Cryogenics in ET: why and how

Et Tower (Vac and Cryo)

Fulvio Ricci

EINSTEIN TELESCOPE
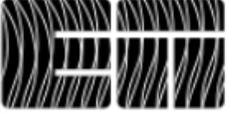
SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

SEZIONE DI ROMA

Talk Outline

- From 2° to 3° generation of GW detectors

- Einstein Telescope sensitivity: how to improve the LIGO/Virgo performances

- Thermal Noise and Cryogenics in GW experiment

- Payload, Cryostat and Cryopumps

- Hunting extra noise sources

- Conclusions

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GW150914 $h = \Delta L/L \sim 10^{-21}$ with $L = 4$ km

(Atomic dimension $\sim 10^{-10}$ m Nuclear dimension $\sim 10^{-15}$ m)

Test mass (mirror) displacement $\sim 4 \times 10^{-18}$ m

ET must do better!

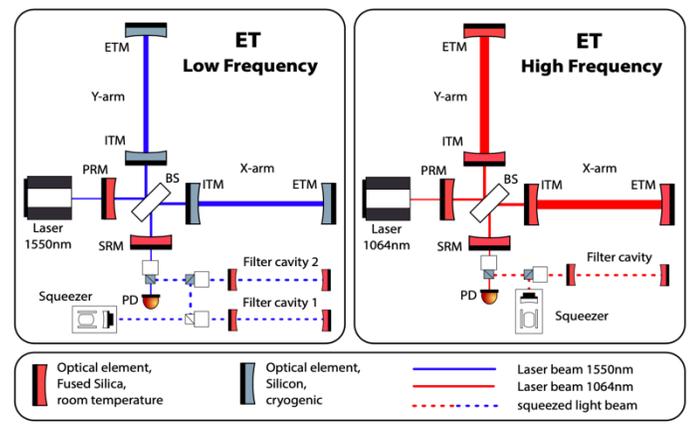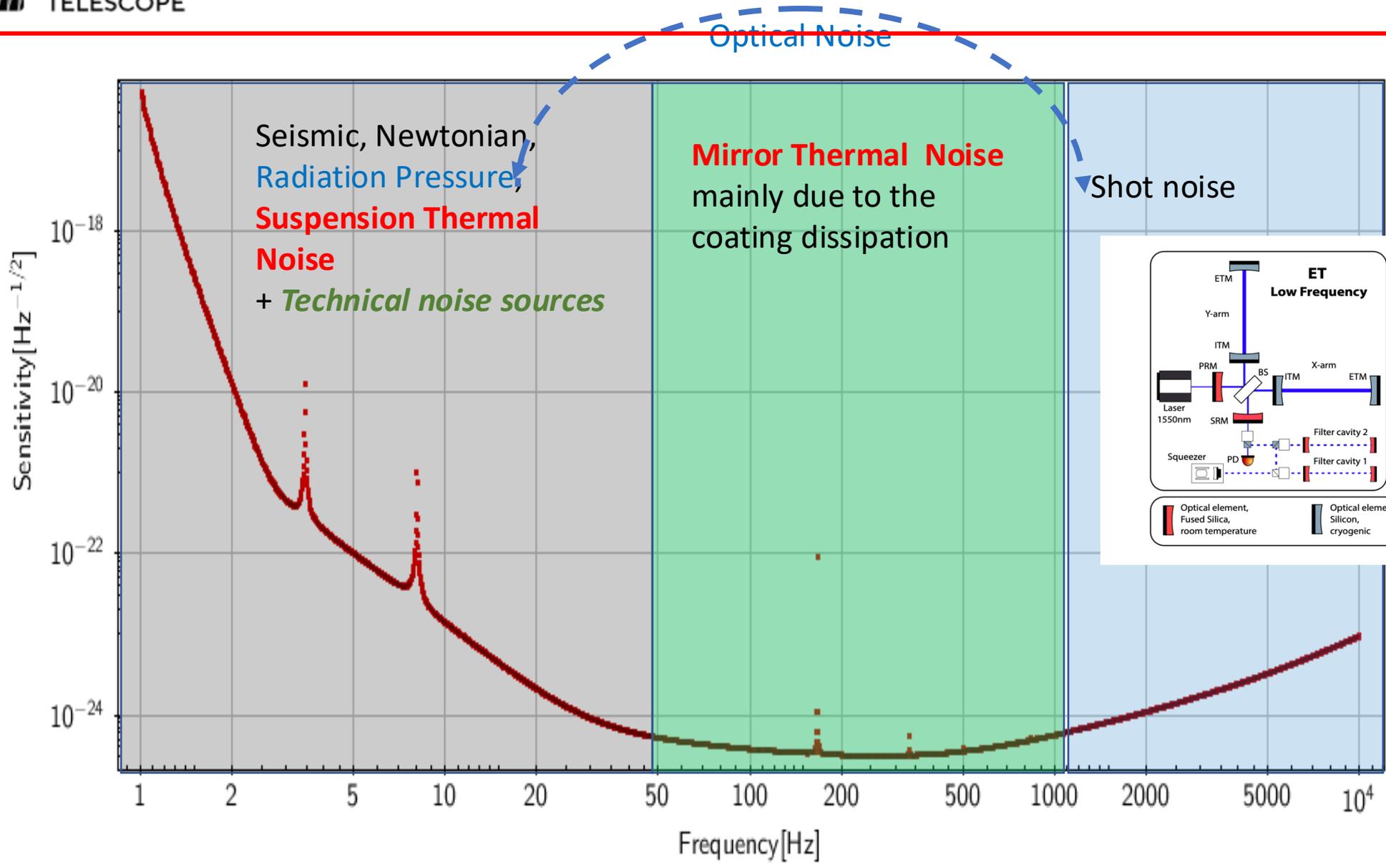# Einstein Telescope (ET)

≥ 10km

Corner halls depth about 200m

ET pioneered the idea of a 3rd generation GW observatory:

- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band
- A dramatic improvement in sensitivity in the low frequency (few Hz – 10Hz) range
- High reliability and improved observation capability

Optical Noise

Seismic, Newtonian,
Radiation Pressure,
Suspension Thermal Noise
+ *Technical noise sources*

Mirror Thermal Noise
mainly due to the coating dissipation

Shot noise

Thermal Noise in a Nuthshell

Thermal Noise is the fluctuation process affecting a physic observable (e.g. the position) of a macroscopic system that is in thermal equilibrium with the surrounding environment.
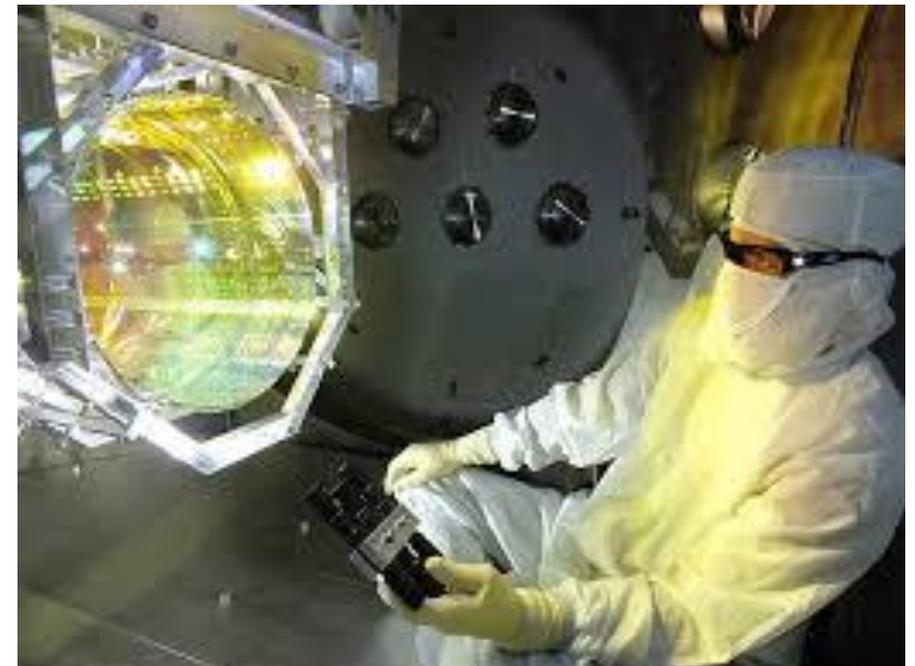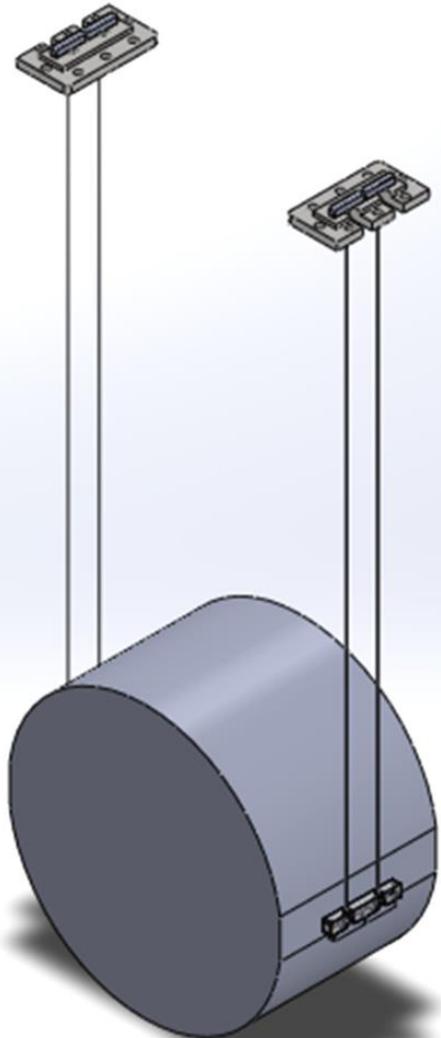
Fluctuation Dissipation Theorem

The relevance of this fluctuations is strictly correlated to

--the dissipation process acting on the system $\gamma(\omega)$

--the system temperature T

Power Spectral Density
of
the Noise Thermal Force

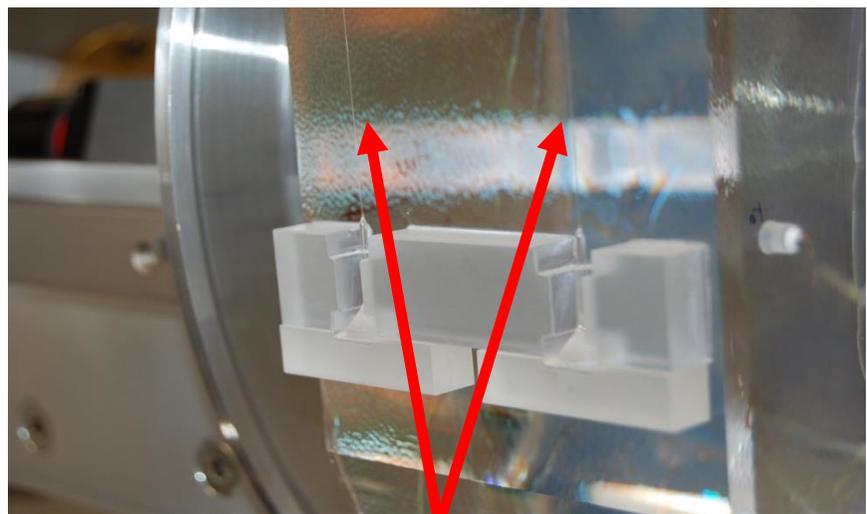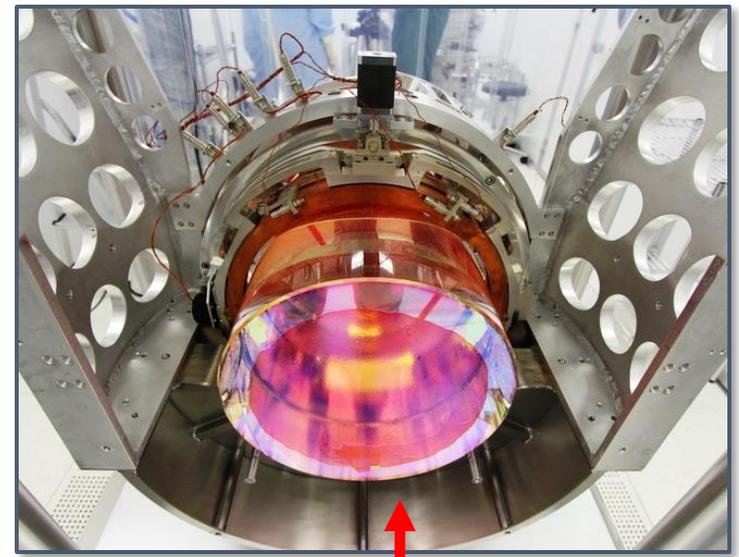$$S_{ff}(\omega) = 4\,k_B\,T\,\gamma(\omega)$$

Beating Thermal Noise @ T=300 K:
2° generation of GW detectors LIGO and Virgo

Strategy : Reduction of the mechanical dissipation by an appropraite material choice

Monolithic system:
SiO_2 Mirror suspended with fiber made of the same material
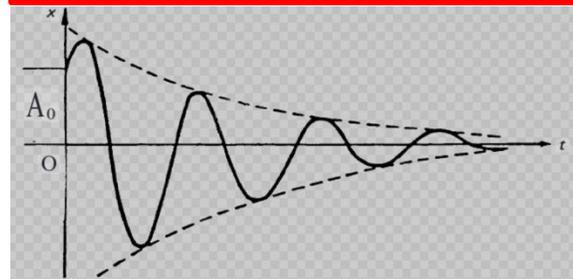

Thin Silica fibers

Silica Bonding procedure to build a monolithic system

40 kg Mirror suspended by means of 4 circular glass fibers, each 400 μm thick

The suspended mirror is a pendulum with a τ > 1 year !!!

