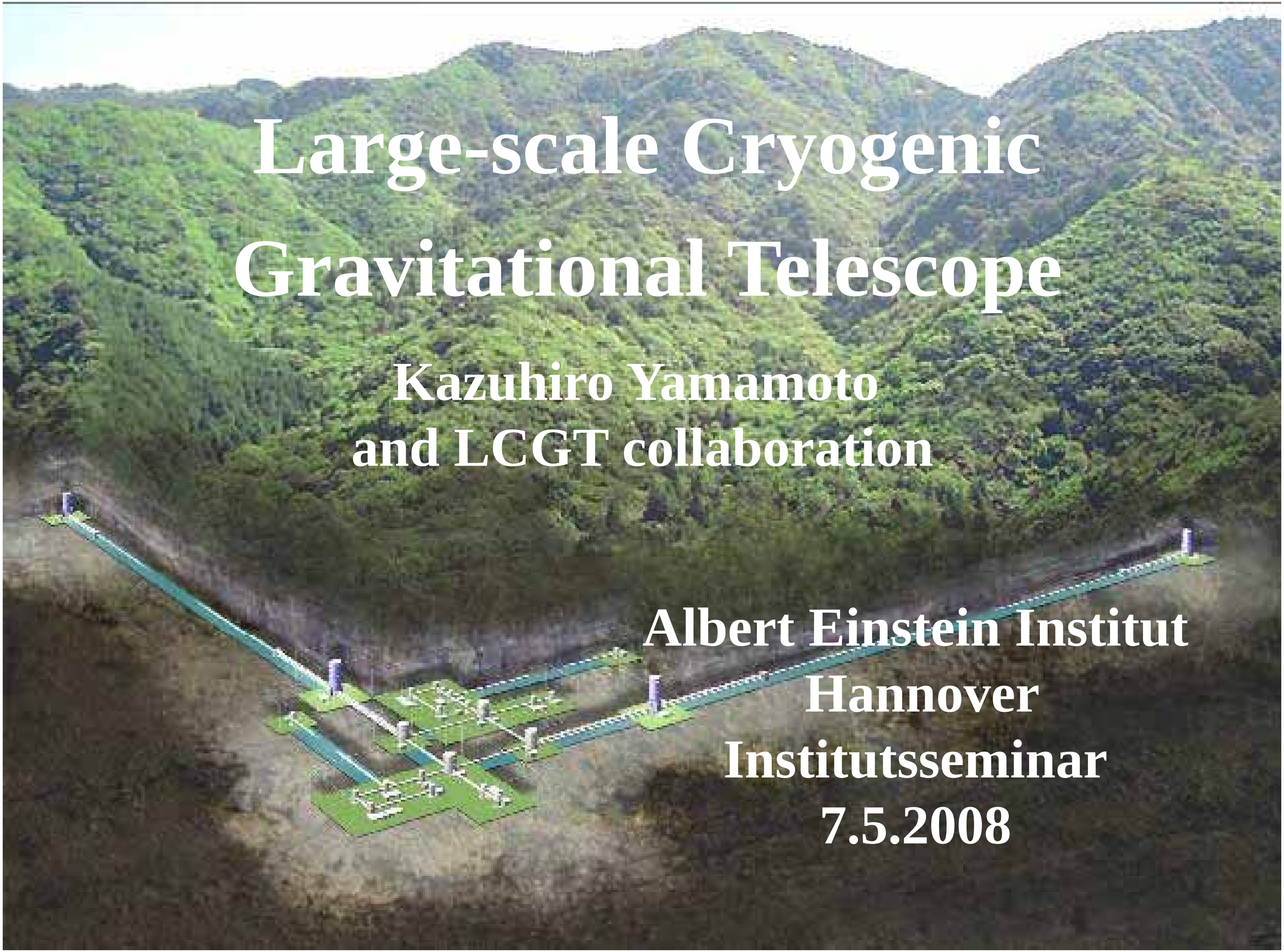


Large-scale Cryogenic Gravitational Telescope

Kazuhiro Yamamoto
and LCGT collaboration

Albert Einstein Institut
Hannover
Institutsseminar
7.5.2008

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 !

K. Kuroda will talk LCGT review at Elba (GWADW workshop)
on next week.

Contents

1. Introduction

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)

Observable distance: 200 Mpc

A few event per a month

Third generation (Einstein Telescope)

Observable distance: 2 Gpc ?

Many events !

Sensitivity of interferometer

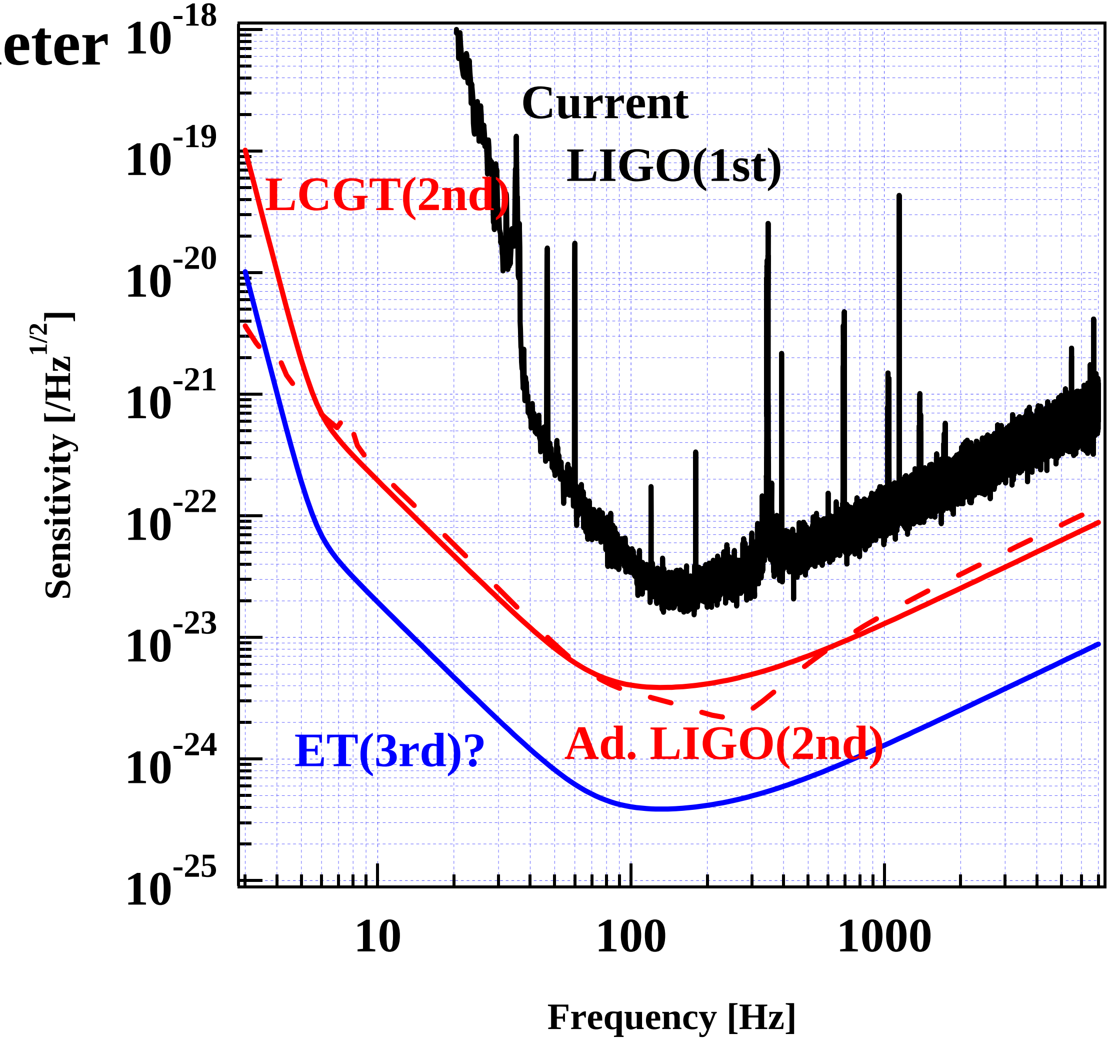
1st generation

↓ **10 times**

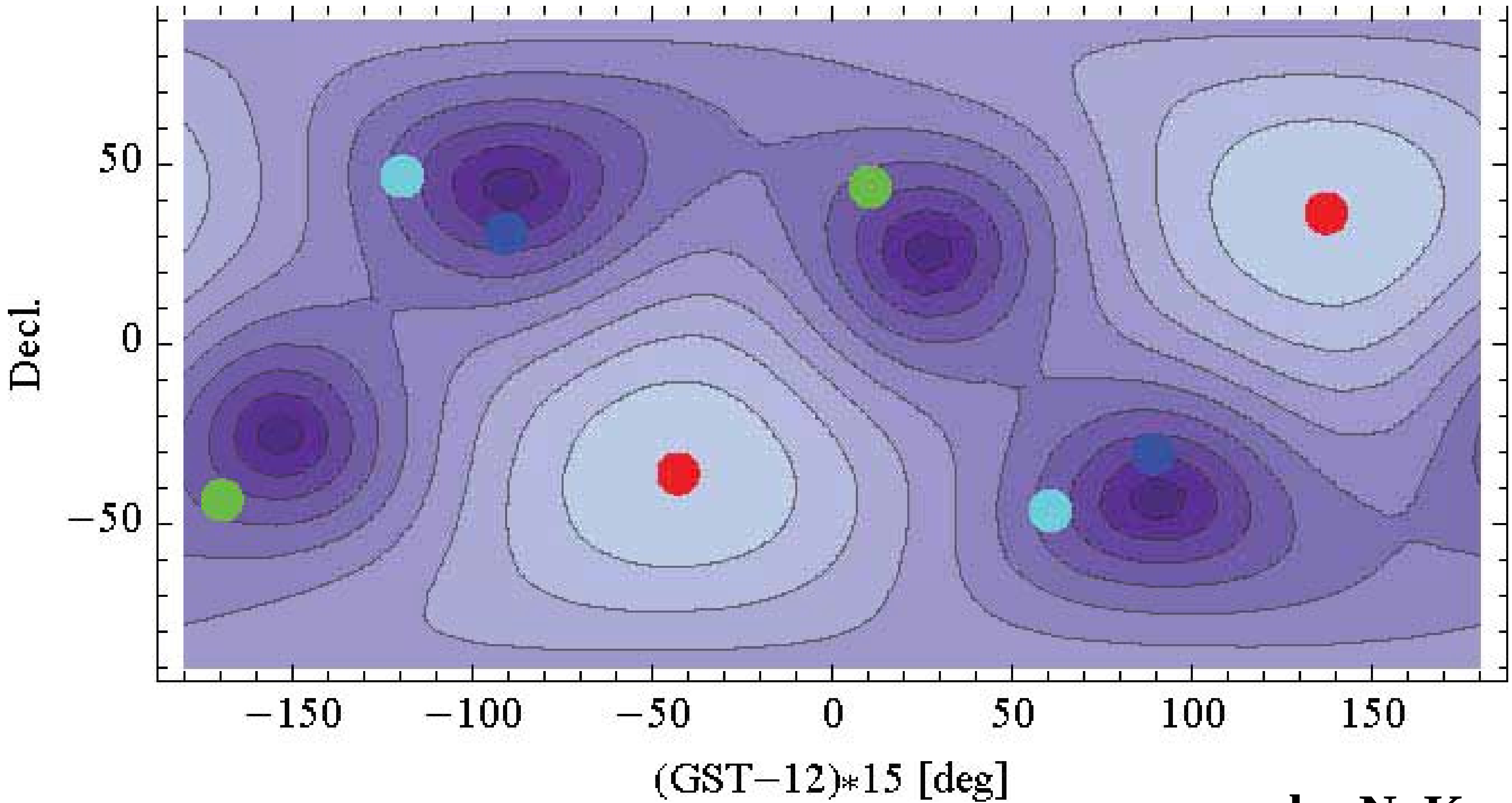
2nd generation

↓ **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 **2 interferometers**

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

How will we construct such an excellent detector ?

smaller noise **2 interferometers**

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 **2 interferometers**

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

Same keywords as those of ET

Noise budget of LCGT

Above 10 Hz

Quantum noise limited

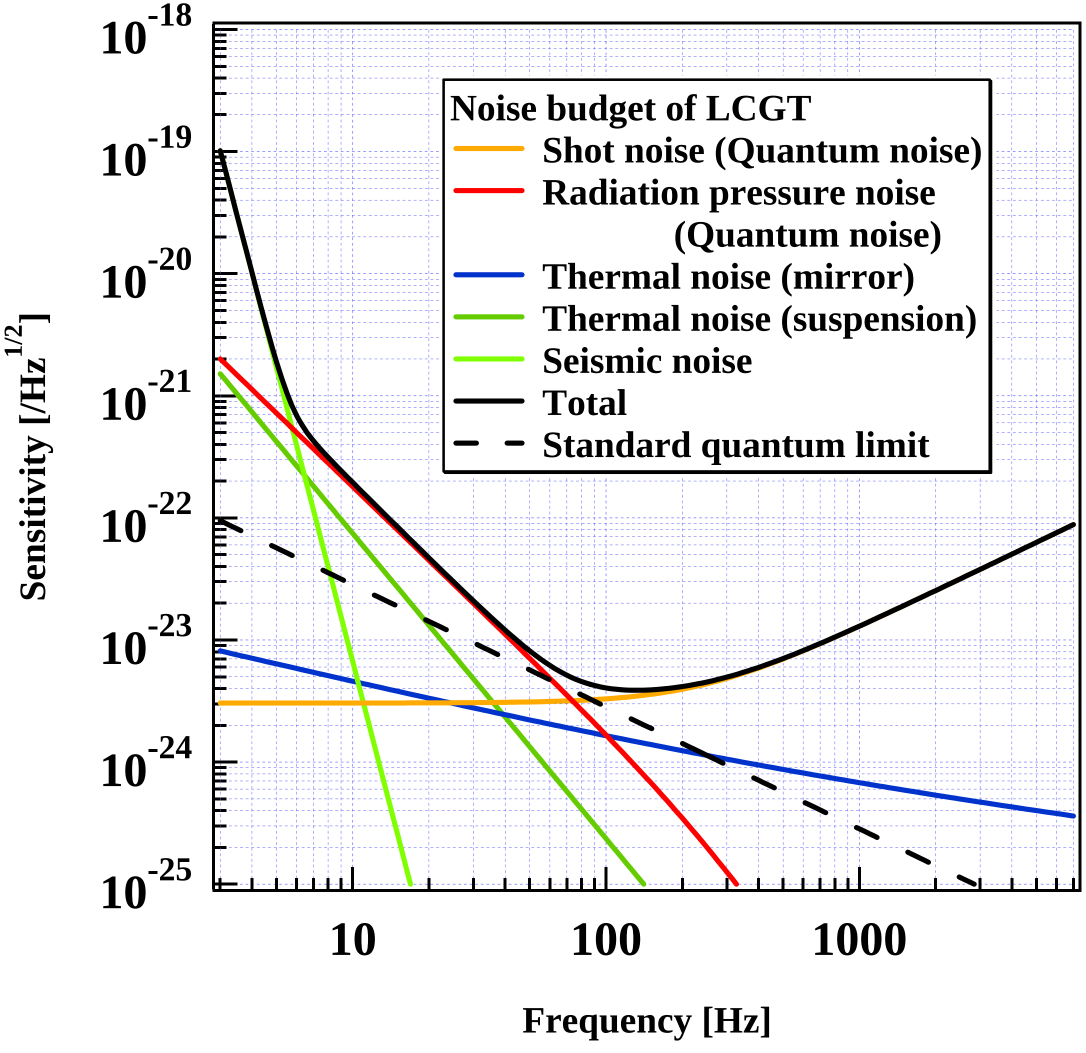
Standard Quantum Limit

Around 80 Hz

Thermal noise

never limits

sensitivity.

