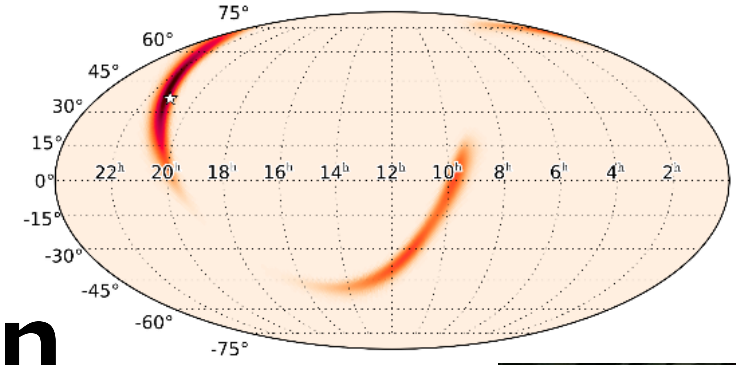
Development of a low frequency vibration isolation system for KAGRA,

and study of the localization of coalescing binaries with a hierarchical network of gravitational wave detectors.

Master’s thesis defense
35-156218
Yoshinori Fujii

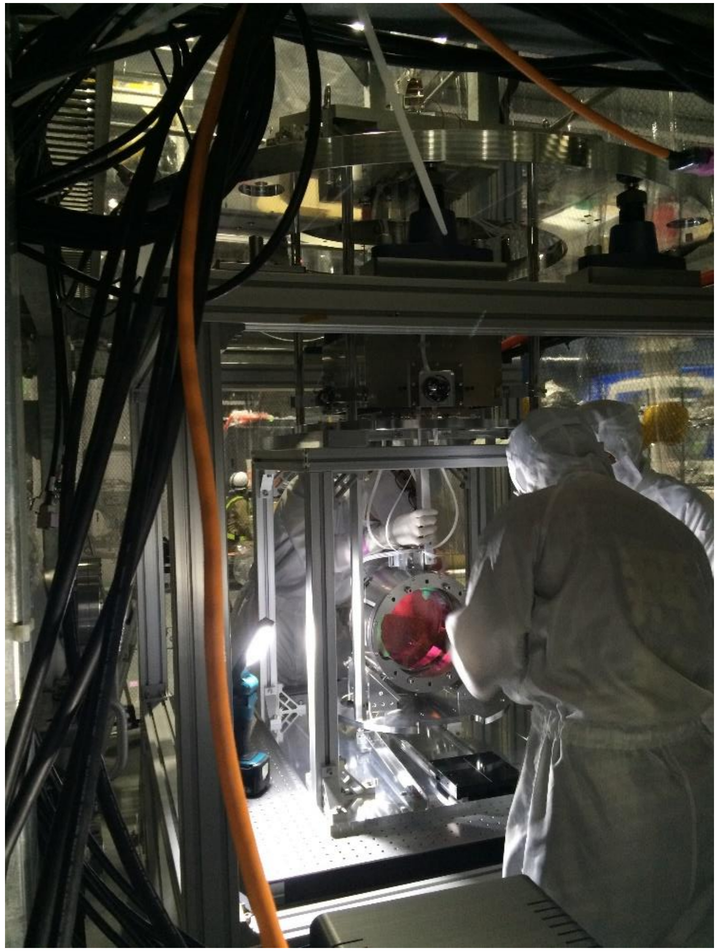
Contents



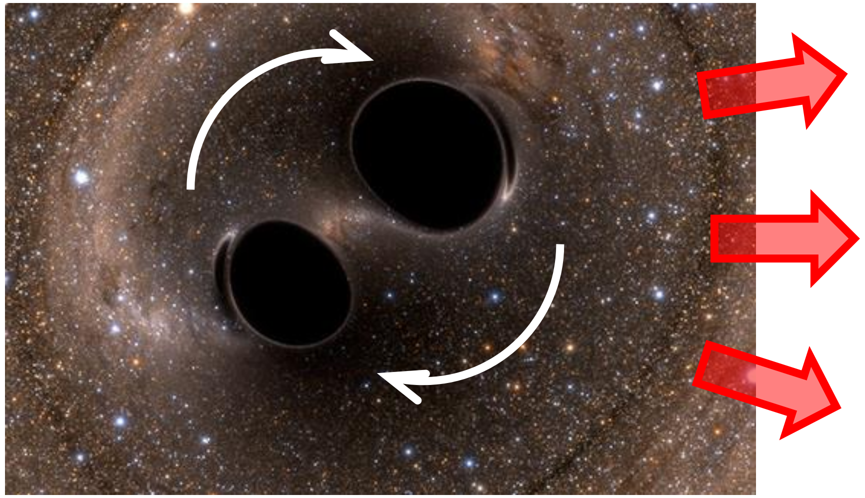
1. Source localization

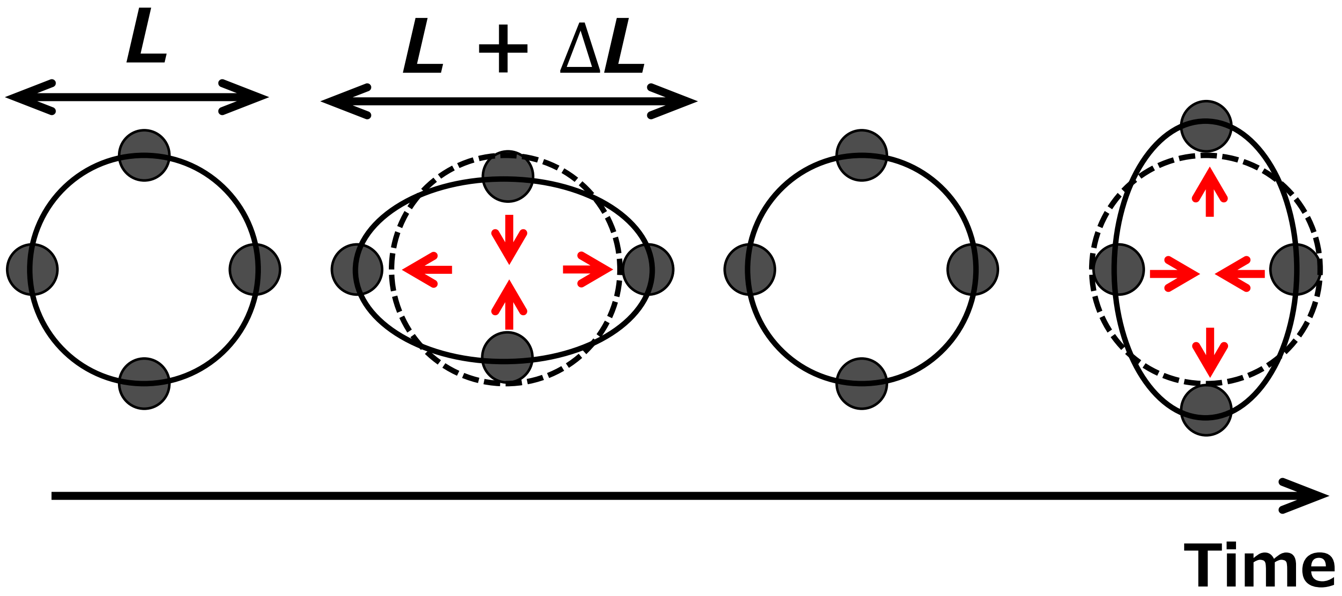
↓

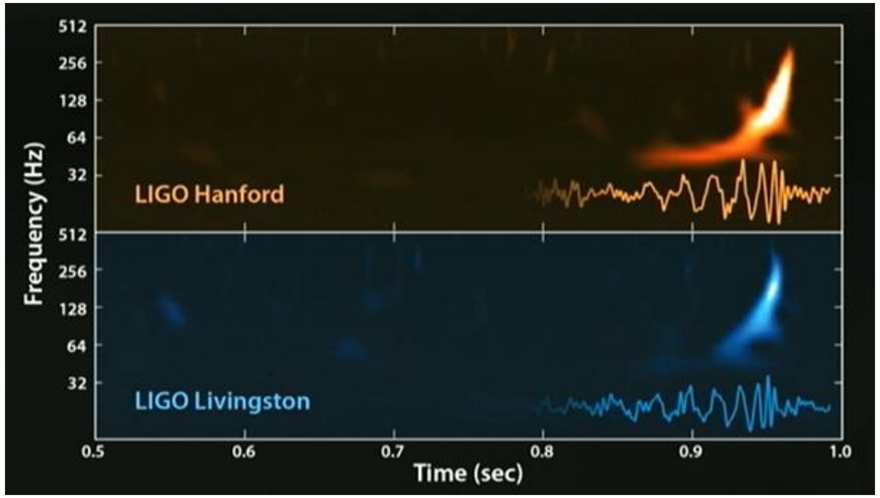
2. Detector development



Gravitational wave







First detection! done!

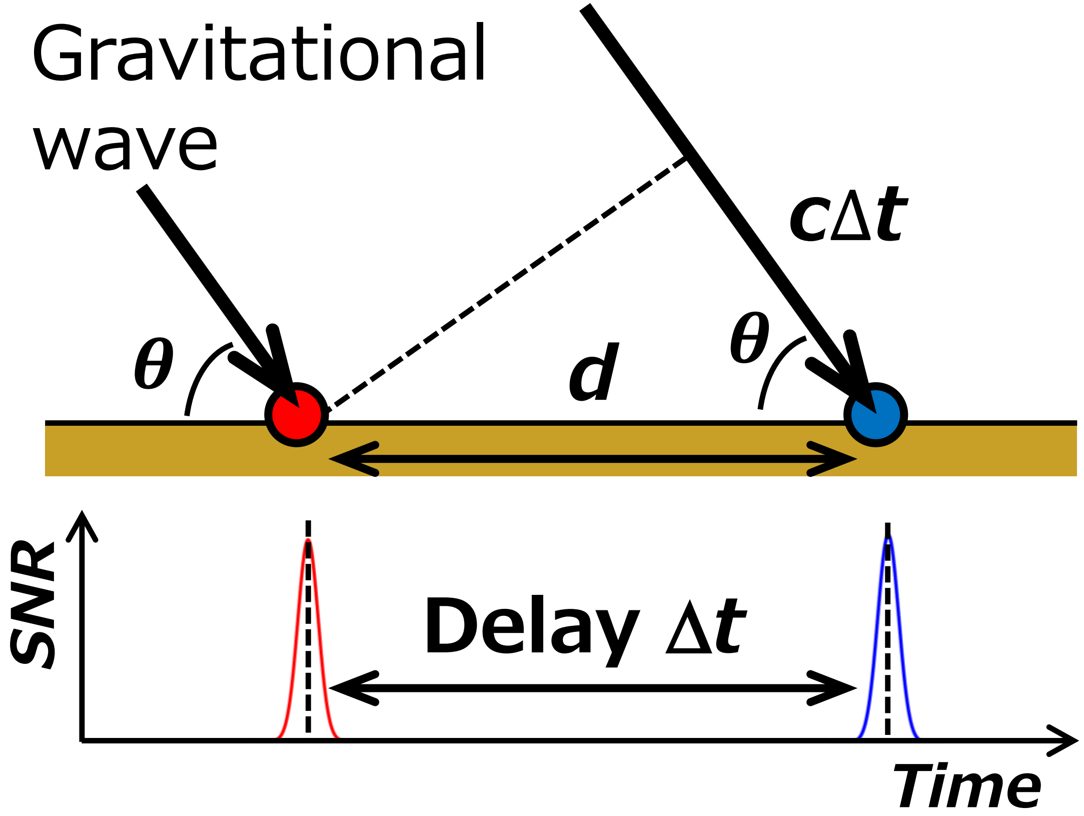
→ New astronomy!

For starting astronomy,

for follow-up observation,

→ Source localization.

From where?



Time delay → Localization

$$\Delta t \longrightarrow \theta$$

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

We want..

Continuous observation

Precise localization

All sky coverage

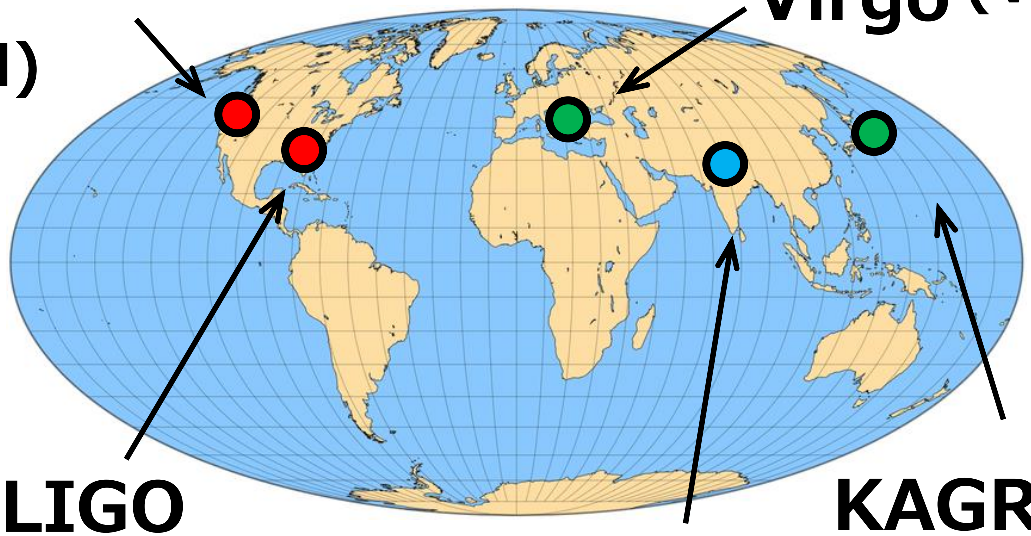
We want..

Continuous observation

Precise localization

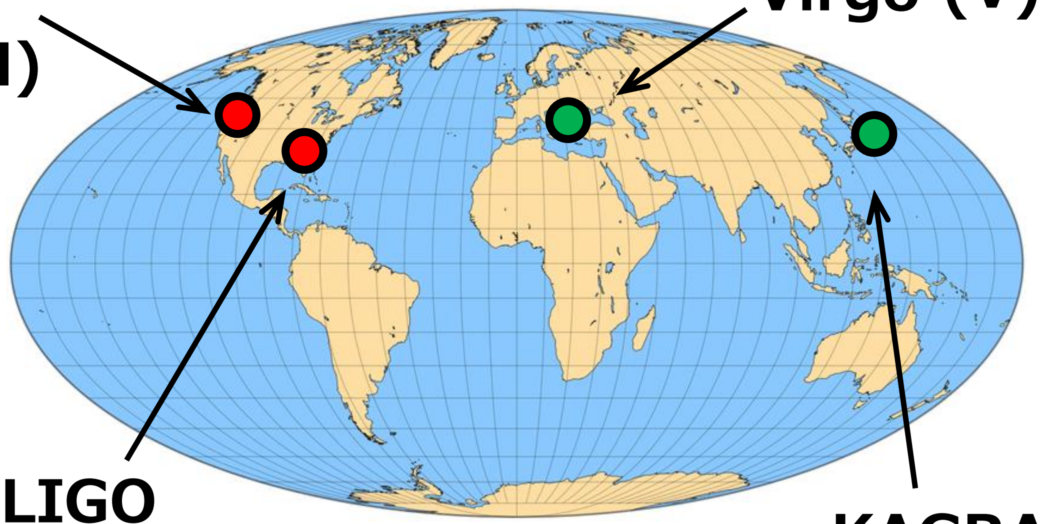
All sky coverage

Source localization
→ **Several detectors!**



Different sensitivities.. OK?

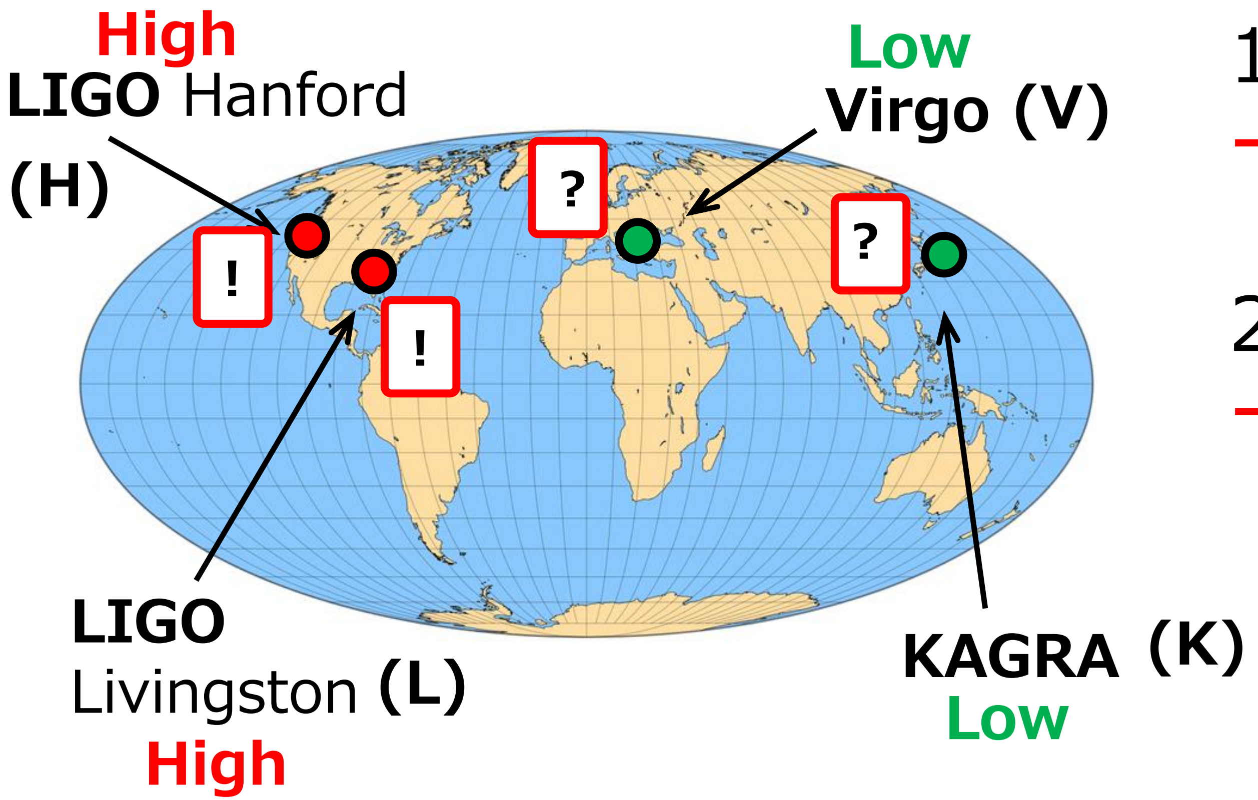
Ex.) SNR > 5 → detection



(At the beginning)

Different sensitivities.. OK?

Ex.) SNR > 5 → detection



(At the beginning)

1) Triple (or more) coincidence
→ Rare

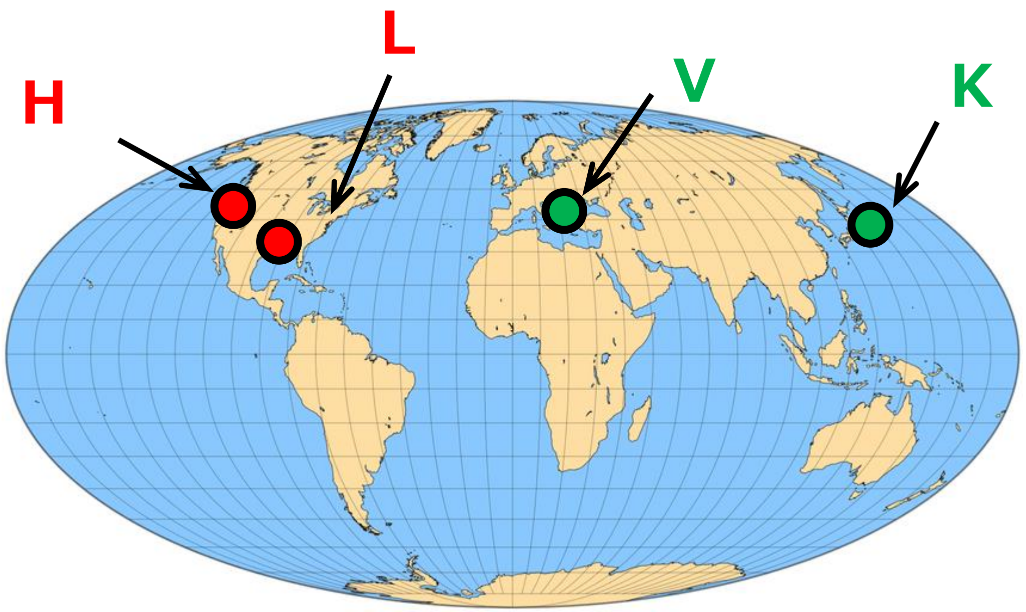
2) Double coincidence
→ Not precise localization

Hierarchical network search

1) Set high/Low sensitivity → higher/lower SNR threshold

2) Analyze high sensitivity detector → low sensitivity detector

Ex.



Hierarchical network search

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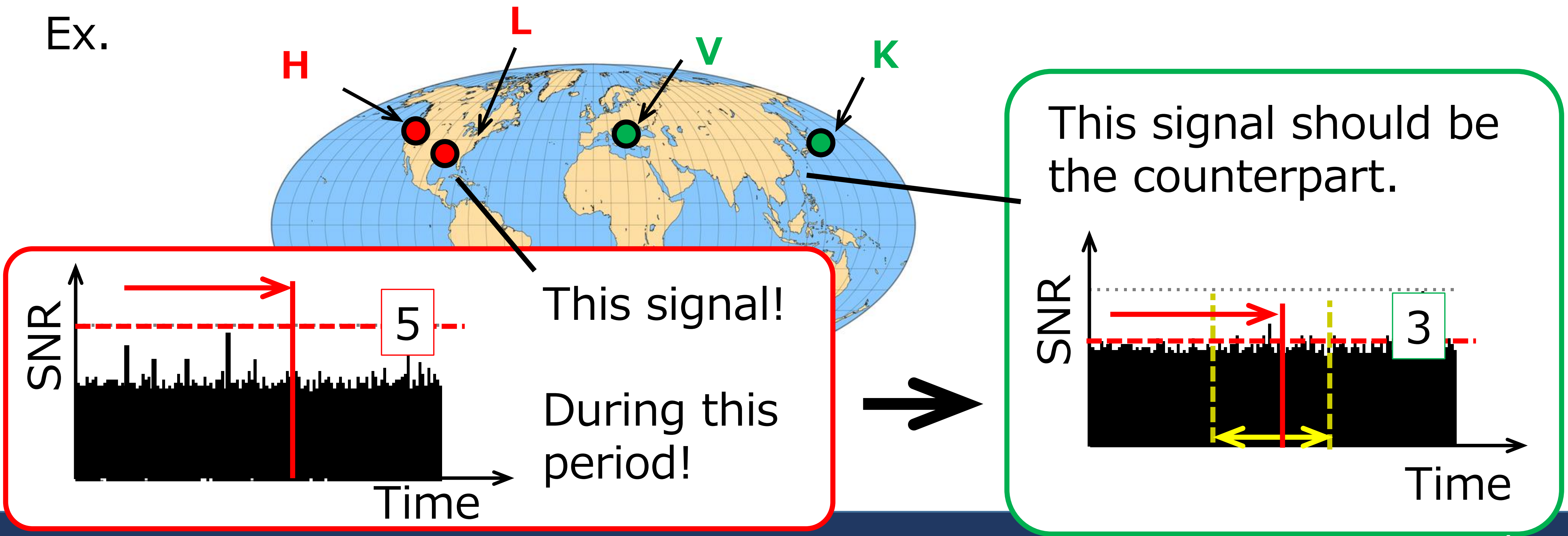


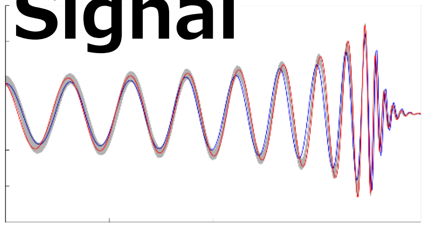
Assumption in calculation

1. GW-EM pipeline for GWs from CBC

1st: MBTA → 2nd: BAYESTAR

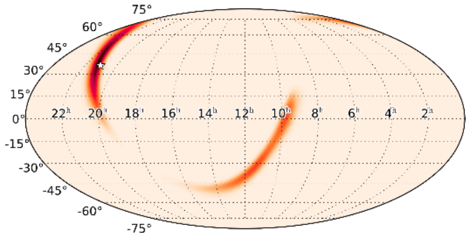
→ GW detectors → MBTA → BAYESTAR → EM telescopes

Signal



Event info:
SNR,
arrival time,
etc.

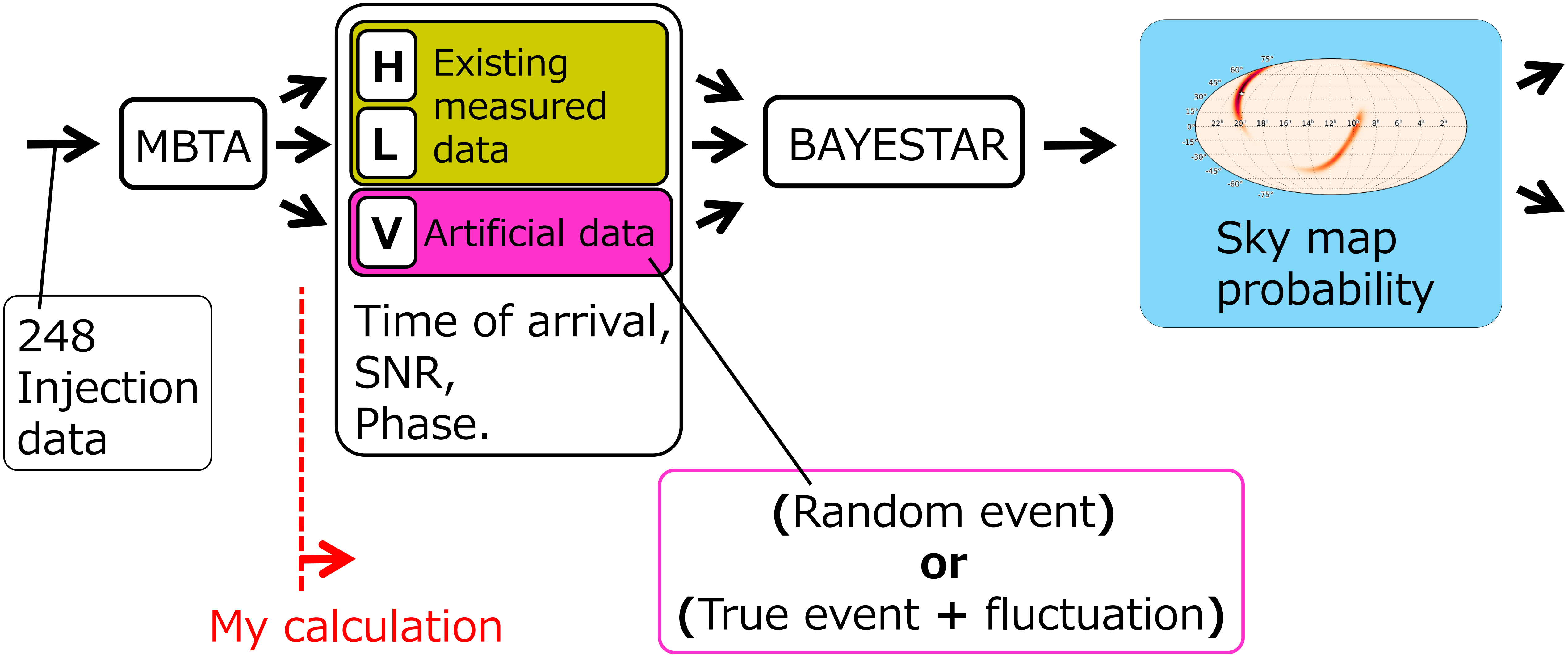
Sky map probability



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

High sensitivity × 2 / Low sensitivity × 1

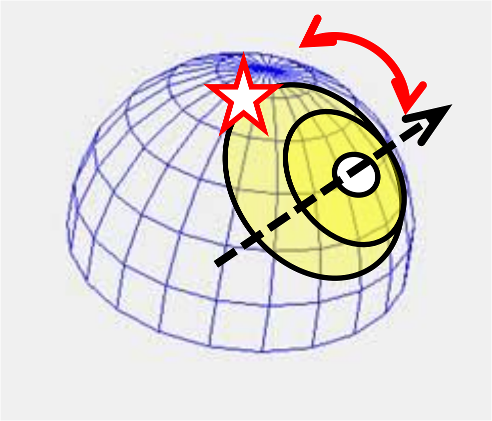
Calculation main flow 1



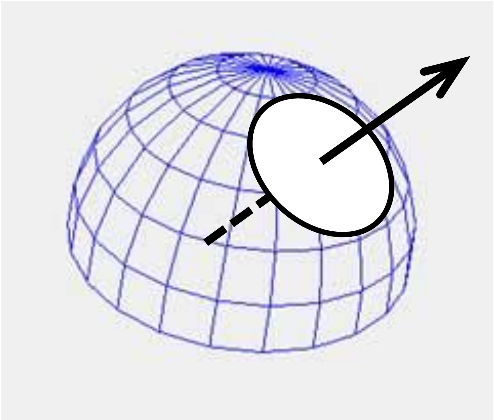
Calculation main flow 2

Localization performance

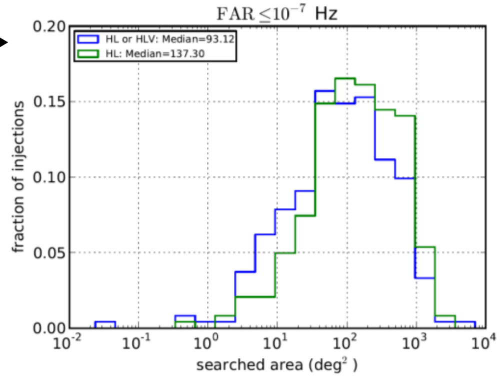
1) **Accuracy**
→ Searched area (deg^2)

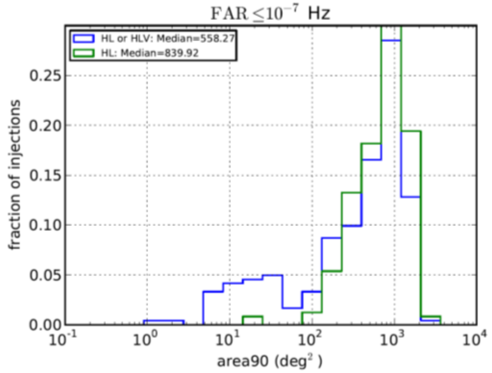


2) **Precision**
→ 90 % confidence area (deg^2)



Histograms from 248 events.

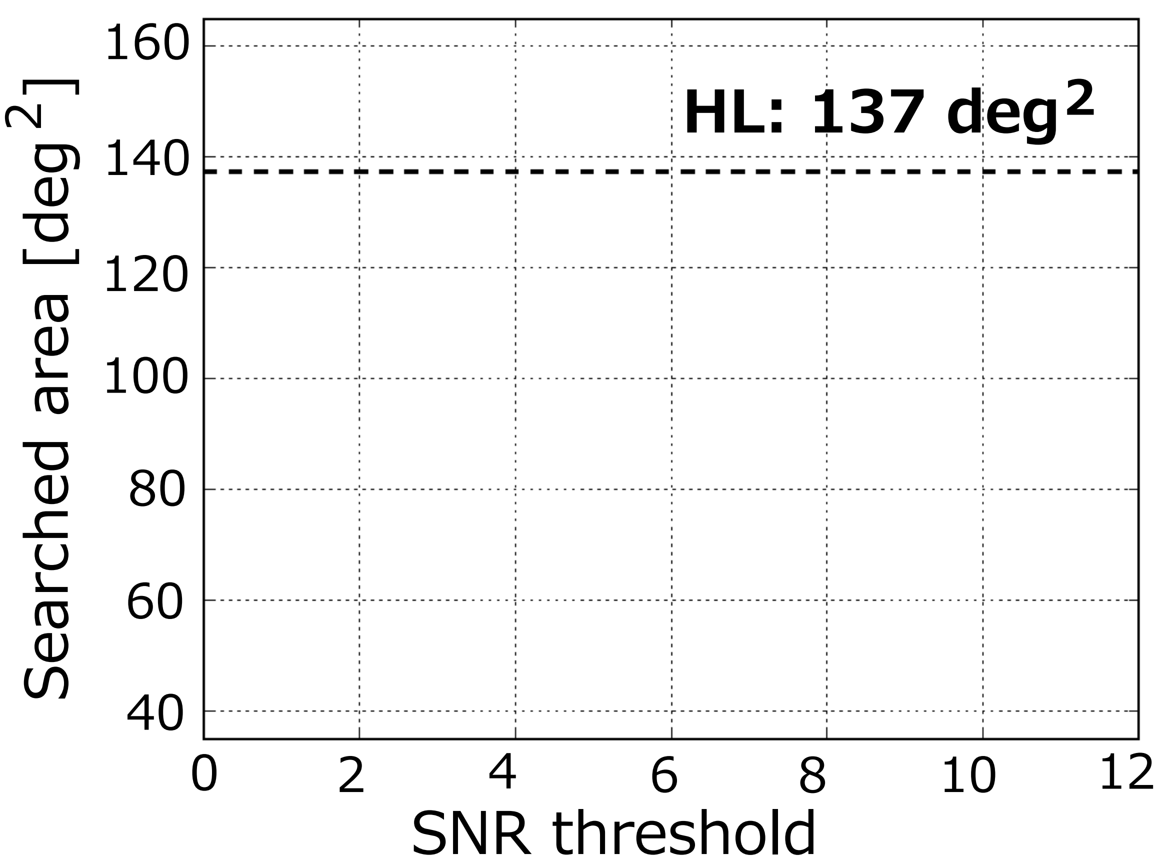


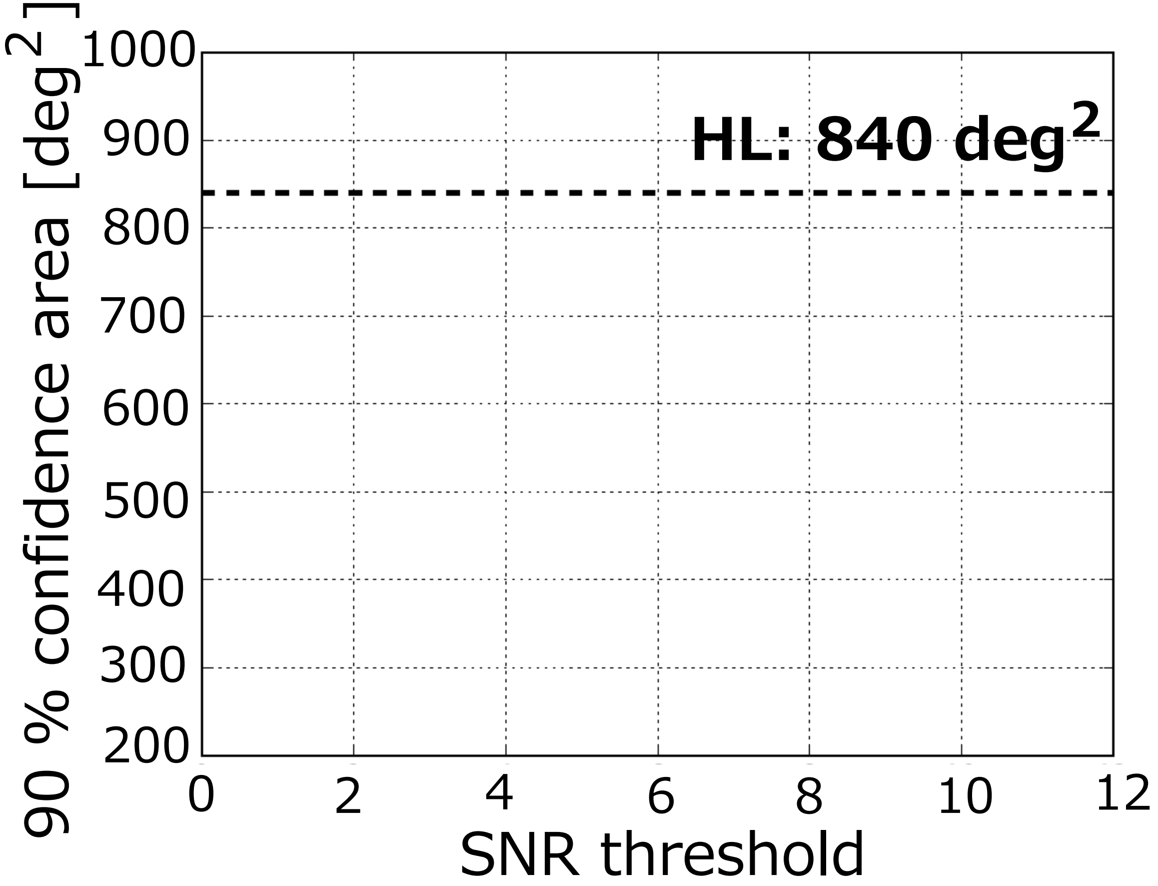


median values

Expected performance, HLV

(SNR threshold for H, L = 5.)