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Bill Fairbank theorem:

William Fairbank (circa 1970)

<< Any experiment is better, if it is done at low temperature>>

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 kT 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

Contribution to the Proceedings of the "LVI" International School "Enrico Fermi "of the Italian Physica Society on "Experimental Gravitation" held in Varenna (1972). Bruno Bertotti editor

Bill Hamilton addendum:

<< Any experiment will be harder, if it is done at low temperature>>
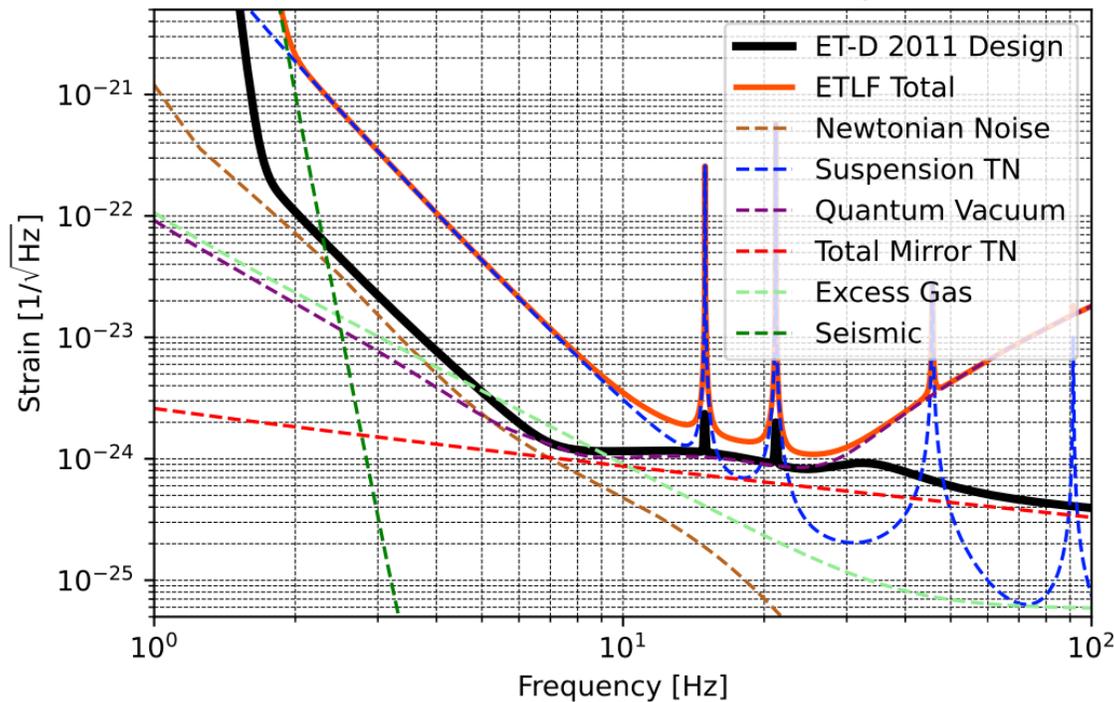
Low Temperature is back!

(following Fairbank's theorem and... Hamilton's lemma)

Low dissipation materials for suspension and cryogenics should reduce the Suspension Thermal Noise contribution lower or equal to that of the Newtonian Noise
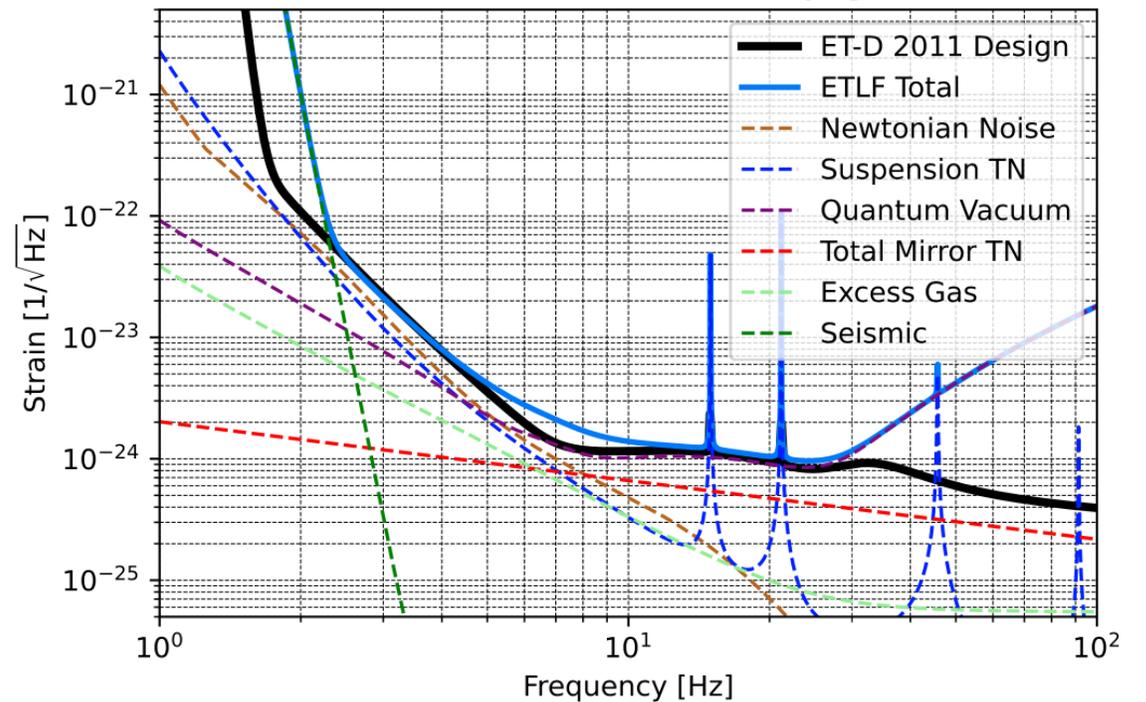On ET-LF we should move from S_iO_2 to Silicon or Sapphire

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The mirror is part of a so called *payload* (*last stage of the mirror suspension*) that will be hosted in a special cryostat connected to the UHV pipes km's long.

➤ It is suspeded to the susperattenuator (long chain of pendula dumping the seimic vibrations)

  ➤ Its position and orientation is controlled to keep the interferometer properly locked

    ➤ Its temperature must be stable and in a range of ~ 10 - 20 K

    ➤ No contamination (and frost!)

    ➤ No extra noise (magnetic, Newtonian, Boiling……………………………)

➤ Heat transfer via Thermal Radiation helps just during the cooling down . Then it does help tto much $\frac{dQ}{dt} \propto T^3 \, \Delta T$

➤ In the stationary status @10 -20 K we **must** rely on heat extration via solid conduction
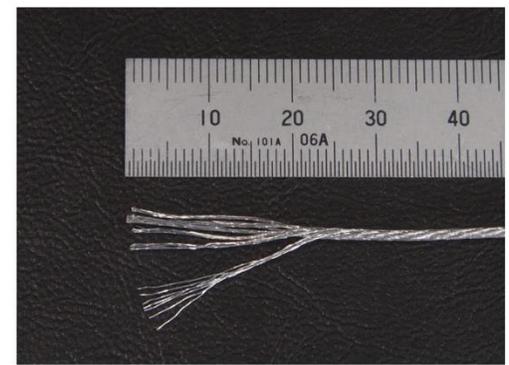
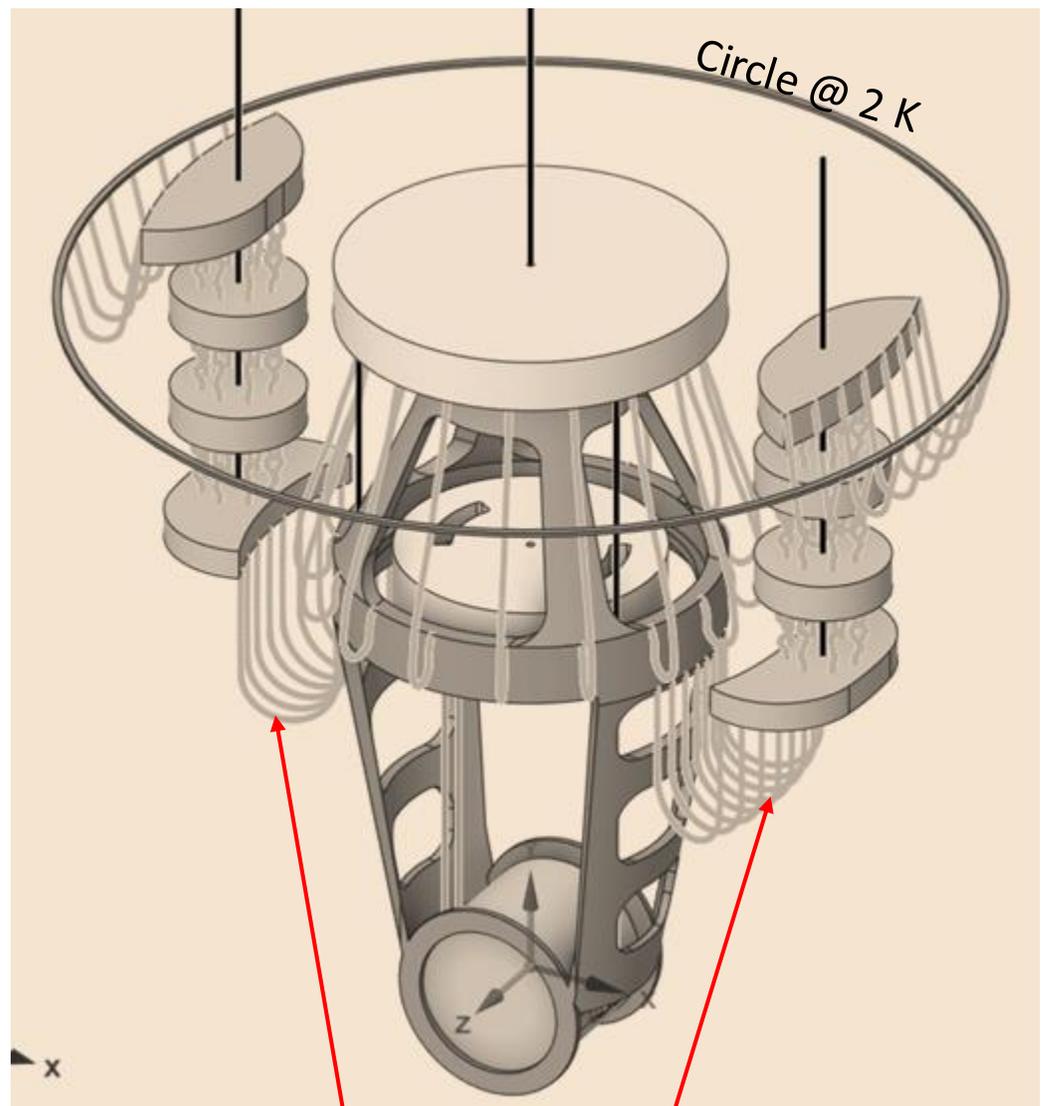➤ *but......**we can not add extra mechanical***

Solution:
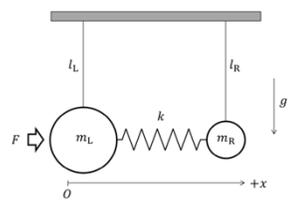Heat extracted via the 4 wire suspensions

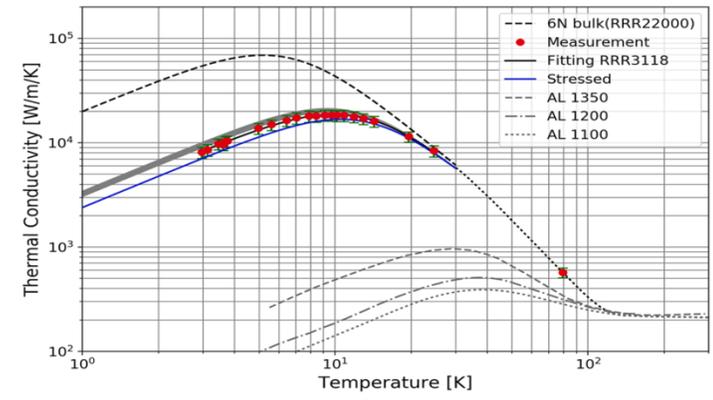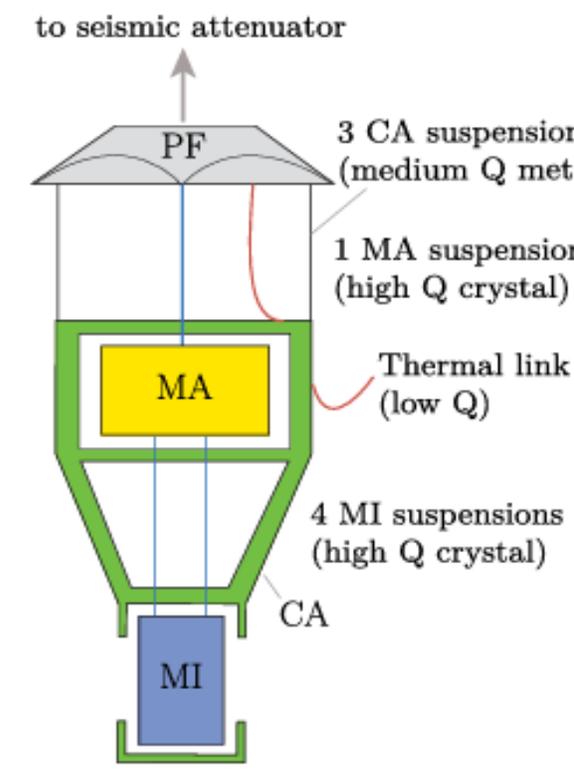Circle @ 2 K

