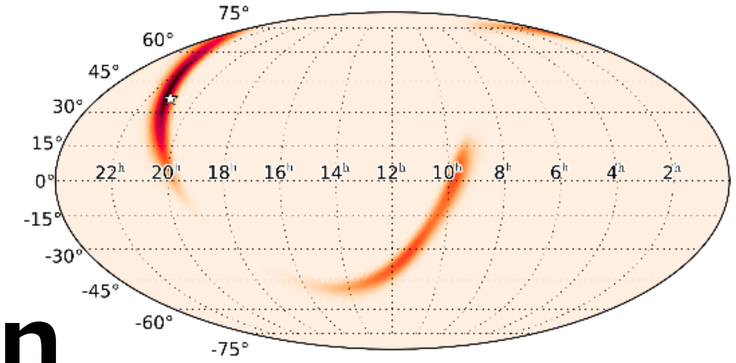
Development of
a low frequency vibration isolation system for KAGRA,
and study of the localization of coalescing binaries
with a hierarchical network of gravitational wave detectors.

Master's thesis defense
35-156218
Yoshinori Fujii

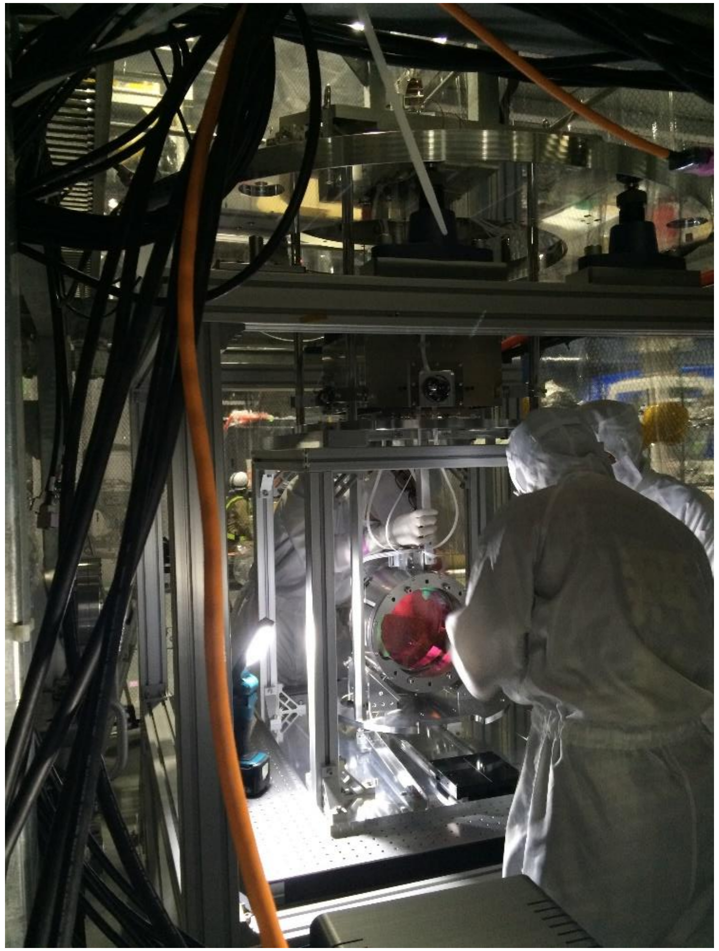
Contents

1. Source localization

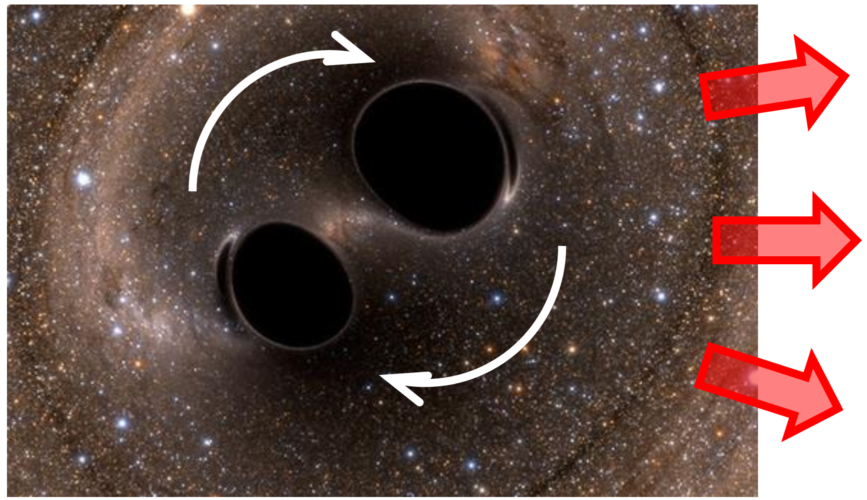


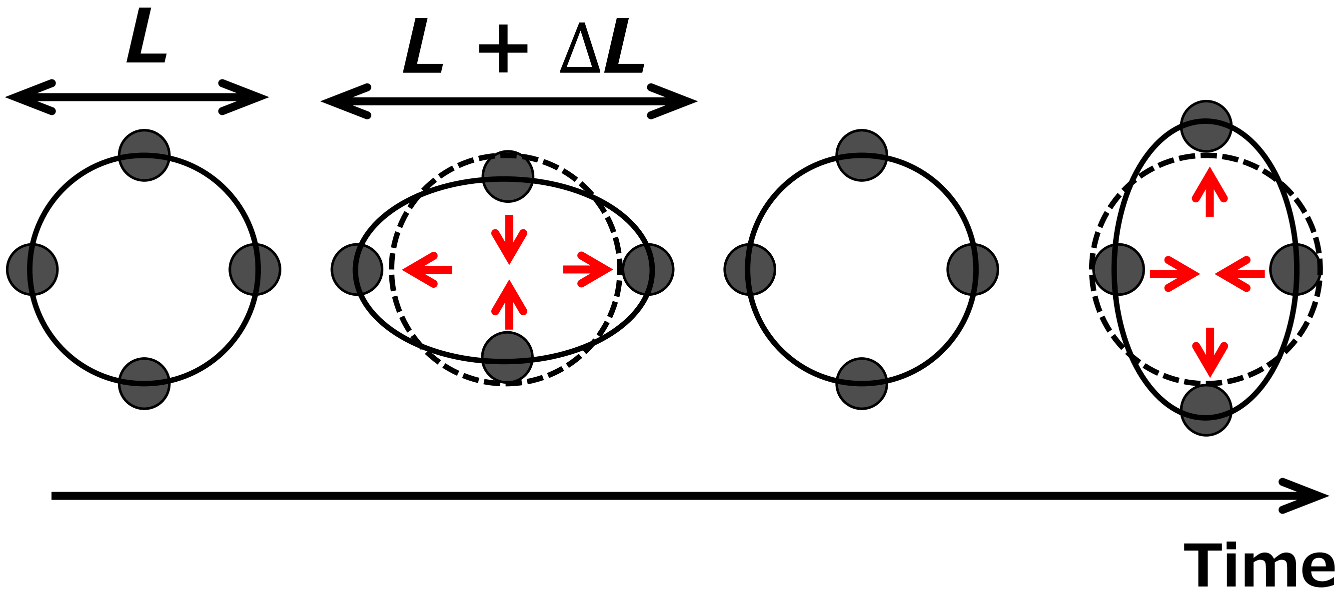
↓

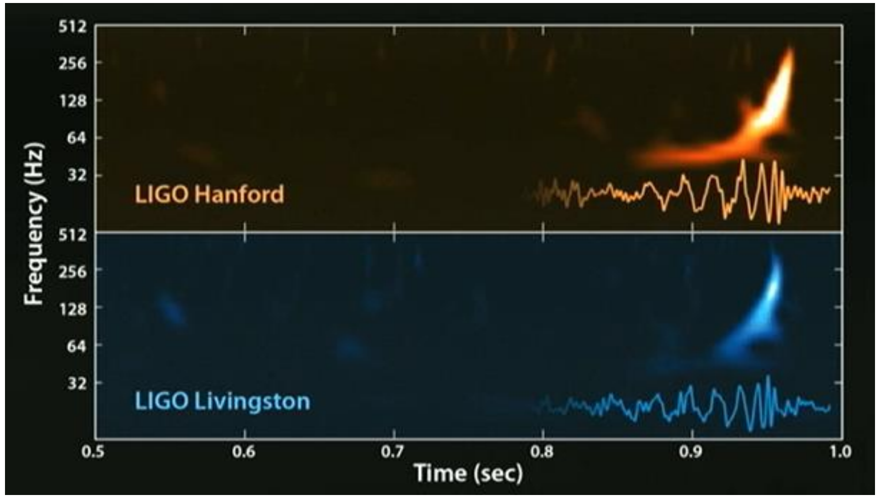
2. Detector development



Gravitational wave







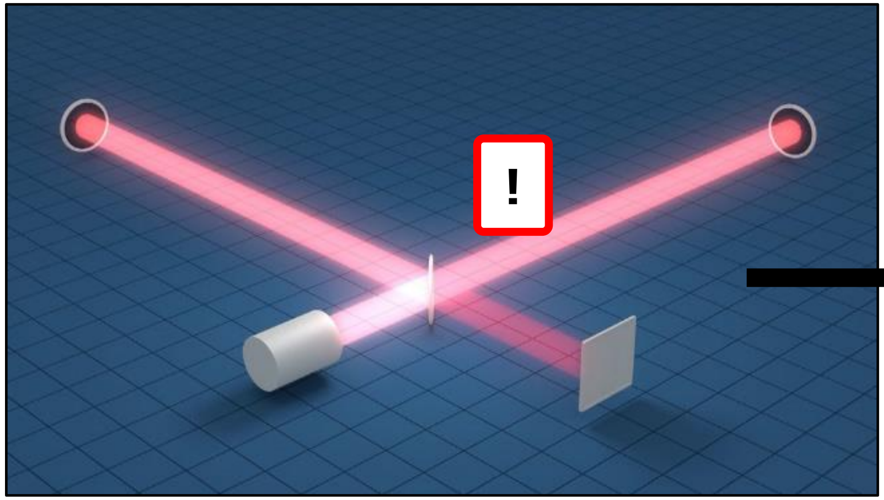
First detection! done!

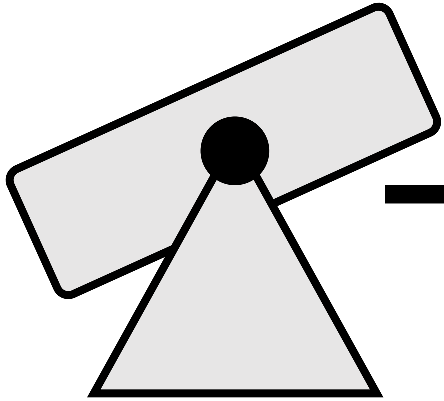
→ New astronomy!

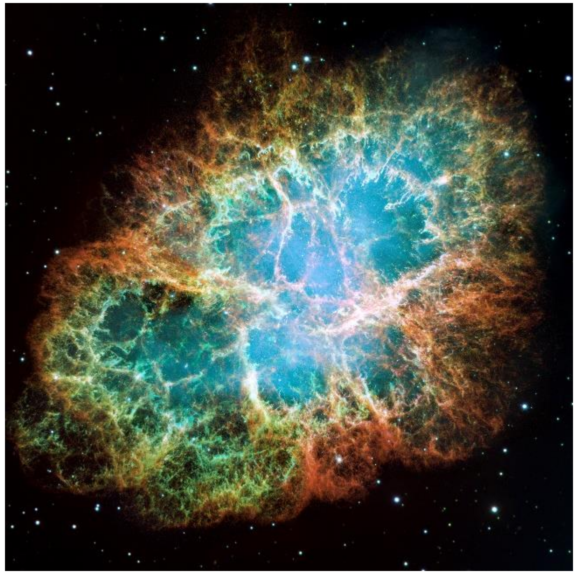
For starting astronomy,

→ Source localization.

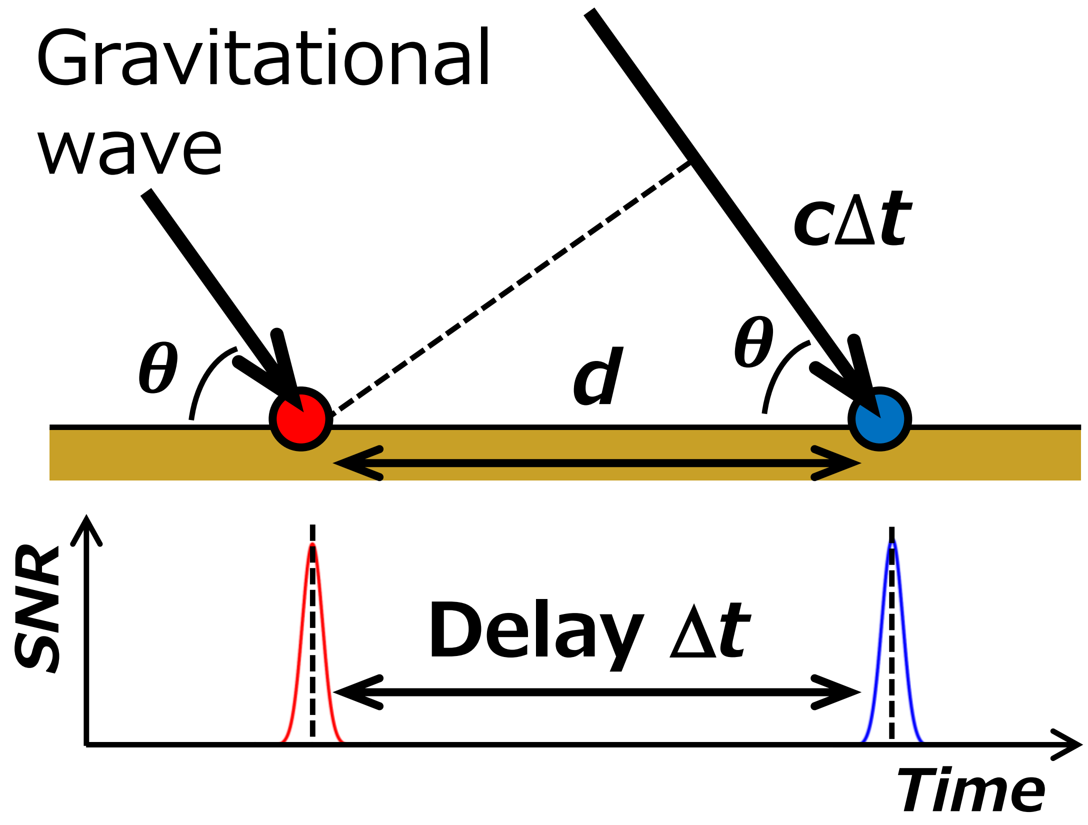
for follow-up observation.







From where?



Time delay → Localization

$$\Delta t \longrightarrow \theta$$

$$\theta = \cos^{-1}\left(\frac{c\Delta t}{d}\right)$$

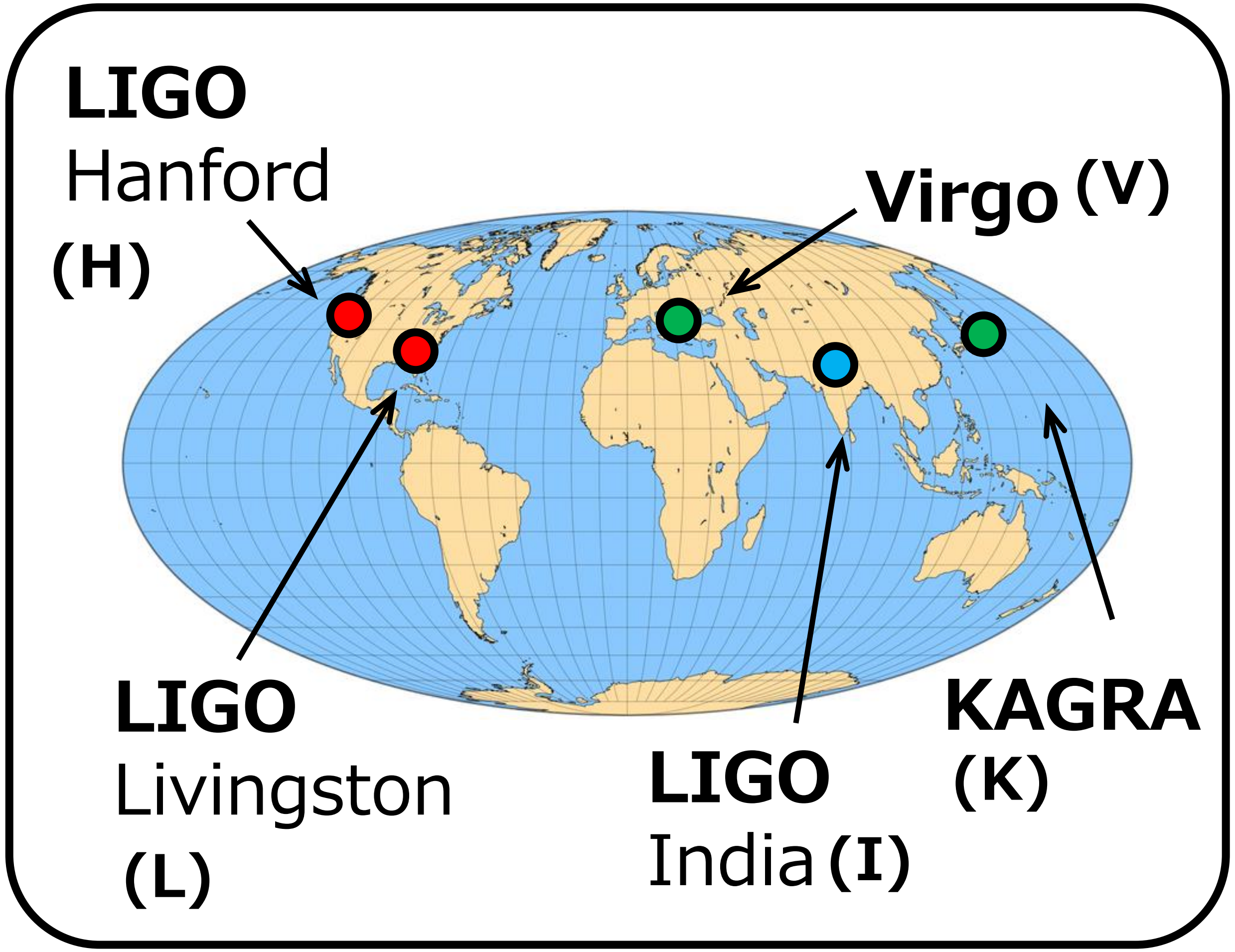
For localization, we want..

→ *Several detectors!*

Continuous observation

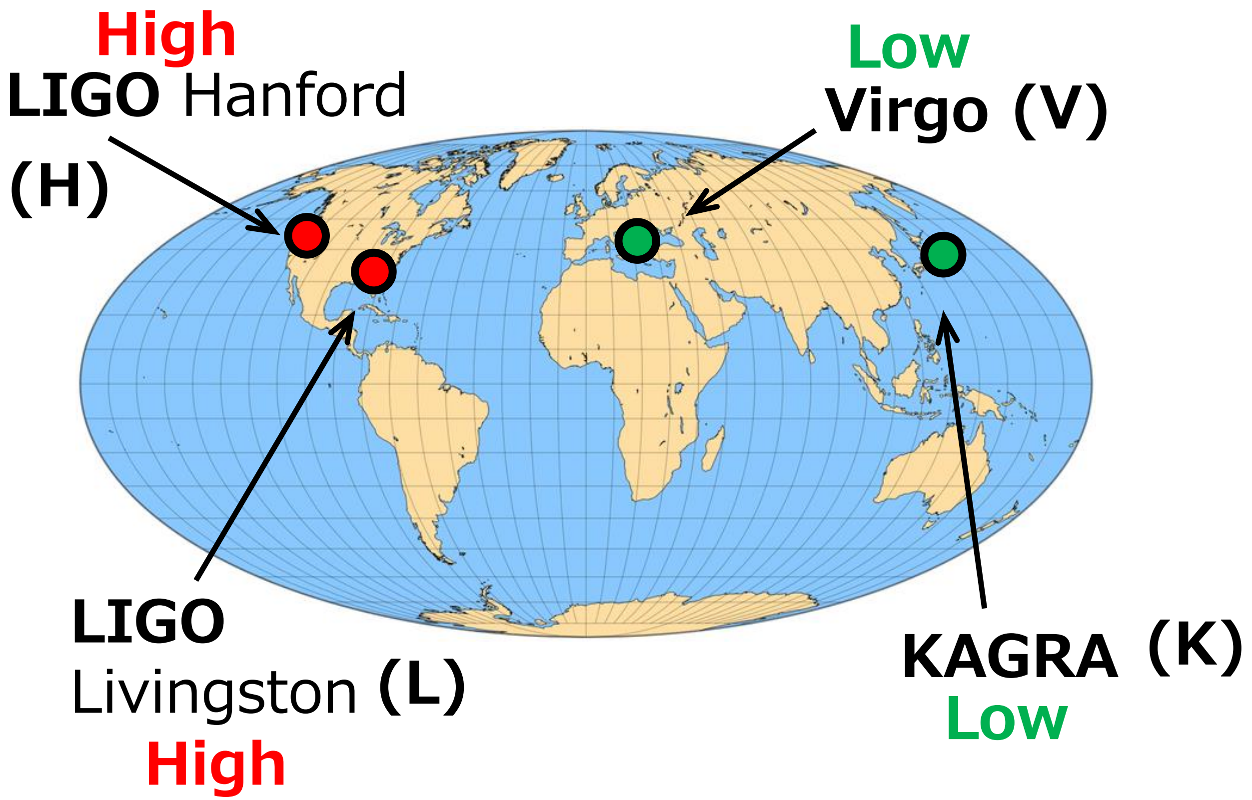
All sky coverage

Precise localization!



Different sensitivities.. OK?

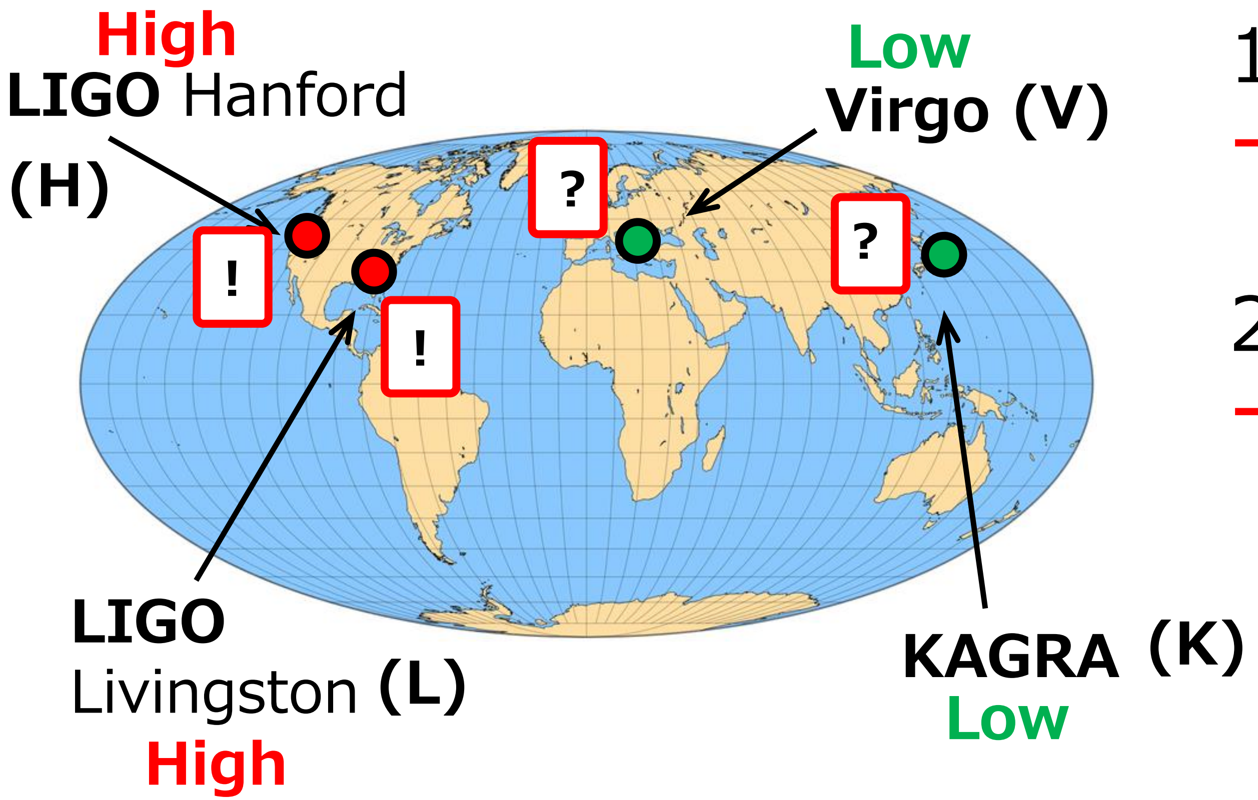
Ex.) SNR > 5 → detection



(At the beginning)

Different sensitivities.. OK?

Ex.) SNR > 5 → detection

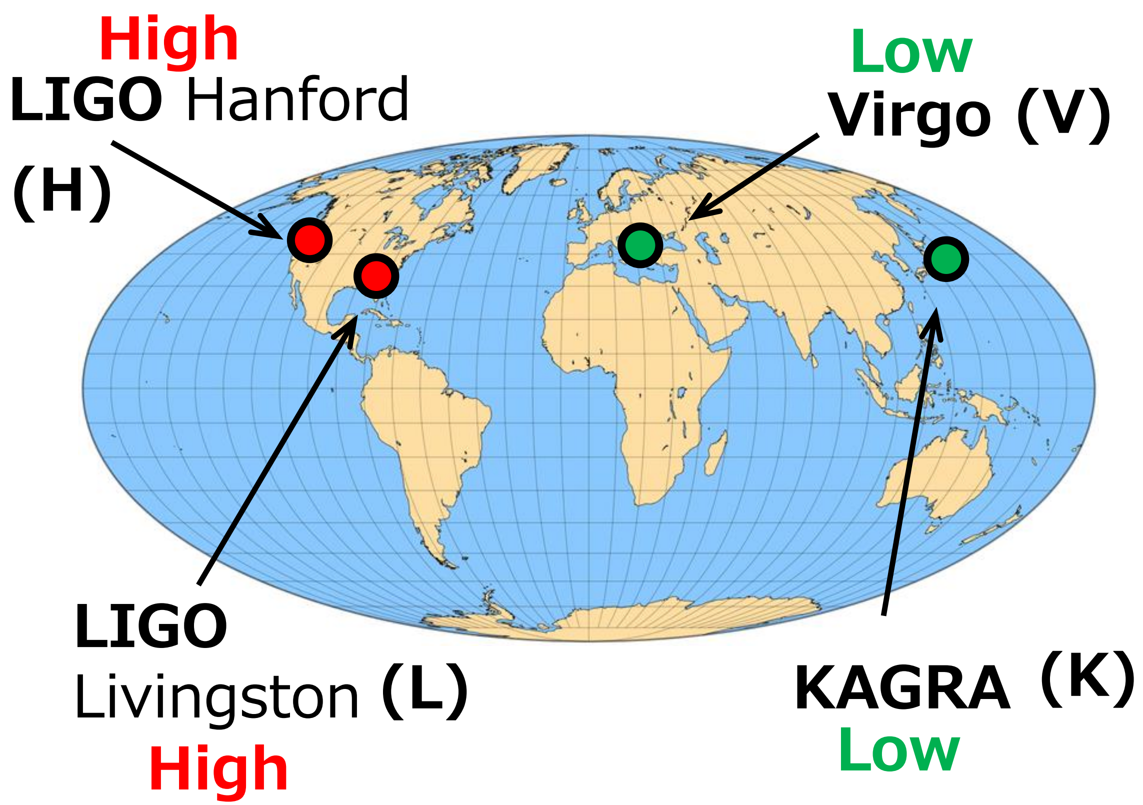


(At the beginning)

1) Triple (or more) coincidence
→ Rare

2) Double coincidence
→ Not precise localization

Hierarchical network search



If

1. A trigger is detected
   by *high sensitivity* detectors
   with ***high SNR threshold***

↓

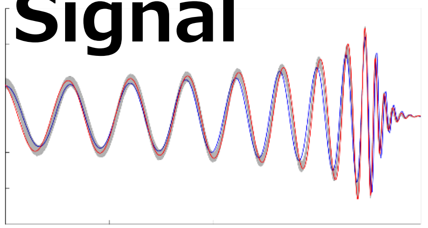
2. Analyze
   low sensitivity detectors
   with ***low SNR threshold***
   using *small time window*.

Assumption in calculation

1. GW-EM pipeline for GWs from CBC

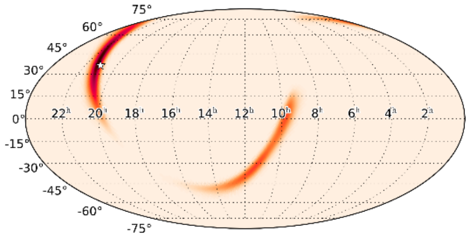
→ GW detectors → [1st MBTA → 2nd BAYESTAR] → EM telescopes

Signal



Event info:
SNR,
arrival time,
etc.

Sky map probability



2. Two LIGOs (70 Mpc), Virgo (20 Mpc)

High sensitivity × 2 / **Low sensitivity × 1**

Calculation main flow 1

248 Injection data

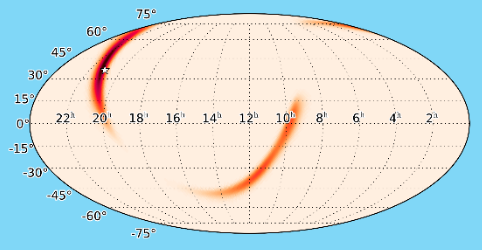
MBTA

H, L: Existing measured data

V: Artificial data

Time of arrival,
SNR,
Phase.

BAYESTAR



Sky map probability

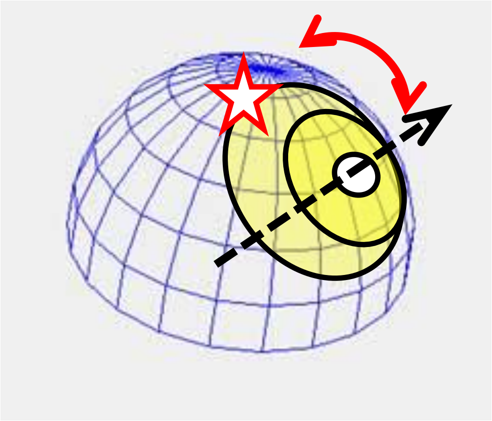
(Random event)
or
(True event + fluctuation)

My calculation

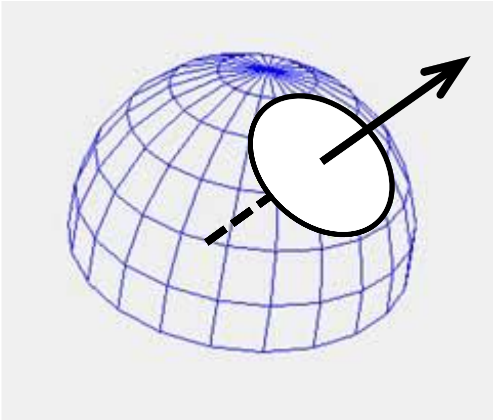
Calculation main flow 2

Localization performance

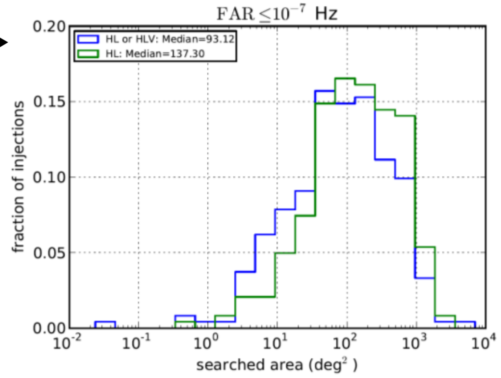
1) **Accuracy**
→ Searched area (deg^2)

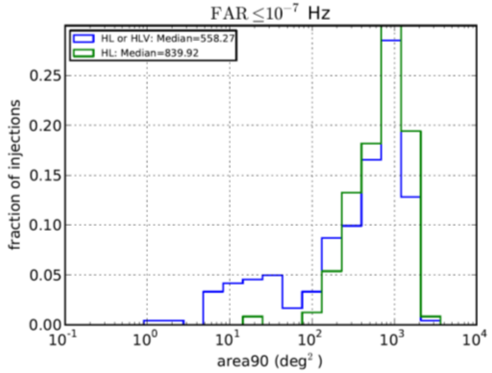


2) **Precision**
→ 90 % confidence area (deg^2)



Histograms from 248 events.

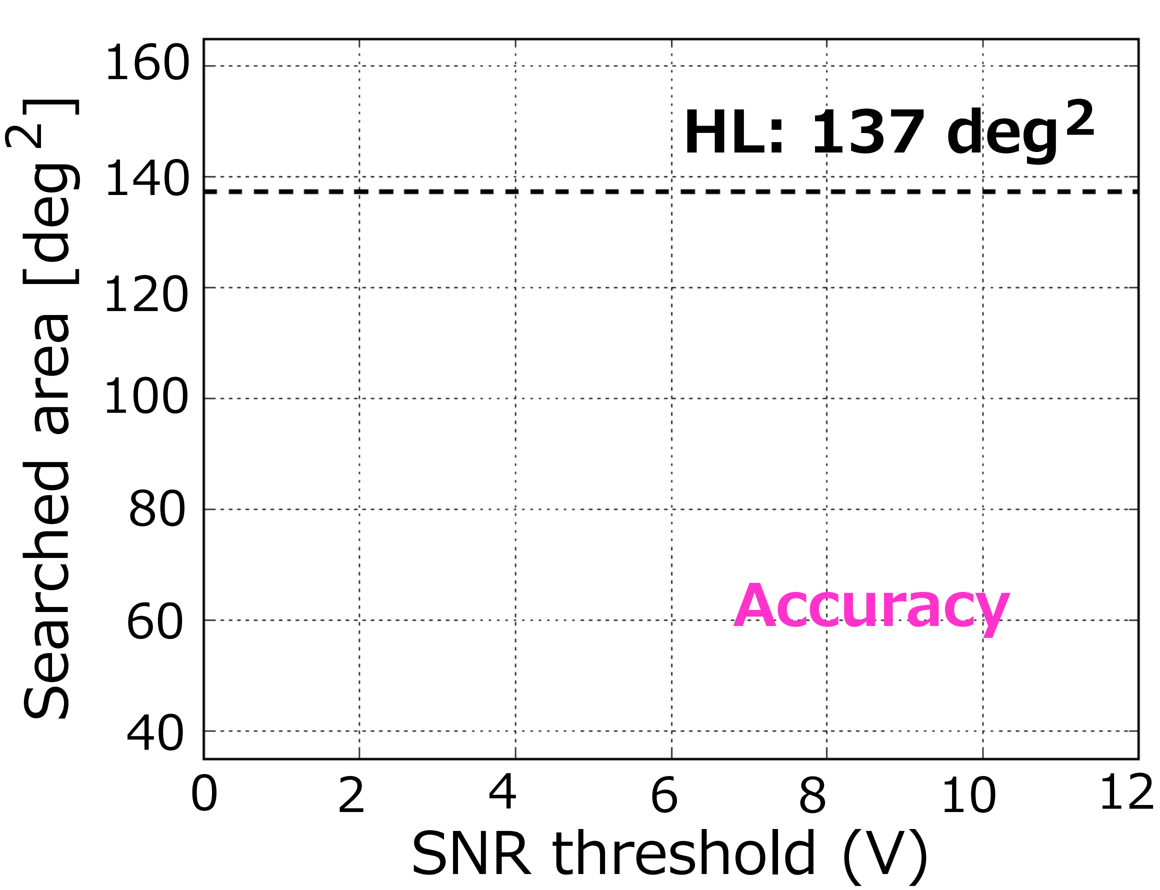


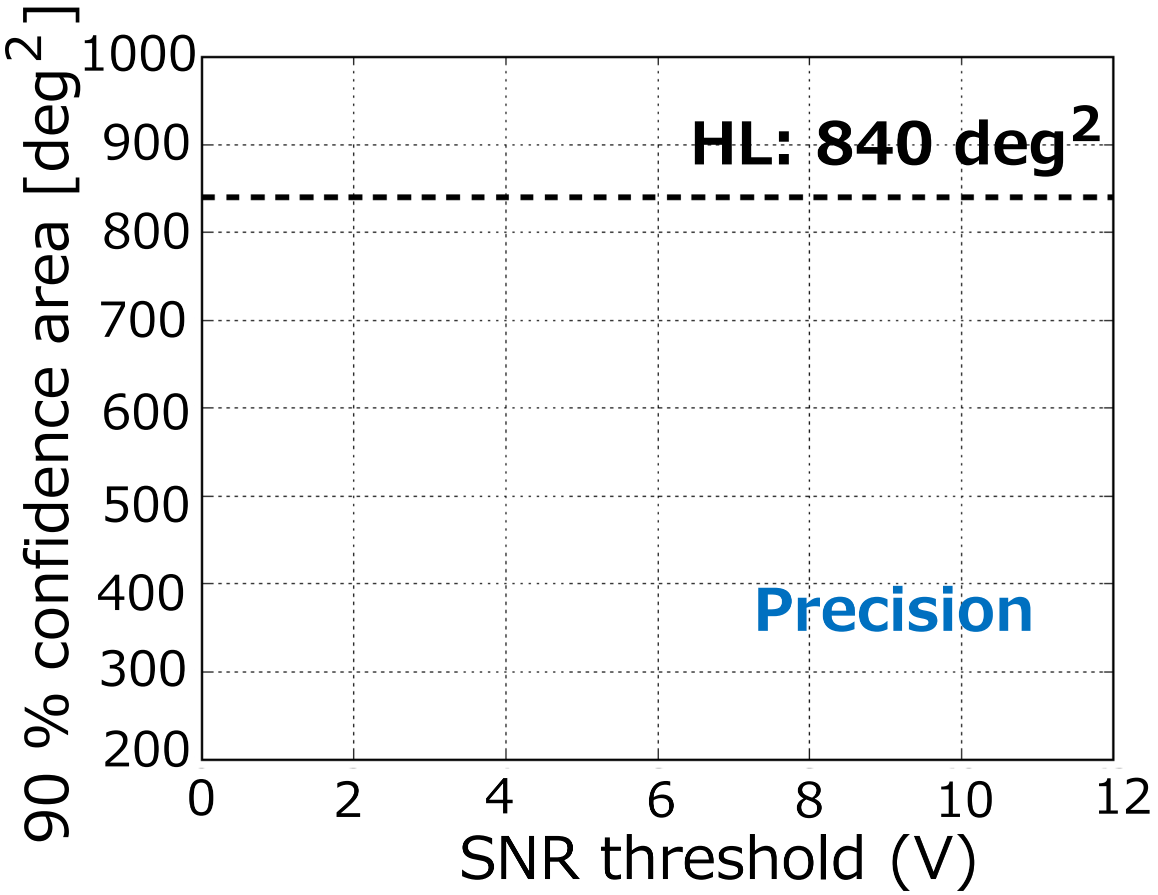


median values

Expected performance, HLV

(SNR threshold for H, L = 5.)