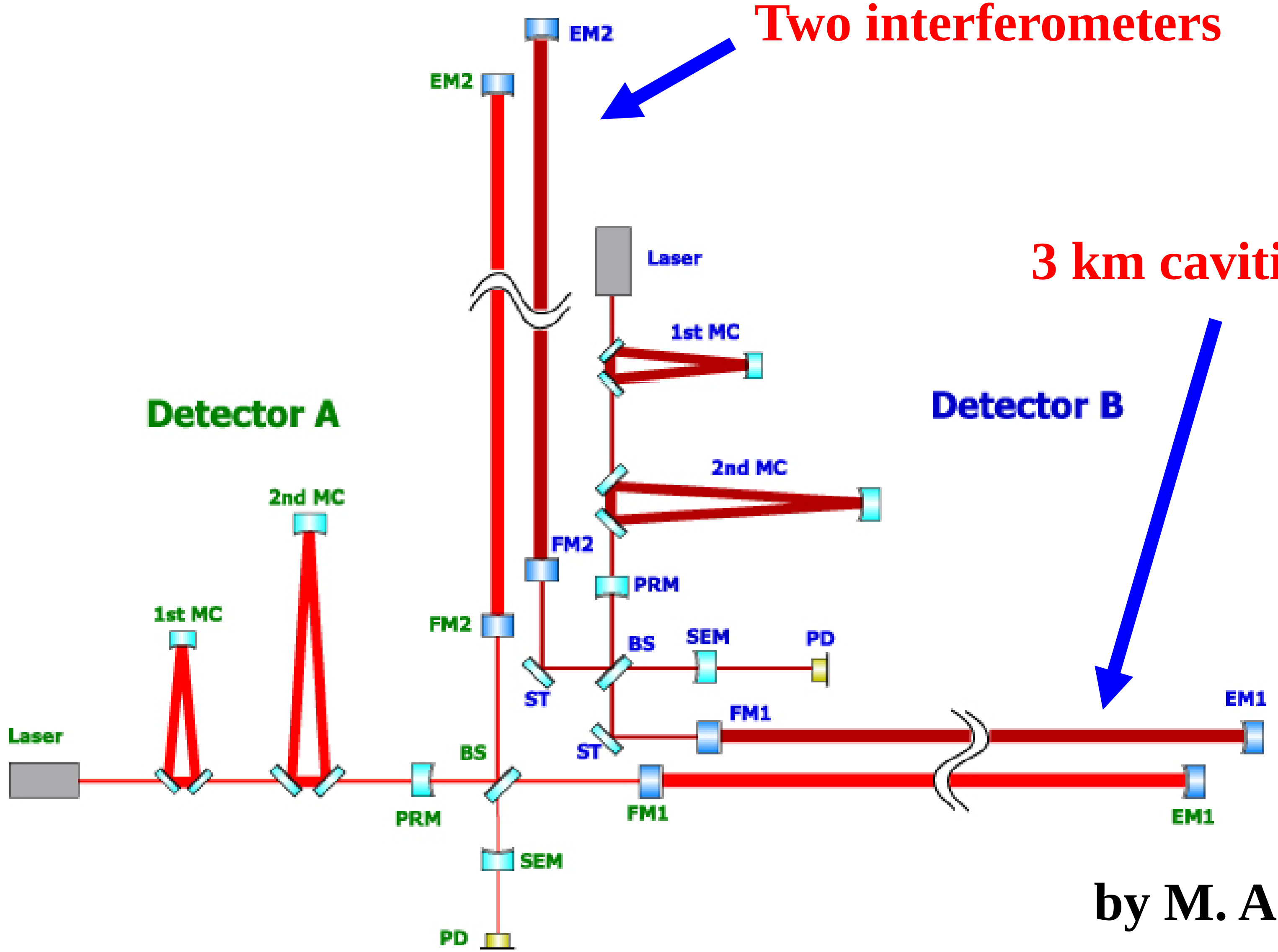


2. Quantum noise

2-1. Configuration of LCGT detector

Two interferometers

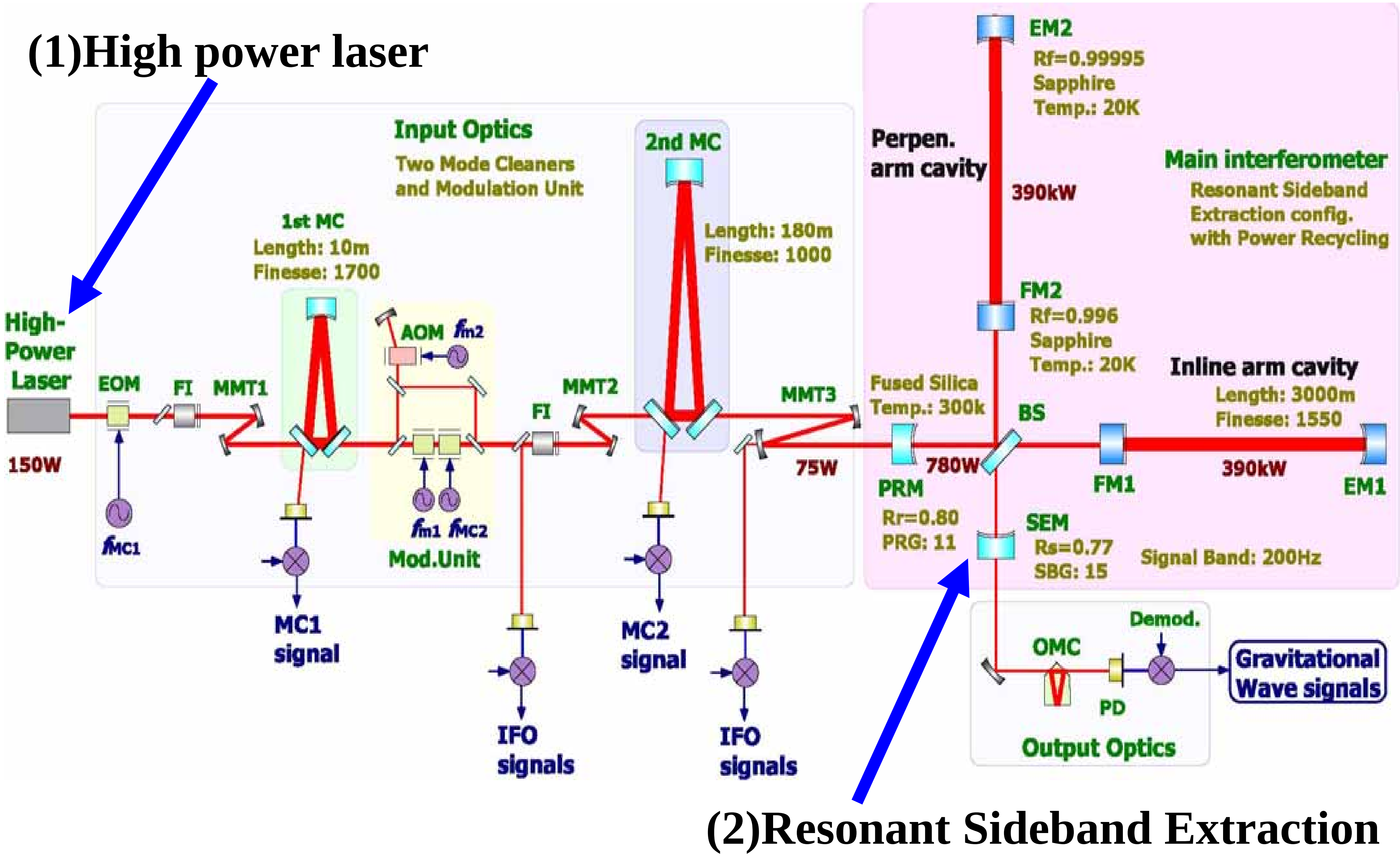
3 km cavities



by M. Ando

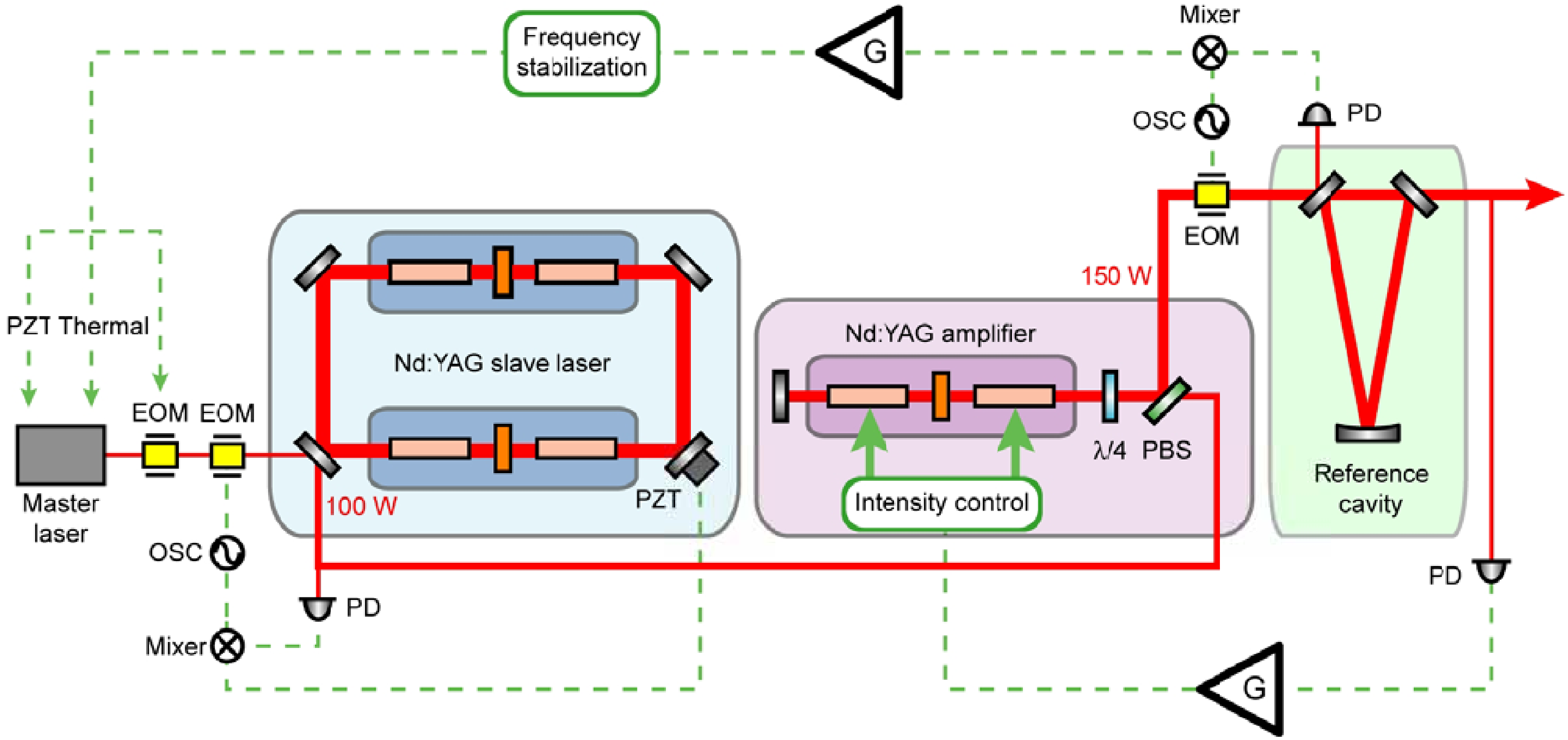
2-2. Configuration of LCGT interferometer

by M. Ando



2-3. High power laser

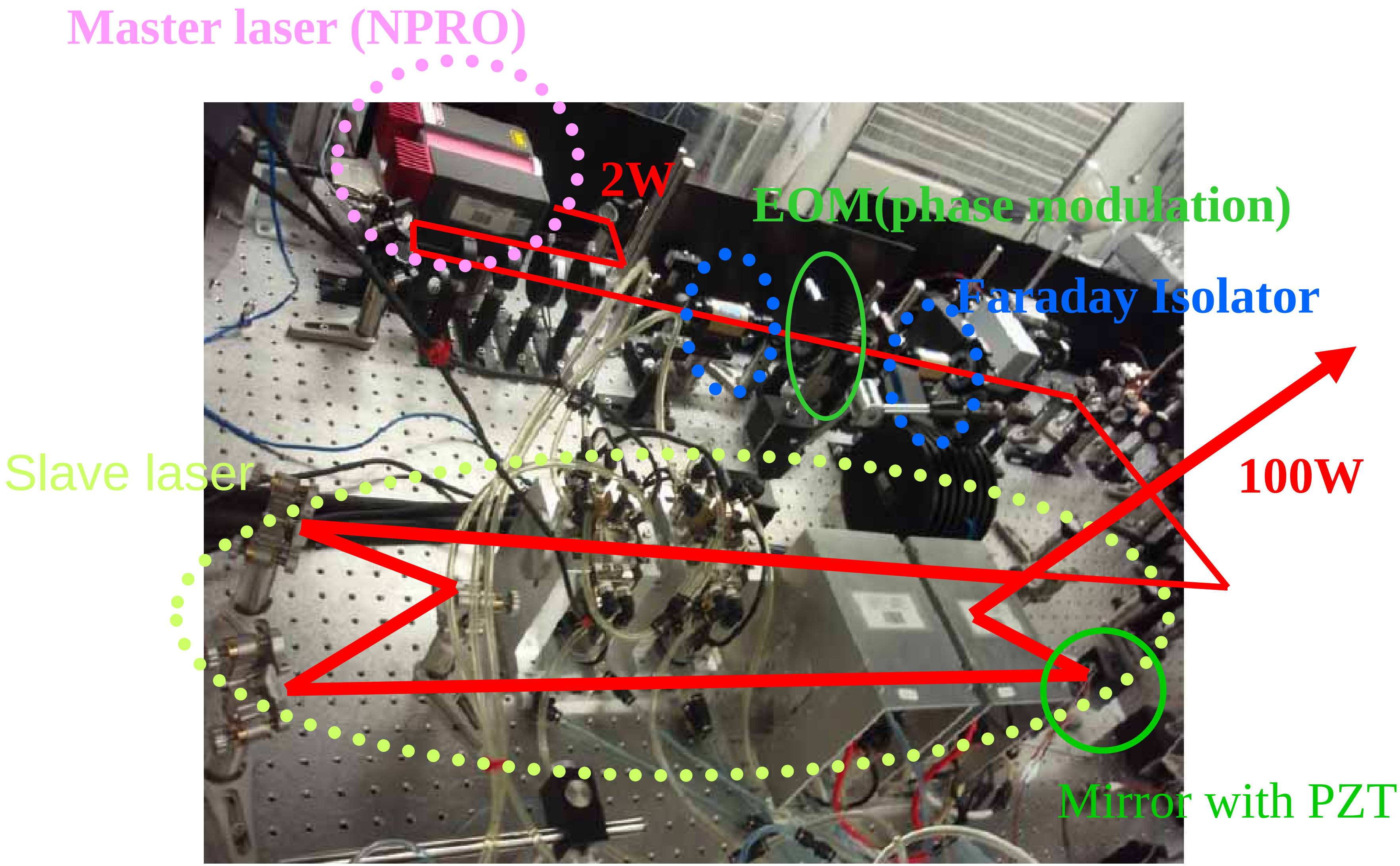
Goal : 150 W **Current status : 100 W**



Development by University of Tokyo and Mitsubishi

K. Takeno *et. al.*, Optics Letters 30 (2005) 2110.
N. Ohmae *et. al.*, Applied Physics Express 1 (2008) 012005.

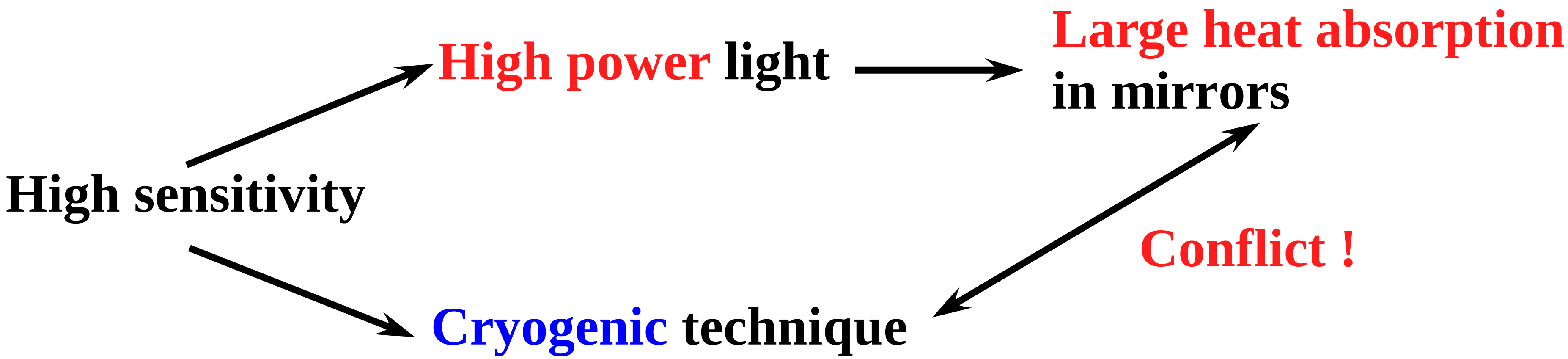
Photograph of laser source



2-4. Resonant Sideband Extraction (RSE)

What ? : One of the interferometer configurations
New mirror between Beam splitter and Photo detector

Why ? : Solution for thermal problem



RSE is magic for low heat absorption with high power light.

This advantage is pointed out in abstract of first RSE paper.

Physics Letters A 175 (1993) 273–276
North-Holland

Resonant sideband extraction: a new configuration for interferometric gravitational wave detectors

J. Mizuno, K.A. Strain, P.G. Nelson, J.M. Chen, R. Schilling, A. Rüdiger, W. Winkler and K. Danzmann
Max-Planck-Institut für Quantenoptik, Ludwig-Prandtl-Strasse 10, W-8046 Garching near Munich, Germany

Received 10 December 1992; revised manuscript received 27 January 1993; accepted for publication 15 February 1993
Communicated by J.P. Vigier

Abstract is in next page. →

Abstract

We introduce a new Fabry-Perot based interferometric gravitational wave detector that, compared with previous designs, greatly decreases the amount of power that must be transmitted through optical substrates to obtain a given light power in its arms. This significantly reduces the effects of wavefront distortions caused by heating due to absorption in the optics, and allows an improved broadband sensitivity to achieved.

(Red by K. Yamamoto)

Recent papers (Broadband RSE, not detuned)

Lock without power recycling

O. Miyakawa *et al.*, Classical and Quantum Gravity 19 (2002) 1555.

Signal extraction scheme with power recycling (Theory)

S. Sato *et al.*, Physical Review D 75 (2007) 082004.

K. Kokeyama *et al.*, in LSC review.

Effect of intensity and frequency noise (Theory)

K. Somiya *et al.*, Physical Review D 73 (2006) 122005.

Main topic is detuned RSE but BRSE is also discussed.

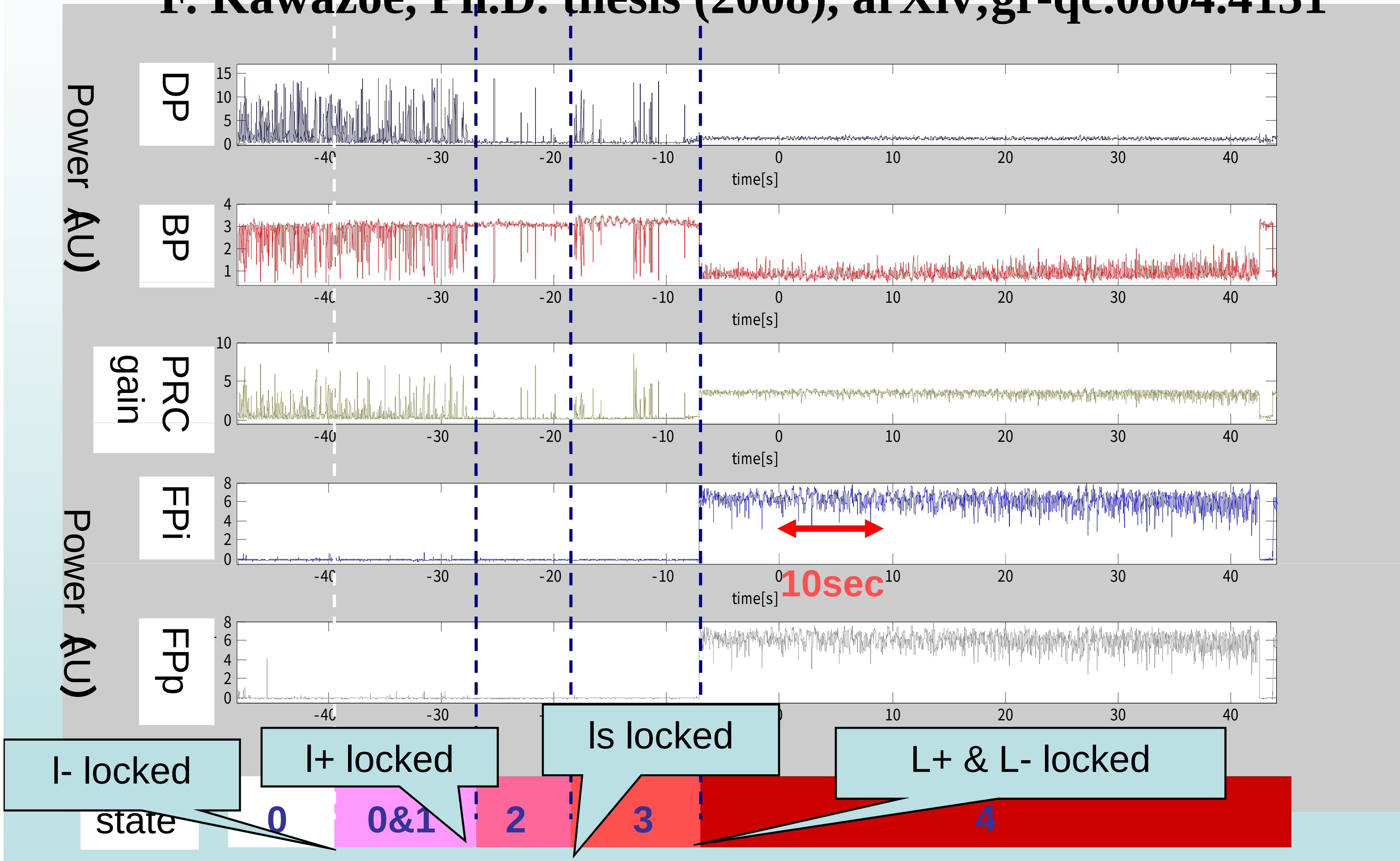
K. Somiya *et al.*, Applied Optics 44 (2005) 3179.

