Status of KAGRA cryogenic suspension

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the New WindowS on the Universe project (NEWS)
General Meeting 2018
@INFN Pisa, Pisa, Italy

Abstract

Current status of KAGRA cryogenic suspension (Especially, sapphire parts)

In past, what did we for cryogenic suspension (under collaboration with Europe) ?

In future, what will we do to improve gravitational wave detector (3rd generation)?

Contents

1. KAGRA
2. Thermal noise
3. R&D in past
4. R&D in future
5. Summary

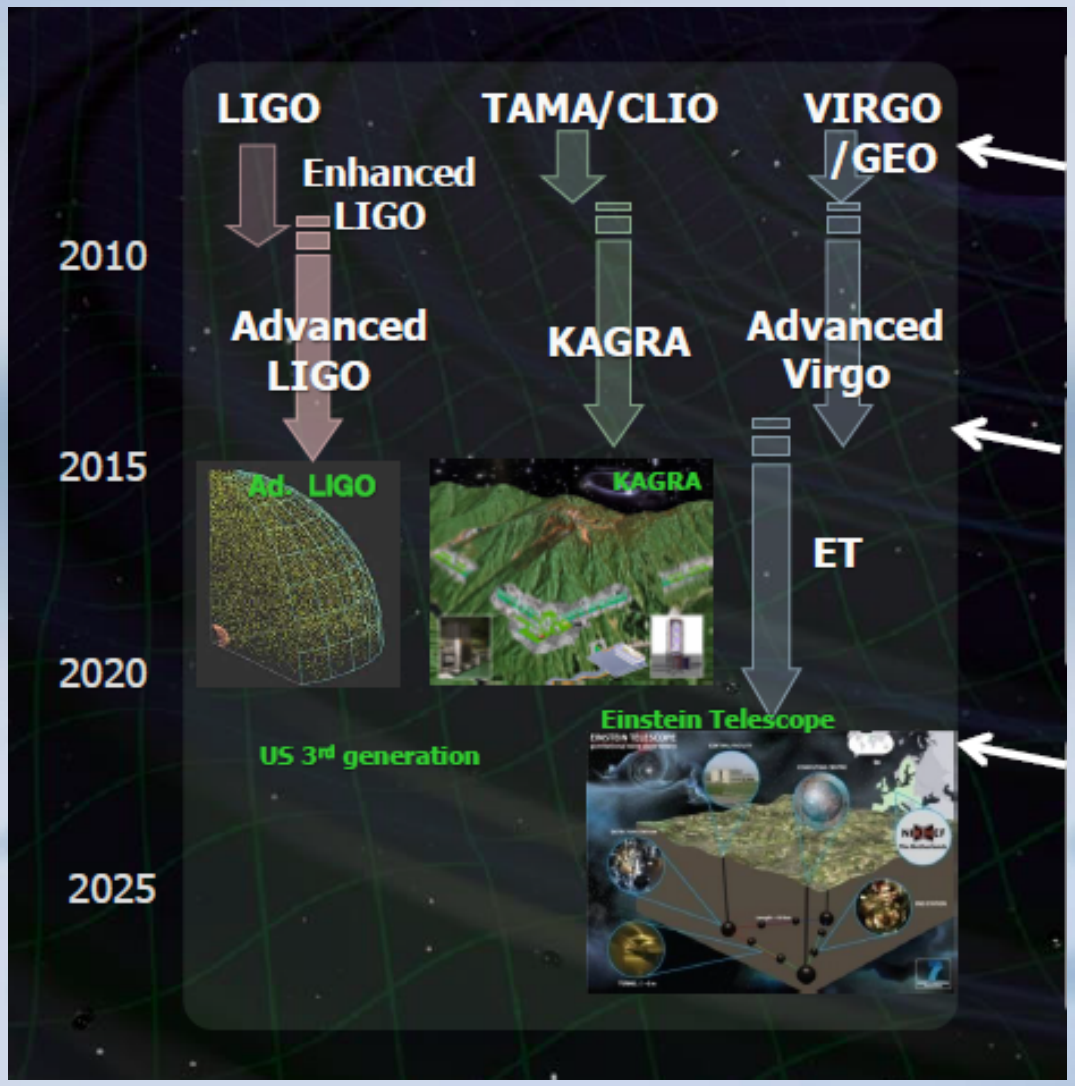
1.KAGRA

KAGRA : 2nd generation gravitational wave detector as like LIGO and Virgo

1.KAGRA

苔山　圭以子、重力波検出器の開発と重力波天文学
（大阪大学電気工学特別講義　2016年6月28日）

1.KAGRA



1st generation : No detection

2nd generation : First detection !

3rd generation : 10 times better sensitivity
NEWS target

安東正樹　重力波望遠鏡KAGRAで見る新しい宇宙の姿
（東大物理学教室談話会　2013年5月31日）

1.KAGRA

Two unique key feature of KAGRA
(1) Underground site with small seismic motion
(2) Cooled mirror and its suspension
to reduce thermal noise (main topic in this talk)
-> 3rd generation adopts these idea.

1.KAGRA

KAGRA is at Kamioka mine, Japan.
About 200km west of Tokyo.

In this mine, there are many facilities for scientific research.

1.KAGRA

KAGRA is at Kamioka mine, Japan.
About 200km west of Tokyo.

In this mine, there are many facilities for scientific research.
Most famous group is neutrino (Kamiokande and SuperKamiokande) because they won Nobel prizes at twice !

Masatoshi Koshiba
Prize share: 1/4

Neutrino astronomy

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

Neutrino oscillation

1.KAGRA

Interferometric gravitational wave detector

Mirrors must be free and are suspended.

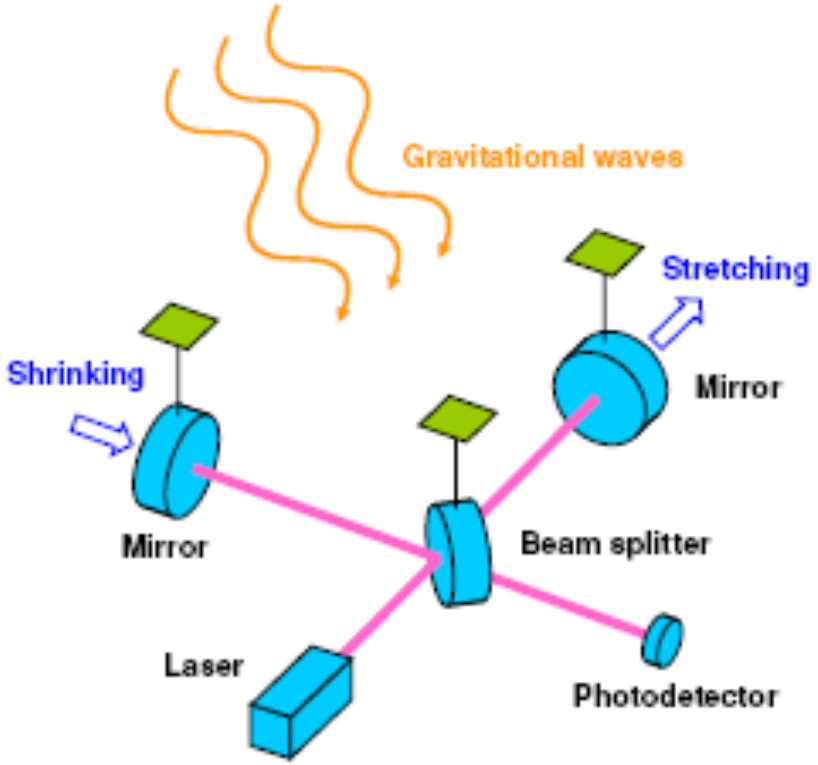
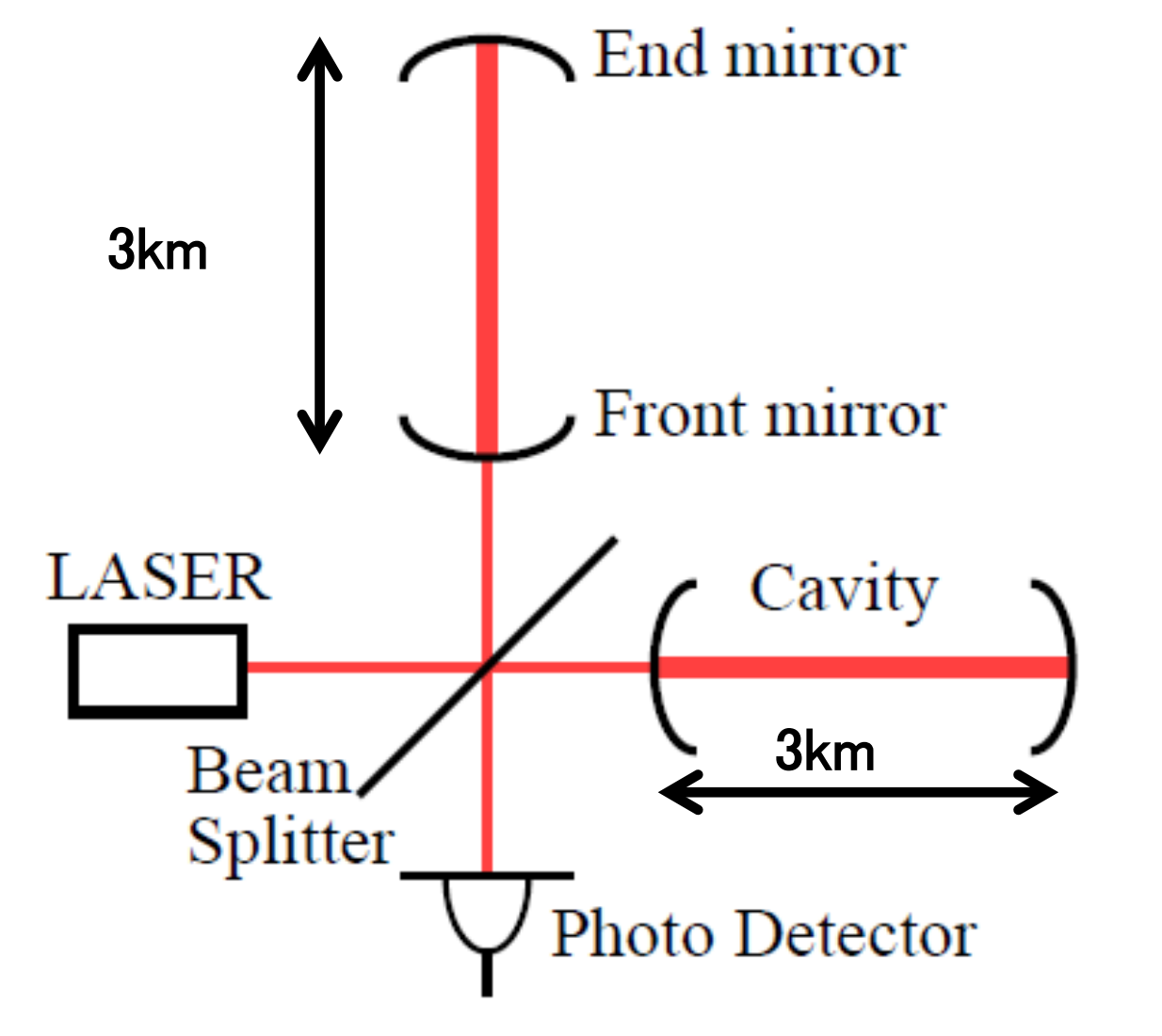


Figure 1. Michelson laser interferometer with suspended mirrors for the detection of gravitational waves.

