Seismic noise and vibration isolation

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Lecture about gravitational wave detector for fresh persons
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0.Abstract

I would like to explain …

(1) Seismic motion

Investigation for silent site selection.

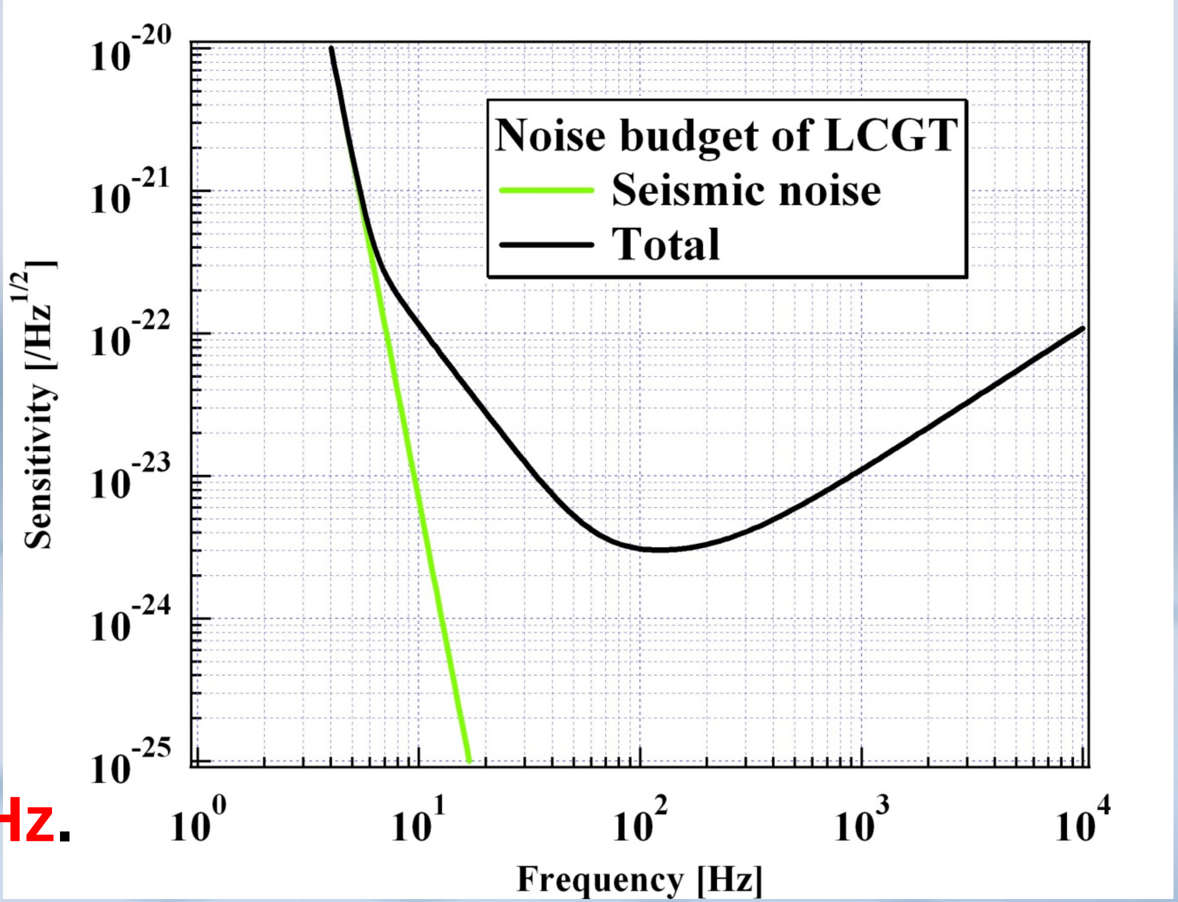
(2) Vibration isolation

How to suppress seicmic noise ?

Contents

1. Introduction

Vibration of ground shakes mirrors.



Seismic noise limits sensitivity below 10 Hz.

Sensitivity wall in low frequency region

1. Seismic noise

How can we reduce seismic noise ?

(1) Small seismic motion site

(2) Excellent vibration isolation system

2. Seismic noise

What is seismic motion ?

If ground is perfectly equivalent to inertial frame, it implies no seismic noise (mirrors must be on inertial frame).

Seismic motion is acceleration. Accelerometer is necessary for measurement.

We often show power spectrum density of displacement, not acceleration. Acceleration spectrum is divided by $(2\pi f)^2$ to convert acceleration to displacement.

2. Seismic noise

Site selection is essential !

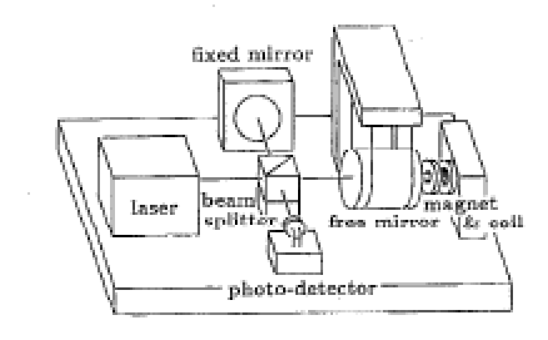
How do we measure seismic motion ?

It is not easy even if seismic motion is typical one …

(a) Excellent (not usual !) commercial accelerometer

(b) Sensor made by ourselves …

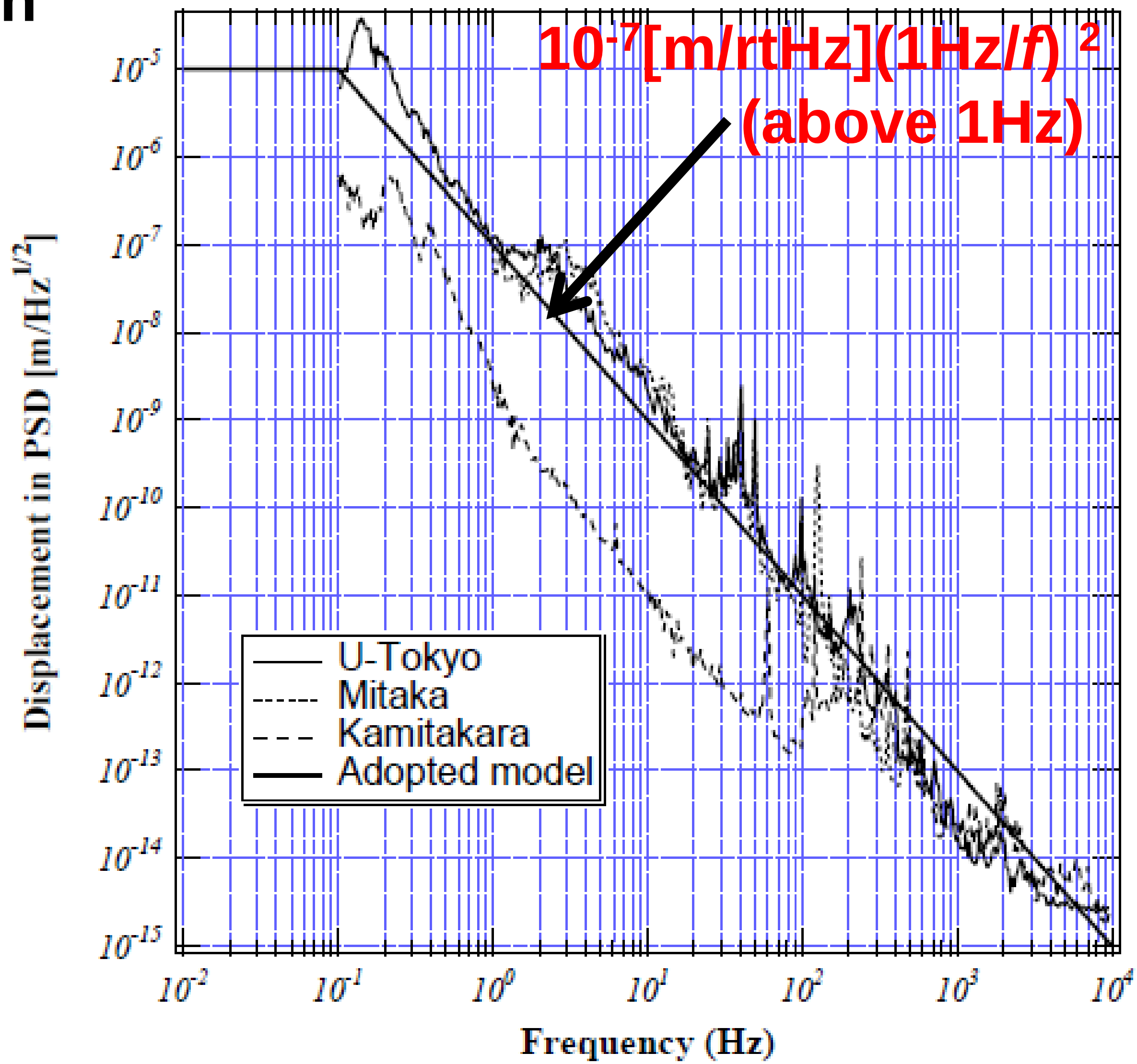
One example : Michelson interferometer



A. Araya *et al*.,
Review of Scientific Instrument
64 (1993) 1337.

2. Seismic noise

Typical seismic motion

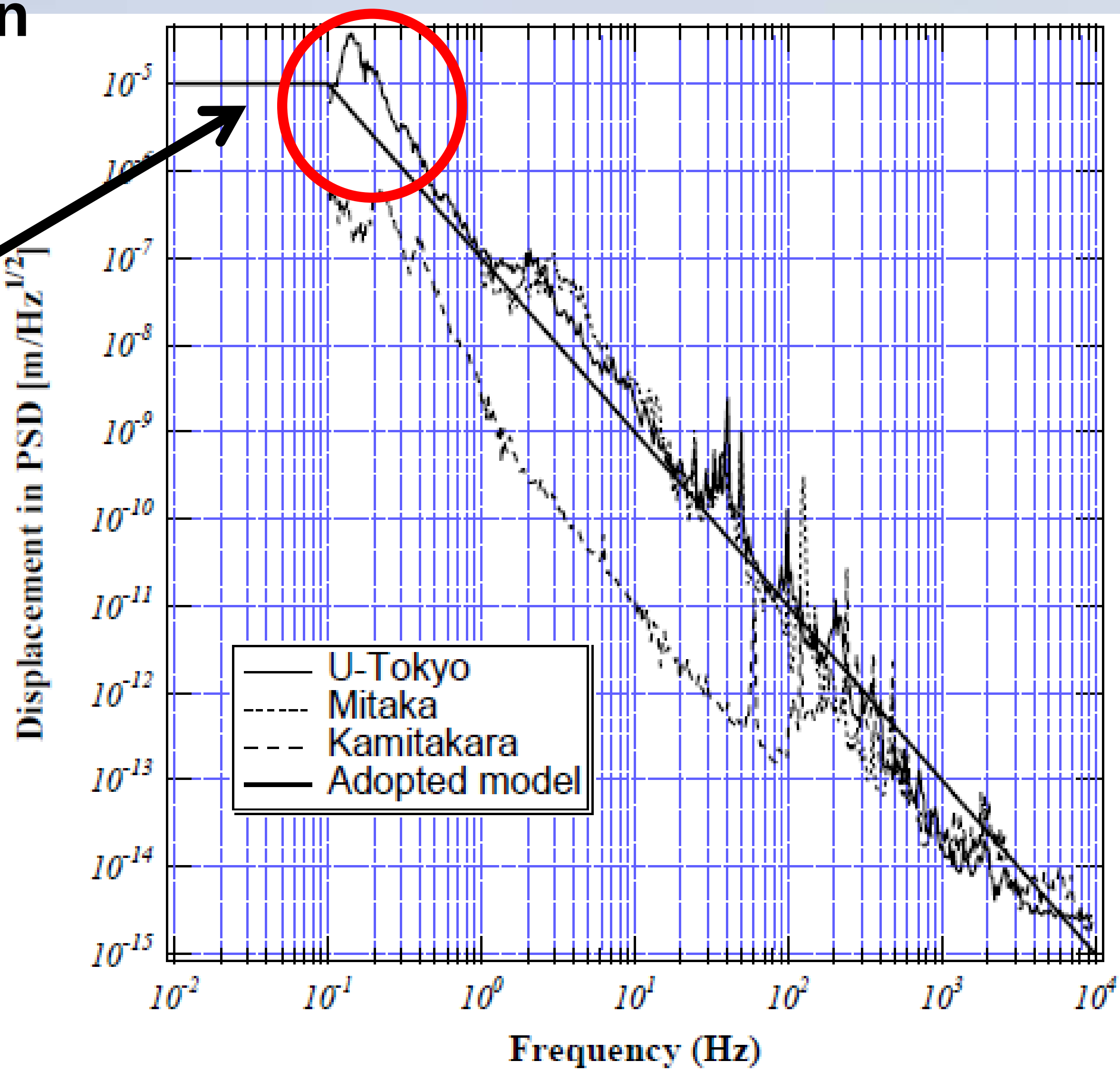


K. Arai, master thesis (1997)

2. Seismic noise

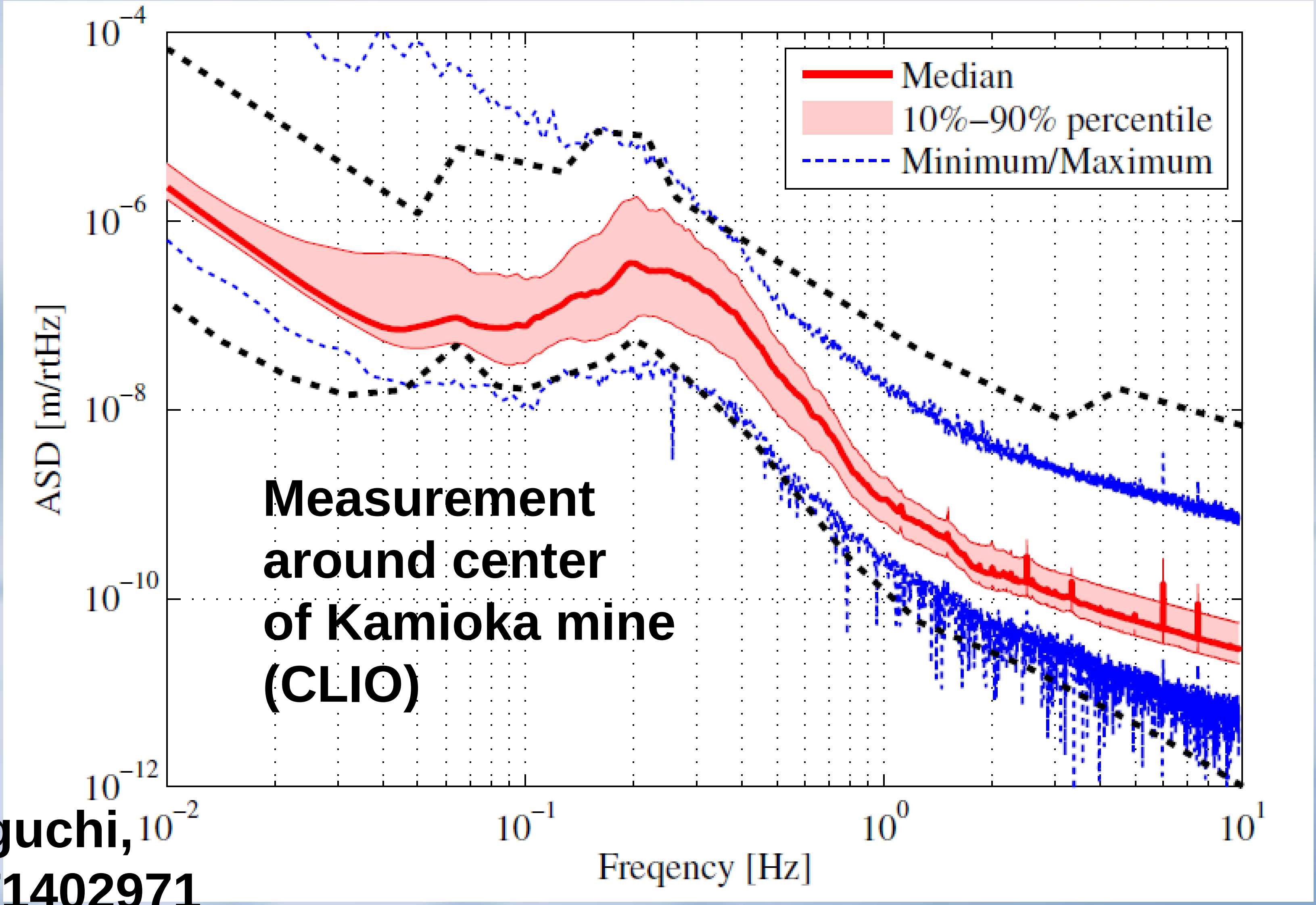
Typical seismic motion

Micro seismic peak (around 0.2 Hz) due to sea waves near coast. Amplitude strongly depends on weather.



K. Arai, master thesis (1997)

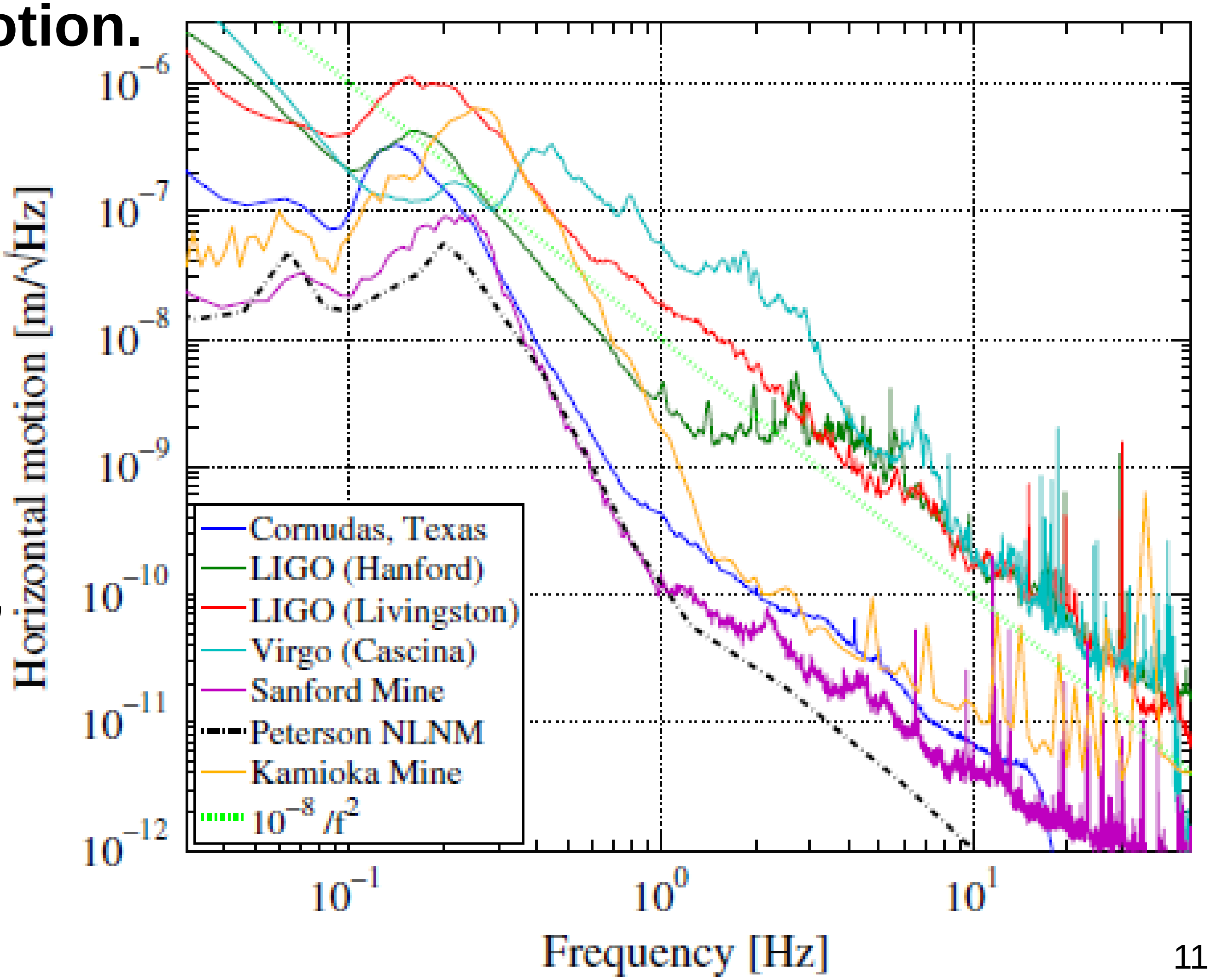
2. Seismic noise



T.Sekiguchi, JGW-T1402971

2. Seismic noise

Under ground site has two orders of magnitudes smaller seismic motion.