P. Beyersdorf *et al.*, Applied Optics 44 (2005) 3413.

And last paper (submitted) is ...

Lock of RSE with power recycling

F. Kawazoe, Ph.D. thesis (2008), arXiv;gr-qc.0804.4131



0: not controlled 1: I- locked 2 : I-, I+ locked 3: I-, I+, Is (central part) locked
4:RSE locked (longest ~15min. disturbed by human activity)

RSE in TAMA300

(Japanese interferometer with 300m cavities)

Purpose : R&D for LCGT

Sensitivity improvement of TAMA300 (high frequency region)

Past work : Design of length control

Future work : Design of alignment control

Installation of system for RSE in 2009

TAMA300 will be first large interferometer with RSE.

3. Seismic noise

Silent site

and good vibration isolation

↓

Kamioka mine

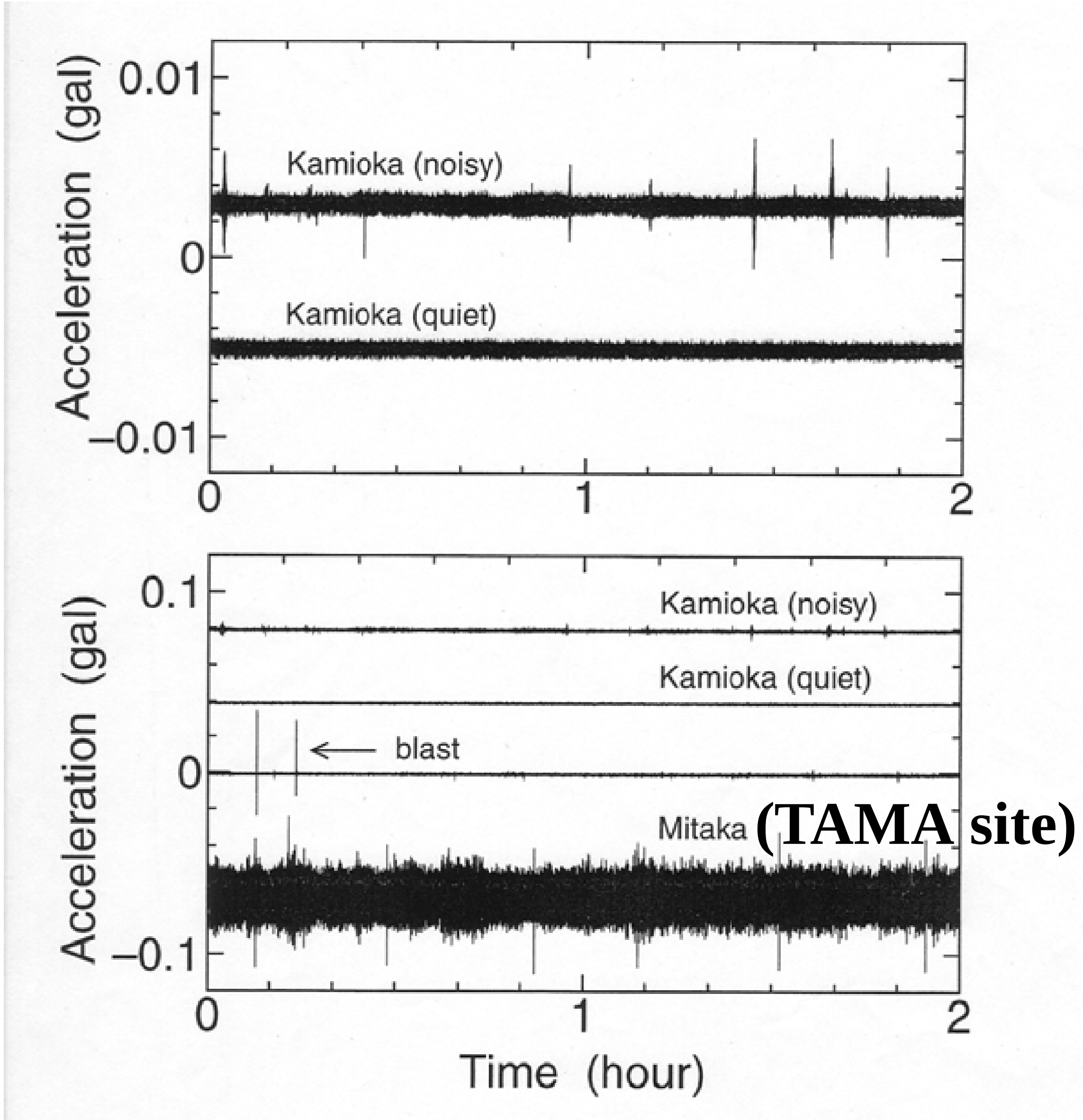
underground site

Small seismic motion

Easy and stable lock

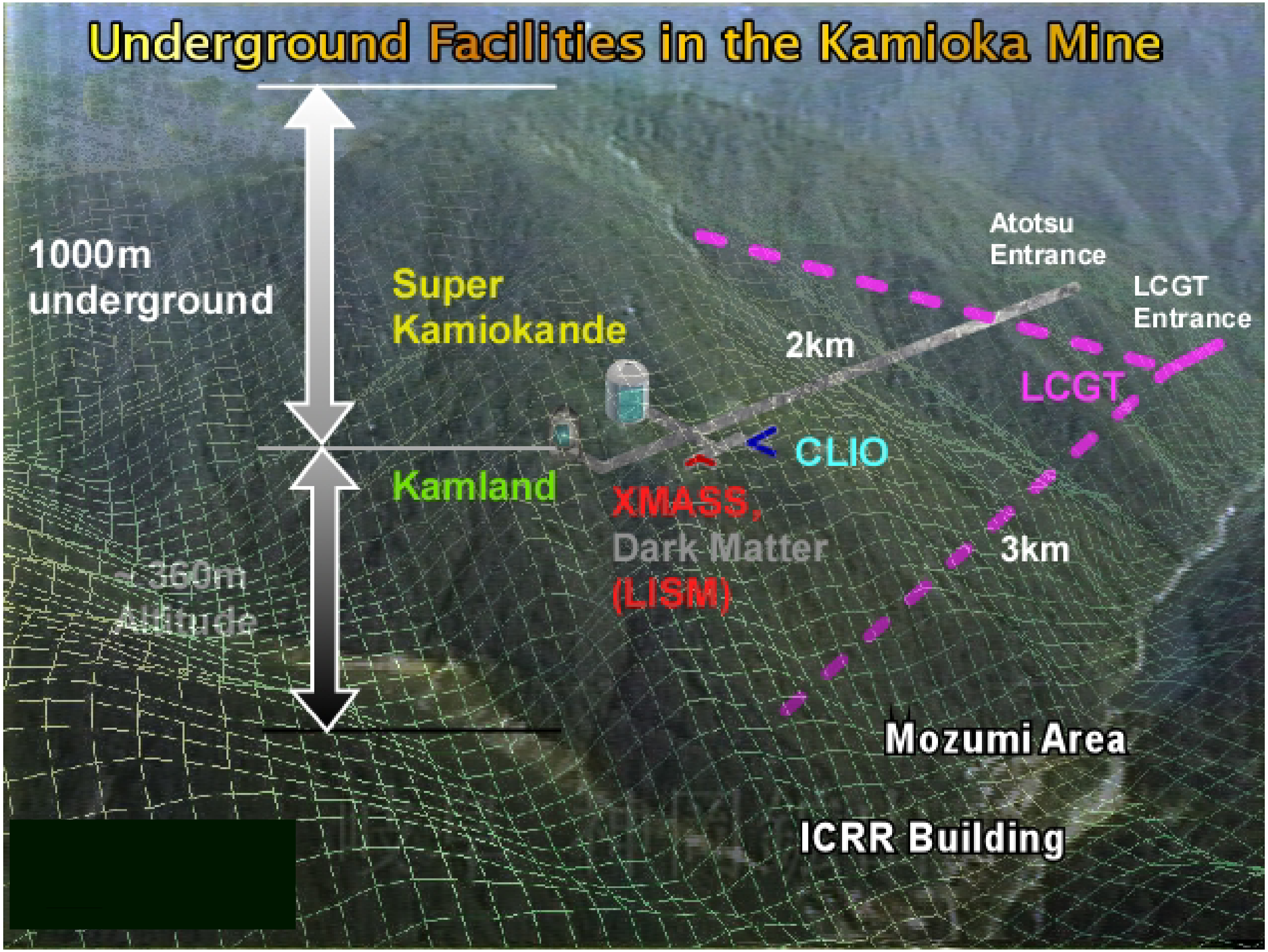
Stable temperature and humidity

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



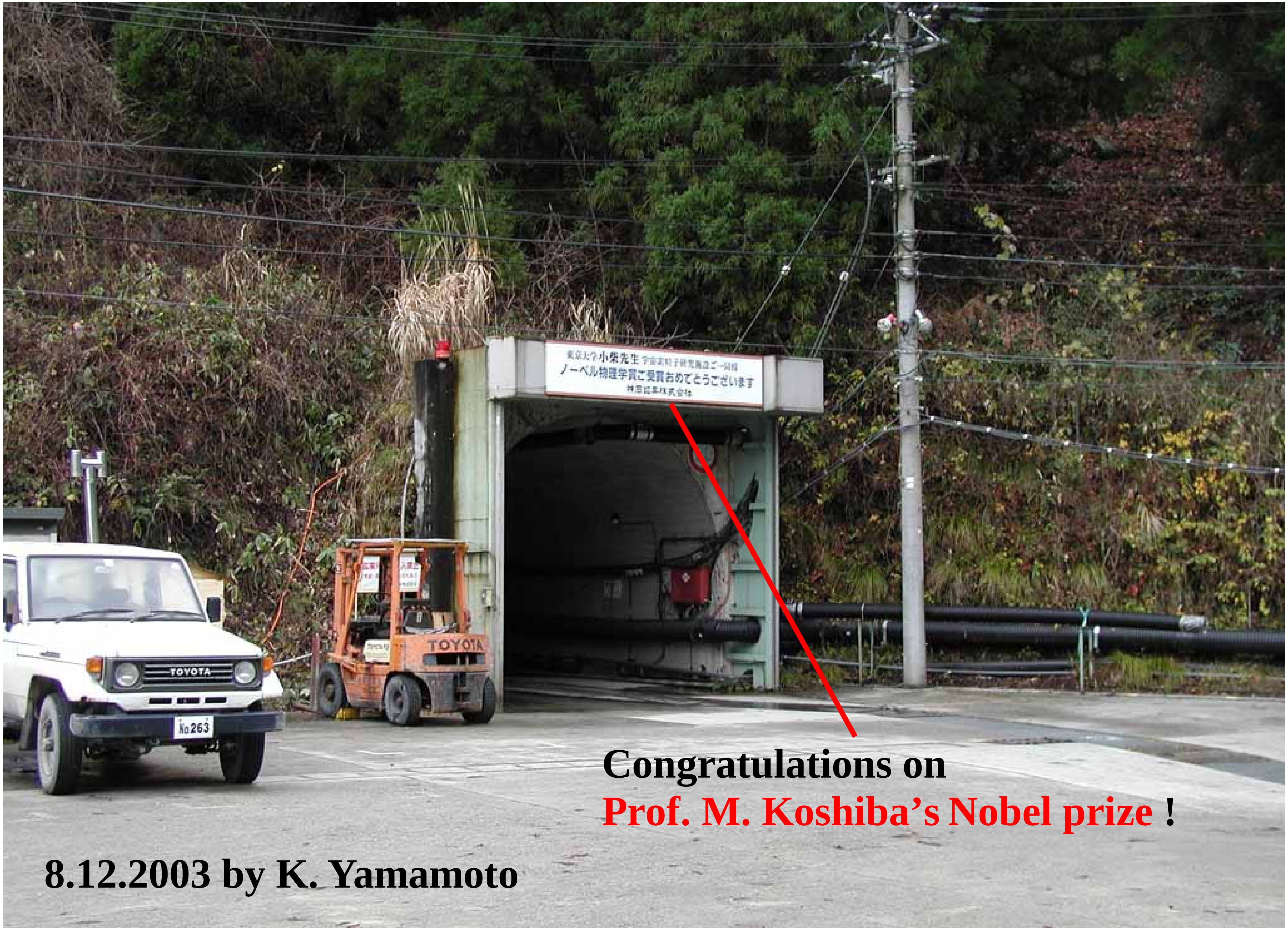
Location of Kamioka mine

Bird view photograph of Kamioka mine (Ikenoyama)



by S. Miyoki

Mine entrance



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

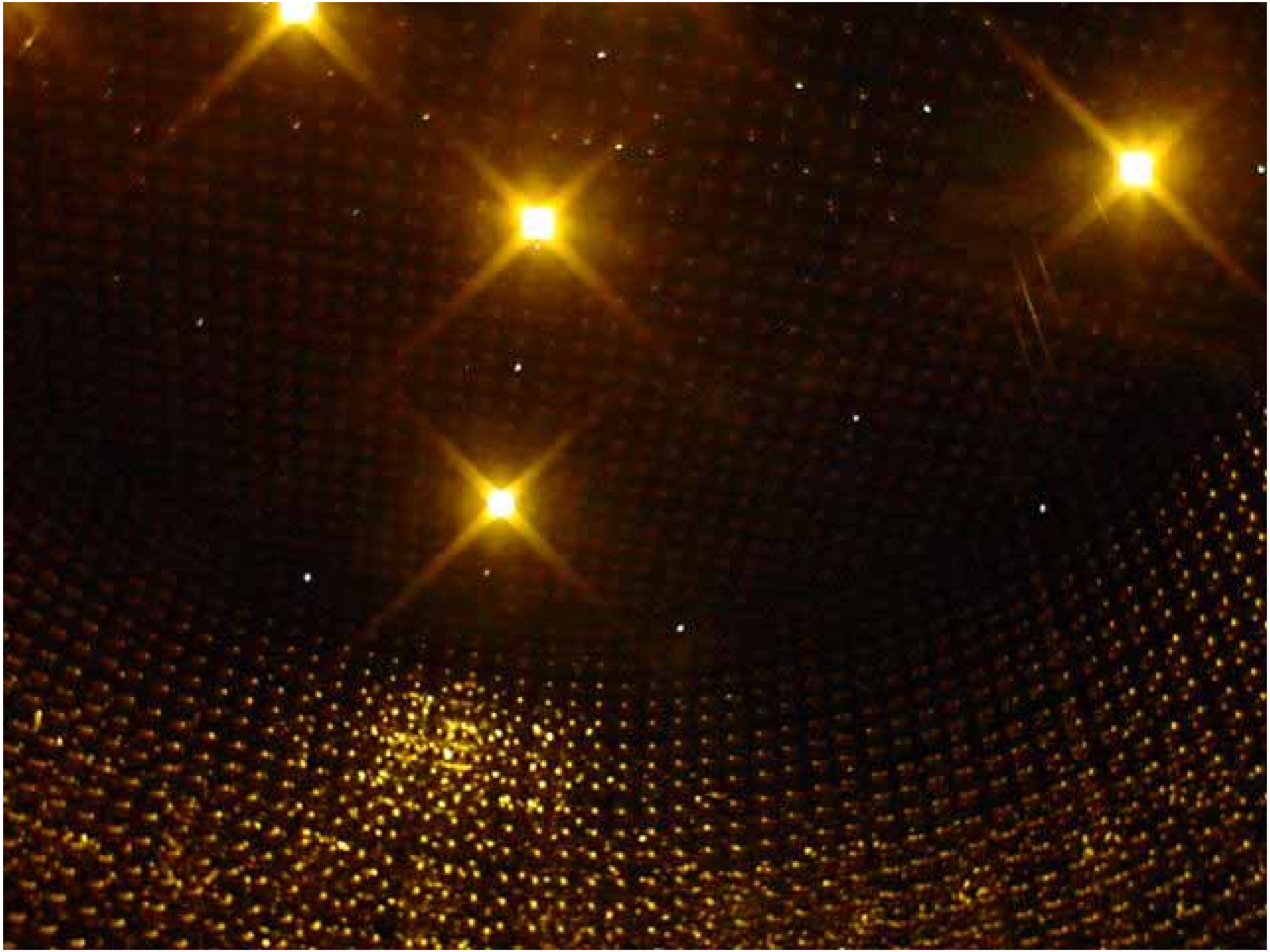
Koshiba group has constructed
Kamiokande in Kamioka mine
and detected
neutrinos from SN1987A.