High performance thermal link with small spring constant for cryogenic applications

Tomohiro Yamada [a,*], Takayuki Tomaru [b,c], Toshikazu Suzuki [c], Takafumi Ushiba [d], Nobuhiro Kimura [e,e], Suguru Takada [f], Yuki Inoue [e,g,h], Takaaki Kajita [a]

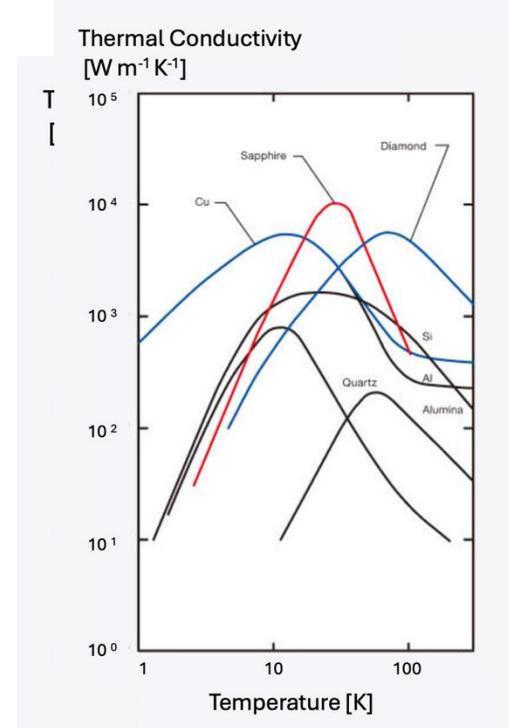Smaller spring constant to reduce overall vibration transfer.

to seismic attenuator

3 CA suspensions (medium Q metal)

1 MA suspension (high Q crystal)

Thermal link (low Q)

4 MI suspensions (high Q crystal)

PF ➜ Platform
MA ➜ Marionette
TL ➜ Thermal links
CA ➜ Cage
MI ➜ Mirror
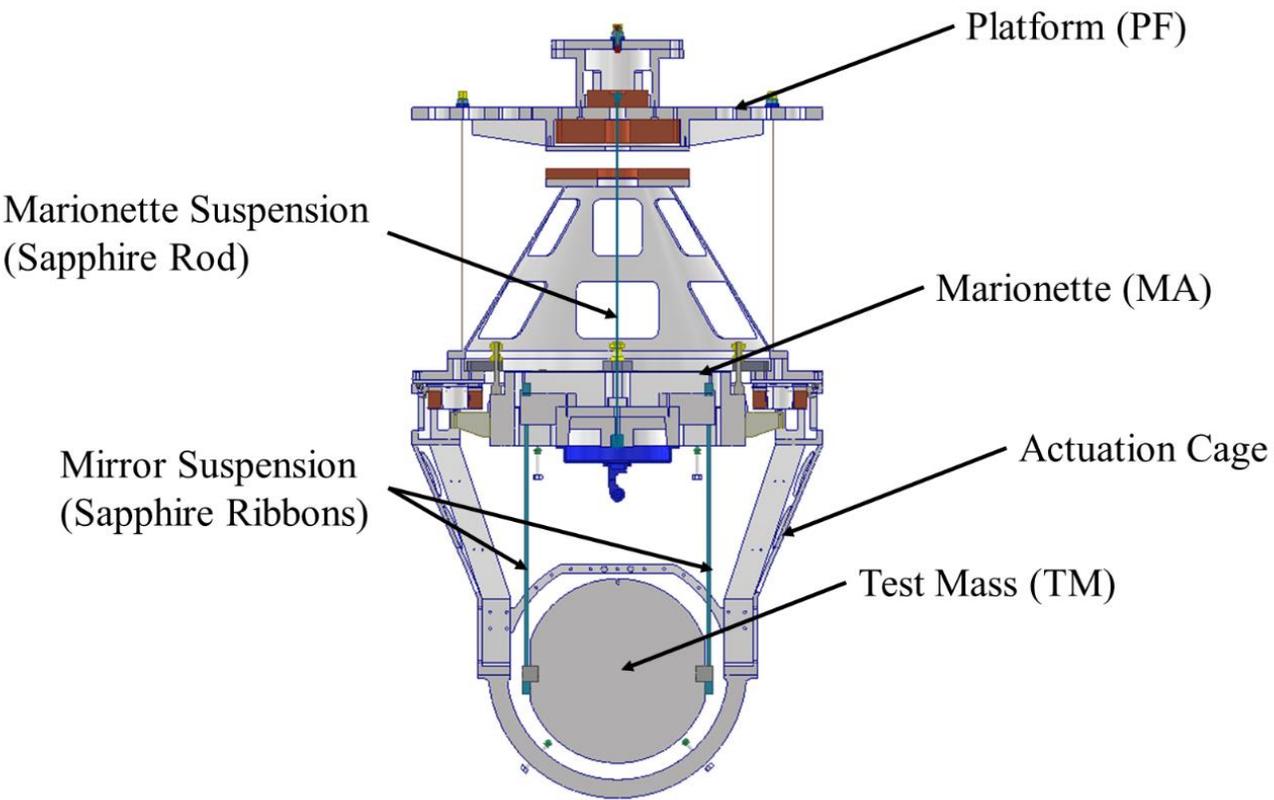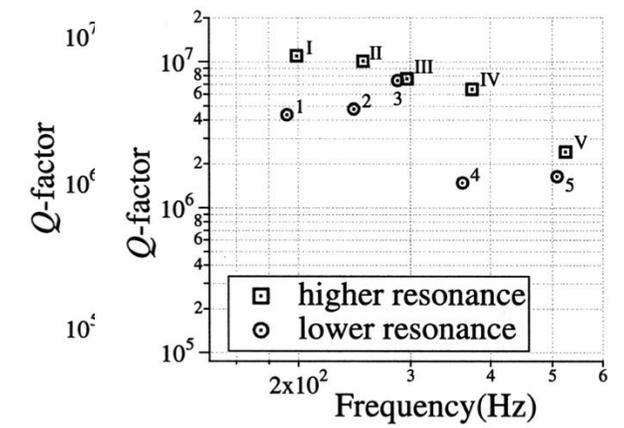
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Heat extracted via the 4 wire suspensions:
Cristals made of <u>Silicon</u> or <u>Sapphire</u>

Excellent thermal conductivity
High Strength,
High Quality factor,

Platform (PF)

Marionette Suspension
(Sapphire Rod)

Marionette (MA)

Mirror Suspension
(Sapphire Ribbons)

Actuation Cage

Test Mass (TM)

Mechanical Tests
in Rome
on Sapphire

T. Uchiyama et al, Phys Lett A 273 (2000) 310

Consumers at 2 K
- ➤ Cryo payloads (0.5 W each)
- ➤ Innermost shields (2 W each)

- ➤ ΔT shield,global < 100 mK
- ➤ He-II-channels: ΔT global< 50 mK   [K]

Diameter ⌣3.0 m
Height ⌣3.8 m
Total weight ⌣300 kg
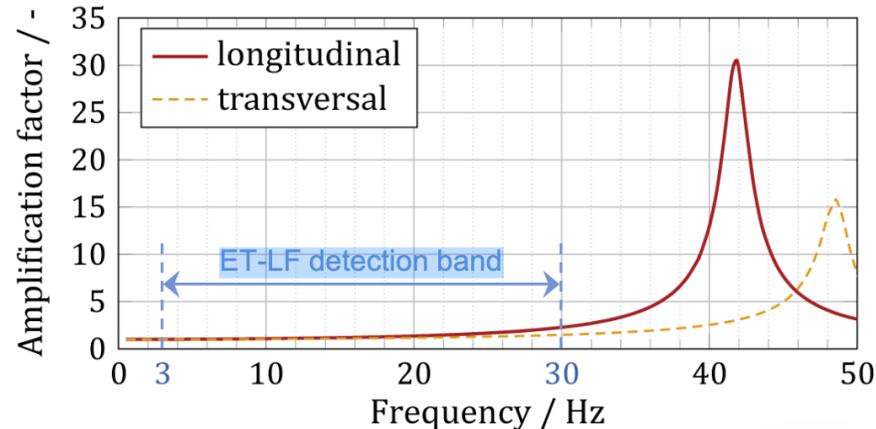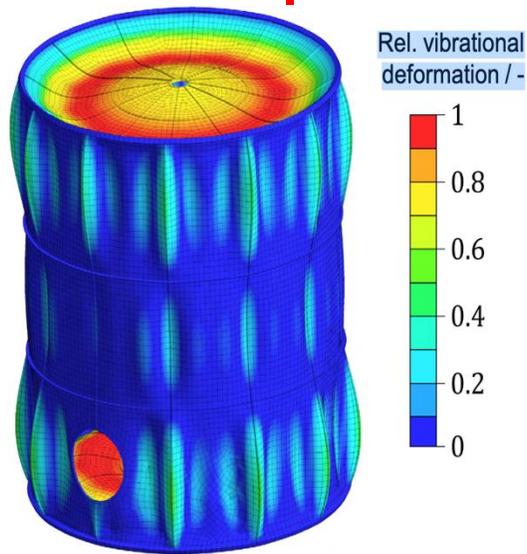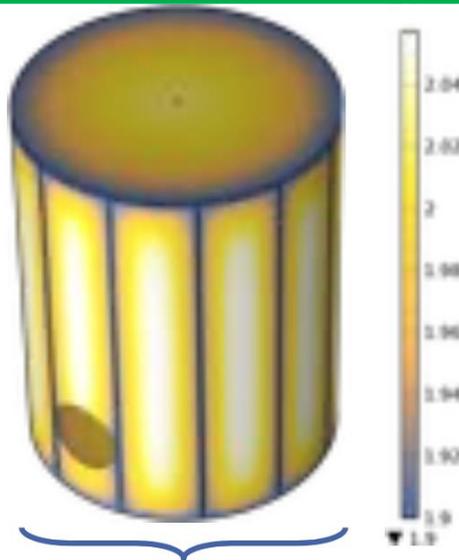Material Al (1xxx series)
Panel thickness 0.5 mm
W_{total} = **2. 0 W**

He II path:
- Circular at the top and bottom
- Vertical on the lateral surface
- He II two fluids model (Landau)

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

He II Vertical channels He II to minimize
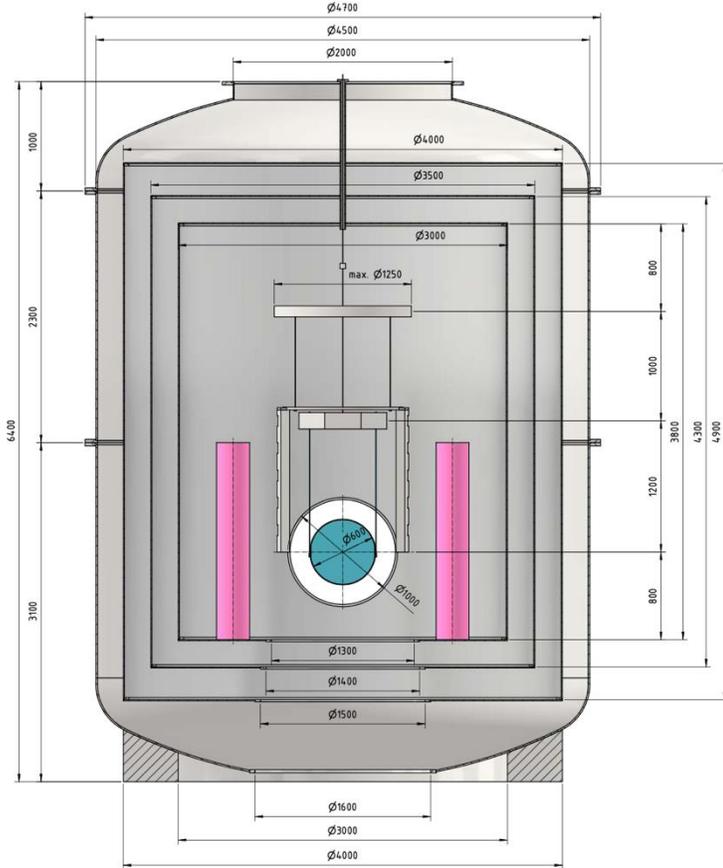
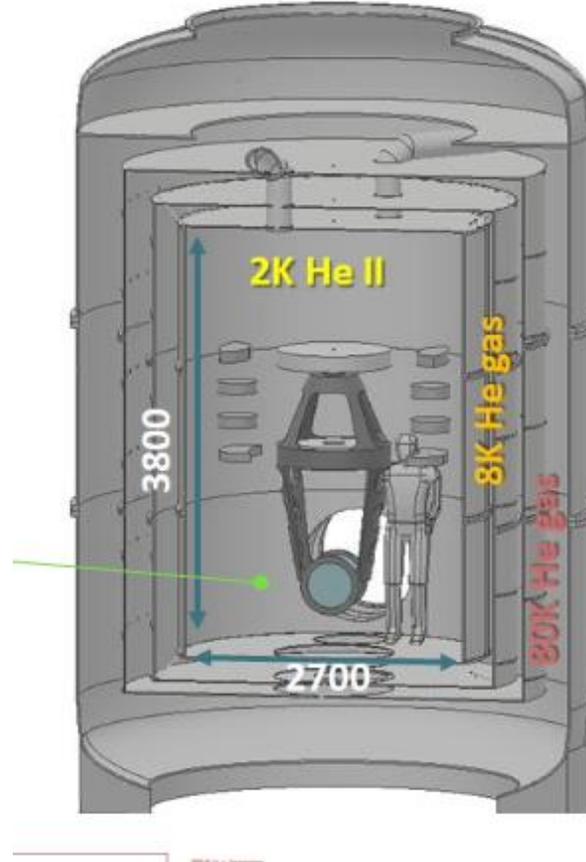 N. coupling along the optical axis