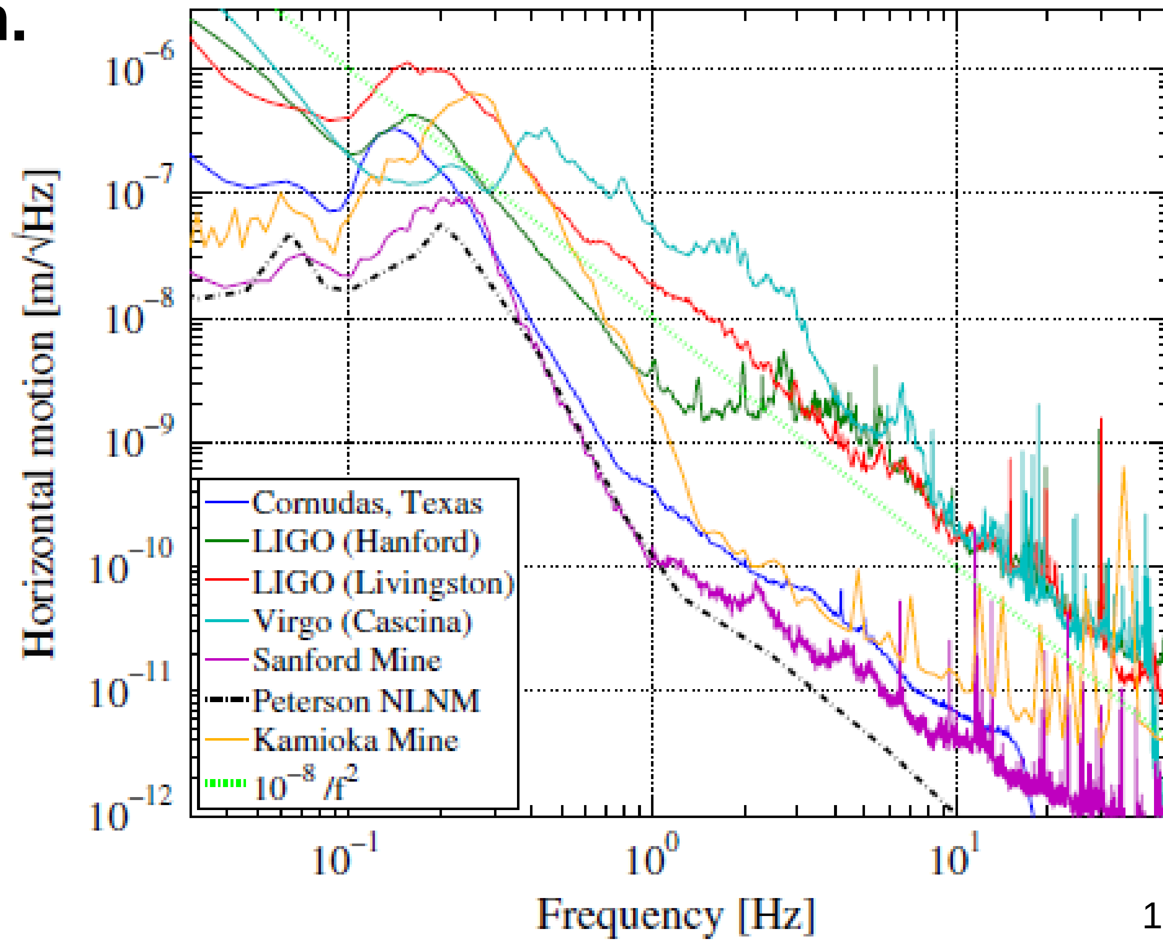
R. X. Adhikari
Reviews of Modern Physics, 86(2014)121.

FIG. 4 (color online). The seismic vibration spectral densities shown for some of the relatively quiet sites of the current GW detector network. Also shown are two promising locations for future low-frequency detectors in the U.S.: the 4100 ft level of the Sanford Underground Lab and a surface site near El Paso, TX. The USGS New Low Noise Model (Peterson, 1993) is included as a reference. All the spectra here [with the exception of Kamioka (Aso and Araya, 2012)] are estimated using Welch's method but with median instead of mean averaging so as to better reject non-Gaussian transients.

noise

of magnitudes

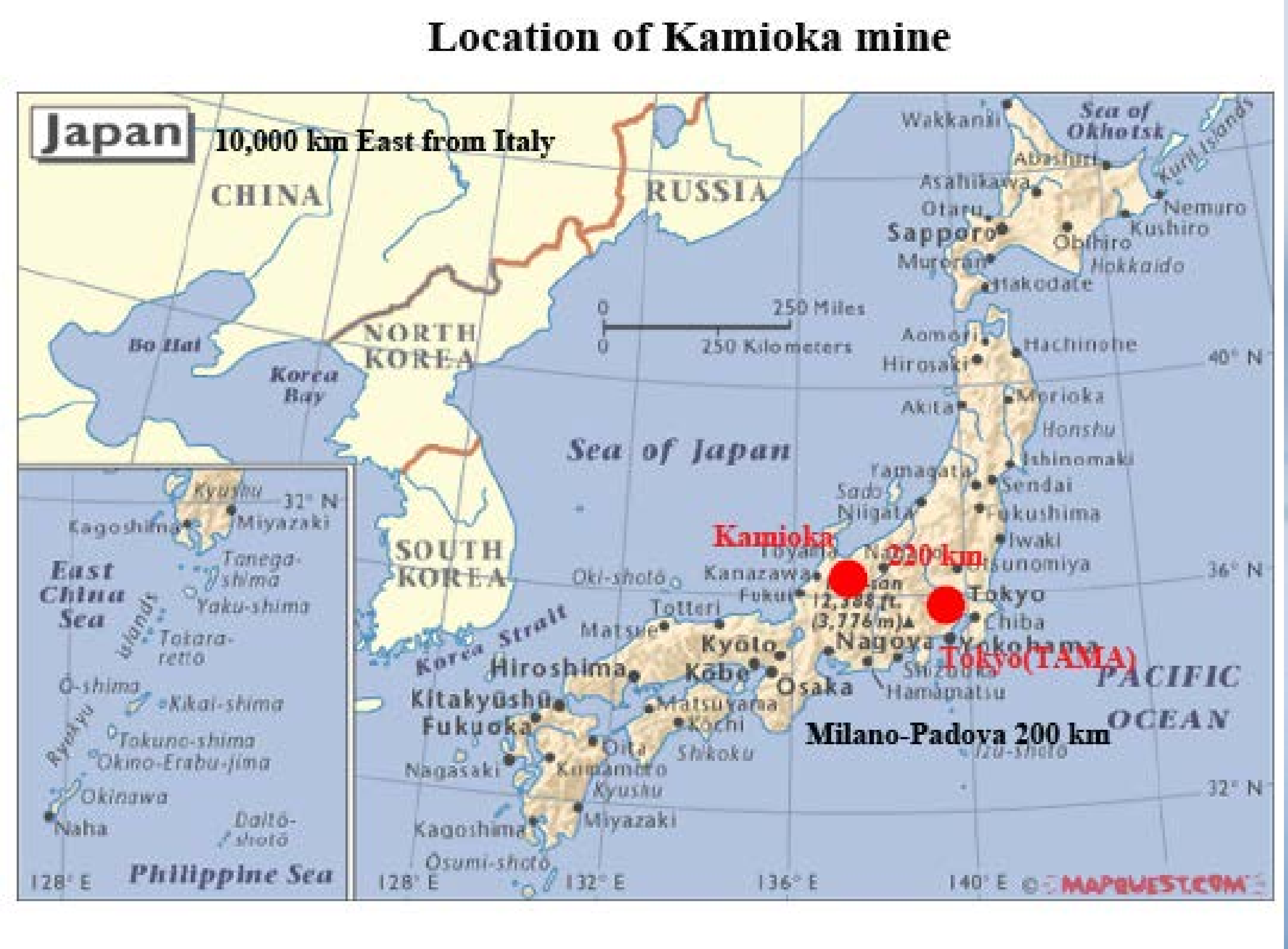
smaller seismic motion.



R. X. Adhikari
Reviews of Modern Physics, 86(2014)121.

2. Seismic noise

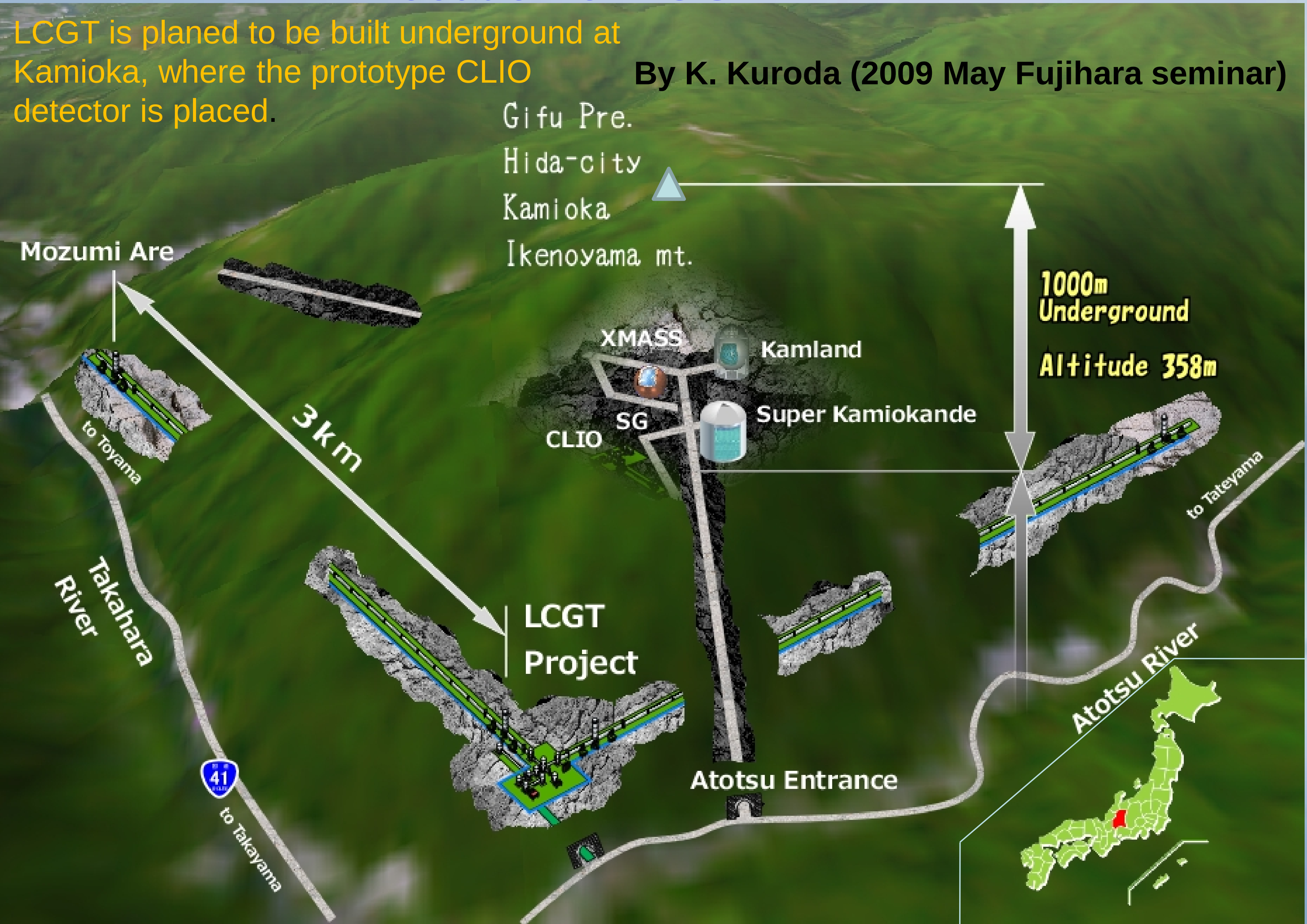
Where is Kamioka mine ?



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)

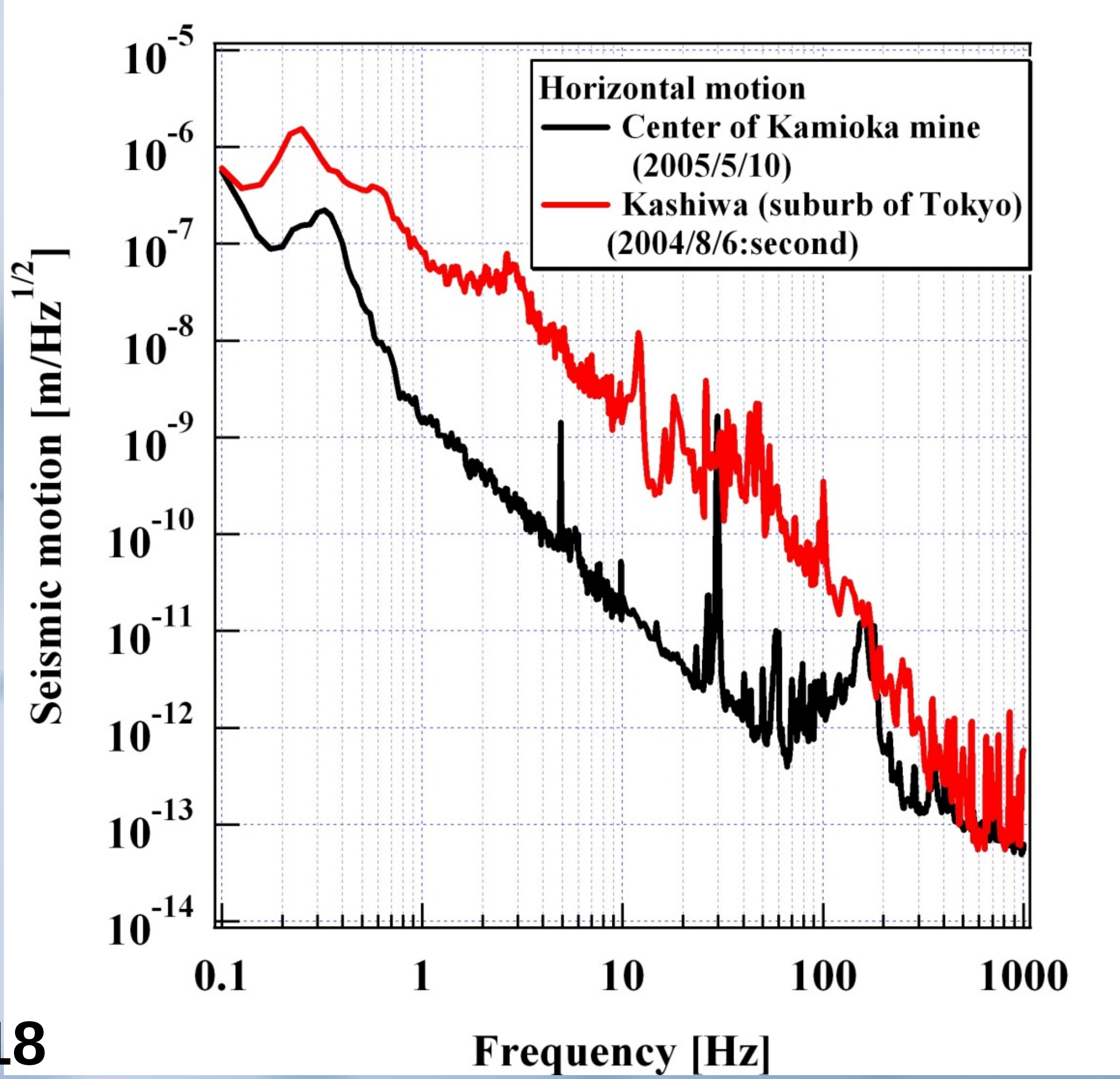


2. Seismic noise

Many people measured seismic motion in Kamioka mine.

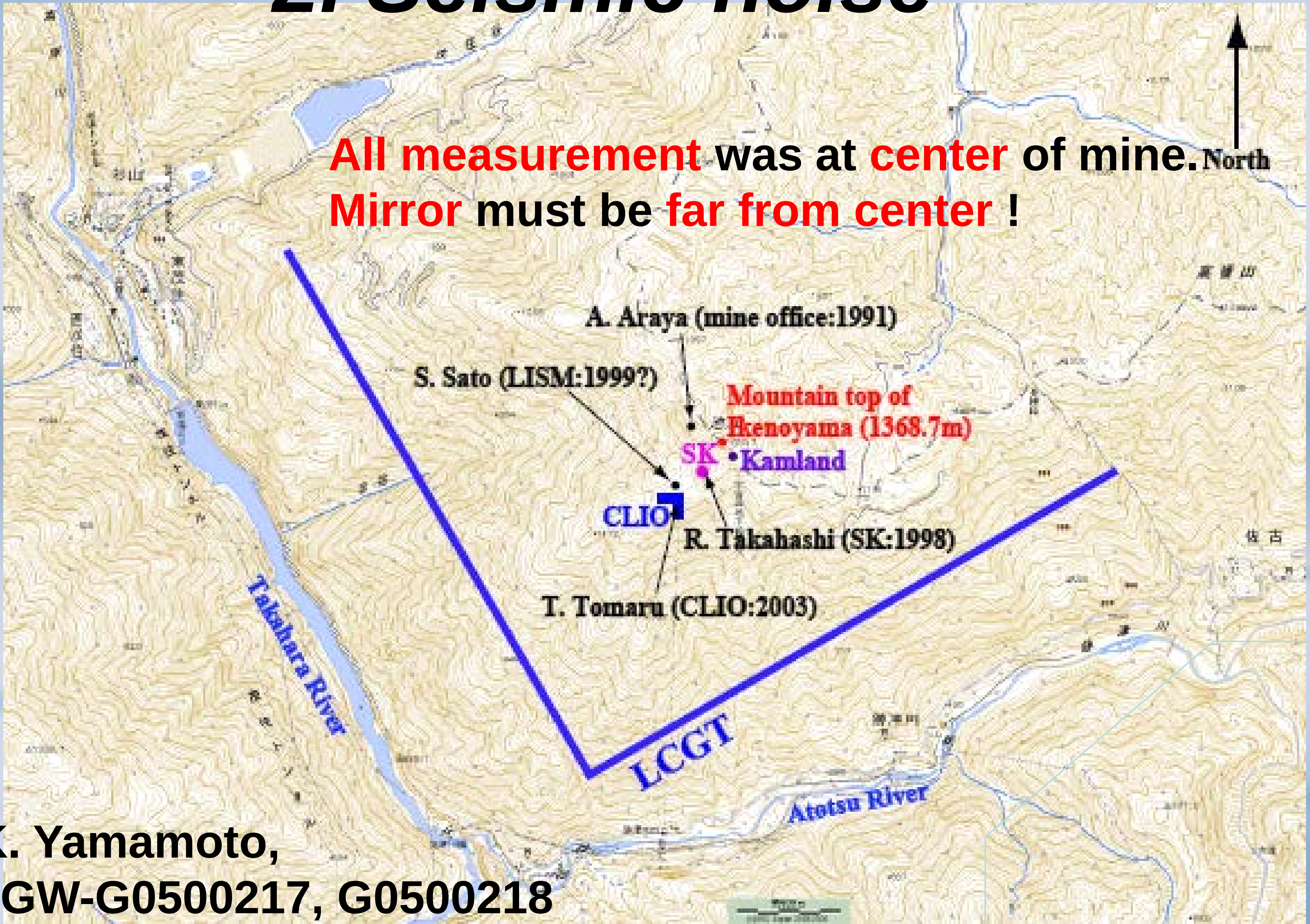
100 times smaller seismic motion at center of Kamioka mine.

