Large-scale Cryogenic Gravitational wave Telescope

Kazuhiro Yamamoto
and LCGT collaboration

Universita Degli Studi Di Padova
19.2.2010

0. Abstract

Review of Large-scale Cryogenic Gravitational wave Telescope (LCGT)

Japanese future interferometer project

Caution !

I will focus the attention on my previous work.

Cooling mirrors and suspensions
Seismic motion at underground site

Better review: K. Kuroda *et. al.*,
Progress of Theoretical Physics Supplement 163 (2006) 54.
http://ptp.ipap.jp/link?PTPS/163/54
46 pages !

Proceeding of Amaldi 8 is coming soon.

Contents

1. Introduction

Gravitational wave : Ripple of spacetime

Prediction of gravitational wave (1916 : A. Einstein, General Relativity)

Indirect proof : Observation of period of binary pulsar

(Nobel prize (1993) : R.A. Hulse, J.H. Taylor Jr.)

No direct detection

Purpose of detection of gravitational wave

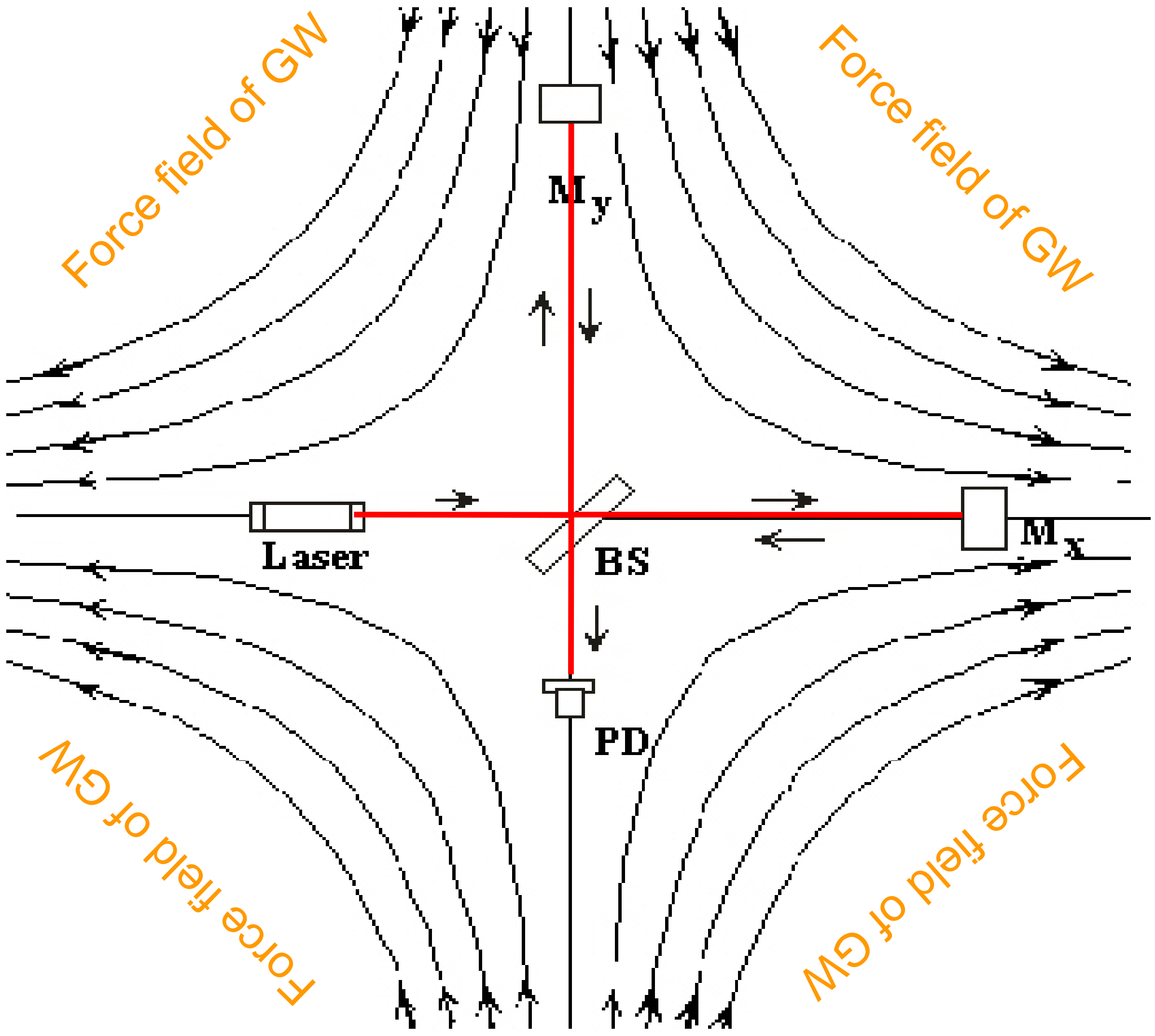
Physics : Experimental check of theory of gravitation

Astronomy : New window for observation of universe

Compact binary coalescence, Supernova, Pulsar,
Gravitational wave background, and so on

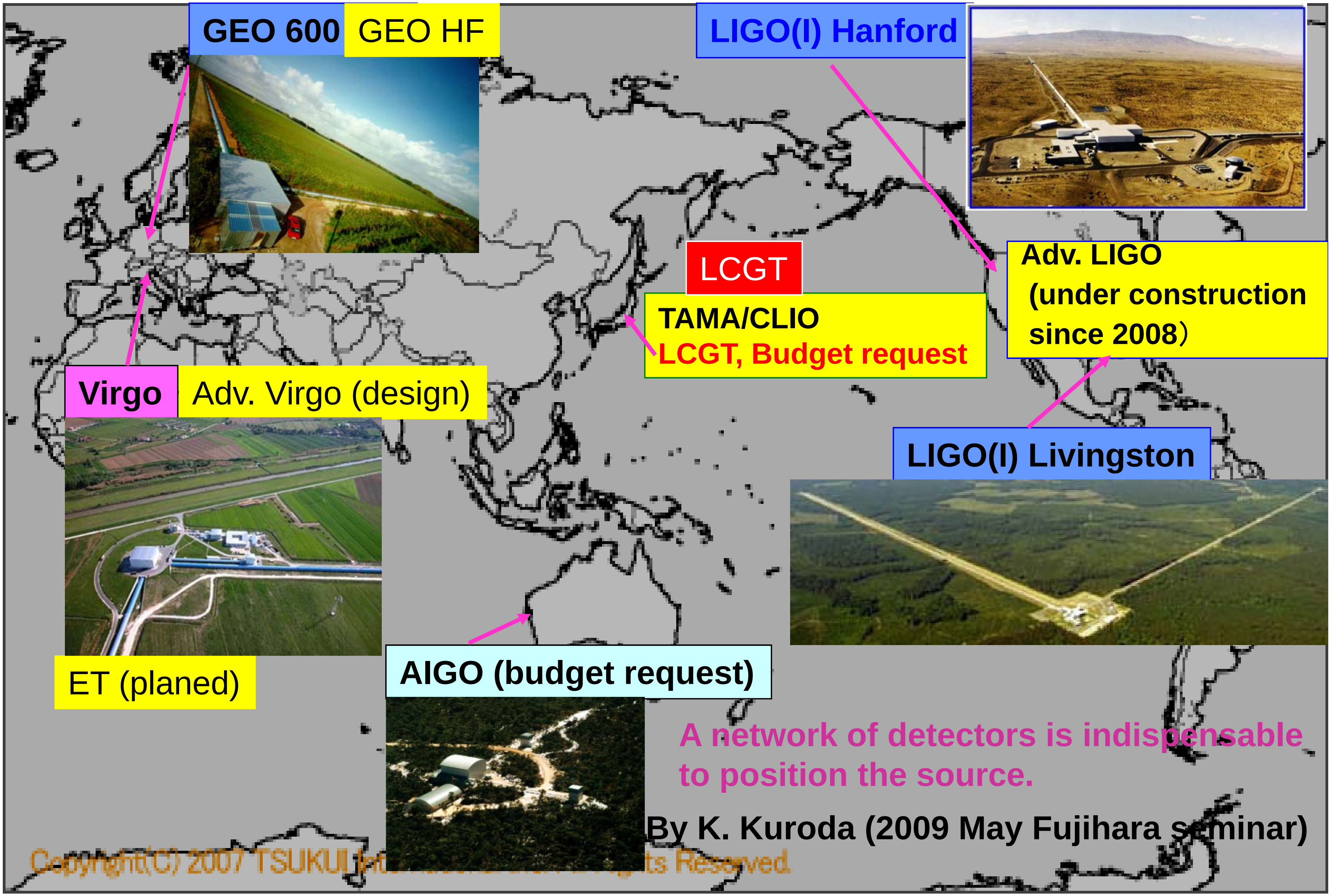
Detection of Gravitational wave by Laser interferometer

By K. Kuroda (2009 May Fujihara seminar)



- Suspended mirror (Mx) and suspended beam splitter (BS) behave as test masses for GW
- Michelson Interferometer measures differential displacement between two arms
- Typical magnitude of the event at Virgo cluster is 10^{-14} rad, 10^{-18} m for 1km baseline
- To increase phase sensitivity, optical path is folded many times using Delay-Line, Fabry-Perot, and so on

World wide network for GW astronomy



Generations of interferometric gravitational wave detector

First generation (Current interferometer)

Observable distance: 15 Mpc
(Chirp wave from neutron star binary coalescence)
A few event per a century

Second generation (LCGT, Advanced LIGO, Advanced VIRGO)

Observable distance: 200 Mpc
A few event per a month

Third generation (Einstein Telescope)

Observable distance: 2 Gpc ?
Many events !

Sensitivity of interferometer

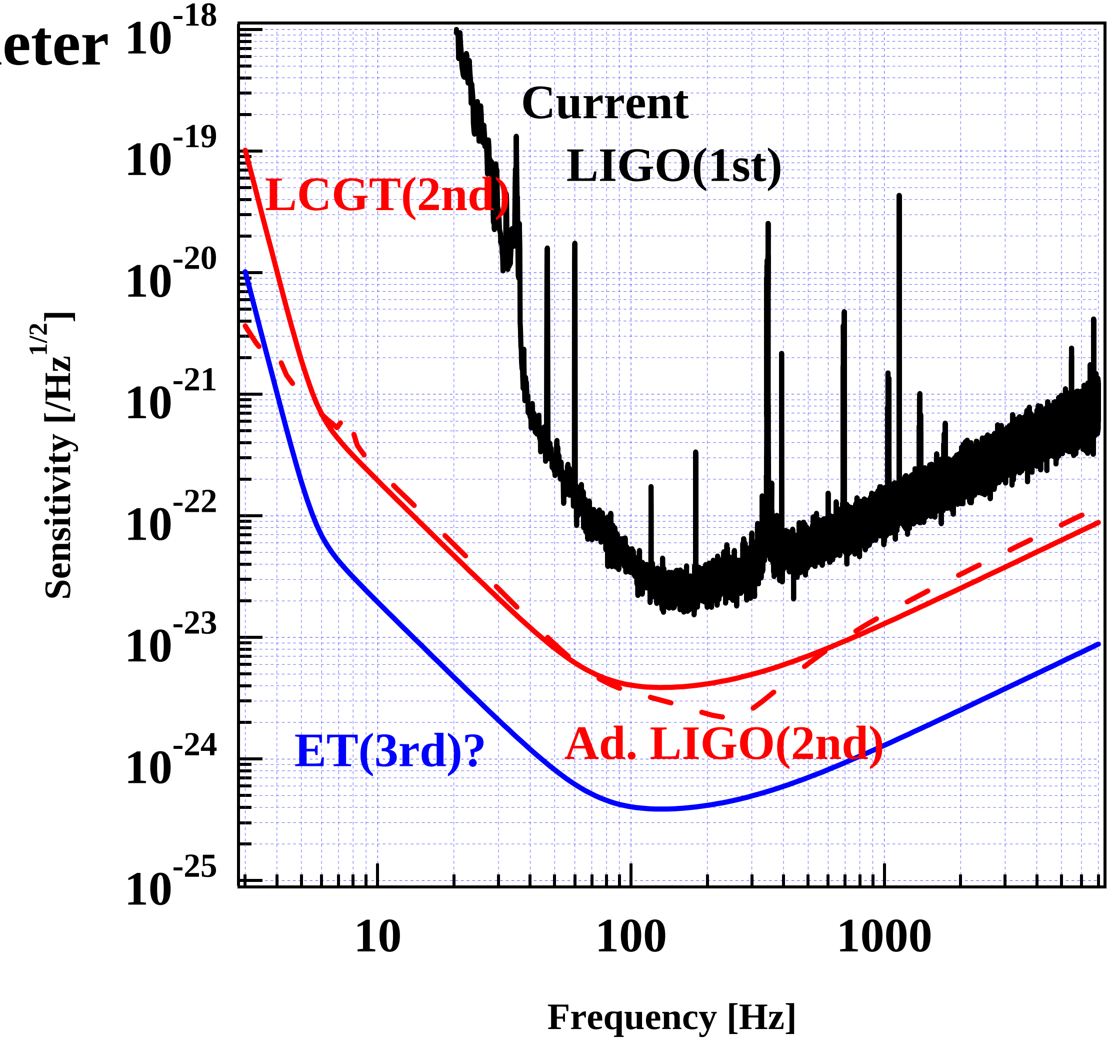
1st generation

↓ 10 times

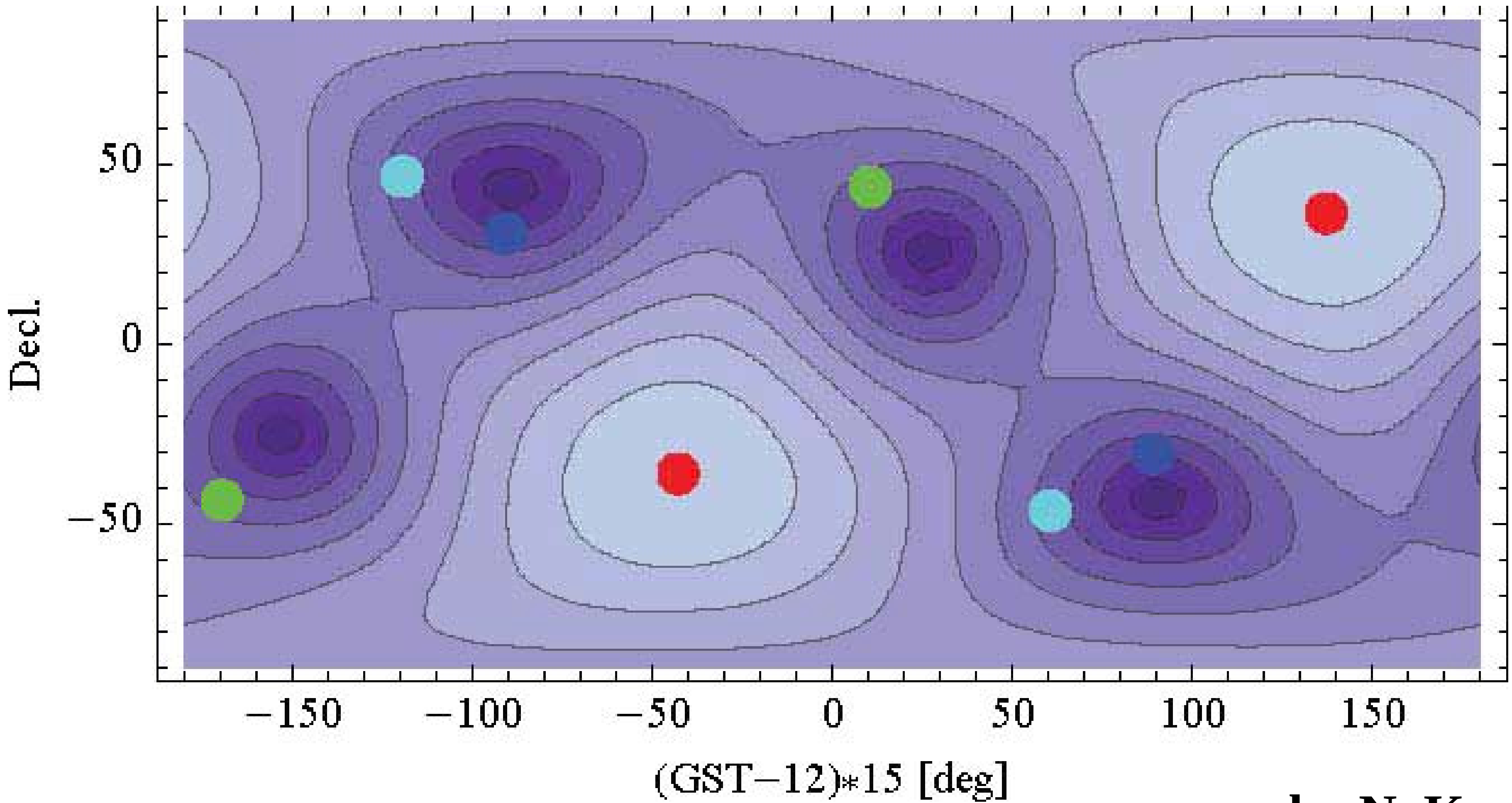
2nd generation

↓ 10 times ?

3rd generation



International network of GW observation



by N. Kanda

LCGT plays an complementary role with interferometers in U.S.A. and Europe.

