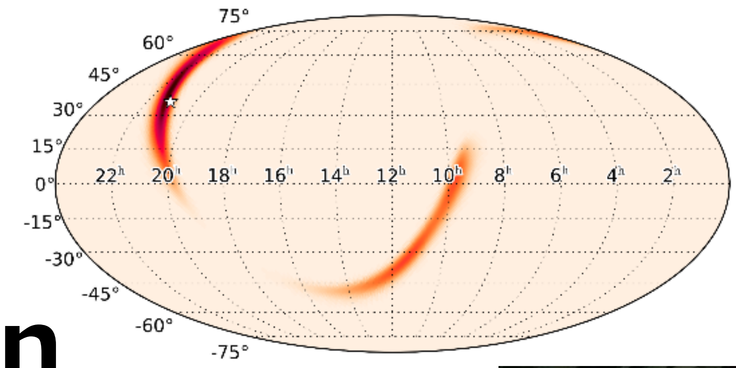
Development of
a low frequency vibration isolation system for KAGRA,
and study of the localization of coalescing binaries
with a hierarchical network of gravitational wave detectors.

Master’s thesis defense
35-156218
Yoshinori Fujii

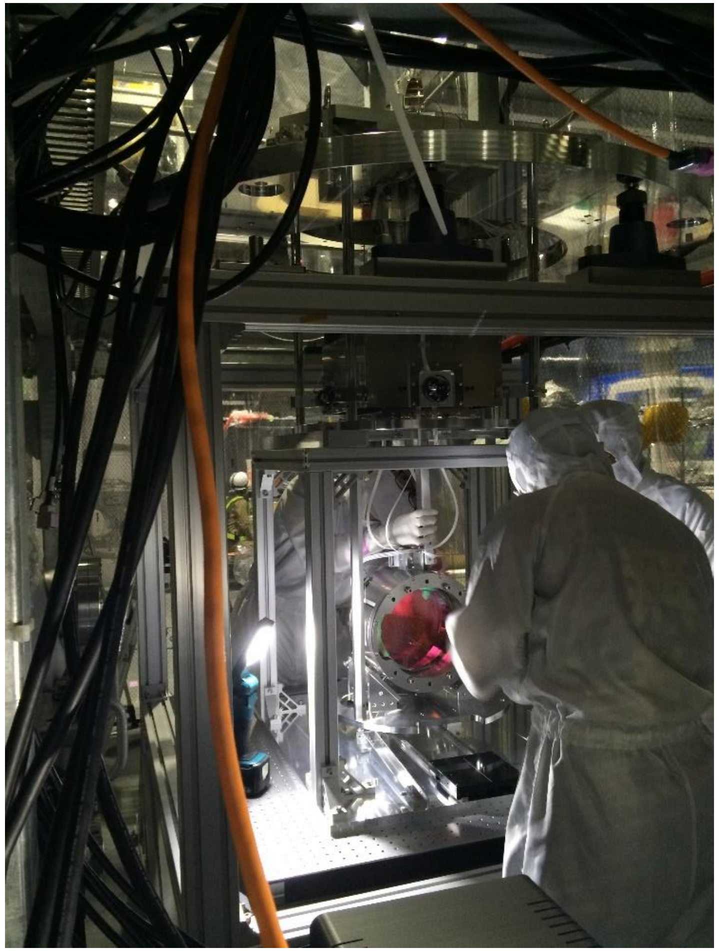
Contents



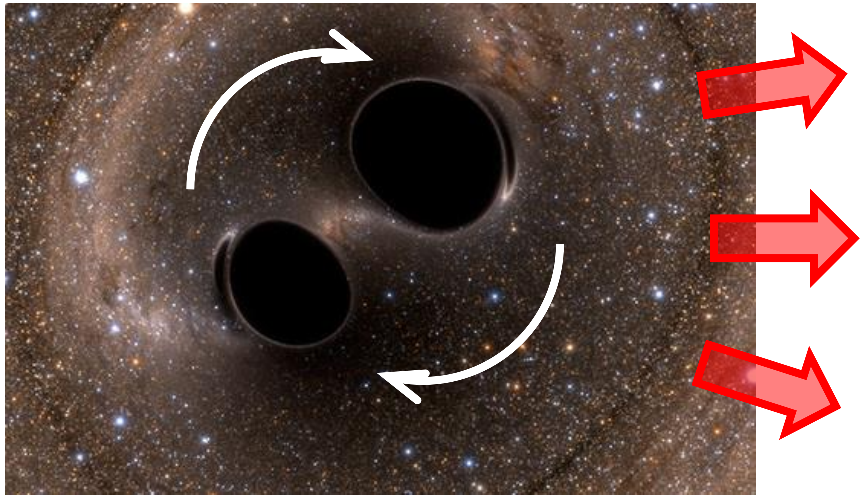
1. Source localization

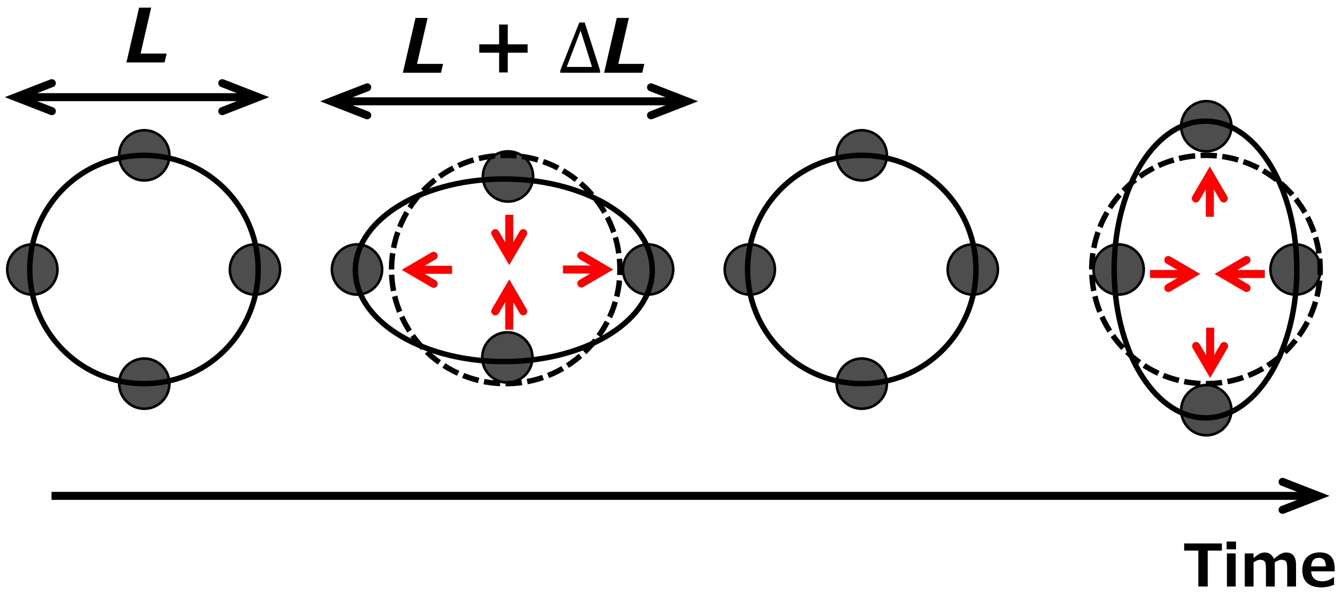
↓

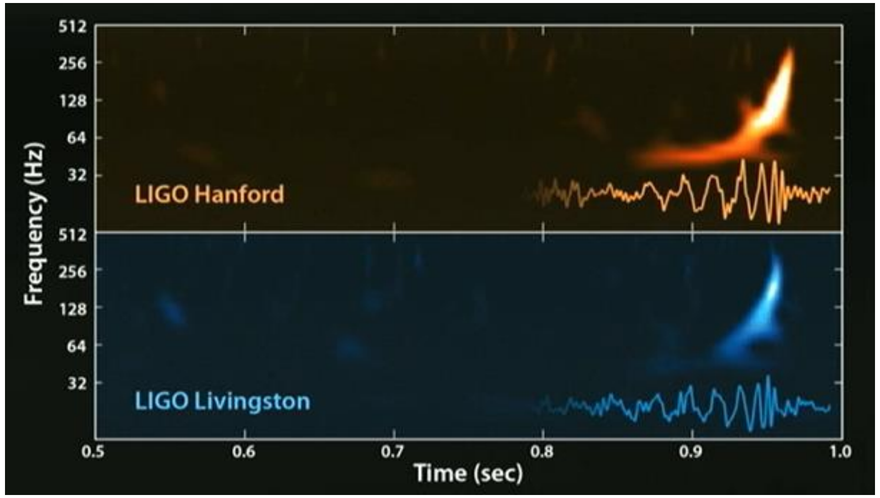
2. Detector development



Gravitational wave







First detection! done!