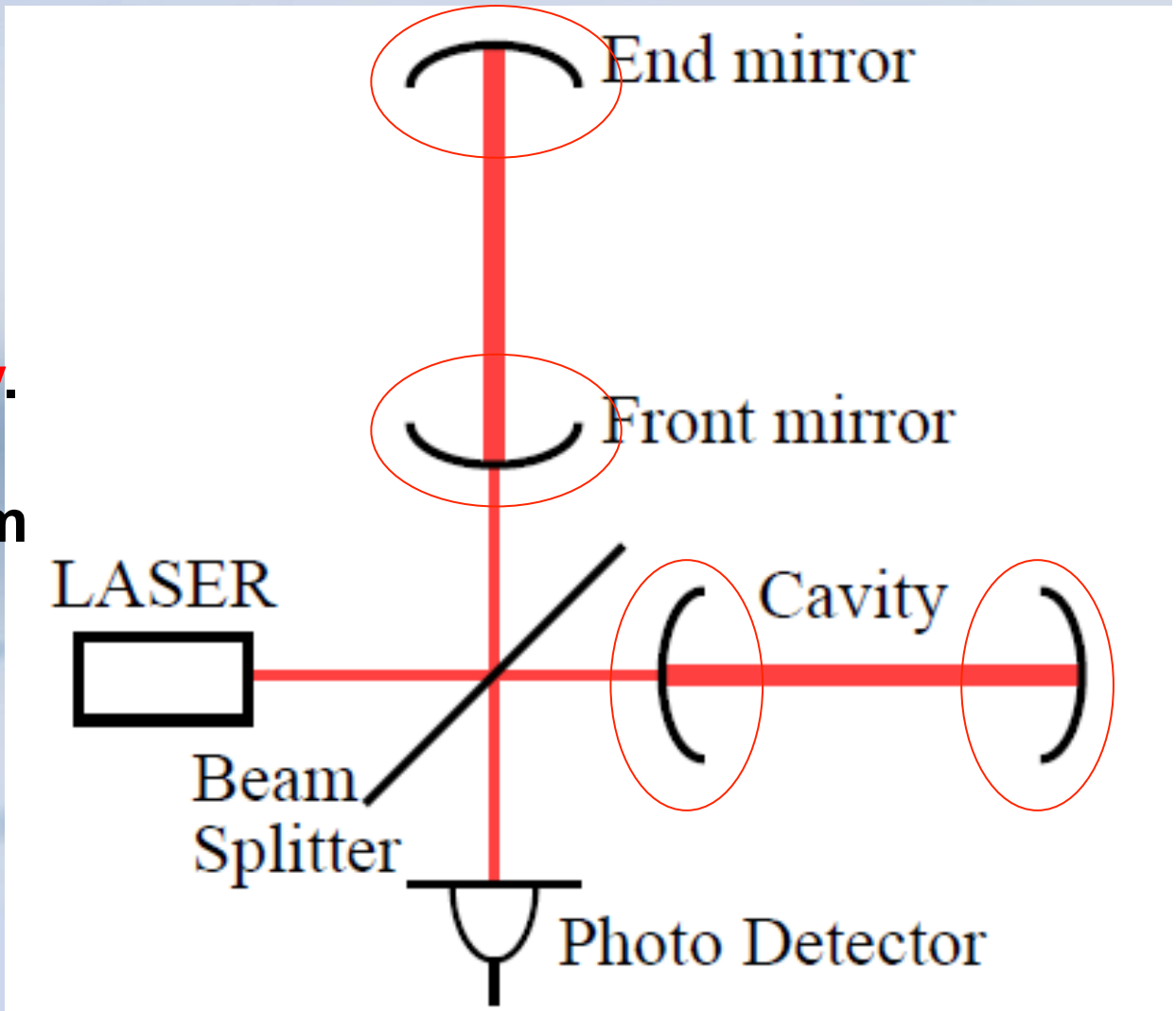
S. Kawamura, Classical and Quantum Gravity 27 (2010) 084001.

1.KAGRA


End mirror
3km
Front mirror
LASER
Cavity
3km
Beam
Splitter
Photo Detector

1.KAGRA

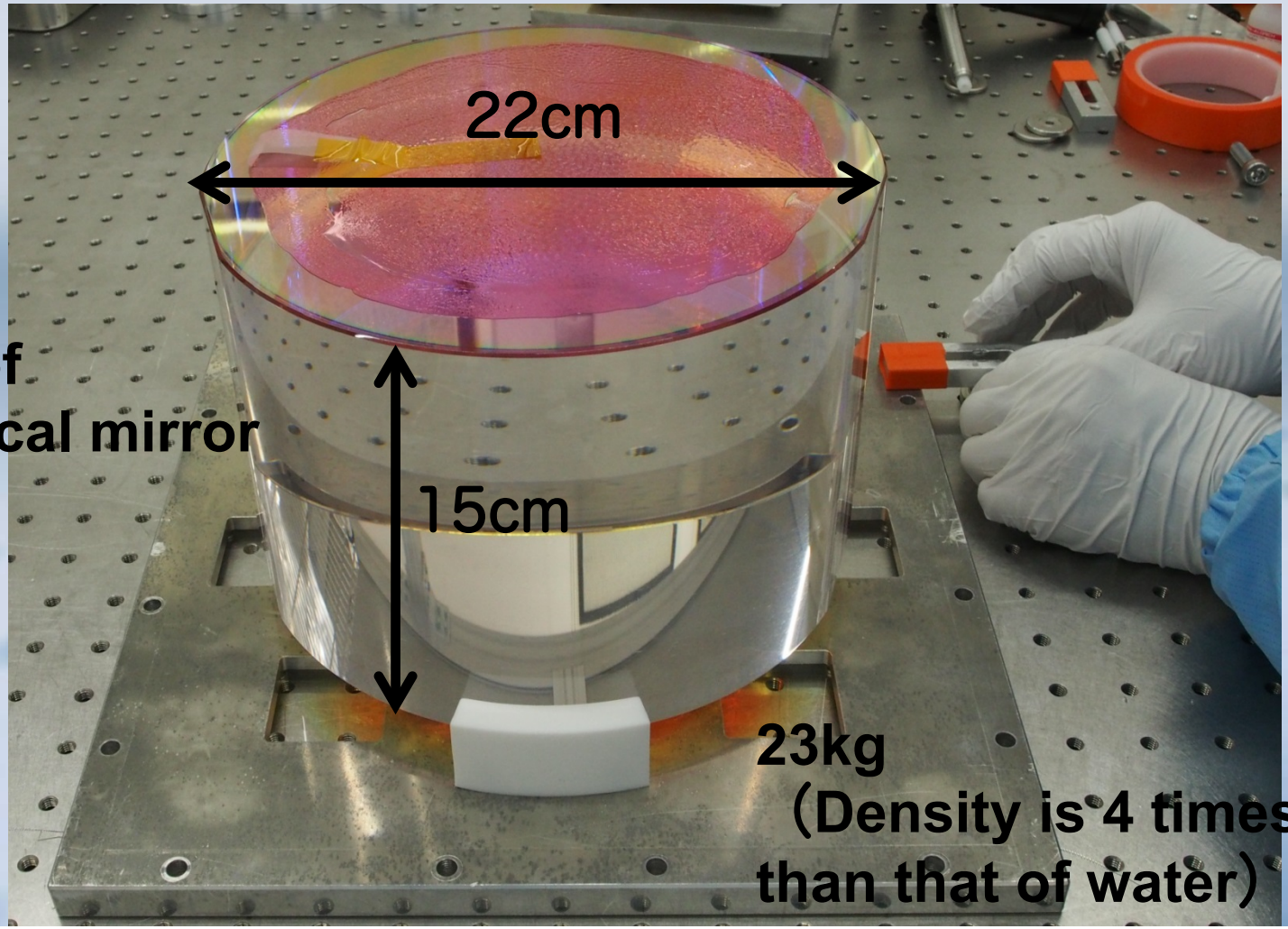
In order to sensitivity, Fabry-Perot cavities are installed in both arms.
Four (not two !) mirrors are necessary.
These four mirrors in KAGRA are made from sapphire.
These sapphire mirrors are cooled down (about 20K).



1.KAGRA

2 extra sapphire mirrors and 2 practical sapphire mirrors have already been delivered. Other 2 practical mirrors will be delivered in 2018.