Contour: LCGT sensitivity
Circles: Best sensitivity direction (LCGT, LIGO Hanford, LIGO Livingston, VIRGO)

How will we construct such an excellent detector ?

smaller noise

3 fundamental noise sources

Quantum noise (shot noise and radiation pressure noise)

Quantum limit of interferometric measurement

Seismic noise

Motion of ground

Thermal noise

Energy from heat bath
(Mechanical vibration of suspension and mirror itself)

How will we construct such an excellent detector ?

smaller noise

3 fundamental noise sources

Quantum noise (shot noise and radiation pressure noise)

High power laser   Resonant Sideband Extraction

Seismic noise

Silent underground site   Vibration isolation system

Thermal noise

Cryogenic technique

How will we construct such an excellent detector ?

smaller noise

3 fundamental noise sources

Quantum noise (shot noise and radiation pressure noise)

High power laser   Resonant Sideband Extraction

Seismic noise

Silent underground site   Vibration isolation system

Thermal noise

Cryogenic technique

Noise budget of LCGT

Above 10 Hz

Quantum noise limited

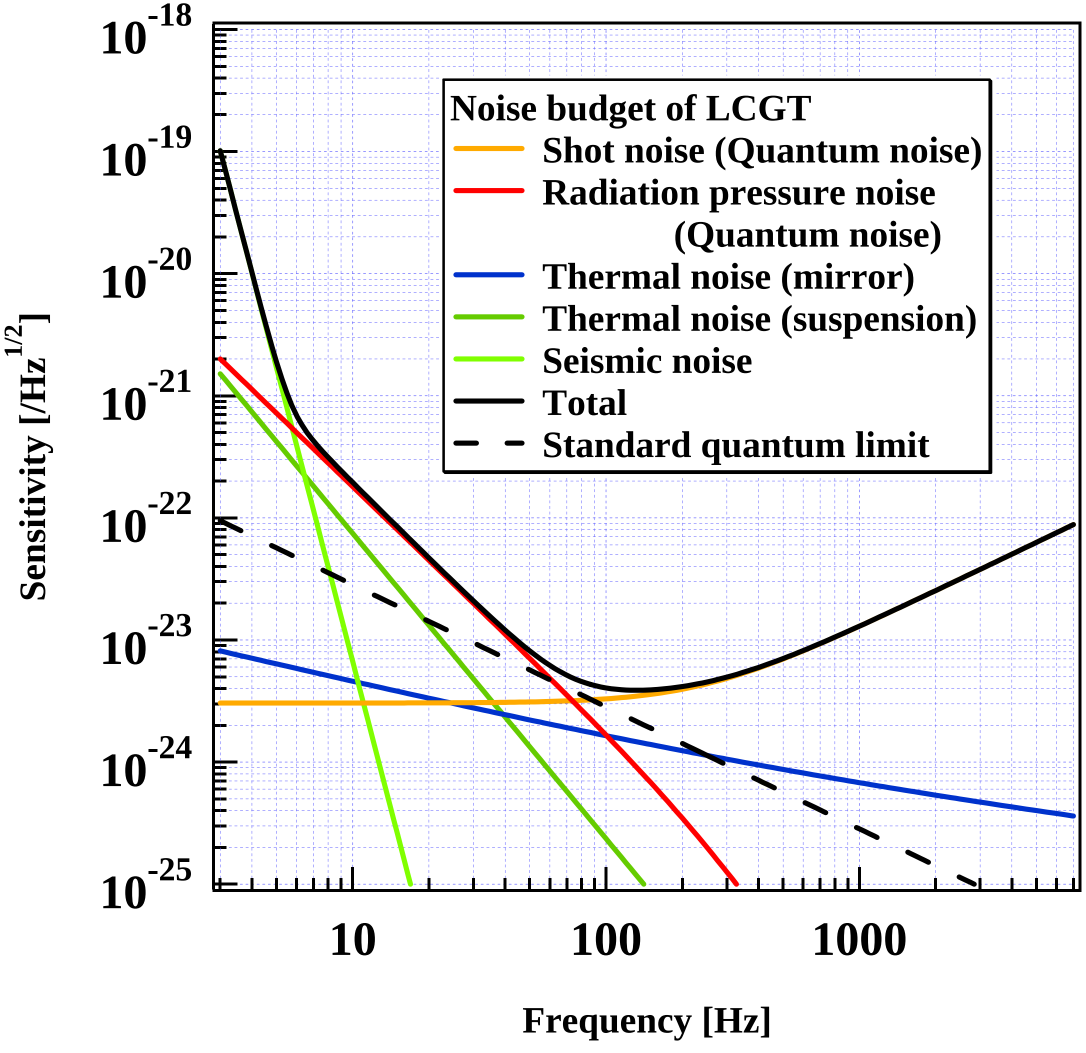
Standard Quantum Limit

Around 80 Hz

Thermal noise

never limits

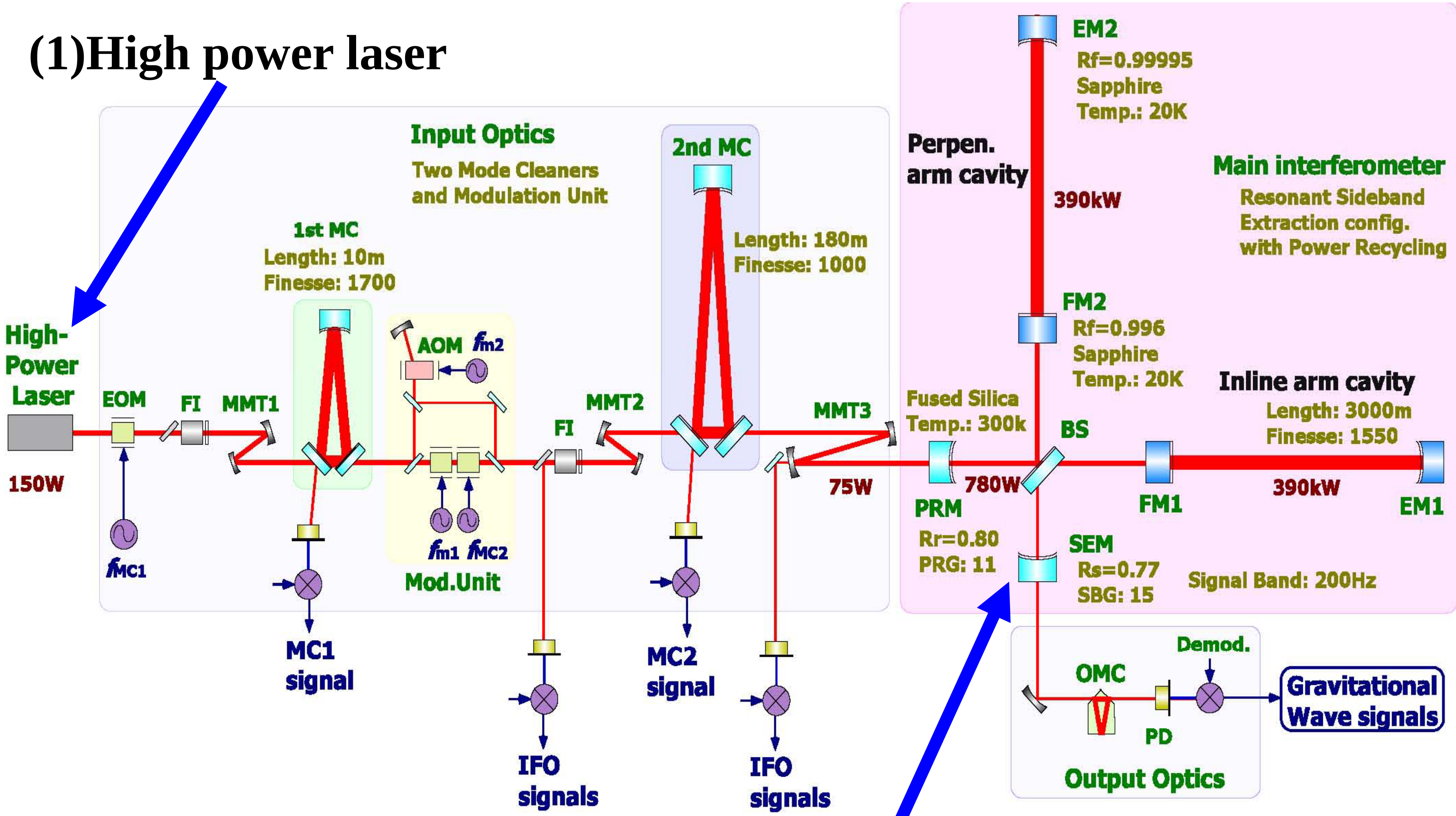
sensitivity.



Configuration of LCGT interferometer

by M. Ando

(1)High power laser



(2)Resonant Sideband Extraction

Einstein Telescope : 3rd generation interferometer project in Europe

10 times better sensitivity than that of 2nd generation

Same keywords as those of LCGT

Silent underground site, Cryogenic technique

Of course, ET needs more tricks ...

Gravity gradient noise

Silent underground site and noise subtraction scheme

Thermal noise

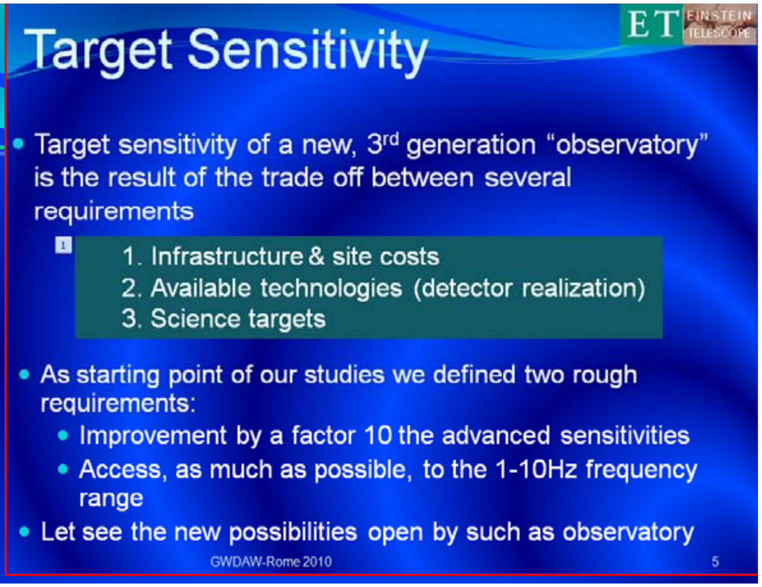
Cryogenic technique

Mirror substrate: Sapphire (LCGT), Silicon (ET)
Other thermal noise suppression scheme
Khalili cavity ? Waveguide grating mirror ?
Larger or Higher Laguerre-Gaussian mode beam ?

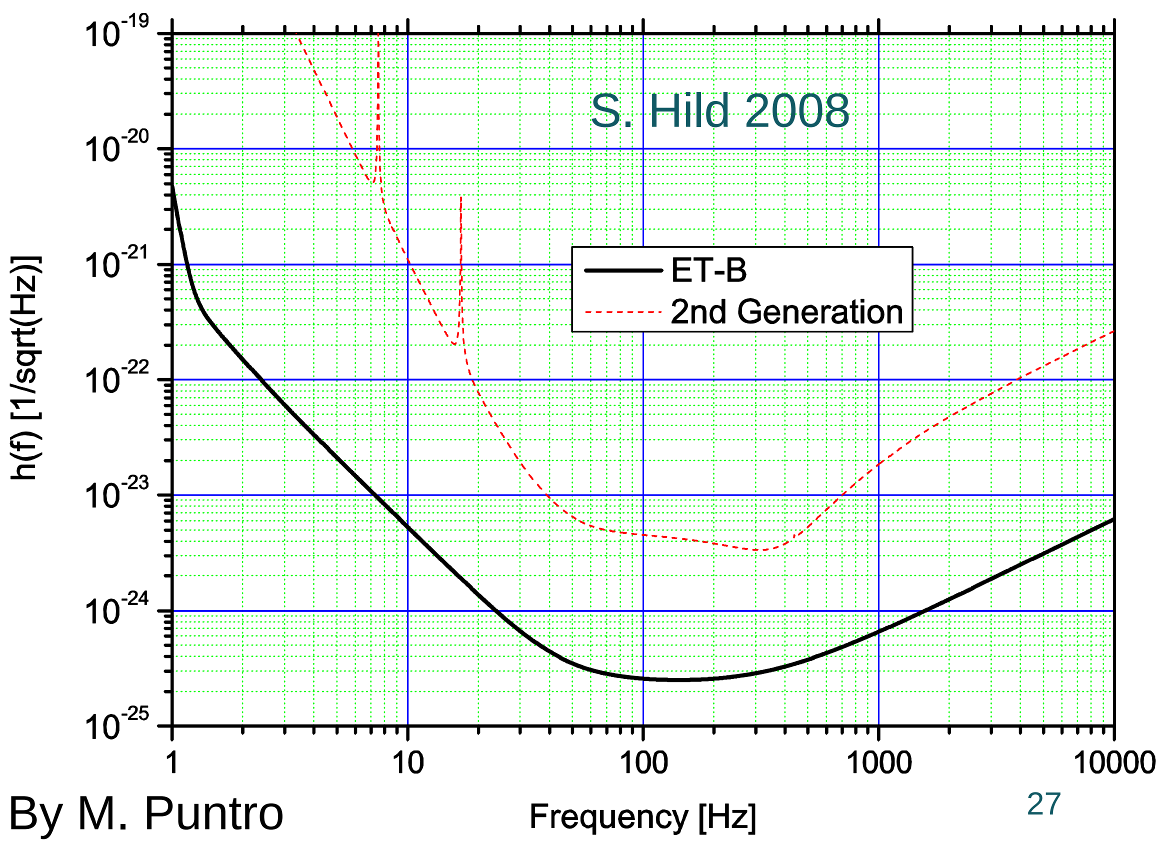
LCGT and ET have common R&D items.

ET Sensitivity (ET-B)

- As previously stated (slide #5), the target sensitivity is build through a series of compromises
- Considering a list of "conventional" technologies and 10km arms it is "feasible" to have:



- Very low frequency sensitivity still to be justified (refinement under evaluation)
- Compatibility between high freq and low freq technologies probably too challenging
  - Need of a multi-detectors solution

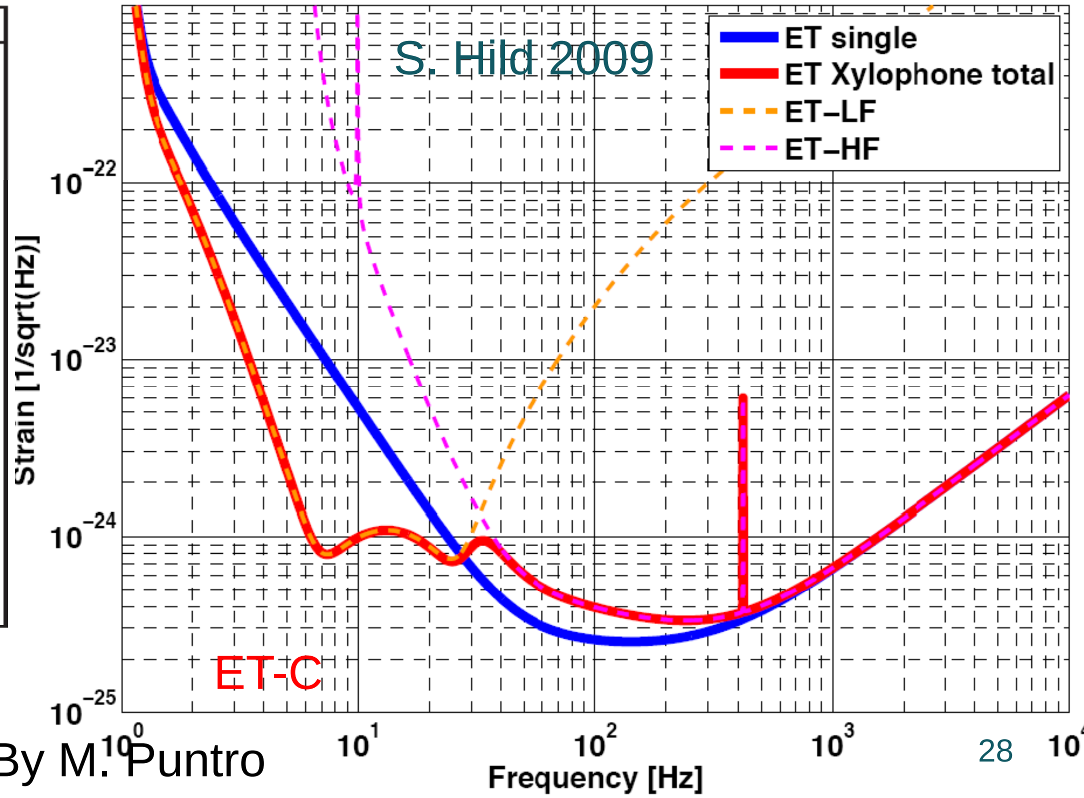


By M. Puntro

Xylophone design

- In a Xylophone design (Shoemaker 2001, DeSalvo 2004) the sensitivity of an observatory is build through 2 or more detectors specialized in different frequency bands
  - This could permit to separate the difficulties (i.e.) to realize a cryogenic detector compliant with several MW circulating in the FP cavities

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	Fused Silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	62 cm / 30 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	10 dB	10 dB
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	12 cm
Clipping loss	1.6 ppm	1.6 ppm
Suspension	Superattenuator	5 × 10 m
Seismic (for $f > 1$ Hz)	$1 \cdot 10^{-7}\,m/f^2$	$5 \cdot 10^{-9}\,m/f^2$
Gravity gradient subtraction	none	factor 50