Expected performance, HLV

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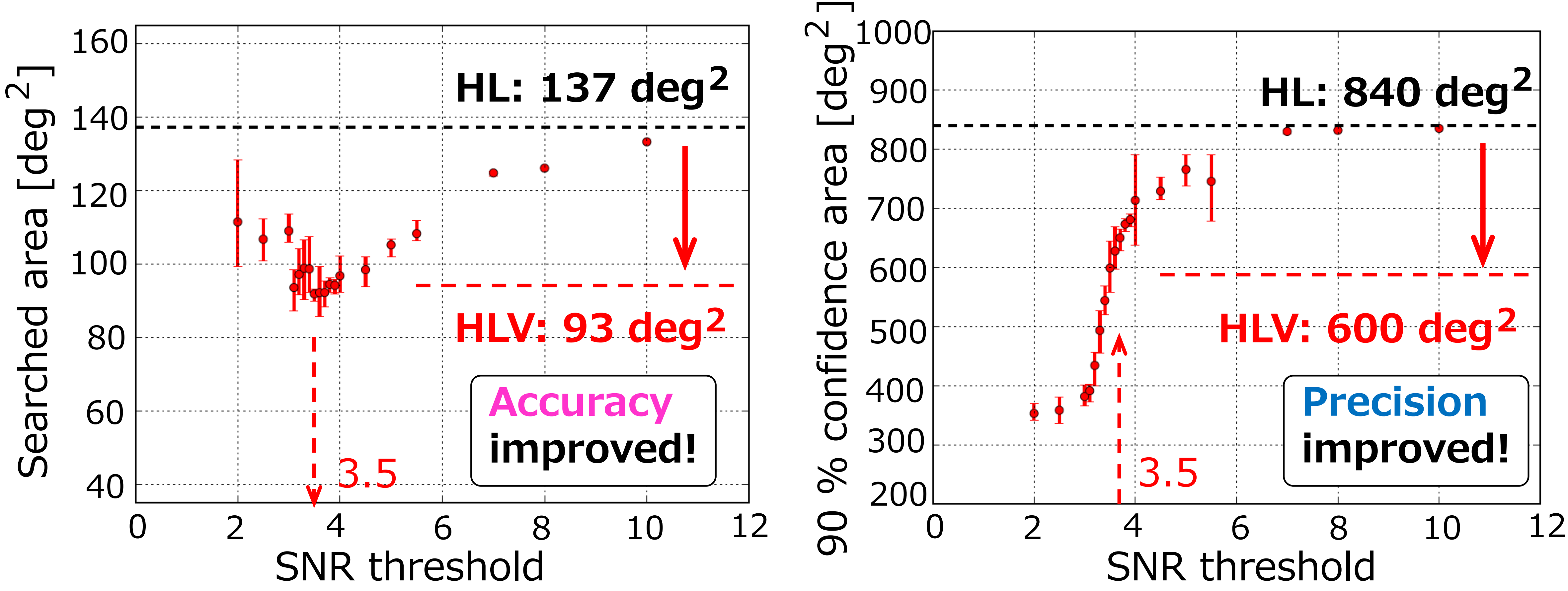
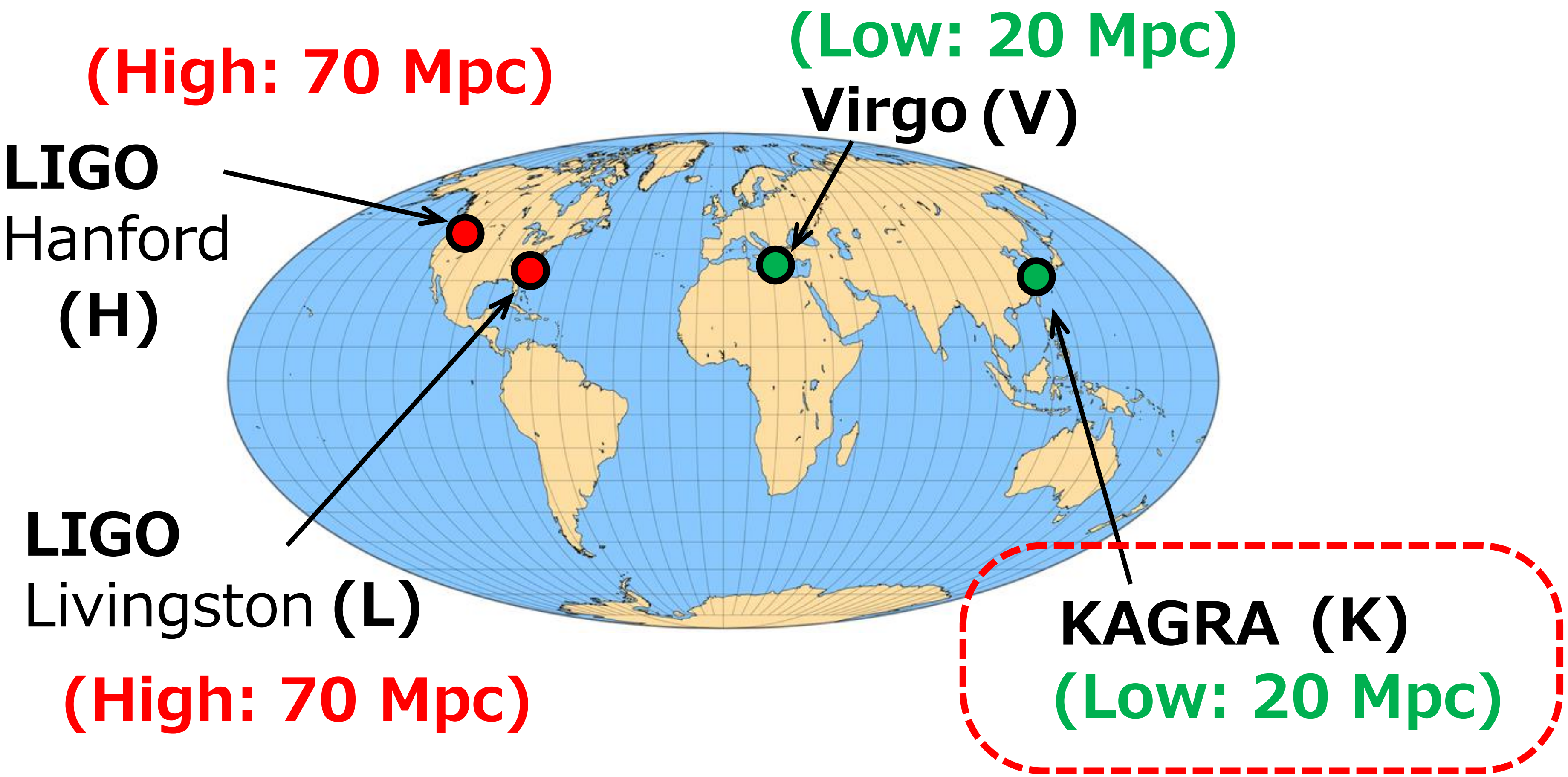


→ By including low sensitivity detector,
errors on sky maps will be reduced by a factor of ~ 0.7 than HL.

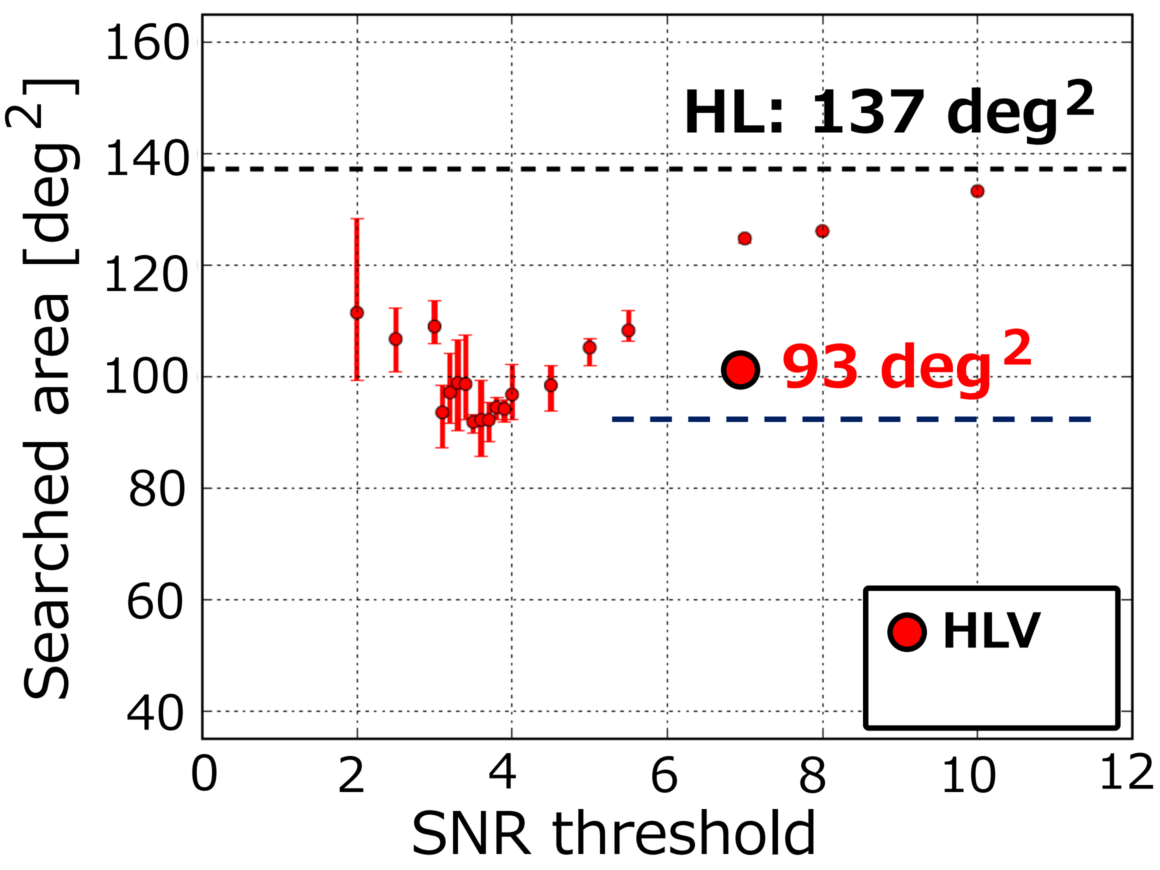
How about 4 detectors, HLVK?

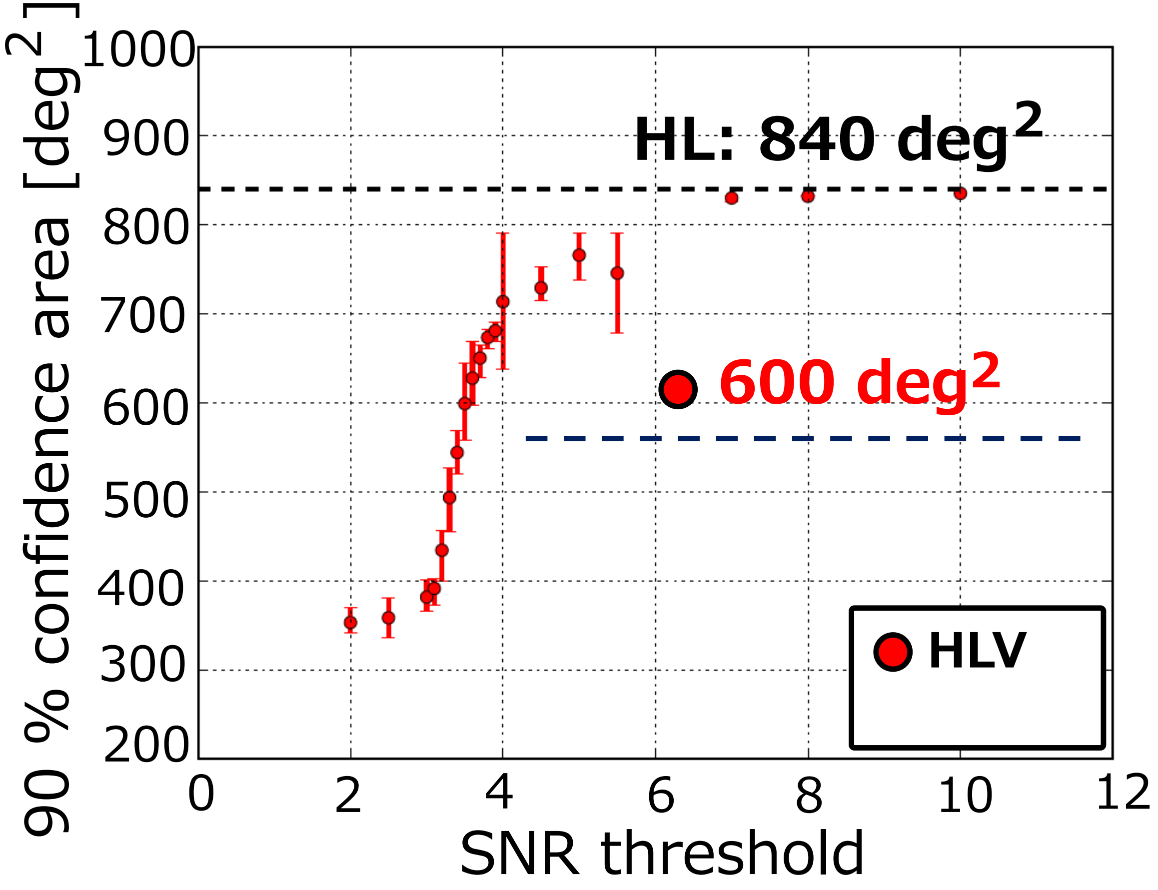


(Assumed situation)

Expected performance, HLVK

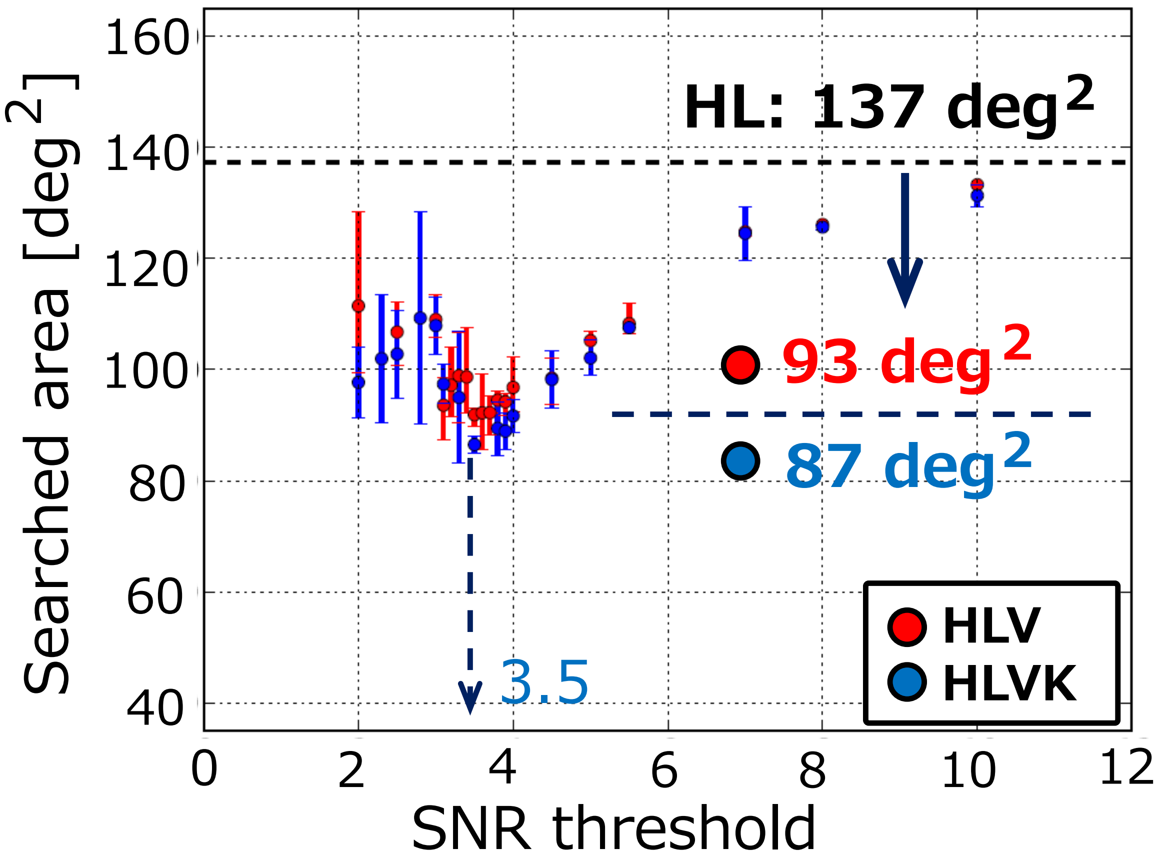
(SNR threshold for H, L = 5.)

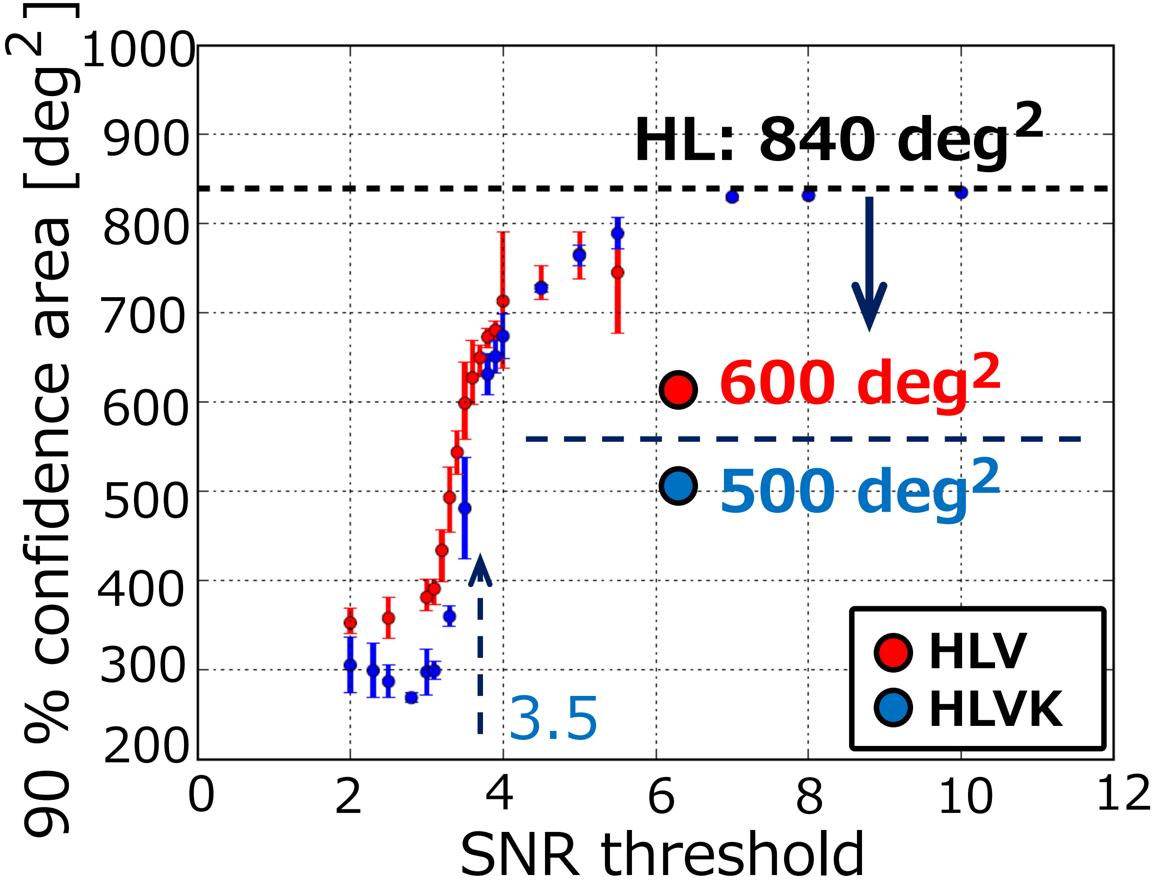




Expected performance, HLVK

(SNR threshold for H, L = 5.)





Accuracy → Not so improved..
Precision → improved!

➔ 4th detector contributes to EM follow-up!

Summary 1

A localization with a hierarchical network is demonstrated.
(From sky maps → first time.)

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),

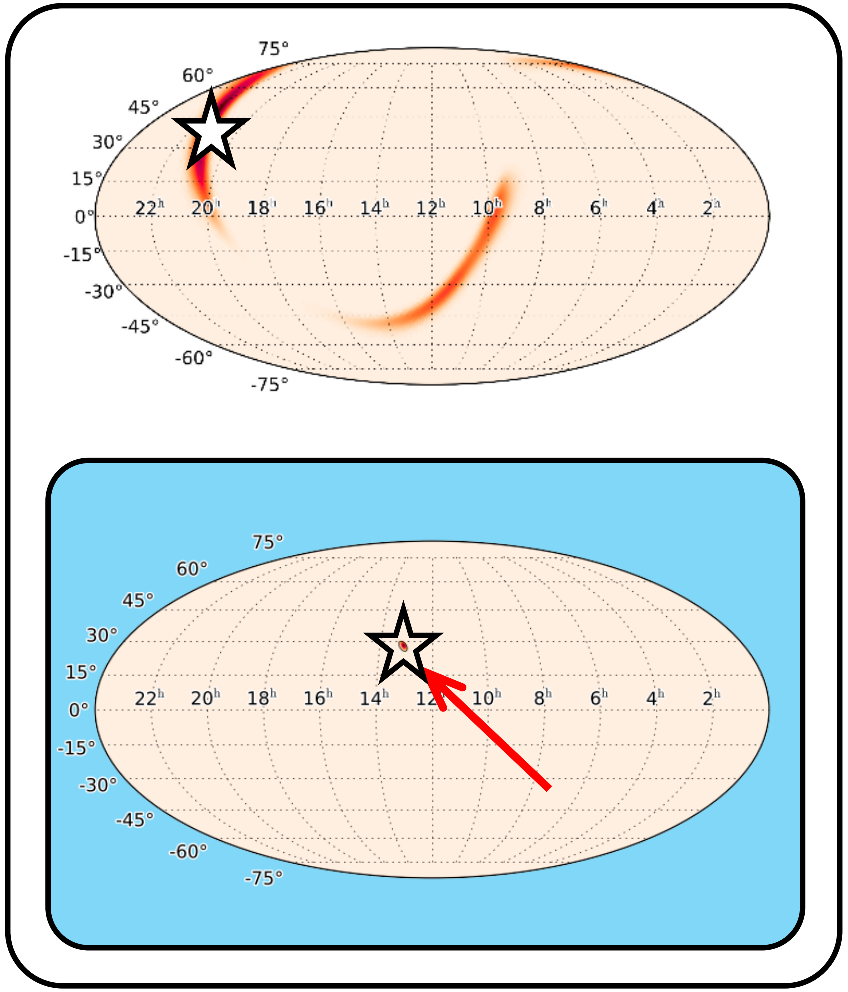
Accuracy: HLV ~ HLVK
Precision: reduced by a factor of ~ 0.8 than HLV.

→ ***4th detector can contributes!***

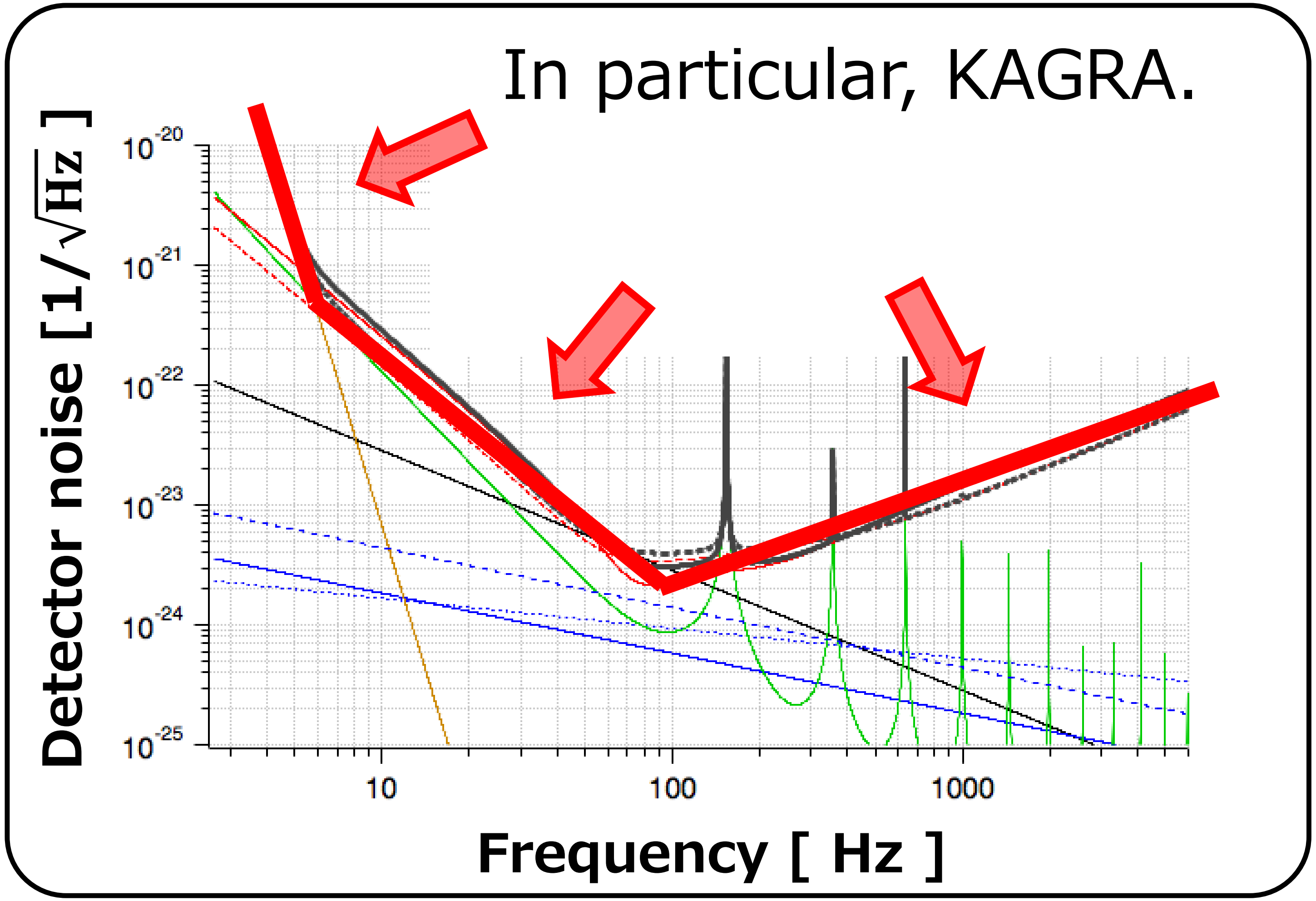
→ ***useful for follow-up observation!***

Source localization → detector development

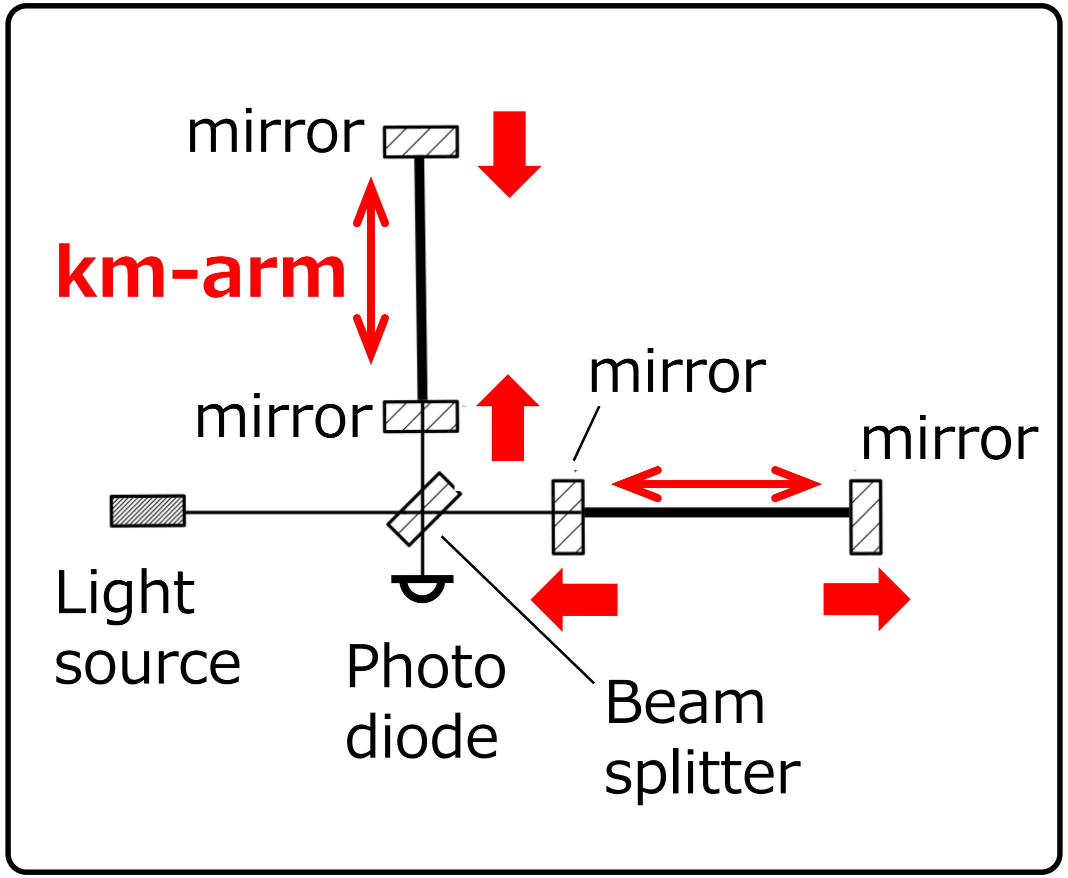
We want ..



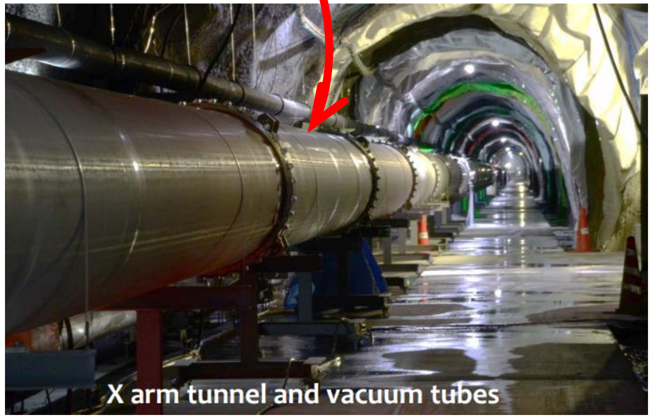
Necessary to improve sensitivity!