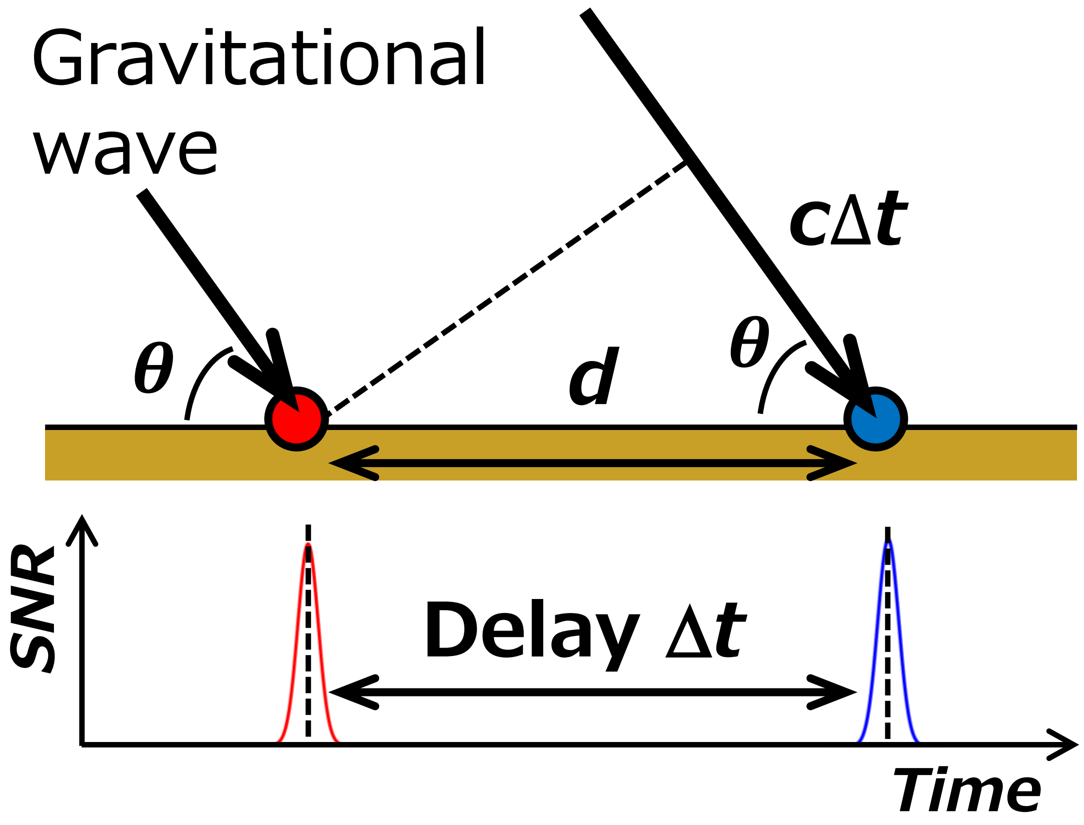
→ New astronomy!

For starting astronomy,

→ Source localization.

for follow-up observation.

From where?



Time delay → Localization

$$\Delta t \longrightarrow \theta$$

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

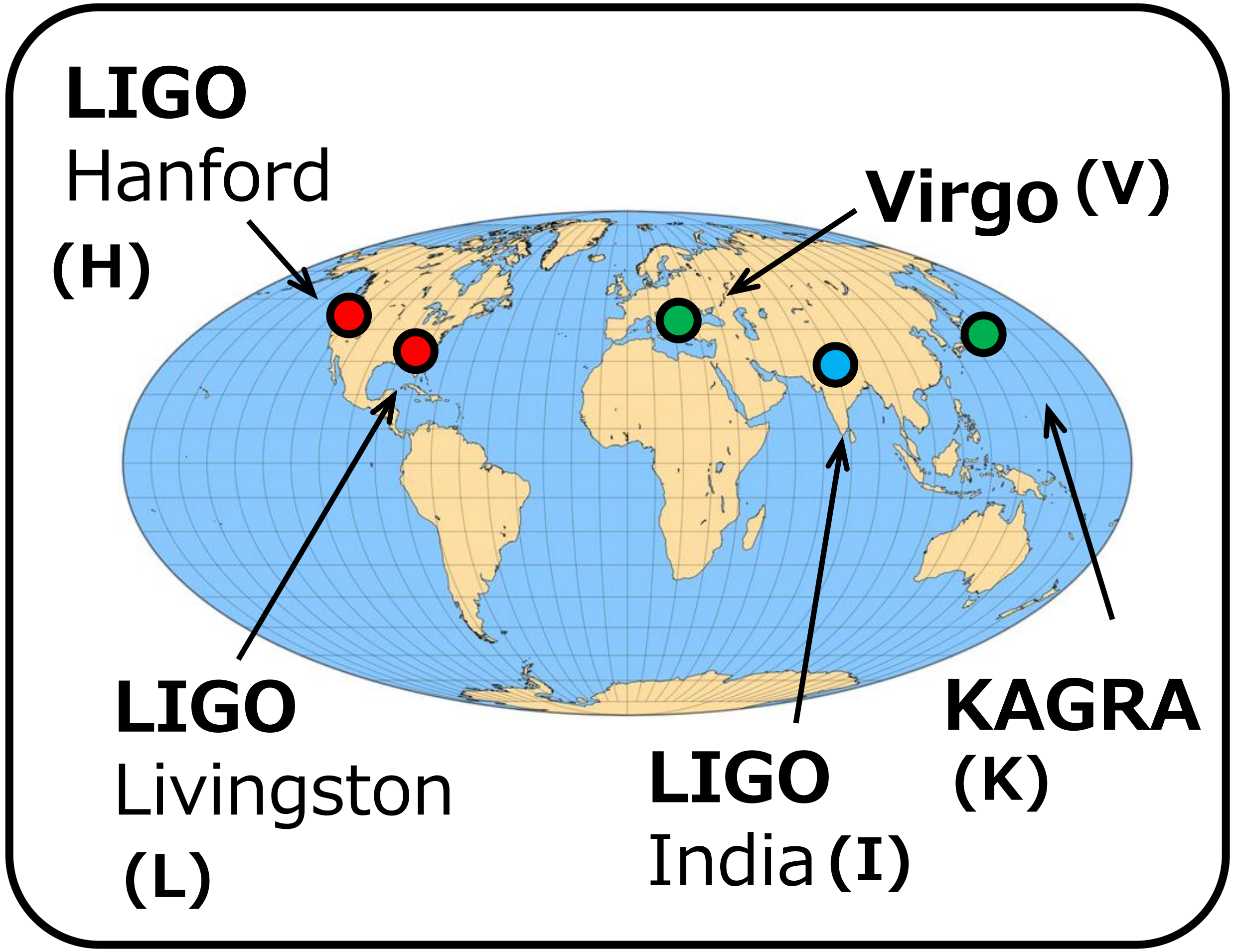
For localization, we want..

→ Several detectors!

Continuous observation

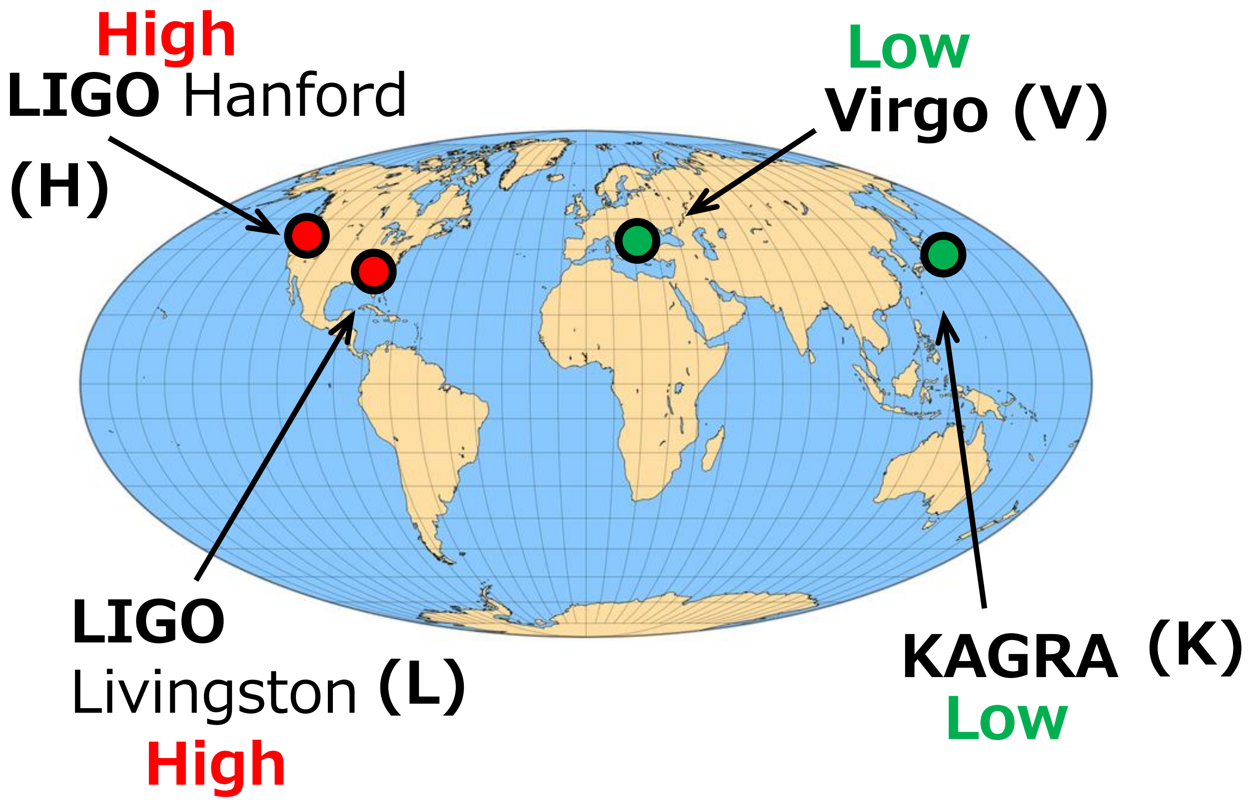
Precise localization

All sky coverage



Different sensitivities.. OK?