By M. Puntro

2. Seismic noise

Silent site

↓

Kamioka mine

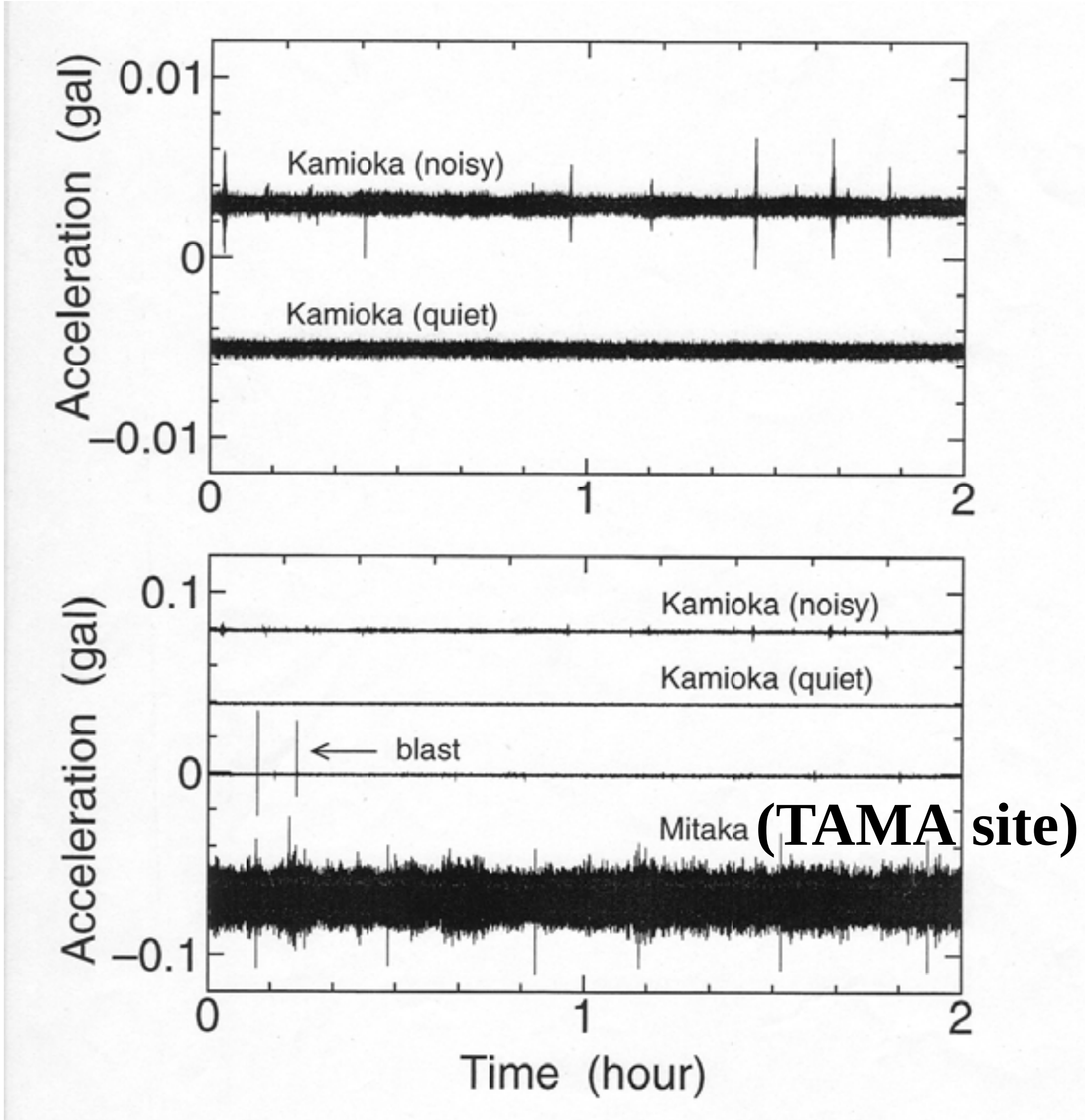
underground site

Small seismic motion

Easy and stable lock

Stable temperature and humidity

S. Sato *et al.*,
Physical Review D
69 (2004) 102005.

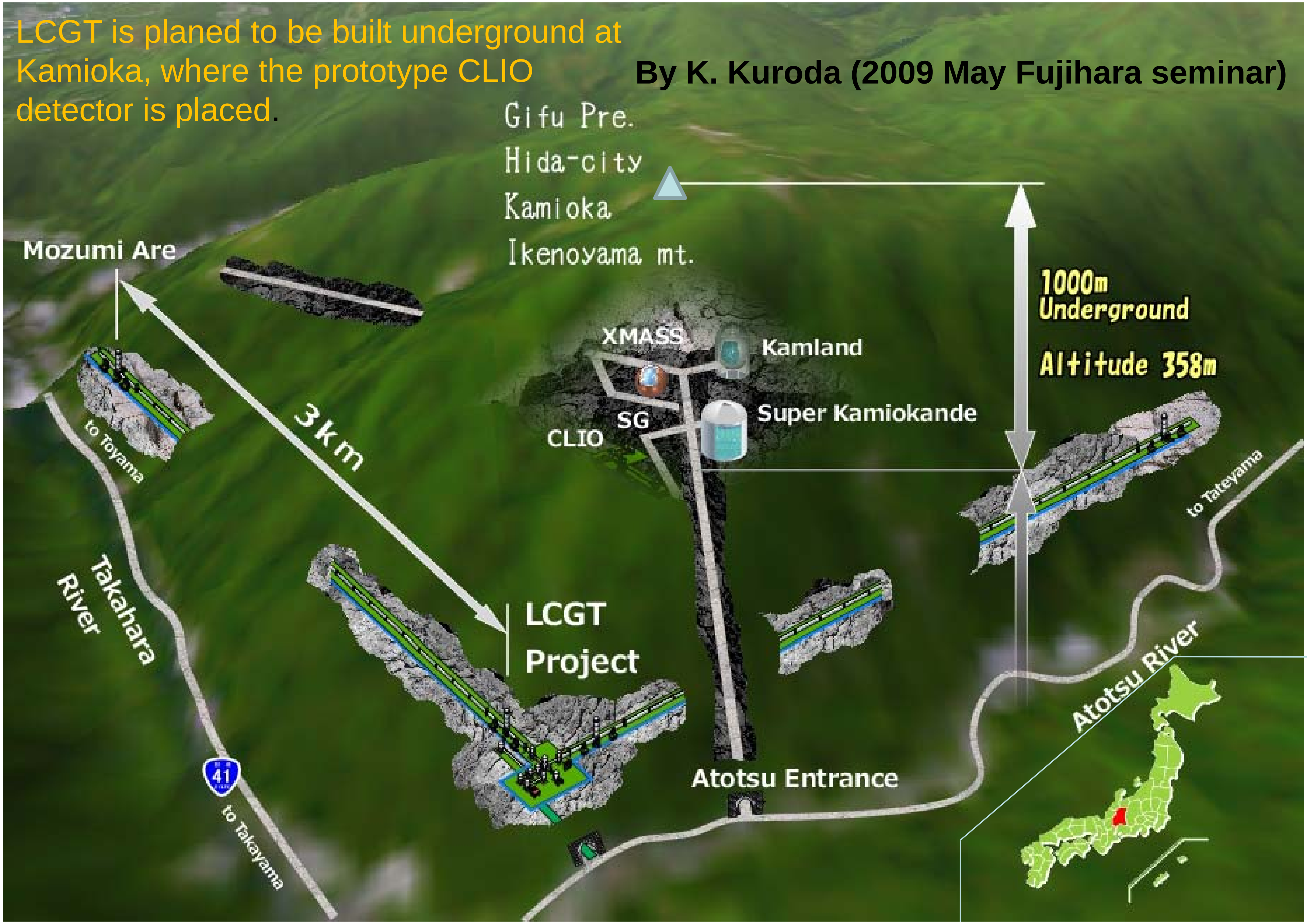


Location of Kamioka mine

Location of LCGT

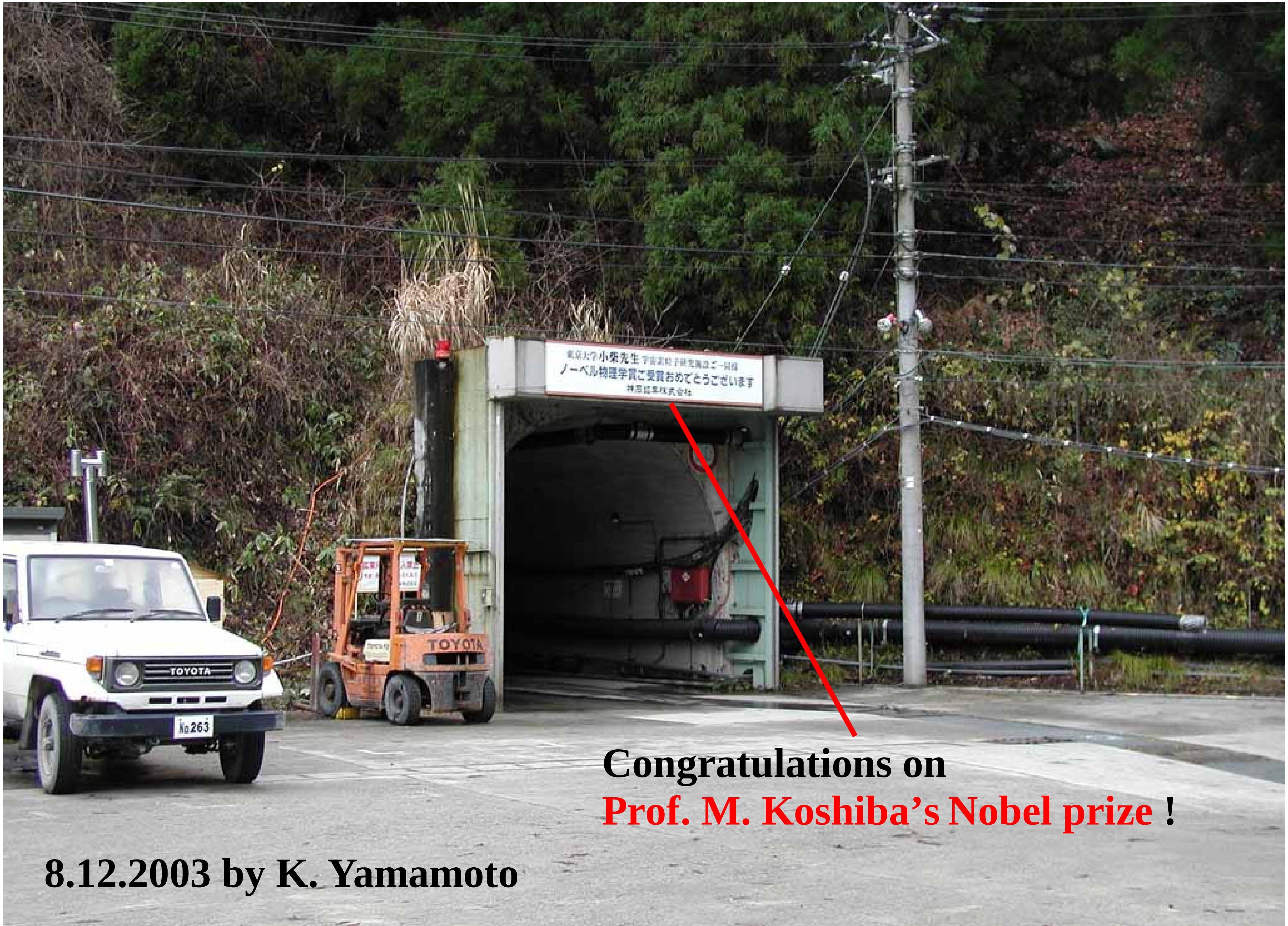
LCGT is planed to be built underground at Kamioka, where the prototype CLIO detector is placed.

By K. Kuroda (2009 May Fujihara seminar)



by O. Miyakawa

Mine entrance



Congratulations on
Prof. M. Koshiba’s Nobel prize !

8.12.2003 by K. Yamamoto

Prof. M. Koshiba won
Nobel prize
for pioneering contributions
to astrophysics, in particular
for the detection of cosmic neutrino.

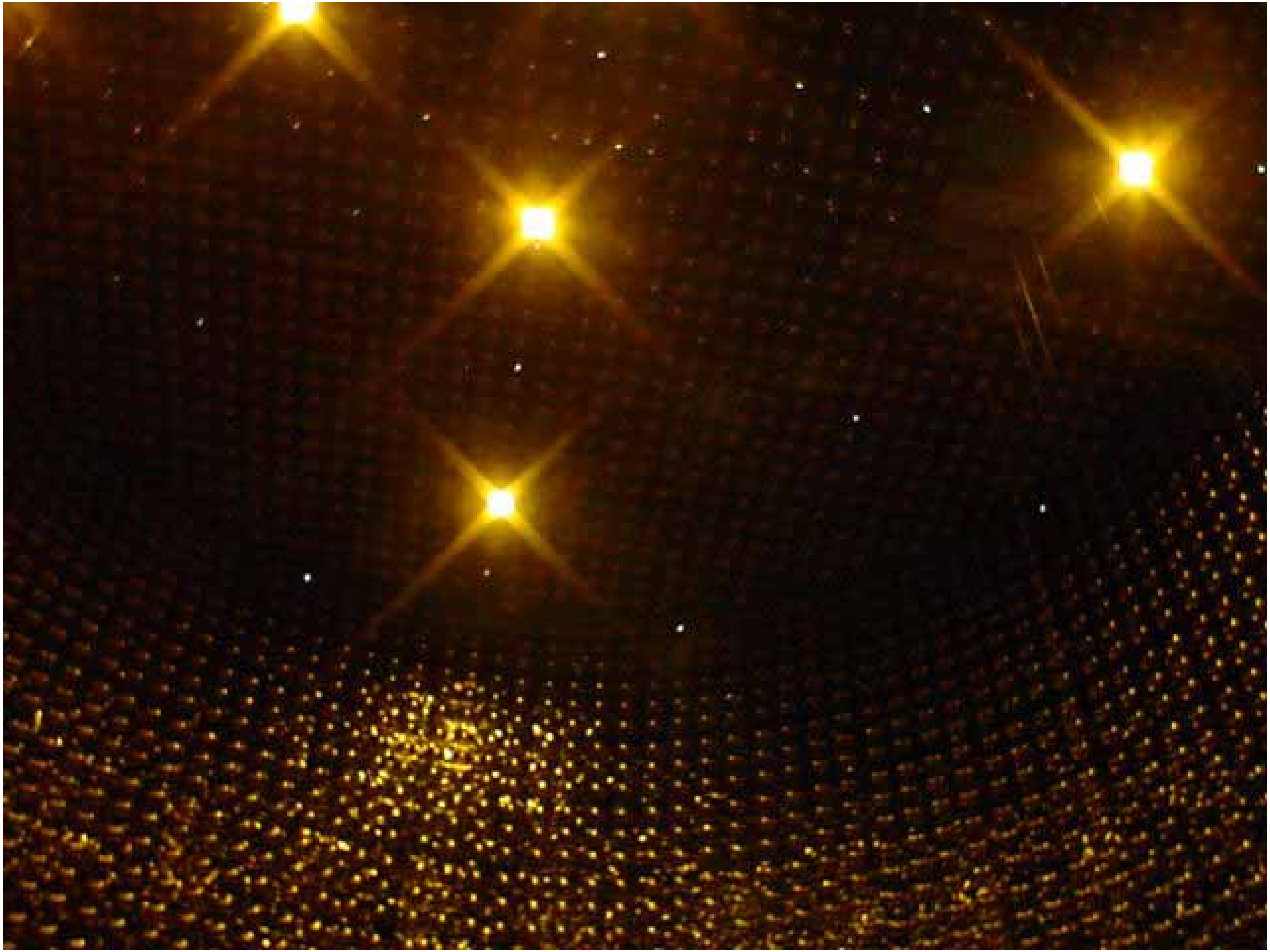
Koshiba group has constructed
Kamiokande in Kamioka mine
and detected
neutrinos from SN1987A.

10.12.2002 by Hans Mehlin

http://nobelprize.org/nobel_prizes/physics/laureates/2002/koshiba-photo.html

SuperKamiokande

16.2.2006
by K. Yamamoto



What is CLIO ?

CLIO (Cryogenic Laser Interferometer Observatory)

Prototype for LCGT

Demonstration of thermal noise suppression by cooling mirror

LCGT and CLIO site : Kamioka mine

100 m arm length

References

M. Ohashi *et al*., Classical and Quantum Gravity 20 (2003) S599.

S. Miyoki *et al*., Classical and Quantum Gravity 21 (2004) S1173.

S. Miyoki *et al*., Classical and Quantum Gravity 23 (2006) S231.

K. Yamamoto *et al*., Journal of Physics:Conference Series 122 (2008) 012002.

T. Akutsu *et al*., Classical and Quantum Gravity 25 (2008) 184013.

K. Agatsuma *et al*., Proceedings of Amaldi 8 (Classical and Quantum Gravity) accepted.

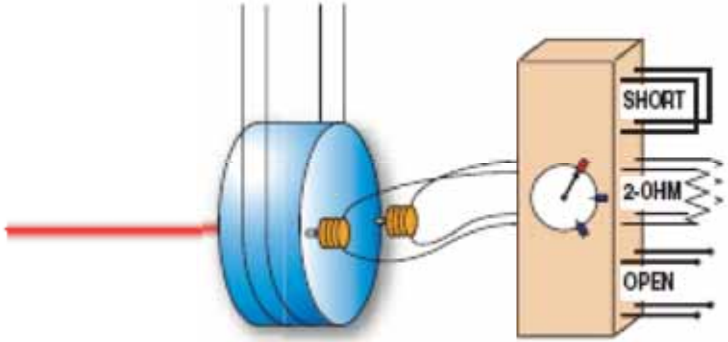
K. Agatsuma *et al*., Phys. Rev. Lett. 104 (2010) 040602.

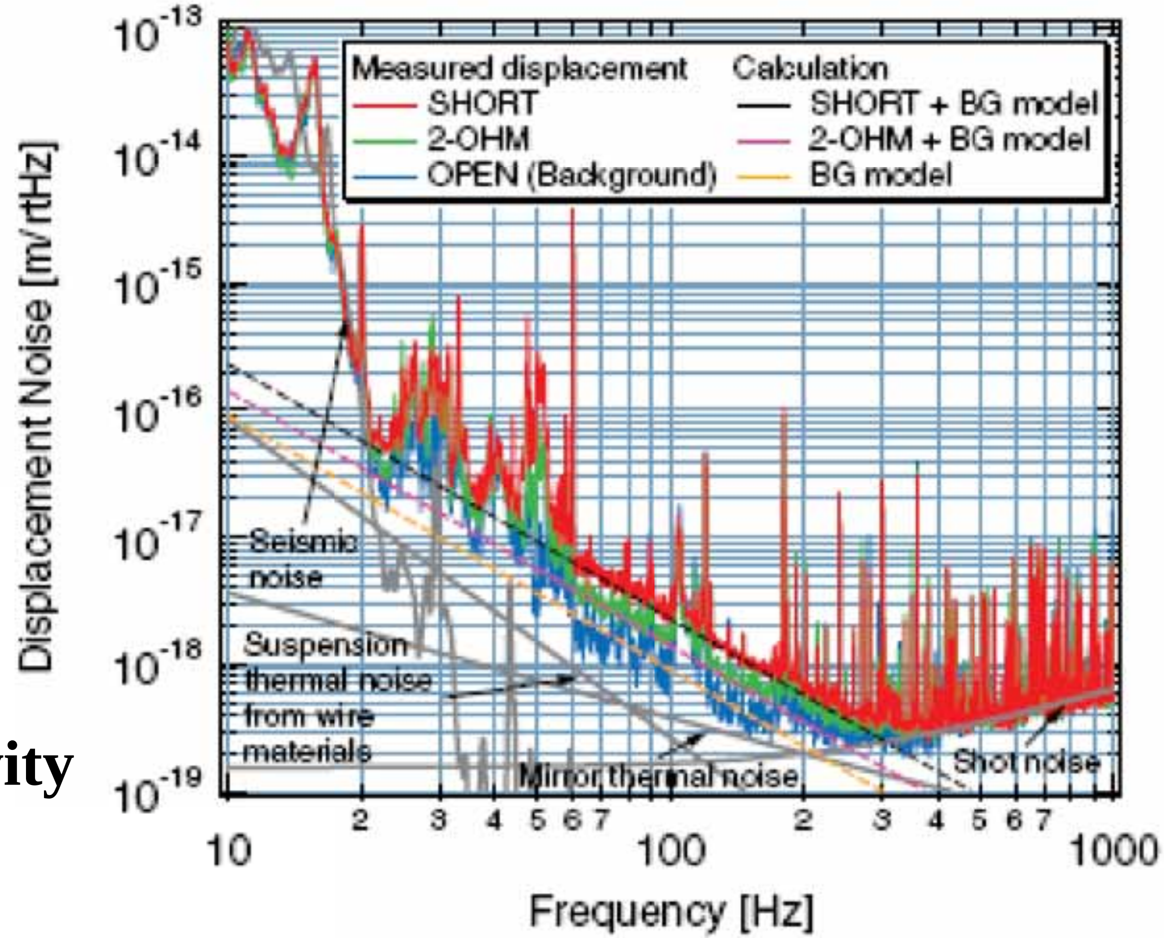
K. Agatsuma *et al*., Phys. Rev. Lett. 104 (2010) 040602.

"Direct Measurement of Thermal Fluctuation of High-Q Pendulum"

(Room temperature, dissipation of coil magnet actuator,

Mass: 1.8 kg, Resonance: 0.8 Hz, Q-value: ~10^5)



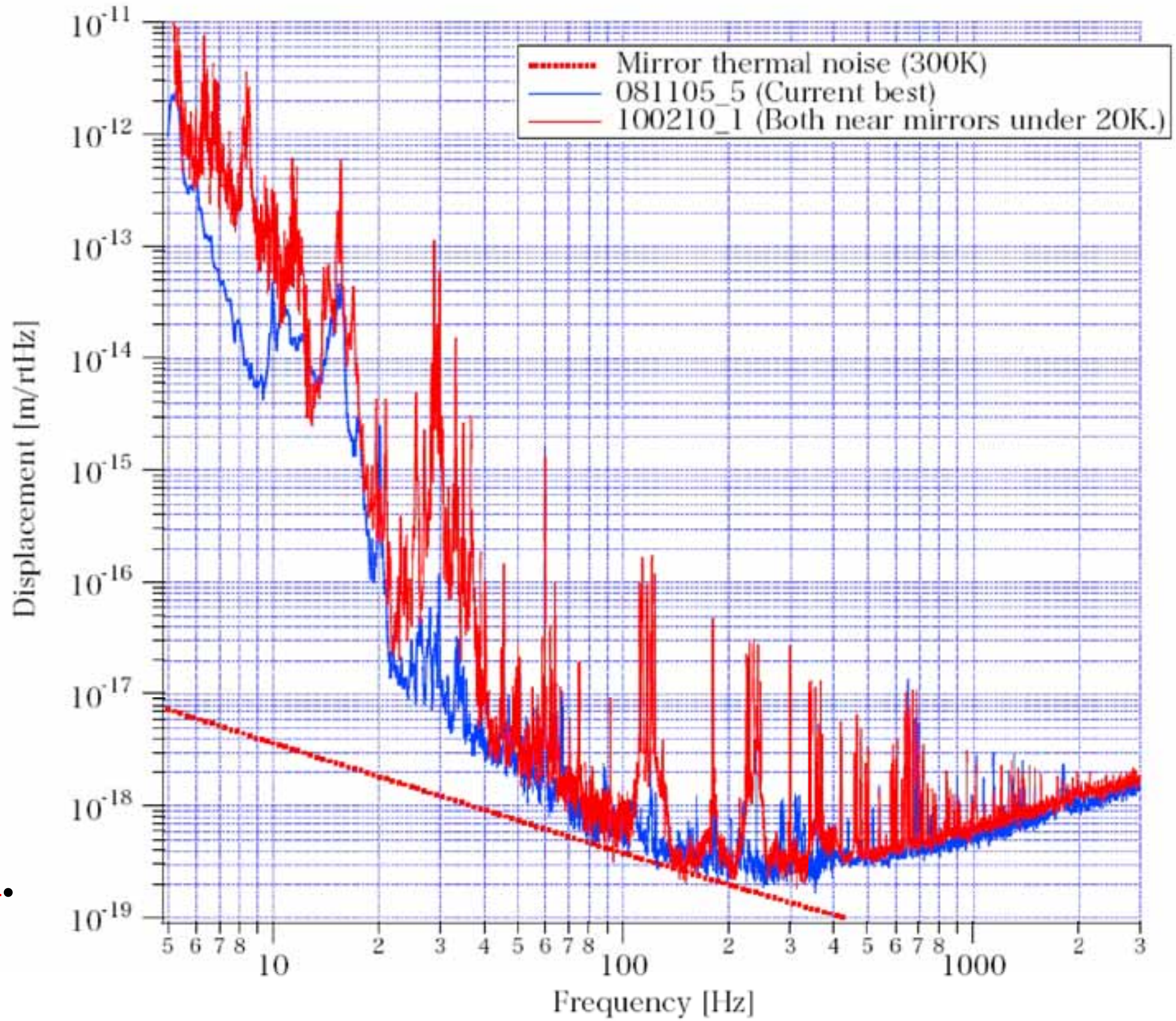


Change of resistance

↓

Change of observed sensitivity as theoretical prediction

Cryogenic experiment of CLIO is in progress.