Photo of
a practical mirror

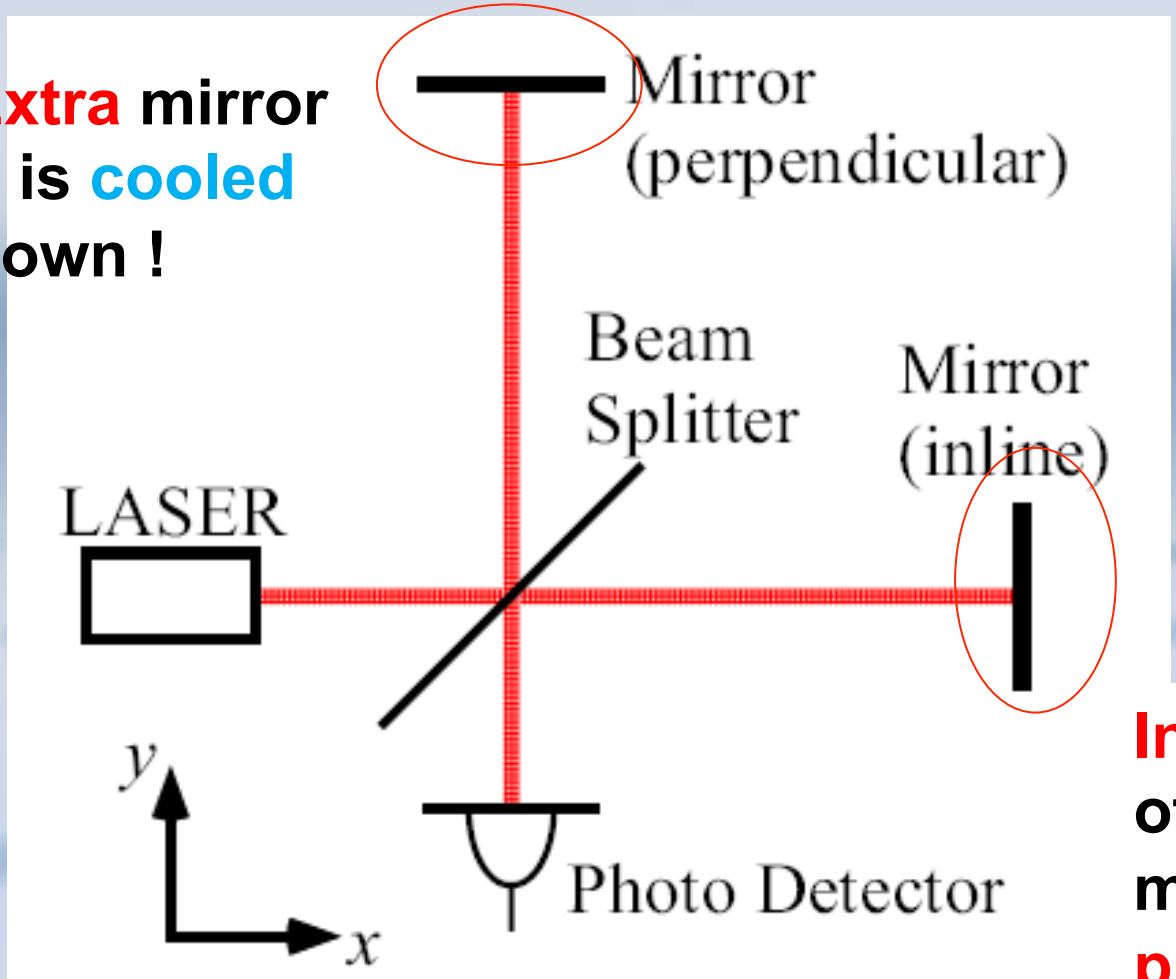


23kg
(Density is 4 times larger than that of water)

1.KAGRA

2018 spring：Test run of cryogenic simple Michelson interferometer(with 2 sapphire mirrors)

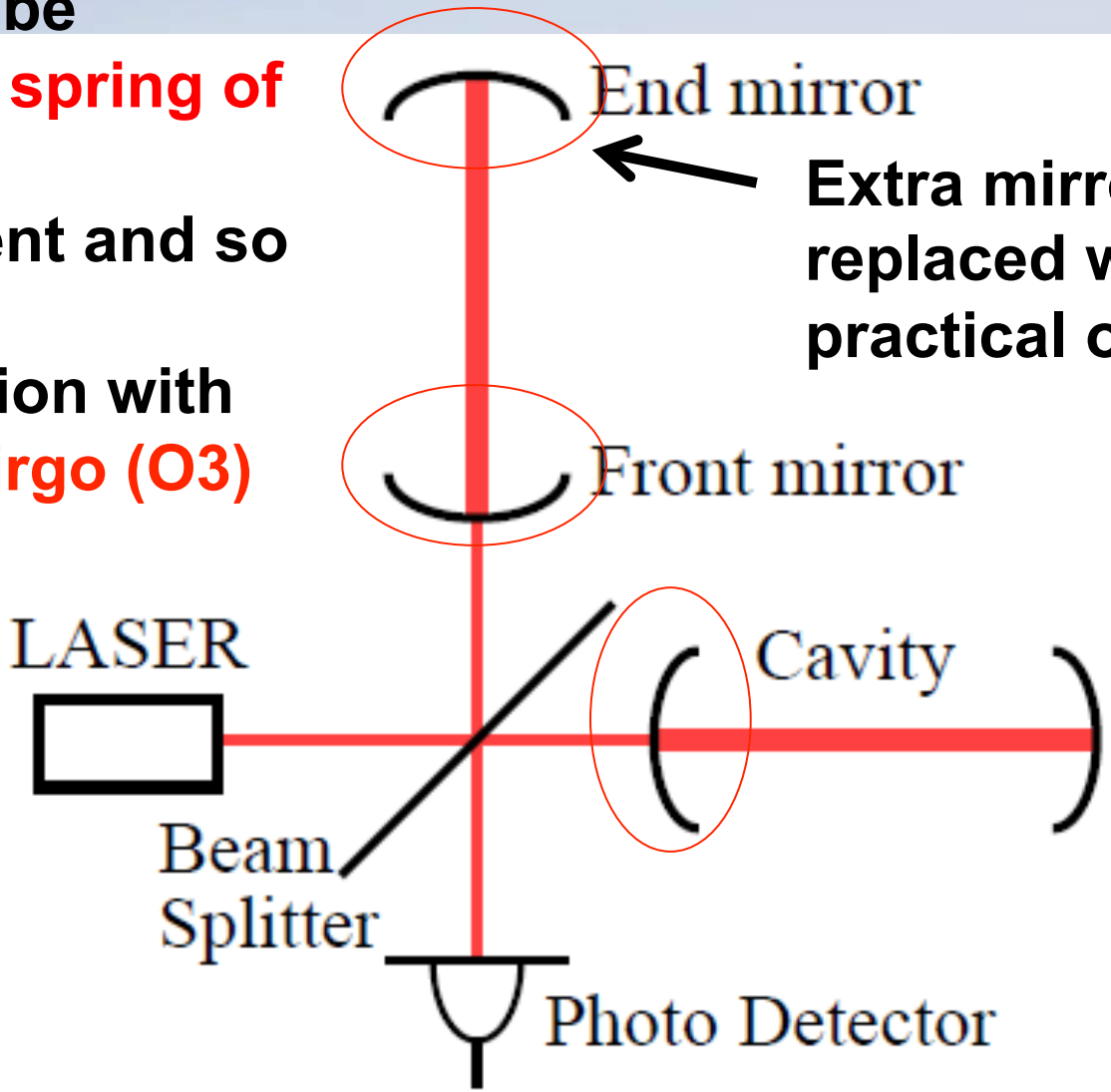
Extra mirror
It is cooled down !



Installation of practical mirror is in progress.

1.KAGRA

Other three practical mirrors will be installed by spring of 2019.
-> Adjustment and so on.
-> Observation with LIGO and Virgo (O3)



1.KAGRA

First practical sapphire mirror was transported to KAGRA site on 9th of March 2018 (Friday of last week !).
On 8th of March, this mirror in clean room in University of Toyama was shown to mass media.
Almost all main newspapers and televisions came.

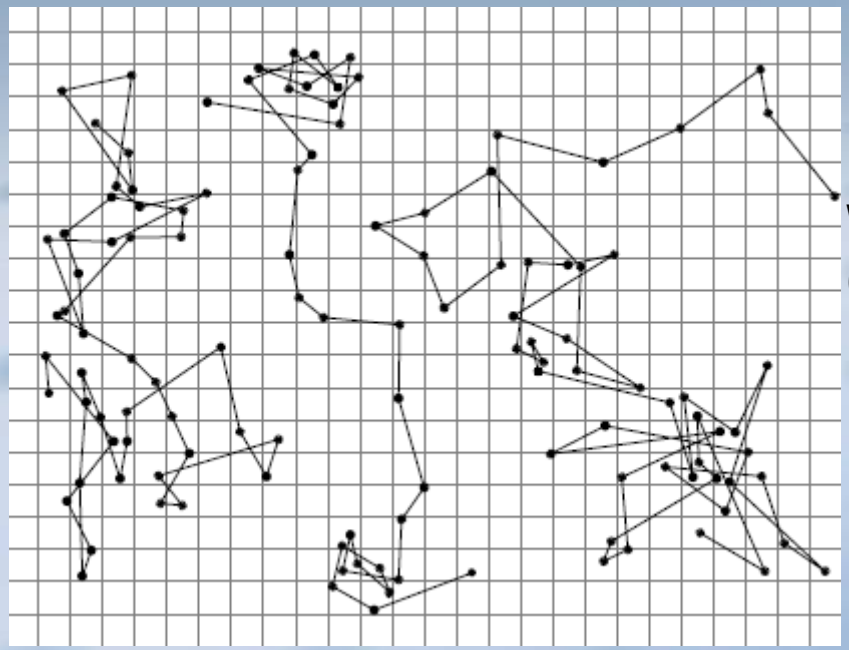
https://www.u-toyama.ac.jp/education/news/2018/0312a.html

https://www.jiji.com/jc/article?k=2018030801061&g=soc

2. Thermal noise

Thermal noise : Fluctuation by random energy flow from heat bath

Most famous example
Robert Brown : Random motion of small particles whose diameter is around 1 μm in water
R. Brown, Philosophical Magazine 4 (1828) 161.