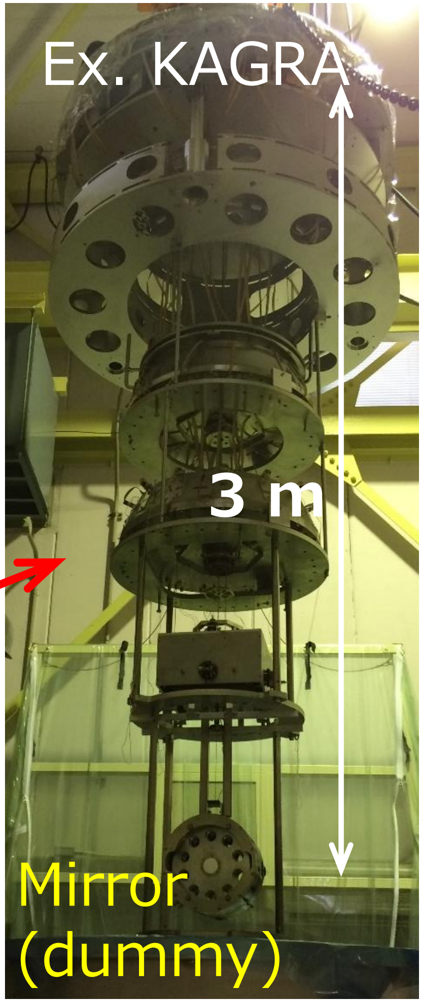
Gravitational wave detector



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



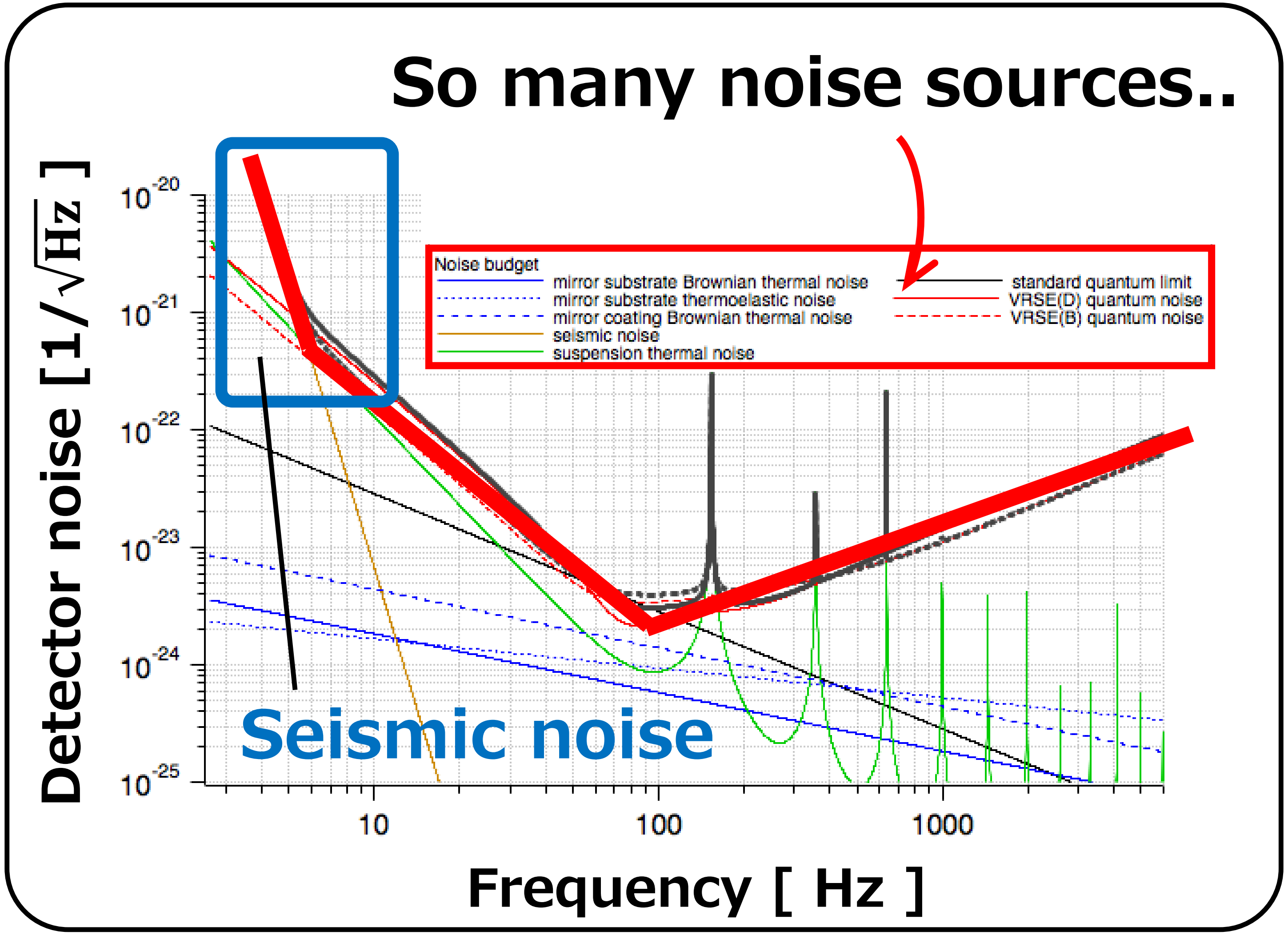
4) Suspended core optics



Detector noise

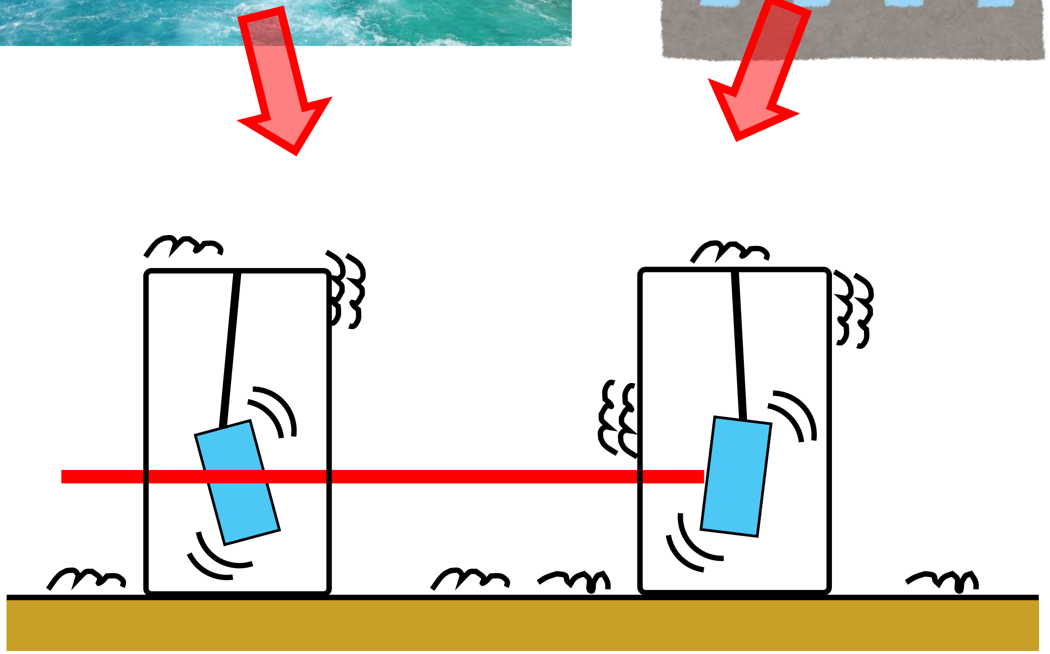
- Quantum noise
- Thermal noise
  …
- **Seismic noise**

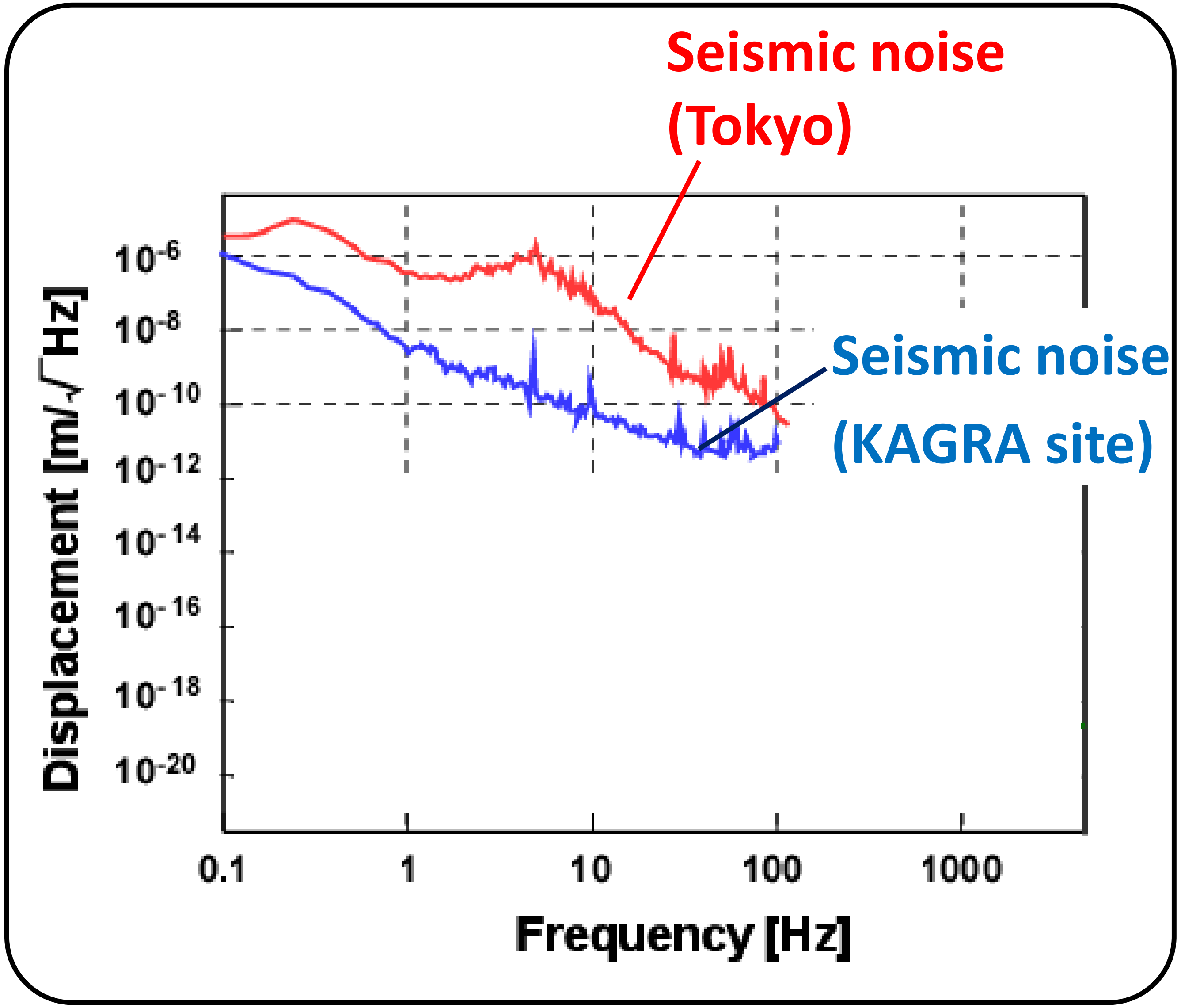
mirror oscillation
→ Necessary to suppress



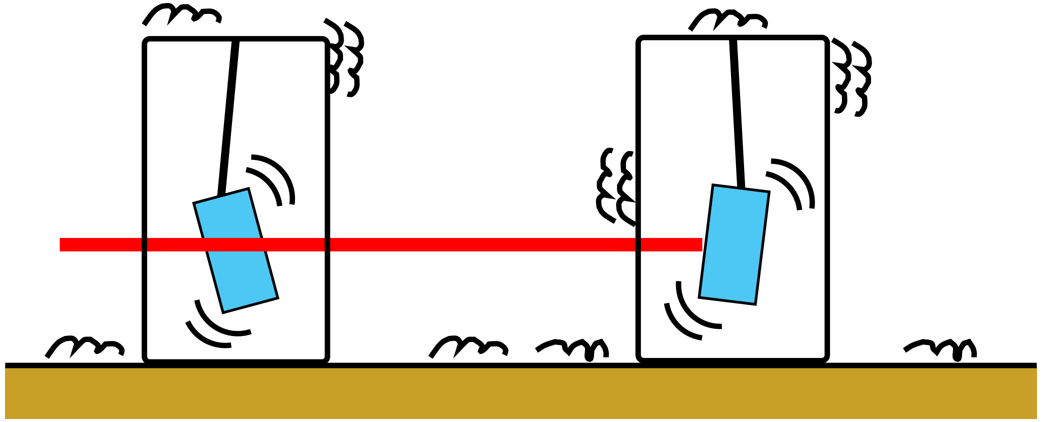
In case of KAGRA

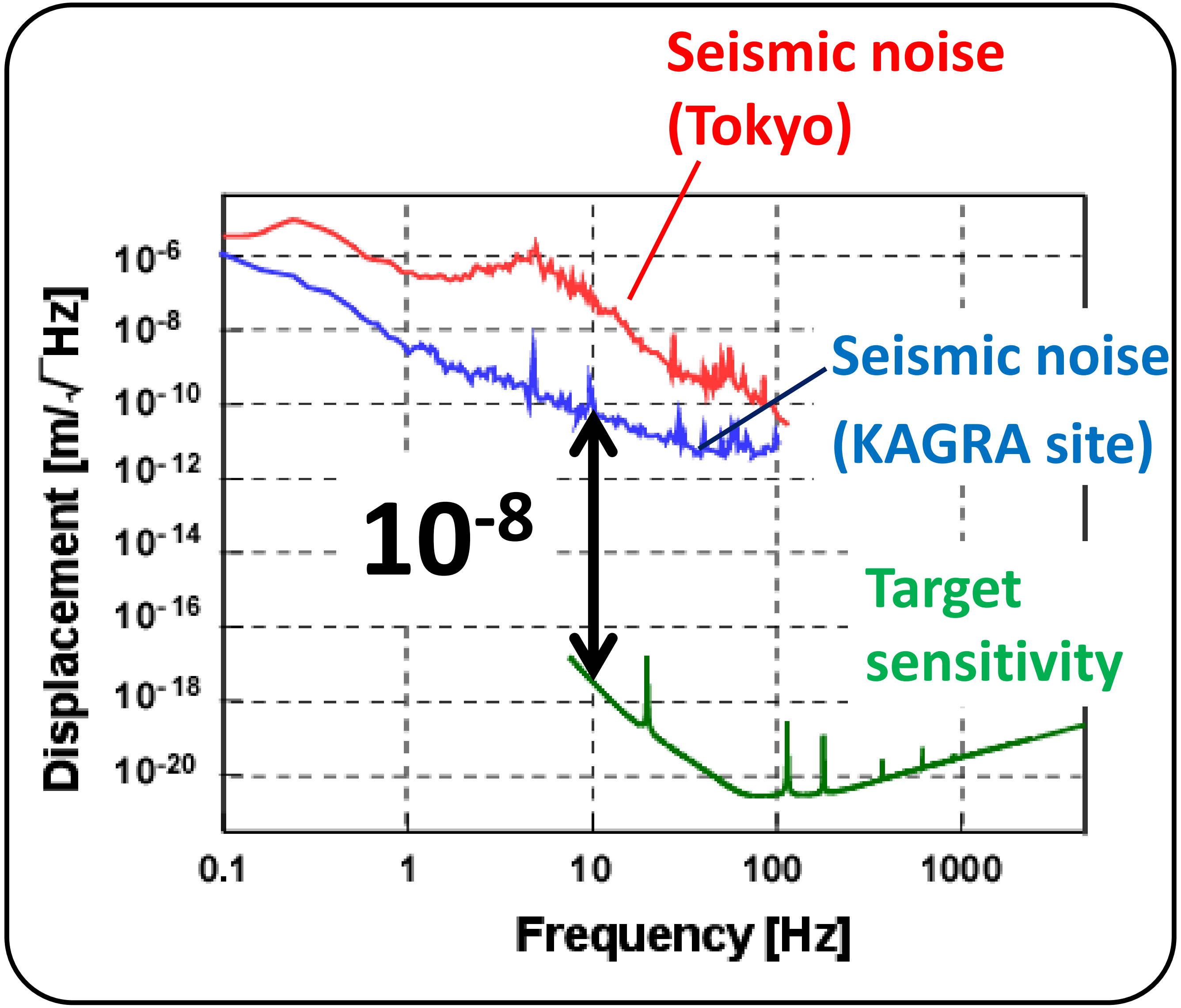
Seismic noise



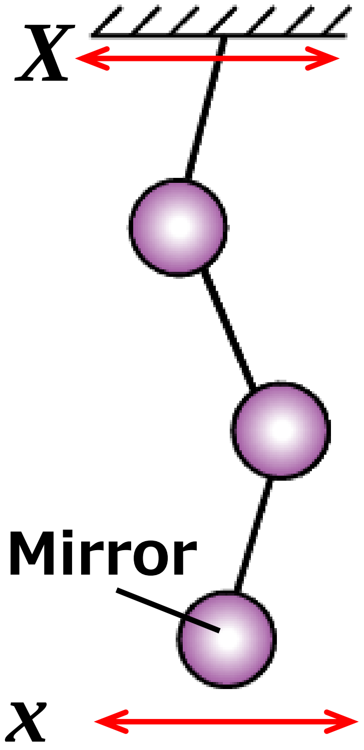


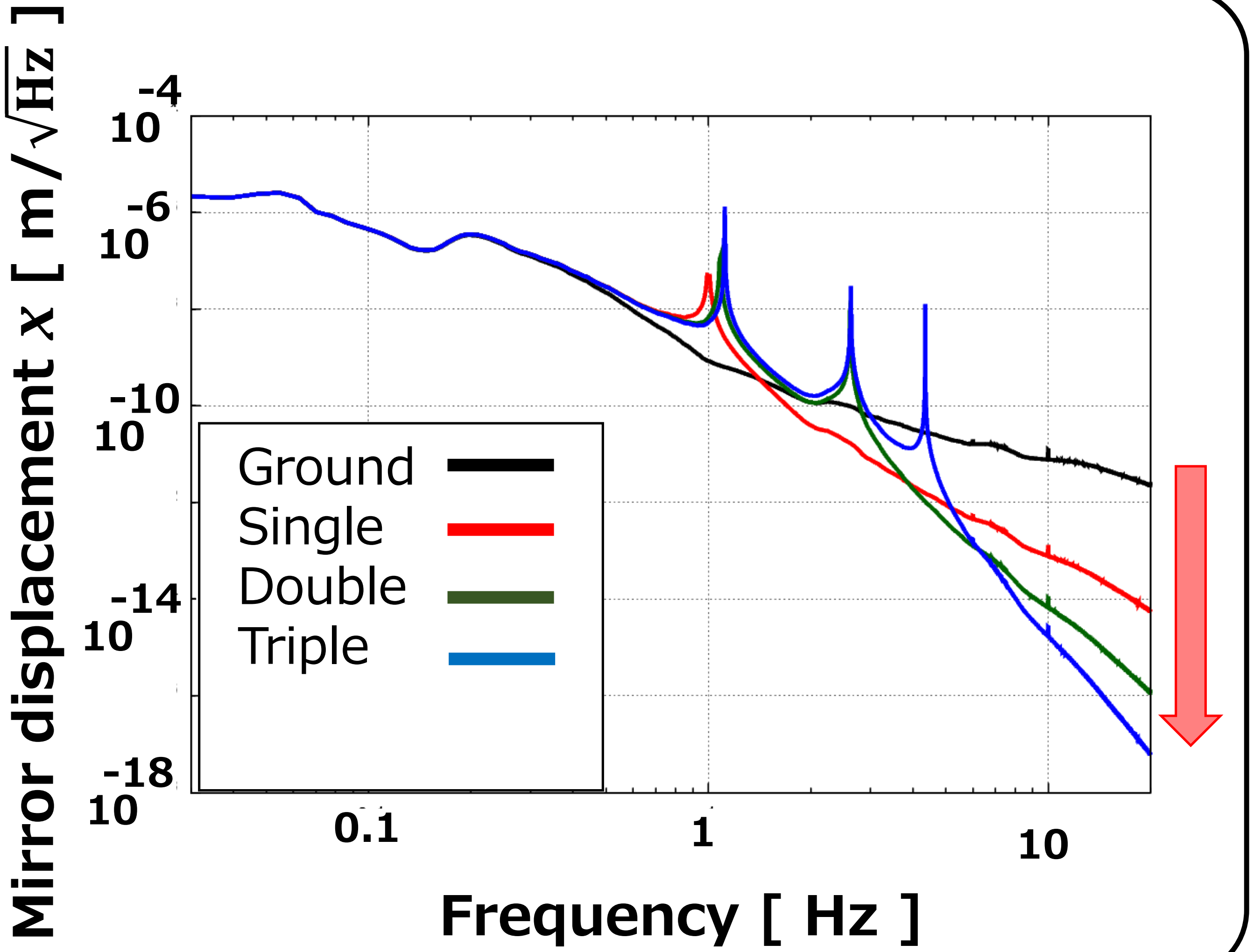
Seismic noise



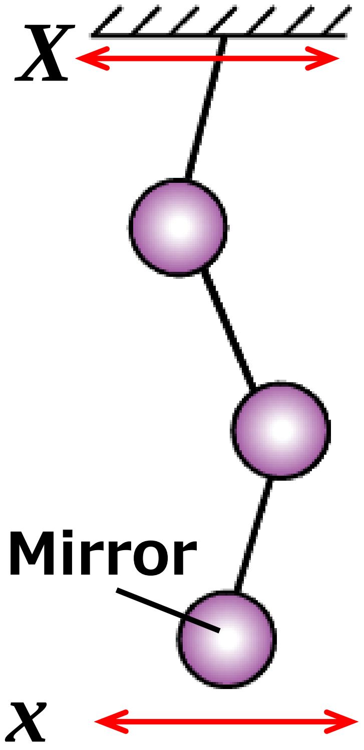


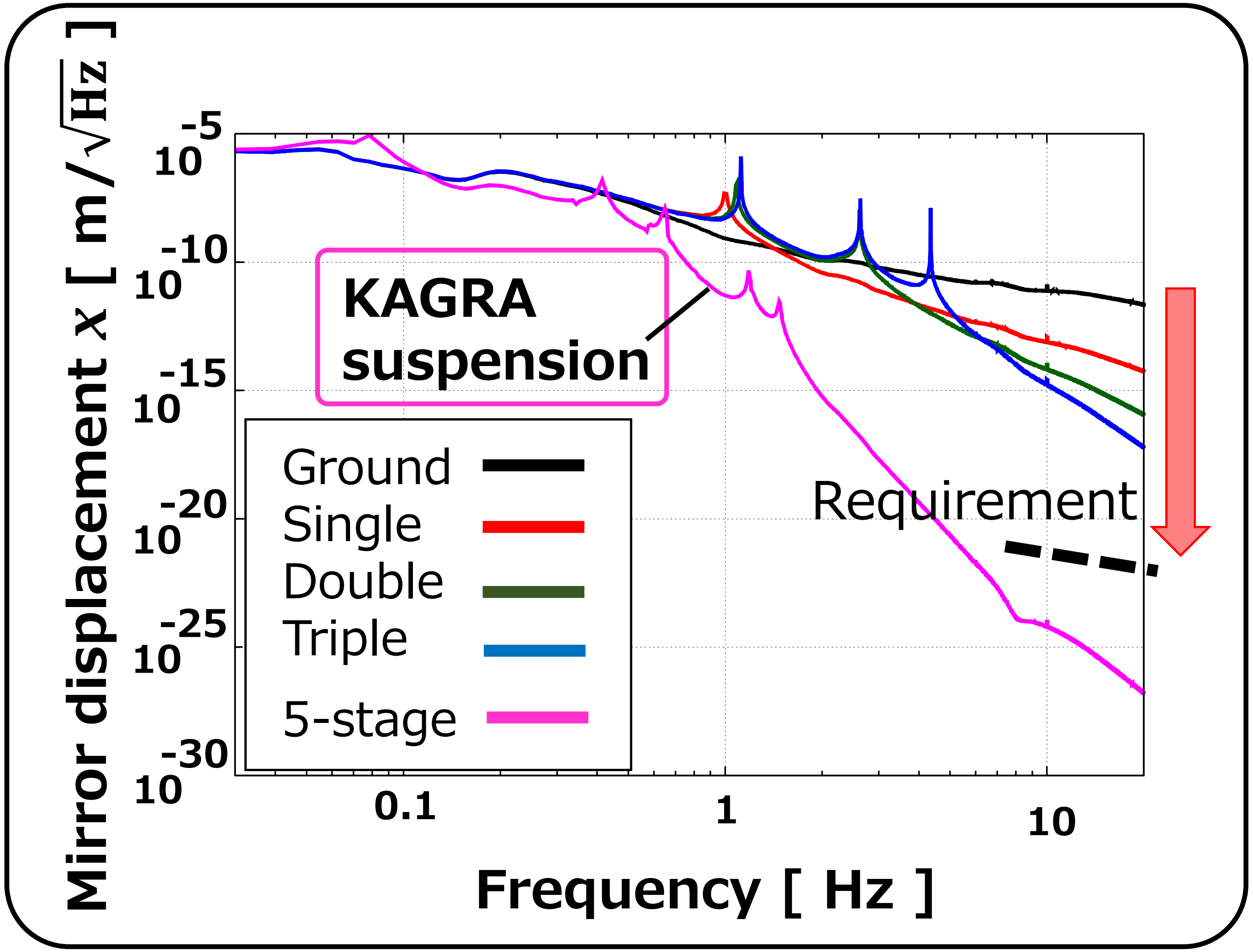
Seismic attenuation

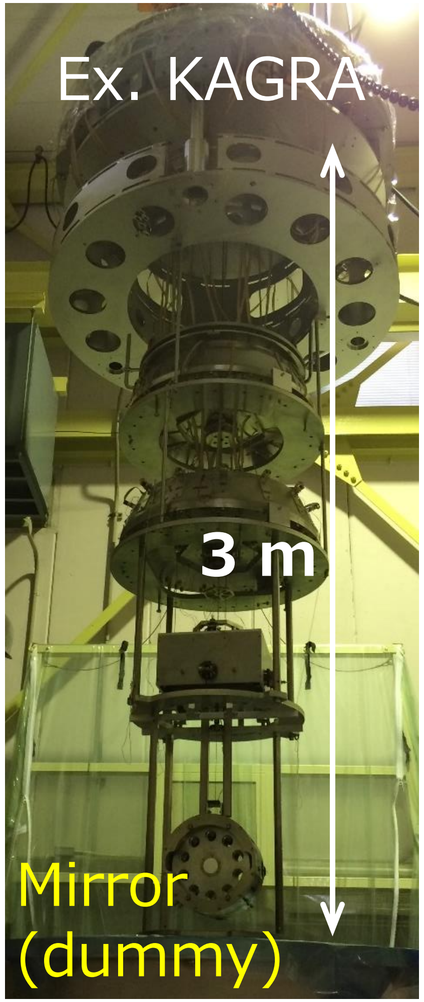




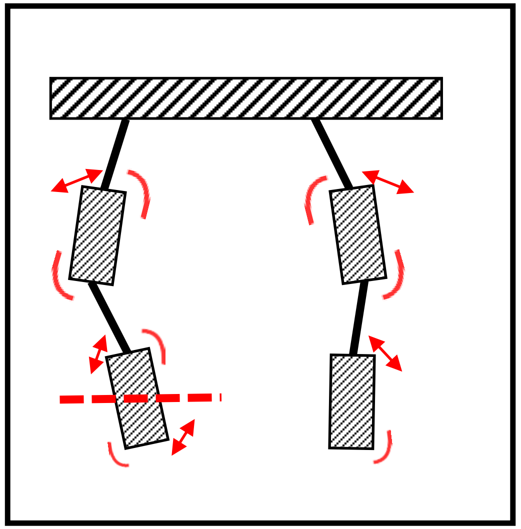
Seismic attenuation







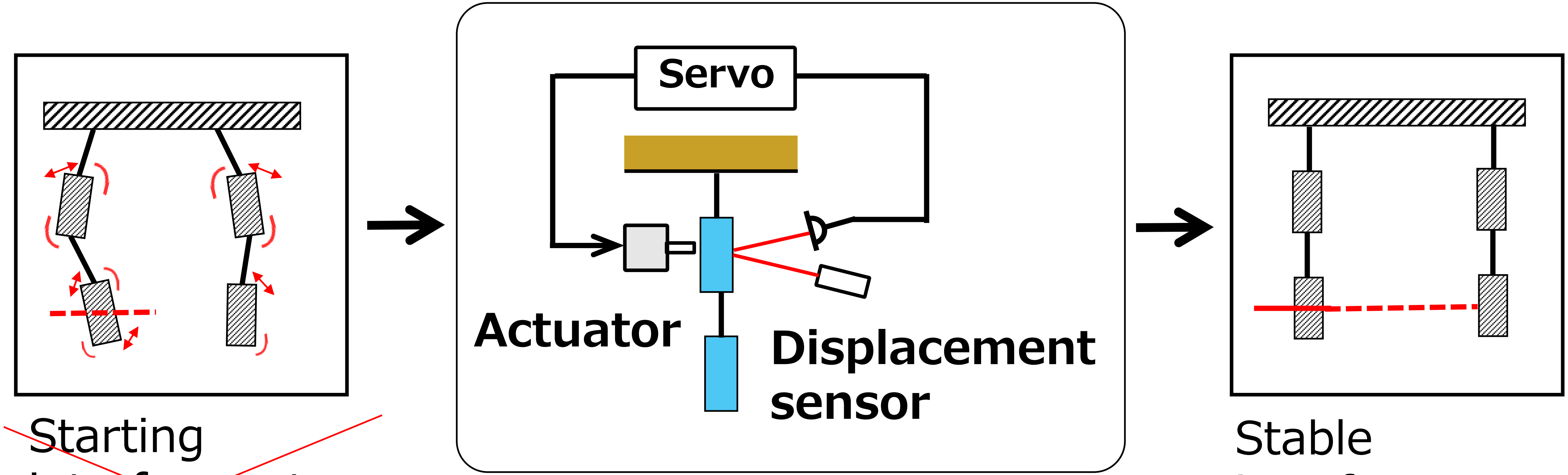
Resonance damping & drift compensation



~~Starting interferometer operation~~

Resonance damping & drift compensation

→ *Active control*

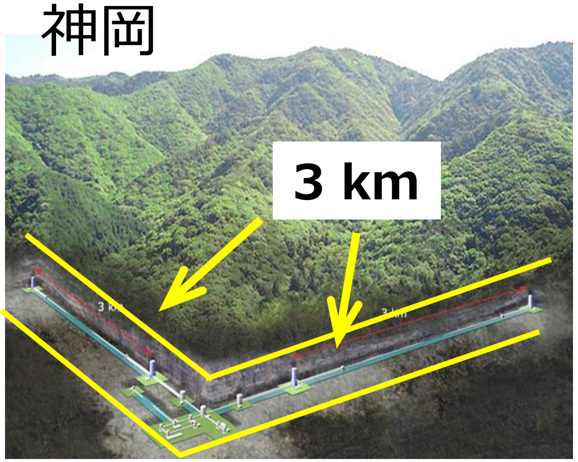


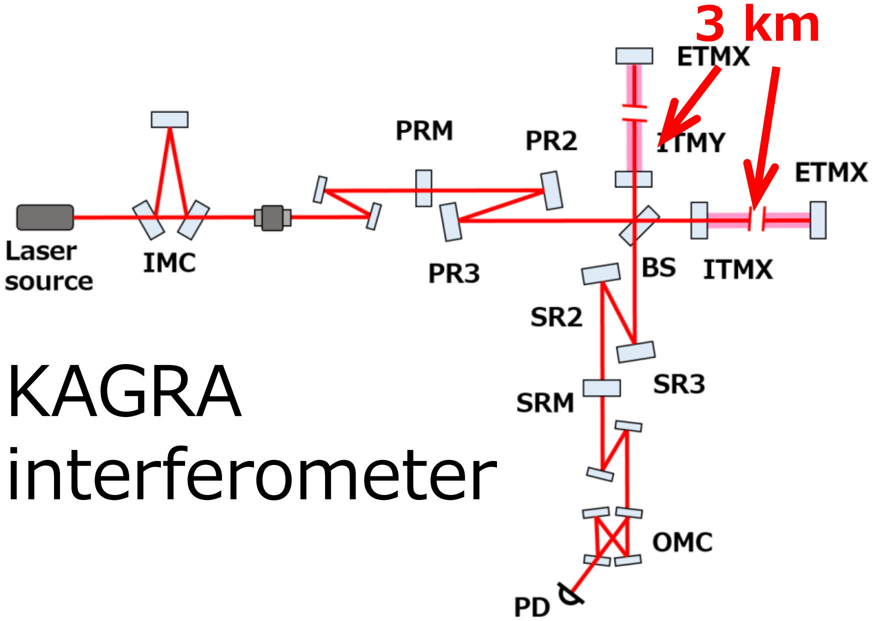
~~Starting interferometer operation~~

Stable interferometer operation

KAGRA project

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



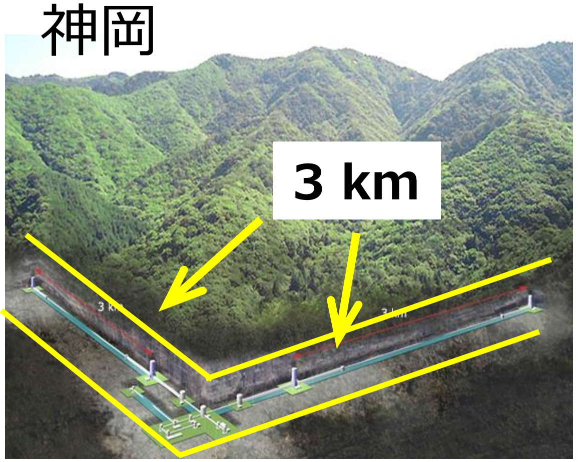


KAGRA interferometer

KAGRA project

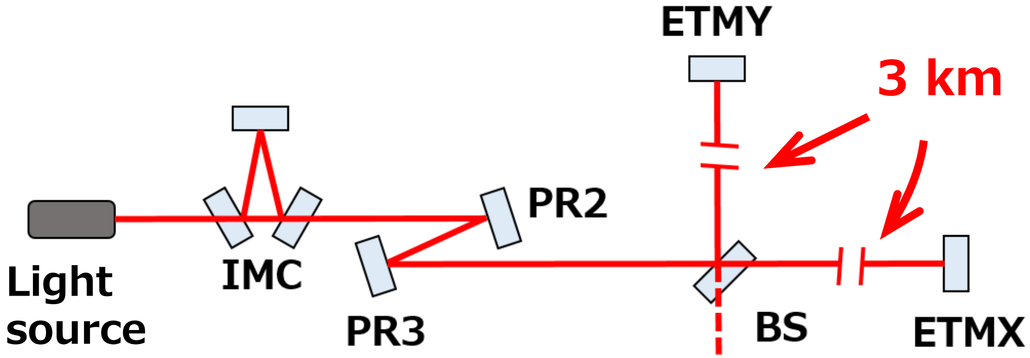
KAGRA

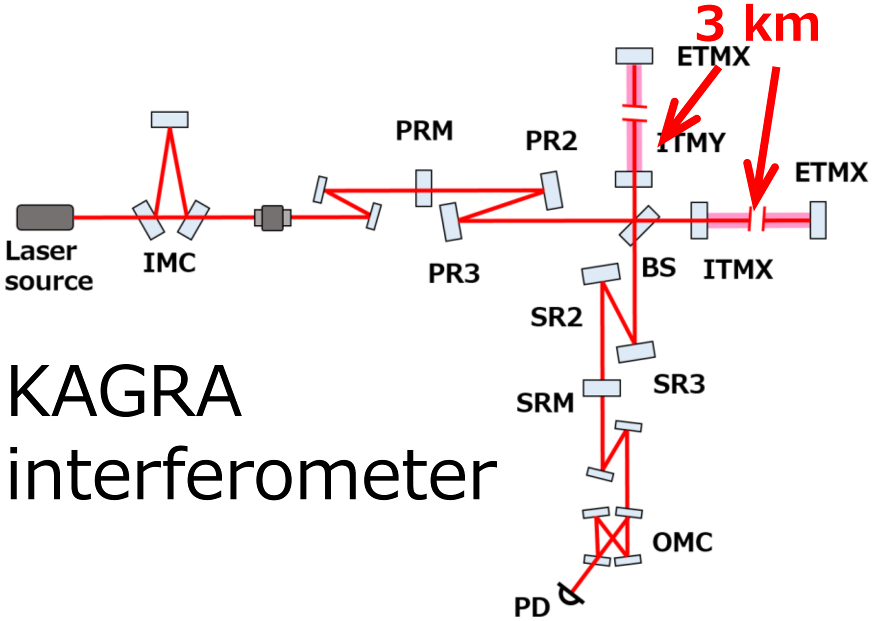
1) Japanese detector
2) now being developed
3) underground



iKAGRA

1) test run in 2016
2) Simple interferometer



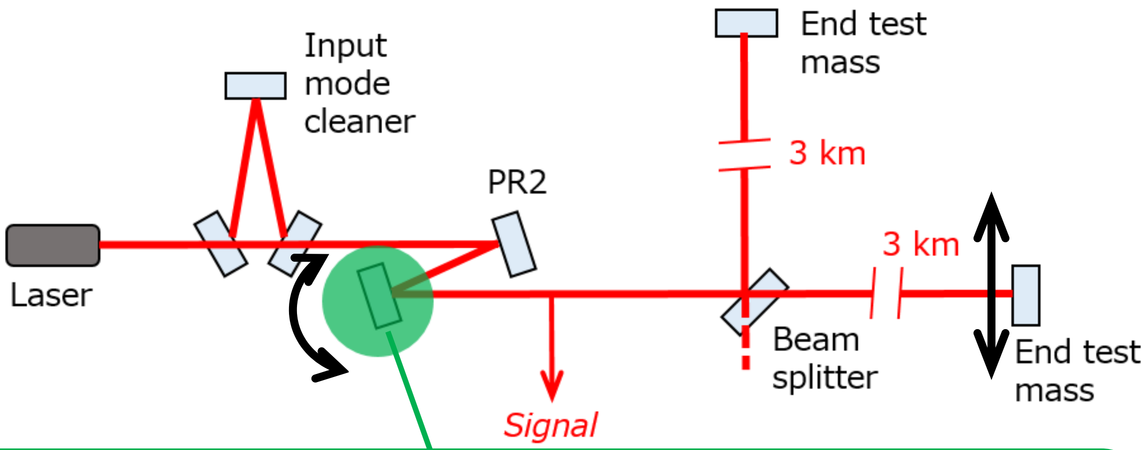


KAGRA interferometer

iKAGRA suspension development

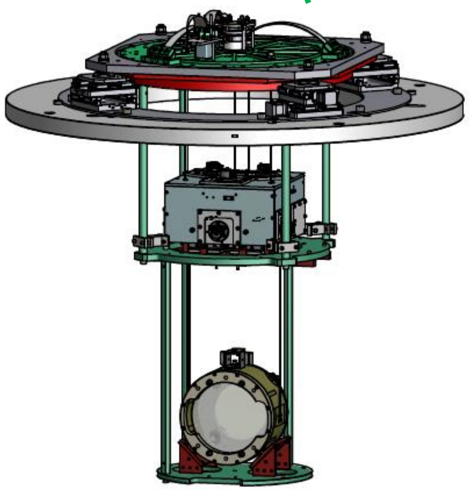
Development work:

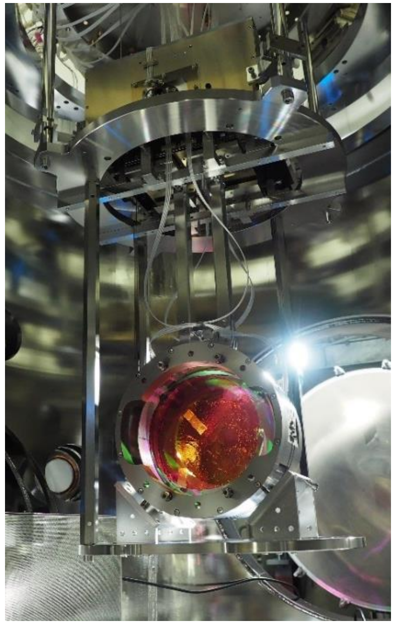
1) Assembly
2) Performance test
3) Upgrading for KAGRA



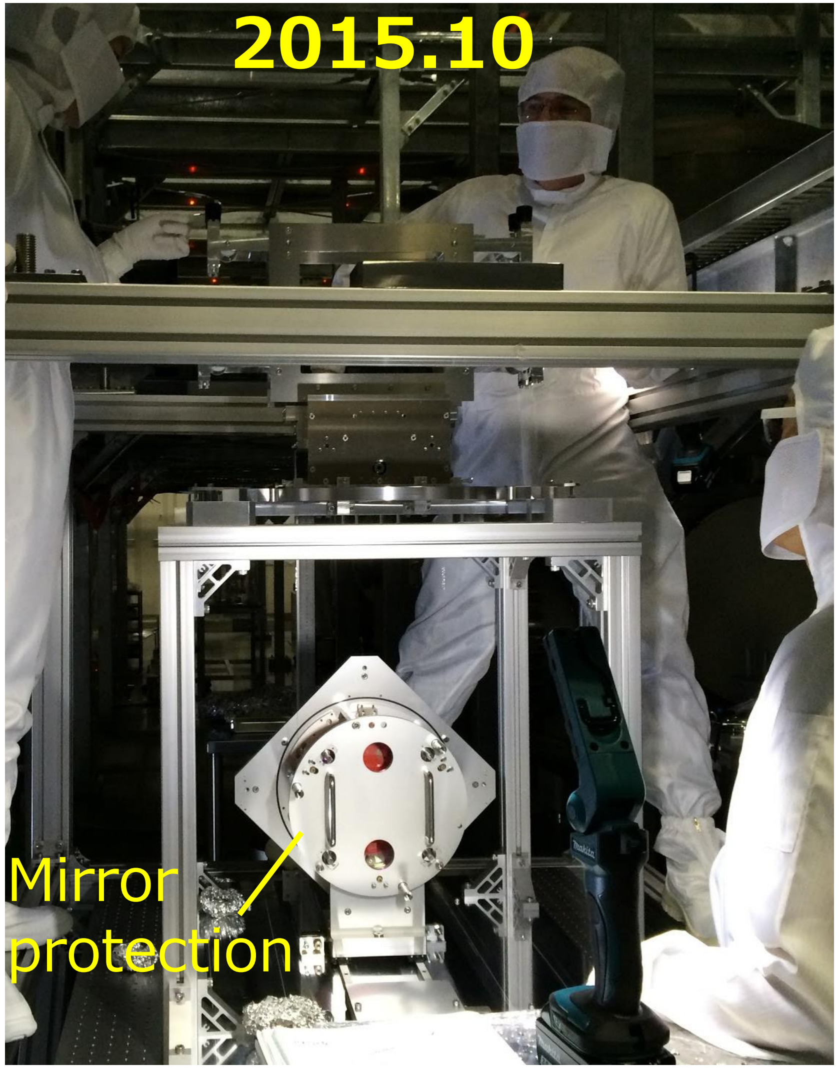
iKAGRA suspension:

Alignment mirror of iKAGRA
for initial alignment
for stable operation.