Sensitivity at 20 K

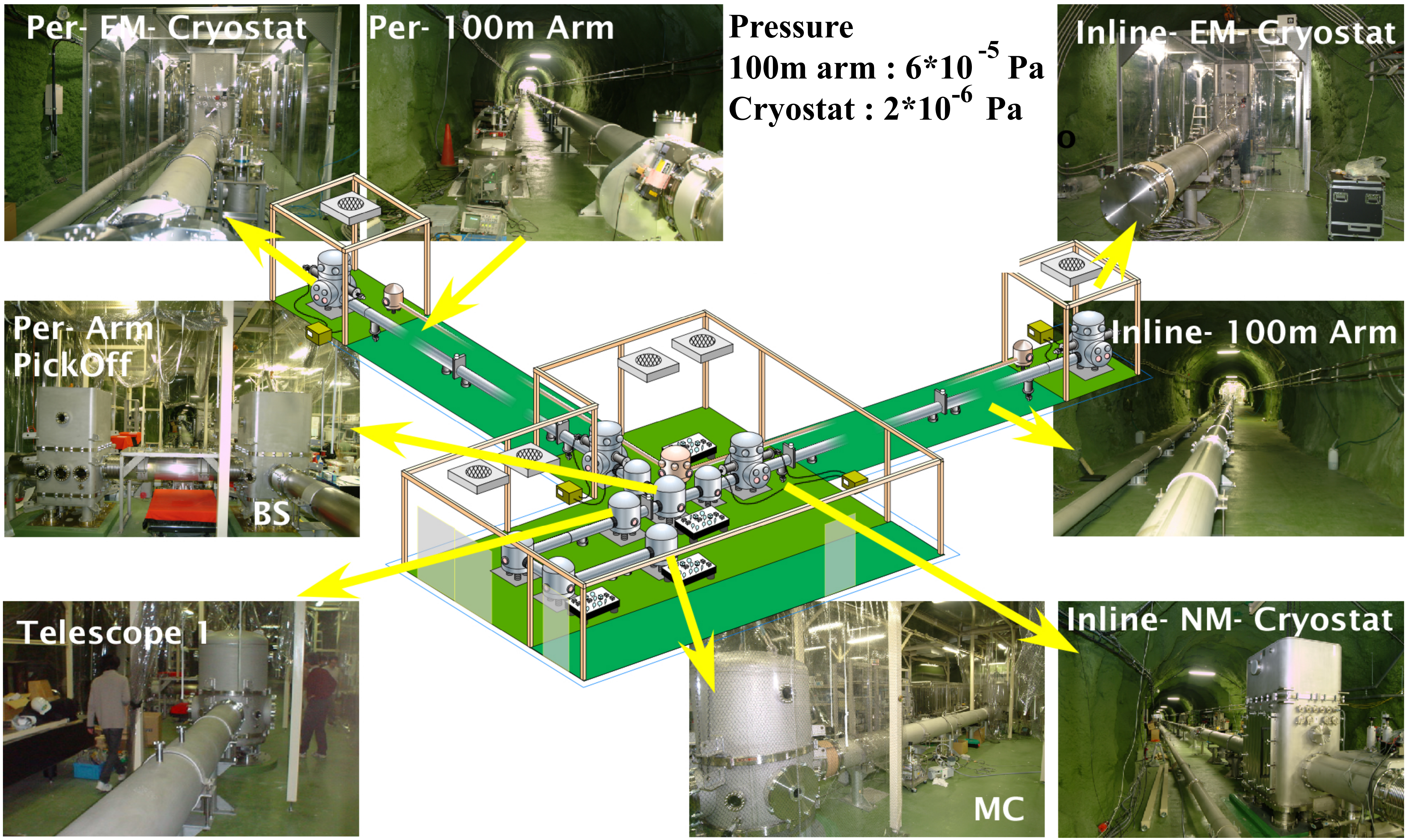
is comparable with

best sensitivity at 300 K.

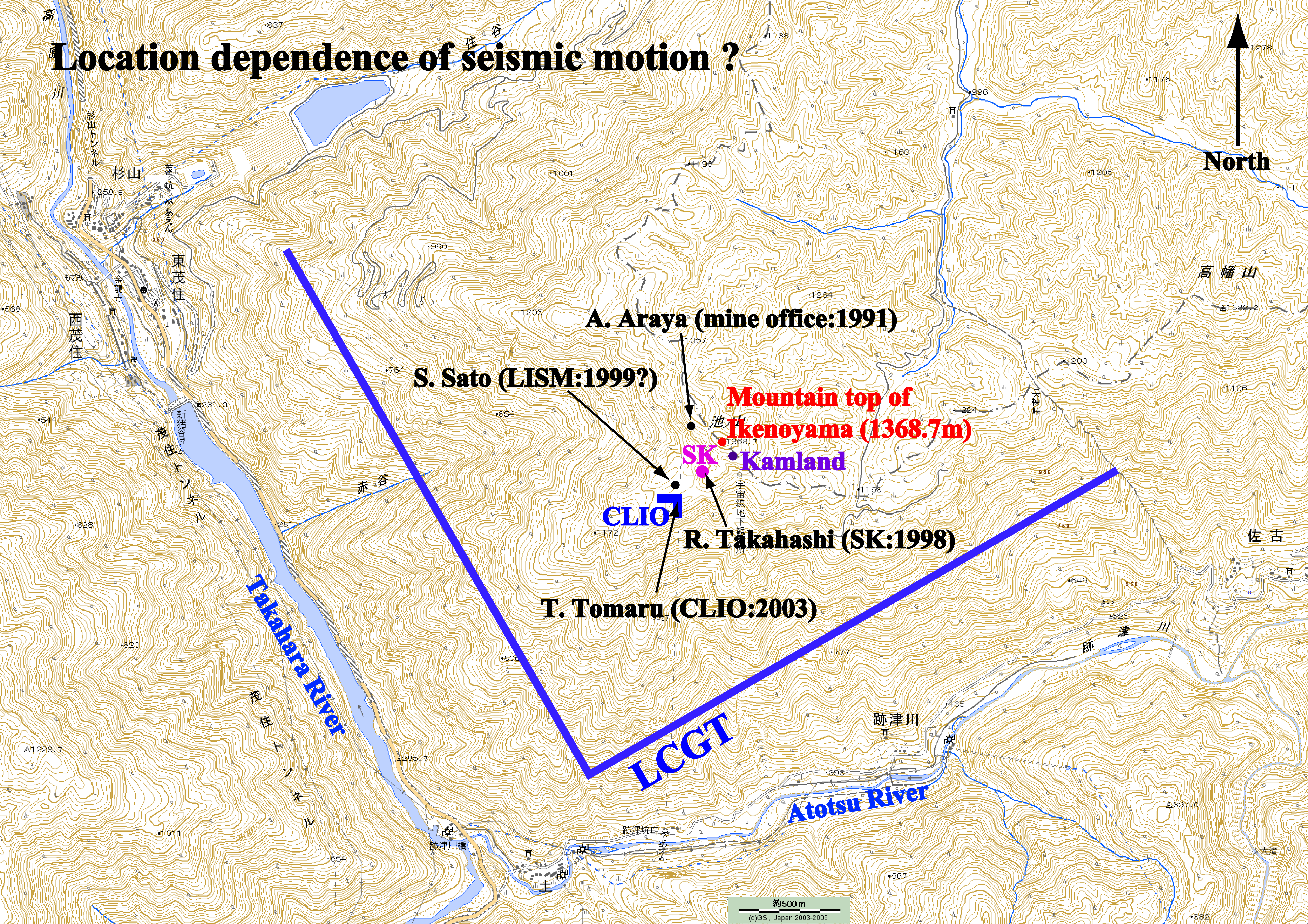
Photographs of CLIO interferometer

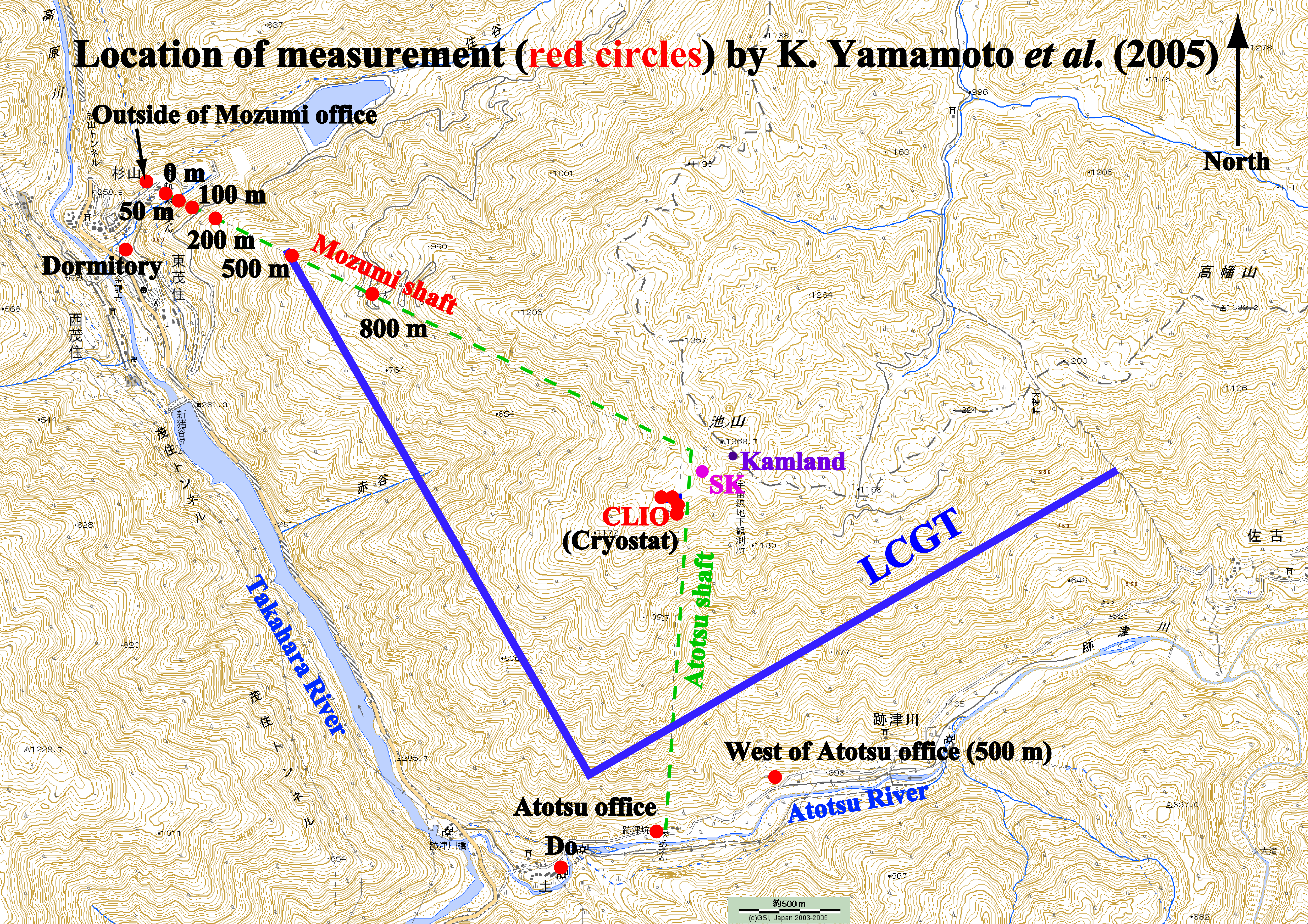
by S. Miyoki and S. Telada

Pressure
100m arm : $6*10^{-5}$ Pa
Cryostat : $2*10^{-6}$ Pa



Location dependence of seismic motion ?




Location of measurement (red circles) by K. Yamamoto et al. (2005)
North
Outside of Mozumi office
0 m
50 m
100 m
200 m
500 m
800 m
Dormitory
Mozumi shaft
Kamland
SK
CLIO
(Cryostat)
Atotsu shaft
LCGT
Takahara River
West of Atotsu office (500 m)
Atotsu office
Atotsu River
Do
池ノ山
高幡山
佐古
跡津川
約500 m
(c)GSI, Japan 2003-2005

Fixed accelerometer

Outside of mine
(mine entrance)

< 1 Hz
(Outside of mine) =(CLIO)

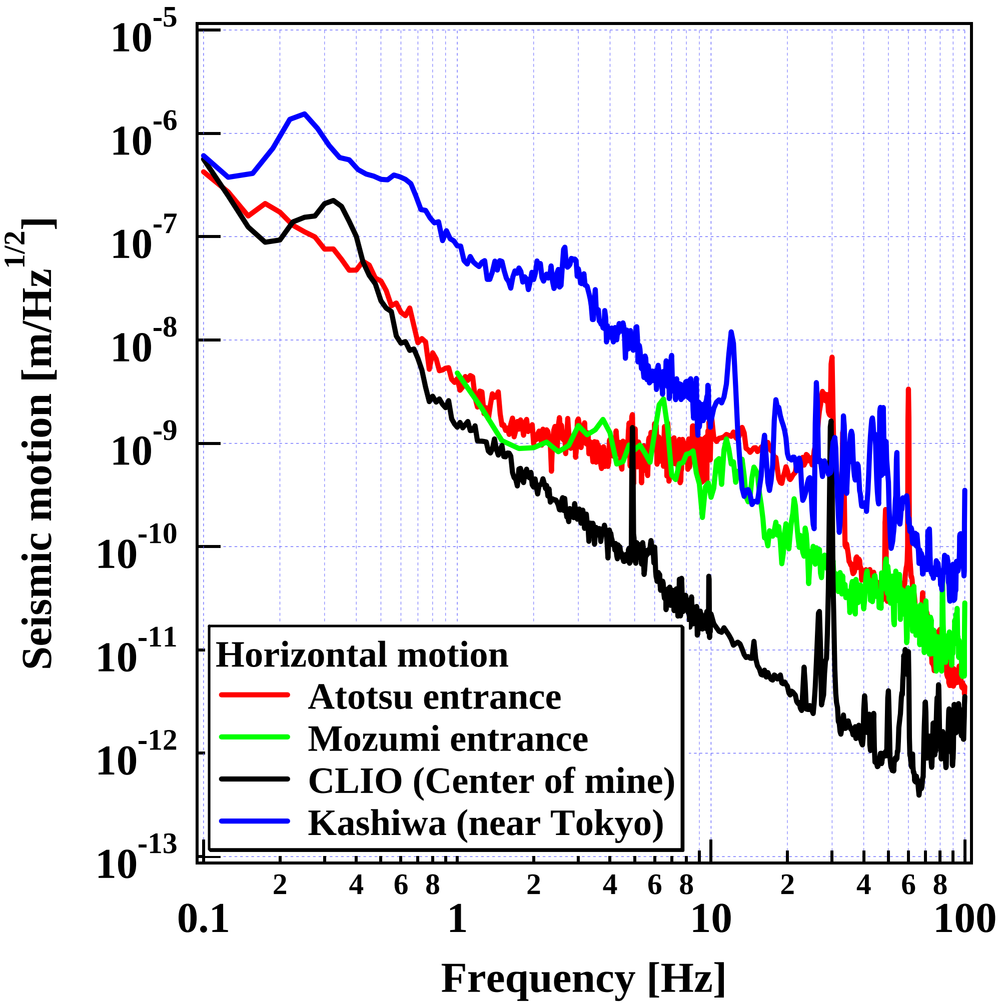
> 1 Hz
(Outside of mine) > (CLIO)

> 10 Hz
(Outside of mine) =(Tokyo)

Vertical motion is similar to horizontal one.

Results of other locations are similar.
Underground is essential.

K. Yamamoto *et al.* (2005)



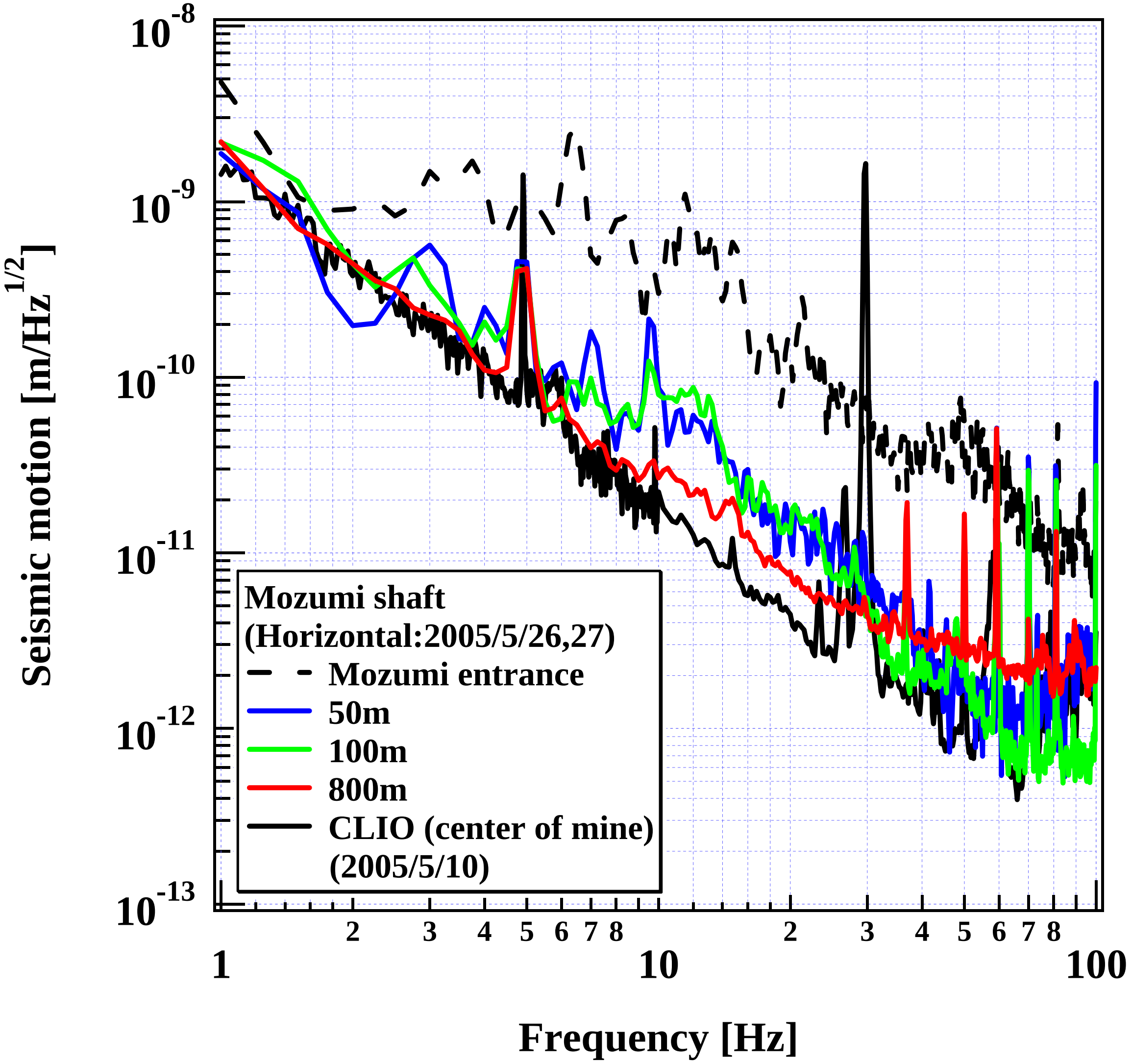
K. Yamamoto *et al.* (2005)

Inside of mine

(Mozumi shaft)

> 50 m

silent sufficiently !