However …



K. Yamamoto,
JGW-G0500217, G0500218

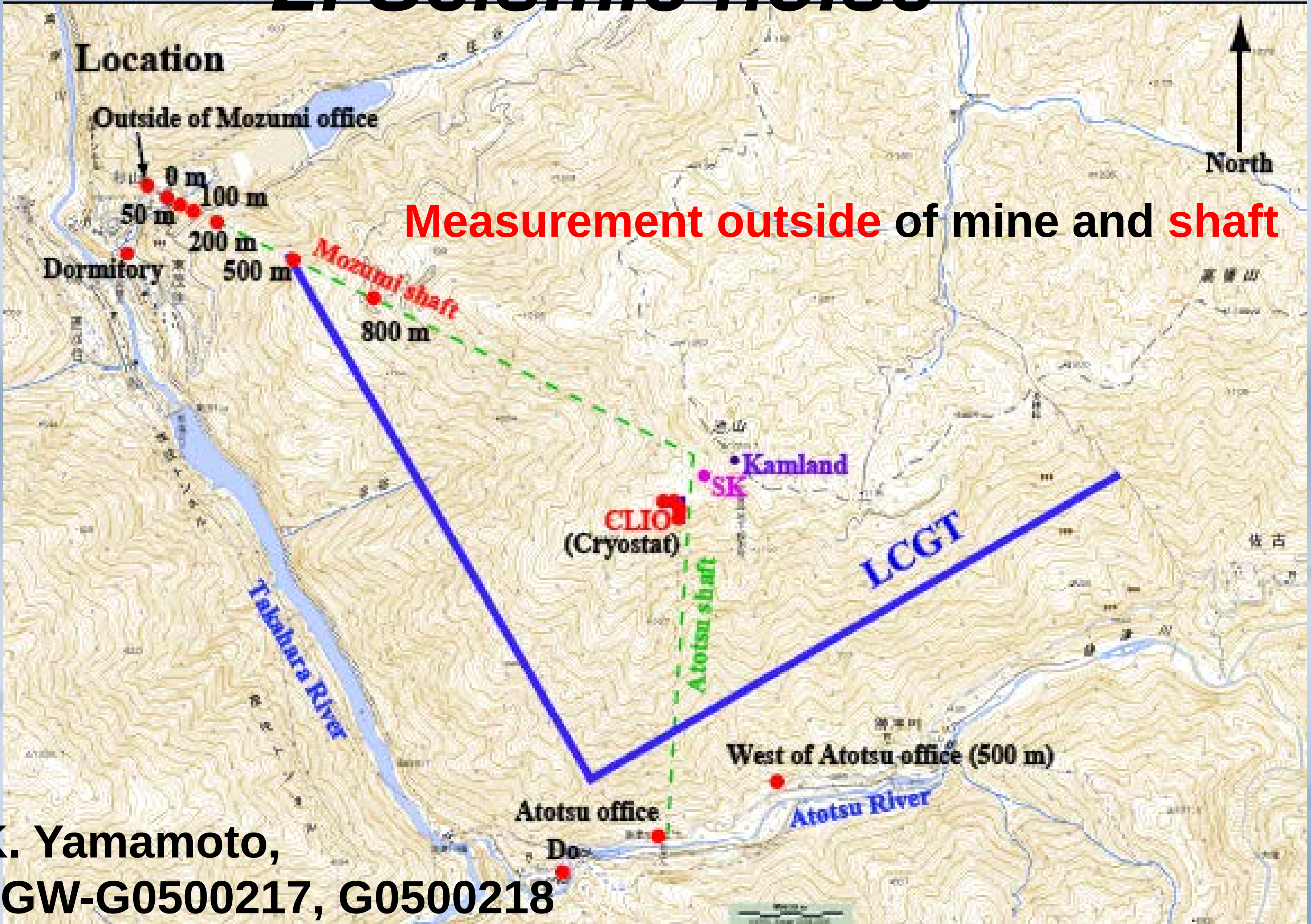
2. Seismic noise



All measurement was at center of mine.
Mirror must be far from center !

K. Yamamoto,
JGW-G0500217, G0500218

2. Seismic noise



K. Yamamoto,
JGW-G0500217, G0500218

2. Seismic noise

Measurement at Atotsu office

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JGW-G0500217, G0500218

2. Seismic noise

Outside of Mozumi office

K. Yamamoto,
JGW-G0500217, G0500218

2. Seismic noise

Measurement apparatus

K. Yamamoto,
JGW-G0500217, G0500218

2. Seismic noise

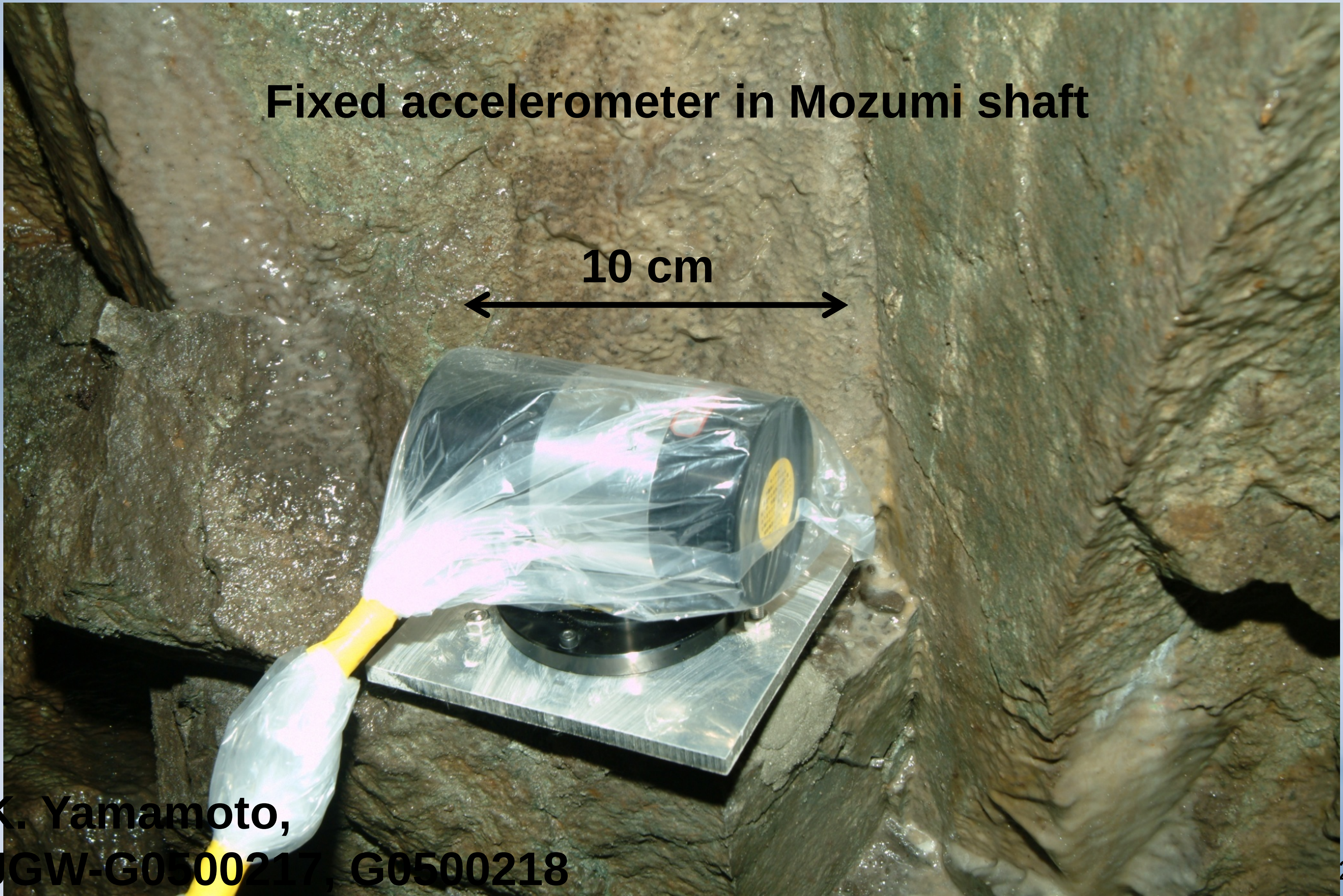
K. Yamamoto,
JGW-G0500217, G0500218

Truck

2. Seismic noise

K. Yamamoto,
JGW-G0500217, G0500218

2. Seismic noise



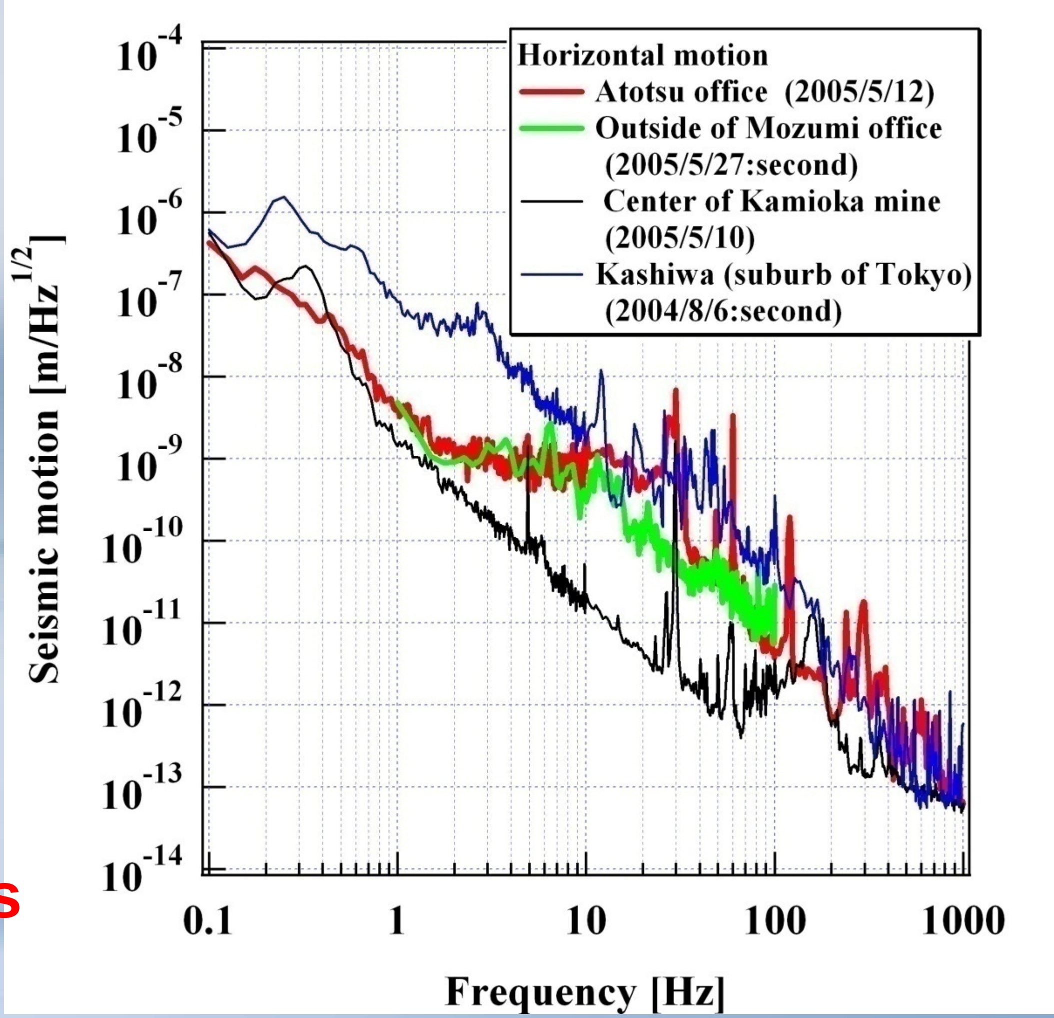
K. Yamamoto,
JGW-G0500217, G0500218

2. Seismic noise

Outside of mine
<1 Hz
(Outside of mine)
=(Center of mine)
>1 Hz
(Outside of mine)
>(Center of mine)

Vertical motion is similar to horizontal one.

Results of other locations are similar.



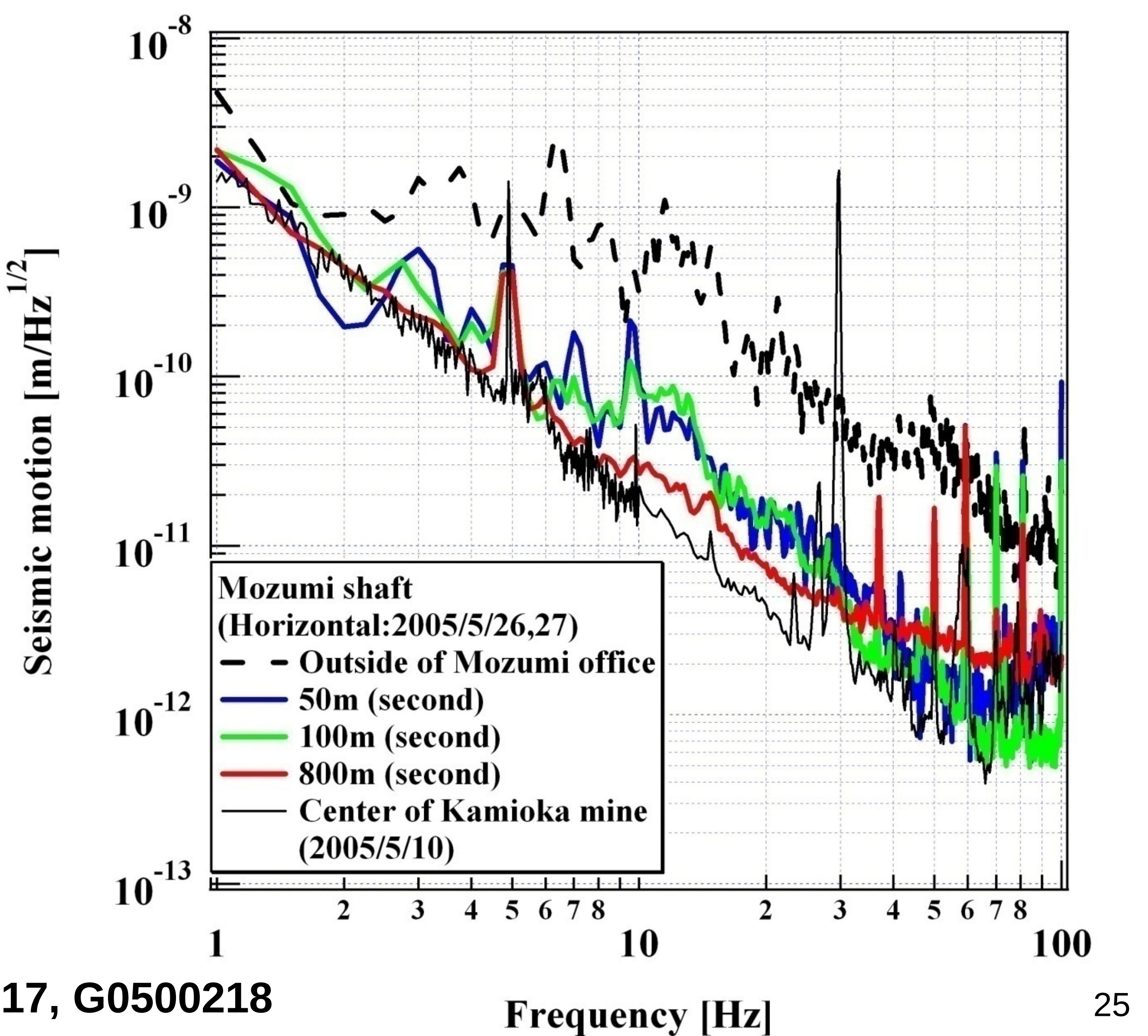
K. Yamamoto, JGW-G0500217, G0500218

2. Seismic noise

Inside of mine

> 50 m
Silent sufficiently !

Main mirrors
50 m from ground



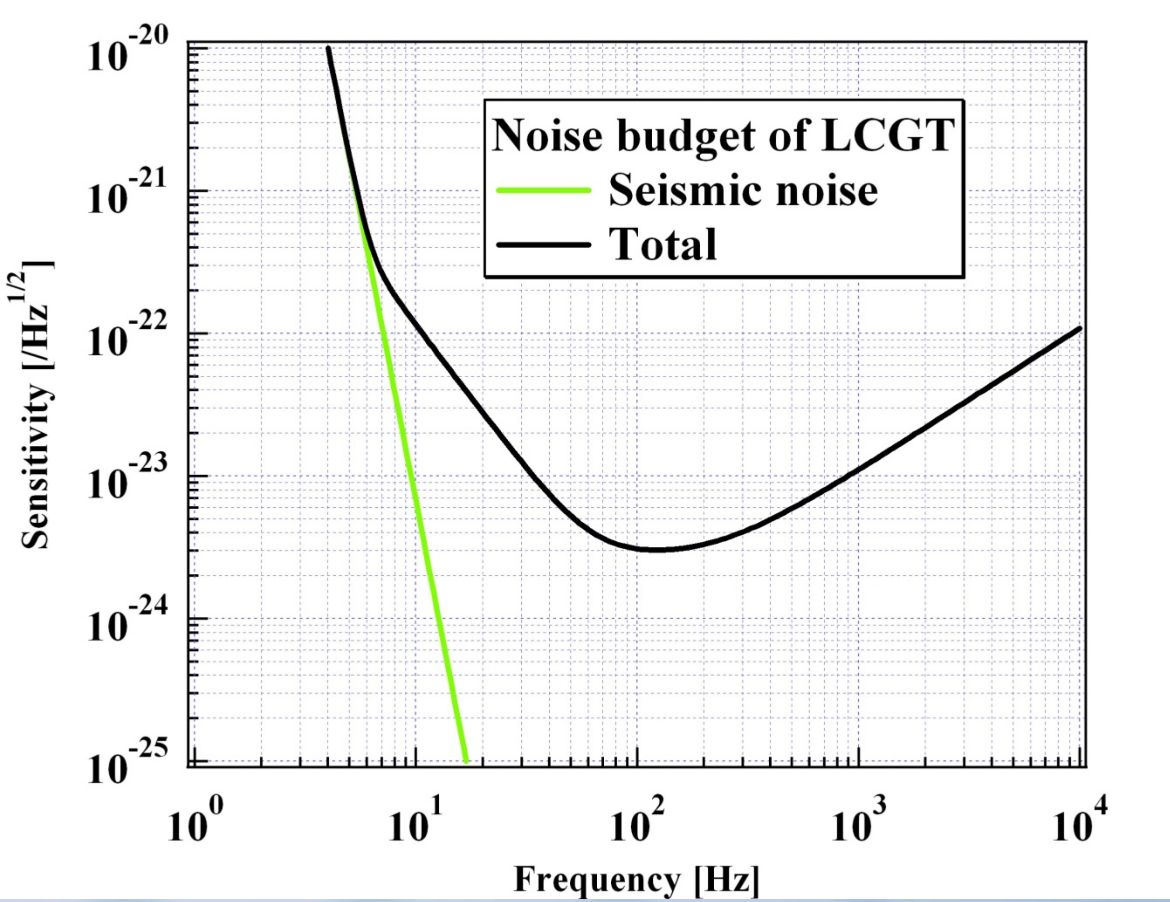
K. Yamamoto, JGW-G0500217, G0500218

2. Seismic noise

Mirror displacement around 10Hz must be below 10^{-19} m/rtHz.

Seismic motion around 10Hz is 10^{-11} m/rtHz even at Kamoka.

At least 8 (in typical, 10) orders of magnitude vibration isolation is necessary !



2. Seismic noise

Mirror displacement around **10Hz** must be below **10^{-19} m/rtHz**.

Seismic motion around 10Hz is **10^{-11} m/rtHz** even at Kamoka !

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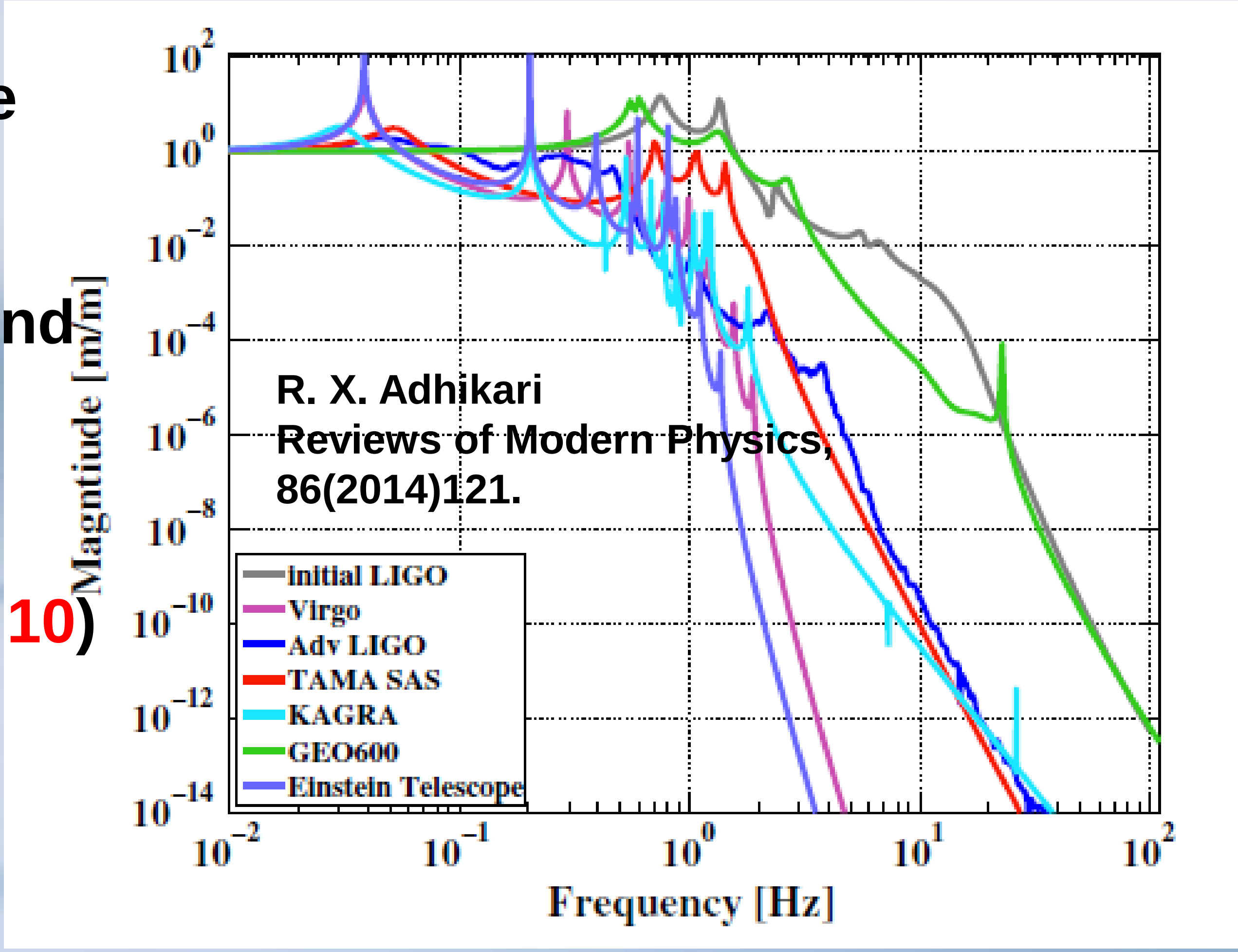


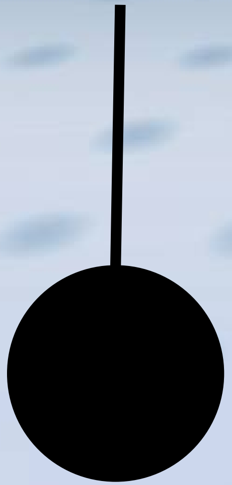
No silver bullet ! We need many tricks !