ET Cryostat

Mirror temperature = 10 - 20 K will extend the detector sensitivity band down to 2 Hz .
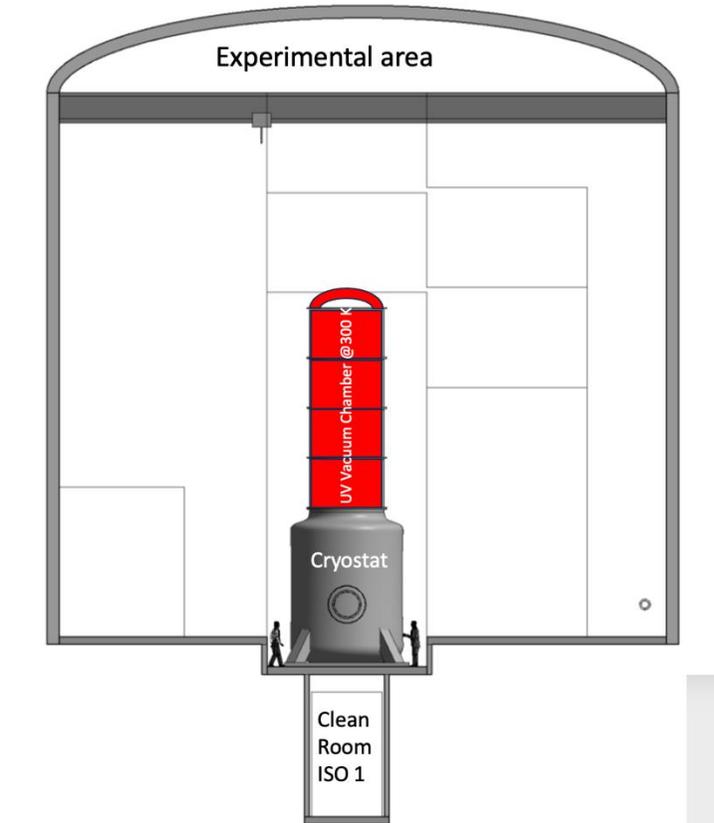

Cryostat Dimension

Cryostat Temperatures

Cryostat & UV Chamber in the Underground lab
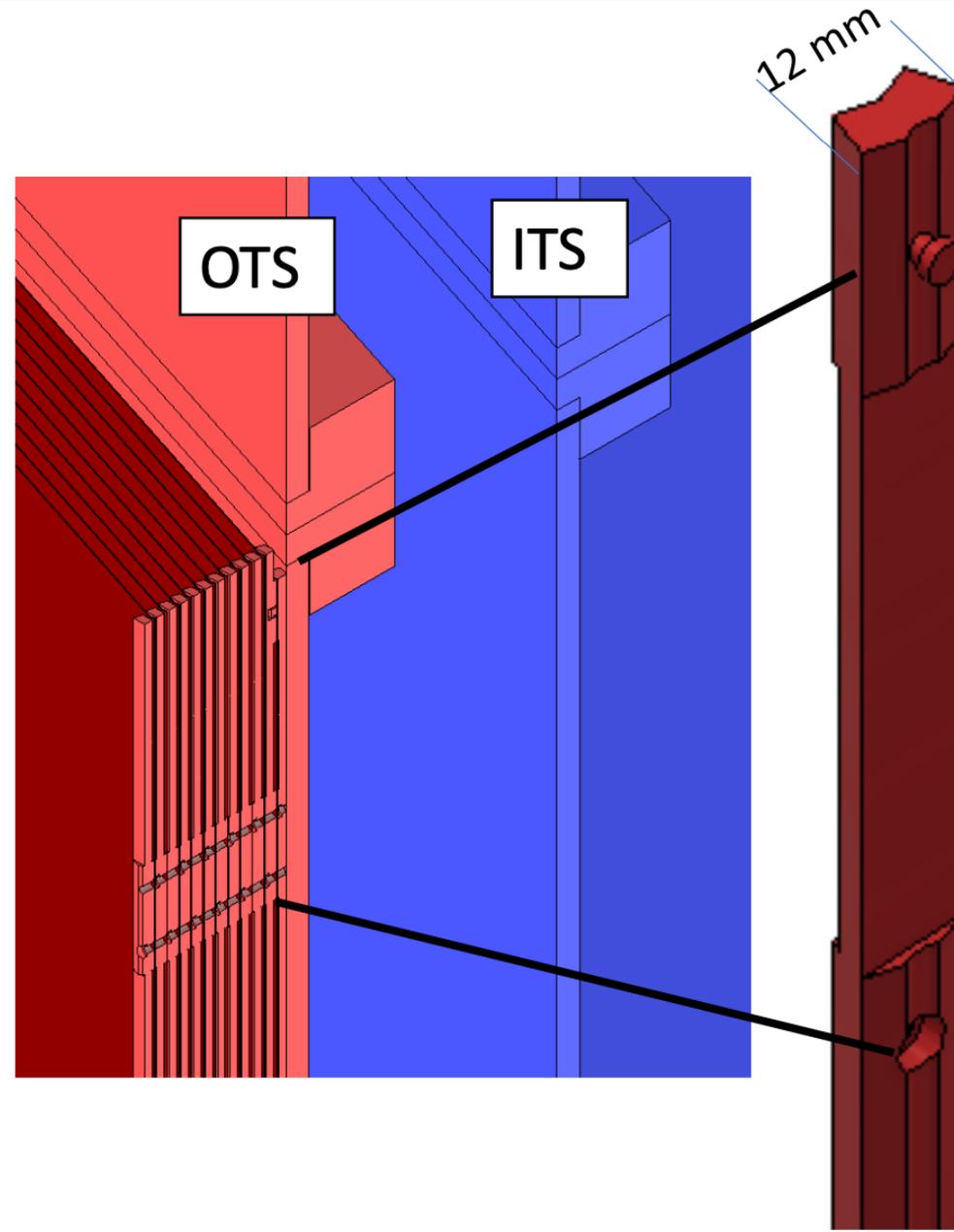
- *Multiple low emissivity aluminum foils* supported by *insulating rods* at each corner
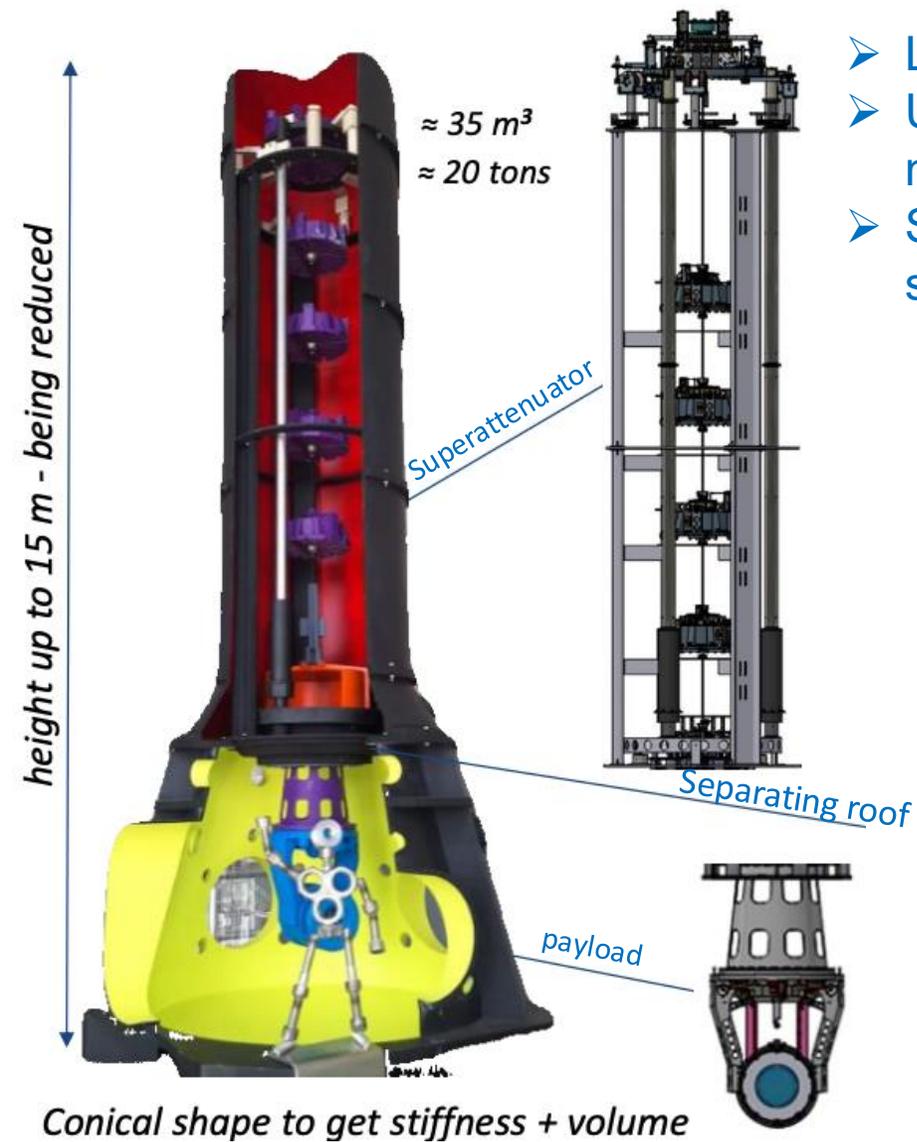 (n_{layers} >15).

- Distance between each foil 4 mm

12 mm

OTS

ITS

Emissivity measurements to optimise thermal shield performance

ET-LF Tower design

height up to 15 m - being reduced

≈ 35 m³
≈ 20 tons

Superattenuator

Separating roof

payload

Conical shape to get stiffness + volume
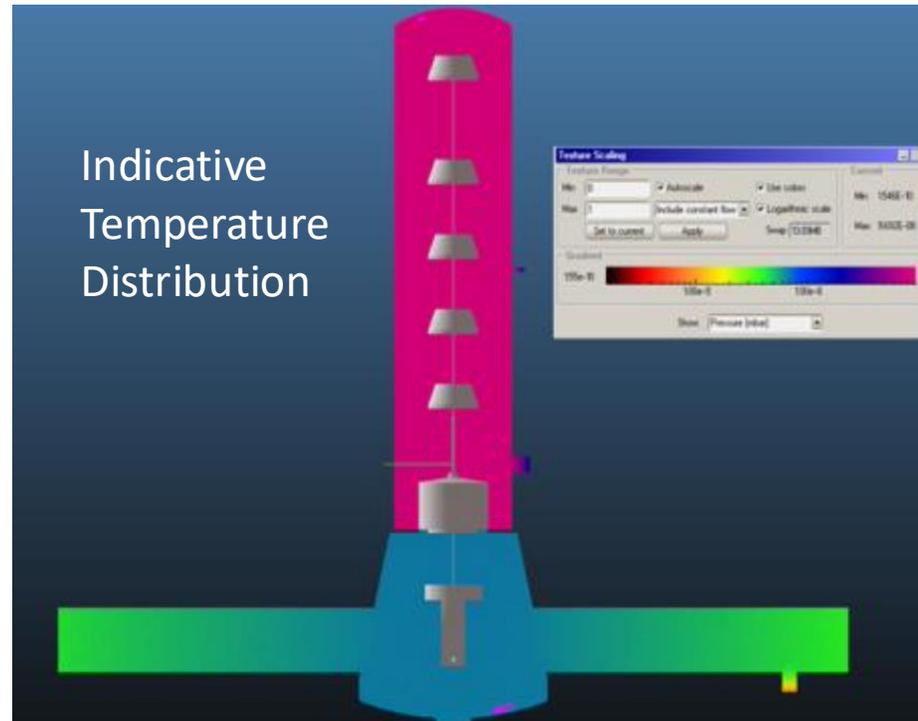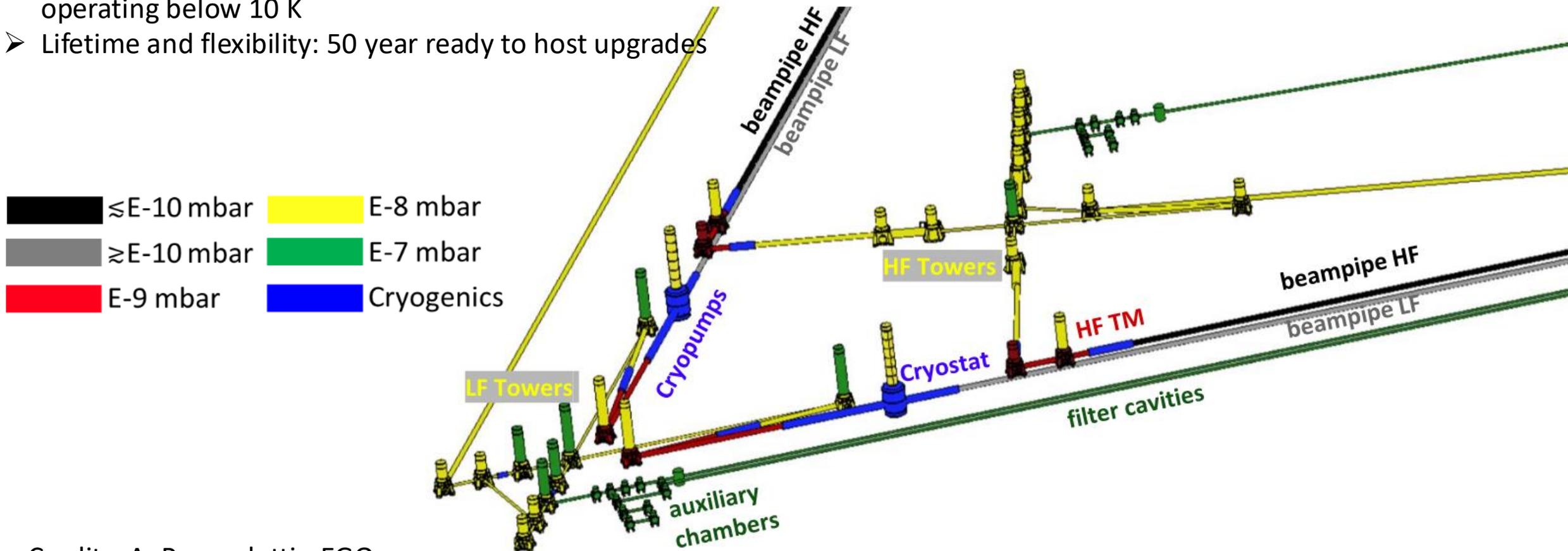
➢ Lower part: the cryostat housing payload with the test mass (main mirror)
➢ Upper compartment: room temperature vacuum chamber hosting suspension mechanics and control devices for seismic attenuation
➢ Separation by a differential pumping system: it allows compromises on suspension materials and reduces gas loads in UHV areas.