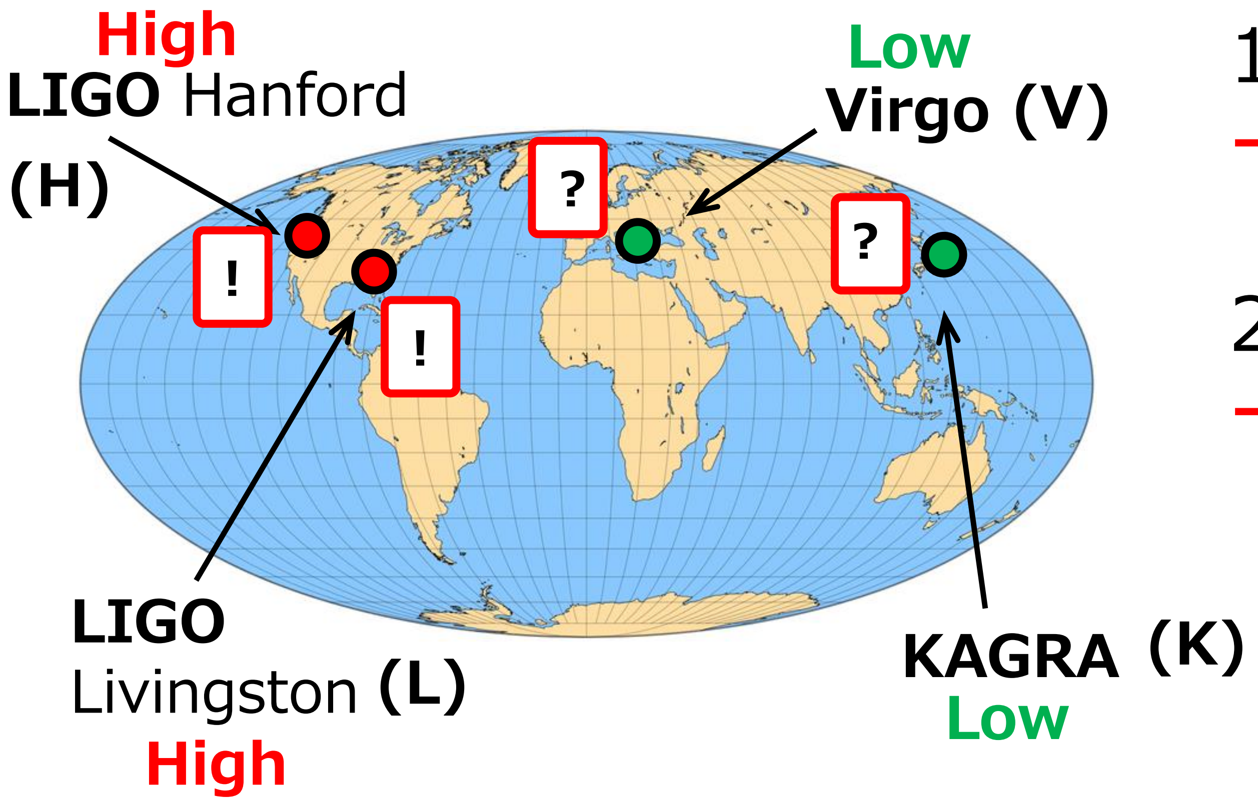
Ex.) SNR > 5 → detection



(At the beginning)

Different sensitivities.. OK?

Ex.) SNR > 5 → detection



(At the beginning)

1) Triple (or more) coincidence
→ Rare

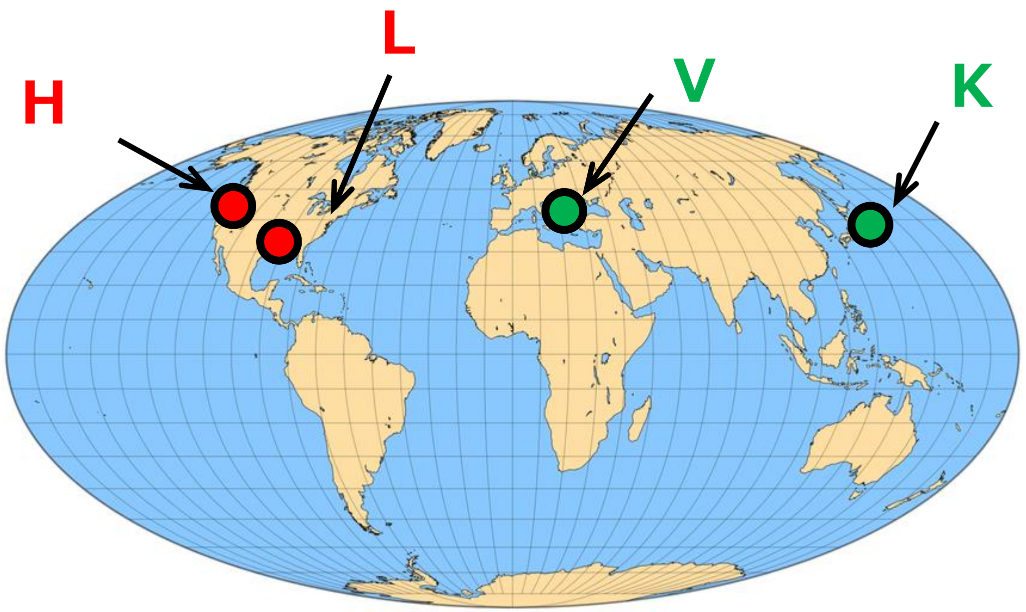
2) Double coincidence
→ Not precise localization

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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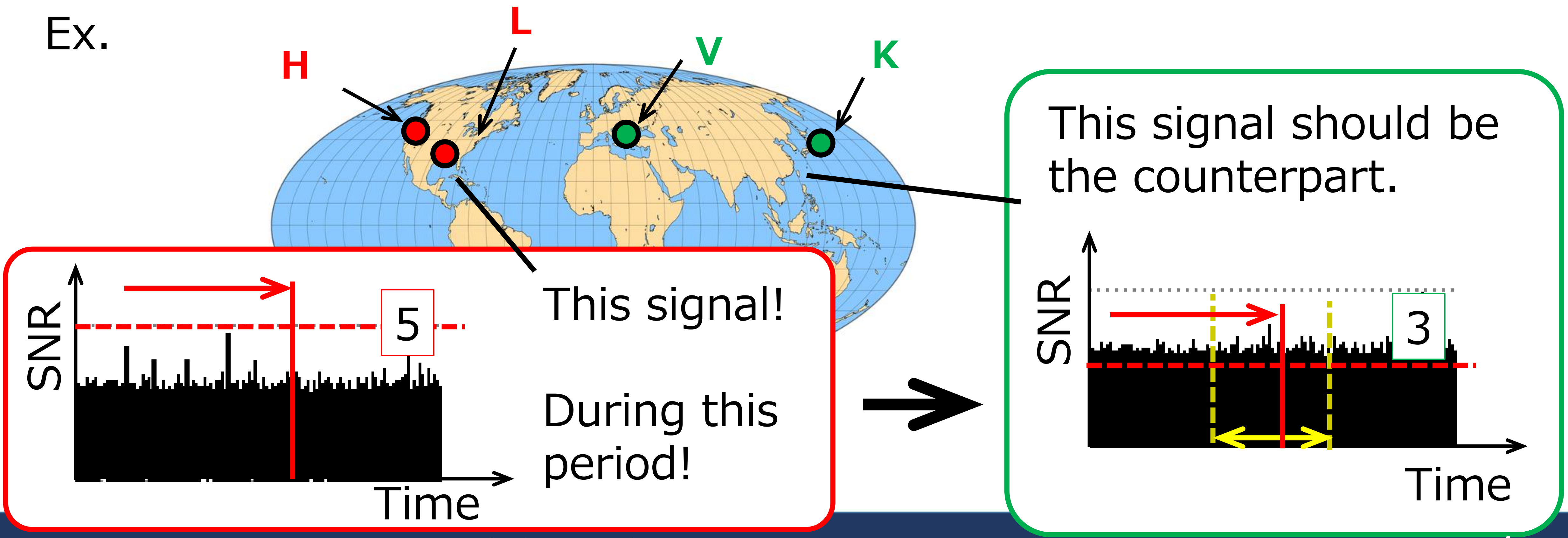
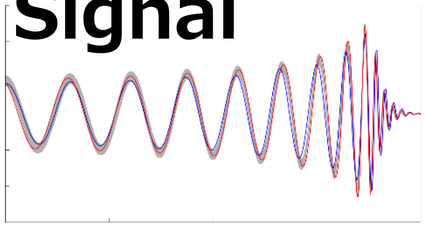


Assumption in calculation

1. GW-EM pipeline for GWs from CBC

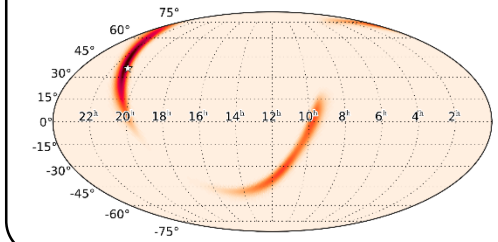
→ GW detectors → [1st: MBTA → 2nd: BAYESTAR] → EM telescopes

Signal



Event info:
SNR,
arrival time,
etc.