3. Vibration isolation

Mirrors must be suspended because they should act as like free mass.

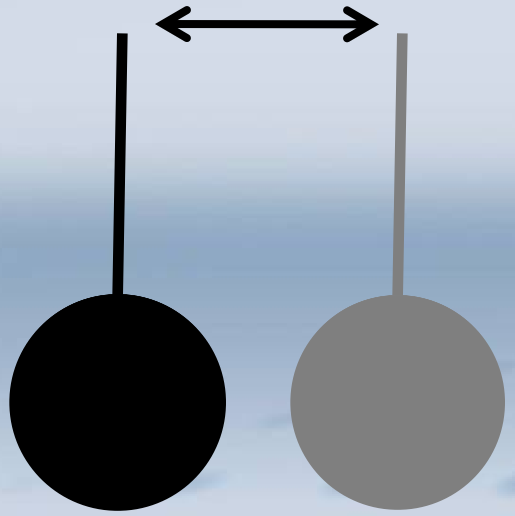
Otherwise, transfer function from gravitational wave to detector output is too small.

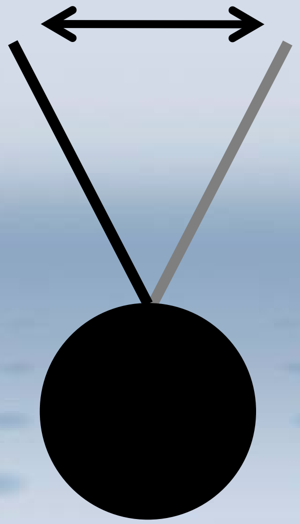
"Suspended" mirror is also isolated from seismic motion.



3. Vibration isolation

Mirrors are suspended.



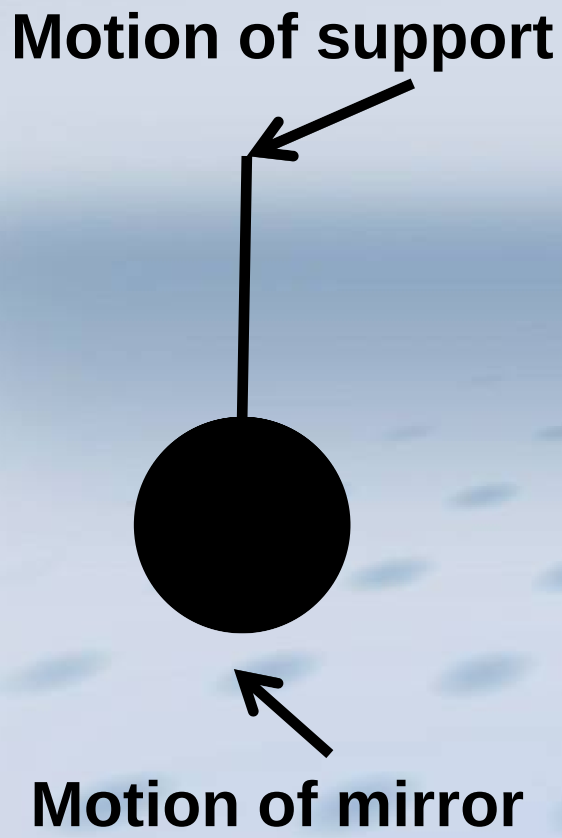


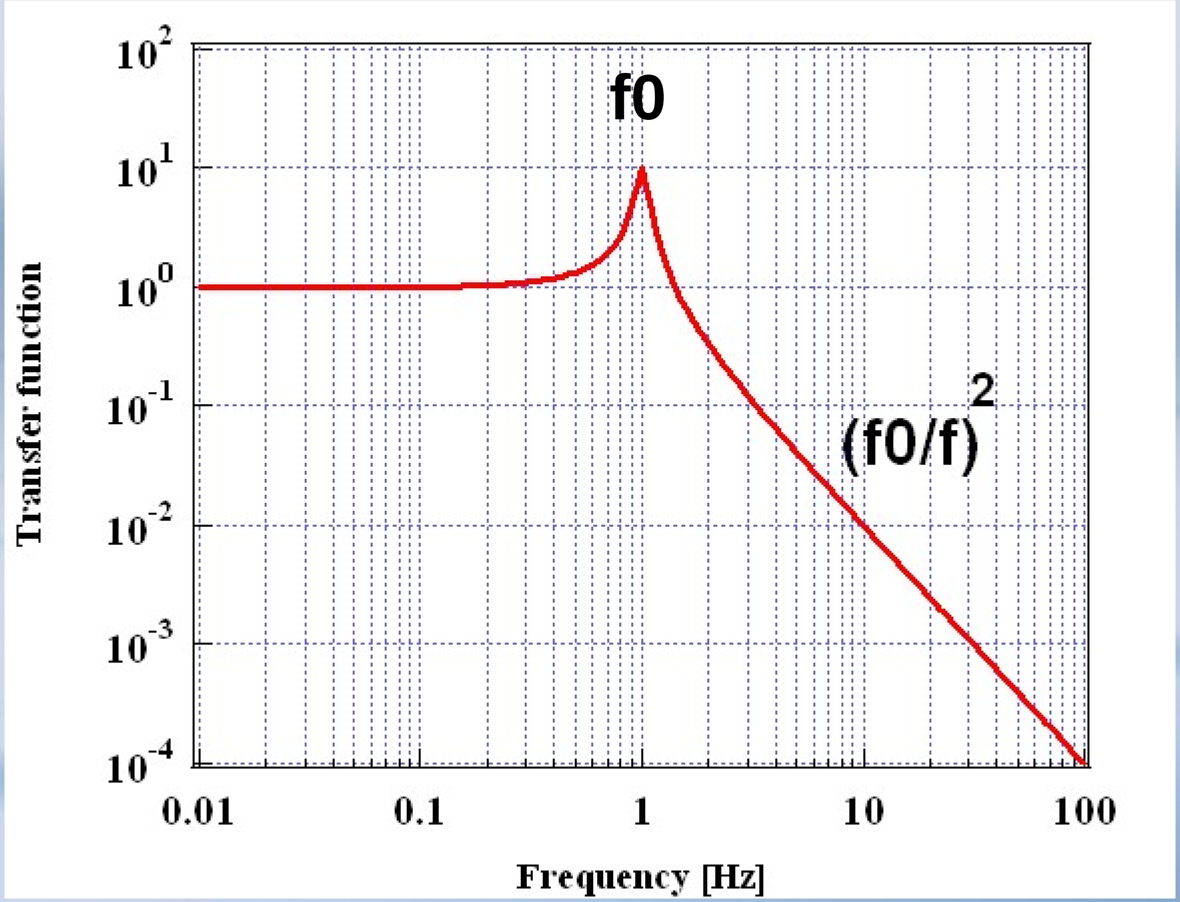
Slow motion
Mirror follows
motion of support point.

Rapid motion
Mirror can not follow
motion of support point.

3. Vibration isolation

Transfer function : (Motion of mirror)/(Motion of support)





3. Vibration isolation

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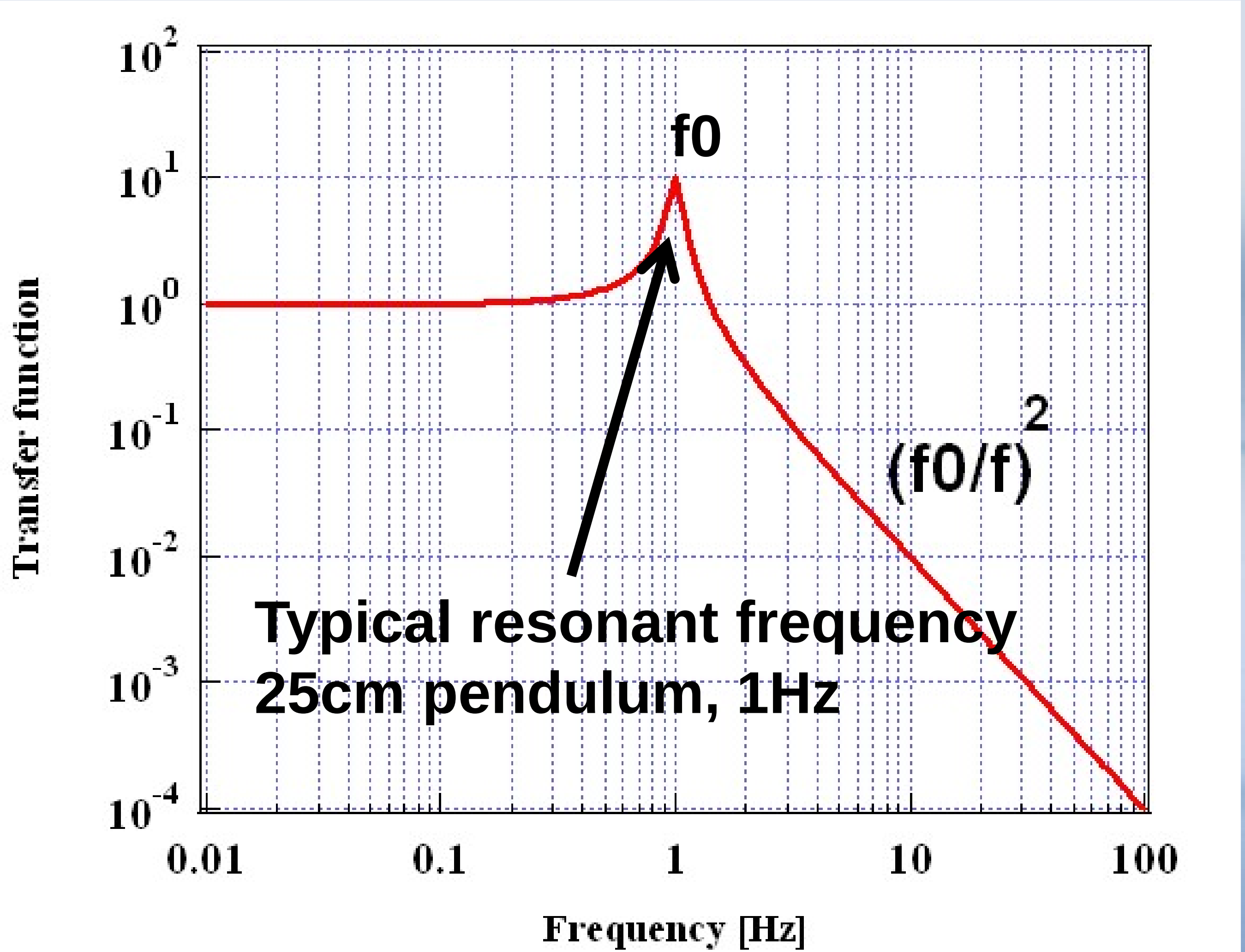
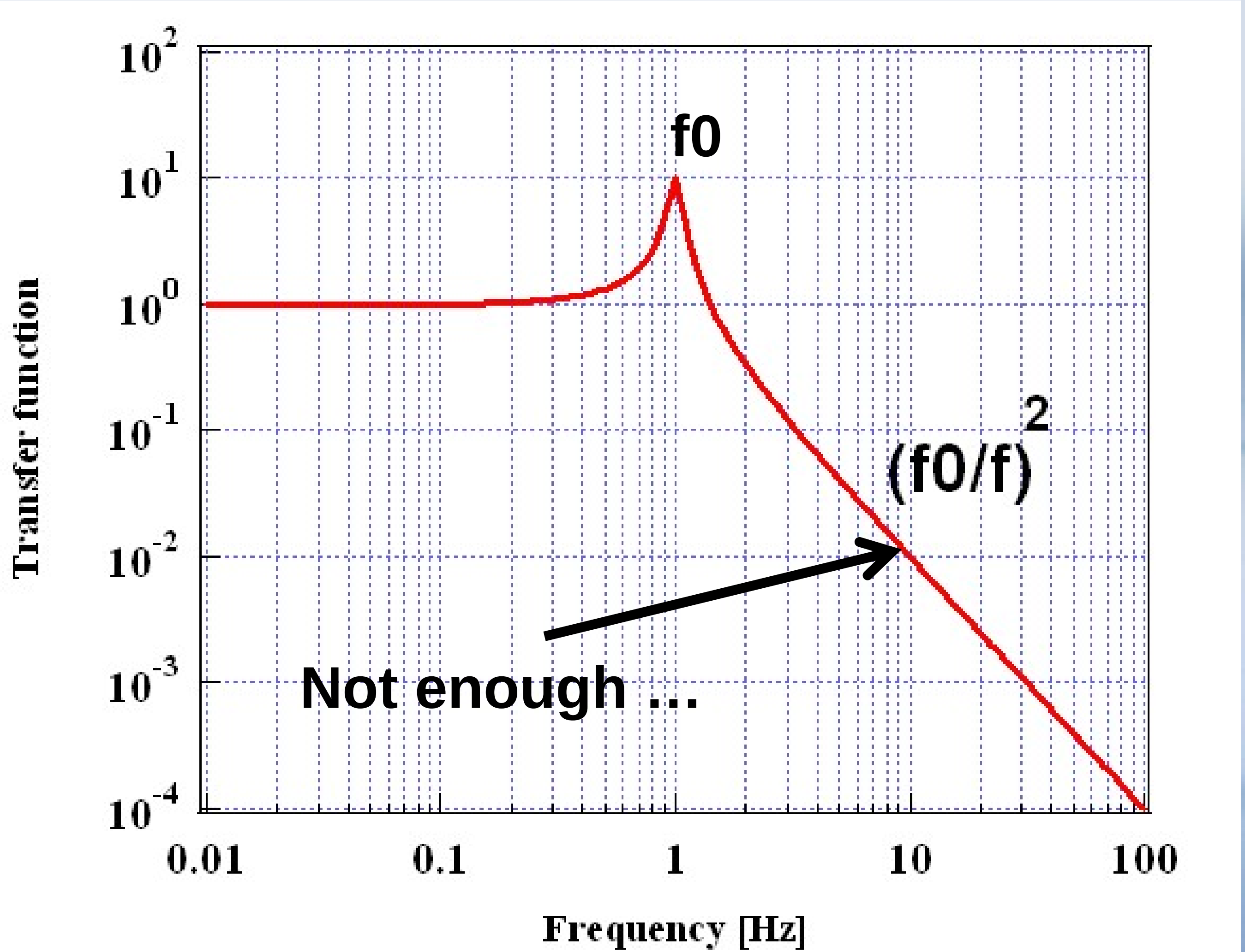


1. Seismic noise

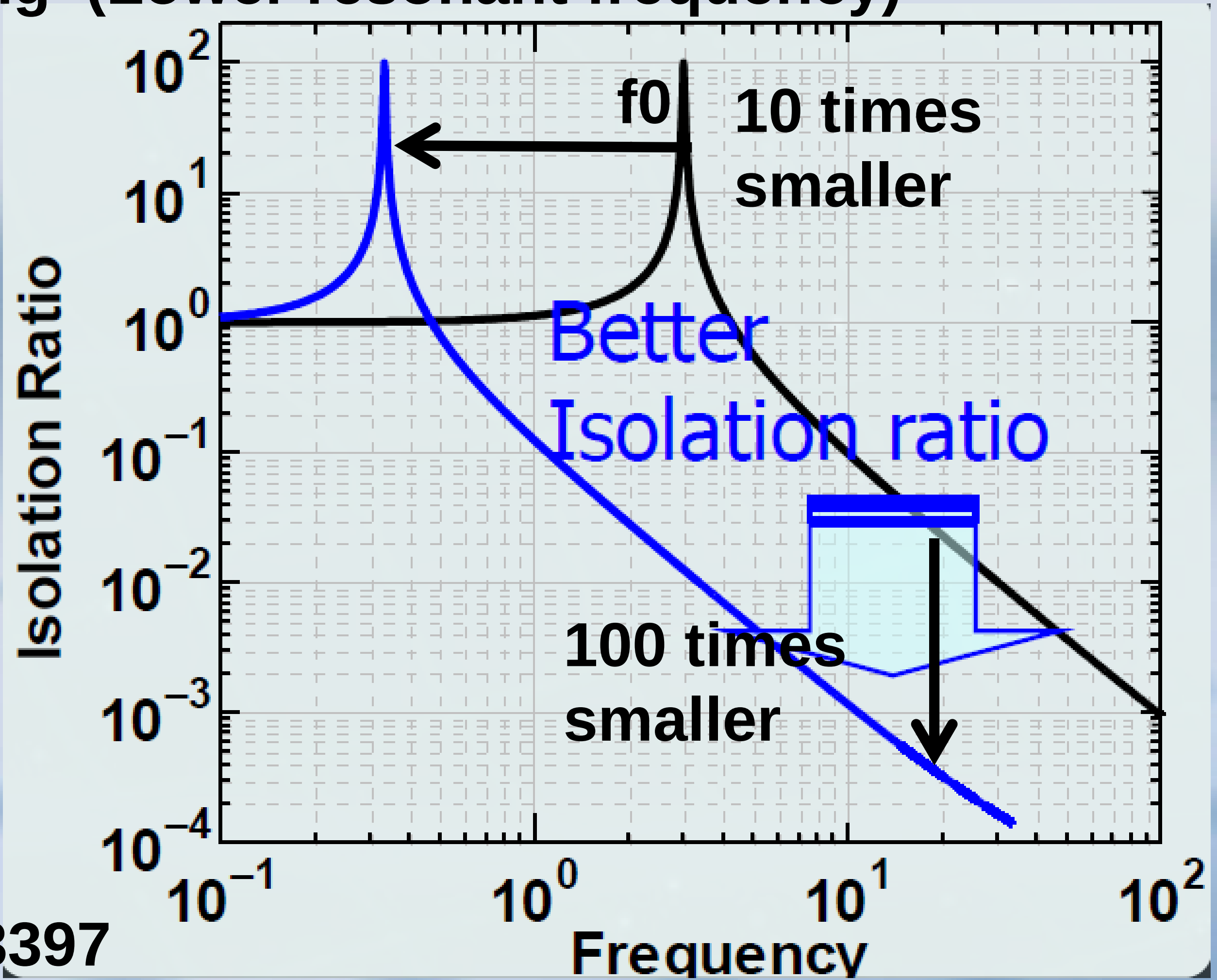
Transfer function : (Motion of mirror)/(Motion of support)



3. Vibration isolation

How to improve isolation ratio ?

