Cryogenic workshop summary in GWADW 2021

Paola Puppo (INFN-Roma)
Kazuhiro Yamamoto (Toyama)
May 21th 2021

Cryogenic Session: Tuesday May 18th (hour 1)

CE and Voyager project

Kevin Kuns (MIT)
Realizing Cosmic Explorer 2 with LIGO A+ or Voyager Technology

Sebastien Biscans (MIT LIGO)
Suspension design for Cosmic Explorer

Yehonathan Drori (Department of Physics and Astronomy, Amherst College, Amherst, Massachusetts 01002)
Optical Refrigeration for an Optomechanical Amplifier

Juliedson Reis (Brazil)
Theoretical Effective Emissivity for the LIGO Voyager Test Masses

CE and Voyager project

Voyager (A+) is cryogenic (room temperature) upgrade of current LIGO facility.

Cryogenic is a choice of CE2.

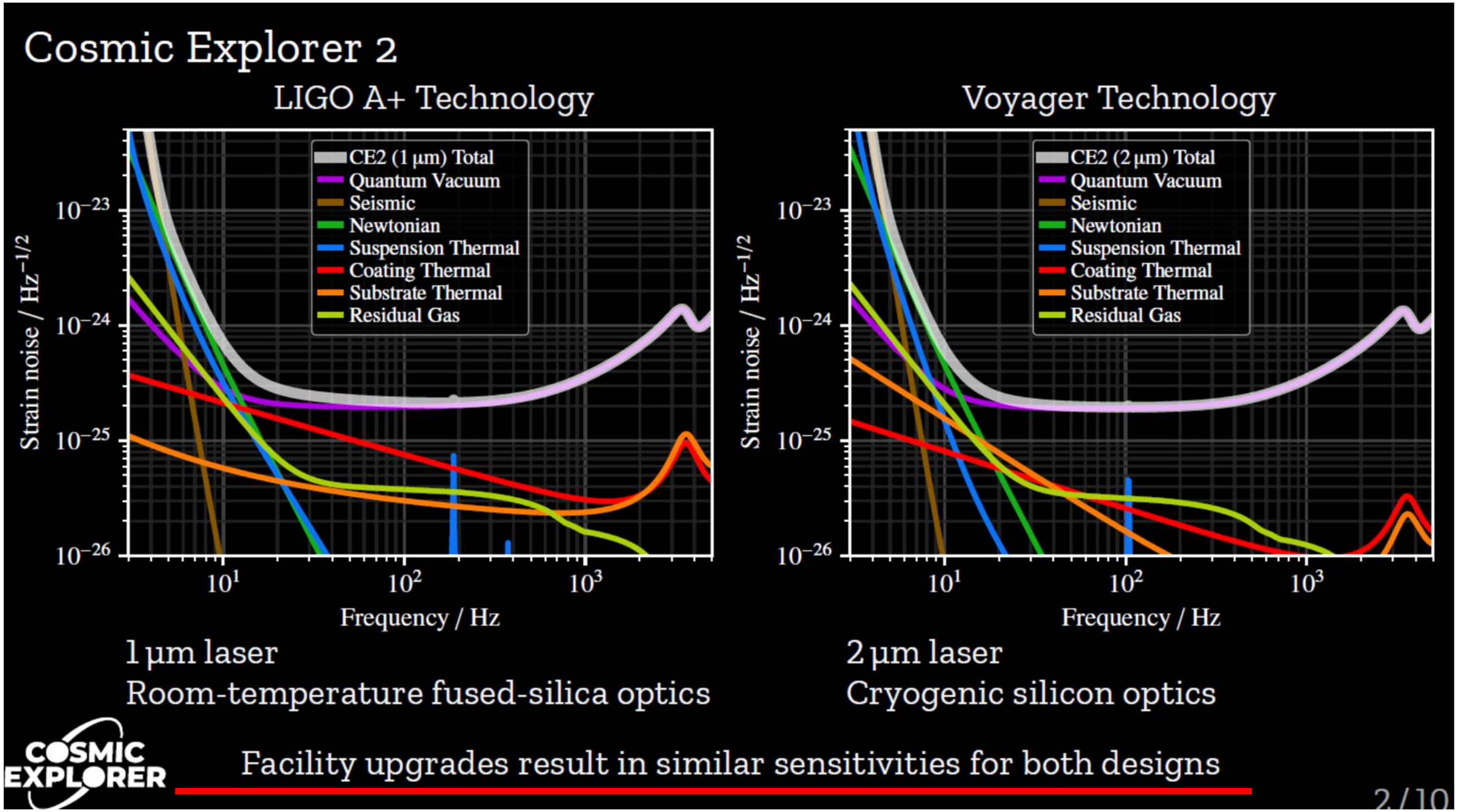
CE2 based on A+(room temperature) and Voyager (cryogenic) (Kuns)

CE2 suspension design based on A+(room temperature) and Voyager (cryogenic) (Biscans)

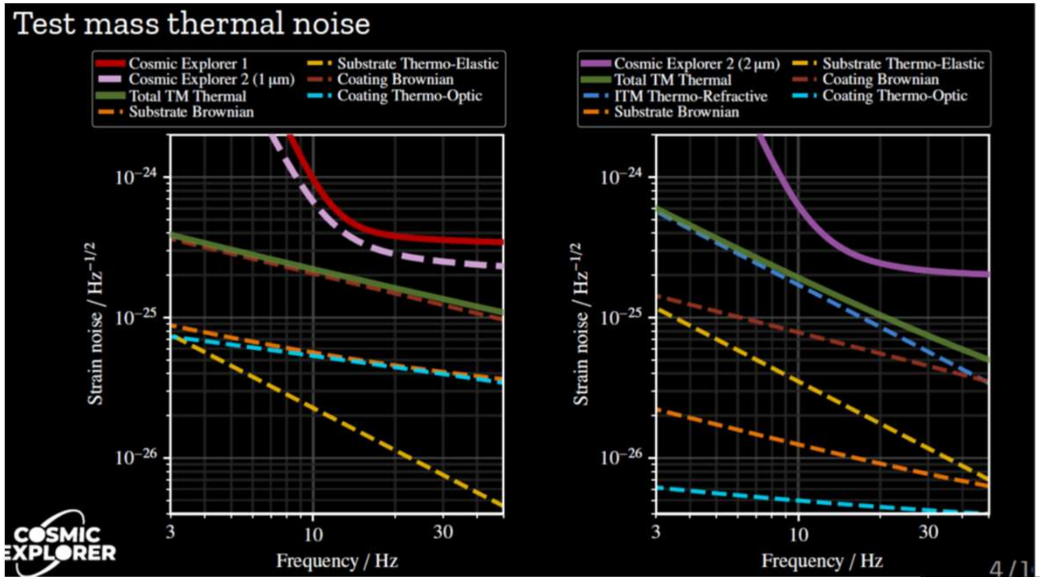
New type cryocooler (Voyager); Optical Refrigeration for an Optomechanical Amplifier (Drori)

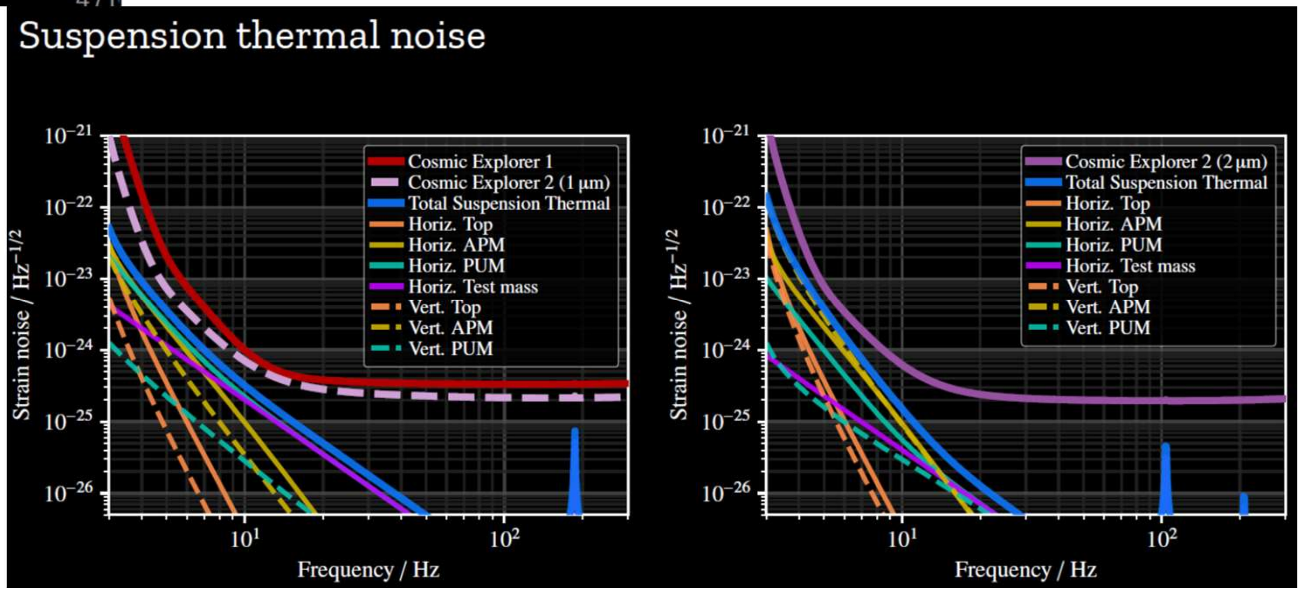
Black body radiation as bulk phenomena (Reis)

Kevin Kuns (MIT) Realizing Cosmic Explorer 2 with LIGO A+ or Voyager Technology



Kevin Kuns (MIT) Realizing Cosmic Explorer 2 with LIGO A+ or Voyager Technology

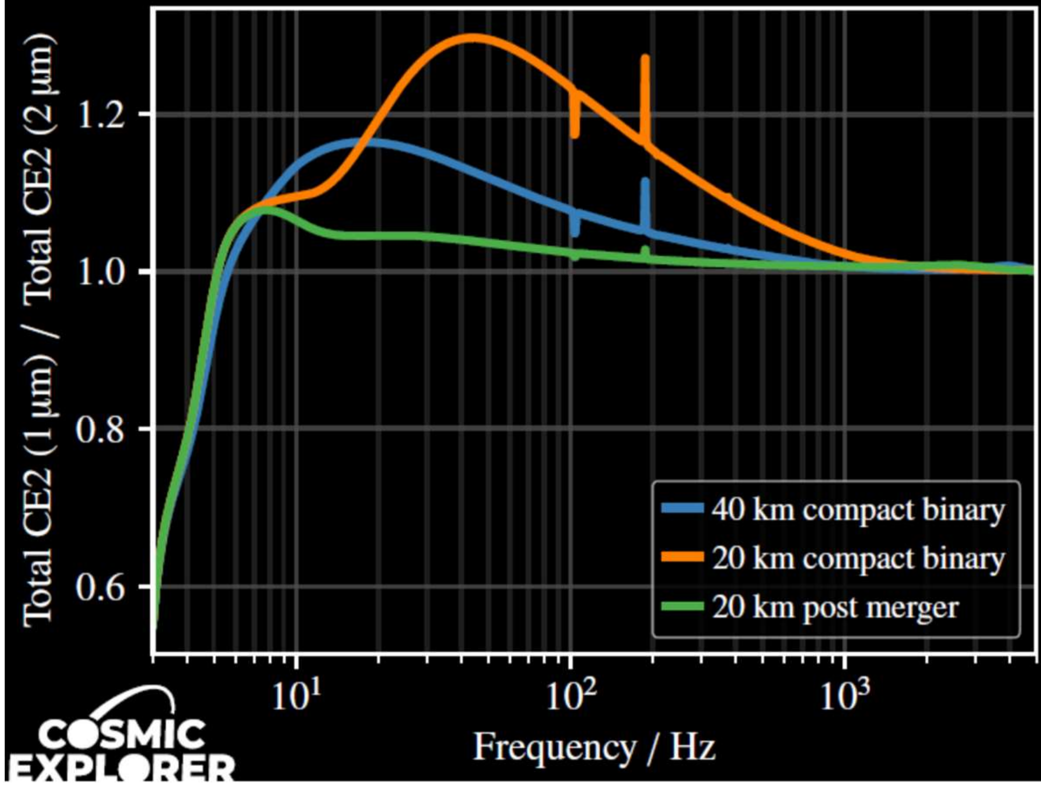




Kevin Kuns (MIT) Realizing Cosmic Explorer 2 with LIGO A+ or Voyager Technology

Summary

- CE2 can reach similar strain sensitivities using either evolved LIGO A+ or Voyager technology



- Risk mitigation in the event that significant challenges are discovered in one of the technologies
- However, many required R&D activities (Newtonian noise suppression, inertial isolation, …) are common to both realizations of CE2
- Many generations of detector technologies are expected to be used in the CE observatories
- Voyager technology has greater potential for increased arm powers in the future

