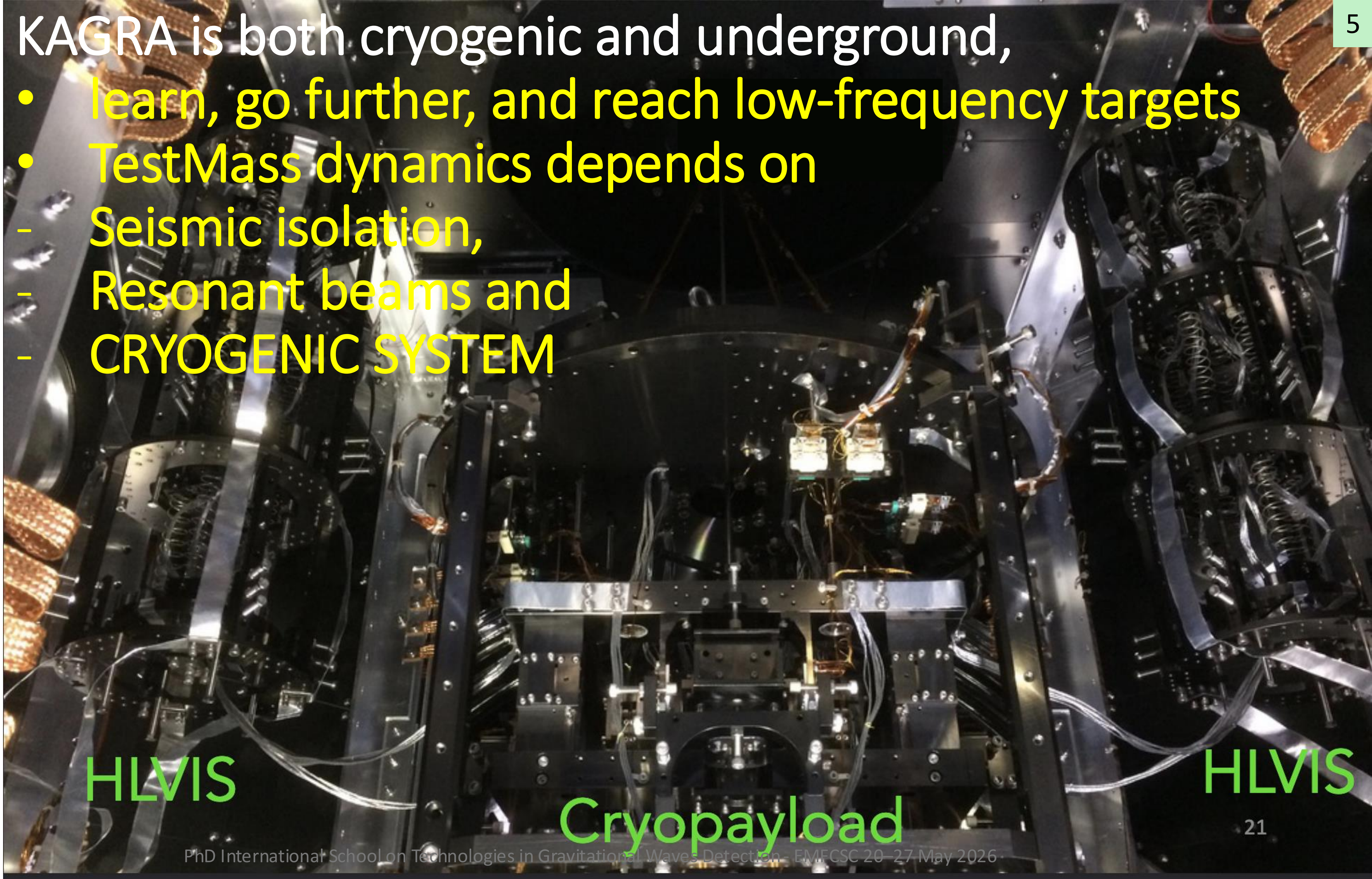
Cosmic Explorer (U.S.A., Silicon, 40km) (very preliminary)

Cryogenics versus low frequency:

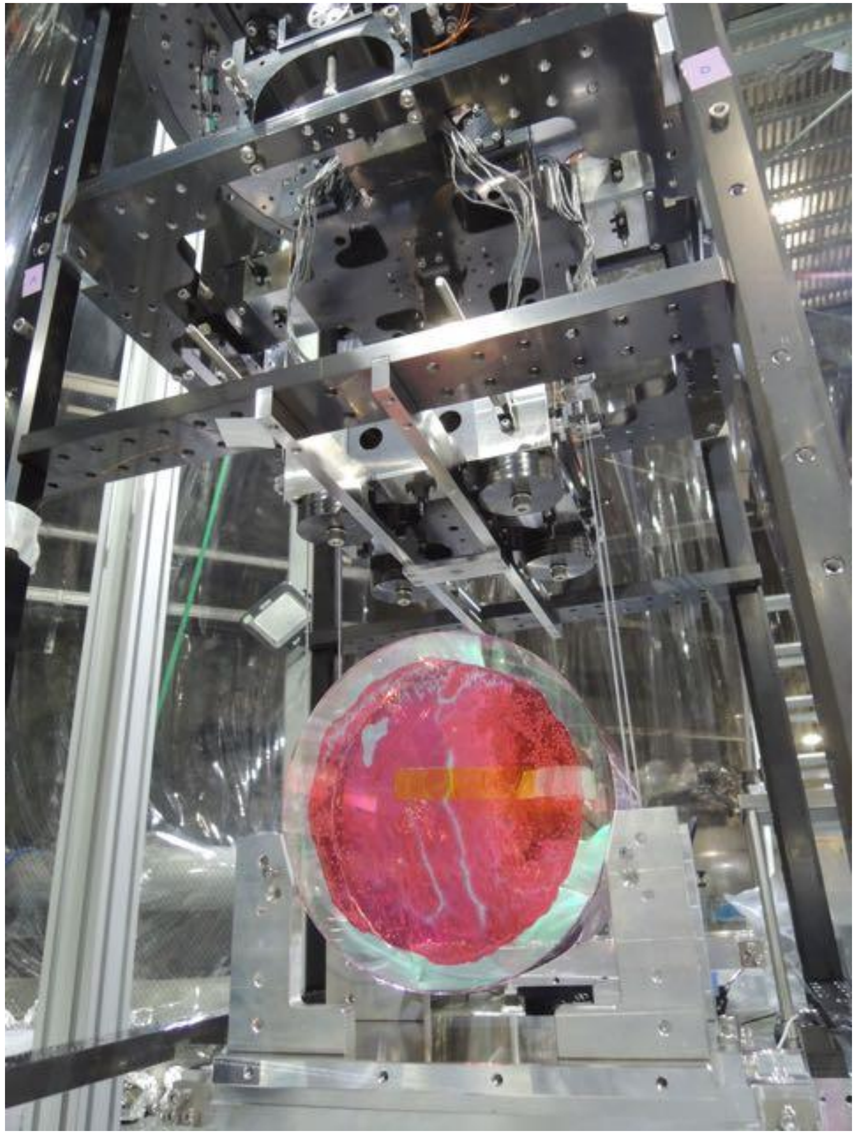
often too easily *assumed* as feasible….

KAGRA is both cryogenic and underground,

- learn, go further, and reach low-frequency targets
- TestMass dynamics depends on
- Seismic isolation,
- Resonant beams and
- CRYOGENIC SYSTEM



Cryogenics: Introduction, TM materials

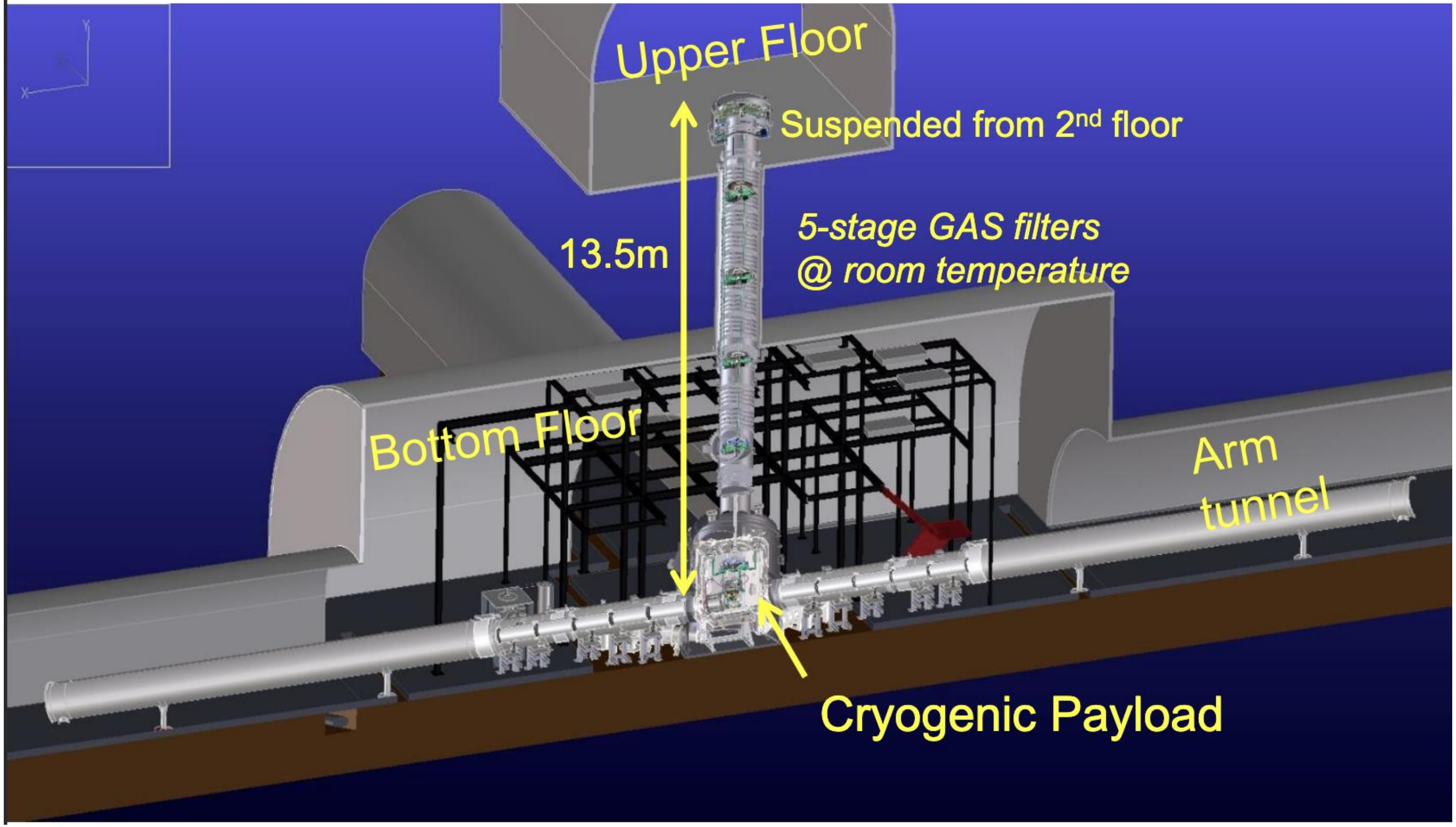


KAGRA: test mass and suspension are made of Al_2O_3

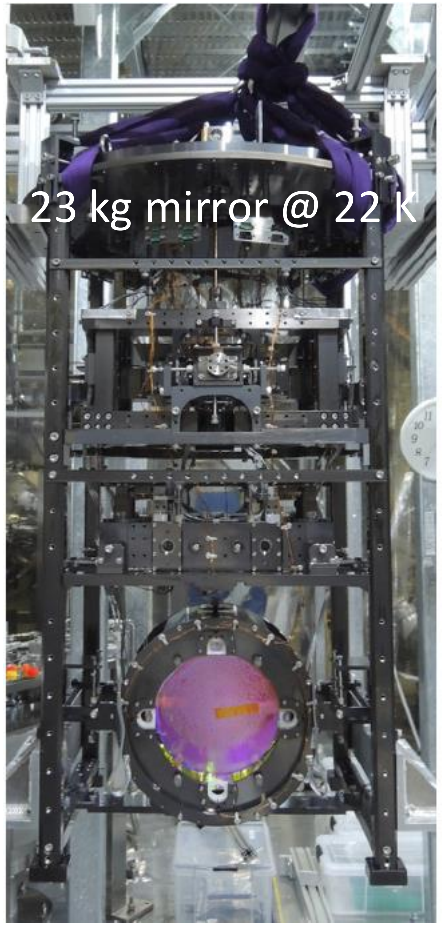
T. Akutsu et al., Progress of Theoretical and Experimental Physics, (2021) 05A101

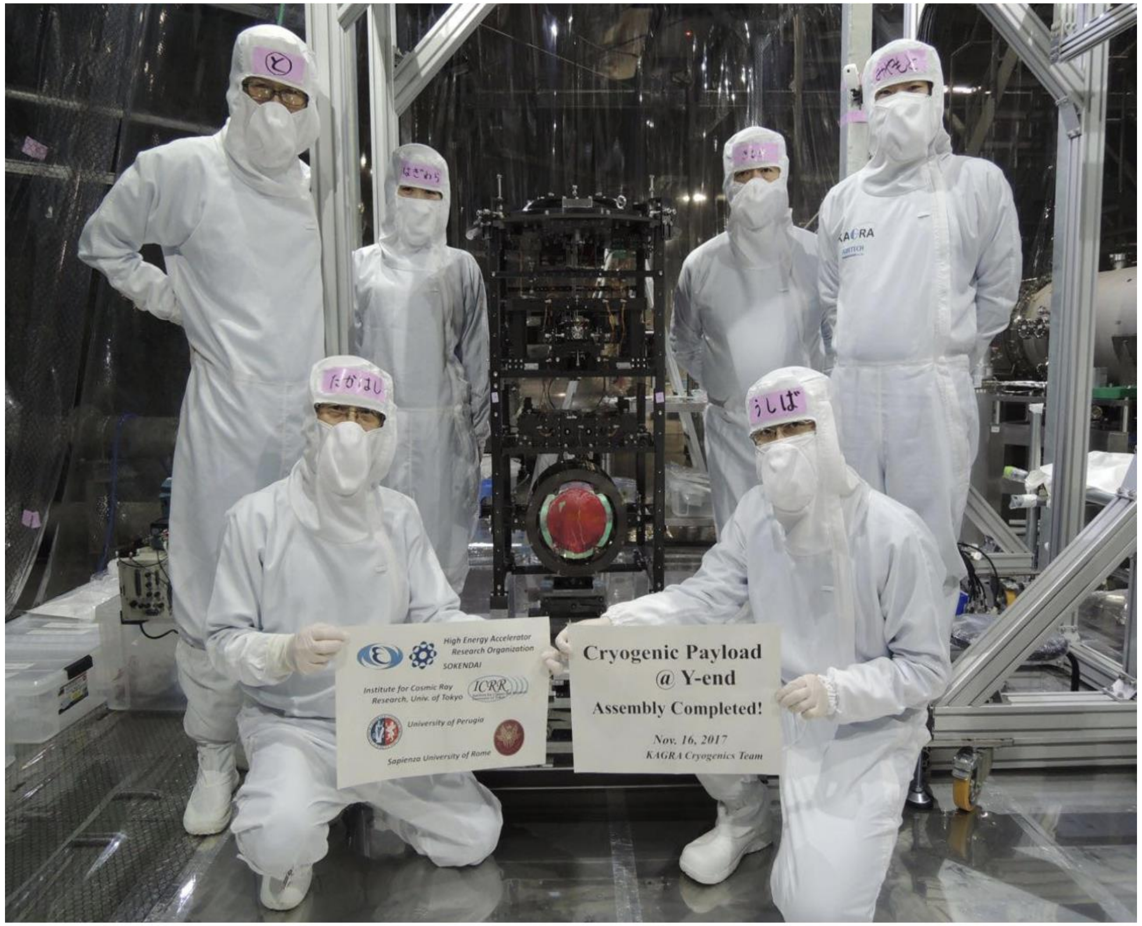
The cryogenic experience Japanese detector KAGRA

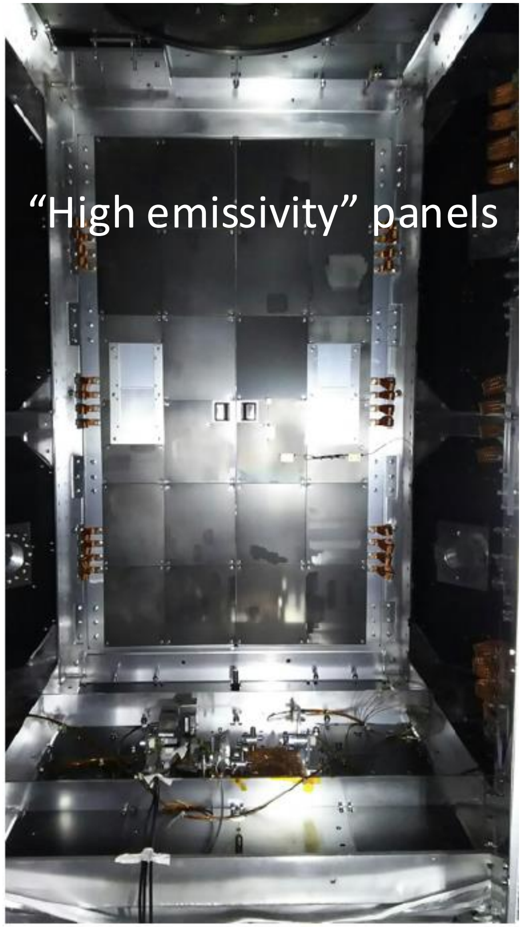
9-stage 13.5-m suspension for vibration isolation with a cryogenic mirror



KAGRA implemented cryogenics in 2017



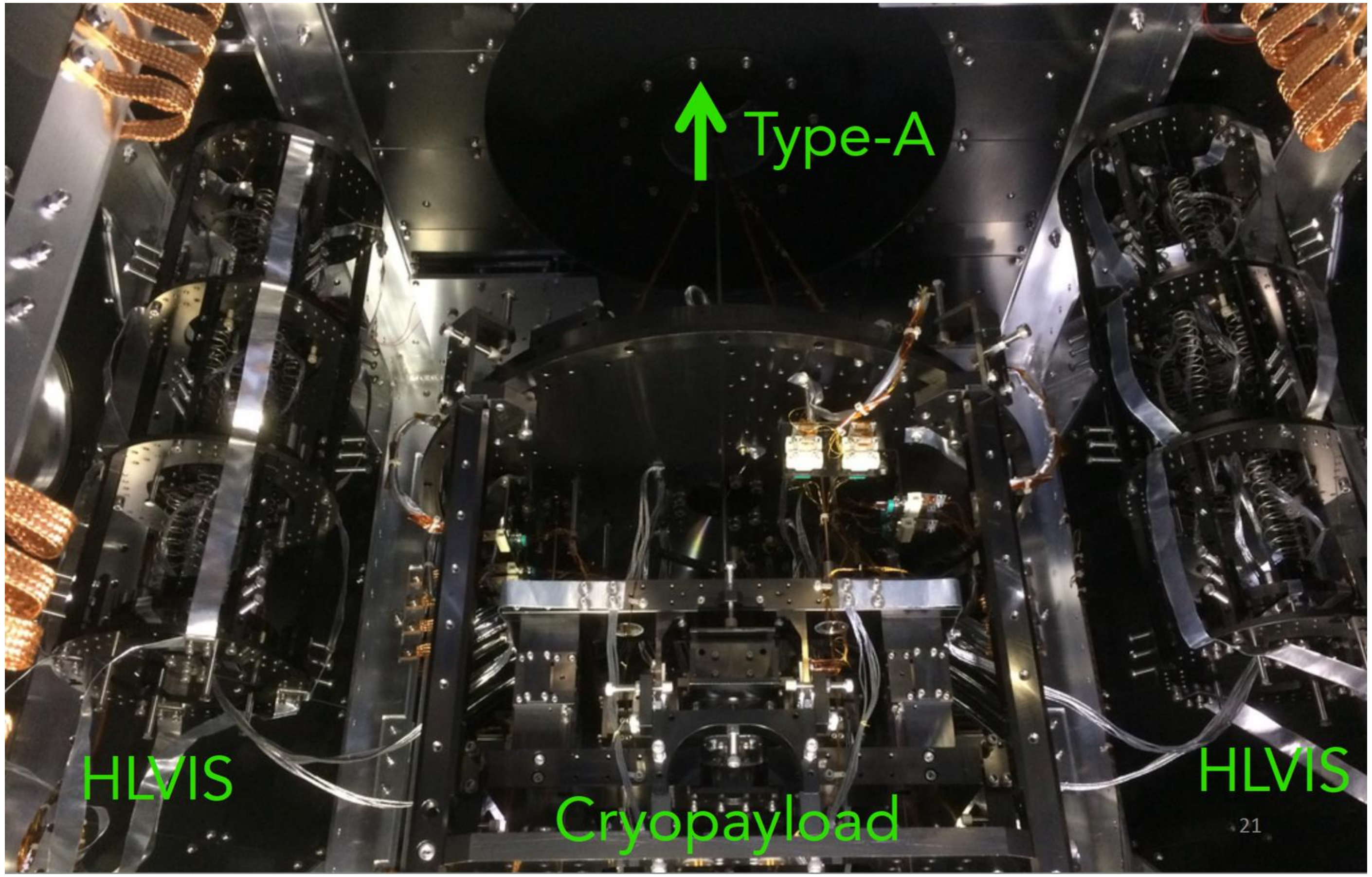


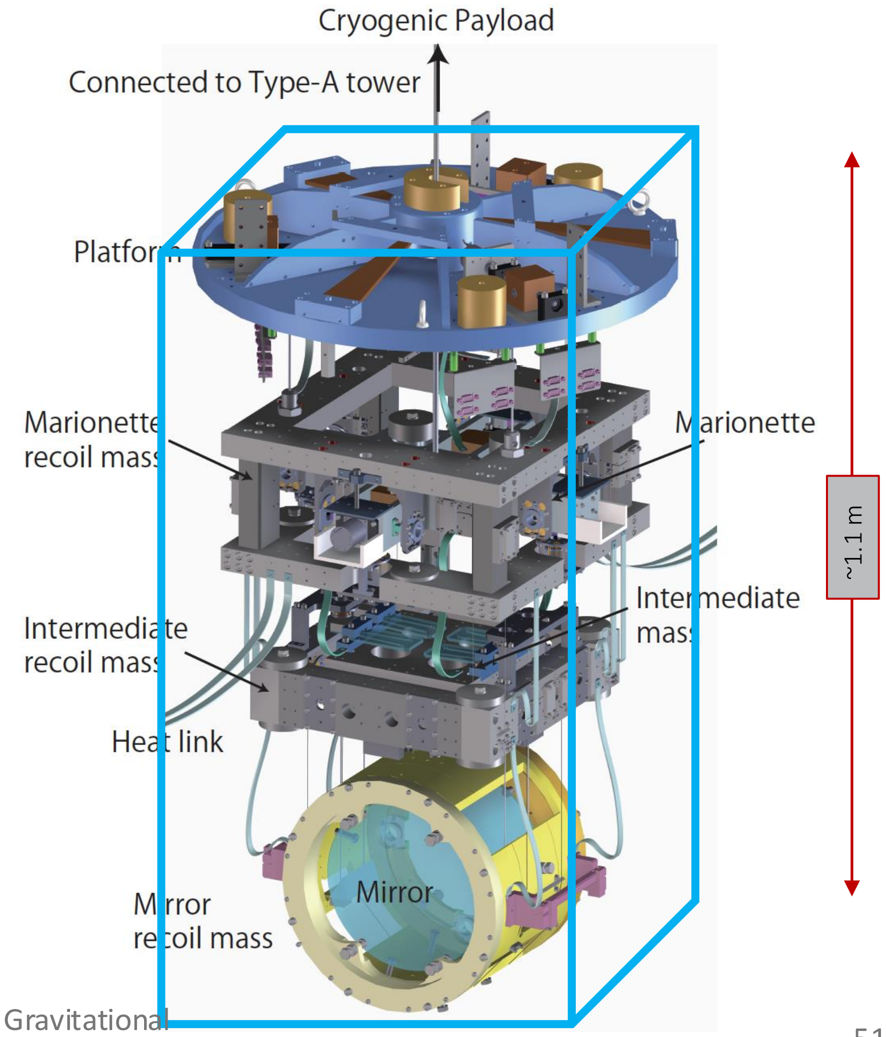


- It uses Pulse Tube technology, 1 month potential transient time (reasoonable), effective for avoiding frost: 70 days
- Present limits are determined by the issue of avoiding frost, and relies on very long pumping phase before cooling, **=> the cryostat/cryopumpimg system architecture plays quite a signigicant role**

Virgo + KAGRA experiences

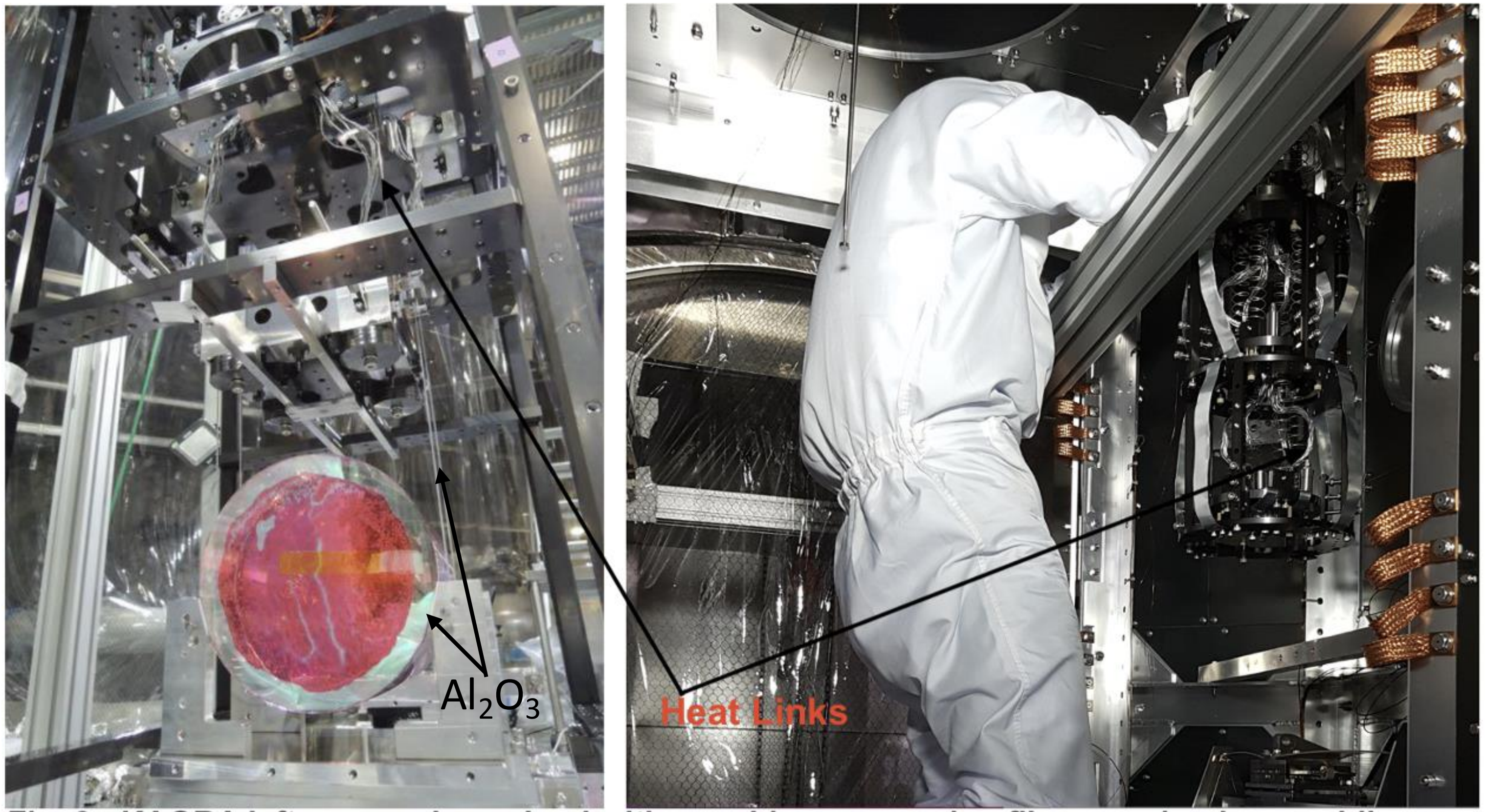
- ❖ KAGRA is essential to expand Virgo experience ➔ a very good framework even if the overall cold mass load is significantly smaller (overall into the cryostat ~240 kg)
- ❖ For ET a factor ~x 7 in payload volume is expected, just the test mass being ~x 10 (211 kg)