Softer spring (Lower resonant frequency)



M. Ando, JGW-G1503397

3. Vibration isolation

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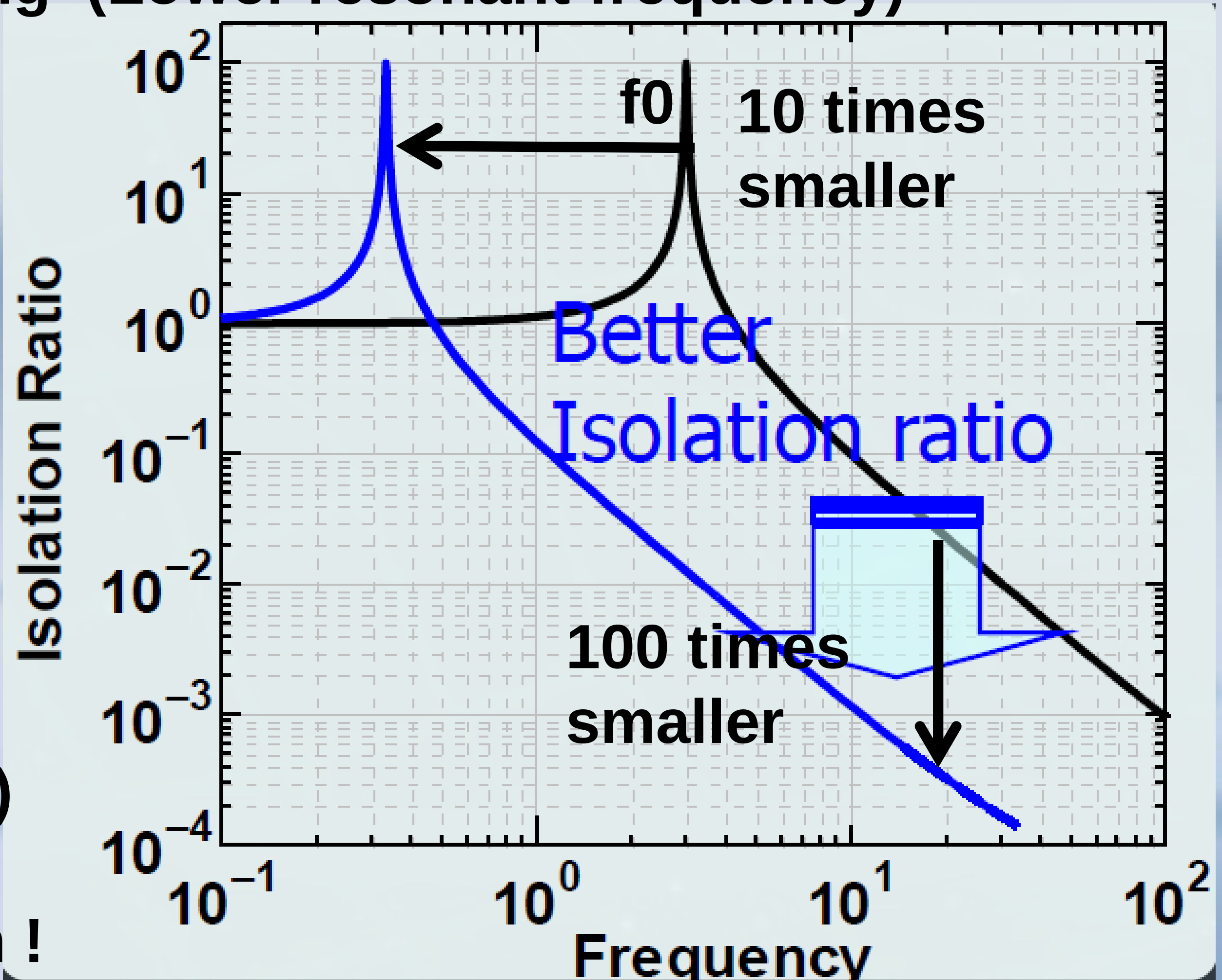


Pendulum
f0 ~ $l^{-1/2}$
(l is length.)
1Hz : 25cm
0.1Hz : 25m !

3. *Vibration isolation*

How to improve isolation ratio ?

Soft pendulum with reasonable size

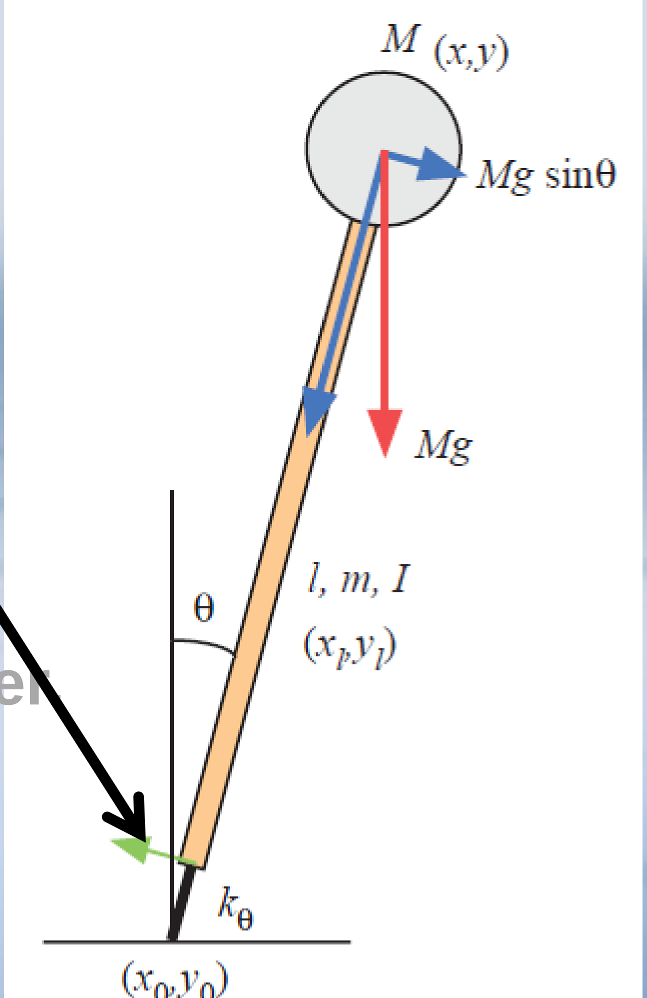
Inverted pendulum

Elasticity : Positive spring constant

Gravity : Negative spring constant

Both spring constants cancel each other

30mHz resonance is feasible.



A. Takamori, LCGT design document (2004)

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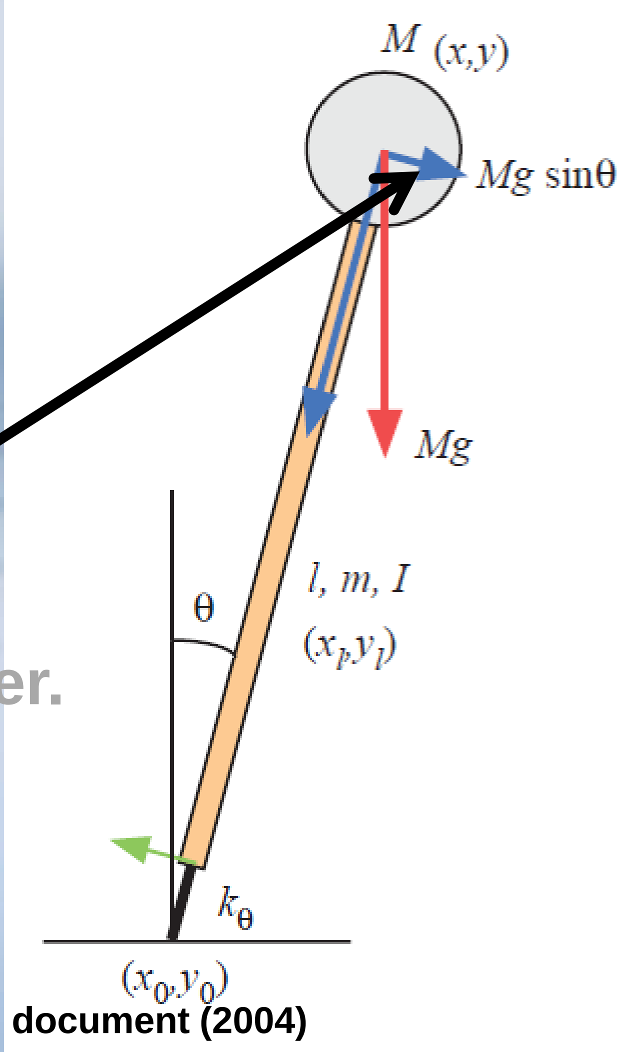

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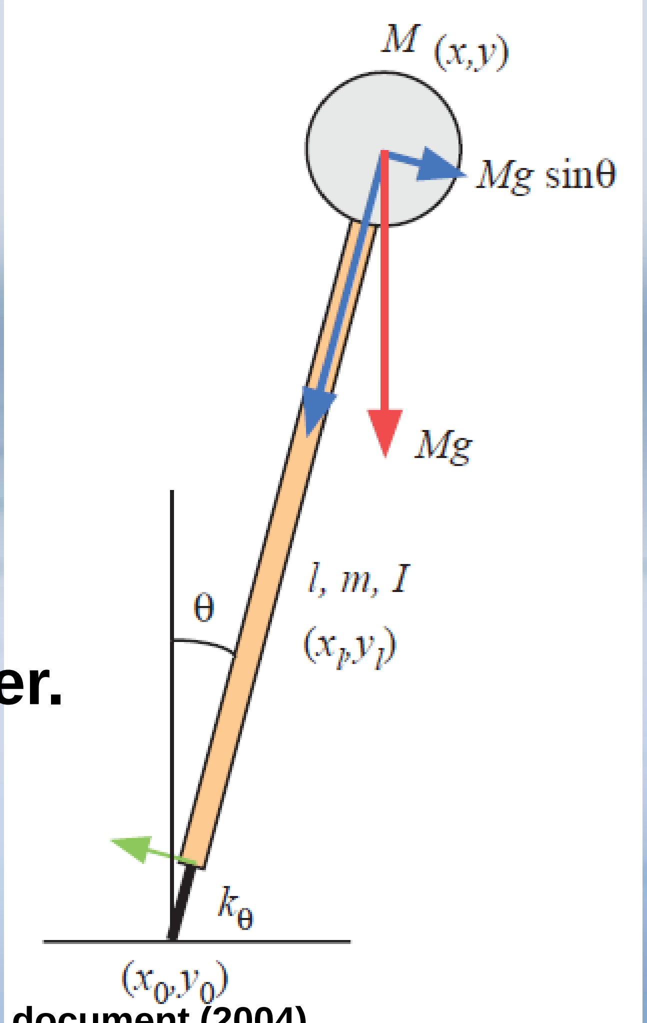
30

$$k_{\mathrm{eff}} = \frac{k_\theta}{l^2} - \left(\frac{m}{2} + M\right)\frac{g}{l}$$



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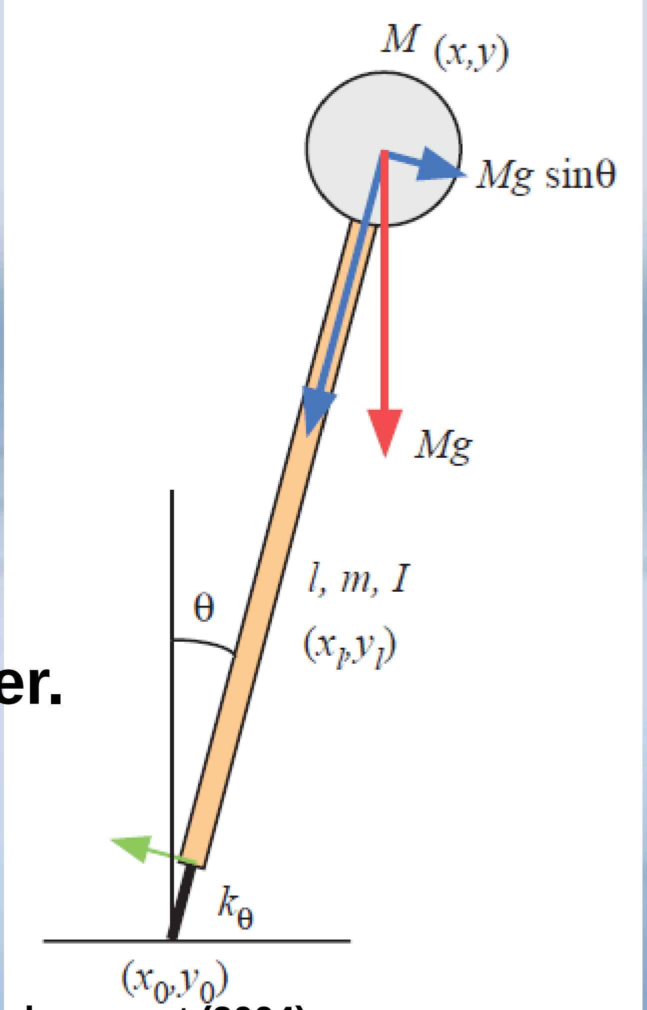

A. Takamori, LCGT design document (2004)

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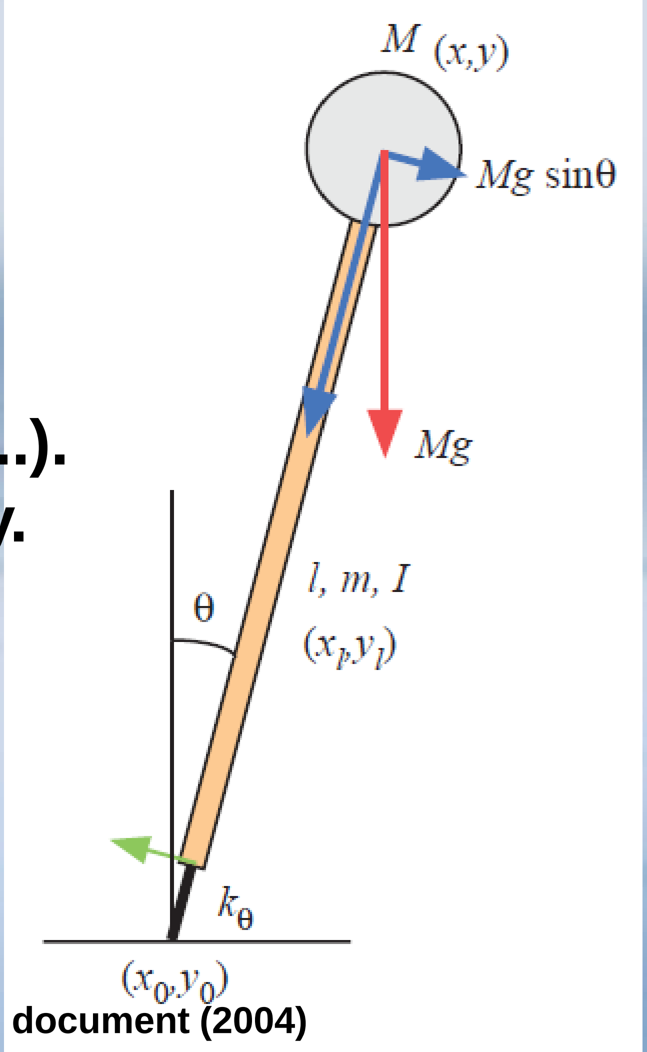


Drawbacks
(1)Soft spring can be broken easily (tilt..).
Control system or limiter are necessary.

(2)Elasticity depends on temperature.
Small temperature change causes drastic change of resonant frequency.

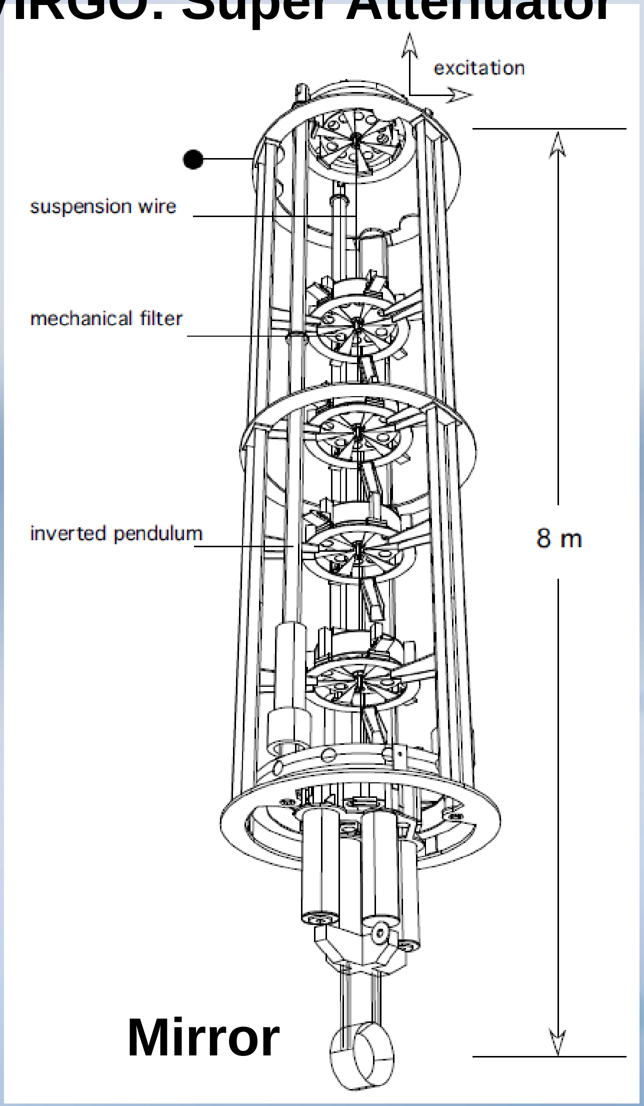
A. Takamori, LCGT design document (2004)

3. Vibration isolation

How to improve isolation ratio ?

Multiple pendulum

VIRGO: Super Attenuator

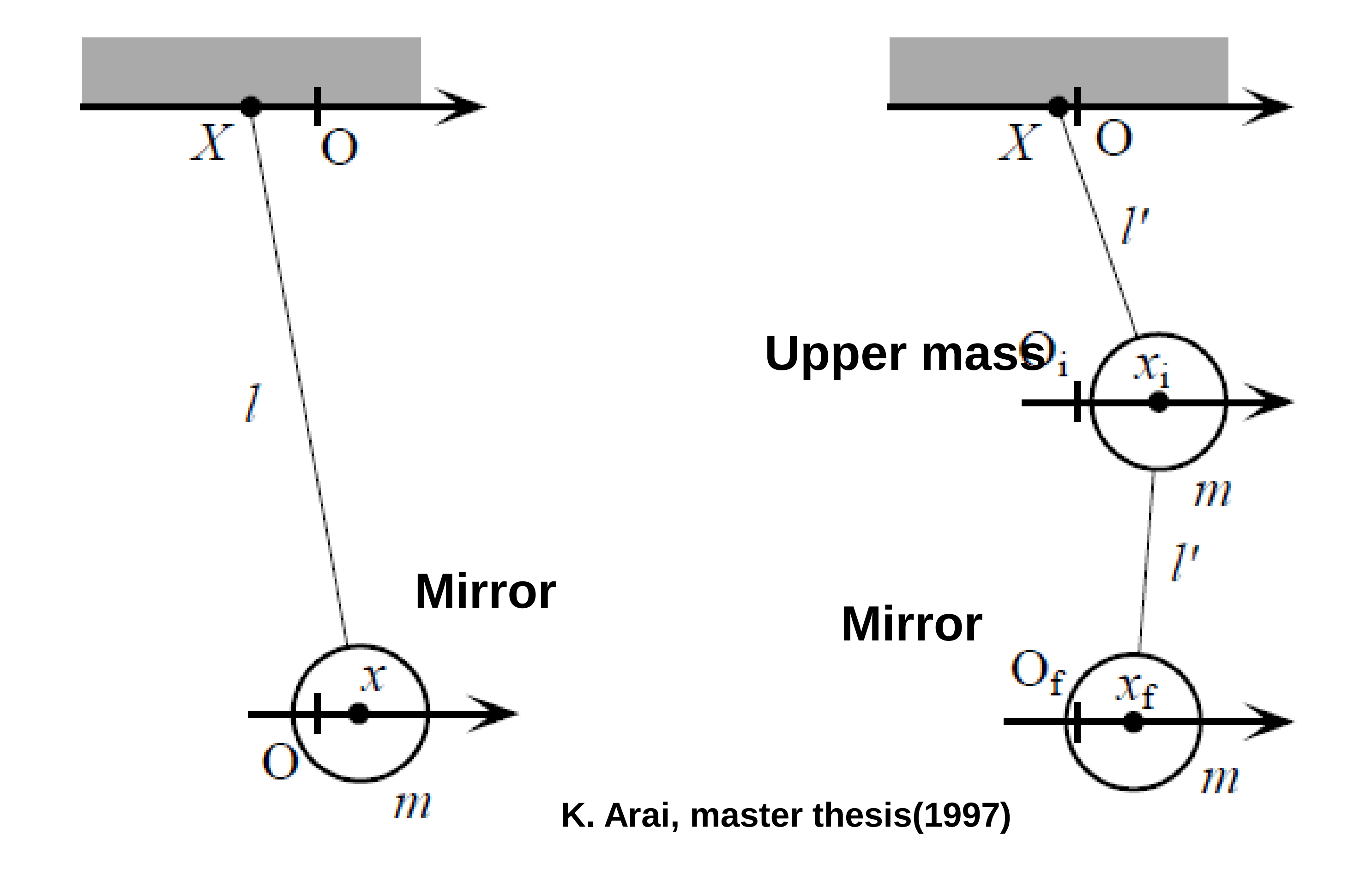


M. Punturo, GWDAW Rome 2010

3. Vibration isolation

How to improve isolation ratio ?