Main mirrors

50 m from ground

3. Thermal noise

Cryogenic sapphire mirror (20K) and pendulum (sapphire fiber)

T. Uchiyama *et al.*, Physics Letters A 242 (1998) 211.

T. Tomaru *et al.*, Physics Letters A 301 (2002) 215.

Merit of cooling mirror and suspension

Technique for cooling mirror and suspension

4-1. Merit of cooling mirror and suspension

(1) Thermal noise

T. Uchiyama *et al.*, Physics Letters A 261 (1999) 5.
T. Uchiyama *et al.*, Physics Letters A 273 (2000) 310.
K. Yamamoto *et al.*, Physical Review D 74 (2006) 022002.

(2) Thermal lens

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

(3) Parametric instability

K. Yamamoto *et al.*,
Journal of Physics:Conference Series 122 (2008) 012015.

(4)Cosmic ray particles

K. Yamamoto *et al.*, Physical Review D 78 (2008) 022004.

(1) Thermal noise

Fluctuation-Dissipation Theorem

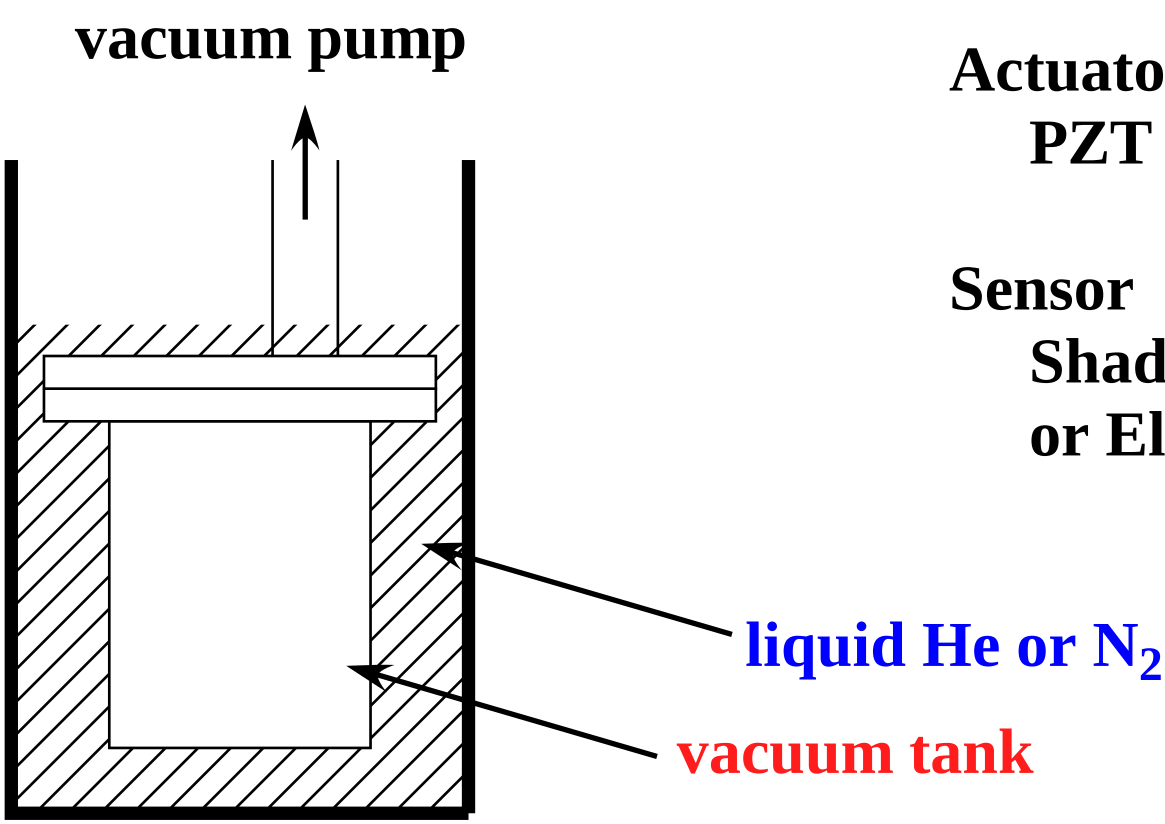
$G^{1/2}$ **is proportional to** $T^{1/2}\,\phi^{1/2}(T)$.

- $G^{1/2}$: **Thermal noise amplitude**
- $T^{1/2}$: **Temperature**
- $\phi^{1/2}(T)$: **Mechanical loss** → **Temperature dependence**

Mechanical loss at low temperature is necessary.

Measurement of mechanical loss at low temperature

Vacuum tank in liquid He or N_2



Ring down method
  Measurement of decay time of resonant motion

Actuator
  PZT or Electrostatic actuator

Sensor
  Shadow sensor
  or Electrostatic transducer

Thermal noise of suspension

Measurement of decay motion of sapphire fiber

Sapphire fiber

$Q = 1/\phi = 5*10^6$

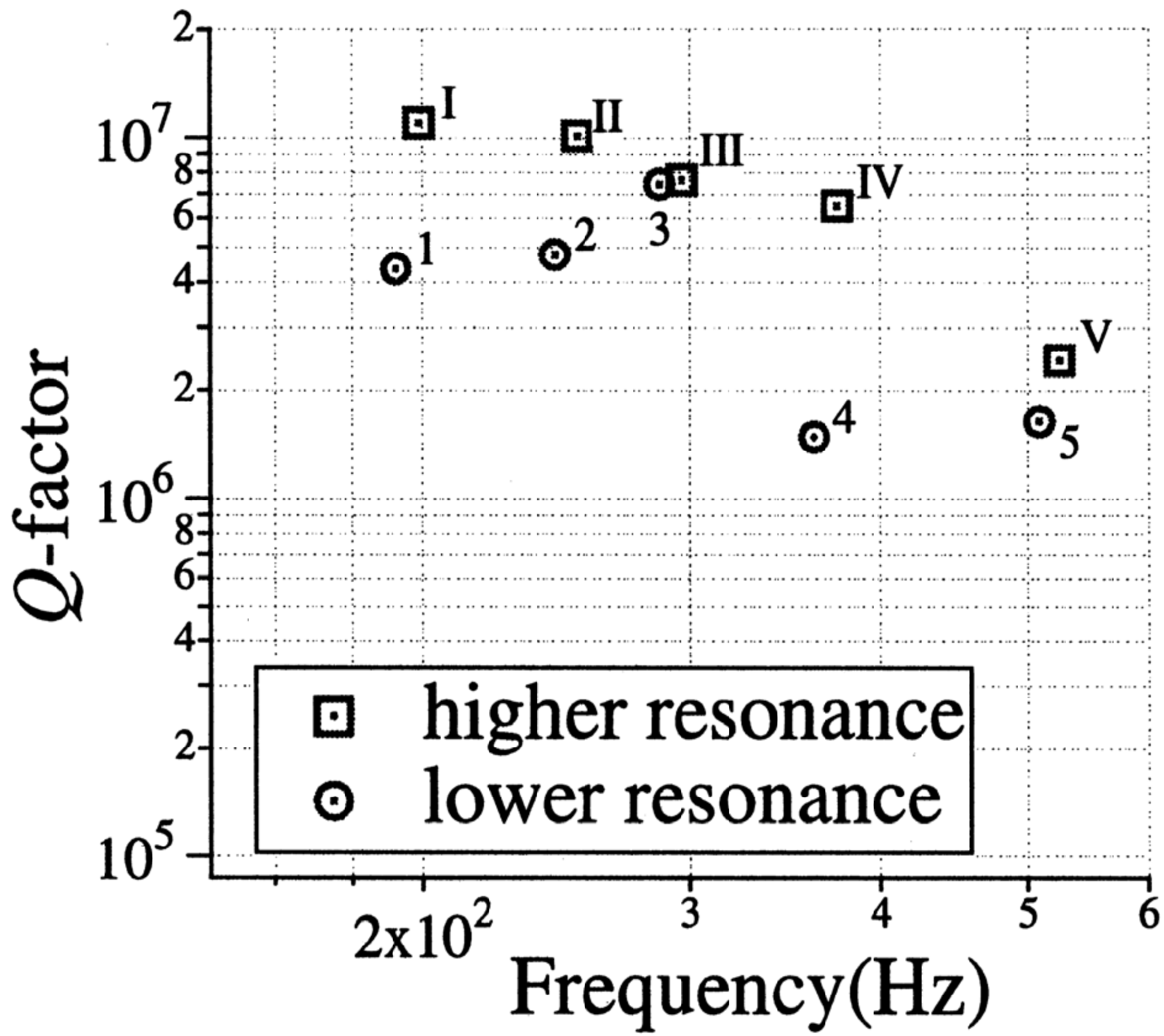
↓

Pendulum

Q : the order of 10^7

Sufficiently small loss

Pendulum thermal noise is smaller than quantum noise above a few Hz.



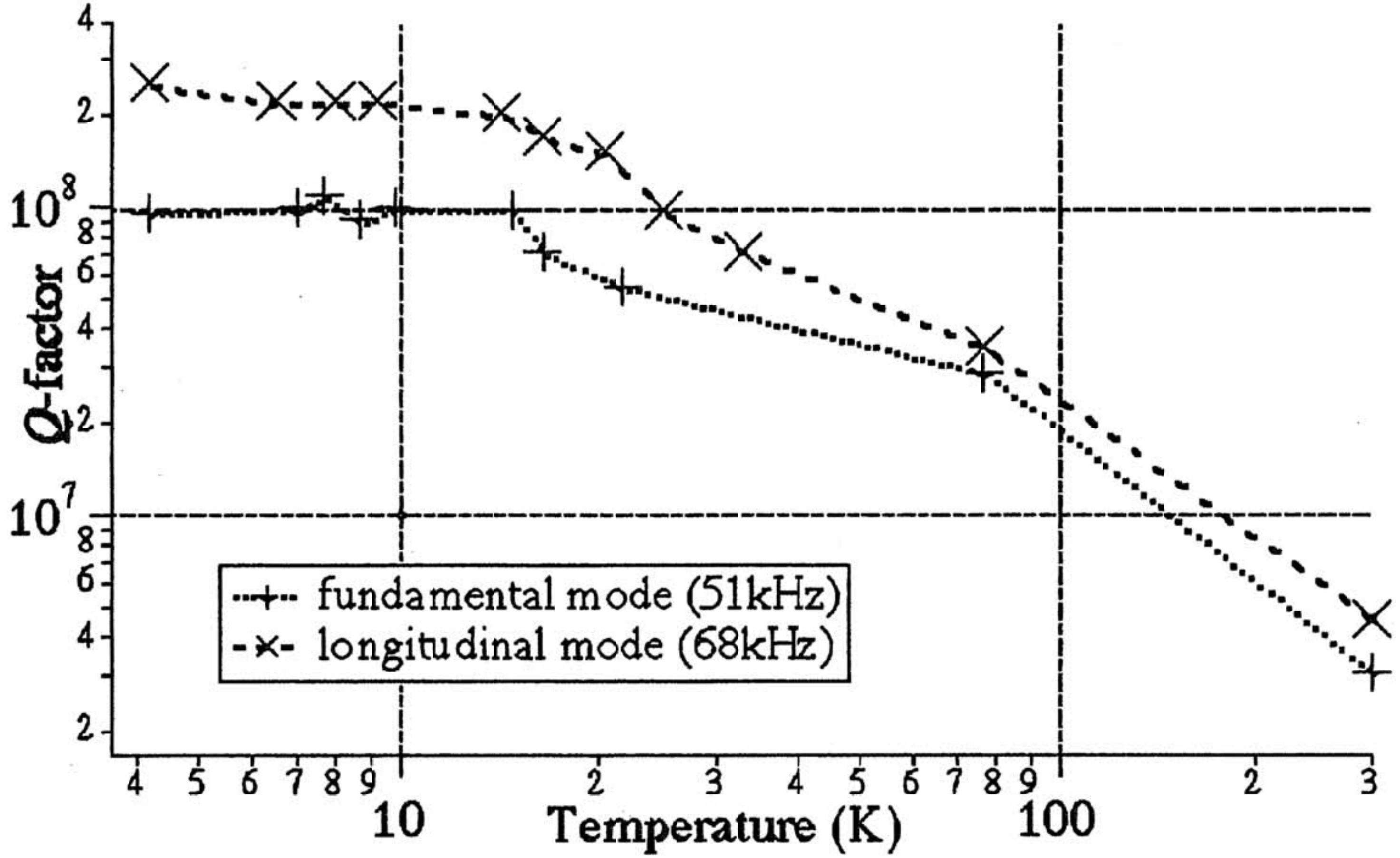
T. Uchiyama *et al.*, Physics Letters A 273 (2000) 310.

Thermal noise of mirror substrate

Measurement of decay motion of cylindrical sapphire bulk

$Q = 1/\phi = 10^8$

Sufficiently small loss



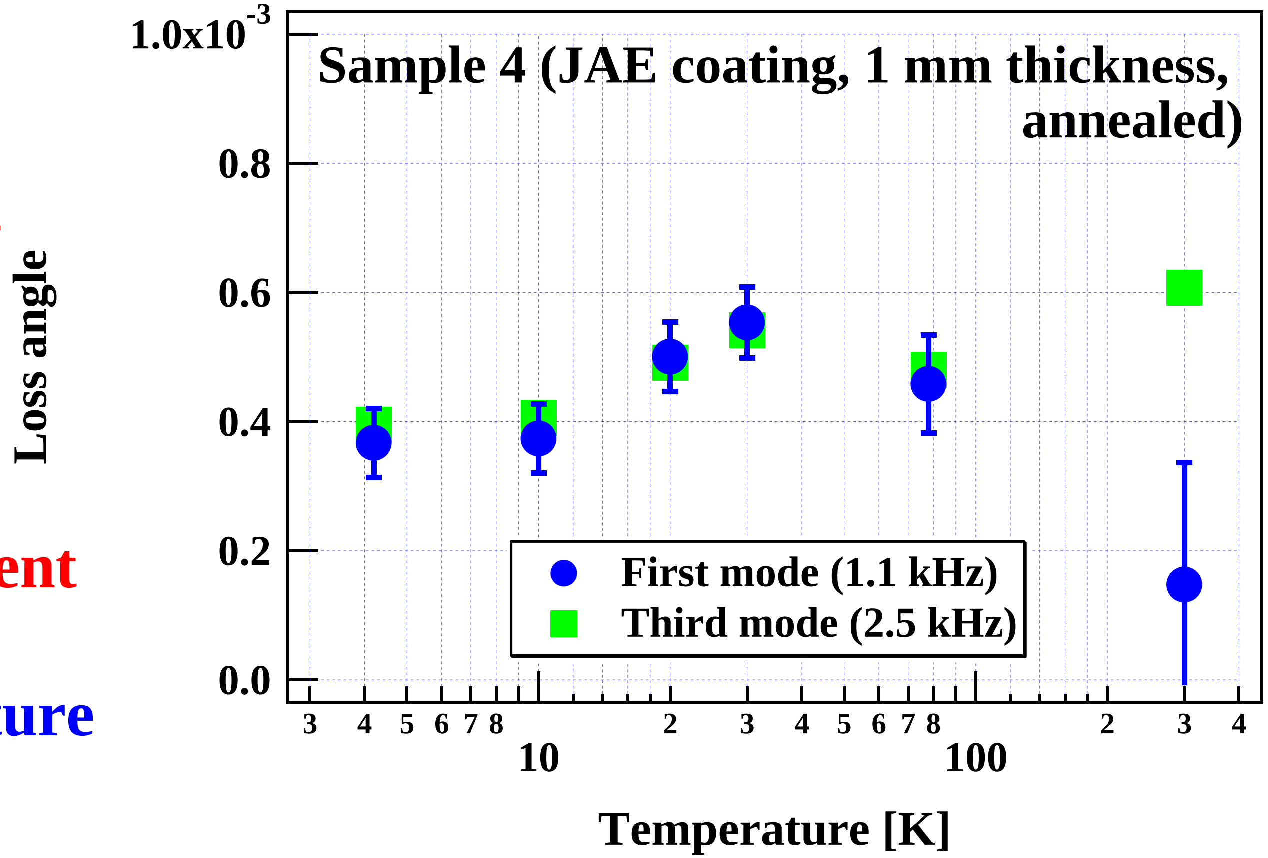
T. Uchiyama *et al.*, Physics Letters A 261 (1999) 5.

Thermal noise of reflective coating

Measurement of decay time of sapphire disk with and without coating

ϕ = (4 - 6) *10^{-4}

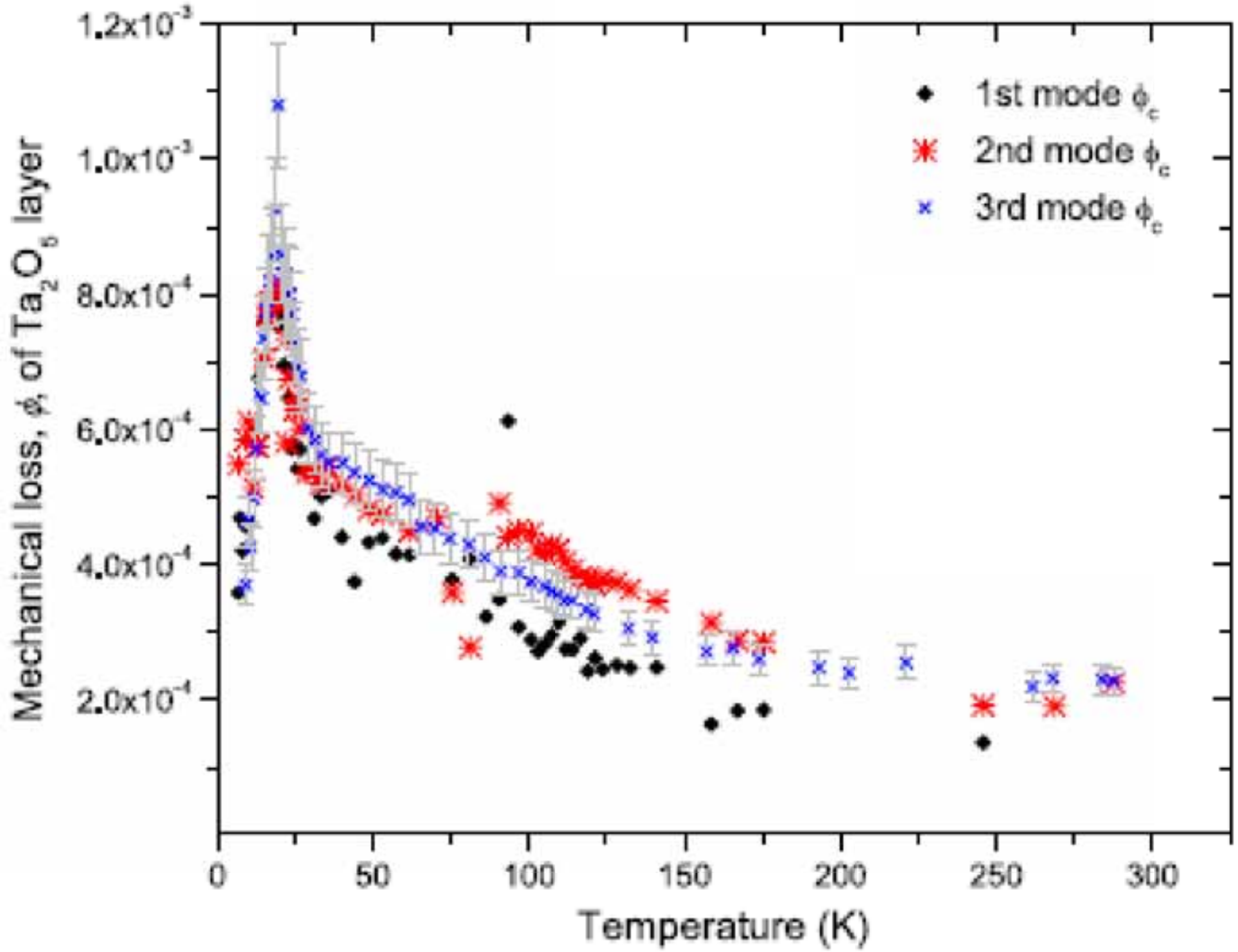
first measurement coating loss at low temperature



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

However, Glasgow group discovered loss peak around 20 K !