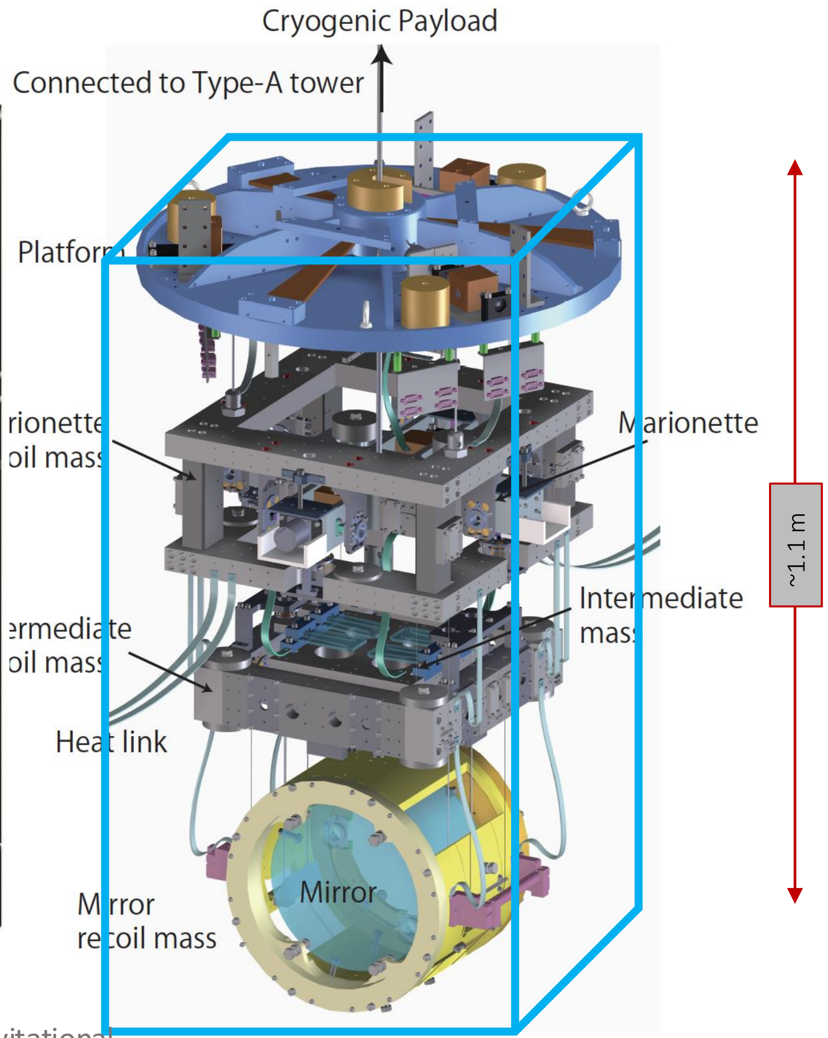




Virgo + KAGRA experiences

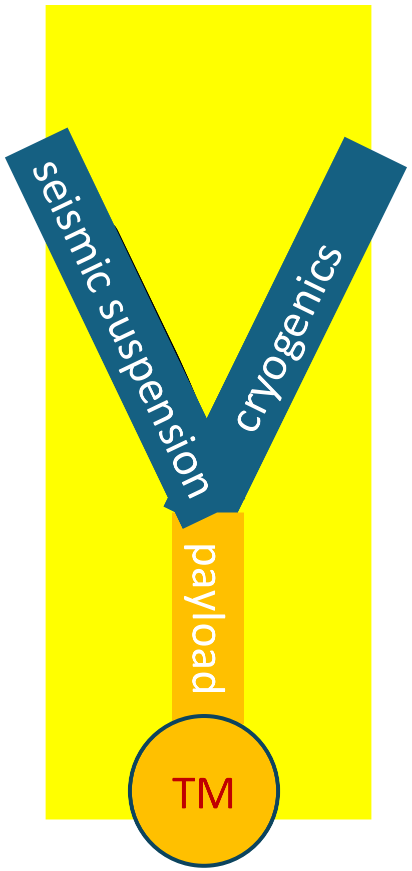
- ❖ KAGRA is essential to expand Virgo experience ➔ a very good framework even if the overall cold mass load is significantly smaller (overall into the cryostat ~240 kg)
- ❖ For ET a factor ~x 7 in payload volume is expected, just the test mass being ~x 10 (211 kg)



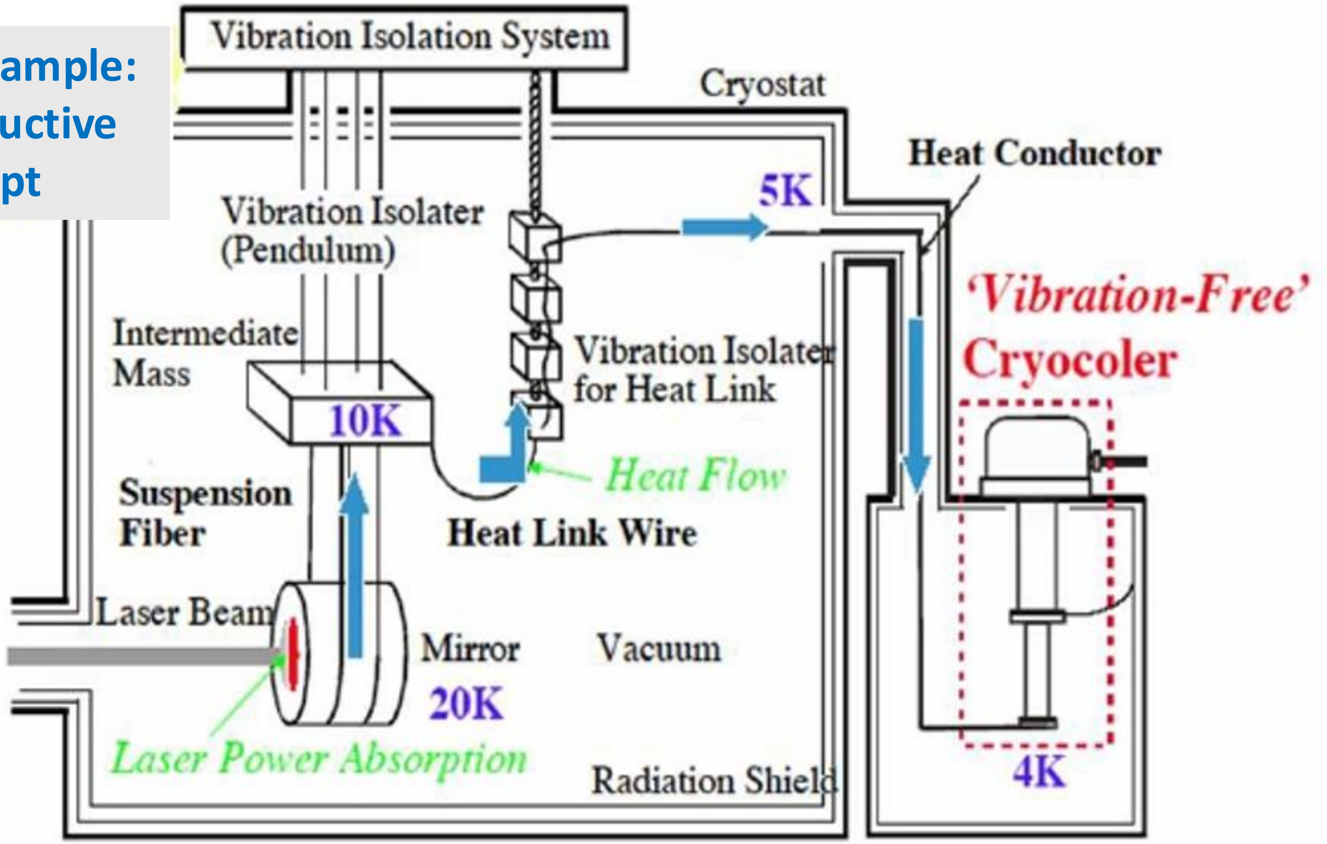


- ❖ special materials will be used to enhance thermal extraction

More complex and constrained design due to cryogenics



Pioneering Example: KAGRA, Conductive cooling concept



<u>The mirror dynamics is NOT determined just by the controlled seismic isolation system</u>

- <u>Contact coupling</u> : the mechanical plant of the thermal connection strongly matters
- <u>The overall technical noise of cryogenics</u> must not contaminate the displacement RMS achieved using the seismic isolation
- <u>Non-contact coupling</u>: the structural modes of the thermal shields, sustained by seismic, or cryogenic technical, vibration produce straylight noise

6 - Some basics thermodynamics considerations

How to evaluate the cooling efficiency

In a steady-state cryogenic system the useful thermal power extracted at the cold head of a refrigerator is directly proportional to the change in specific enthalpy

$$\dot{Q}_C = \dot{m}\,(h_{out} - h_{in})$$

of the working fluid between the inlet and outlet

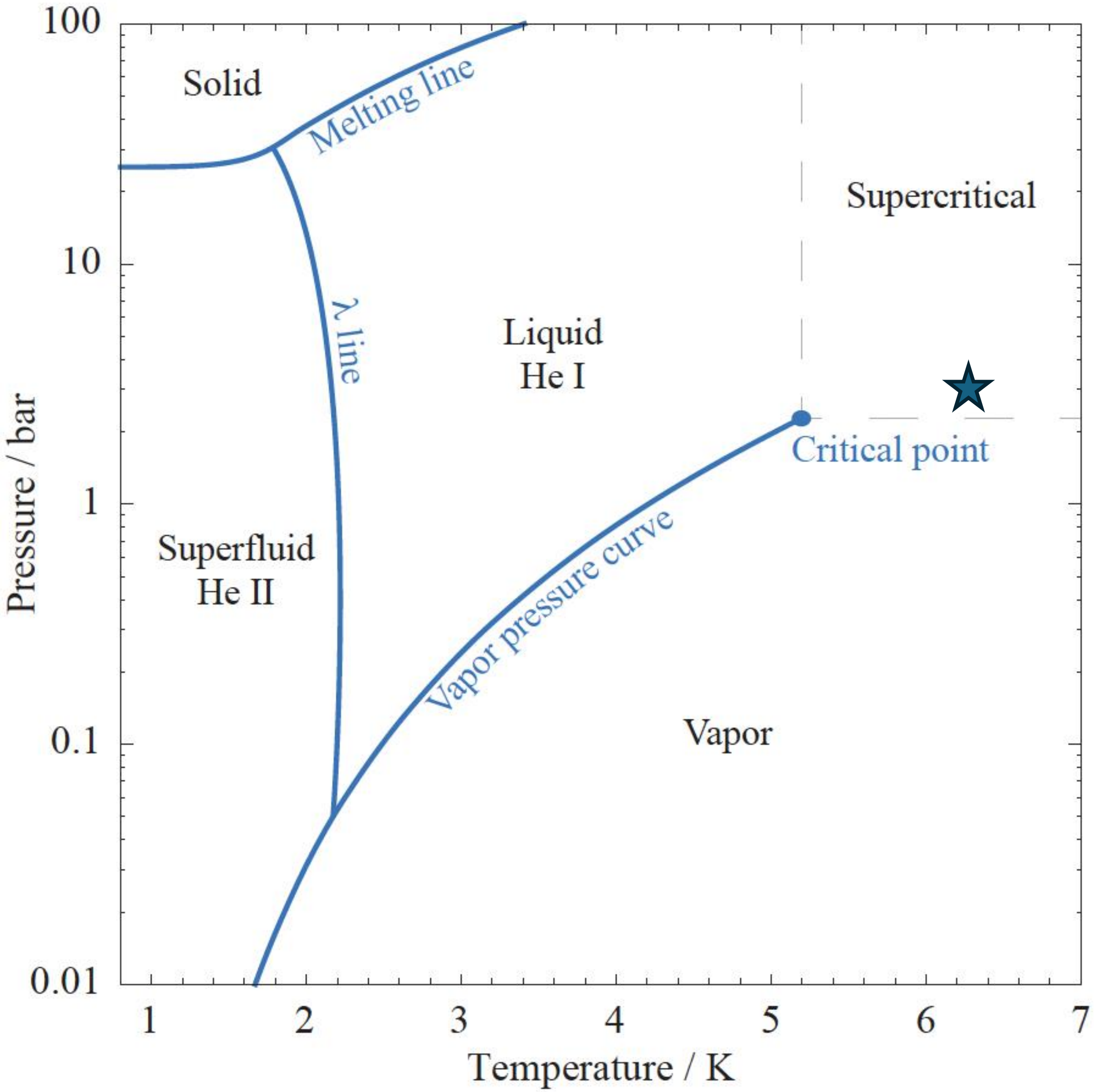
However, what matters is ***Figure of Merit*** (FOM), the actual efficiency of the process: it is the percentage ratio relative to an ideal Carnot cycle, which in turn depends on the mechanisms of internal entropy generation

$$\Delta S_{generated}$$

Example, in case of LHe at 4.21 K @ 1 bar he enthalpy drop entirely utilizes the latent heat of vaporization of helium $\Delta h_{evap} \approx 30$ kJ/kg because the thermal exchange occurs under quasi-isothermal conditions, this significantly reduces entropy generation due to thermal conduction => FOM ~ 30%

^{4}He phase diagram

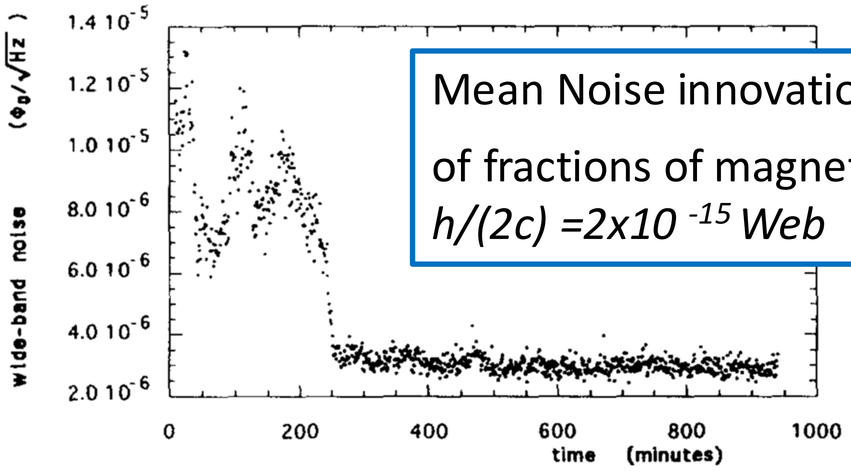
Below the $\lambda > 2.17$ K, the liquid undergoes a second-order phase transition described by the two-fluid model (a viscous, entropic normal component and a zero-entropy superfluid component).



region of SHE
($T_C > 5.2$ K and $P_C > 2.27$ bar)

Excellent for heat extraction and for fluid-dynamics modelling, this is a dense monophase fluid where no continuous transition between liquid and gas occurs. Let's choose $T_{SHE} = 6$ K and $P_{SHE} = 3$ bar

- **Cooling down with cryogenic liquids**: He II shield at 2K using superfluid (→"vibration free") He.
- **Cooling down with Pulse Tube cryocoolers** (like in KAGRA): refrigeration lines with soft thermal links, mechanical decoupling of compressor and cold head, active cancellation systems…

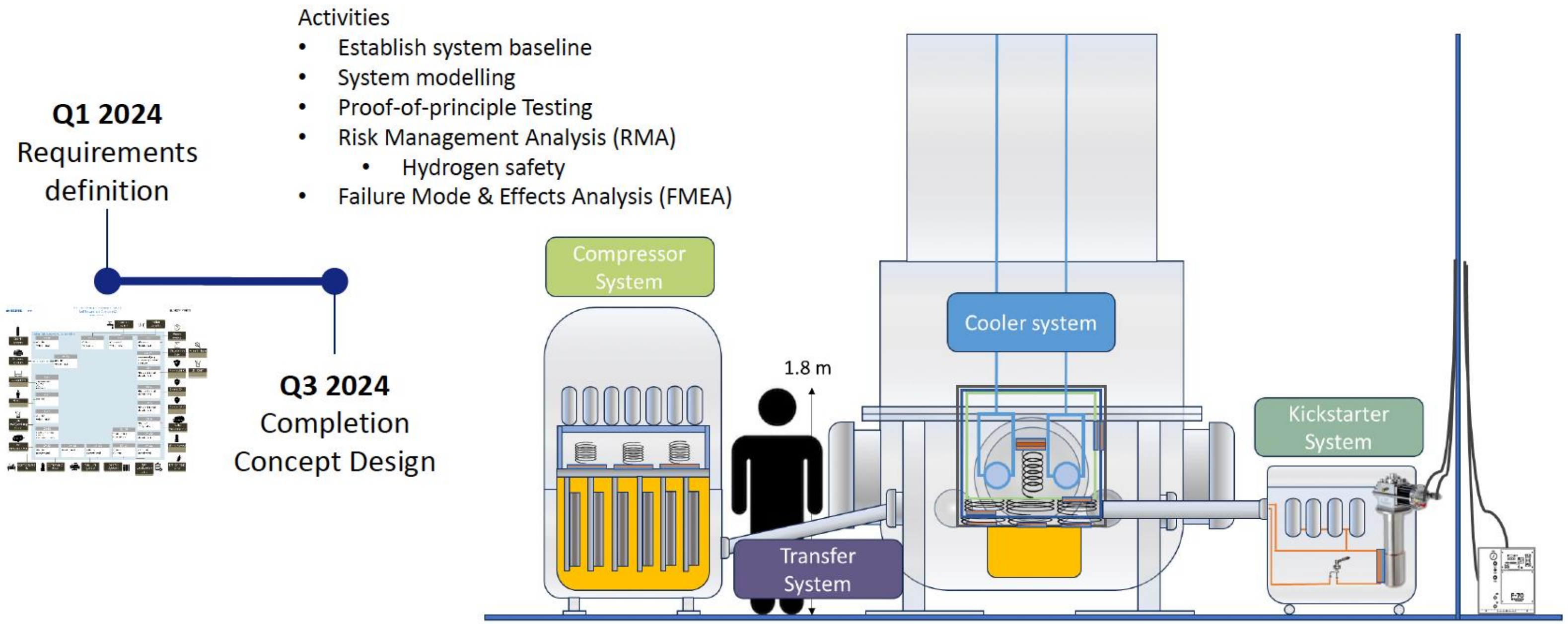


Mean Noise innovation measured in terms of fractions of magnetic quantum flux ϕ_o = *h/(2c) =2x10 $^{-15}$ Web*

He II two fluids model (Landau)
$\vec{v}_{nor} + \vec{v}_{super} = \vec{0}$

Development approach for ETpathfinder

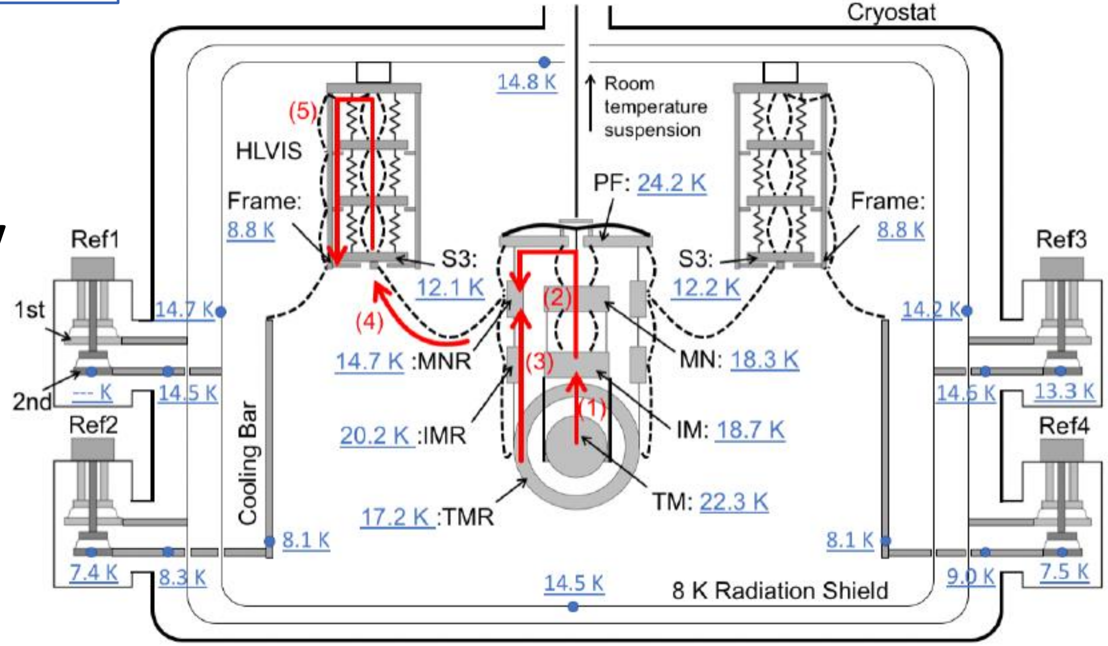
Used for space experiments and suitable for small cold masses



- Gas captured releasing the heat of adsorption ΔH_{ads} , always higher than latent heat vapor due to intermolecular bing energy through Van der Waals forces with the carbon matrix
- This excess enthalpy must be continuously removed by an upstream auxiliary system (e.g., a Pulse Tube).
- Thermal regeneration continuously required ➔ FOM very low (2%)
- Cooling down a 200 kg mass requires ~ 15 kg of activated carbon. Indeed the cold mass expected for ET is ~900 kg, and who takes care of the inner thermal shields (other ~600 kg) ?
- PTs are then in the game and their compressors are all in the underground.. or LHe bath system are required
- The active part must be very close to the payload

Pulse Tube (KAGRA)

Used for mid size experiments, very convenient and plug-play

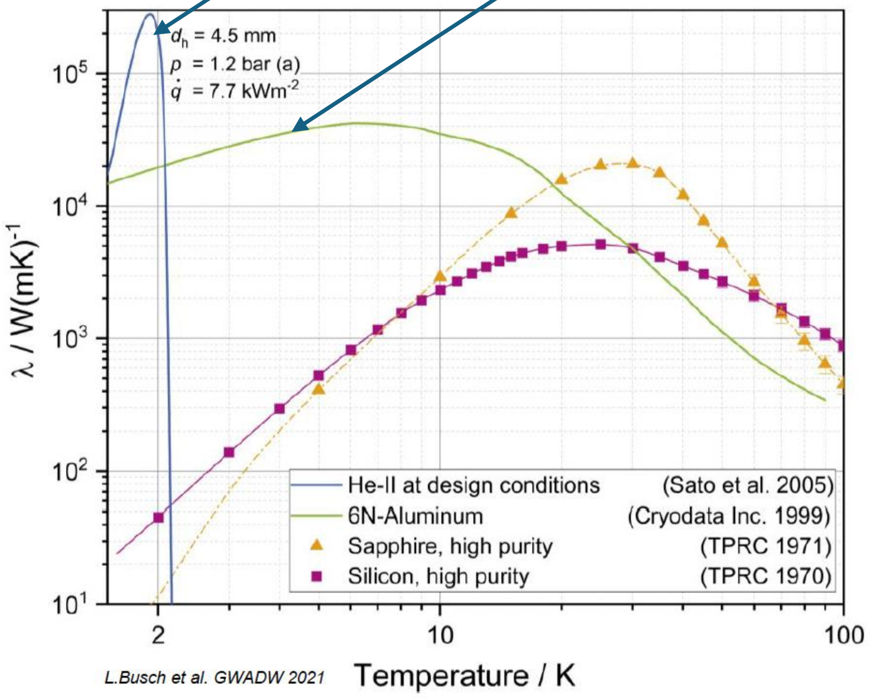


- Modified Stirling cycle without, moving parts, the Pulse Tube cryocoolers operate via periodic pressure oscillations in a closed cycle. There is no continuous macroscopic mass flow; instead, there is a time-averaged enthalpy flow:
- Super practical, plug and play, it does not require other auxiliary systems
- thermal exchange between the helium and the solid matrix of the regenerator (rare earths) is never perfectly reversible.
- In this case the FOM is higher ~5% but still small

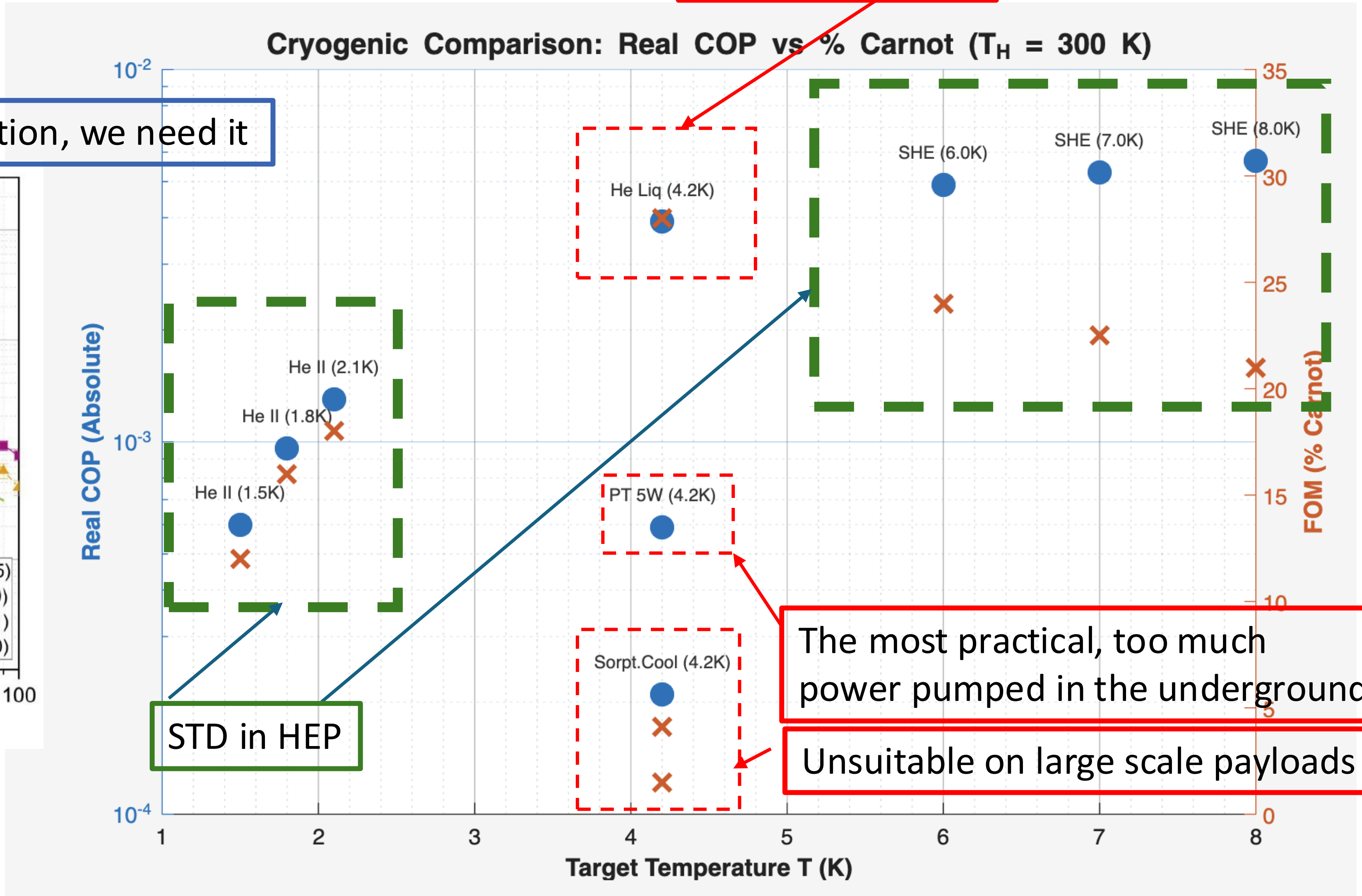
Be practical !

