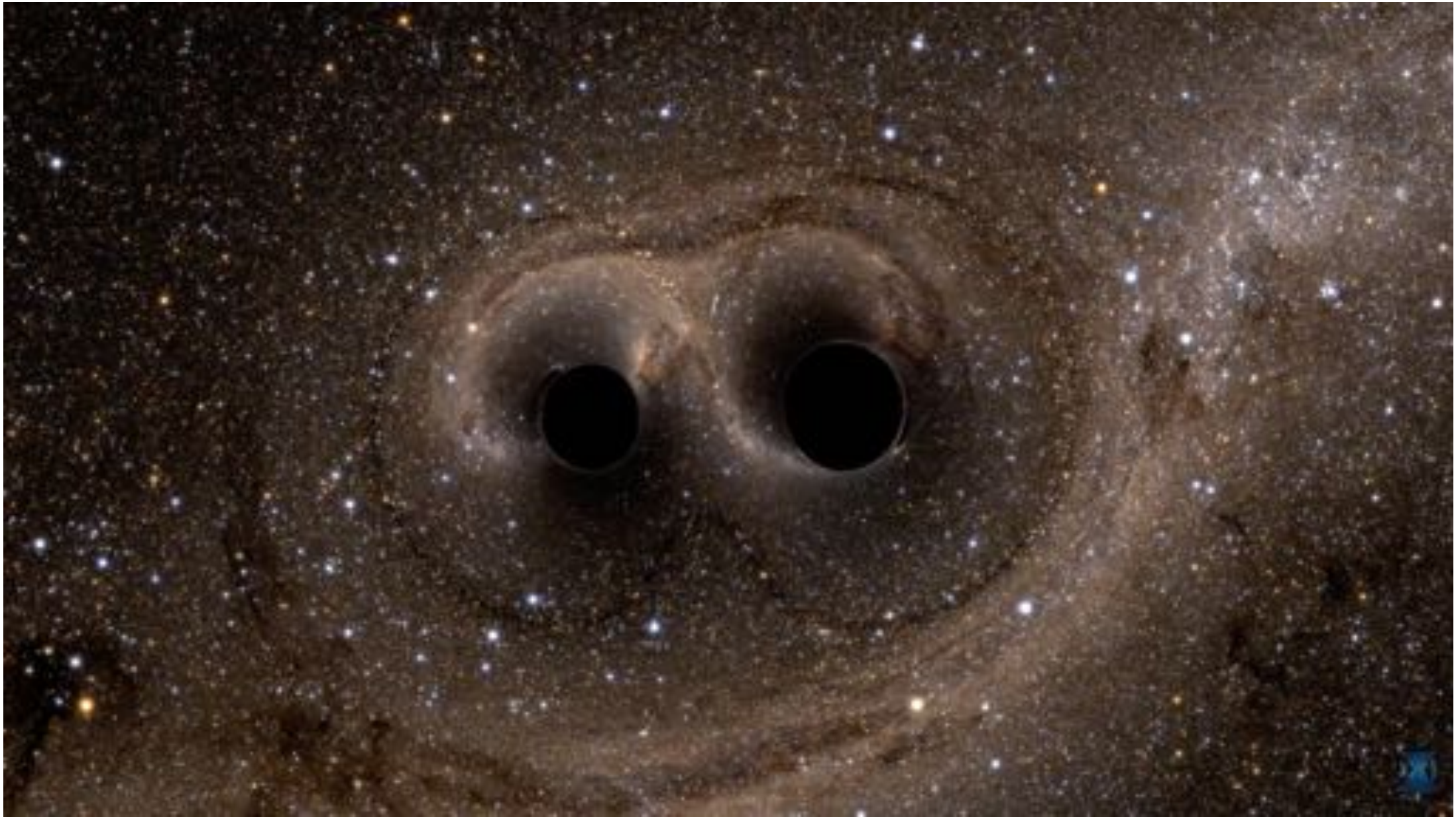
ADVANCED TECHNOLOGIES IN KAGRA;
-LARGE-SCALE CRYOGENIC GRAVITATIONAL WAVE TELESCOPE-

16, Jan., 2020

The 39th Symposium on Engineering in Astronomy

Takayuki TOMARU

GW Science Project, NAOJ



Public Alerts (until Jan. 15)

GraceDB — Gravitational-Wave Candidate Event Database

HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION | LOGIN

https://gracedb.ligo.org/

LIGO/Virgo O3 Public Alerts

Detection candidates: 41

SORT: EVENT ID (A–Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR
S191216ap	MassGap (>99%)	Dec. 16, 2019 21:33:38 UTC	GCN Circulars Notices | VOE		1 per 2.8035e+15 years
S191215w	BBH (>99%)	Dec. 15, 2019 22:30:52 UTC	GCN Circulars Notices | VOE		1 per 31.485 years
S191213ai	NSBH (85%), Terrestrial (15%)	Dec. 13, 2019 15:59:05 UTC	GCN Circulars Notices | VOE		1 per 1.5816 years
S191213g	BNS (77%), Terrestrial (23%)	Dec. 13, 2019 04:34:08 UTC	GCN Circulars Notices | VOE		1.1197 per year
S191212q	Terrestrial (51%), NSBH (49%)	Dec. 12, 2019 08:27:28 UTC	GCN Circulars Notices | VOE		1.0631 per year
S191205ah	NSBH (93%), Terrestrial (7%)	Dec. 5, 2019 21:52:08 UTC	GCN Circulars Notices | VOE		1 per 2.5383 years

Until O2

- BBH : 10
- BNS : 1

O3 (Candidates at 2020.Jan.15)

- BBH : 29
- BNS : 5
- NSBH : 5
- Undefined : 6

about 1 event/week

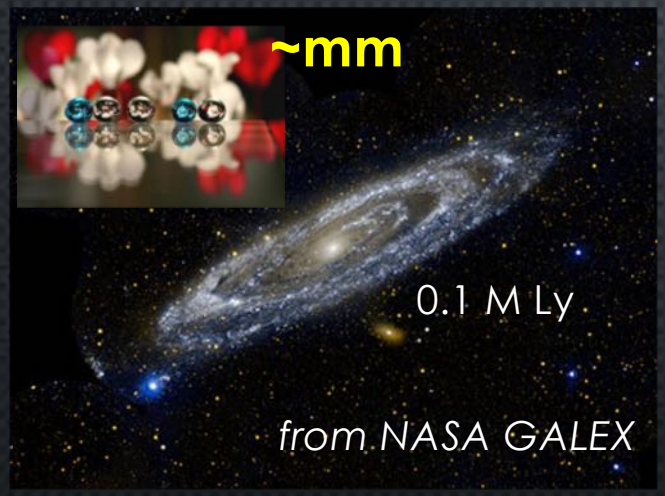
GW Amplitude

Strong > EM >> Week >> ・ ・ ・ >> Gravity

~ 0.1 ~ 0.01 ~ 10^{-5} ~ 10^{-38}

We need to detect gravitational wave amplitude of the order of 10^{-24} (displacement of 10^{-24}m /1m) to do GW astronomy because gravity interaction is pretty small.

10^{-24} = 涅槃寂静 in Japanese unit

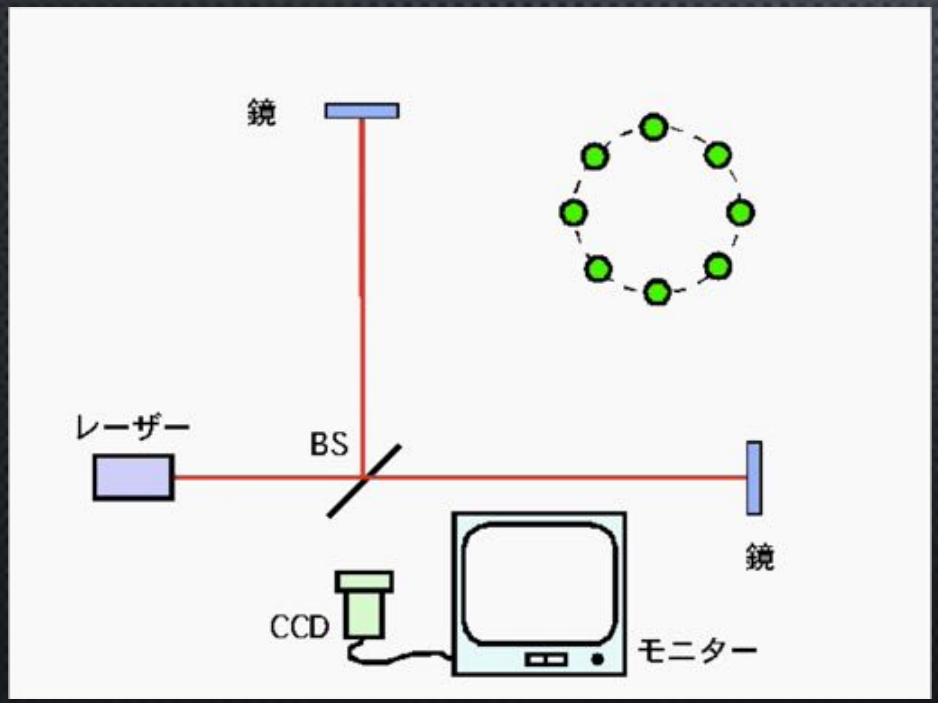


This size corresponds to search a bead in our Galaxy.