Indicative Temperature Distribution

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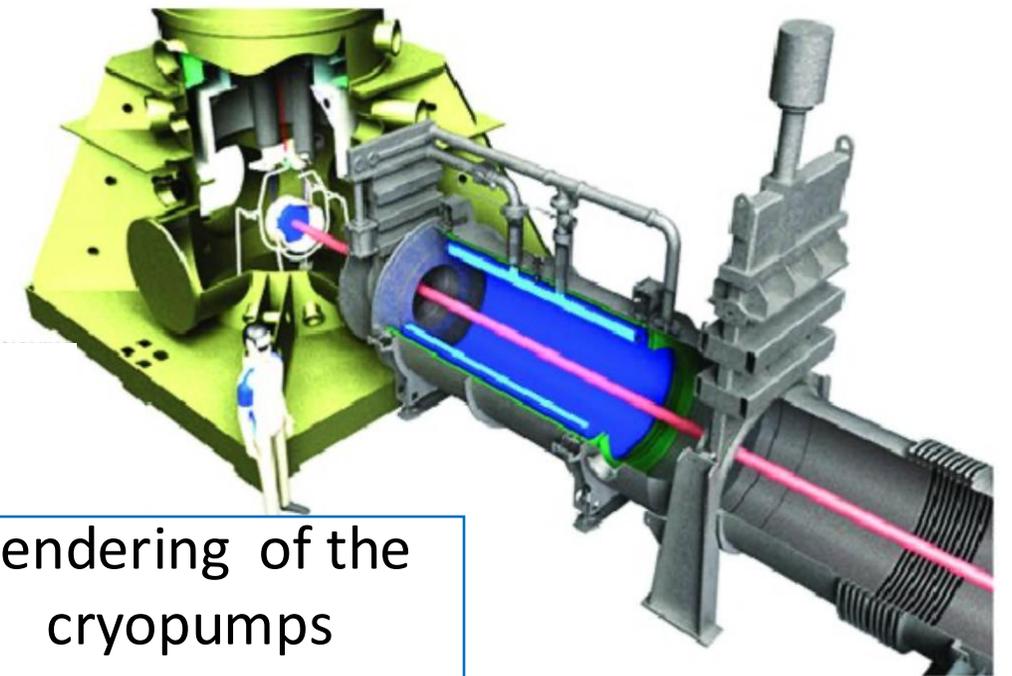- Beampipes: Ø 1 m, 60–120 km long, hosting the laser beam, E+5 m² **UHV chambers of unprecedented size !**
  Towers: 45 to 120 chambers up to tens of m³ plus auxiliaries, hosting world-class optics, 100+ km of cabling, ~100 tons of precision mechanics - all unbaked.
- Cryopumps: very-large-scale pumps combining Towers and Beampipe Cryostats: housing ET most sensitive payloads, operating below 10 K
- Lifetime and flexibility: 50 year ready to host upgrades

Legend:
- ≲E-10 mbar (black)
- ≳E-10 mbar (grey)
- E-9 mbar (red)
- E-8 mbar (yellow)
- E-7 mbar (green)
- Cryogenics (blue)

Credits: A. Pasqualetti - EGO

- Concentric cryopumps in the 1 m diameter beam pipes, needed bot for ET-HF and ET-LF.

- In ET-LF the 1 m inner diameter cryopumps must extend up to 20 m in the beam pipes to reduce the solid angle of room-temperature thermal radiation. The main parts must be operated at 80 K with baffles at 10 K.

- Cryopumps will protect the UH vacuum of the km long pipes after the intervention on the test mass towers (*ET commissioning phase*)

- Cryopumps in ET- LF will prevent frost formation on mirror.
  - ✓ Requirement driven by optical and thermal reasons (T must be stable as the cavity finesse of interferometer arms.)
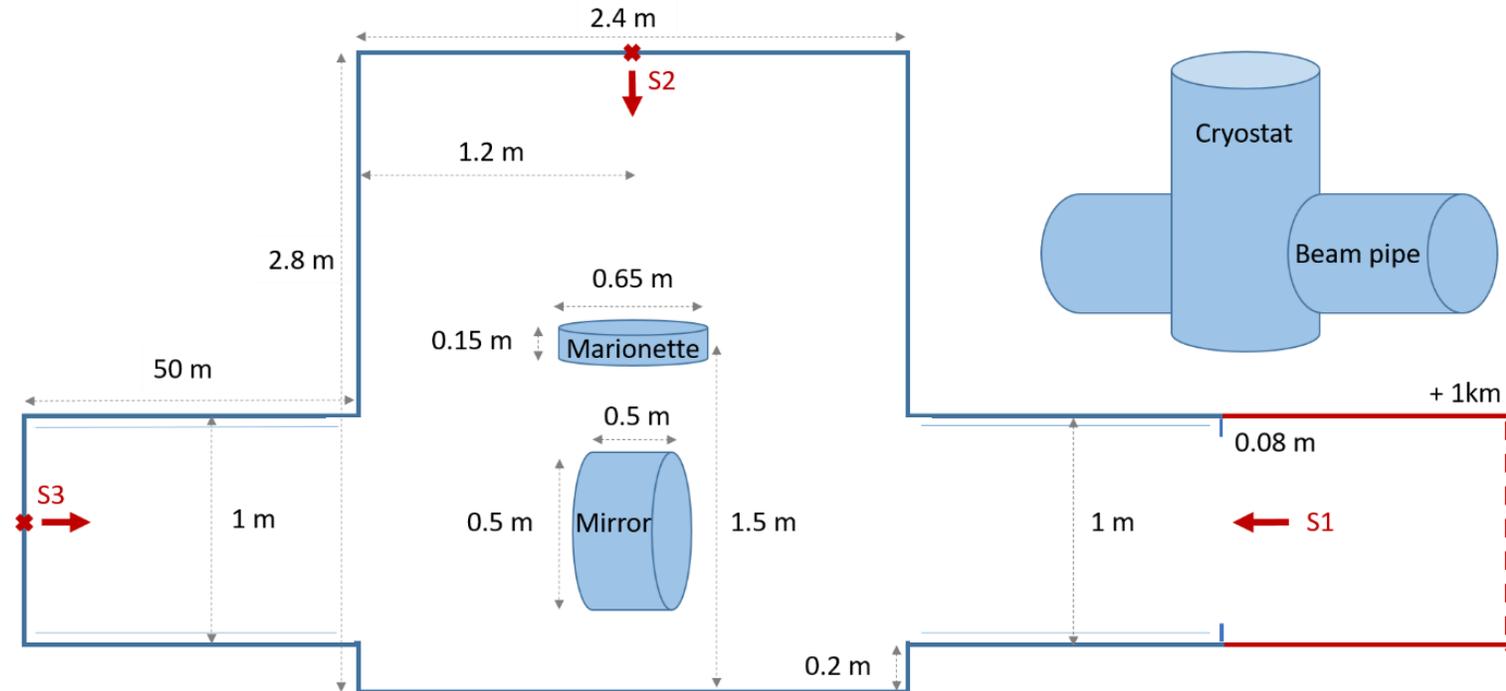 - ✓ H_2 pumping needed (cryopump section at 3.8 K).

Rendering of the cryopumps installed in Virgo

Complete LF-model established

- ➢ Cryostat with 10-20 K mirror
- ➢ First outgassing source: 10 km beam pipe (on the right in the model)
- ➢ Second outgassing source: upper tower source (with developed pre-concept for semi-closure drastically reduced to $2 \cdot 10^{-9}$ $Pa \cdot m^3/s$ for H_2 and H_2O each)
- ➢ Third outgassing source: adjacent tower source (10^{-7} and 10^{-6} $Pa \cdot m^3/s$ for H_2 and H_2O)

First outcome of the study: *beam pipe vacuum strongly decoupled from the mirror tower*

➤ *Montecarlo Simulation* carried on using the software code ProVac3D developed @ KIT Code was experimentally validated and extensively in the domain energy fusion R&D . (X. Luo, C. Day, Fusion Engineering and Design 85 (2010) 1446–1450).

➤ All gas sources managed (non-sticky and sticky molecules)

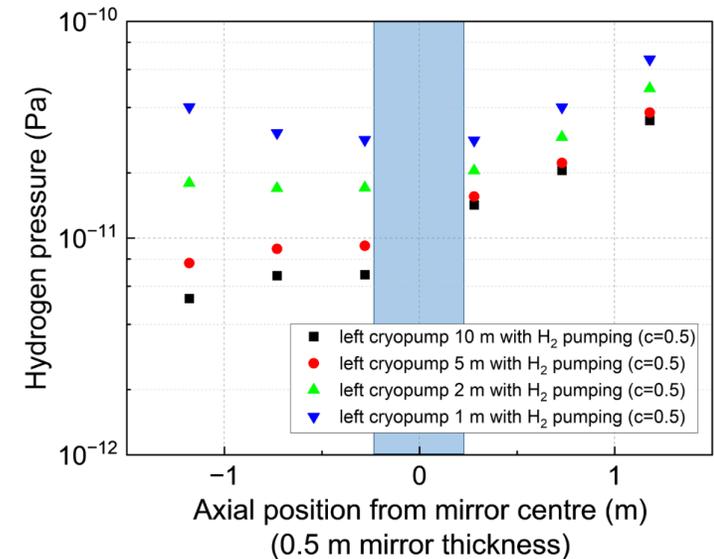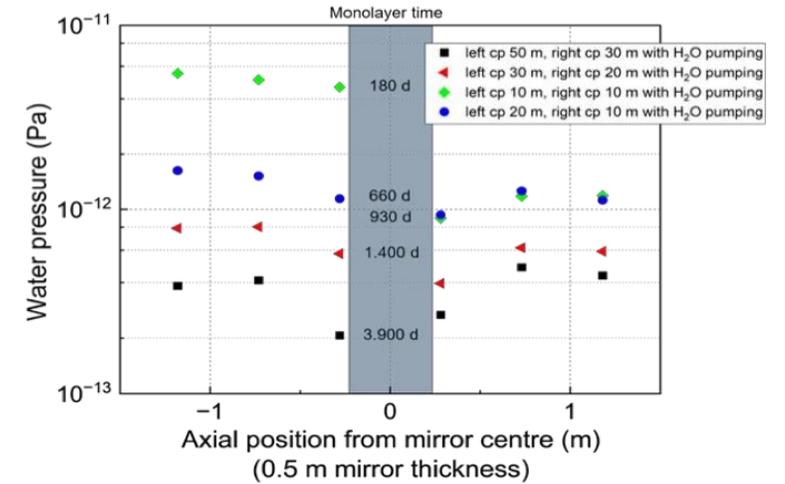*Simulation Outcome fulfilling the pressure requirements*

H_2: $3·10^{-11}$ Pa, H_2O: $1·10^{-12}$ Pa

Hydrogen pumping needed only on the left side for the adjacent tower flow

Cryopumps:
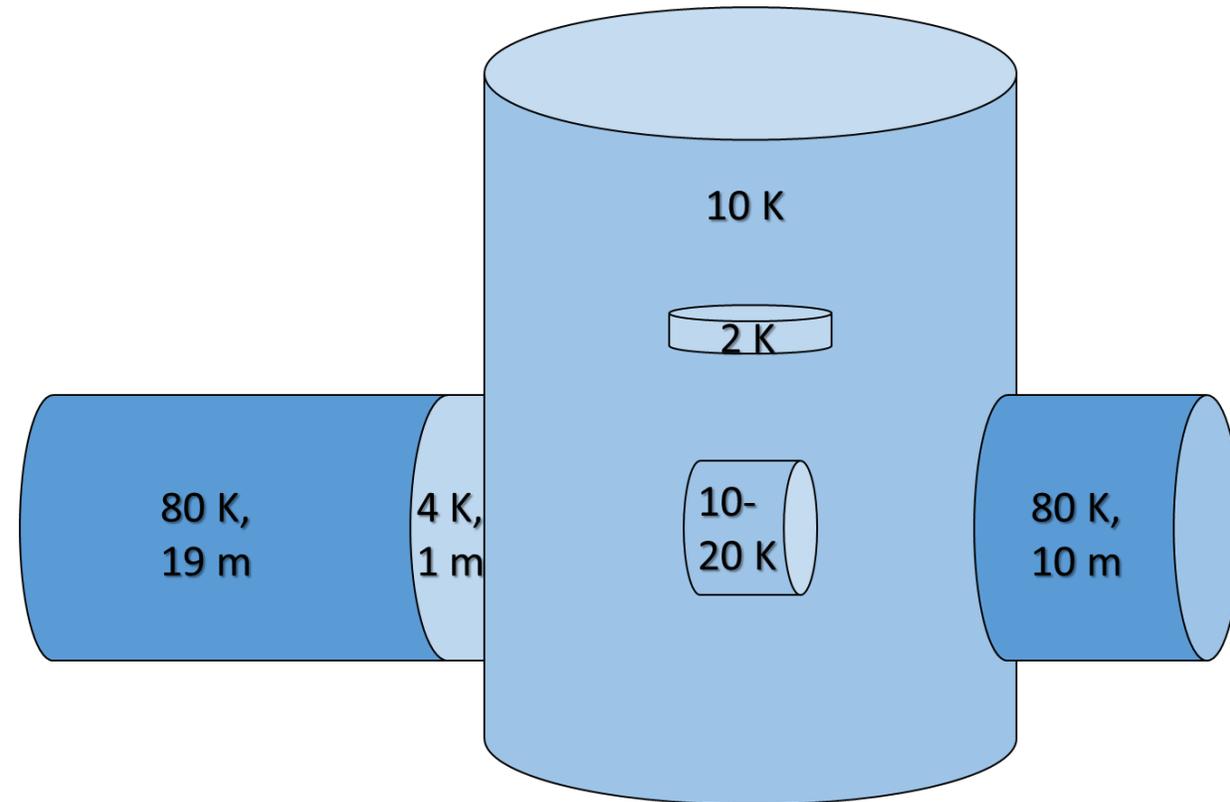H_2O: 20 m on the left + 10 m right
H_2: 1 m left