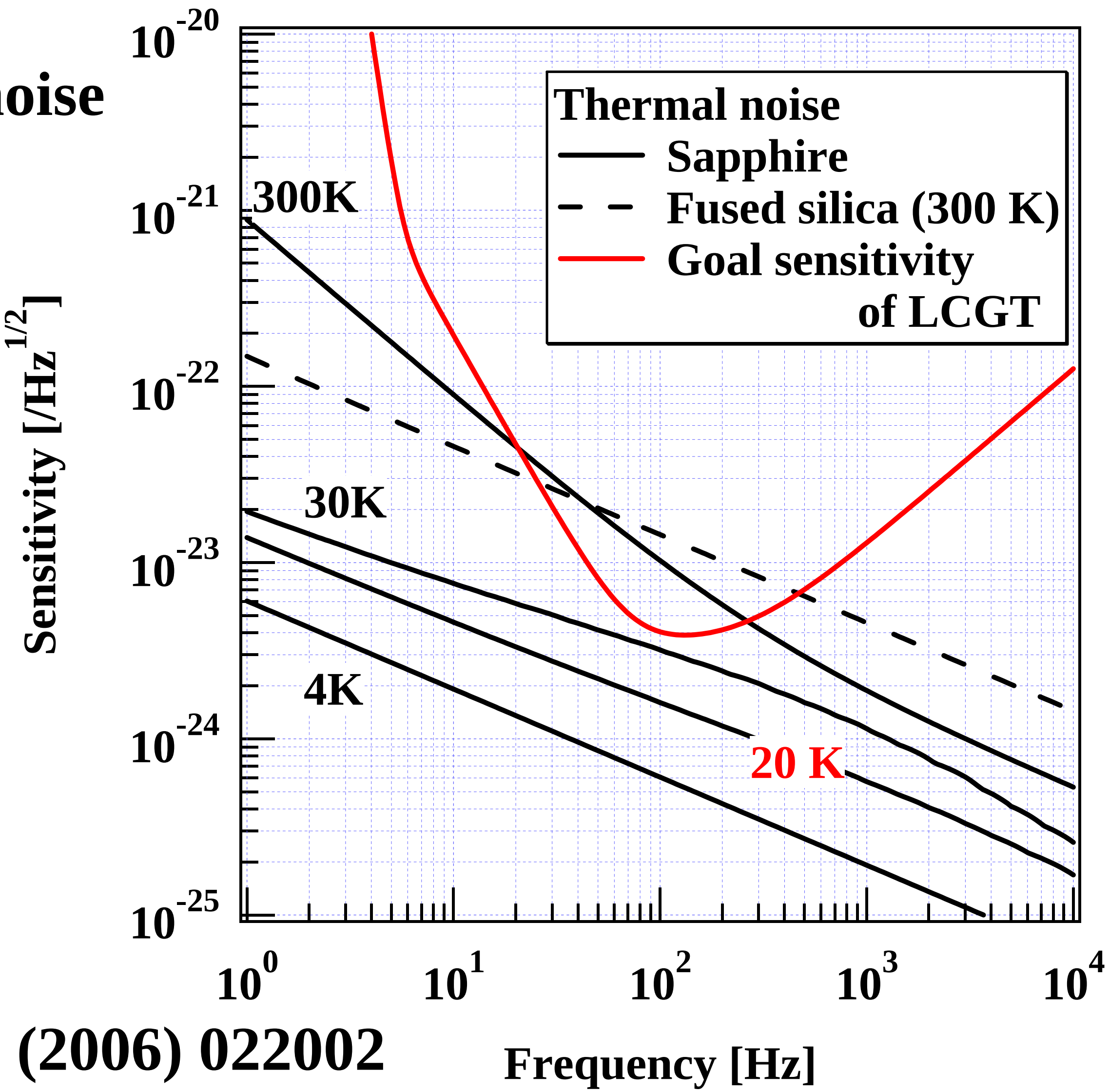
Difference of vender ???
Investigation is necessary.



I. Martin *et al.*, Classical and Quantum Gravity 25 (2008) 055005.

Summary of mirror thermal noise

Mirror thermal noise in LCGT



K. Yamamoto et al.,

Physical Review D 74 (2006) 022002

(2) Thermal lens

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

Thermal lens : Optical deformation of mirror by power absorption

Thermal gradient
and temperature coefficient of refractive index

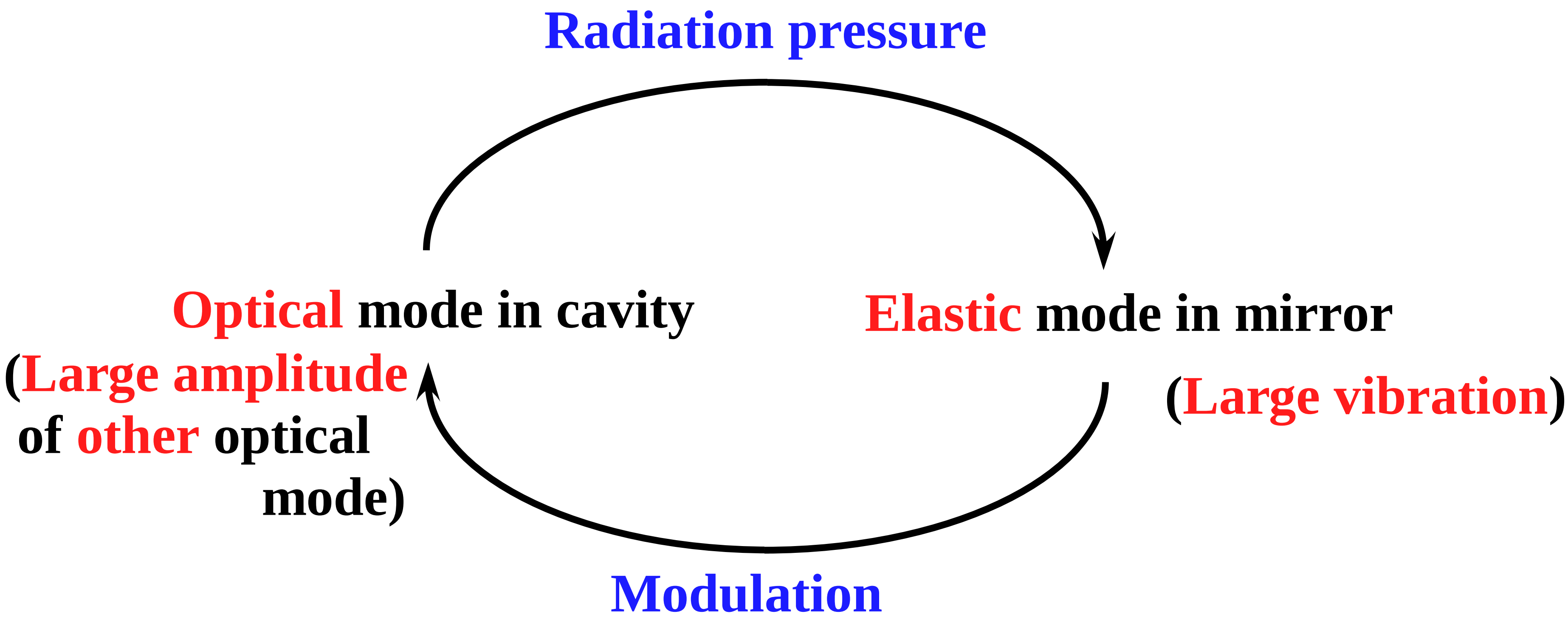
At low temperature (Sapphire)

Large thermal conductivity : No thermal gradient
Small temperature coefficient of refractive index

Thermal lens effect is negligible.

(3) Parametric instability

K. Yamamoto *et al.*,
Journal of Physics:Conference Series 122 (2008) 012015.



V.B. Braginsky *et al.*, Physics Letters A 287 (2001) 331.

(3) Parametric instability

K. Yamamoto *et al.*,
Journal of Physics:Conference Series 122 (2008) 012015.

Less serious problem (than that of Advanced LIGO)

Number of unstable modes

Advanced LIGO : 20 ~ 60 LCGT : 2 ~ 4

Mirror curvature

Advanced LIGO : Instability strength strongly depends on mirror curvature.

LCGT : Instability strength weakly depends on mirror curvature.

Why ?

Mirror material (LCGT:Sapphire, Ad. LIGO:fused silica)

Larger beam in Advanced LIGO to reduce thermal noise

← Thermal noise reduction

(4)Cosmic ray particles

K. Yamamoto *et al.*, Physical Review D 78 (2008) 022004.

Process of cosmic-ray excitation

(i) Passage of cosmic ray particle in mirrors

(ii) Energy deposition and temperature gradient

(iv) Thermal stress and elastic vibration of mirror

At low temperature (Sapphire)

Large thermal conductivity
Small specific heat → Fast thermal relaxation

Decay time of thermal stress

Room temperature : about 1000 sec
Cryogenic temperature : about 10 msec

Since thermal stress disappears immediately in cryogenic mirror, the effect of cosmic ray particles is small.

How about these merit of cooling mirror and suspension in Einstein Telescope ?

(1) Thermal noise

LCGT : Sapphire at 20 K

ET : Silicon at 20 K or 120 K ?

Thermal expansion is zero.

→ Thermal noise by thermoelastic damping is zero.

Temperature tuning system is necessary.

Some methods to suppress the coating thermal noise

Khalili cavity ? Waveguide grating mirror ?

Larger or Higher Laguerre-Gaussian mode beam ?

(2) Thermal lens

Thermal conductivity of silicon at low temperature is high.

→ Small thermal gradient

Temperature coefficient of refractive index ? Absorption in silicon ?

Waveguide grating mirror (all reflective)

→ Thermal lens and substrate absorption is not problems.

How about these merit of cooling mirror and suspension in Einstein Telescope ?

(3) Parametric instability

Parametric instability depends on configuration of interferometer.

Some tricks for thermal noise suppression make instability serious.

Investigation is necessary.

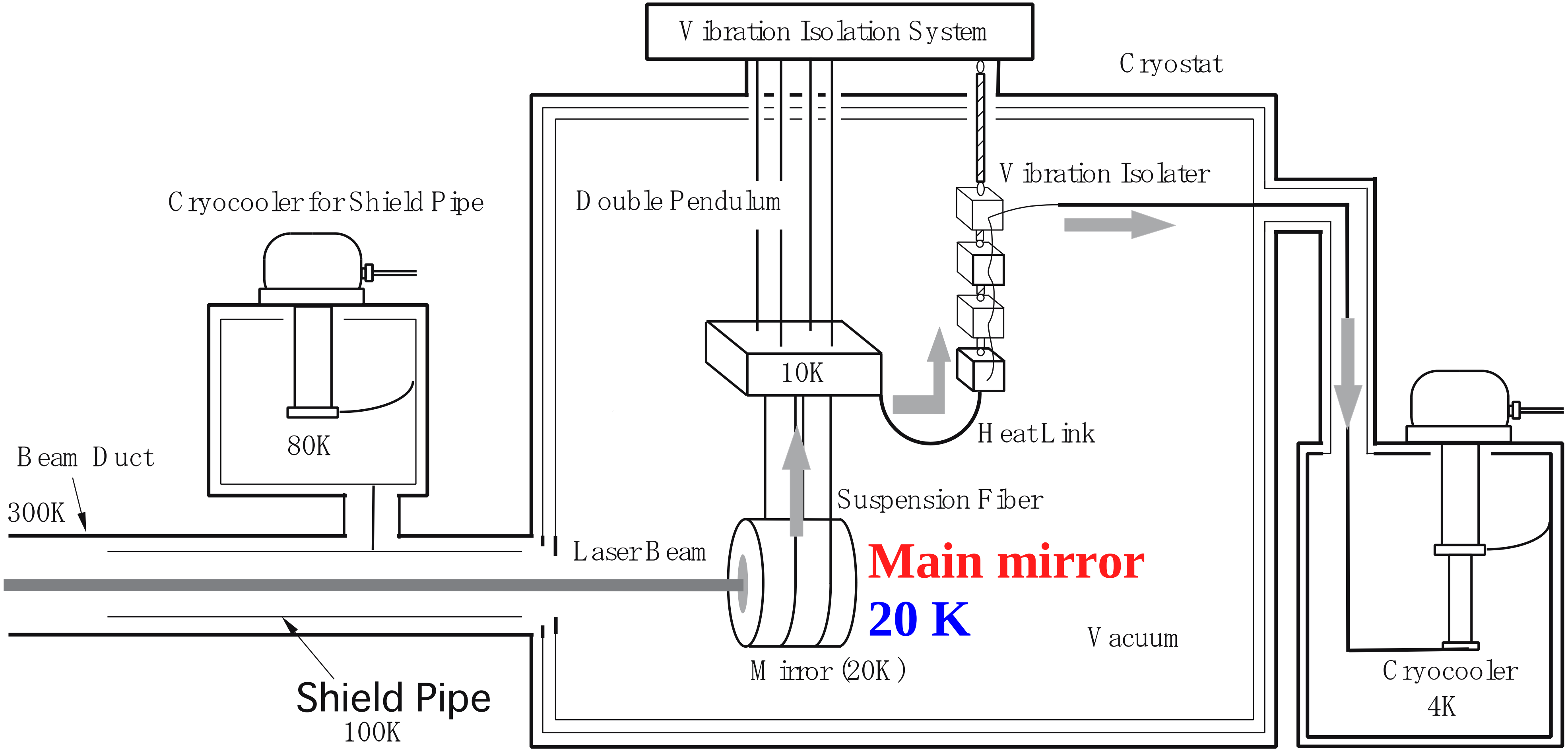
K. Yamamoto ET-029-09

(4)Cosmic ray particles

This effect is small as like LCGT.

4-2. Technique for cooling mirror and suspension

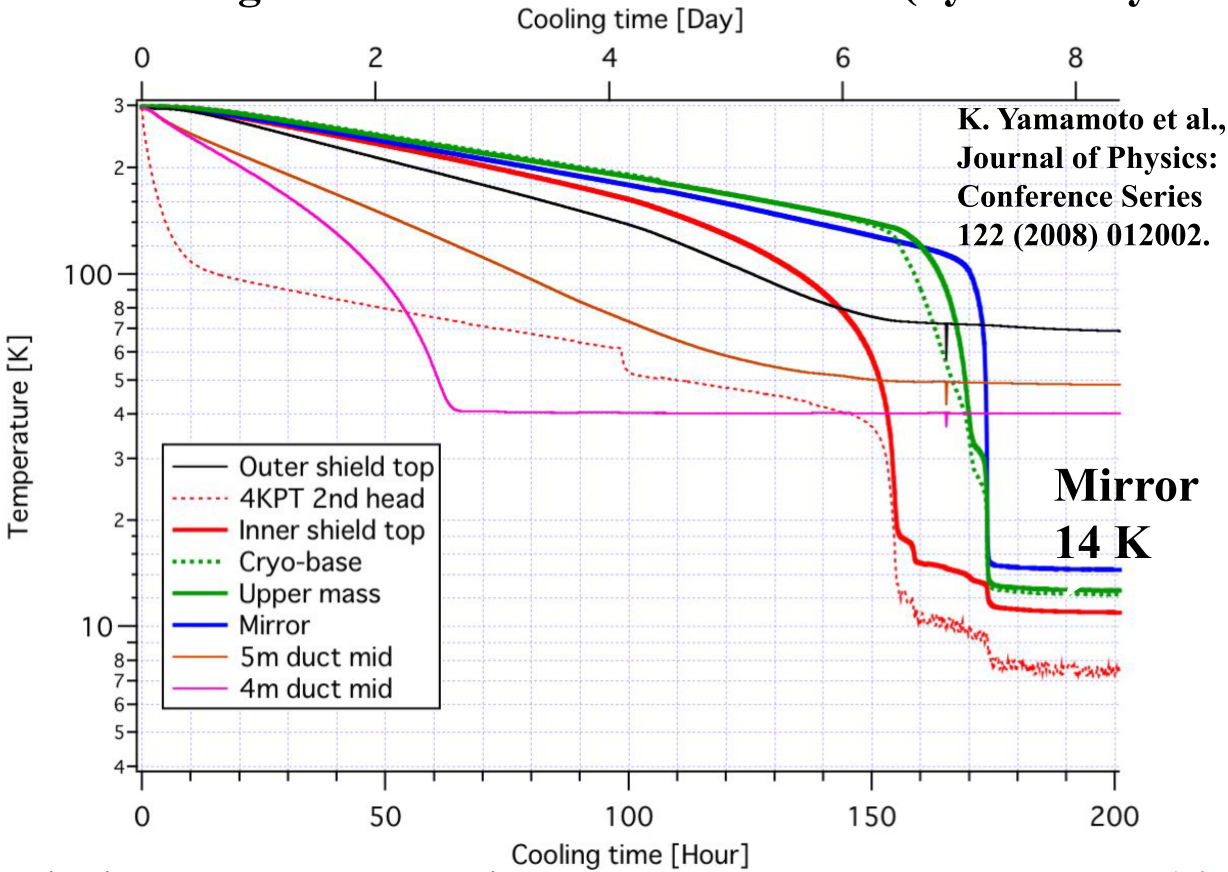
Schematic view of cryostat (by T. Tomaru)



CLIO cryostat have already been installed

(different scale from that of LCGT).