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*., Proceedings of Amaldi 7

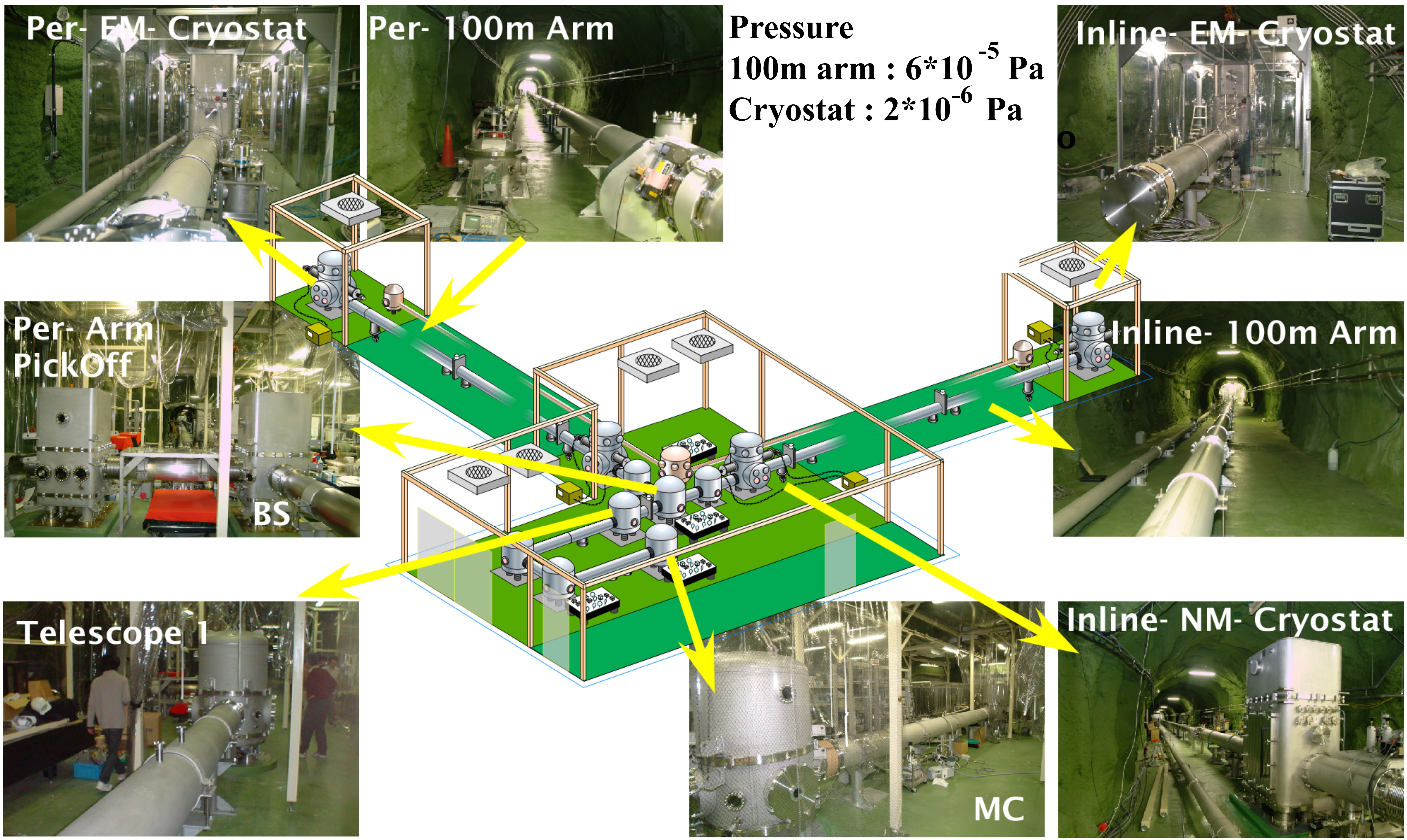
(Journal of Physics:Conference Series) accepted.

S. Miyoki will talk CLIO review at Elba (GWADW workshop) on next week.

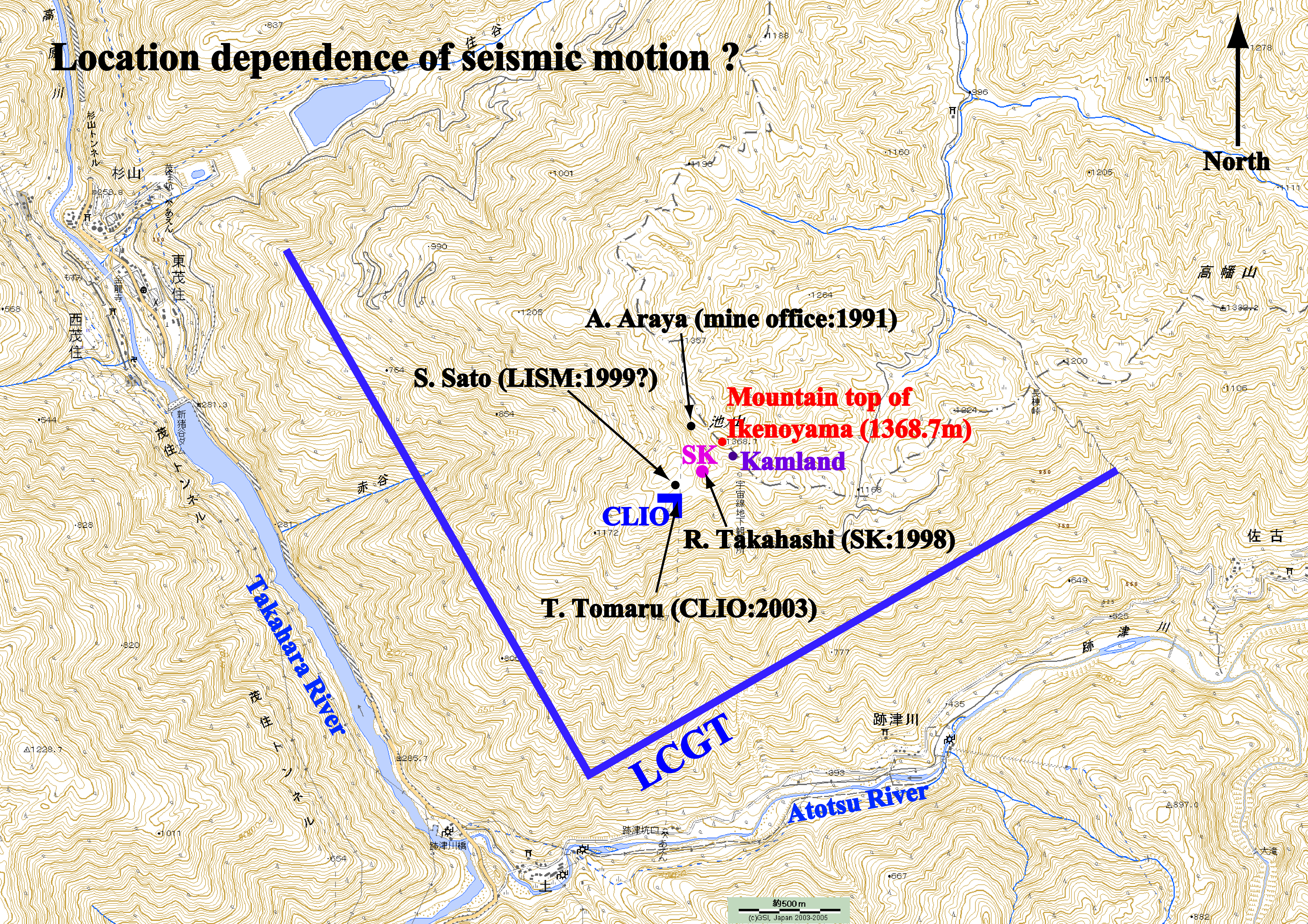
Photographs of CLIO interferometer

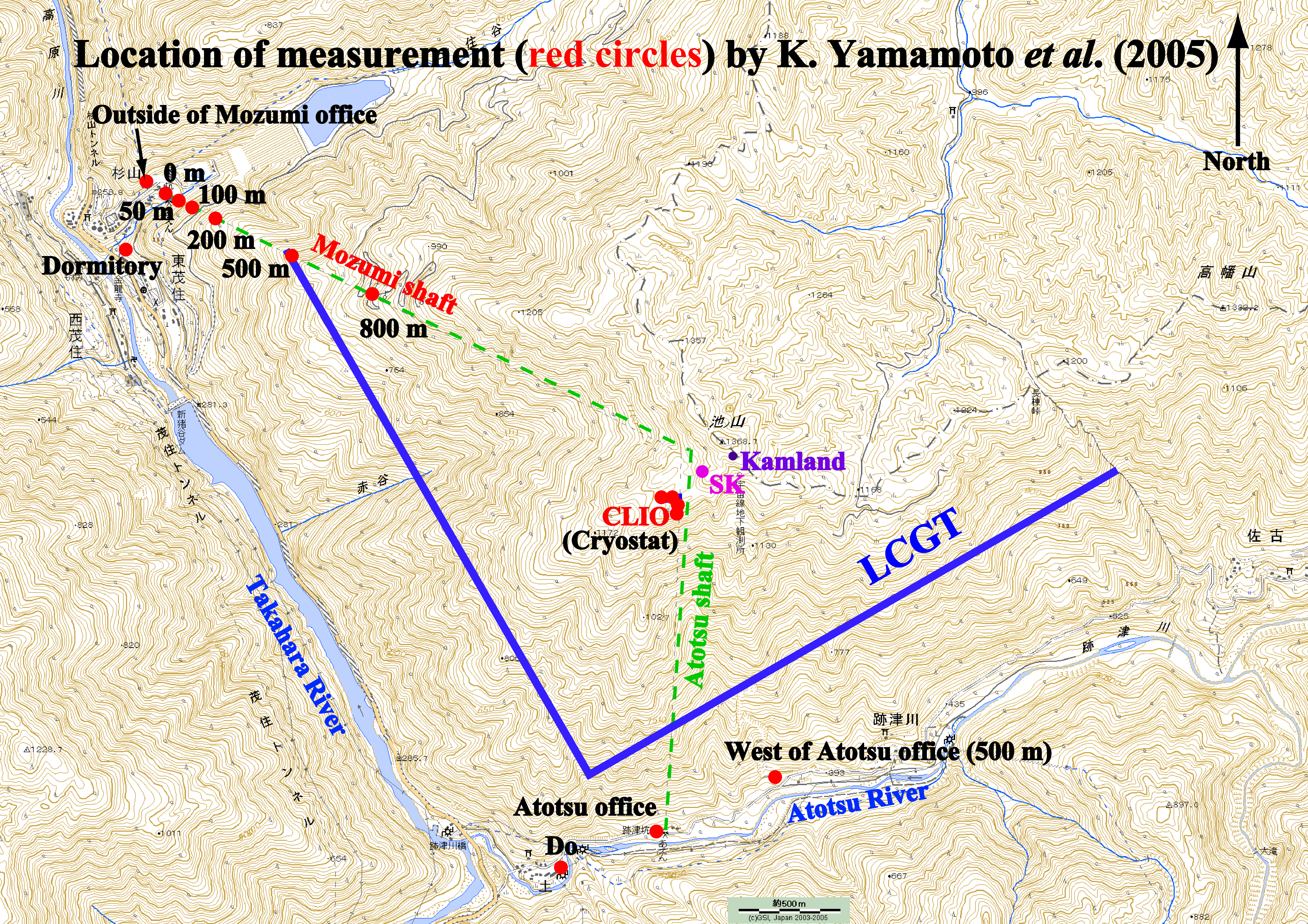
by S. Miyoki and S. Telada

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
Do
Atotsu River

Fixed accelerometer

Outside of mine
(mine entrance)

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

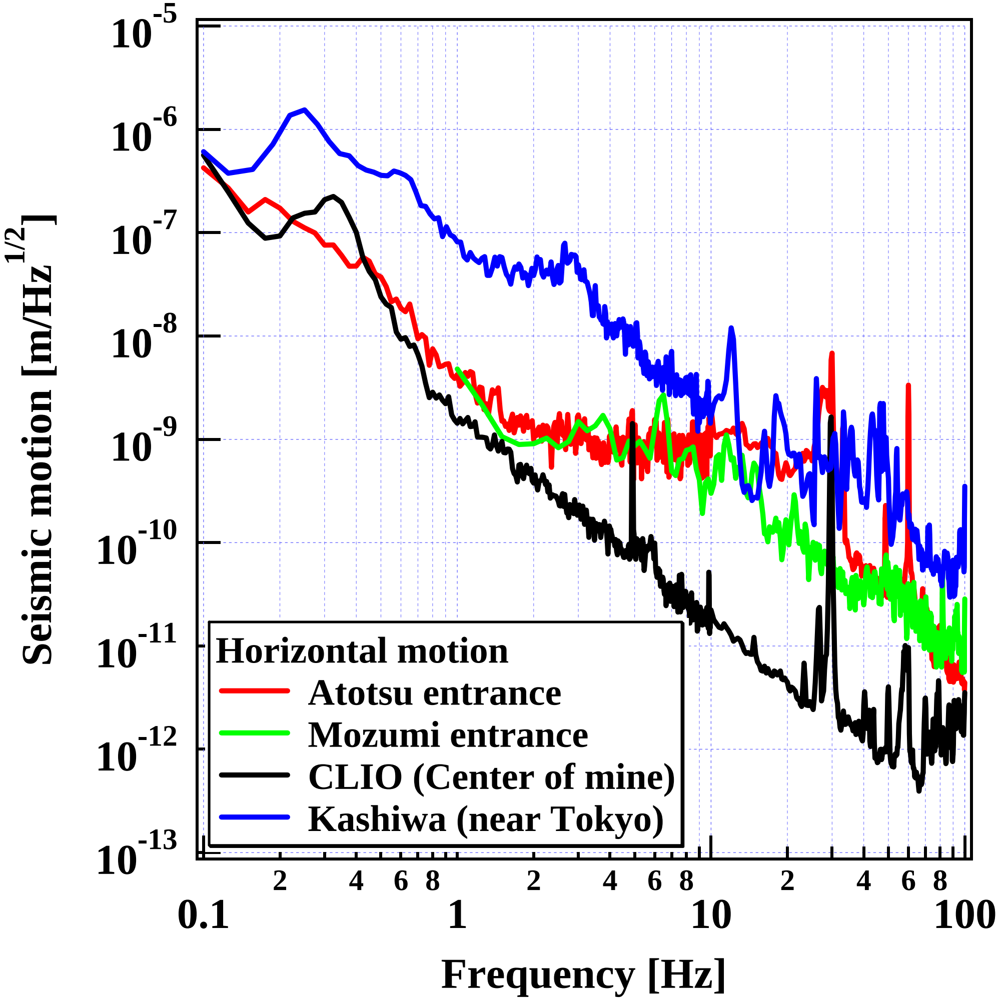
> 1 Hz
(Outside of mine)>(CLIO)

>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)



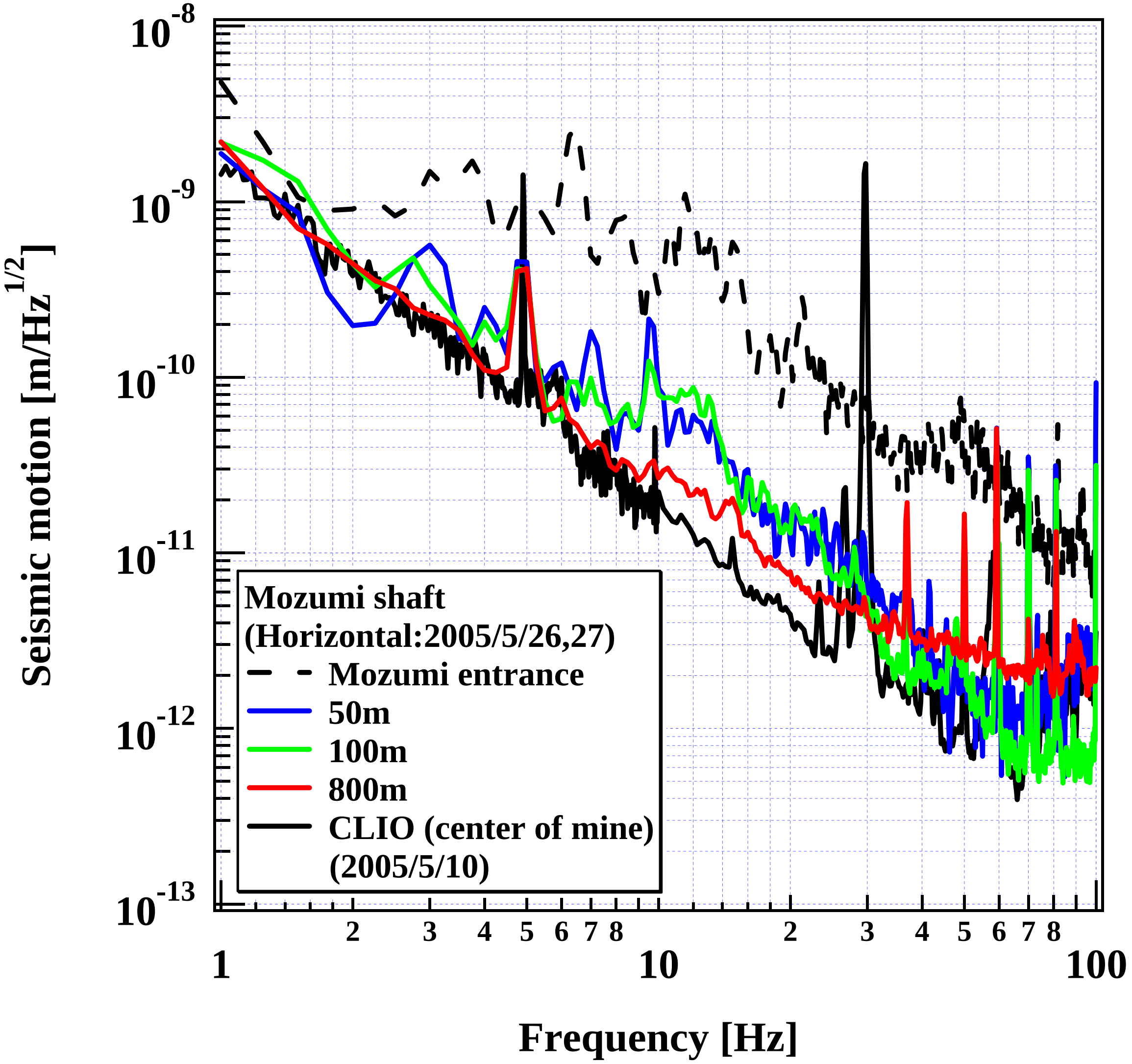
K. Yamamoto ***et al.*** **(2005)**

Inside of mine

(Mozumi shaft)

> 50 m

silent sufficiently !



Main mirrors

50 m from ground

CLIO sensitivity in low frequency region

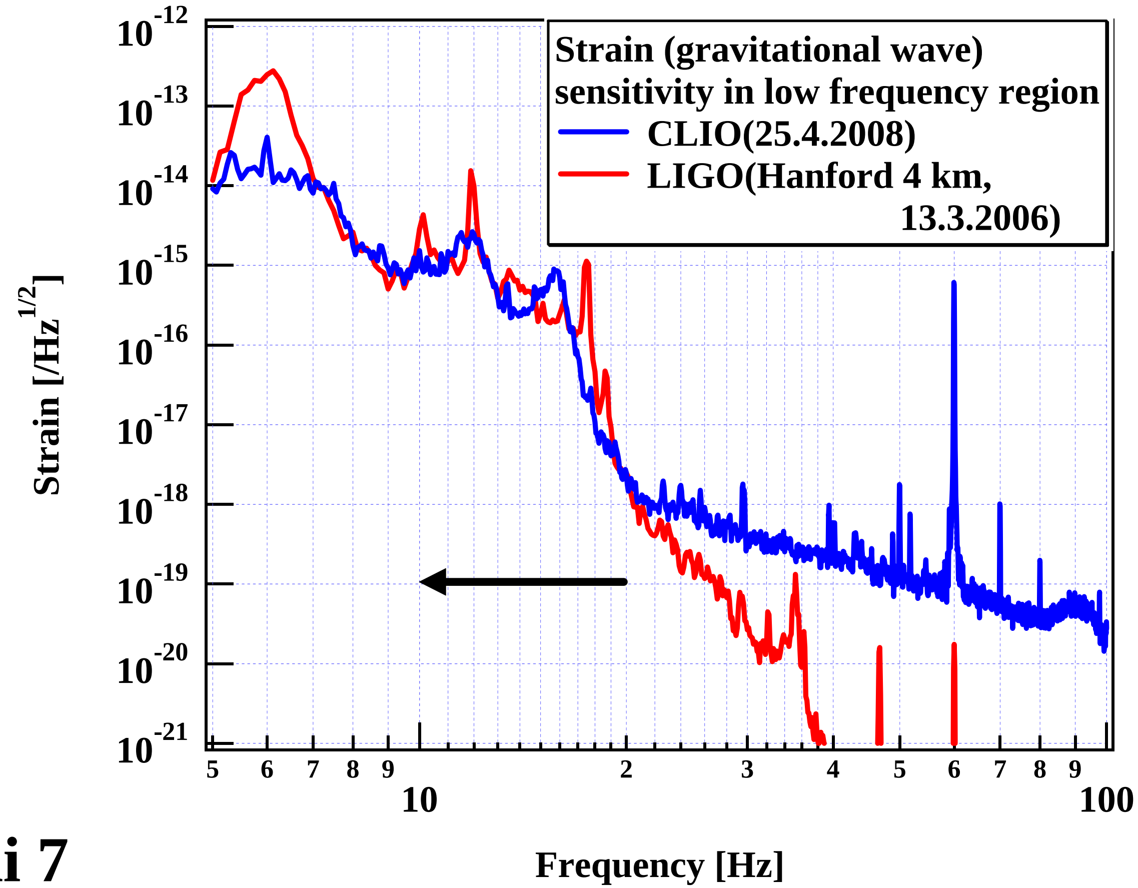
by T. Uchiyama

< 20Hz

Gravitational wave sensitivity
(not displacement !)
is comparable with that of LIGO (4km) !