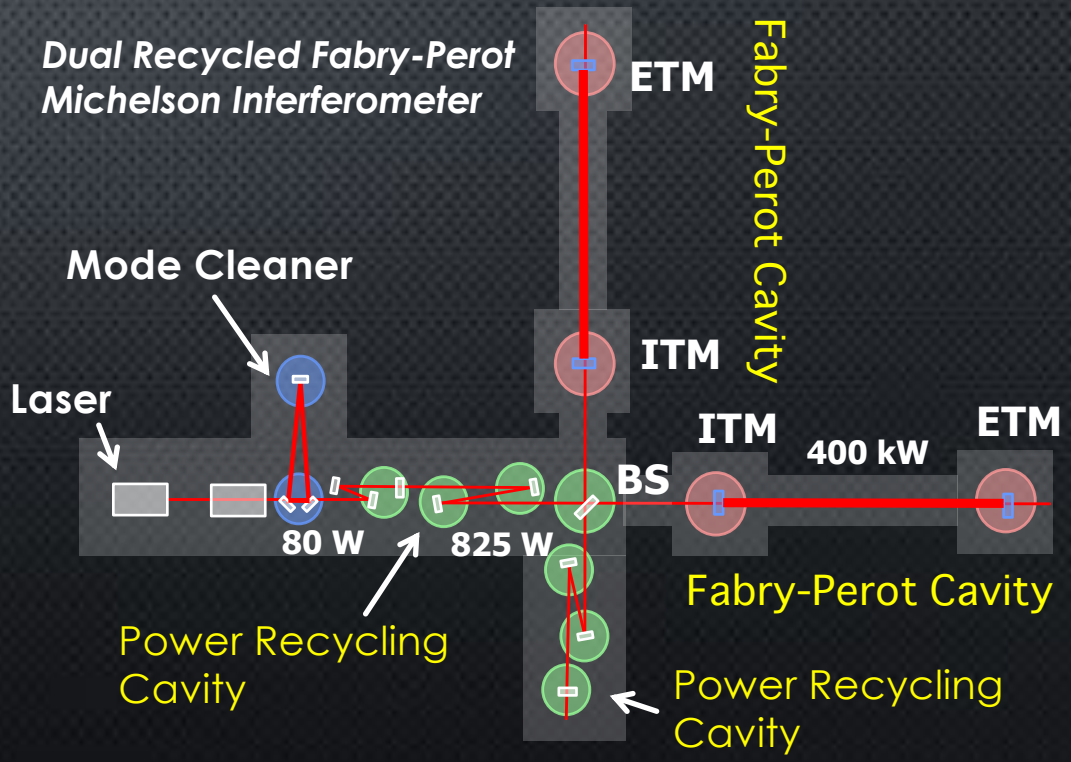
$$h \propto \frac{1}{r} \Rightarrow Event\ Number \propto V$$

Principle of GW Measurement by Michelson Interferometer

When length difference between both interferometer arms are occurred by GW, leakage of light will be dropped onto CCD.