COSMIC EXPLORER

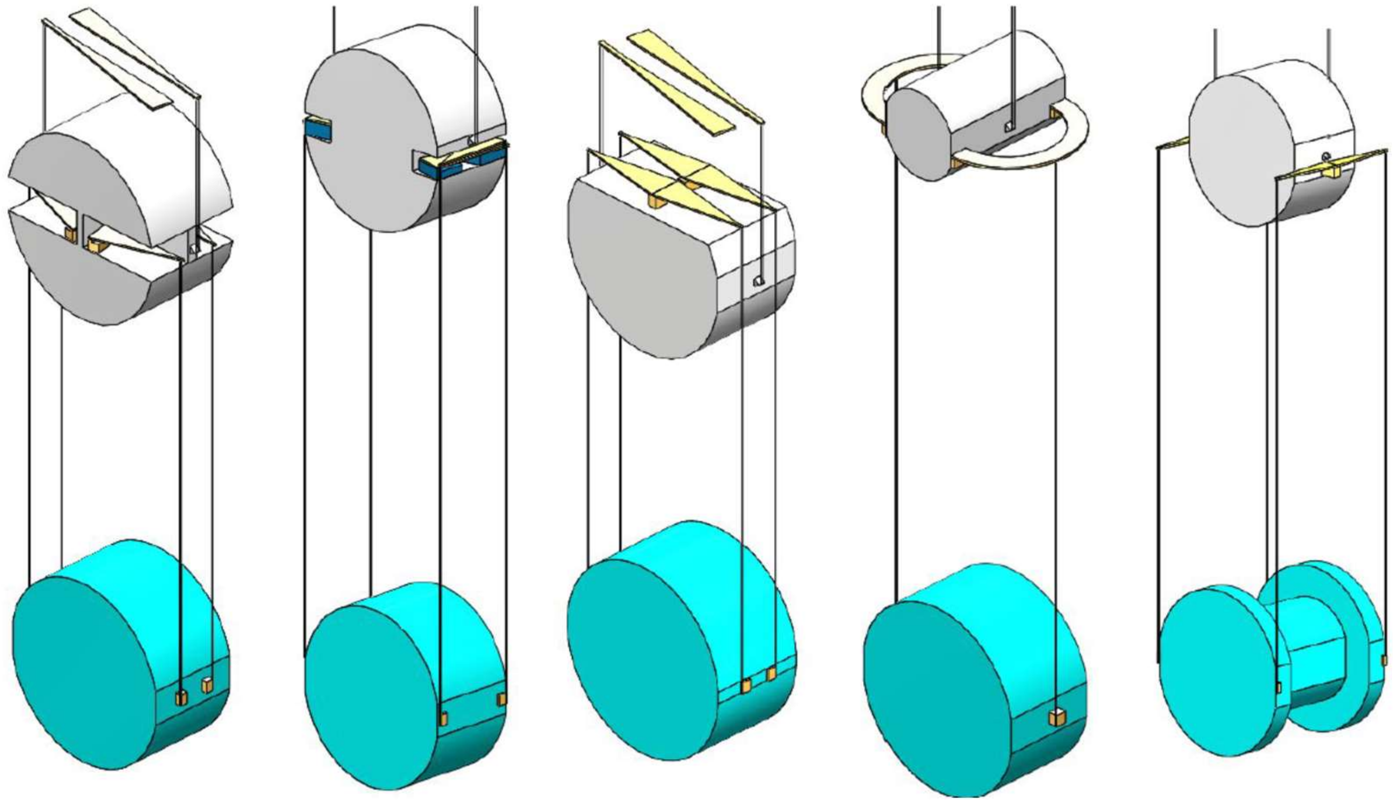
Sebastien Biscans (MIT LIGO) Suspension design for Cosmic Explorer

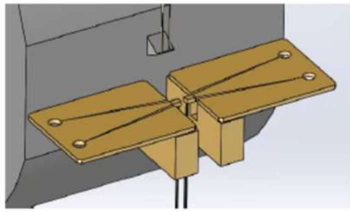
Keys of suspension for CE2

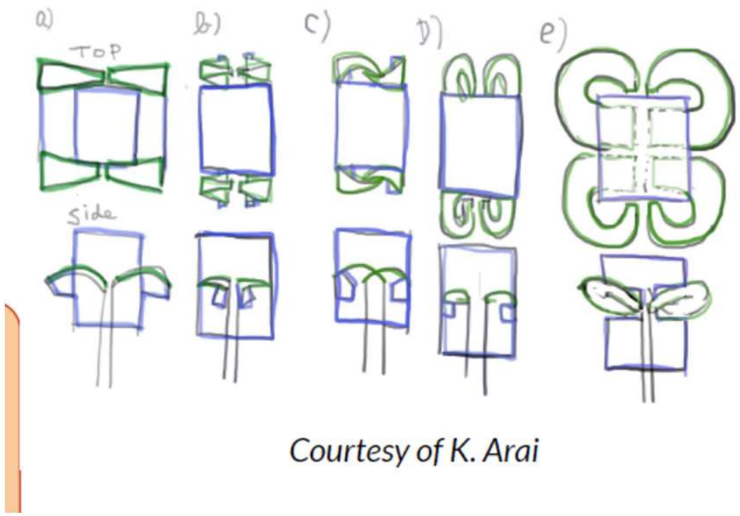
(1)If cryogenic is adopted, fibers are made from silicon.

(2)Resonant frequencies are 3Hz at most. Soft (vertical) blade springs are necessary.

- A lot of designs considered...



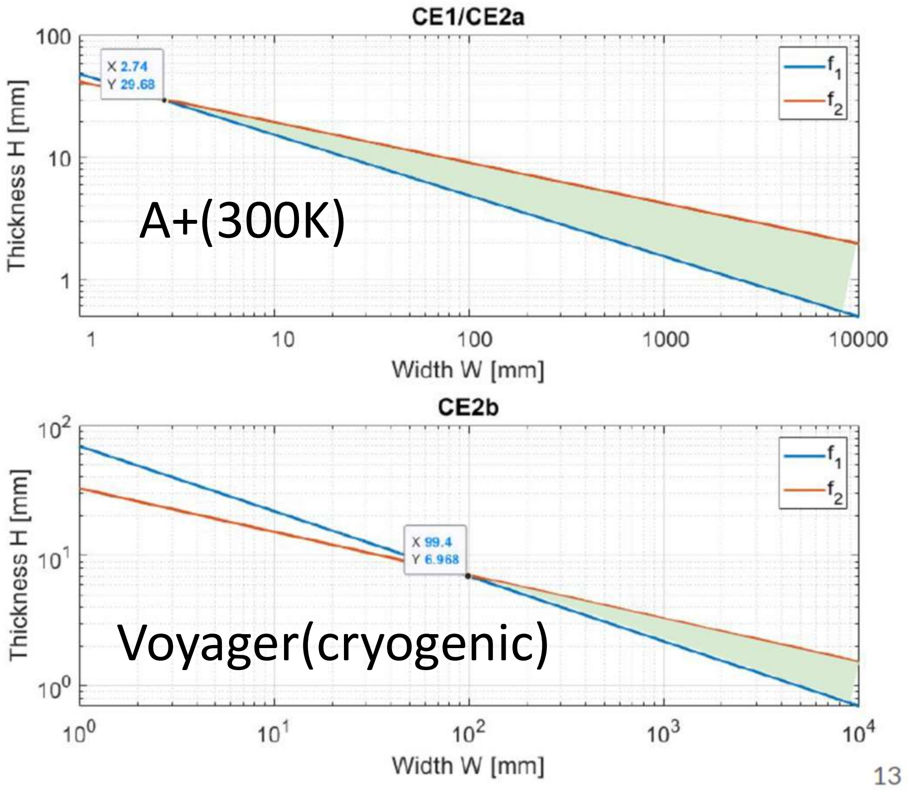




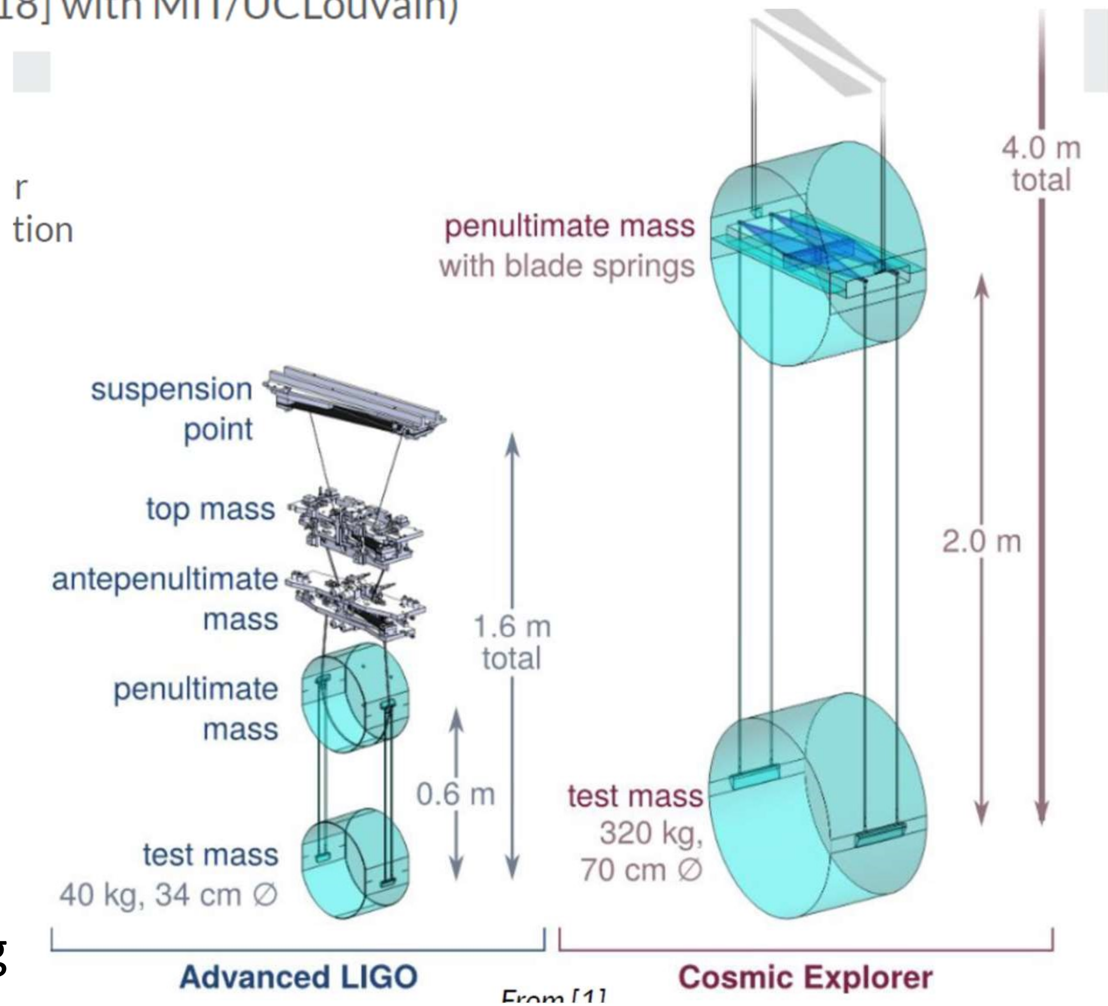
Courtesy of K. Arai

Sebastien Biscans (MIT LIGO) Suspension design for Cosmic Explorer

- Using silicon put stringent requirements on the suspension design, but might be doable
- More ideas still to be explored (i.e. Euler springs [18] with MIT/UCLouvain)



Acceptable parameter region for blade spring



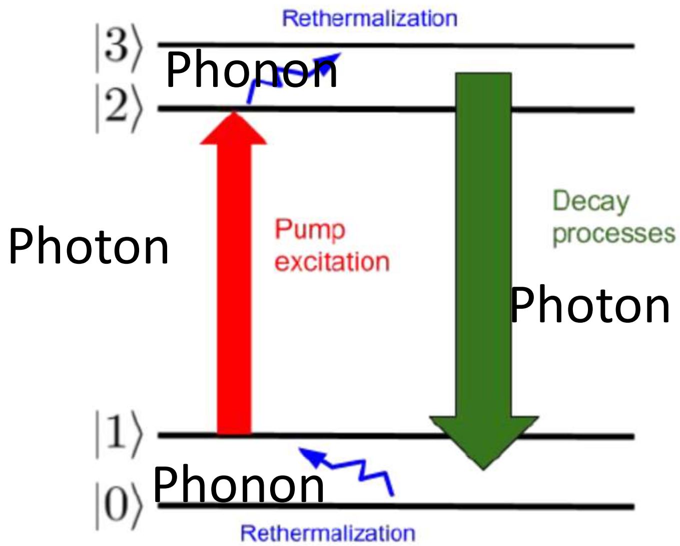
Yehonathan Drori (Department of Physics and Astronomy, Amherst College, Amherst, Massachusetts 01002) Optical Refrigeration for an Optomechanical Amplifier

Potential Cooling Choices

Type of Cooling	Vibration Free?	Can Cool at 123 K?
Mechanical: Pulse tube/Stirling Cycle	No	Yes
Thermoelectric Cooling	Yes	No (limit of ~155 K)
Radiative Cooling Geometrical limit	Yes	Yes
Optical Refrigeration No geometrical limit	Yes*	Yes*