➢ **Maximum allowable deposition: 1-2 H_2O MonoLayers (ML)** (1 ML of H_2O ➜ 0.27 nm tick)

➢ Requiremente driven mainly by laser power absorption issue for tight thermal budget of mirror at constant T
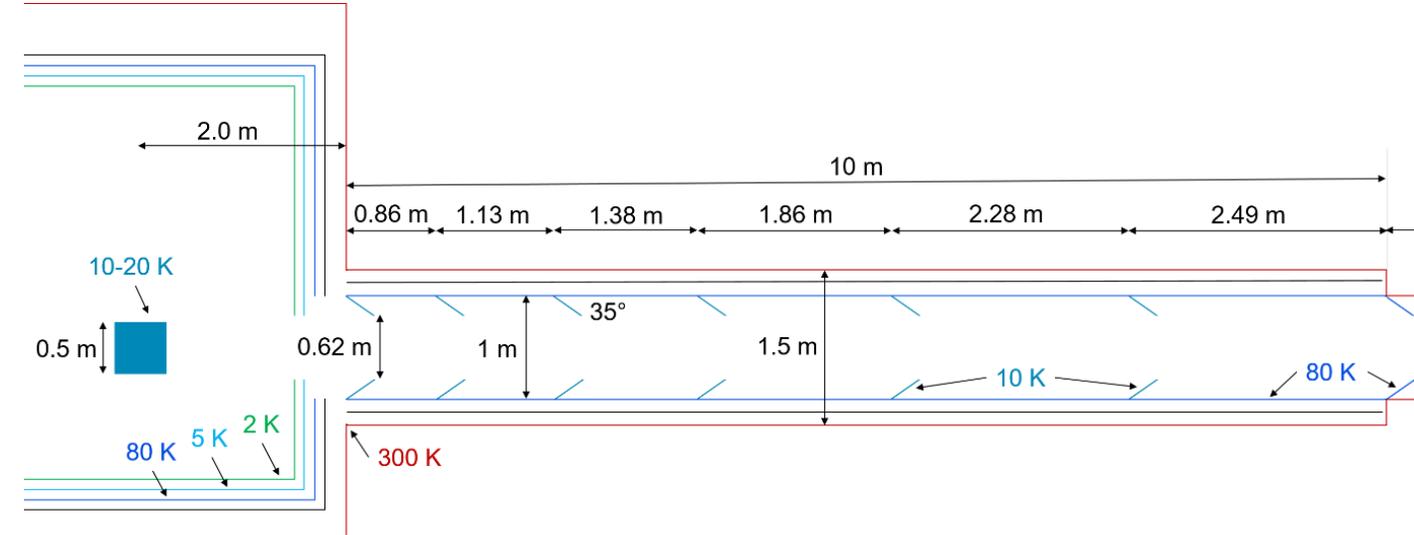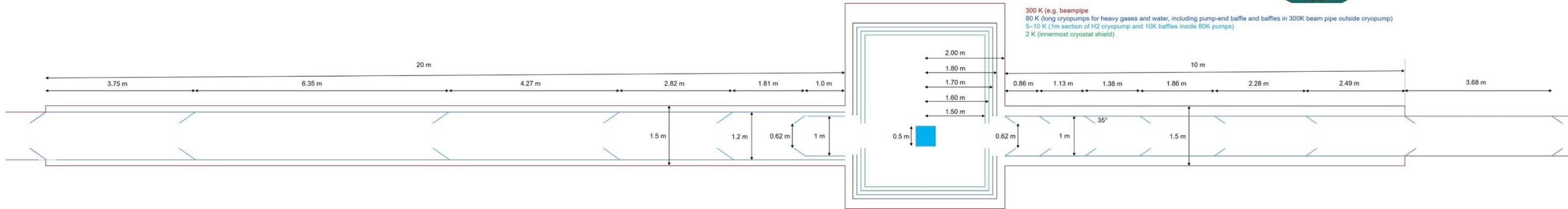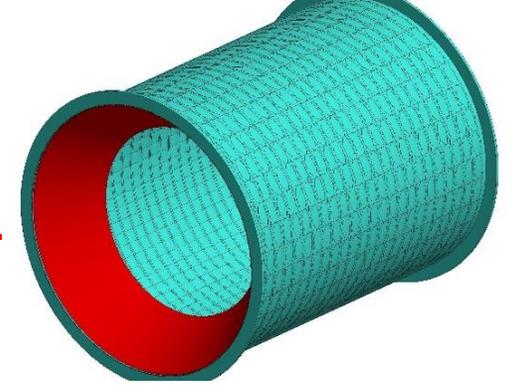
Result:

➢ Frost formation rate depends on design for 80 K

➢ ICE Formation of 1 ML (H_2O) in a time scale of 2 years

10 K

2 K

10-20 K

80 K, 19 m

4 K, 1 m

80 K, 10 m

Cryopumps as thermal radiation traps
Tubular cryopumps with inner baffles

300 K (e.g. beampipe
80 K (long cryopumps for heavy gases and water, including pump-end baffle and baffles in 300K beam pipe outside cryopump)
5–10 K (1m section of H2 cryopump and 10K baffles inside 80K pumps)
2 K (innermost cryostat shield)

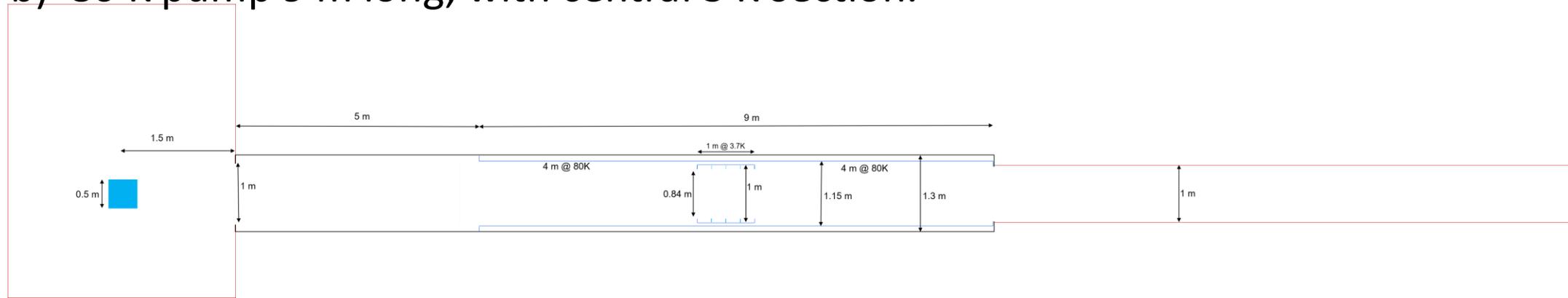| Thermal load on:	ε of mirror	ε of mirror	ε of mirror	ε of mirror
	0.01	0.1	0.3	0.5
Mirror	1.3 mW	13 mW	37 mW	59 mW
Cryostat	262 mW	253 mW	232 mW	213 mW
3.7 K	1.65 W	1.65 W	1.65 W	1.65 W
10 K	43 W	43 W	43 W	43 W
80 K	7.1 kW	7.1 kW	7.1 kW	7.1 kW

➢ HF with inverted aim: protecting 10 km beam pipe from thegas flow from the tower (vented during the commissioning phase).

 ✓ It follows that just one cryopump is needed on the side of the   km long vacuum pipe

➢ Source of outgassing

 ✓ Adjacent tower: $2\cdot10^{-7}$ Pa·m³/s for H_2 and $4\cdot10^{-6}$ Pa·m³/s for H_2O

 ✓ Upper tower hosting the superattenuator: $4\cdot10^{-9}$ Pa·m³/s for H_2 and $2\cdot10^{-8}$ Pa·m³/s for H_2O

 ✓ Lower tower compartment hosting the mirror : $1\cdot10^{-7}$ Pa·m³/s for H_2 and $1\cdot10^{-5}$ Pa·m³/s for H_2O

 ✓ Target pressure $1\cdot10^{-8}$ Pa for H_2, better below

Simulation Outcome fulfilling the pressure requirements

a) Shift the cryopumps 5 m far from the tower,

b) 80 K pump 9 m long, with central 3 K section.

Disclamair: a more accurate heat load study is ongoing

A first evaluation including needs for ET-LF and ET-HF, ends up with the follwing numbers:

100 kW at 80 K and 100 W at 3.7 K

➢ The overall cryogenic cooling budget requires a helium-based cryogenic infrastructure at each vertex of the detector, with compressor stations located on the surface far away from the instrument.

➢ This avoids a direct noise impact from the compressors and an indirect noise impact from underground cooling water systems, which are necessary in case of other cooling technologies.
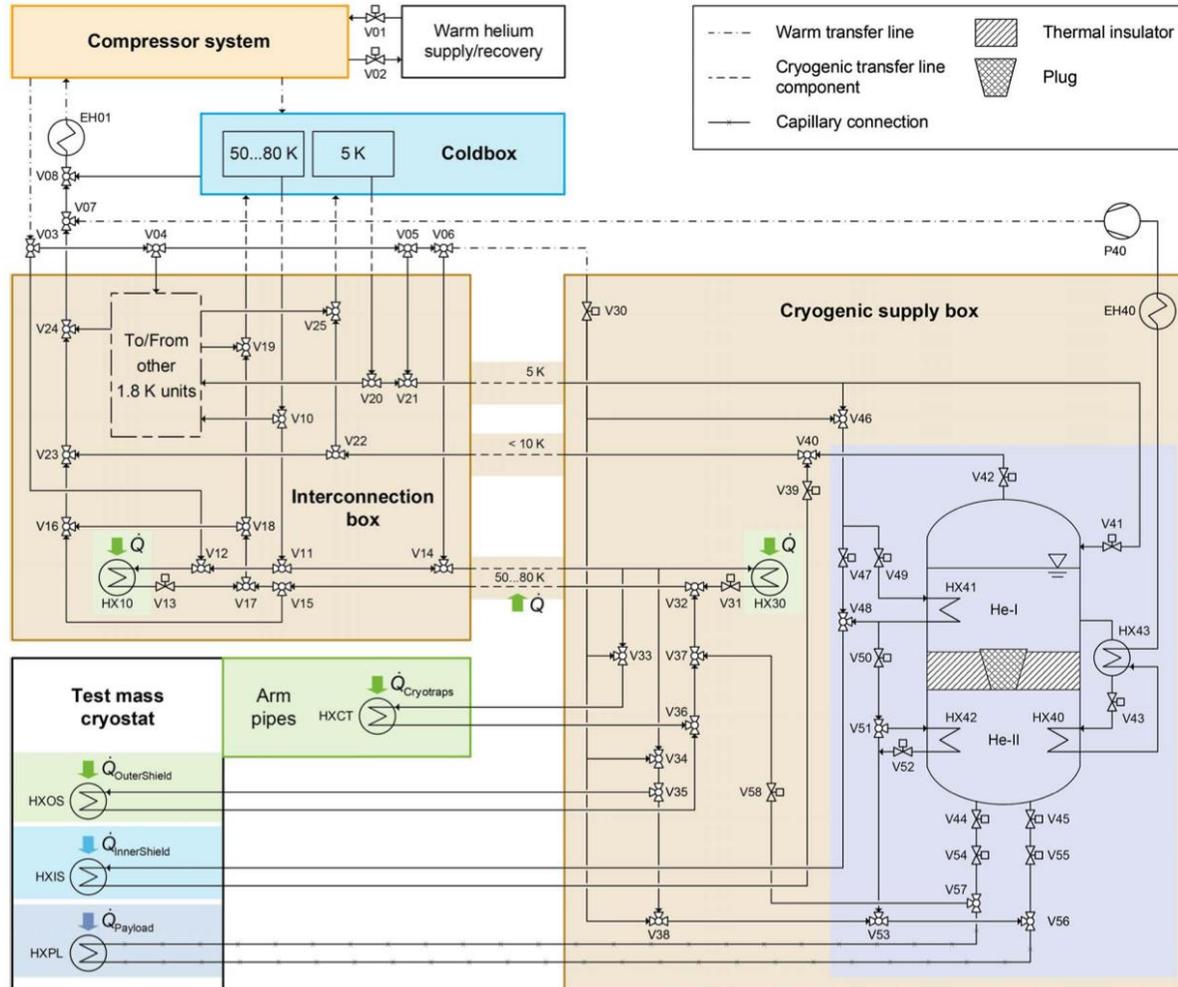
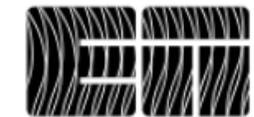Block diagram for helium distribution betw
an underground-located coldbox and a test
mass cryostat.