No vibration, good for the payload

Al6N soft links Conduction, we need it



Very noisy boiling



STD in HEP

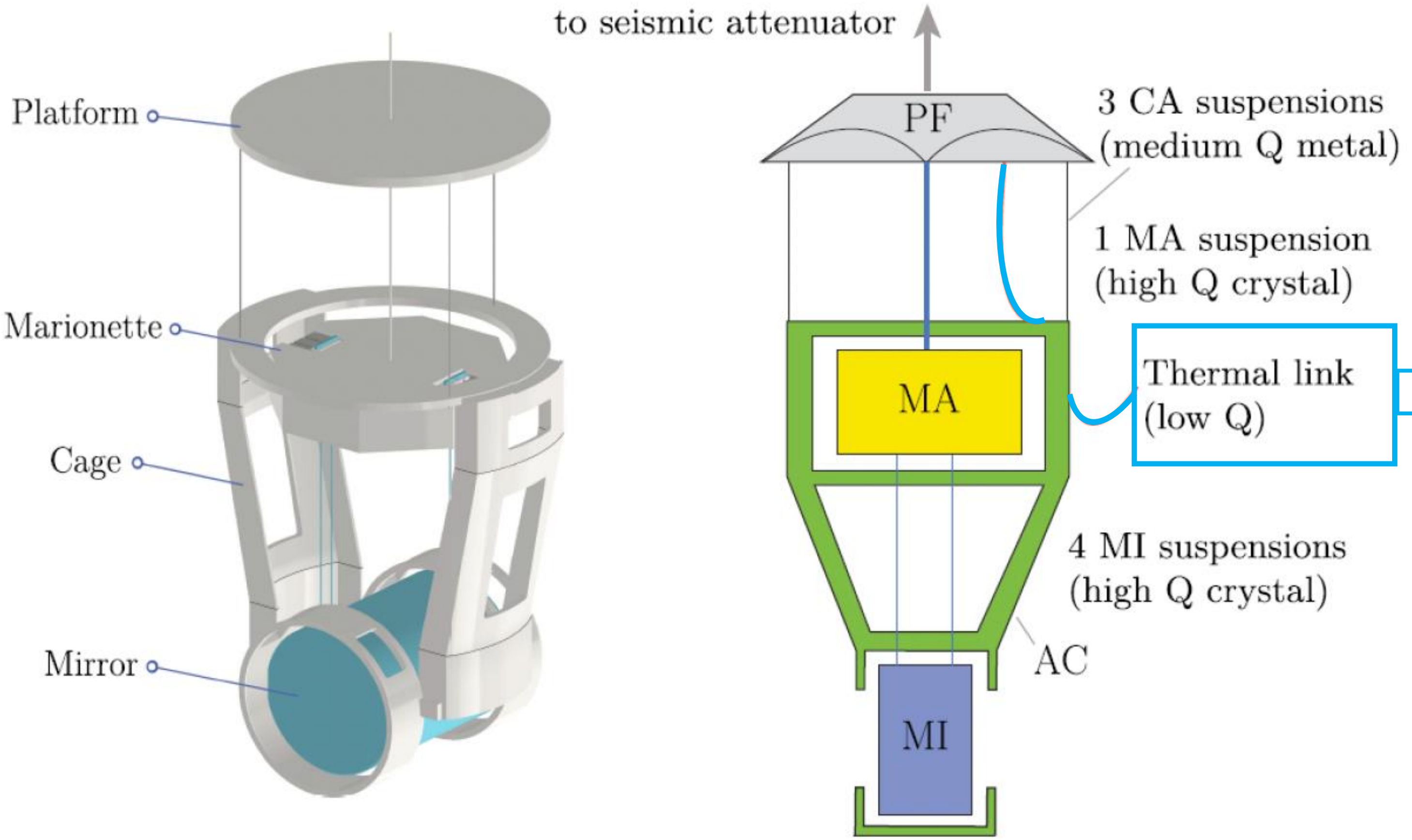
The most practical, too much power pumped in the underground

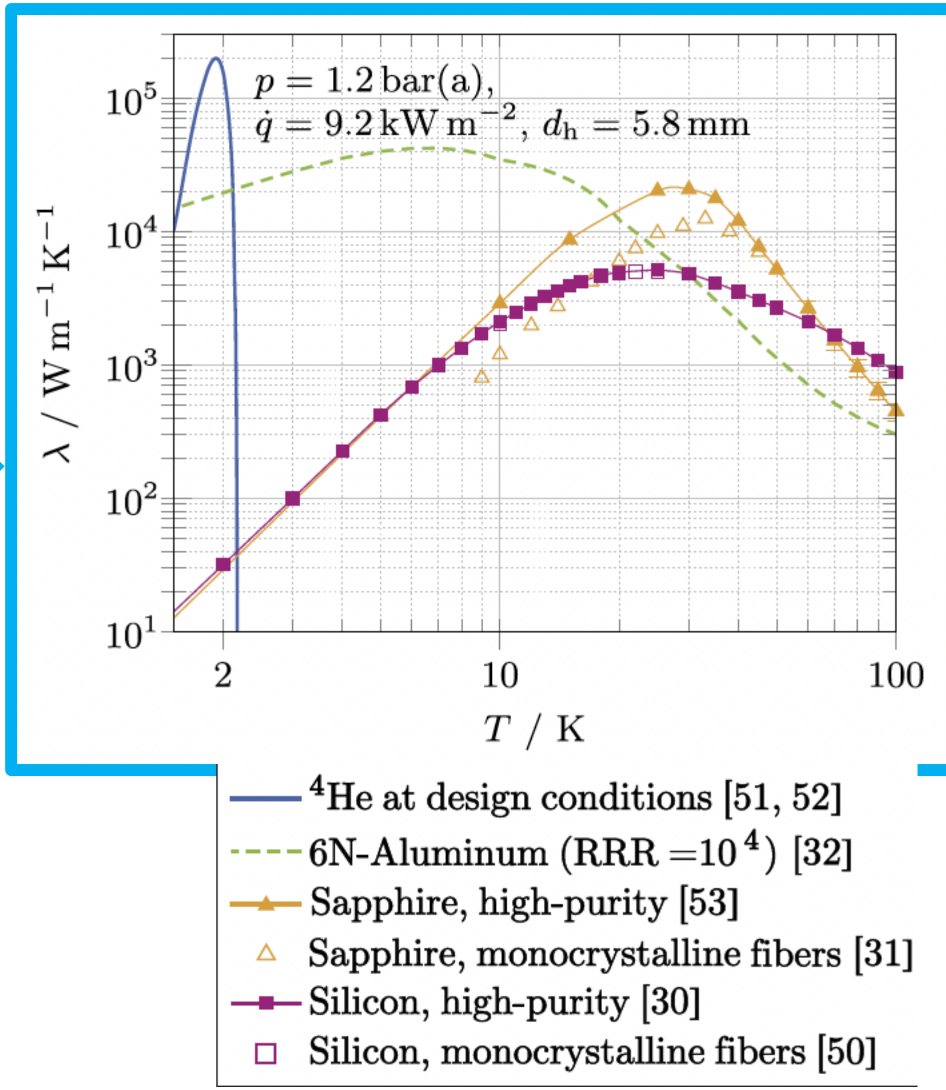
Unsuitable on large scale payloads

The reference solution seems evident BUT: URGENT R&D needed to measure SHE turbulence (unavoidable and needed)

7 - A viable project

Cryogenic payload seed design for ET-LF





X. Koroveshi et al., *Cryogenic payloads for the Einstein Telescope: Baseline design with heat extraction, suspension thermal noise modeling, and sensitivity analyses*, PRD 108, 123009 (2023)

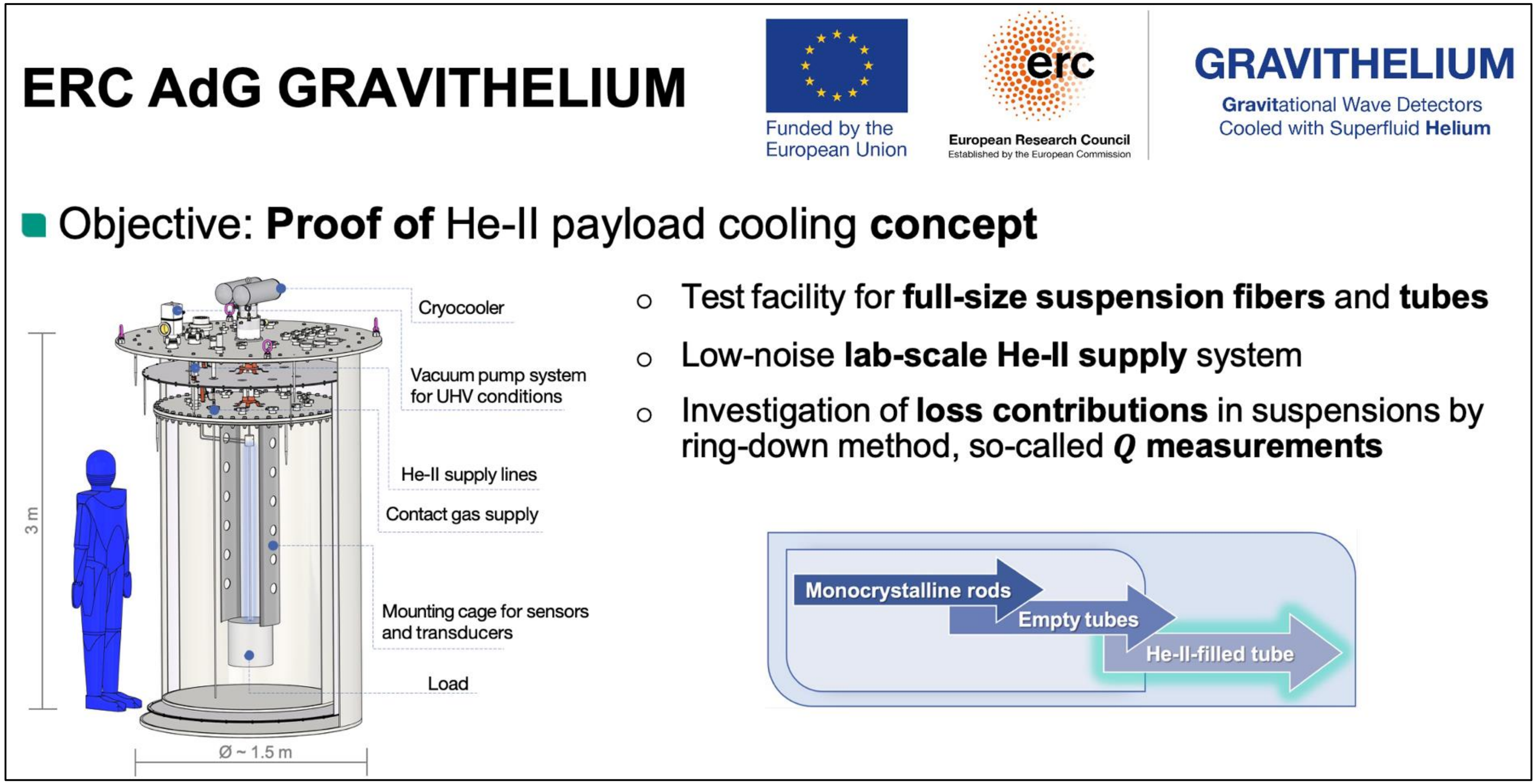
He-II is the new "special material" foreseen

He-II cooling

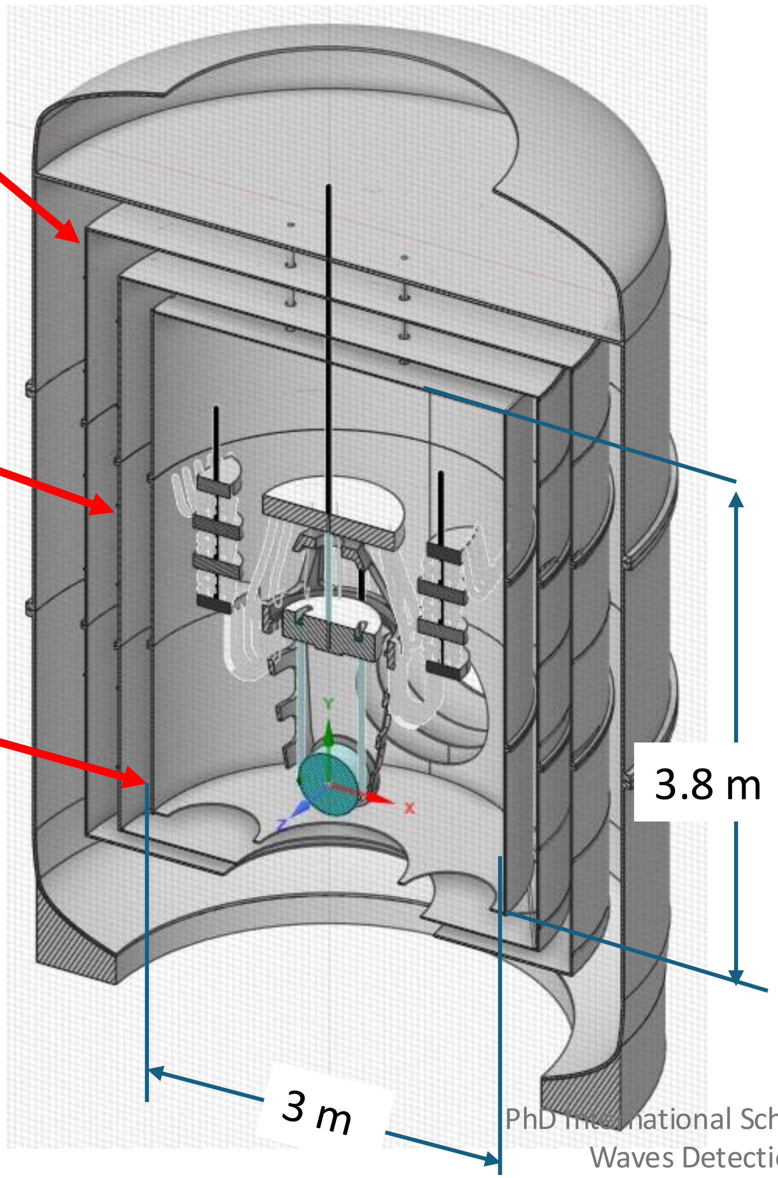
- The system implies that the development of to the section of the cooling system meant to be in mechanical contact with the payload must preserve the displacement noise density at the level of the mirror < **10^{-19} m/sqrt(Hz)@ 3 Hz**

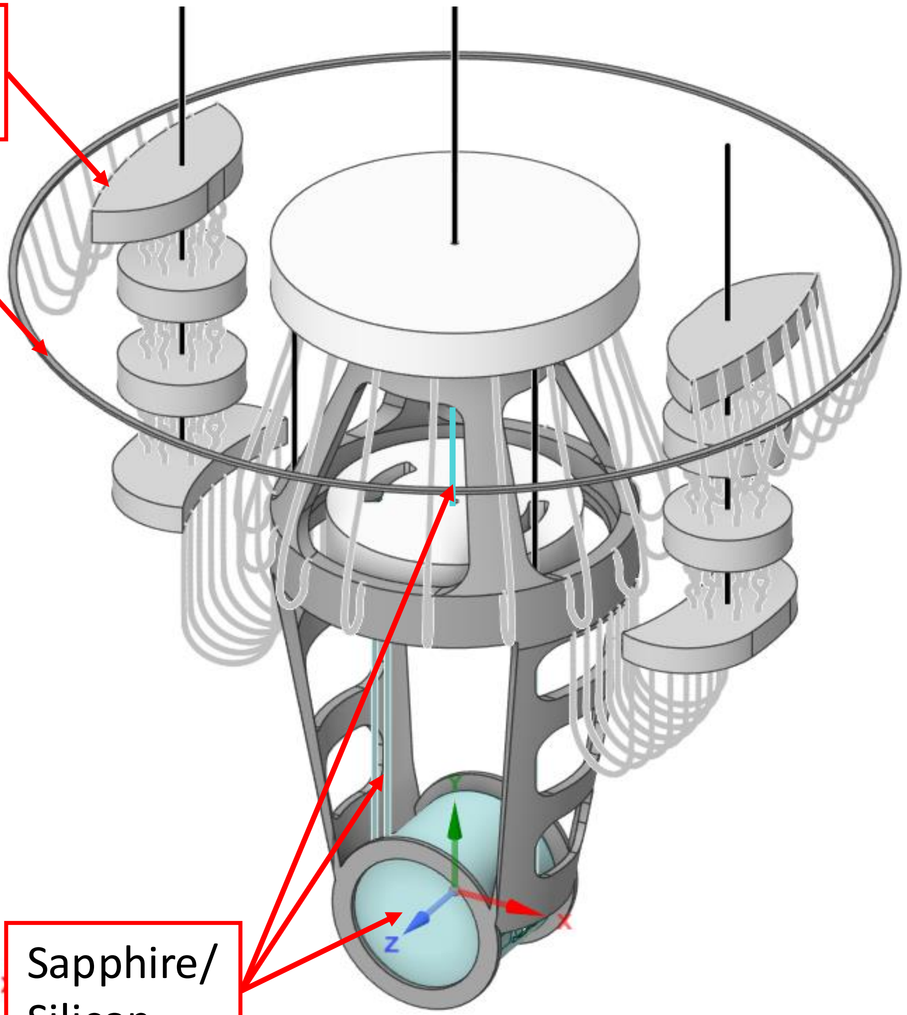
- **The absence of vibration using T below λ separation is a key ingredient to exploit conductive extraction (k > 1E5 W/(m K)) at least at the level of the thermal sink.**

- The R&D effort to reach the payload with He-II is object of GRAVITHELIUM project at KIT (*S. Grohmann ET-0287A-24).*



ET-LF Payload modelled according to a hybrid cooling scheme IMTS cooled with superfluid helium (2K) and soft heat links



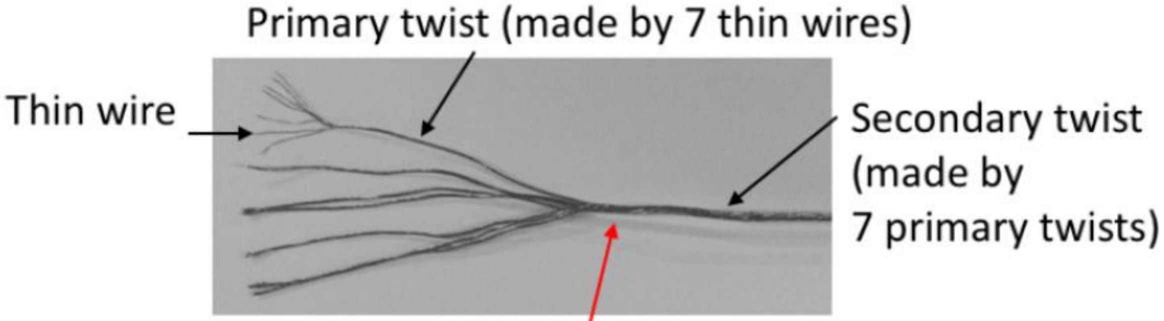


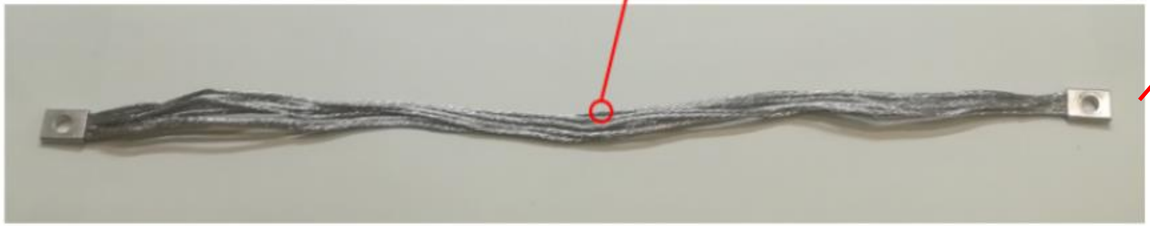
Issue n.1: connection to the heat sink at 2 K (thermalized by He-II)

- As soft as possible (~ 0.2-0.3 N/m), presently an excellent benchmark is the model developed by KA(
  Al6N $7_{100\mu m}x7_{braids}x7_{units}$

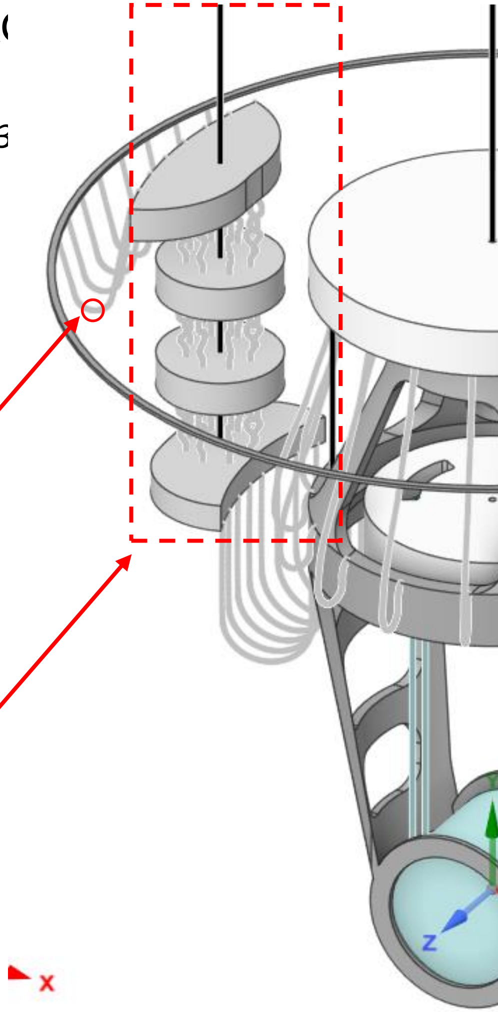
T. Yamada et al., High performance thermal link with small spring constant for cryogenic applications, Cryogenics, 116 (2021), p. 103

- Stationary and transient cooling down have been studied VS the number of links



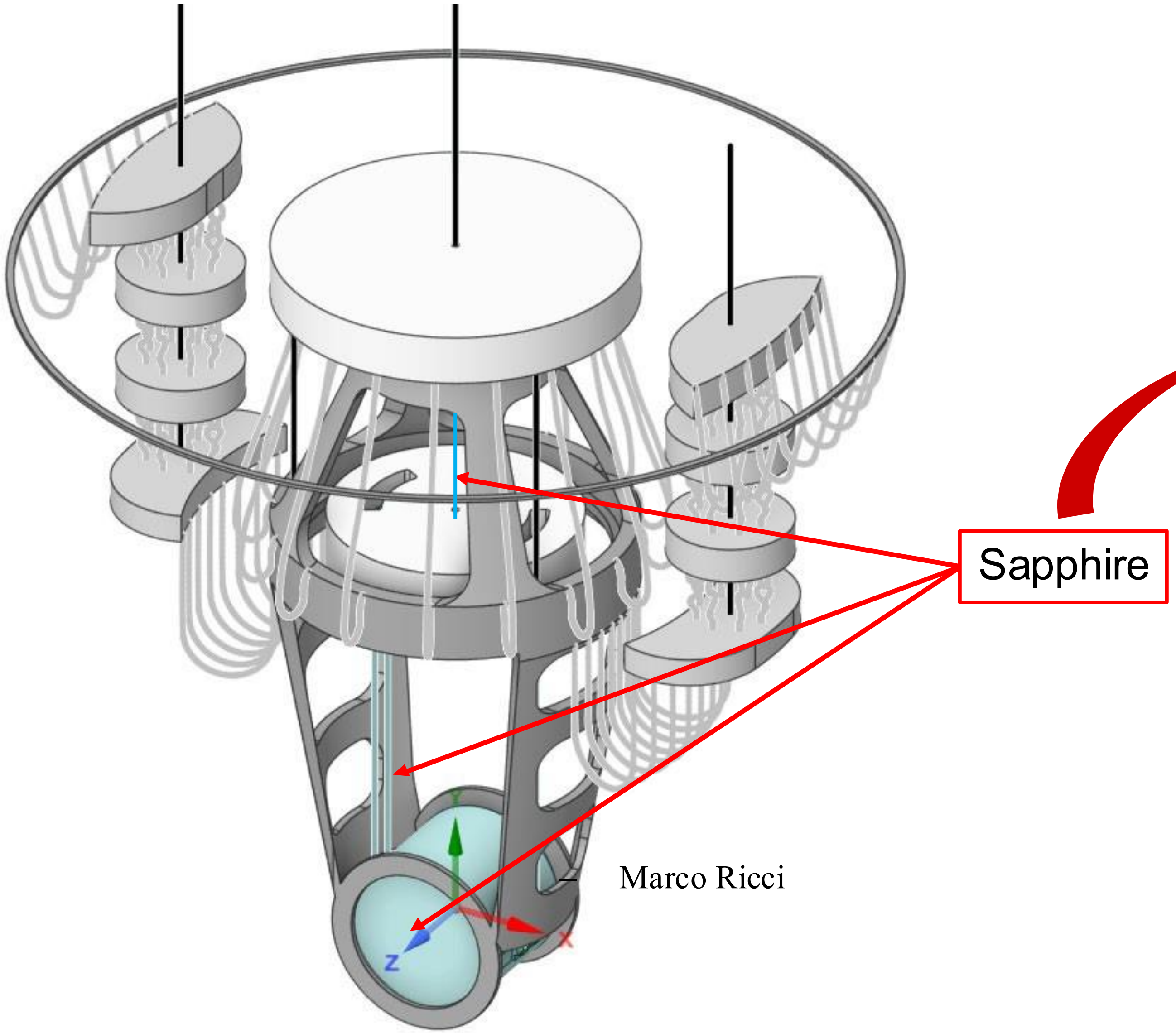


Heat link (7 secondary twists in parallel)



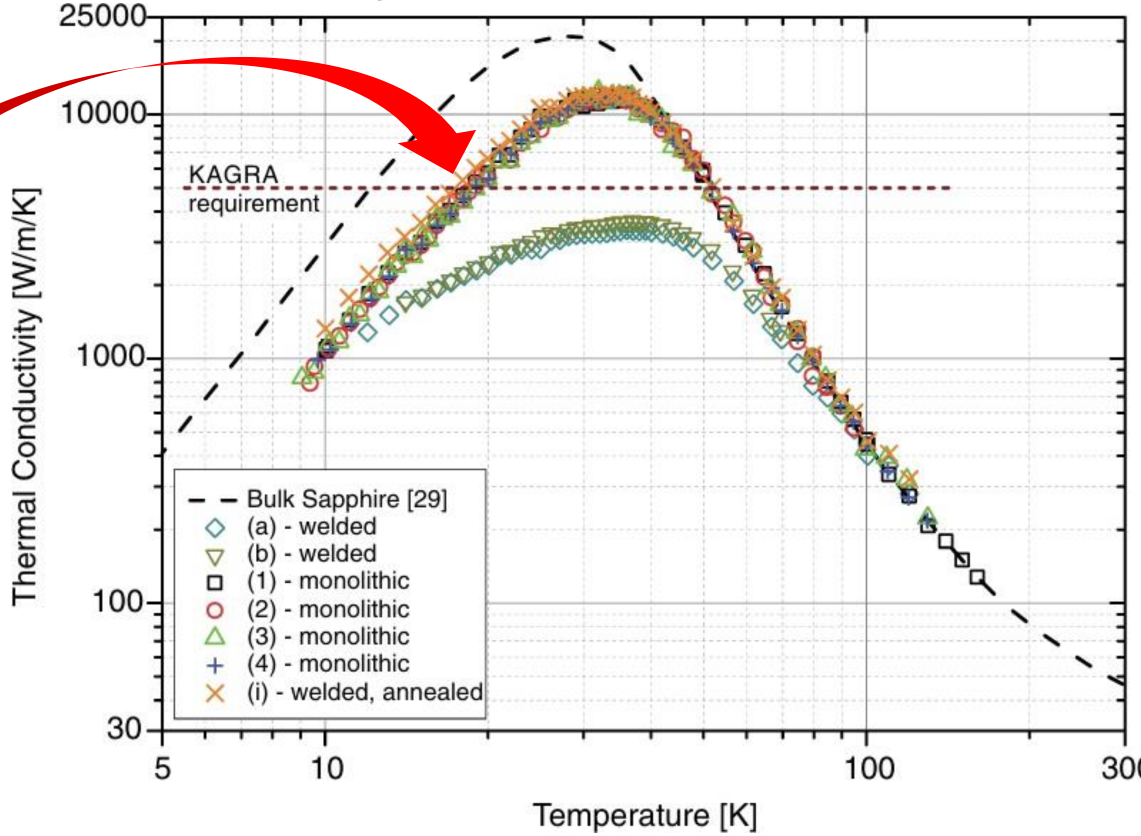
- The link must be equipped with a seismic isolation system in order not to spoil the seismic isolation of the payload
- The link has very high mechanical dissipation => to avoid thermal noise they cannot be connected on the Test mass or on the steering stage

Cryogenic Payload Materials

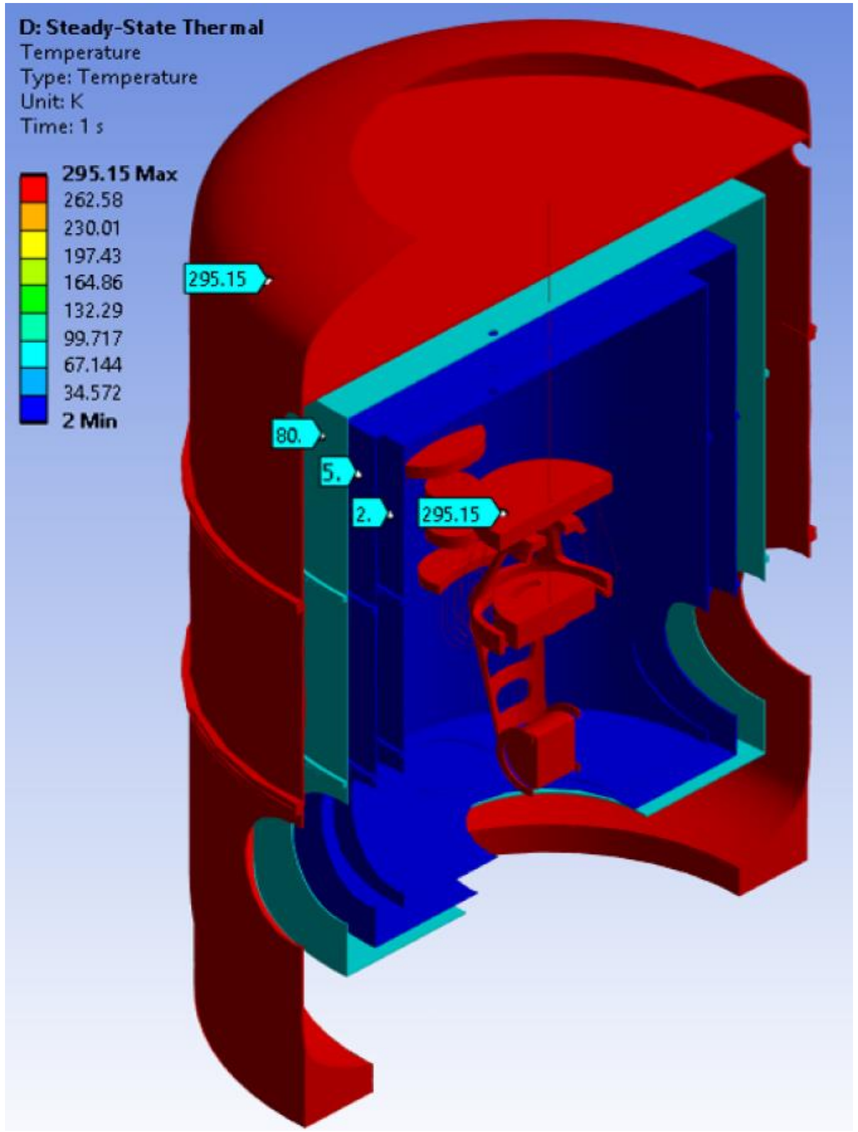


Evaluation of heat extraction through sapphire fibers for the GW observatory KAGRA

A Khalaidovski[1], G Hofmann[2], D Chen[1], J Komma[2], C Schwarz[2], C Tokoku[1], N Kimura[3], T Suzuki[3], A O Scheie[4], E Majorana[5], R Nawrodt[2] and K Yamamoto[1]