Yehonathan Drori (Department of Physics and Astronomy, Amherst College, Amherst, Massachusetts 01002)   Optical Refrigeration for an Optomechanical Amplifier

- Cooling with a laser- familiar ideas from cooling of gases
- Not Doppler shift, but anti-Stokes
    - Mean fluorescence event is of lower wavelength/higher energy than the pump light
- Crystal doped with certain rare earth (RE) ions
- Extra energy comes from phonon bath in host crystal

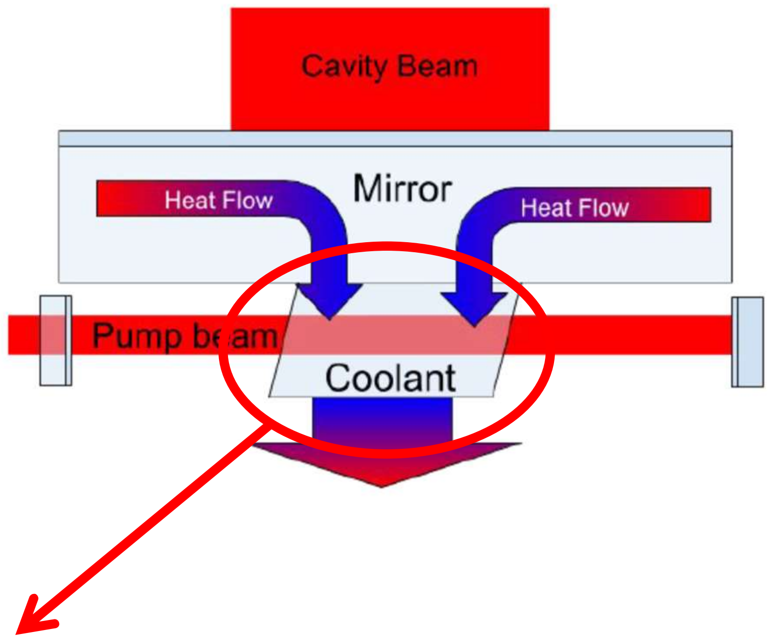


Phonon is converted to photon and escapes.

Yehonathan Drori (Department of Physics and Astronomy, Amherst College, Amherst, Massachusetts 01002) Optical Refrigeration for an Optomechanical Amplifier

Design Considerations

- Shield against fluorescence
  - Choose Ho3+ for transparency and potential for high cooling efficiency
- Good thermal contact with mirror (short thermal link)
- Multipass configuration
- Minimize radiation pressure noise
- Minimize readout contamination (work in progress)



~ gram (~cm)

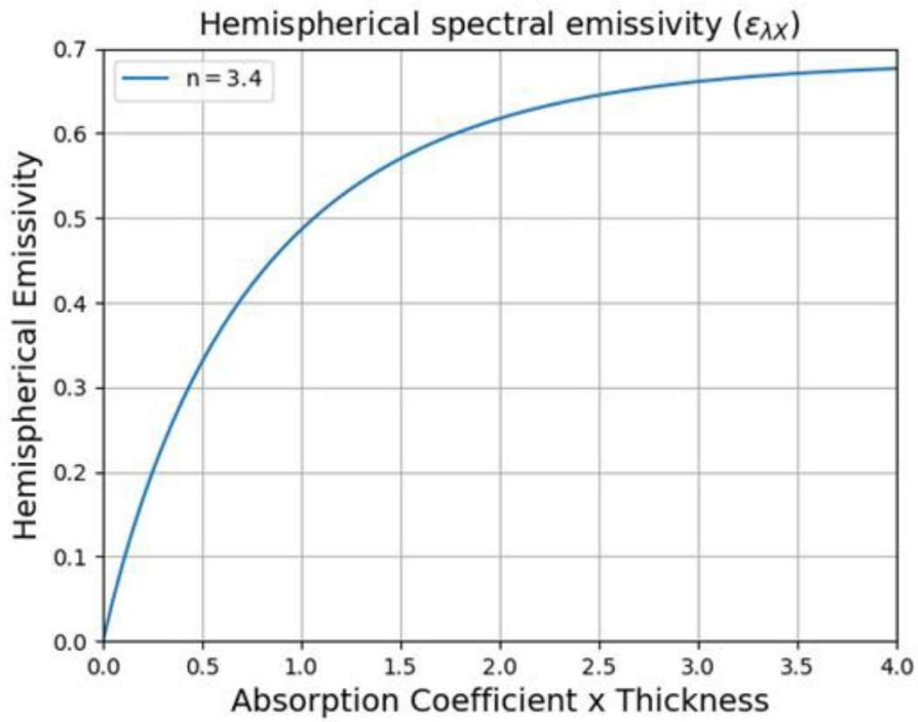
Juliedson Reis (Brazil) Theoretical Effective Emissivity for the LIGO Voyager Test Masses

Black body radiation is surface phenomena. But actually, body phenomena. Silicon at 123K is somehow transparent for far infrared radiation.

- LIGO Voyager: Si test masses at 123 K;
- Si is semi-transparent around the Black Body peak at 123K;
- Thus, emissivity becomes a **bulk phenomenon**.
- According to Gardon (1956):

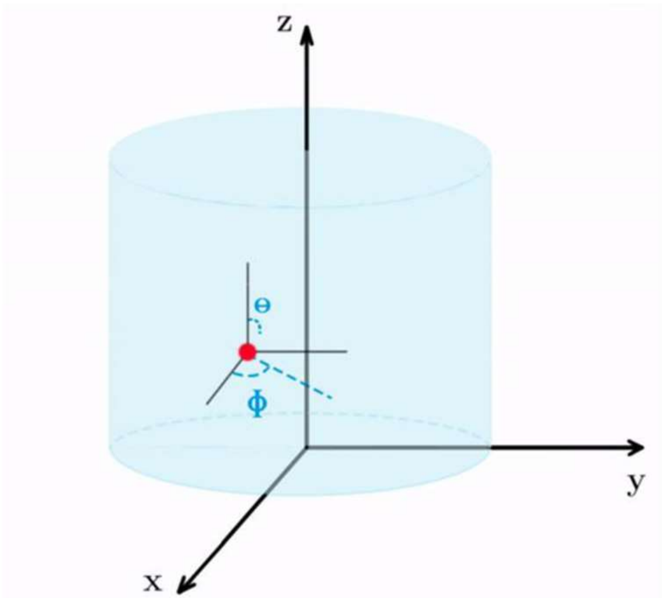
$$\epsilon_{\lambda x} = 2 \cdot \int_0^{\frac{\pi}{2}} \left(1 - e^{-\frac{\alpha_\lambda x}{\cos\gamma}}\right) \Upsilon' \sin\beta \cos\beta d\beta$$

- This method was first suggested to us by Martin Fejer.



Juliedson Reis (Brazil) Theoretical Effective Emissivity for the LIGO Voyager Test Masses

Black body radiation is surface phenomena. But actually, body phenomena. Silicon at 123K is somehow transparent for far infrared radiation.



- We calculated:

I. the mean thickness through a code in Python;

II. the absorption weighted by the Black Body's curve;

III. the effective emissivity for a Si piece.

~0.4 (because of smallness, about 70mm*30mm*10mm)

IV. the effective emissivity for LIGO Voyager test masses and obtained ~ **0.7**

Cryogenic Session

Wednesday May 19th-20th (hour 1)

KAGRA

Nobuhiro Kimura (ICRR)
The cooling scenario of the KAGRA test mass without condensation on the surface toward to O4

Tomohiro Yamada (High Energy Accelerator Research Organization)
Reduction of vibration transfer via heat links in KAGRA cryogenic mirror suspension system

Takafumi Ushiba (ICRR)
Recent upgrade of KAGRA cryogenic payload

Status of KAGRA

"Practical" updates and lessons about cooling at site

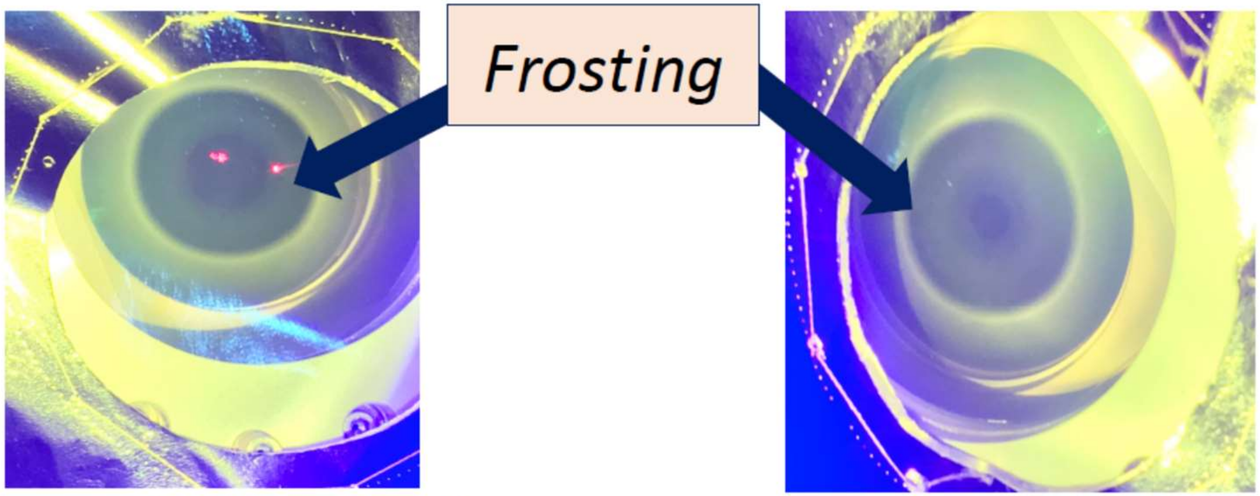
How to avoid condensation of mirrors and windows (Kimura)

Heat links and their vibration isolation (Yamada)

Updates in last 2 years for installed cryogenic payload (Ushiba)

Nobuhiro Kimura (ICRR)

The cooling scenario of the KAGRA test mass without condensation on the surface toward to O4



TM oplev light source side

TM oplev QPD side

How to avoid ? Kimura and his colleagues proposed as follows.

(1)The cryostat is evacuated well (less residual gas).

(2)At first the radiation shields are cooled down (cryo pump).

(3)At last , the mirror and payload is cooled down.

(4)If necessary, the heater works (de-frost).

In order to confirm this method, the experiment of cryostat at KAGRA site was conducted.

Nobuhiro Kimura (ICRR)

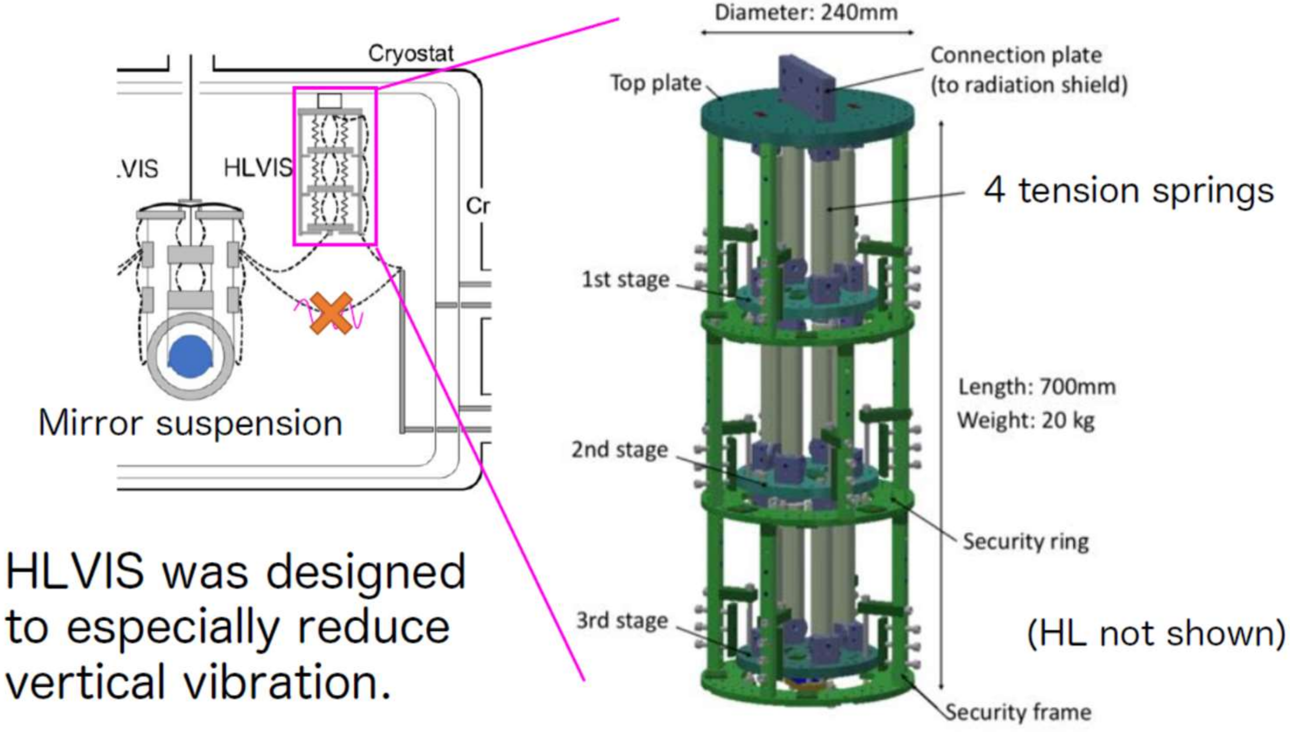
The cooling scenario of the KAGRA test mass without condensation on the surface toward to O4