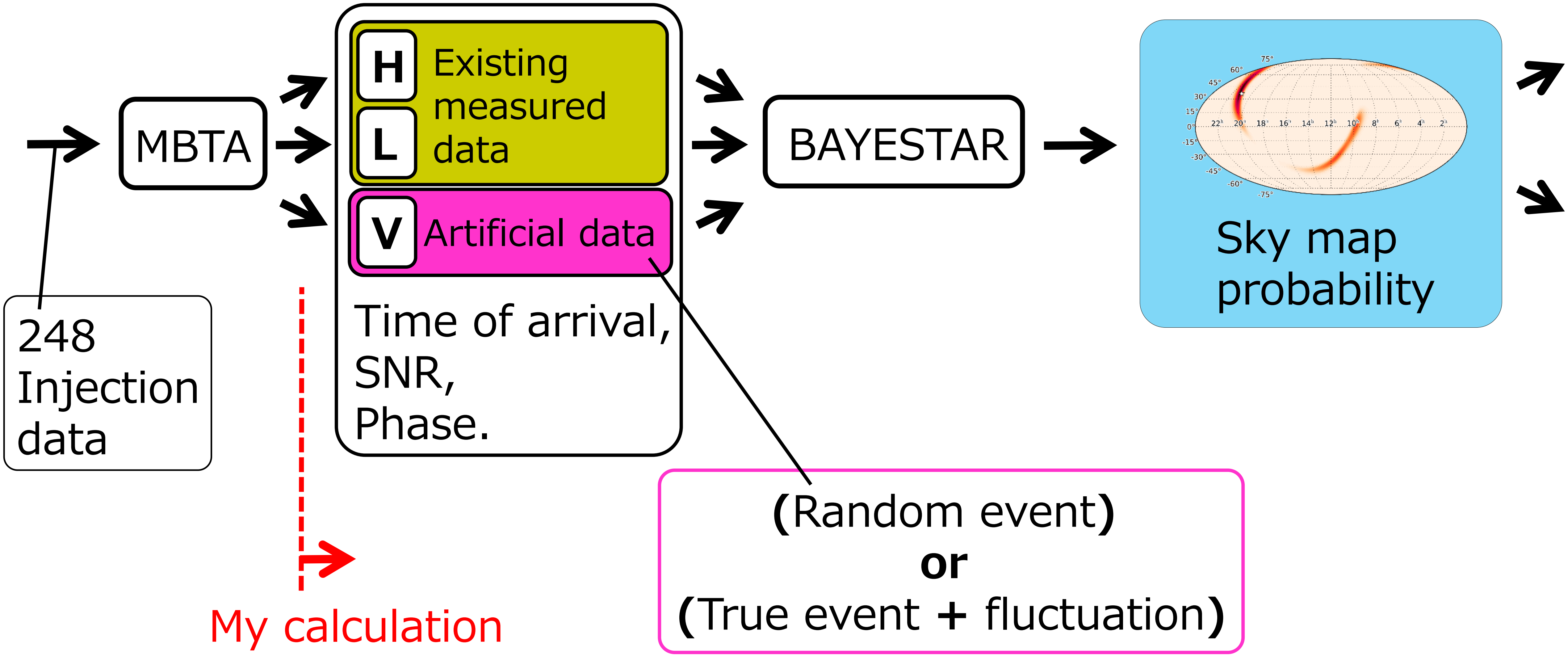
Sky map probability



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

High sensitivity × 2 / Low sensitivity × 1

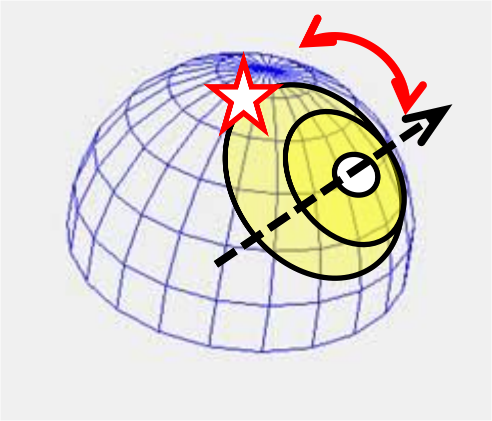
Calculation main flow 1



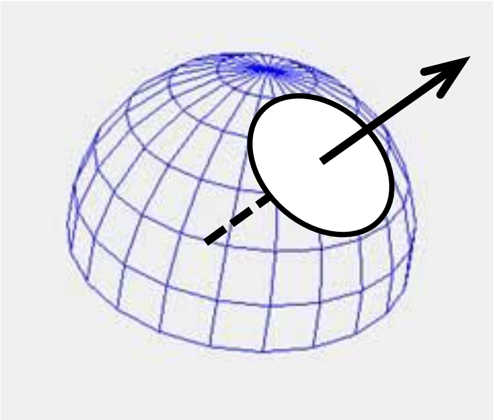
Calculation main flow 2

Localization performance

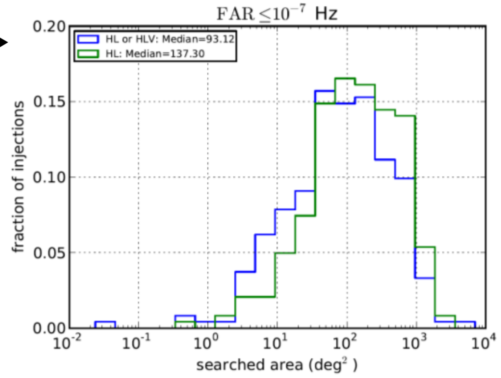
1) **Accuracy**
→ Searched area (deg^2)

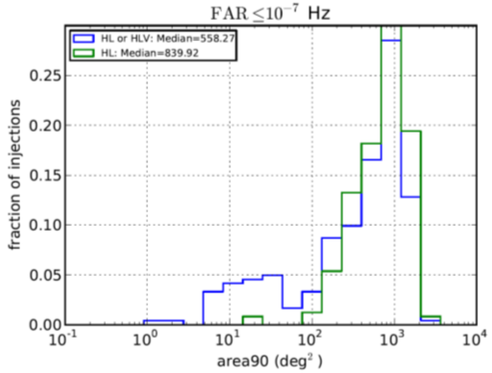


2) **Precision**
→ 90 % confidence area (deg^2)



Histograms from 248 events.