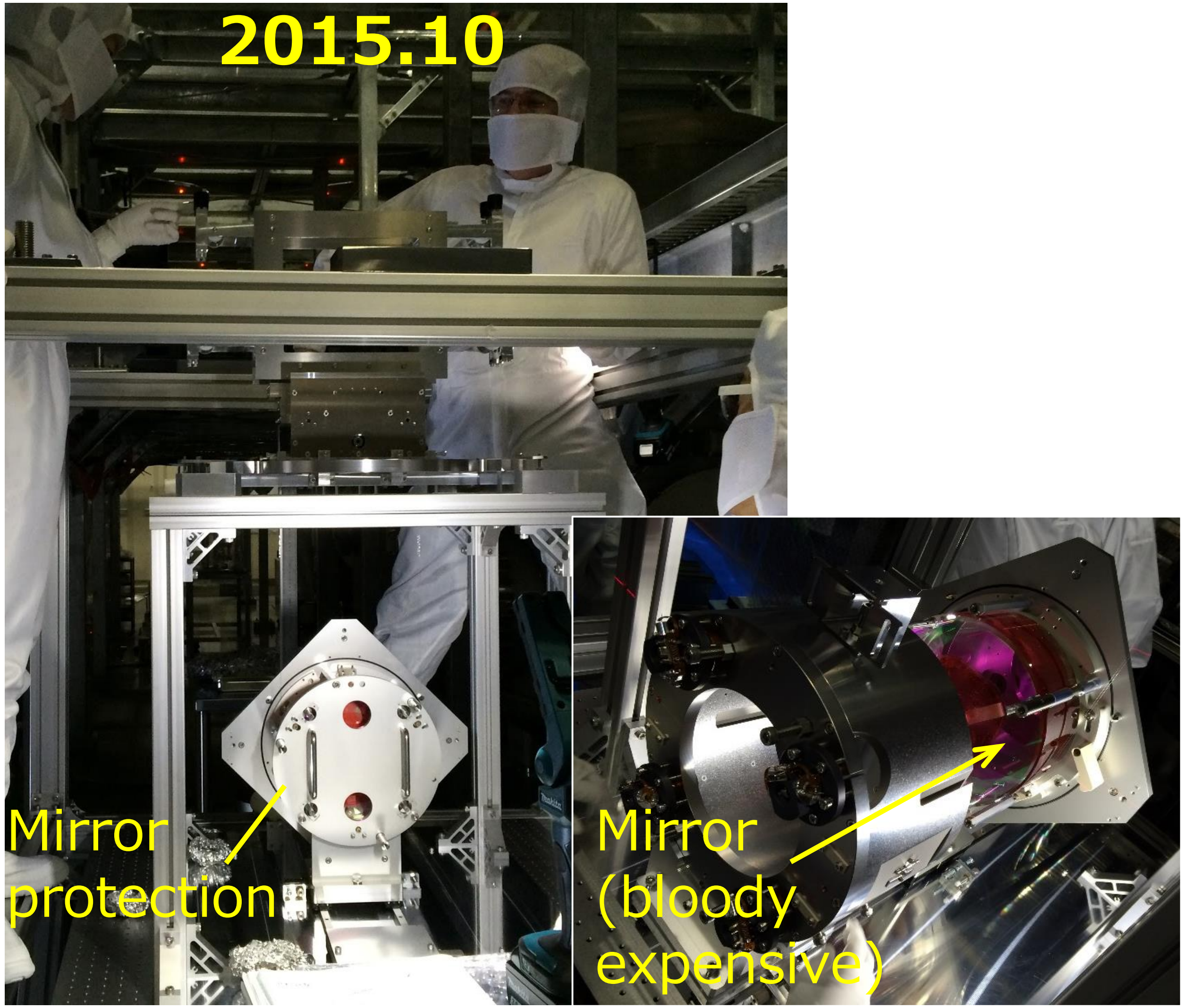




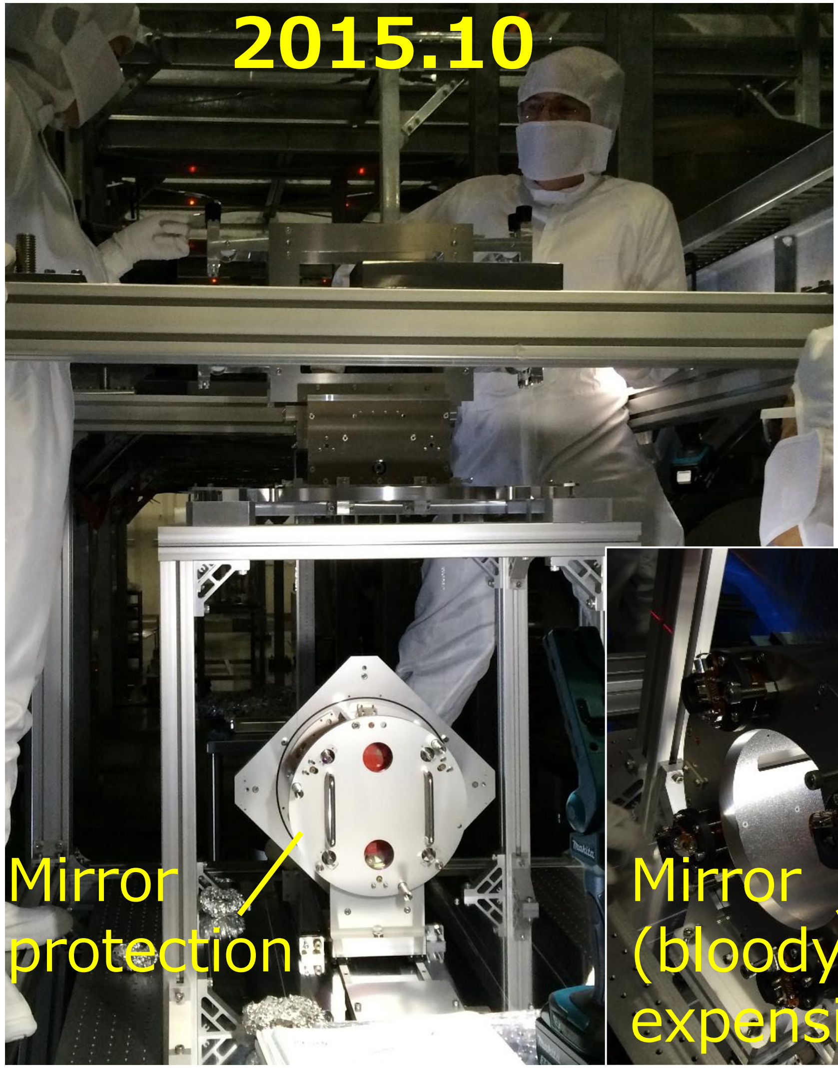
Assembly

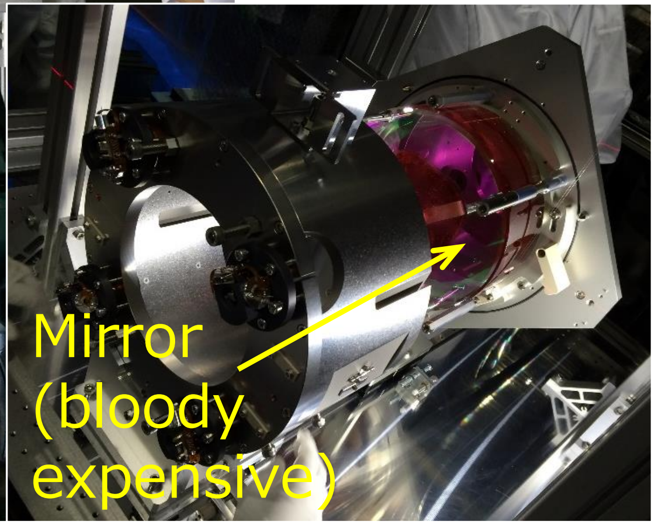


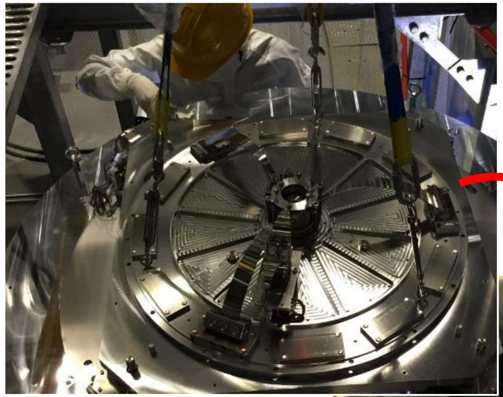
Assembly

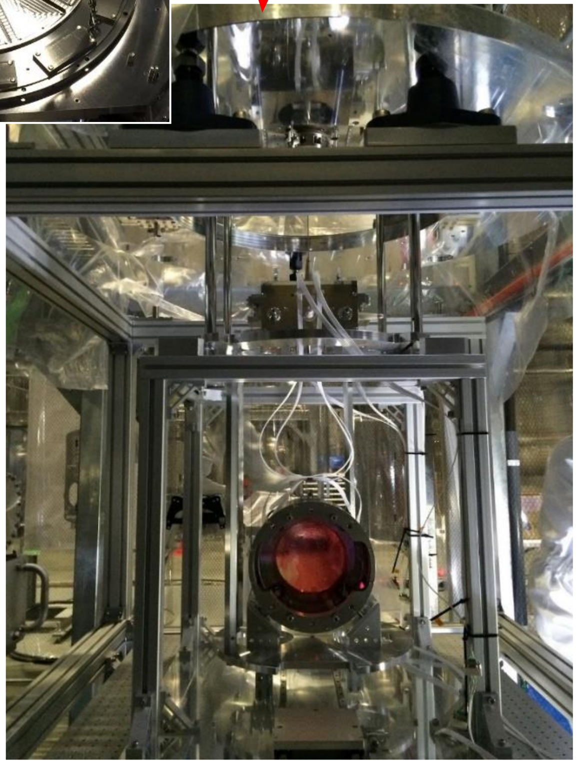


Assembly

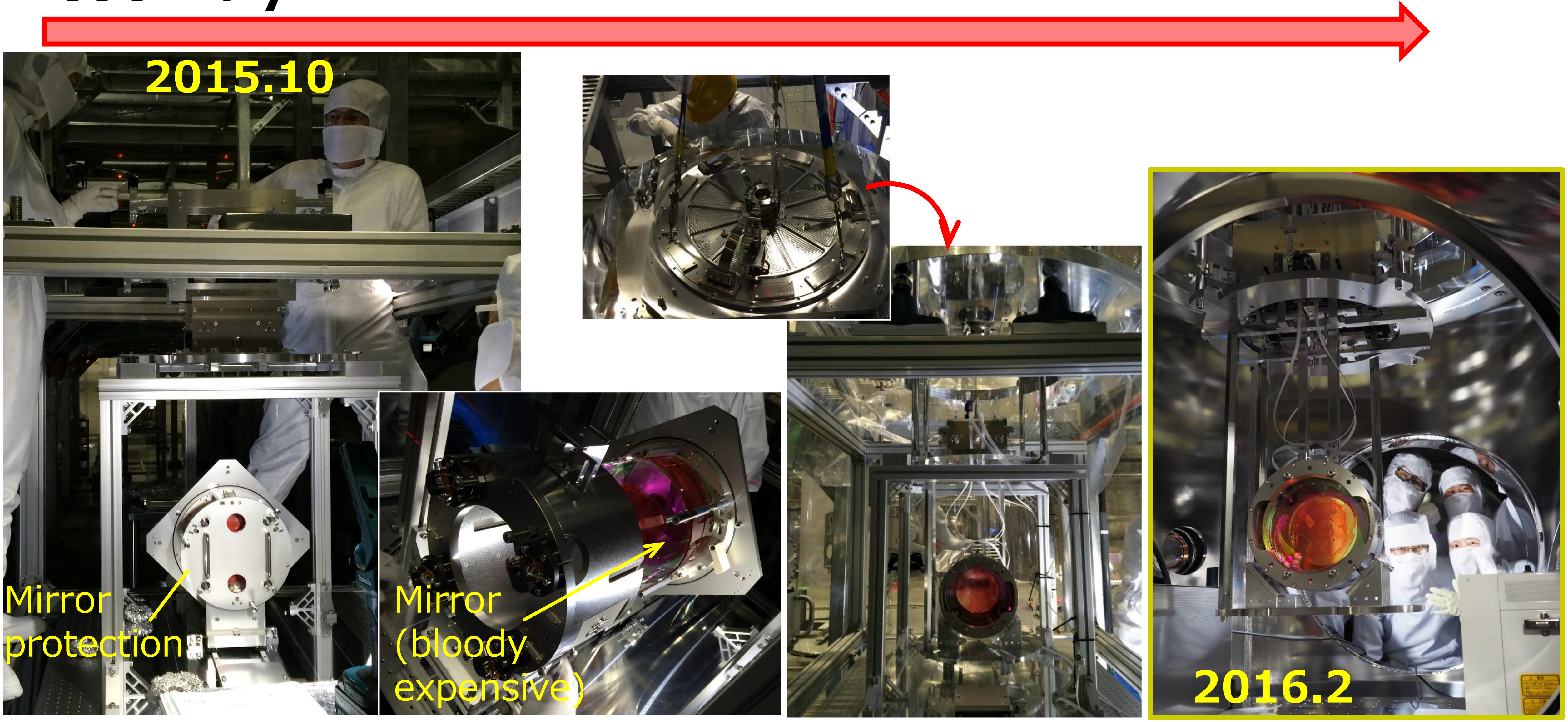




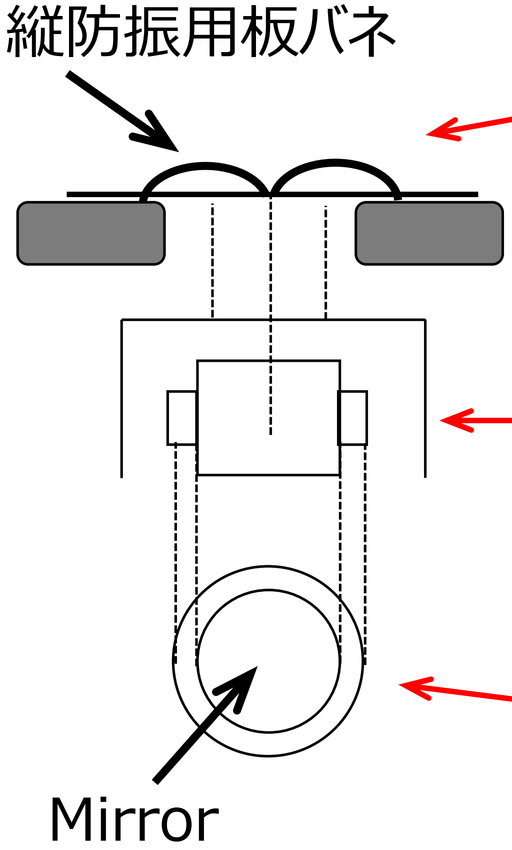


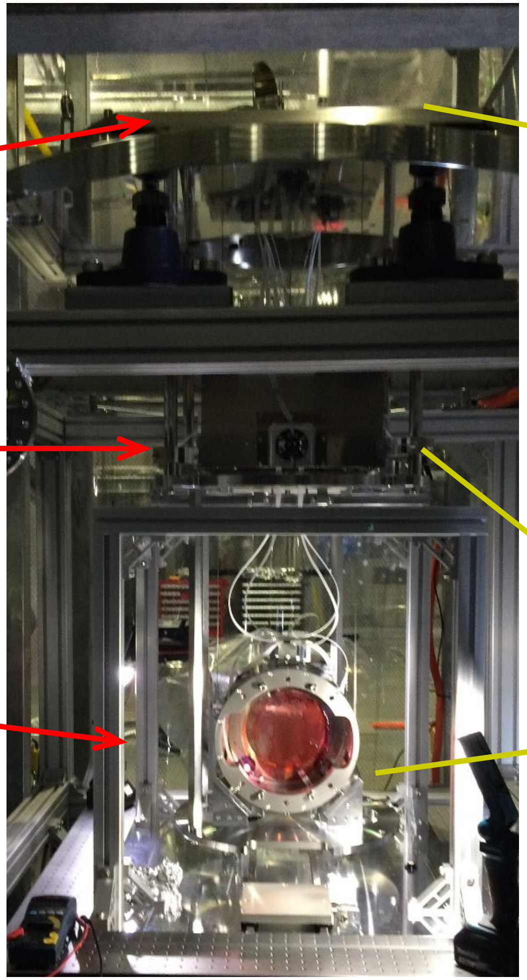


Assembly



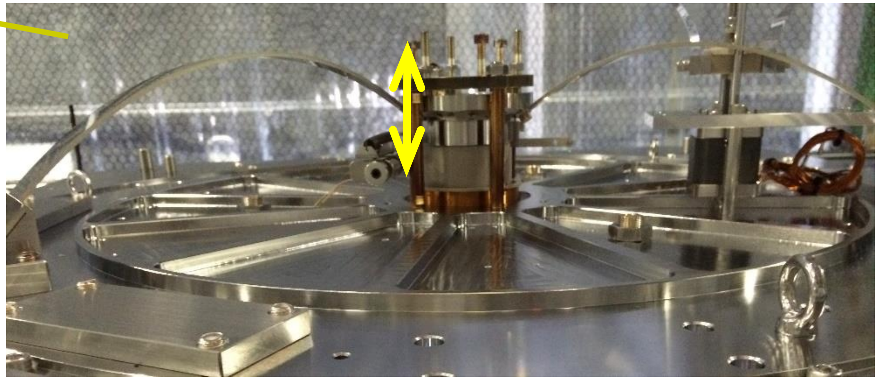
Sensors and actuators



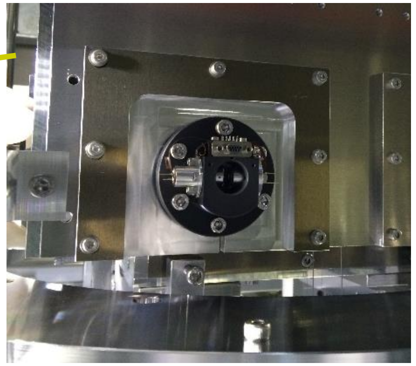


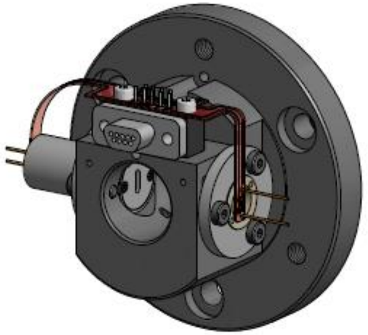
iKAGRA-PR3 SAS

Displacement sensor
and coil-magnet actuator 1

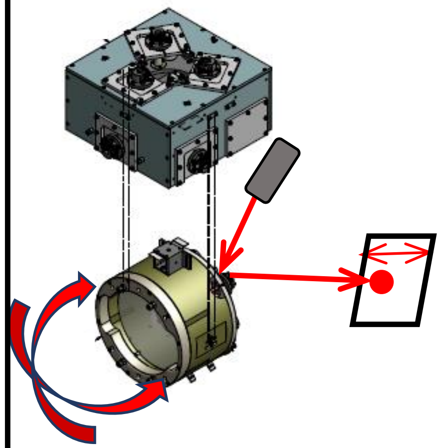


Displacement sensor
and coil-magnet actuator 2





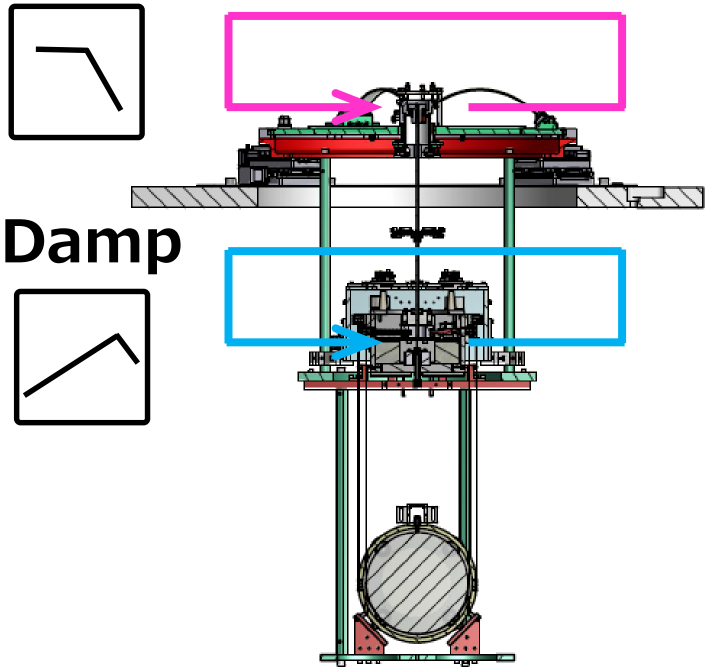
Angular
sensor



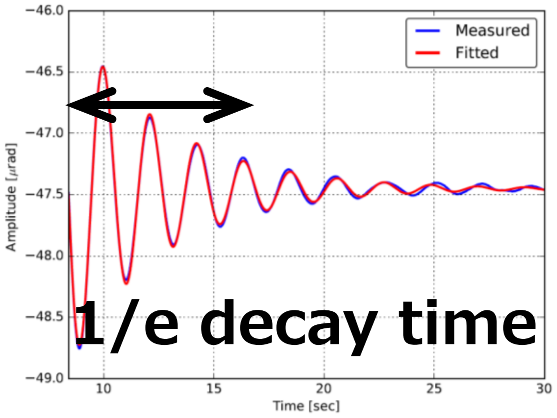
Damping time & measurement

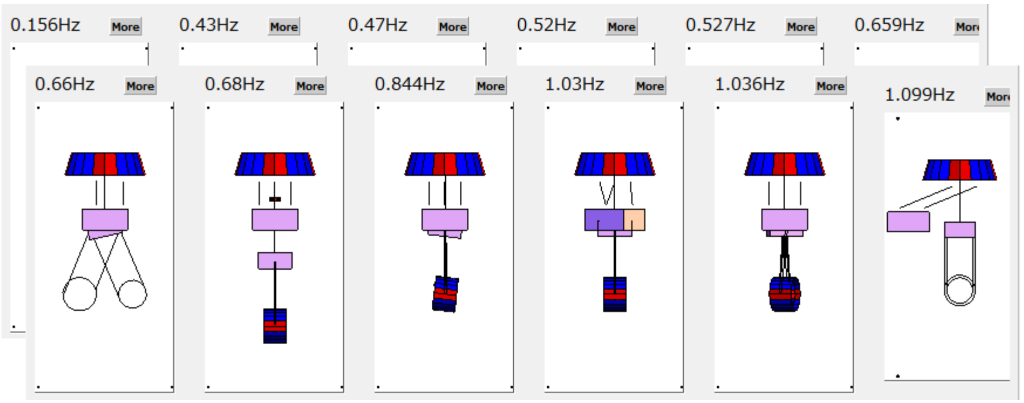
DC

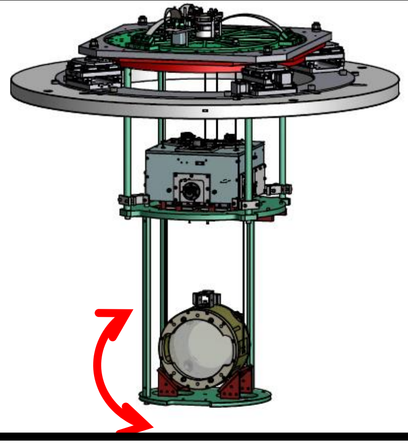
Damp



For damping resonances

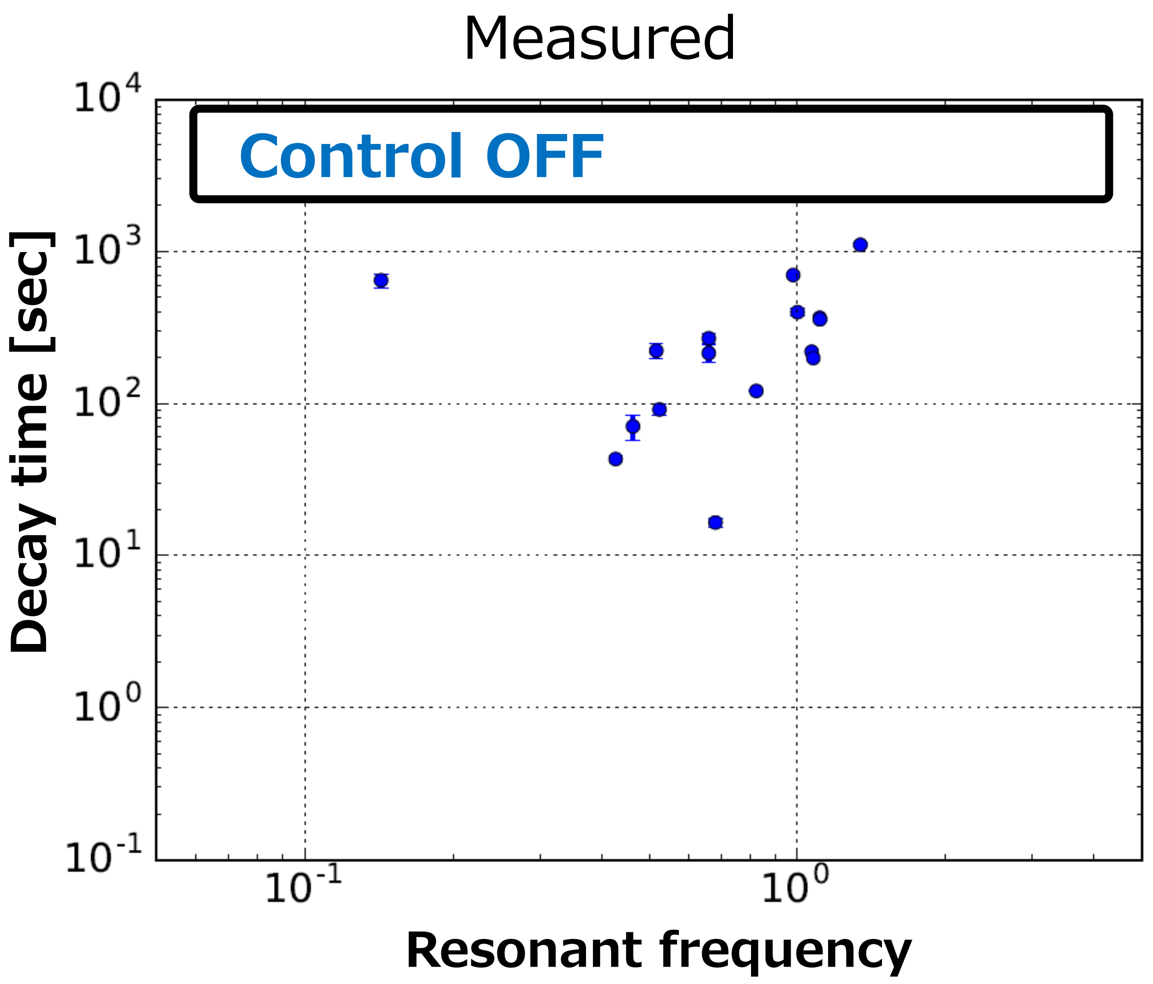


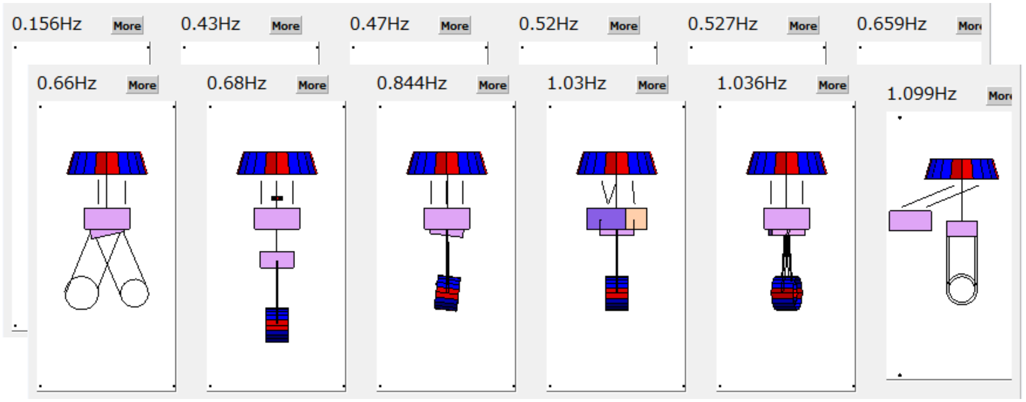


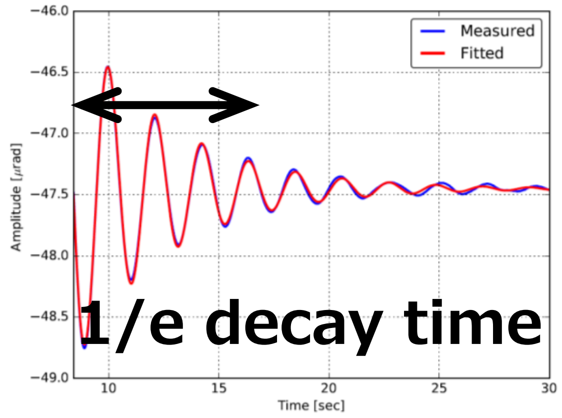


Test 2:
Residual vibration estimation