ET-LF Payload: steady state

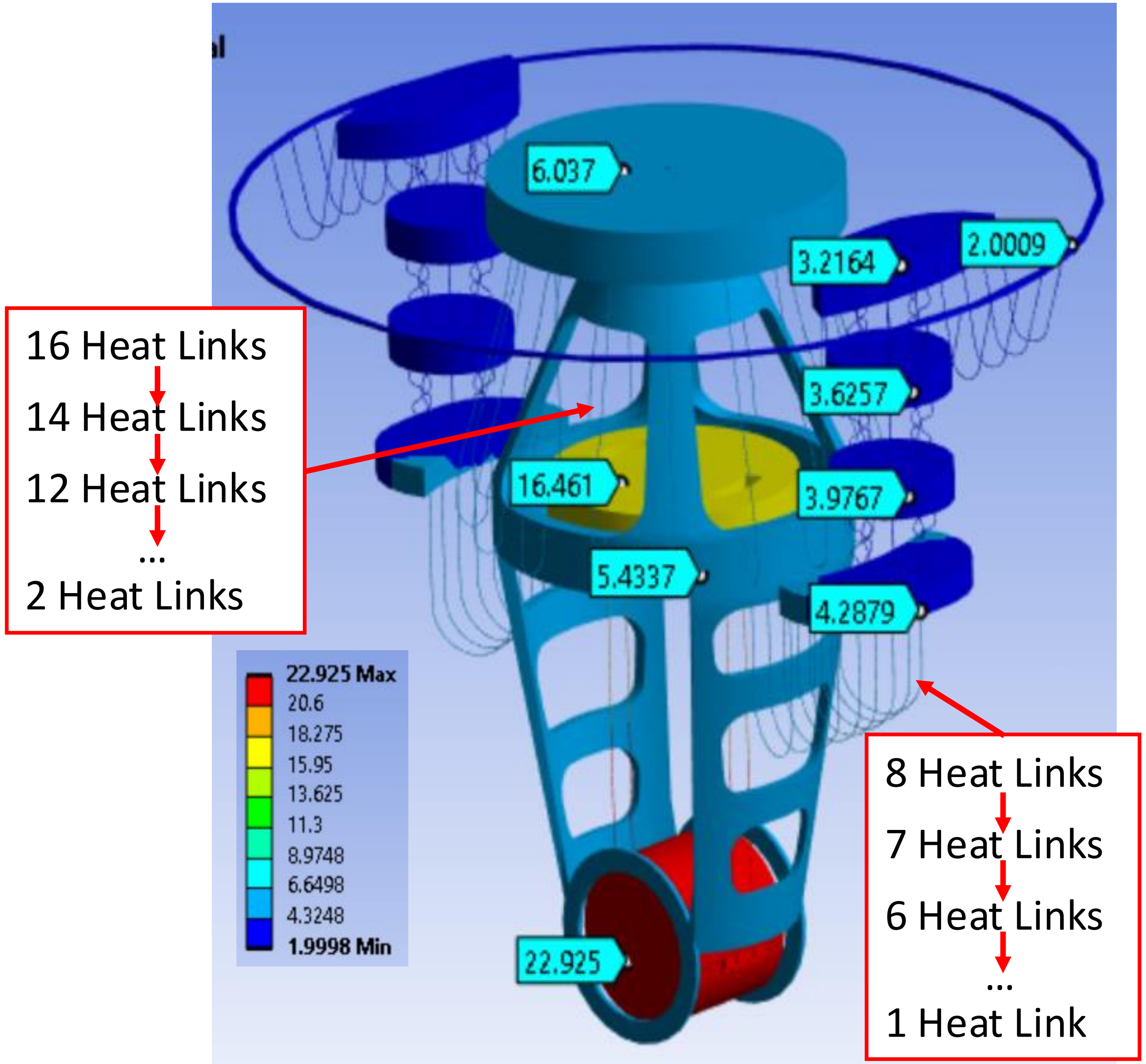


Name	Mass [kg]	I_{xx} [kg m^2]	I_{yy} [kg m^2]	I_{zz} [kg m^2]
Mirror	211	4.56	4.58	5.32
Marionette	211	7.31	12.87	7.08
Actuation Cage	200	62.42	31.17	67.88
Platform	300	19.29	37.57	19.29

Suspension	Length [m]	Diameter [mm]	Material
MI-MA	1.2	2.3	Sapphire
MA-PF	1	6.5	Sapphire
AC-PF	0.825	1	Ti6Al4V
PF-Superattenuator	2.5	5	Ti6Al4V

- Heat bath: 2K on the IITS
- Heat Inputs:
  - 0.5W (worst case scenario) on the mirror (laser absorption, viewports and apertures)
  - 0.38W electrical wires connection on the Actuation Cage

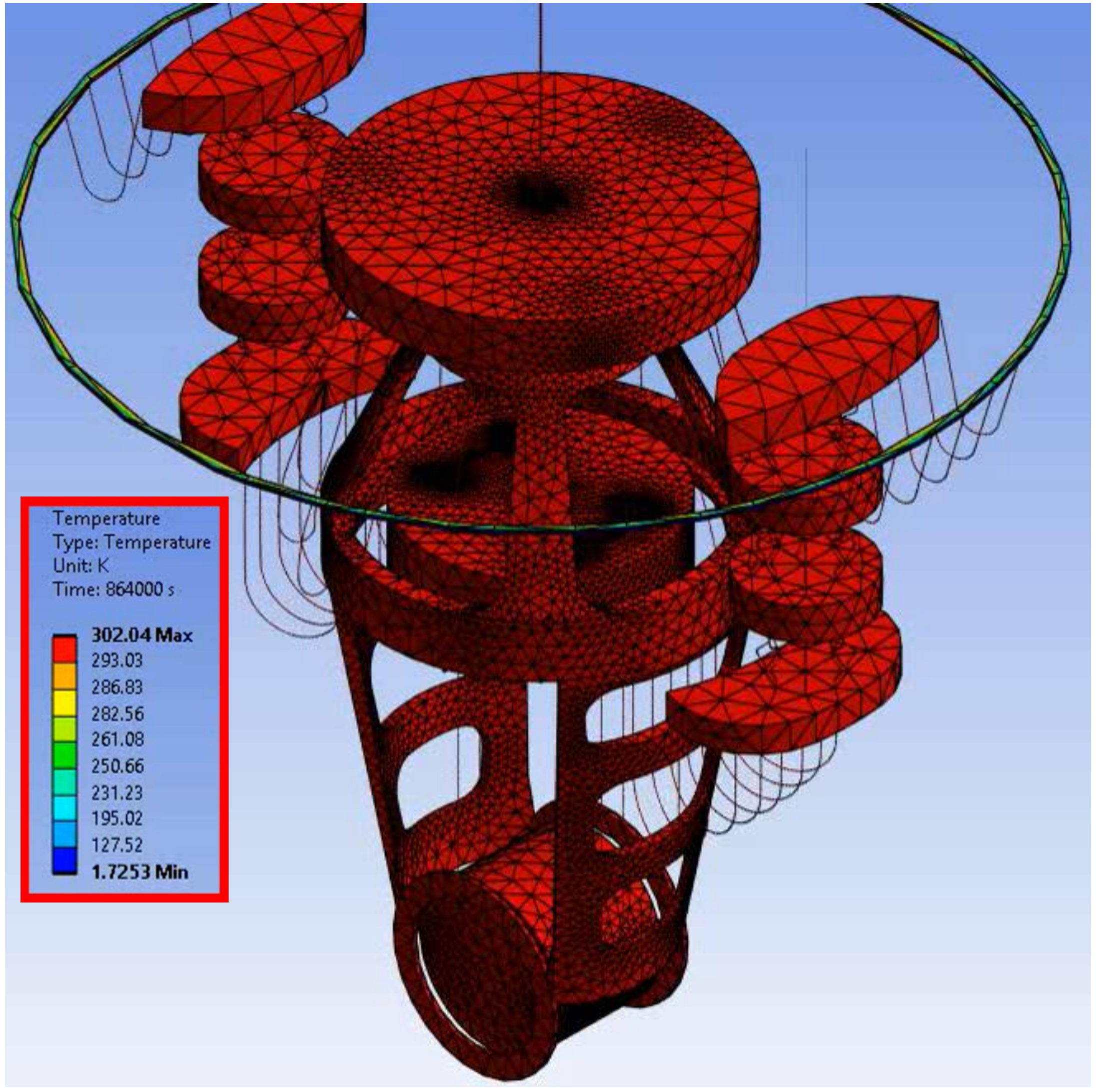
ET-LF Payload: Steady State Thermal Simulation



Heat Link Number	Mirror Temperature #1 [K]
16	22.94
14	22.96
12	22.97
10	23.02
8	23.11
6	23.30
4	23.80
2	27.00

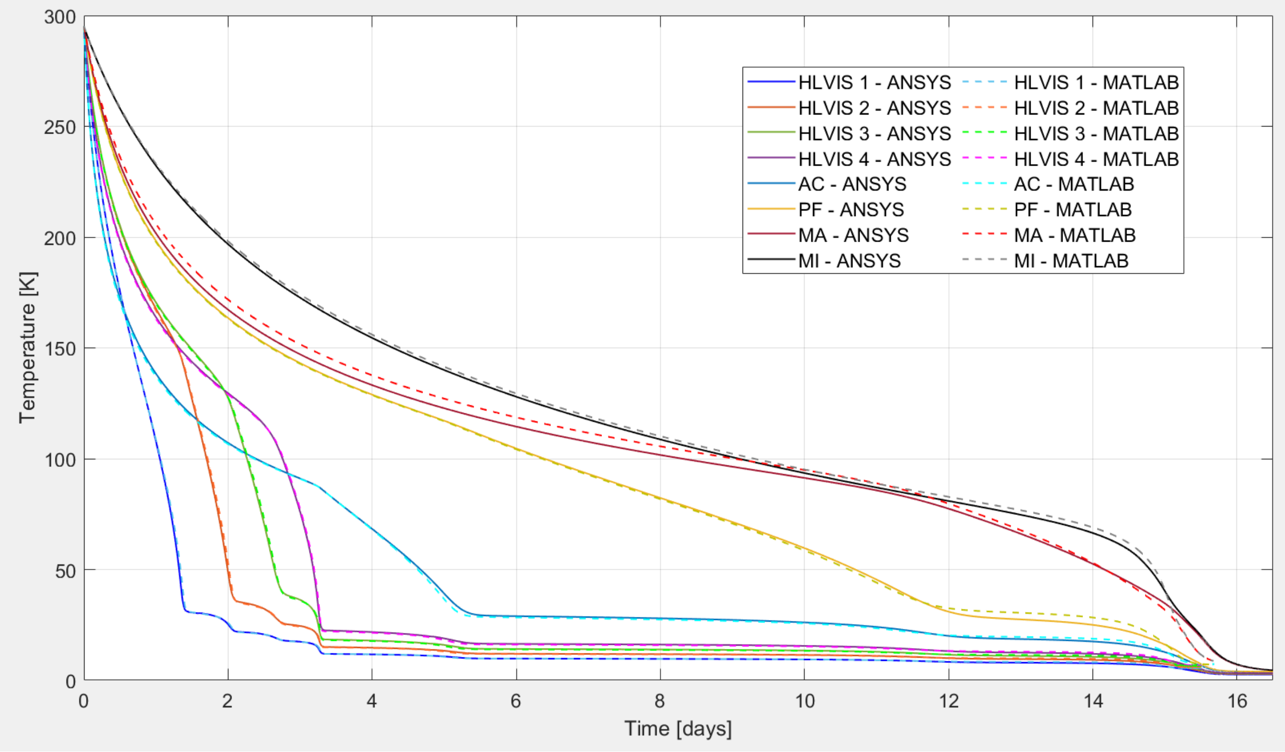
❖ targeted to ~22 K Mirrors, the steady state is not dramatically affected by reducing the N of links to ~ 4

ET-LF Payload: Transient Thermal Simulation



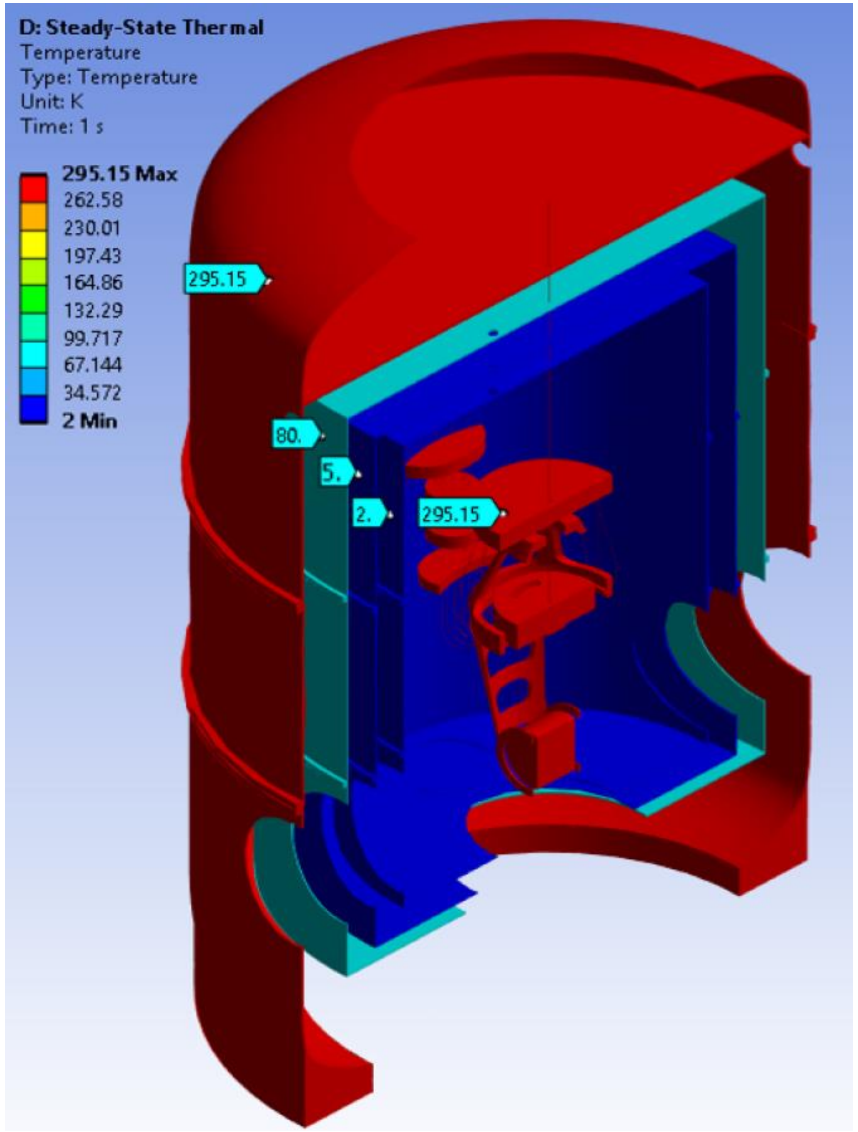
❖ Transient thermal simulations with precooled IITS (2K heat bath)

❖ First 10 days of cooling

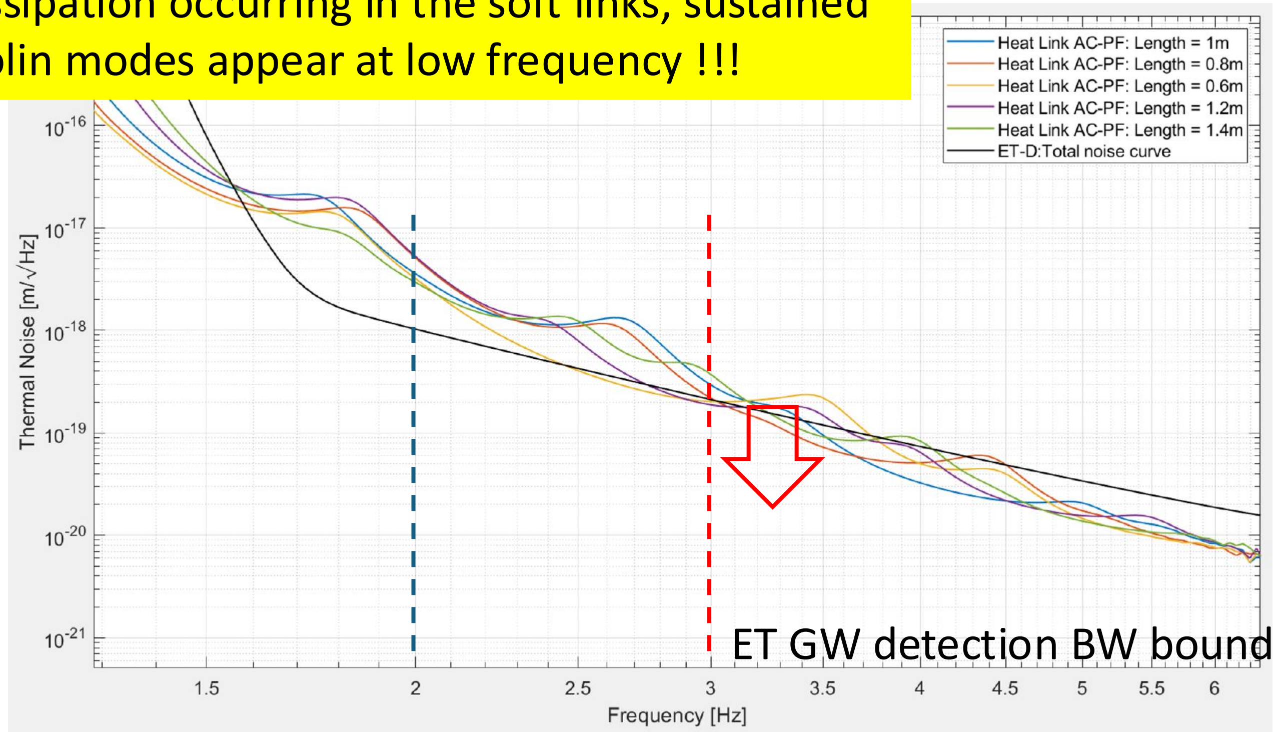


Cooling time with 16 Heat Links → 16.2 days

ET-LF Payload: steady state

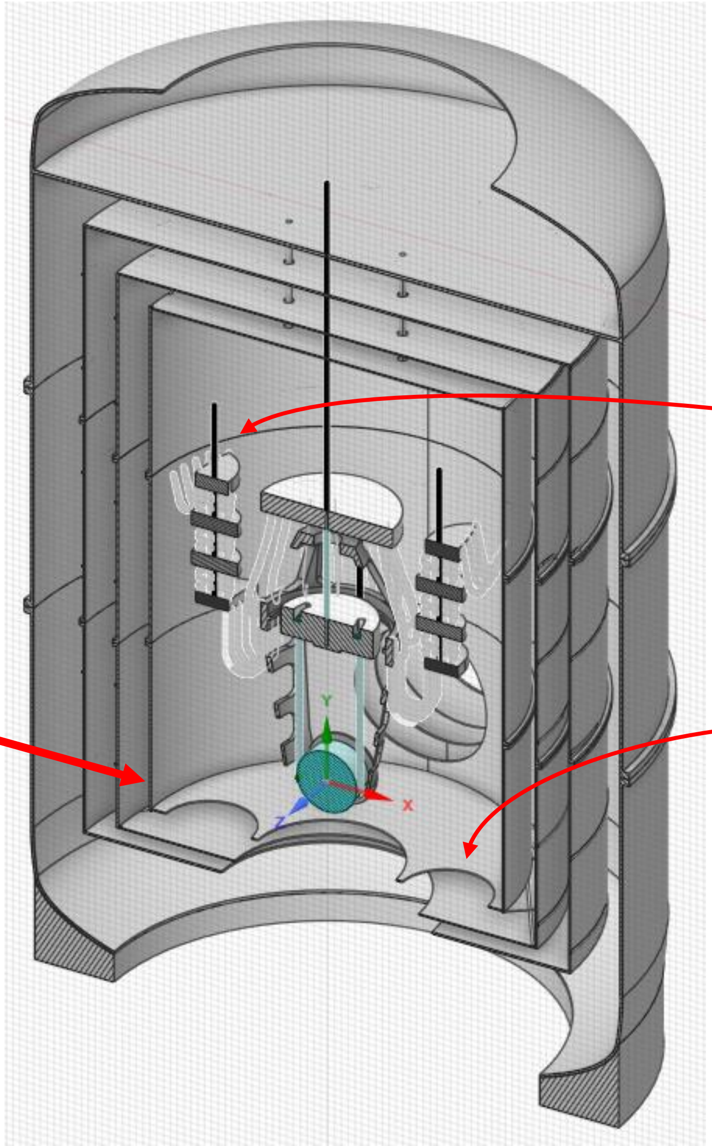


Effect of thermal noise due to the mechanical dissipation occurring in the soft links, sustained violin modes appear at low frequency !!!



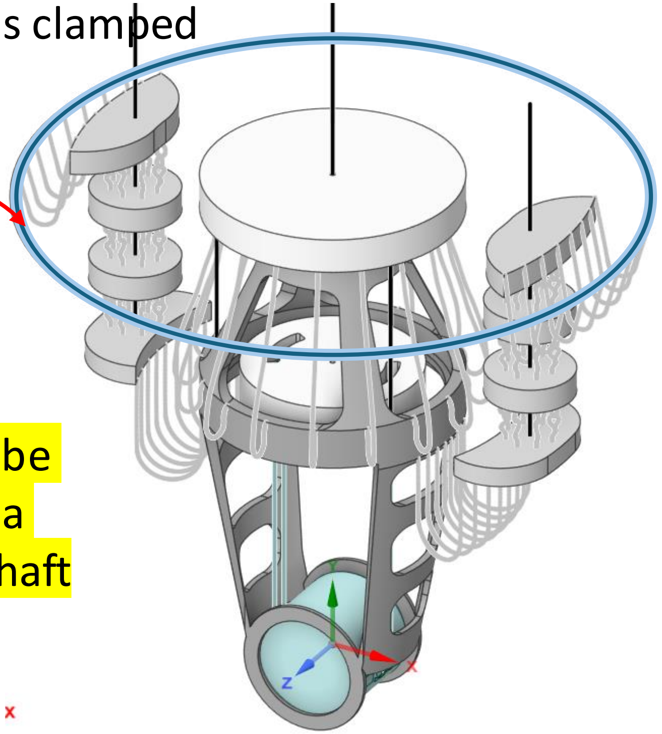
- A significant reduction of the thermal resistance (number of soft links) could be applied once at the steady state
  ➔ mechanical thermal noise reduction + fast cooling
- **Is a mechanical thermal contact switch on the suspended payload feasible ??**

Issue n.2: the heat sink at 2 K



Internal Inner Thermal Shield IMTS 2 K

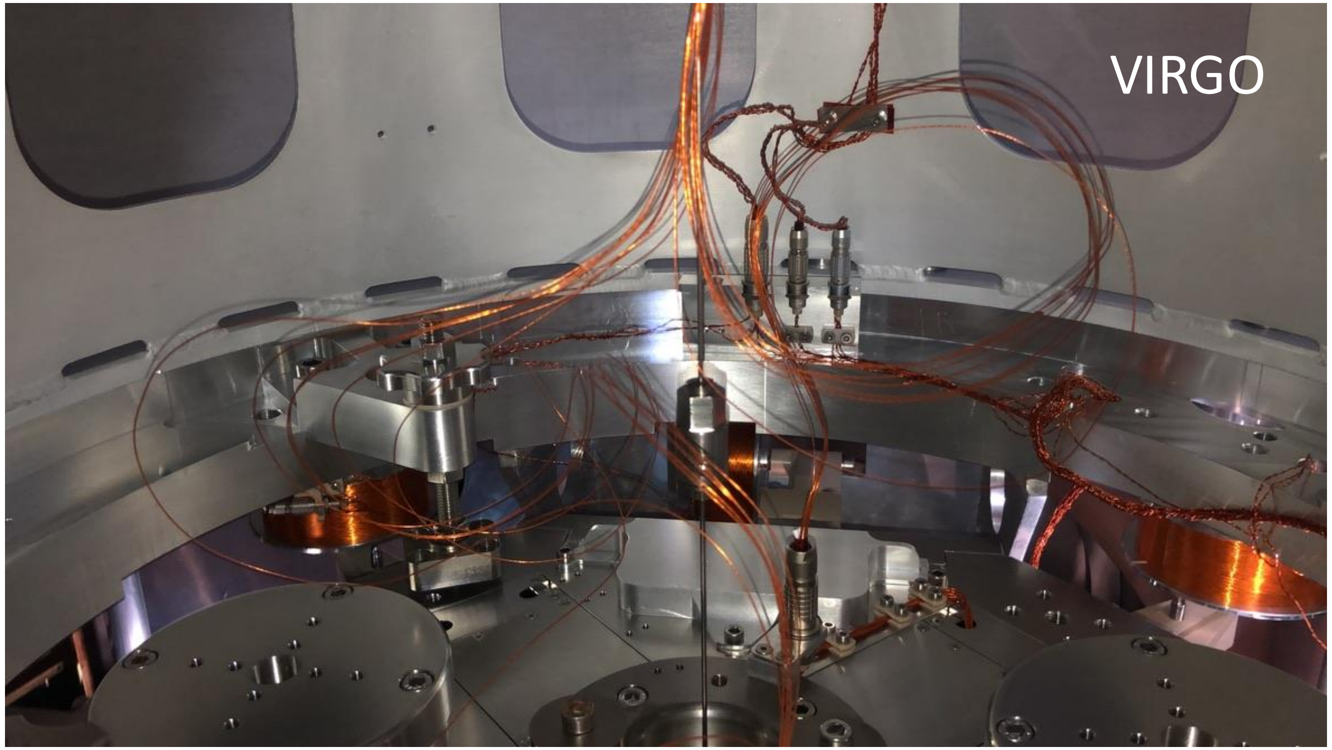
- So far inner IMTS shield at 2 K has been envisaged by VAC-CRYO division. It exploits He-II, quiet and with high thermal conductivity
- The modelling shows that ITS (5 K) or IMTS (2 K) from radiative are equivalently effective on the transient time
- Indeed, the main advantage of He-II is just the quiteness at the heat sink where we the soft links is clamped

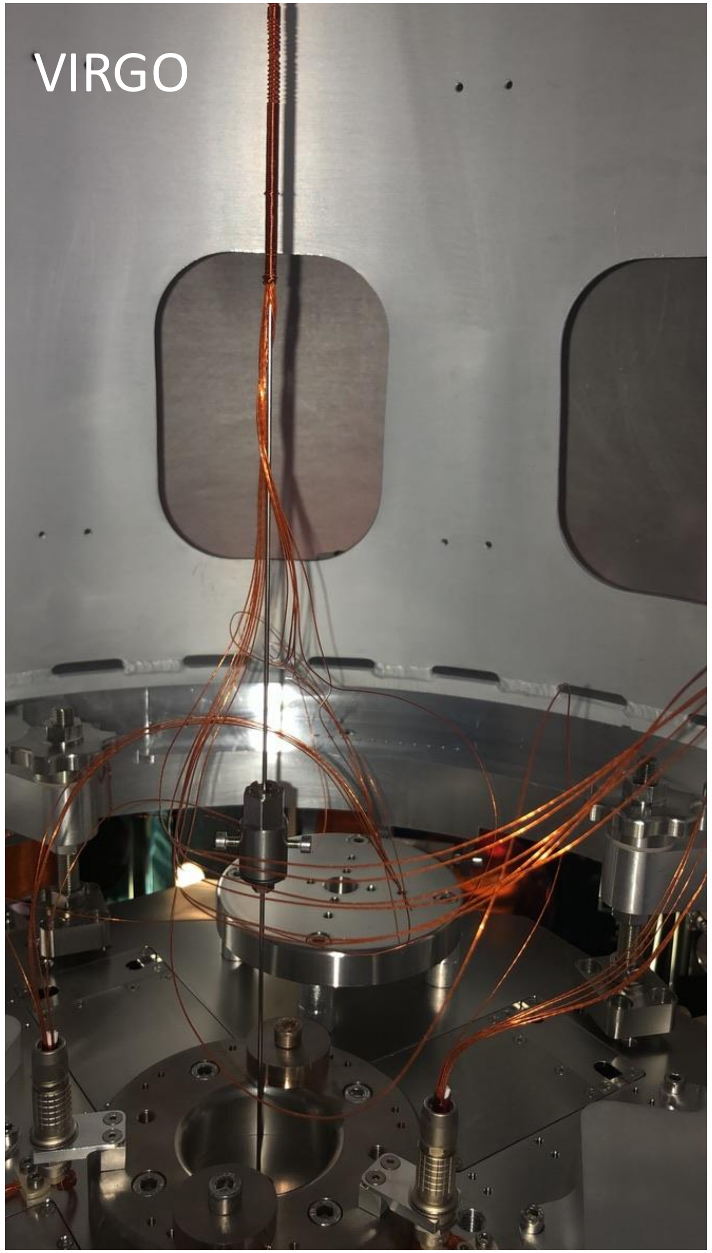


- The big He-II shield could be removed leaving place to a simple and stiff thermal shaft

Issue n.3: wireless balancing of marionette

- Using low dissipative suspension for the mirror steering stage (marionette) implies also avoiding parallel low Q springs
- Virgo case: 14 cables (0.3 mm dia) reach the mirror marionette





Virgo benchmark to study ET cryogenic payload,

the problem of electric cabling w/o worsening thermal noise

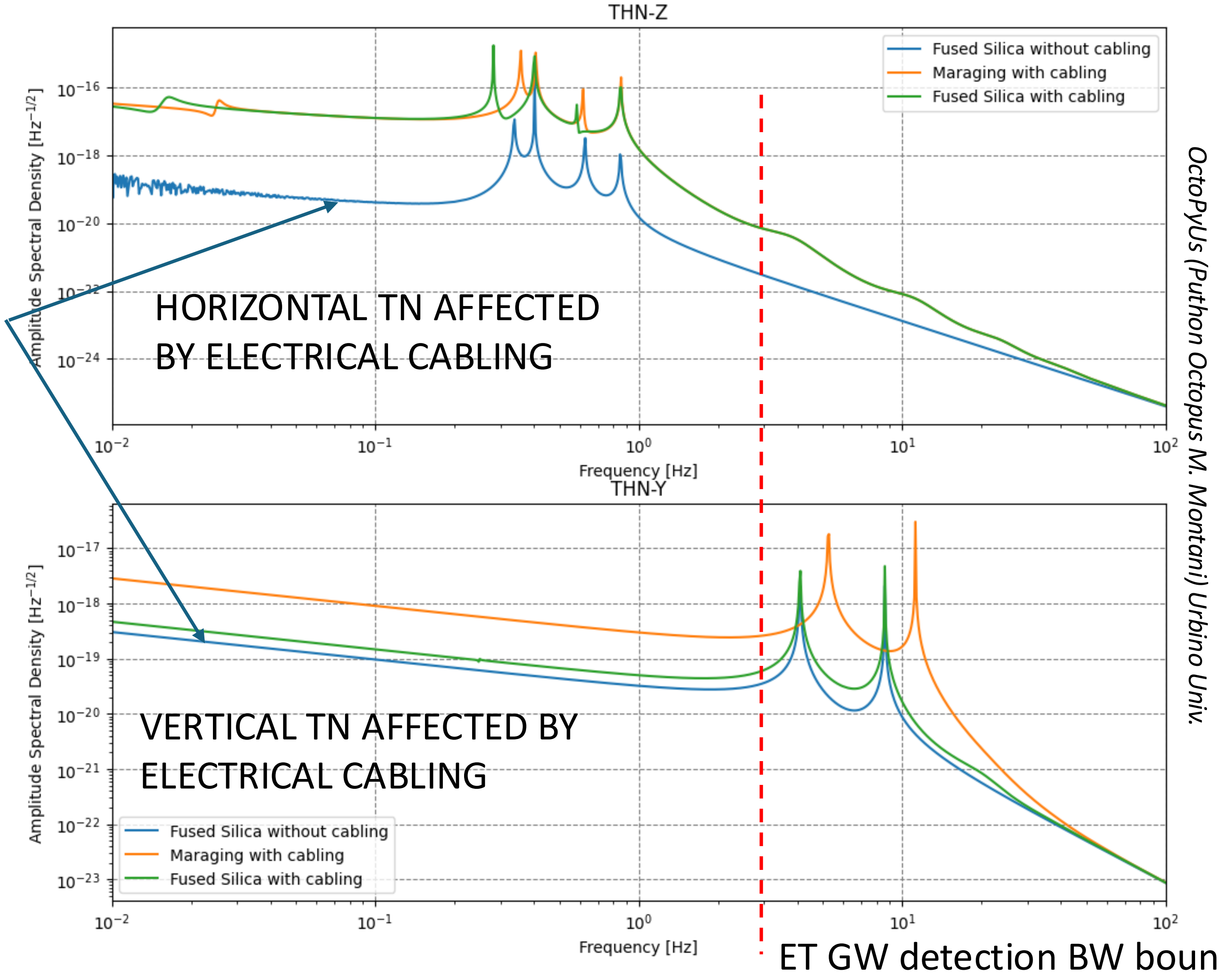
- The marionette is suspended using a Maraging steel wire

- Suppose we want to increase the Q by replacing the Maraging with Fused Silica in order to reduce the mechanical thermal noise.