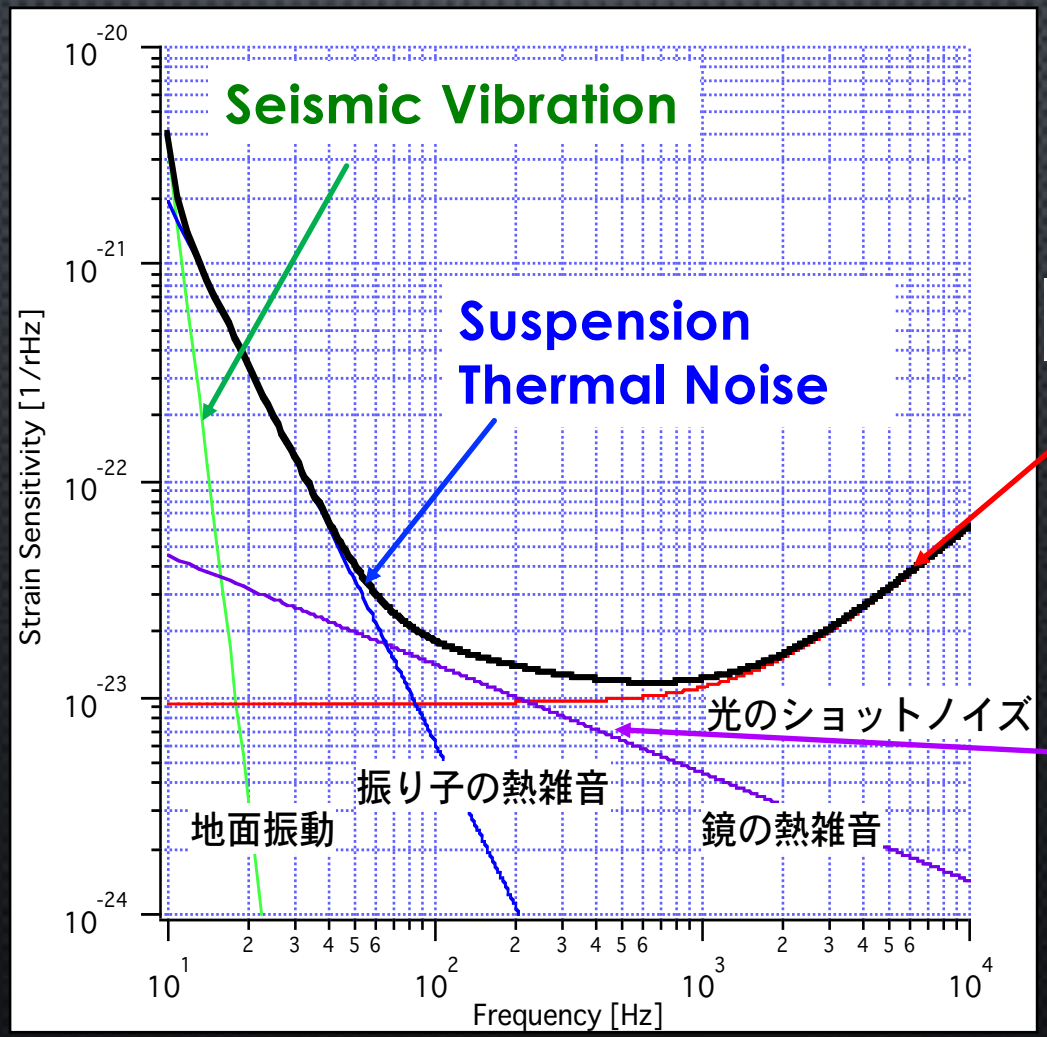


Practical 2nd Generation GW Telescope

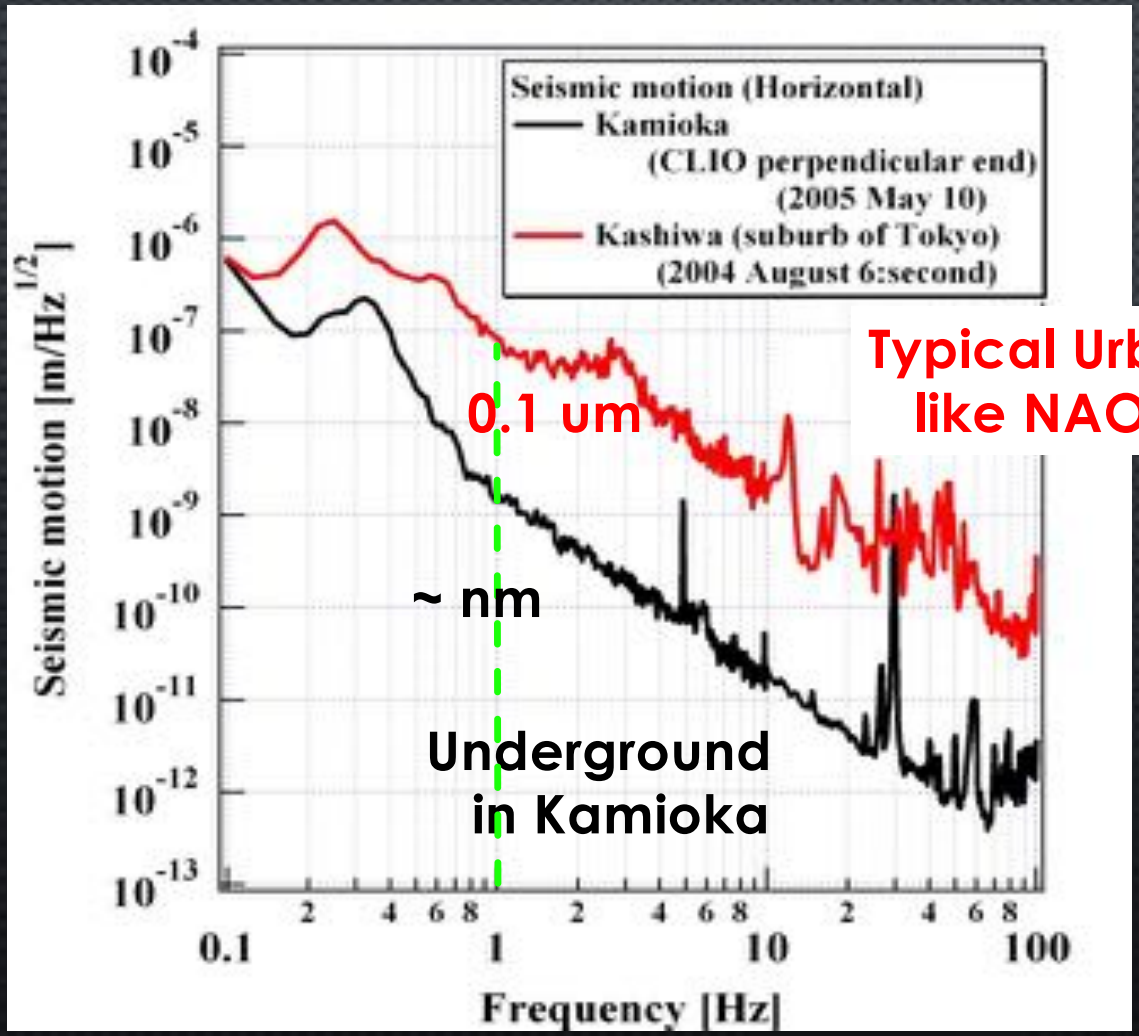


Principle Sensitivity Limitations of Interferometric GW Telescope

Low
Sensitivity
High



Seismic Noise (< 10 Hz)



Typical Urban Area like NAOJ

We need ~ 10^{-20} m/rHz @ 100Hz

Vibration Attenuator

Cryogenic Mirror System

KAGRA

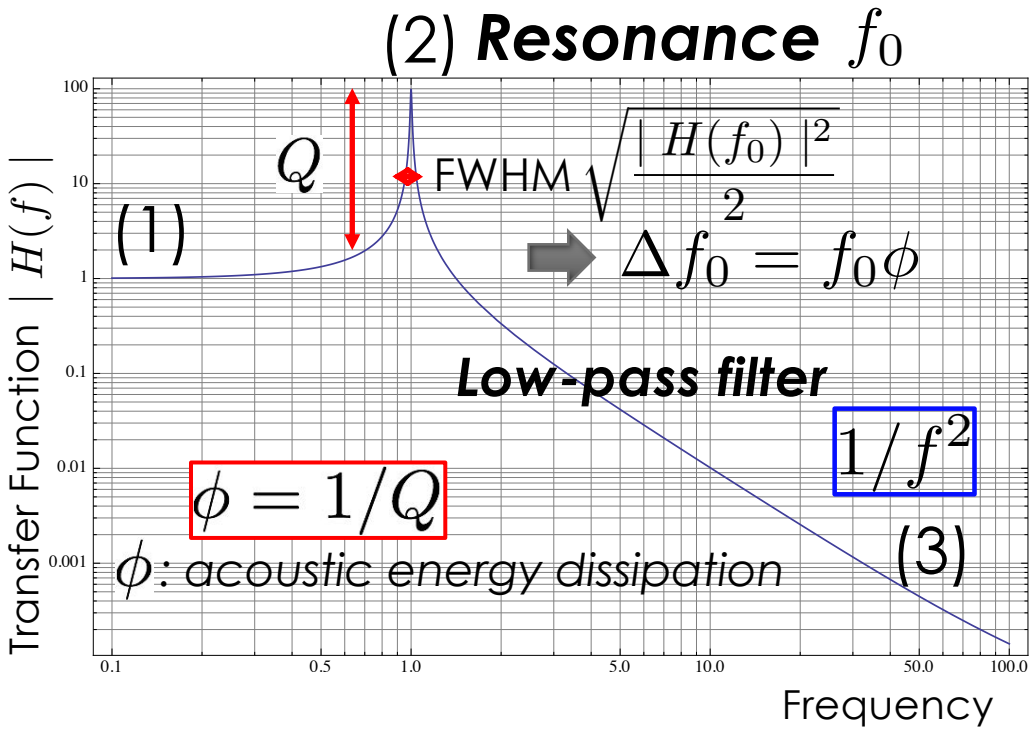
2.5th Generation GW detector

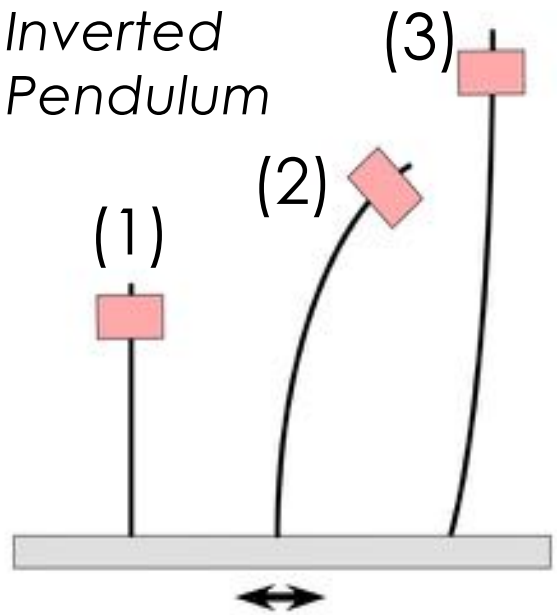
Underground

Vibration Attenuation

Observation band of GW telescopes: dozens – kilo Heltz
We need small vibration only at this band.

Pendulum & Spring consist a good mechanical low-pass filter





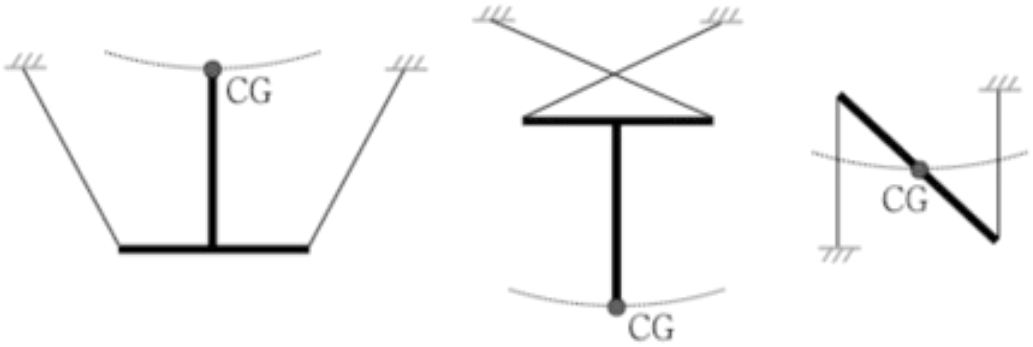
To achieve sufficient vibration attenuation at observation band, we need to make vibration attenuator with the resonance at low frequency.

- 1Hz pendulum = 25cm
- 0.1Hz pendulum = 25m

Resonant frequency of pendulum depends on only its length.

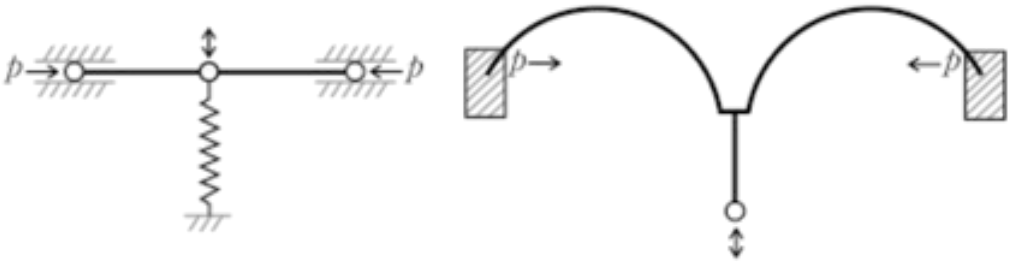
Ideas of compact Vibration Attenuator with low frequency