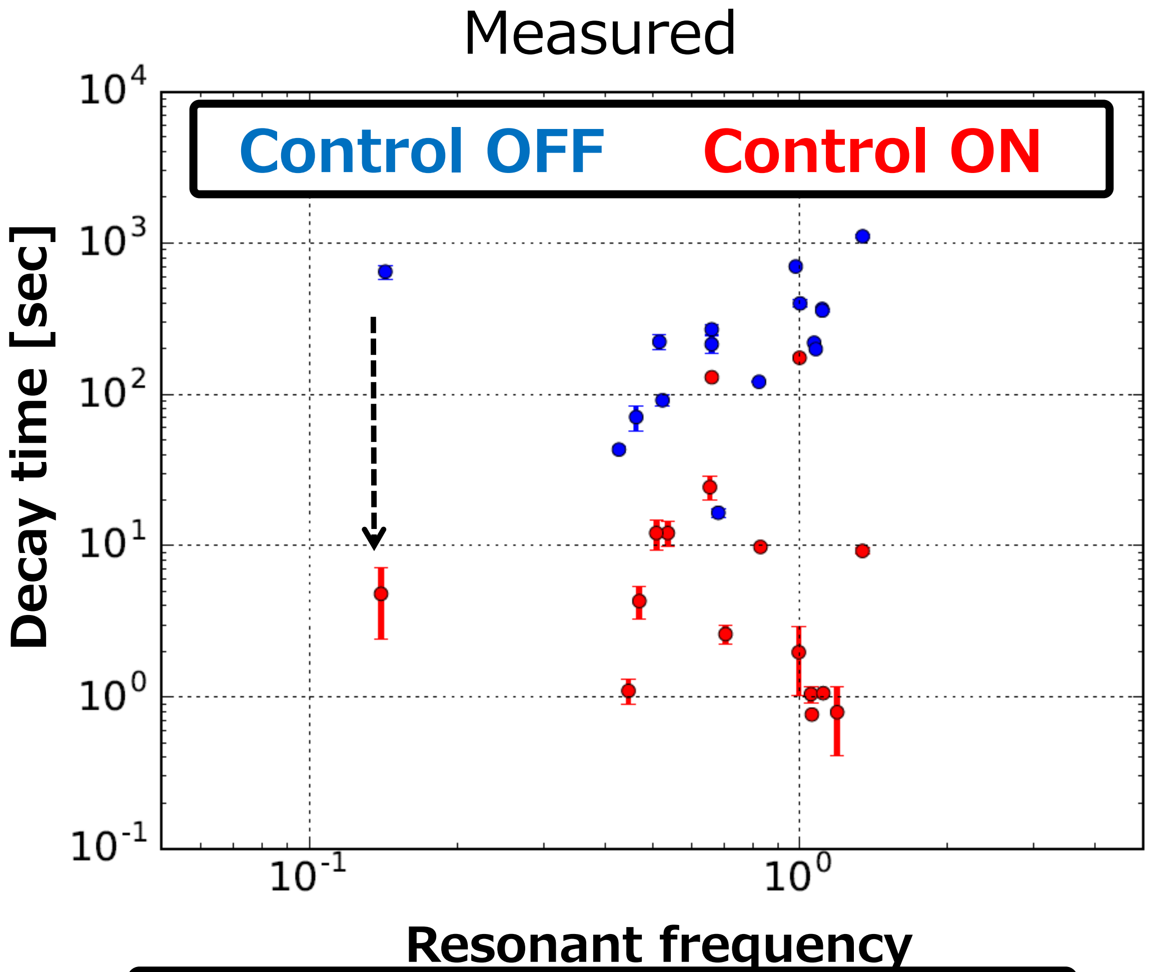
Damping time without damping

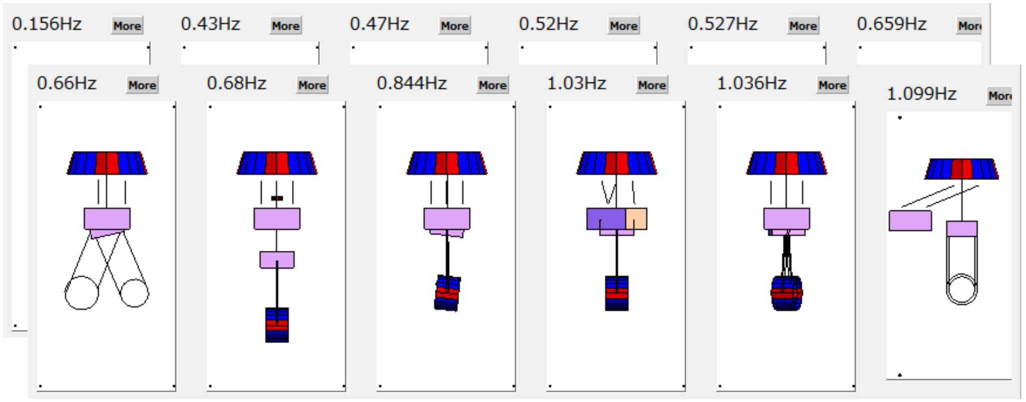


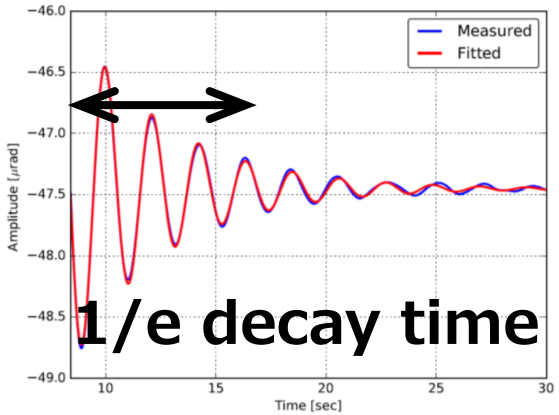




Damping time with damping

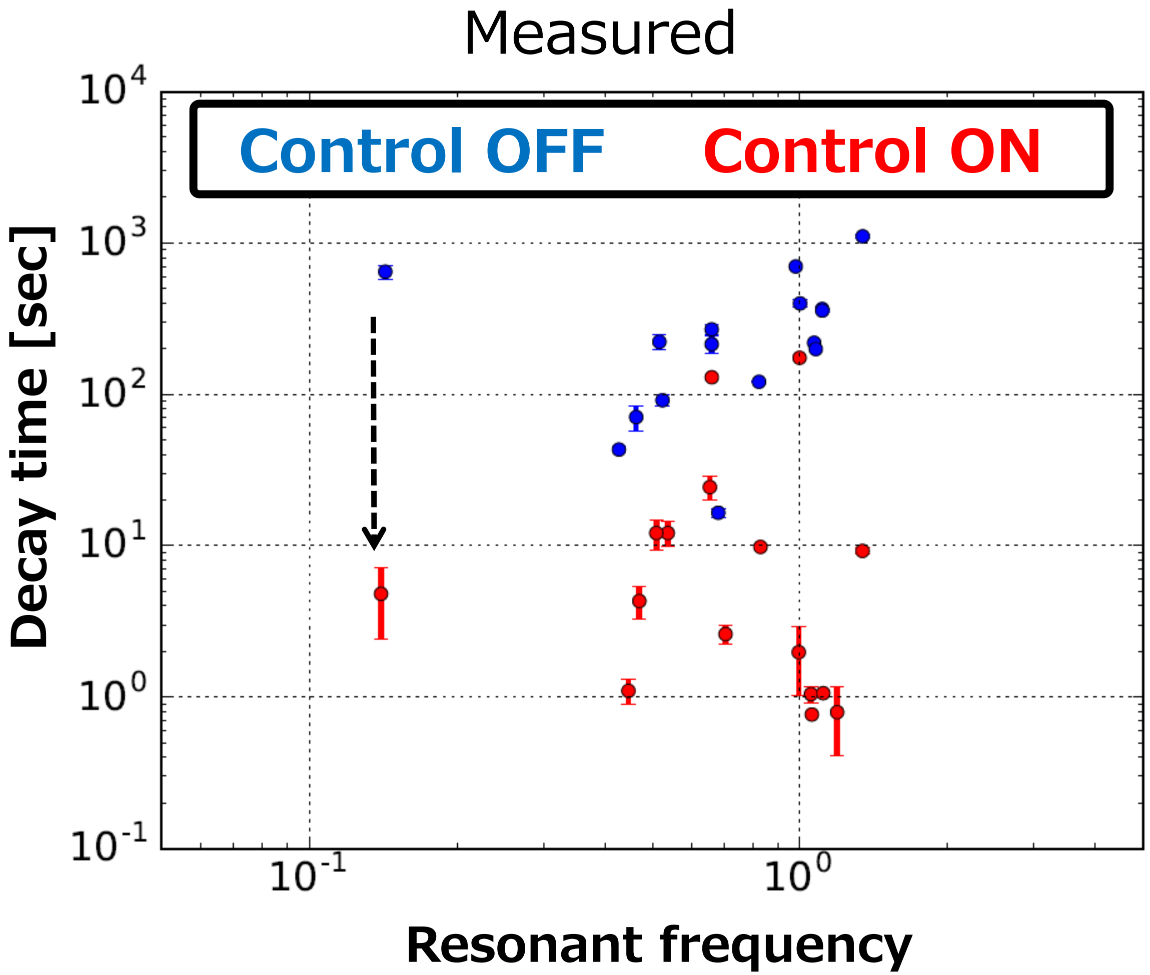


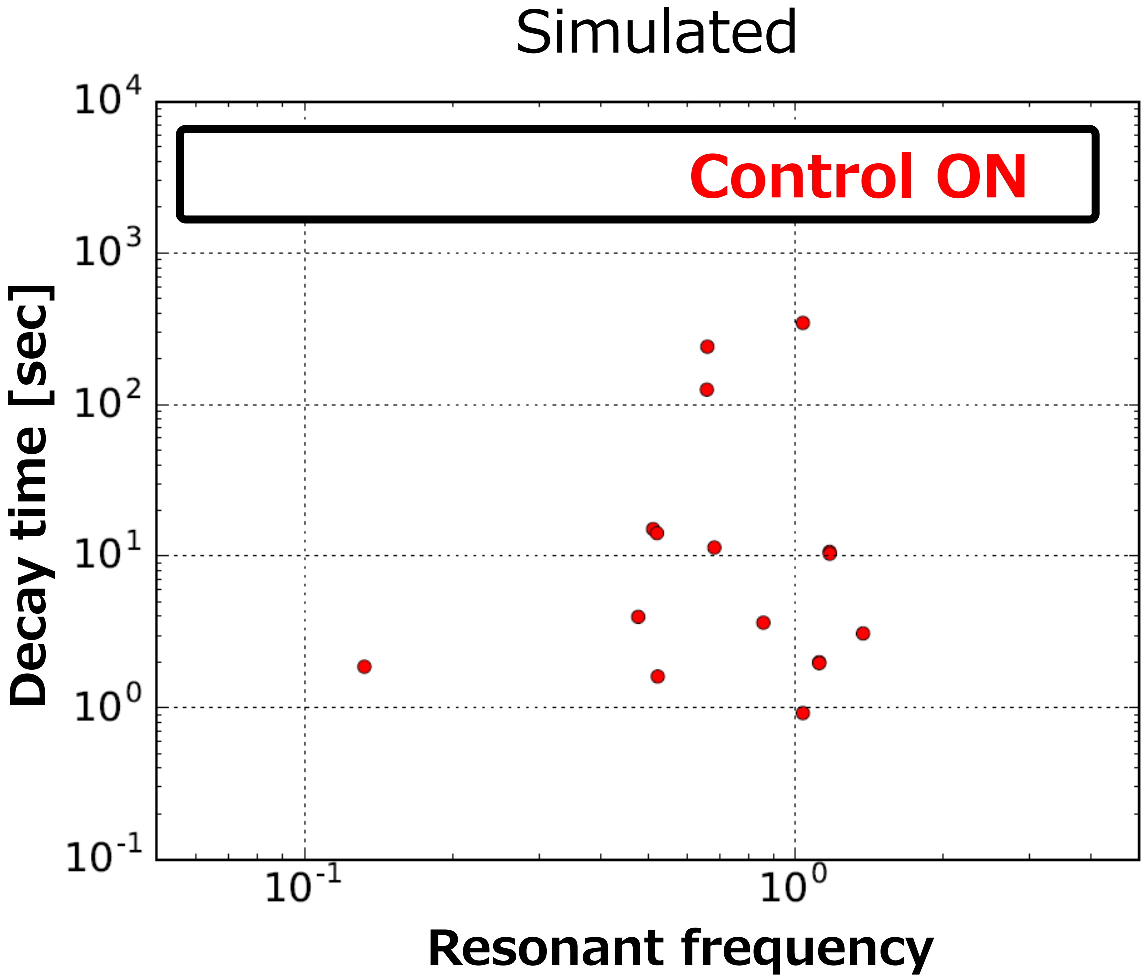




Resonances → damped

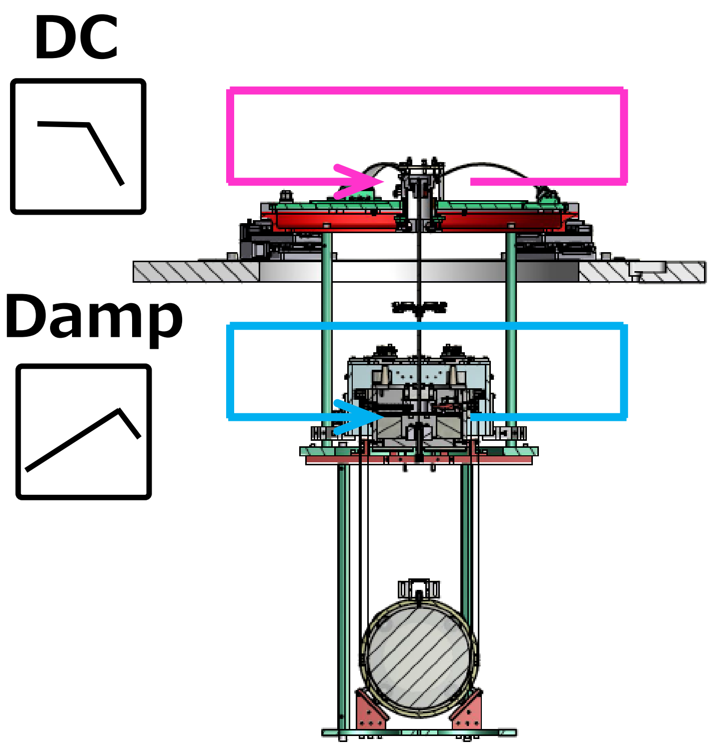
Damping time with damping



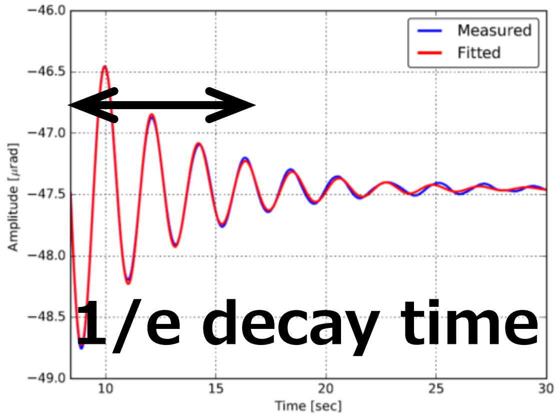


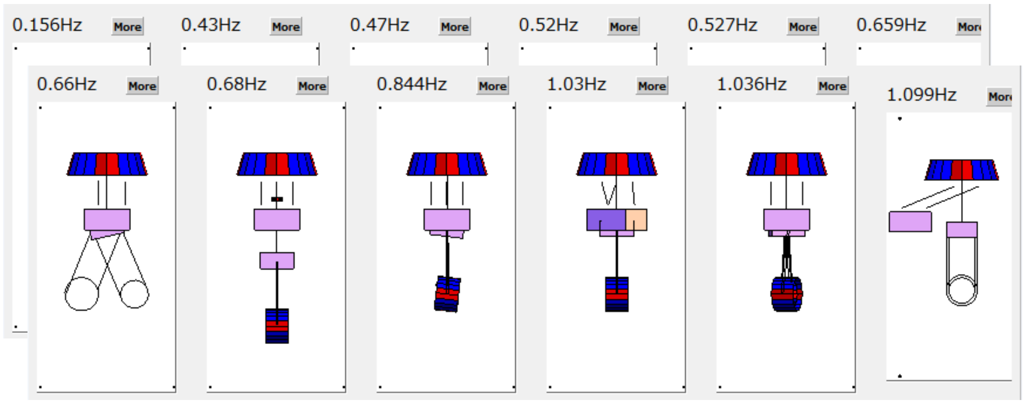
Simulation → consistent with measurement

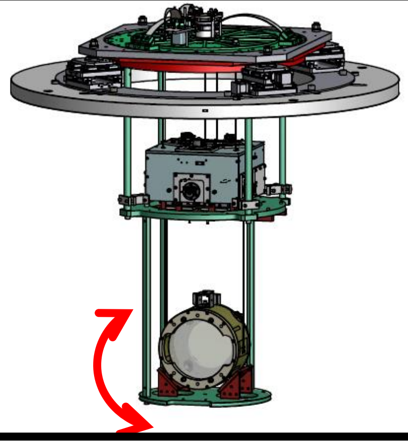
Damping time & measurement



For damping resonances

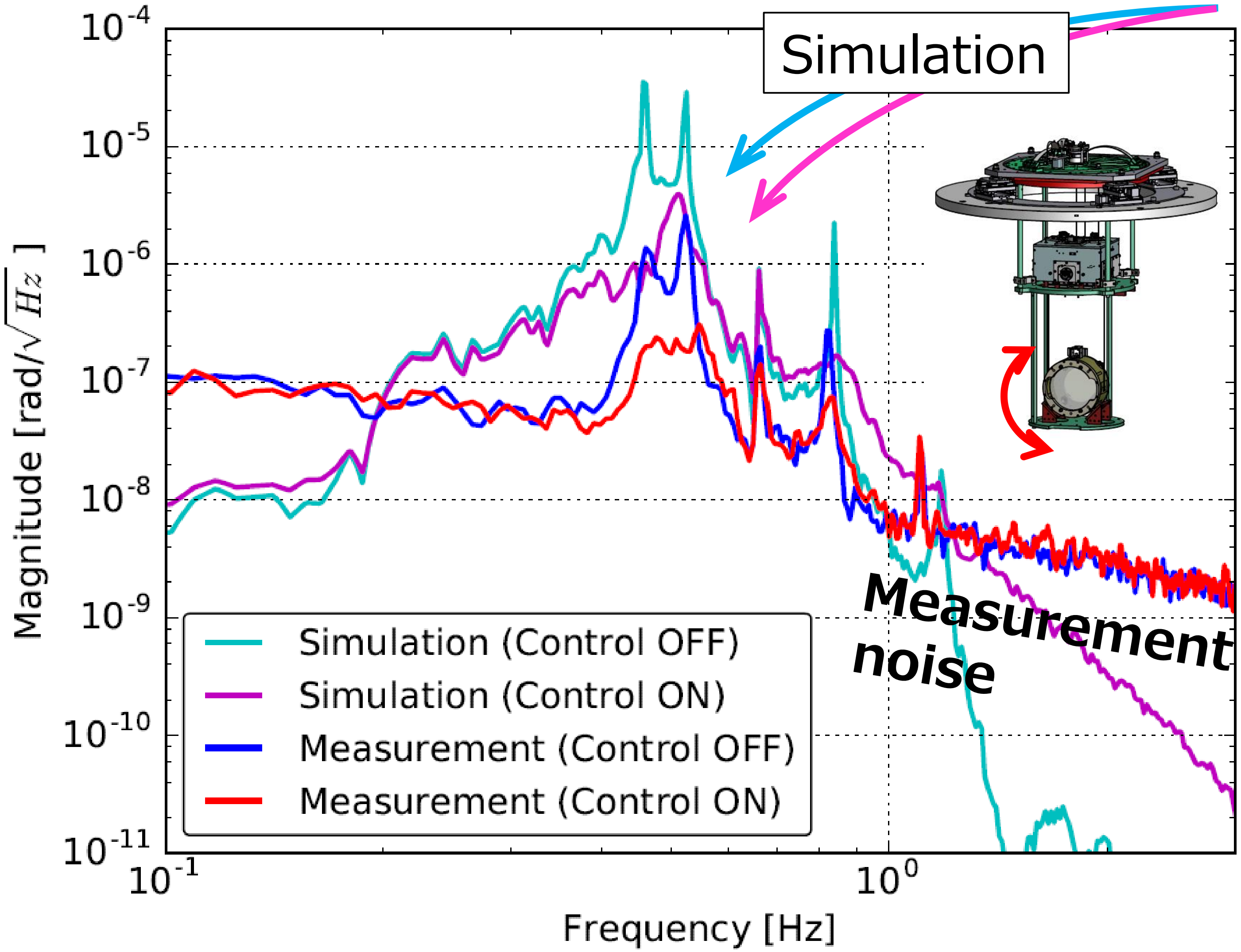






Test 2:
Residual vibration estimation

Performance test 2



Discrepancy ~10

$$\frac{\text{Mirror motion}}{\text{Seismic motion}} \times \text{Seismic motion at KAGRA site}$$

Simulation   Measurement

Lower seismic motion?

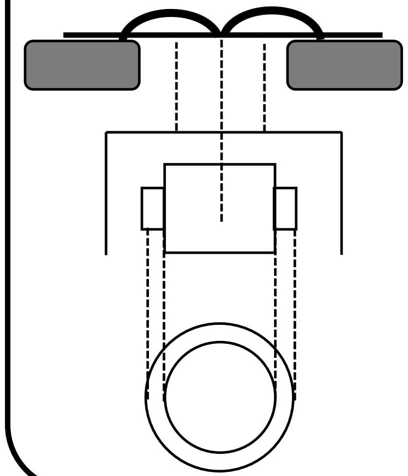
→ Discrepancy $\lesssim$ 10

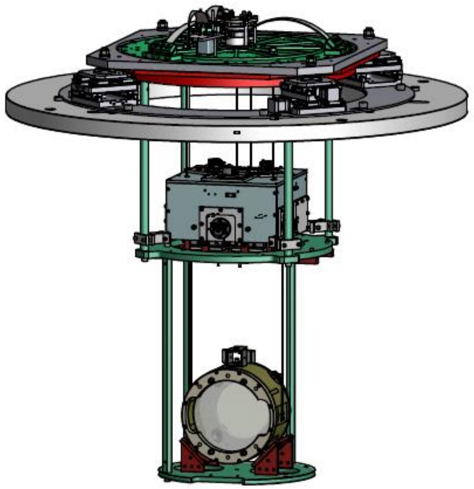
→ For designing, calculate using high seismic noise.

Upgrade: iKAGRA → final KAGRA

In order to meet final requirements:

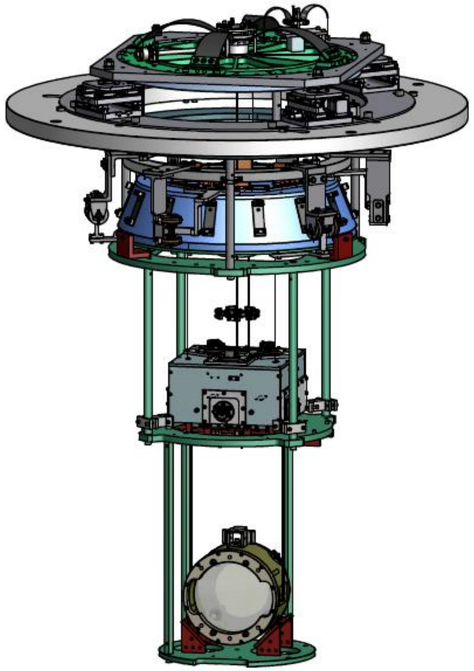
Initial phase

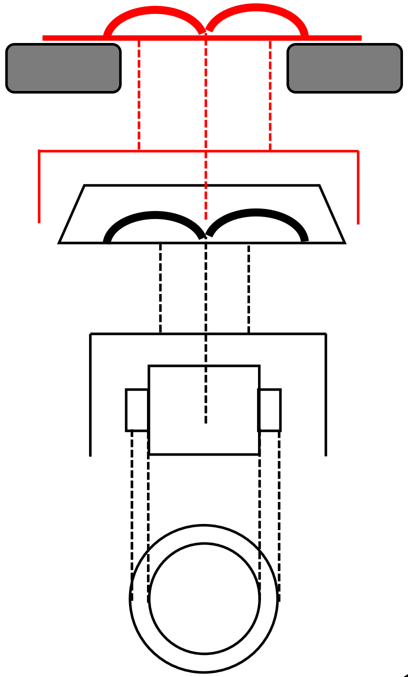




Add one more stage

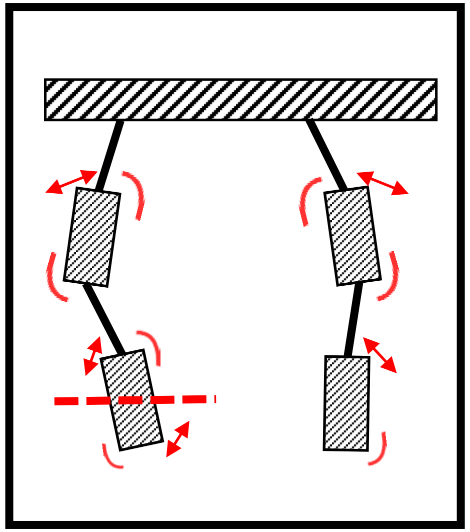
Final phase





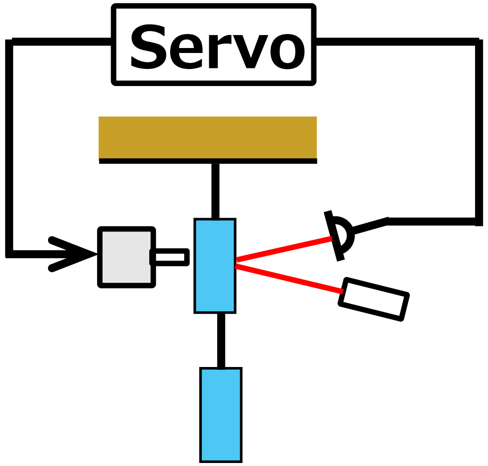
→ **Design active control systems.**

Steps for observation

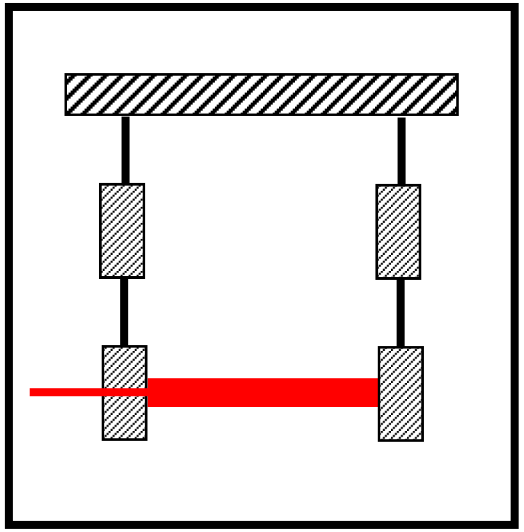


Free swinging

Calm-down phase

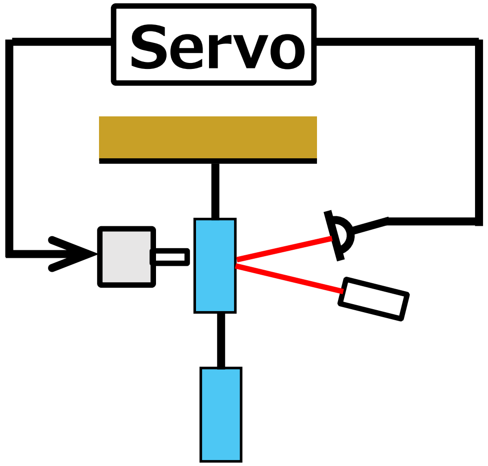


All stages
→ Damping



Interferometer Lock

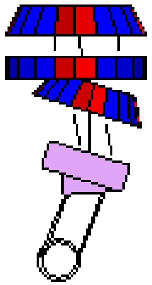
Observation phase

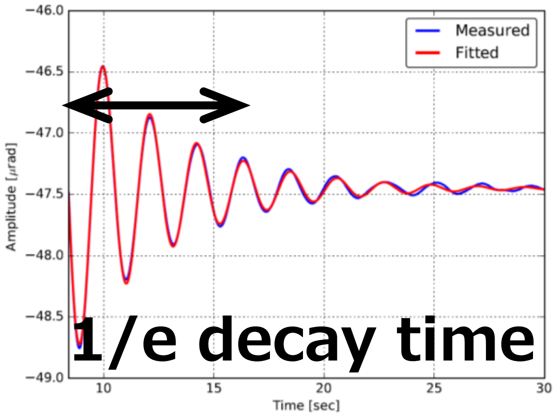


Upper stage
→ Damping

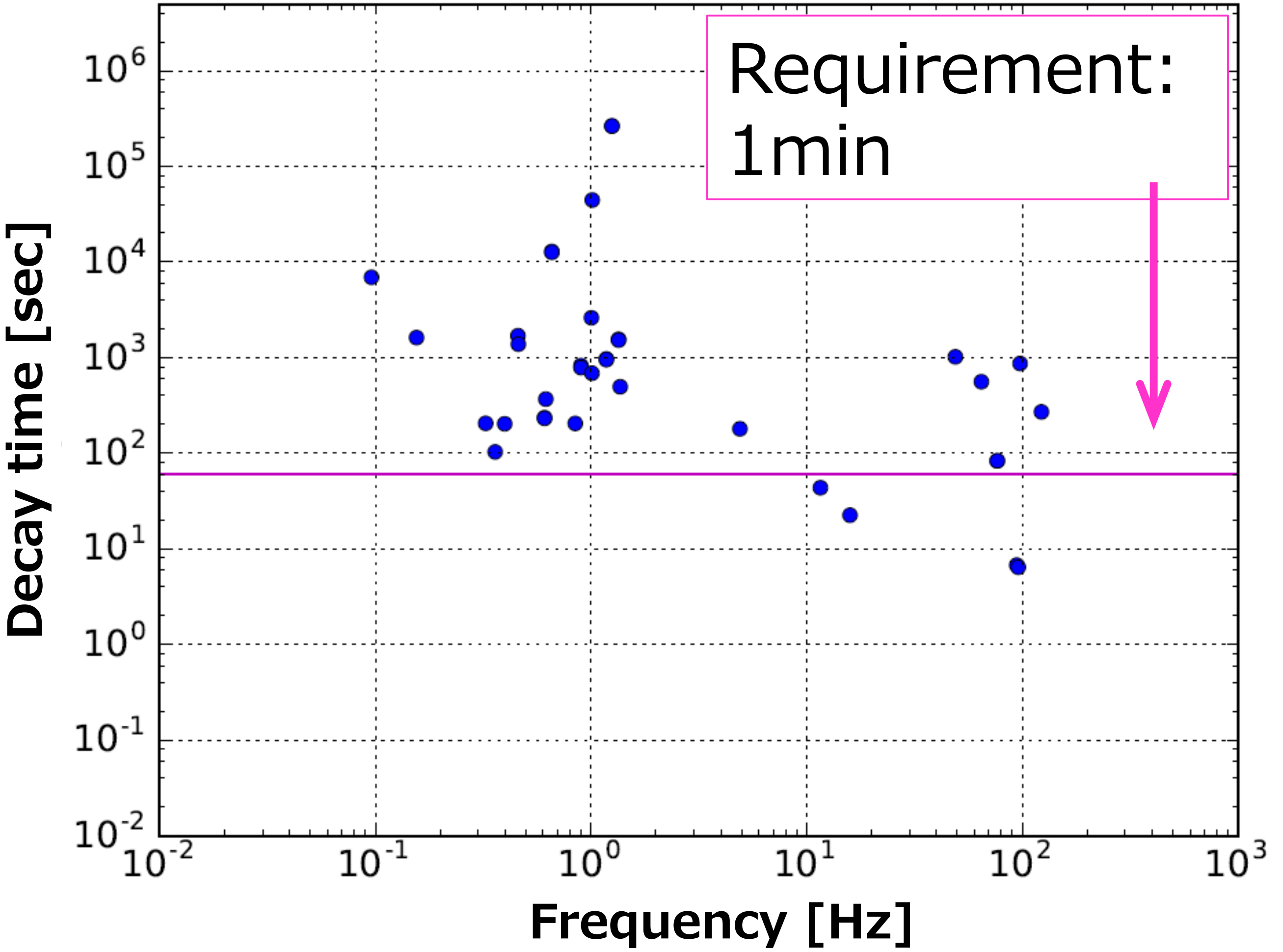
Lower stage
→ Alignment

Clam-down phase:
Suppress large disturbance

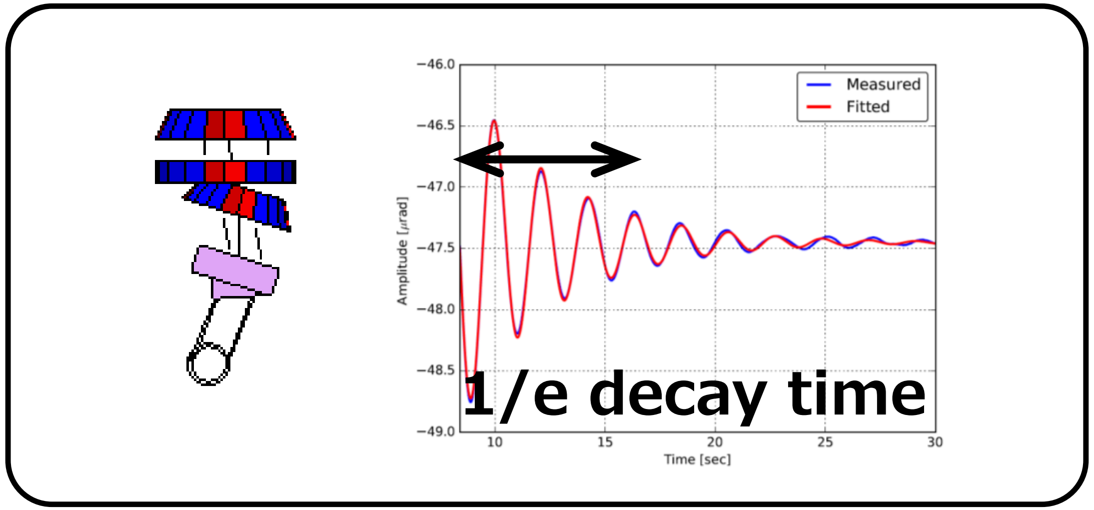


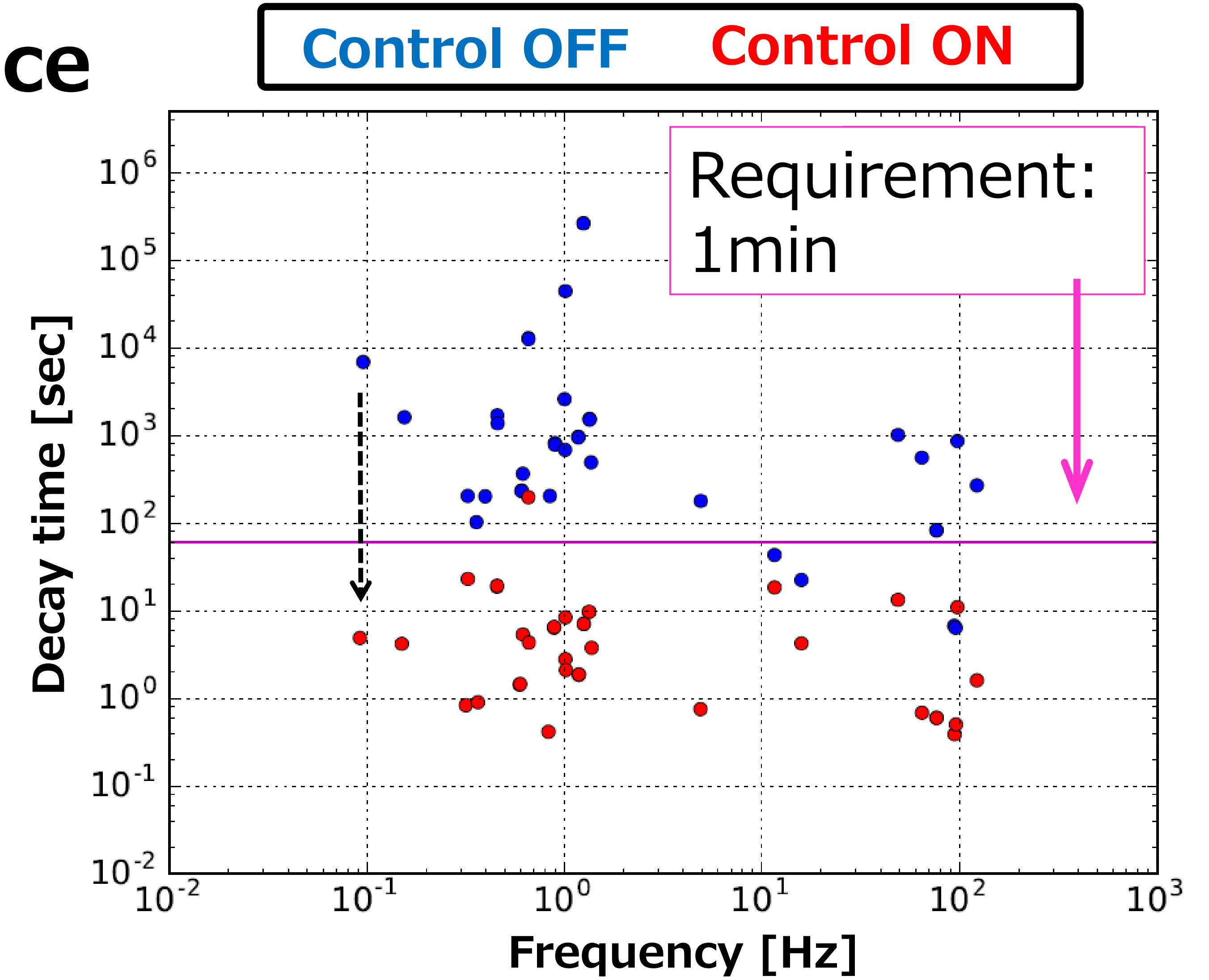


Control OFF

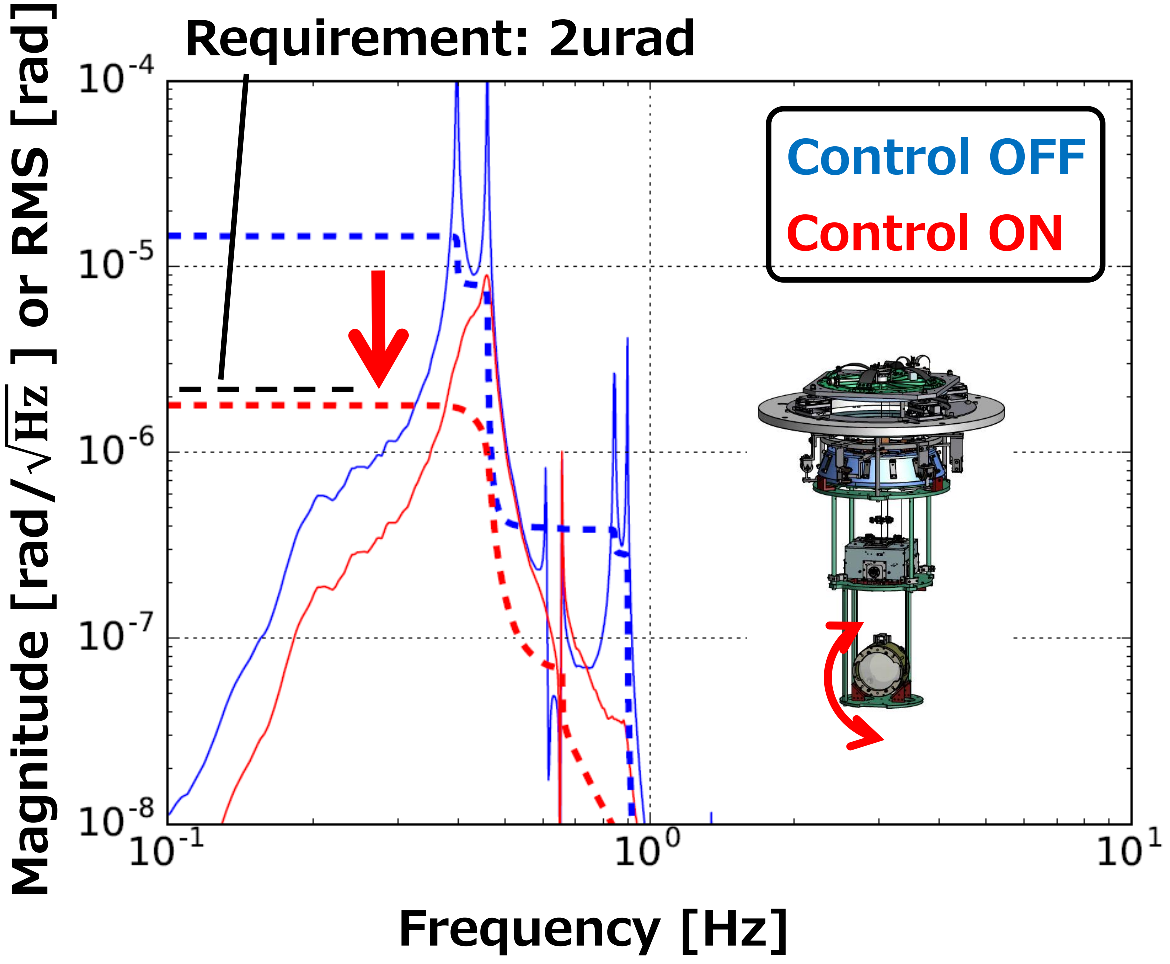


Clam-down phase:
Suppress large disturbance



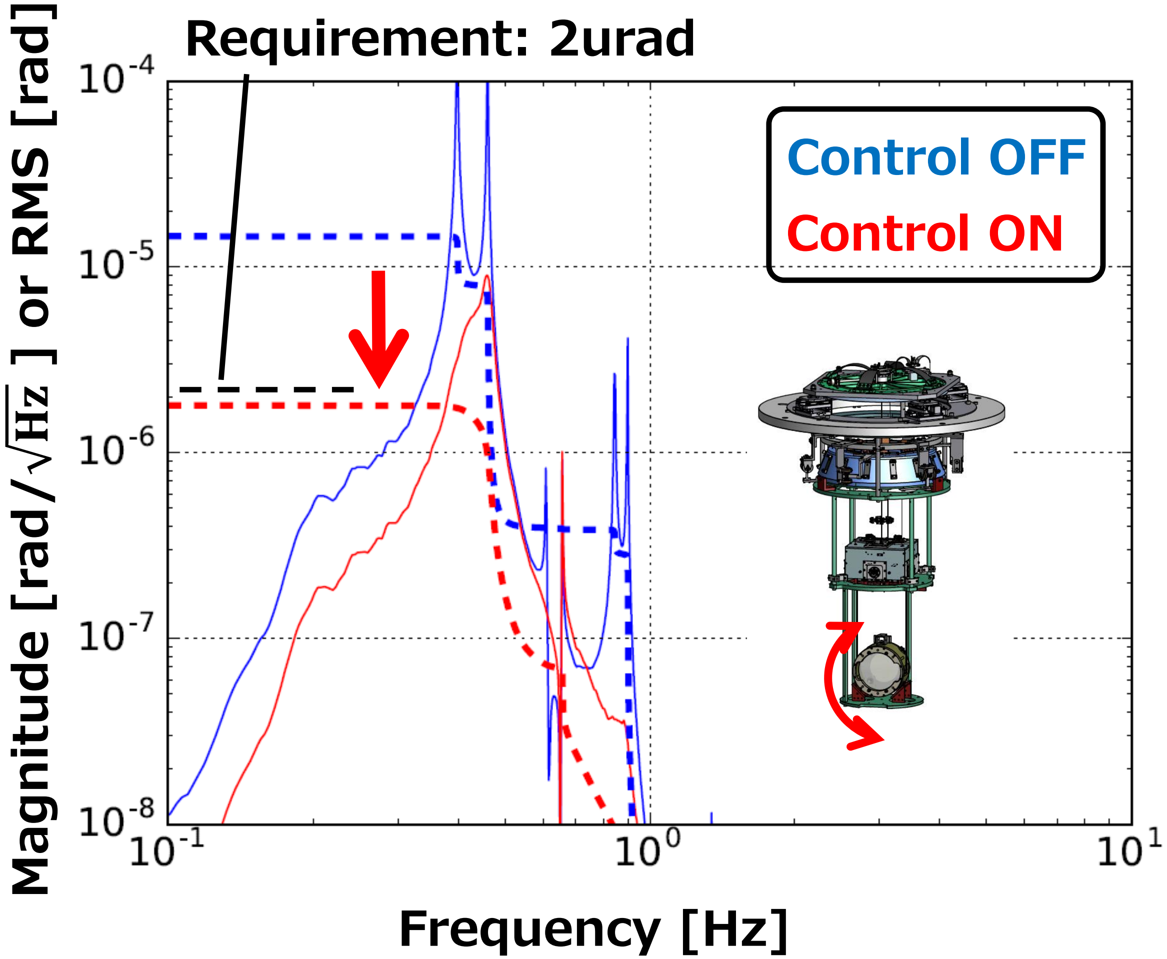


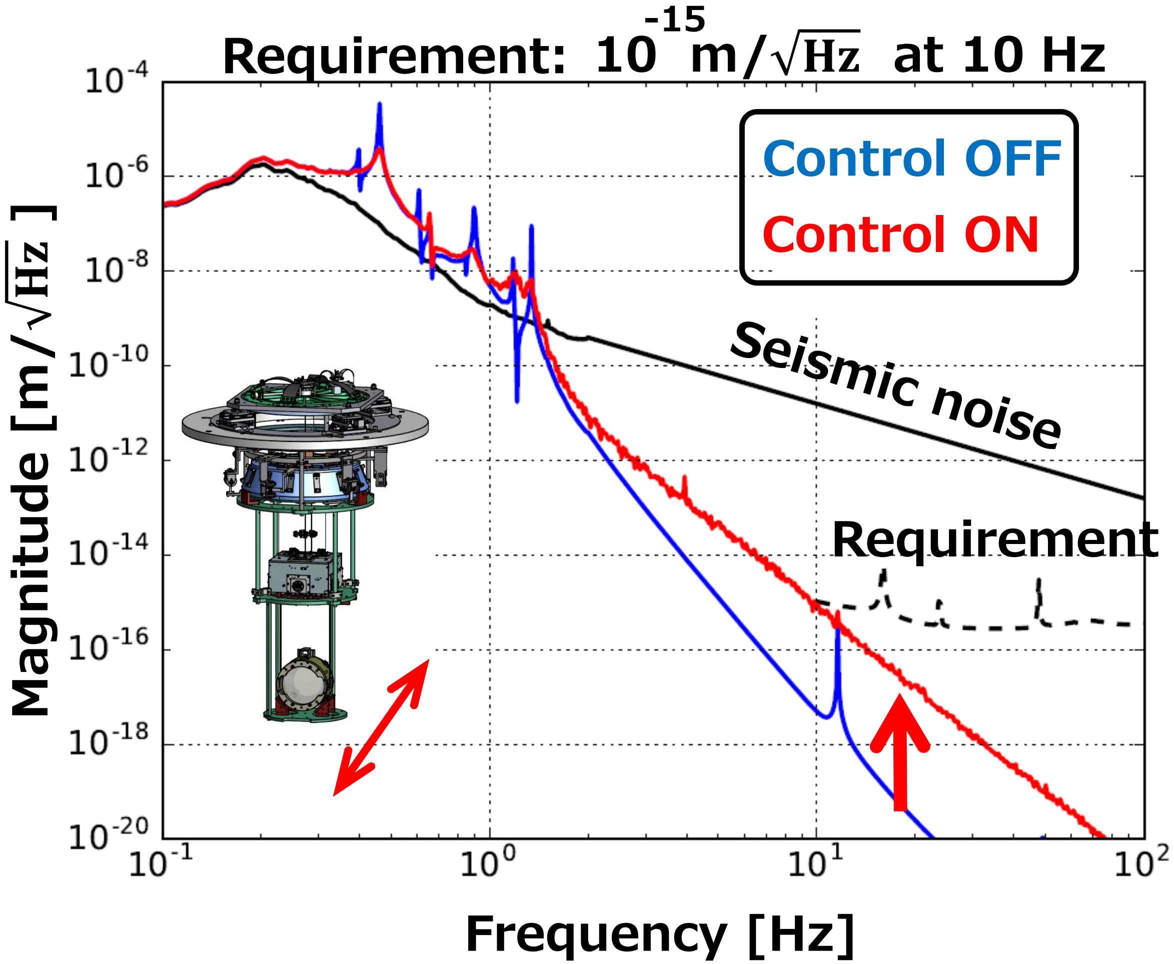
Observation phase:
Suppress RMS (Root Mean Square) & control noise



Observation phase:

Suppress RMS (Root Mean Square) & control noise

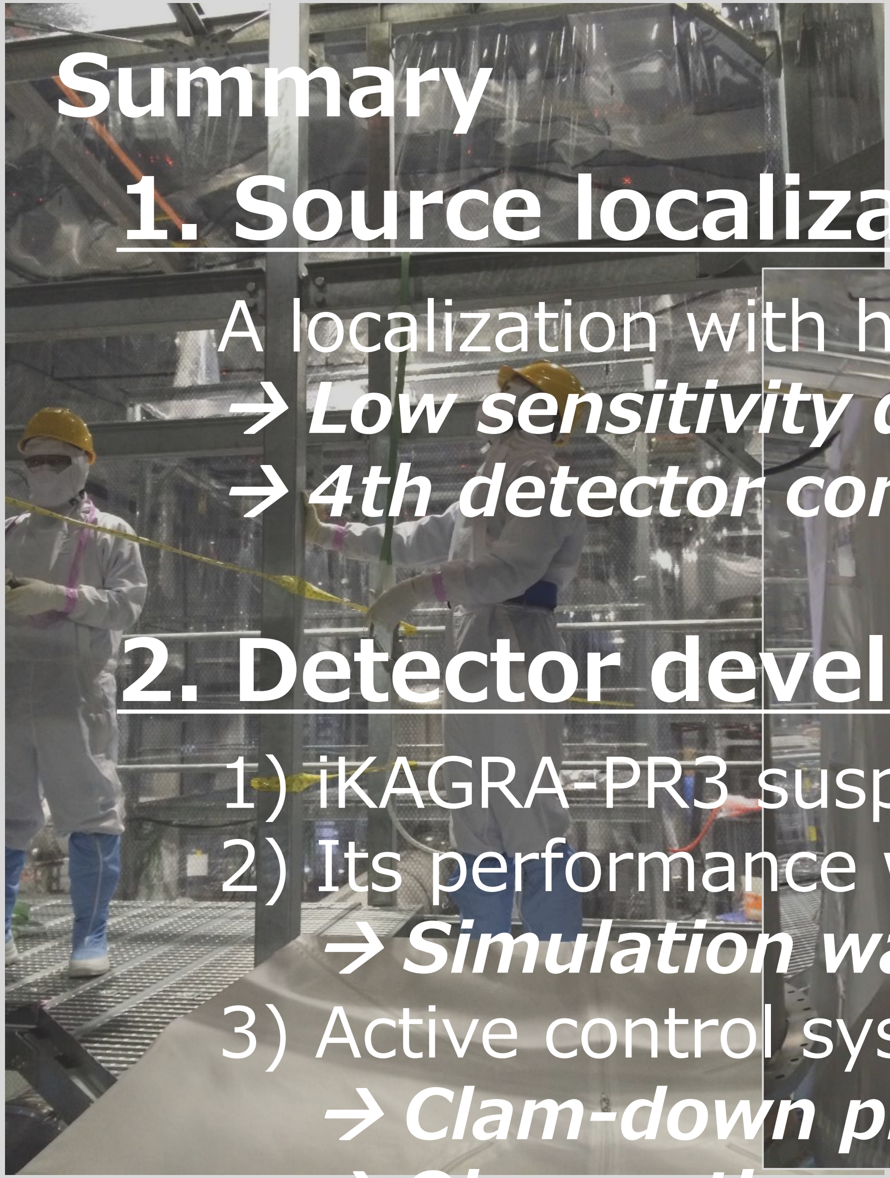


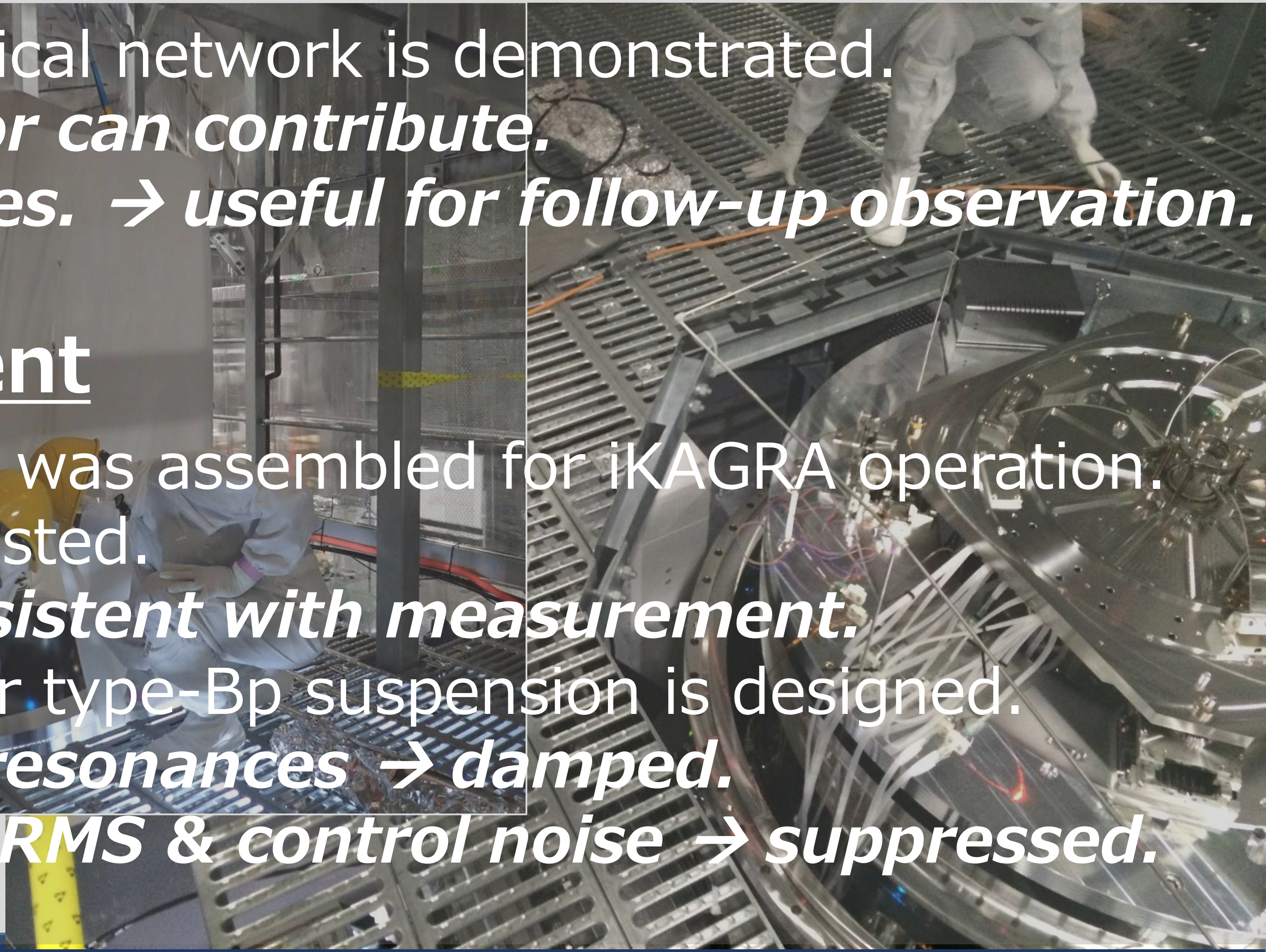


Summary 2

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.***





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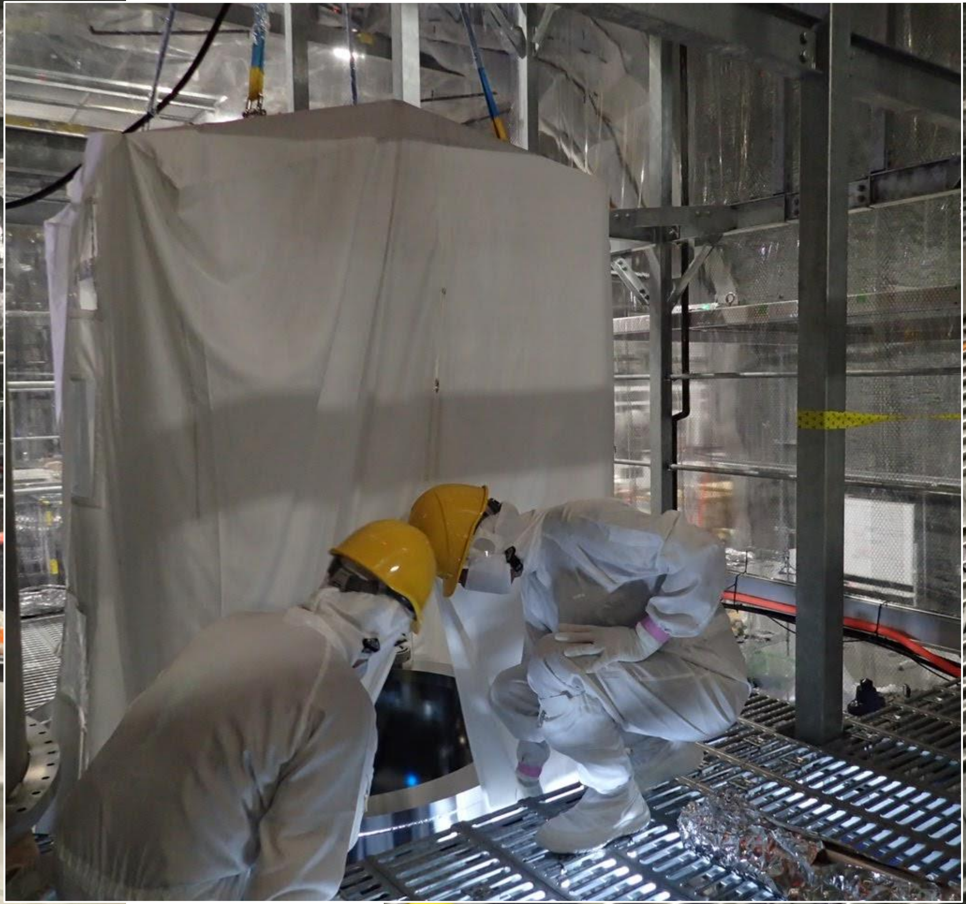
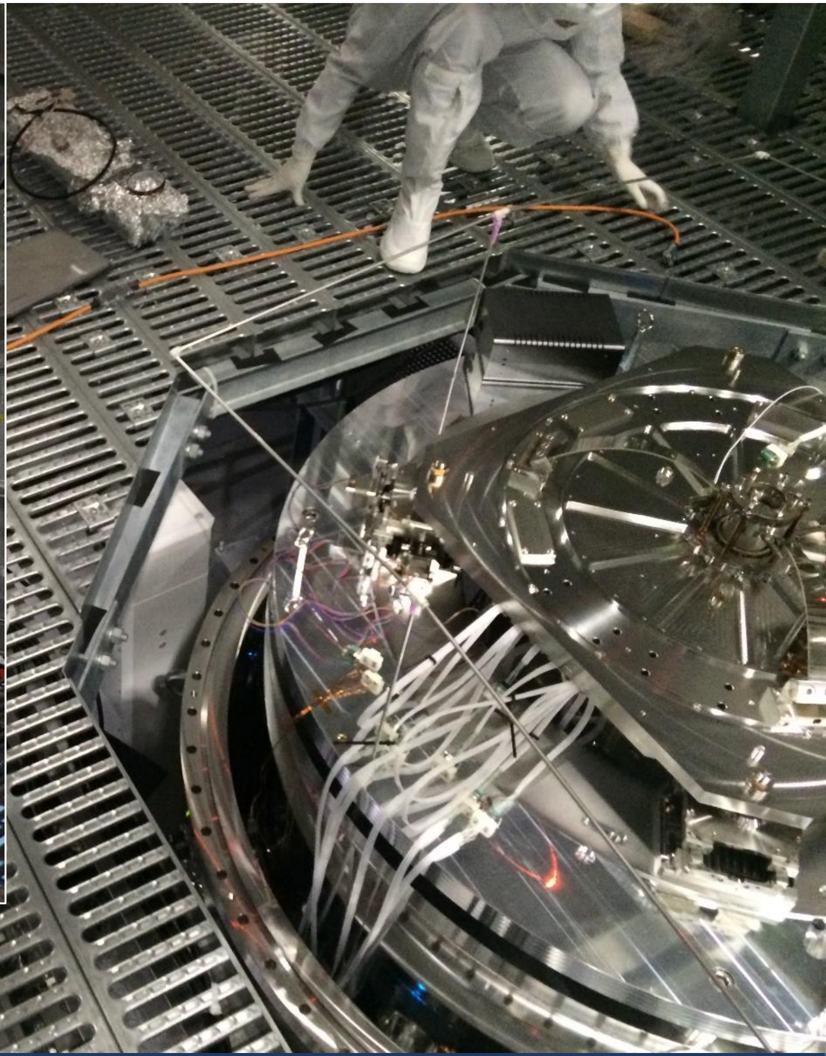
3) Active control system for type-Bp suspension is designed.
   → ***Clam-down phase: resonances → damped.***
   → ***Observation phase: RMS & control noise → suppressed.***

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.***

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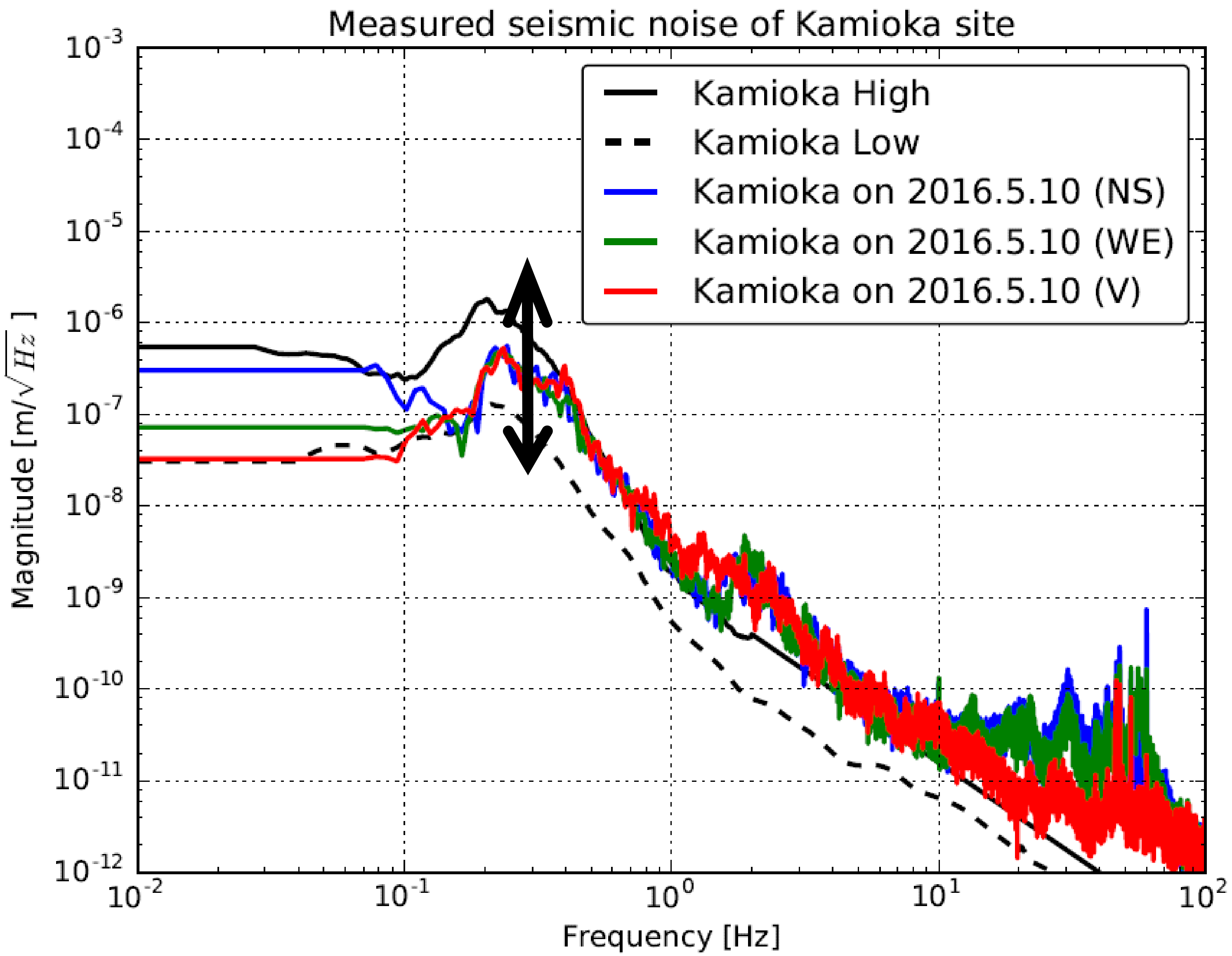
1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
2) Its performance were tested.
→ ***Simulation was consistent with measurement.***
3) Active control system for type-Bp suspension is designed.
→ ***Clam-down phase: resonances → damped.***
→ ***Observation phase: RMS & control noise → suppressed.***

Seismic noise of Kamioka (on 2016.5.10)

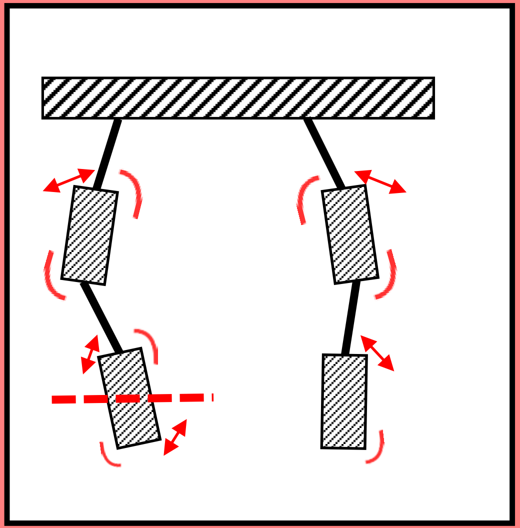


seismic noise was measured on 2016.5.10.

PR3 measurement was conducted on 2016.5.24.

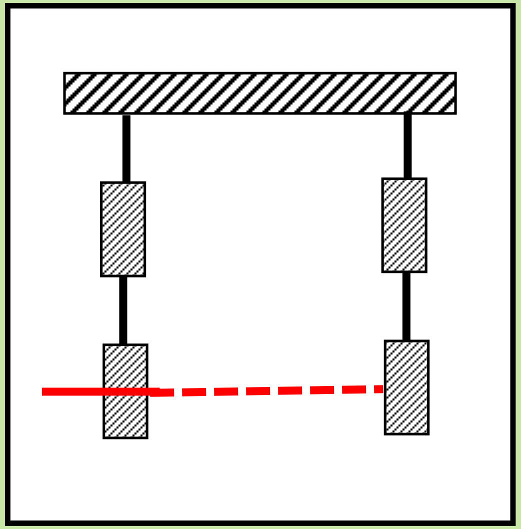
Designing active control system / Control phase

1. Calm-down phase



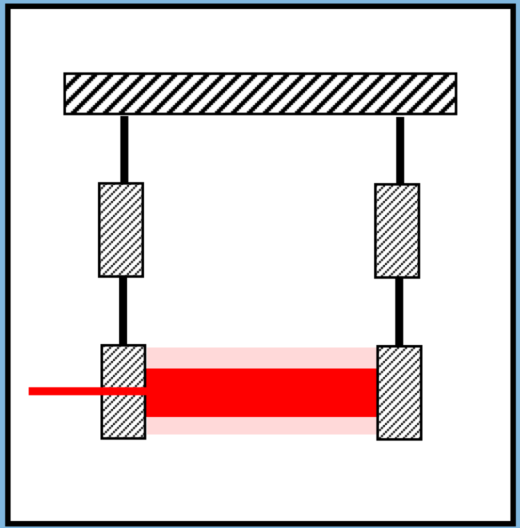
Suppress
large disturbance

2. Lock-acquisition phase



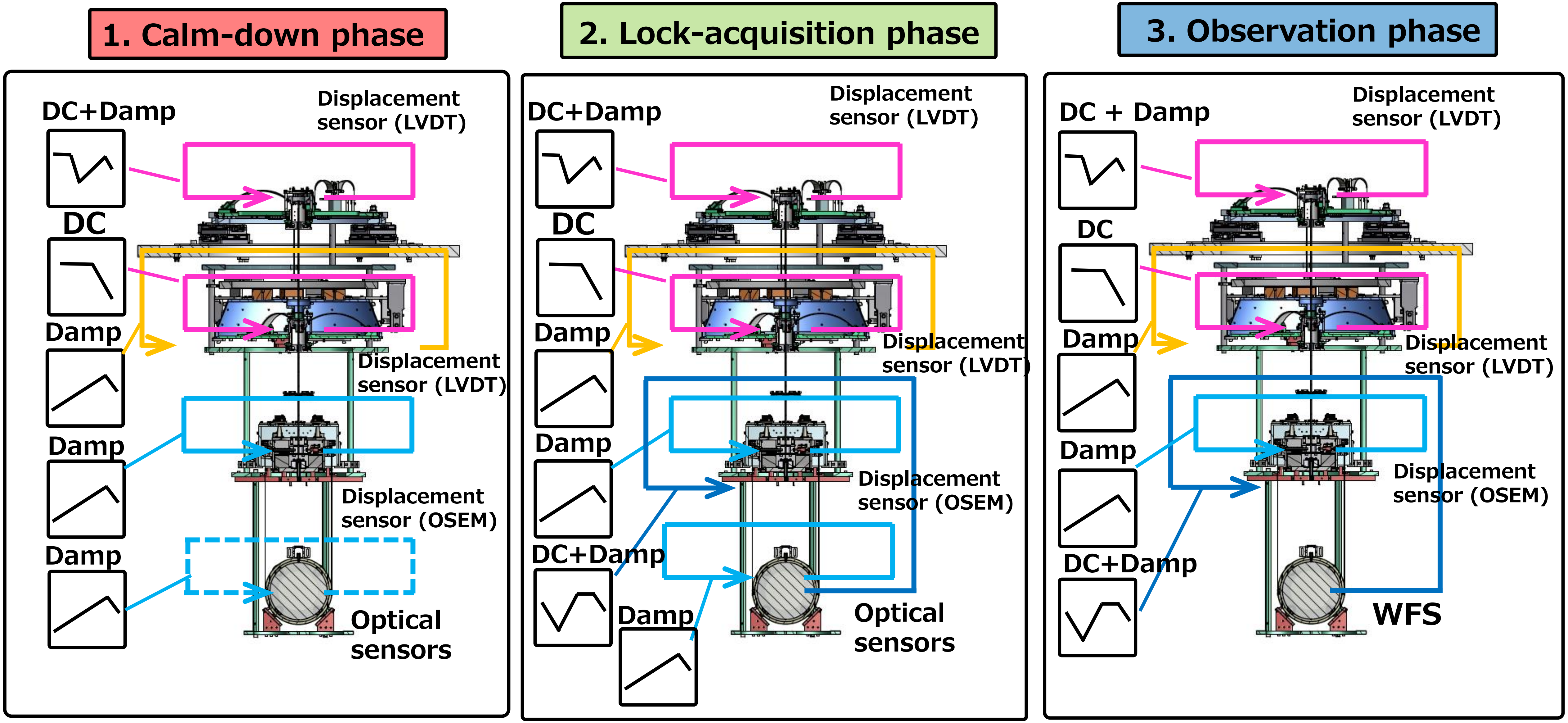
Reduce RMS velocity
RMS angle
(Root-Mean-Square)