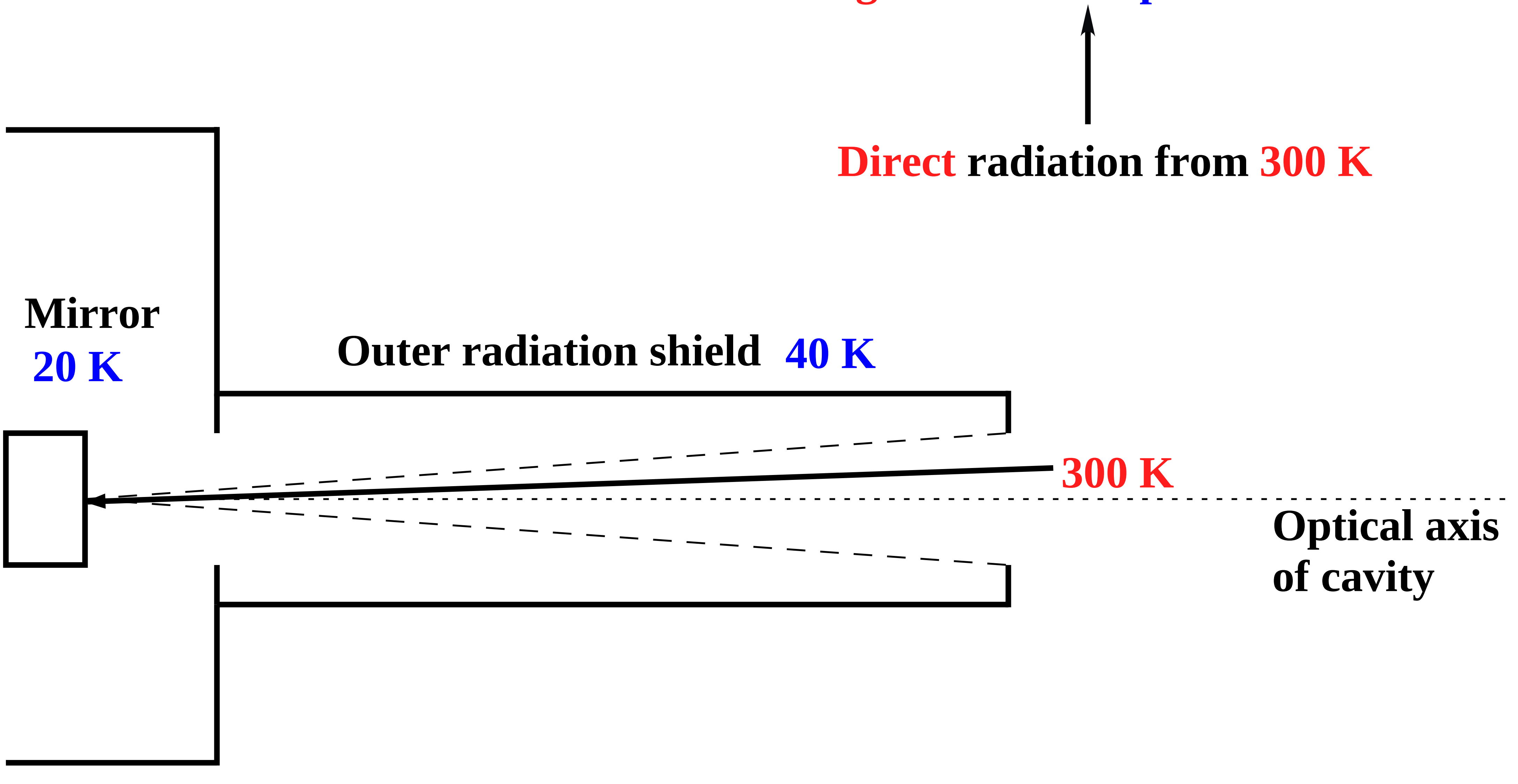
Mirror cooling test in CLIO (by T. Uchiyama)



Within about a week, mirror temperature became about 14 K (mirror temperature must be below 20 K), but ...

Heat into mirrors

Heat into a mirror is about 1000 times larger than the expected value !



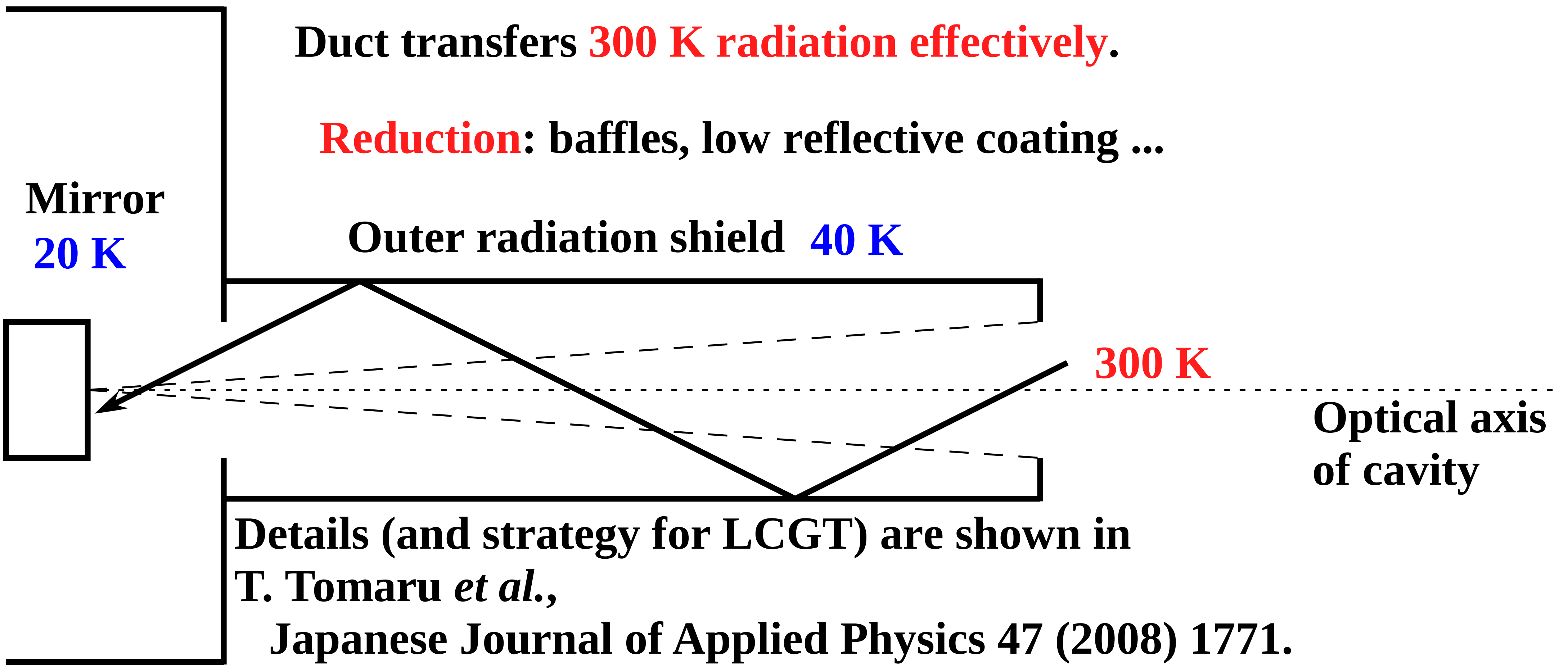
Heat into mirrors

Outer radiation shield does not absorb, but reflects radiation !

Indirect radiation (reflected by shield) from 300 K is large !
(We neglected it ...)

Duct transfers 300 K radiation effectively.

Reduction: baffles, low reflective coating ...



Details (and strategy for LCGT) are shown in
T. Tomaru *et al.*,
Japanese Journal of Applied Physics 47 (2008) 1771.
Journal of Physics:Conference Series 122 (2008) 012009.

Cryocooler

Why ?

Usual case : Liquid nitrogen and helium

Safety and maintenance in mine

↓

Cryocooler

Usual cryocooler : Gifford-McMahon cryocooler

↓ **Large vibration**

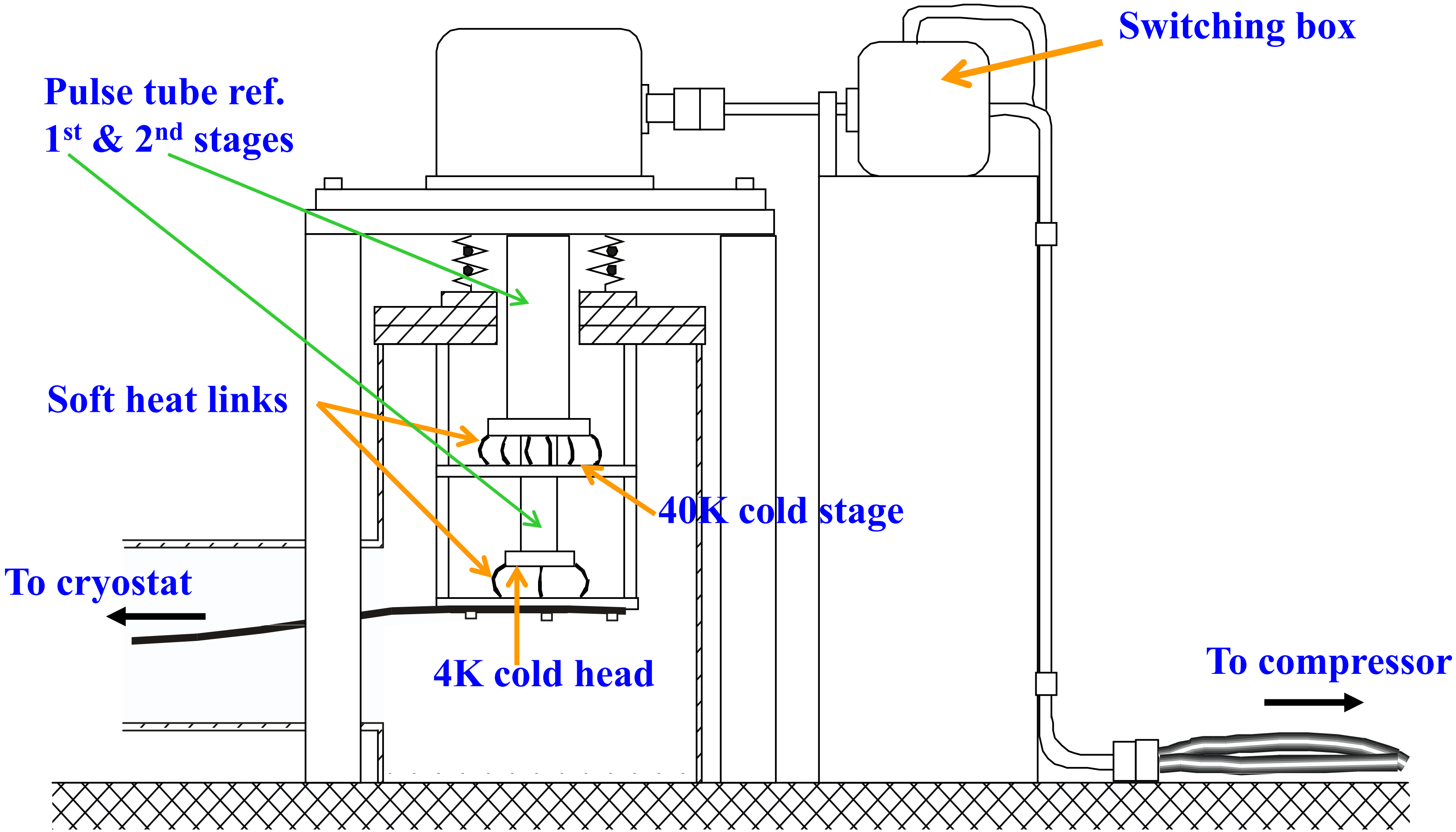
Pulse-tube cryocooler (without solid piston)

But, vibration of commercial one is not enough small.

Quiet refrigerator was developed (design in 2003)

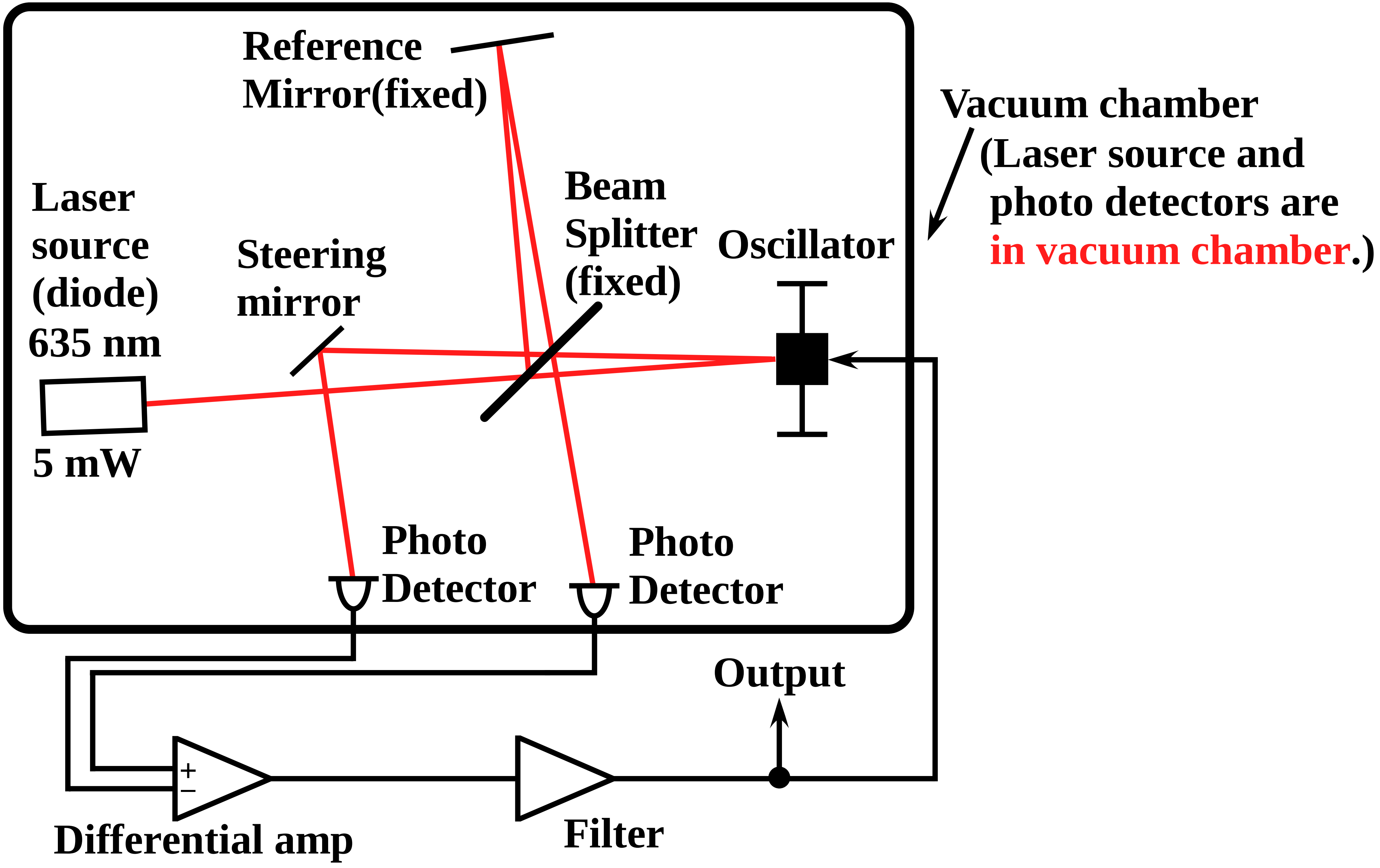
T. Tomaru *et al.*, Classical Quantum Gravity 21 (2004) S1005.
T. Tomaru *et al.*, Cryocoolers 13 (2005) 695.
R. Li. *et al.*, Cryocoolers 13 (2005) 703.

patent: Pa-3 Tomaru et al., 2003; Suzuki et al., 2003.

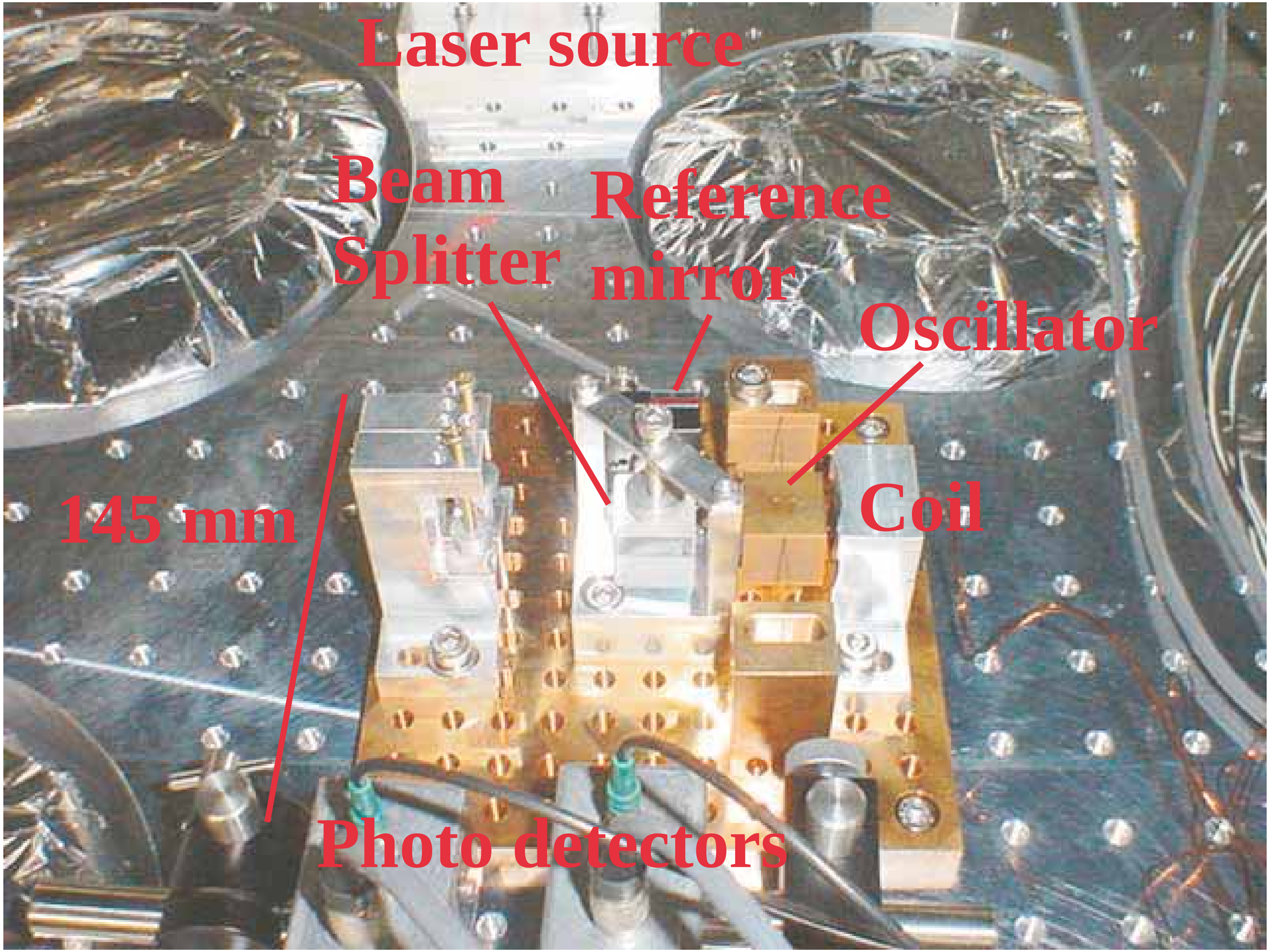


We measured vibration caused by new cryocoolers in Kamioka mine !
(suspension top of CLIO)