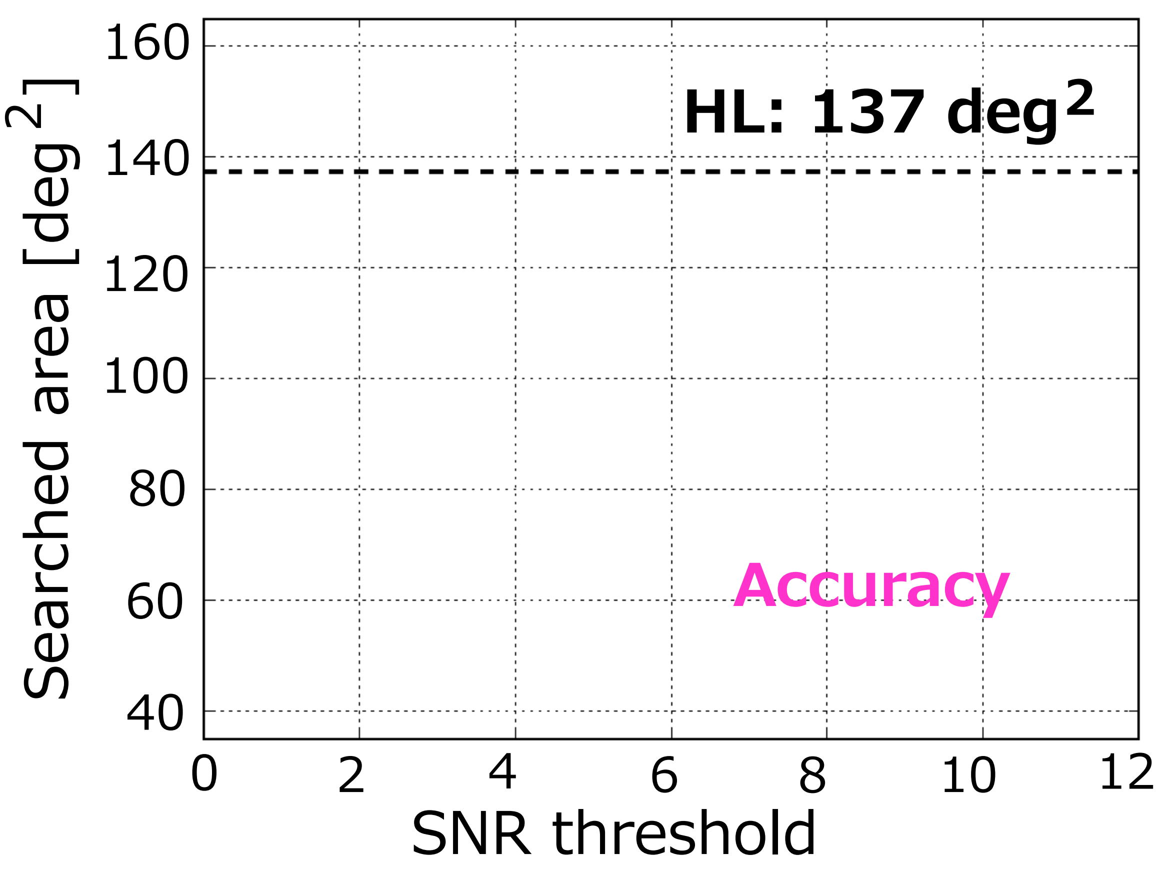


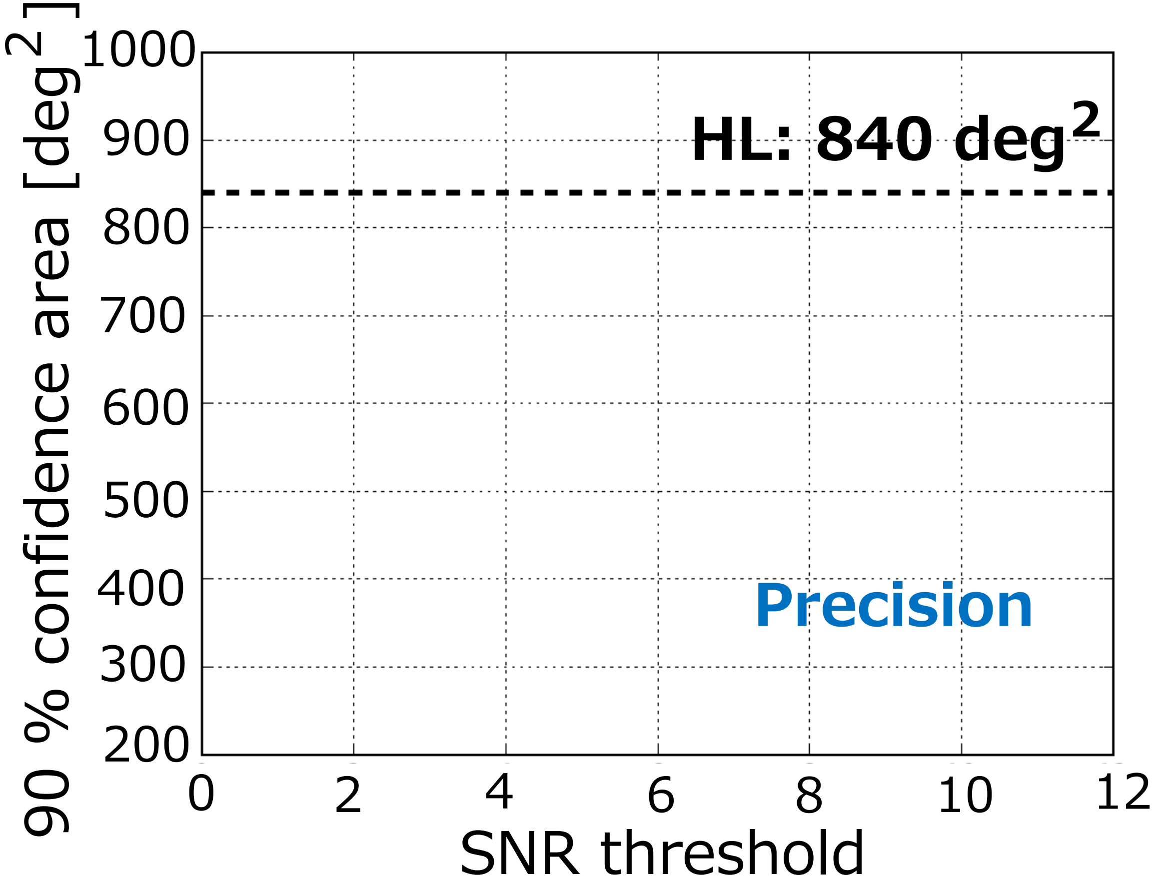


median values

Expected performance, HLV

(SNR threshold for H, L = 5.)





Expected performance, HLV

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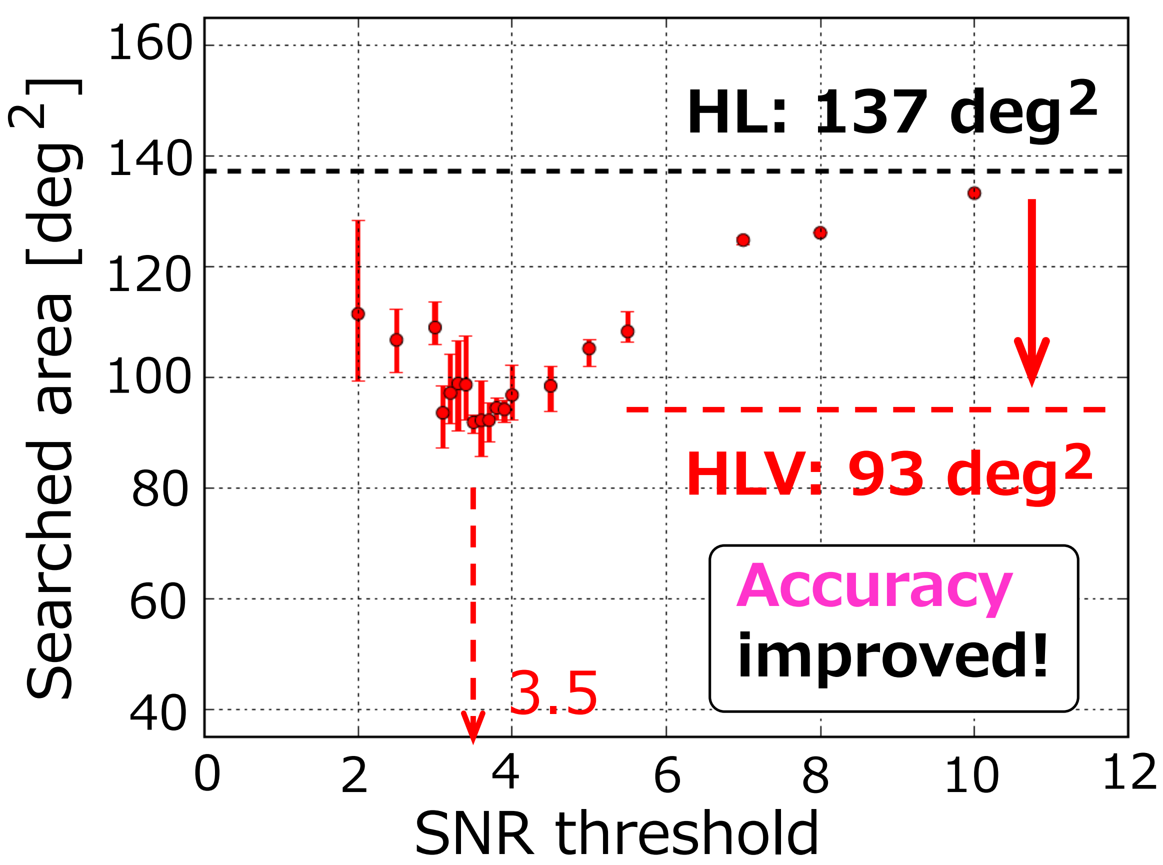
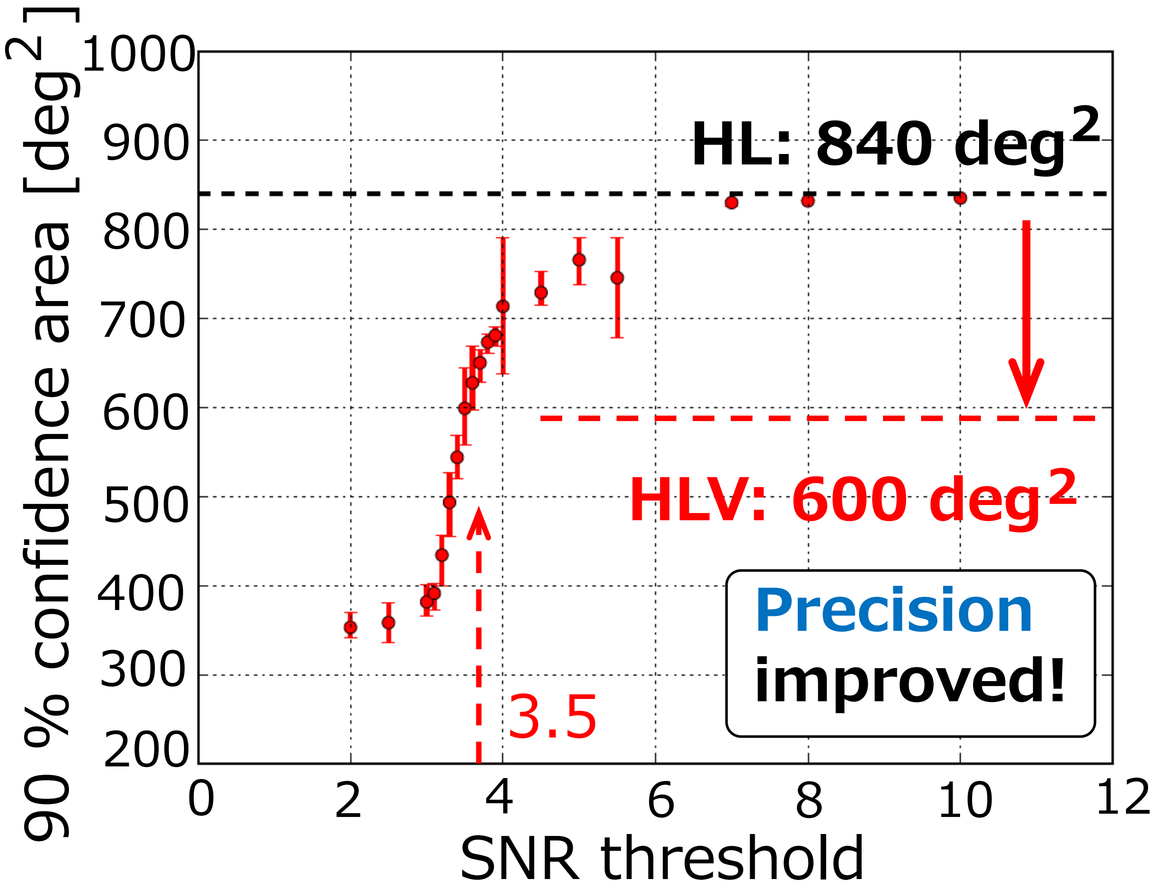
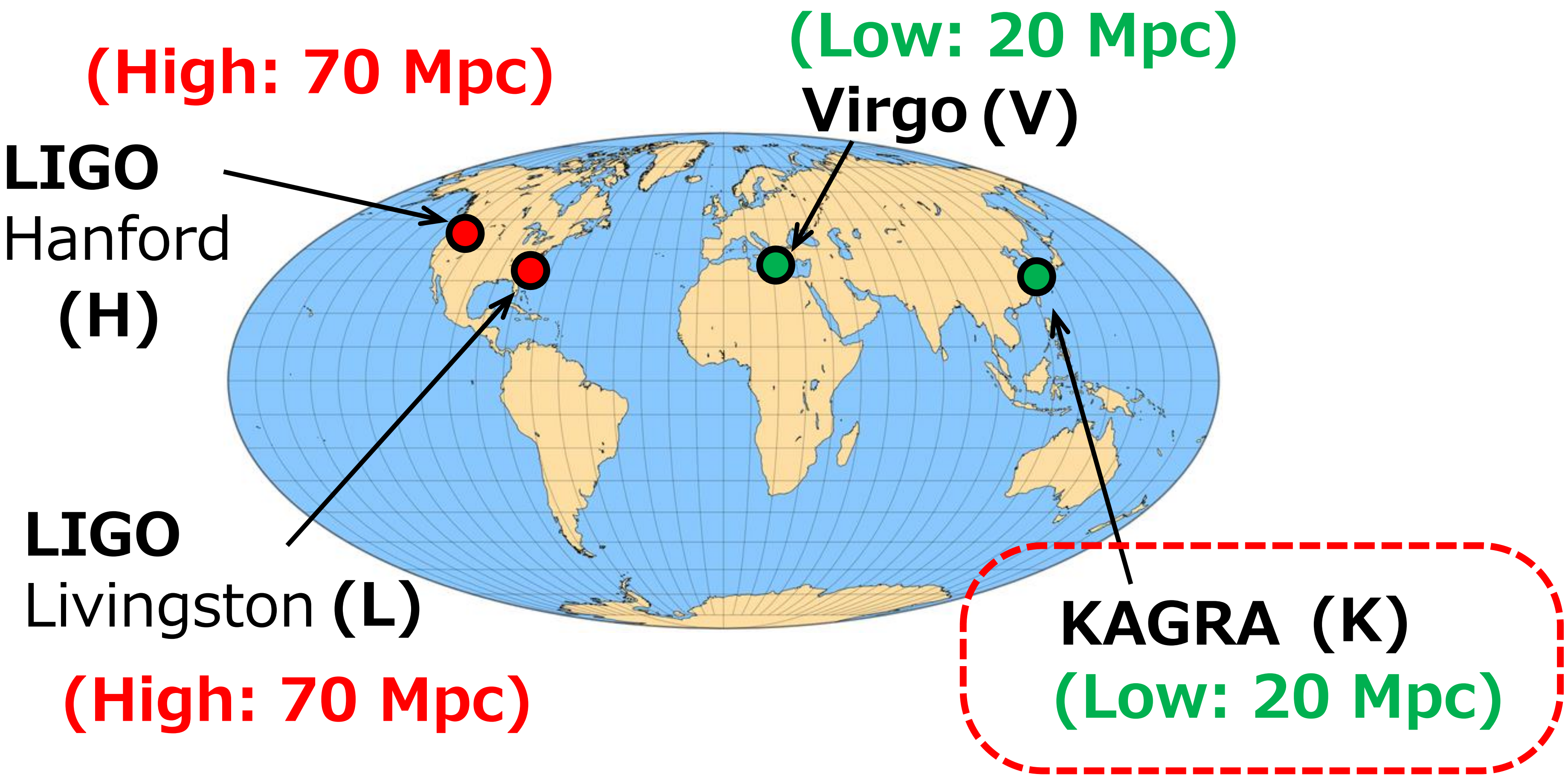