Wikipedia (Brown motion, English)

2. Thermal noise

Theory of Brownian motion:
A. Einstein, Annalen der Physik 17 (1905) 549.

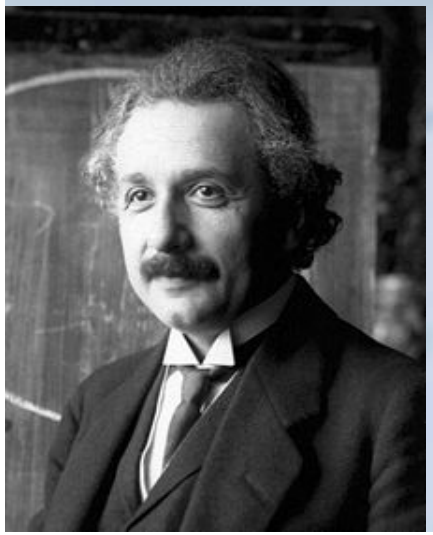
Brownian motion is proportional to temperature.
Viscosity of water causes Brownian motion.

Diffusion of small particles (Brownian motion)

Temperature

$$D = \frac{RT}{N}\frac{1}{6\pi\eta a}$$

viscosity



Wikipedia (A. Einstein, English)

2. Thermal noise

General theorem of thermal noise

Fluctuation-Dissipation Theorem (FDT)

H.B. Callen and R.F. Greene, Physical Review 86 (1952) 702.
R.F. Greene and H.B. Callen, Physical Review 88 (1952) 1387.

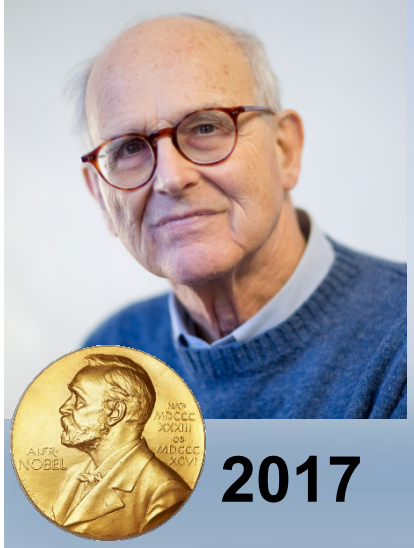
Temperature

$$G(f) = -\frac{4k_{\mathrm{B}}T}{\omega}\mathrm{Im}[H(\omega)]$$

Power spectrum of thermal fluctuation

Imaginary part of susceptibility (dissipation)

2.Thermal noise



2017

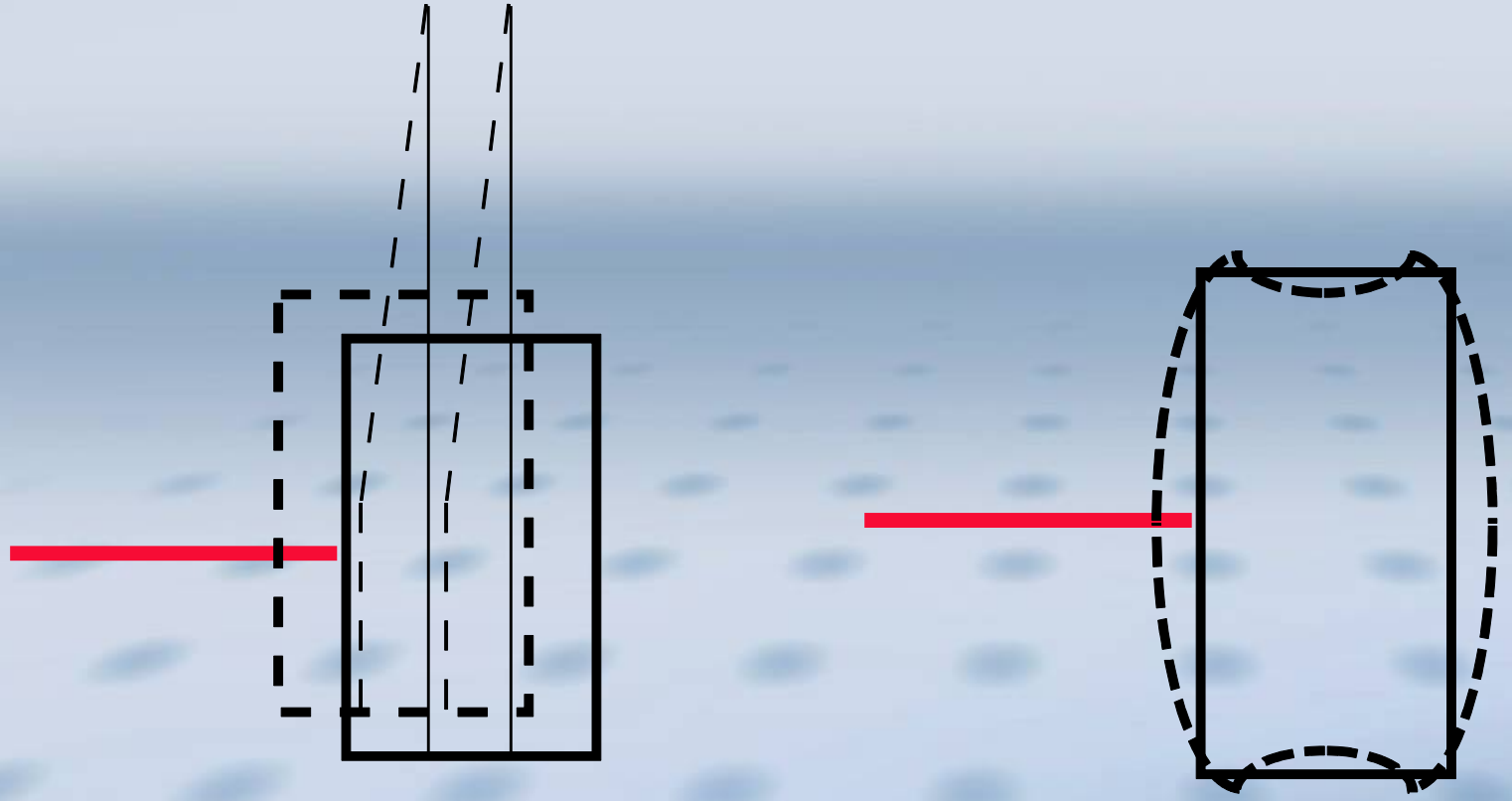
Rainer Weiss, Quarterly Progress Report of Research Laboratory of Electronics of the Massachusetts Institute of Technology 105(1972)54. https://dcc.ligo.org/P720002/public

First feasibility study of interferometric gravitational wave detector

He evaluated many kinds of noise sources. Thermal noise is one of them. His concludes as follows;
Thermal noise can be minimized when we adopt **material with small mechanical dissipation**, aside from **reducing the temperature**.

2. Thermal noise

Thermal noise of suspension and mirror



2. Thermal noise

LIGO and Virgo

Fused silica mirror suspended by fused silica fibers.

Fused silica has not only excellent optical properties but also small dissipation.

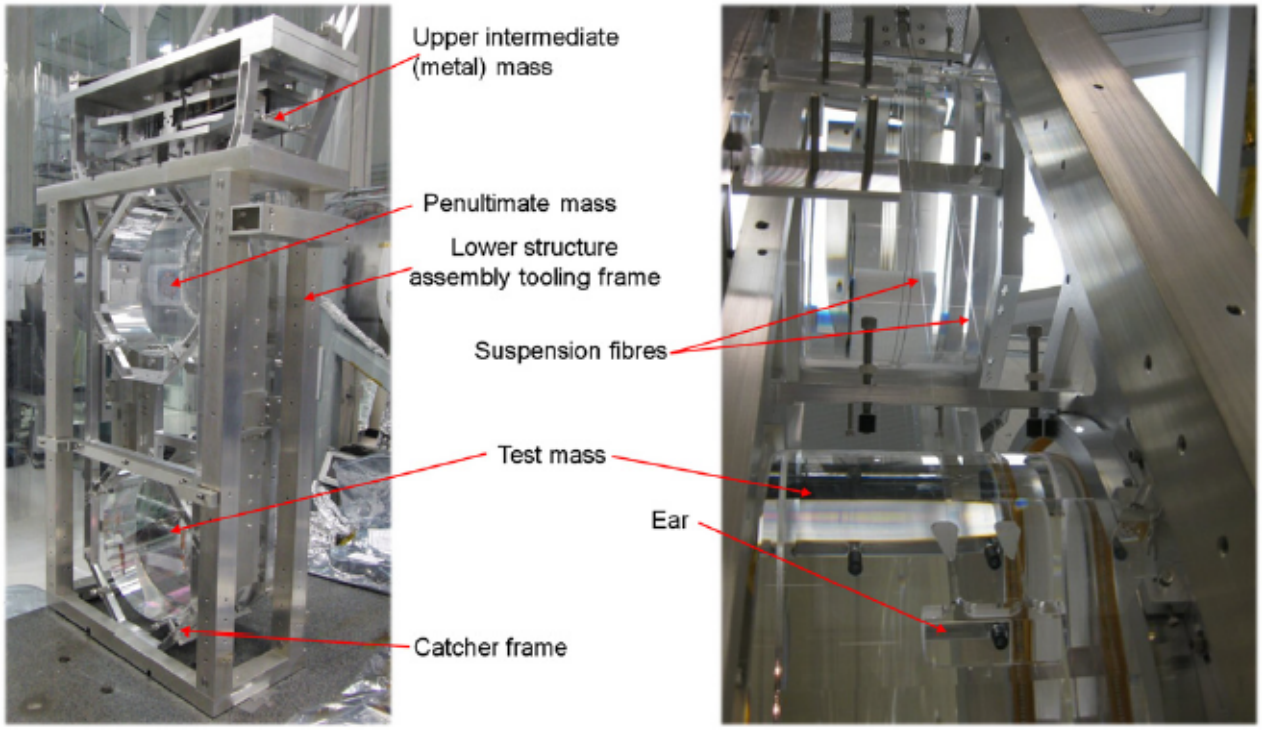


Figure 6. (*a*) Completed monolithic lower stage prototype at the LIGO LASTI test facility, MIT. (*b*) Upward side view of monolithic stage masses showing suspension fibres and attachment ears.