Geometrical idea



Roberts' Linkage X-Pendulum Folding Pendulum

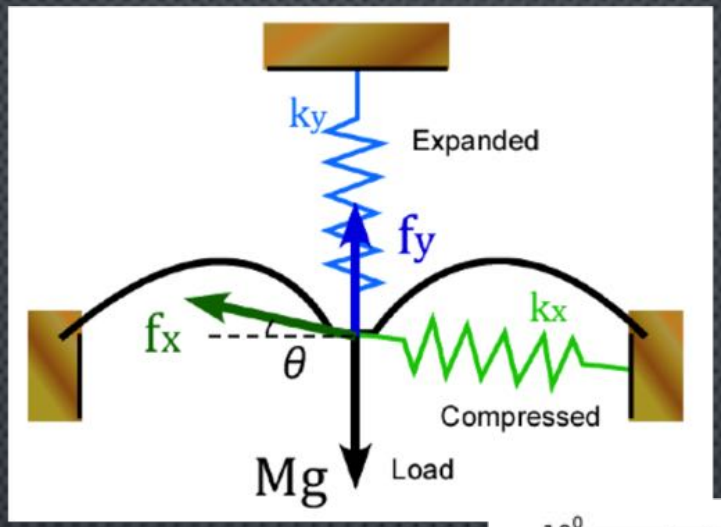
Use of Buckling

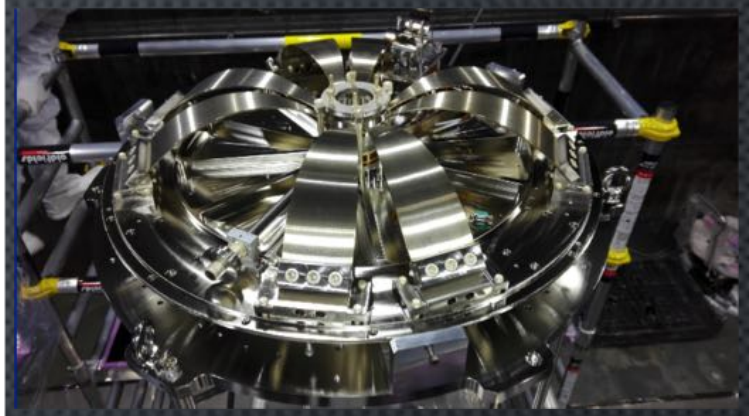


Negative Stiffness Mechanism Geometric Anti-Spring

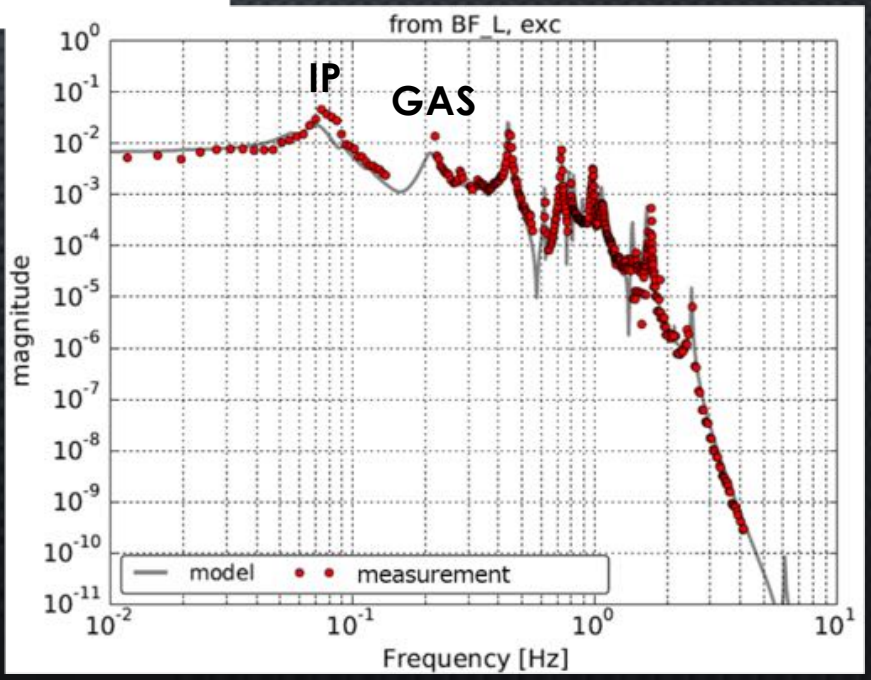
精密工学会誌76, 2010, p1225
Ryutaro Takahashi

Geometric Anti-Spring





Large support From ATC



"Modeling and Simulation of Vibration Isolation System for Large-scale Cryogenic Gravitational-wave Telescope (LCGT)",
関口貴令, 修士論文, 東京大学, 2011

KAGRA Main Mirror Suspension System

Frame-Free Suspension

We excavate upper-floors and vertical holes for Vibration Isolation System. Base of the VIS is put on the upper-floor