→ By including low sensitivity detector,
errors on sky maps will be reduced by a factor of ~ 0.7 than HL.

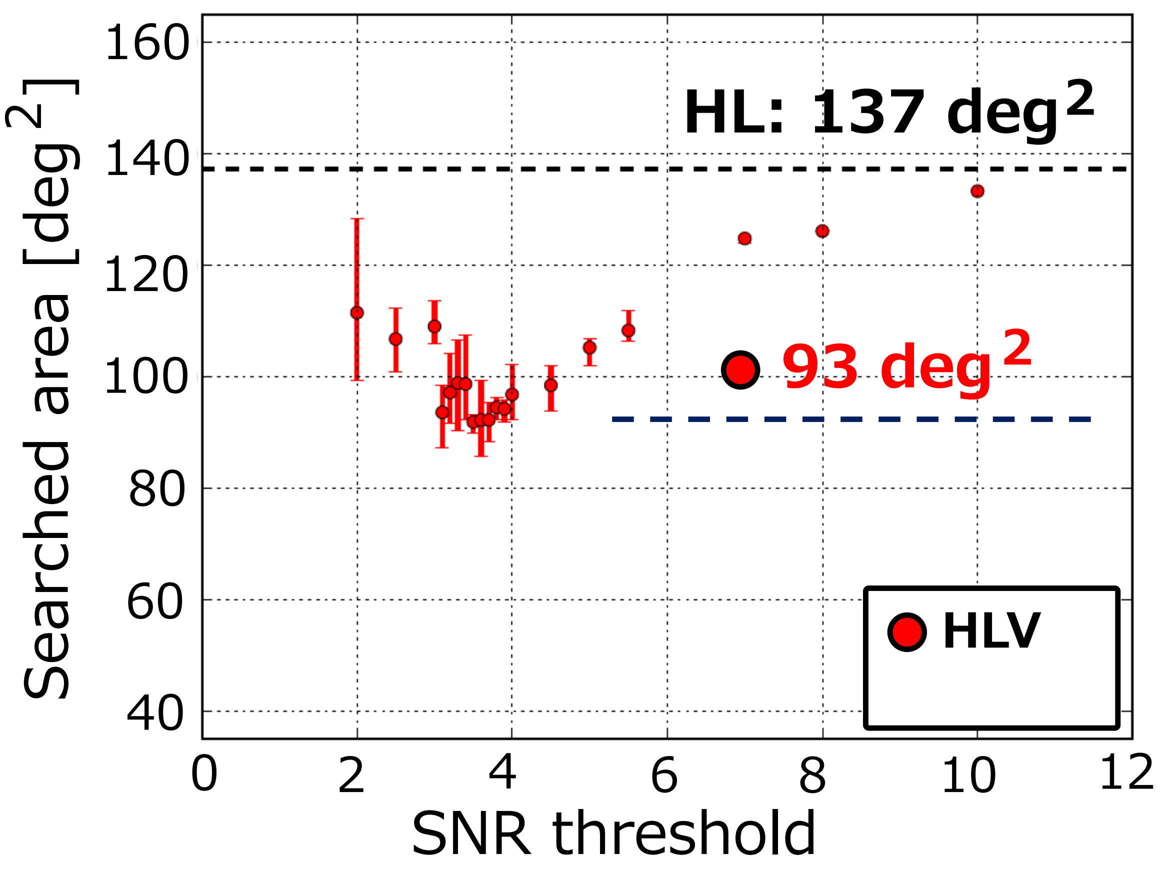
How about 4 detectors, HLVK?