Expected performance, HLV

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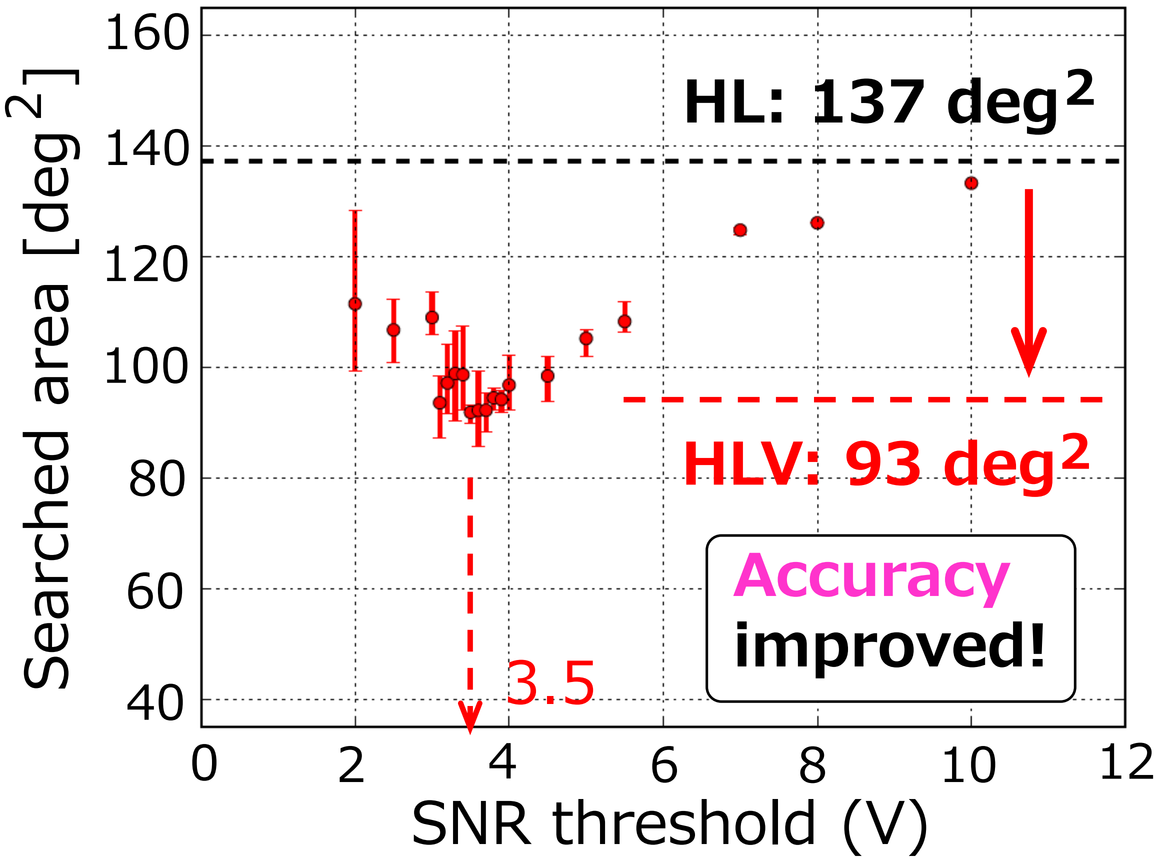
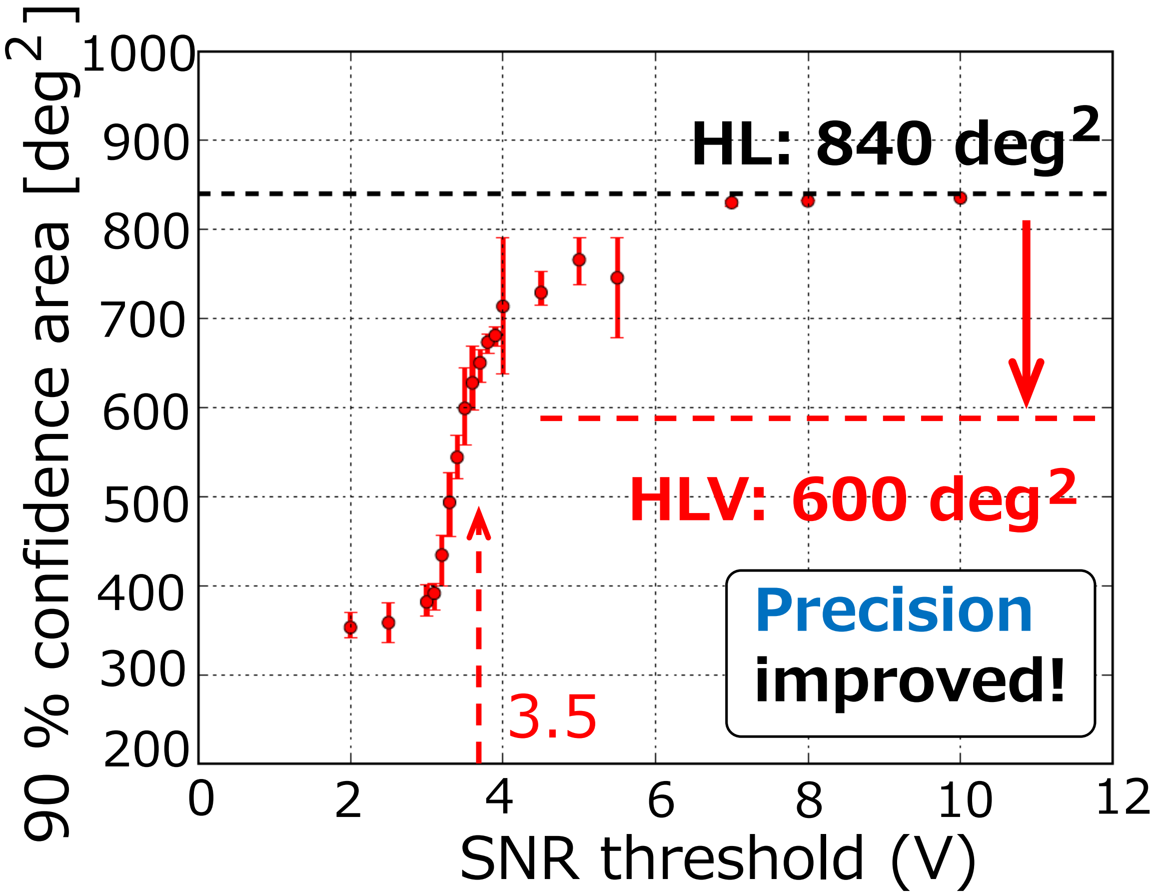
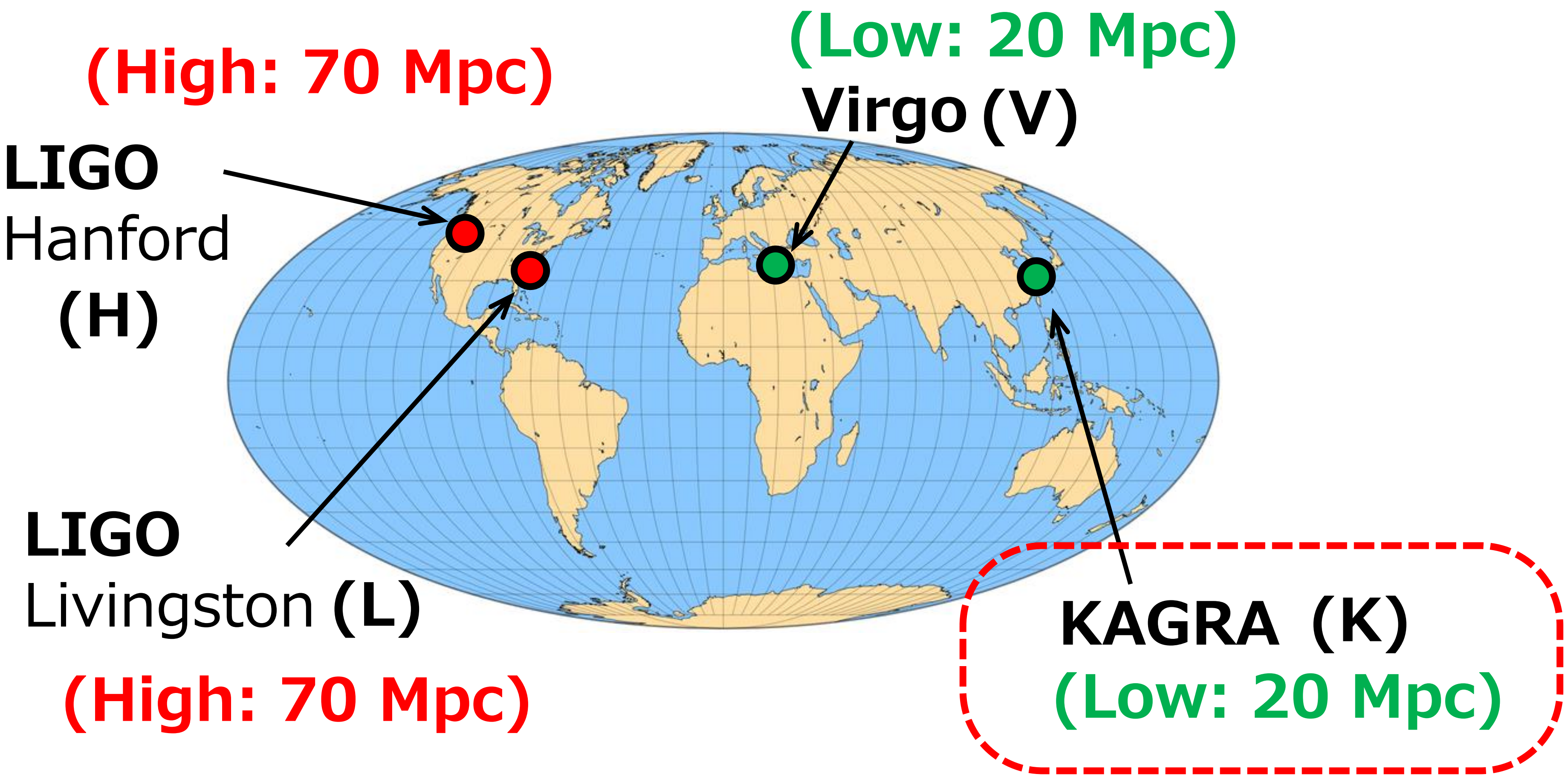




→ By including low sensitivity detector,
errors on sky maps will be reduced by a factor of ~ 0.7 than HL.

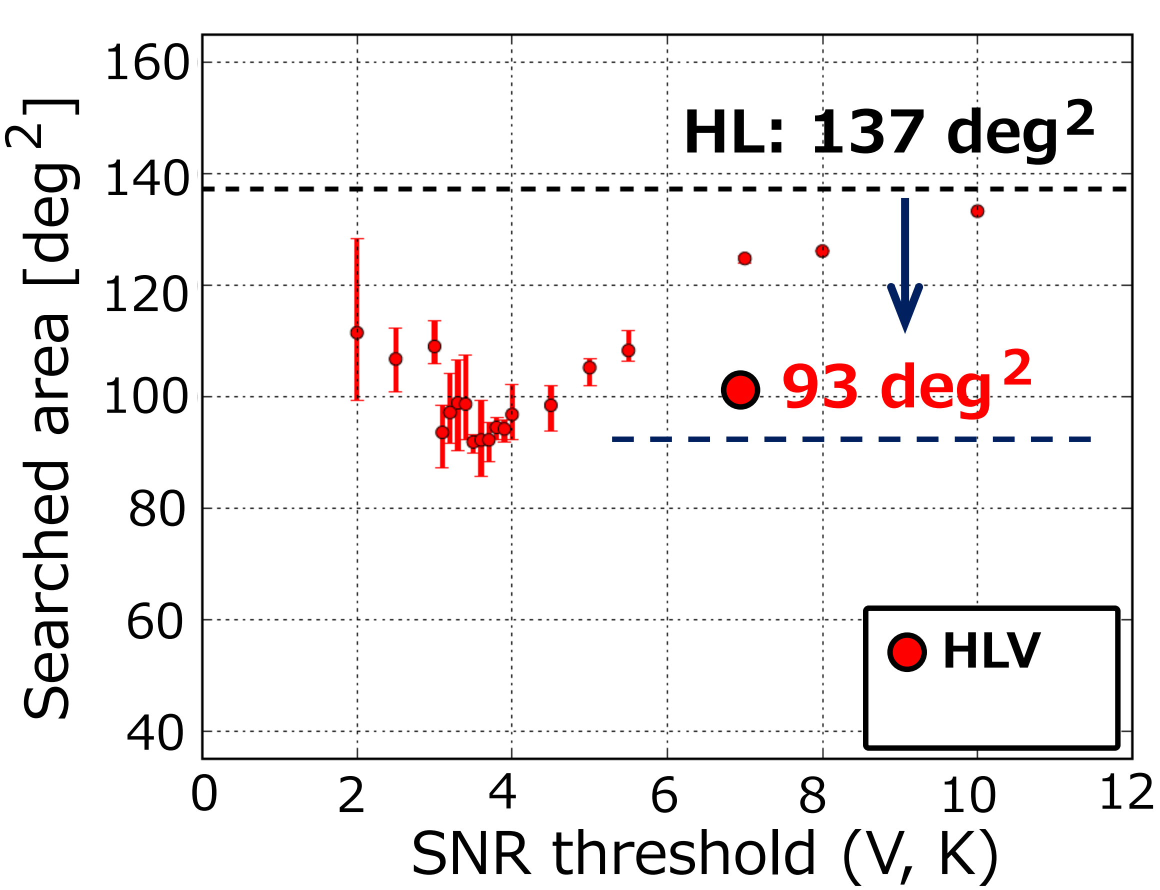
How about 4 detectors, HLVK?

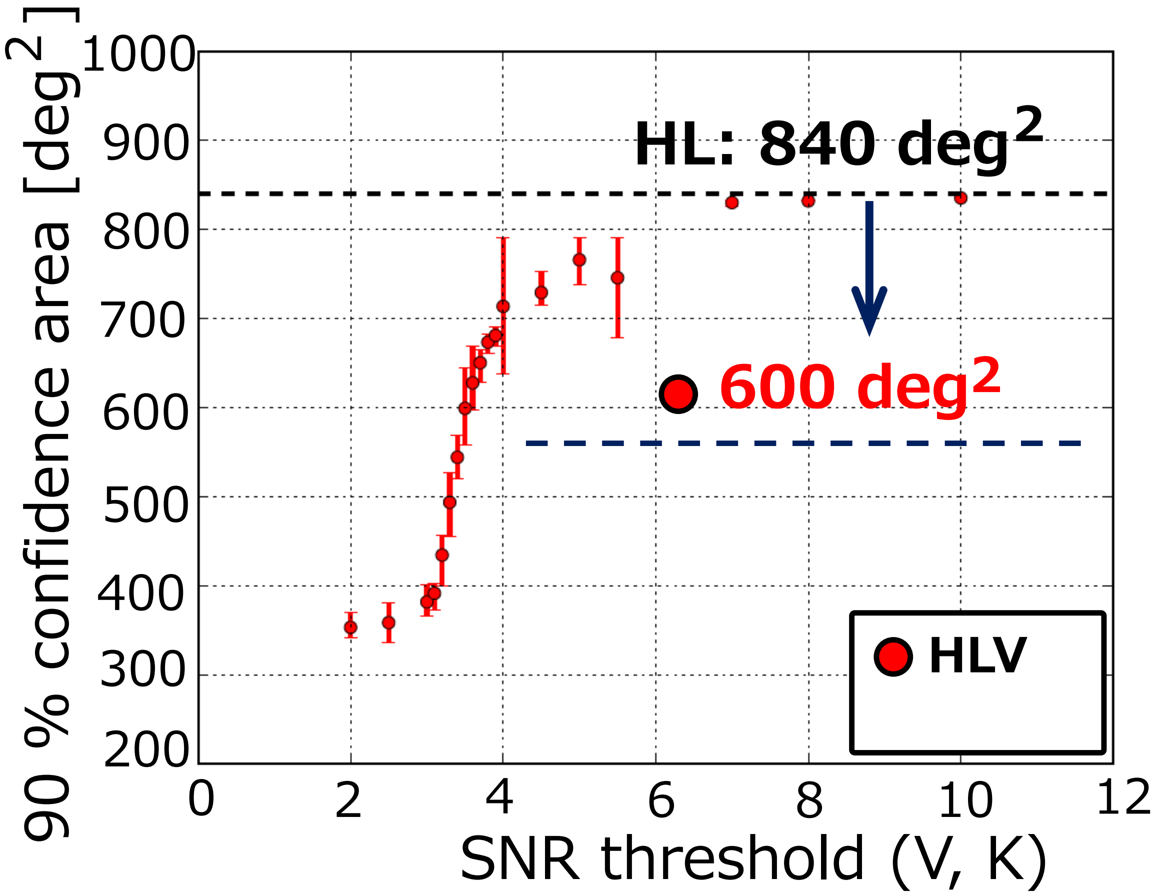


(Assumed situation)

Expected performance, HLVK

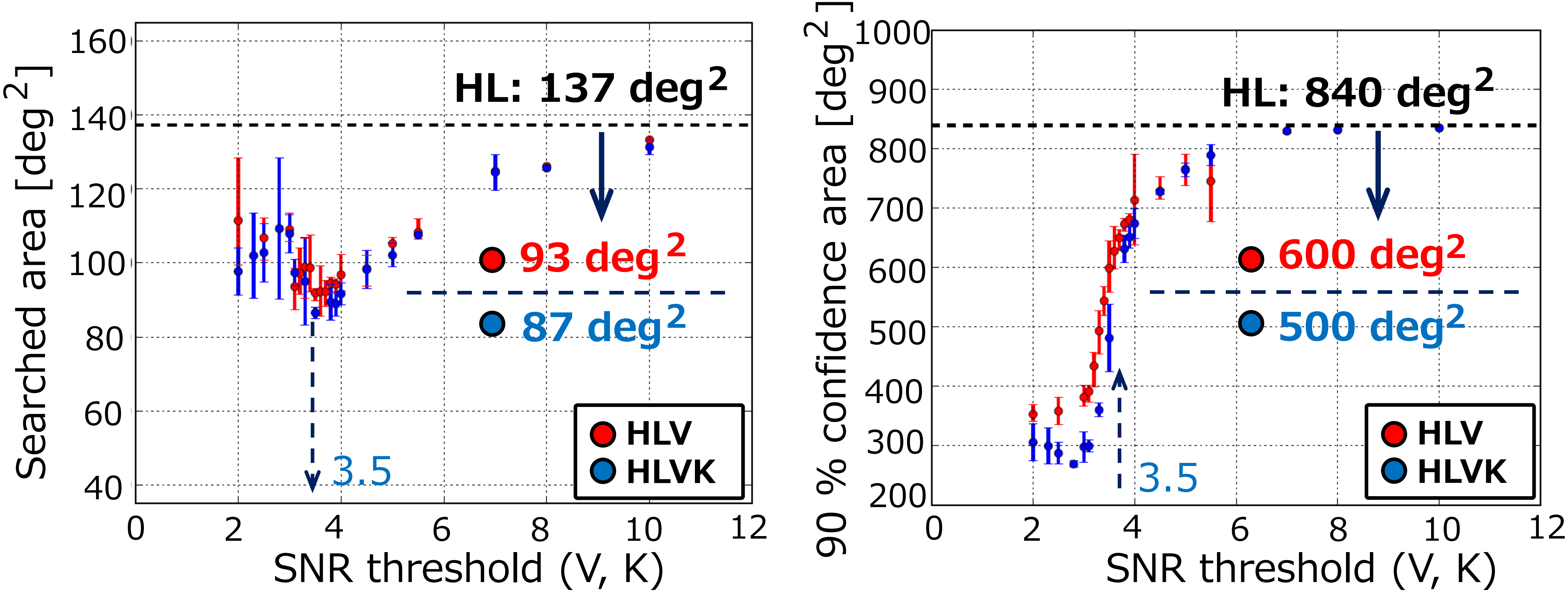
(SNR threshold for H, L = 5.)





Expected performance, HLVK

(SNR threshold for H, L = 5.)



Accuracy → Not so improved..
Precision → improved!

→ 4th detector contributes to improvement!

Summary 1

A localization with a hierarchical network is demonstrated.

In network by 3 GW detectors (70 Mpc ×2 and 20Mpc),

Accuracy
Precision
are reduced by a factor of ~ 0.7 than HL.

→ Low sensitivity detector can contribute!

In network by 4 GW detectors (70 Mpc ×2 and 20Mpc ×2),

Accuracy: HLV ~ HLVK

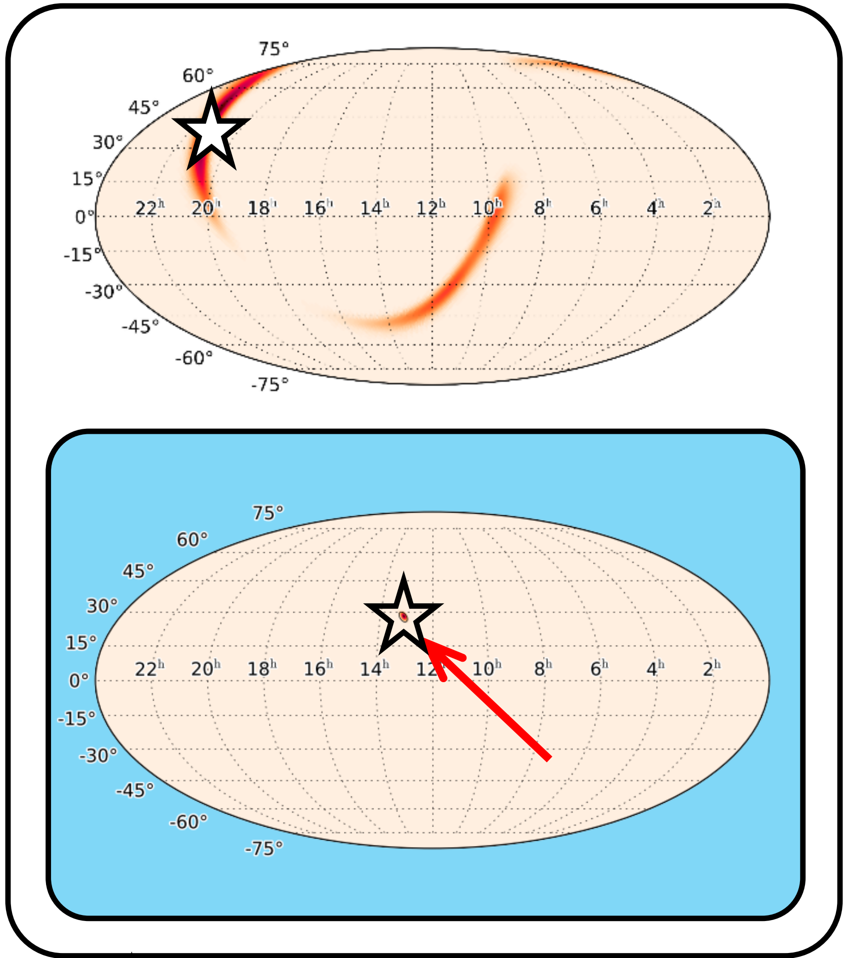
Precision: reduced by a factor of ~ 0.8 than HLV.

→ 4th detector can contributes!

→ useful for follow-up observation!

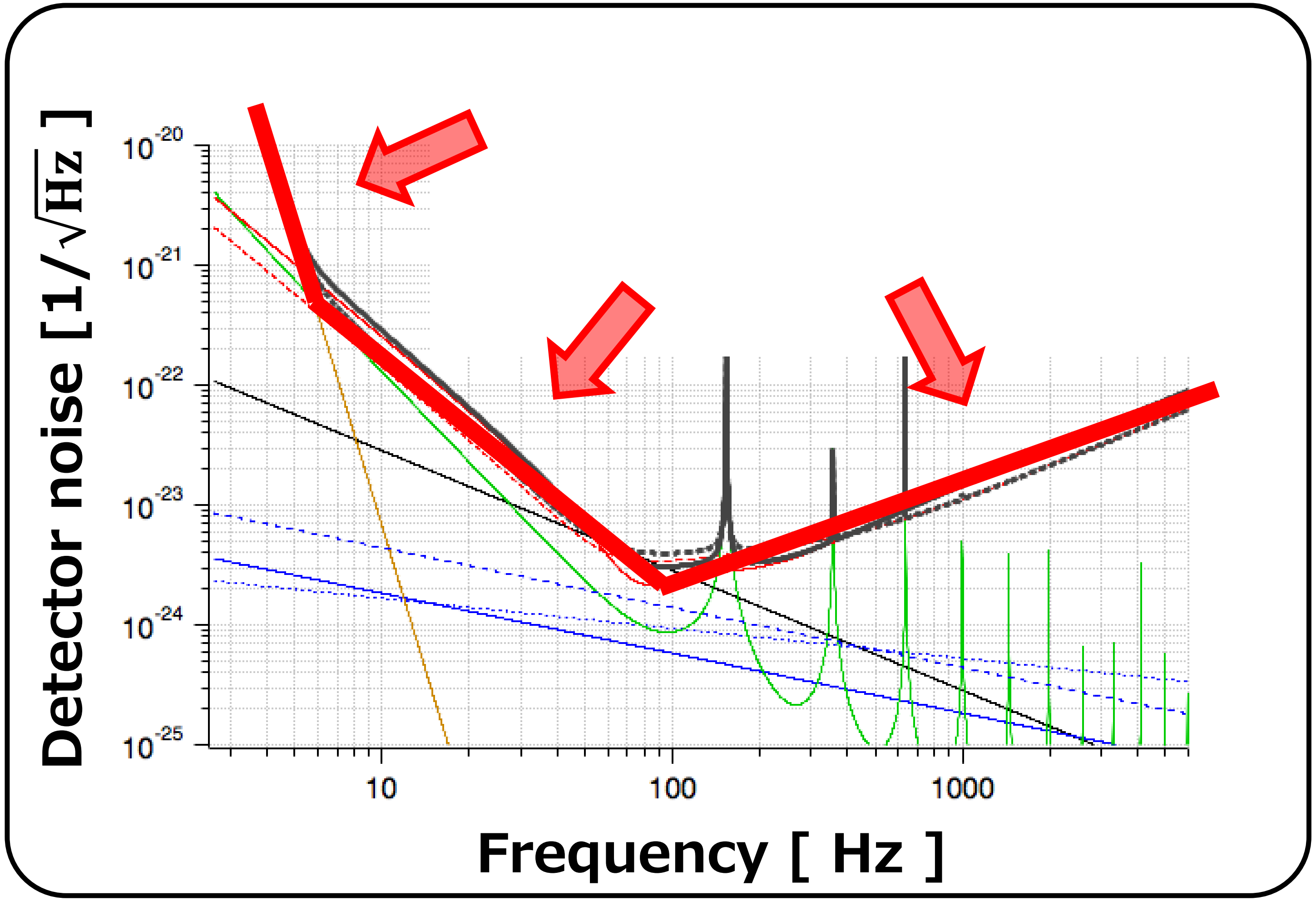
Source localization → detector development

We want ..

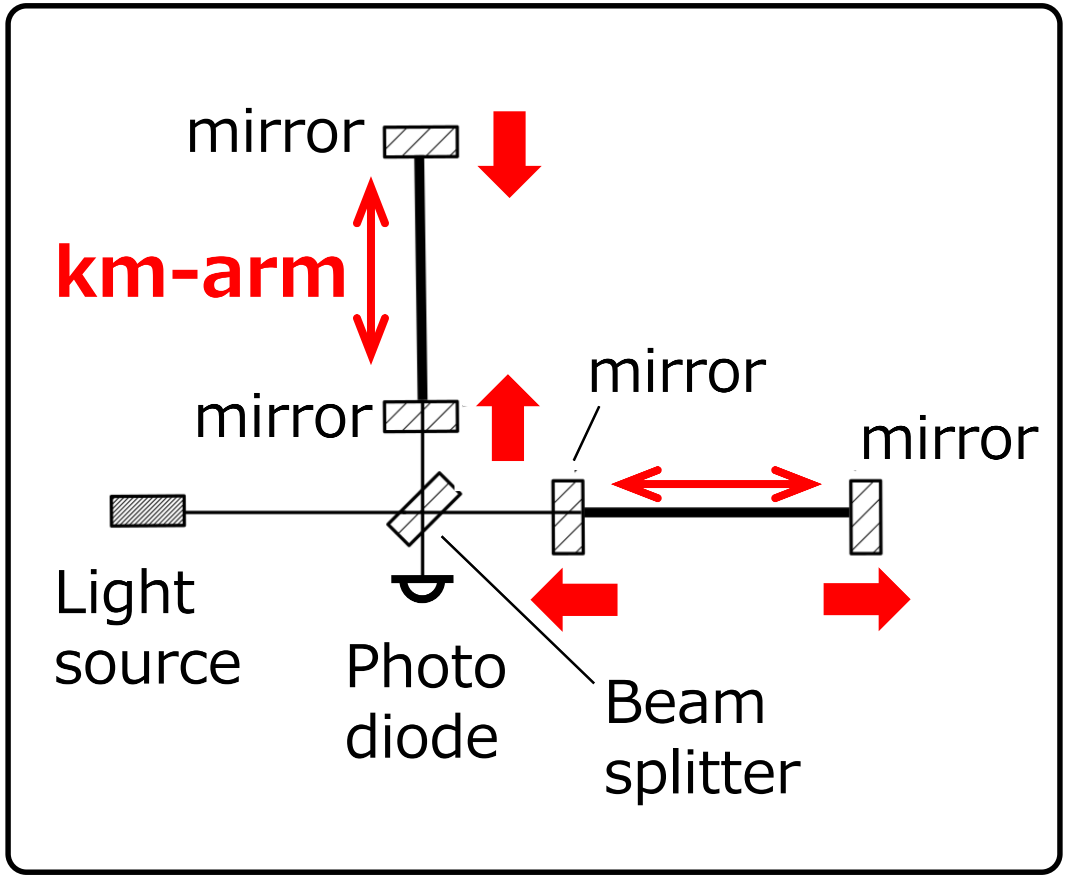


☆ : True position

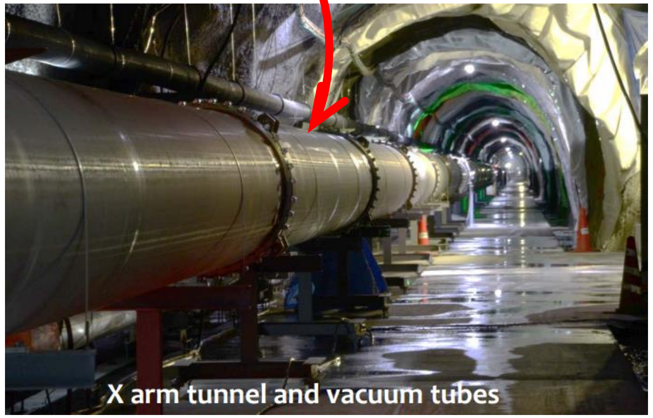
Necessary to improve sensitivity!



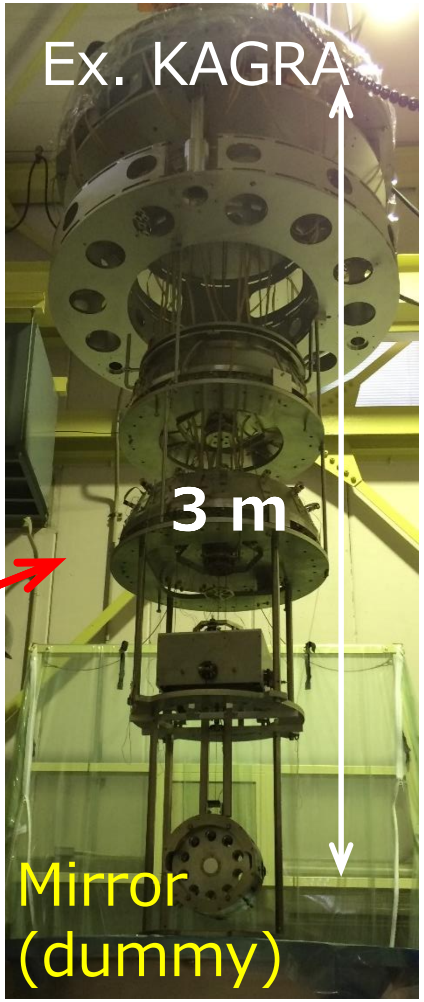
Gravitational wave detector



1) Michelson-based interferometer
2) Fabry-Perot cavities
3) km-arm



4) Suspended core optics



Detector noise

- Quantum noise
- Thermal noise

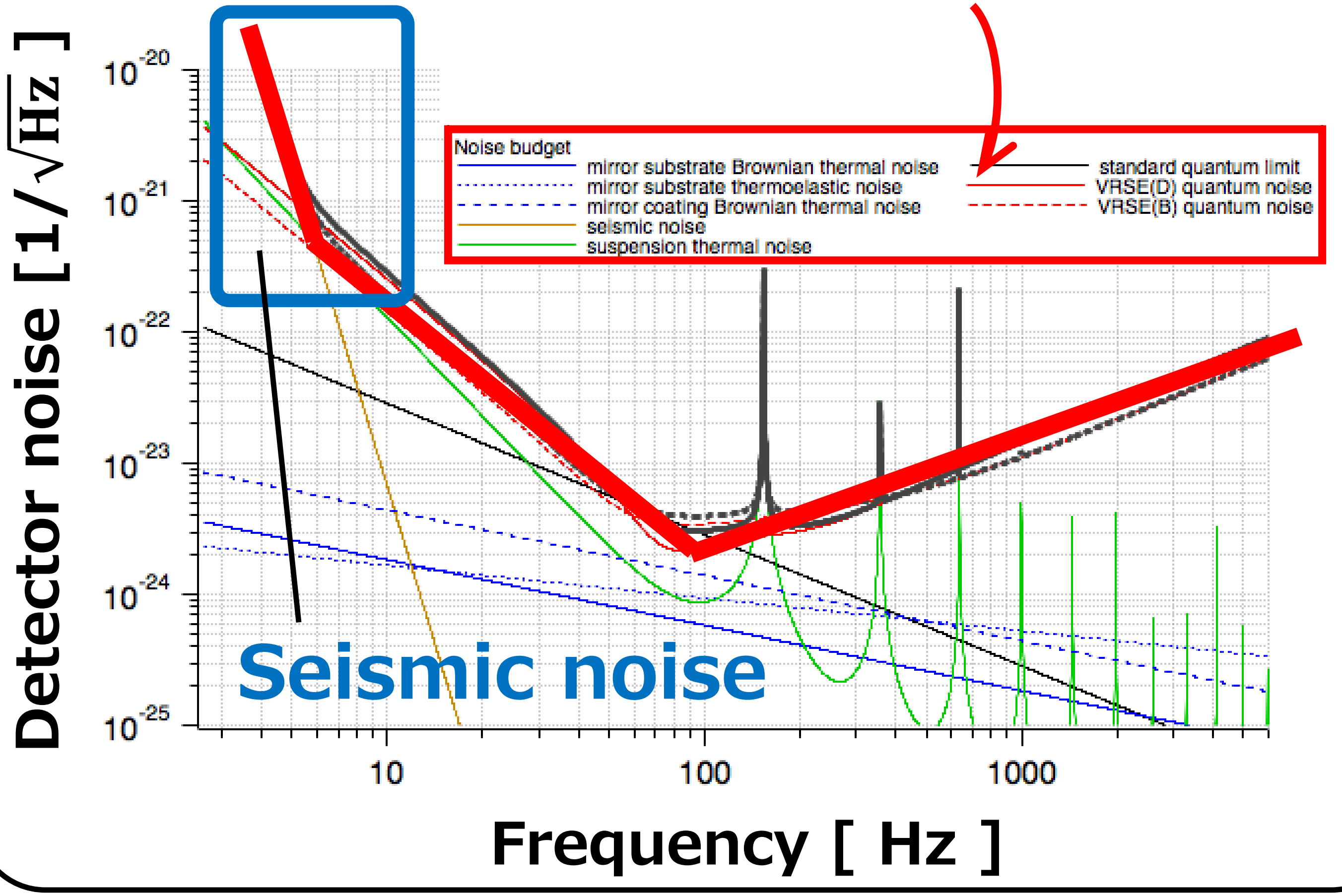
…

- **Seismic noise**

mirror oscillation

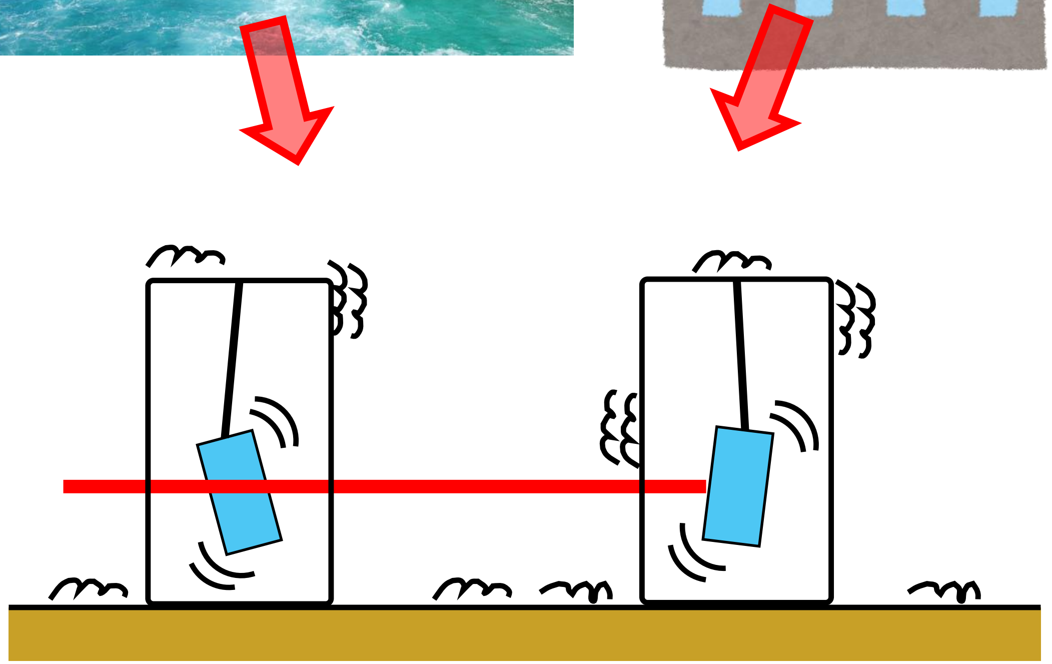
→ Necessary to suppress

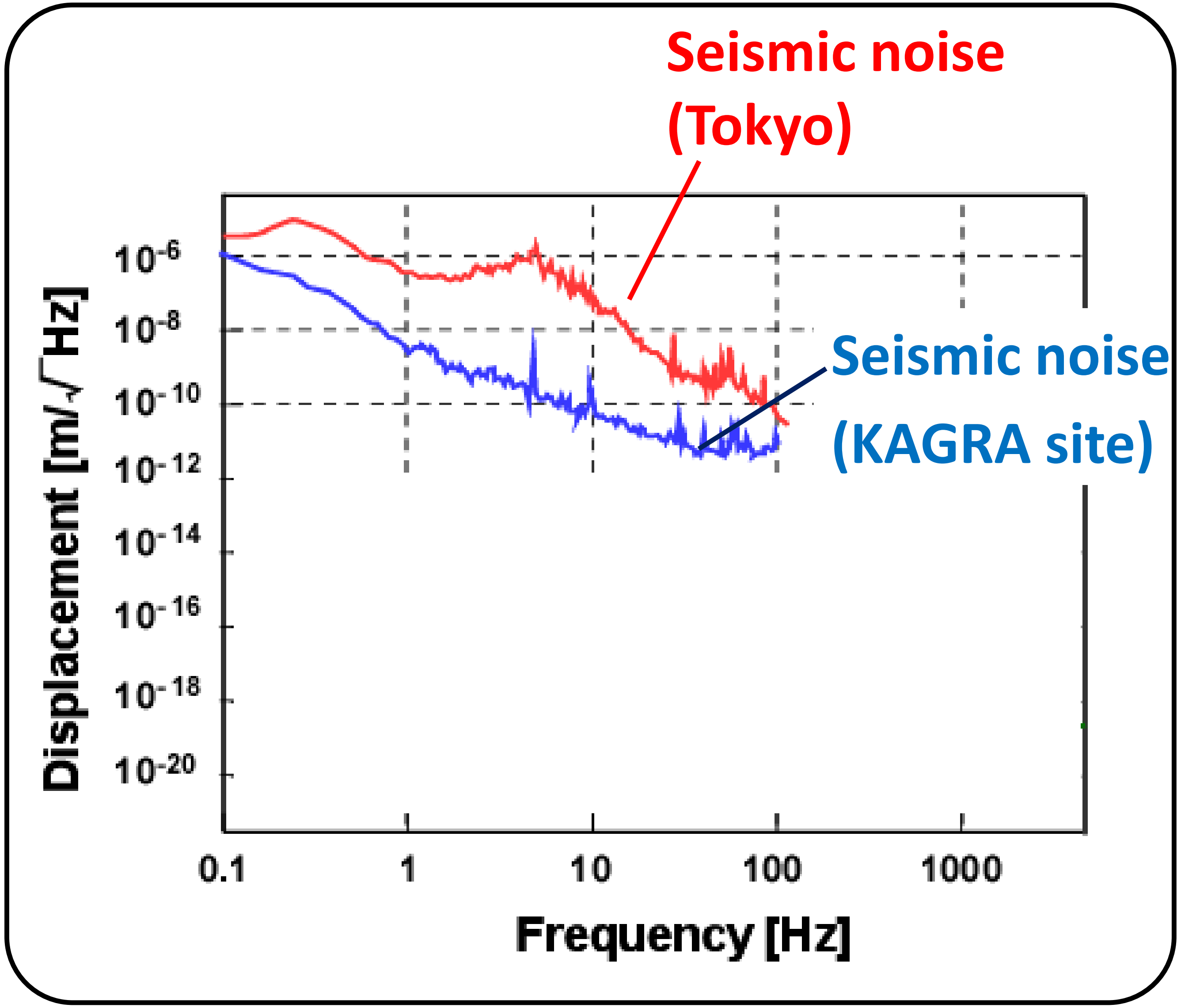
So many noise sources..