Double pendulum as example of multiple pendulum



K. Arai, master thesis(1997)

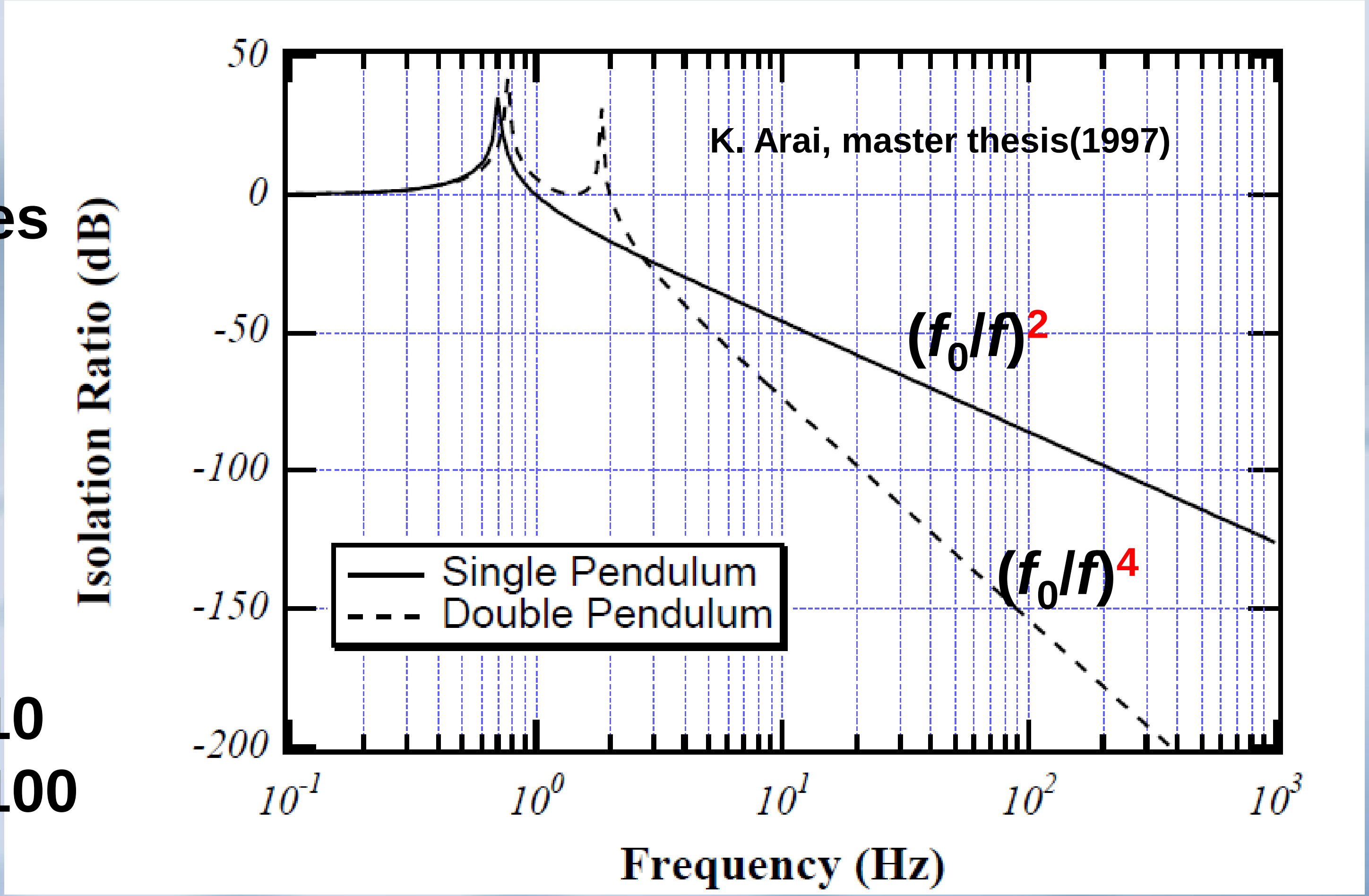
3. Vibration isolation

How to improve isolation ratio ?

Double pendulum as example of multiple pendulum

N-stages

$(f_0/f)^{2N}$



20dB=10

40dB=100

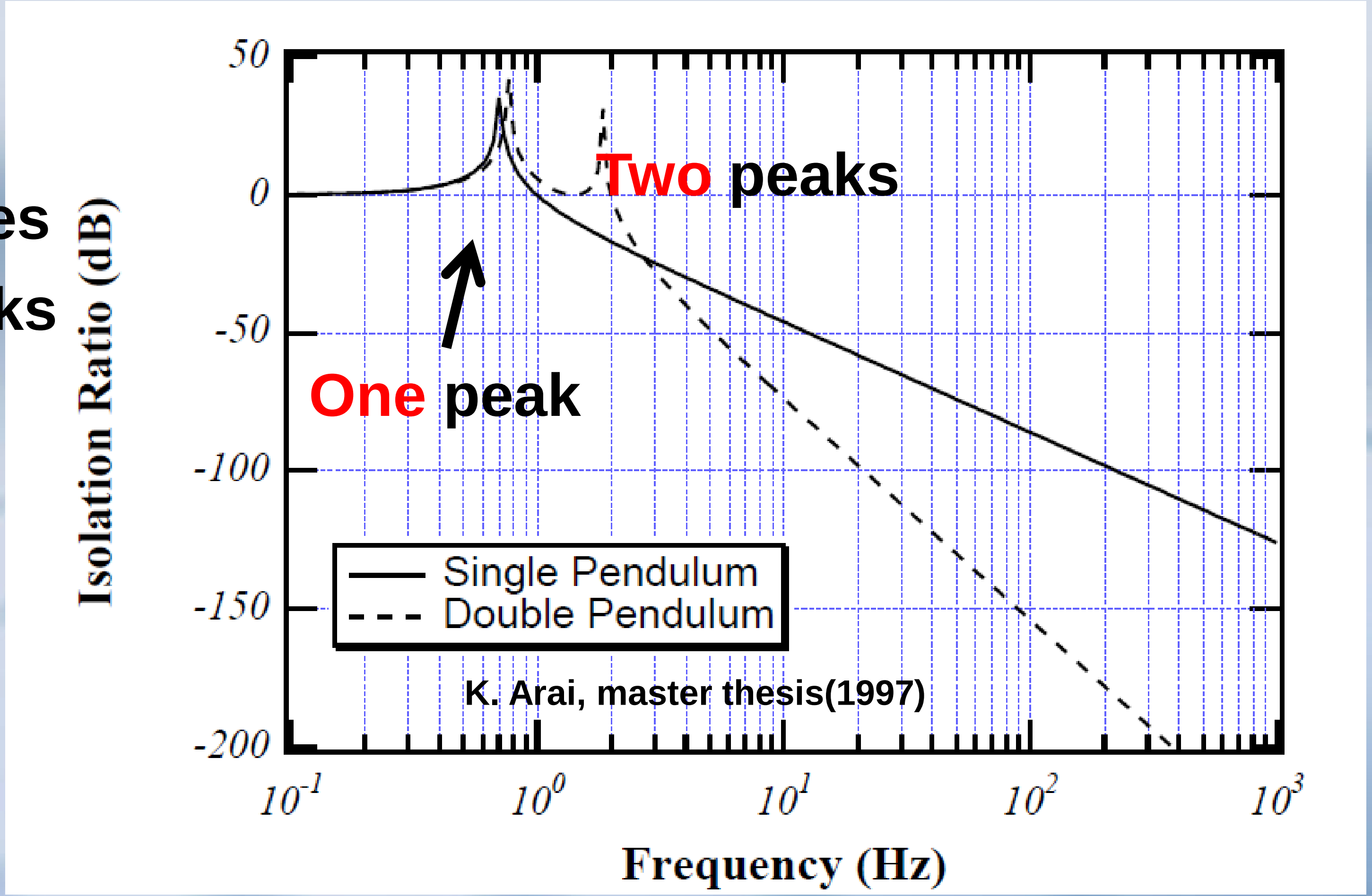
3. Vibration isolation

How to improve isolation ratio ?

Double pendulum as example of multiple pendulum

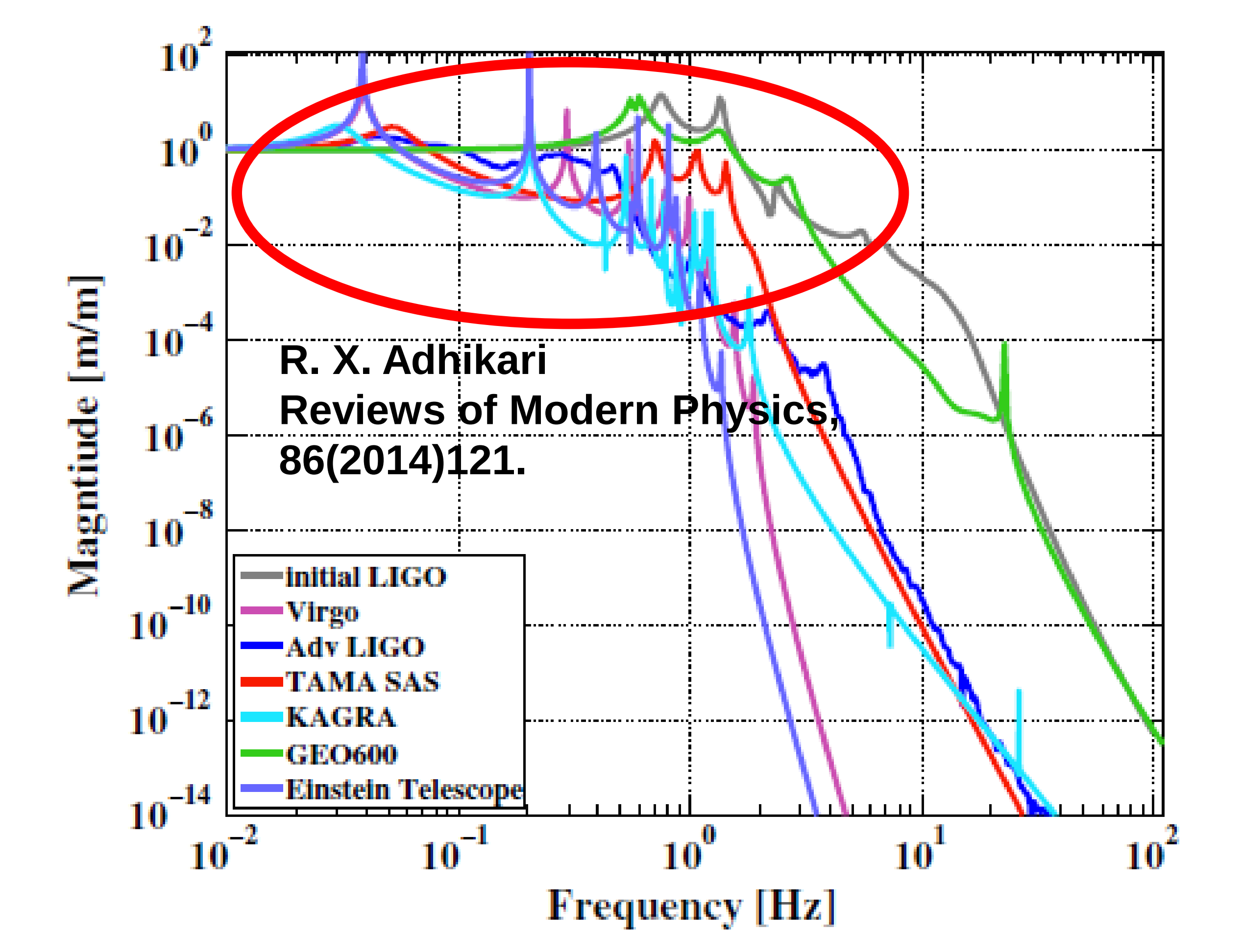
N-stages

N peaks



3. Vibration isolation

We are interested with gravitational wave above 10Hz.
Do we need NOT to take care of vibration below 10 Hz ?



3. Vibration isolation

We are interested with gravitational wave above 10Hz.
Do we need NOT to take care of vibration below 10 Hz ?

Contribution from this low frequency region dominates root mean square of vibration.
Root mean square (RMS) is integral of power spectrum in all frequency region.

In typical case, RMS is on the order of μm. Even at Kamioka, it is several times 10 nm.

Dynamic range for interferometer (detector) is about 1 nm.

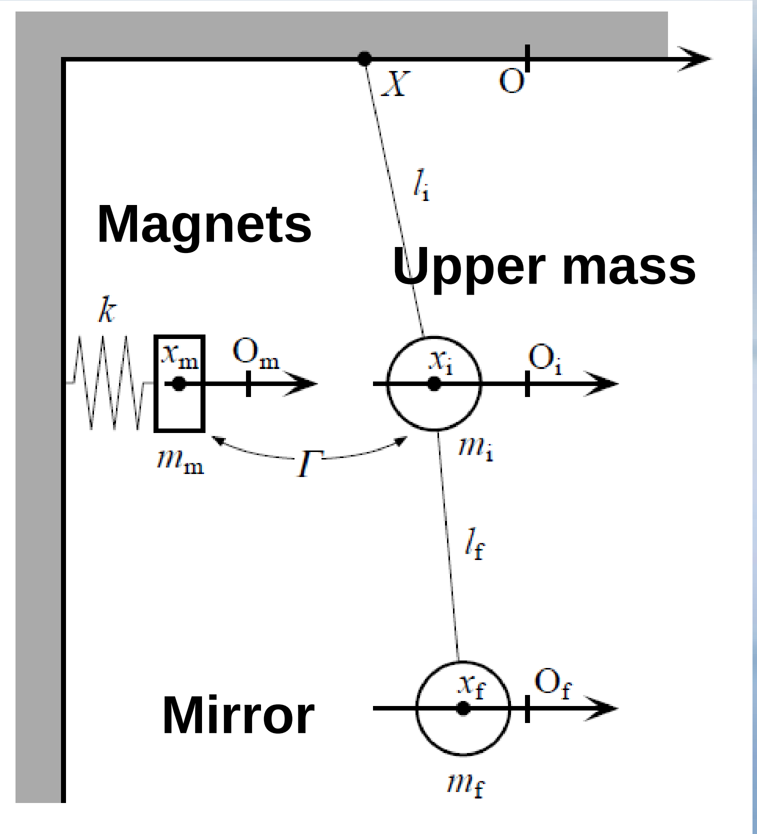
3. Vibration isolation

Dynamic range of interferometer (detector) is about 1 nm.

Control and damping is necessary. Since they could be noise sources, we have to design carefully (weaker effect of control or damping is better).

For example …

Double pendulum
with eddy current damping

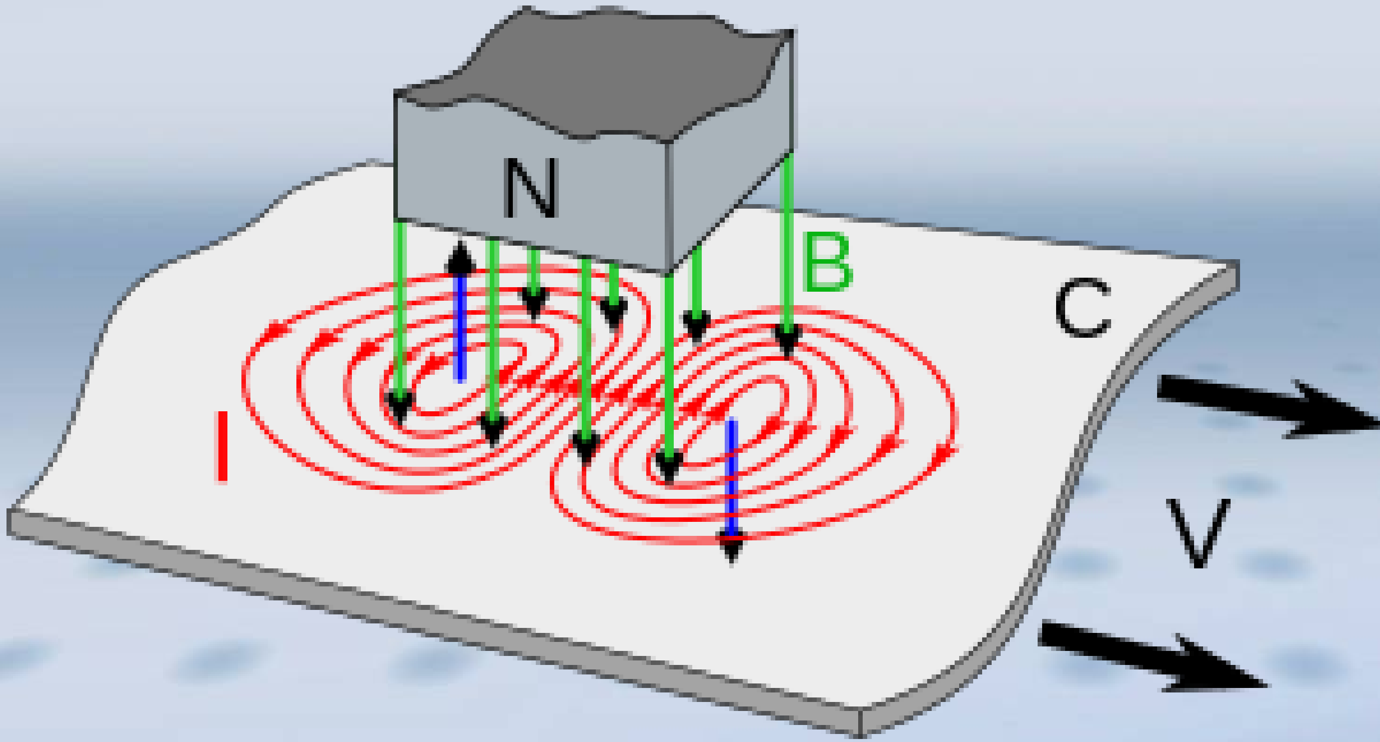


K. Arai, master thesis(1997)

3. Vibration isolation

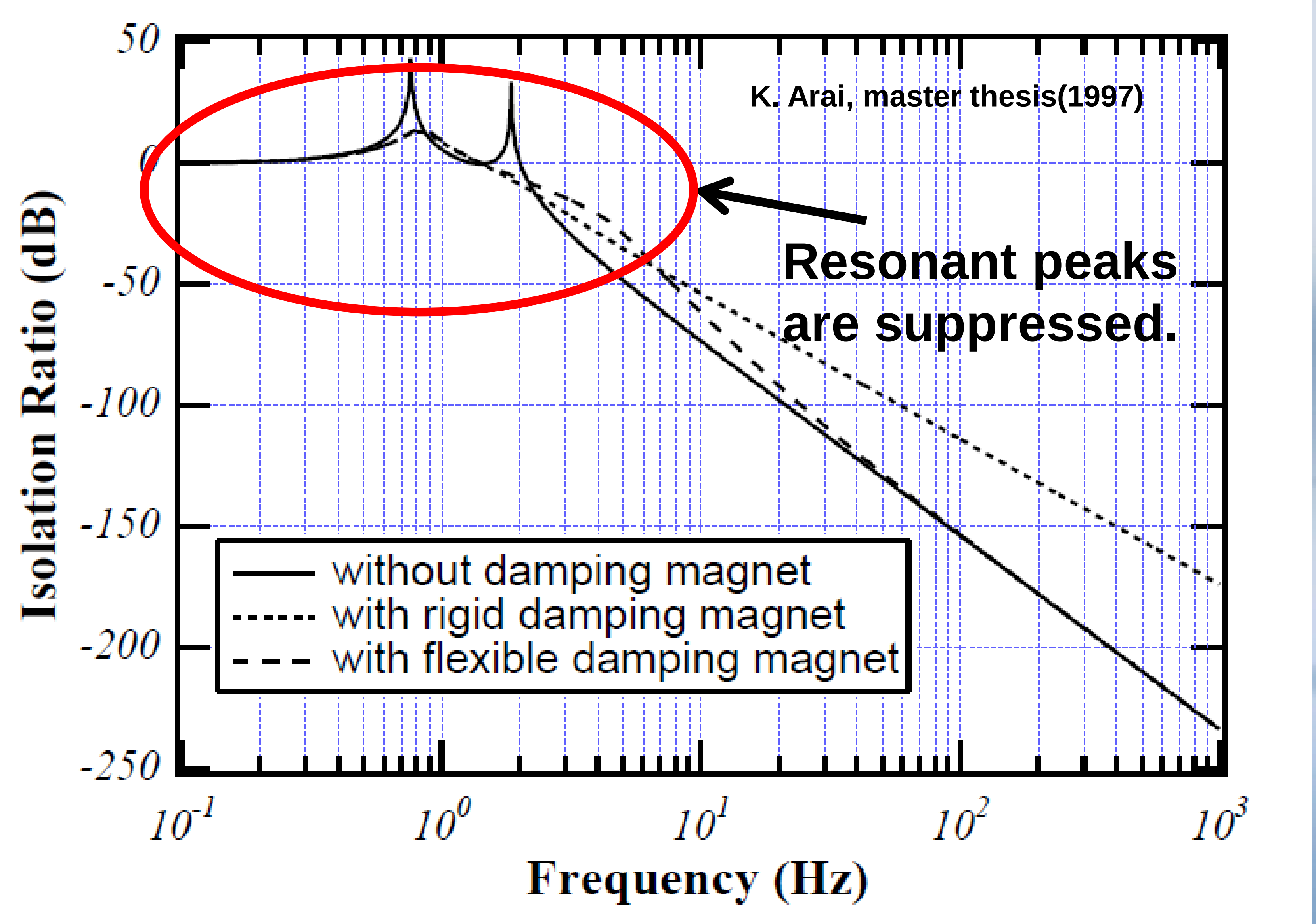
Eddy current damping

Wikipedia Eddy current



Magnets (metal) move near metal (magnets). Eddy current occurs. This electric current in resisitance is dissipation .