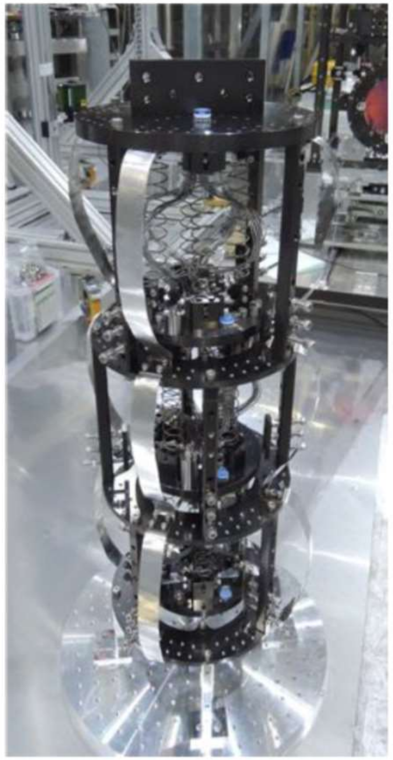
- Frost on the surface of view ports were not appeared during this experiment!
- Following items were confirmed in this experiment;
  - ✓Frost on the view ports are not appeared by proposed cooling scenario.
  - ✓Calibration heaters on the surface of inner radiation shield well worked as defrost heater for view ports on the surface of inner radiation shield up to ~50 K. It will take **2 days** for defrosting for surface of the view ports.
  - ✓Heater on the IM well worked as defrost heater for mirror on the up to ~70 K. It will take **2 days** for defrosting for surface of mirror.
  - ✓Partial pressure measurement of residual gas at each temperature was performed.

It works !

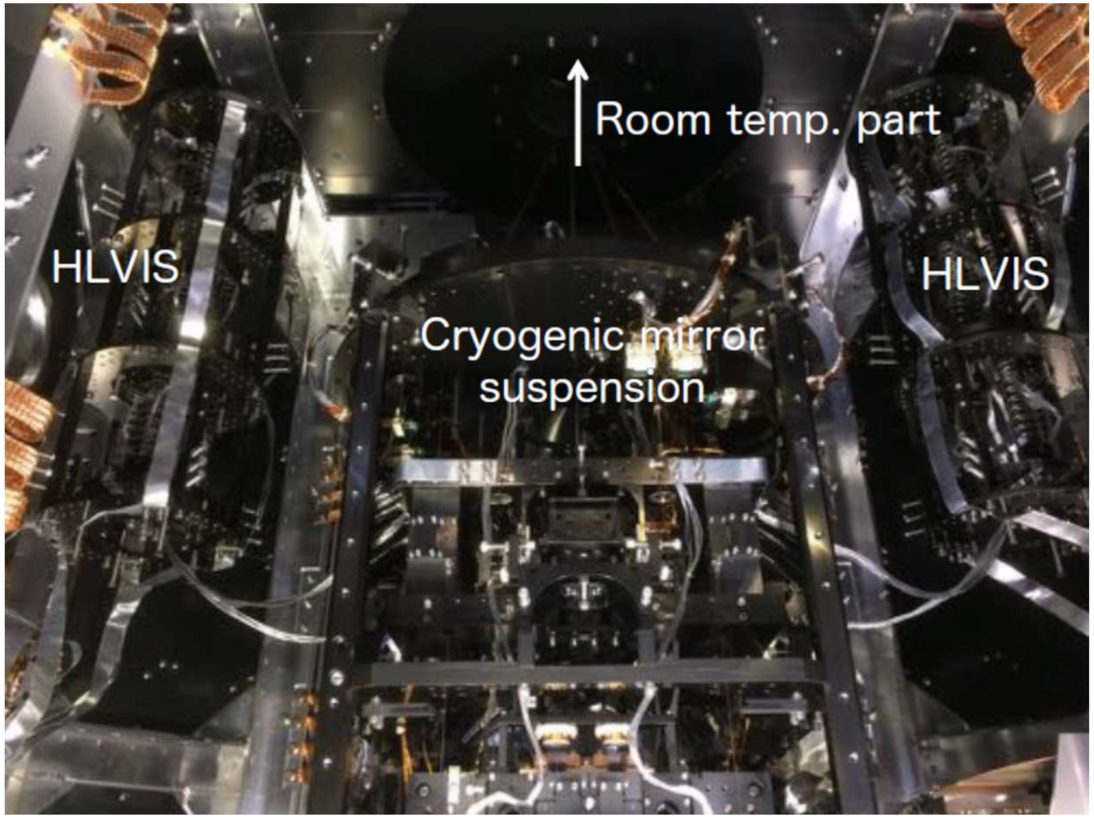
Yamada (High Energy Accelerator Research Organization)
Reduction of vibration transfer via heat links in KAGRA cryogenic mirror suspension system

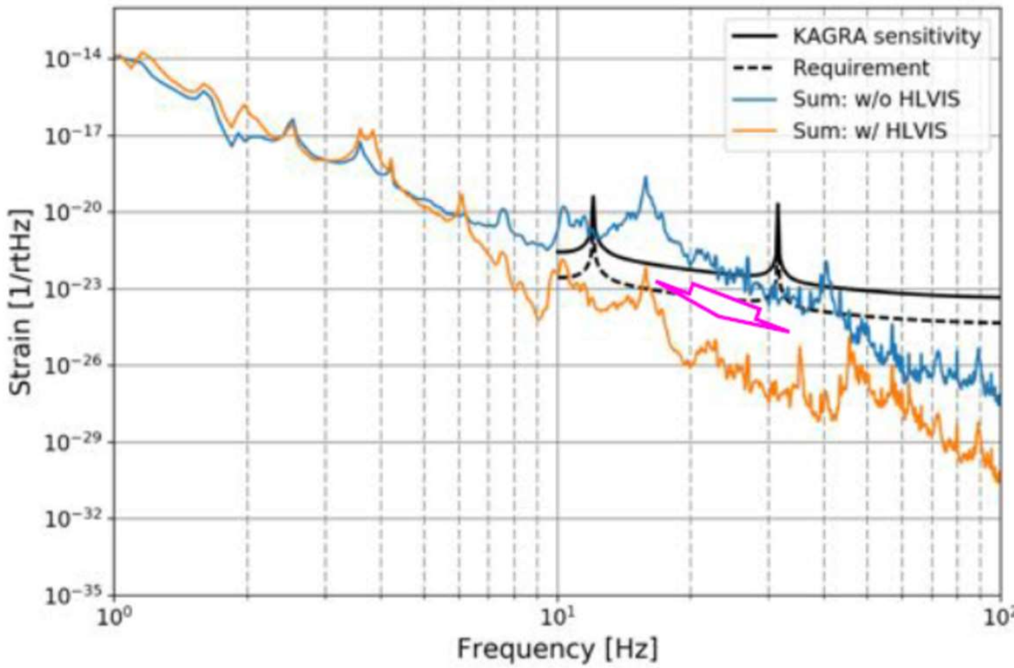
Heat links to cool KAGRA cryogenic payload transfer large vibration. Vibration isolation system is necessary.





Yamada (High Energy Accelerator Research Organization)
Reduction of vibration transfer via heat links in KAGRA cryogenic mirror suspension system





ᑊTM

Vibration inflow is reduced below the sensitivity curve.

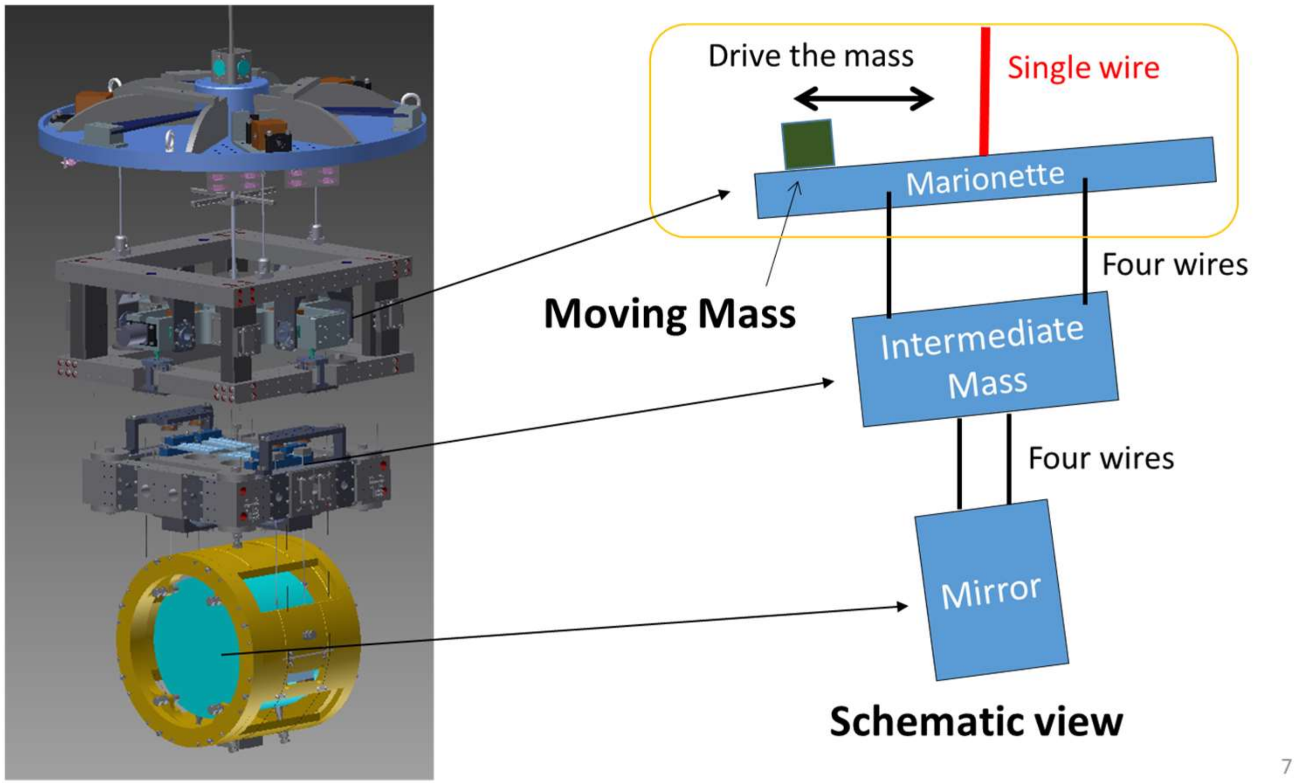
Heat link vibration isolation system in KAGRA cryostat

I'm writing a paper about these results.

Takafumi Ushiba (ICRR)
Recent upgrade of KAGRA cryogenic payload

Moving mass

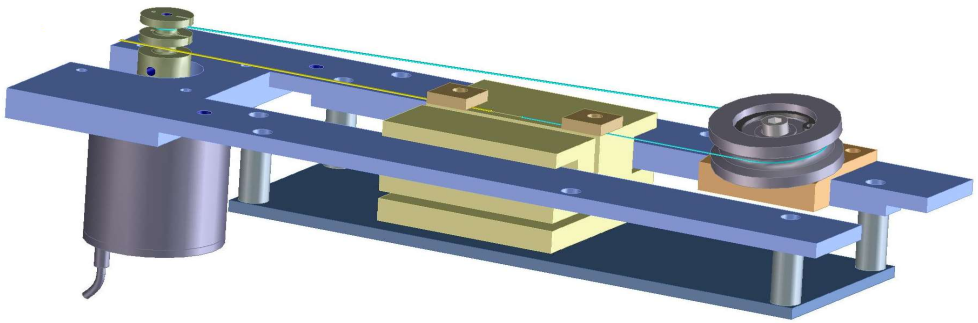
- Since MN is suspended from PF by a single wire, pitch inclination of a mirror need to be adjusted by MN or lower.