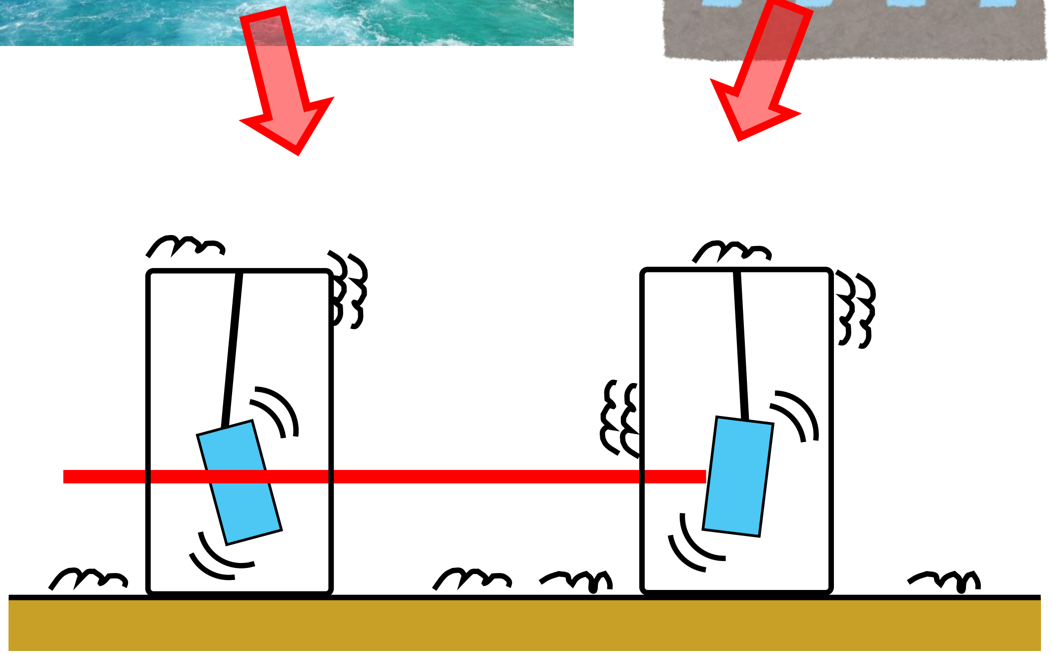
In case of KAGRA

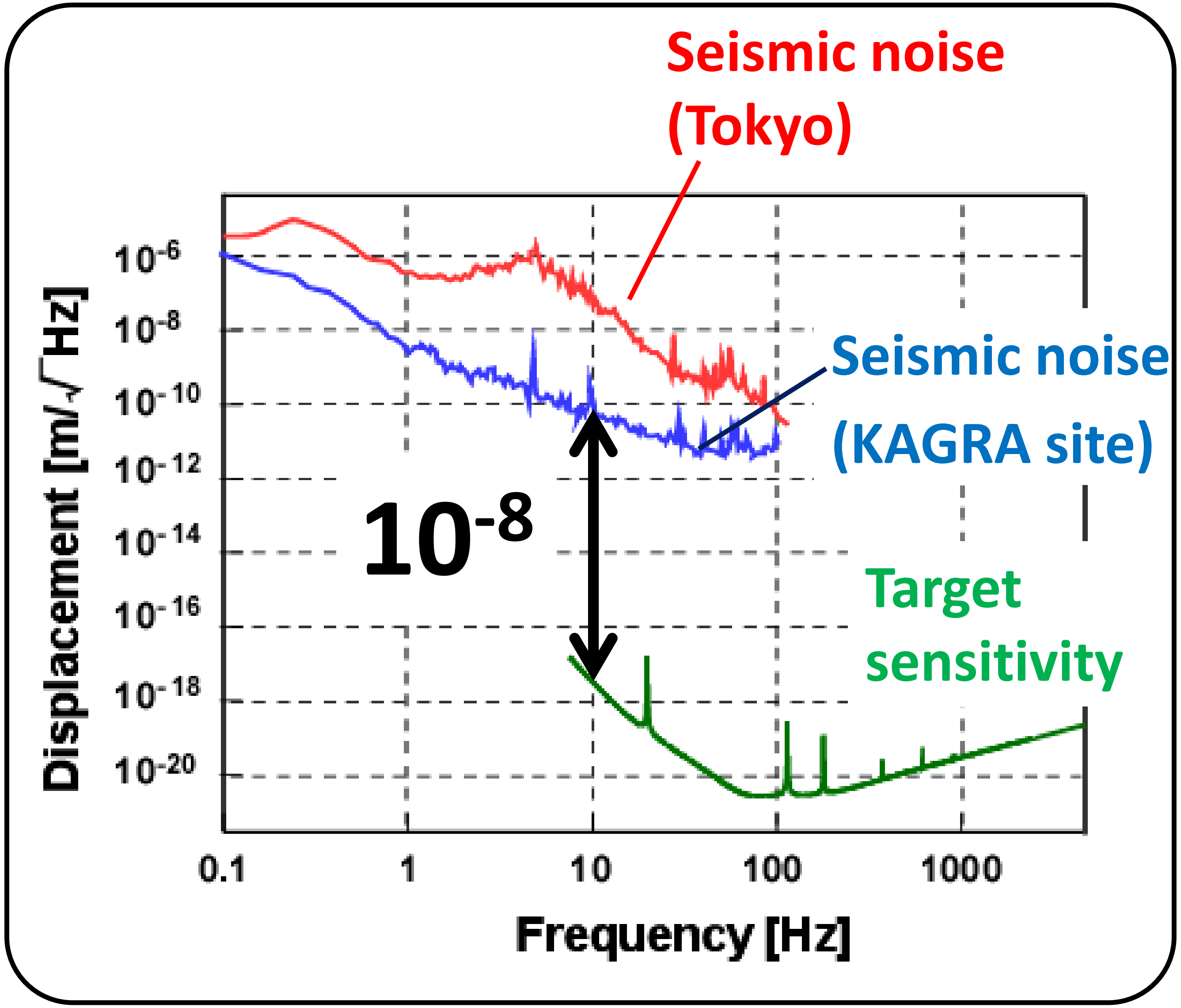
Seismic noise



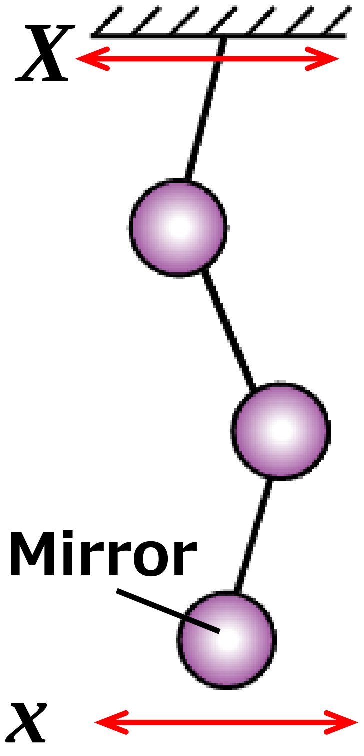


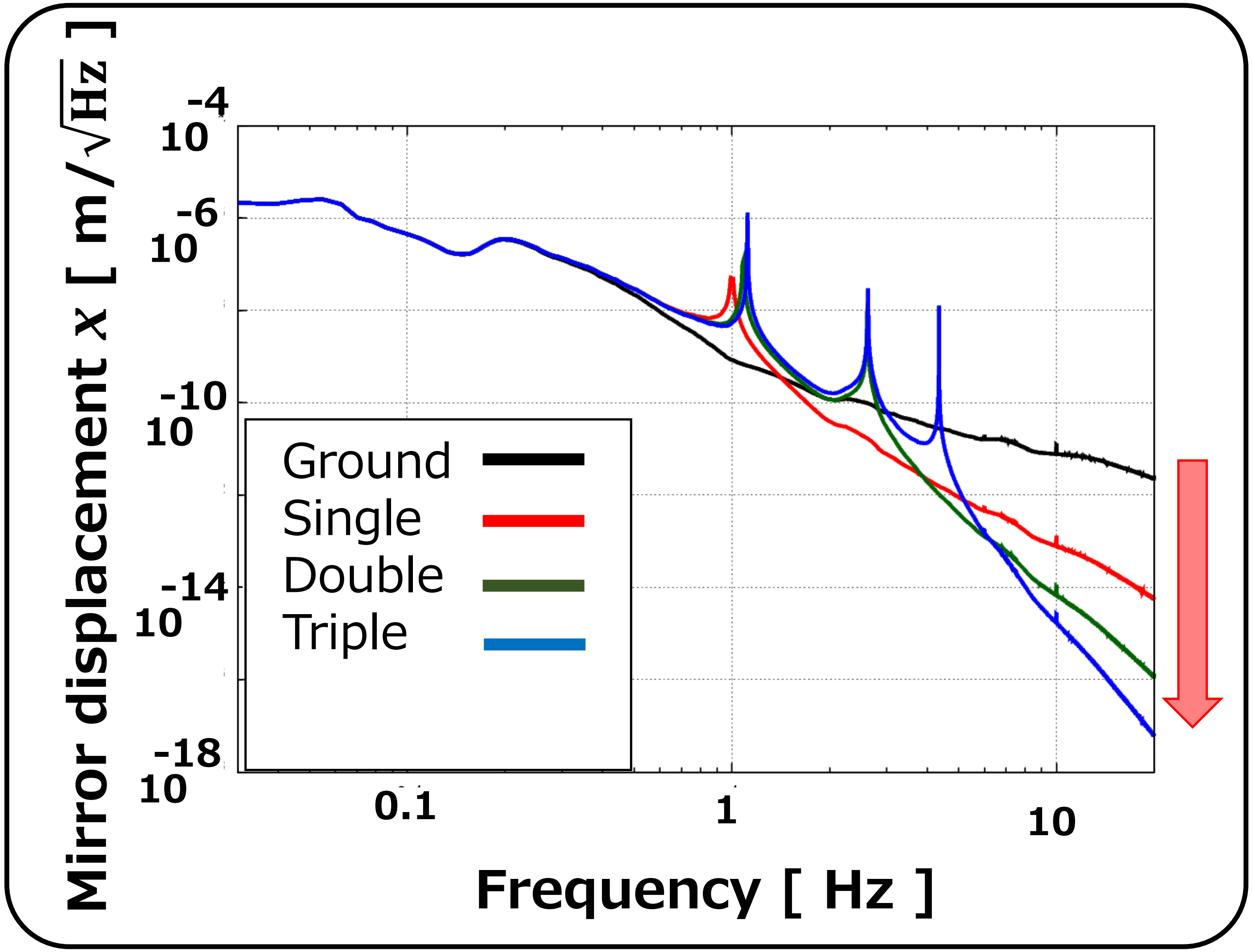
Seismic noise



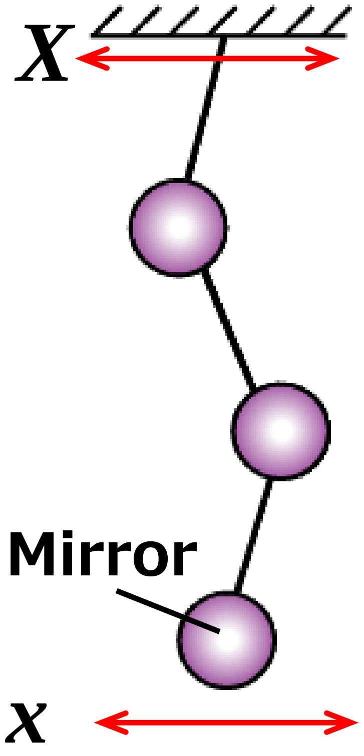


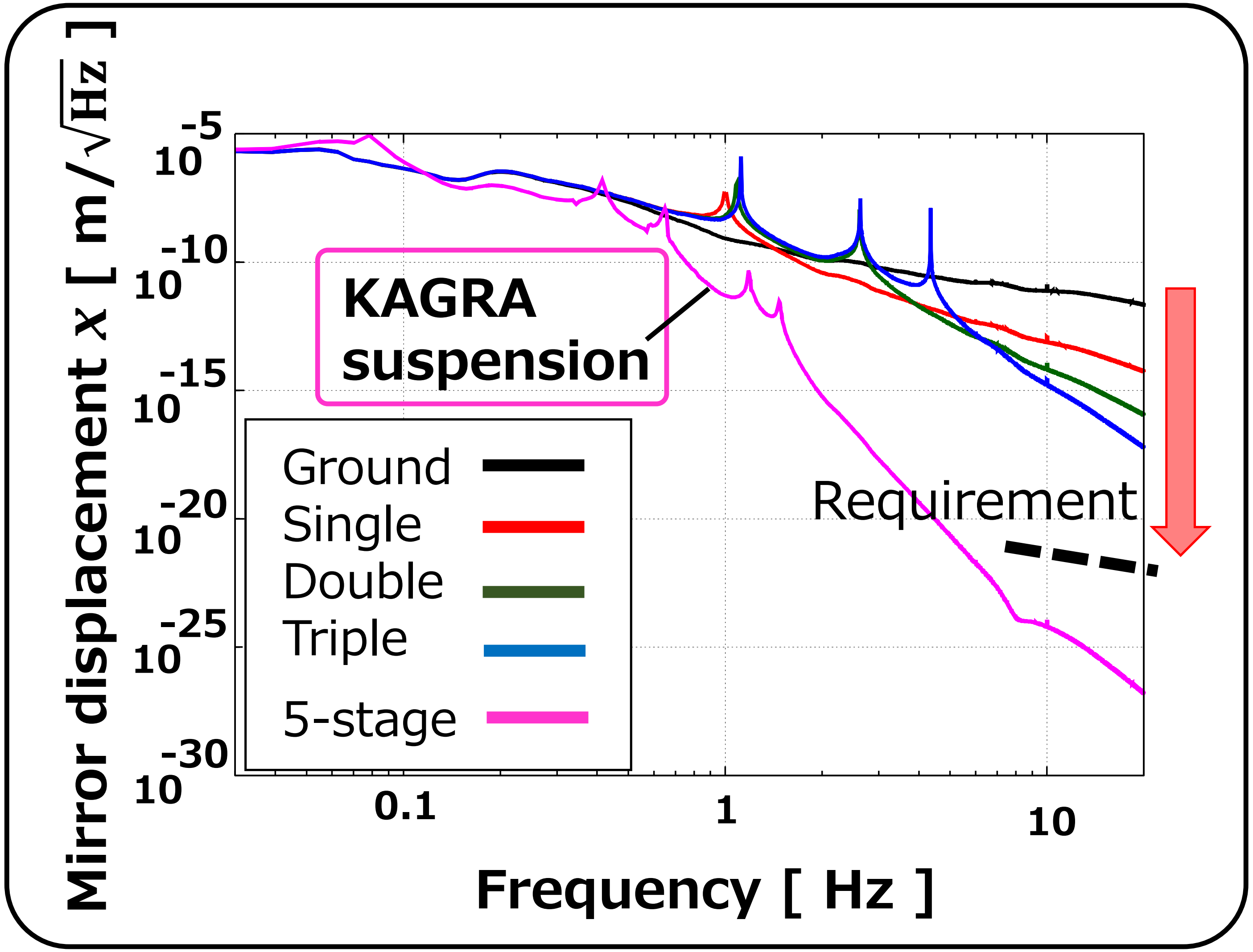
Seismic attenuation

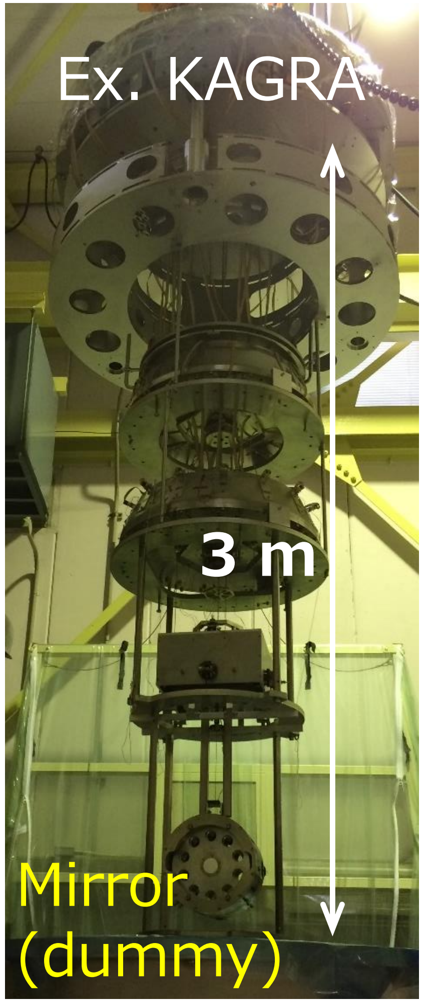




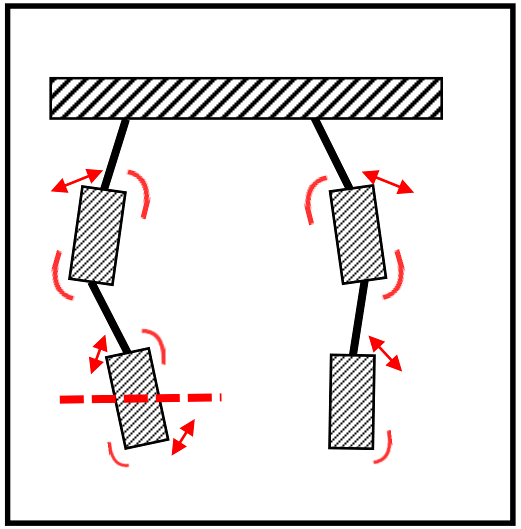
Seismic attenuation







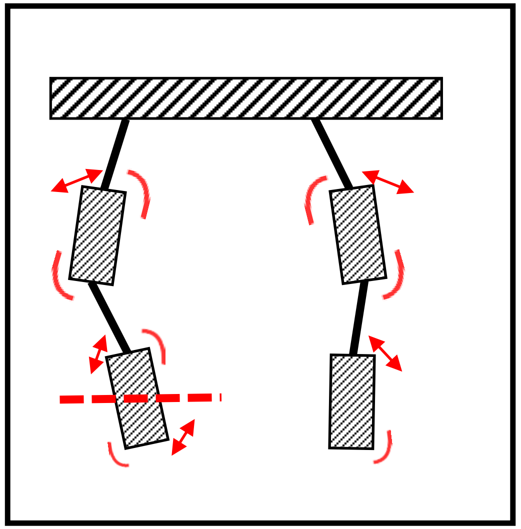
Resonance damping



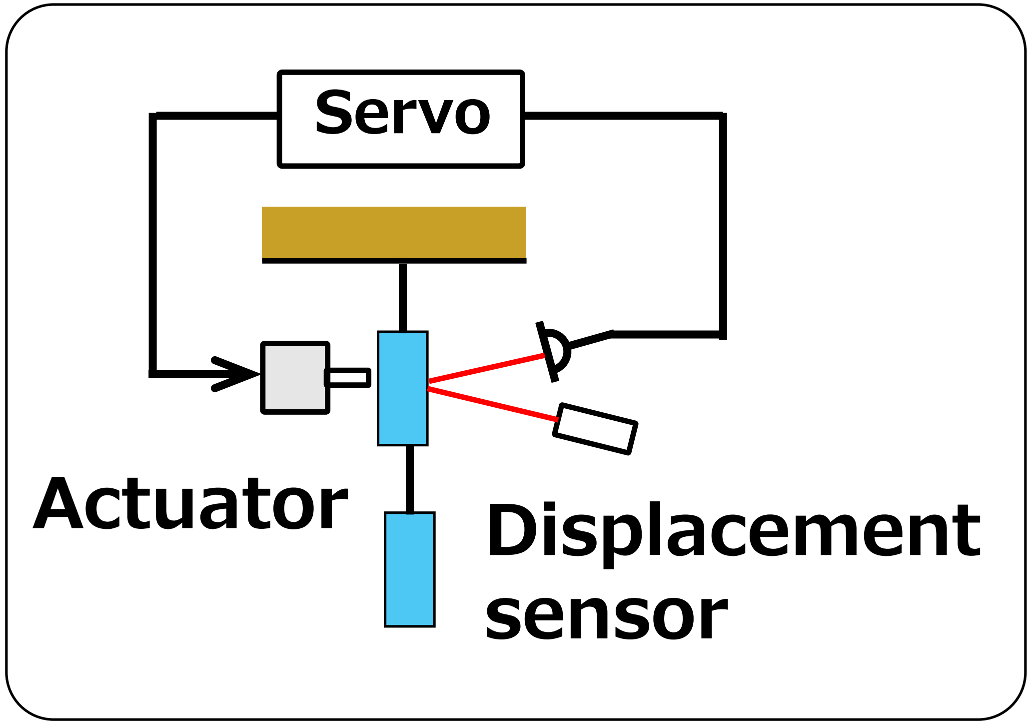
~~Starting interferometer operation~~

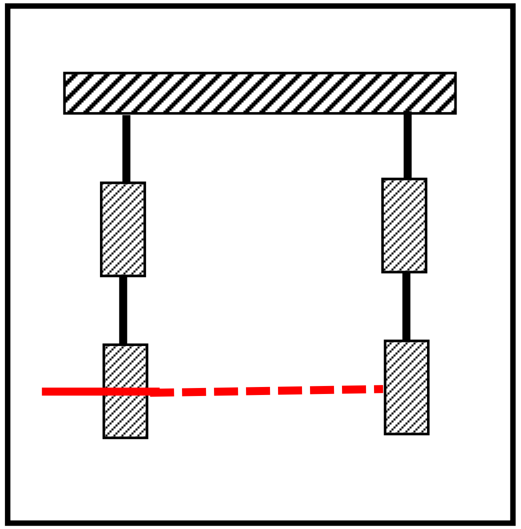
Resonance damping

→ *Active control*



~~Starting interferometer operation~~



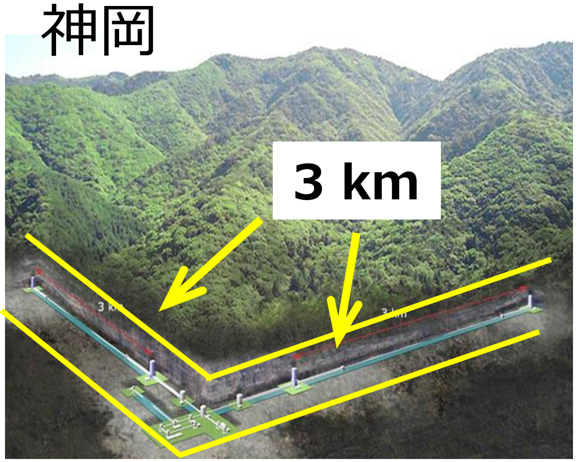


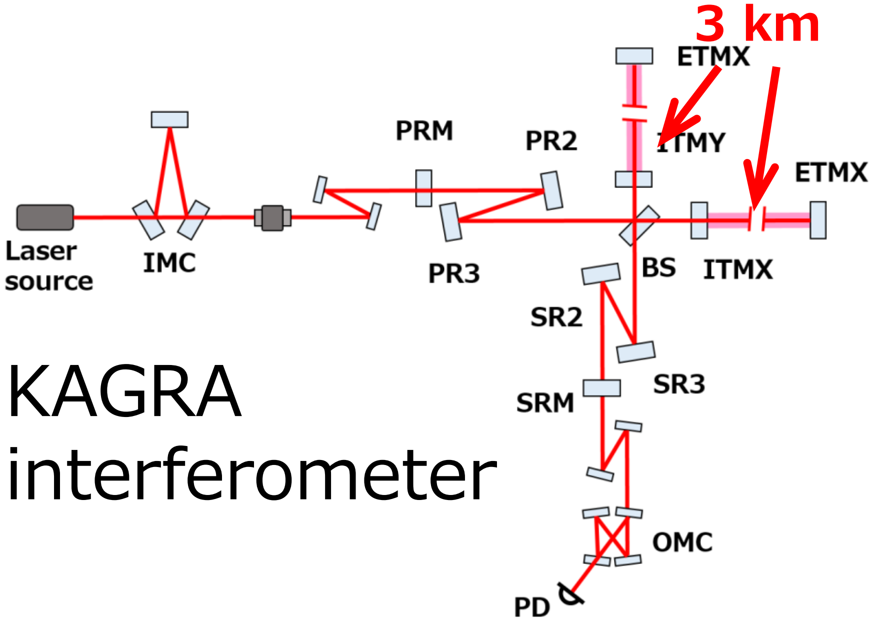
Stable interferometer operation

KAGRA project

KAGRA detector

1) Japanese detector
2) now being developed
3) underground





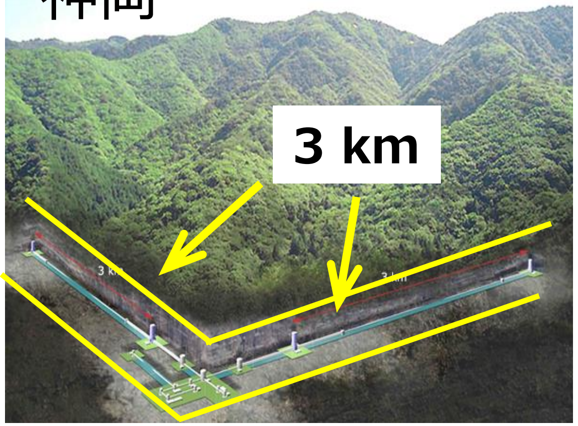
KAGRA interferometer

KAGRA project

KAGRA detector

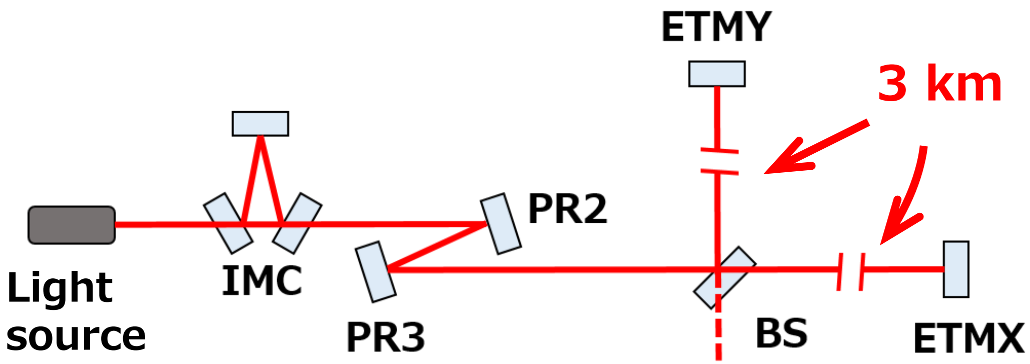
1) Japanese detector
2) now being developed
3) underground

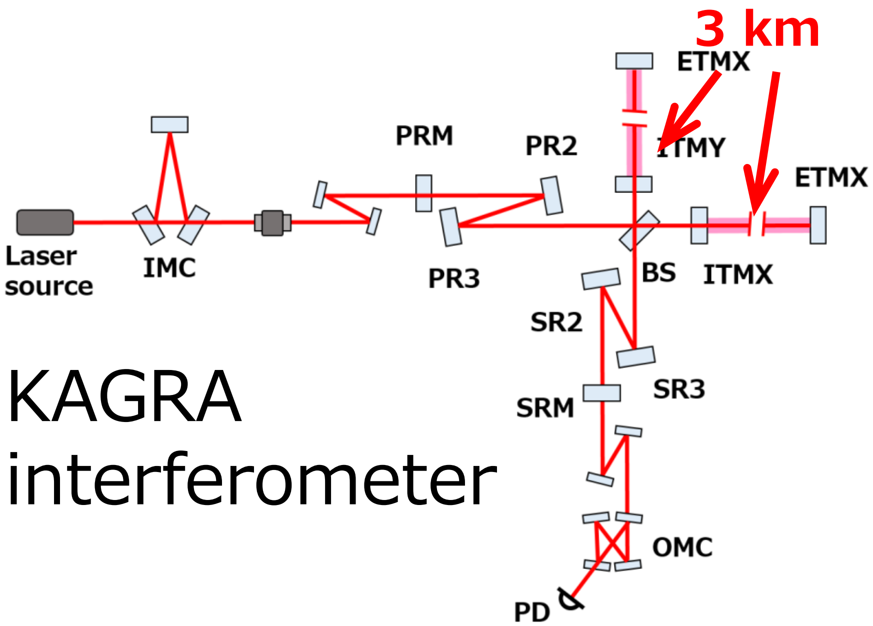
神岡



iKAGRA

1) test run in 2016
2) Simple interferometer



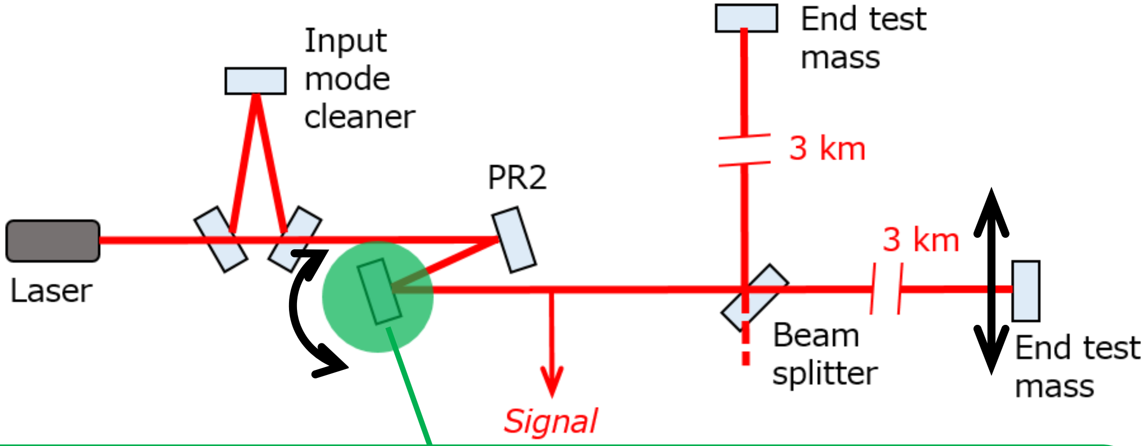


KAGRA interferometer

iKAGRA suspension development

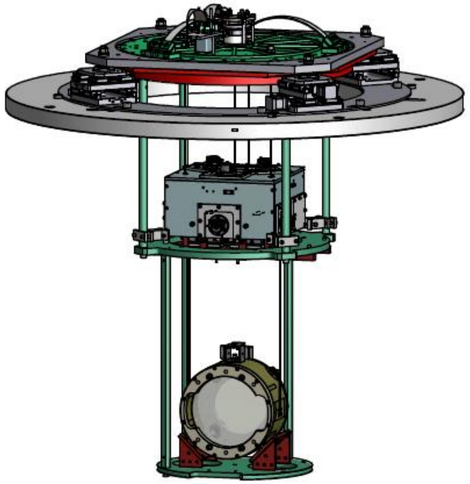
Development work:

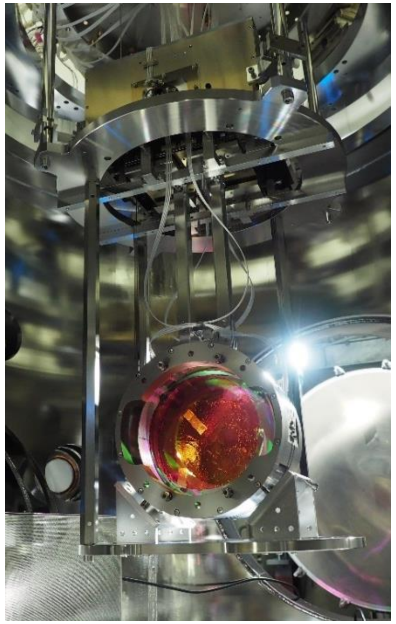
1) Assembly
2) Measurement
3) Upgrade for final phase



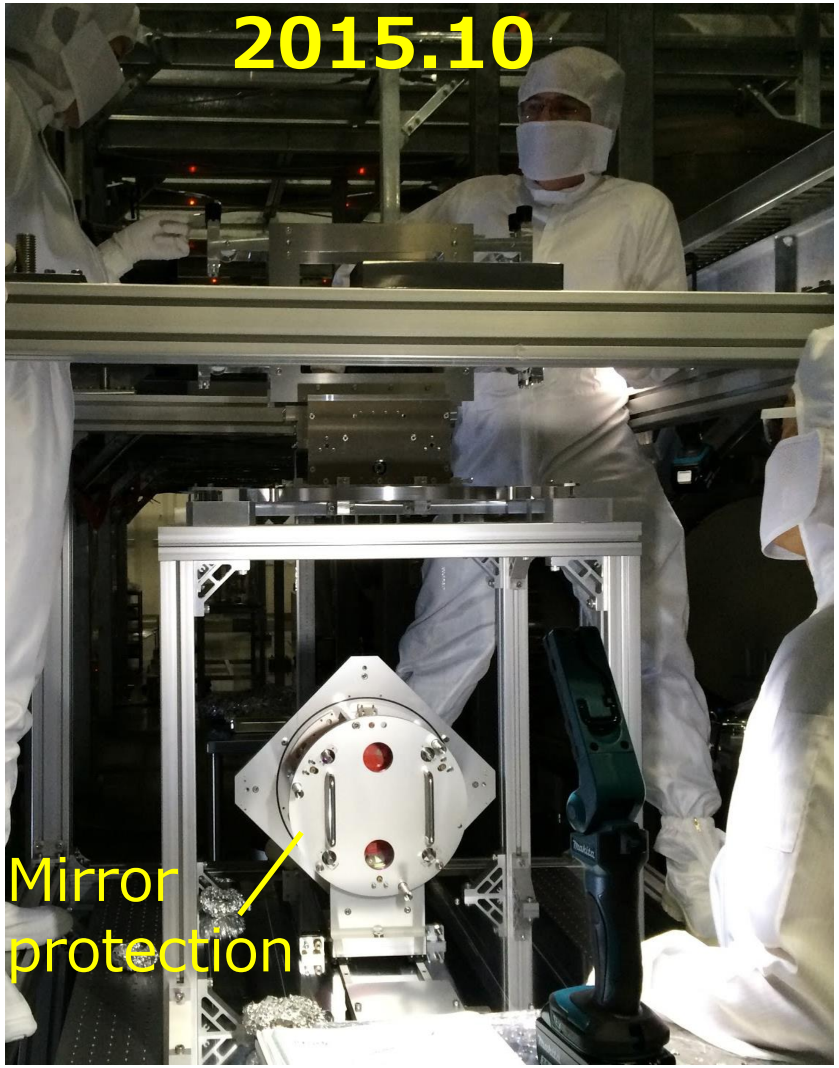
iKAGRA suspension:

Alignment mirror of iKAGRA
for initial alignment
for stable operation.