- The effect is major on the horizontal (passing to high Q suspension for the marionette is meaningless)

- In case of cyogenic payloads the plant is quite different but we expect to see similar effects (similar to Heat link model)

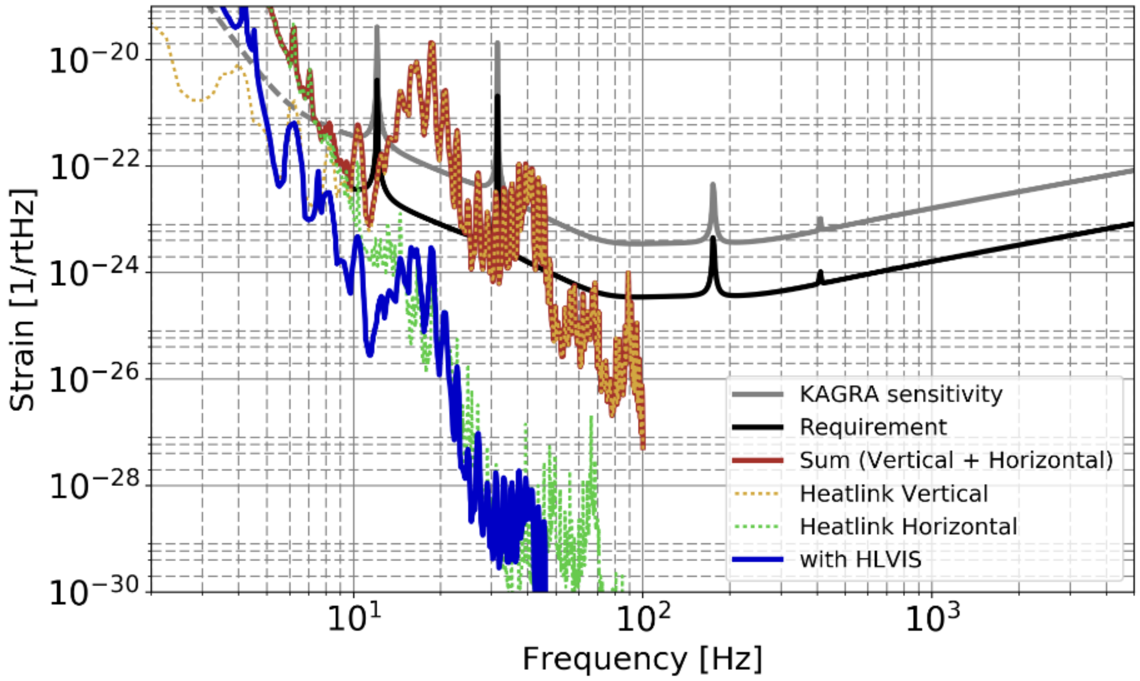
=> Developing wireless balancing requires a dedicated R&D and is remarkably relevant

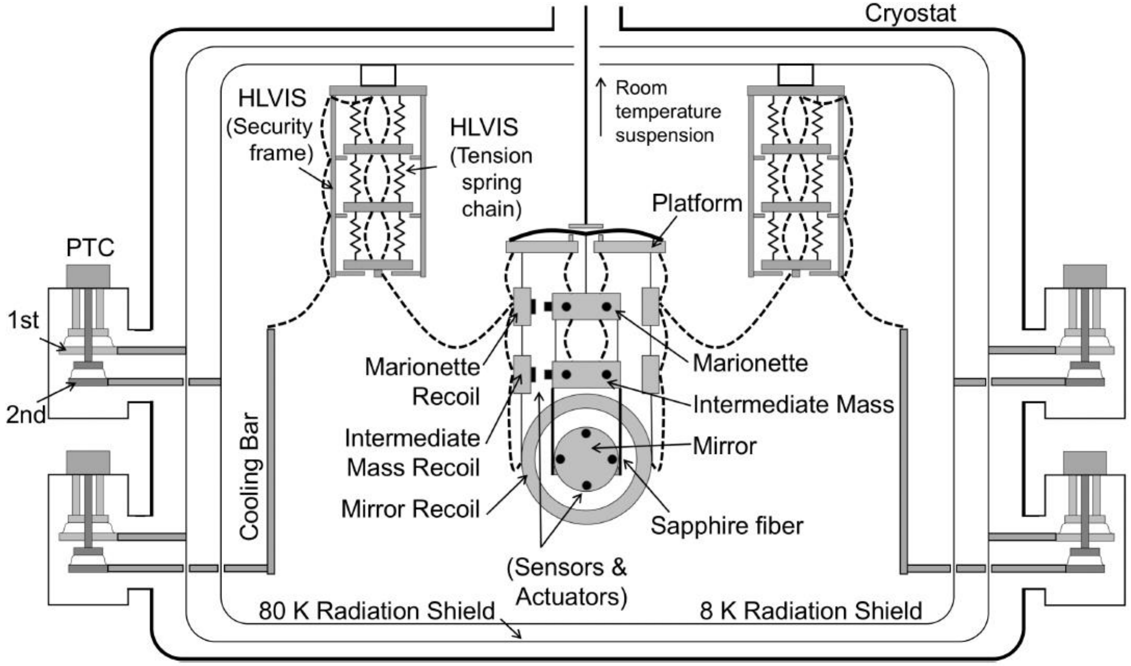


Thermal shield structural dynamics aspects: VIBRATION

DO NOT USE PTs ??? OK, but why ?

Indeed, the auxiliary Heat Link Vertical Isolation System T. Yamada, TAUP 2019 10.1088/1742-6596/1468/1/012217, is very effective – cutoff @ ~3 Hz (=> passive attenuation above 10 Hz ~ 1E-6) works.



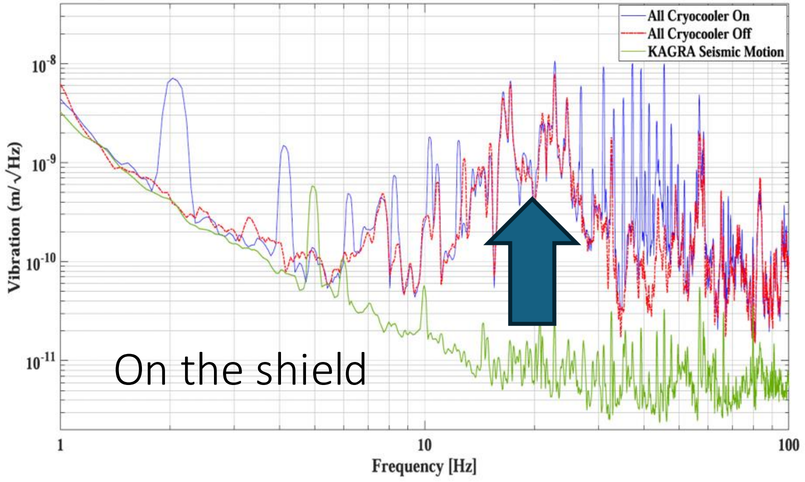


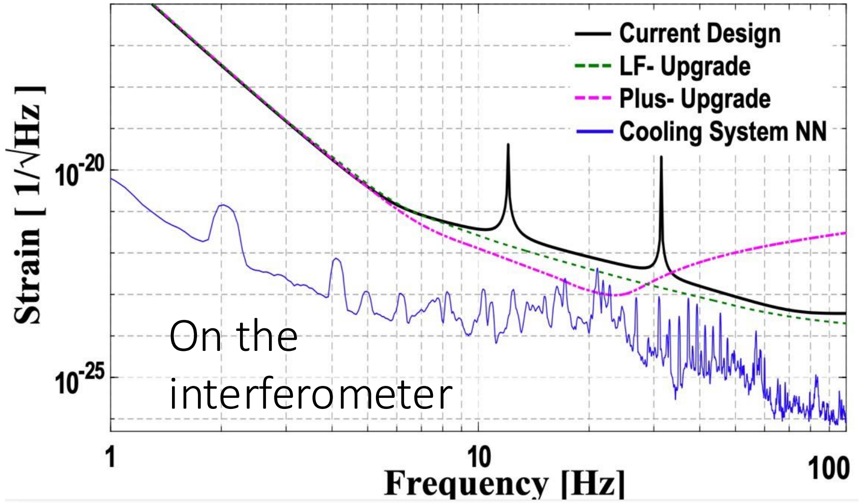
- PTs are very easy to use but the main reason to prefer He-II is not merely related to quiteness, the reasons are more related to the low efficiency that reflects on cost and on power injected in the confined underground space;
- The cut-off of auxiliary attenuator for ET soft links should be at most ~0.1 Hz, feasible but non trivial, R&D needed

Thermal shield structural dynamics aspects Newtonian Noise evaluation

- KAGRA Benchmark, *by R. Bajpai et al. Class. Quantum Grav. 39 (2022) 165004*
- New measurements verify that KAGRA ITS vibration is 1-2 orders of magnitude larger WRT tpo the underground floor

KAGRA





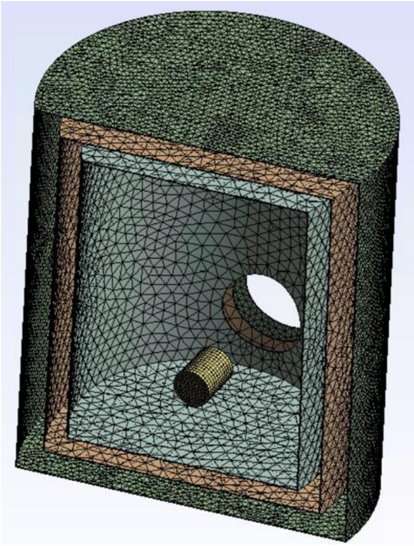
ET

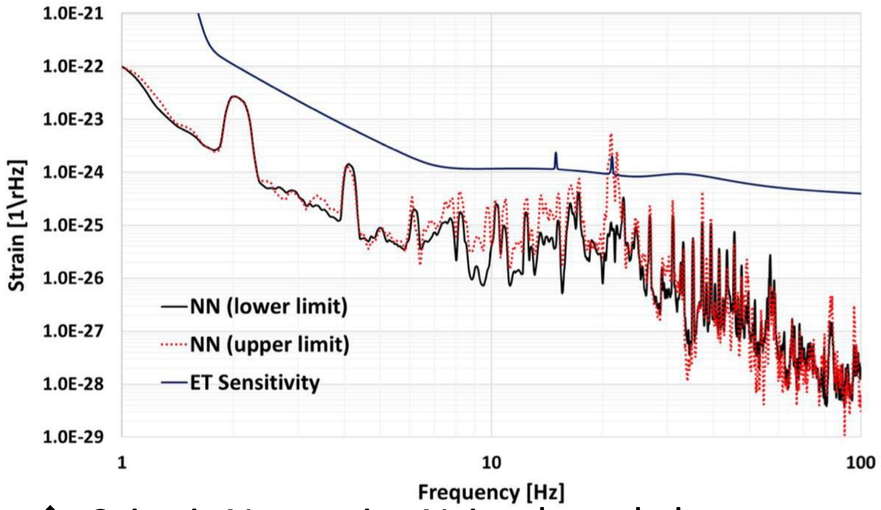
<u>assumptions</u>

- Finite Element evaluation assuming the same vibrational spectra of KAGRA
- ET-like material and geometry– Aluminium shield 10 mm thick

– Silicon mirror dia 470 mm, t=570 mm

– Holes of dia 1000 mm on all 3 shields

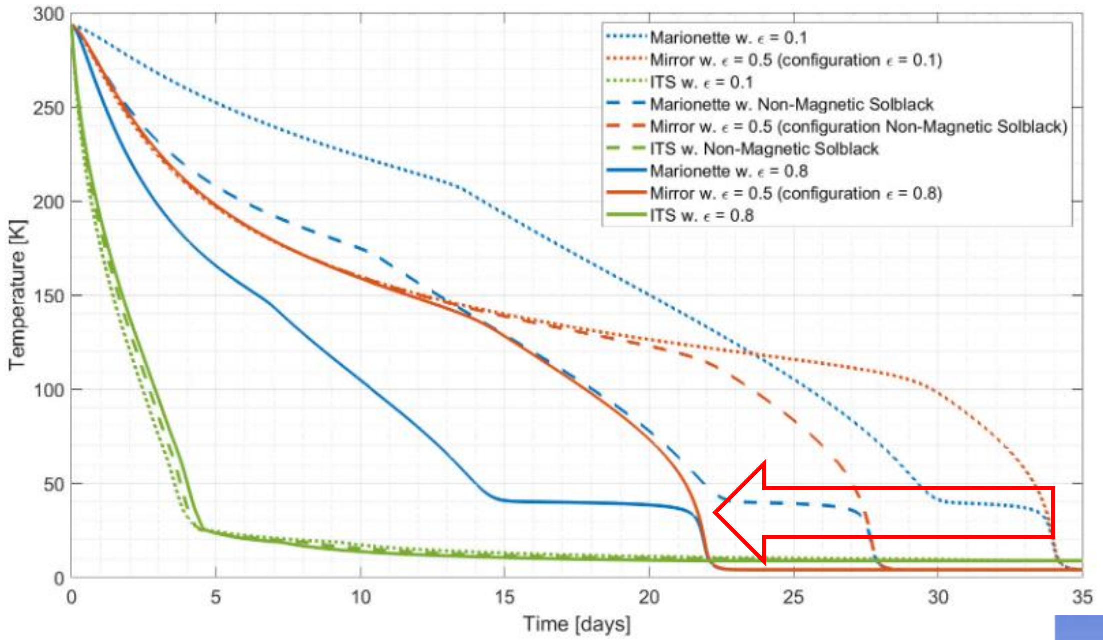




- Seismic Newtonian Noise through the cryostat structure should not be an issue

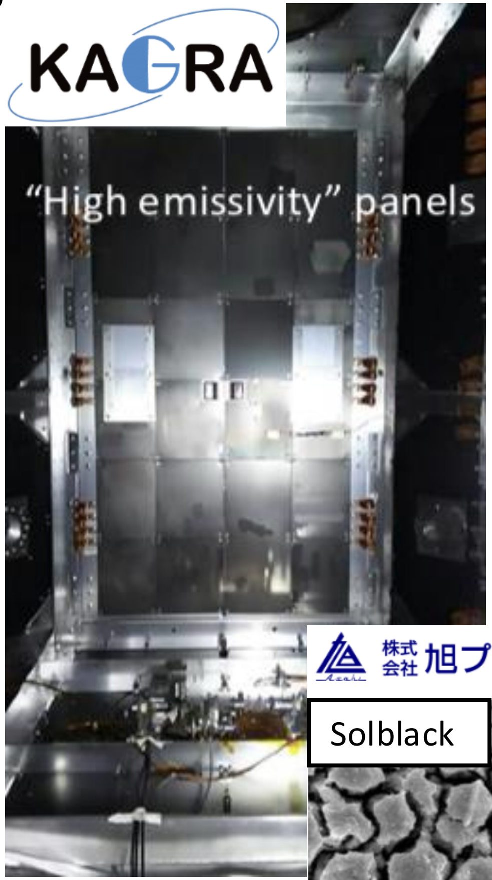
Issue n.4: High emissivity coatings

- Cooling time reduction



- UHV compatible
- Low-Outgassing
- Low residual magnetism

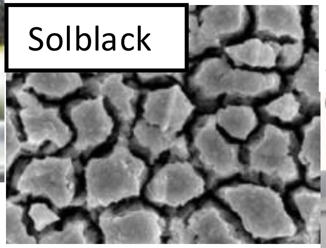
KAGRA



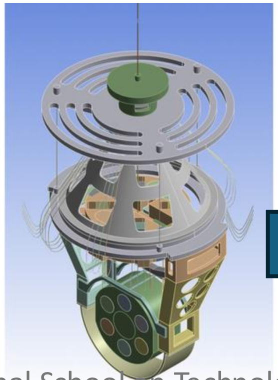
E-TEST

株式会社 旭プレシジョン

Aeroglaze Z307



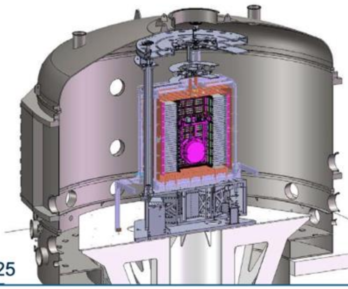
ARC-ETCRYO

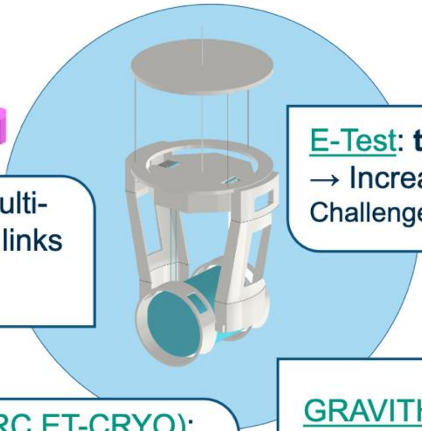


Acktar Advanced Coatings

8 - Quick survey on Prototyping test facilities and modelling

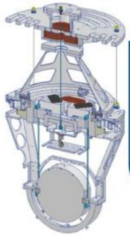
Detector cooling R&D - Test facilities





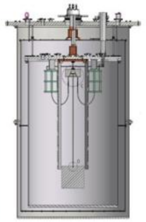
ETPathfinder: **sorption cooler** with multi-stage pre-cooling and „Jelly-fish“ heat links
→ 3 to 100 kg silicon mirrors

E-Test: **thermal radiation cooling**
→ Increase of payload surface from 2 m² to ≈ 100 m²
Challenge: T^4 dependence of the heat flux



Amaldi Research Center (ARC ET-CRYO): **cryocoolers** and KAGRA-like Al6N-heatlinks
→ 75 % scale cryogenic payload and cryostat development

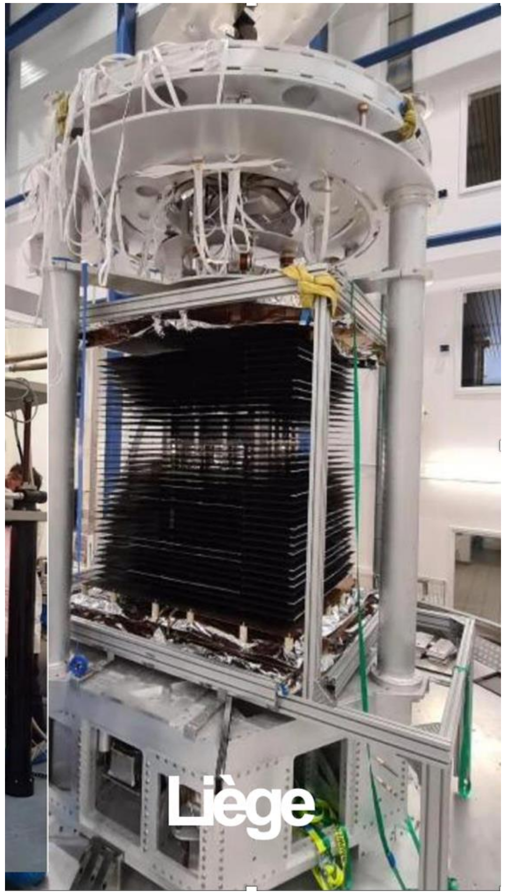
GRAVITHELIUM: **superfluid helium (He-II)**
→ Compatibility of He-II integration in suspensions



23 20.02.2026 X Koroveshi: Overview ET-ISB Vacuum & Cryogenics Division EINSTEIN TELESCOPE

R&D: Large Scale Prototypes

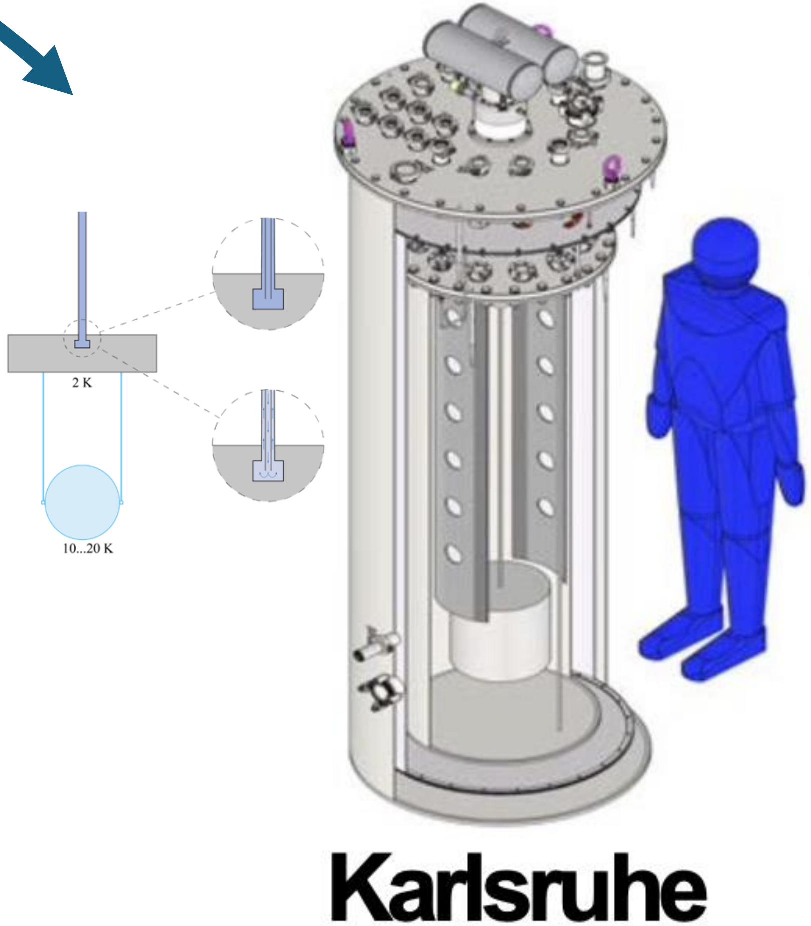
Ideally radiative non-contact



The realistic design described in this talk

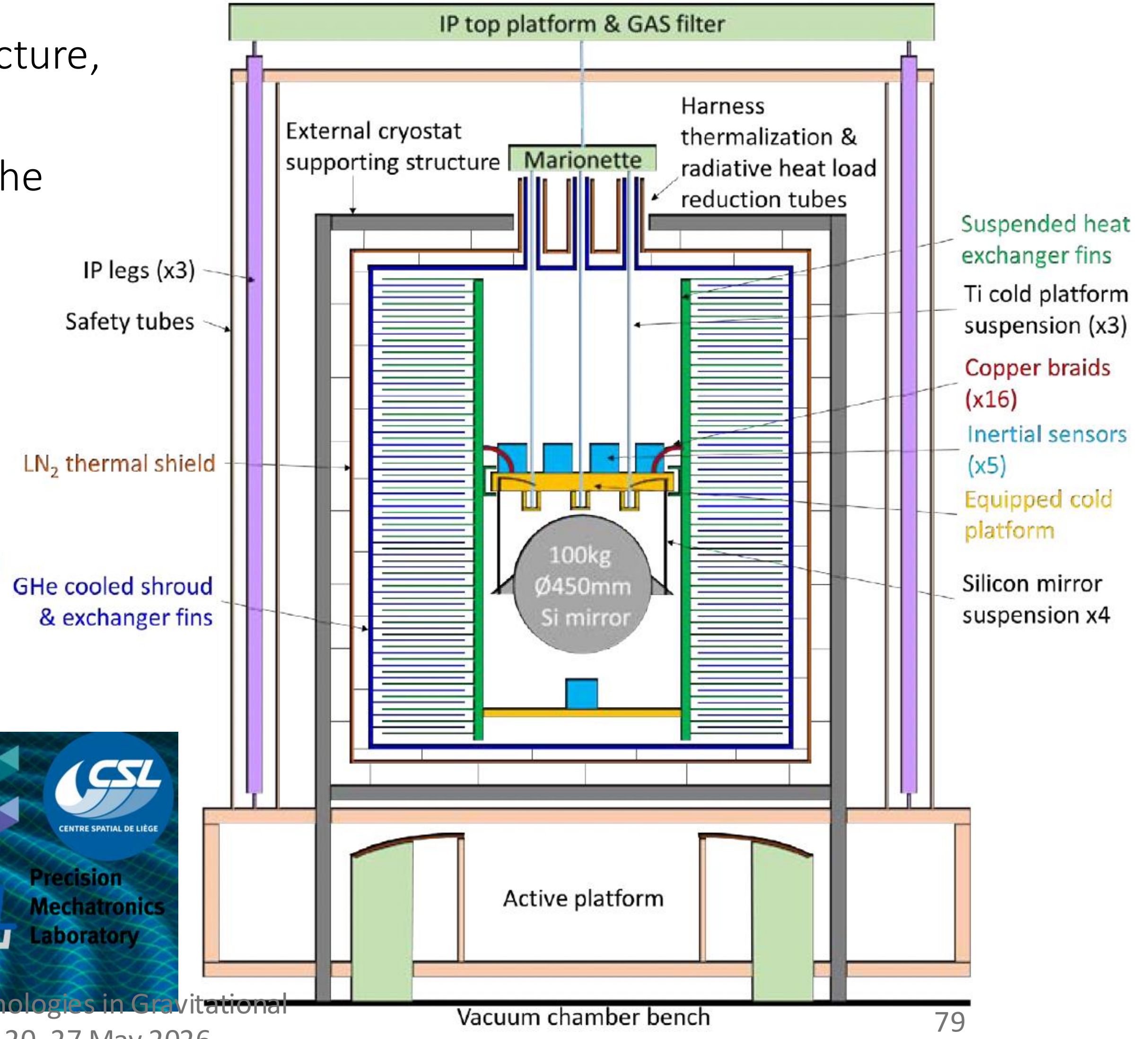
Open issues and practical challenges

Ideally conductive contact for cryofluids



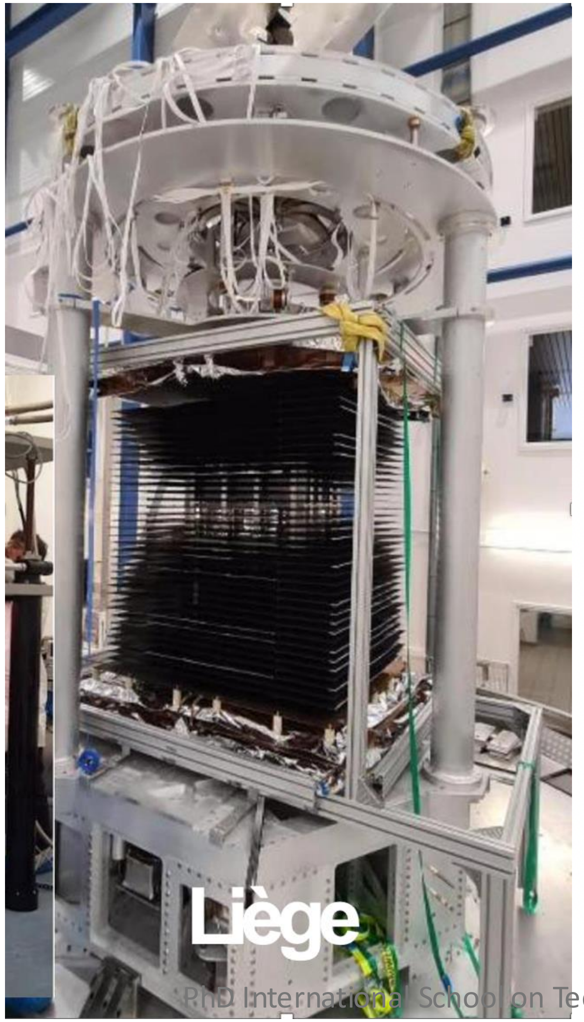
Payload cooling R&D using thermal radiation