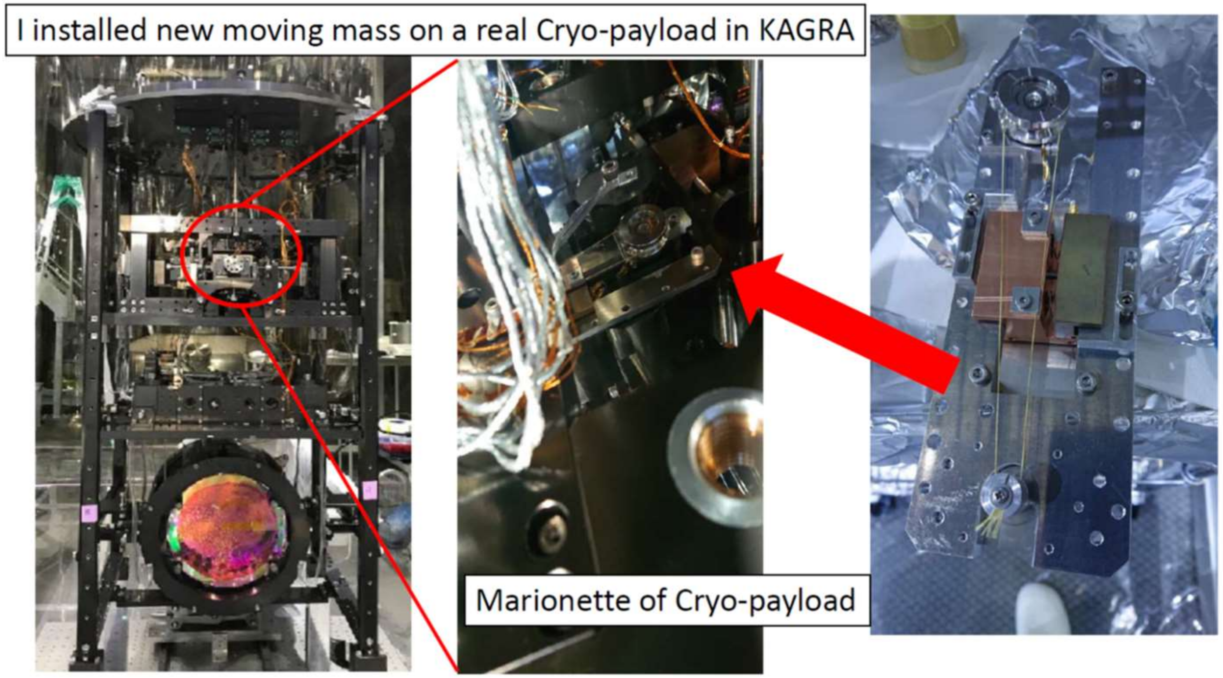


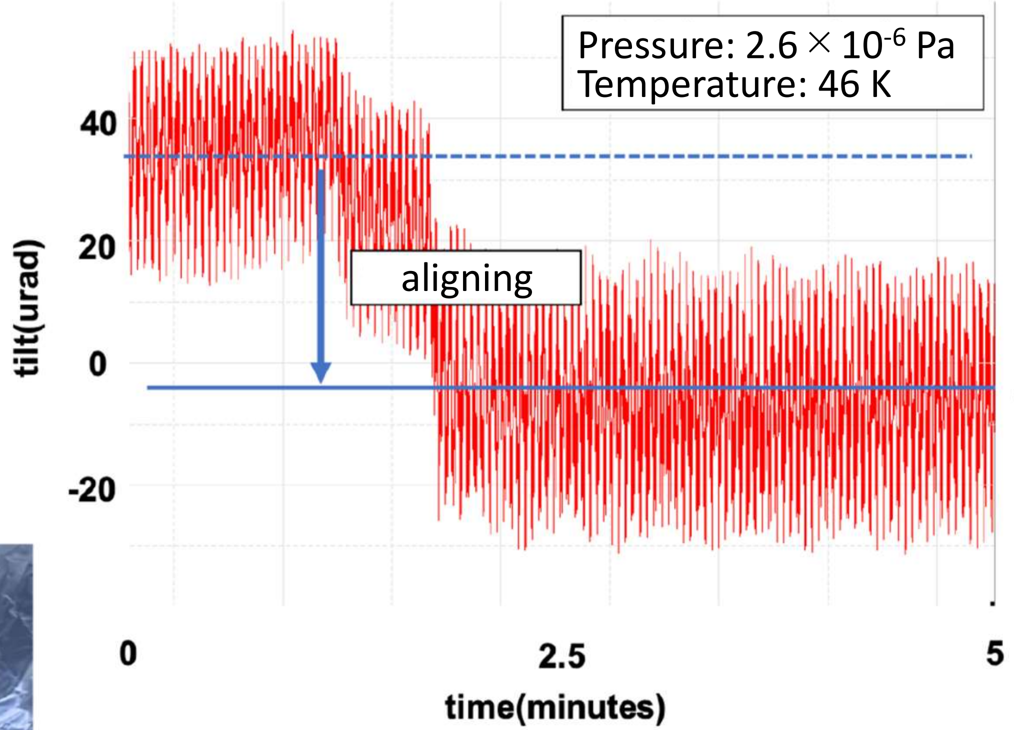
Due to complex structure, old systems are sometimes stuck after moving several times.

-> New system was developed and installed in KAGRA cryostat.

Takafumi Ushiba (ICRR)
Recent upgrade of KAGRA cryogenic payload







New system works in KAGRA cryostat (46K).

Cryogenic Session: Tuesday May 18th (hour 2)

ET project

Fulvio Ricci (Univ. Sapienza, INFN, Rome)
Cryogenics and Vacuum for the Einstein Telescope project

Ettore Majorana (Univ. Sapienza, INFN, Rome)
Outline of cryogenic payload compliance with Einstein Telescope

Henk Bulten (Vrije Universiteit Amsterdam/Nikhef)
Cryogenics and water migration in ET pathfinder

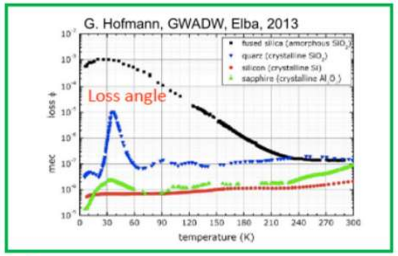
Lennard Busch, Xhesika Koroveshi and Steffen Grohmann (Karlsruhe Institute of Technology (KIT))
Helium-based cooling concept of the ET-LF interferometer

Instrument Science Board Cryogenics and Vacuum for the 3G-GW Einstein Telescope

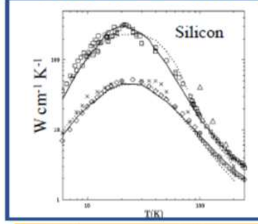
Fulvio Ricci

AMALDI RESEARCH CENTER

Cryogenic Monolithic Suspensions



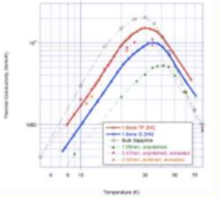
Materials for mirror suspension wires

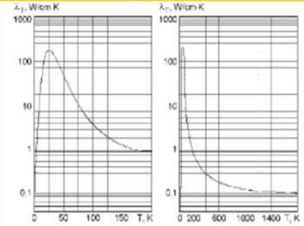


Sparavigna, Amelia Carolina
Role of nonpairwise interactions on phonon thermal transport
0.1103/PhysRevB.67.144305

Report of Allen Scheie NSF-IREU student hosted at the university of Rome Sapienza

Thermal cond. Sapphire (samples with different ϕ and surface status)





Sapphire
Dobrovinskaya, Elena and Lytvynov, Leonid and Pishchik, Valerian: Properties of shappire (1970), https://dx.doi.org/10.1007/978-0-387-85695-7%7B%5C_%7D2

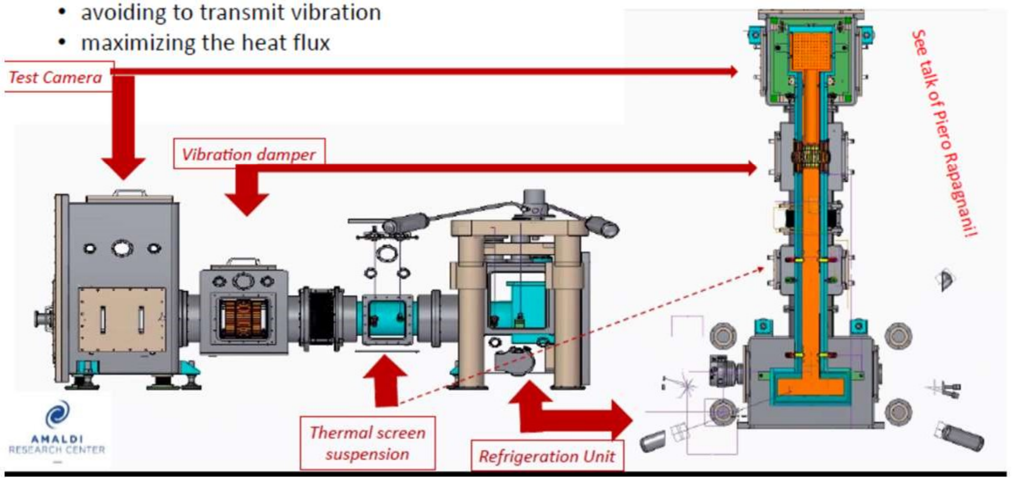
Cooling System

Protype Construction on the way

The issue is how to bring the refrigeration power

- avoiding to transmit vibration
- maximizing the heat flux

In orange the refrigeration path
In bleu the thermal screen
In grey the vacuum chamber



Vacuum Tubes

Scaling the VIRGO experience

Standard approach

- Stainless steel 304L (4 mm thick), cleaning, welding, baking procedures
- Tube construction and firing far from the site

Negative impact

- Cost too high (just the cost of the raw material ~20 M€)
- Bake out in the underground environment problematic
- Logistic issues ➔ about ~11,000 elements (12 m) to be transported

Main issues related to cryogenics

- Heat extraction from a heavy mirror and suspension wires for a cryogenic payload
- Cooling Time
- Safety : a crucial issue when we operate in the underground environment)
- Mirror pollution due to the temperature gradients
- VIBRATIONS and EXTRA ACOUSTIC NOISE!!!

Cryogenics: R&D

In addition to the ET design effort, we will discuss and promote R&D for improved detectors, for example for future ET upgrades.

The scope of this division includes work on:

- Simulation of particle sources and shields in the cryostat
- Development of ultra-low noise LF payload cooling systems
- Experimental investigations on LF payload operation, incl. local control

Open point

Numerical study of the cryotrap configuration

-Numerical evaluation of the geometrical factor for the radiative heat transfer

-Molecular conduction evaluation via montecarlo

Payload cooling time

- We need to reduce it (up to 1 week per mirror)
- use of the He gas exchange, a complex solution in a real GW interferometer
- Use a telescopic system to transmit the refr. power via solid

Vacuum & Cryogenics: Preliminary questions

Before the complete design document, we must address urgent issues following from the current design, for example:

- Diameter and bakeout conditions of the pipe arm tubes
- Desired cool-down and warm-up times
- Heat load on the LF mirrors

Outline of cryogenic payload compliance with Einstein Telescope LF

E. Majorana [Univ. Sapienza], P. Puppo [INFN Roma], P. Rapagnani [Univ. Sapienza], P. Ruggi [EGO]
on behalf of the payload group in Rome

GWDAW2021
May-18-2021

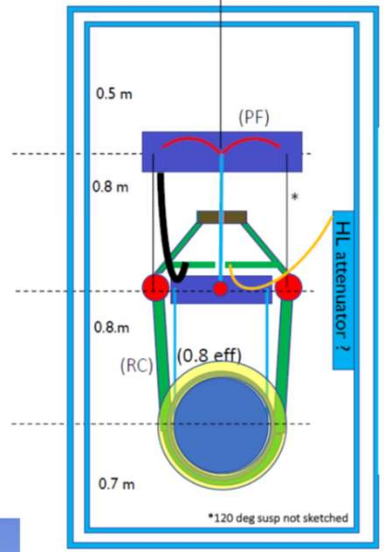
A sustainable approach

- Analyse carefully the target
- Experience with present detectors
- Widening the collaboration and gathering financial resources
- Develop experimental facilities and identify the know-how
- Aligning priorities and wisely schedule viable R&D milestones

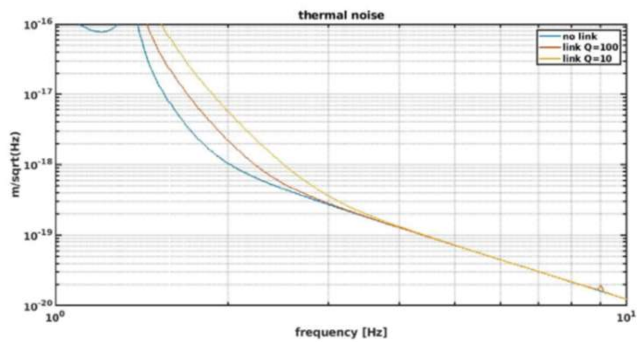
a meaningful TD ?