Schematic view of interferometer for vibration measurement



Interferometer



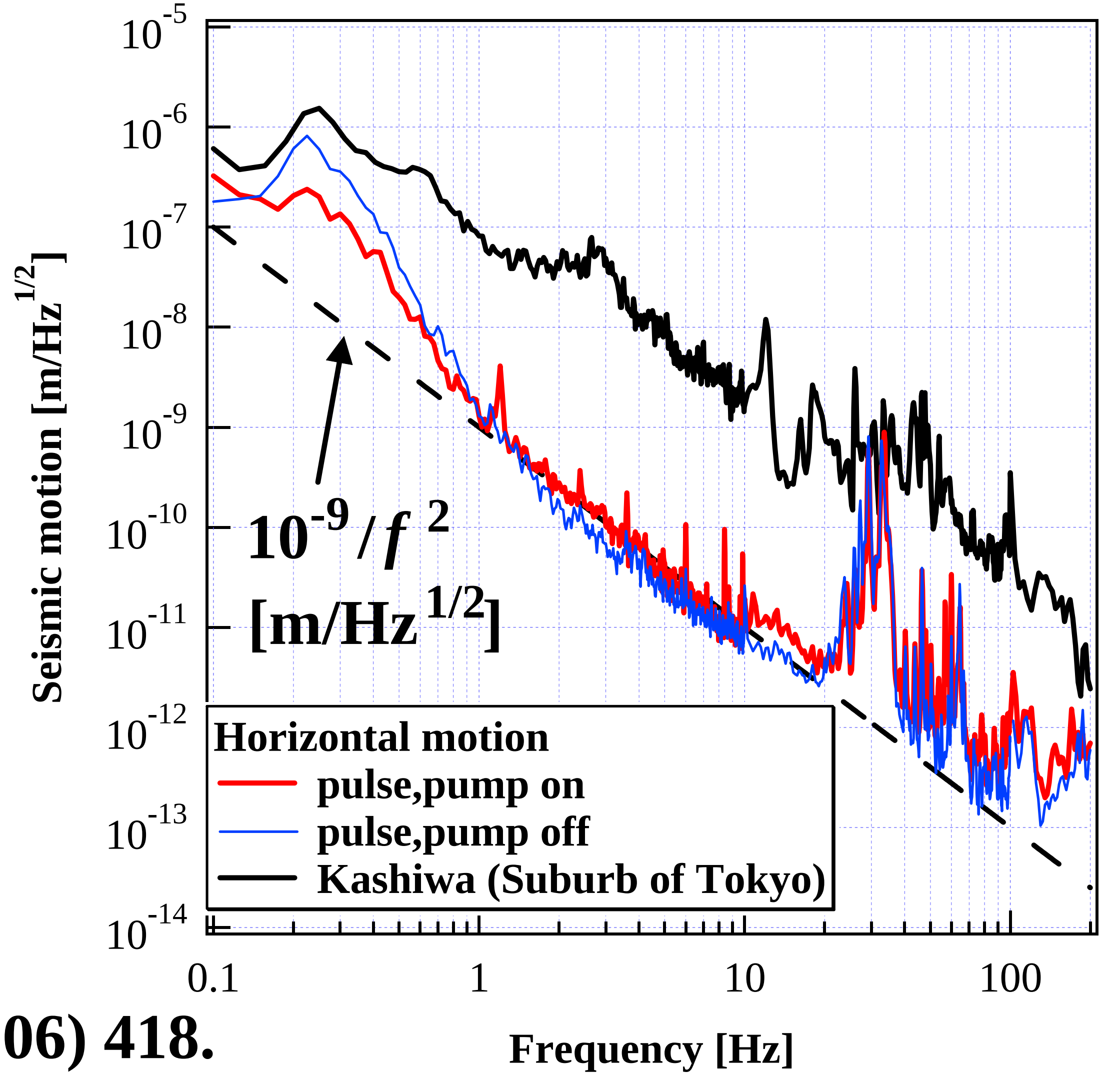
Results(1)

floor level (1 Hz-100 Hz)

$10^{-9}/f^{2}$ [m/Hz$^{1/2}$]

Cryocoolers do not increase vibration.

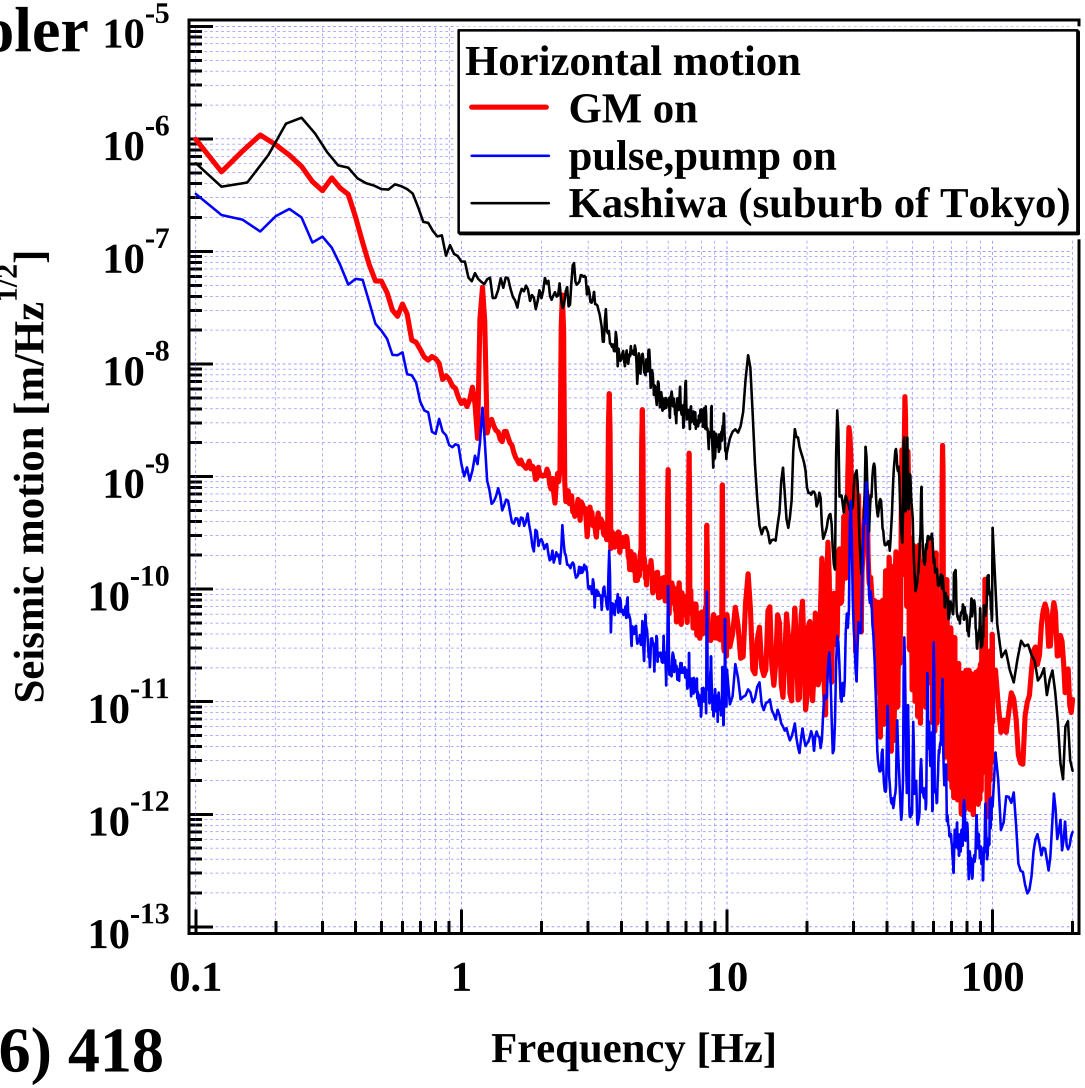
K. Yamamoto et al., Journal of Physics: Conference Series 32 (2006) 418.



Result(2)
Gifford-McMahon cryocooler

GM cryocooler increases vibration.

Above 30 Hz
Kashiwa (Tokyo) level !

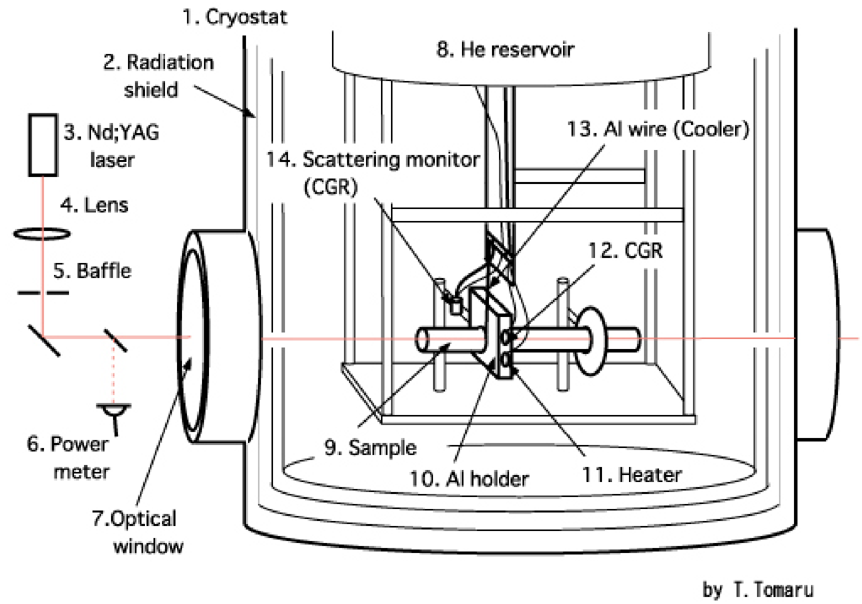


K. Yamamoto et al.,
Journal of Physics:
Conference Series 32 (2006) 418

Heat absorption in sapphire

Goal : 20 ppm/cm

Calorimetric measurement at low temperature



Short thermal relaxation time
High sensitivity measurement

Large thermal conductivity
Small specific heat

Sample	LCGT (5K)	Stanford	UWA
Hemex	-	-	24
Hemlite	90 - 99	-	-
CSI White	88 - 93	-	-
CSI White	-	-	3.4
CSI White	-	-	40
CSI White	-	47	-
CSI White	-	25	-

ppm/cm

Result : 100 ppm/cm

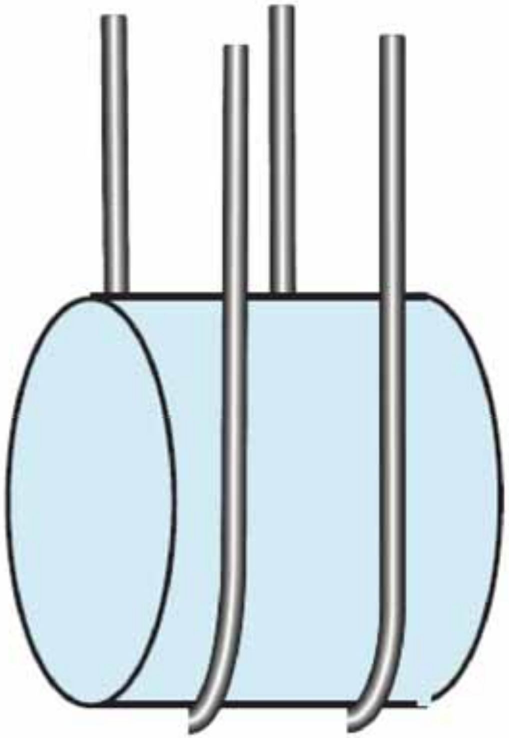
Recently, smaller values are reported (10-50 ppm/cm?).

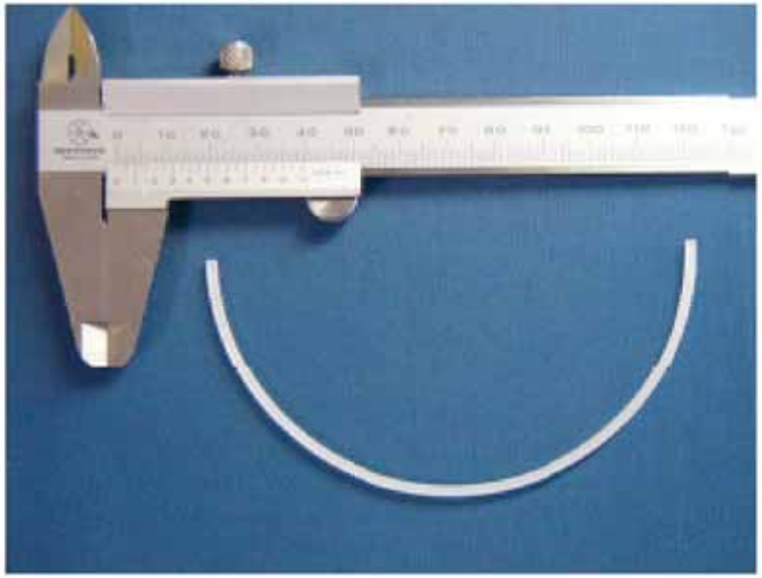
Our R&D is in progress.

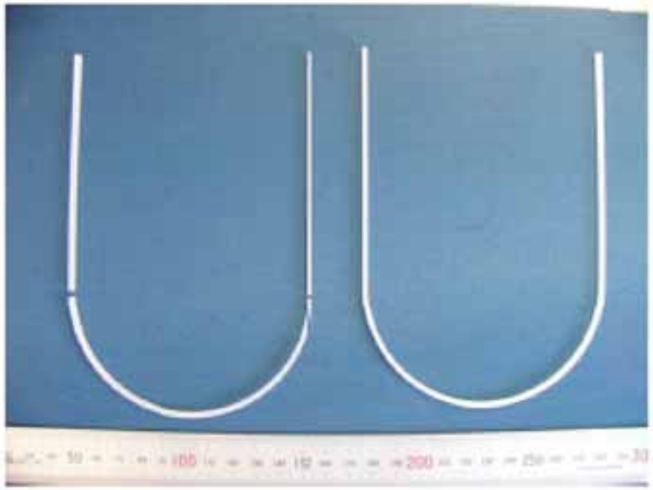
T. Tomaru *et al*., Physics Letters A 283(2001)80.

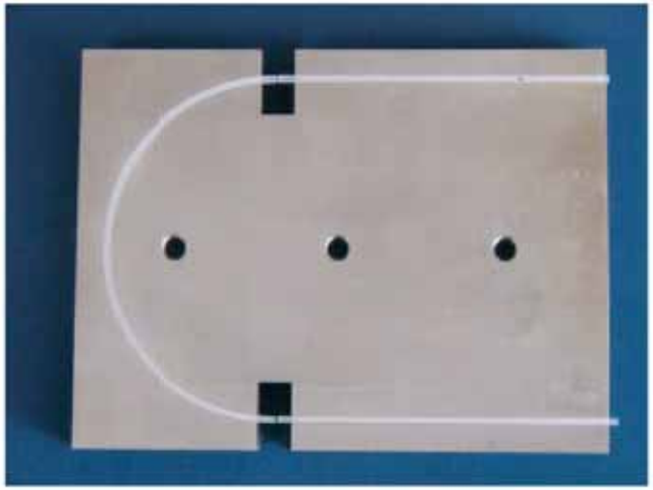
Sapphire mirror suspended by sapphire rods

(1)Making rods : Mechanical cutting









Samples in photo are smaller than LCGT mirror.

Sapphire mirror suspended by sapphire rods

(2)Sapphire-sapphire bonding

Direct bonding

(optical contact + diffusion bonding, without bonding agent, with heating)

Hydroxide-catalysis bonding

(polish + aqueous solution of potassium hydroxide, at room temperature)

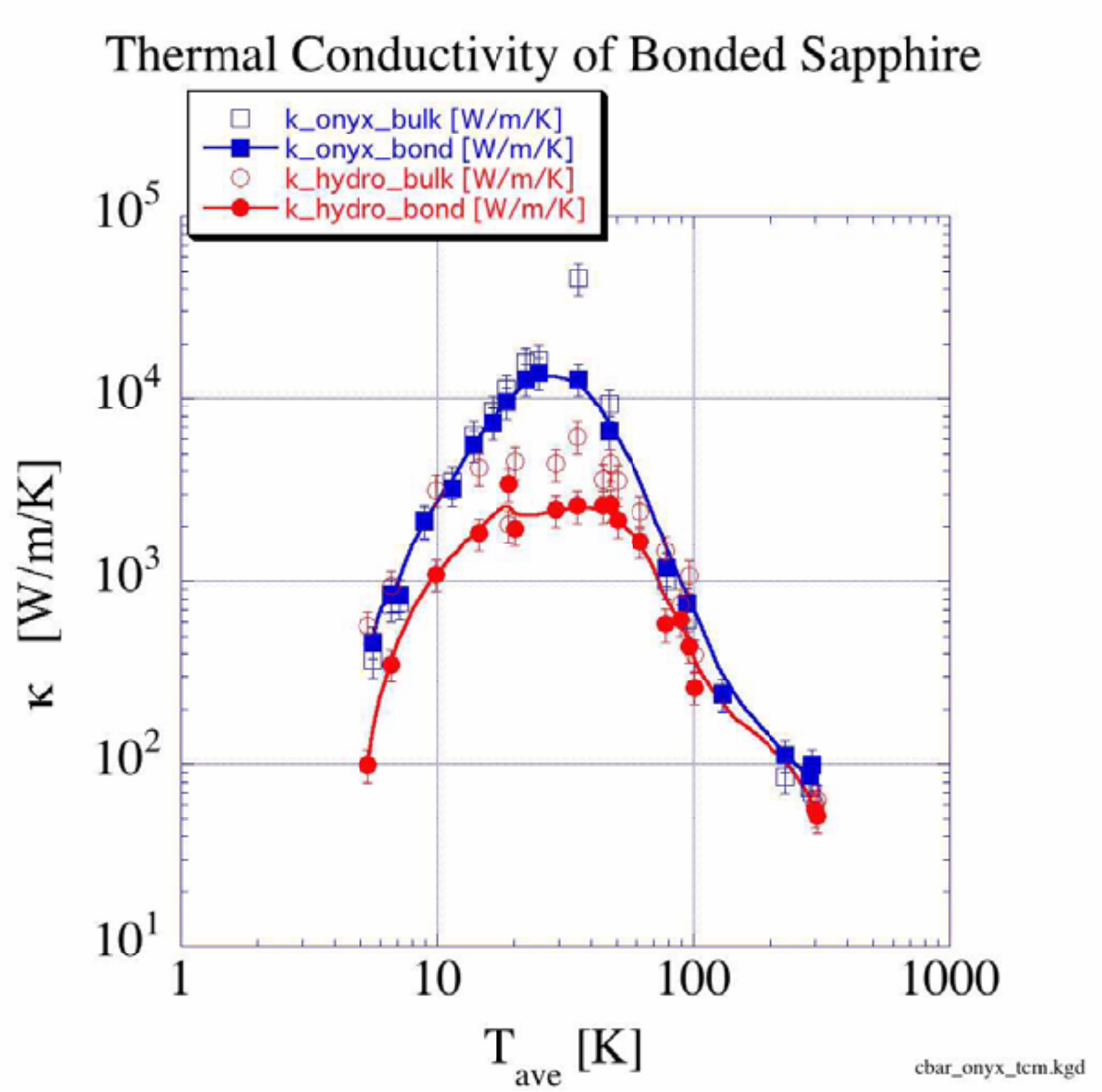
Thermal conductivity: OK

Strength: OK

Q-value of suspension: ?

R&D is in progress.
(other method (glue) also is tested.)

T. Suzuki *et al*., Journal of Physics: Conference Series 32 (2006) 309.



Other Cryogenic R&D papers

Mirror contamination

S. Miyoki *et al.*, Cryogenics 40 (2000) 61; 41 (2001) 415.

Actuator for cryogenic mirror

N. Sato *et al.*, Cryogenics 43 (2003) 425.

4. Summary

LCGT: Japanese 2nd generation interferometric gravitational wave detector

10 times better sensitivity than that of current LIGO and VIRGO
Complementary role with interferometers in U.S.A. and Europe

Quantum noise (shot noise and radiation pressure noise)
High power laser   Resonant Sideband Extraction

Seismic noise
Silent underground site   Vibration isolation system

Thermal noise
Cryogenic technique

Same keywords as those of Einstein Telescope (European 3rd generation)

Most important and serious problem is

budget !!!

About 100 millions Euro

Thank you for your attention !

Vi ringrazio molto per la vostra attenzione ！

ご静聴ありがとうございました。