3. Observation phase



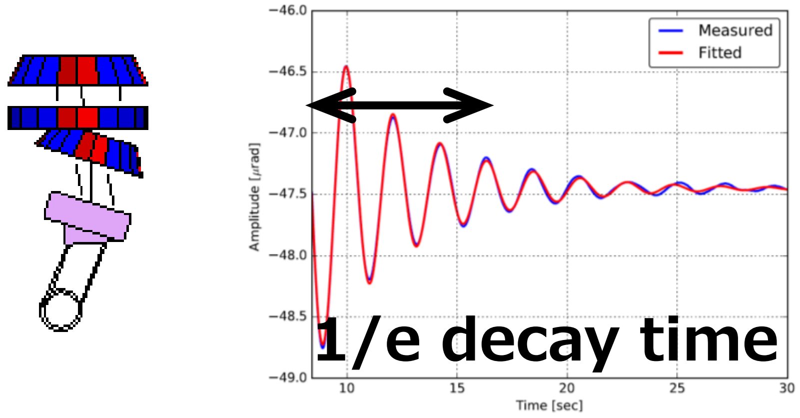
Keep position
with low noise
control

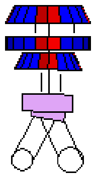
Designing active control system / Type-Bp SAS



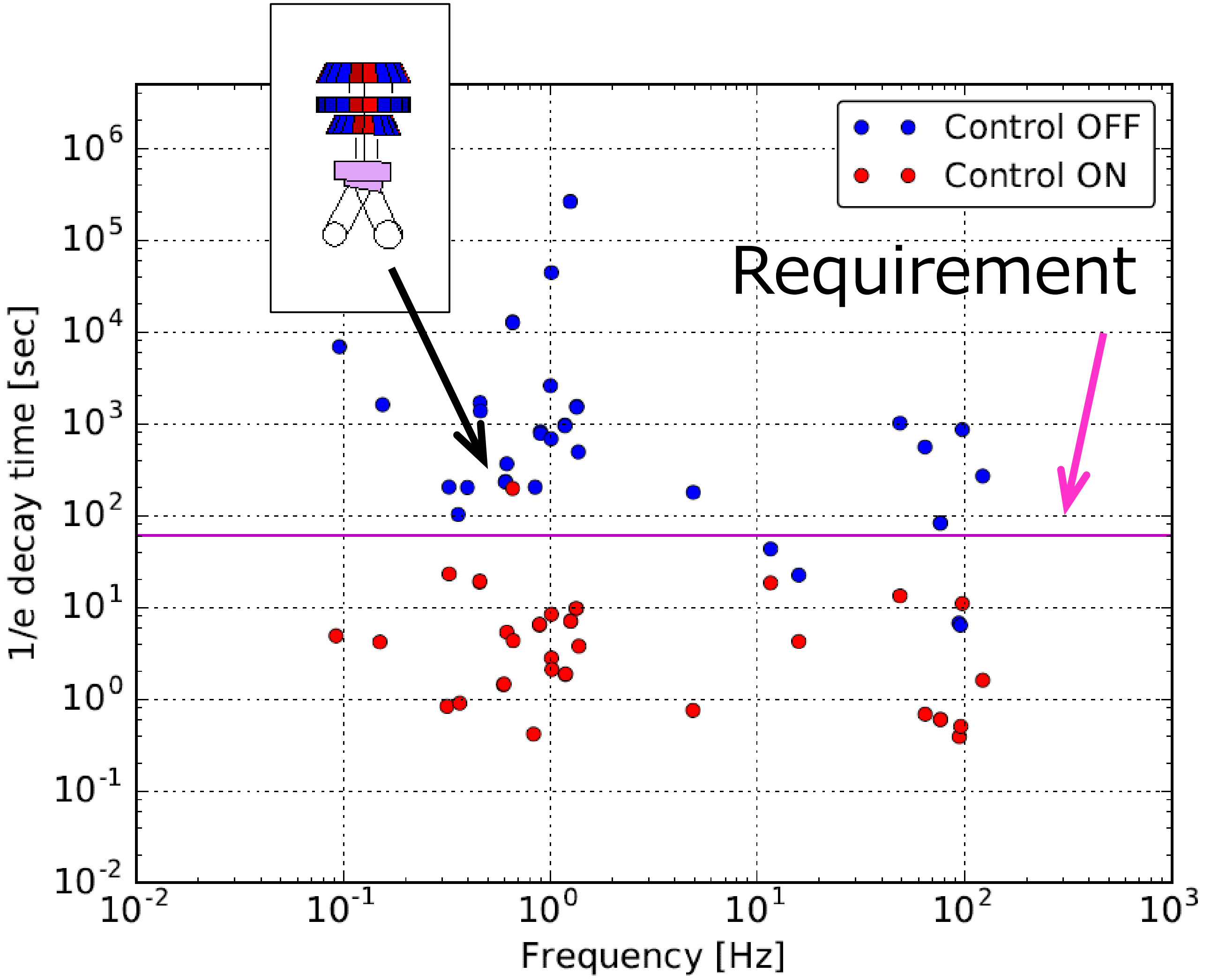
Designing active control system 1

Calm-down phase:
Suppress large disturbance



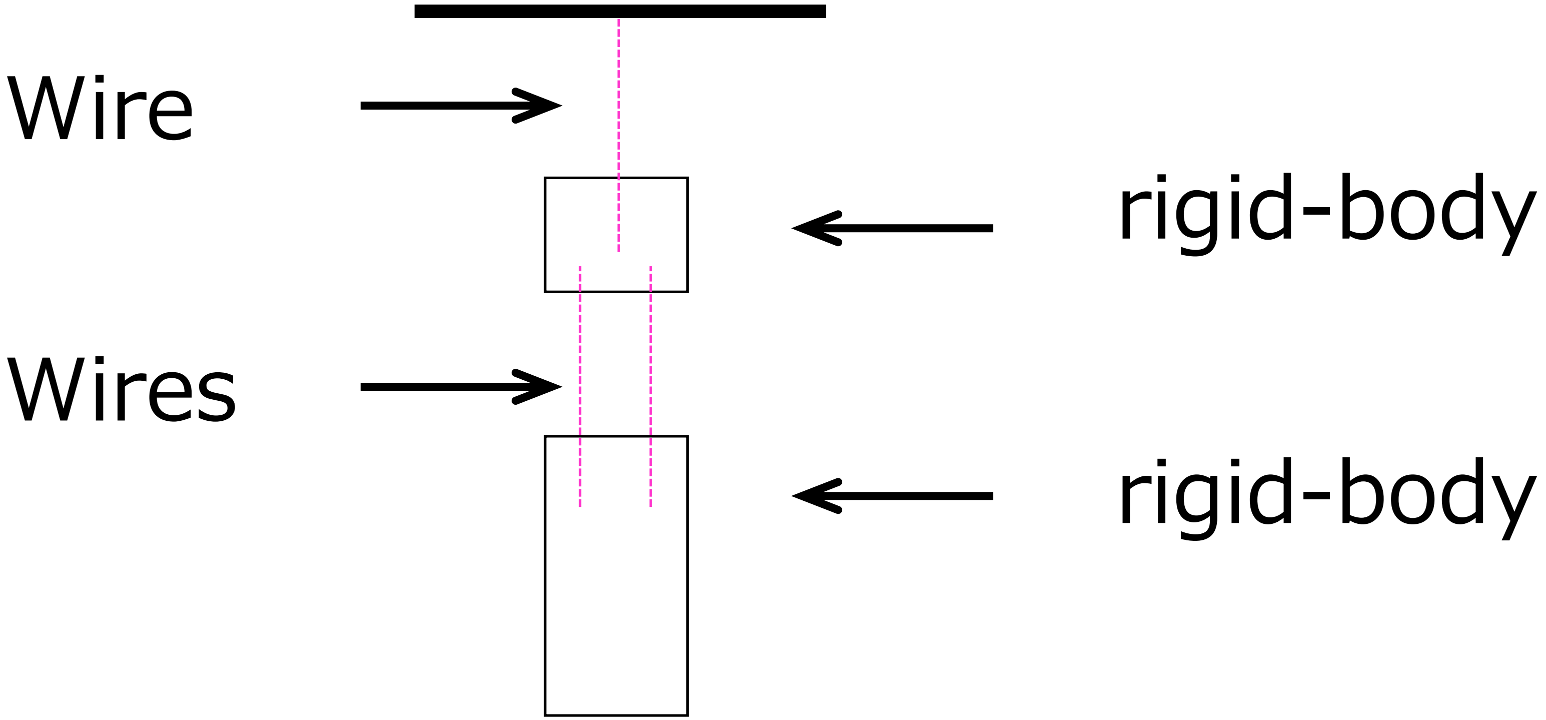


Not disturb operation
→ No problem.

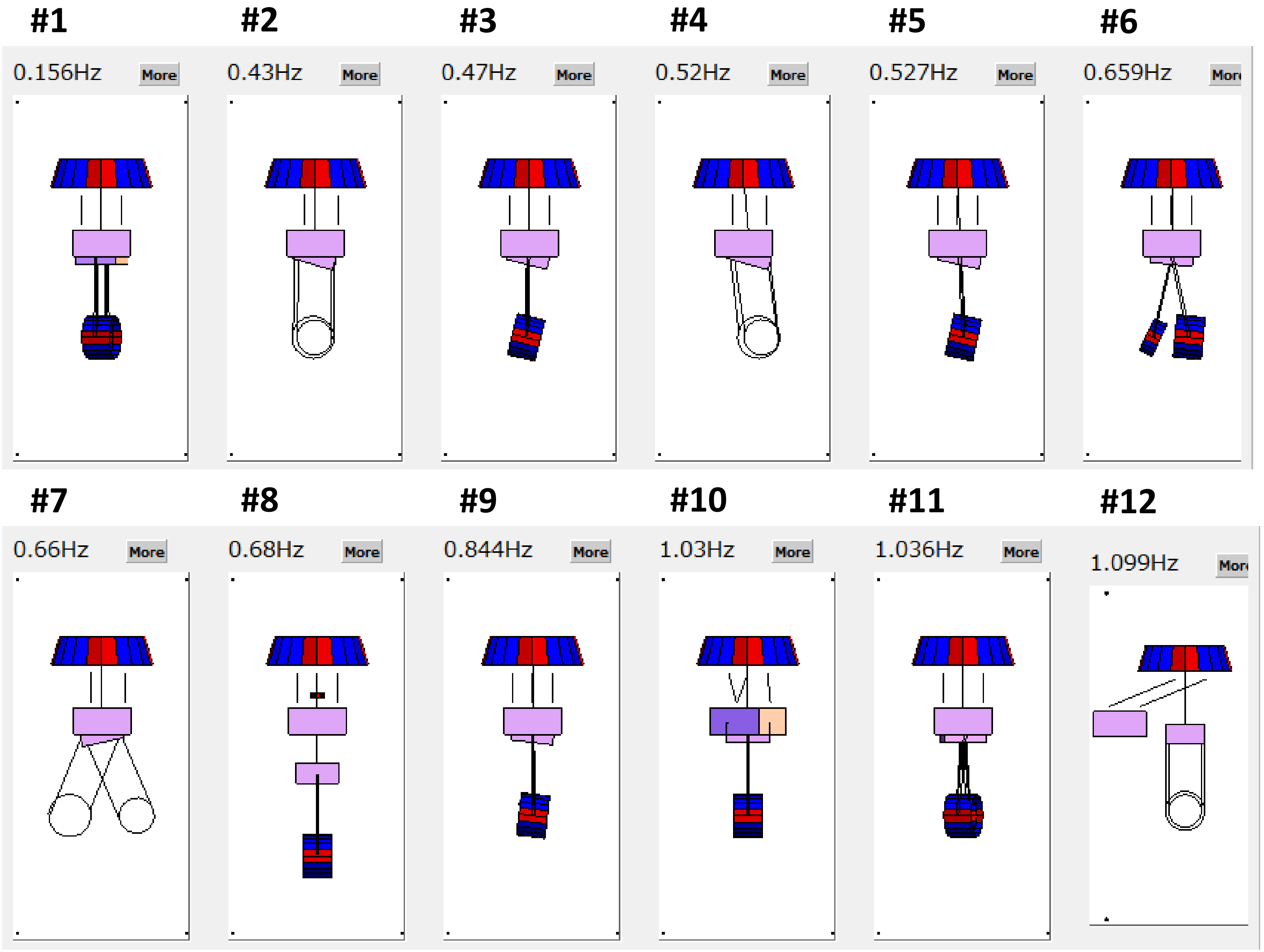


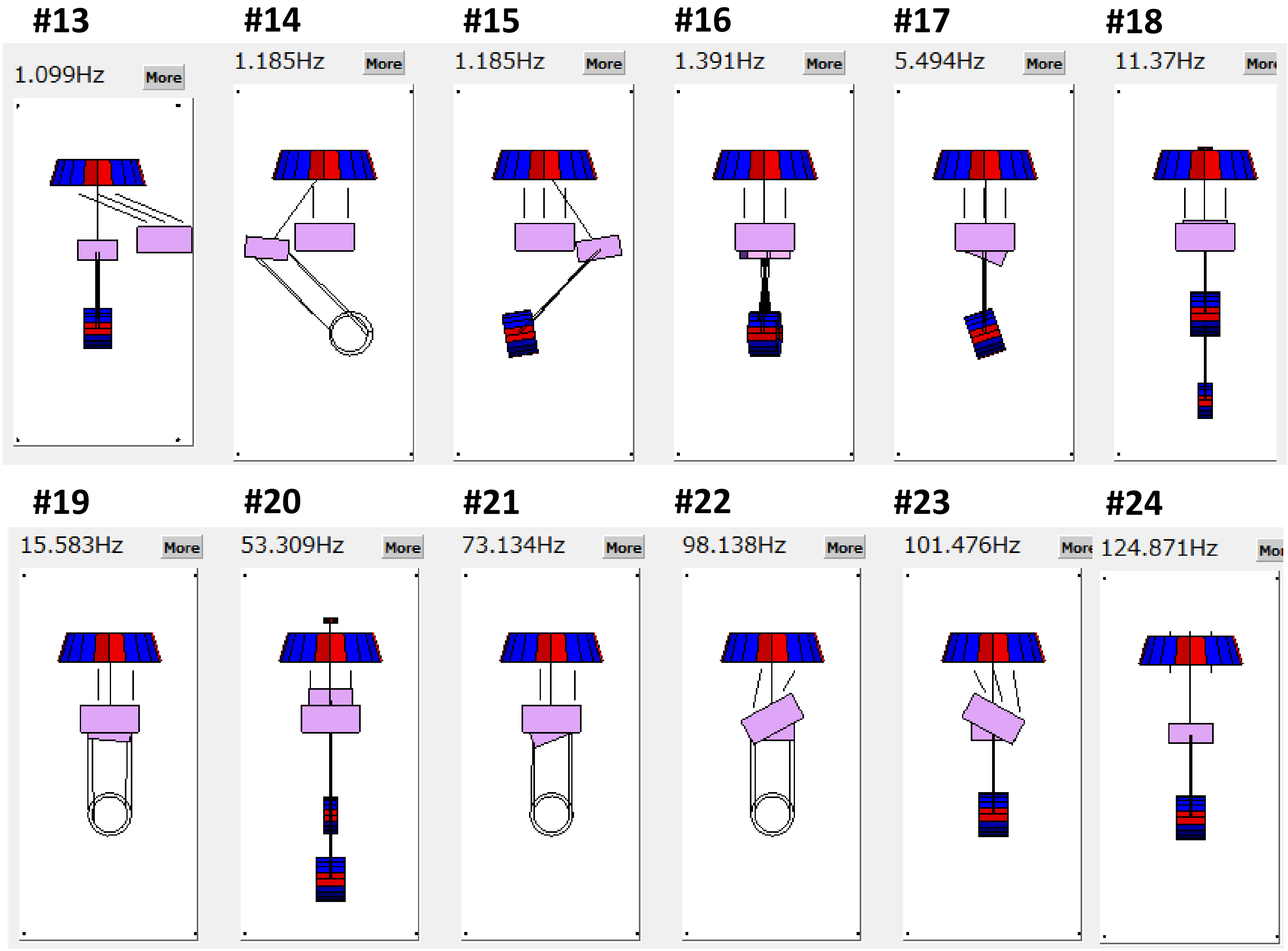
(if all sensors available)

Simulation model: Based on rigid-body

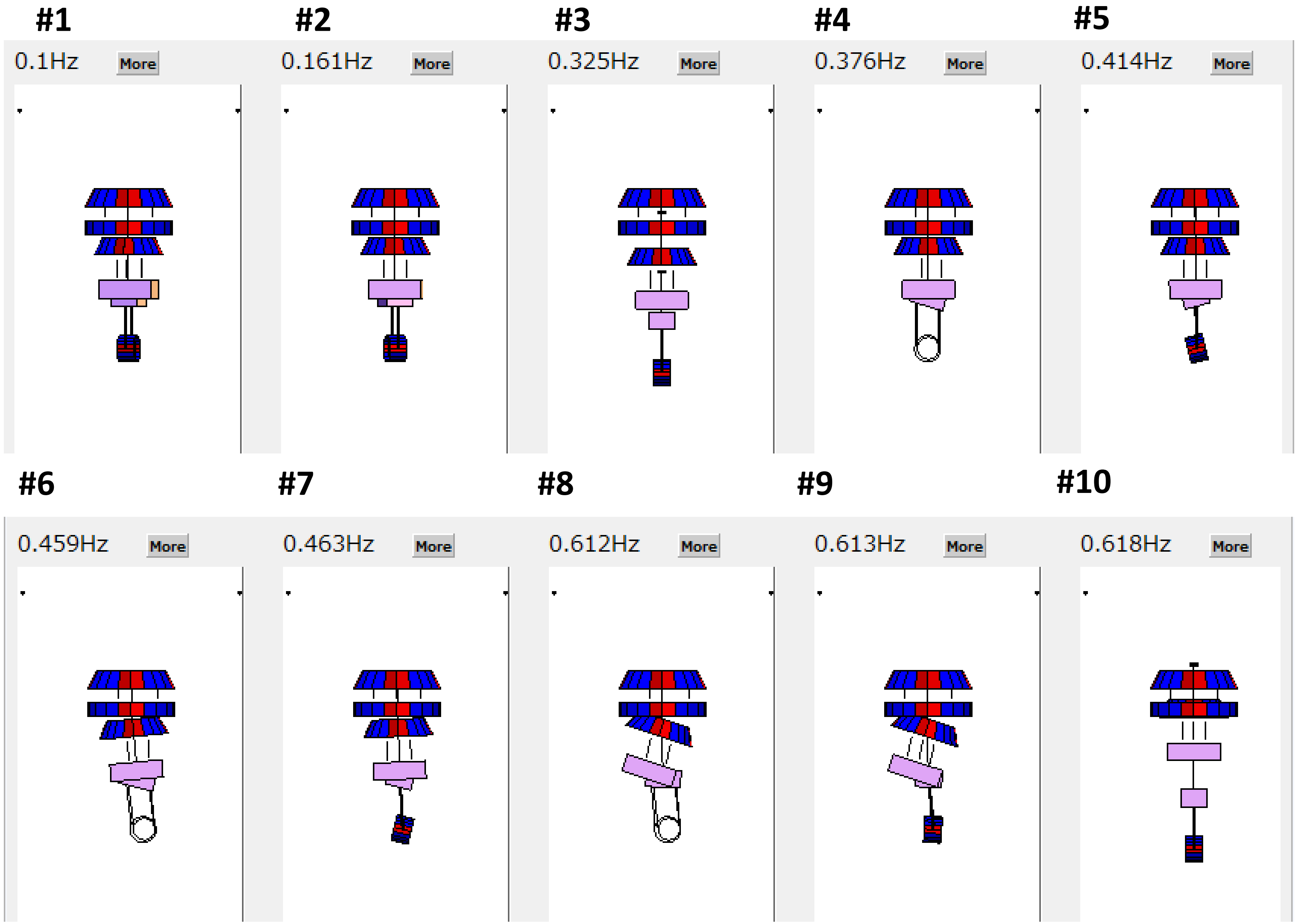


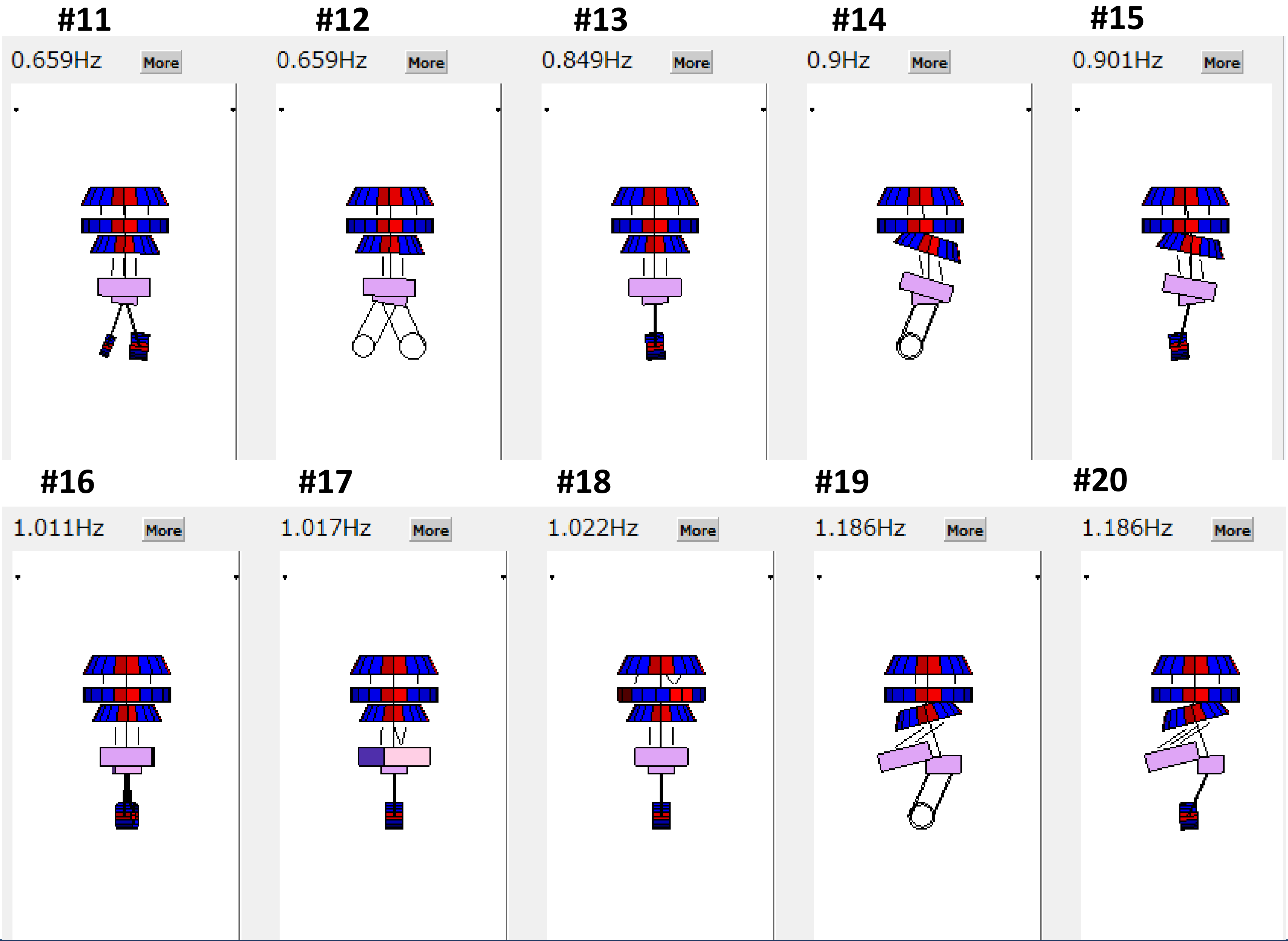
TypeBpp SAS
Eigen mode List : 24 modes

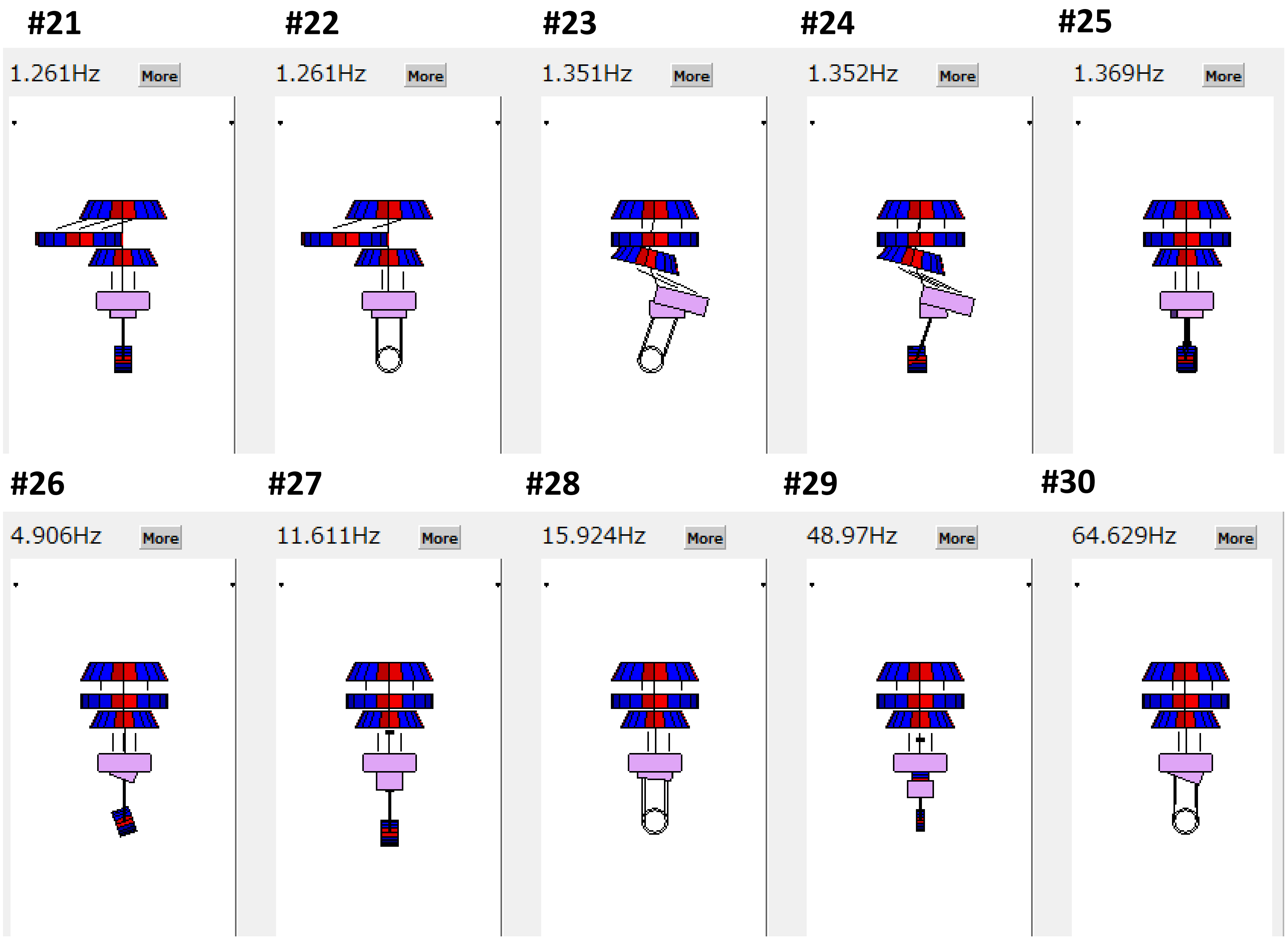



#13
1.099Hz
More
#14
1.185Hz
More
#15
1.185Hz
More
#16
1.391Hz
More
#17
5.494Hz
More
#18
11.37Hz
#19
15.583Hz
More
#20
53.309Hz
More
#21
73.134Hz
More
#22
98.138Hz
More
#23
101.476Hz
#24
124.871Hz

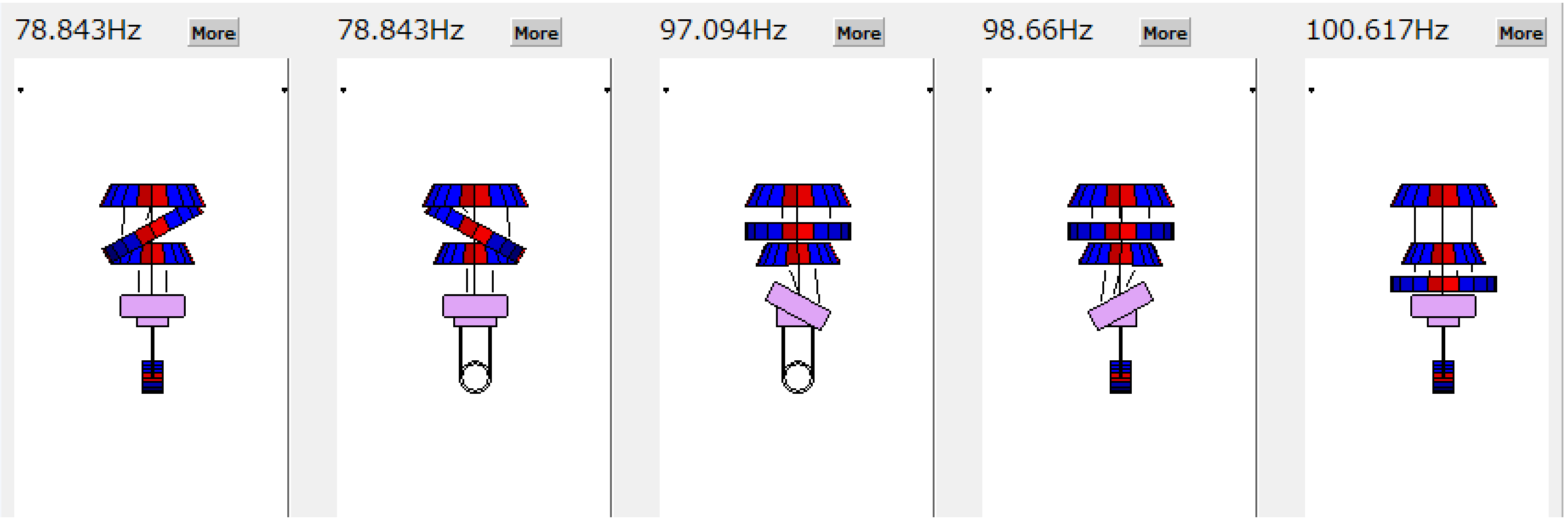
TypeBp SAS
Eigen mode List : 36 modes



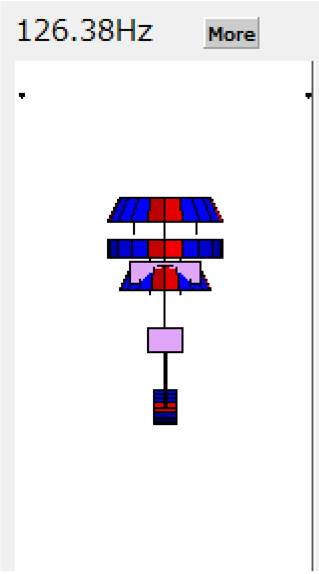

#11
0.659Hz
More
#12
0.659Hz
More
#13
0.849Hz
More
#14
0.9Hz
More
#15
0.901Hz
More
#16
1.011Hz
More
#17
1.017Hz
More
#18
1.022Hz
More
#19
1.186Hz
More
#20
1.186Hz
More

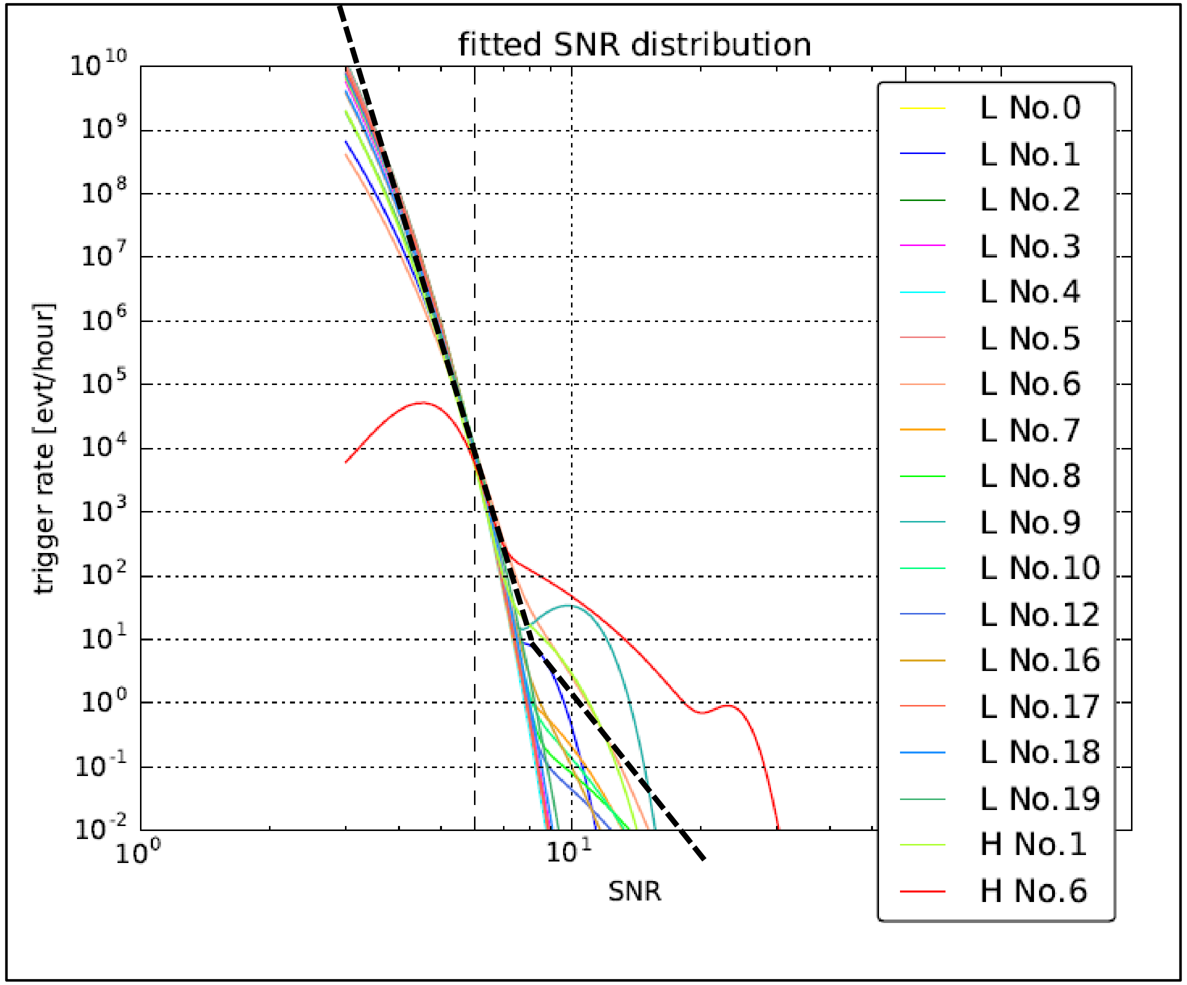

#21
1.261Hz
More
#22
1.261Hz
More
#23
1.351Hz
More
#24
1.352Hz
More
#25
1.369Hz
More
#26
4.906Hz
More
#27
11.611Hz
More
#28
15.924Hz
More
#29
48.97Hz
More
#30
64.629Hz
More