2.Thermal noise

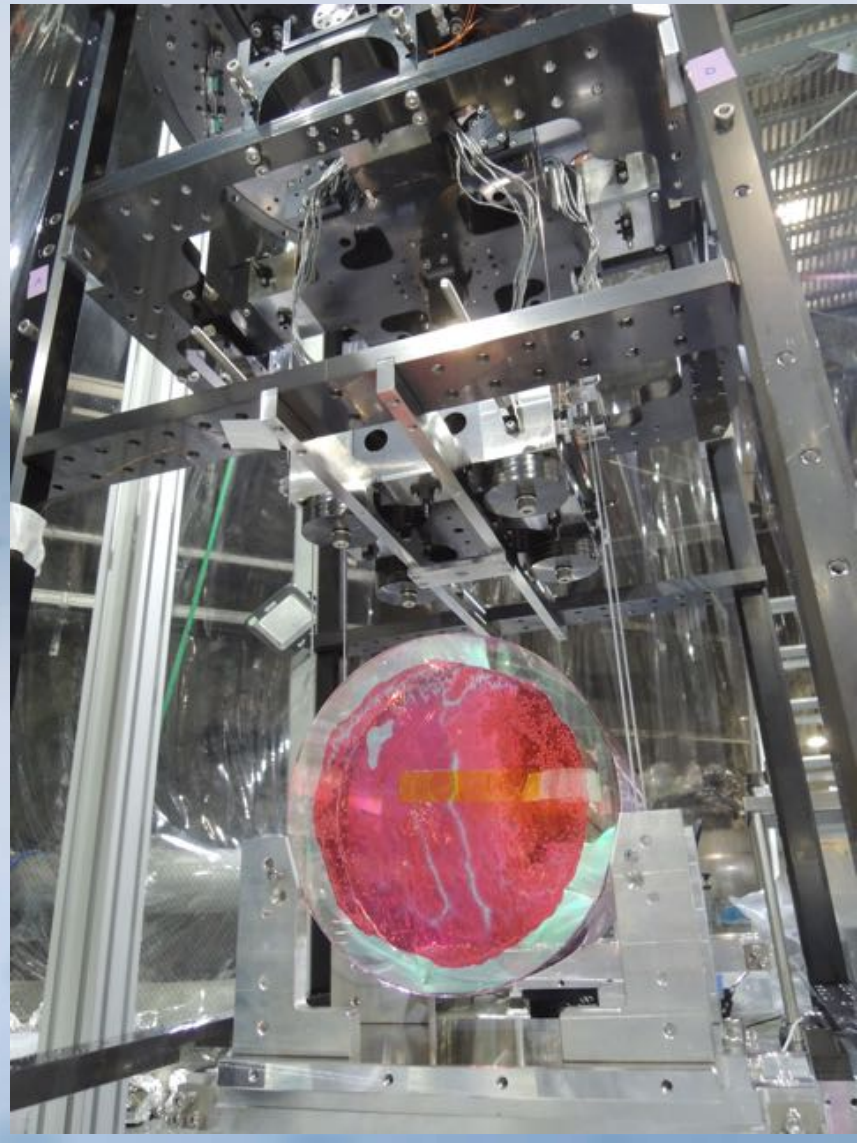
KAGRA

Sapphire mirror suspended by sapphire fibers.

Fused silica has huge mechanical dissipation at low temperature.

Sapphire has smaller dissipation at lower temperature.

Since thermal conductivity of sapphire at low temperature is large, sapphire fibers work as heat path.



3.R&D in past

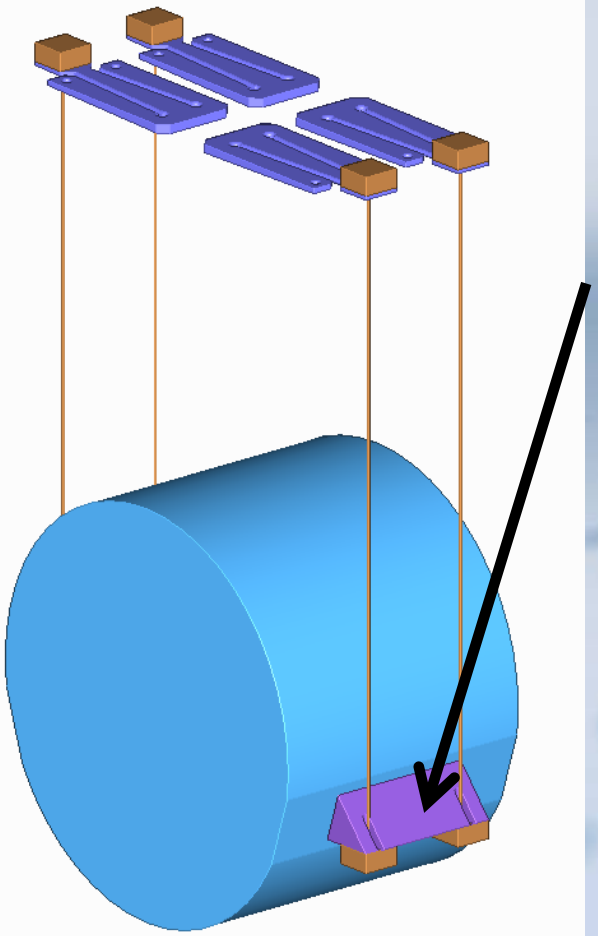
ELiTES: ET-LCGT interferometric Telescope Exchange of Scientists

Grant for collaboration about cryogenic between KAGRA and ET

European 7th Framework Programme
Marie Curie action (Mar. 2012 - Feb. 2017)
Researcher in Europe can visit Japan for KAGRA.
They support development of KAGRA.
Here, I introduce details of one example;
HCB between sapphire mirror and ears.

3.R&D in past

Sapphire suspension :



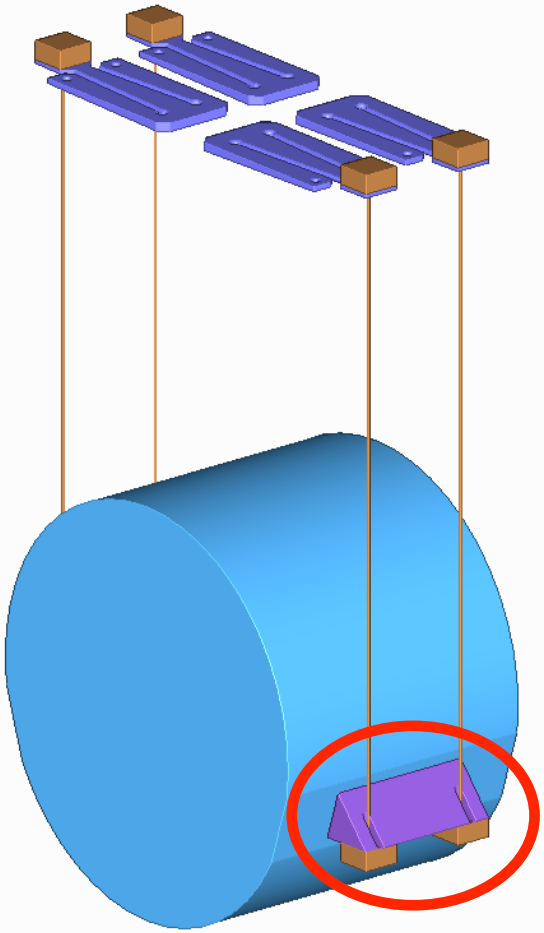
Connection between mirror and fibers is crucial point.

KAGRA adopts sapphire ears for this connection.

Connection between mirror and ears must be strong.
Hydroxide Catalysis Bonding (HCB) is adopted. This bonding is based on chemical reaction.

3.R&D in past

Sapphire suspension :

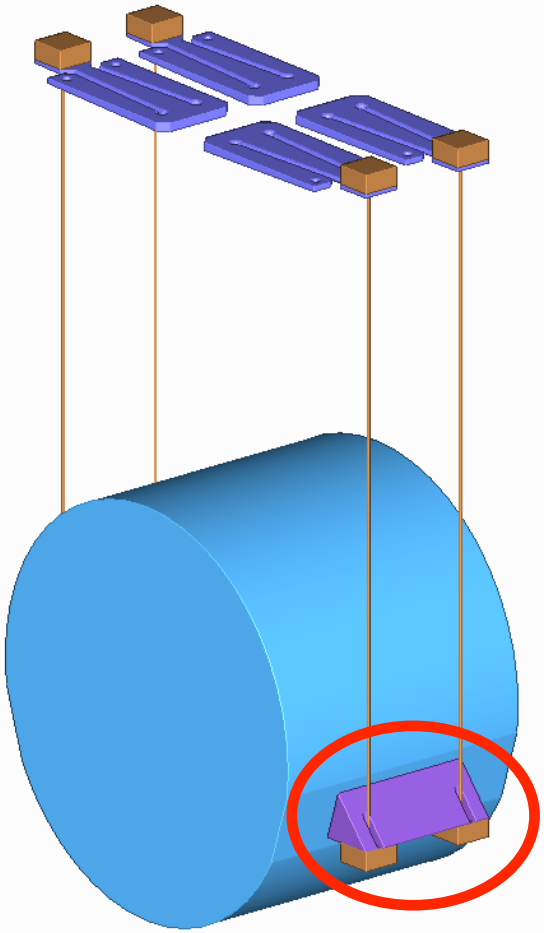


HCB is also used in LIGO and Virgo between fused silica mirror and fused silica ears. So, HCB works well between fused silica at room temperature.

However, we were not sure that HCB works well in KAGRA (between sapphire mirror and ears at cryogenic temperature). This topic was investigated under ELiTES.