Upper Floor

14m

4-stage GAS filters
@ room temperature

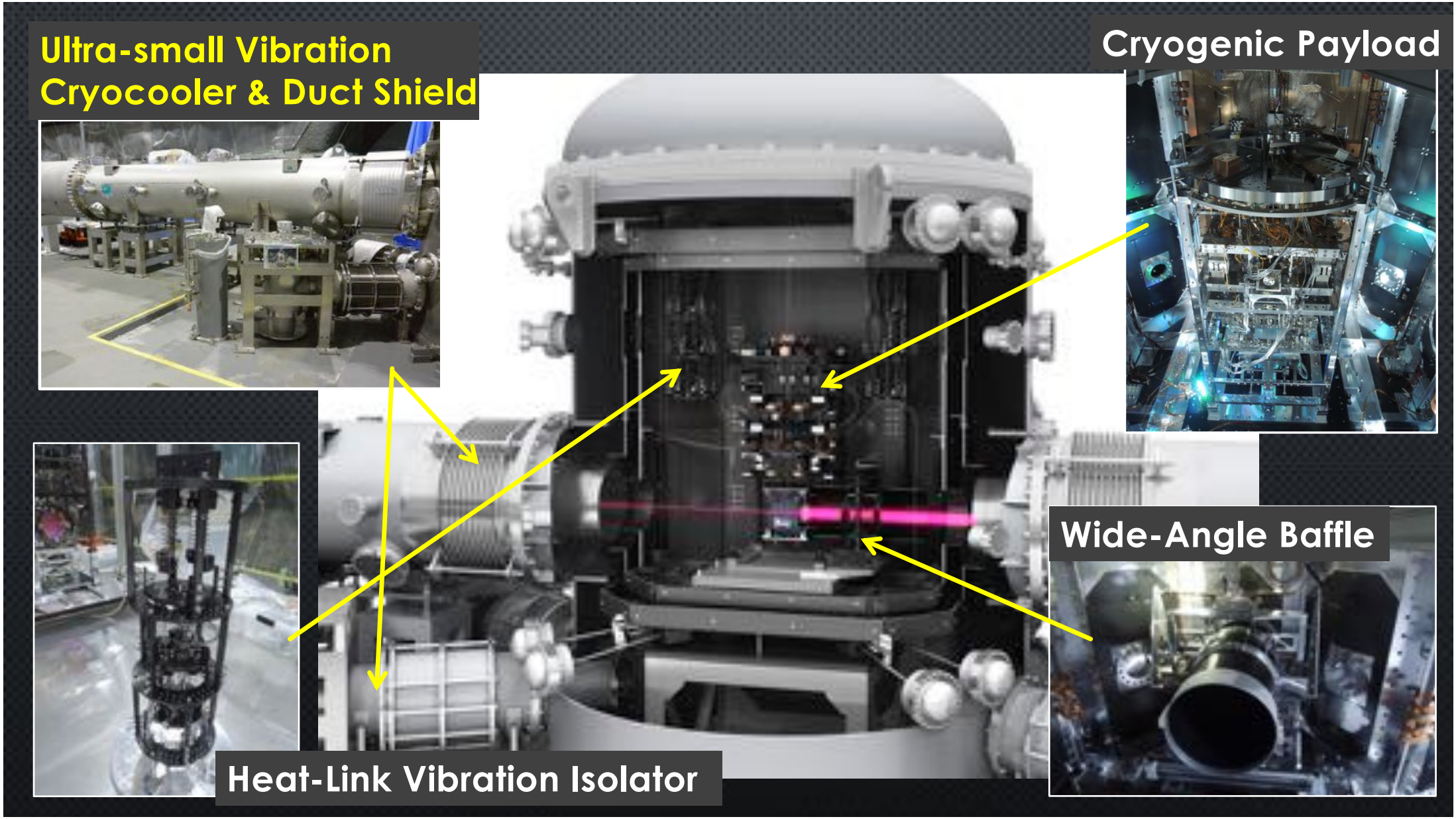
Cryogenic part

Arm tunnel

Bottom Floor

Main Cryostat

Duct Shield

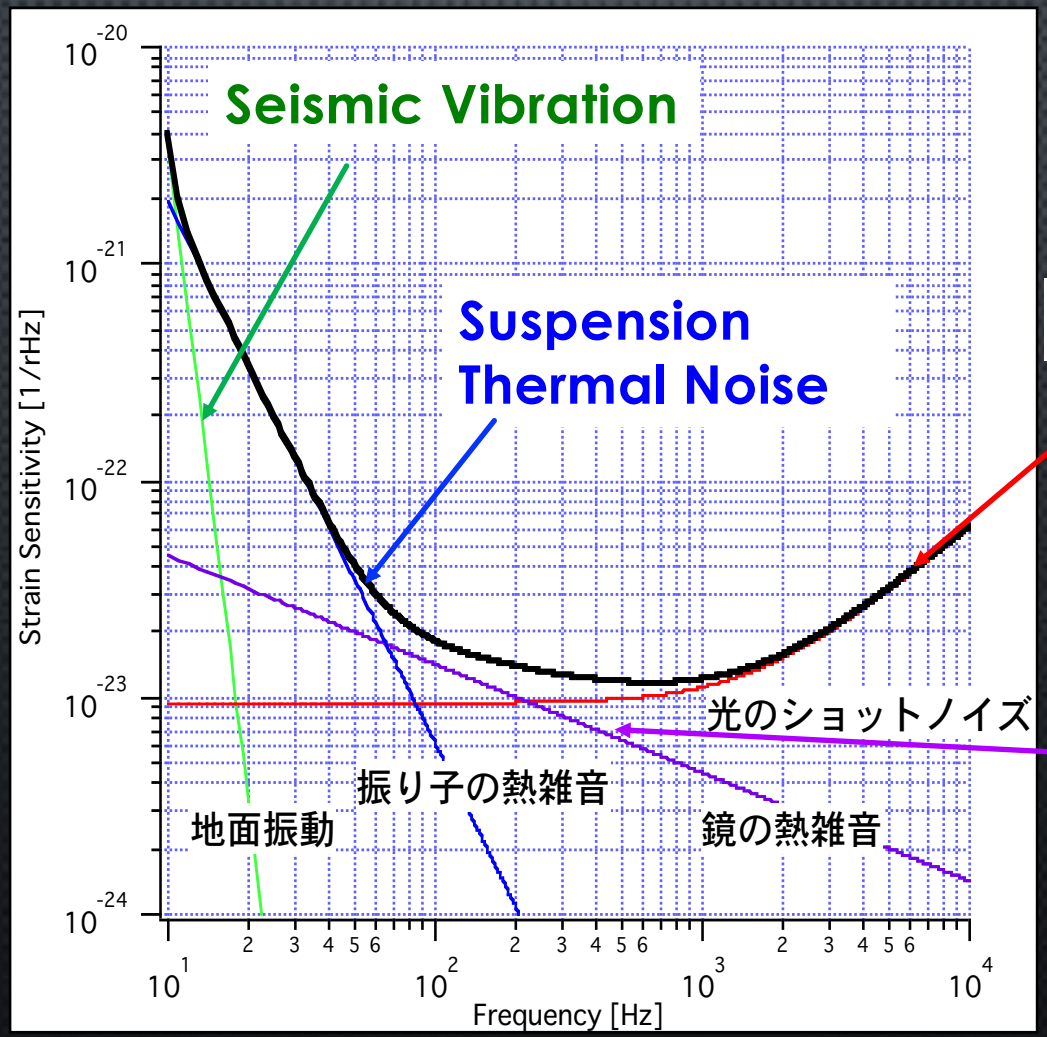

Ultra-small Vibration
Cryocooler & Duct Shield
Cryogenic Payload
Wide-Angle Baffle
Heat-Link Vibration Isolator

Principle Sensitivity Limitations of Interferometric GW Telescope

Low

Sensitivity

High



Cryogenic Mirror Suspension

Thermal Noise

Temperature

$$\sqrt{x(\omega)^2} \propto \sqrt{T\,\phi}$$

Acoustic loss

We found that single crystalline sapphire has very small acoustic loss at cryogenic temperature

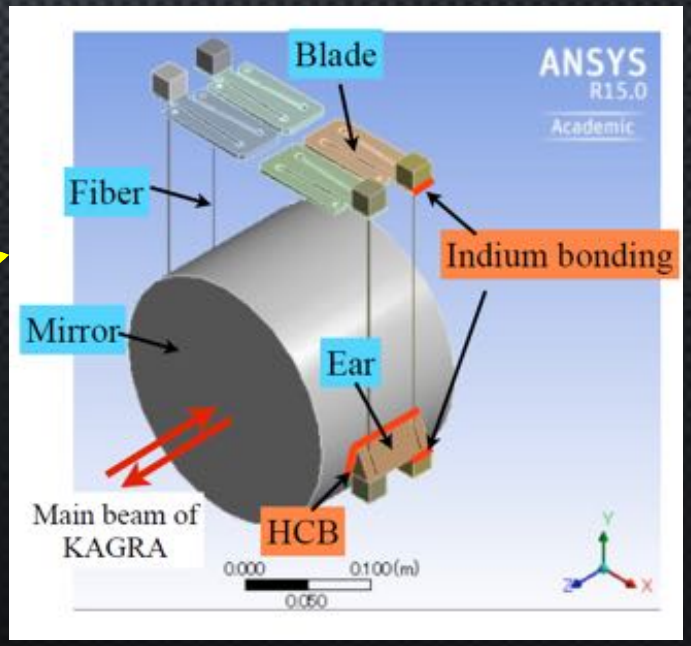
Sapphire @ 20K

$$\phi = 5 \times 10^{-9} \quad \text{(bulk)}$$
$$\phi = 1 \times 10^{-7} \quad \text{(fiber)}$$

Typical value of acoustic loss Of sapphire at room temp. is ~10^{-6}

Single Crystalline Sapphire Bulk

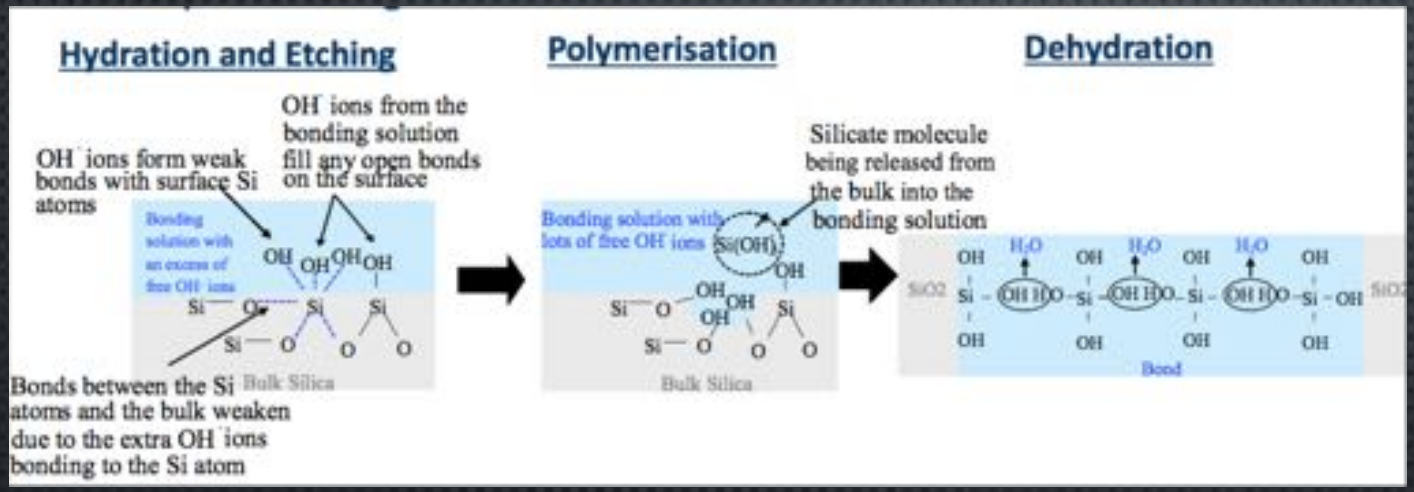
But We need to make this complex structure with monolithic sapphire condition to reduce thermal noise of the mirror suspension system.