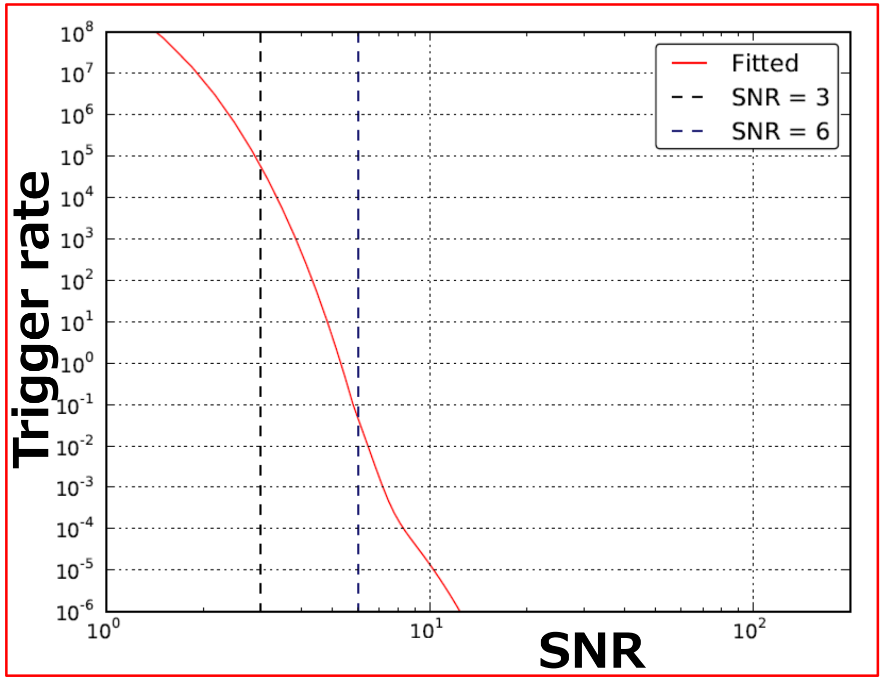
#31 #32 #33 #34 #35



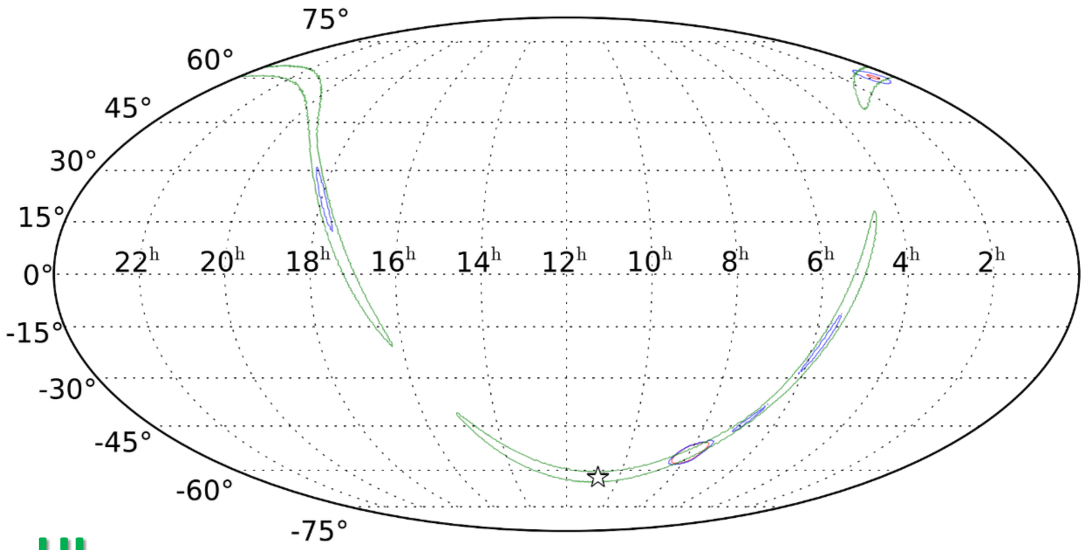
#36



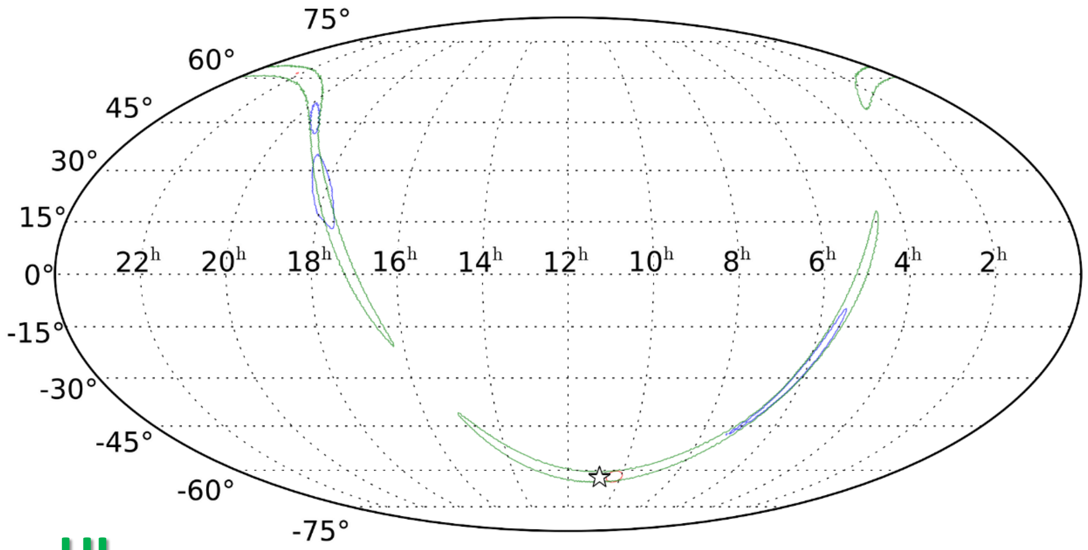

fitted SNR distribution
trigger rate [evt/hour]
SNR
L No.0
L No.1
L No.2
L No.3
L No.4
L No.5
L No.6
L No.7
L No.8
L No.9
L No.10
L No.12
L No.16
L No.17
L No.18
L No.19
H No.1
H No.6


Trigger rate
SNR
Fitted
SNR = 3
SNR = 6

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



HL
HL + Vrandom
HL + Vrandom + Krandom



HL
HL + Vinj
HL + Vinj + Kinj

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)

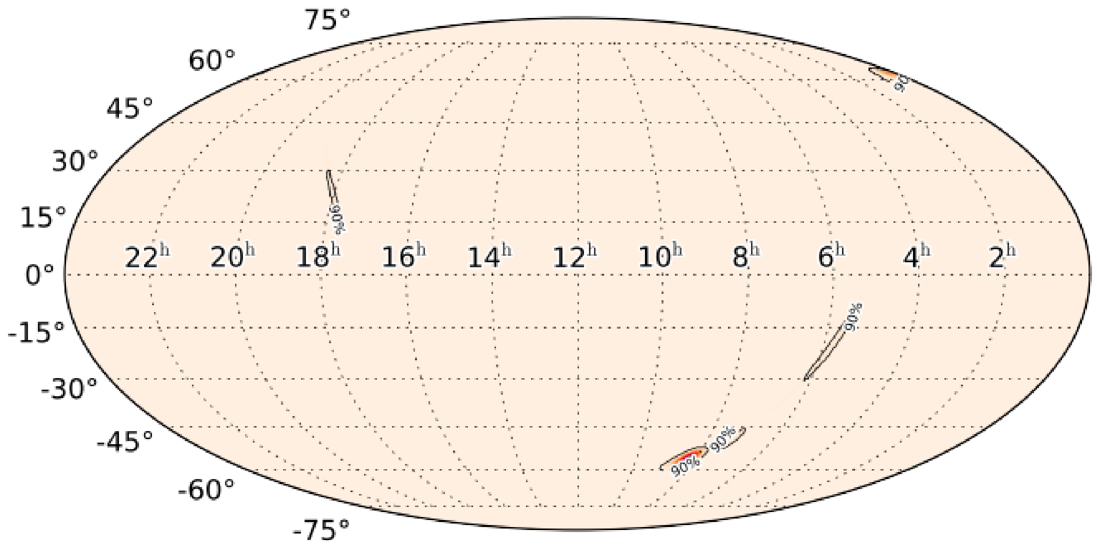
Case 1: worst case
HL+Vr, or HL
(Based on ***FAP***)

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)

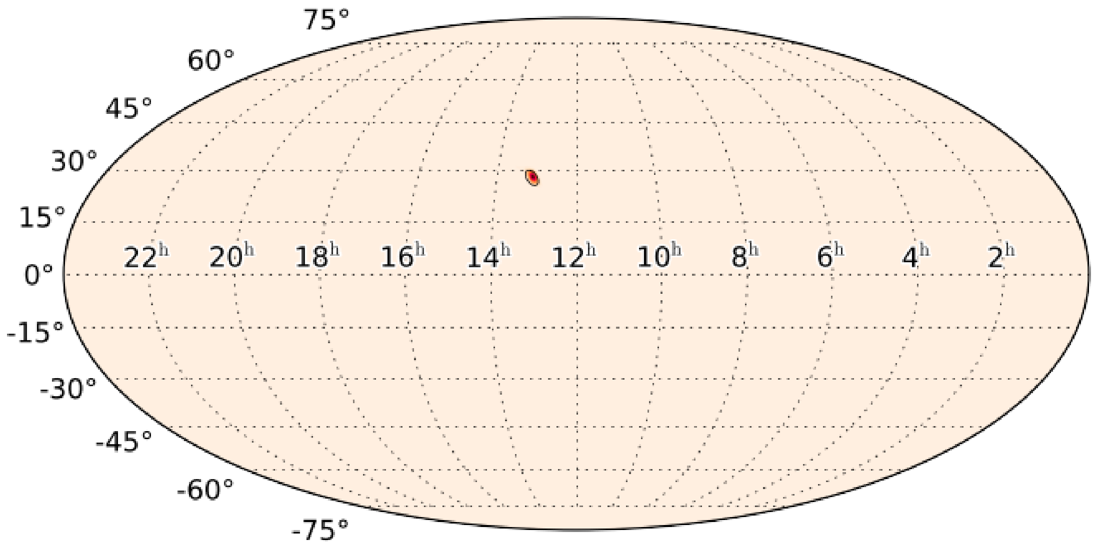
Expected localization performance / by HLV

HL+Vrandom



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

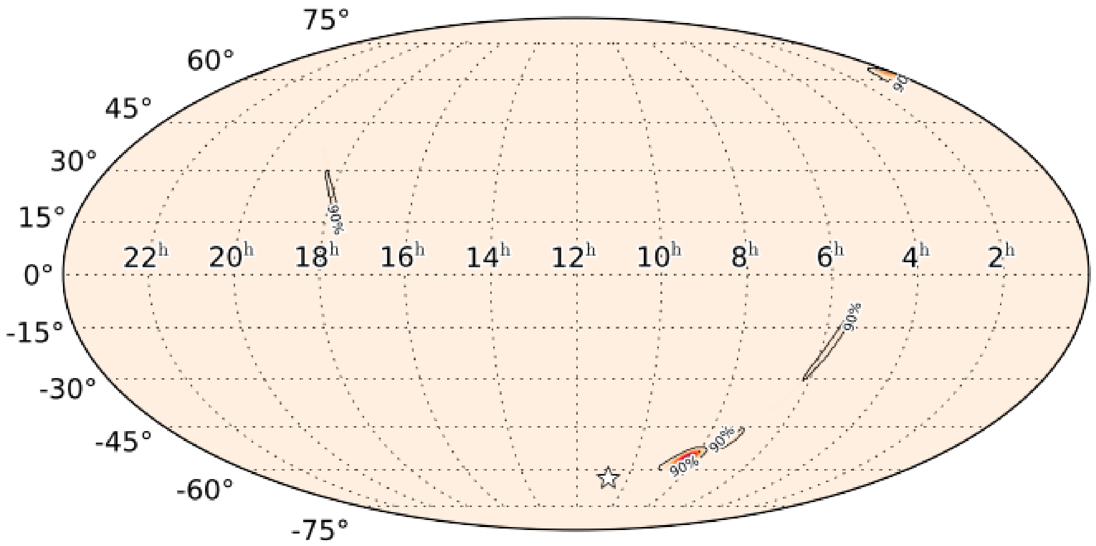
HL+Vinjection



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

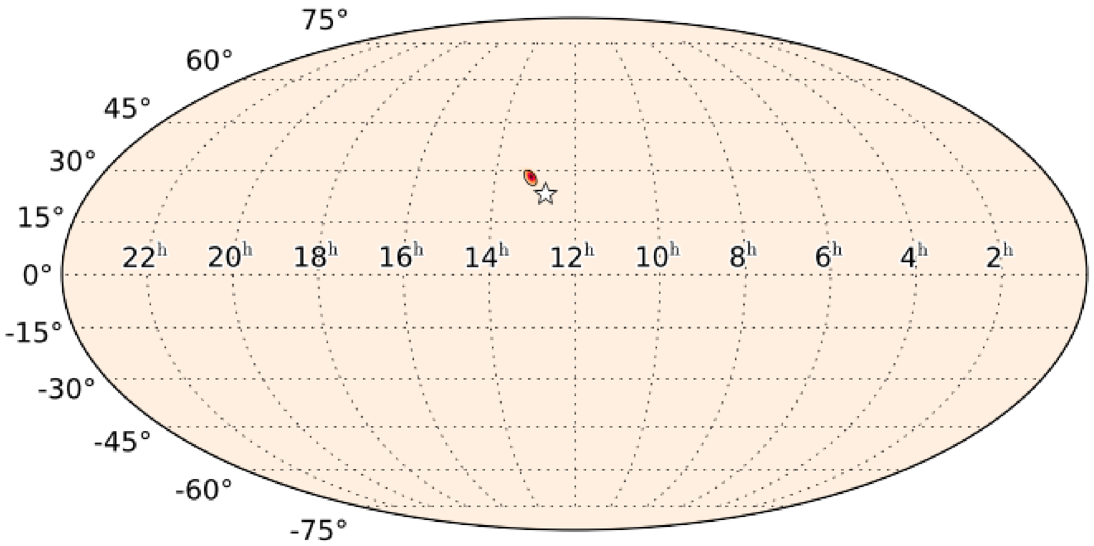
Expected localization performance / by HLV

HL+Vrandom



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

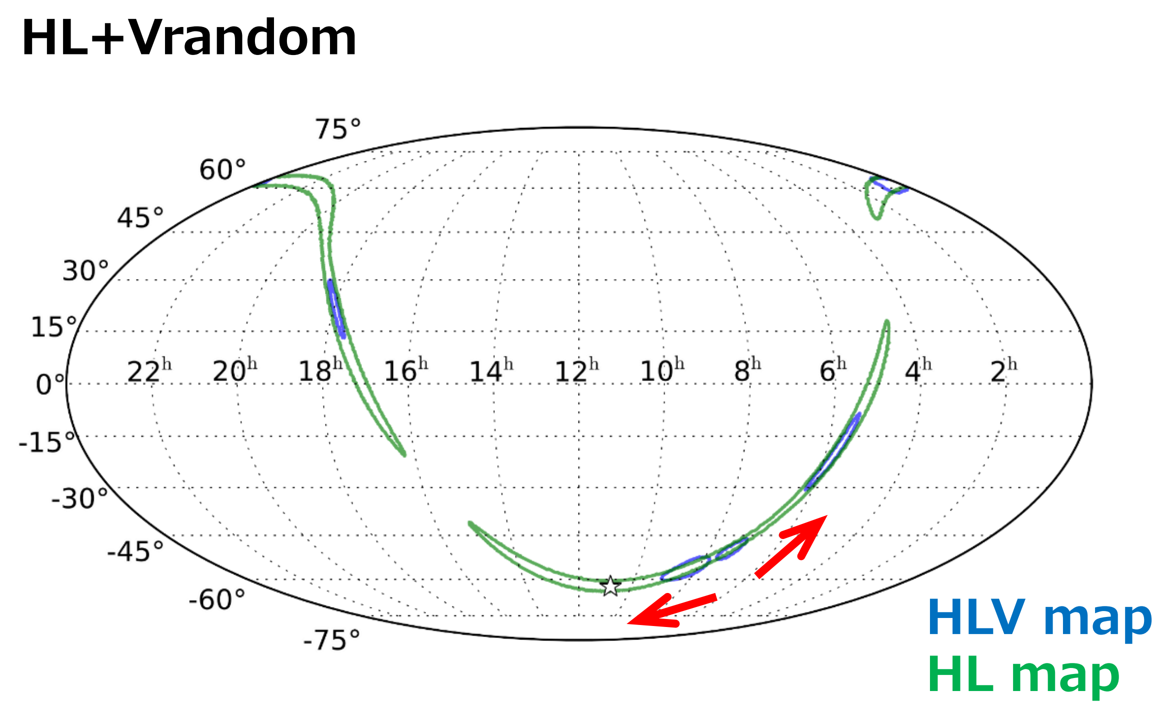
HL+Vinjection

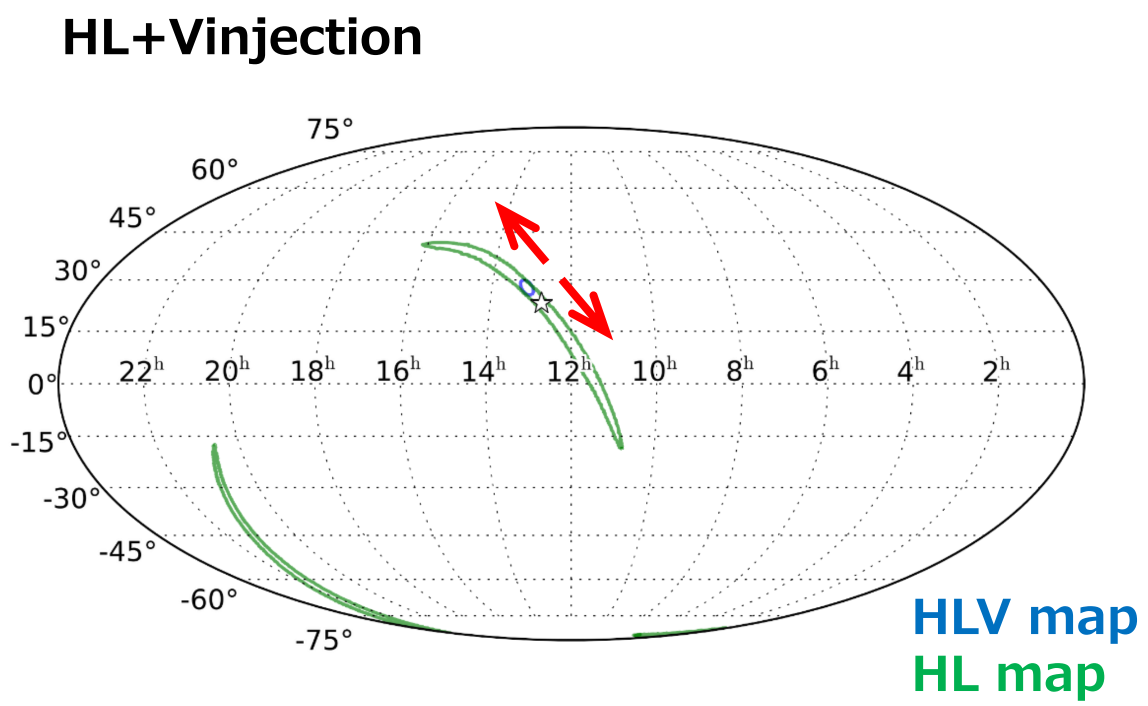


SNR (H)	SNR (L)	SNR(V)
16.5	17.1	3.9

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

Expected localization performance / by HLV

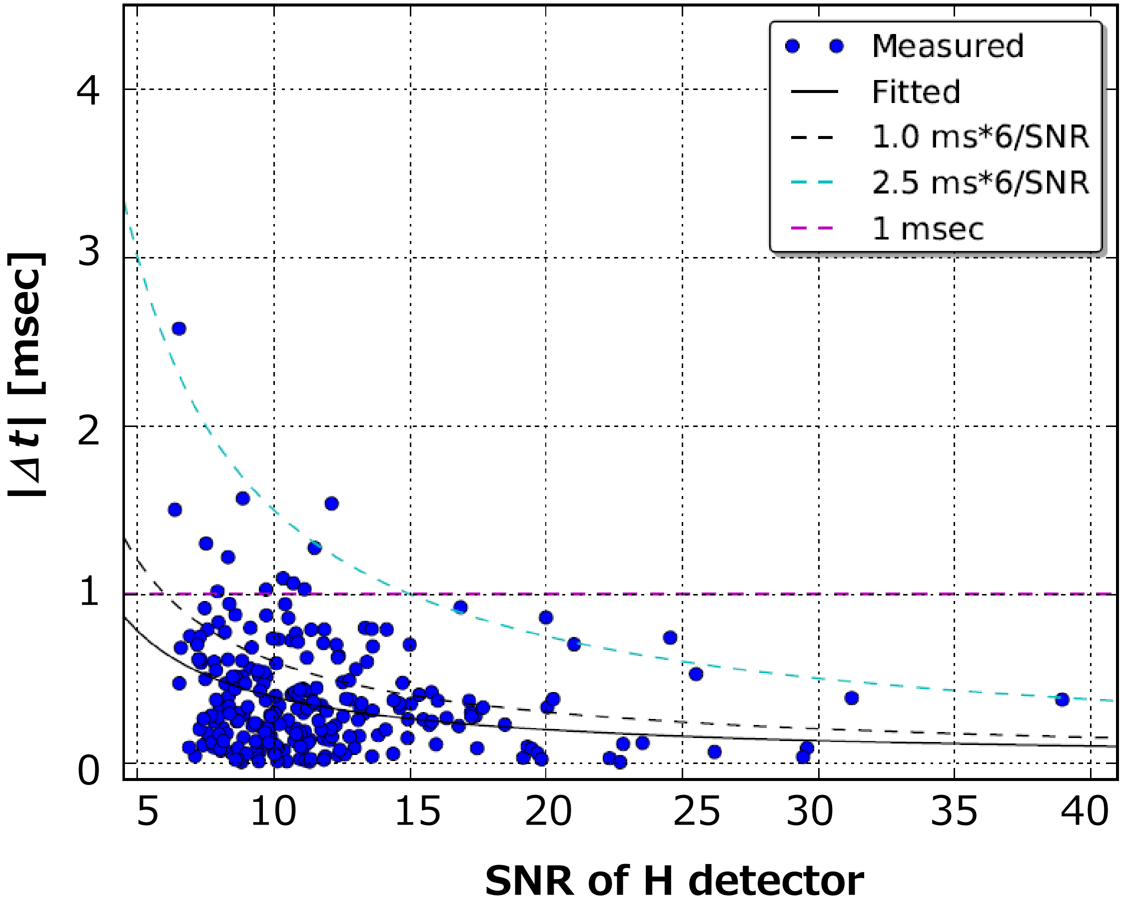




- In this hierarchical network search,
  HLV sky map → If there is no EM-counterpart in HLV map, HL map.
- It will be useful for GW-EM follow-up observation.

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)

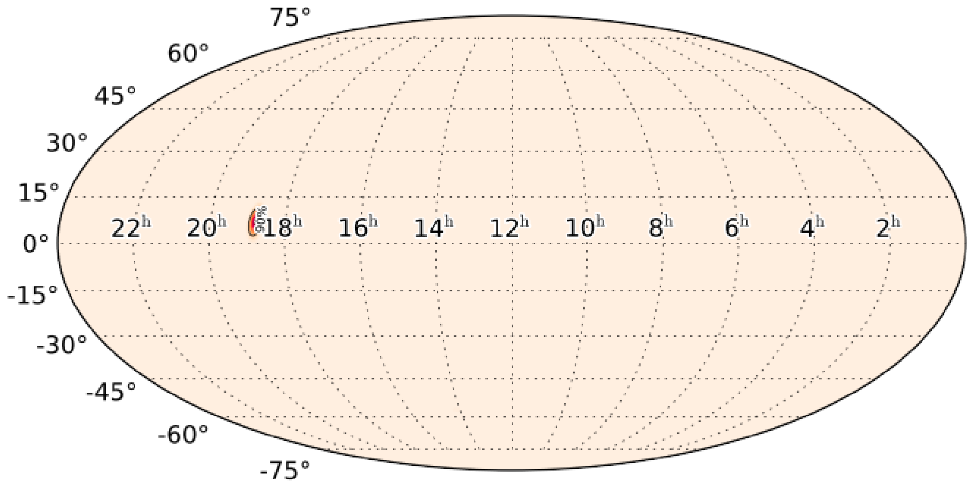
Case 3: Realistic case

HL+Vr, HL+Kr, HL+Vr+Kr,
HL+Vi, HL+Ki, HL+KVi+Ki,
HL+Vr+Ki, HL+ViKr, or HL

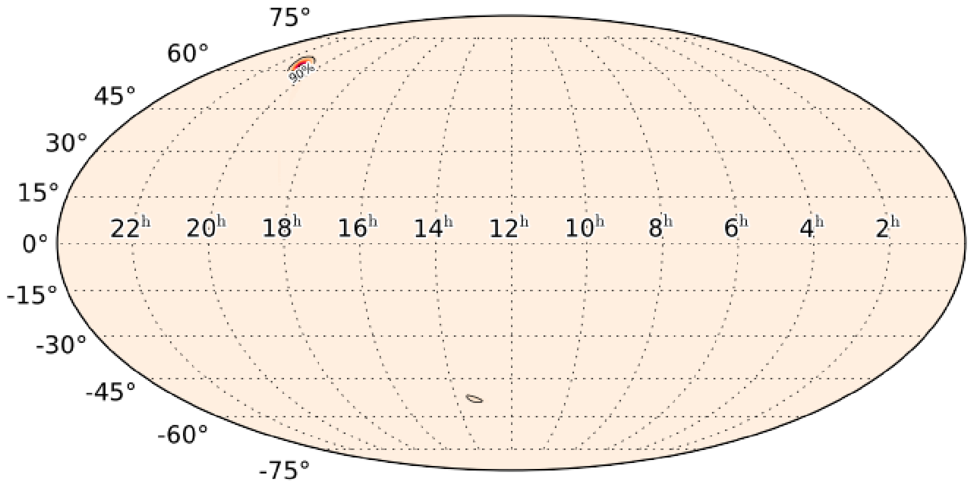
(Based on ***FAP*** and ***SNR***th)

Expected localization performance / by HLVK

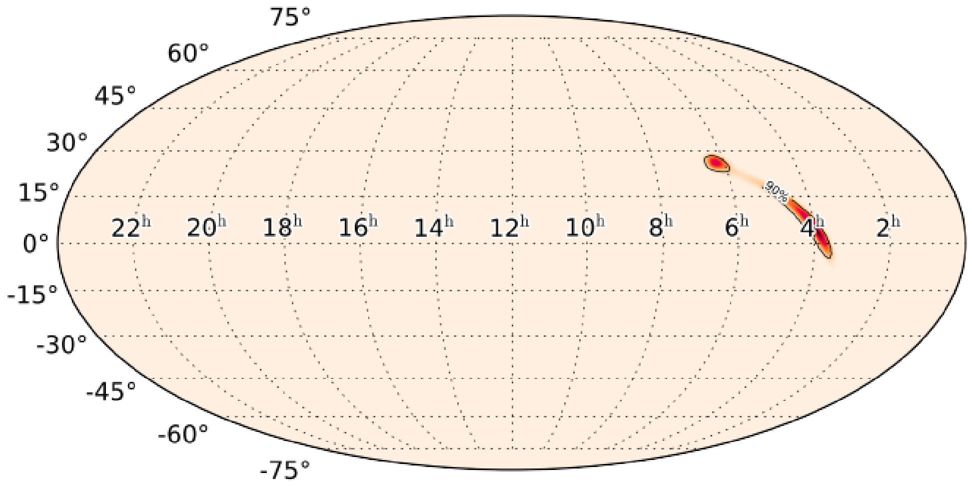
HL + Vi + Ki



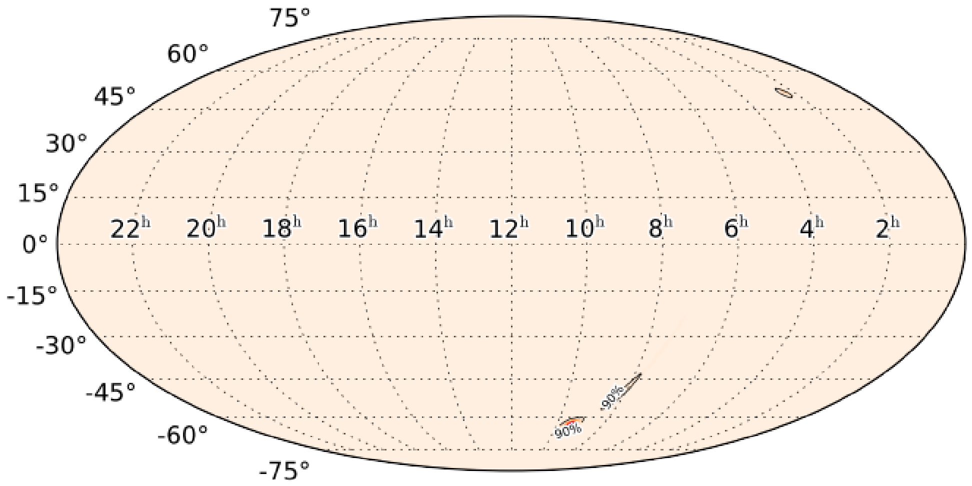
HL + Vr + Kr



HL + Vr + Ki

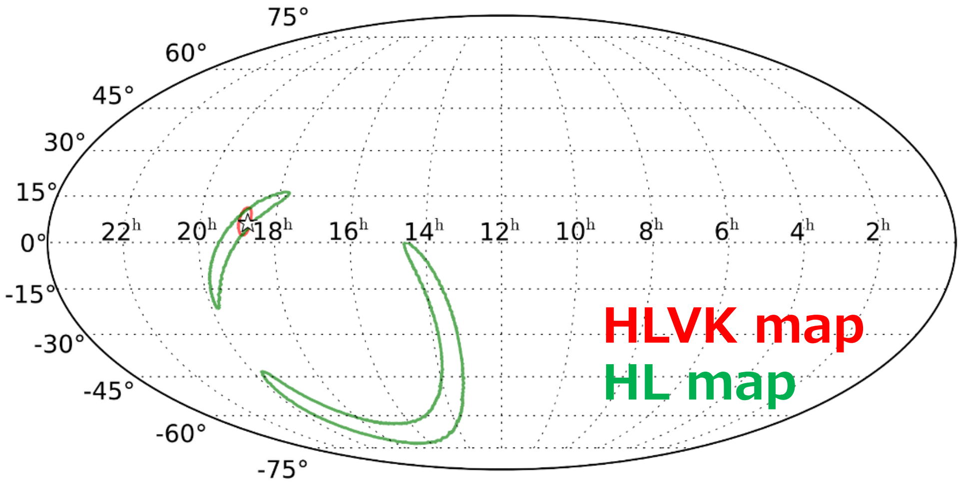


HL + Vi + Kr

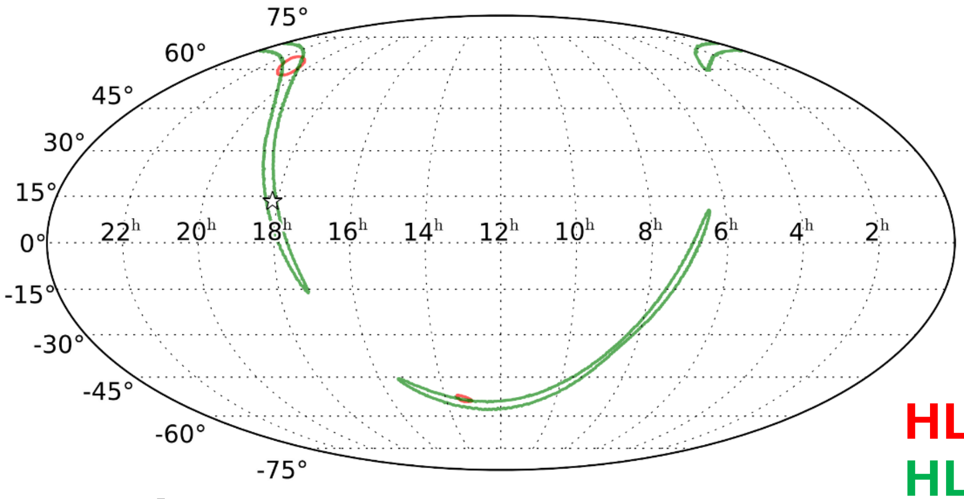


Expected localization performance / by HLVK

HL + Vi + Ki

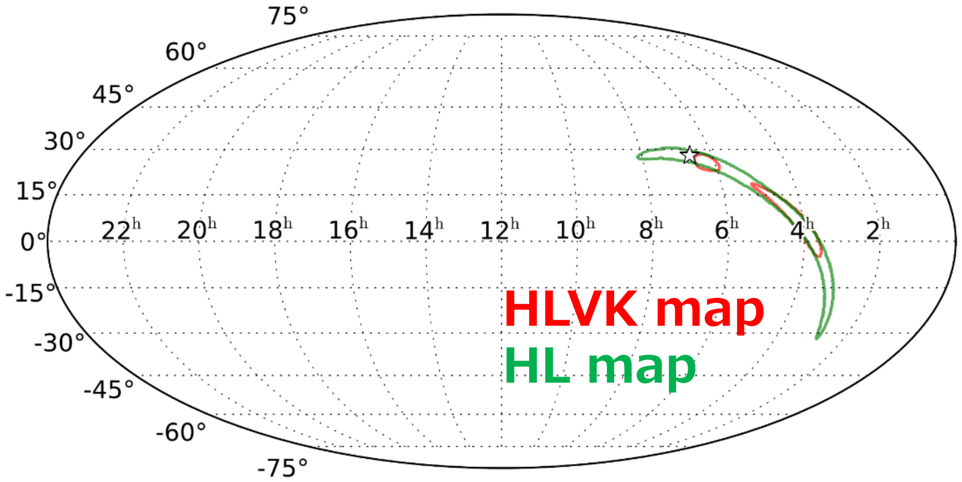


HL + Vr + Kr

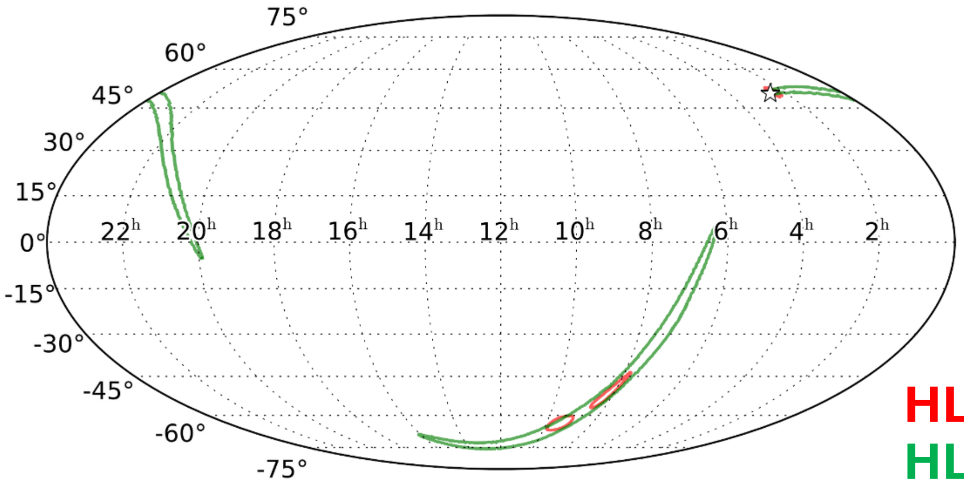


HLVK map
HL map

HL + Vr + Ki



HL + Vi + Kr



HLVK map
HL map