3.R&D in past

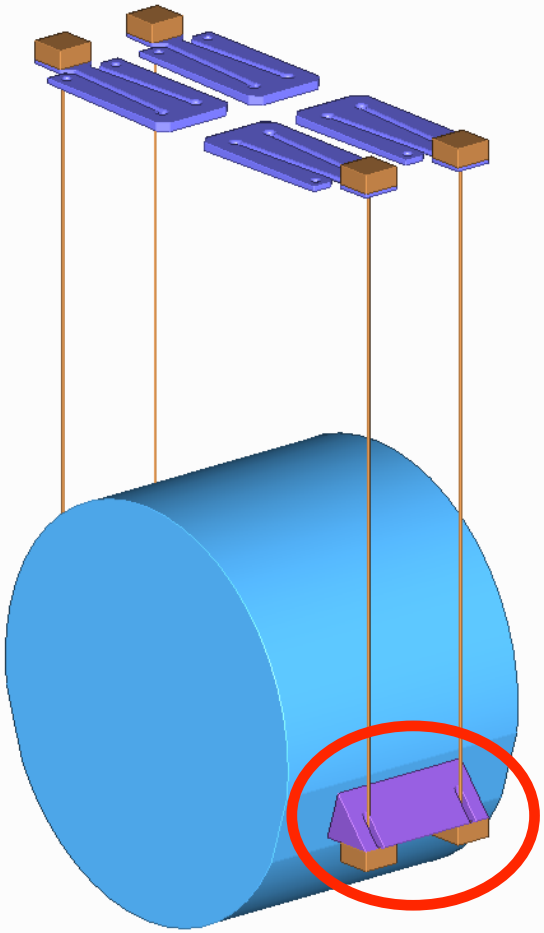
Sapphire suspension :



First of all, University of Glasgow, which is charge of HCB in LIGO, kindly taught details of HCB.

3.R&D in past

Sapphire suspension :



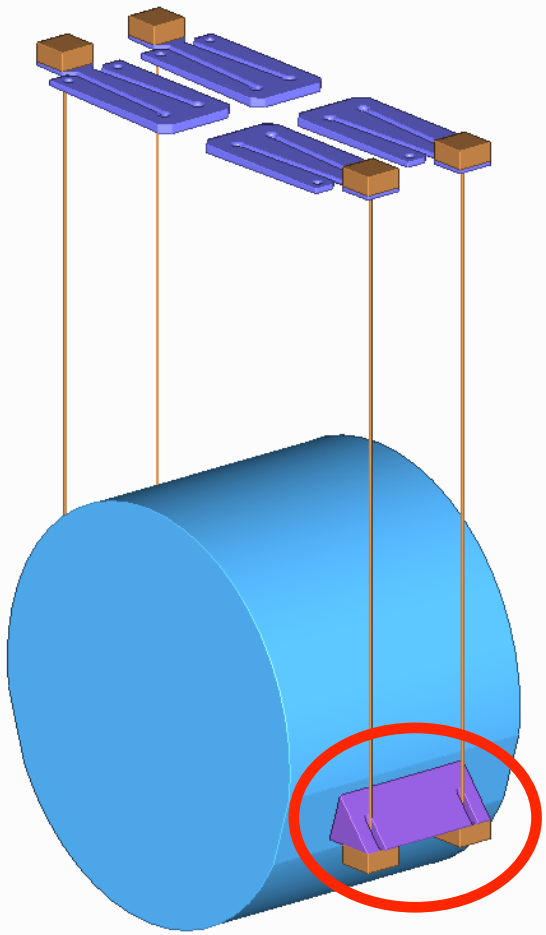
(1)Strength between sapphire parts is enough large at low temperature.

Conclusion
It is enough strong to support sapphire mirror (23kg) even at cryogenic temperature.

K. Haughian et al., Classical and Quantum Gravity 32 (2015) 075013.

3.R&D in past

Sapphire suspension :

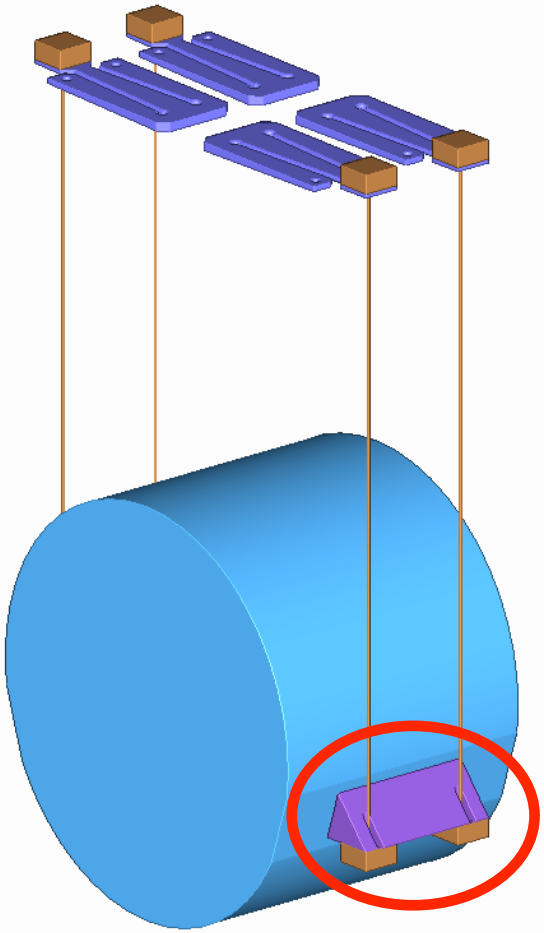


(2) Thermal resistance of HCB

Conclusion
Thermal resistance is enough small at cryogenic temperature.
Mirror temperature can be around 20K.
D. Chen, Ph.D. thesis (2015, The University of Tokyo)
(supported by Friedrich-Schiller-Universitaet Jena)
https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=5622

3.R&D in past

Sapphire suspension :



(3) Mechanical dissipation (contribution to thermal noise) is small.

Conclusion
Thermal noise by HCB is smaller than goal sensitivity.

K. Haughian *et al.*, Physical Review D 94 (2016) 082003.

3.R&D in past

Sapphire suspension :

Our investigation revealed that HCB is appropriate for KAGRA.

Next problem is how to apply to practical mirror and ears. KAGRA adopts method developed by Virgo ;Box.

Università degli Studi di Perugia supports to develop box.

3.R&D in past

First cryogenic payload with sapphire (extra) mirror was installed !

3.R&D in past

Other topics of ELiTES from refereed journal papers

Indium bonding between ears and fibers

G. Hofmann et al., Classical and Quantum Gravity 32(2015)245013.

Sapphire fiber thermal conductivity

A. Khalaidovski et al.,
Classical and Quantum Gravity 31 (2014) 105004.

Mechanical loss of coating at cryogenic temperature

E. Hirose et al.,
Physical Review D 90(2014) 102004.

3.R&D in past

Other topics of ELiTES from refereed journal papers

Investigation about vibration of radiation shield

F. Frasconi et al.,
Meas. Sci. Technol. 25 (2014) 015103.

D. Chen et al.,
Classical and Quantum Gravity 31(2014) 224001.

3.R&D in past

European members of ELiTES

France : LMA Lyon

Germany: Hannover, Jena

Italy: Rome, Sannio

Netherlands: NIKHEF

United Kingdom: Glasgow,
University of West Scotland

4. R&D in future

Most important message in this talk

KAGRA wins Core to Core program (JSPS) !
It can be a counter part of NEWS.

April 2018 - March 2023
Estimated amount : 18,000,000 yen (140,000Euro) per year.

This grant will support communication fees in many conferences, workshops, seminars and short term student's staying in several universities, institutes and sites.

Fee to organize workshops and seminars can be supported. As like ELiTES, we can organize workshop every year if necessary. It is discussion item.

4. R&D in future

Partner universities and institutes for Core to Core program

USA : Caltech (core institute) and collaborating Univs.
UK : Glasgow Univ. (core institute) and collaborating Univs.
Germany : MPQ (core institute)
Italy : EGO (core institute) and collaborating Univs.
Australia : UWA (core institute) and collaborating Univs.
France : CNRN (core institute)
Korea : Sogang Univ. (core institute) and Collaborating Univs.
India : IUCAA (core institute) and collaborating Univs.
China : BNU (core institute) and collaborating Univs.
Taiwan : NTU (core institute)
Vietnam : HNUE (core institute)
Netherland : Nikhef from maybe mid-FY2018 or FY2019.

4. R&D in future

KAGRA wins Core to Core program (JSPS) !
It can be a counter part of NEWS.

Main members (especially, for Europe and U.S.A.)
of organization of this program

Chief : Shinji Miyoki
(Institute for Cosmic Ray Research, The University of Tokyo)
For Europe (thermal noise) : Kentaro Somiya
(Tokyo Institute of Technology)
For Europe (cryogenics) : Takayuki Tomaru
(KEK, High Energy Accelerator Research Organization)
For U.S.A. : Yoichi Aso
(National Astronomical Observatory of Japan)

4. R&D in future

KAGRA wins Core to Core program (JSPS) !
It can be a counter part of NEWS.

OK, what will we do exactly in research ?
3rd generation is target.

Here I show my personal list about cryogenics.
This is not perfect one. But I expect to stimulate discussion.