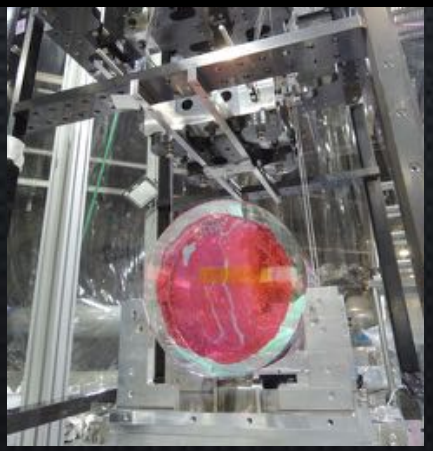
Hydroxide-Catalysis Bonding

Very strong oxide-crystal contact

NaOH, KOH, Na_2SiO_3→ kind of water glass



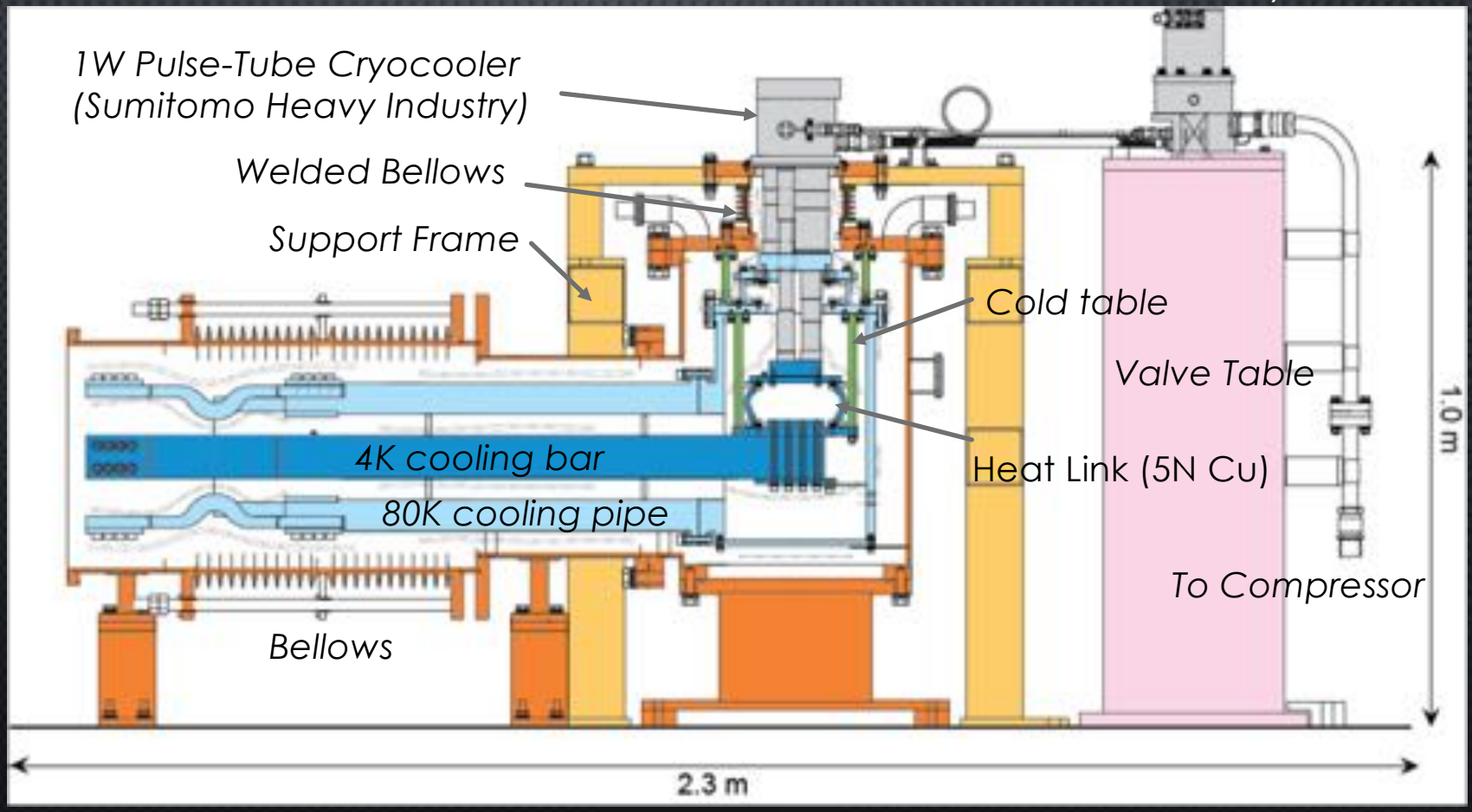
Semi-monolithic sapphire suspension



- Need high quality polish on contact surfaces, typically λ/10 ~λ/5
- Don't need to heat treatment
- Mechanical strength is comparable with crystal itself.
- This bonding technology was developed for SiO2 contacts.
  But we confirmed that this is applied to other oxidized materials
  (We confirmed to bond for Alumina and Stainless steel.)
- HCB keeps sufficient strength even at cryogenic temperature.
- Its acoustic loss is not so small.

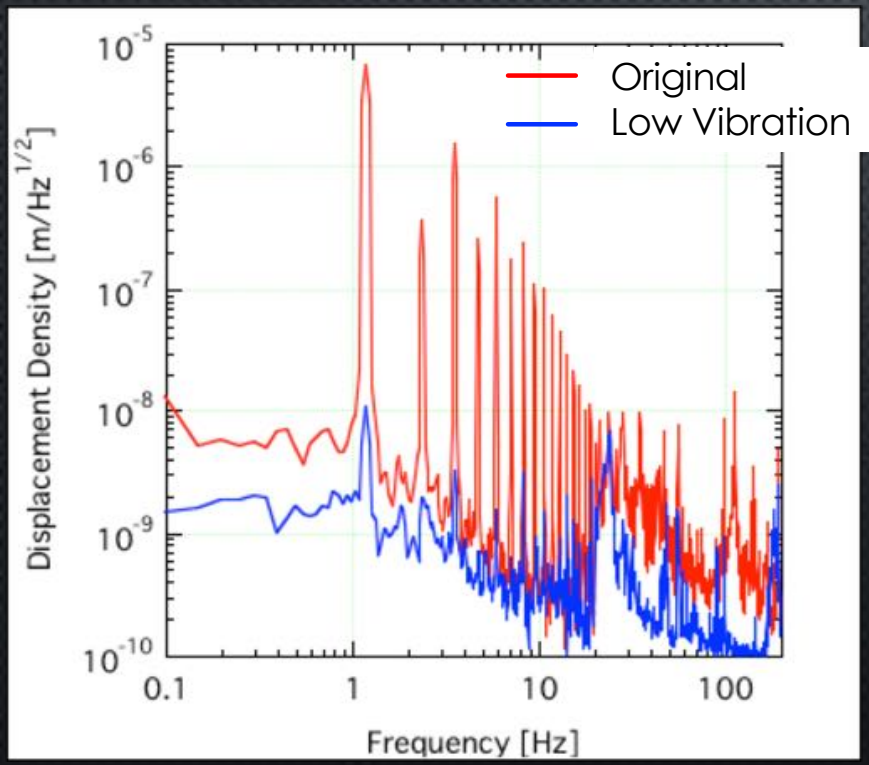
Ultra-low Vibration 4K-Cryocooler System

T. Tomaru et. al.,Cryocoolers 13, (2005) 695-702
C. Tokoku et al., AIP Conference Proceedings **1573**, 1254 (2014)

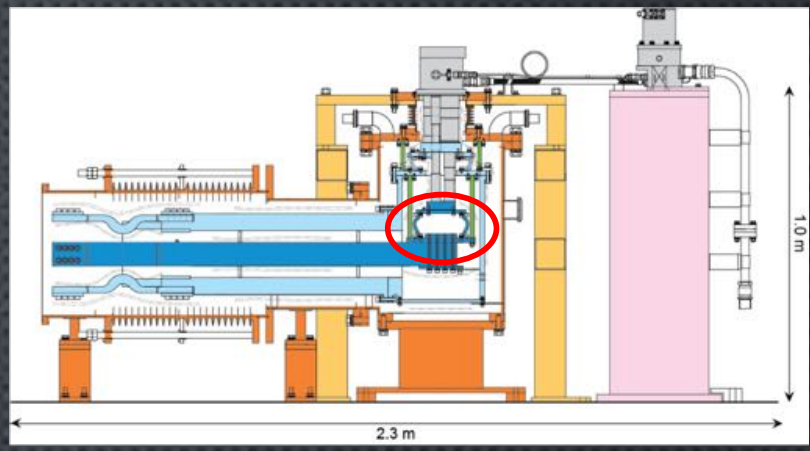


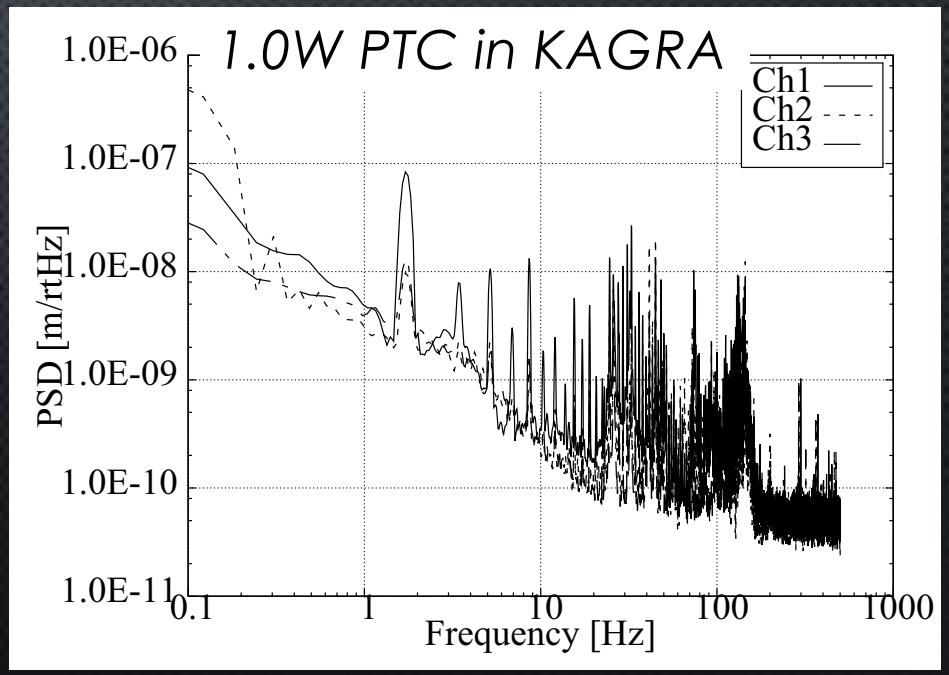
Vibration Spectrum

0.5W PTC in CLIO



Pure Al (5N) heat links are used.