Heat Links effect on thermal noise

Thermal noise increase due to cryogenic link



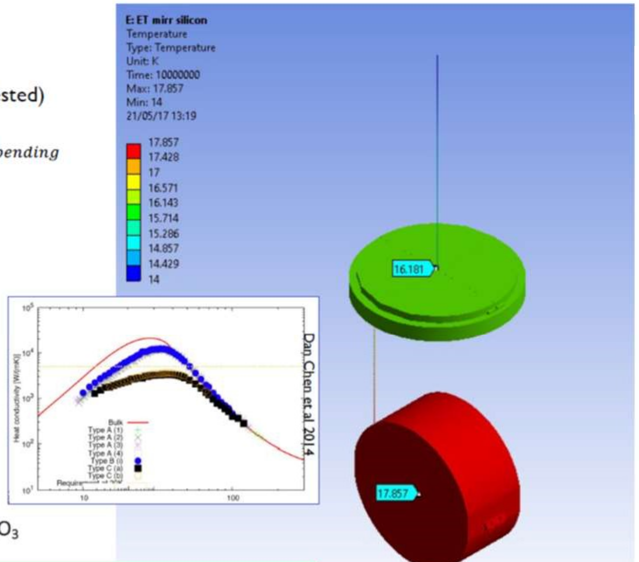
Link RM - PF: AL $E=6.9*10^{10}$; $\rho=2700$
L=1m; d=2mm; N=8;



Thermal Studies

Using sapphire rods

- Si Test Mass: 140 kg (Sapphire 150 mm thick also tested)
- TM Sapphire wires: 2.2 mm Ø - Length: 0.8 m + $2\lambda_{bending}$
- Marionette Wire: Sapphire Diam 5.0 mm
- Upper point: 14K
- Radiation component not included so far

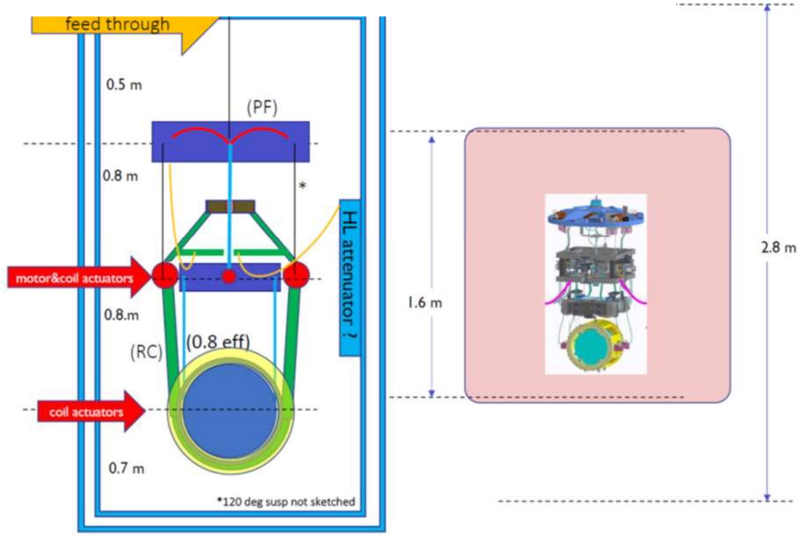


- ➢ The system can be cooled down.
- ➢ Notice the realtively massive marionette (for AdV+ we adopt 180 kg).
- ➢ Consistent with the cryostat room
- ➢ The system works for both Si and Sapphire
- ➢ Al6N HL, capability of building 80-90-cm-long Al_2O_3

- No HL included
- No radiation included, so far

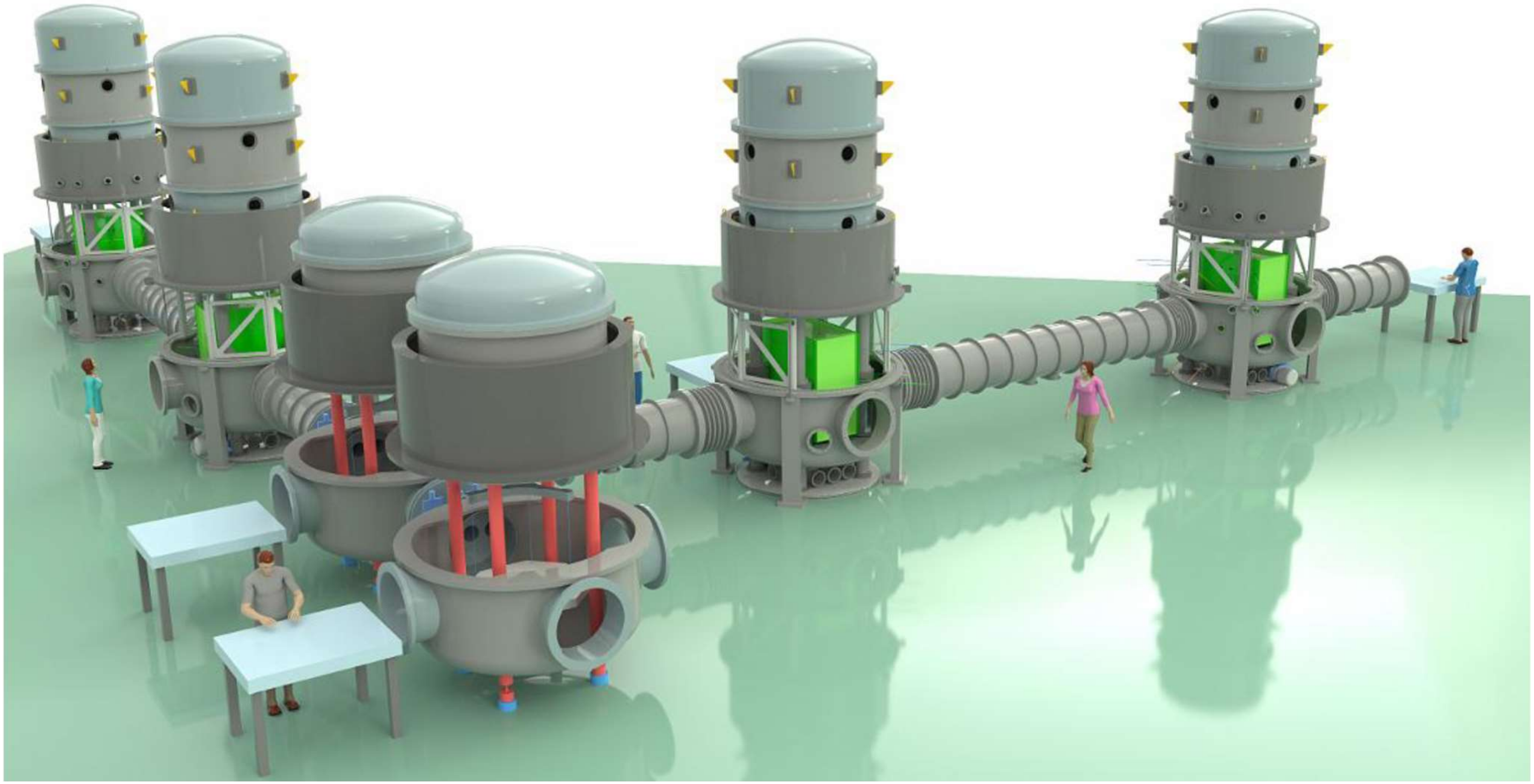
Controls

First set of seed parameters



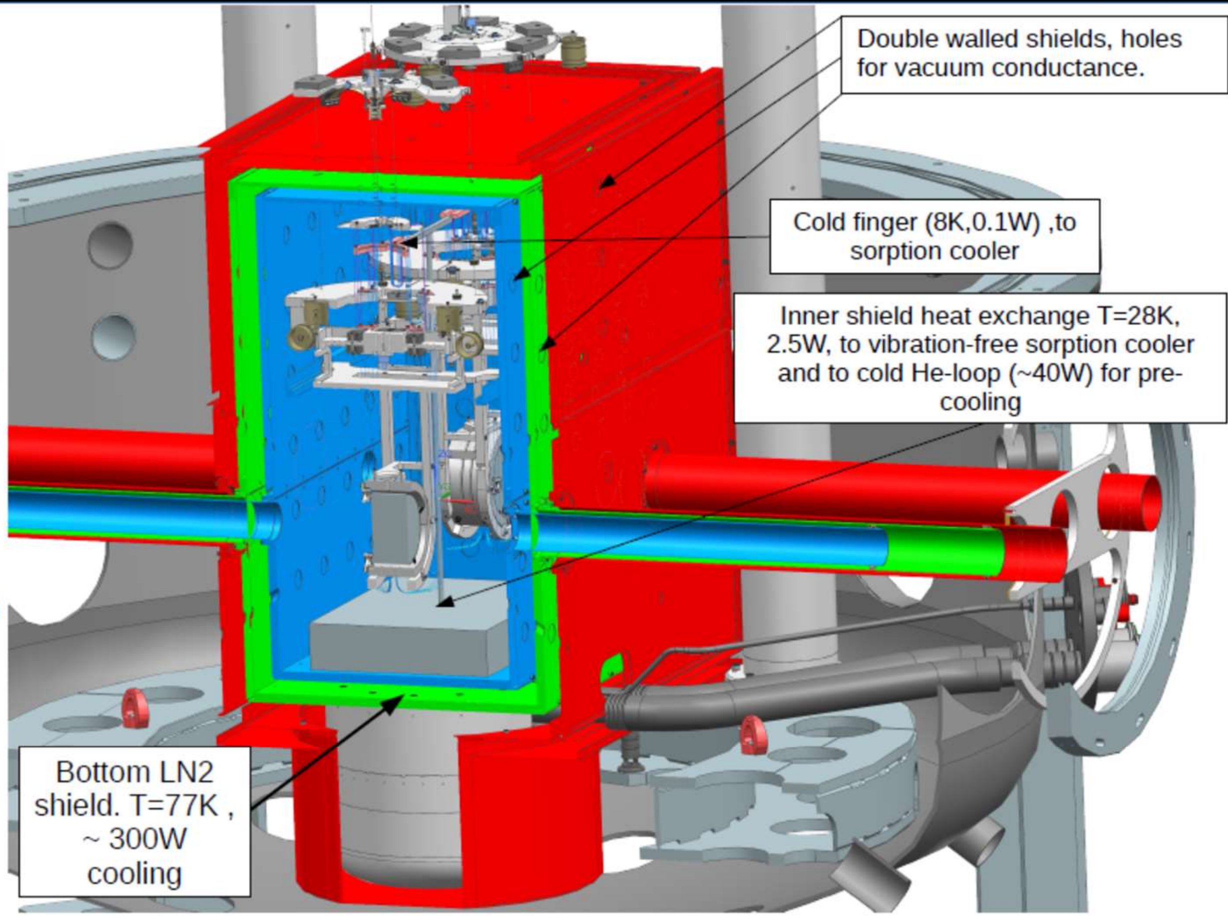
Cryogenics and Water Migration in ETpathfinder

GWADW 2021, May 18
H.J. Bulten, for the ETpathfinder collaboration



Cooling of mirrors, ETpathfinder concept

- Steady-state: about 300W of cooling power at 80K, 2.5W at 30K, and 0.1W at 8K needed.
- Liquid nitrogen @80K, sorption coolers at 30K, 8K, switchable Helium cooler @30K for initial cool-down.
- Conductive cooling of mirror limited by heat resistance of monolithic suspension: max ~30 mW of conductive power. Therefore, a small sorption cooler suffices for the 8K temperature.
  - Sorption coolers: thermal compressor, negligible pressure ripple. See talk Marcel ter Brake, Arvi Xhahi.
- Heat links of sorption cooler to marionette, reaction mass: ultra-pure Al (KAGRA design), 32 wires with 0.15 mm diameter.
- 3 sets of thermal shields: passive (red), LN2-cooled (green), inner shields (blue) at ~30K.
- Pipes around the beam to shield the mirror from thermal radiation: contain conical baffles at the end (not shown), about 50 mm opening diameter.



Mirrors: 2x3.5 kg Si – emissivity ~ 0.5. Marionette, reaction mass, safety structure ~2x21 kg Al-6063; emissivity 0.9 for radiative cool-down, Inner shield: double-walled Al-6063; total mass 130 kg. Options with inside black (emissivity 0.9) or shiny (0.1). Outer shield: mass 180 kg. Emissivity 0.1, option inside 0.9.