4. R&D in future

R&D item list

(1)Huge mirror to reduce radiation pressure noise
(2)Small absorption (heat load) mirror to reduce thermal noise
(3)Reflective coating with small mechanical dissipation to reduce mirror thermal noise
(4)Fiber investigation to reduce suspension thermal noise
(5)Improvement of bonding
(6)Vibrations isolation of heat link to reduce external vibration effect
(7)Cryocooler with small vibration
(8)Shorter initial cooling (warming up) time
(9)Mirror contamination problem

4. R&D in future

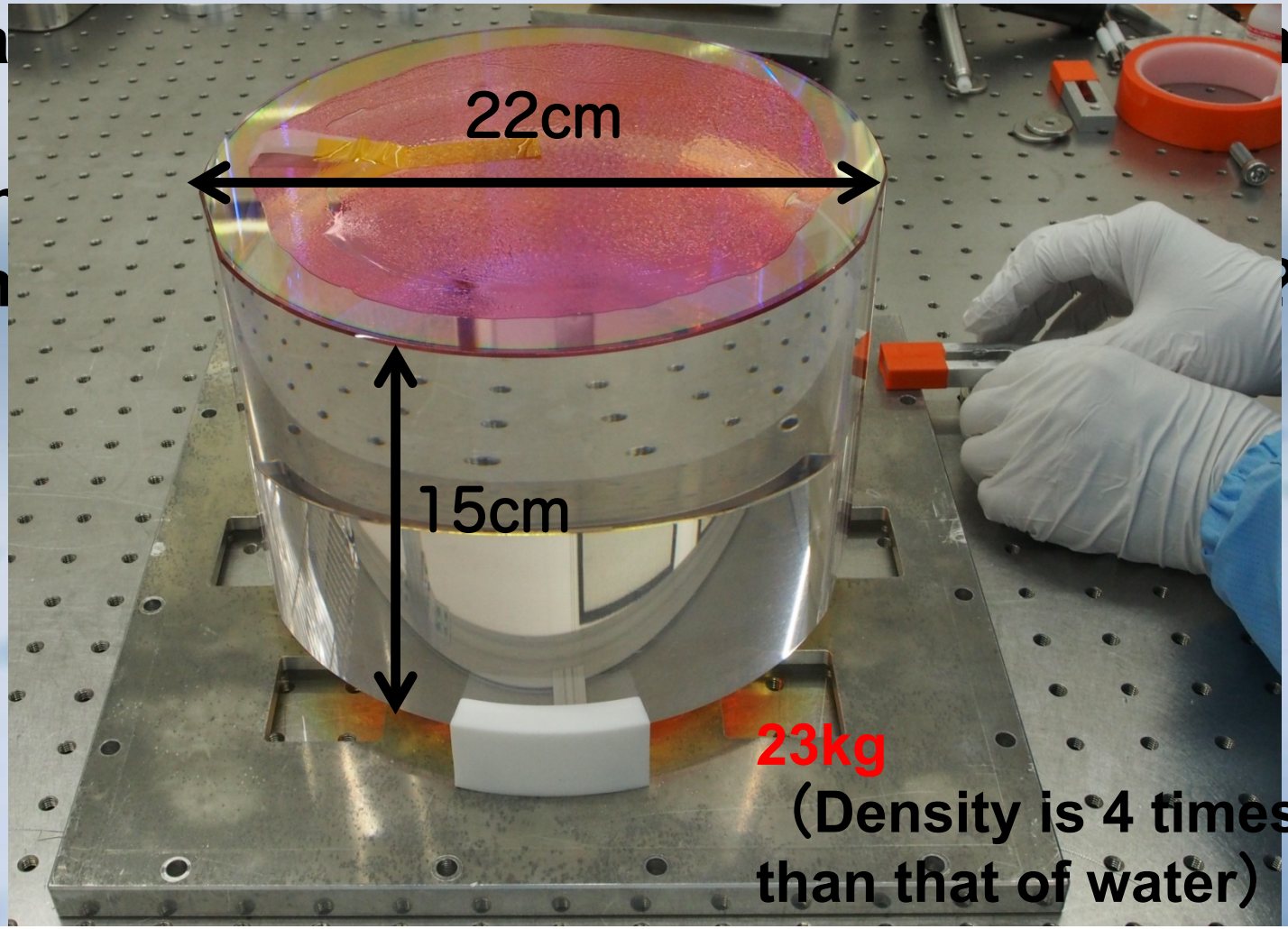
(1) Huge mirror to reduce radiation pressure noise

Back action by reflected photo is smaller when mirror is heavier.
2nd generation mirrors : on the order of 10kg
3rd generation mirrors : on the order of 100kg ?

4. R&D in future

(1) Huge mirror to reduce radiation pressure noise

Back a… mirror … 2nd ger… 3rd gen…



23kg
(Density is 4 times larger than that of water)

4. R&D in future

(1) Huge mirror to reduce radiation pressure noise

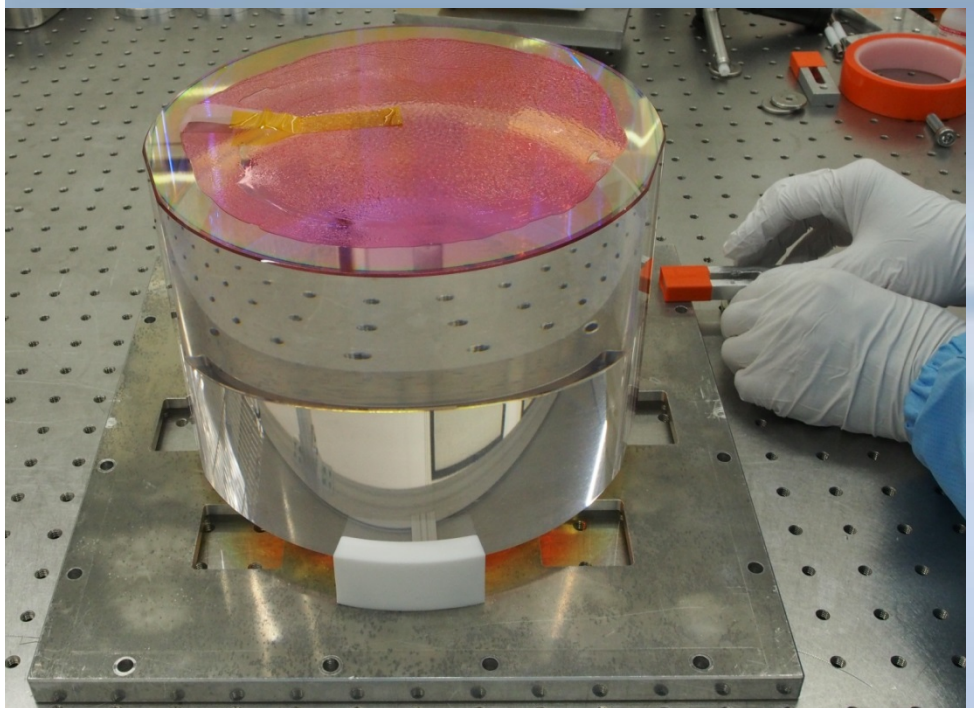
Back action by reflected photo is smaller when mirror is heavier.
2nd generation mirrors : on the order of 10kg
3rd generation mirrors : on the order of 100kg ?

How to make huge bulk with best quality ?
How to polish and apply coating with best quality ?
How about other material, silicon ?

4. R&D in future

(2) Small absorption (heat load) mirror to reduce thermal noise

Smaller heat load implies lower temperature, in other words, smaller thermal noise.



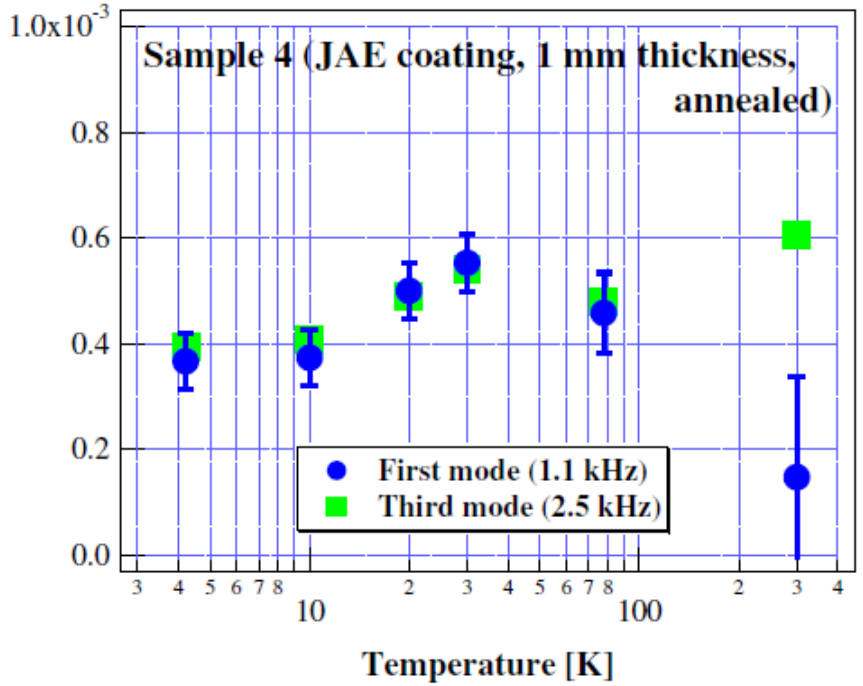
Current status
Heat load : about 1W

10 times smaller heat load means 3 times smaller thermal noise.

4. R&D in future

(3) Reflective coating with small mechanical dissipation to reduce mirror thermal noise

Reflective coating mechanical dissipation dominates mirror thermal noise. Lower dissipation at lower temperature is necessary.



K. Yamamoto *et al.*,
Physical Review D 74 (2006) 022002.

4. R&D in future

(4) Fiber investigation to reduce suspension thermal noise

For smaller thermal noise
Smaller dissipation, other geometry, ….