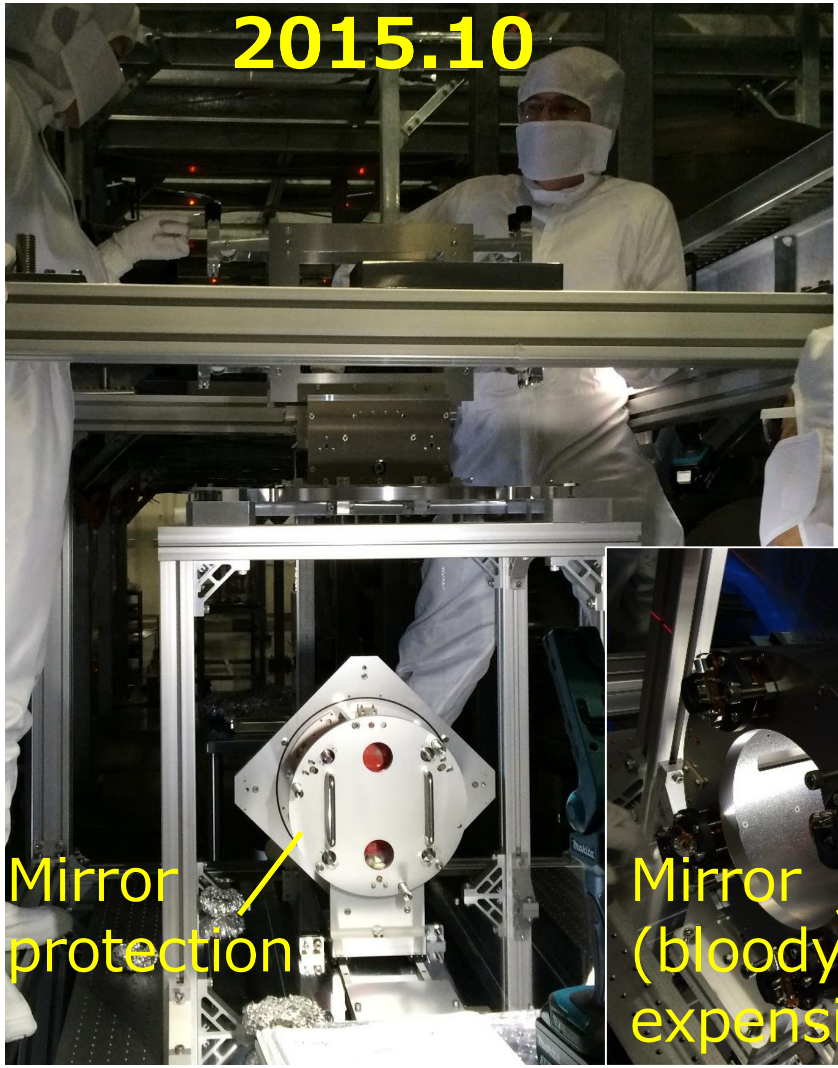


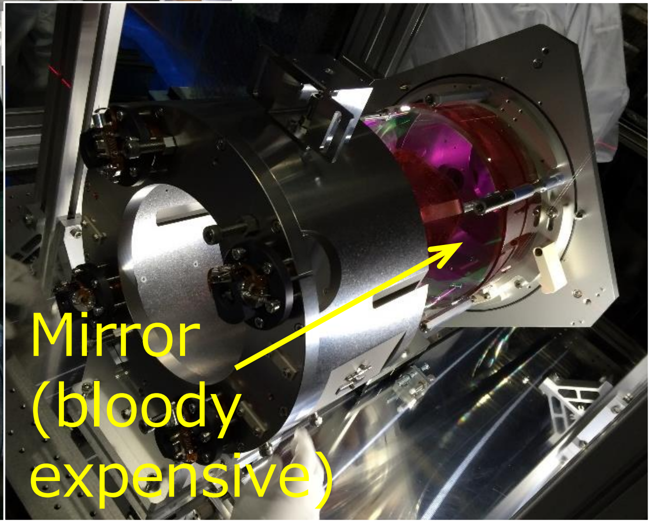


Assembly

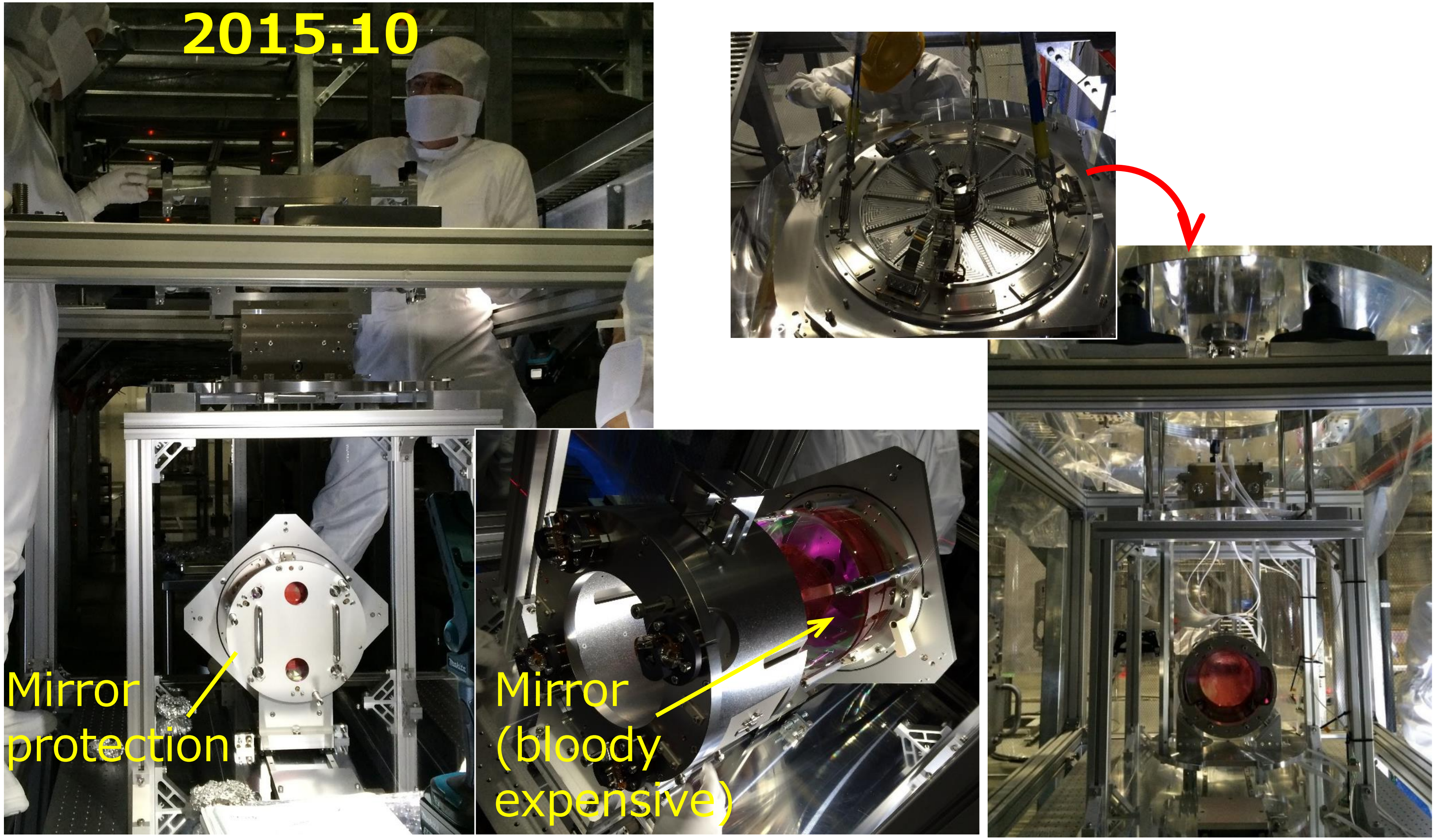


Assembly

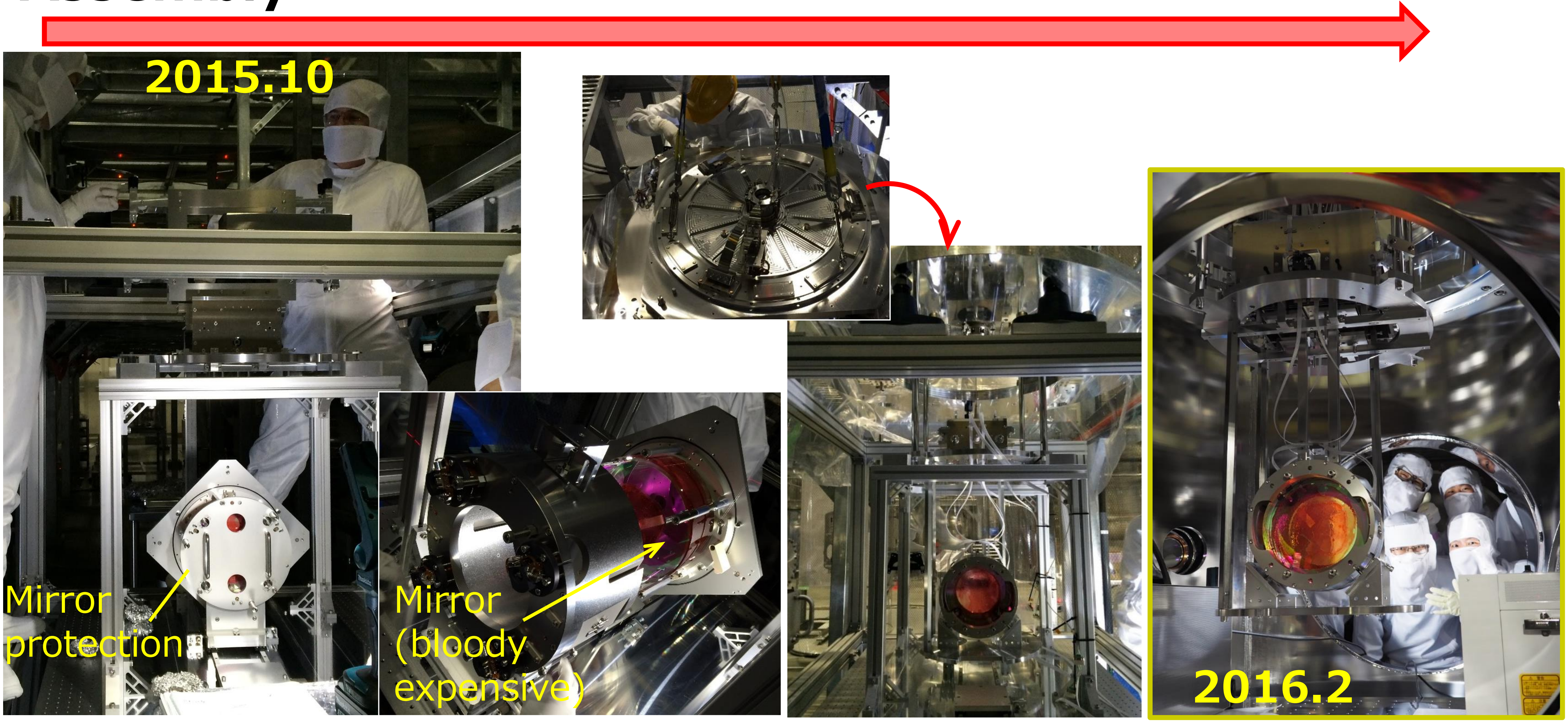




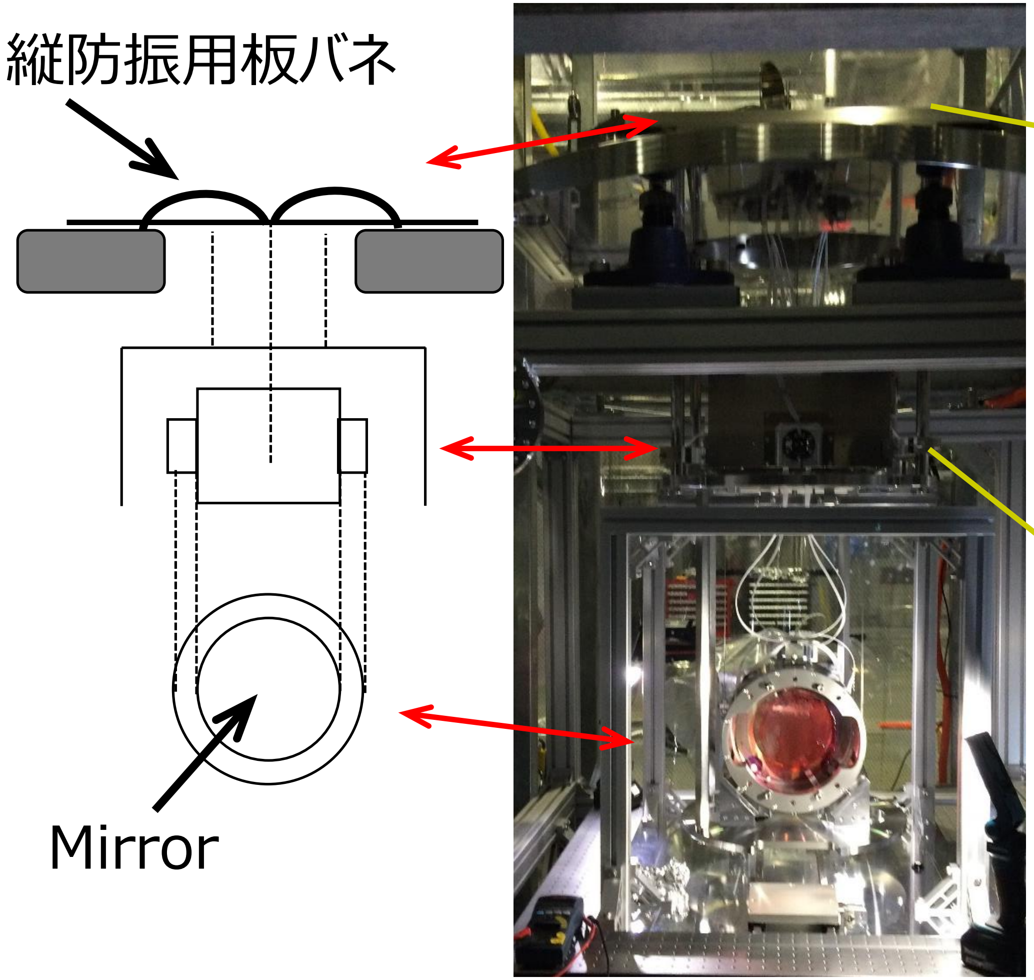
Assembly



Assembly

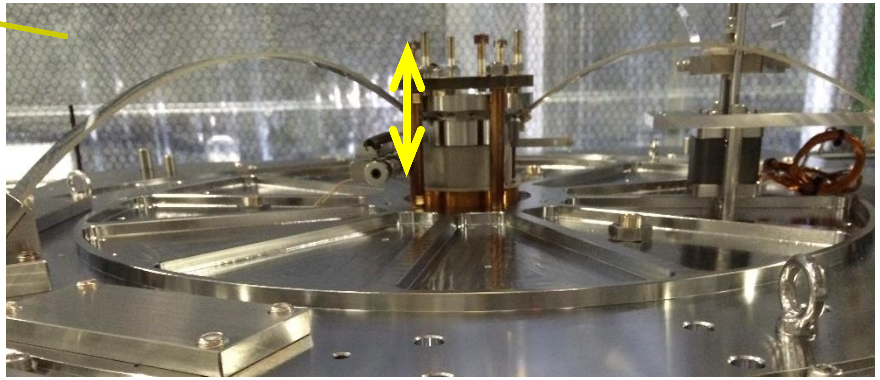


Sensors and actuators

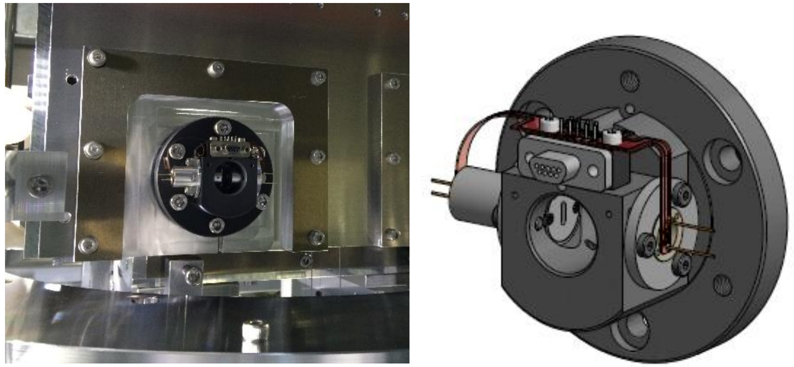


iKAGRA suspension

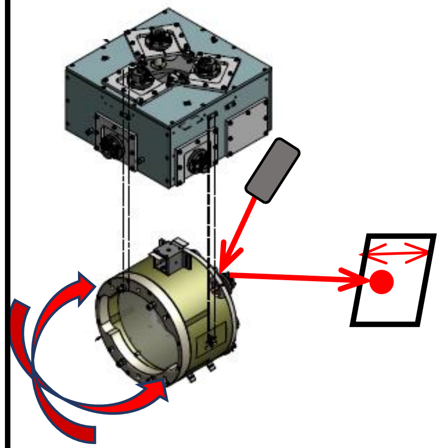
Displacement sensor and coil-magnet actuator 1



Displacement sensor and coil-magnet actuator 2

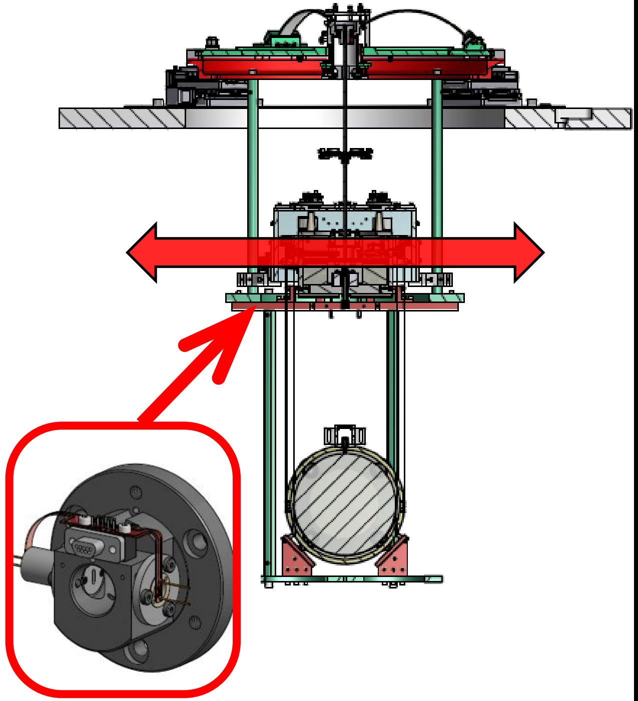


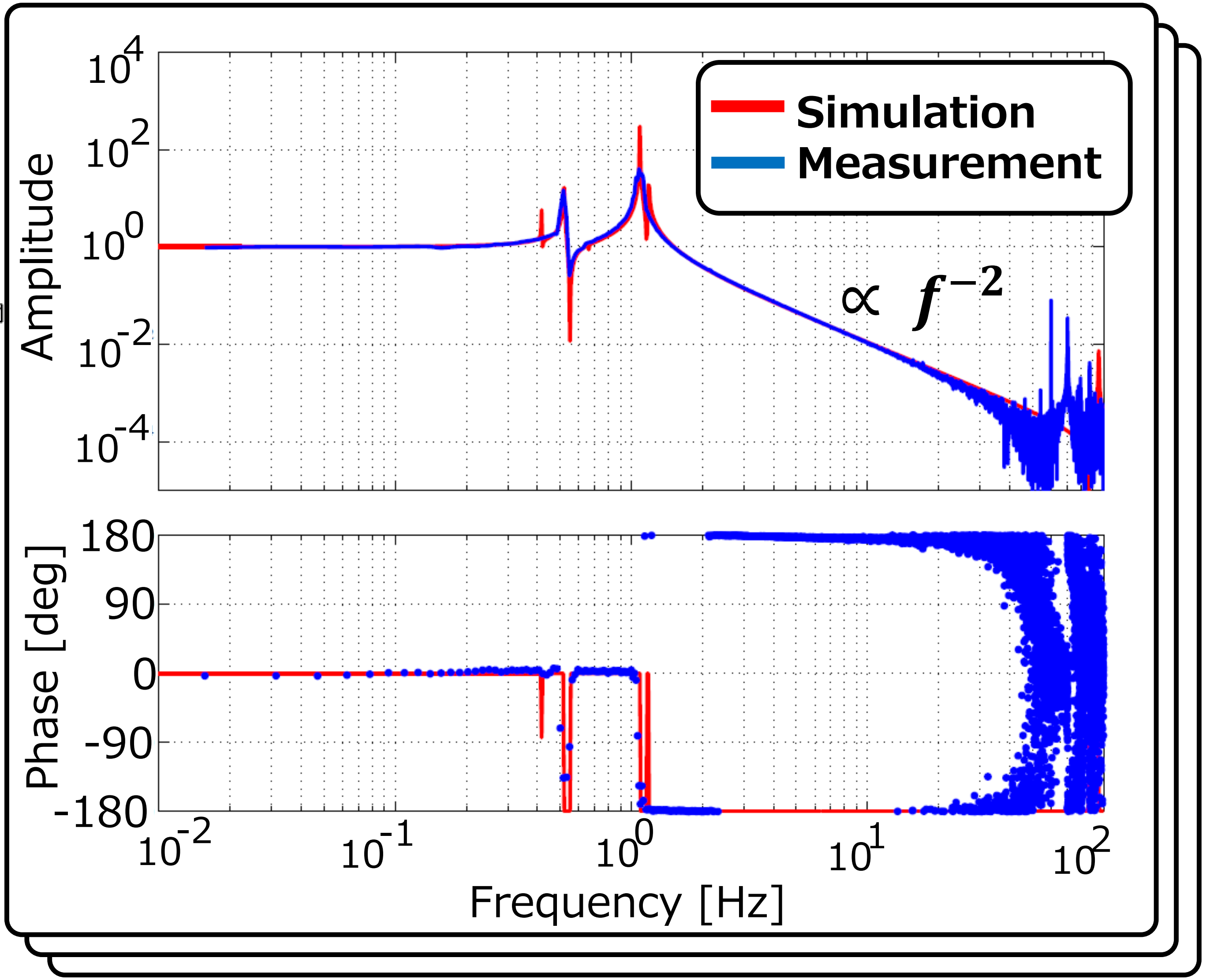
Angular sensor



1. Frequency response

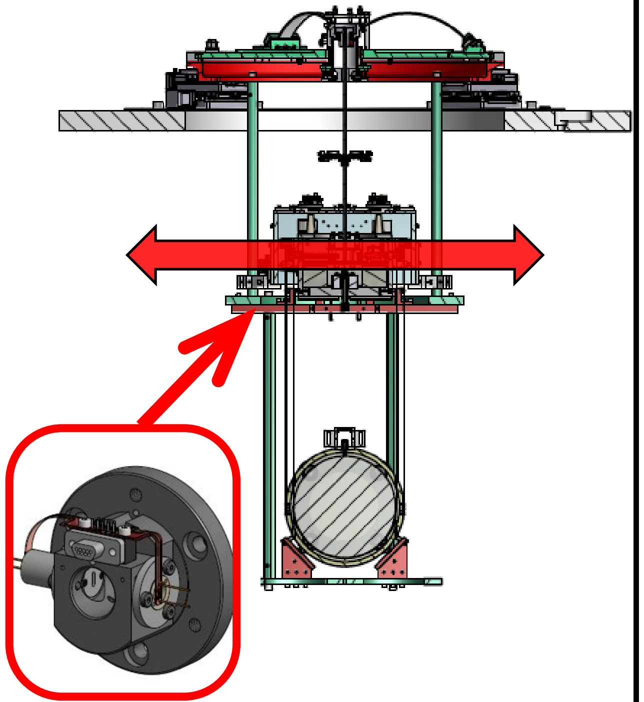
For each Components:

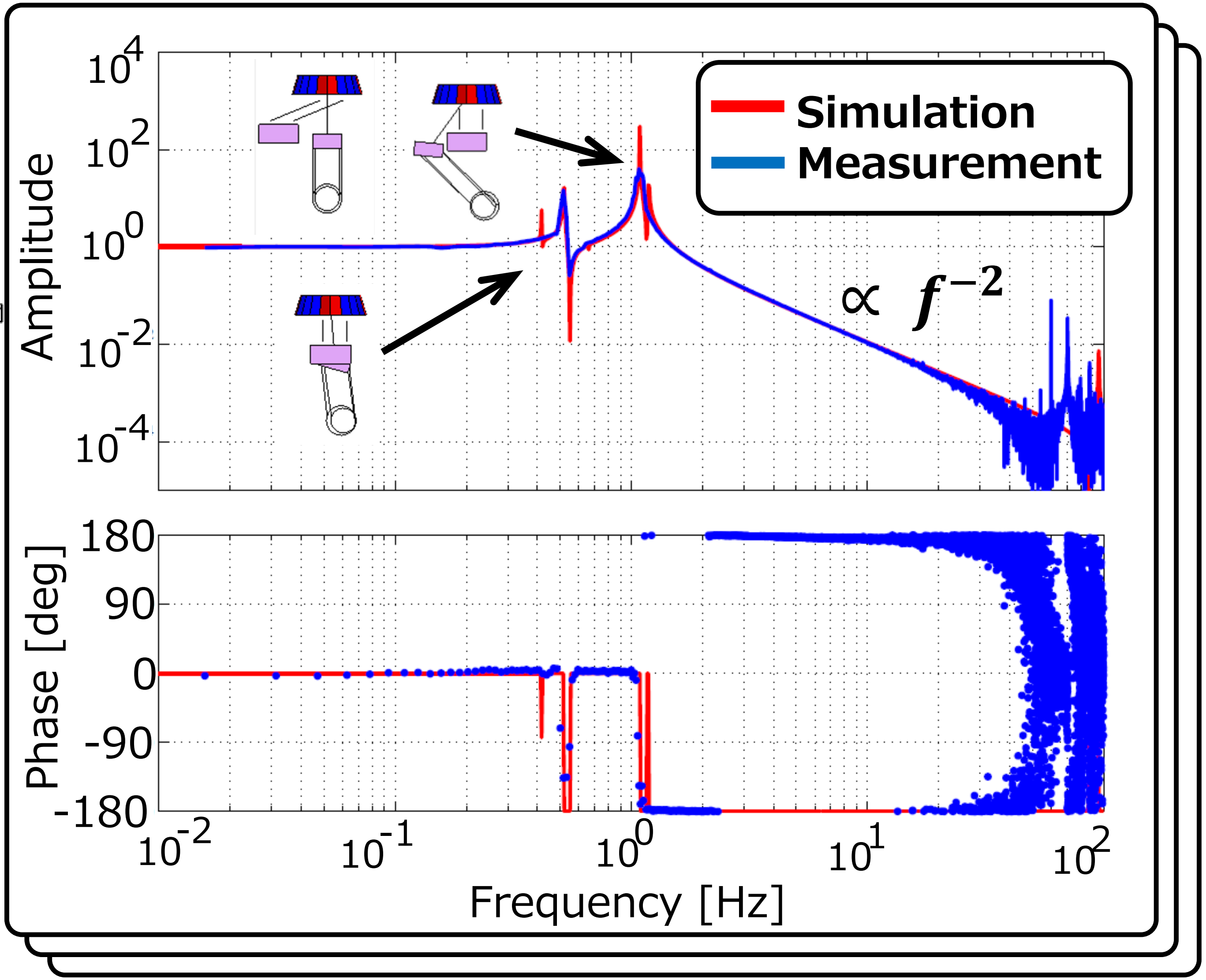




1. Frequency response

For each Components:





1)Measurement

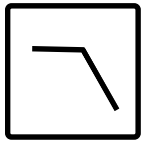
→ *Consistent with Simulation*

2) Components

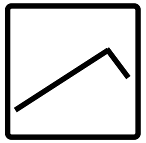
→ *Pendulum*

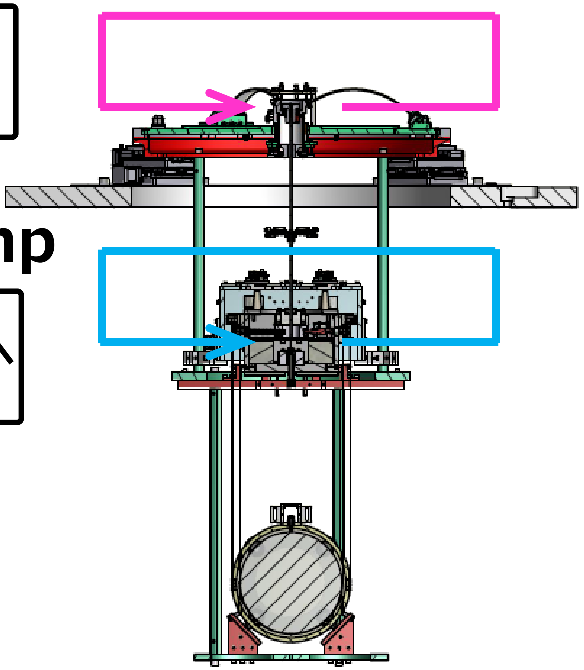
2. Decay time

DC

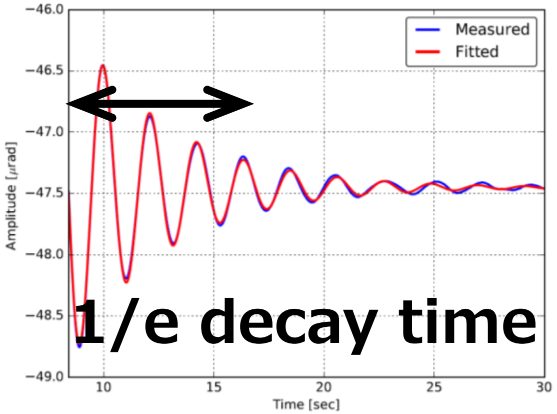


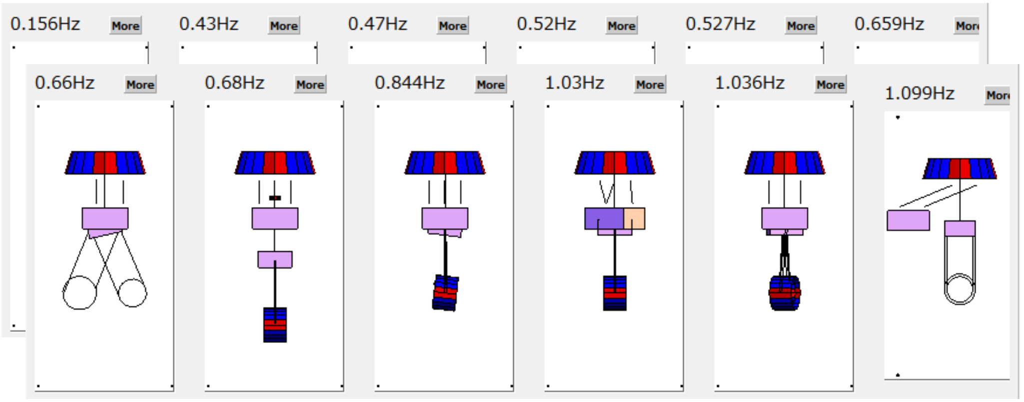
Damp



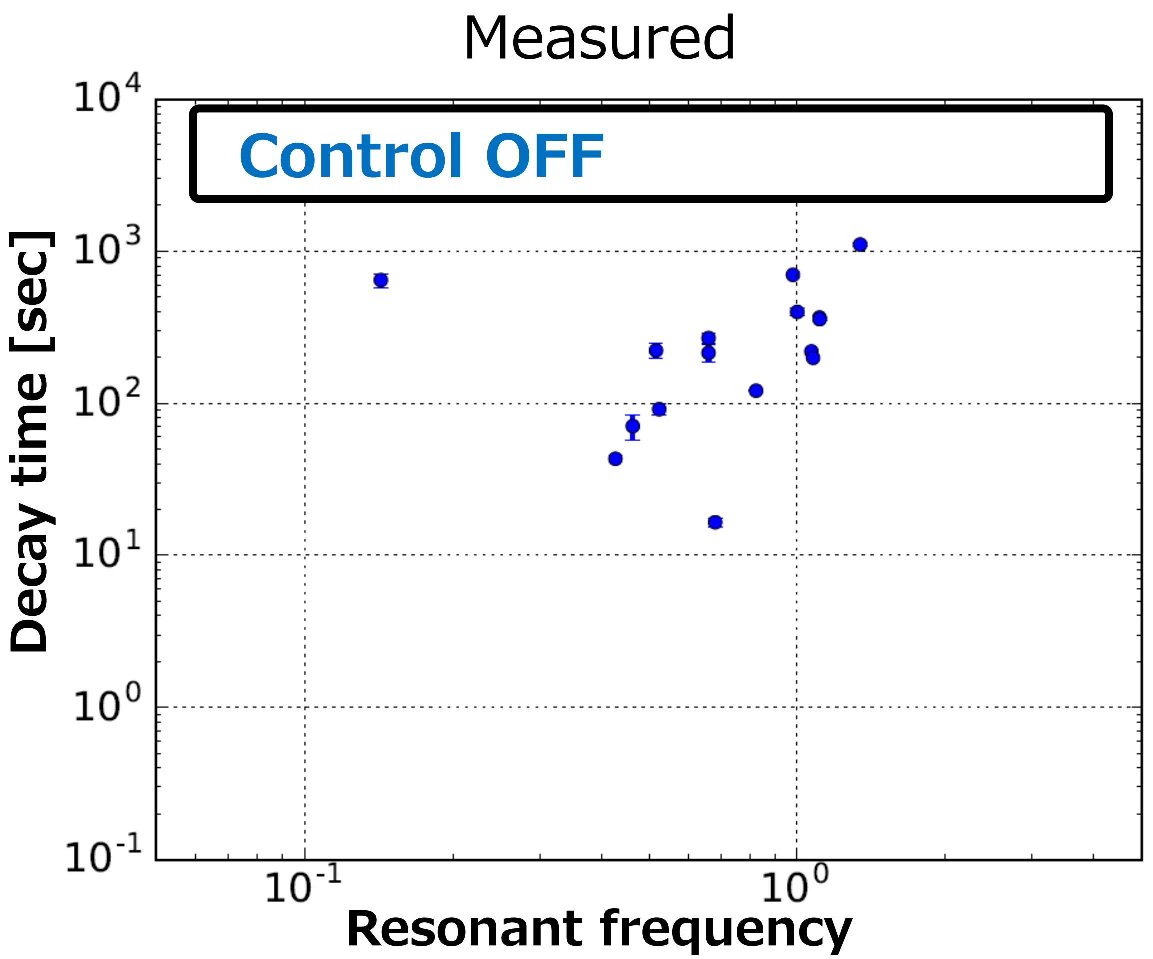


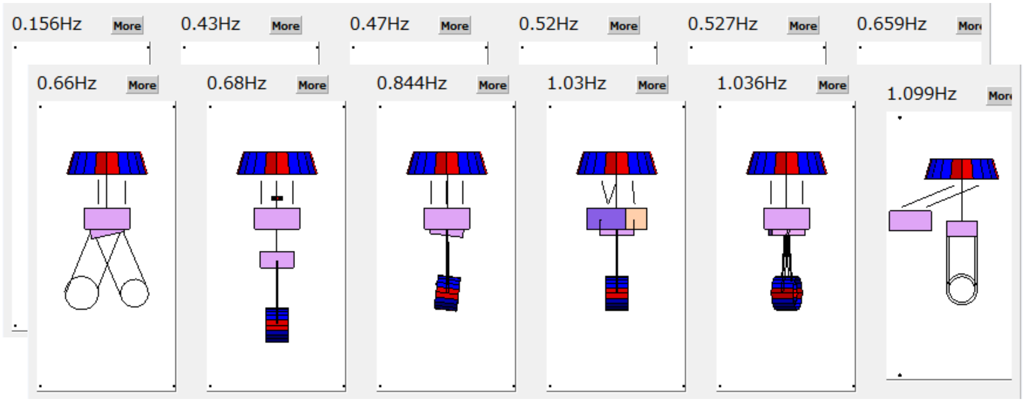
For damping resonances

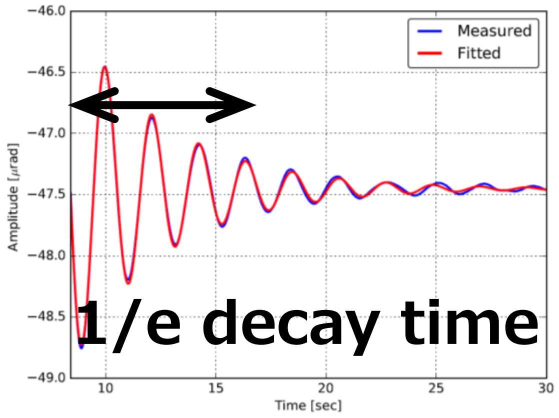




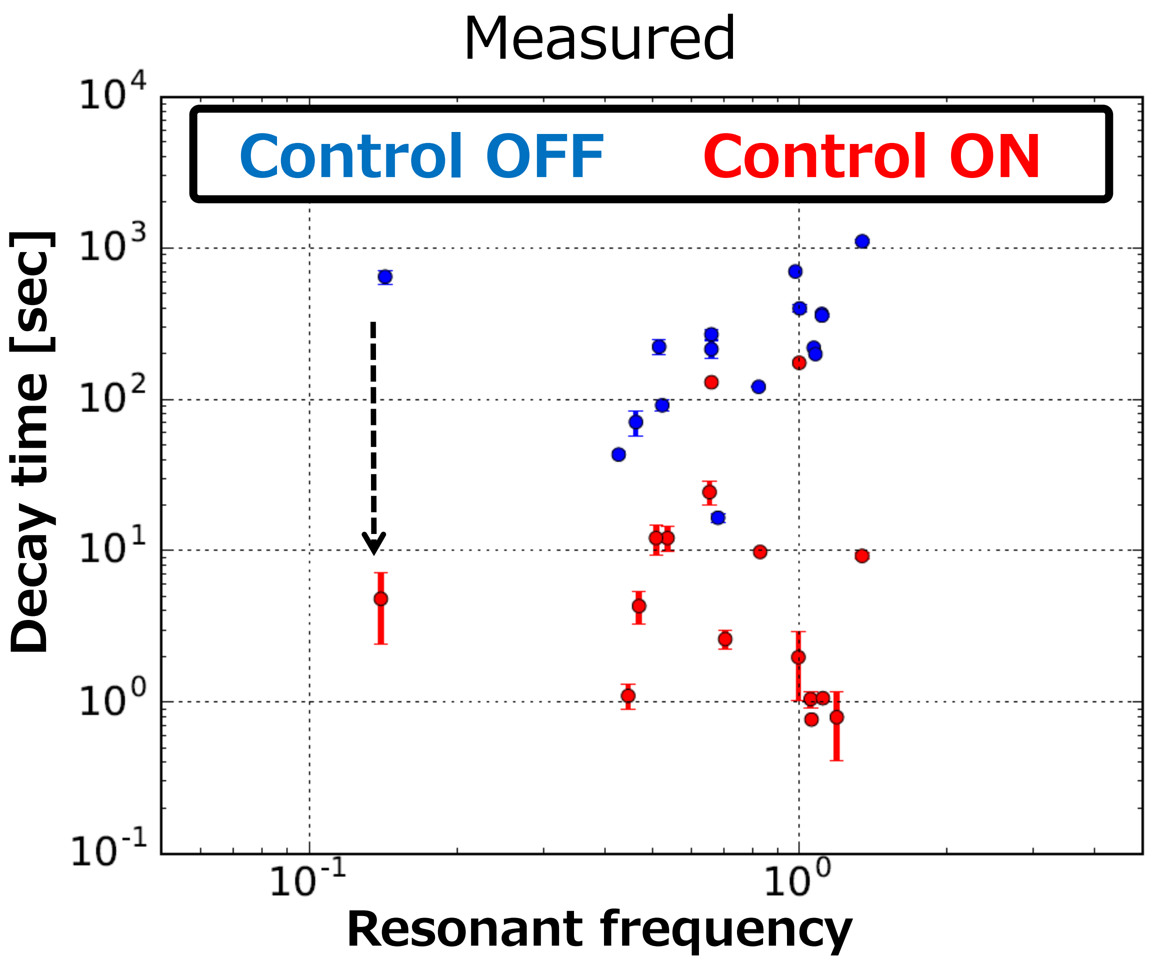
2. Decay time without damping

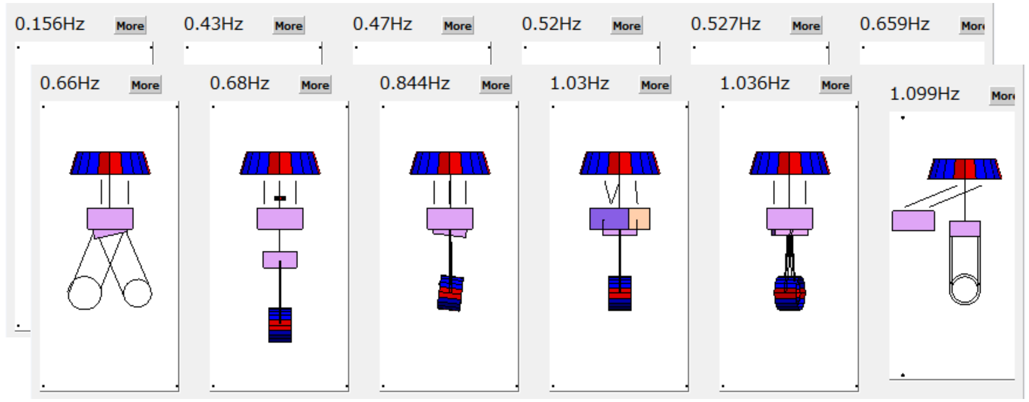


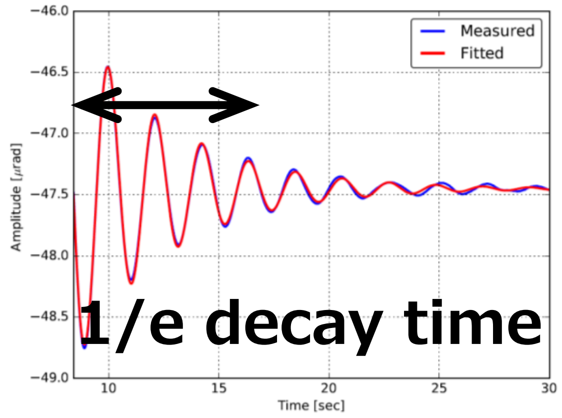




2. Decay time with damping

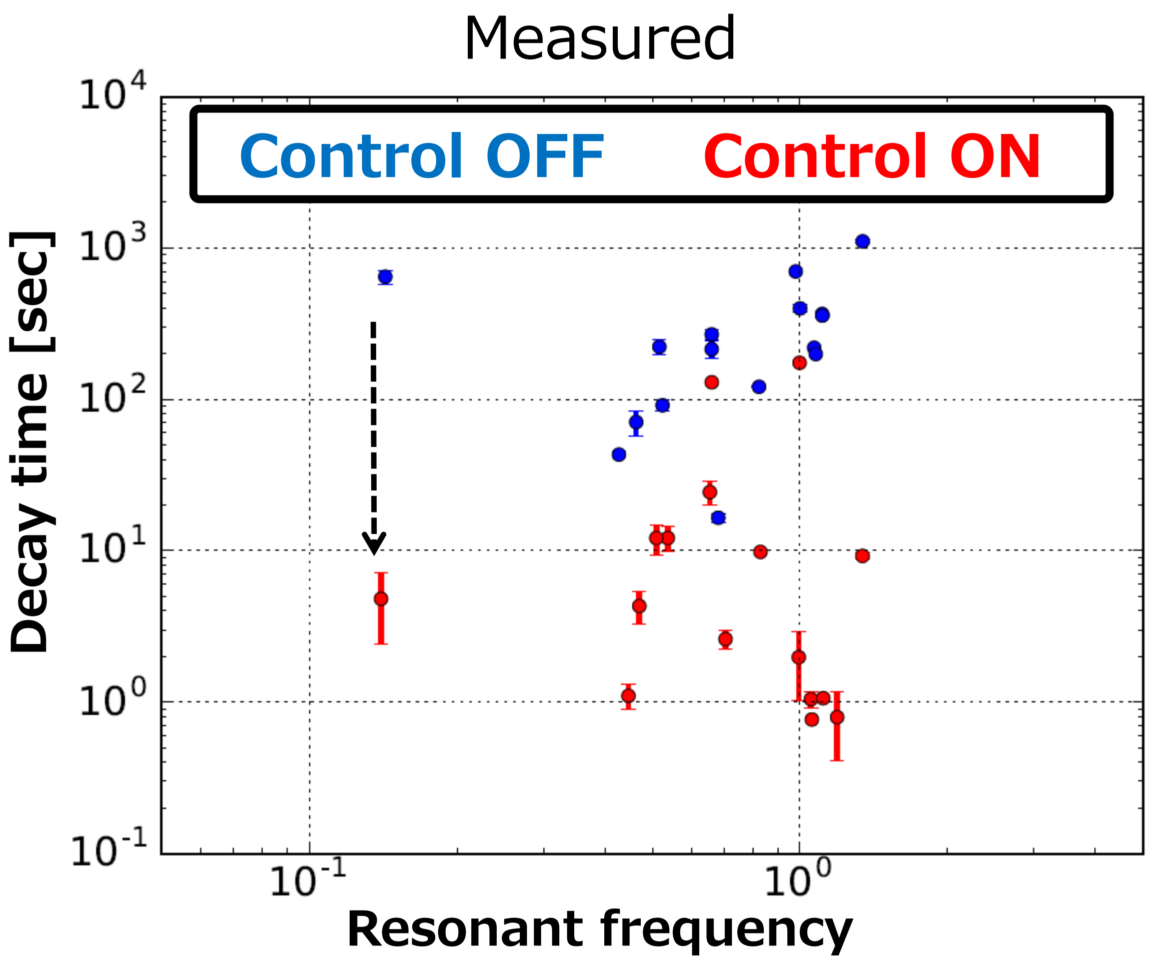


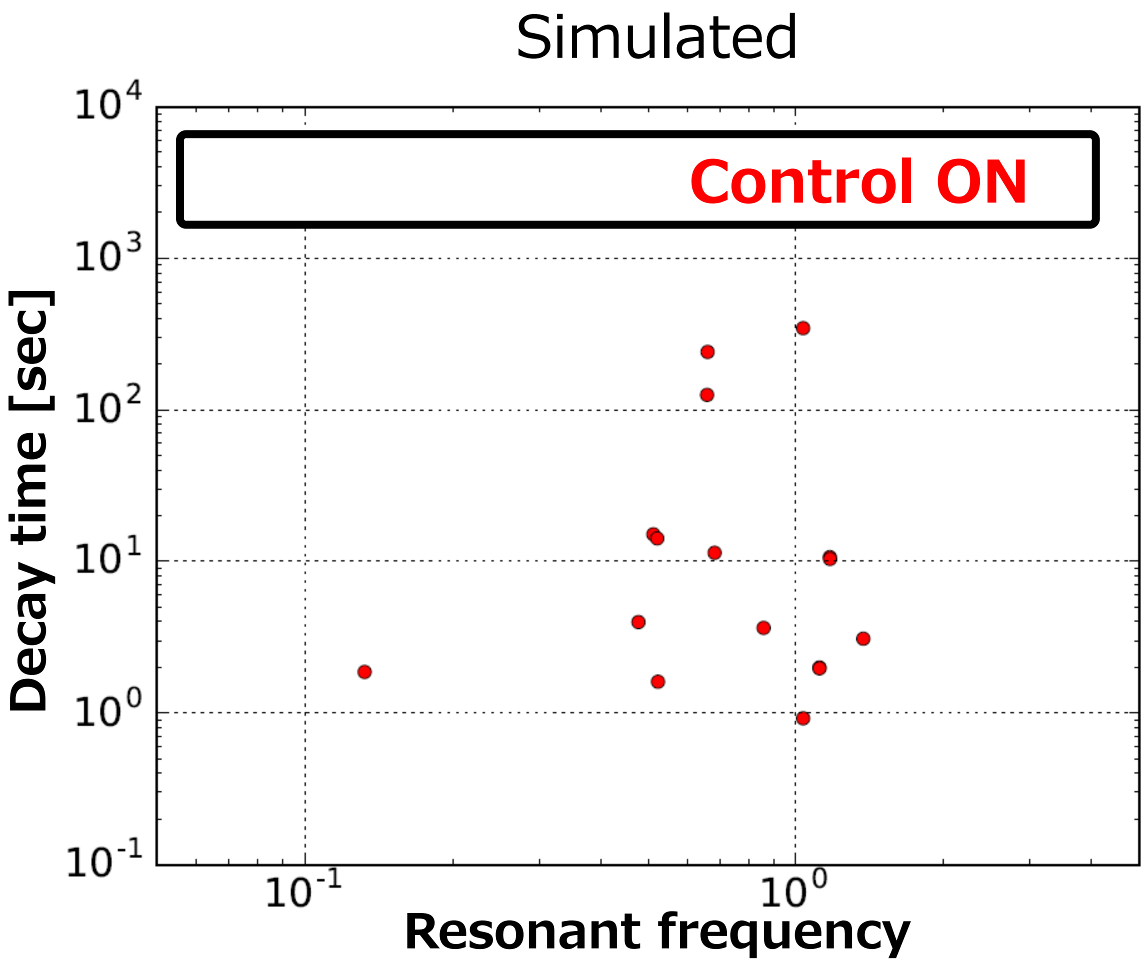




Resonances → damped

2. Decay time with damping

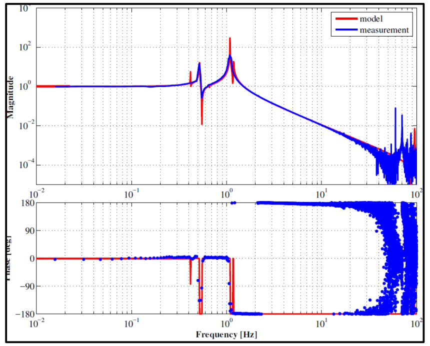




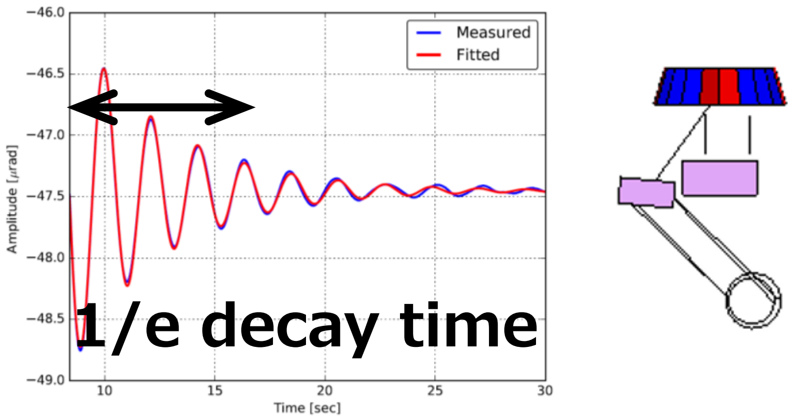
Simulation → consistent with measurement