3. Vibration isolation



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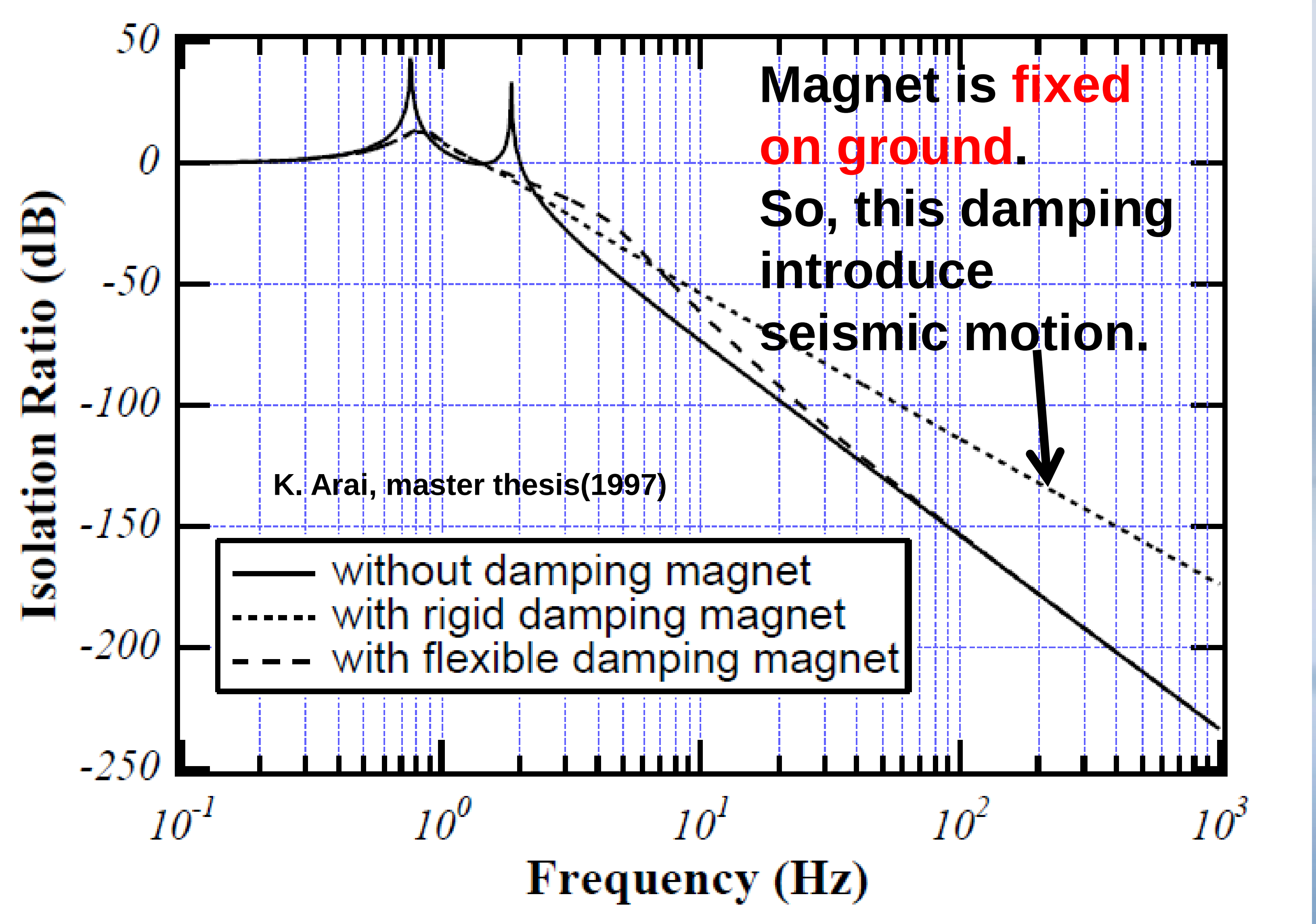

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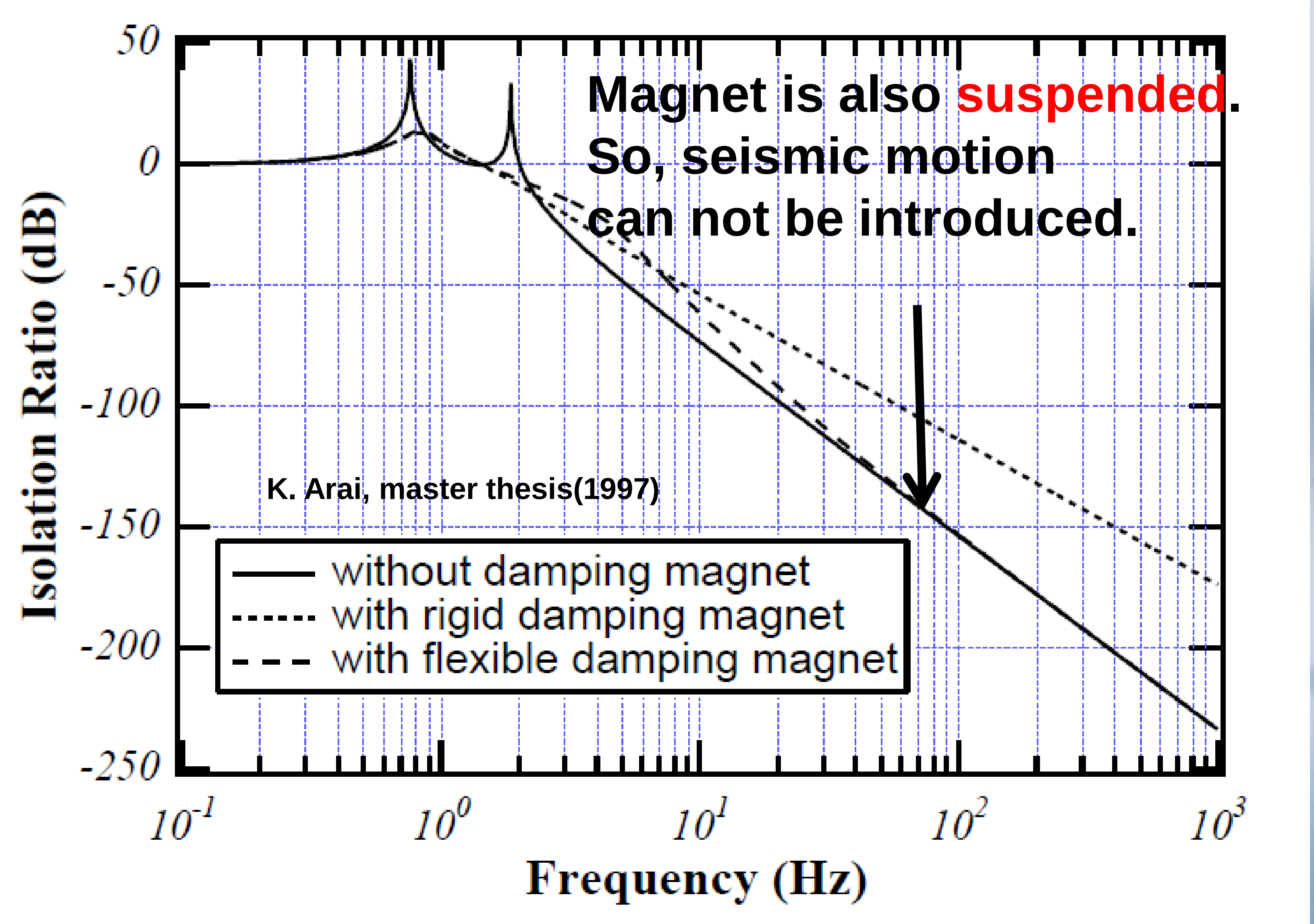
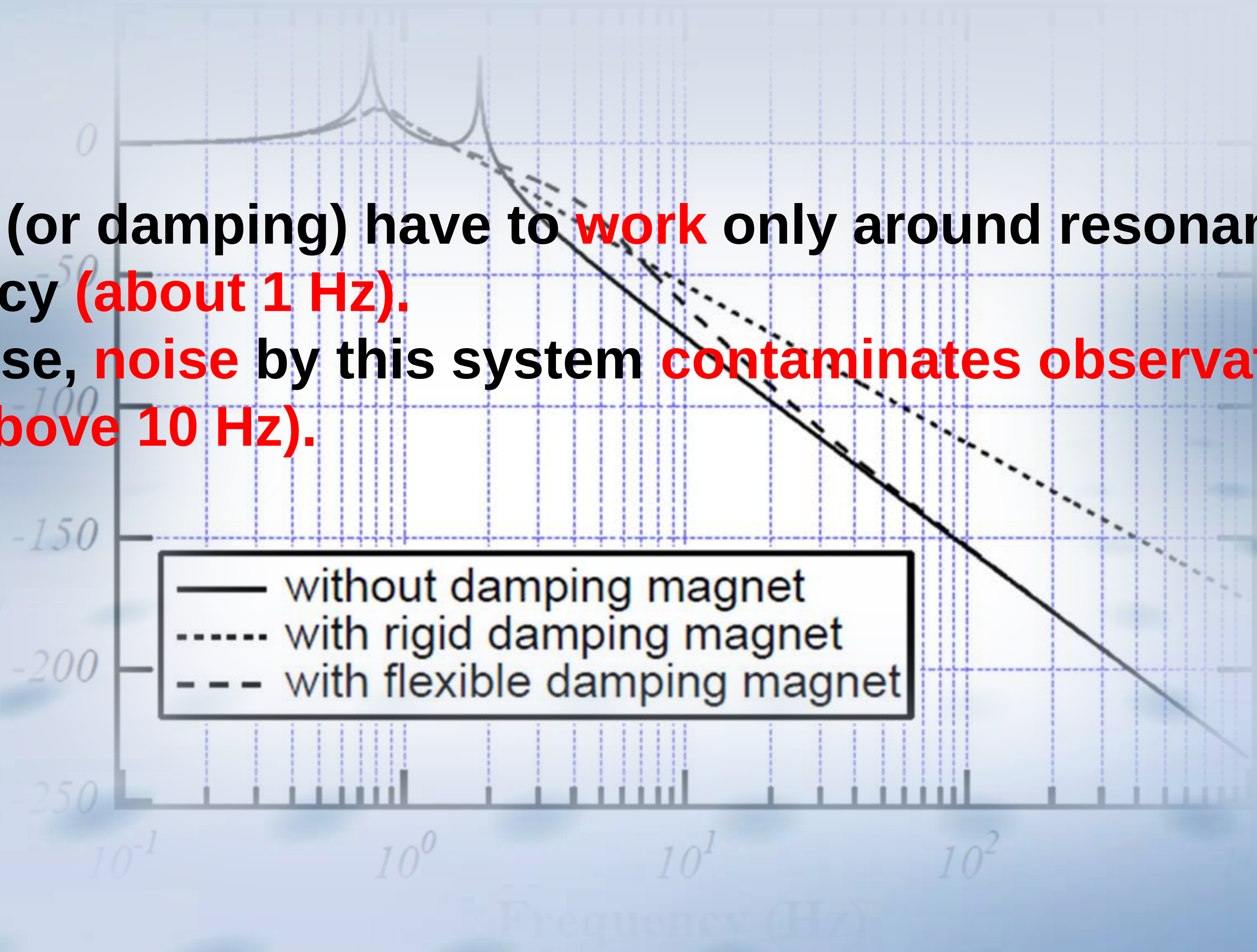


3. Vibration isolation



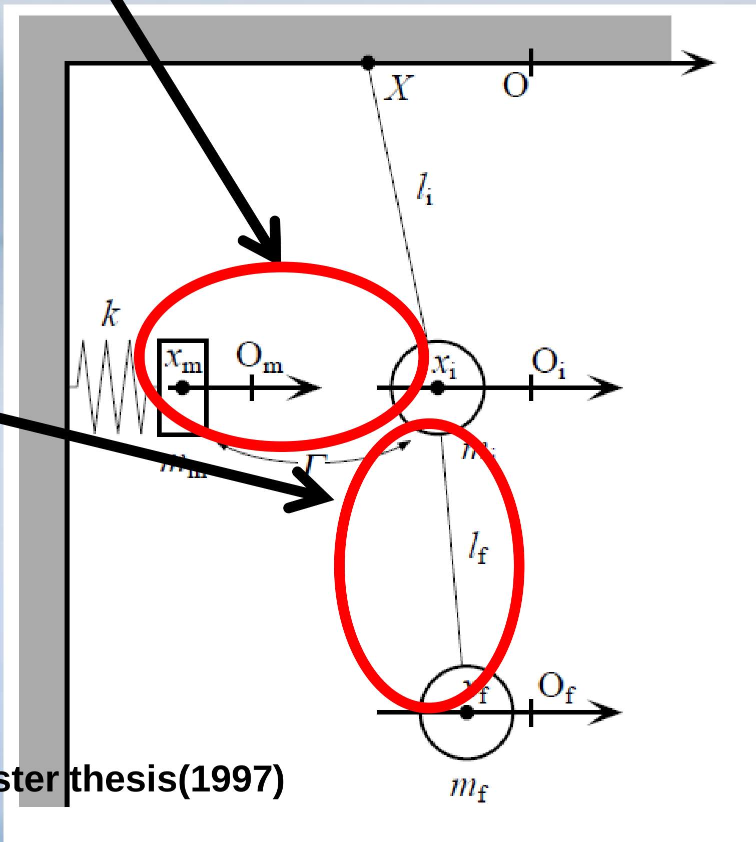
Control (or damping) have to work only around resonant frequency (about 1 Hz).
Otherwise, noise by this system contaminates observation band (above 10 Hz).

3. *Vibration isolation*

Only upper mass is applied eddy current damping.

It can suppress resonant motion because both masses move.

On the other hand, noise by damping can not be transferred to mirror because stage between upper mass and mirror act as vibration isolation.



K. Arai, master thesis(1997)

3. Vibration isolation

Passive vs Active

Eddy current damping -> Passive (without any power supply)

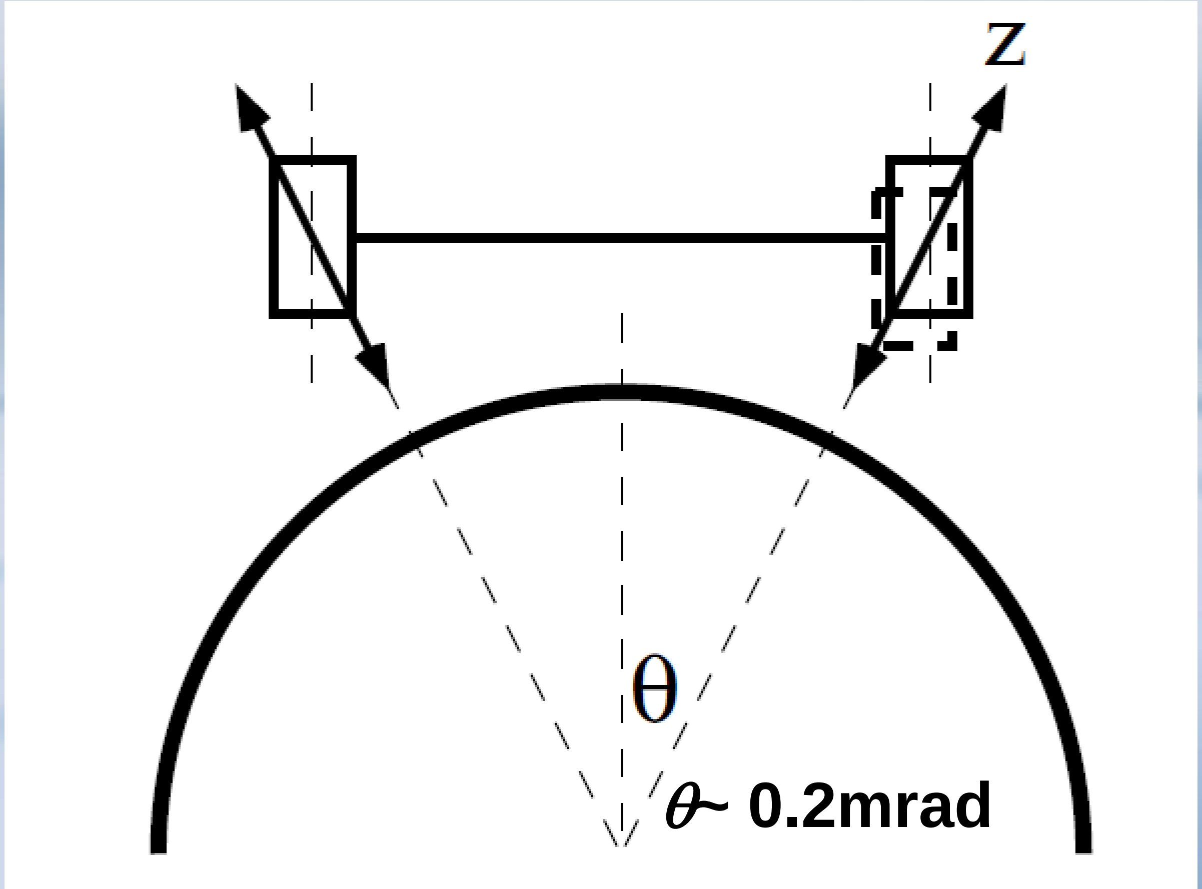
Active (with power supply) : For example, monitors and actuators. Active system is more complicate. On the other hand, we can use some tricks.

However, points for design are same; Control (or damping) works only around resonant frequency (about 1 Hz).
On the contrary, we have to stop it in observation band

3. Vibration isolation

Vertical vibration isolation

Is it problem ? Yes, due to curvature of Earth !



1. Seismic noise

Vertical vibration isolation

Imperfection of suspension (differences between wires …) make coupling between vertical and horizontal motion. In other words, vertical seismic motion causes not only vertical motion of mirror, but also horizontal one.
Roughly speaking, the ratio is 1/100 or 1/1000.

In the case of KAGRA, baseline has 1/300 gradient to drain water.