➢ No underground LN2 (safety)
➢ One He refrigerator at each vertex
  ✓ (Remote) surface compressors
  ✓ Underground coldbox
  ✓ Interconnection box to several cryogenic
    supply boxes (1 for each tower/cryostat)
    up to c. 500 m long transfer lines
  ✓ 1-phase cooling H2O cryopumps/outer shield
  ✓ 1-phase cooling H2 cryopumps/inner shields
  ✓ Optional He-II payload cooling/inner shield

Cryoplant noise: preliminary study
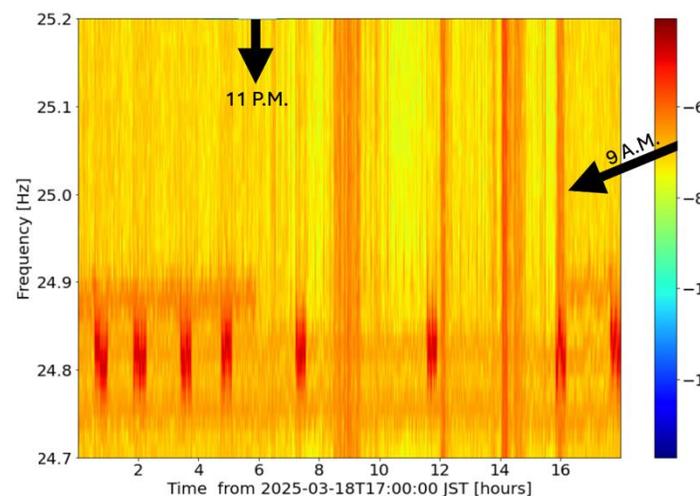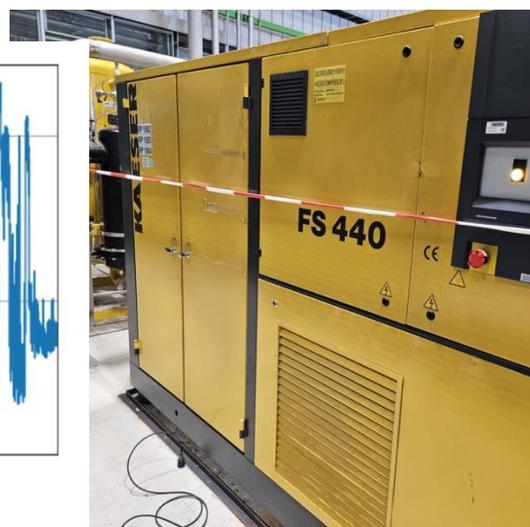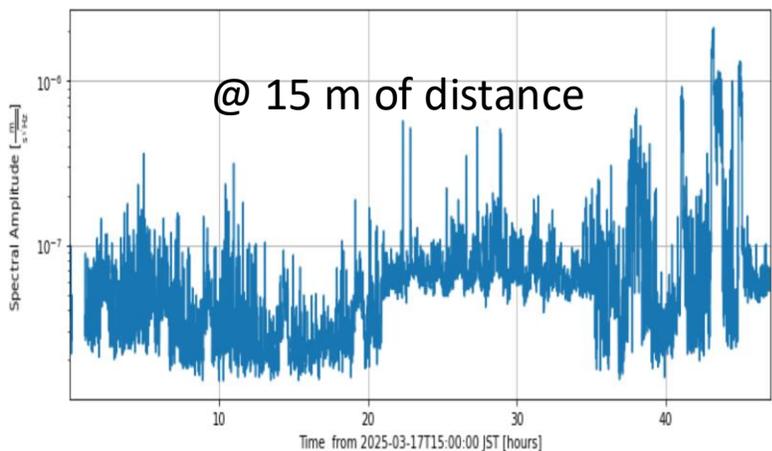
CERN –SRM18

ISSP_UTokyo-Kashiwa

The Goal
- Characterize environmental noise from cryogenic plants and their devices and find characteristic signature
- Gather relevant information for the design of ET and its infrastructure
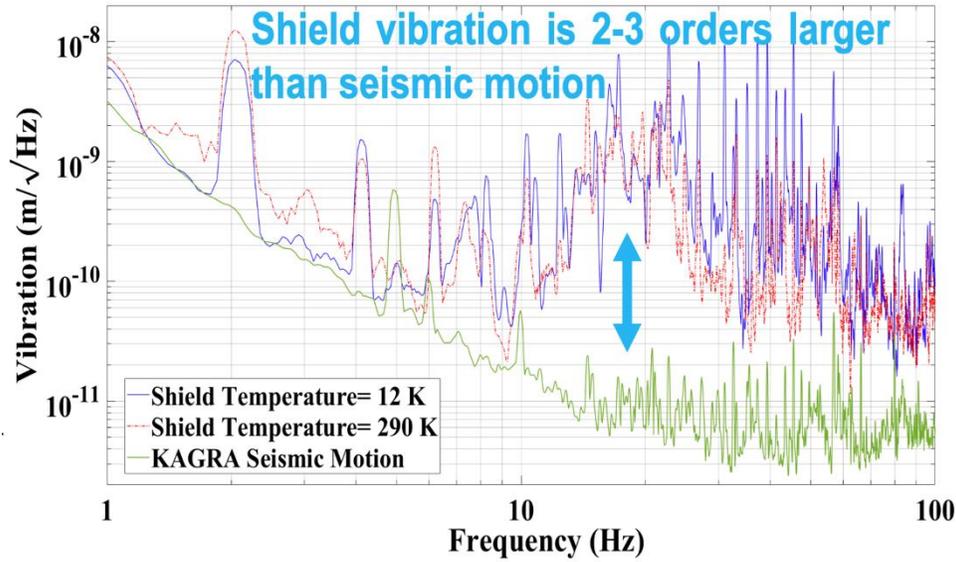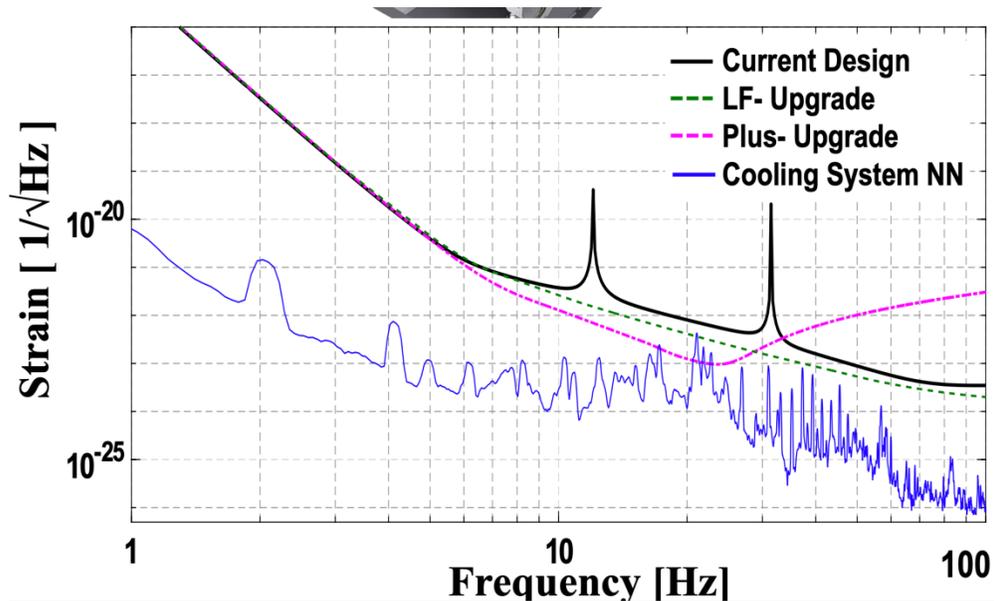
Preliminary measurements

@ 15 m of distance

*The frequency signature of the Kaeser **rapidly decays with distance**. Beyond 30 m, we do not find any clear signature of this compressor.*

Newtonian noise evaluation due to the cryogenic system
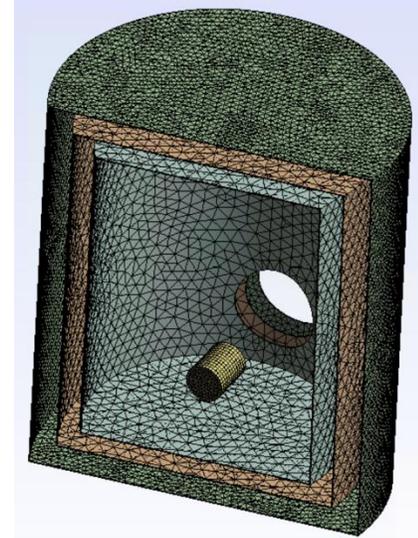
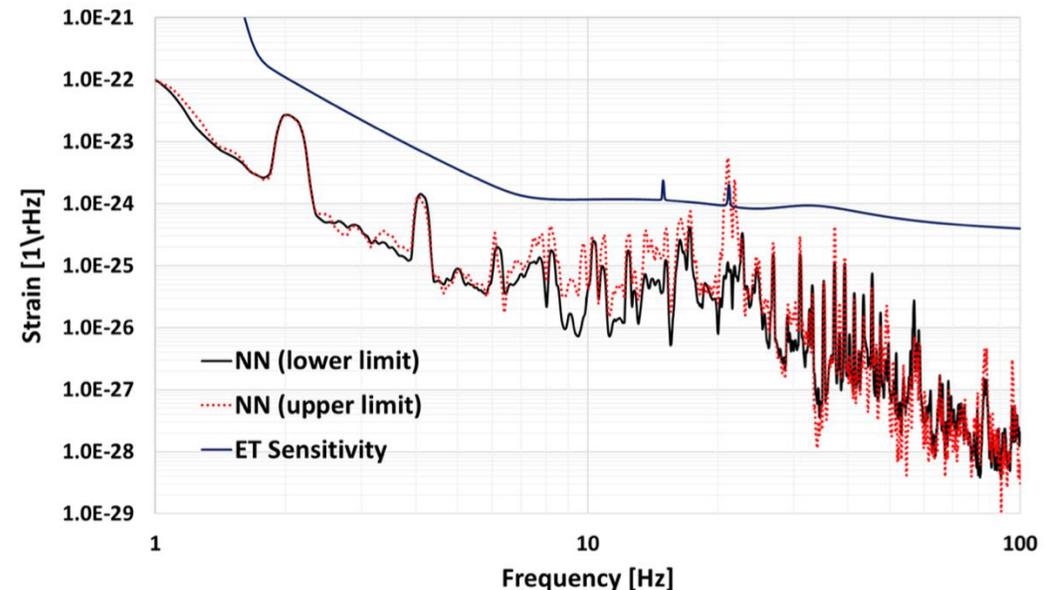*credits:Rishabh Bajpai (rishabh.bajpai@nao.ac.jp)*

KAGRA   ET

➢ Finite Element evaluation assuming the same vibrational specta of KAGRA

➢ Materiai and geometry
– Aluminum shield 10 mm thick
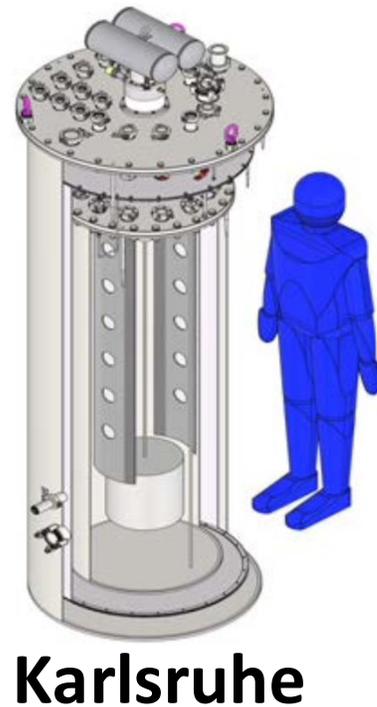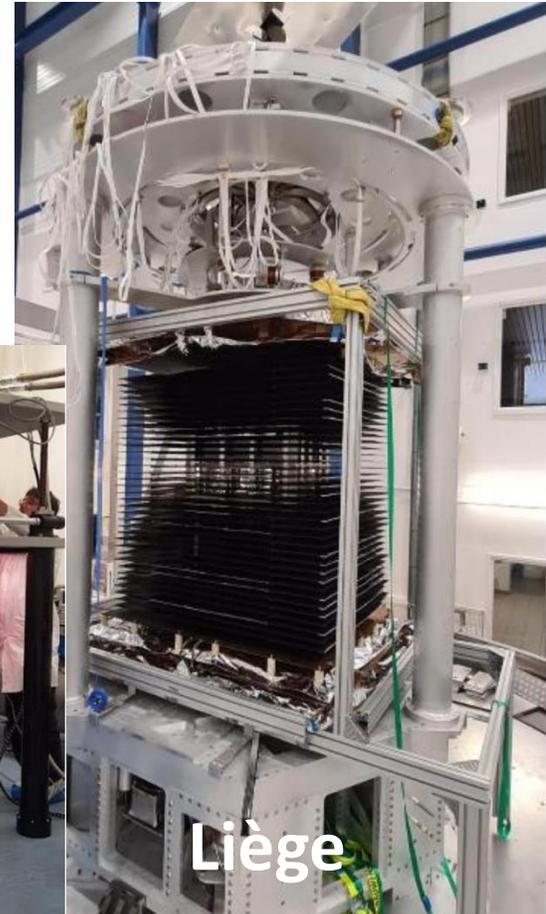– Silicon mirror Φ 470 mm, t=570 mm
– Holes of Φ 1000 mm on all 3 shields

Some of the labs involved in ET cryo-R&D…. *and many others are missing in this list*

- ➢ Amaldi Research Center at Sapienza University of Rome,
- ➢ ET-Pathfinder, Maastricht University
- ➢ University of Glasgow
- ➢ University of Liège, Centre Spatial de Liège

Rome

Karlsruhe

Maastritch

Glasgow

Liège

Conclusions

➢ Cryogenics is essential for third-generation (3G) gravitational-wave (GW) detectors to achieve the sensitivity required to explore the Universe's dark epoch.