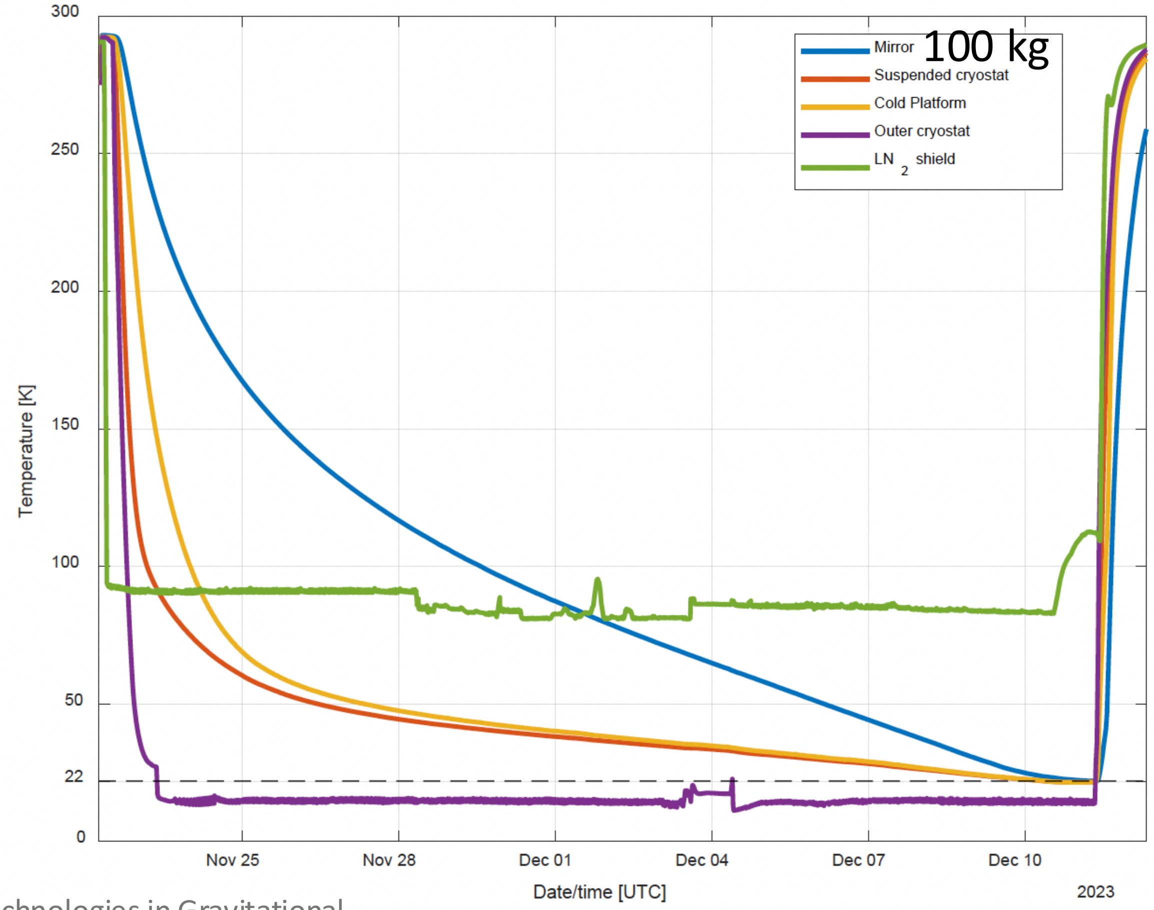
- Concept: Increase of payload surface from ≈ 2 m^2 to ≈ 80 m^2
- Issues:
  - It uses soft links and crystal suspensions into the payload structure, **but the payload is mechanically disconnected from the sink**
  - Structural vibration of the marionette due to contribution of the enhanced surface (indeed, that is a radiator)
  - XHV compatibility
  - Payload integration and accessibility
  - Payload balancing and control (standard practice to align and operate it so far is not envisaged)
  - It uses LN2
  - The system is slow but excellent to cool-down a single Test Mass, and worked
  - It uses a high-performance Inertial Platform



Payload cooling R&D using thermal radiation

Radiation cooling studies in E-TEST,
a spectacular effort

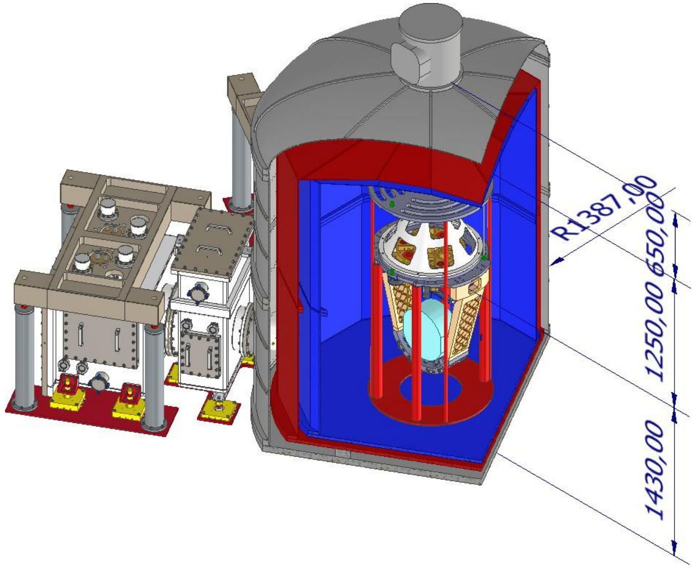


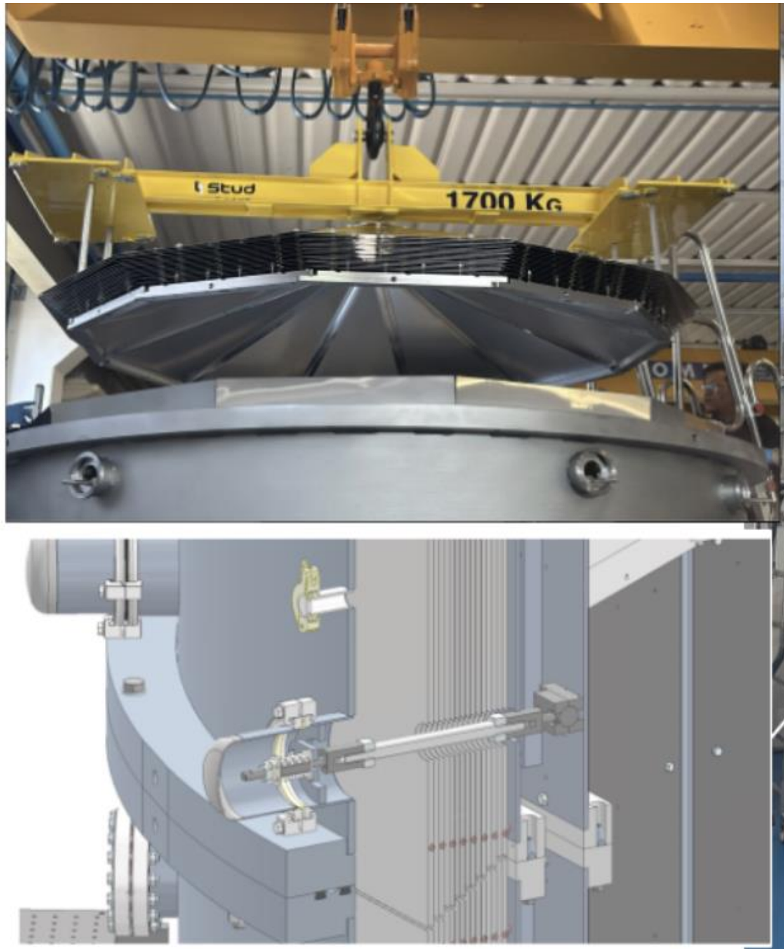


ARC-ETCRYO, C75 a ~ in scale payload and cryostat system (3 m diameter)

- Cooling down modelled
- High emissivity coatings
- Rigid-Multi-Layer on OTS
- 4 PT (Cryomech 420-425)
- Suspended cooling ducts

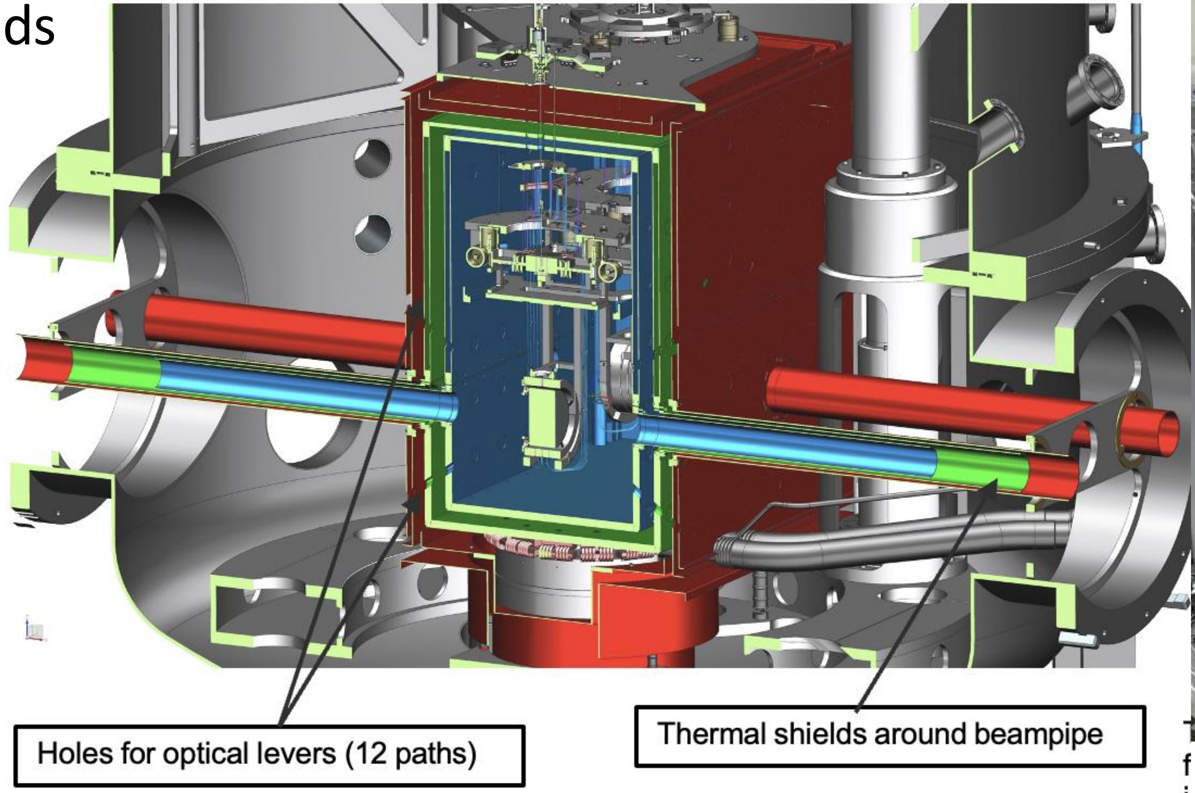
Scope: testing
~1:1 payload with Crystal
suspensions (mario/mirr)

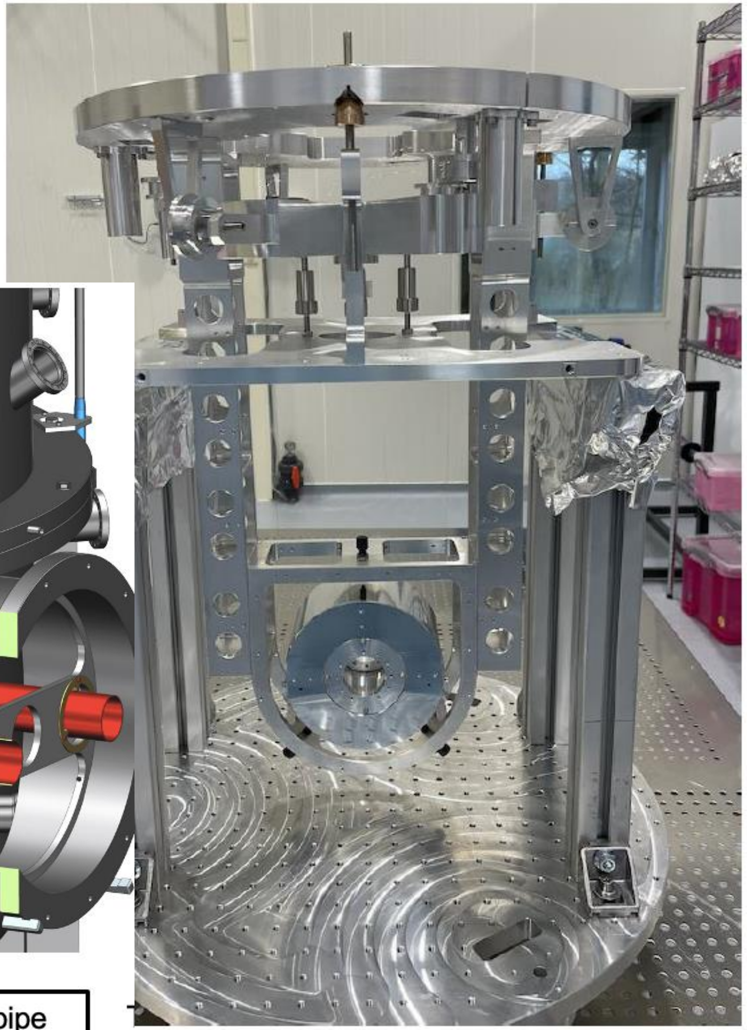




ET Pathfinder

- Test of sorption cooler
- Kickstarter cooling (JT)
- Small mirrors (few kg), unsuitable to validate large scale payloads
- Useful to test coatings and material properties
- Useful to test high performance vibration mitigation under the thermal shields





Conclusions

The cooling of a 200 kg test-mass hosted by an 800 kg articulated structure at few K IS NOT a technological challenge

Cooling-down with mechanical constraints impacting on the structural dynamics of the payload and then on the control noise reflected on its position is a BIG CHALLENGE.

Cooling-down a test-mass that is indeed a mirror that is a core optical element of an interferometer is a BIG CHALLENGE

Reasonable cryogenic payload and cryostat designed and modelled considering ET specifications and the most critical aspects.

The mechanical aspects concerning the use of crystalline suspensions are indeed the most demanding aspects towards effective payload design

Cryogenics is interlaced with Vacuum, controlled electromechanics, interferometry and optics. ET is the opportunity to merge these branches of research and to enjoy the challenge

NOT USED

Several institutes involved

- Why crystalline TM suspension
- Projects involved in the design and test of TM Suspension
- Production
- Characterization
- Designs summary

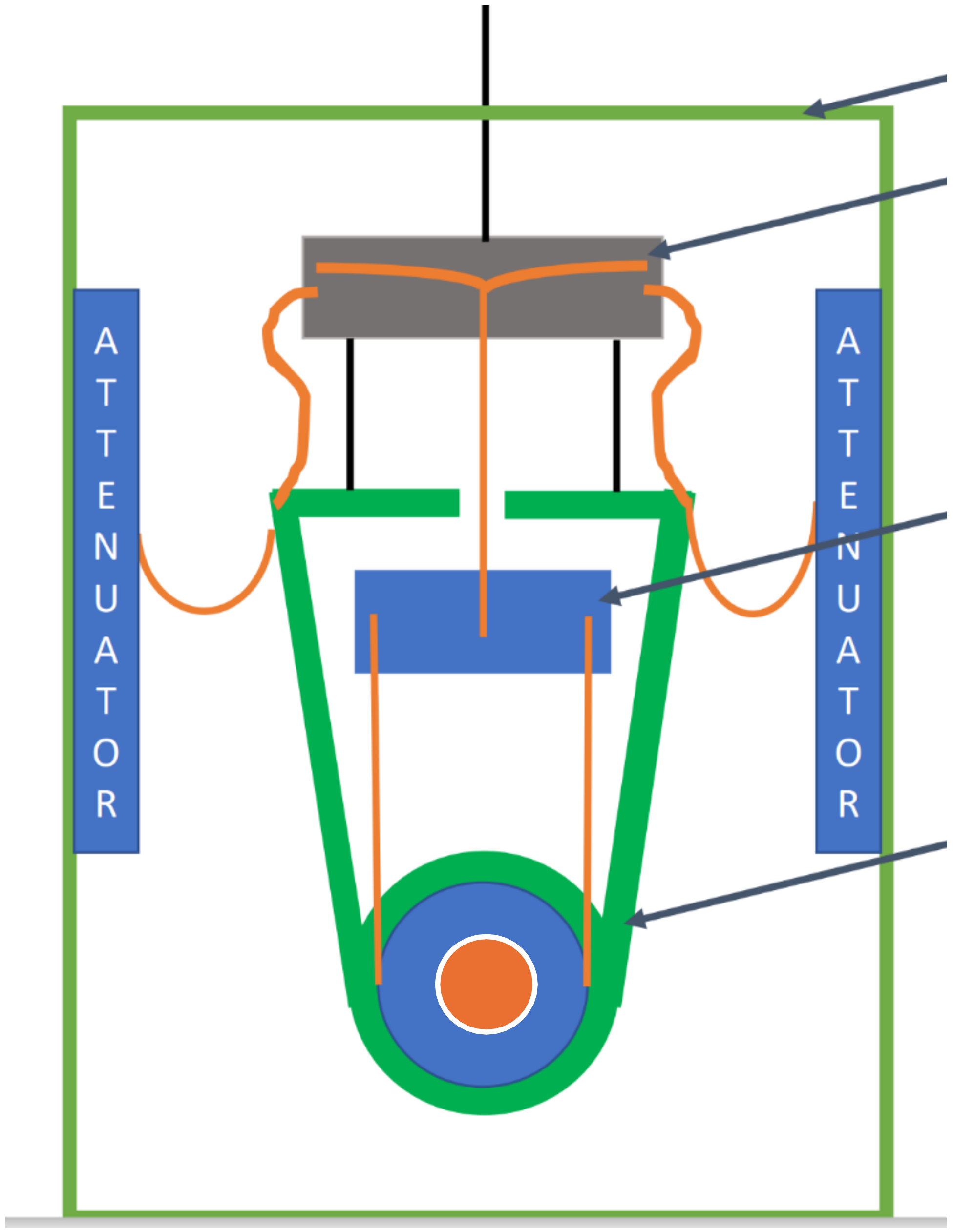
Why crystalline TM suspension

ET will integrate cryogenic technology:

Identify suitable materials for both suspensions and substrates that must have:

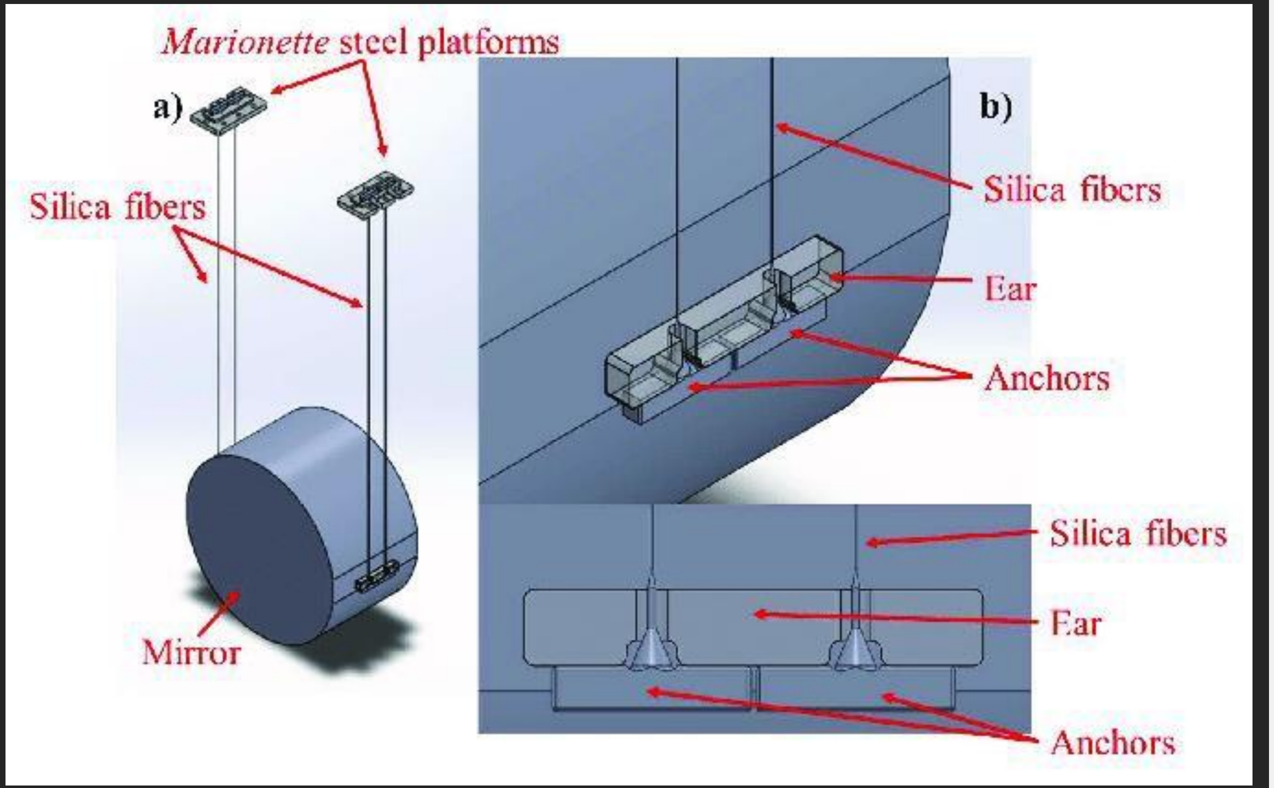
- good thermal conductivity => no fused silica
- low thermal noise => no metals and no fused silica
- high breaking strength => exceptional surface quality

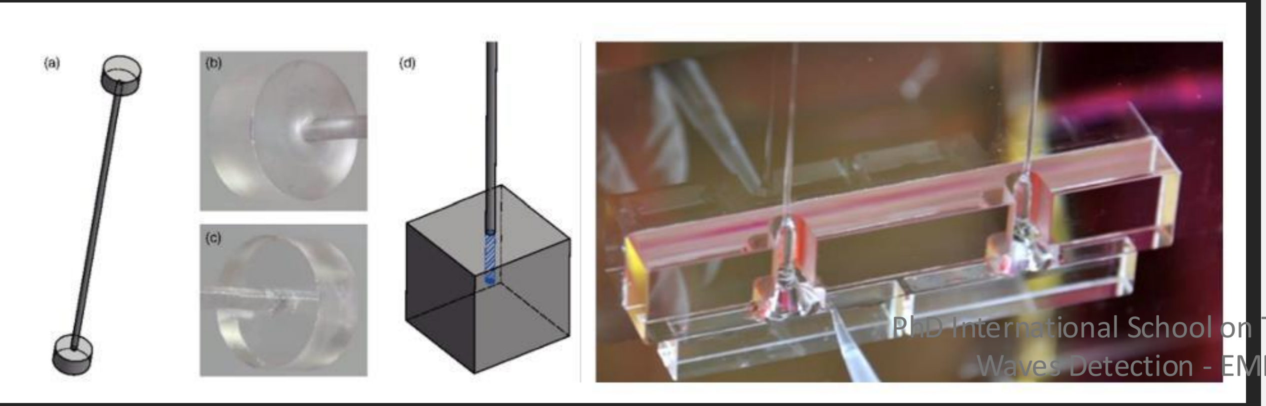
Silicon and sapphire emerged as interesting candidates.

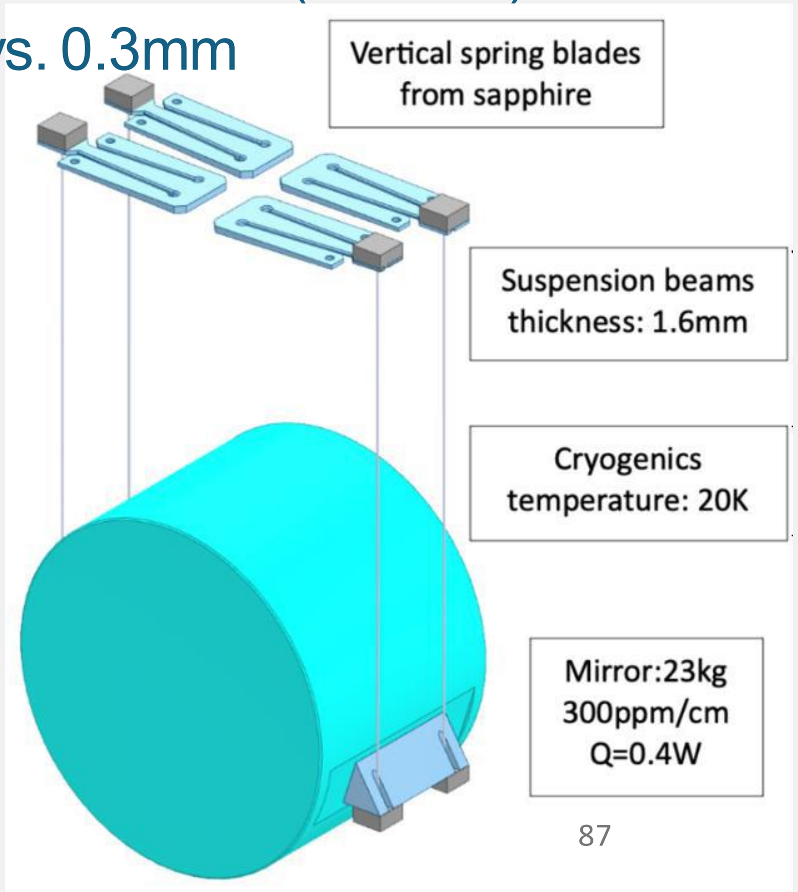


Fused silica vs. crystalline suspension

- Melting vs. growing => fiber and heads/anchors
- Elastic vs. Brittle => the biggest issue is the head of suspensions
  - Φ: 0.2mm VS 2.3-3 mm (Al_2O_3-Si)
  - Δl: 7.5mm vs. 0.3mm