From point of view of manufacture,
Easier production method, …

Fibers with nail head

4. R&D in future

(5) Improvement of bonding

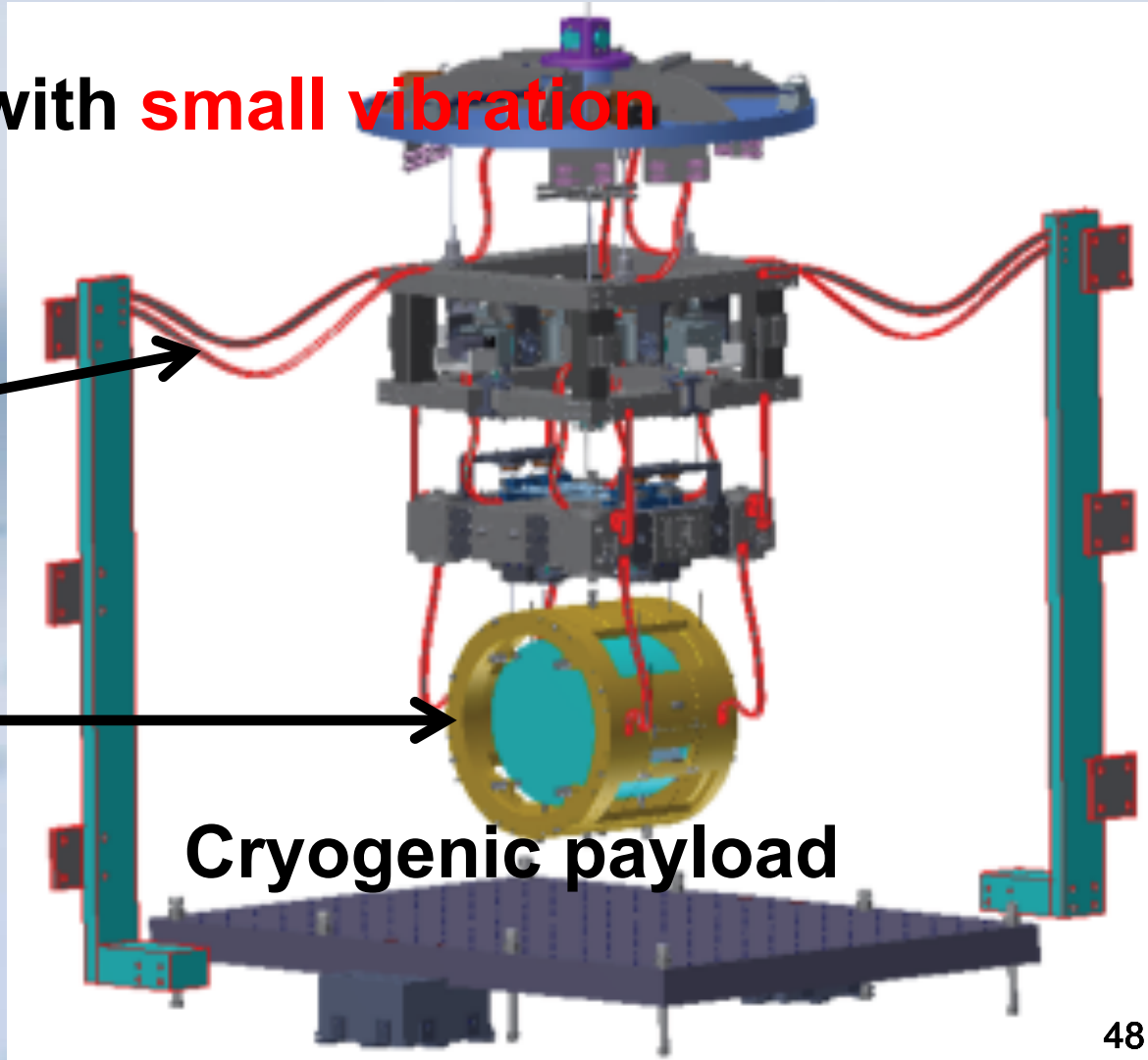
For smaller thermal noise
Smaller dissipation, ….

From point of view of manufacture,
Easier production method, …

4. R&D in future

(6) Vibration isolation of heat link to reduce external vibration effect

(7) Cooling system with small vibration

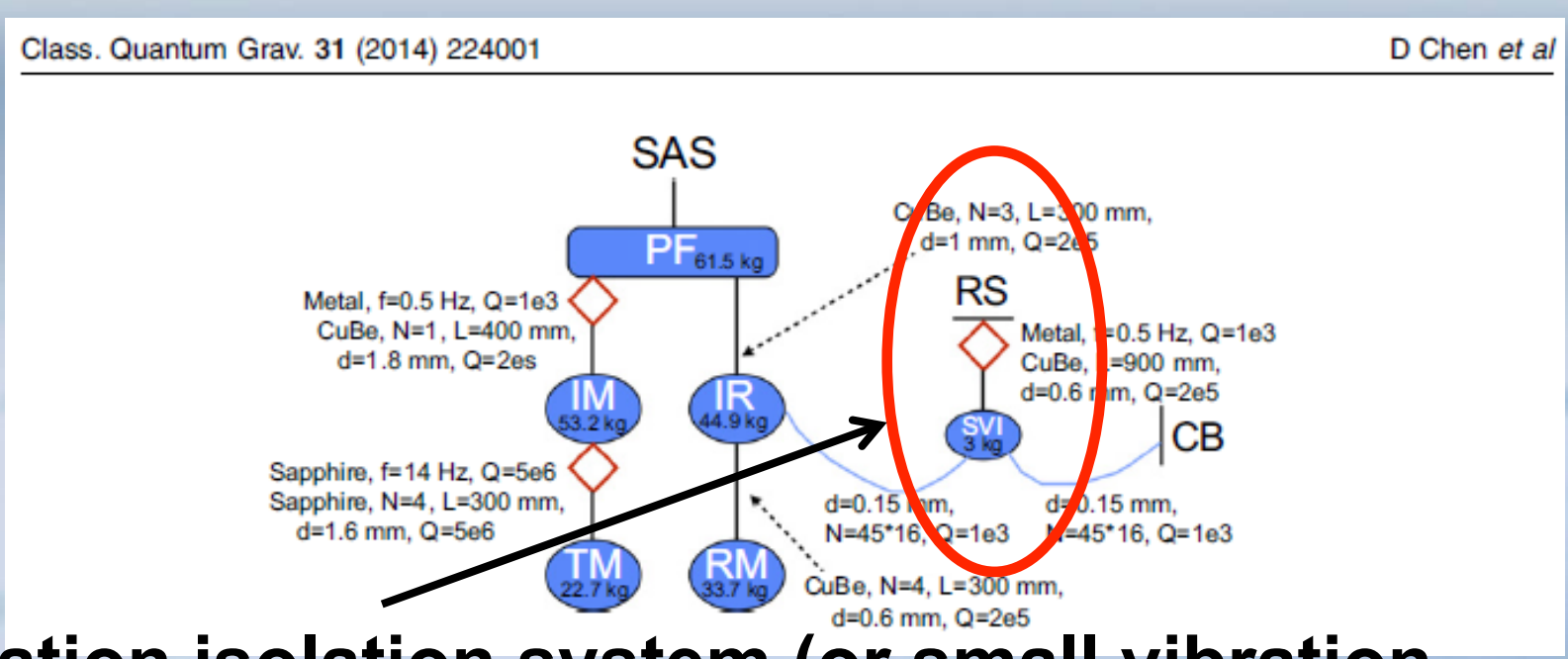


4. R&D in future

(6) Vibration isolation of heat link to reduce external vibration effect

(7) Cooling system with small vibration

Heat link can transmit vibration !



Vibration isolation system (or small vibration cooling)

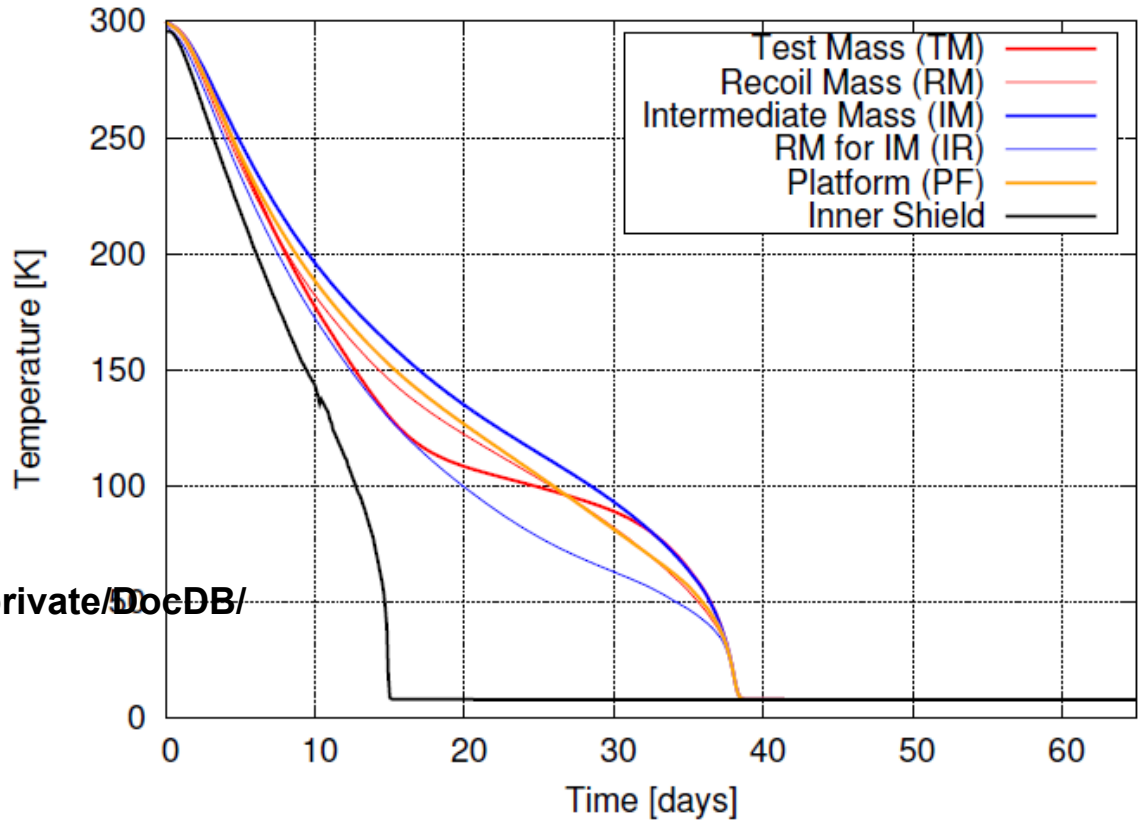
4. R&D in future

(8)Shorter initial cooling (warming up) time

Initial cooling time is about 1 month.

Y. Sakakibara, Ph.D. thesis (2015, The University of Tokyo)

https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=3314



4. R&D in future

(9)Mirror contamination problem

Cooled mirror is contaminated by residual gas. It must be removed.

5. Summary

KAGRA : Cryogenic gravitational wave detector
All four sapphire mirrors will be installed by 2019 spring. KAGRA intends to join O3.

In development of cryogenic part, ELiTES supported and many refereed journal paper were published.

KAGRA wins Core to Core program to support international communication(April 2018-Mach 2023). This could be counter part of NEWS.

Kazuhiro showed his personal idea about research topics for NEWS.

Thank you for your attention !