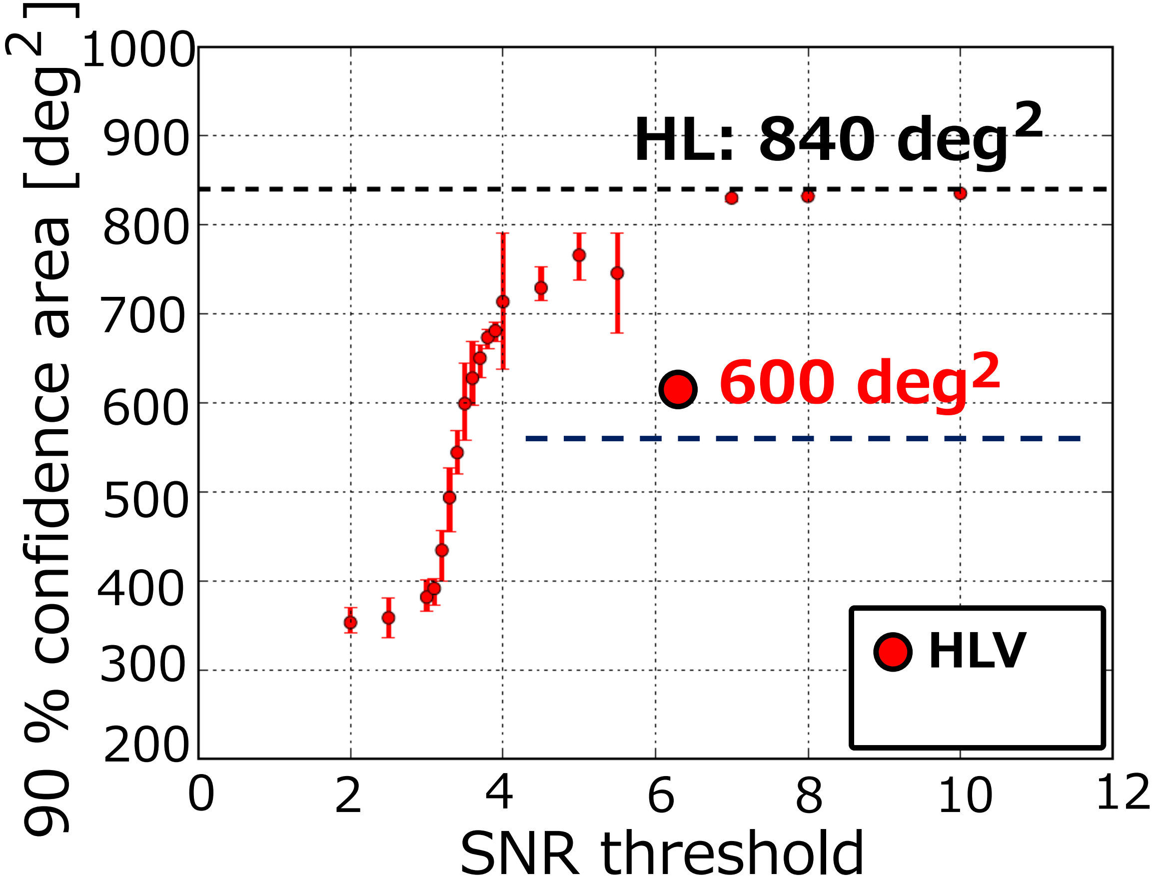


(Assumed situation)

Expected performance, HLVK

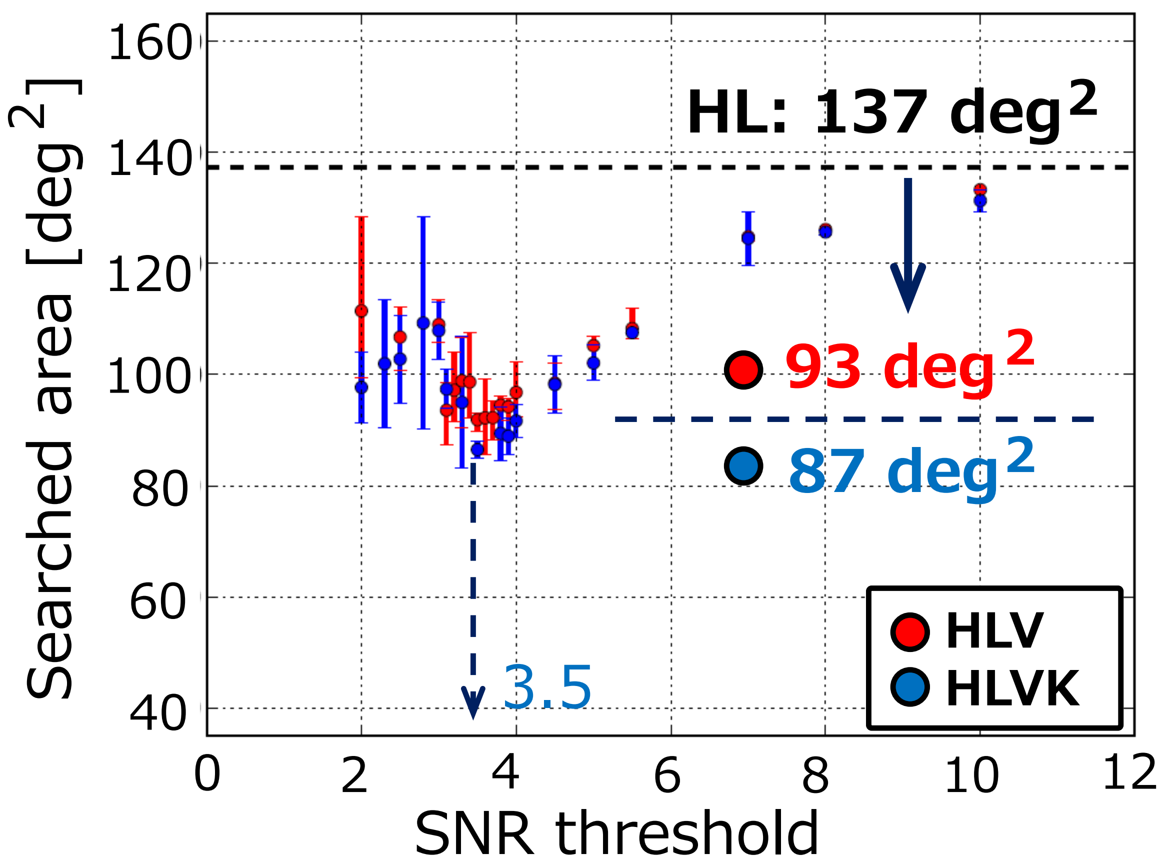
(SNR threshold for H, L = 5.)