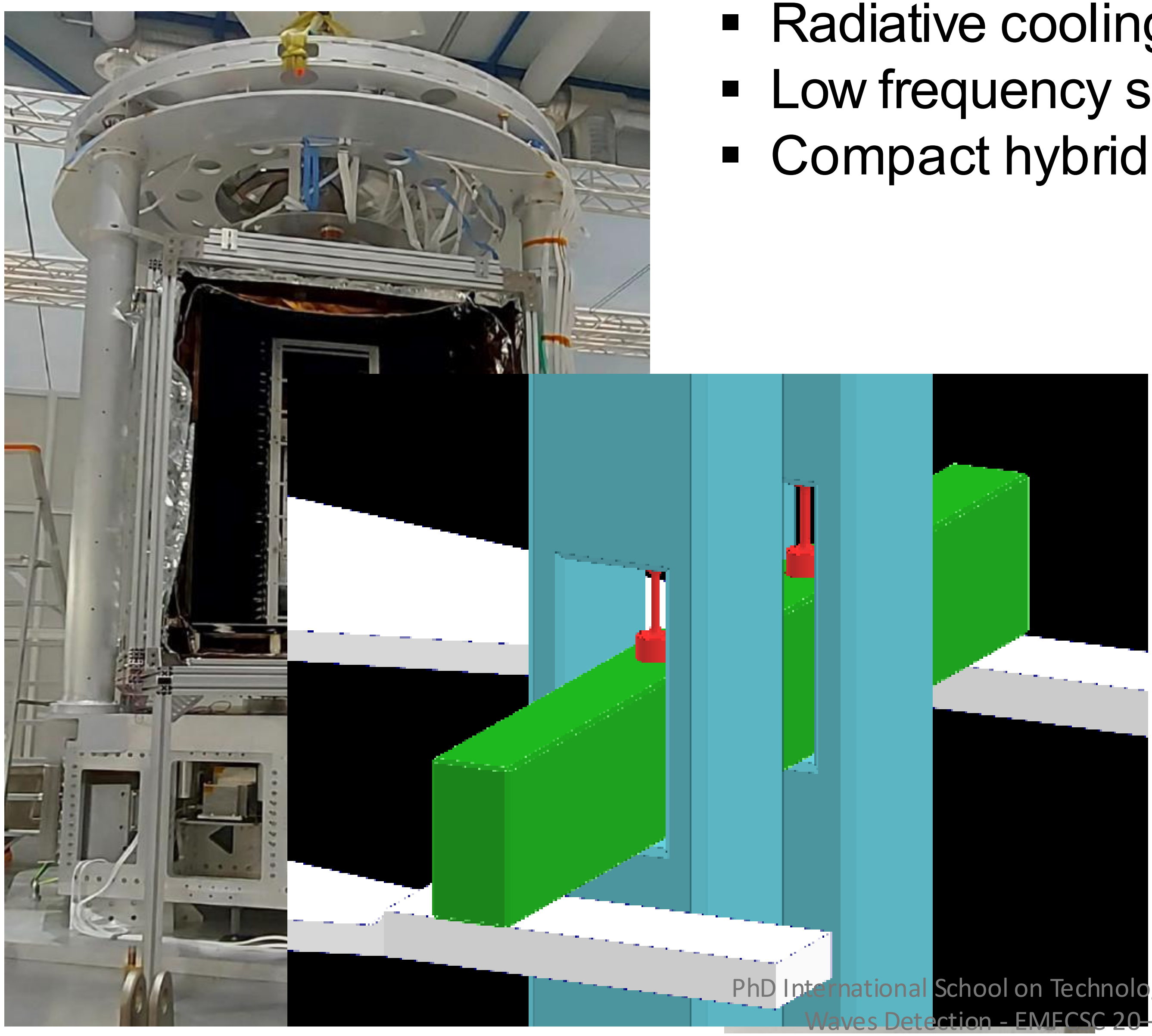






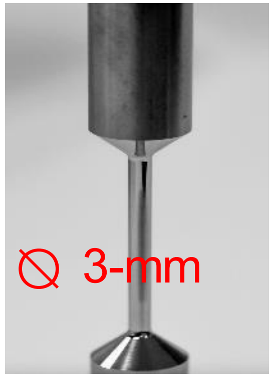
E-TEST in a nutshell

- Large silicon mirror (100 Kg)
- Cryogenic temperature (20 K)
- Radiative cooling
- Low frequency seismic isolation (10 mHz)
- Compact hybrid suspension (4.5 m high)

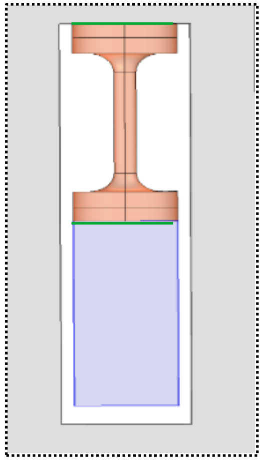


We are investigating

Improving the manufacturing process



Alternative design, based on fibers in compression

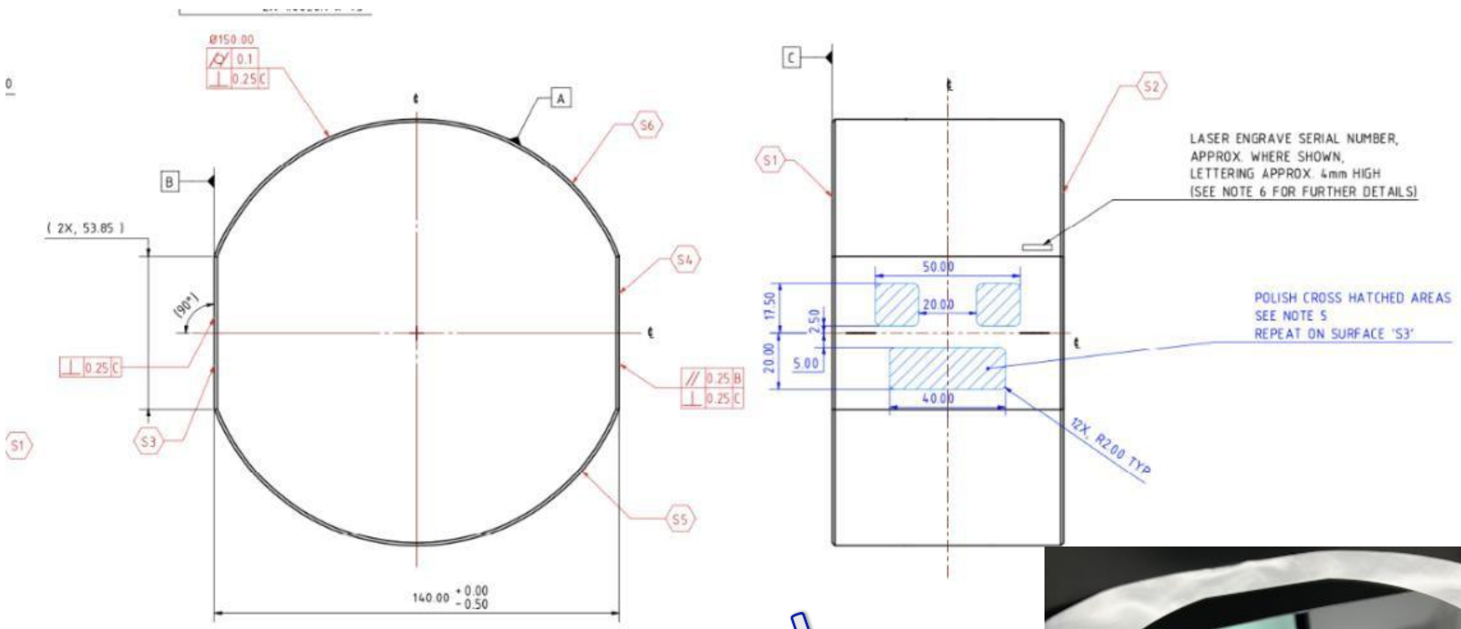


https://arxiv.org/abs/2212.10083

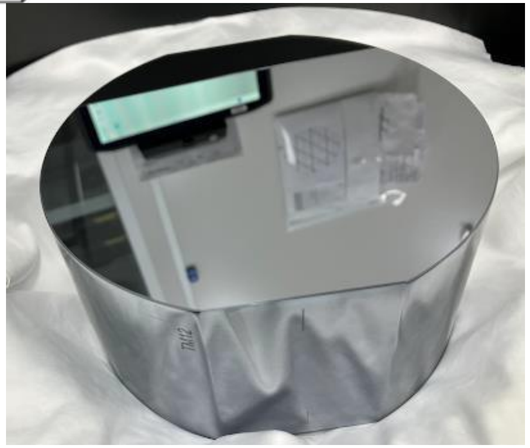
https://www.etest-emr.eu/prototype-2/

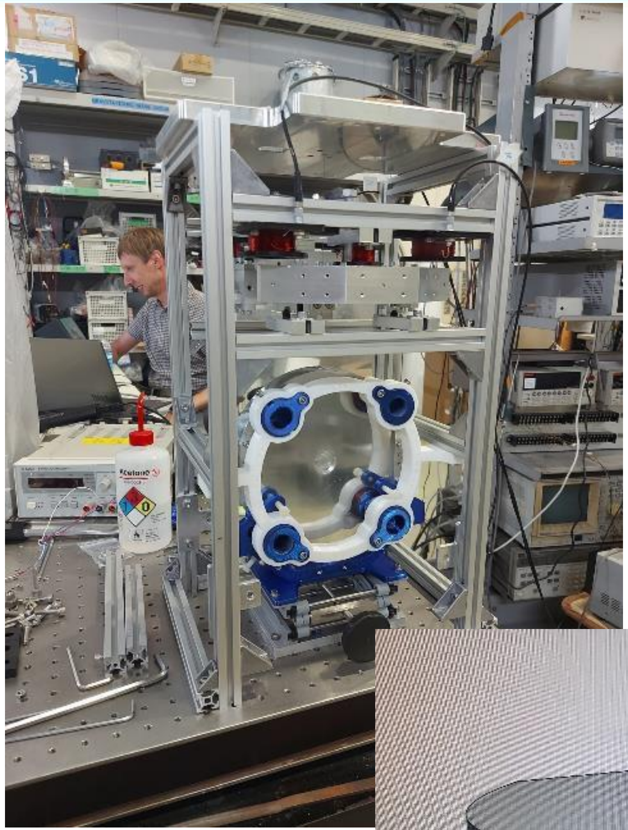
Need: Silicon suspension for 3kg mirrors

- **Looking for a collaboration to develop slicon suspension for our pristine 3kg mirrors.**
- Nikhef and UM are already overloaded with other aspects of Etpathfinder (and Virgo, ET…), so we will not be able to have a large team to take the lead here.
- Can contribute 1 postdoc or phd-student (TBD) and 250k for materials.
- Mirrors (produced by Zeiss) come with polished flats offering different configurations (see blue shaded area).



Anyone interested to help?

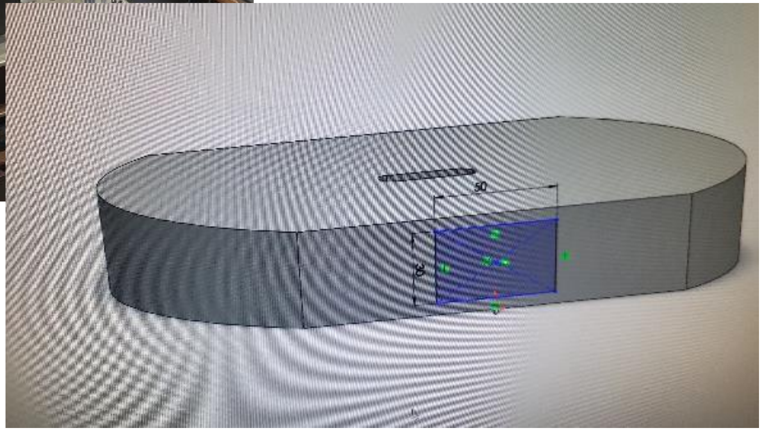


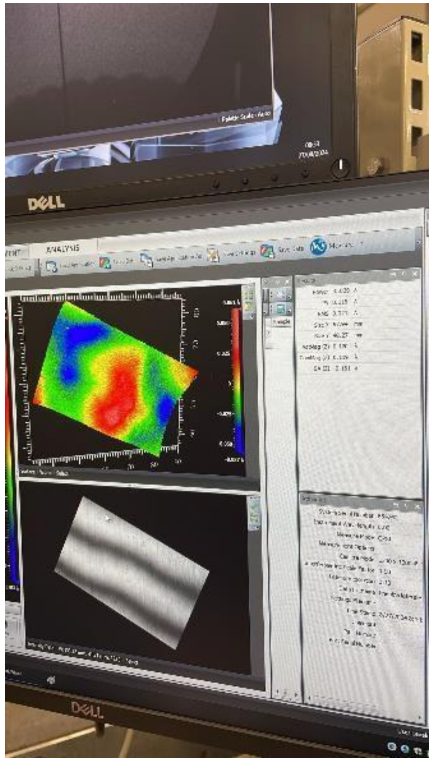


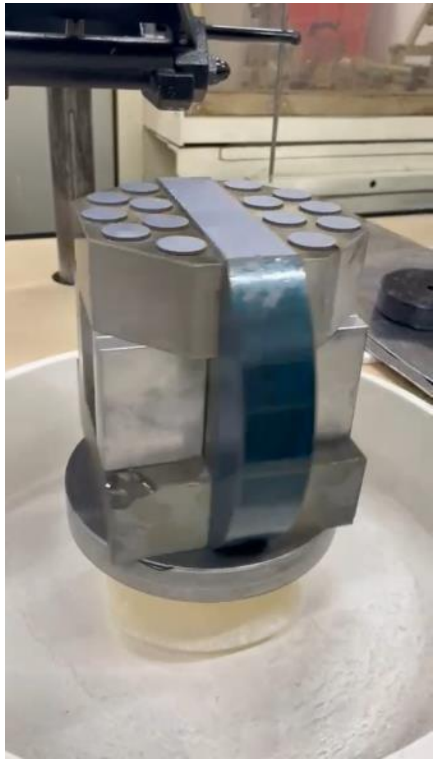
Work at ICRR

3. Crystalline suspension phase III: everything in silicon

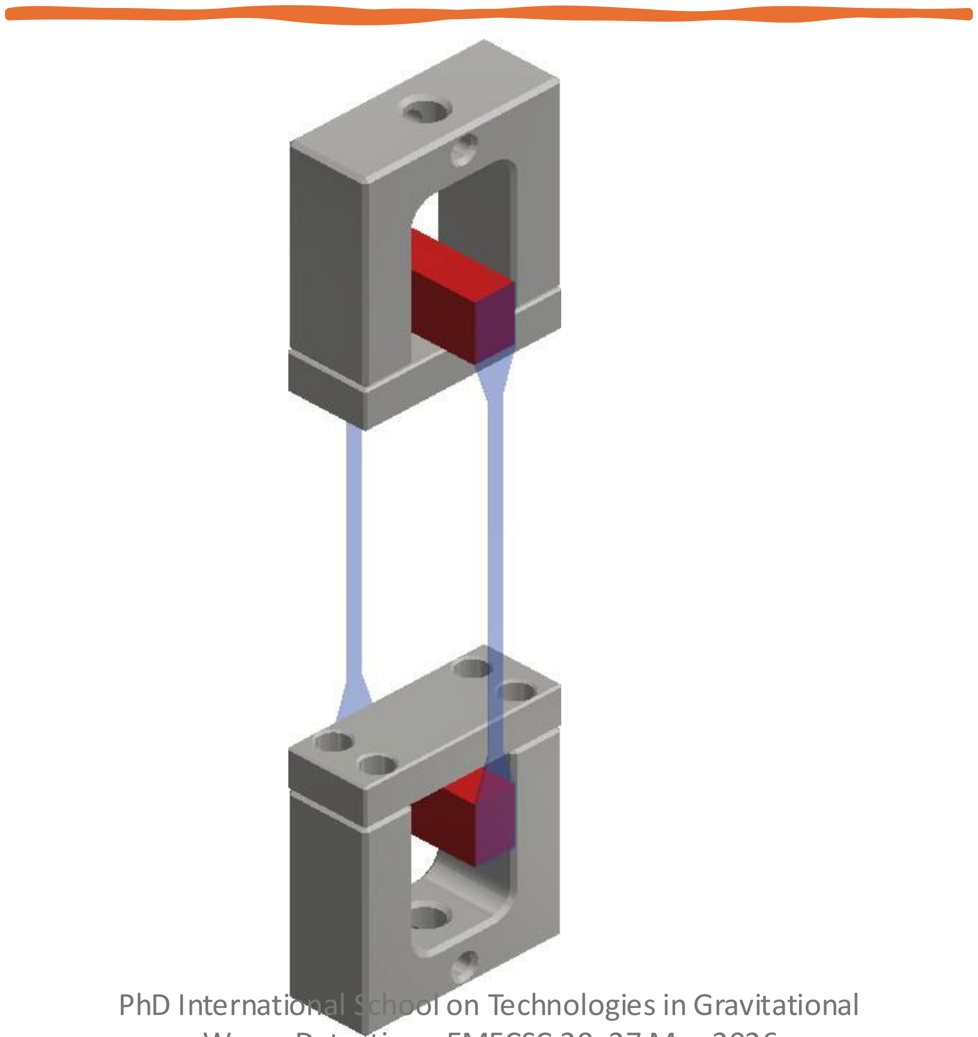
- Specifications and needs to be defined







Amaldi Research Center (ARC Sapienza-Roma)

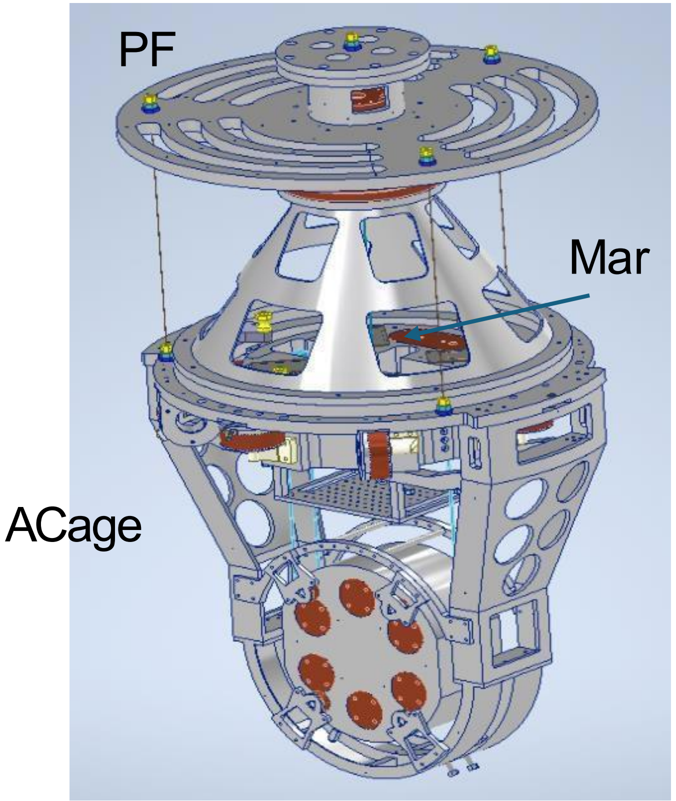


ARC

In ARC lab in Rome «La Sapienza"

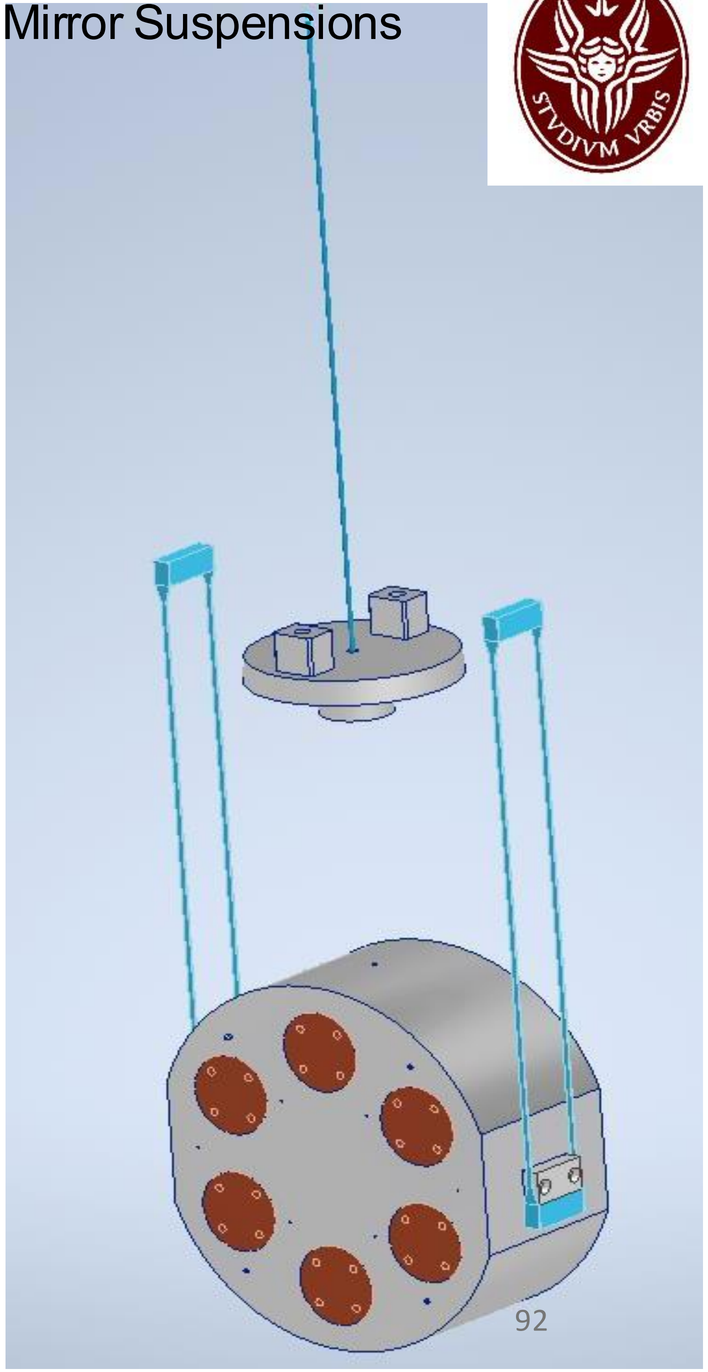
- ~1:1 payload prototype designed and currently under construction
- Uses solid conduction and soft heat links.
- No seismic isolation system, hosted in a 3m dia cryostat.
- The main focus is on sapphire, due to its favourable mechanical properties,

but also Si suspensions can be adopted.

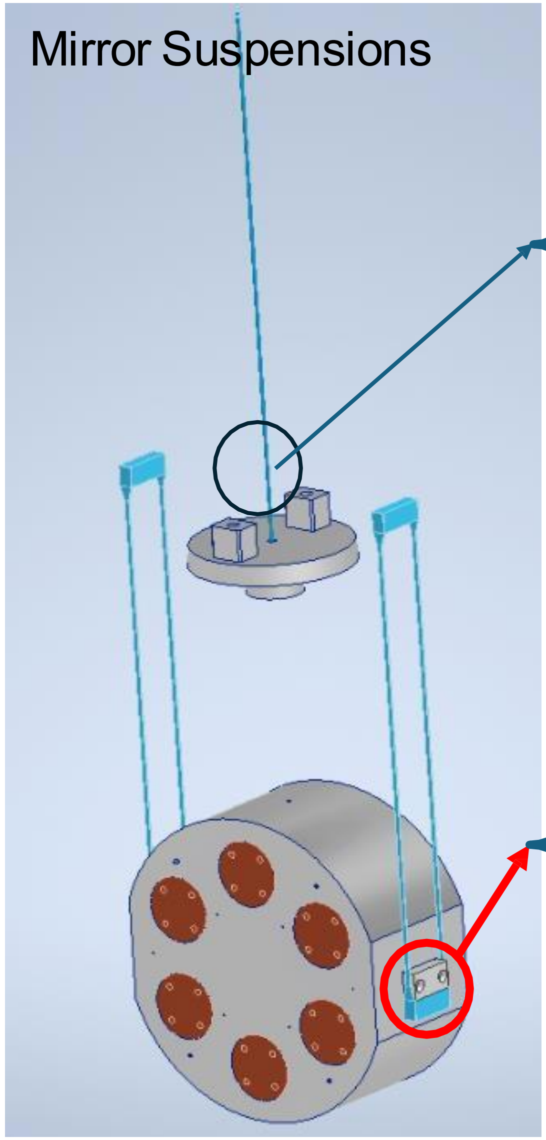


-Mar-PF CoM2CoM ~0,8m
-Mar-Mir CoM2CoM ~0,7m
-initially, no blades
(we have just the central part, to be tested)

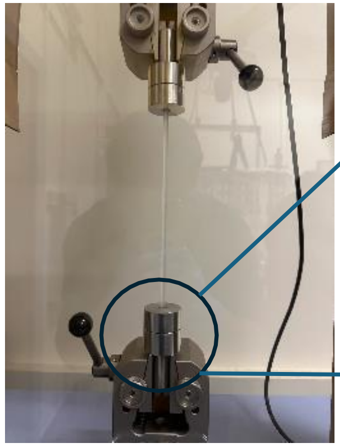
-Mir ~125kg (0.45m dia)
-Mar ~125kg

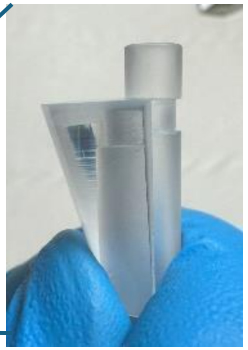


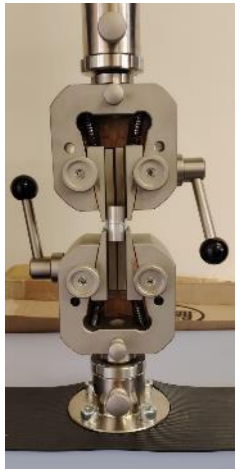
ARC



Testing new mechanical lock for the marionette

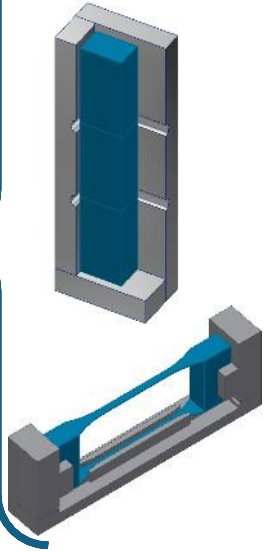






We are also considering the use of glues such as Sumiceram or Stycast.

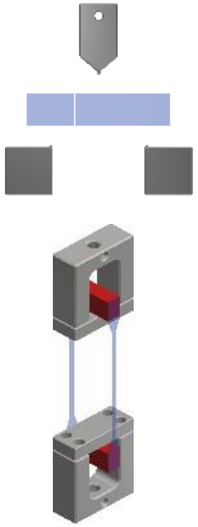
1. Bonding Phase (HCB)

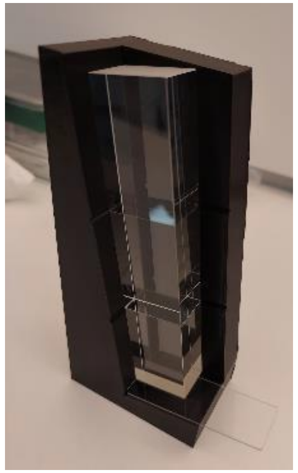


3 Blocks

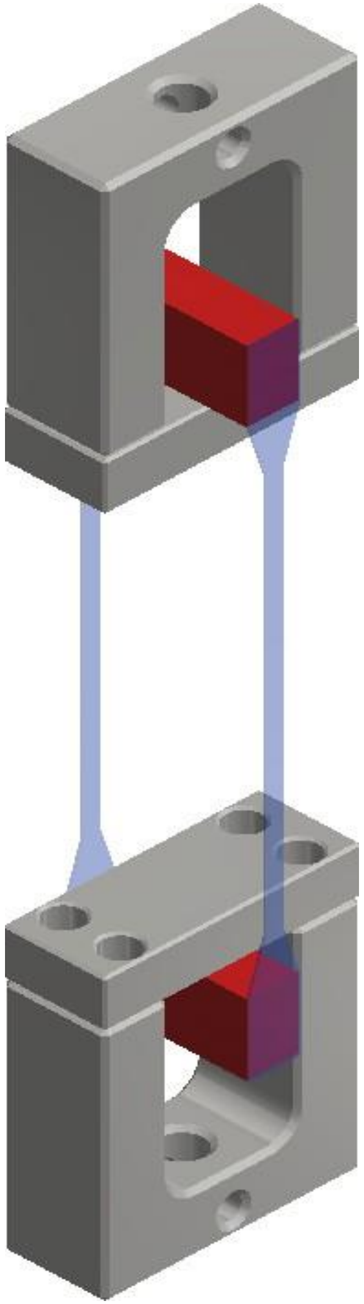
Ribbons + blocks

2. Testing Phase



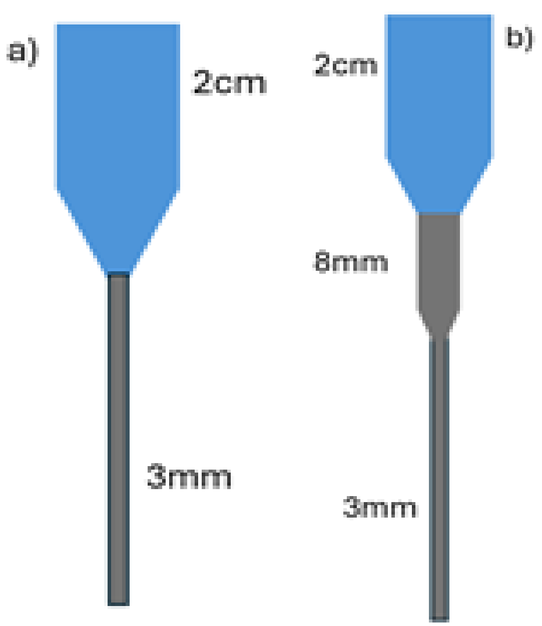


Bonding phase ongoing (Glasgow collab)