(CLIO:100m)

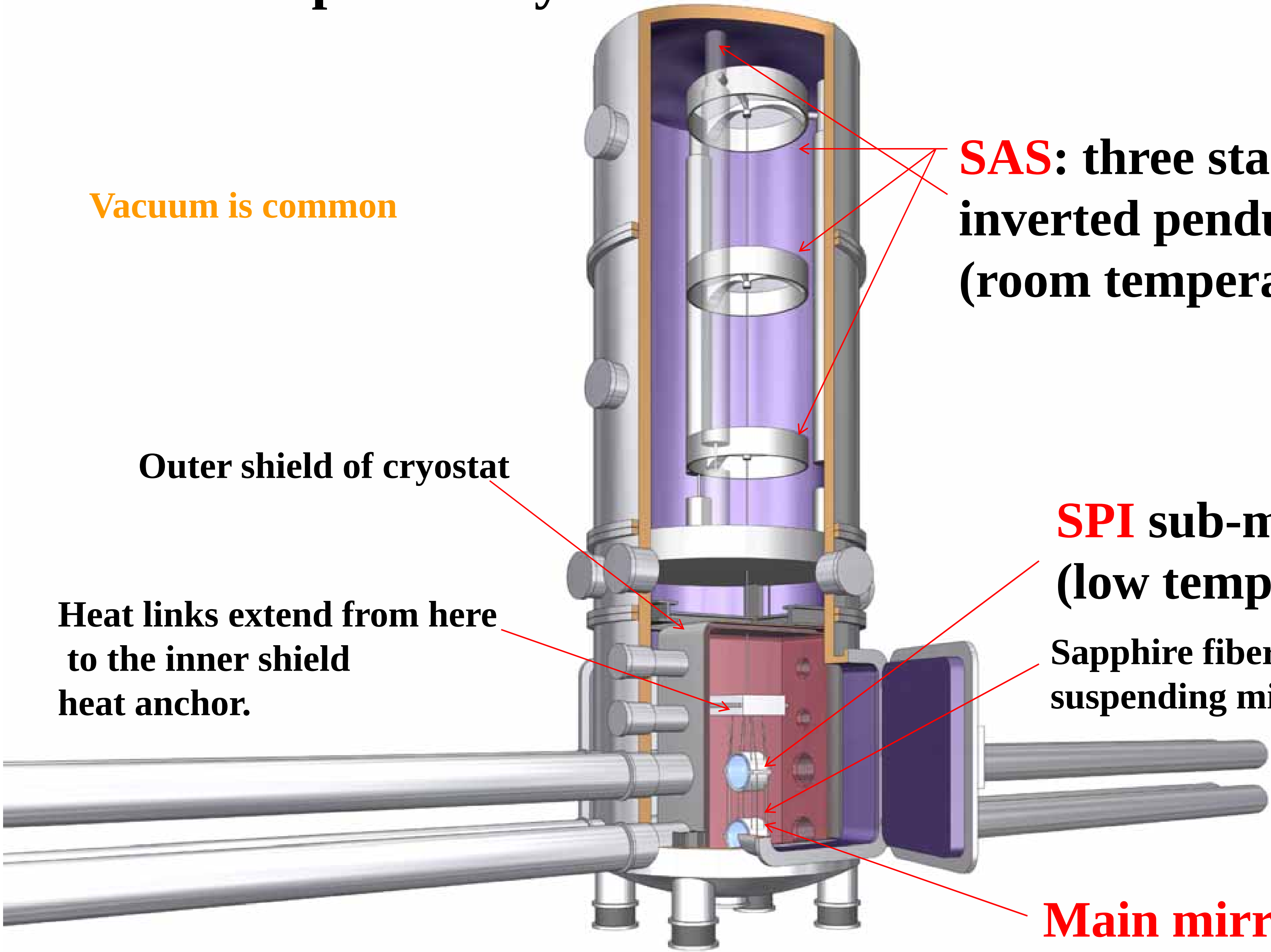
small seismic motion



K. Yamamoto *et al.*, Proceedings of Amaldi 7 (Journal of Physics: Conference Series) accepted

LCGT Suspension system

by S. Miyoki and Nikken sekkei



SAS (Seismic Attenuation System)

References

S. Marka *et al*., Classical and Quantum Gravity 19 (2002) 1614.
A. Takamori *et al*., Classical and Quantum Gravity 19 (2002) 1621.
A. Takamori, Ph.D. thesis (2003) http://t-munu.phys.s.u-tokyo.ac.jp/theses/takamori_d.pdf

4 SAS have already been installed in TAMA300.

Purpose : R&D for LCGT

Sensitivity improvement (low frequency region)

and Easy lock acquisition of TAMA300

Past work : Lock of power recycled Fabry-Perot Michelson interferometer

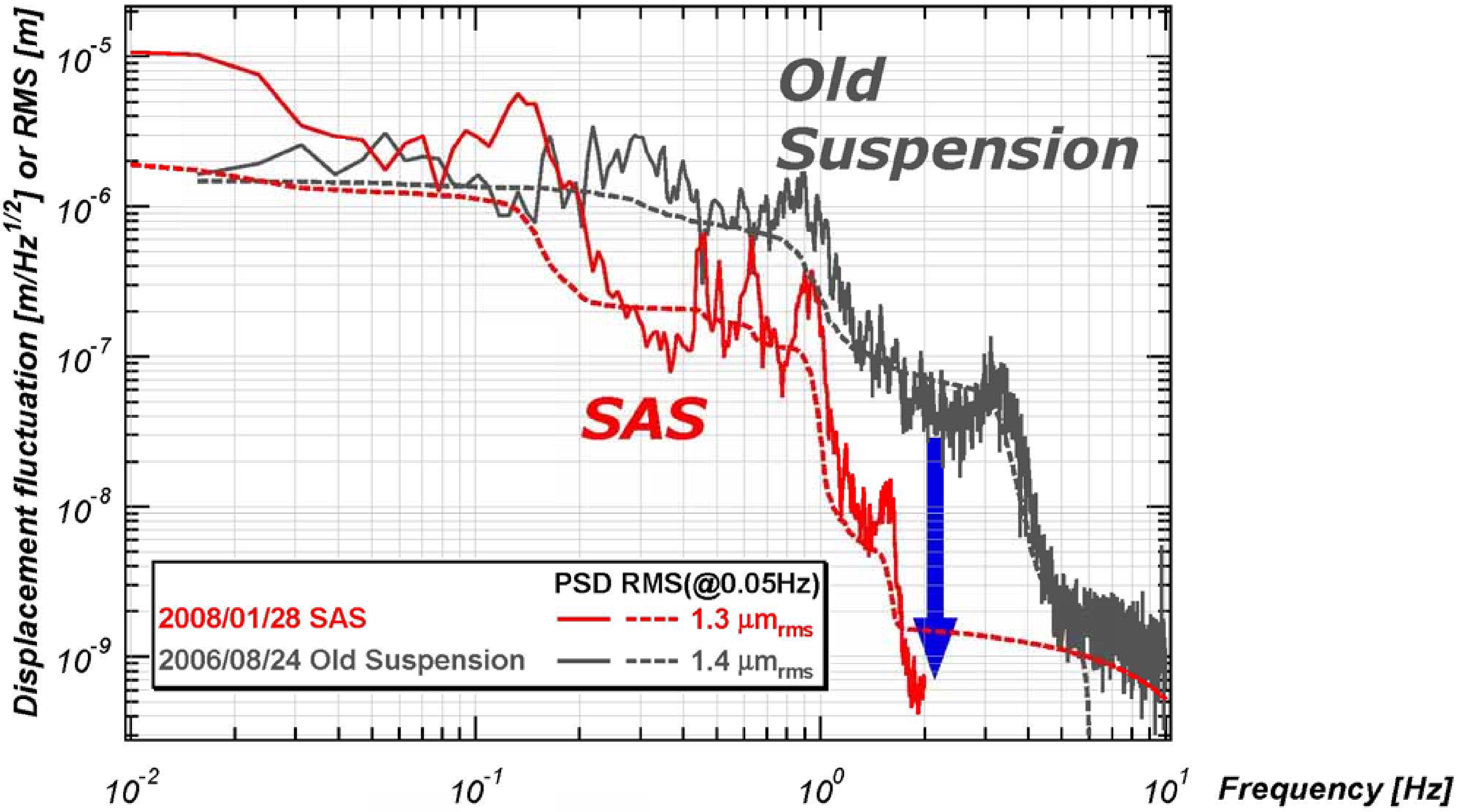
Test in short term (results: next page)

Future work : Sensitivity improvement at around 100 Hz

Test in long term (evaluation of drift)

Evaluation in observation run (this summer)

Short term test of SAS

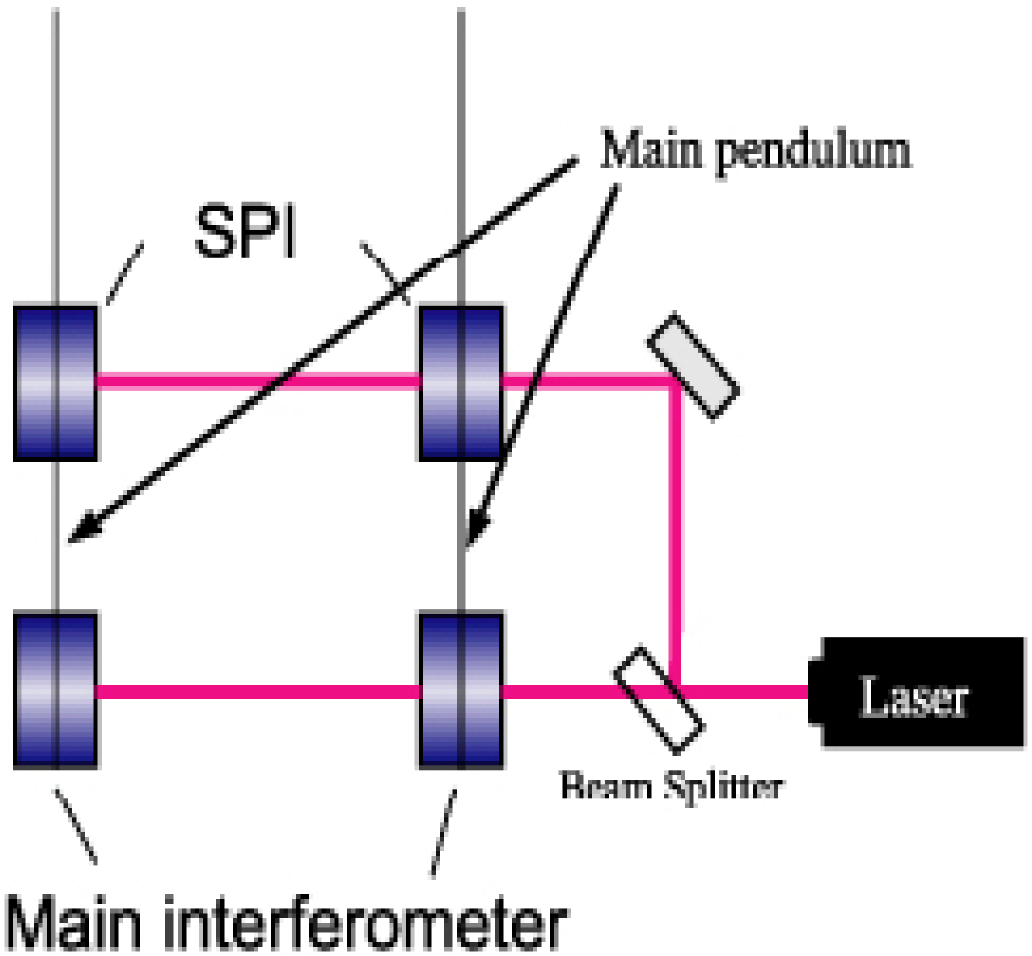


10 times smaller seismic noise **above 0.2 Hz**

by K. Arai

SPI(Suspension Point Interferometer) (not Platform !)

Test mass of LCGT is connected to a cooling system by a heat link that introduces mechanical noise. A suspension point interferometer (SPI) is introduced to maintain high attenuation of seismic and mechanical noise without degrading high heat conductivity.



Y. Aso *et al*., Physics Letters A 327 (2004) 1.
Ph. D. thesis (2006) http://t-munu.phys.s.u-tokyo.ac.jp/theses/aso_d.pdf

Y. Aso won the first GWIC thesis prize !
(13.7.2007: Amaldi 7)

by K. Yamamoto

4. 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 lensing

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

(3) Parametric instability

K. Yamamoto *et al.*, Proceedings of Amaldi 7 (Journal of Physics:Conference Series) accepted.

(4)Cosmic ray particles

K. Yamamoto *et al.*, submitted in this week ?

(1) Thermal noise

Fluctuation-Dissipation Theorem

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

$G^{1/2}$: **Thermal noise amplitude**

$T^{1/2}$: **Temperature**

$\phi^{1/2}(T)$: **Mechanical loss** → **Temperature dependence**

Mechanical loss at low temperature is necessary.

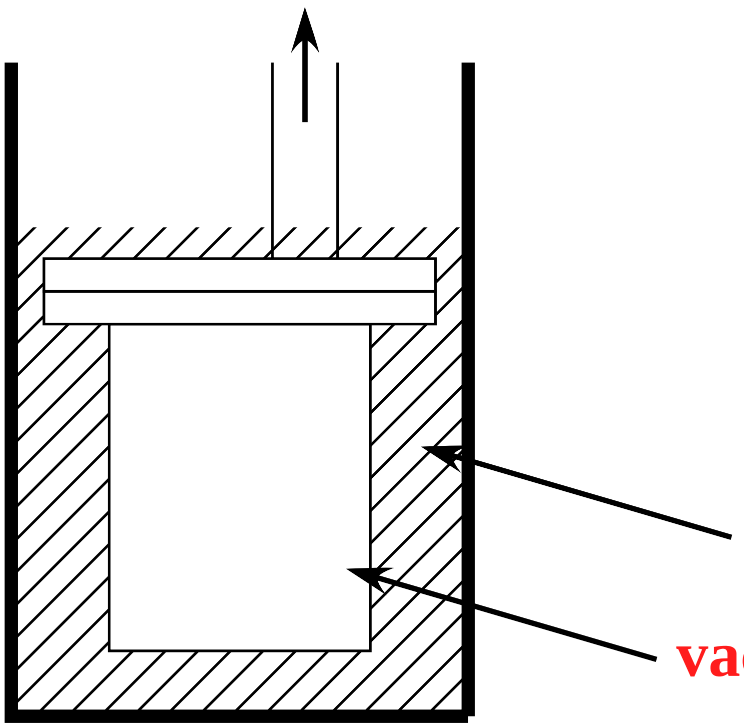
Measurement of mechanical loss at low temperature

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

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

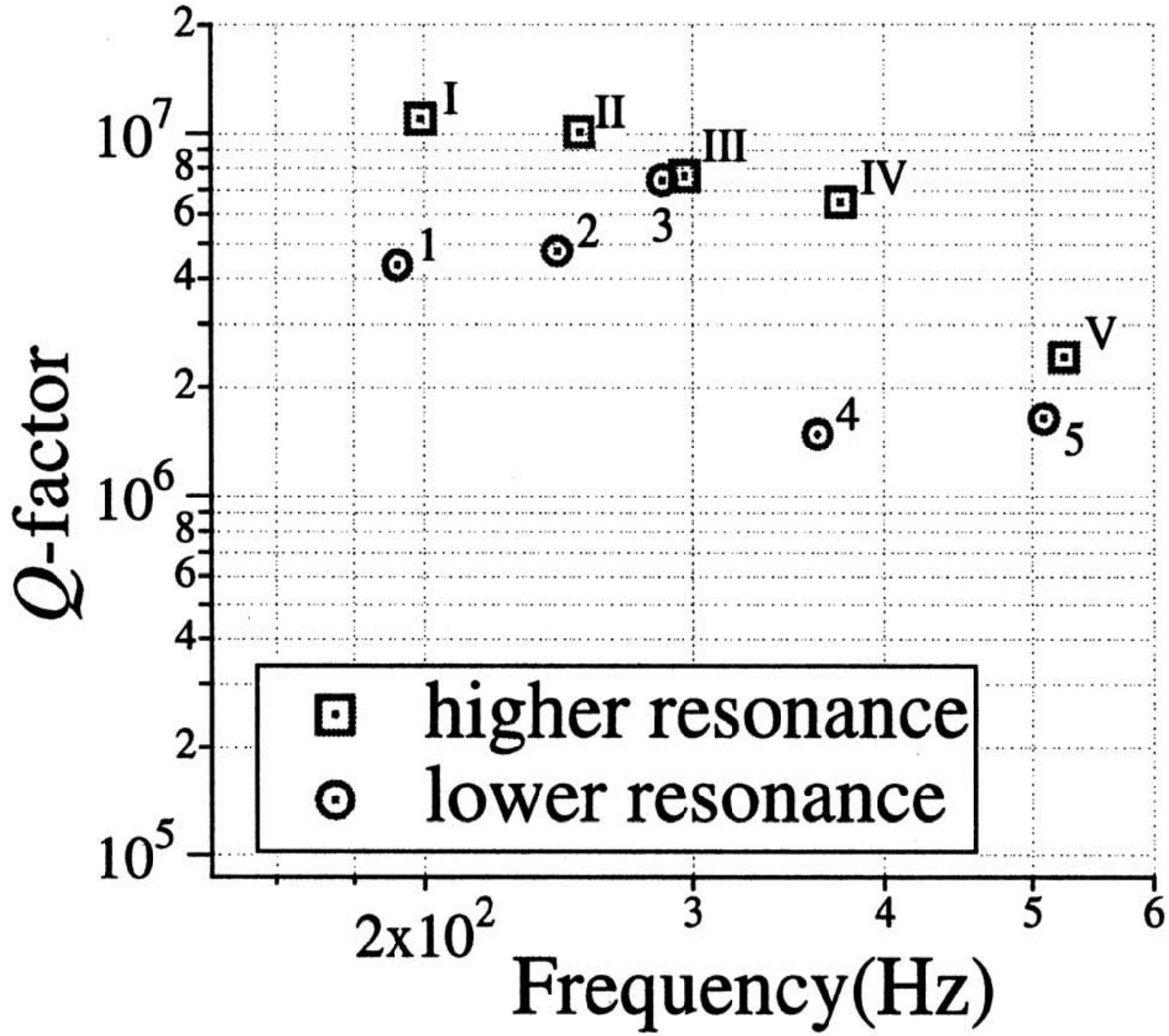
↓

Pendulum

$Q = 1/\phi = 8*10^7$

Sufficiently small loss

Pendulum thermal noise is smaller than quantum noise above 2 Hz.