Measurement:

1. Frequency response



2. Damping time



Suspension
→ *Pendulum*

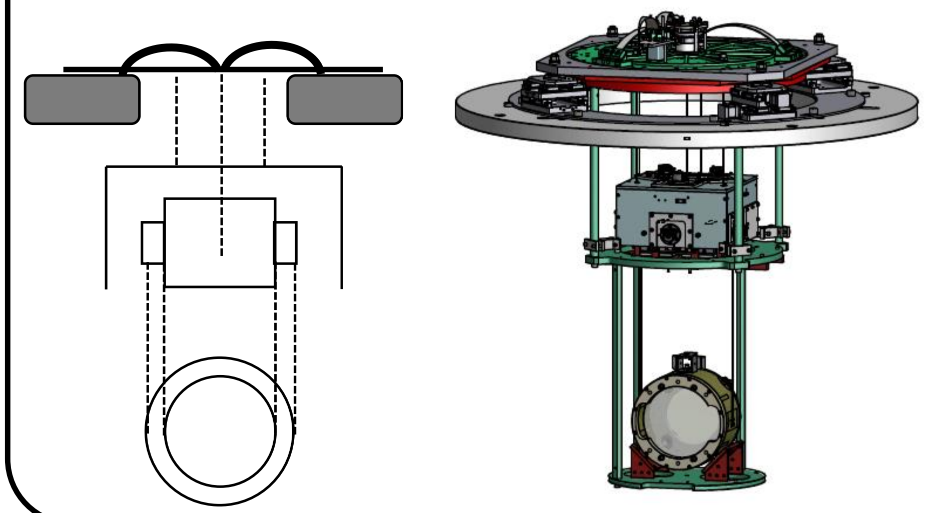
Resonances
→ *Damped*

Measurement
→ *Consistent with simulation*

Upgrade: iKAGRA → final KAGRA

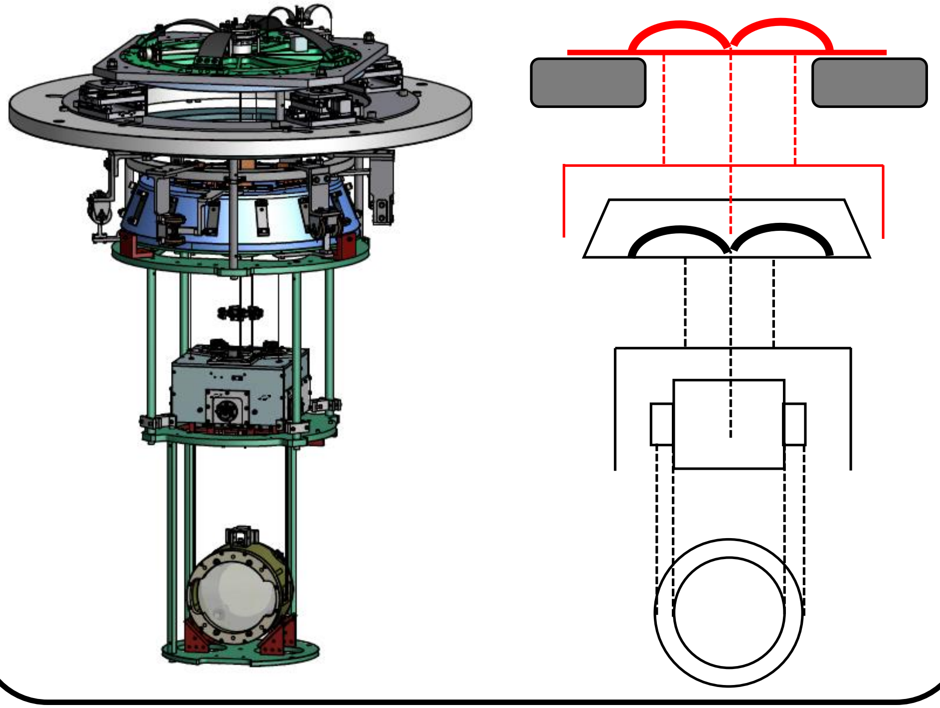
In order to meet final requirements:

Initial phase



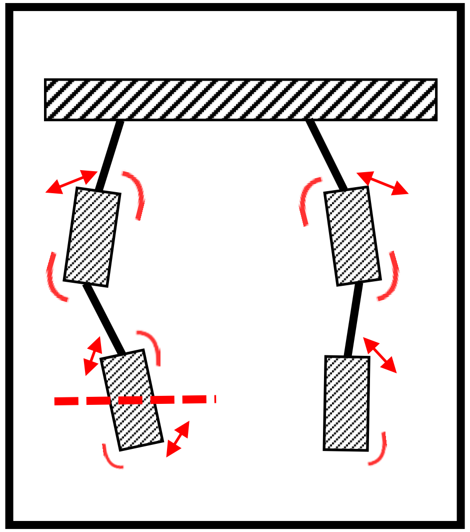
Add one more stage

Final phase



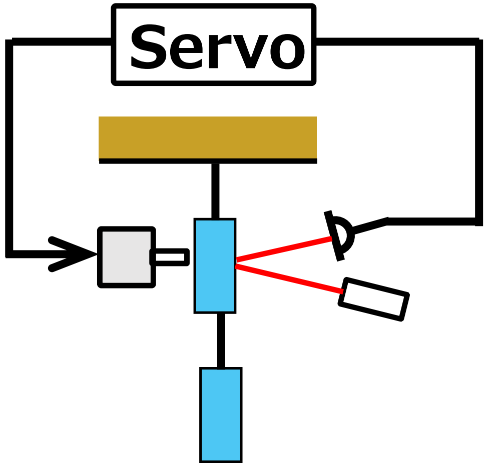
→ **Design active control systems.**

Steps for observation

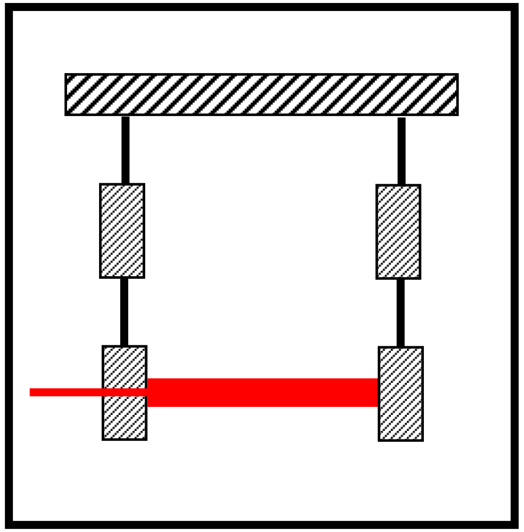


Free swinging

Calm-down phase

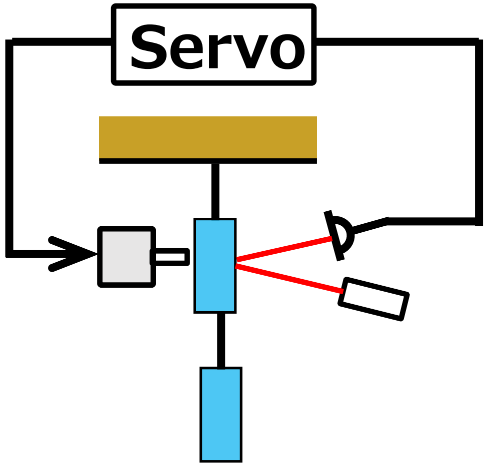


All stages
→ Damping



Interferometer Lock

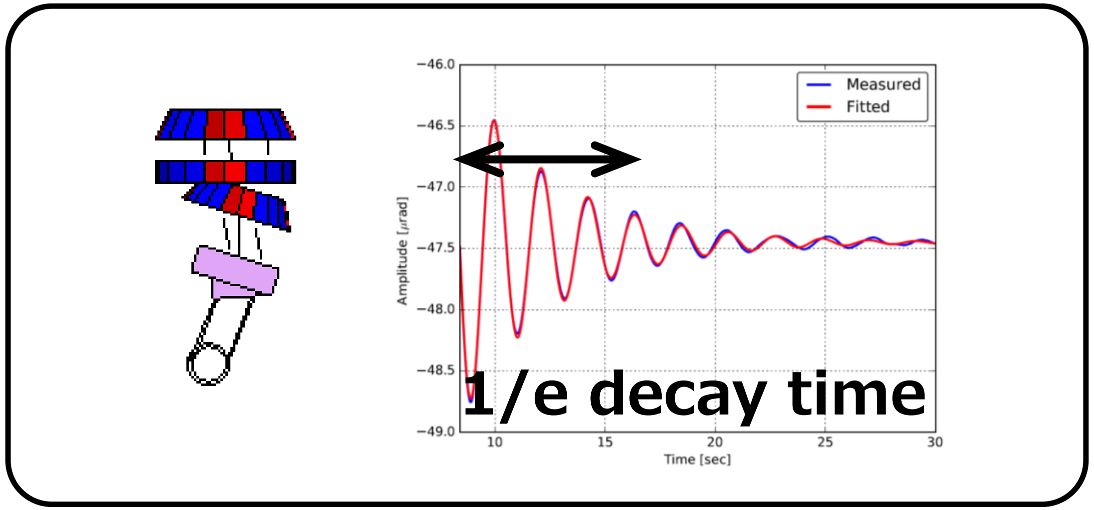
Observation phase

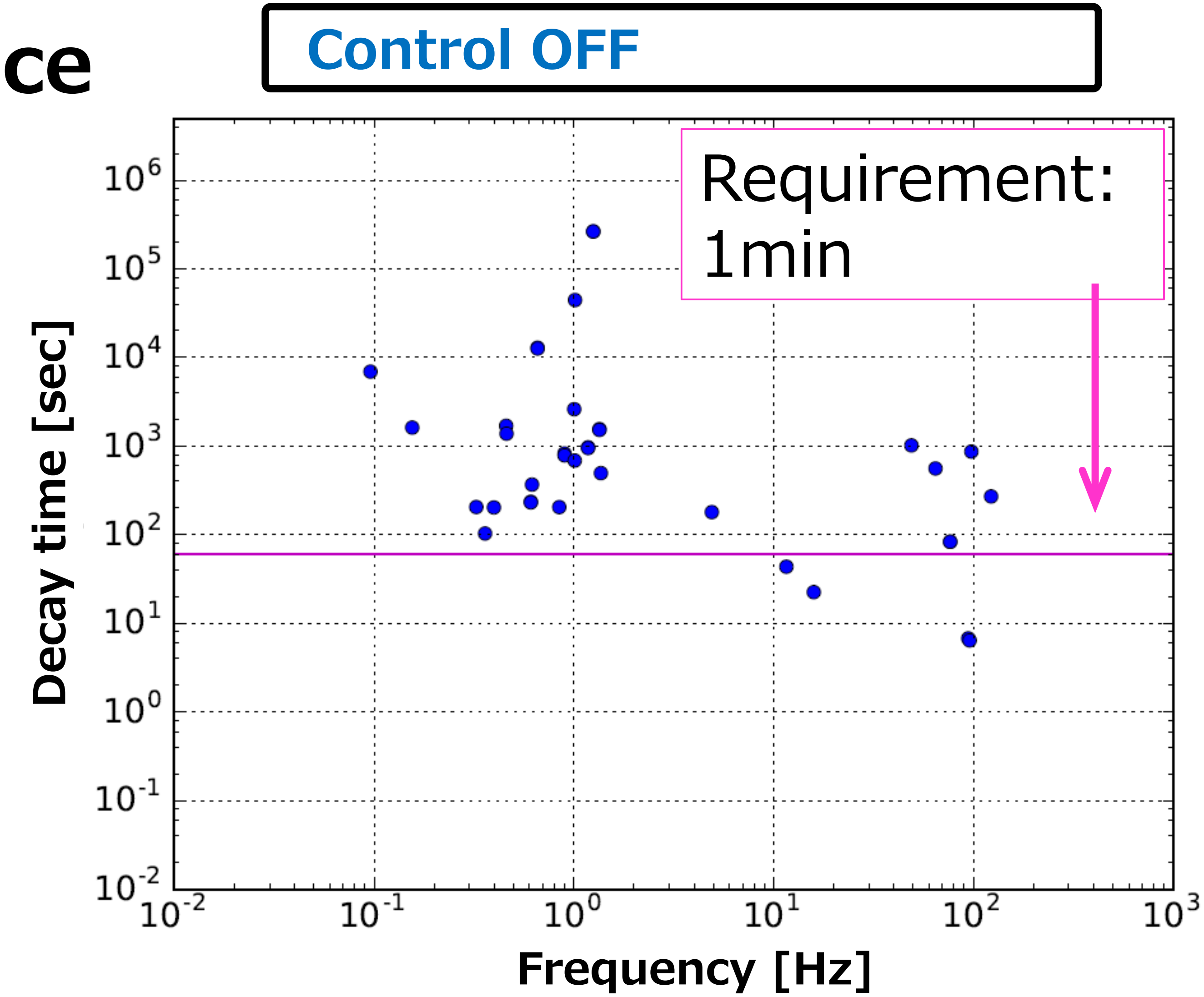


Upper stage
→ Damping

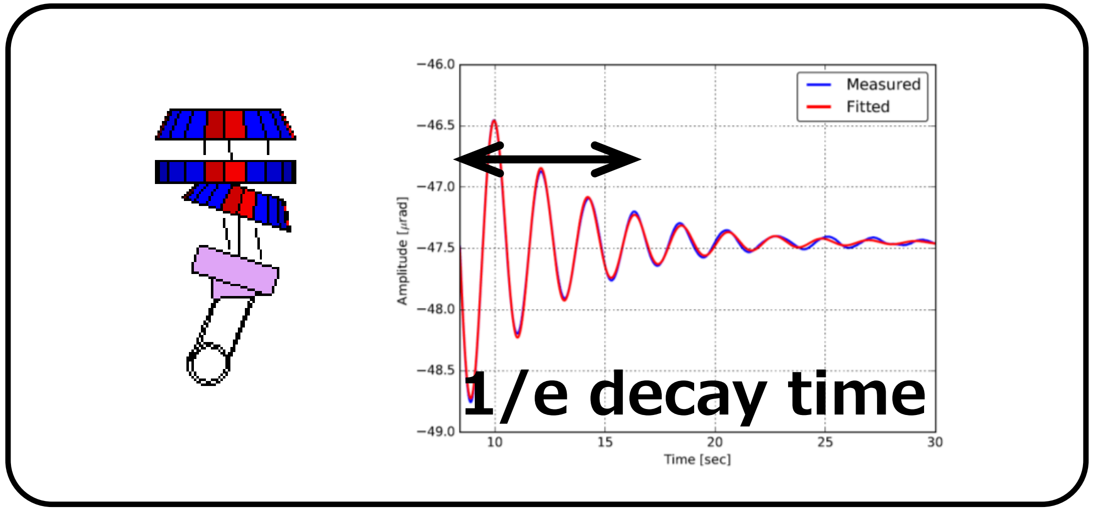
Lower stage
→ Alignment

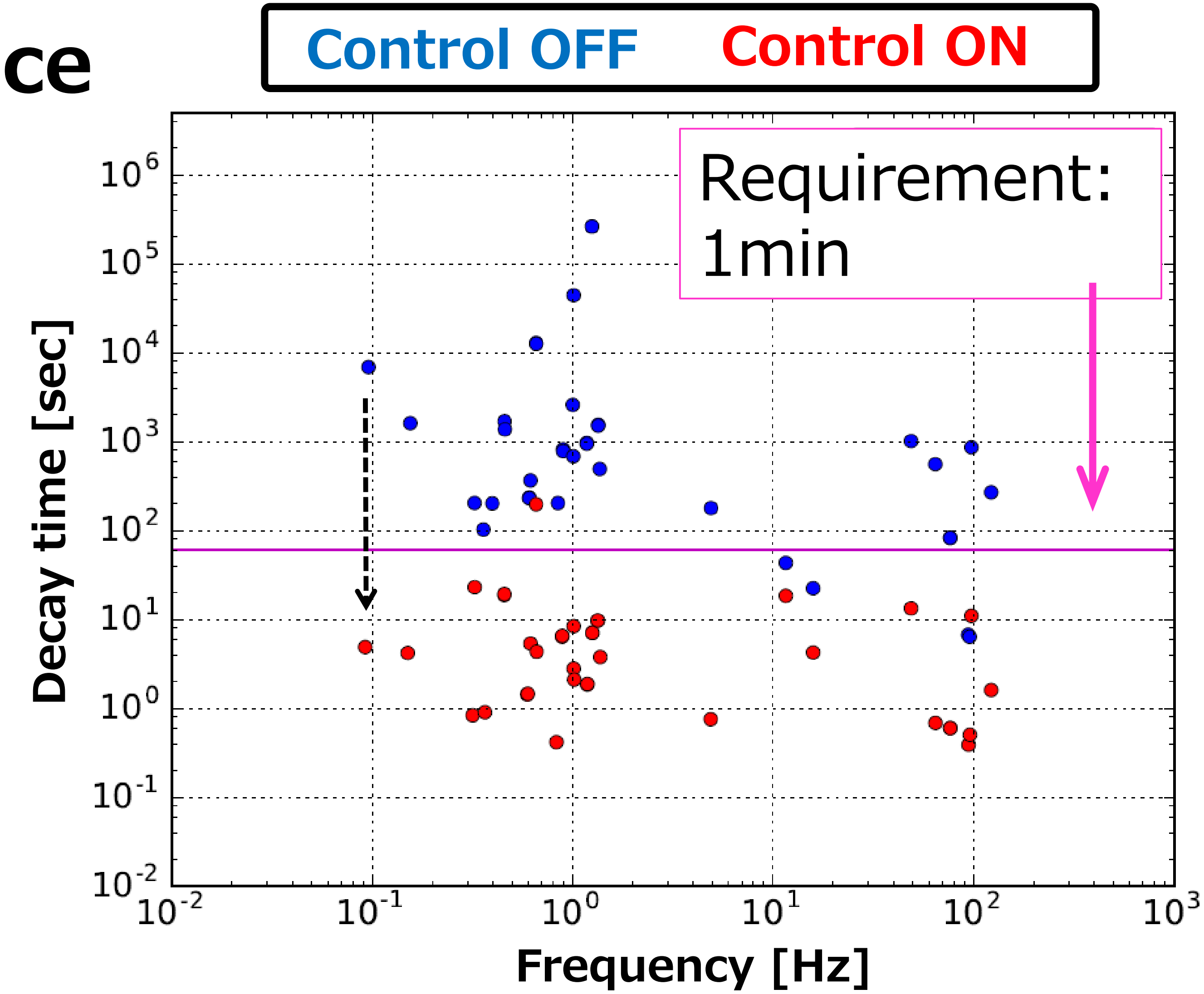
Calm-down phase:
Suppress large disturbance



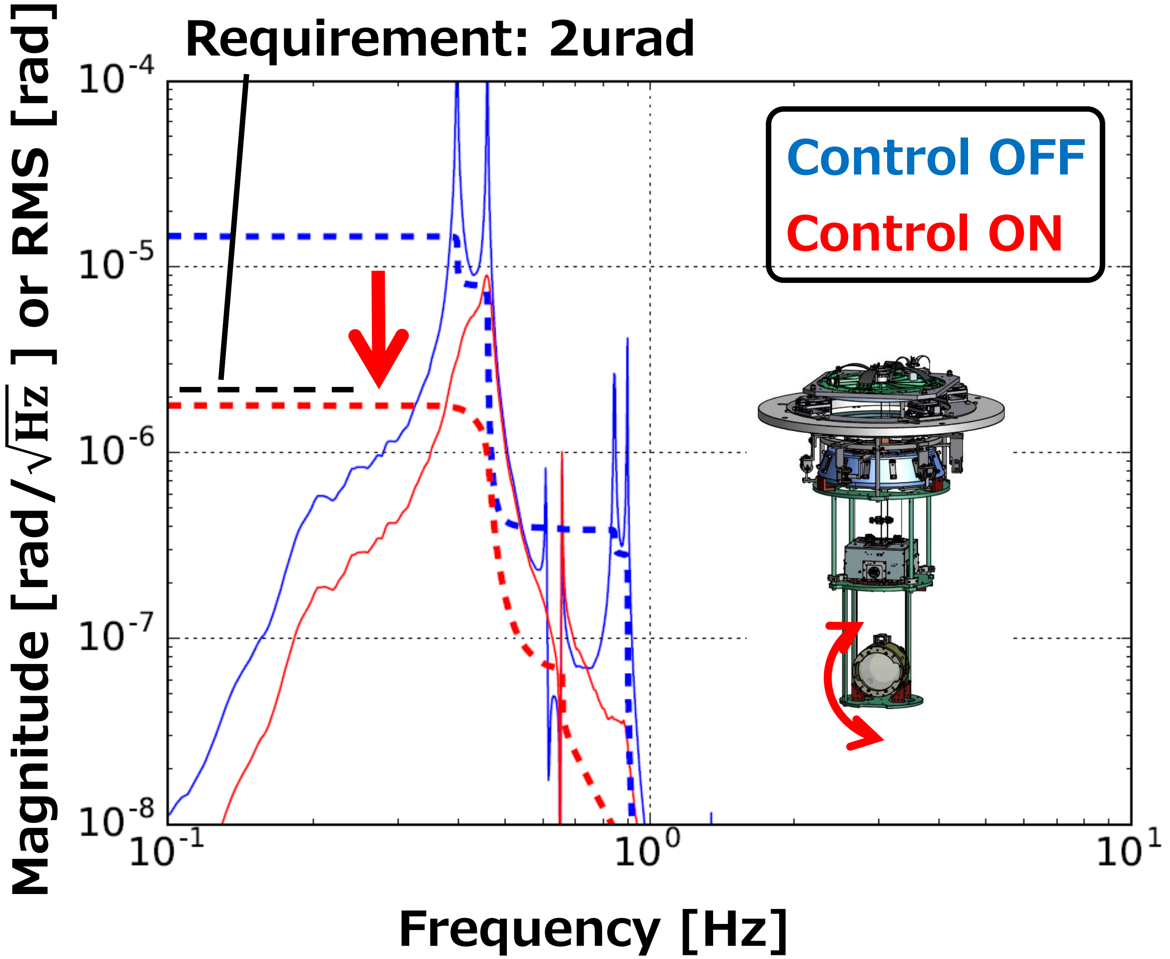


Calm-down phase: Suppress large disturbance

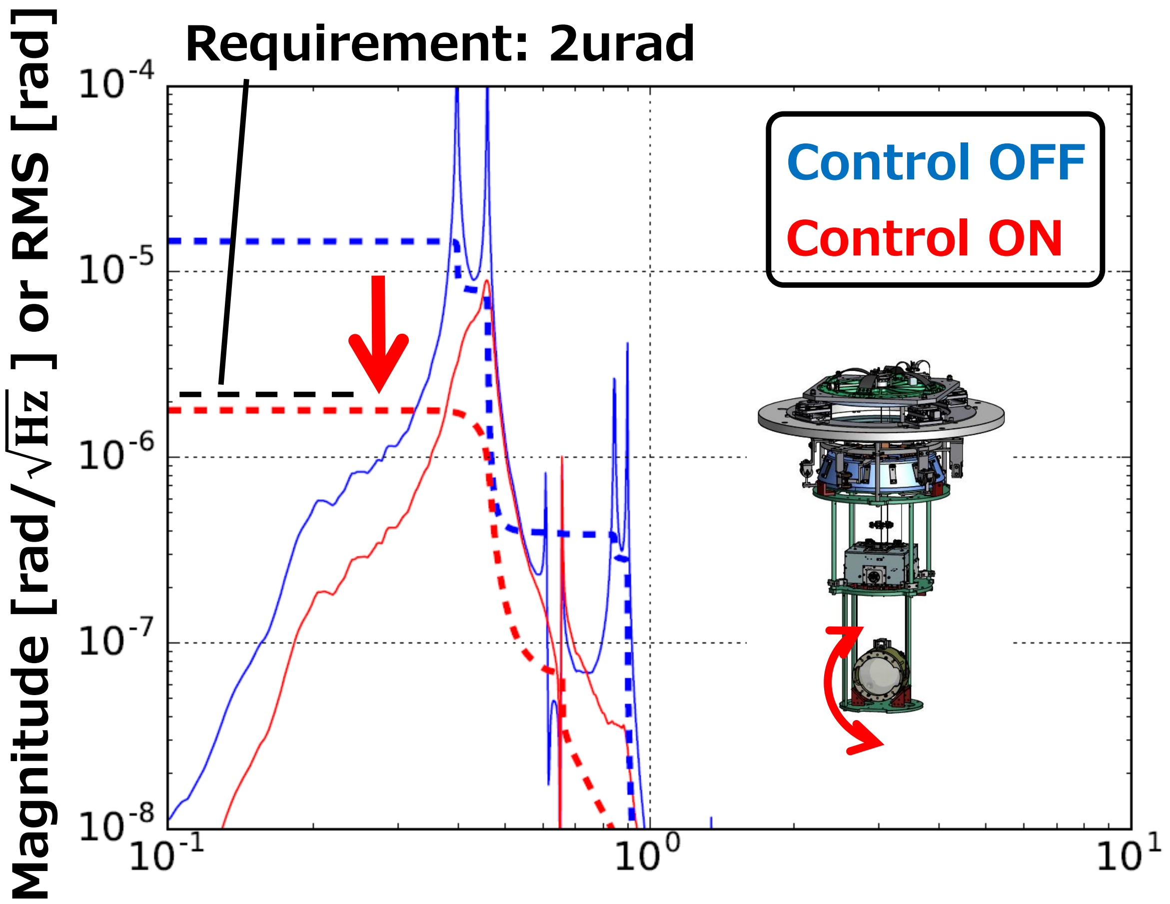


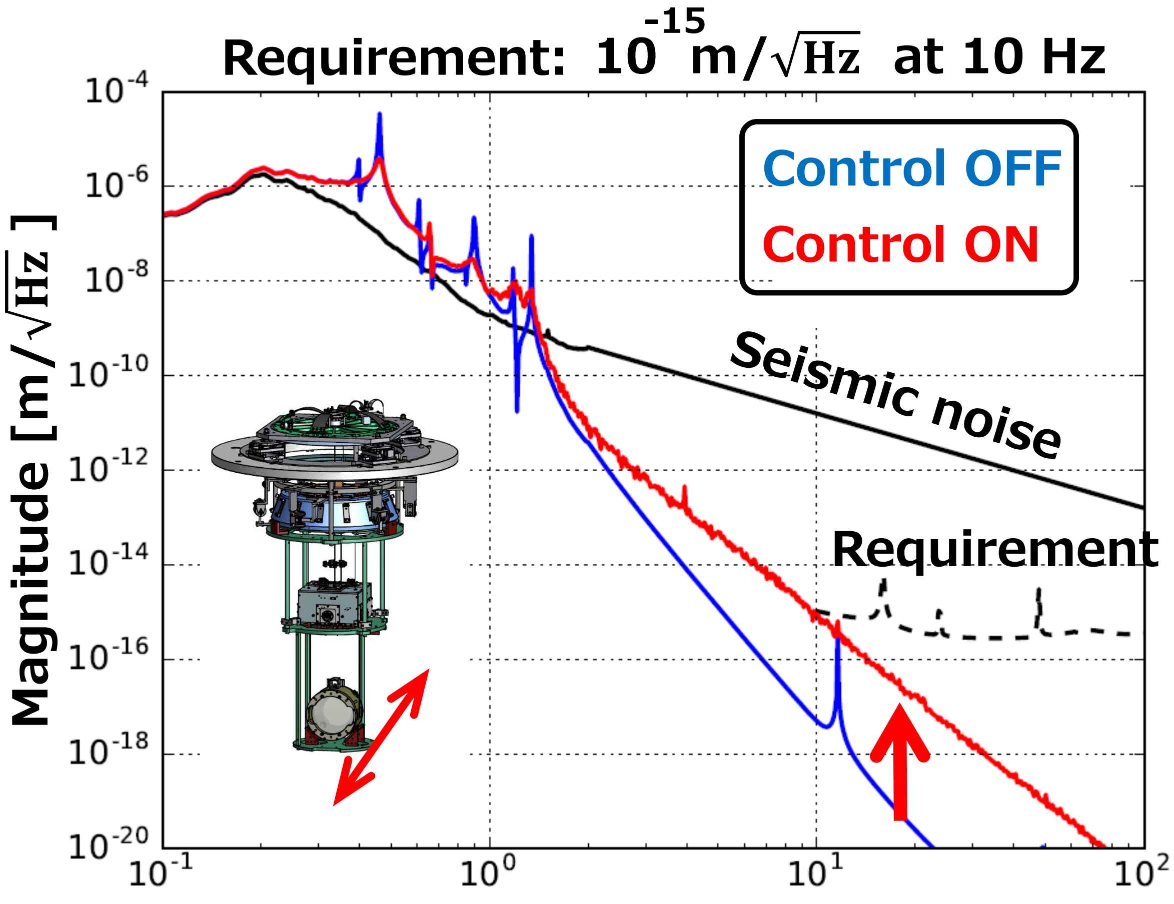


Observation phase:
Suppress RMS (Root Mean Square) & control noise



Observation phase:
Suppress RMS (Root Mean Square) & $\boxed{\text{control noise}}$





Summary 2

1) An iKAGRA suspension was assembled for iKAGRA operation.
2) Its performance were tested.
   → ***Measurement: consistent with simulation.***

3) Active control system for a suspension is designed.
   → ***Clam-down phase: resonances → damped.***
   → ***Observation phase: RMS & control noise → suppressed.***

Summary

1. Source localization

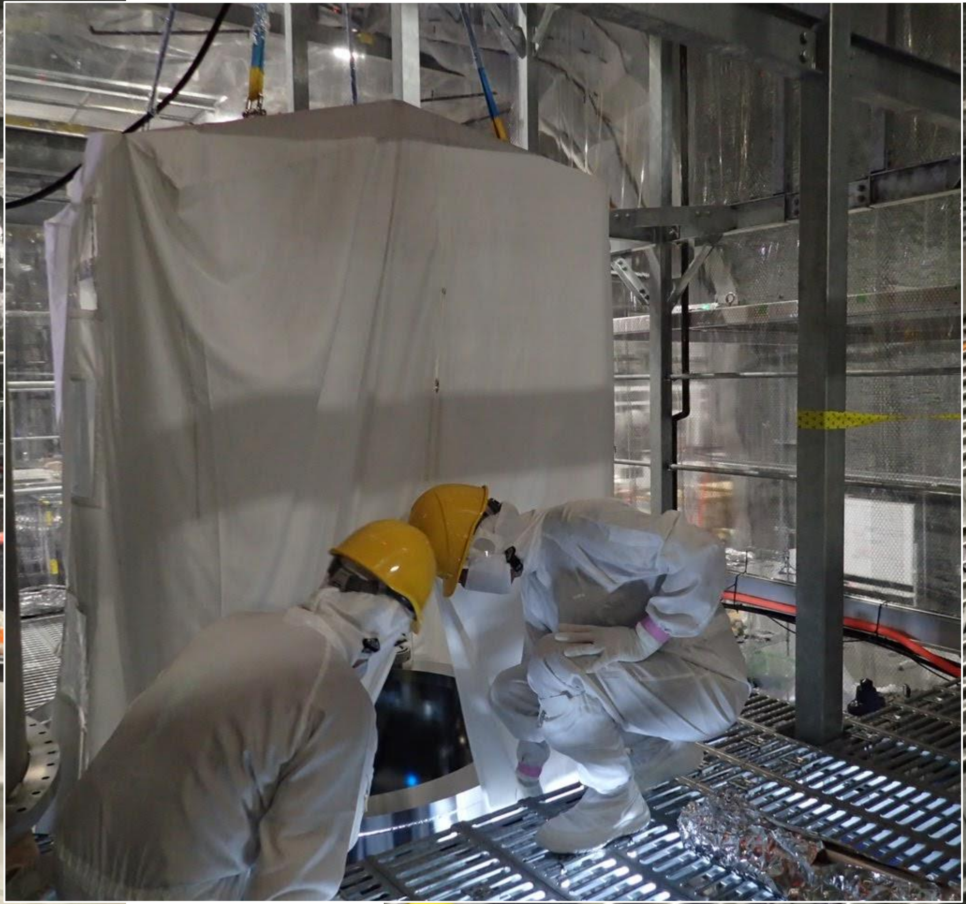
A localization with hierarchical network is demonstrated.
→ ***Low sensitivity detector can contribute.***
→ ***4th detector contributes. → useful for follow-up observation.***

2. Detector development

1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
2) Its performance were tested.
→ ***Simulation was consistent with measurement.***
3) Active control system for type-Bp suspension is designed.
→ ***Clam-down phase: resonances → damped.***
→ ***Observation phase: RMS & control noise → suppressed.***

Back up

Modern NINJAs in the Kamioka mine.