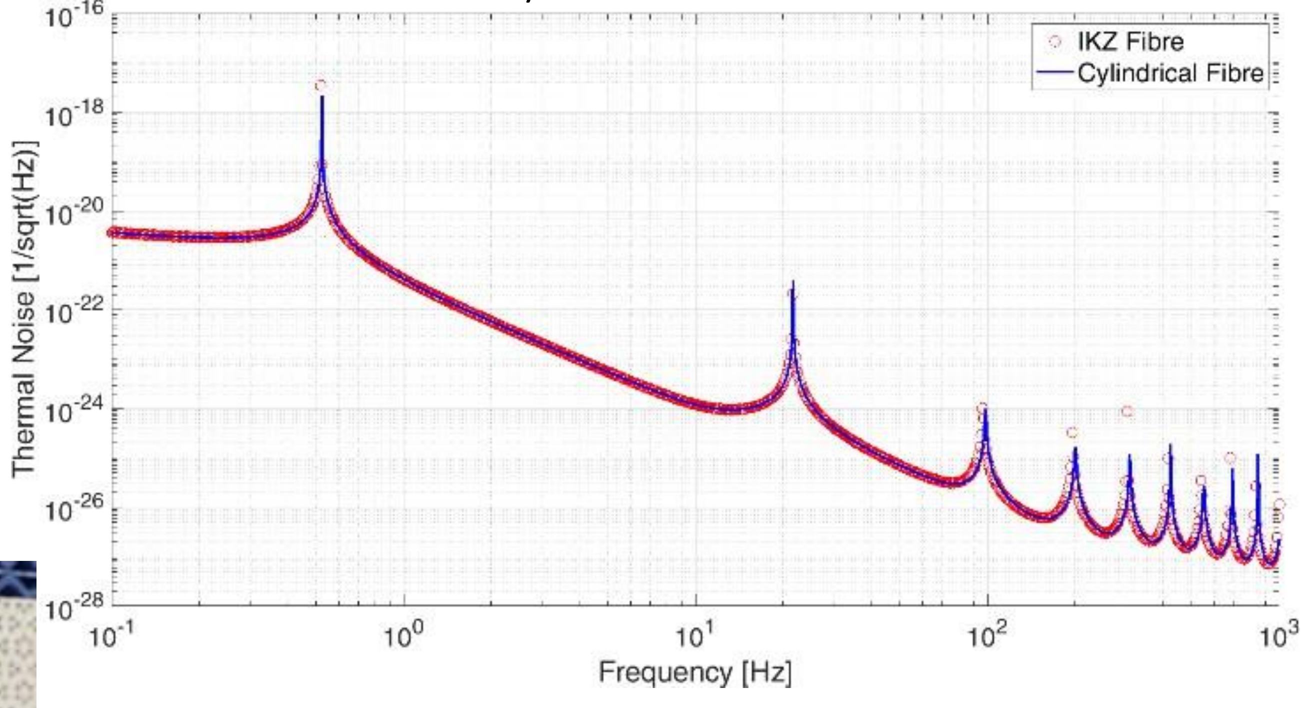


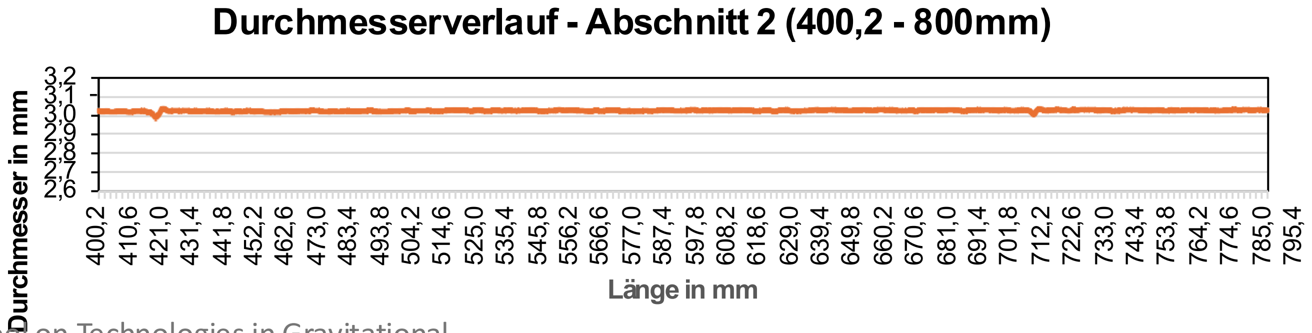
https://web.infn.it/einsteintelescope/index.php/it/home-it-it/infrastrutture-e-labs/arc-etcryo

IKZ



See the nice talk of Iryna Buchovska



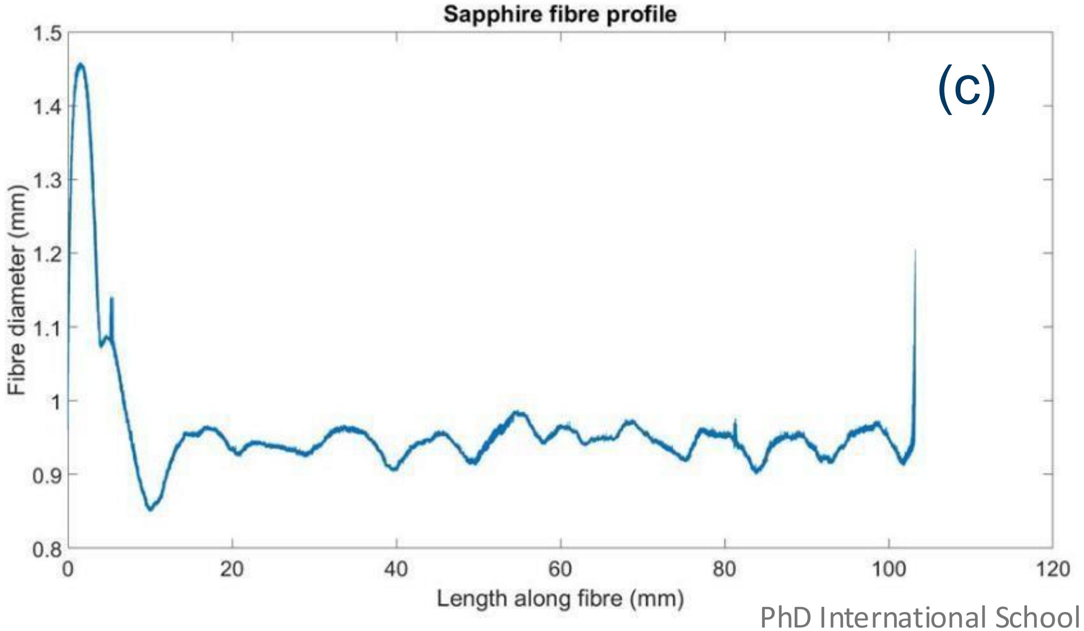


UNIVERSITY OF GLASGOW

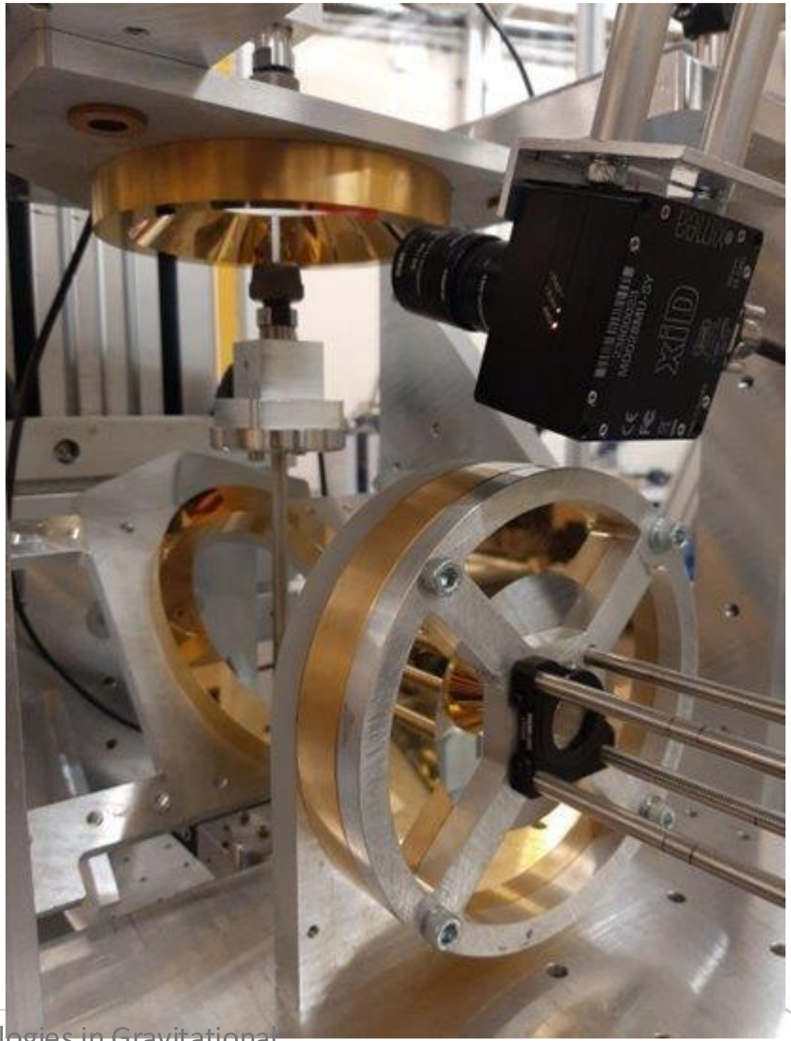
Sapphire Fibres

Sapphire fibres produced (a) by laser heated pedestal growth method (b). Capability to produce:

- 1mm diameter, low diameter variation (c),
- up to 350mm long,
- peak stress of 792MPa almost double typical quoted value of 440MPa,
- Indicates good surface quality.



(a)



(b)

Research conducted *by Dr. Jack Callaghan*

Work on Sapphire

Sapphire Laser Welding

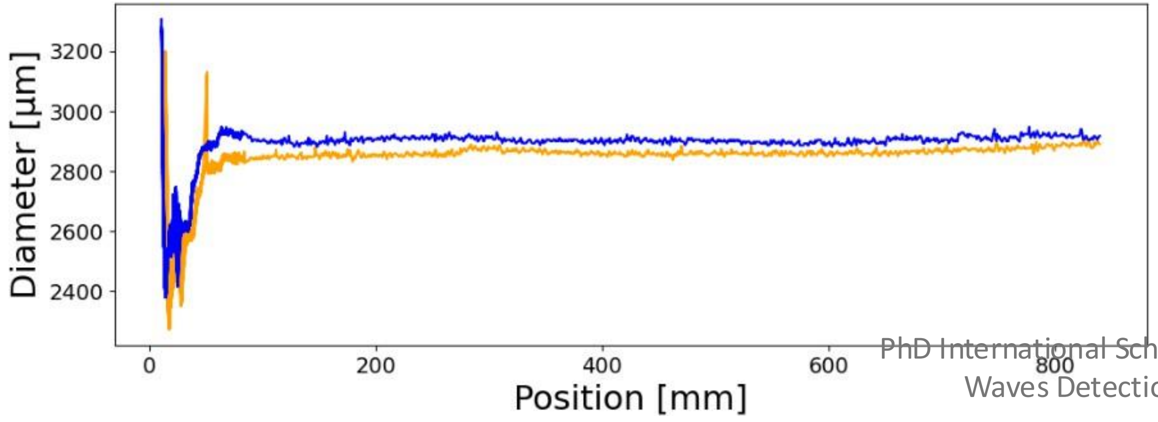
- Successfully welded sapphire to sapphire fibres of varying millimetre diameters
- Characterisation work ongoing:
    - Mechanical loss
    - Thermal conductivity
    - Tensile strength
    - Crystallography

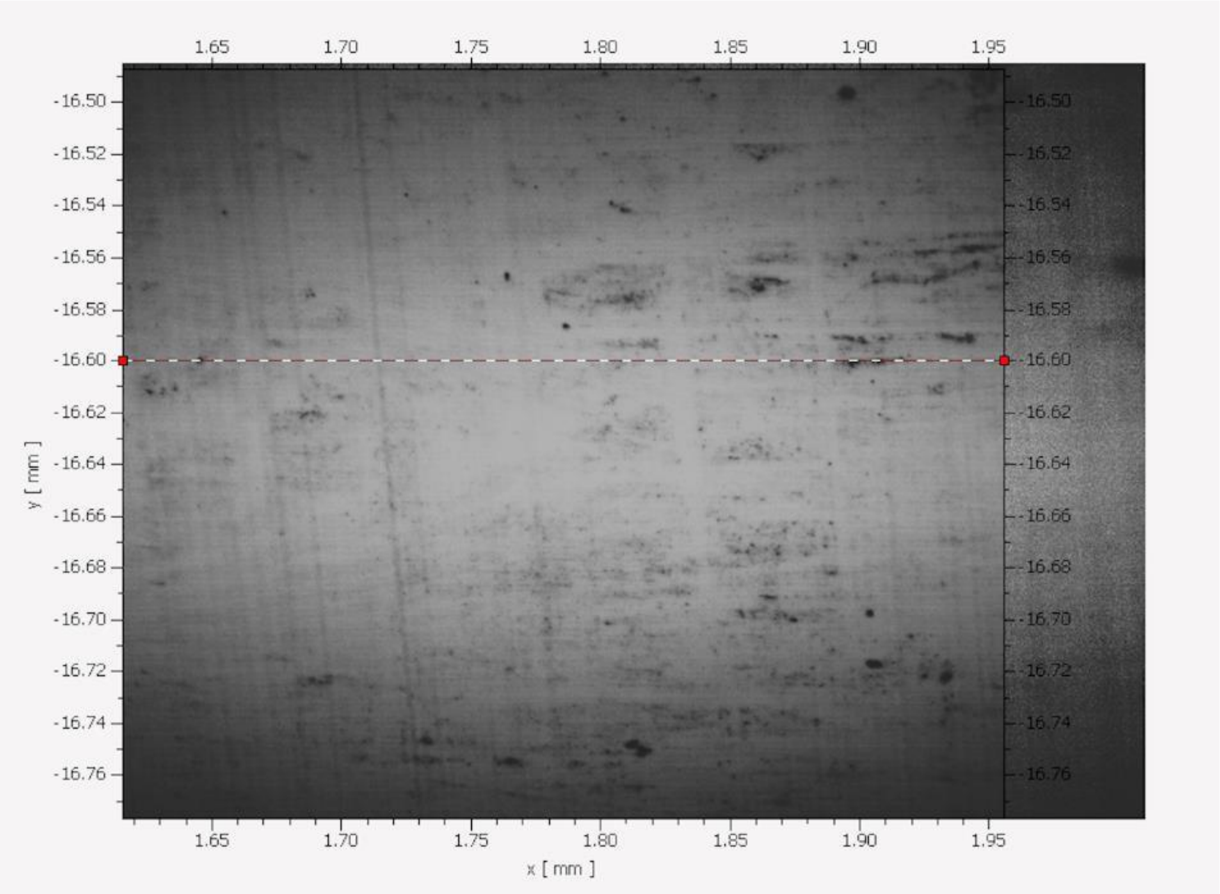
Contacts:
- Jennifer Docherty
- Alan Cumming

Silicon fibres

- More than 10 fibres of length from 64cm to 116cm are characterized at Glasgow
- Lowest diameter variation: 4.1%
- Surface quality overall good, with minor chips and indentations

Profile of the fibre

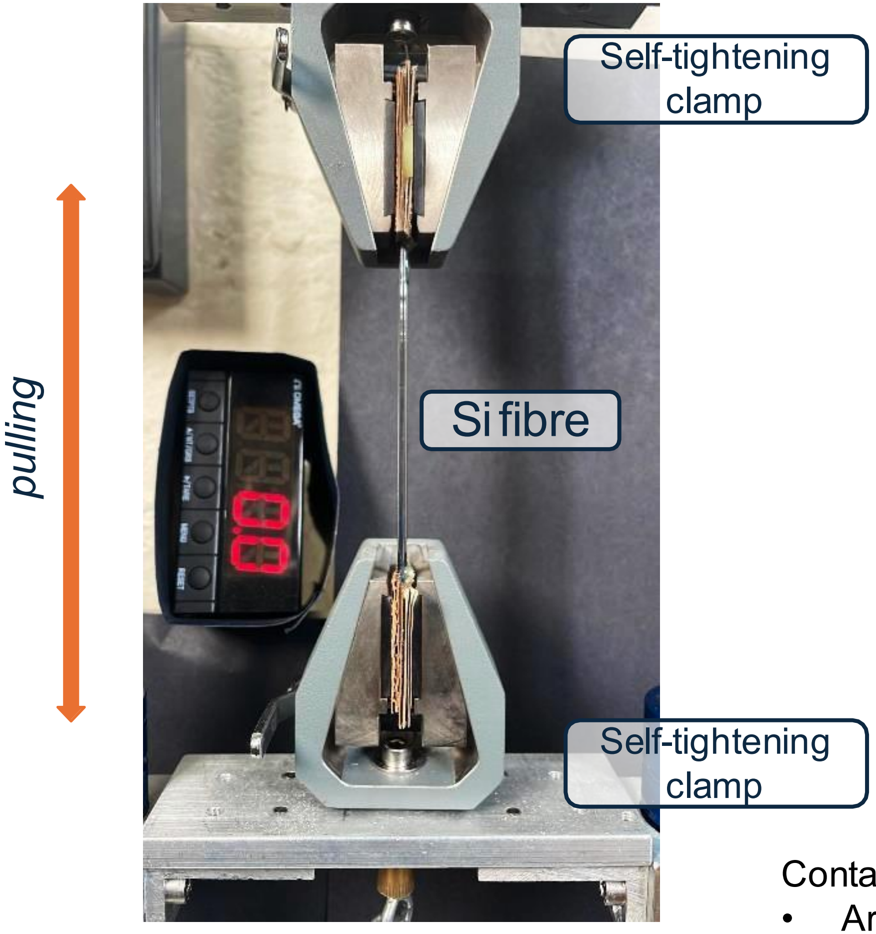




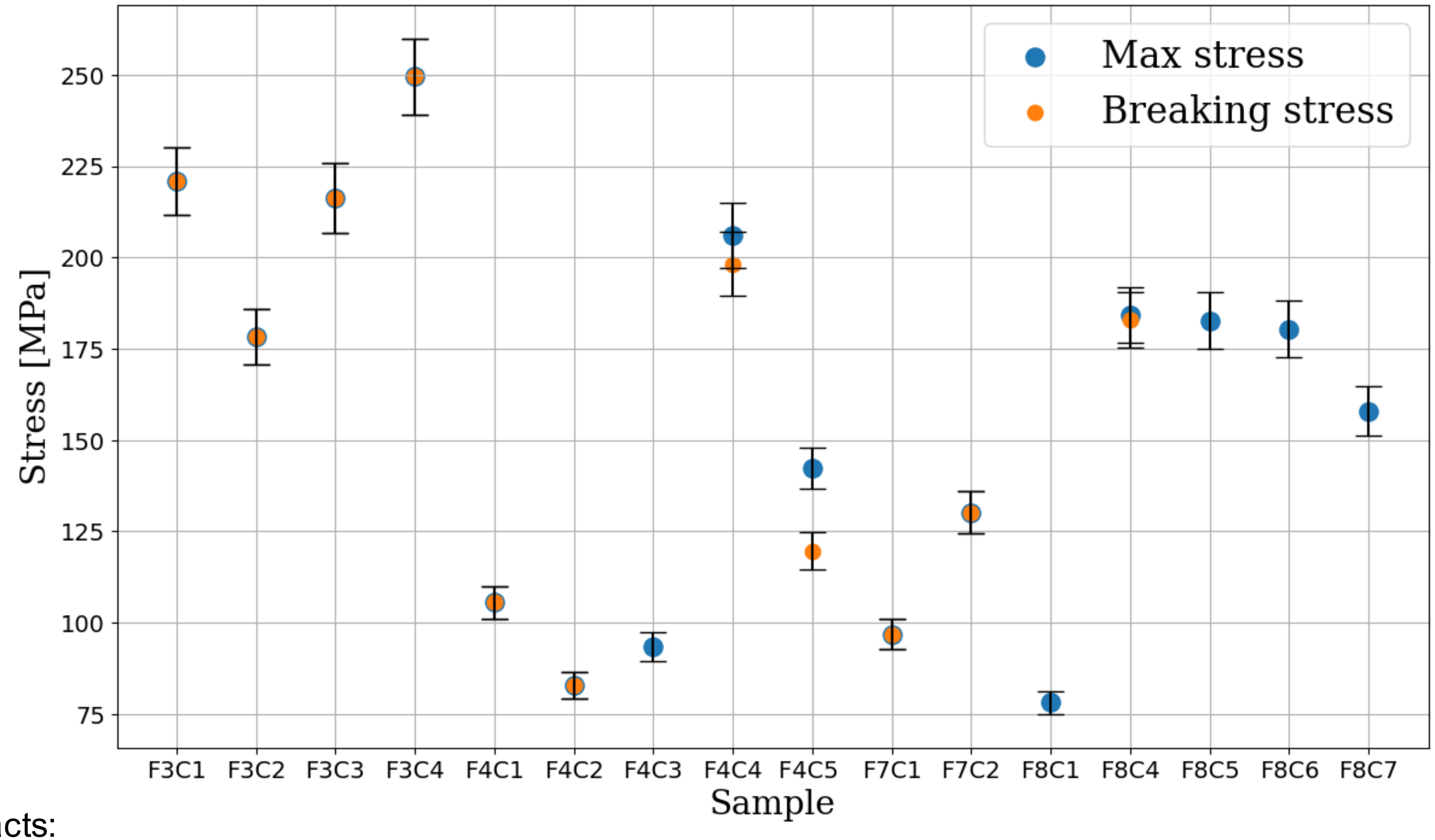
Close-up images taken on a Polytec microscope

Breaking strength tests of fibres

Setup



Tensile stress results

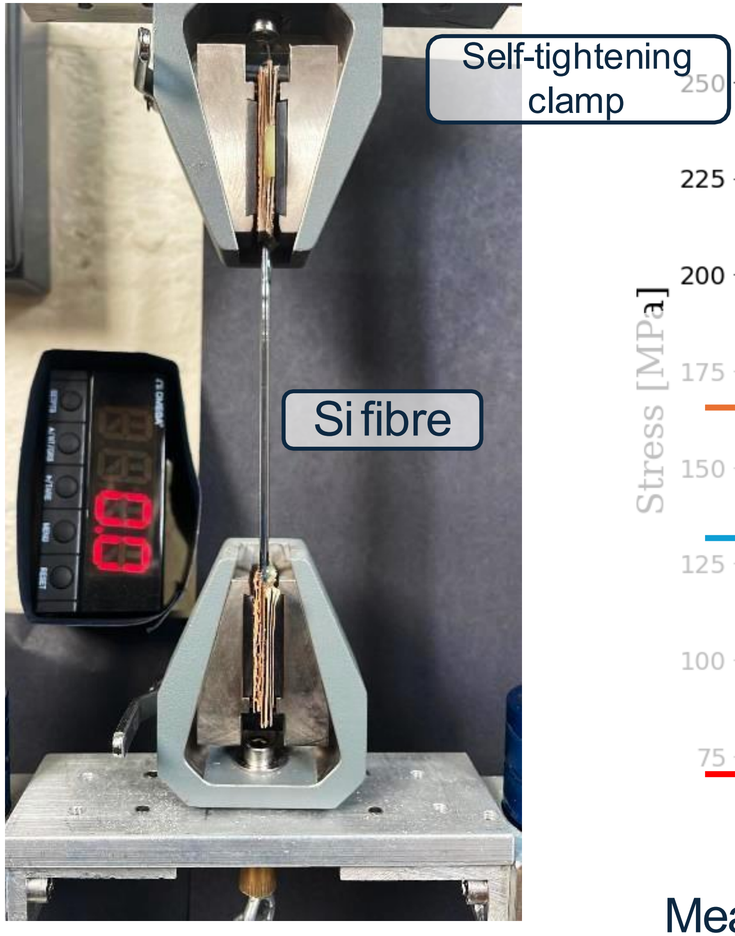


Contacts:
- Ardiana Nela
- Karl Tholand

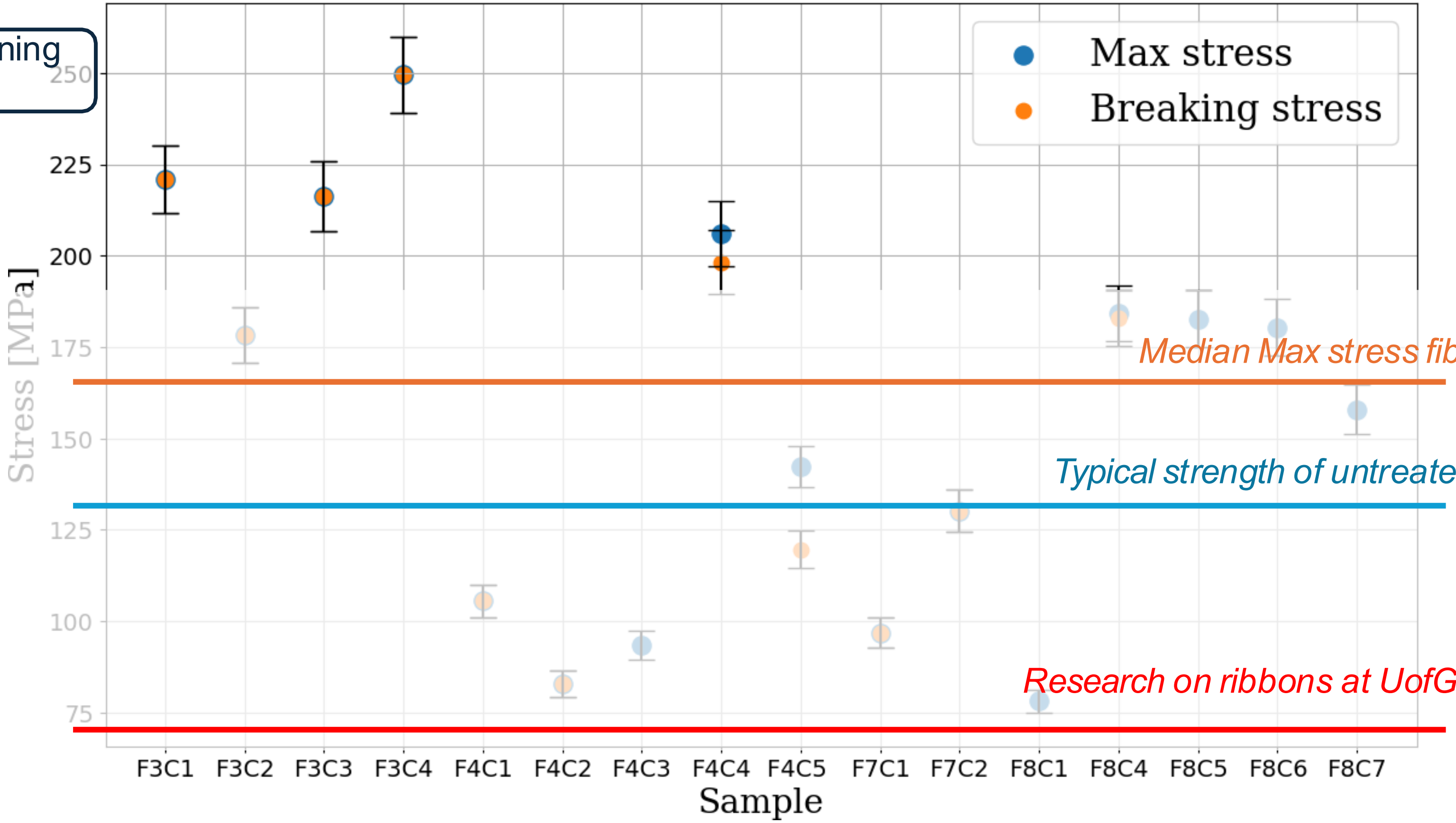
Breaking strength tests of fibres

Setup

pulling

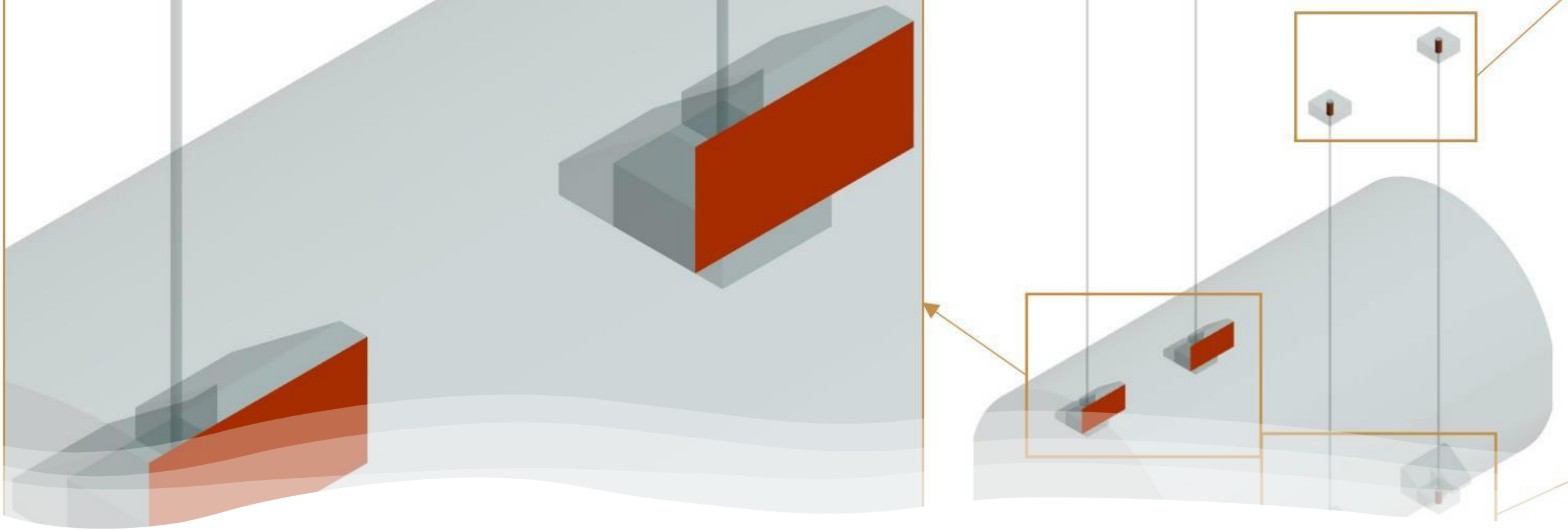


Tensile stress results



Measured breaking stress is a lower limit due to alignment challenges

1. Graeme Eddols: LIGO-G2101011-v1
2. 2. A V Cumming et al 2014 Class. Quantum Grav. 31 025017



Perugia/Camerino labs

- Involved in the design of the samples (IKZ, UMPT, Impex, …)
- Mechanical test and structural analysis of crystalline samples
- HCB bonding
- Mechanical simulation
- ….