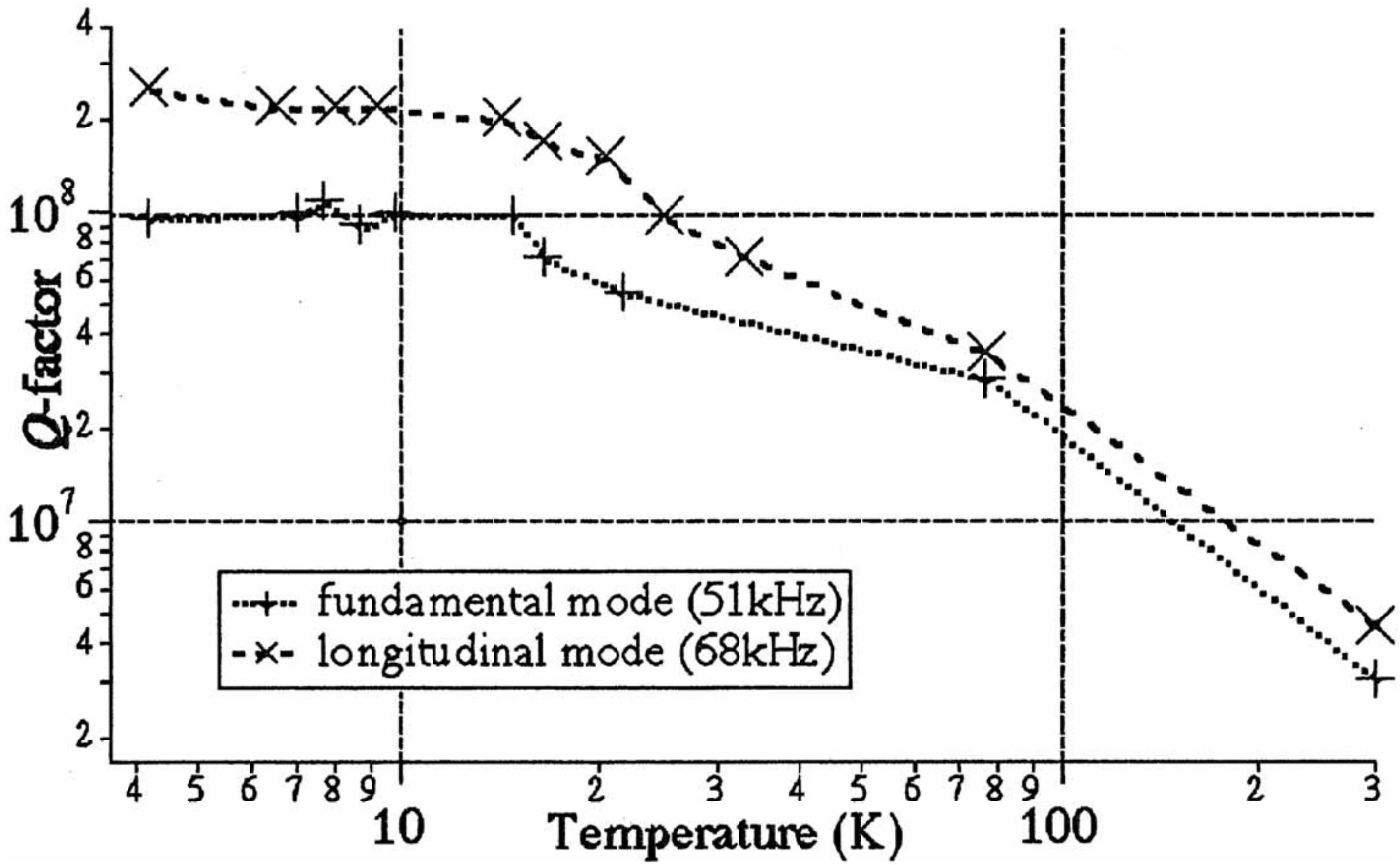
T. Uchiyama *et al.*, Physics Letters A 273 (2000) 310.

Thermal noise of mirror substrate

Measurement of decay motion of cylindrical sapphire bulk

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

Sufficiently small loss



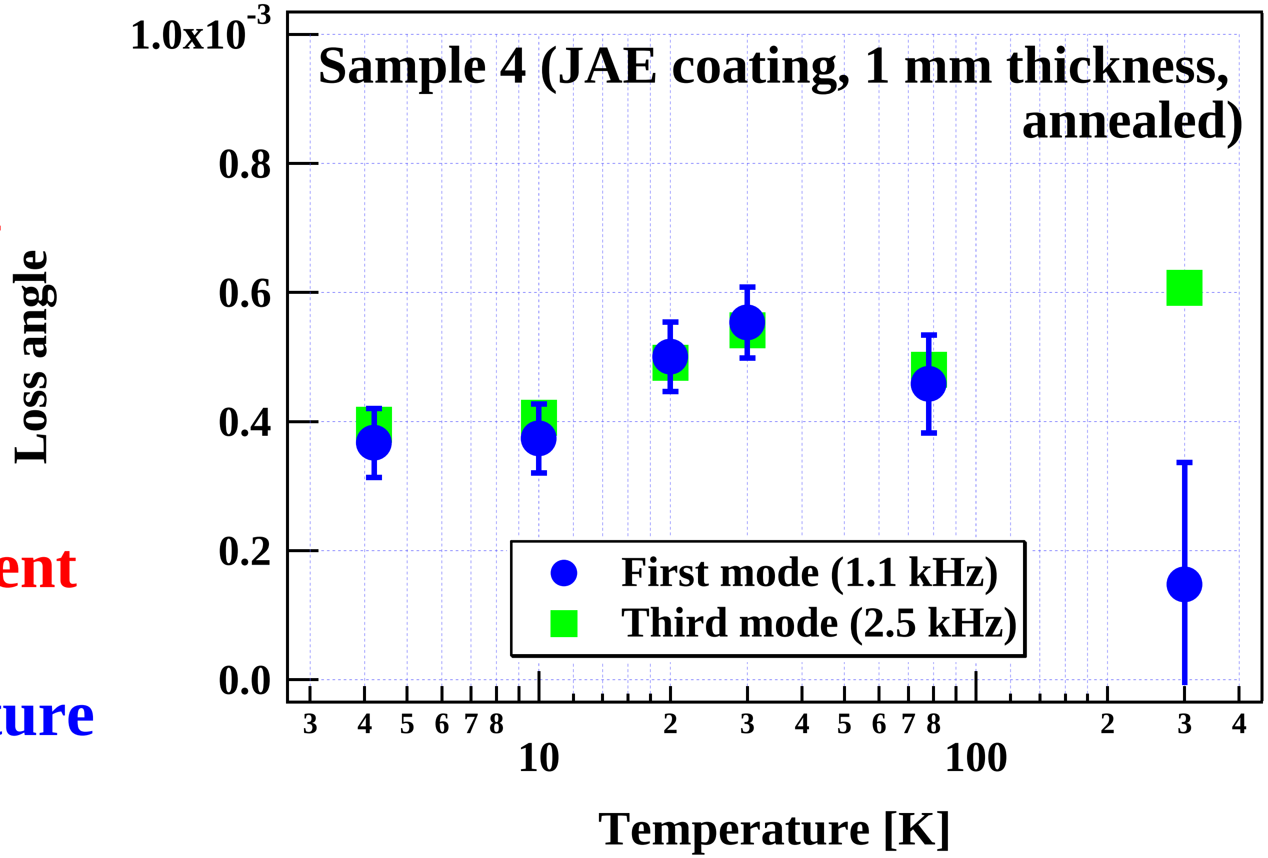
T. Uchiyama *et al.*, Physics Letters A 261 (1999) 5.

Thermal noise of reflective coating

Measurement of decay time of sapphire disk

with and without coating

ϕ = (4 - 6) *10^{-4}

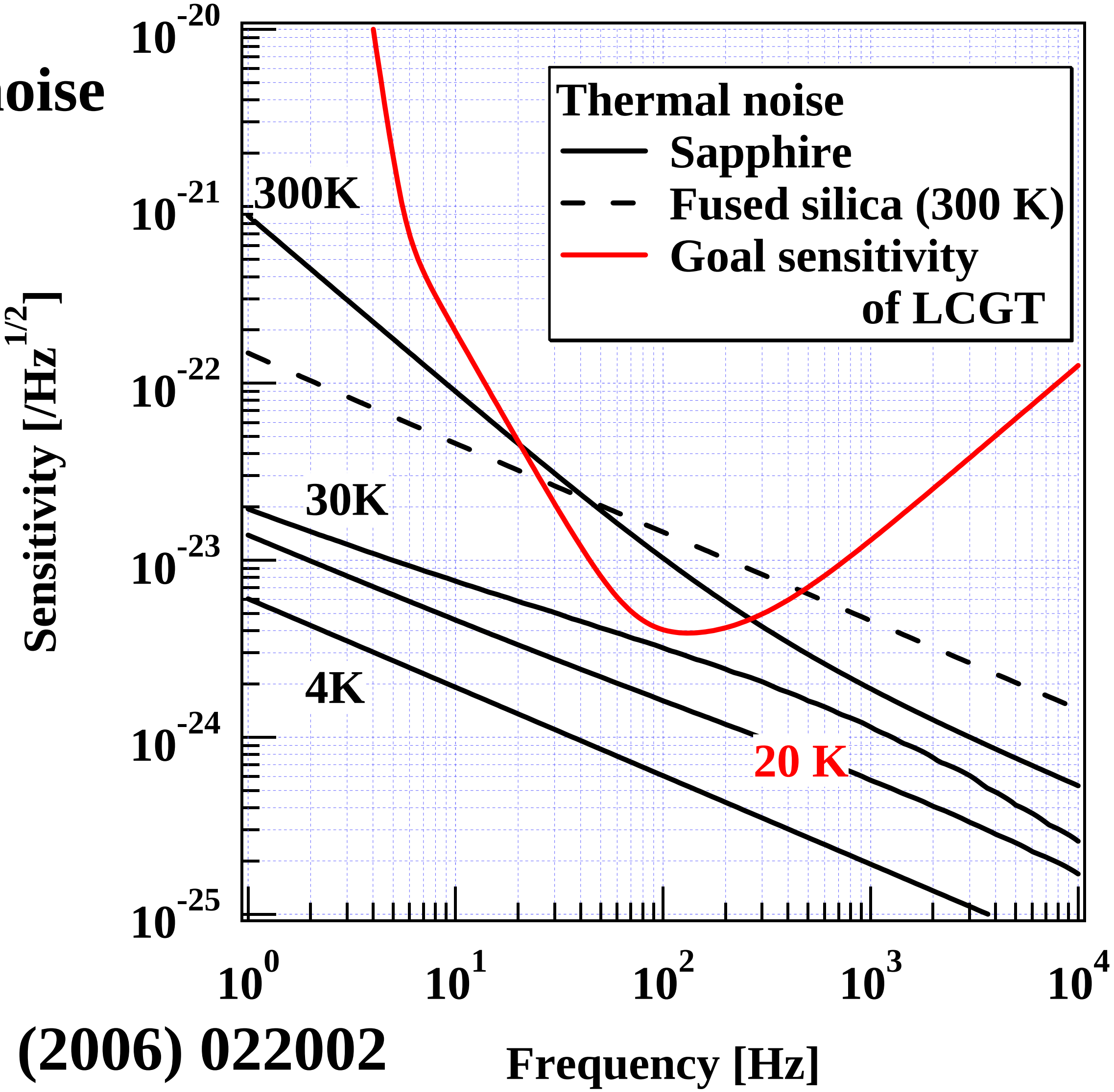


first measurement
coating loss
at low temperature

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

Summary of mirror thermal noise

Mirror thermal noise in LCGT



K. Yamamoto et al.,

Physical Review D 74 (2006) 022002

(2) Thermal lensing

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

Thermal lensing : Thermal gradient
and temperature coefficient of refractive index

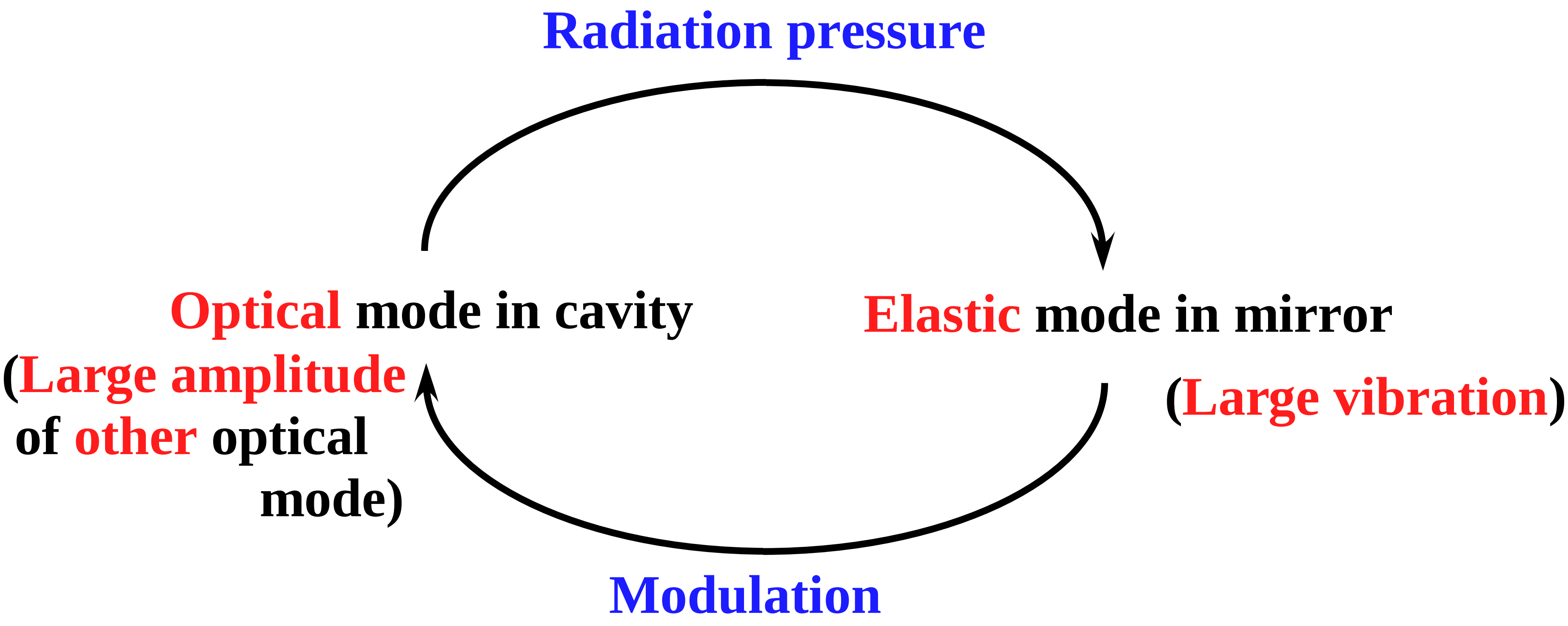
At low temperature (Sapphire)

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

Thermal lensing effect is negligible.

(3) Parametric instability

K. Yamamoto *et al.*, Proceedings of Amaldi 7 (Journal of Physics:Conference Series) accepted.



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

(3) Parametric instability

K. Yamamoto *et al.*, Proceedings of Amaldi 7 (Journal of Physics:Conference Series) accepted.

Less serious problem (than that of Advanced LIGO)

Number of unstable modes

Advanced LIGO : 20 ~ 60 LCGT : 2 ~ 4

Mirror curvature

Advanced LIGO : Stability strength strongly depends on mirror curvature.

LCGT : Stability 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.*, submitted in this week ?

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**

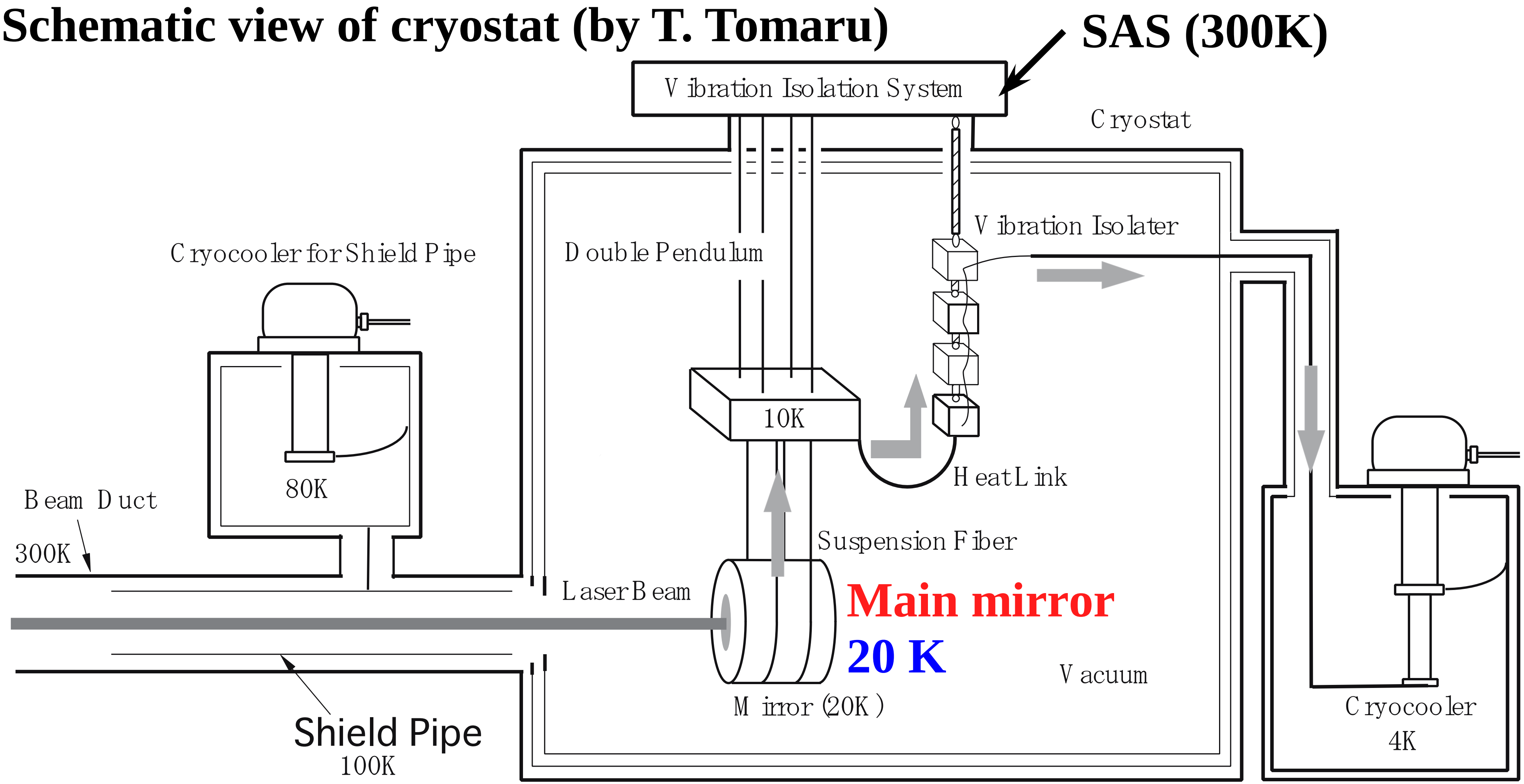
Decay time of thermal stress

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.