3. Vibration isolation

Vertical vibration isolation

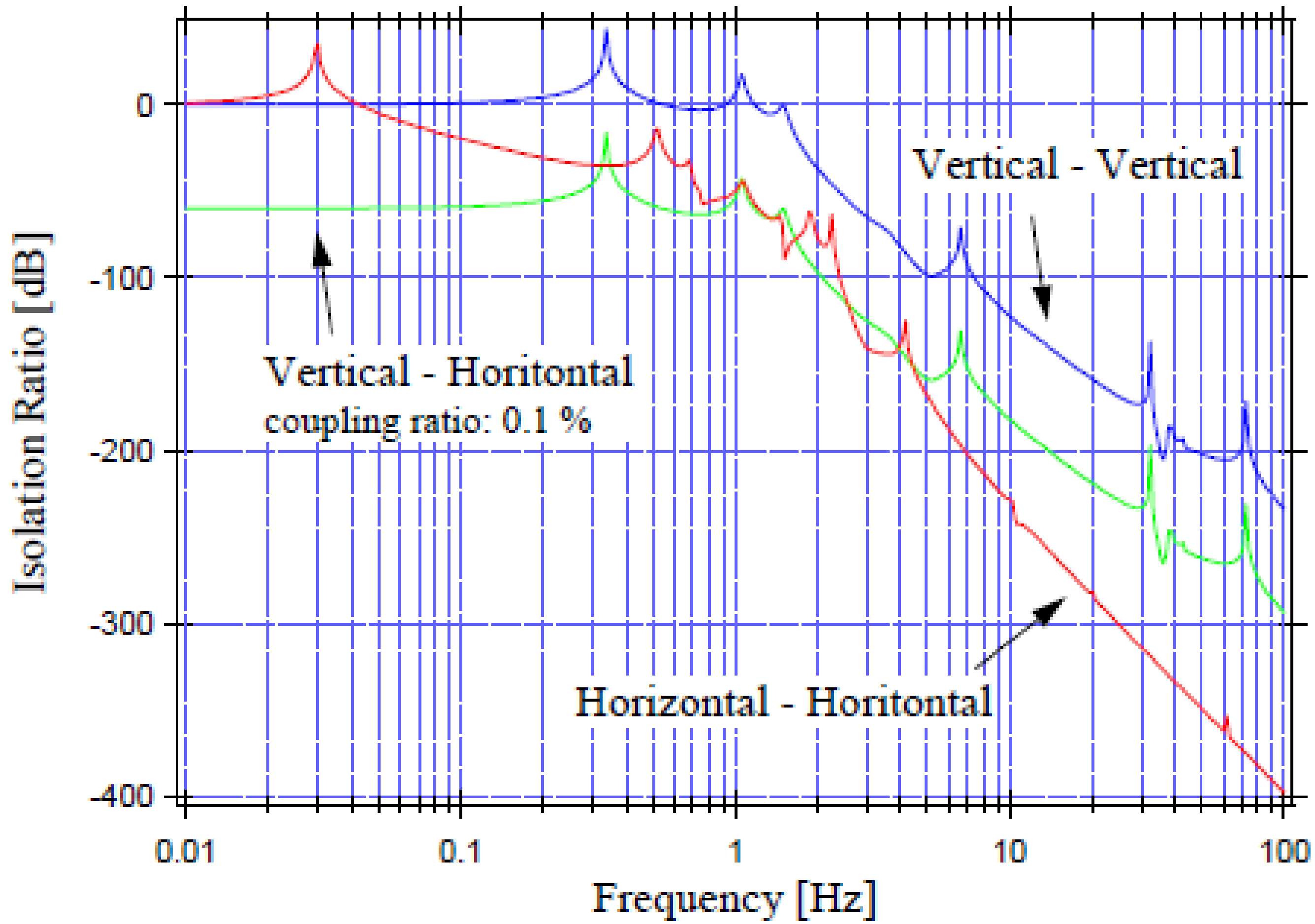
Spring constant *k* (resonant frequency) of vertical motion is higher than that of horizontal motion in usual.

Typical resonant frequency
Horizontal 1 Hz, Vertical 10 Hz

Summary
(1)Vertical-horizontal coupling
(2)Higher vertical resonant frequency
->Vertical motion effect is larger.

3. Vibration isolation

Vertical vibration isolation



A. Takamori, LCGT design document (2004)

3. Vibration isolation

Vertical vibration isolation

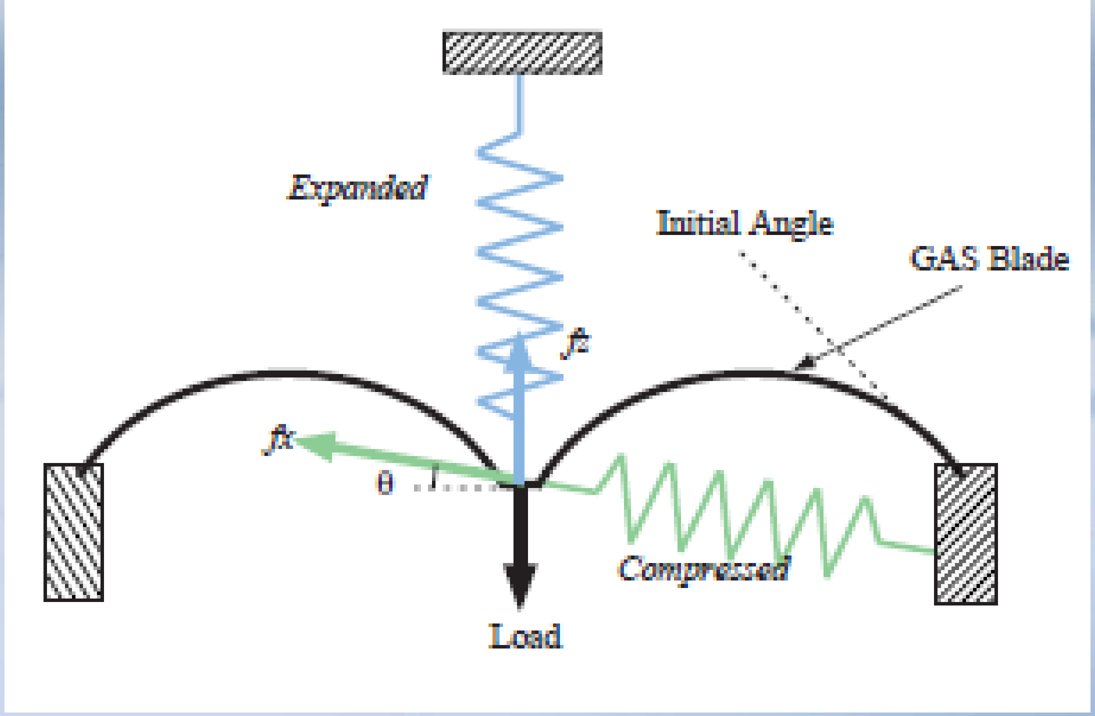
Softer vertical spring has larger stretch from natural length.
Vertical resonant frequency is proportional to $k^{1/2}$.
Stretch from natural length is proportional to k.

Resonant frequency	Stretch from natural length
10 Hz	2.5 mm
1 Hz	25 cm
0.1Hz	25 m

3. Vibration isolation

Vertical vibration isolation

Soft vertical spring with reasonable size
KAGRA adopts Geometrical Anti Spring (GAS).



3. Vibration isolation

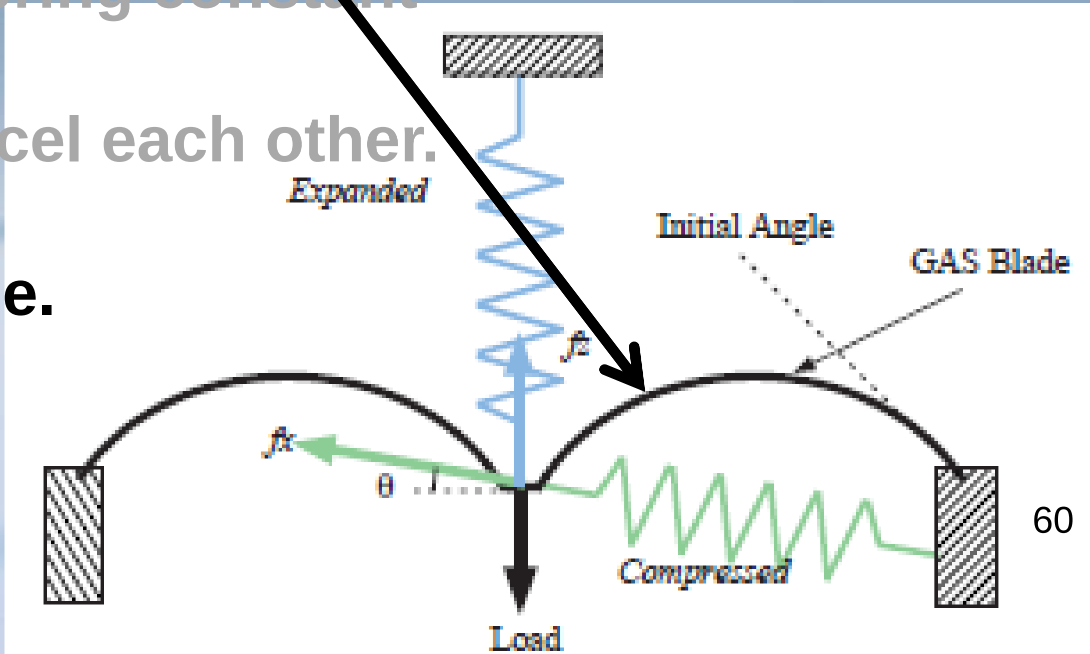
Vertical vibration isolation
Soft vertical spring with reasonable size

Geometrical Anti Spring (GAS)
Elasticity : Positive spring constant

Compression : Negative spring constant

Both spring constants cancel each other.

0.2 Hz resonance is feasible.



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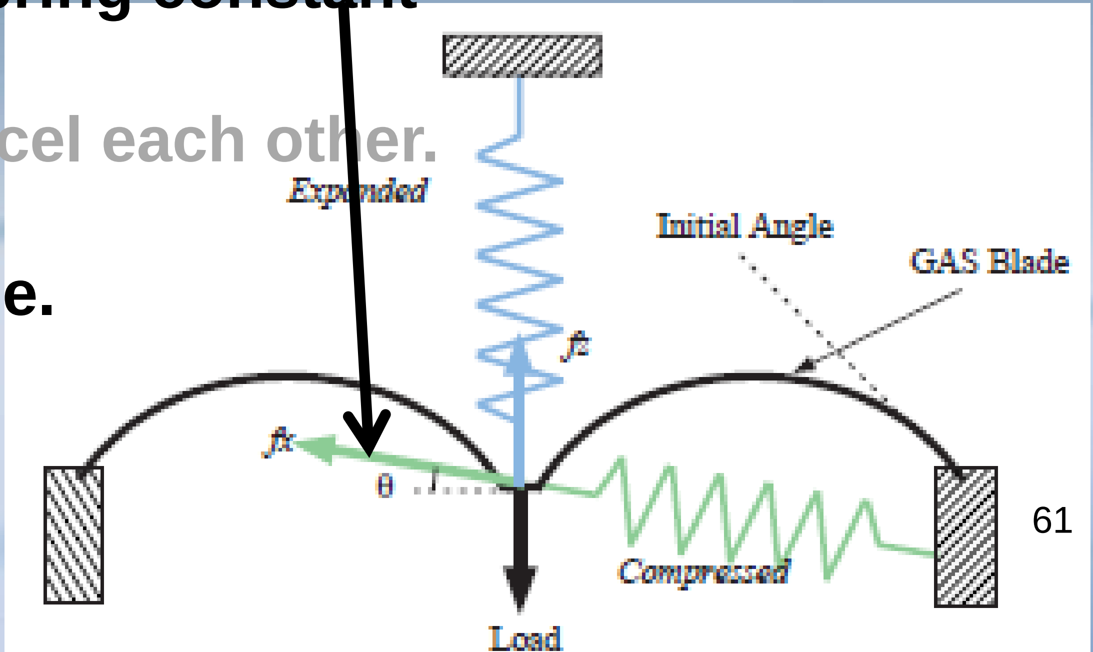
Both spring constants cancel each other.

0.2 Hz resonance is feasible.



A. Takamori, LCGT design document (2004)

3. Vibration isolation

Vertical vibration isolation
Soft vertical spring with reasonable size

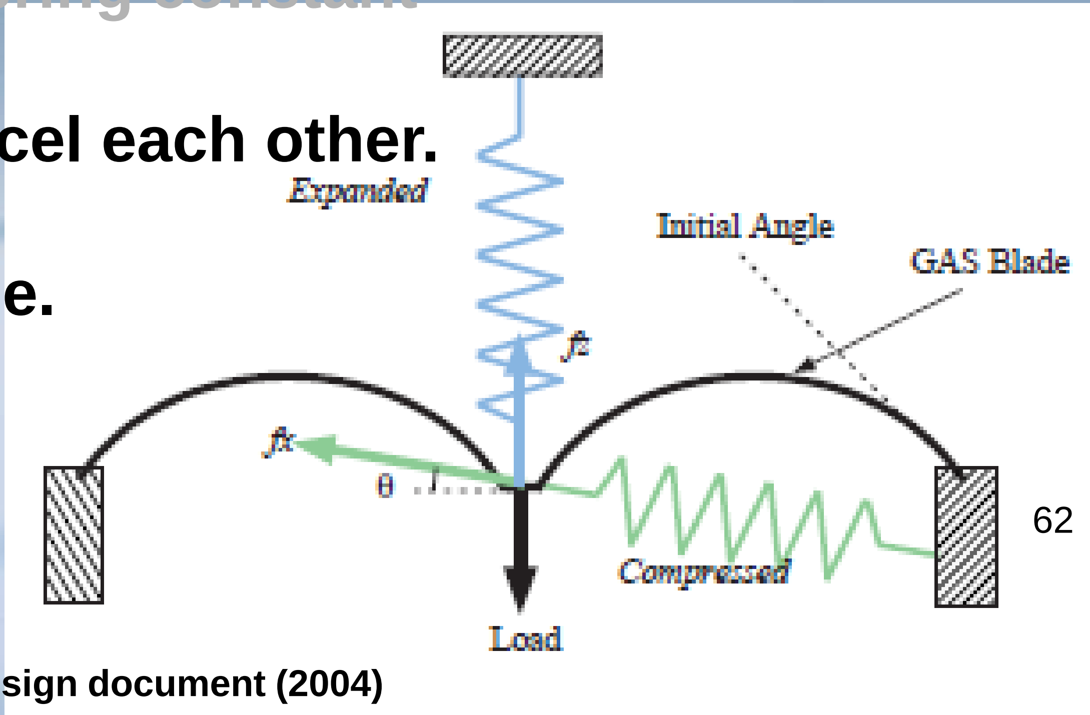
Geometrical Anti Spring (GAS)
Elasticity : Positive spring constant

Compression : Negative spring constant

Both spring constants cancel each other.

0.2 Hz resonance is feasible.

Same drawbacks
of inverted pendulum …



A. Takamori, LCGT design document (2004)

4. Summary

Summary of seismic motion

Typical seismic motion :

10^{-7}[m/rtHz](1Hz/f)^2 (above 1Hz)
Microseismic peak is around 0.2 Hz.

Underground site is excellent.

100 times smaller seismic motion

Depth of mirror must be more than 50 m.
If not so, seismic motion is not so small even if the site is country side …

4. Summary

Summary of vibration isolation

At least 8 (in typical, 10) orders of magnitude vibration isolation is necessary.

Not only horizontal but also vertical motion must be supressed.

Soft vibration isolation with reasonable size
Cancel of positive and negative spring constant

Multiple pendulum to enhance vibration isolation ratio

Control and damping to suppress resonant motion is necessary. But they have to work only around resonant frequency (about 1 Hz). Otherwise, noise by this system contaminates observation band (above 10 Hz).

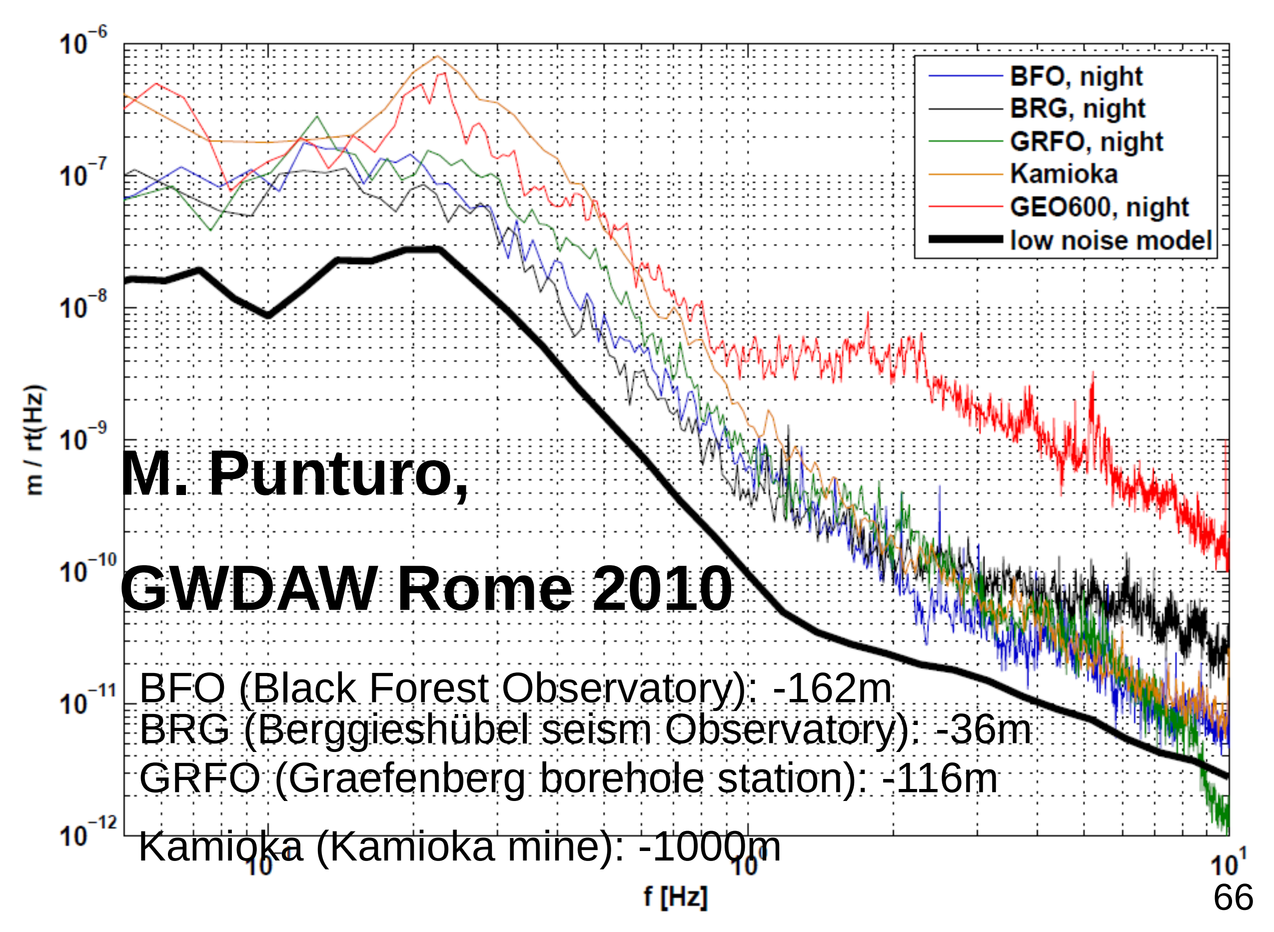
Thank you for your attention !

1. Seismic noise

(1) Small seismic motion site

Where is silent sites ? **Underground !**

Kamioka mine



M. Punturo,

GWDAW Rome 2010

BFO (Black Forest Observatory): -162m
BRG (Berggieshübel seism Observatory): -36m
GRFO (Graefenberg borehole station): -116m
Kamioka (Kamioka mine): -1000m

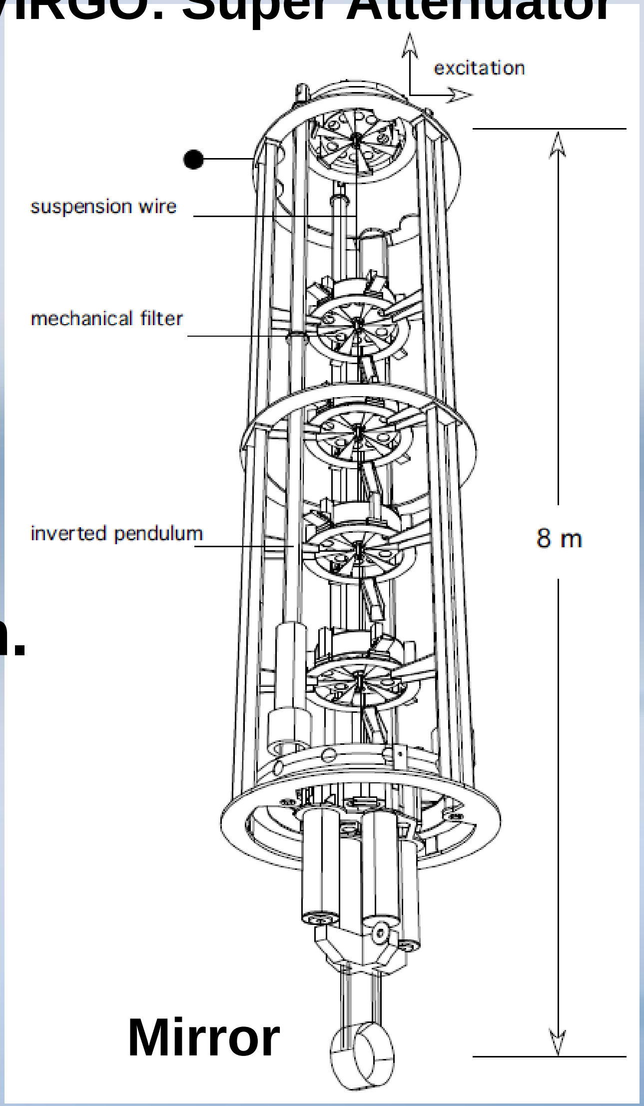
1. Seismic noise

(2) Good vibration isolation system

Unfortunately, single pendulum does not have enough isolation for gravitational wave detection.

We need multi stage isolation system.

VIRGO: Super Attenuator



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3. Vibration isolation

Vertical vibration isolation

Stack : rubber and spring.