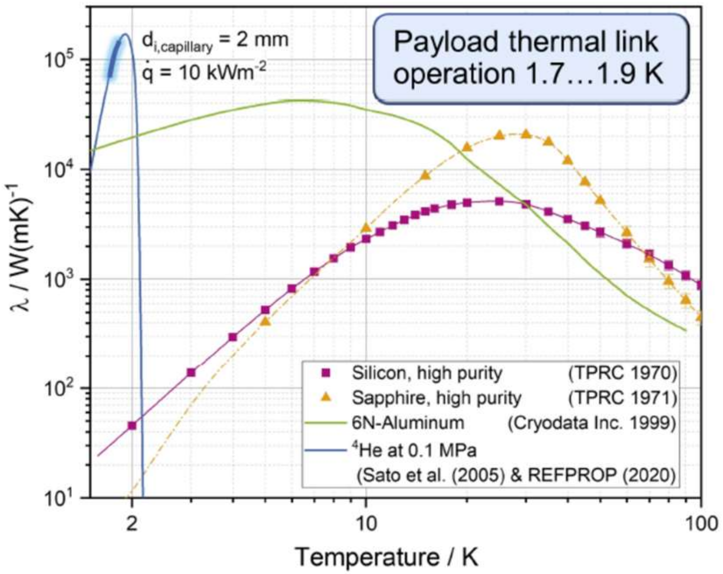
Helium-based cooling concept of the ET-LF interferometer

Lennard Busch
Xhesika Koroveshi
Steffen Grohmann

Gravitational Wave
Advanced Detector Workshop
17-21 May 2021

He-II hollow capillaries as heatlinks of ET-LF payload

Karlsruhe Institute of Technology

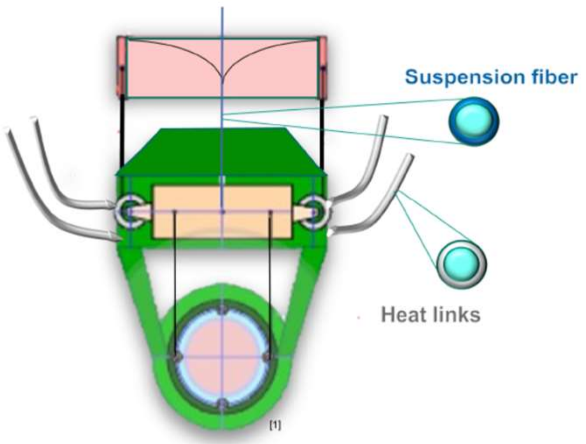


Lower thermal dissipations

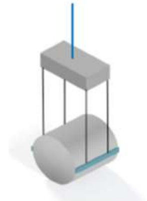
- Cryogenic temperatures
- Dissipation-free superfluid component in He-II

Integration of He-II filled capillary into payload

Karlsruhe Institute of Technology



- He-II filled capillary ($\text{Ø} \leq 3\ mm$)
- Hollow capillary as **suspension fiber**
  - Marionette
  - Mirror (?)



- Hollow capillary as external **heat links**

Source: [1] Payload design from P.Rapagnani: ET LF-Main Features and Constrains (26.04.21)

Cryogenic Session

Wednesday May 19th-20th (hour 2)

R&D's

Satoshi Tanioka (ICRR, The University of Tokyo.)
Optical loss study of the cryogenic molecular layer using a folded cavity for future gravitational-wave detectors

Luisa Spallino (LNF - INFN)
Impact on Vacuum Requirements by Cryogenically Cooled Mirrors for Gravitational Wave Detection

Marcel ter Brake, Arvi Xhahi, Harry Holland (University of Twente)
Sorption-based vibration-free cryogenic cooling for ET and ETPathFinder

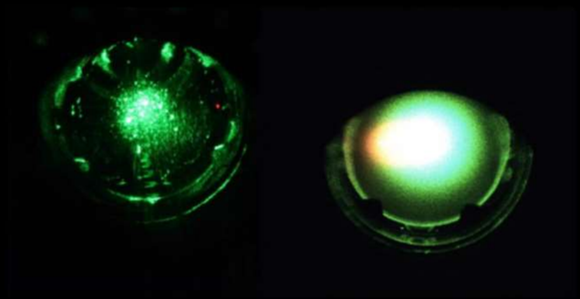
Satoshi Tanioka (ICRR, The University of Tokyo.)

Optical loss study of the cryogenic molecular layer using a folded cavity for future gravitational-wave detectors

- Future gravitational-wave detectors (GWDs) will employ cryogenically cooled test masses to improve the sensitivity.
- A cryogenic mirror in the GWD can suffer from the formation of the molecular layer on its surface.
- The optical loss induced by the molecular layer can prevent the cryogenic operation of a cryogenic GWD.

May 20, 2021 2

CML formation on KAGRA test mass



http://klog.icrr.u-tokyo.ac.jp/osl/?r=9377

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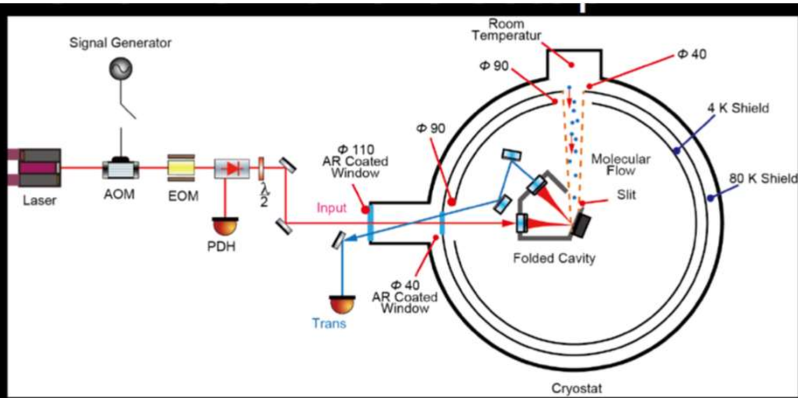
Folded cavity to characterize this effect



- ✓ The cavity is cooled down to 10 K.
- ✓ A folding mirror is exposed to the room temperature vacuum. -> CML formation

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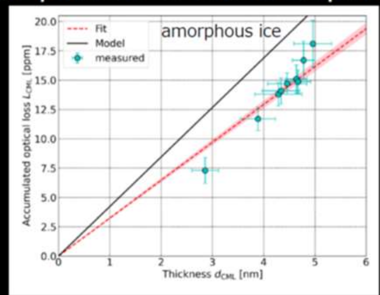
Comparison to the amorphous ice model



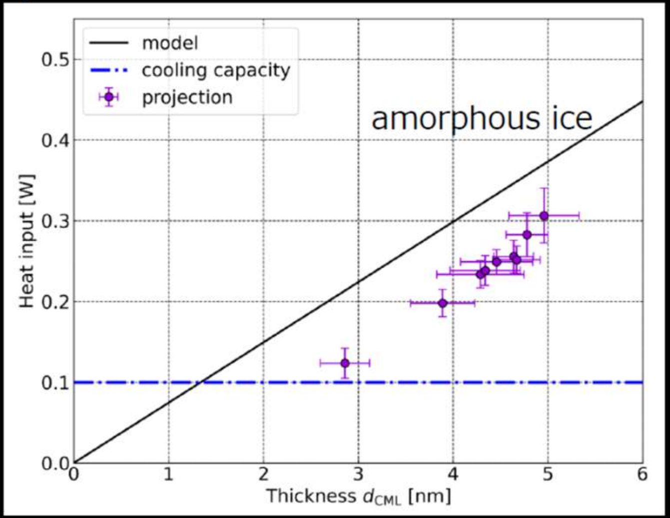
Lambert-Beer Law is assumed

$L_{CML} = 2\alpha d_{CML}$

α: absorption coefficient

- ✓ Assumed that the scattering is negligible.
- ✓ Smaller than compared to the amorphous ice model.

Implication to the ET



18 kW intra-cavity power

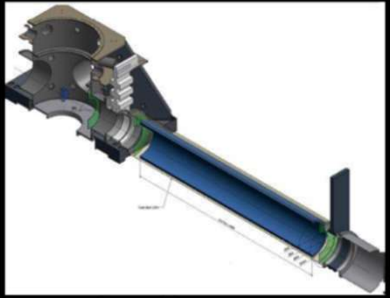
✓ The heat input induced by the CML can exceed the cooling capacity even a few nanometer thickness.

How to solve?

✓Passive way

✓better vacuum level

✓longer cryotrap

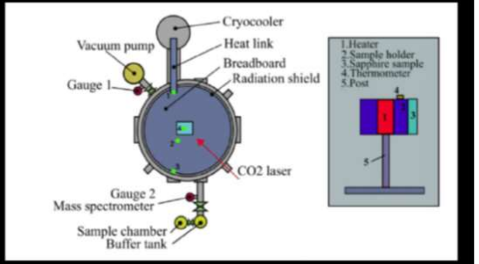


http://www.et-gw.eu/images/ET_Image_Gallery/vac6.jpg

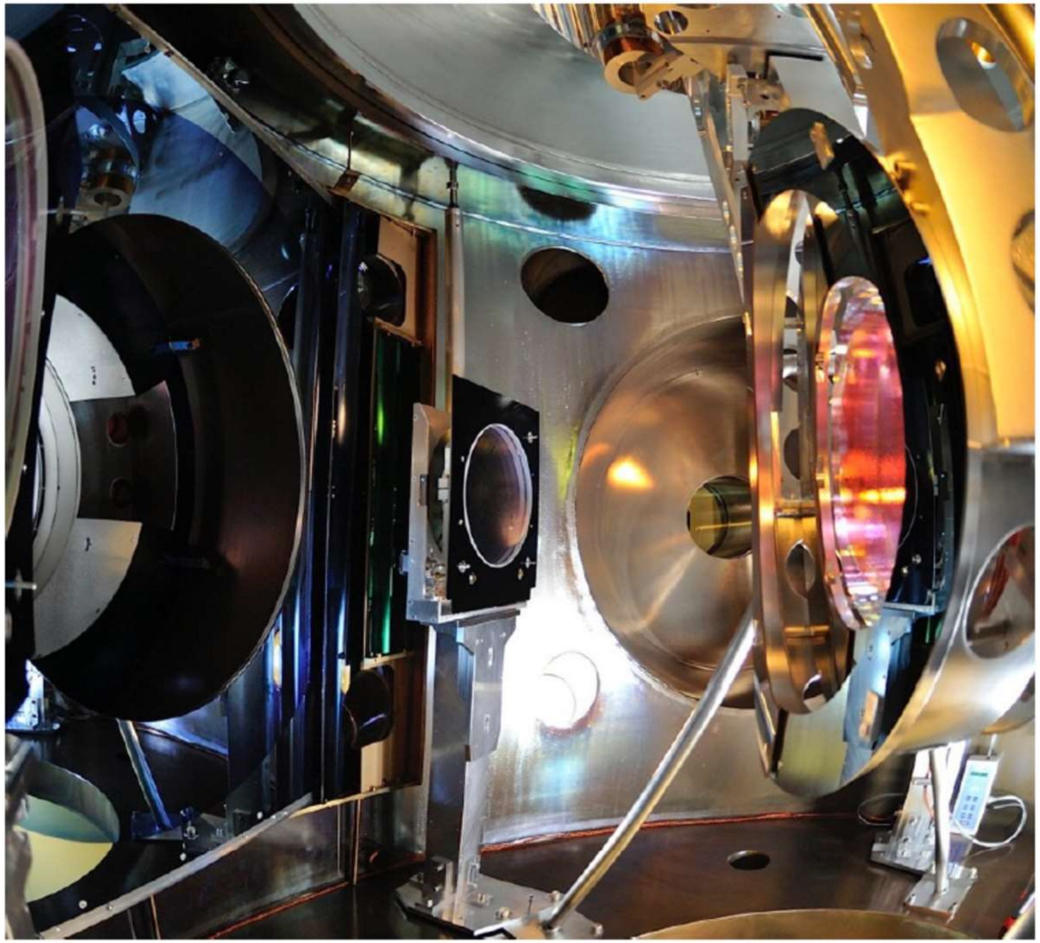
✓Active way

✓heating up the mirror

✓utilize CO_2 laser



K. Hasegawa, Ph.D Thesis (2020)



GWADW2021 Gravitational Wave Advanced Detector Workshop

Online 2021

Impact on Vacuum Requirements by Cryogenically Cooled Mirrors for Gravitational Wave Detection

L. Spallino[1], M. Angelucci[1], A. Pasqualetti[2], K. Battes[3], C. Day[3], S. Grohmann[3], E. Majorana[4], F. Ricci[4], and R. Cimino[1]