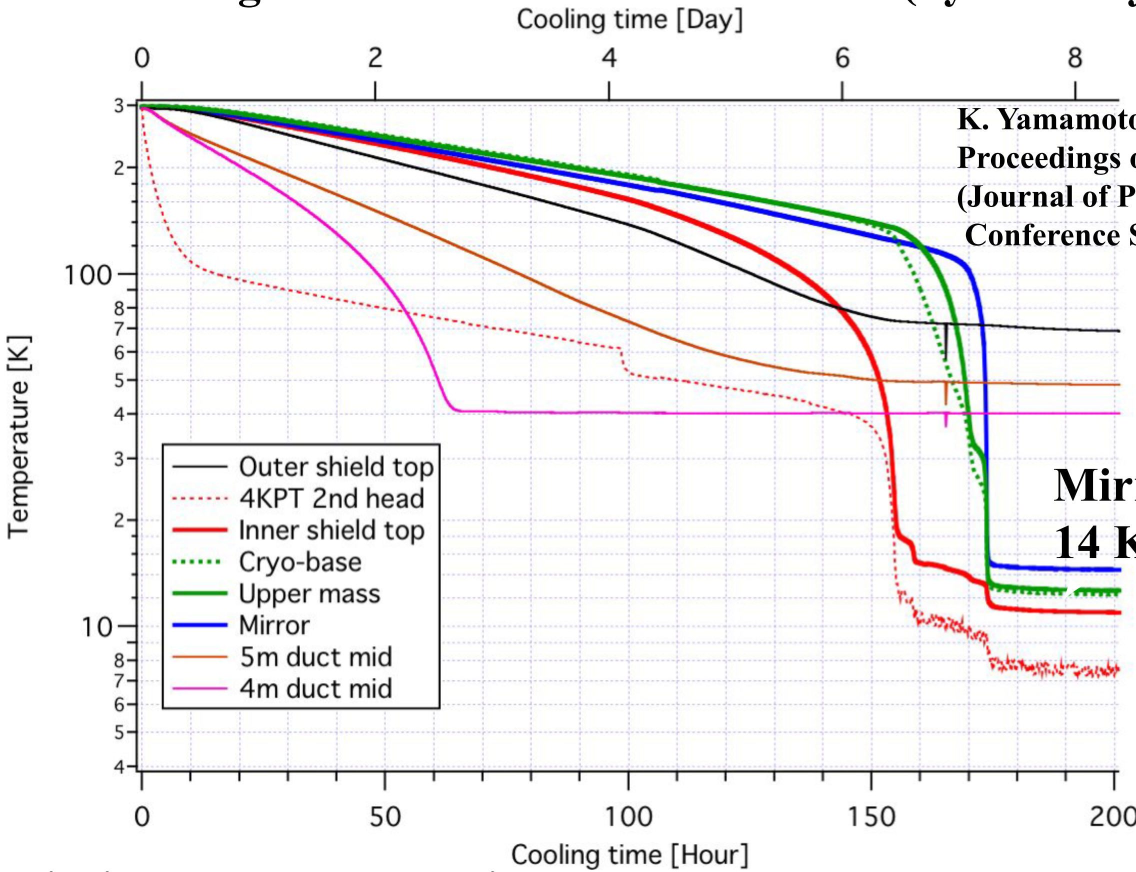
4-2. Technique for cooling mirror and suspension

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)



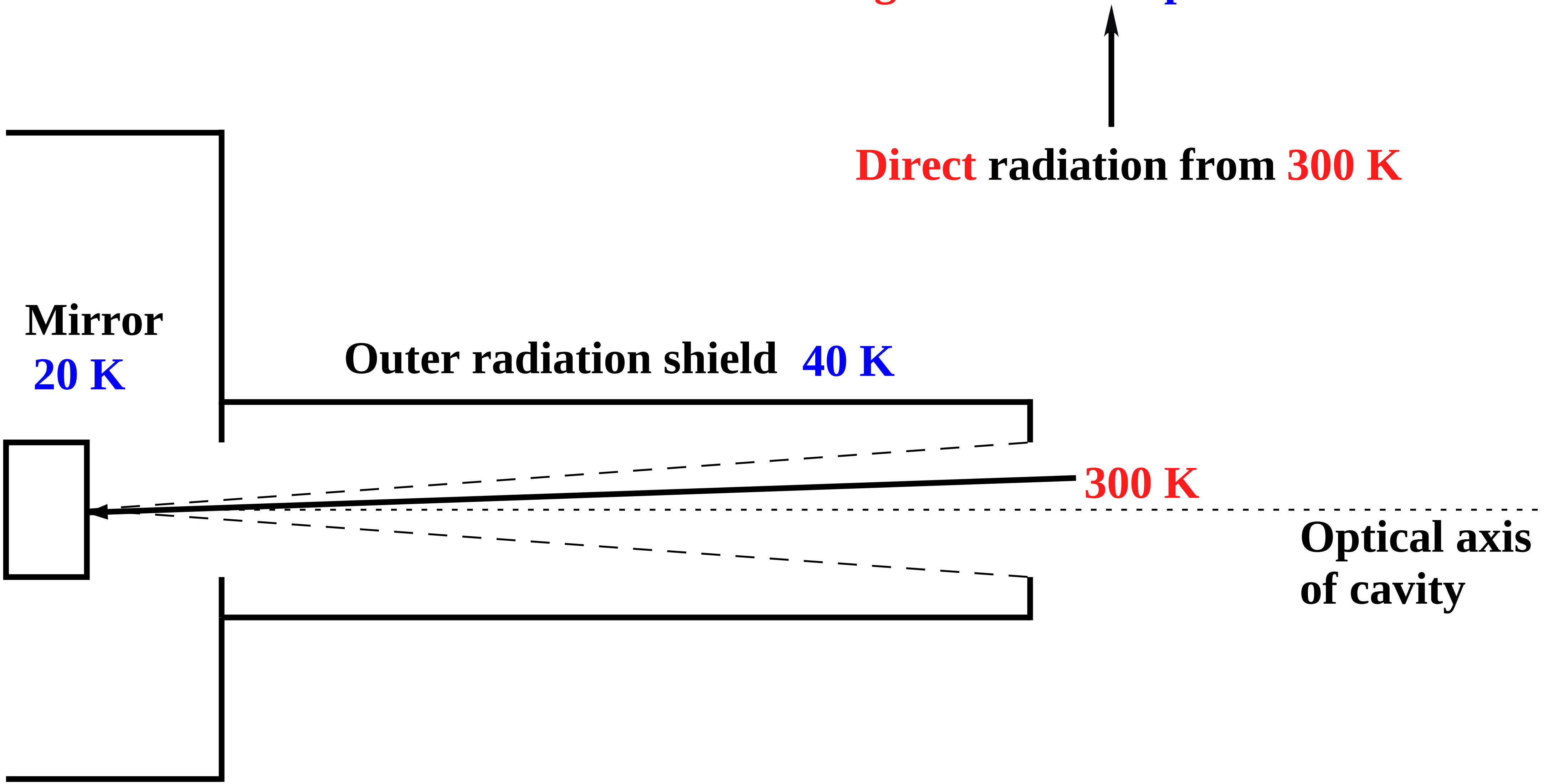
K. Yamamoto et al., Proceedings of Amaldi 7 (Journal of Physics: Conference Series) accepted.

Mirror 14 K

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 !



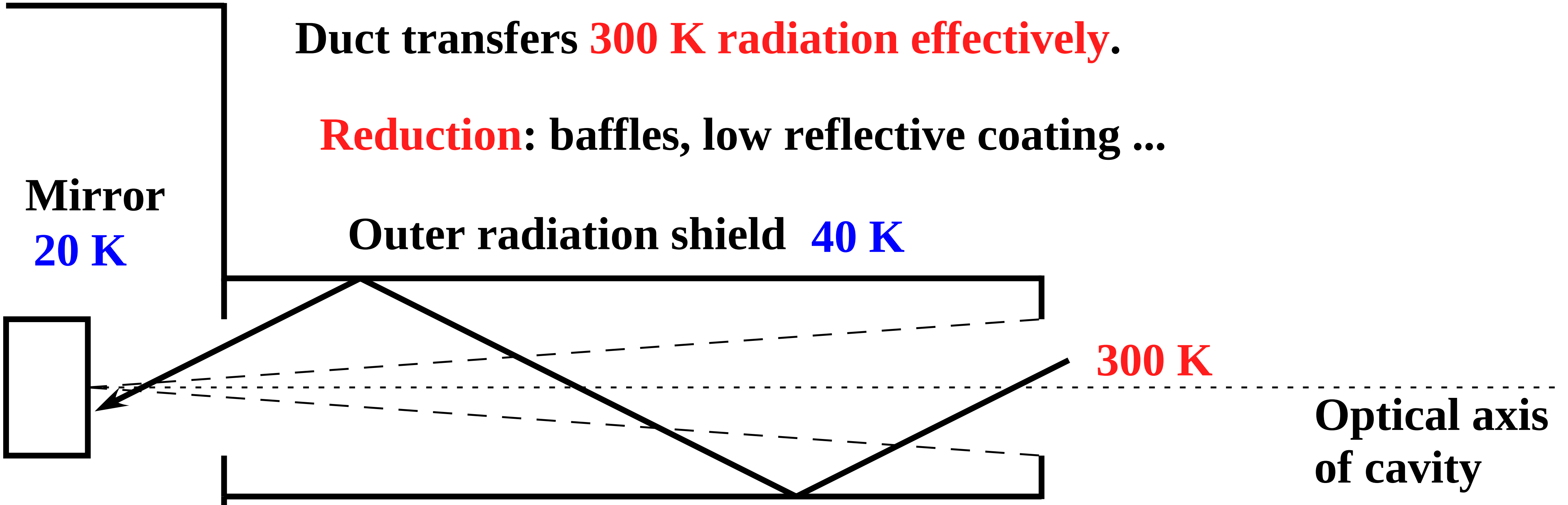
Heat into mirrors

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.
Proceedings of Amaldi 7(Journal of Physics:Conference Series)
accepted.

Cryocooler

Why ?

Usual case : Liquid nitrogen and helium

Safety and maintenance in mine

↓

Cryocooler

Usual cryocooler : Gifford-McMahon cryocooler

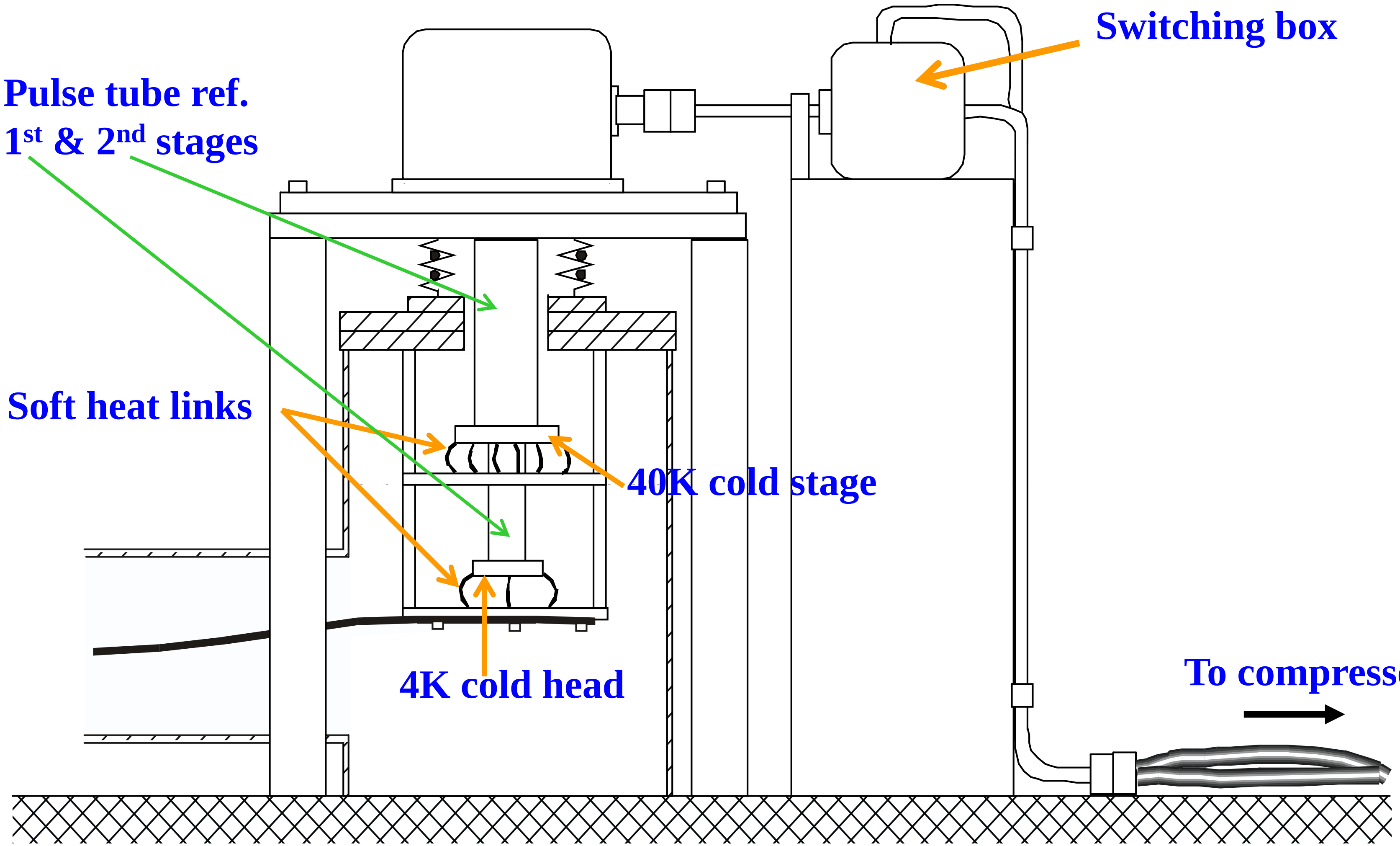
↓ **Large vibration**

Pulse-tube cryocooler (without solid piston)

But, vibration of commercial one is not enough small.

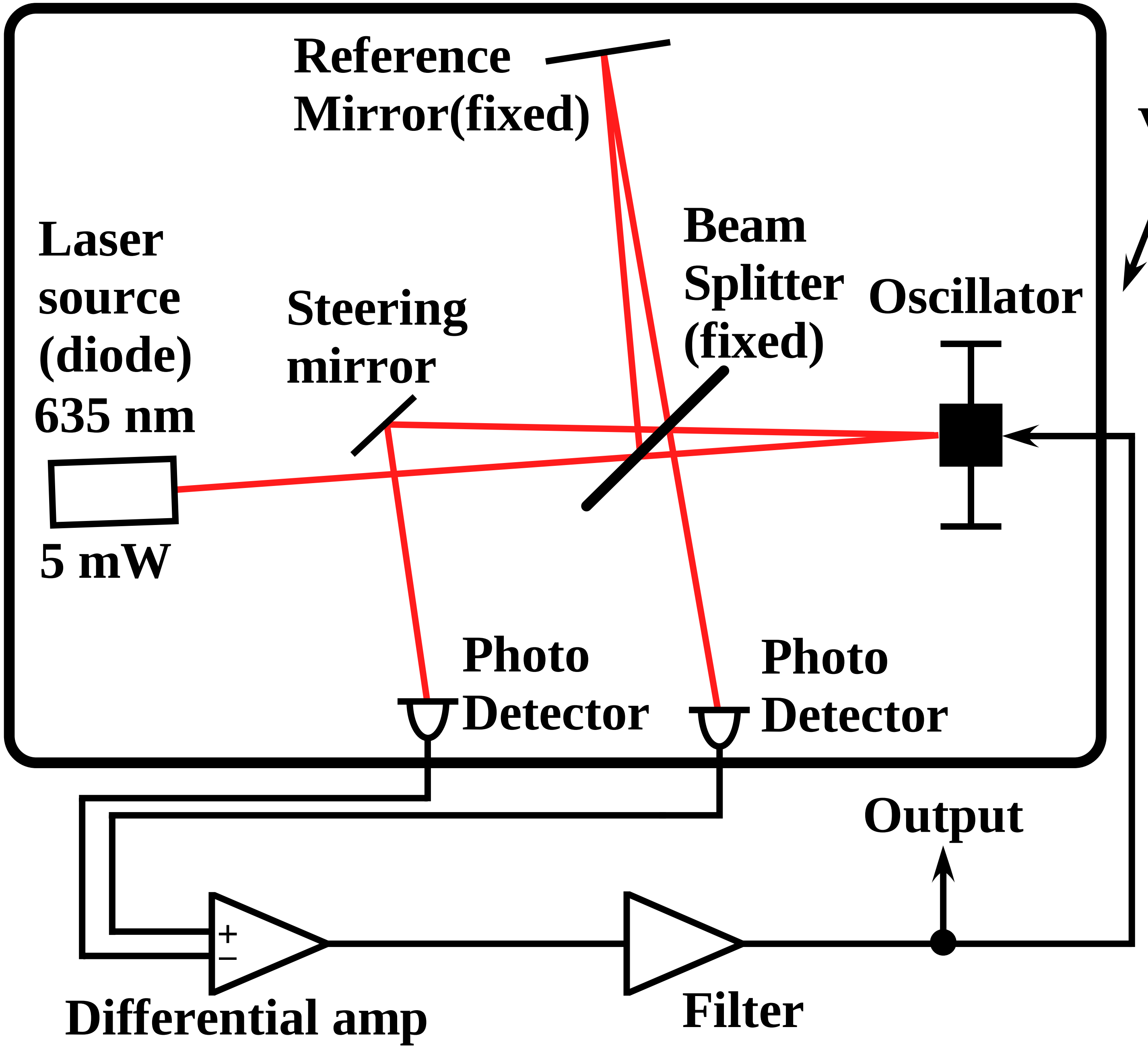
Quiet refrigerator was developed (design in 2003)

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.