➢ The Einstein Telescope Low-Frequency (ET-LF) design represents a significant experimental challenge with the potential for outstanding scientific outcomes.

➢ Despite a relatively high mirror operating temperature (10–20 K), the demanding detection technique necessitates the development of novel solutions.

➢ We must develop and thoroughly test new techniques that leverage specialized materials.

➢ A cryoplants must be designed to ensure an exceptionally low level of mechanical noise.

➢ Strong need for significant interaction and collaboration between academia and industry

EXTRA Slides

Resonant Bars @ Low Temperature

JULY 1972, VARENNA (COMO) ITALY
V.B. BRAGYNSKY   J.W. WEBER   R.H. DICKE   W.M. FAIRBANK

The Use of Low-Temperature Technology in Gravitational Experiments.
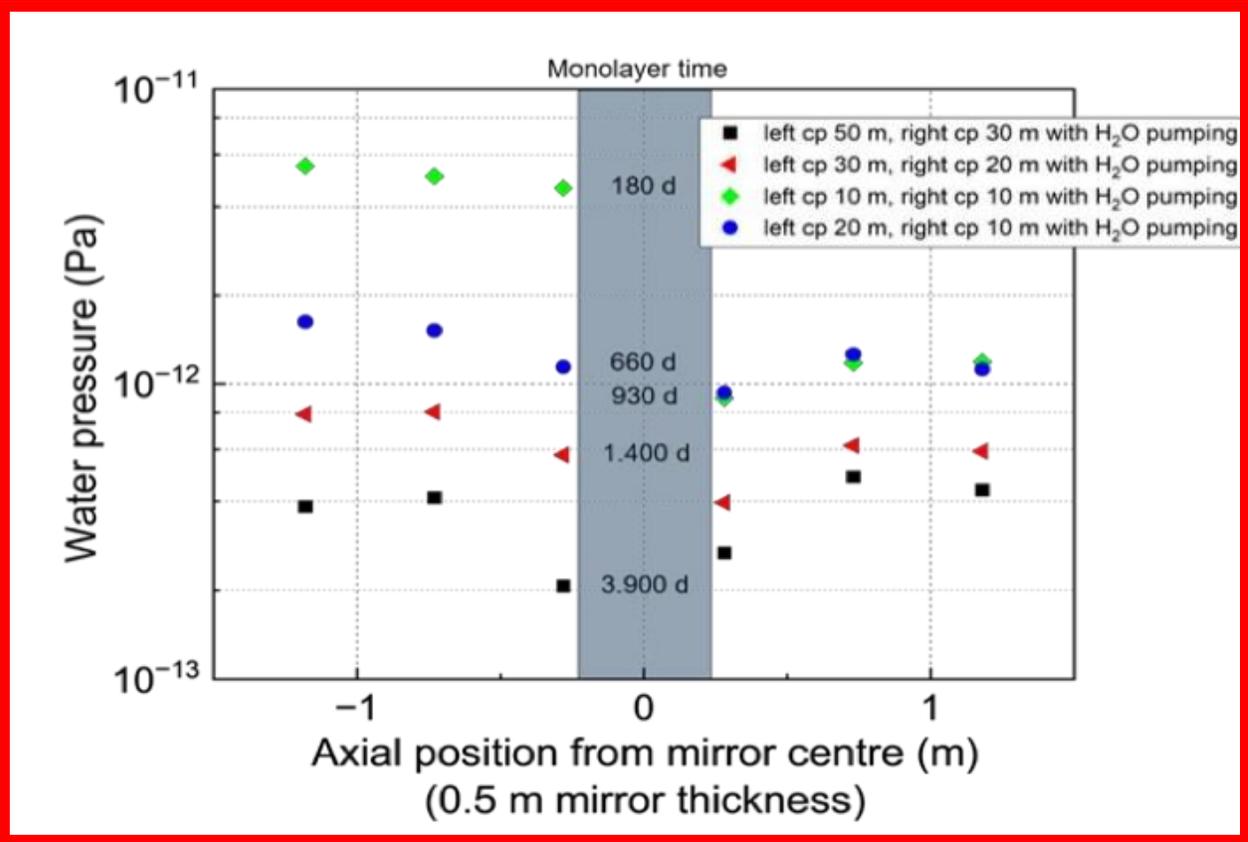
W. M. FAIRBANK

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}.

The reason

....

one

The

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 kT thermal noise, thermal expansion, thermal electromotive force, creep, etc…

Montecarlo study to design **ET Cryotraps** and limit the frost
TPMC code ProVac3D, experimentally validated and
extensively used for developments in fusion

- ➢ Cryopumps are directly coupled to the cryostat.
  - ➢ They must reduce the radiation thermal input from the km long pipes @300 K (inner diameter of the pipes 1 m)
  - ➢ They should protect the UH vacuum of the km long tubes after the intervention on the test mass zone
- ➢ Cryopumps (LF): Frost formation on mirror the main driver
  - ✓ Maximum allowable deposition of 1 ML water ice: not driven by optical reasons but by limited cooling budget and extra laser power absorption.
  - ✓ H_2 pumping

Extremely low pressures for all species ($<10^{-13}$ mbar) except H_2

ET configuration studies to make the project more robust
COst Benefit Analysis - CoBA

Analysis of the scientific perspectives
under possible variations of the detector
design:

➢ how the science output changes in the
   absence of the low-frequency instrument

➢ how the science output changes in
   function of the detector geometry
- triangle, 10km arms
- 2L, 15 km arms at 45°
- 2L, 15 km arms almost parallel
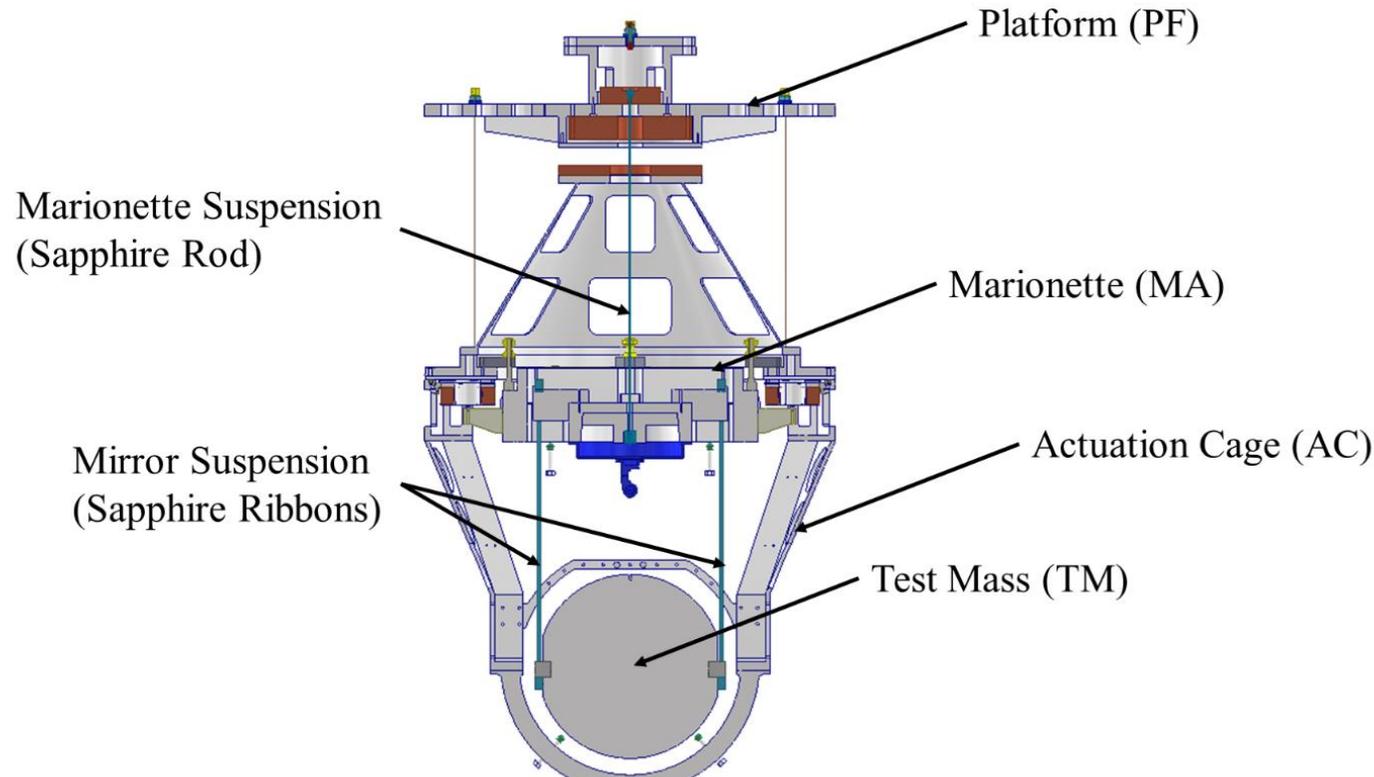- ……………

Outcome: a comparison of the scientific
returns for the various options

Meuse-Rhine

~ 1165 km

Sardinia
Sos Enattos

➢ Mirror is kept in HUV environment, e.g no heat gas exchange

➢ Heat transfer via Thermal Radiation helps just during the cooling down $\quad \frac{dQ}{dt} \propto T^3 \, \Delta T$
   (Temperature T too low)

➢ In the range of 10 -20 K we **must** rely on heat extration via solid conduction

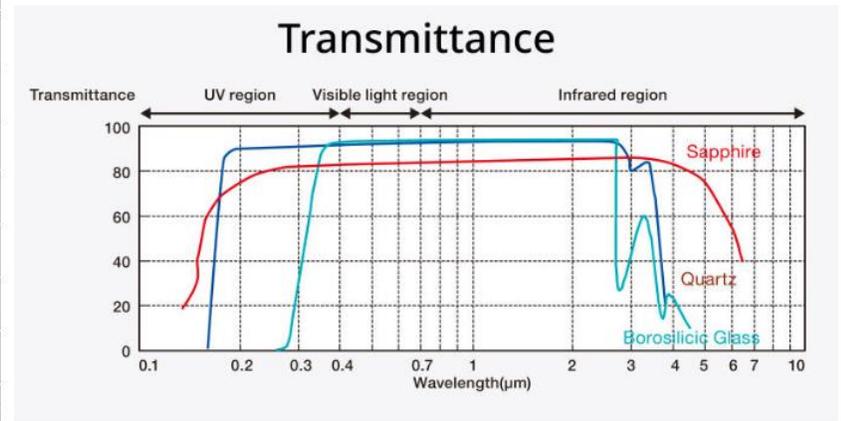*..but......**we can not add extra mechanical dissipation***

Platform (PF)

Marionette Suspension
(Sapphire Rod)

Marionette (MA)

Actuation Cage (AC)

Mirror Suspension
(Sapphire Ribbons)

Test Mass (TM)

Solution:
Heat extracted via the 4 wire suspensions: in this case they are *Long Cristals* (made of Silicon or Sapphire)

Sapphire

Typical Orientation of Single-Crystal Sapphire

Single Crystal Al$_2$O$_3$

Poly-crystal Al$_2$O$_3$

Density (*1)		g/cm^3	JIS R 1634	3.97		
Water Absorption		%	JIS C 2141	0		
Mechanical Characteristics	Vickers Hardness HV9.807N	GPa	JIS R 1610	a Plane	22.5	
	Flexural Strength 3 P.B.	MPa	JIS R 1601	a Plane c Axis	690	
	Compressive Strength	MPa	JIS R 1608	2,940		
	Young's Modulus of Elasticity	GPa	JIS R 1602	470		
	Poisson's Ratio	–		Parallel to Axis c / Vertical to Axis c	0.18	
	Fracture Toughness (SEPB)	MPa · m$^{1/2}$	JIS R 1607	2.1		
Thermal Characteristics	Coefficient of Linear Thermal Expansion	40-400°C	×10^{-6}/K	JIS R 1618	Parallel to Axis c / Vertical to Axis c	7.7 / 7.0
		40-800°C			Parallel to Axis c / Vertical to Axis c	8.8 / 7.9
	Thermal Conductivity 20°C	W/(m · K)	JIS R 1611	42		
	Specific Heat Capacity	J/(g · K)	JIS R 1611	0.75		
	Thermal Shock Temperature Difference (Put in Water, Relative Method)	°C	JIS R 1648	180		
Electrical Characteristics	Dielectric Strength	kV/mm		48		
	Volume Resistivity	20°C	Ω · cm	JIS C 2141	>10^{14}	
		300°C			10^{12}	
		500°C			10^{11}	
	Dielectric Constant (1MHz)	–		Parallel to Axis c / Vertical to Axis c	11.5 / 9.3	
	Dielectric Loss Angle (1MHz)	(×10^{-4})		<1		
	Loss Factor	(×10^{-4})		–		
Chemical Characteristics	Nitric Acid (60%) 90°C ,24H	(Weight Loss) mg/cm^2	–	≒ 0.00		
	Sulphuric Acid (95%) 95°C ,24H			≒ 0.00		
	Sodium Hydroxide (30%) 80°C ,24H			≒ 0.00		

Transmittance

Optical Refractive Index

*According to our research.

Major R&D Facilities in ET (incomplete)

ET – expression of interest

The Collaboration above the threshold of 1700 members