Summary

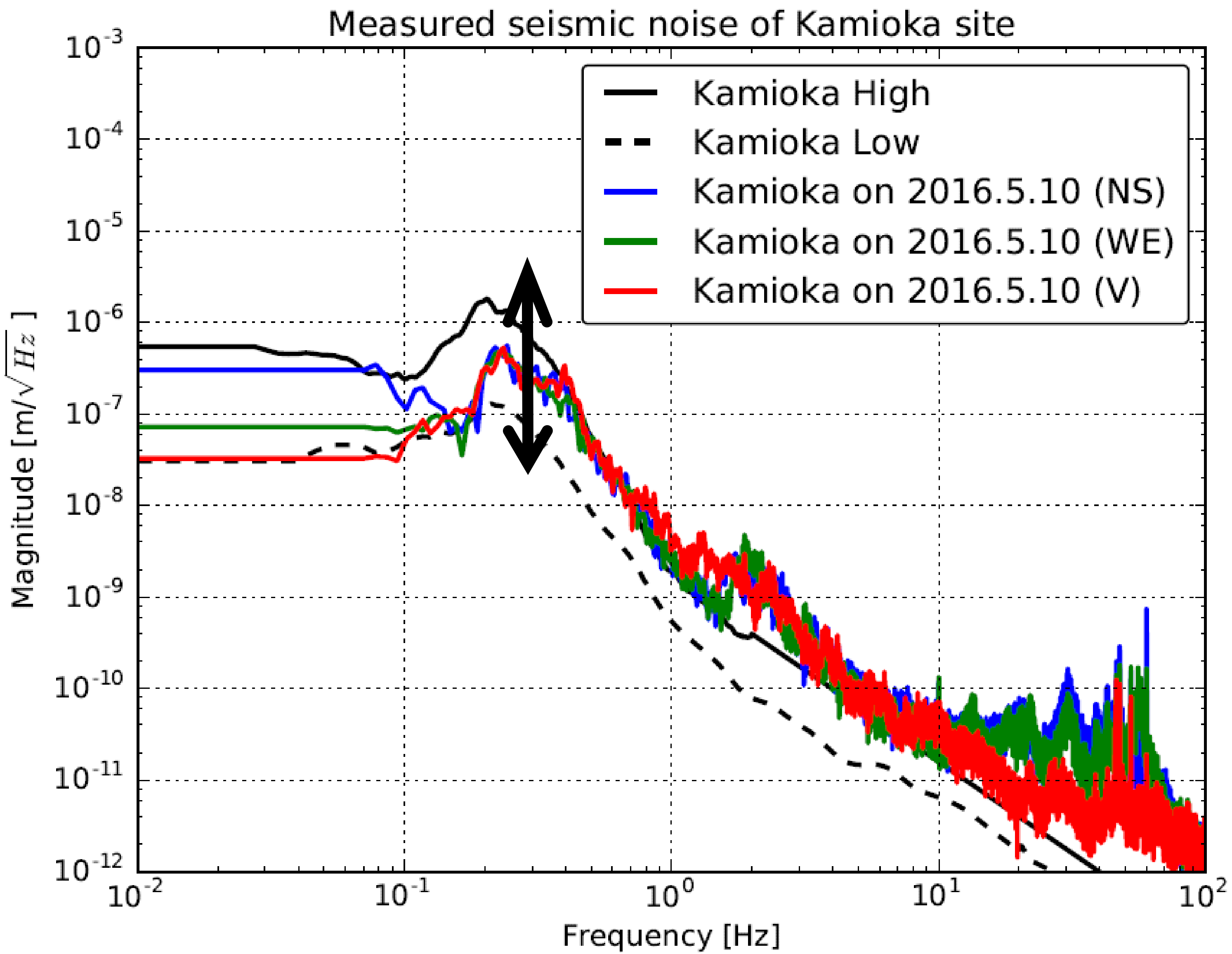
1. Source localization

A localization with hierarchical network is demonstrated.
→ ***Low sensitivity detector can contribute.***
→ ***4th detector contributes. → useful for follow-up observation.***

2. Detector development

1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
2) Its performance were tested.
→ ***Simulation was consistent with measurement.***
3) Active control system for type-Bp suspension is designed.
→ ***Clam-down phase: resonances → damped.***
→ ***Observation phase: RMS & control noise → suppressed.***

Seismic noise of Kamioka (on 2016.5.10)

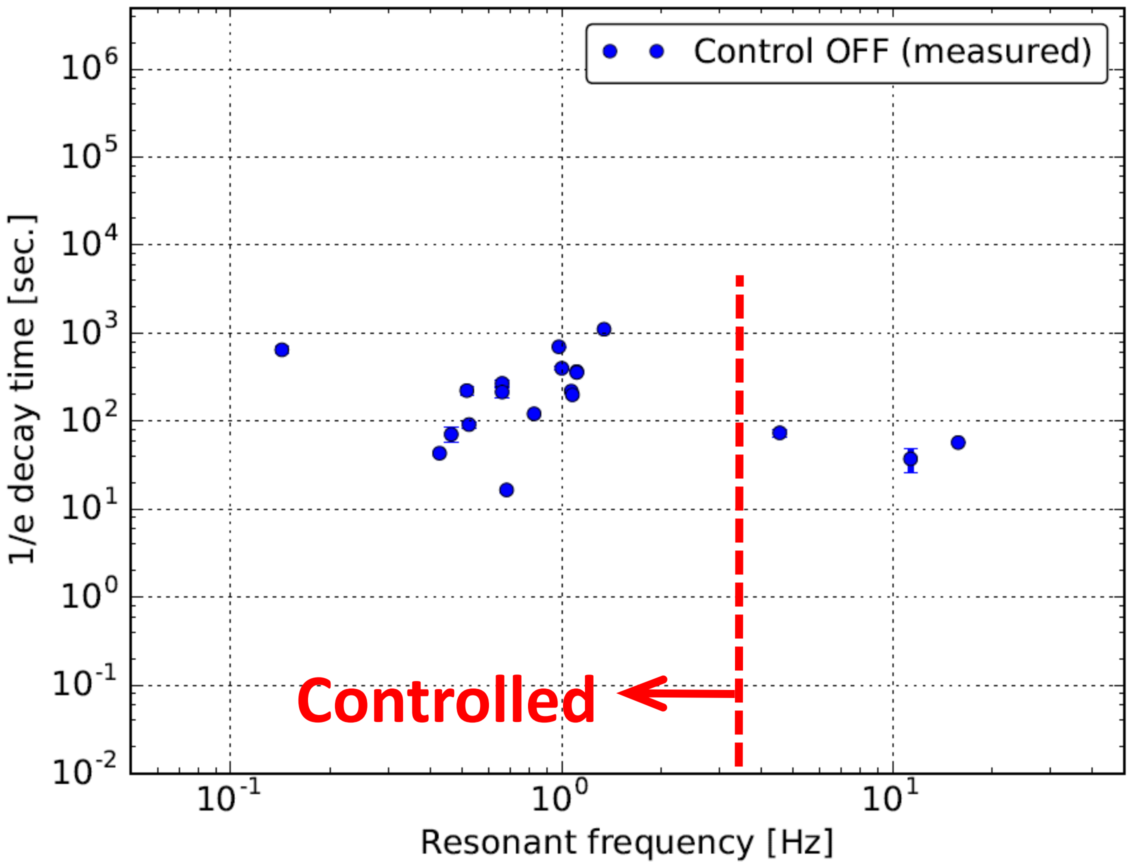


seismic noise was measured on 2016.5.10.

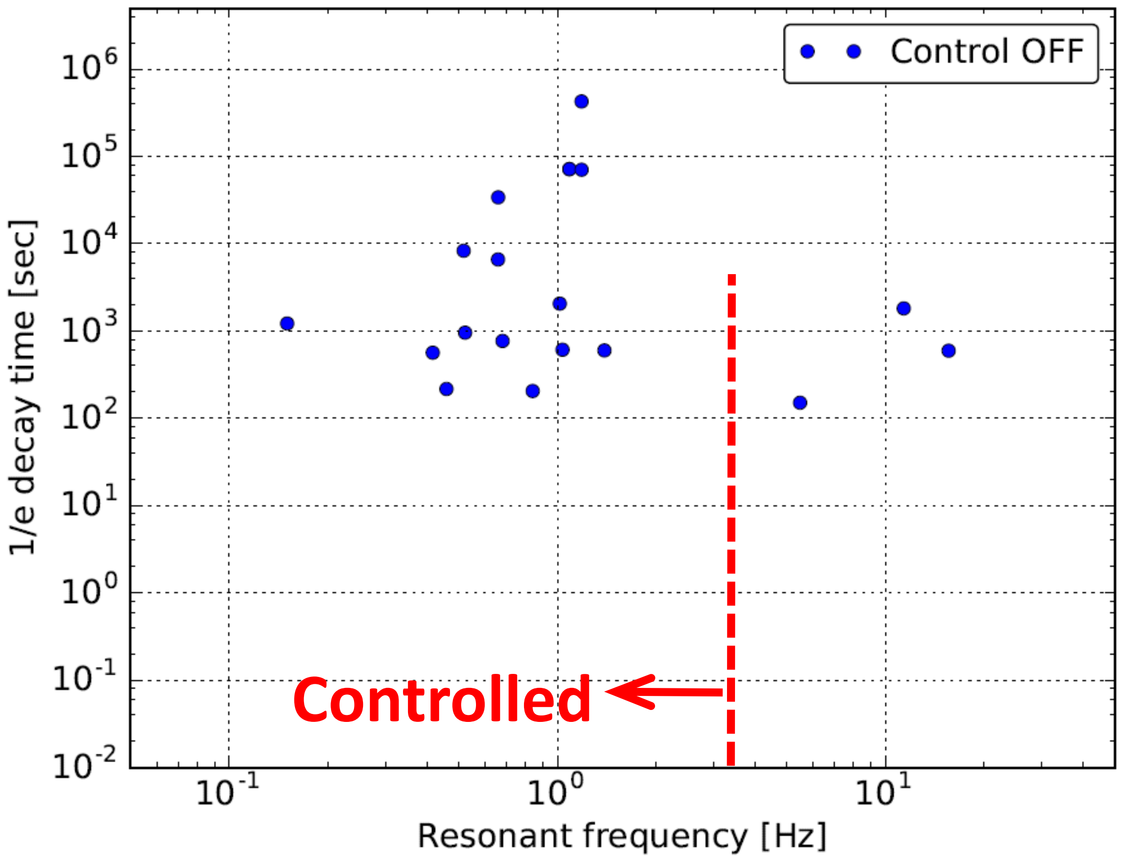
PR3 measurement was conducted on 2016.5.24.

Performance test 1

Measured

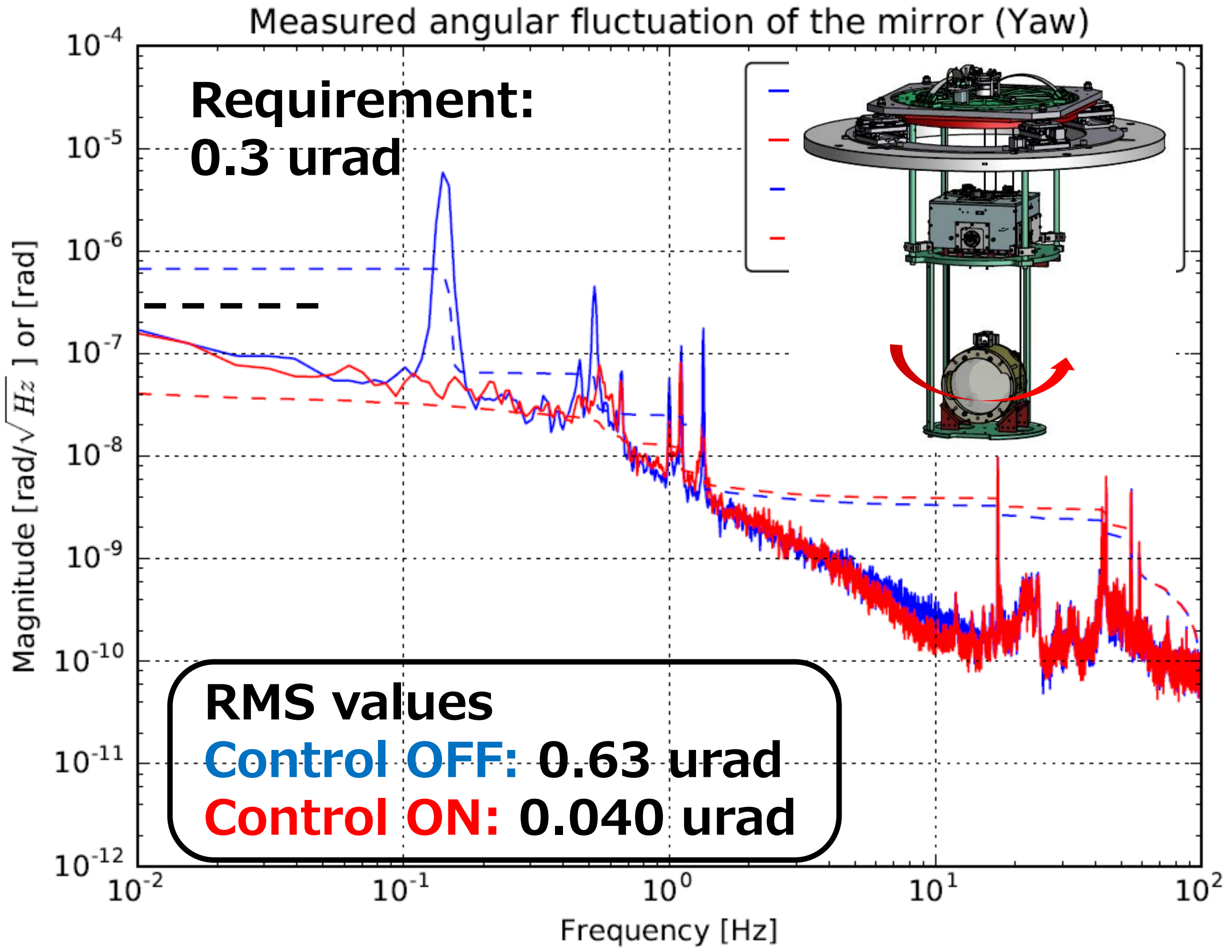


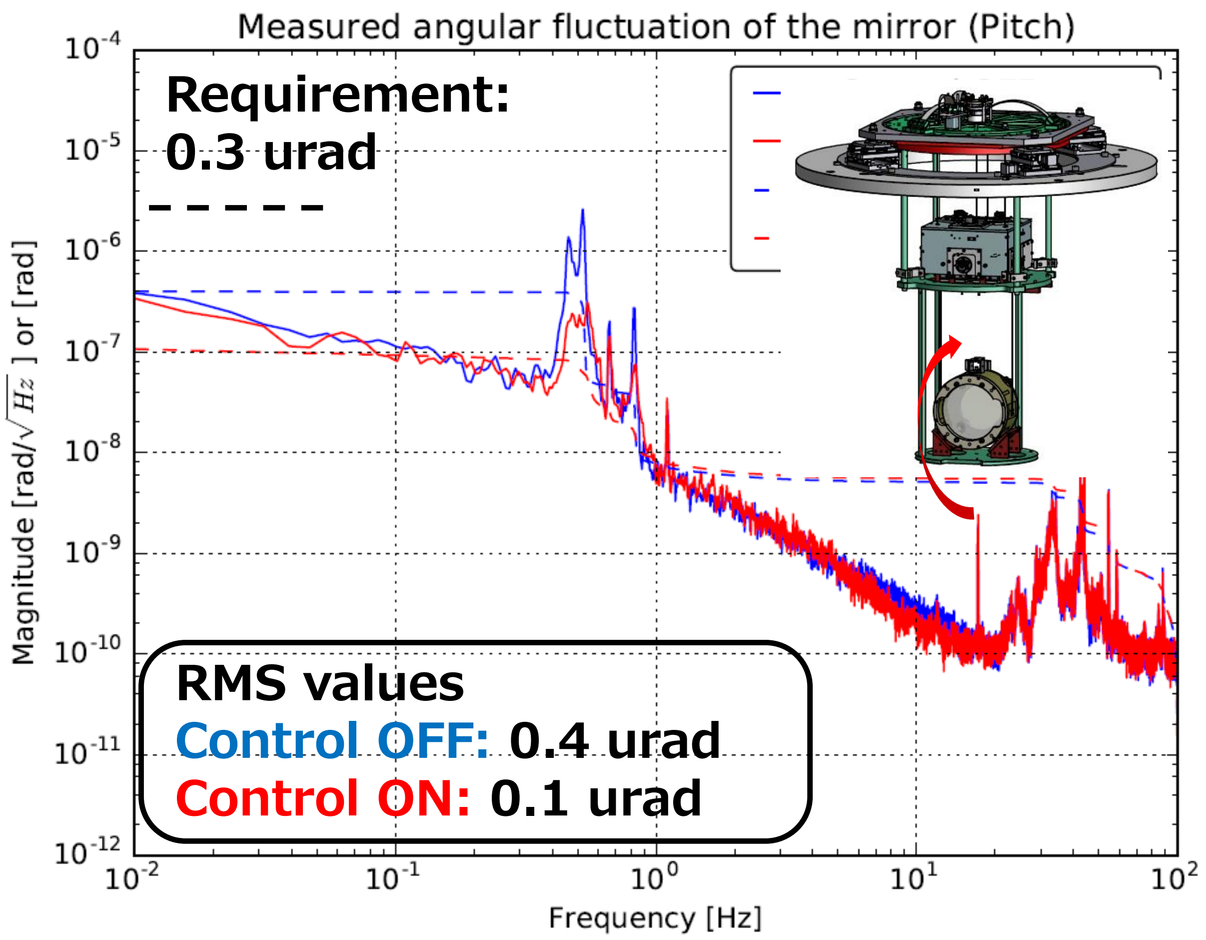
Simulated



1) Control OFF → Necessary to feedback measurement.

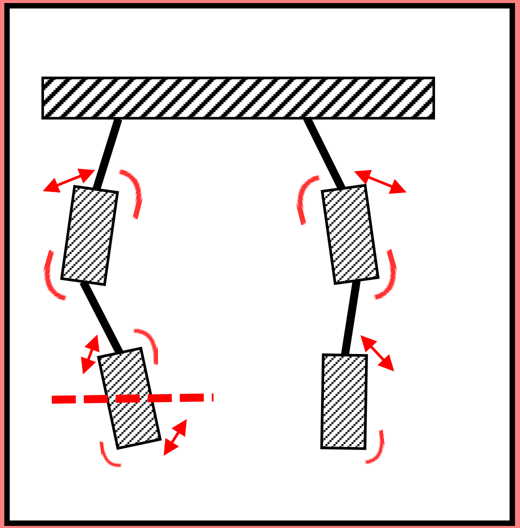
Angular fluctuation of the mirror





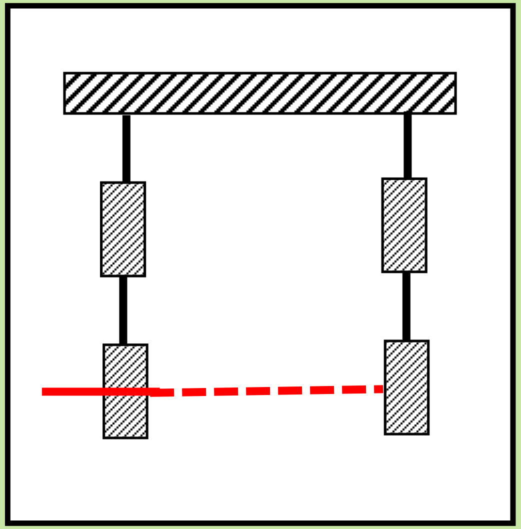
Designing active control system / Control phase

1. Calm-down phase



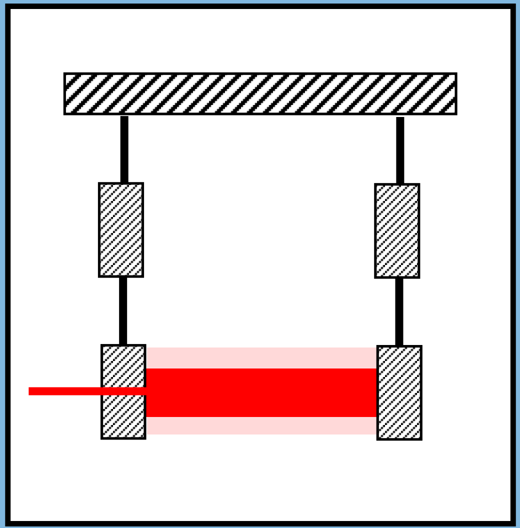
Suppress
large disturbance

2. Lock-acquisition phase



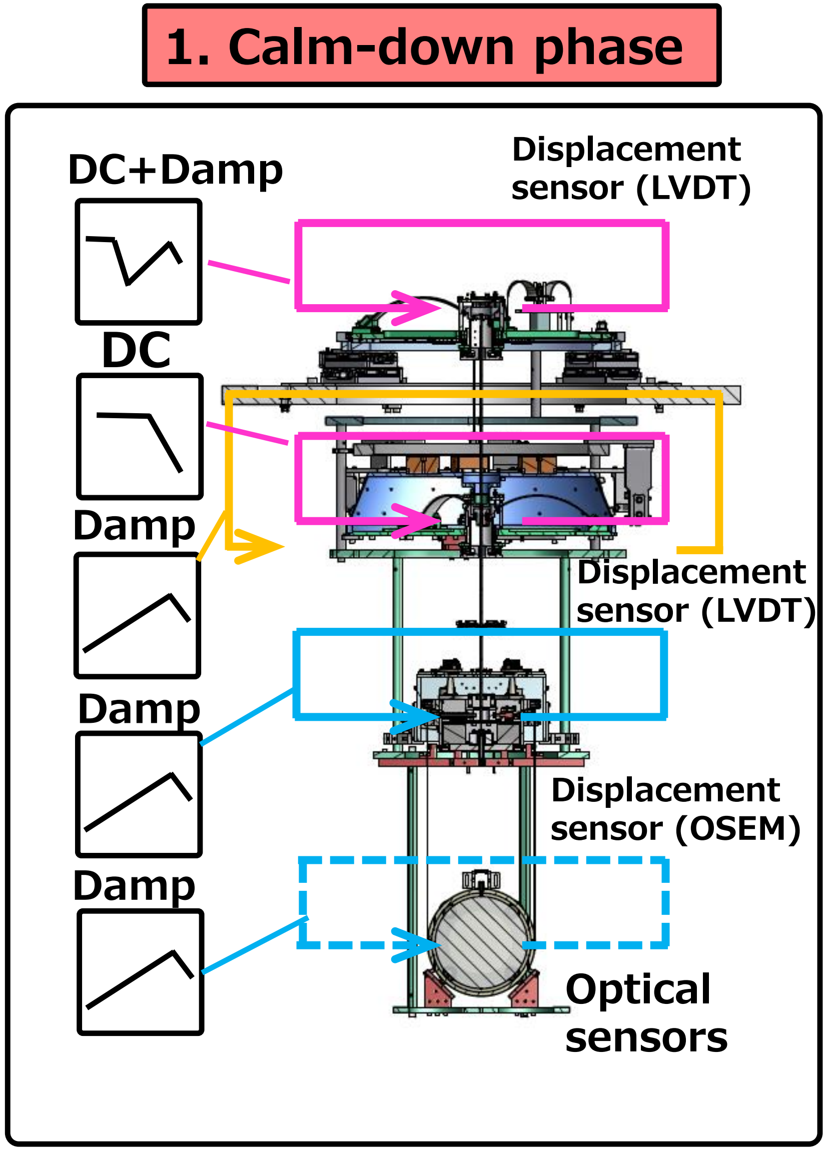
Reduce RMS velocity
RMS angle
(Root-Mean-Square)

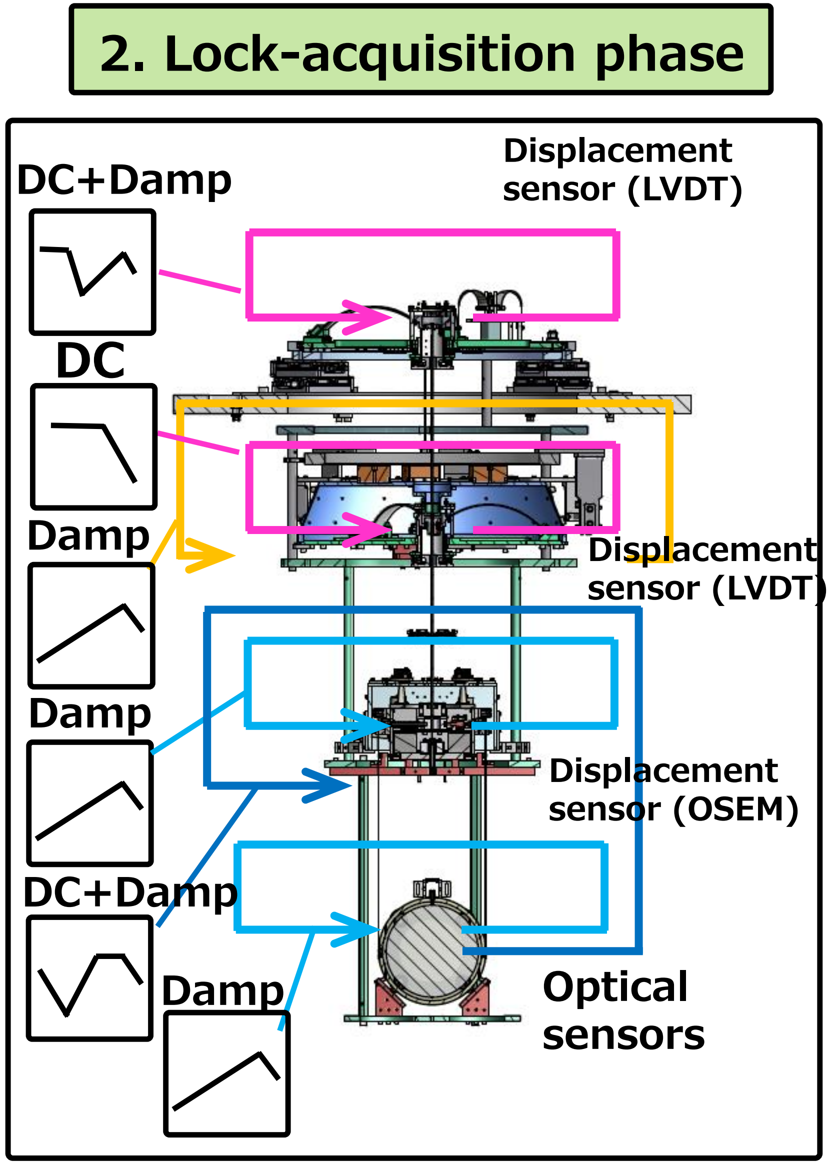
3. Observation phase

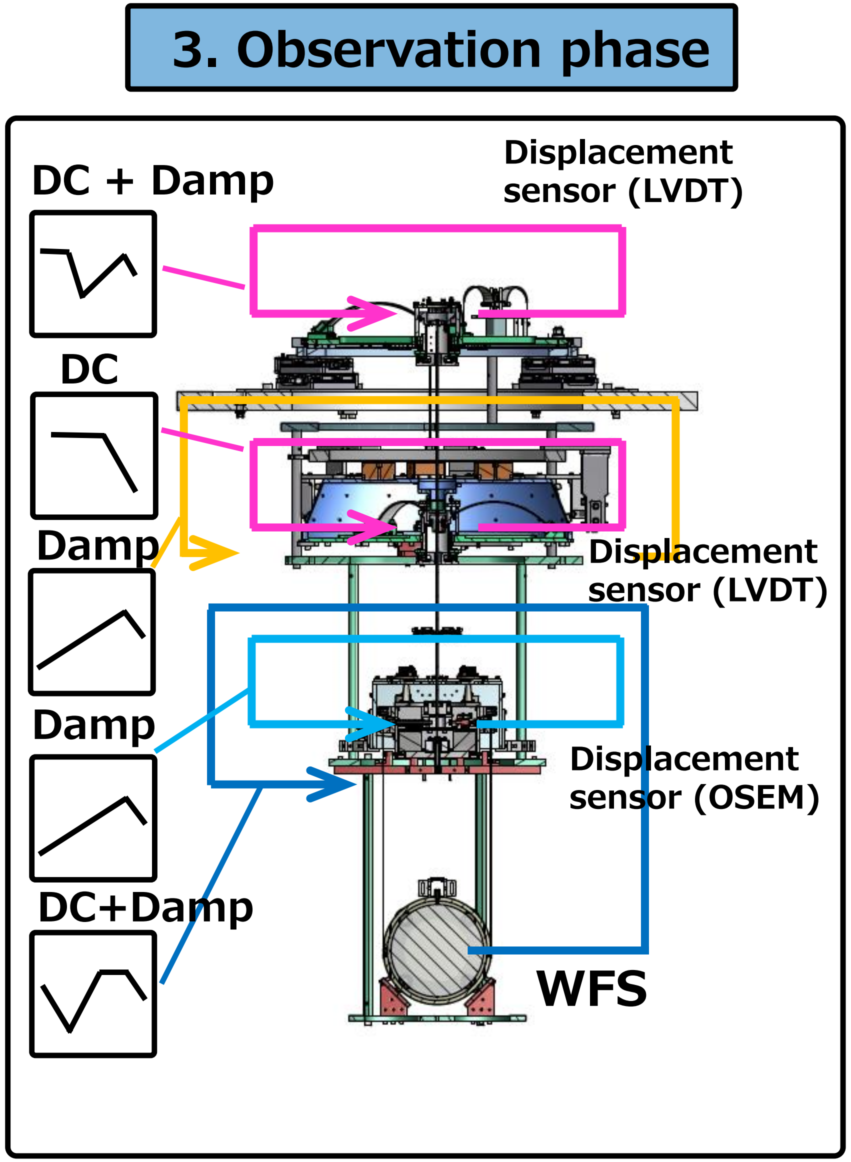


Keep position
with low noise
control

Designing active control system / Type-Bp SAS

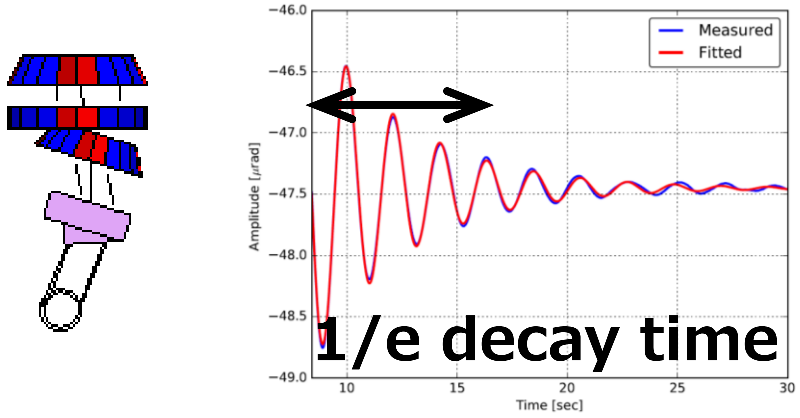


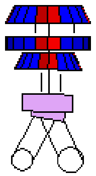




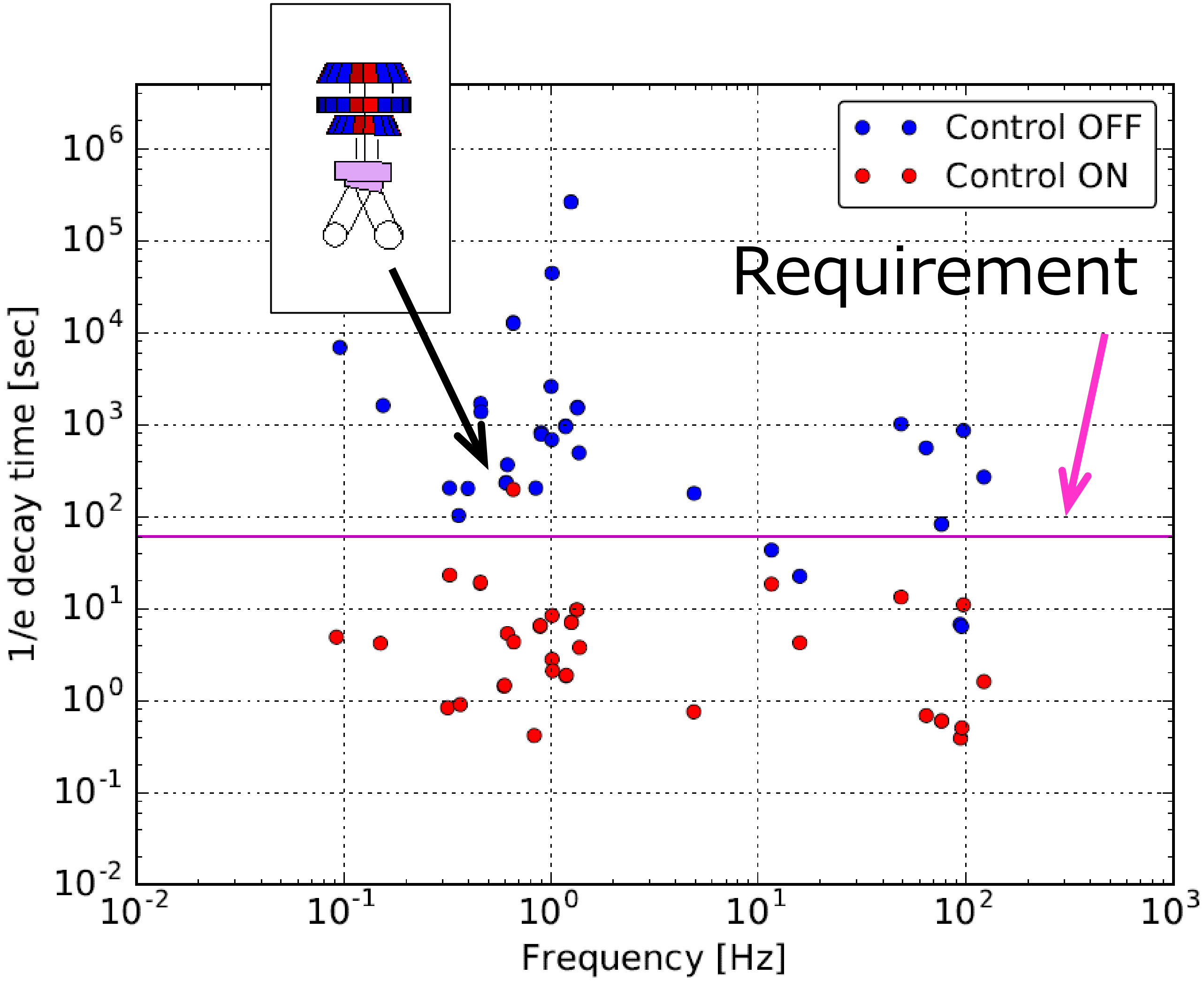
Designing active control system 1

Calm-down phase:
Suppress large disturbance



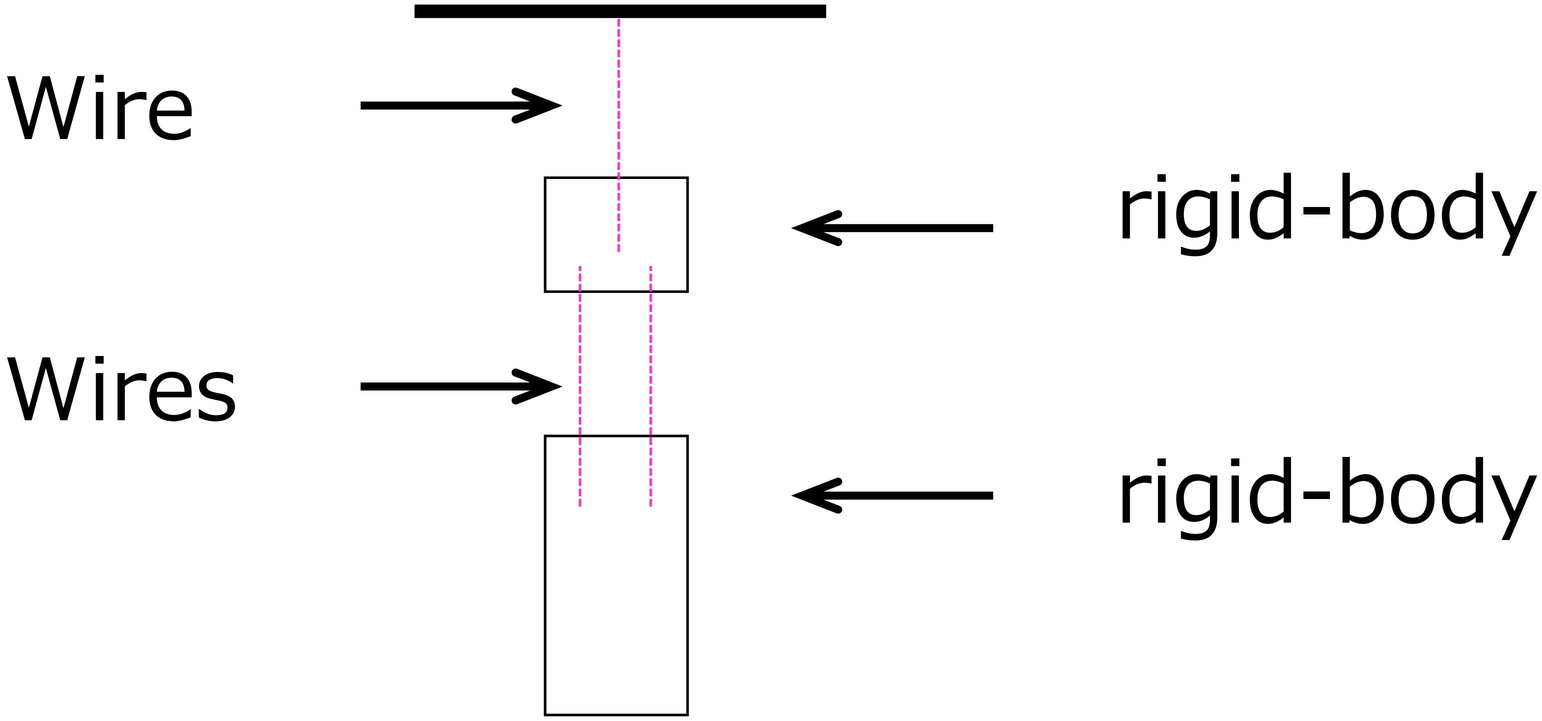


Not disturb operation
→ No problem.