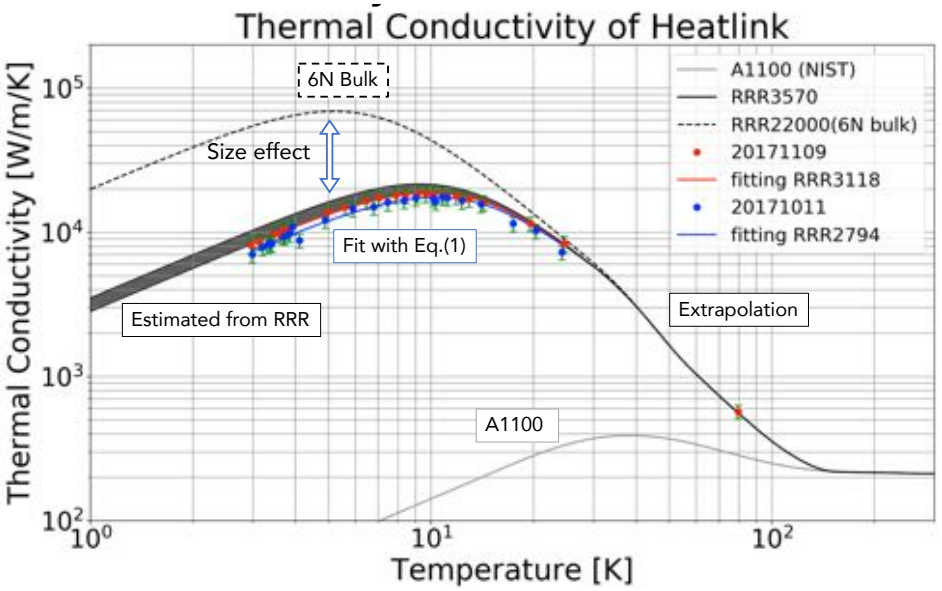


Pure Cu (5N) heat links are used.

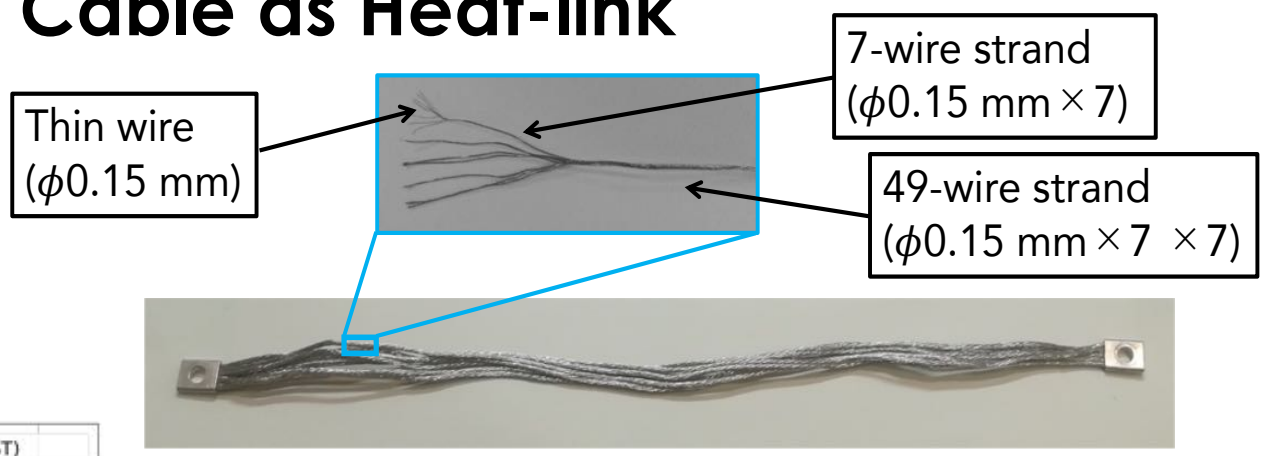
Very Soft 6N Al Stranded Cable as Heat-link

By T. Yamada

Spring constant of stranded Cable is smaller than single Wire. $k = \frac{P^2}{N}$.



Size effect dominates conductivity



Stranded-cable type heat link (ϕ0.15 mm × 7 × 7 × 7)

- Result (Resonant frequency)

	Area	5N	6N
ϕ1mm single	0.8 mm^2	64 Hz	64 Hz
45 wires strand	0.8 mm^2	9.6 Hz	9.8 Hz

$k \propto f^2$ 1/6.5

Spring constant: 1/43

Observation Network for Gravitational Wave

aLIGO (Hanford), 4km
70-80Mpc for NS-NS

LIGO India
will start from
2025

aVIRGO (Pisa), 3km
~55Mpc

KAGRA (Kamioka), 3km
will start from 2019

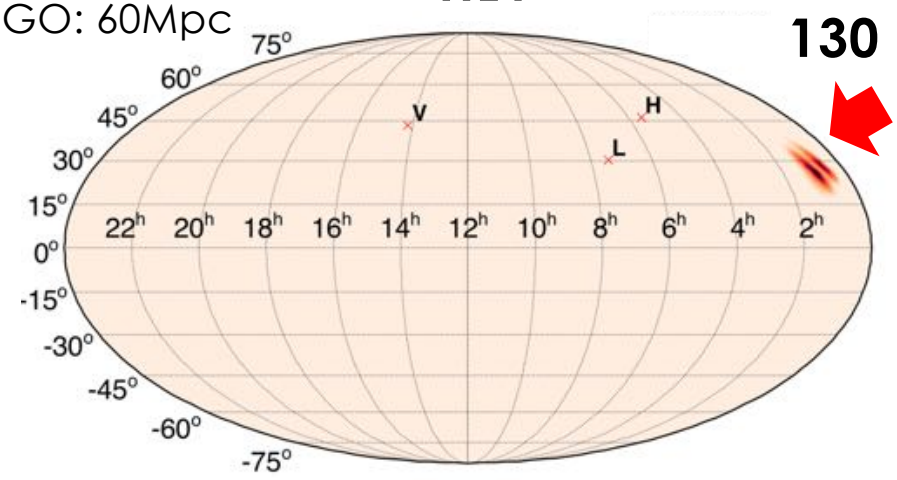
aLIGO
(Livingston), 4km
120-130Mpc

Event Localization

- Improvement of precision of Luminosity Distance
- Investigation of event distribution
- Improvement of successful detection by Follow-up observation

LIGO: 120Mpc
VIRGO: 60Mpc

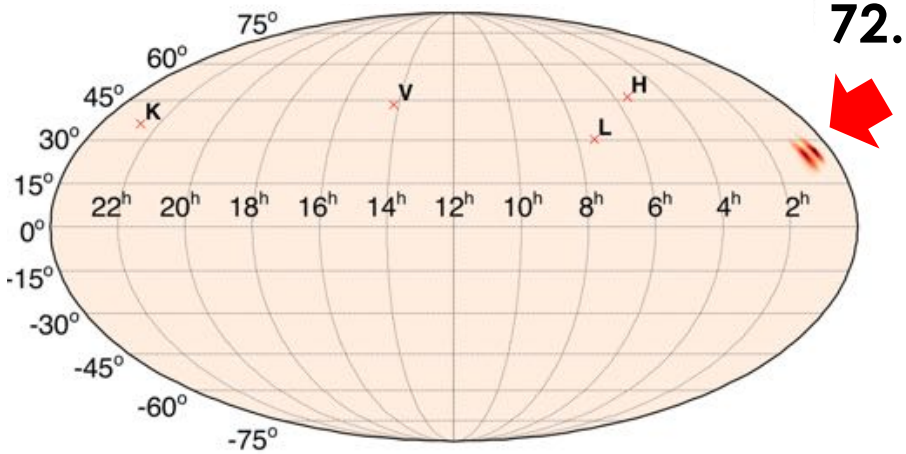
HLV



130 deg²

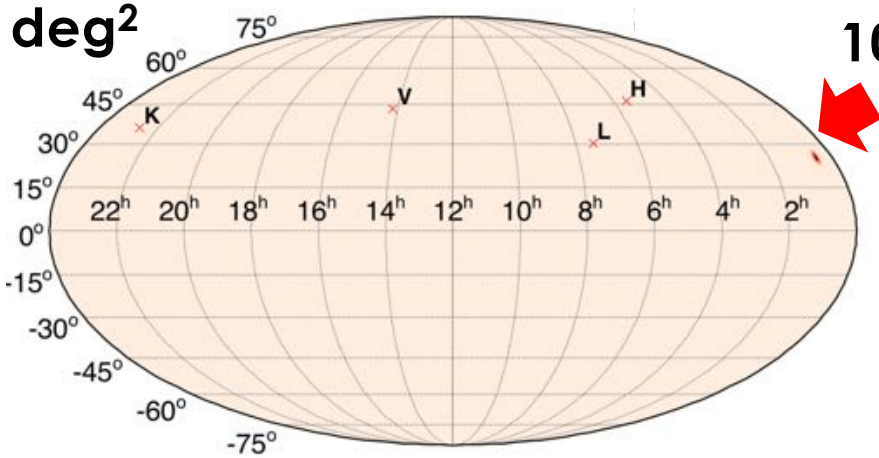
10 Times!