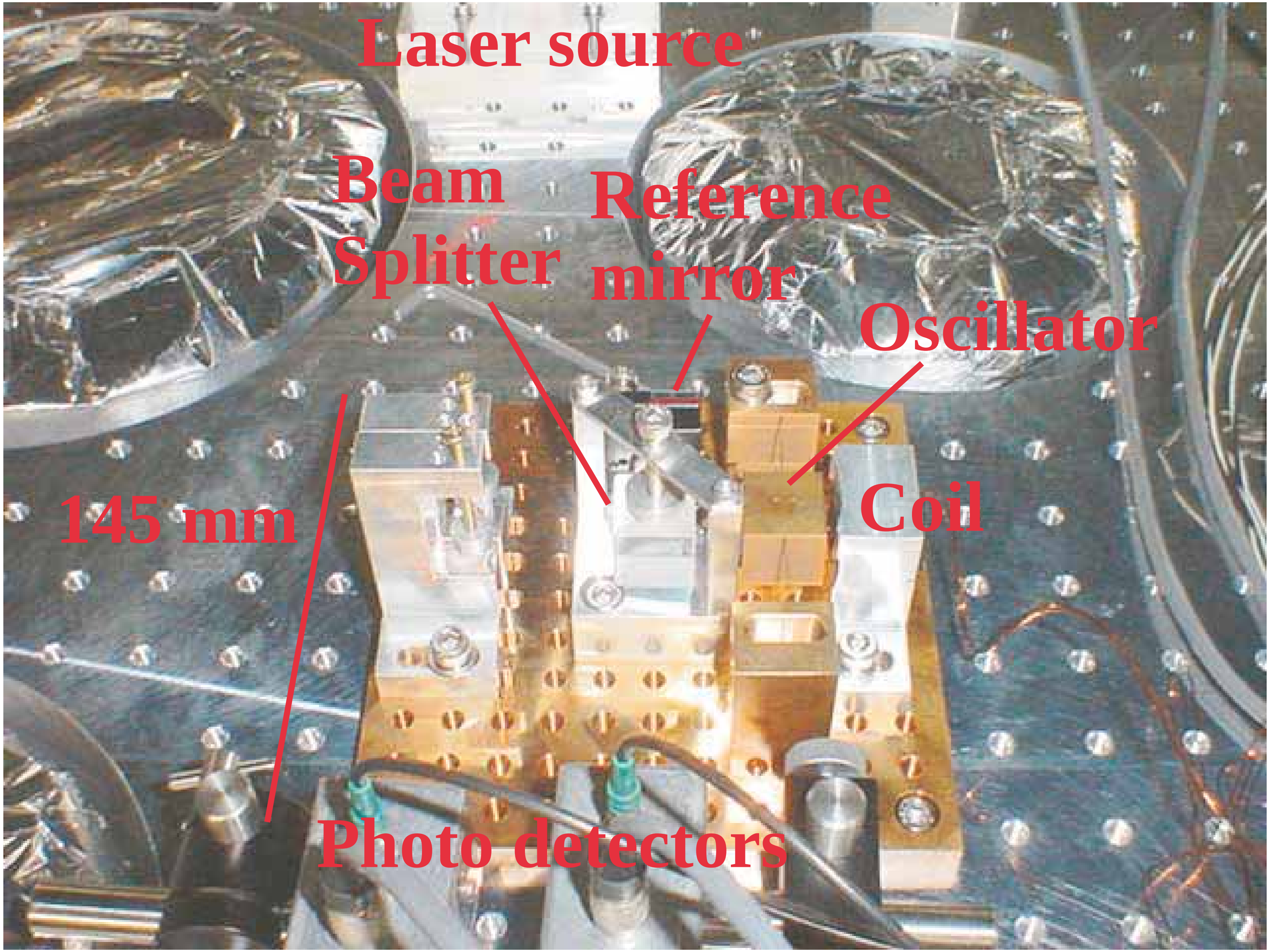
We measured vibration caused by new cryocoolers in Kamioka mine !
(suspension top of CLIO)

Schematic view of interferometer for vibration measurement



Vacuum chamber
(Laser source and photo detectors are in vacuum chamber.)

Interferometer

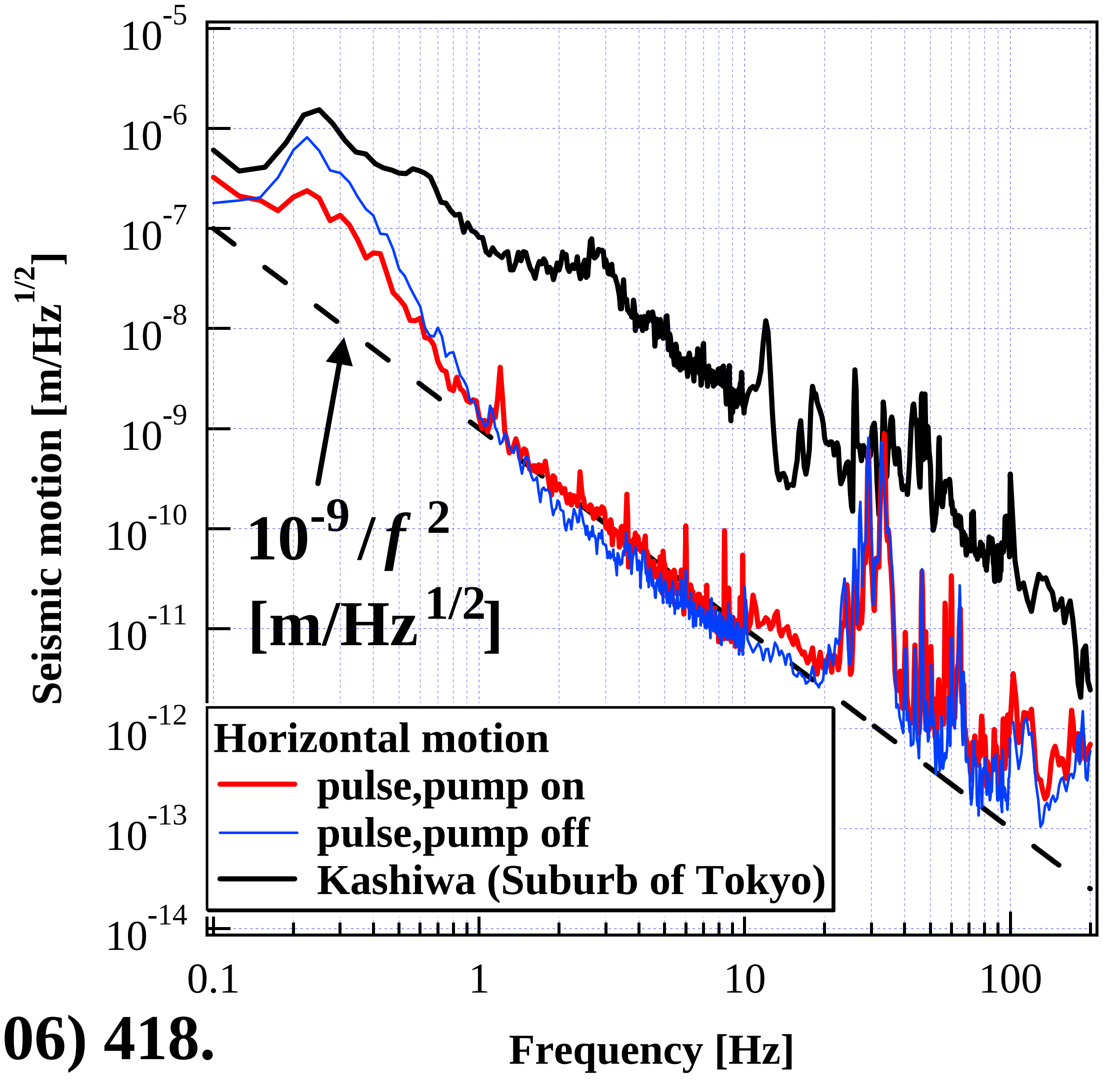


Results(1)

floor level (1 Hz-100 Hz)

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

Cryocoolers do not increase vibration.



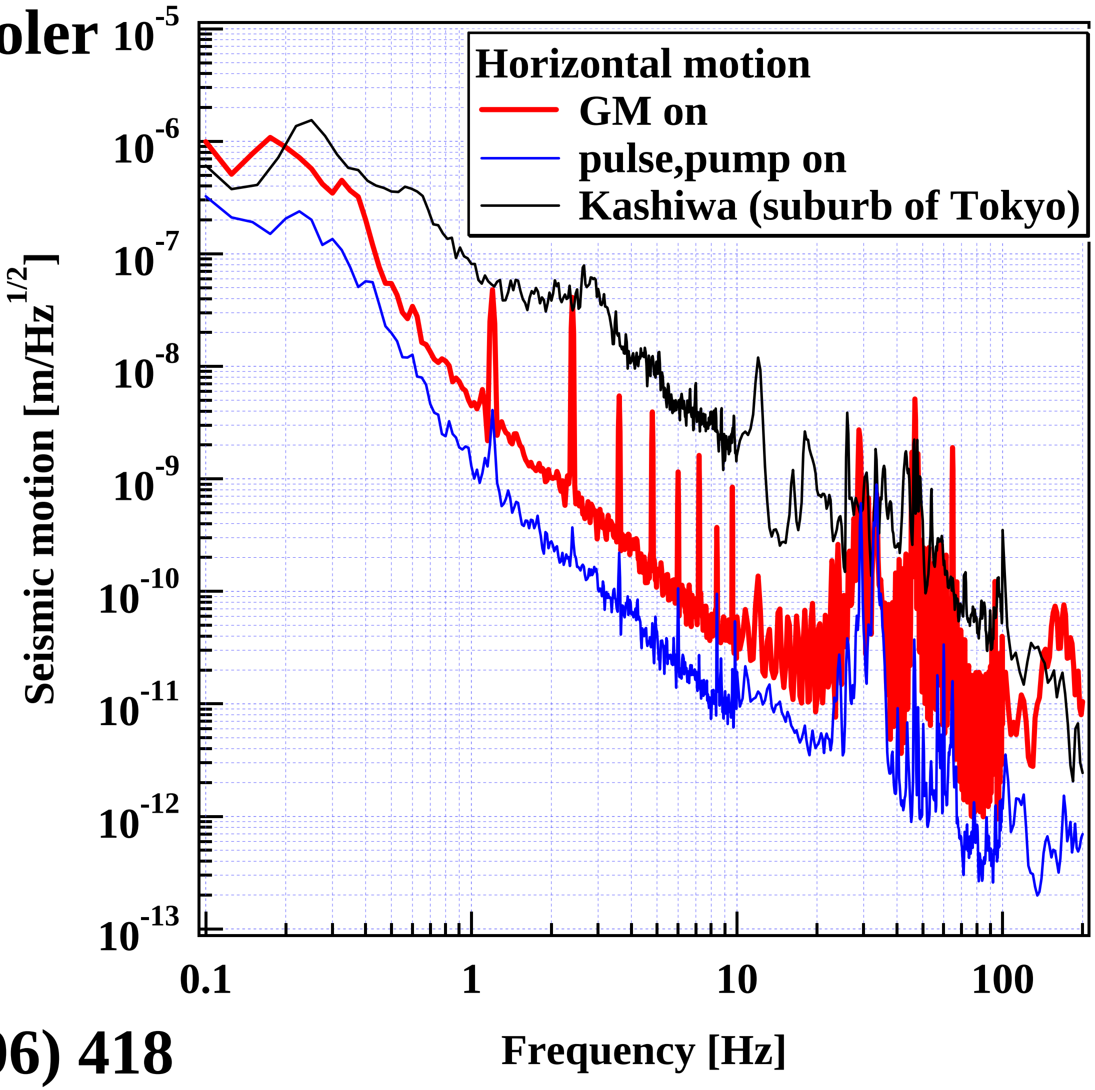
K. Yamamoto et al., Journal of Physics: Conference Series 32 (2006) 418.

Result(2)
Gifford-McMahon cryocooler

GM cryocooler
increases vibration.

Above 30 Hz
Kashiwa (Tokyo) level !

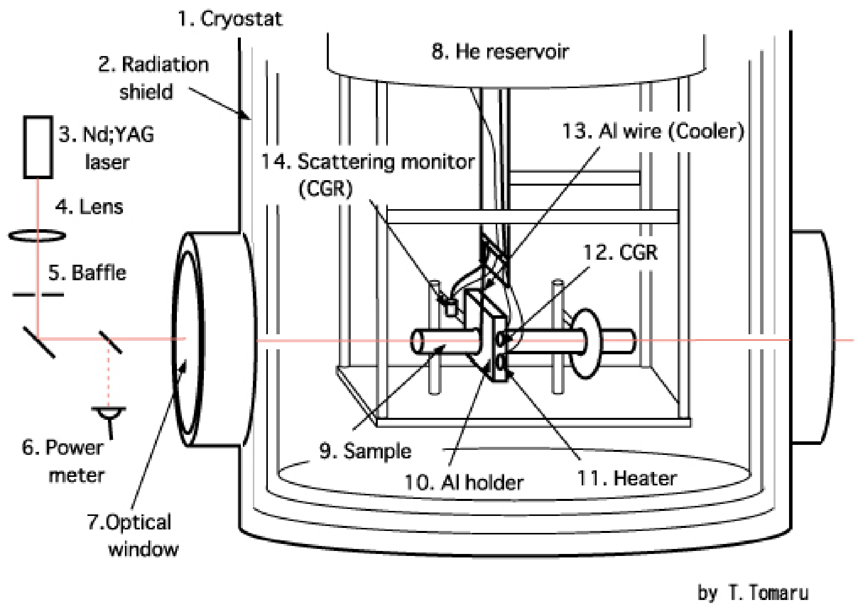
K. Yamamoto et al.,
Journal of Physics:
Conference Series 32 (2006) 418



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 also in progress.

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

Sapphire mirror-Sapphire fiber bonding

Direct bonding

(optical contact + diffusion bonding, without bonding agent)

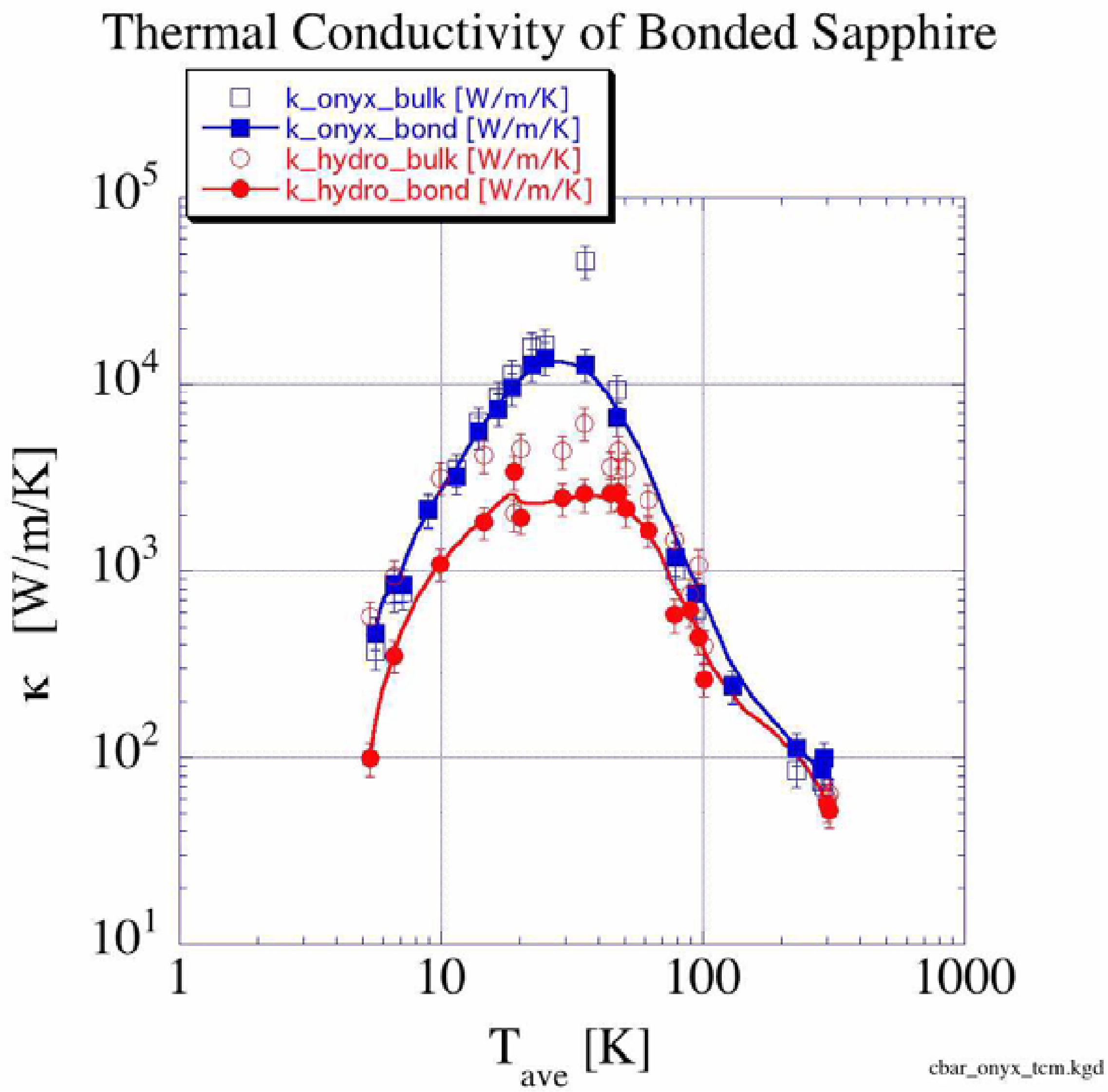
Thermal conductivity: OK

Strength: OK

Q-value of suspension: ?

R&D is in progress.
(other method 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.

5. Summary

LCGT: Japanese 2nd generation interferometric gravitational wave detector

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

2 interferometers

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

Seismic noise
Silent underground site   Vibration isolation system (SAS, SPI)

Thermal noise
Cryogenic technique

Most important and serious problem is

budget !!!

About 100 millions Euro

Thank you for your attention !

Vielen Dank
fuer Ihre Aufmerksamkeit !

ご静聴ありがとうございました。