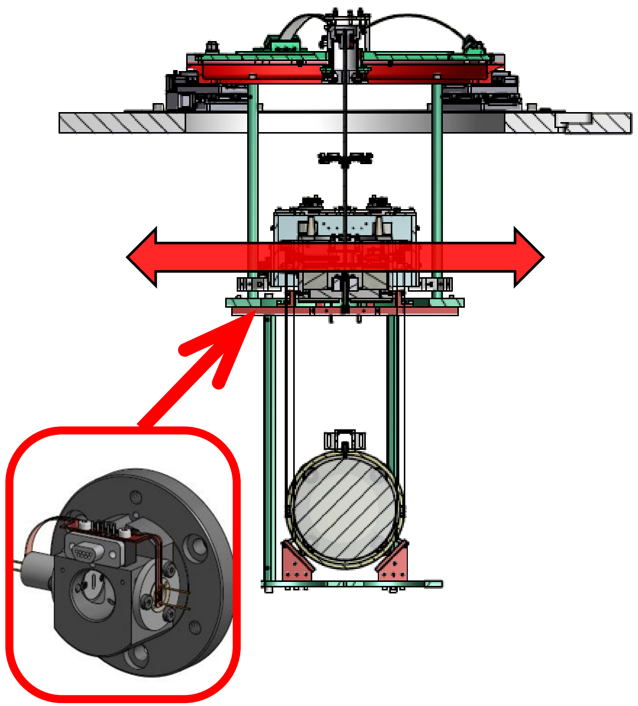
(if all sensors available)

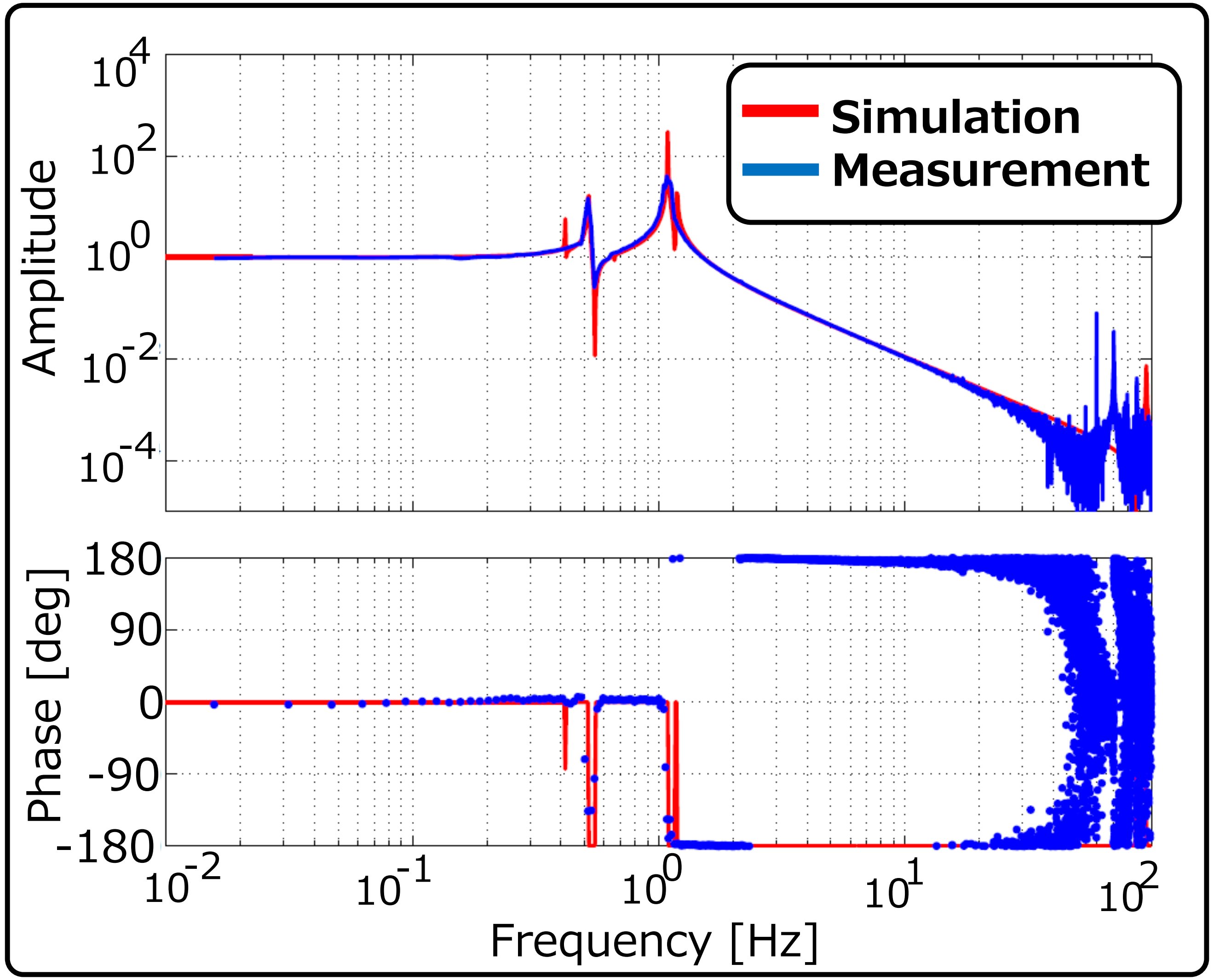
Simulation model: Based on rigid-body



1. Frequency response

For each Components:





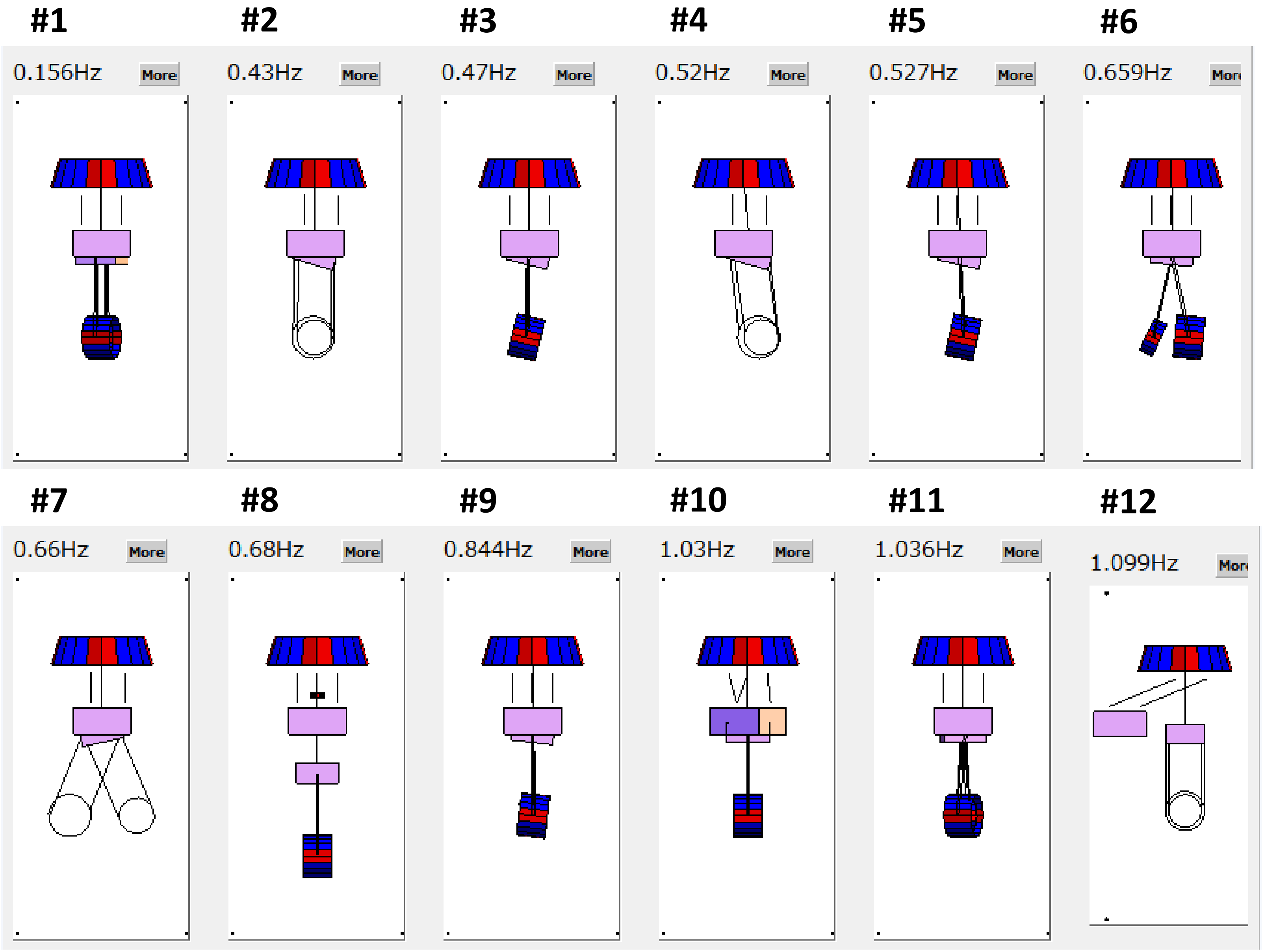
Band width: 0.02 Hz

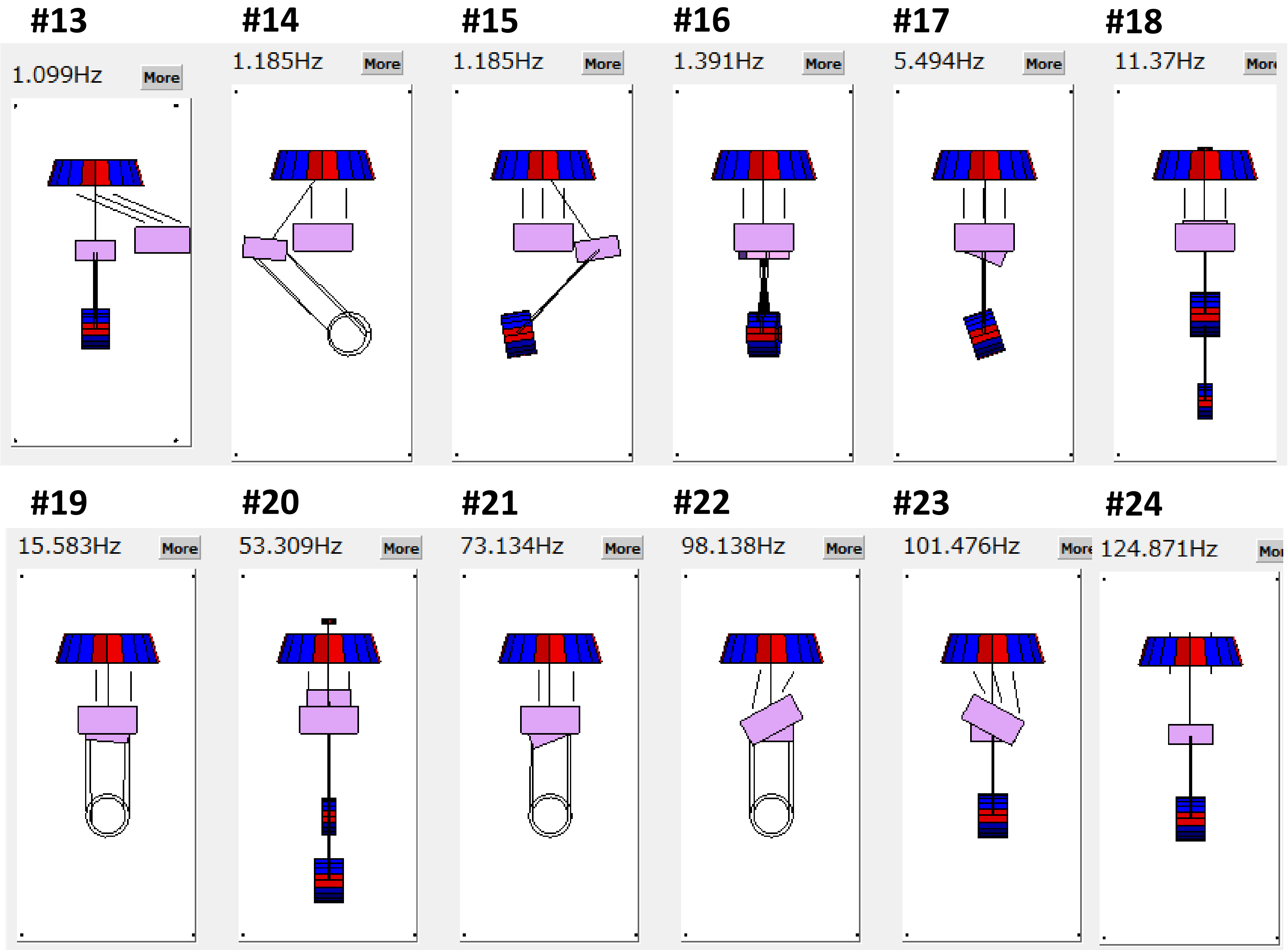
Window: Hanning

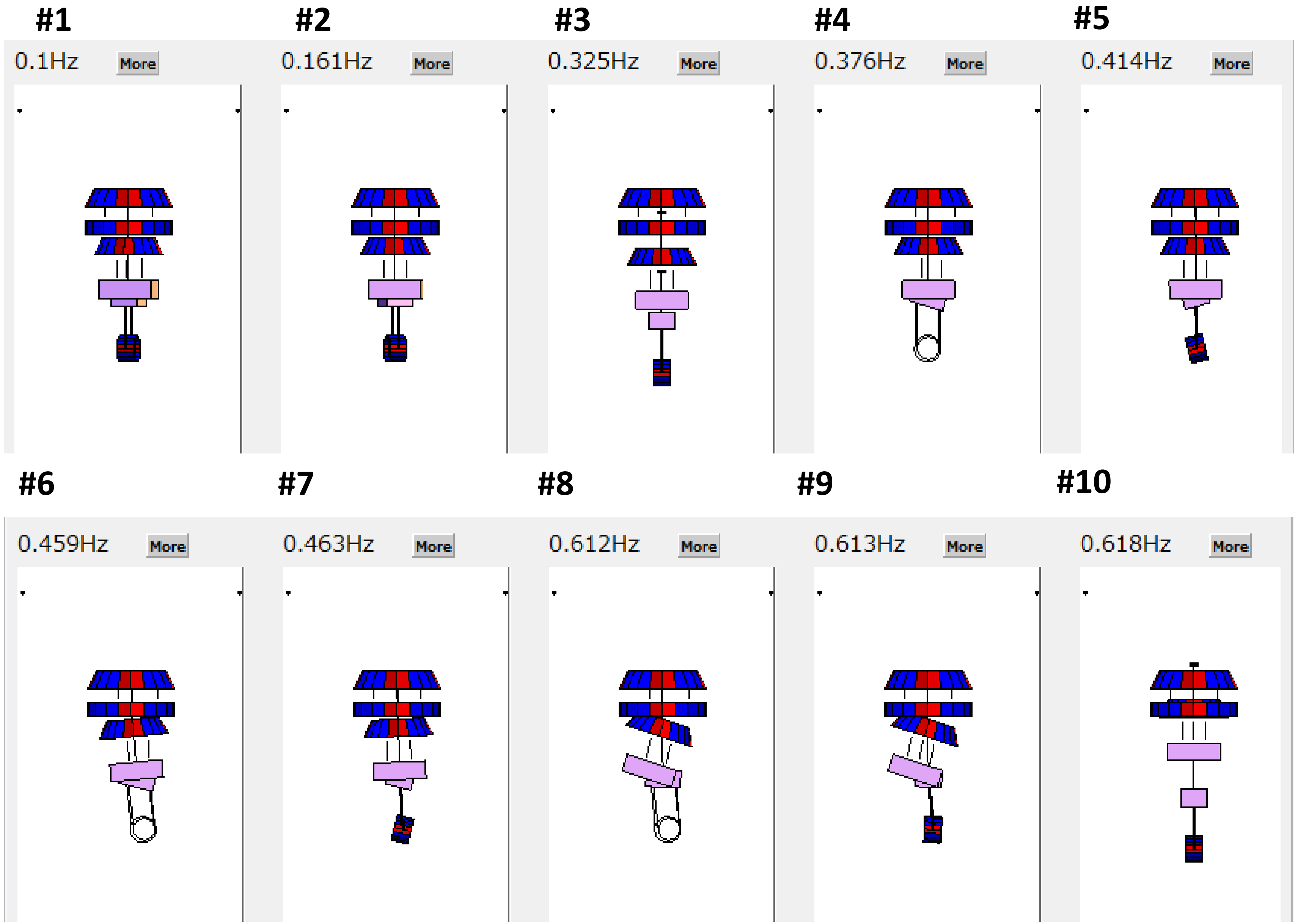
Overlap: 50 %

Average: 5

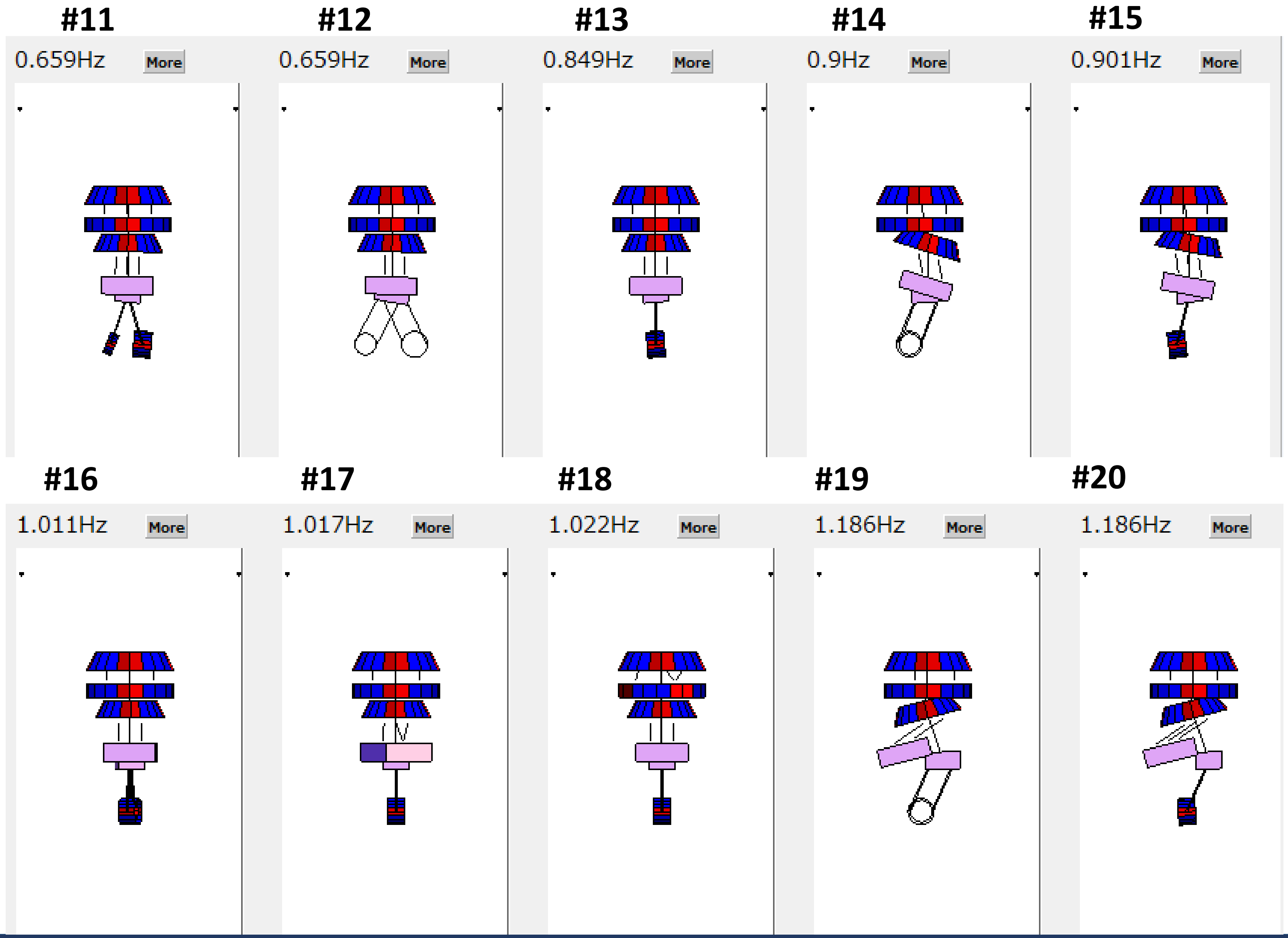
TypeBpp SAS
Eigen mode List : 24 modes



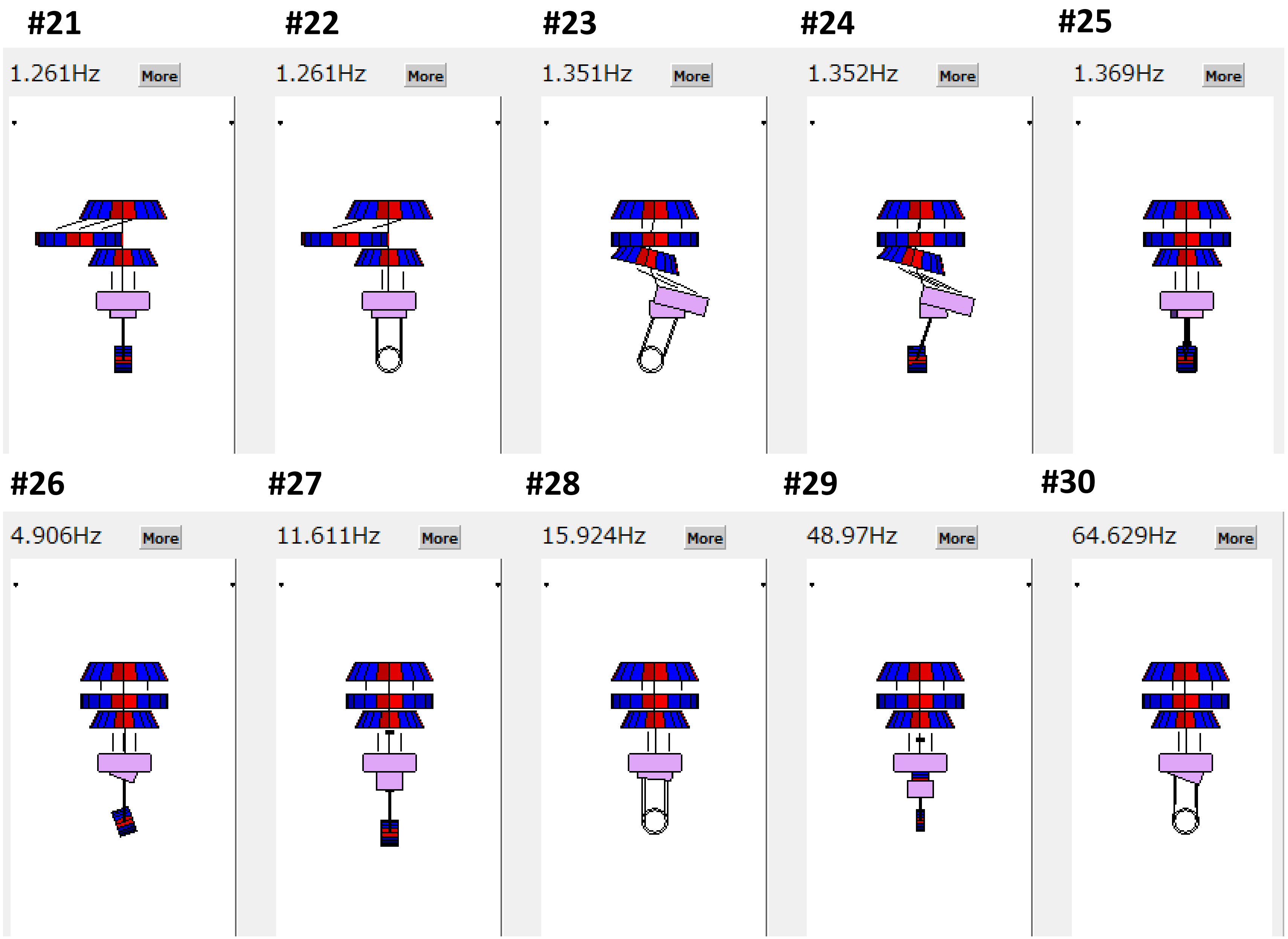

#13
1.099Hz
More
#14
1.185Hz
More
#15
1.185Hz
More
#16
1.391Hz
More
#17
5.494Hz
More
#18
11.37Hz
#19
15.583Hz
More
#20
53.309Hz
More
#21
73.134Hz
More
#22
98.138Hz
More
#23
101.476Hz
#24
124.871Hz



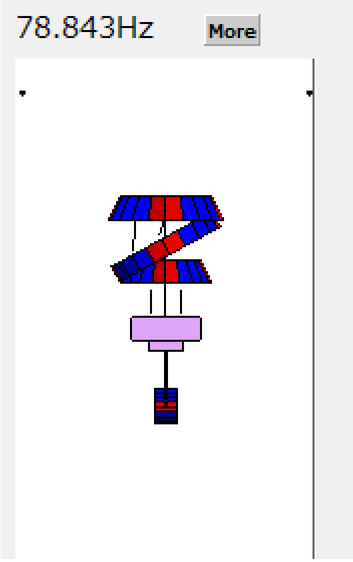
TypeBp SAS
Eigen mode List : 36 modes



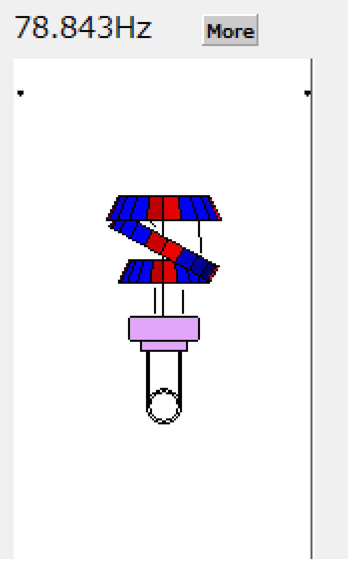
#11
0.659Hz
More
#12
0.659Hz
More
#13
0.849Hz
More
#14
0.9Hz
More
#15
0.901Hz
More
#16
1.011Hz
More
#17
1.017Hz
More
#18
1.022Hz
More
#19
1.186Hz
More
#20
1.186Hz
More


#21
1.261Hz
More
#22
1.261Hz
More
#23
1.351Hz
More
#24
1.352Hz
More
#25
1.369Hz
More
#26
4.906Hz
More
#27
11.611Hz
More
#28
15.924Hz
More
#29
48.97Hz
More
#30
64.629Hz
More

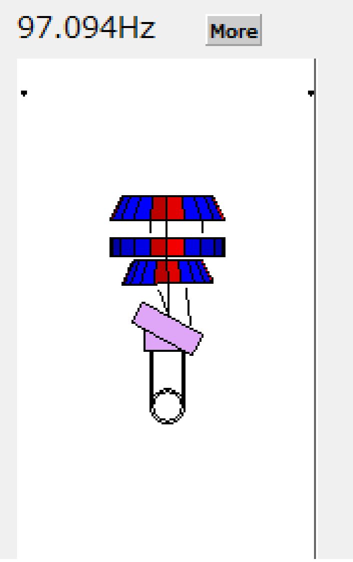
#31



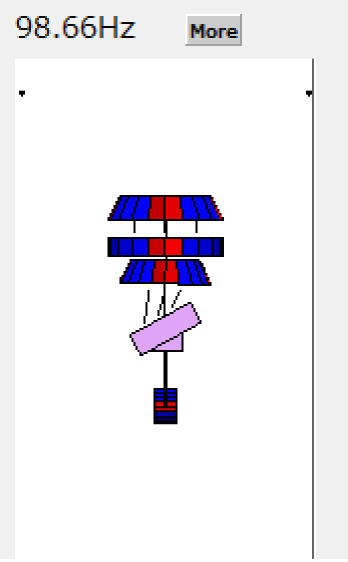
#32



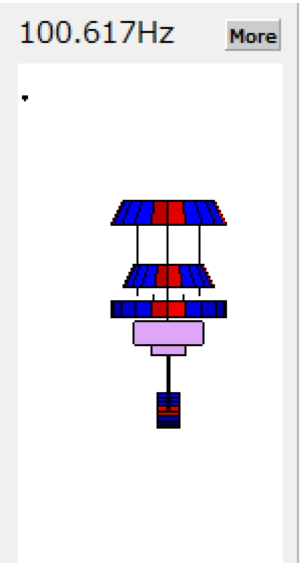
#33



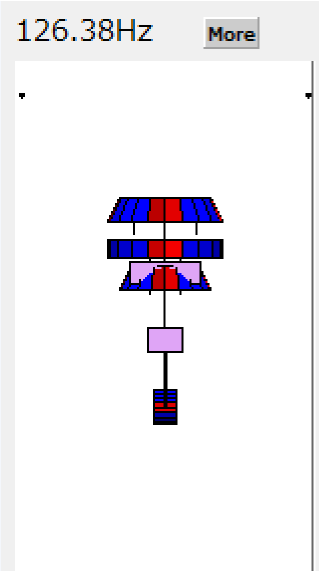
#34

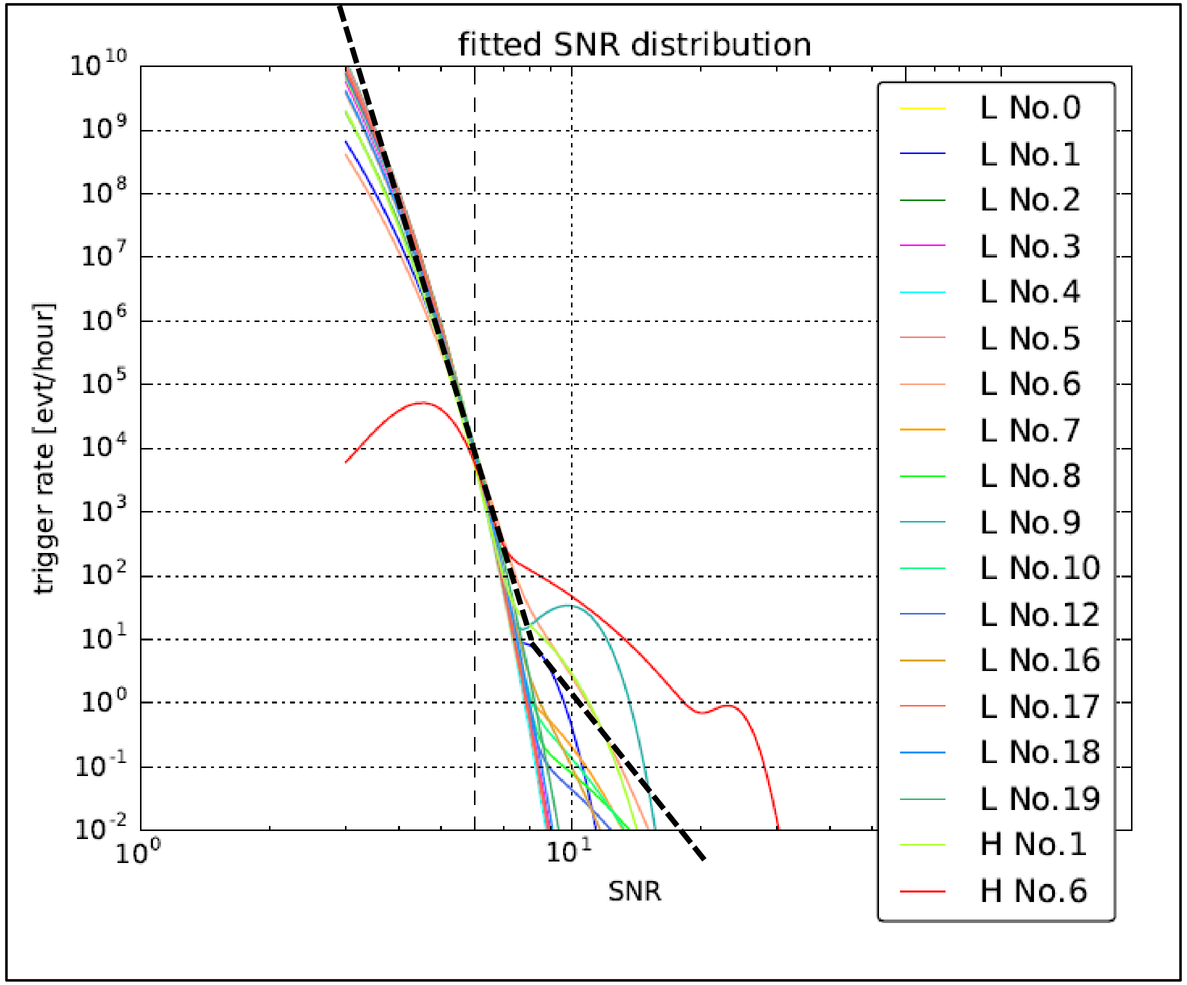


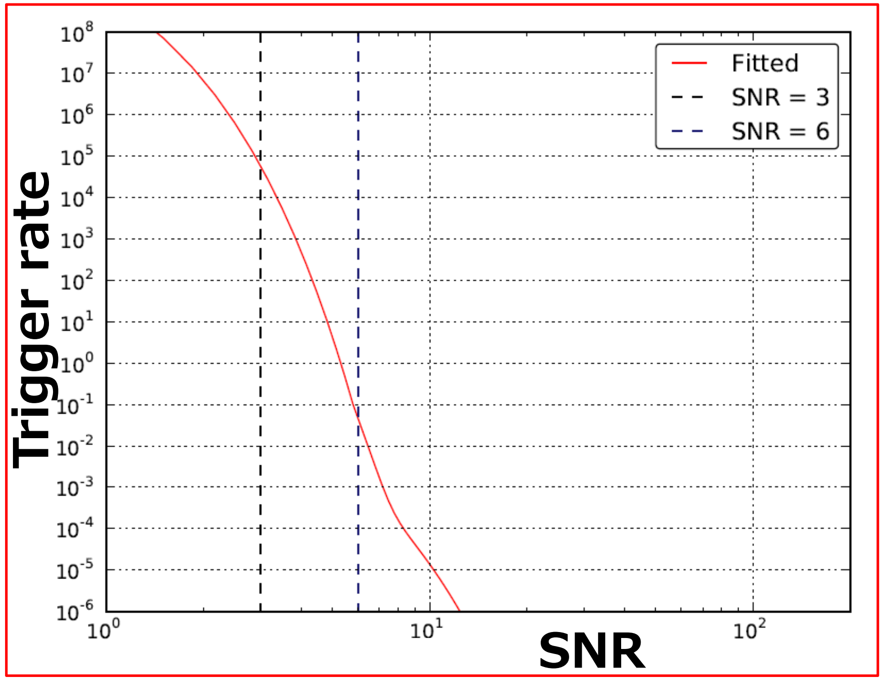
#35



#36




fitted SNR distribution
trigger rate [evt/hour]
SNR
L No.0
L No.1
L No.2
L No.3
L No.4
L No.5
L No.6
L No.7
L No.8
L No.9
L No.10
L No.12
L No.16
L No.17
L No.18
L No.19
H No.1
H No.6

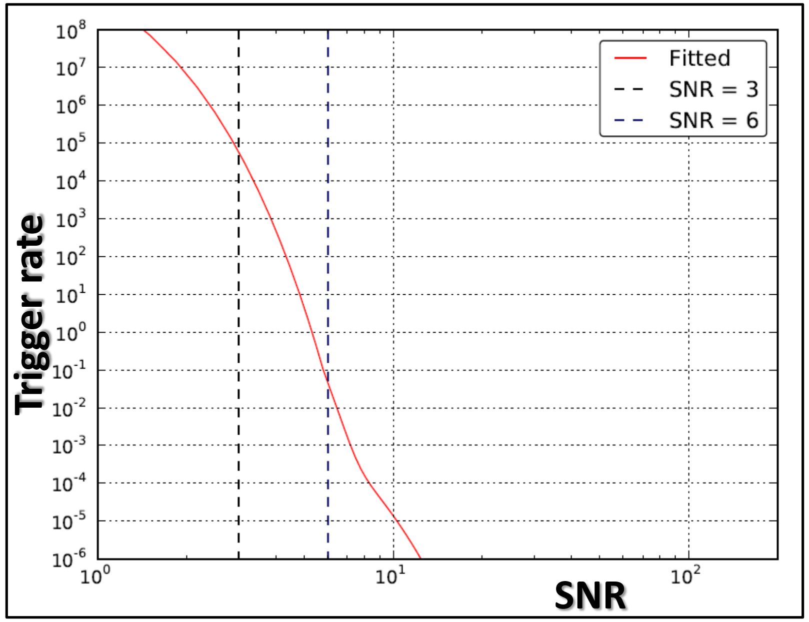

Trigger rate
SNR
Fitted
SNR = 3
SNR = 6

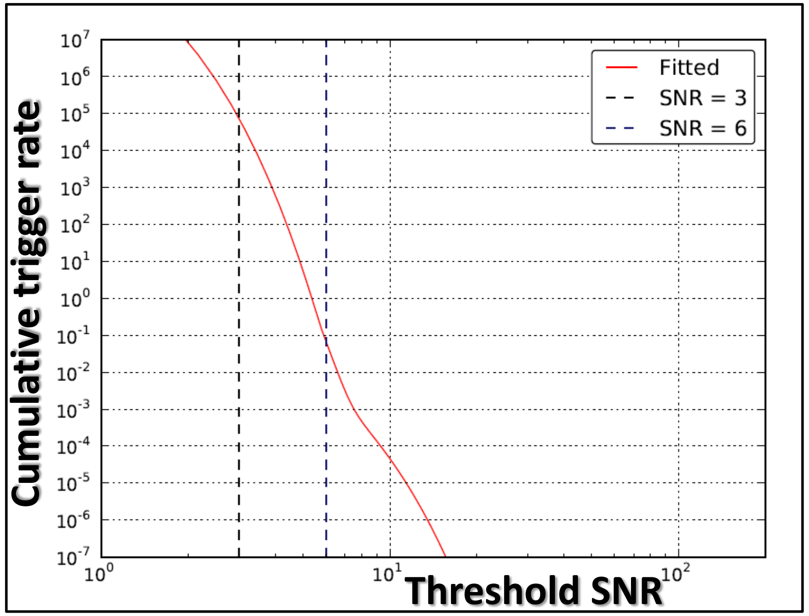
Calculation setup : False Alarm Probability (FAP)

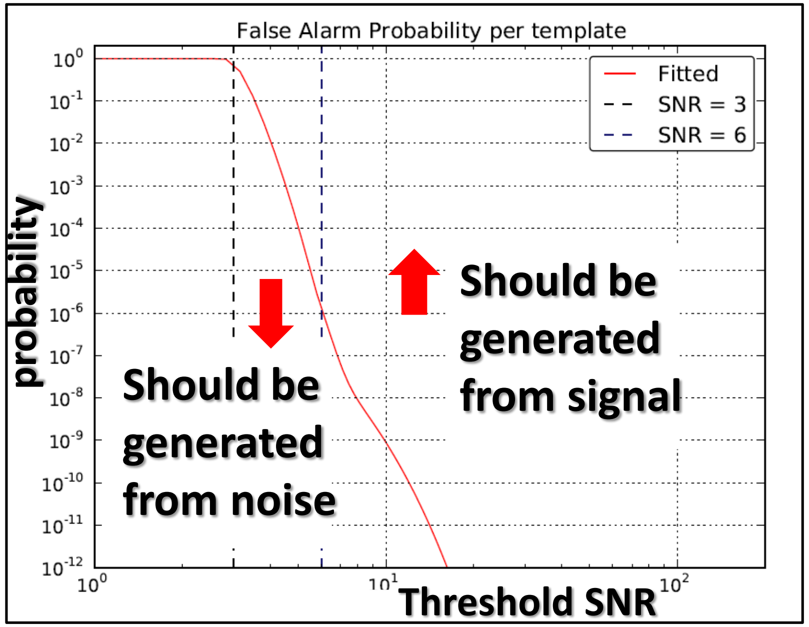
SNR distribution (per template)

Cumulative SNR distribution (per template)

False Alarm Probability (per template)







FAP = $1 - \exp(-R \times T)$

R = cumulative rate of background triggers per template, above a given threshold, per template,

T = analyzing time for the V1 (less sensitive detector)

Calculation setup / 3 detector network by HLV

2. Transform HL into ***HLV*** coincidences.

1) Generating V1 triggers → 2) Mixing V1 triggers

V1 trigger based on random parameters : Vr (from noise)

SNR = random following measurement
Timing = tH1 or tL1
+ random [-35ms:35ms]
Phase = random $[0:2\pi]$

V1 trigger based on injection parameters : Vi (from signal)

SNR = metadata + Gauss(0,1)
Timing = metadata
+ Gauss(0,0.66 ms*$\frac{6}{\mathrm{SNR}}$)
Phase = measured + Gauss(0,0.25 rad)

Case 1: worst case
HL+Vr, or HL
(Based on ***FAP***)

Case 2: best case
HL+Vi, or HL
(Based on ***SNR***th)

Case 3: Realistic case
HL+Vr, or HL+Vi, or HL
(Based on ***FAP*** and ***SNR***th)

Mixing triggers: HL → HL or HLV

Considered 3 patterns :

Case 1: HL → HL or HL + random V

If p > FAP, otherwise

→ **Noise-based trigger, or HL**

Case2: HL → HL, or HL + V based on injection

If V1 SNR < threshold, otherwise

→ **Signal-based trigger, or HL**

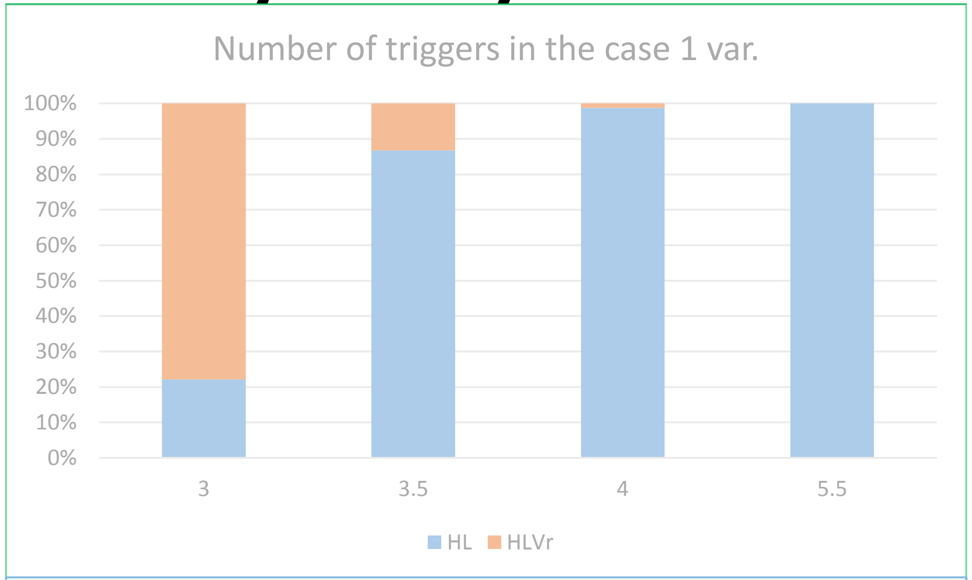
Case 3: HL → HL, or HL + random V, or HL + V based on injection

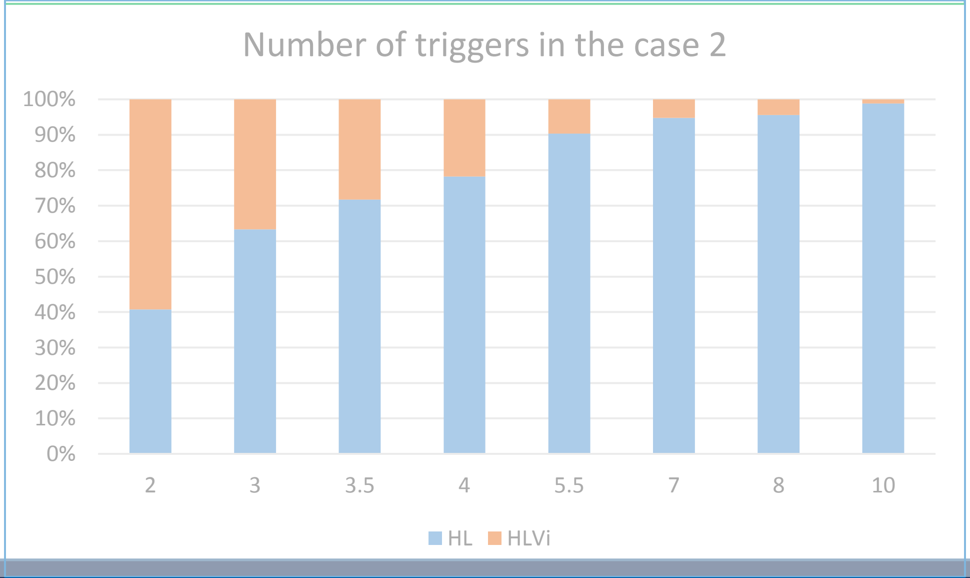
If p > FAP and V1 SNR < threshold, If p < FAP , If p > FAP and V1 SNR > threshold