HLVK (8Mpc)



72.7 deg²

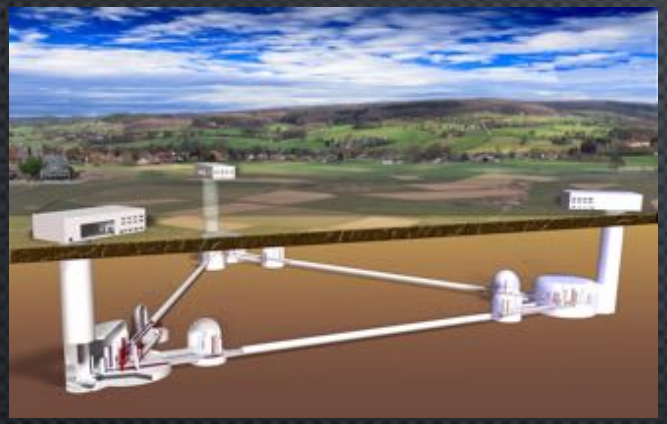
HLVK (25Mpc)



10.3 deg²

KAGRA: 2.5nd Generation GW Detector

Einstein Telescope (Europe), 10km



Cosmic Explorer (USA), 40km

Collaboration in Technologies

KAGRA Upgrade in Near Future

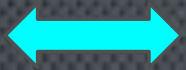
10km scale Asian Telescope?

Internationalization?

Did you really understand my talk?

Should be no problem

Domestic Group — Scientists



English

Oversea Group — Scientists

Large issue is internal domestic group

To do fundamental improvement, we need long-term education from young age.
We need to expect improvement of Japanese education system

In the case of GW Science Project

- Scientist: Japanese & non-Japanese
- Engineer: Only Japanese
- Technician: no
- Student: Japanese & non-Japanese

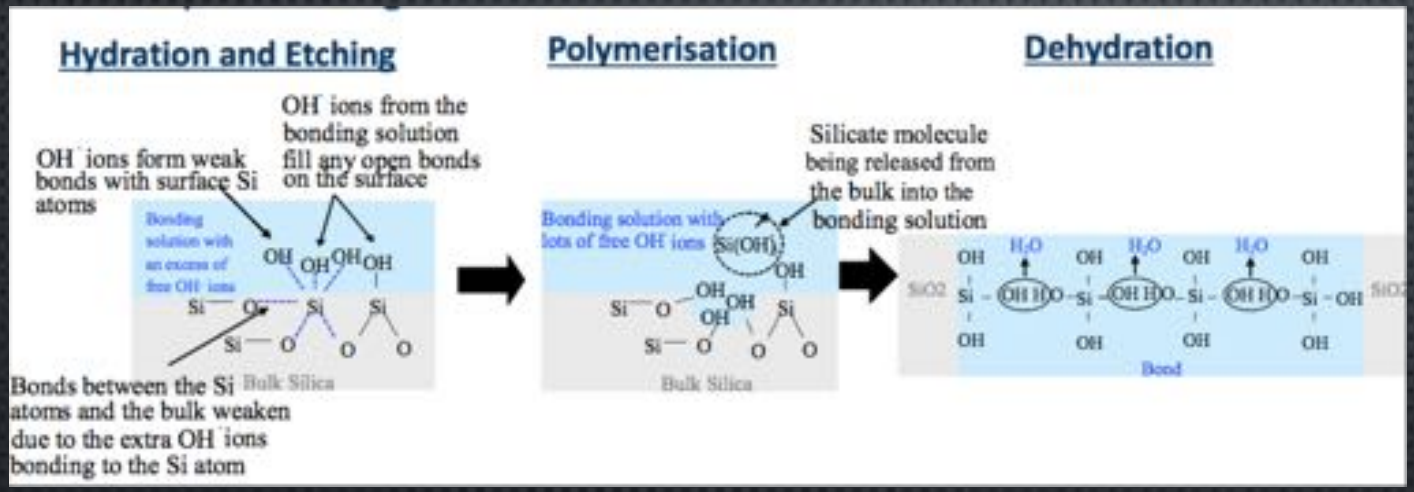
} It is not so easy to have good Communication in English

- Office worker: Only Japanese but fluent English speaker

Hydroxide-Catalysis Bonding

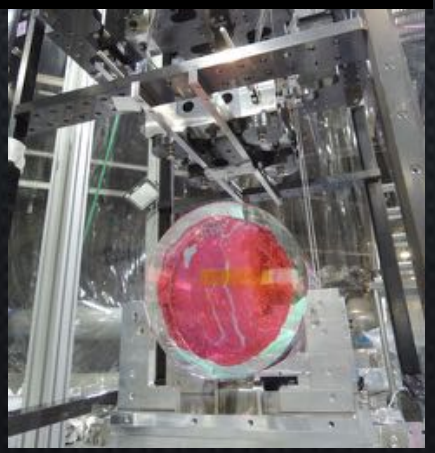
非常に強い結晶接合
Very strong oxide-crystal contact

水ガラスの一種
NaOH, KOH, Na_2SiO_3→ kind of water glass



準モノリシックな
サファイアサスペンション

Semi-monolithic
sapphire suspension



高精度の表面研磨が必要。典型的にはλ/10 ~λ/5

- Need high quality polish on contact surfaces, typically λ/10 ~λ/5
- Don't need to heat treatment　熱処理不要
- Mechanical strength is comparable with crystal itself.
- This bonding technology was developed for SiO2 contacts.
  But we confirmed that this is applied to other oxidized materials
  （We confirmed to bond for Alumina and Stainless steel.）
- HCB keeps sufficient strength even at cryogenic temperature.
- Its acoustic loss is not so small.　機械的損失は大きい。

強度は結晶そのもの
と同程度

他の酸化物・
酸化皮膜を持つ
材料にも使える

極低温でも使える

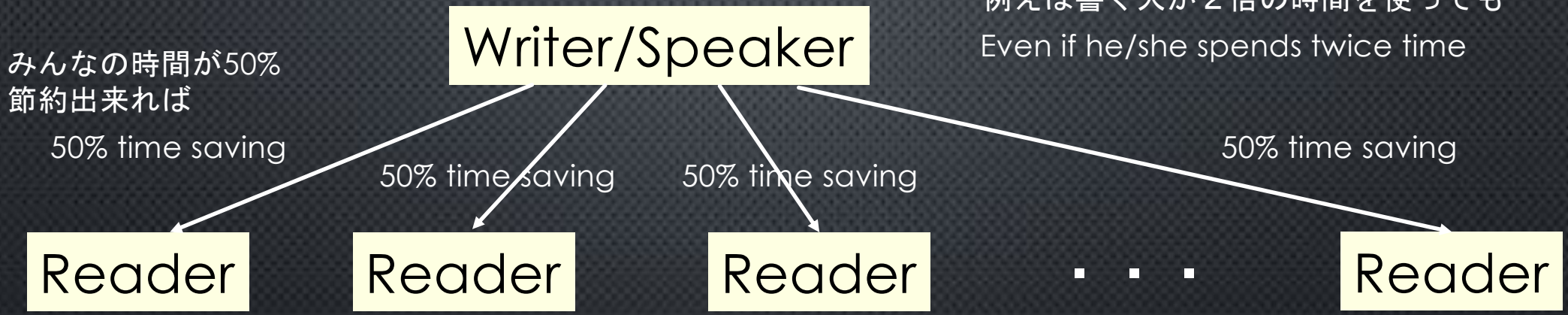
My idea is to use both Japanese and English

アイデアとしては日本語と英語両方を使う

Especially in e-mail.　特にemail !

例えば書く人が２倍の時間を使っても

Even if he/she spends twice time



We can expect large efficiency in total

全体としての効率は非常に大きい。

And above all, most important thing is to understand discussion by everyone.

なにより、みんなが理解出来ることが一番大事。