[1]Laboratori Nazionali di Frascati (LNF-INFN)
[2]European Gravitational Observatory (EGO)
[3]Karlsruhe Institute of Technology (KIT)
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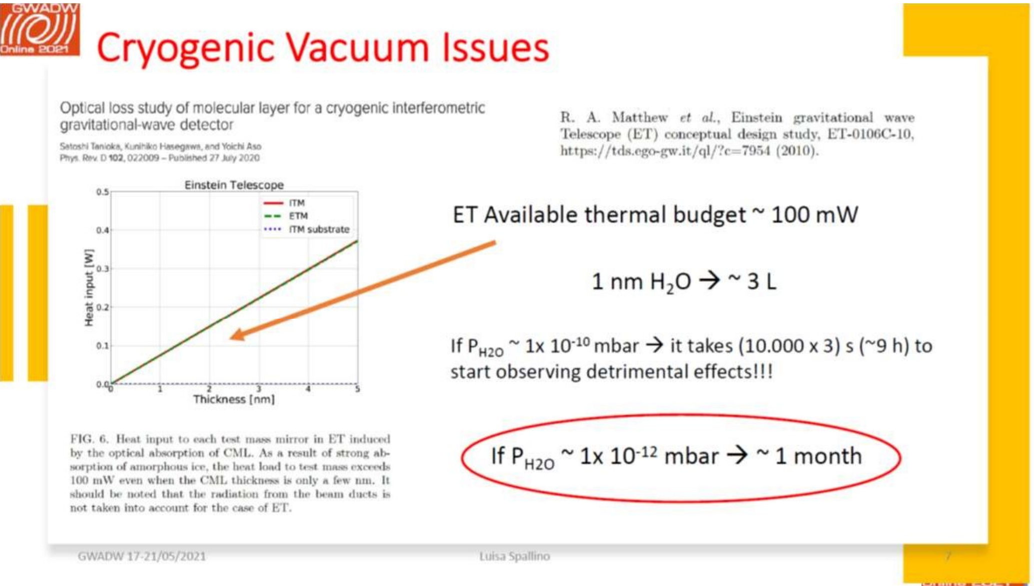
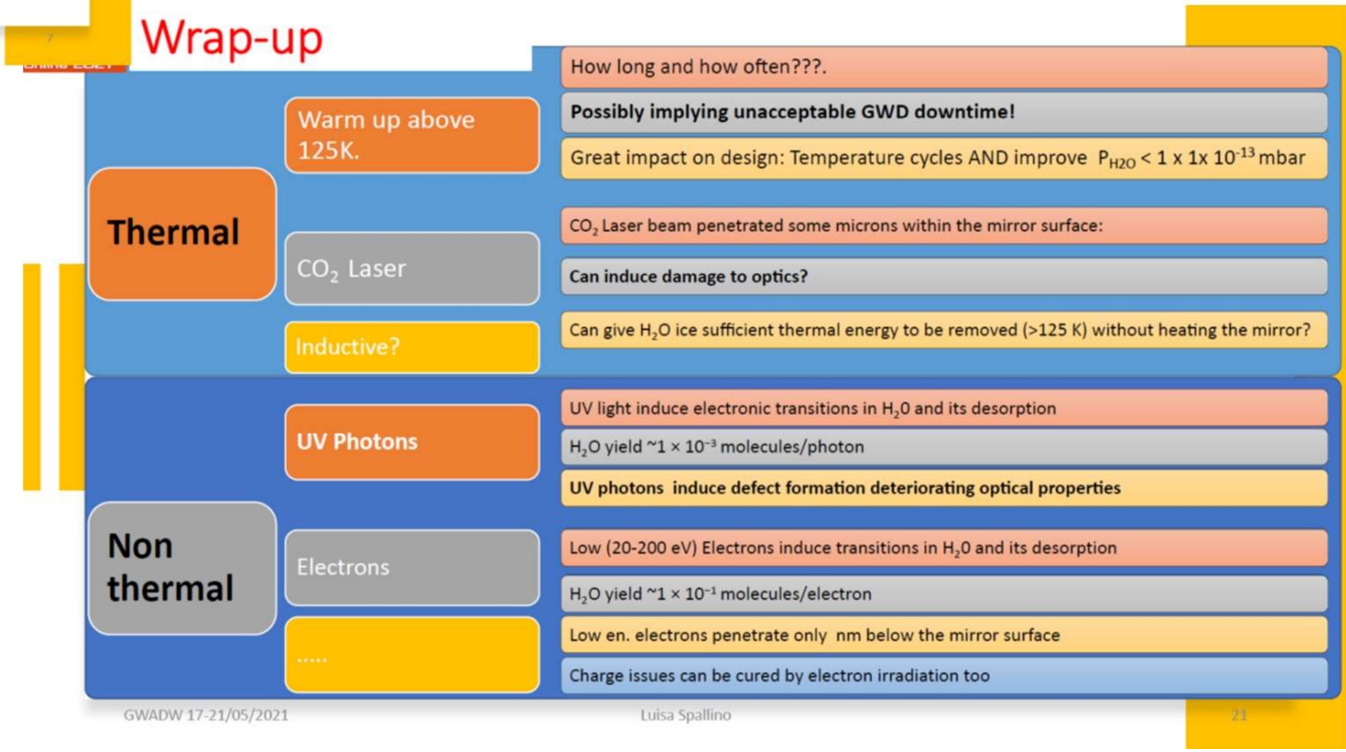
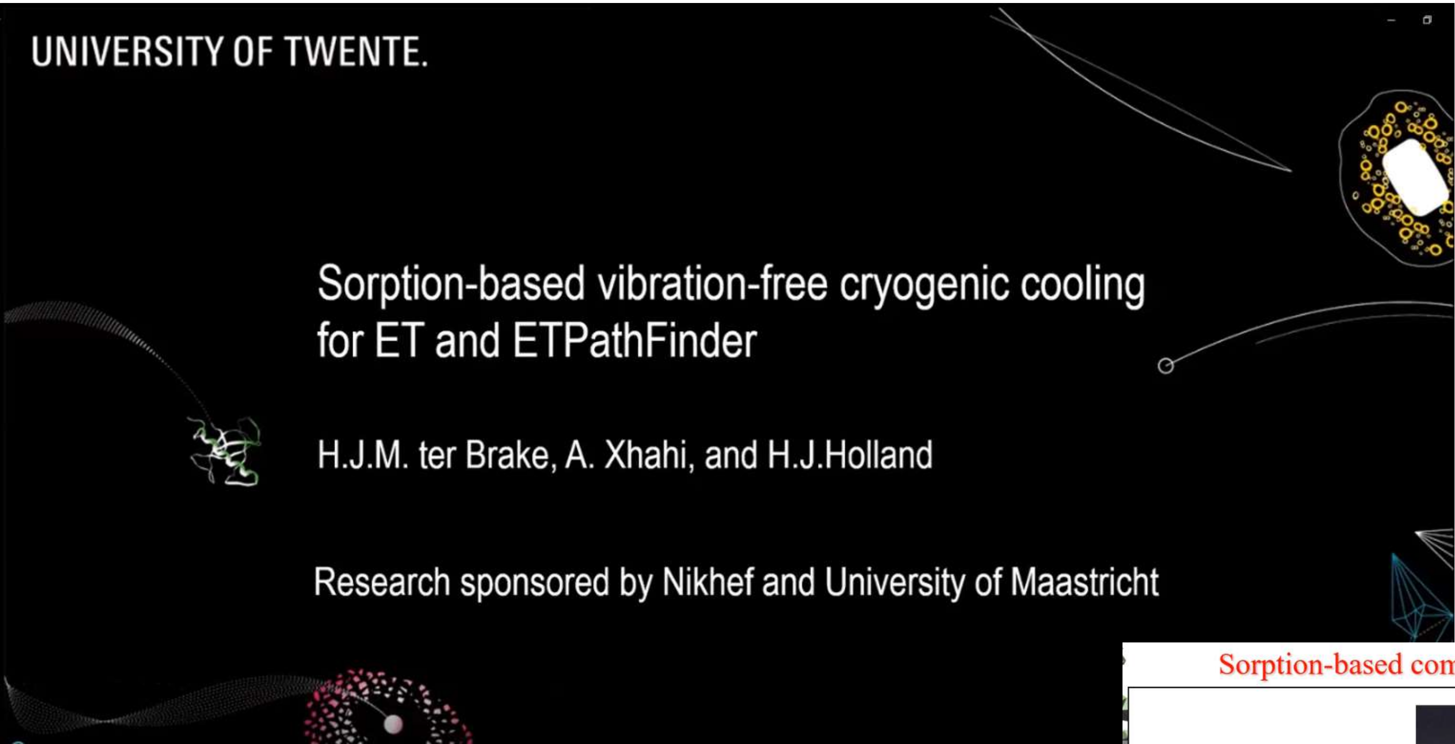
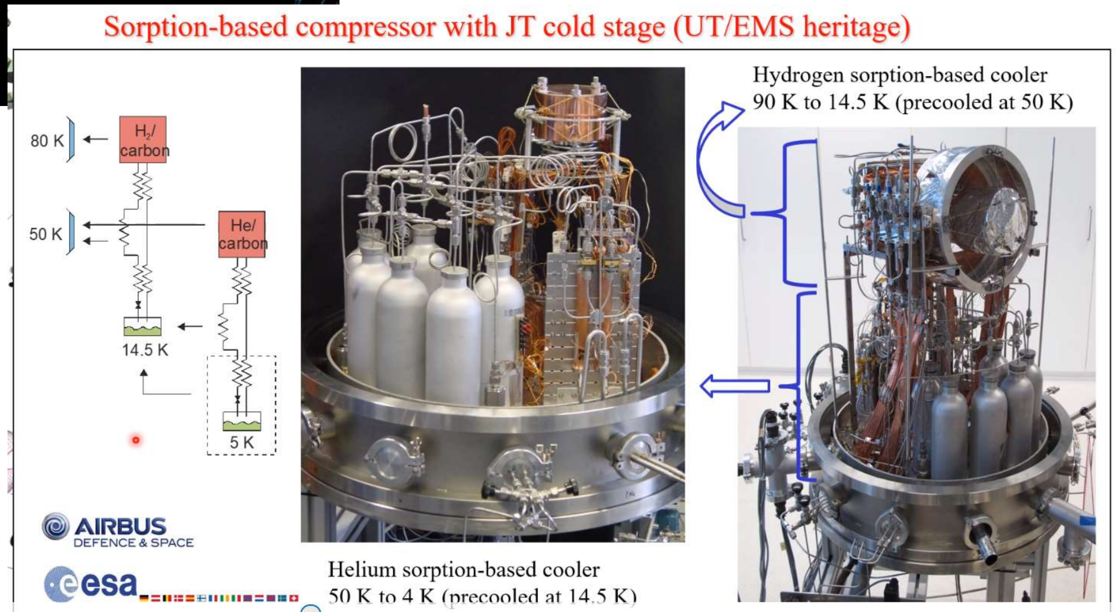


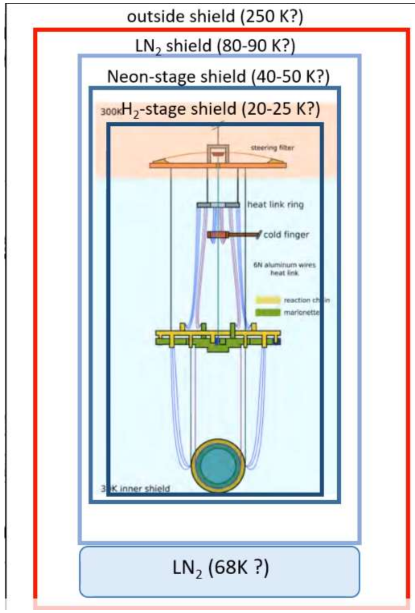
Issues on water pressure…

Mitigation strategies…..



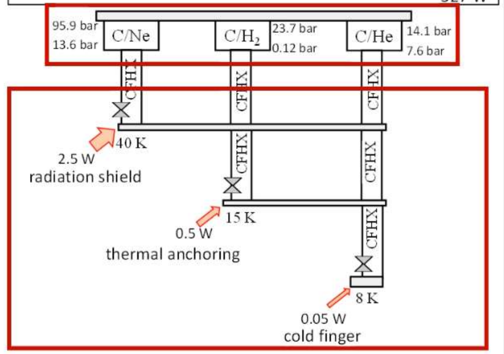

UNIVERSITY OF TWENTE.
Sorption-based vibration-free cryogenic cooling
for ET and ETPathFinder
H.J.M. ter Brake, A. Xhahi, and H.J.Holland
Research sponsored by Nikhef and University of Maastricht


Sorption-based compressor with JT cold stage (UT/EMS heritage)
80 K
50 K
H2/ carbon
He/ carbon
14.5 K
5 K
AIRBUS DEFENCE & SPACE
esa
Hydrogen sorption-based cooler
90 K to 14.5 K (precooled at 50 K)
Helium sorption-based cooler
50 K to 4 K (precooled at 14.5 K)



ELT design-based (3 stages, cold finger at 8K)

T heat sink	Ne	H_2	He	Total
80 K	25 cells 313 W	5 cells 80 W	12 cells 146 W	42 cells 63 liter 505 W
70 K	17 cells 206 W	4 cells 63 W	5 cells 58 W	26 cells 39 liter 327 W



Sorption compressor unit in separate vacuum box

Conclusions on vibration-free cooling of ETPF cold finger

- Sorption cooler chain is modular;
- Most power and largest number of cells in neon stage > prototype will be made of that stage;
- Lowering heat sink from 80 K to 70 K reduces the number of cells and the power by about 35%;
- Increasing cold finger T from 8K to 15 K (yes or no He) reduces the number of cells and the power by about 30%;

cold-finger temperature			heat-sink temperature 80 K	heat-sink temperature 70 K
	8 K	# cells	42	26
		Volume (ltr)	63	39
		Power (W)	505	327
	15 K	# cells	30	21
		Volume (ltr)	45	32
		Power (W)	382	261

Sorry no time to introduce details but 4 posters !

Mitigation of the electrostatic charge on test mass mirrors in gravitational wave detectors (Marco Angelucci, LNF-INFN)

Towards low suspension thermal noise of cryogenic torsion pendulums with crystalline fibres (Ching Pin Ooi, The University of Tokyo)

Beam suspensions for cryogenic mirrors (Riccardo DeSalvo, Università del Sannio)

Auxiliary Suspension Modelling for Glasgow Cryogenic Interferometer Facility (Victoria Graham, University of Glasgow)

We thank all the speakers!