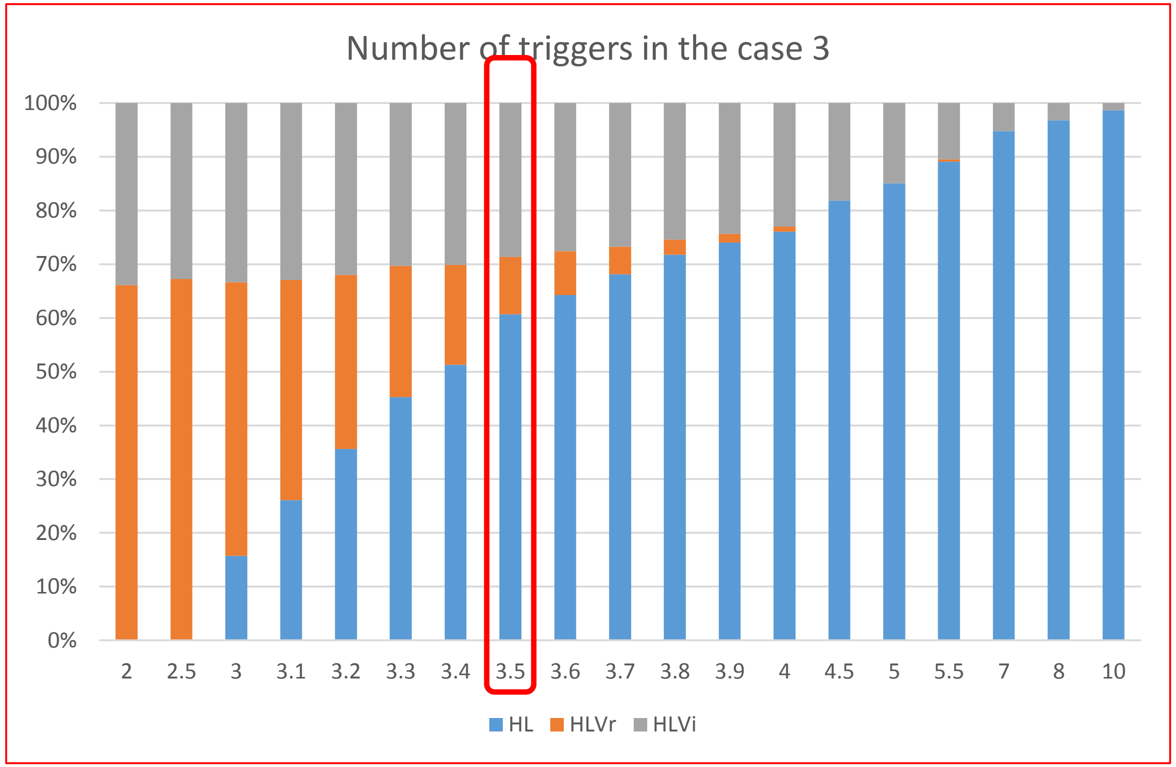
→

1. **Noise-based trigger, or**
2. **signal-based trigger, or**
3. **HL**

Update the sky localization performance in the case 3 : Summary of sky localization performance







<u>3.5</u>

29 %

11 %

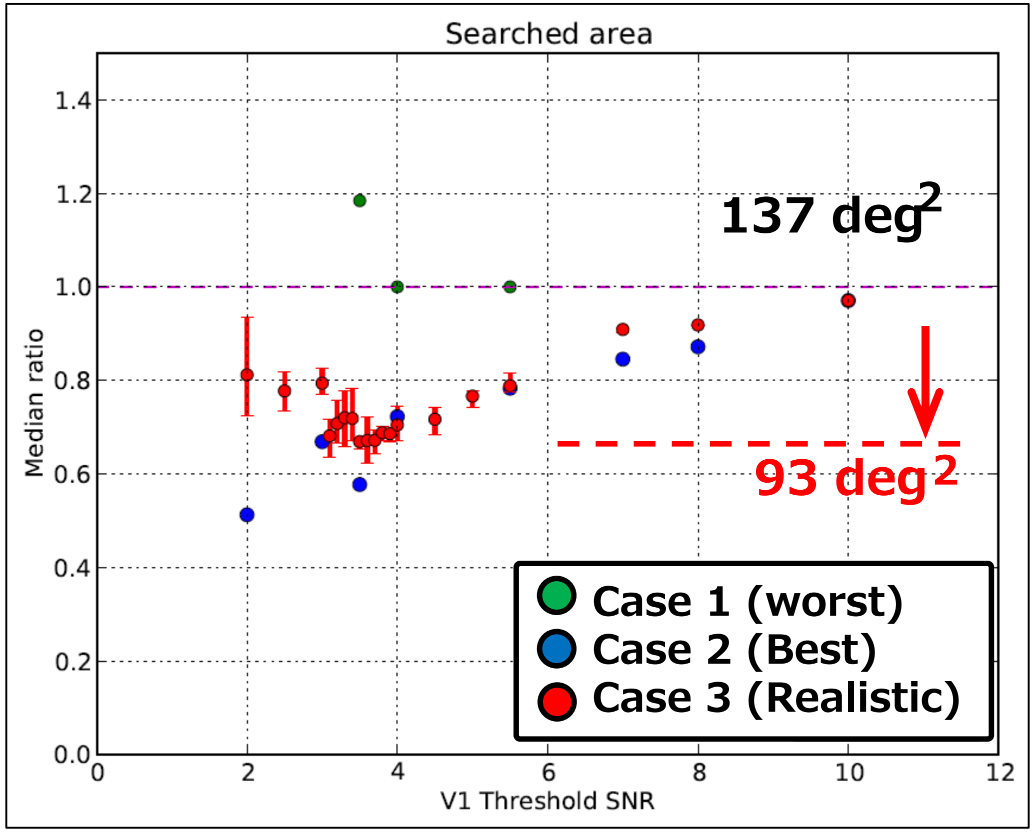
60 %

HLVi = HL + Vinjection

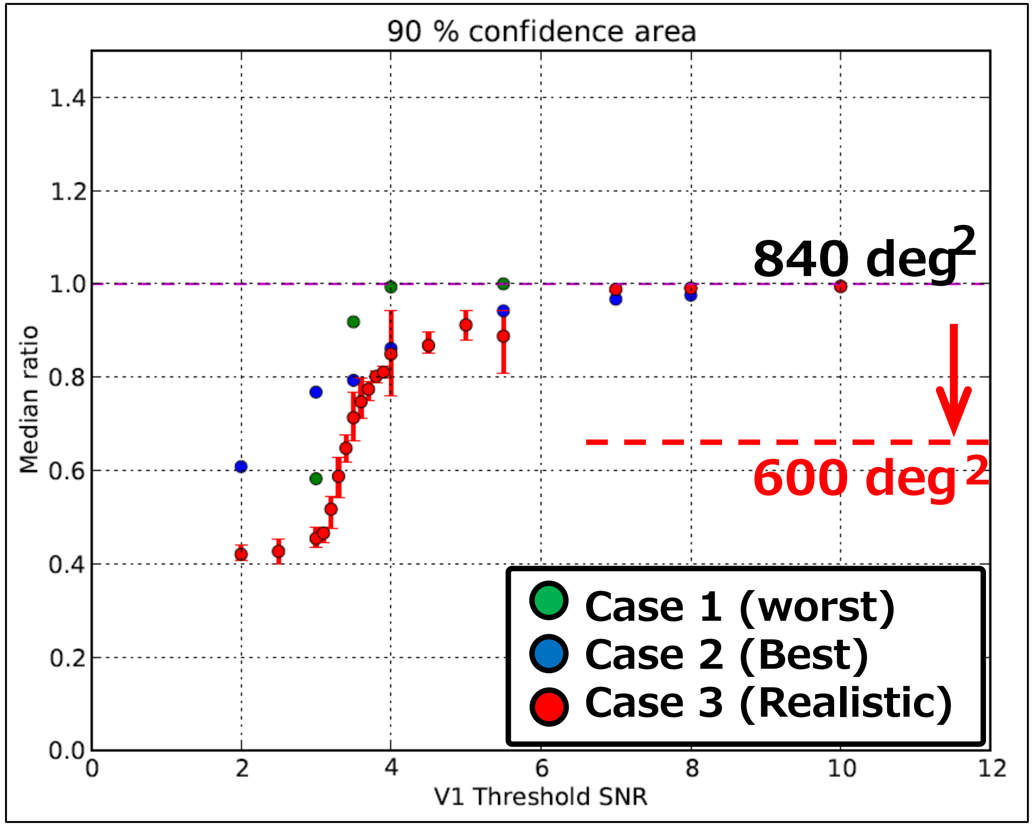
HLVr = HL + Vrandom

HL

Optimization of Virgo threshold :

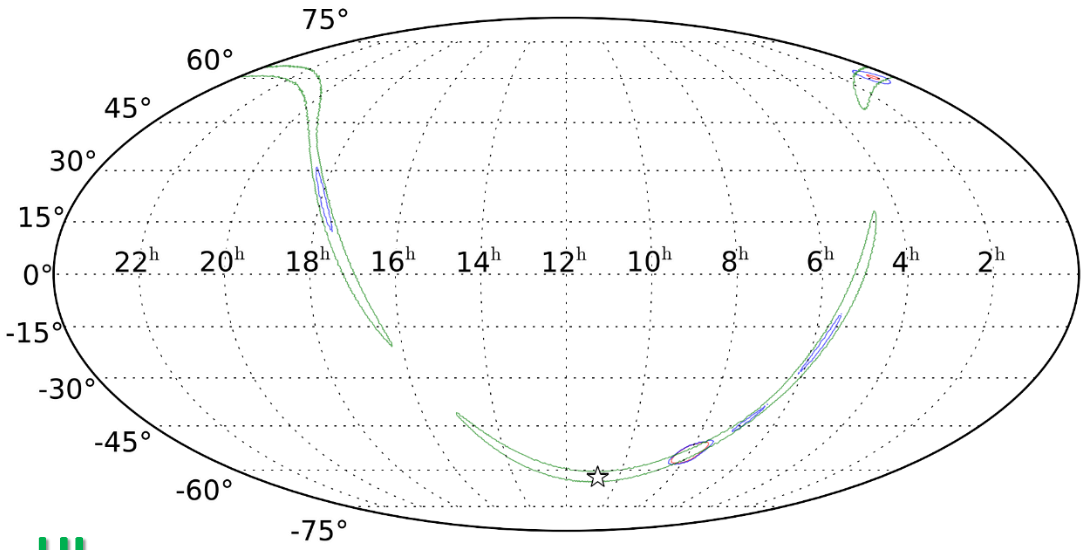


SNR threshold for H, L = 5.

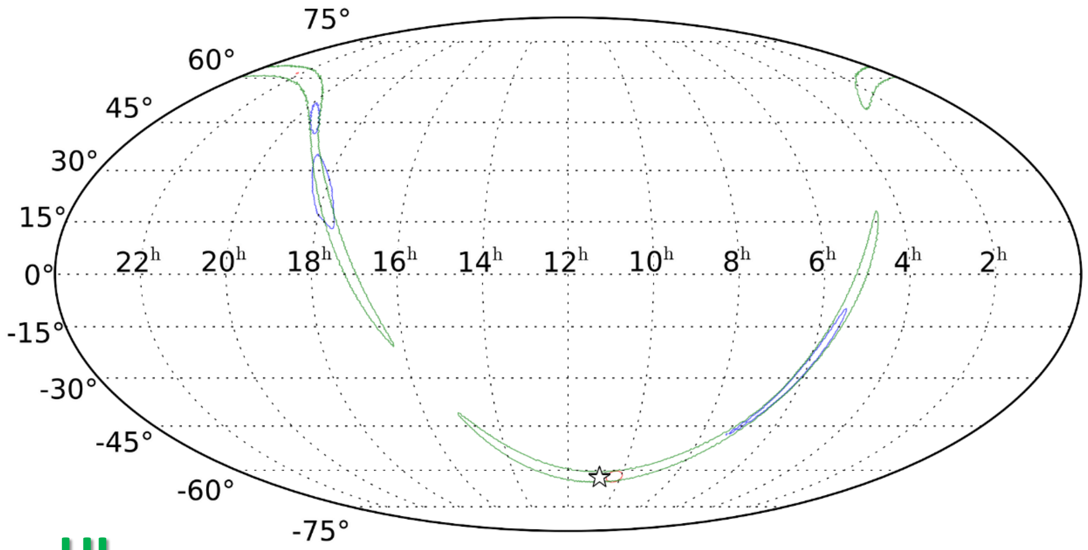


SNR threshold for H, L = 5.

*** Start to generate skymaps with 4 detector (V1, K1 threshold = 3.5)**



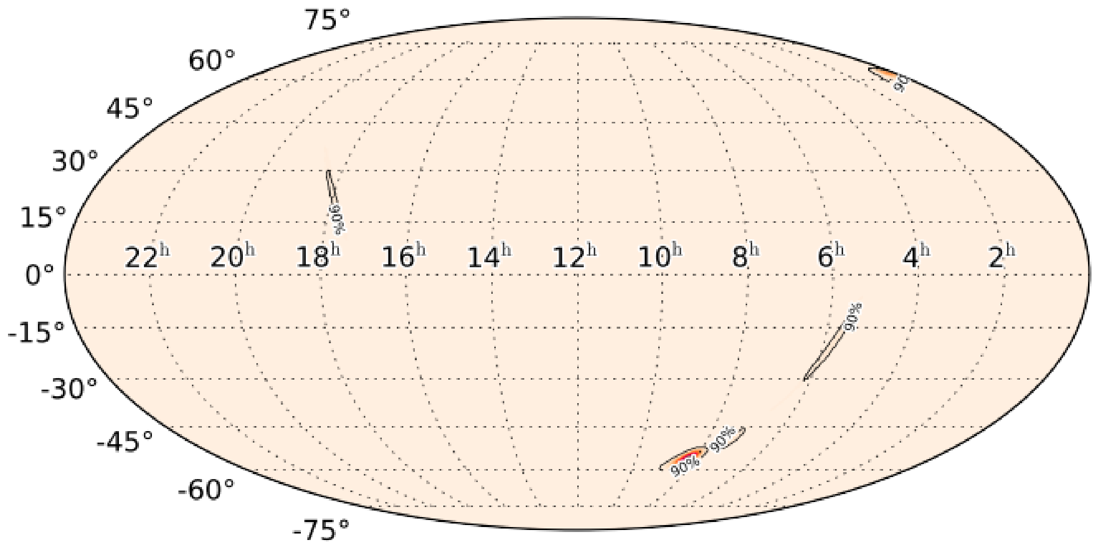
HL
HL + Vrandom
HL + Vrandom + Krandom



HL
HL + Vinj
HL + Vinj + Kinj

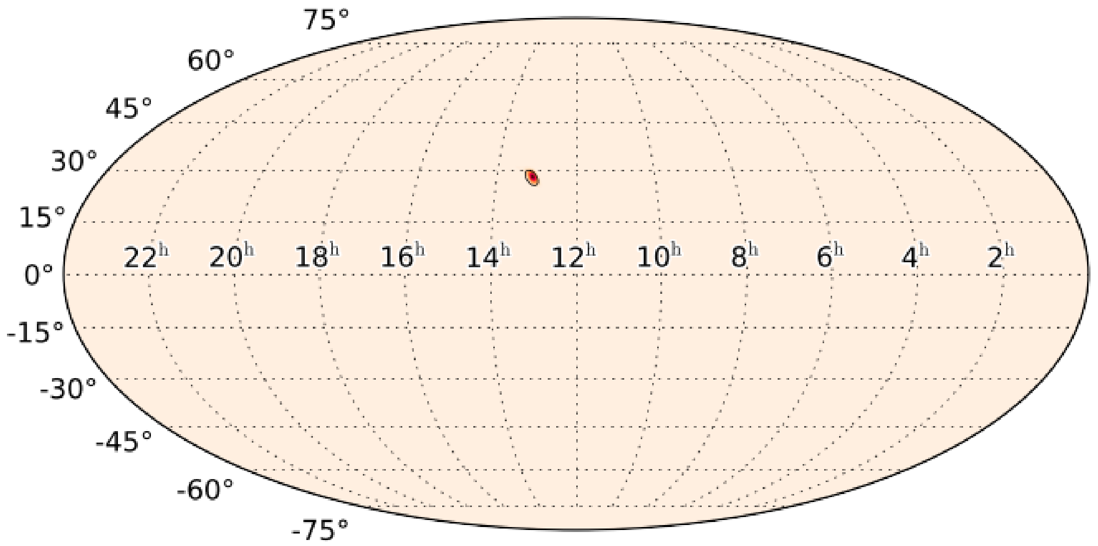
Expected localization performance / by HLV

HL+Vrandom



SNR (H)	SNR (L)	SNR(V)
12.8	11.5	4.5

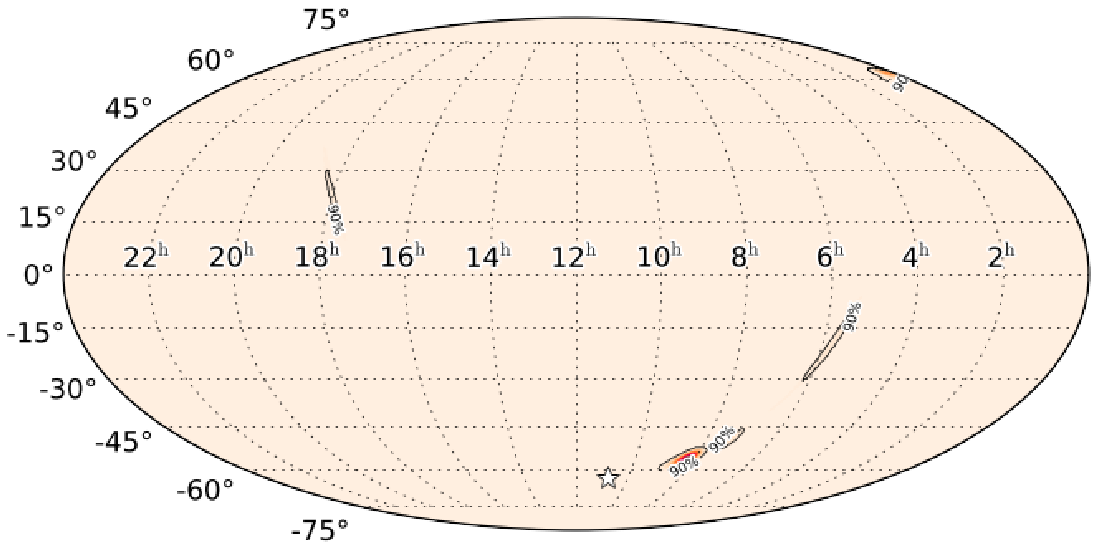
HL+Vinjection



SNR (H)	SNR (L)	SNR(V)
16.5	17.1	3.9

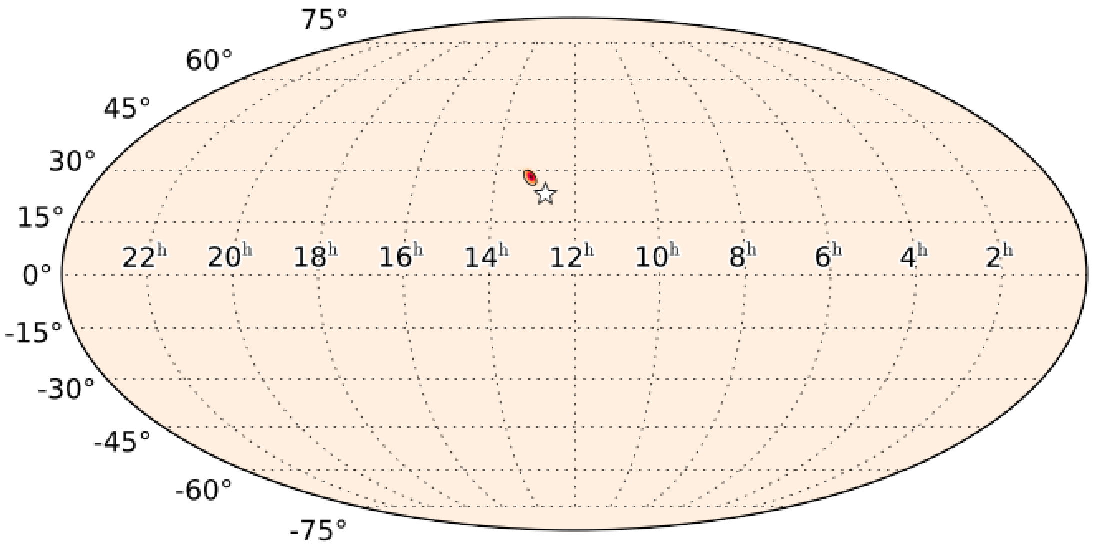
Expected localization performance / by HLV

HL+Vrandom



SNR (H)	SNR (L)	SNR(V)
12.8	11.5	4.5

HL+Vinjection

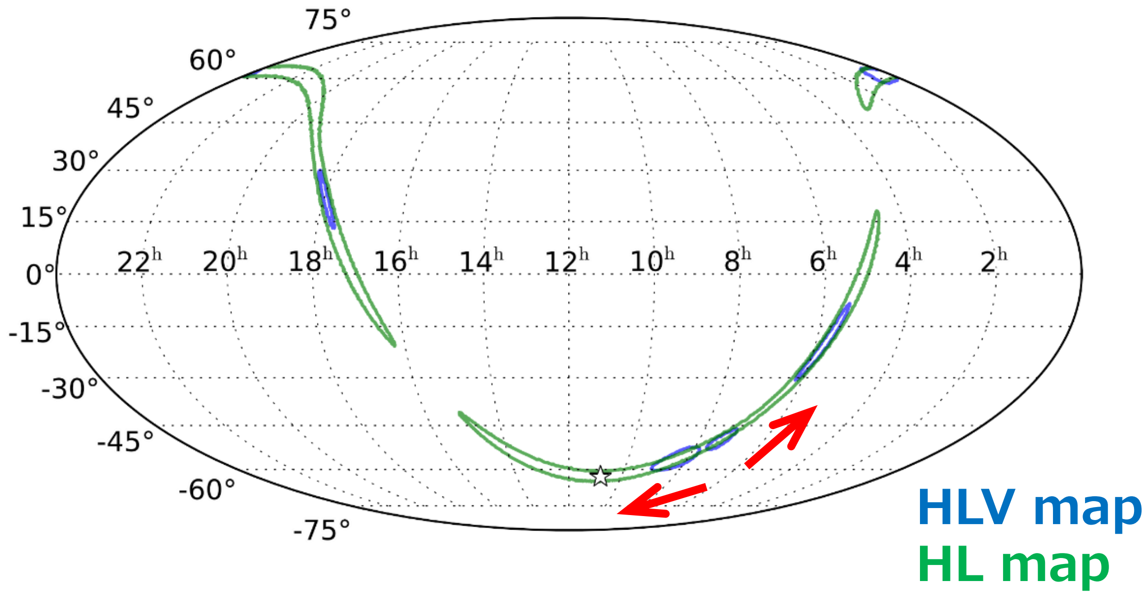


SNR (H)	SNR (L)	SNR(V)
16.5	17.1	3.9

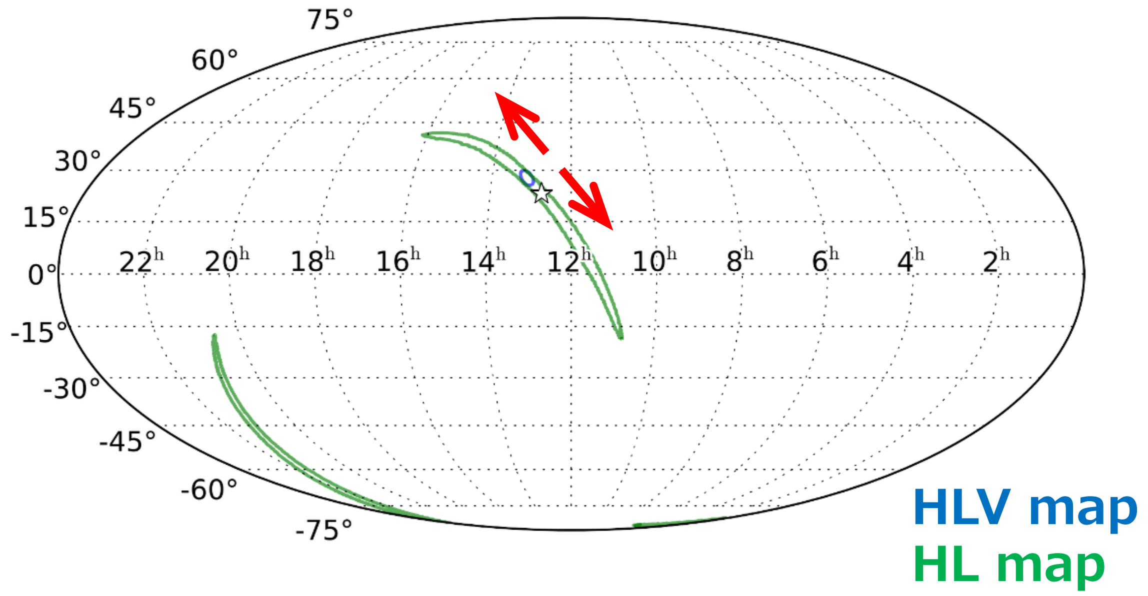
- Typical sky maps in this method
  → sometimes fail to predict the location within 90 % confidence area.

Expected localization performance / by HLV

HL+Vrandom



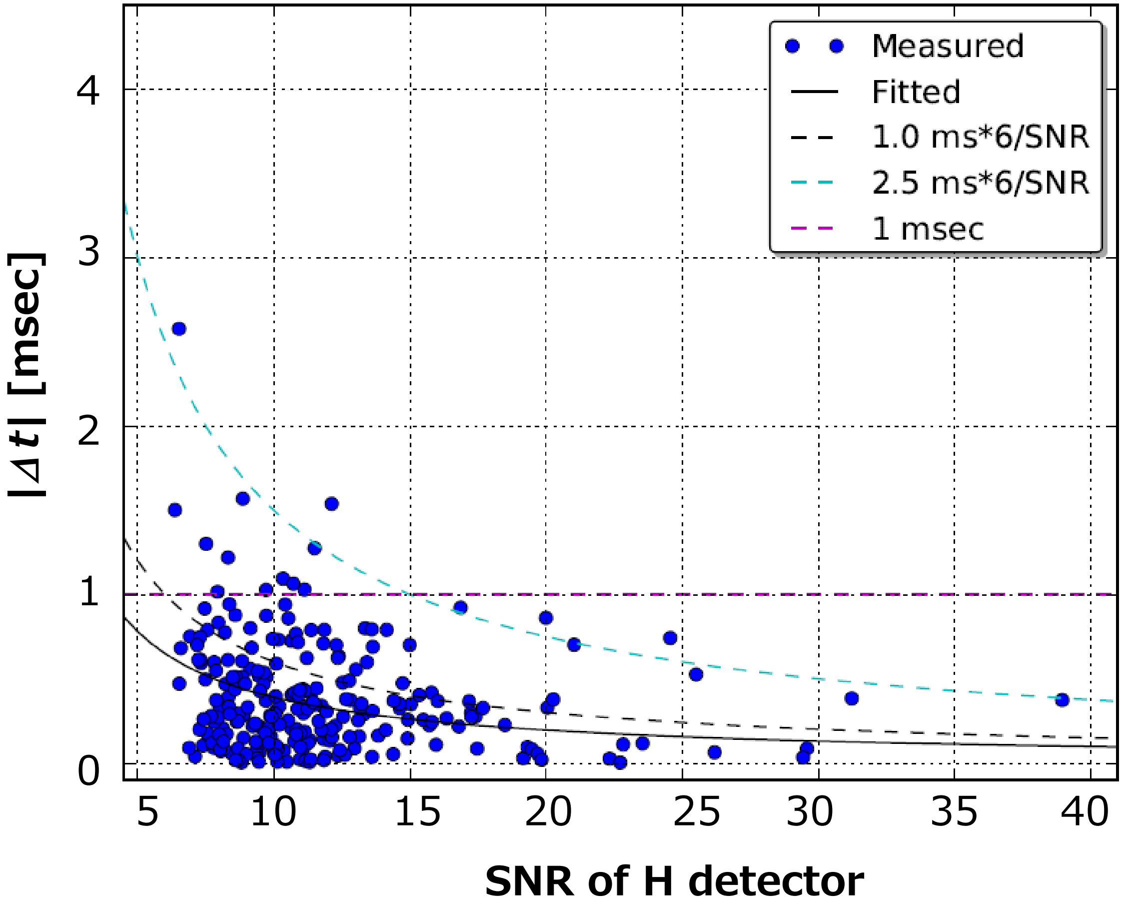
HL+Vinjection



- In this hierarchical network search,
  HLV sky map → If there is no EM-counterpart in HLV map**, HL map**.
- It will be useful for GW-EM follow-up observation.

For further accuracy improvement:

Measured uncertainties on arrival time vs. SNR.



Relation between timing error and SNR

Detected arrival timing has some uncertainties Δt due to:

1) calibration uncertainty
2) discrepancies of templates.

and so on.

If SNR becomes large, Δt becomes small.

Since, accuracy largely depends on Δt,

For further improvement of accuracy,
→ Necessary to reduce timing error
→ Necessary to improve sensitivity of GW detectors.

Calculation setup / 4 detector network by HLVK

2. Transform HL into ***HLVK*** coincidences.

1) Generating V1 triggers → **2) Mixing V1 triggers**

V1 trigger based on random parameters : Vr, Kr

SNR = random following measurement
Timing = tH1 or tL1
+ random [-35ms:35ms]
Phase = random $[0:2\pi]$

V1 trigger based on injection parameters : Vi, Ki

SNR = metadata + Gauss(0,1)
Timing = metadata
+ Gauss(0,0.66 ms$*\frac{6}{\mathrm{SNR}}$)
Phase = measured + Gauss(0,0.25 rad)

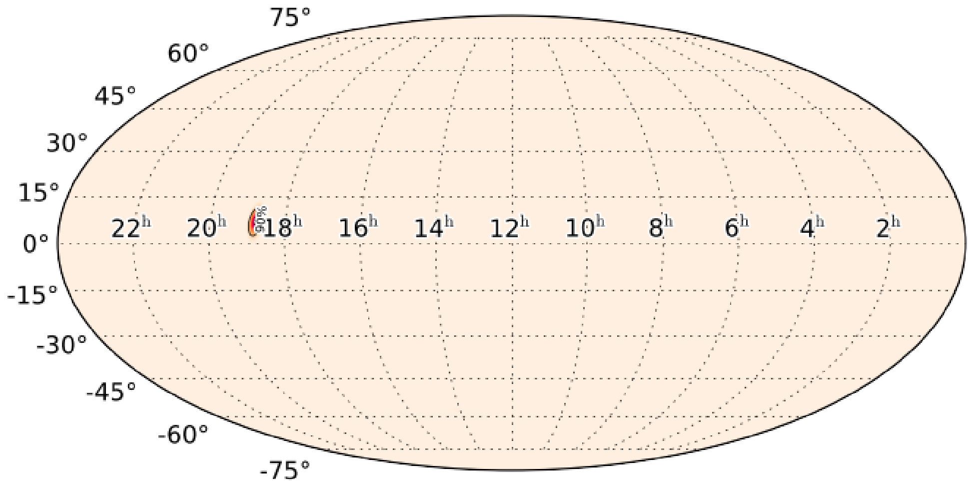
Case 1: worst case
HL+Vr, HL+Kr, HL+Vr+Kr or HL
(Based on ***FAP***)

Case 2: best case
HL+Vi, HL+Ki, HL+Vi+Ki or HL
(Based on ***SNR***th)

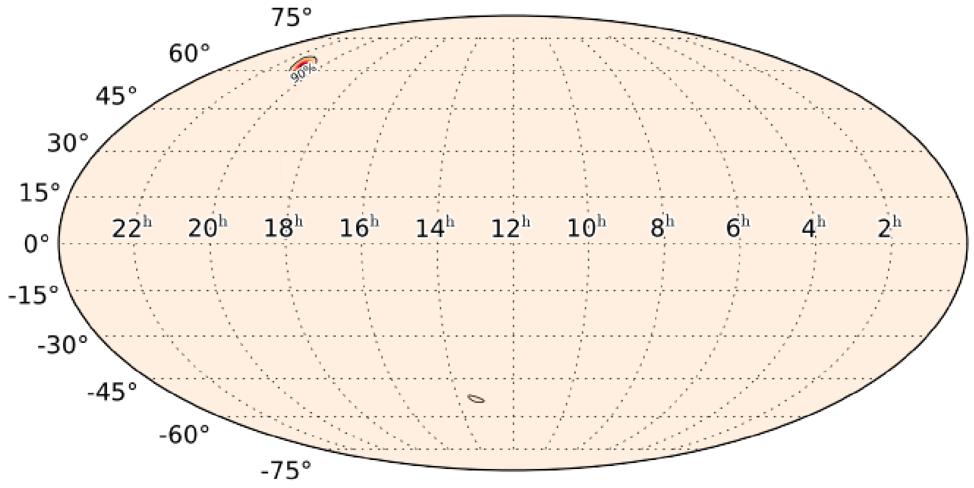
Case 3: Realistic case
HL+Vr, HL+Kr, HL+Vr+Kr,
HL+Vi, HL+Ki, HL+KVi+Ki,
HL+Vr+Ki, HL+ViKr, or HL
(Based on ***FAP*** and ***SNR***th)

Expected localization performance / by HLVK

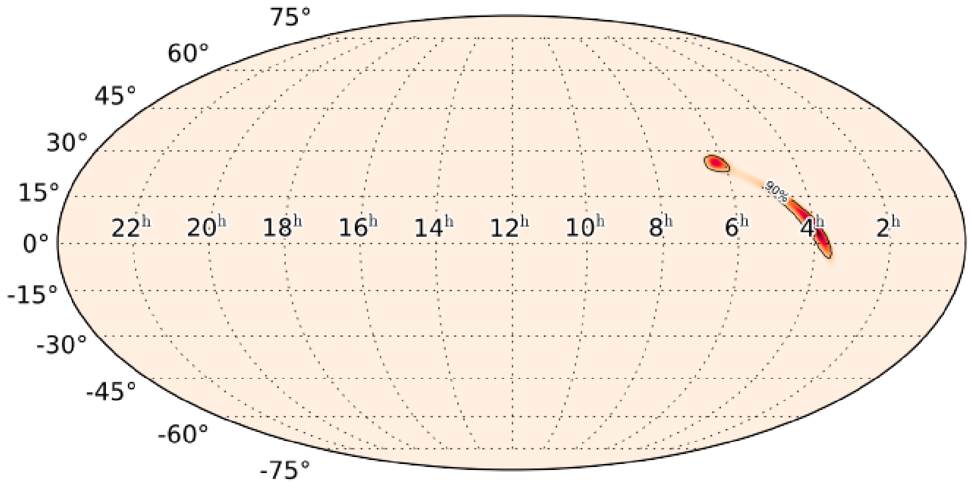
HL + Vi + Ki



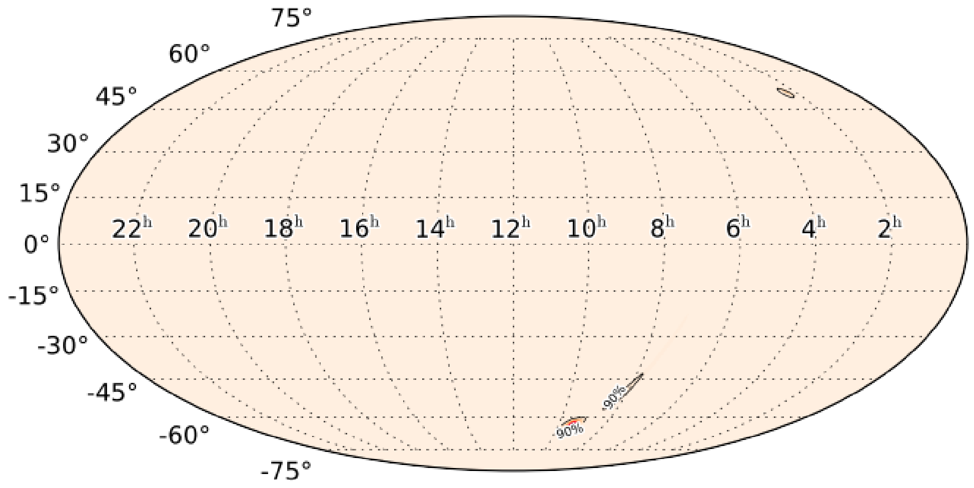
HL + Vr + Kr



HL + Vr + Ki

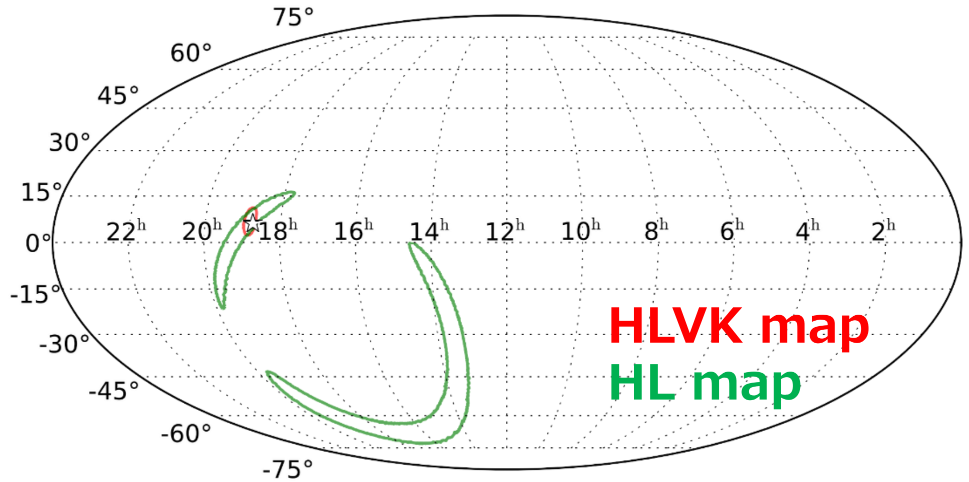


HL + Vi + Kr

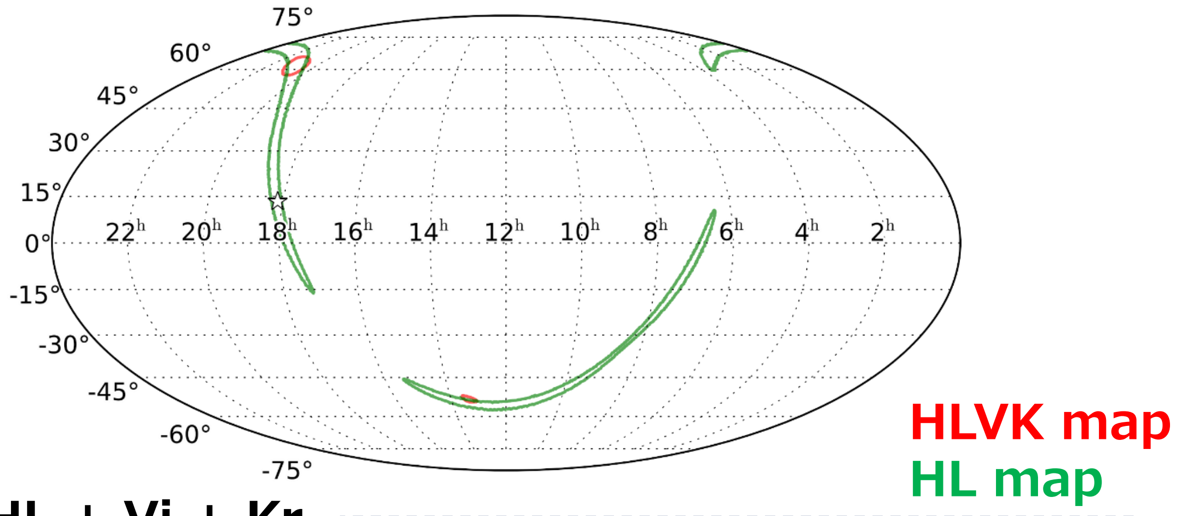


Expected localization performance / by HLVK

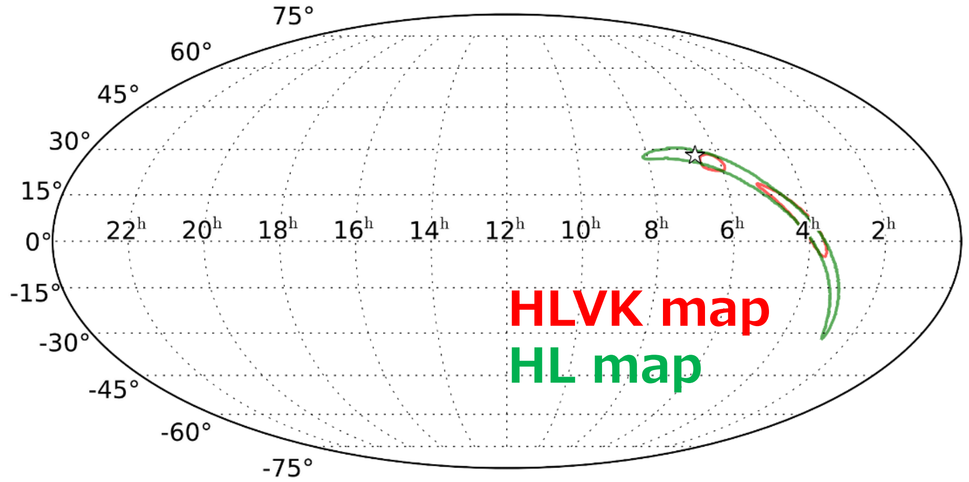
HL + Vi + Ki



HL + Vr + Kr



HL + Vr + Ki



HL + Vi + Kr