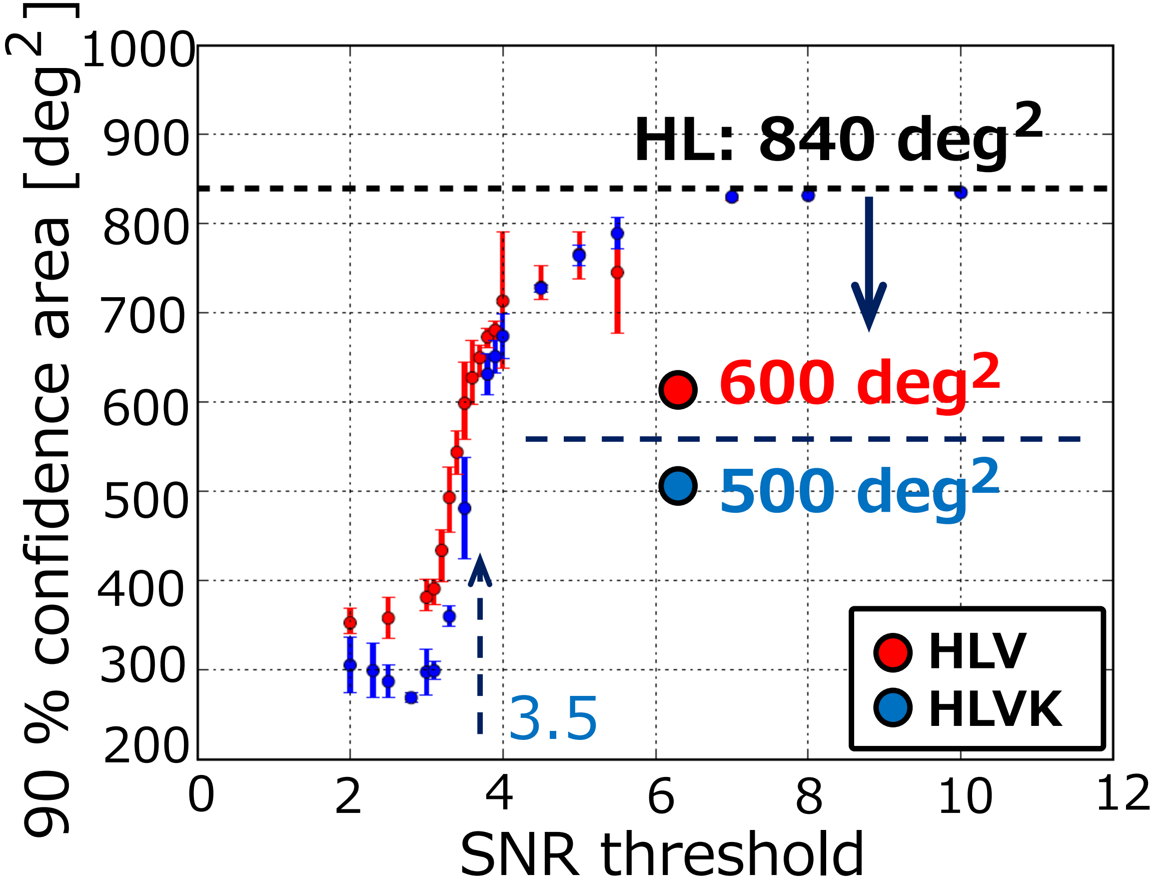




Expected performance, HLVK

(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),

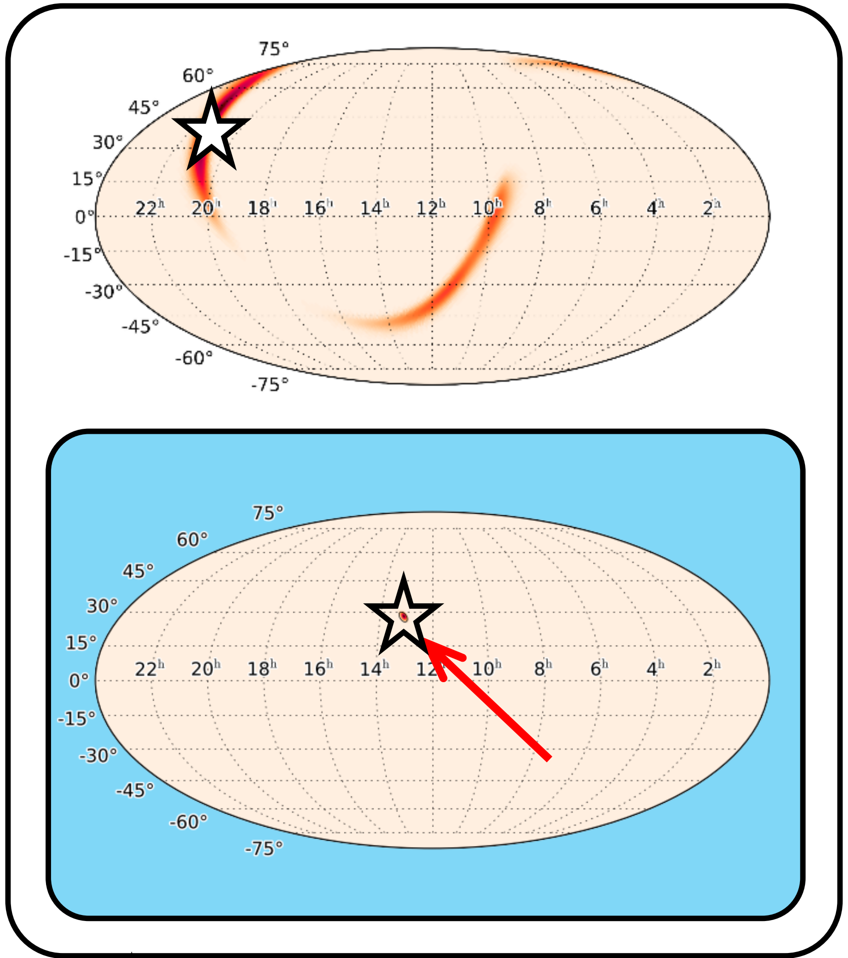
Accuracy: HLV ~ HLVK
Precision: reduced by a factor of ~ 0.8 than HLV.

→ ***4th detector can contributes!***

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

Source localization → detector development

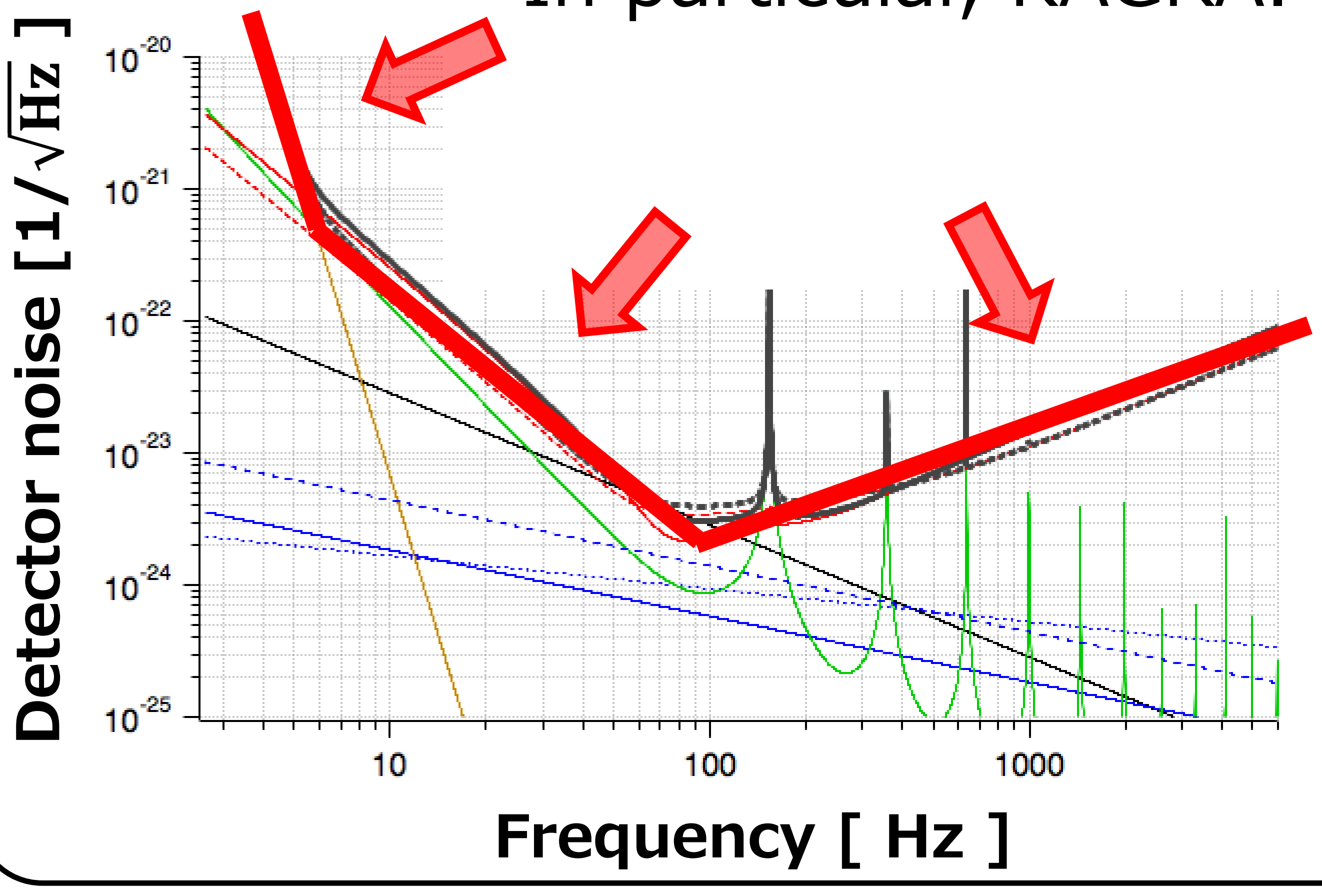
We want ..



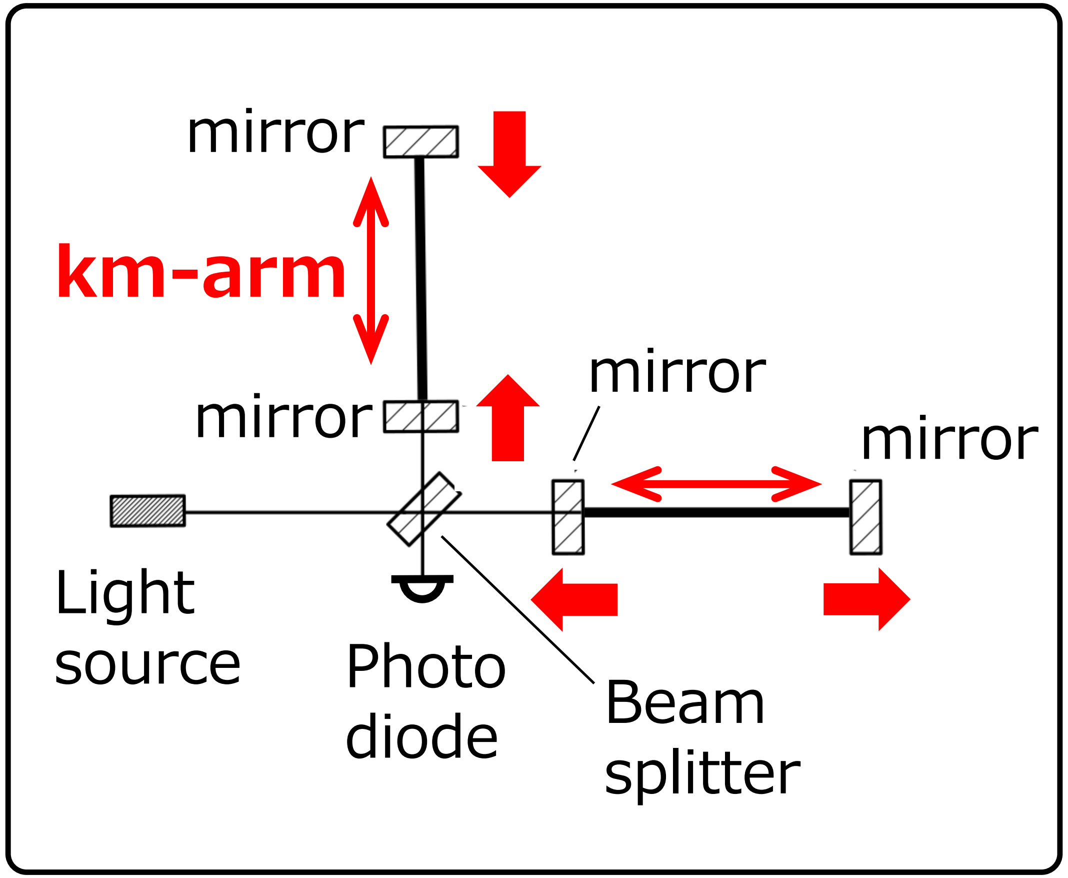
☆ : True position

Necessary to improve sensitivity!

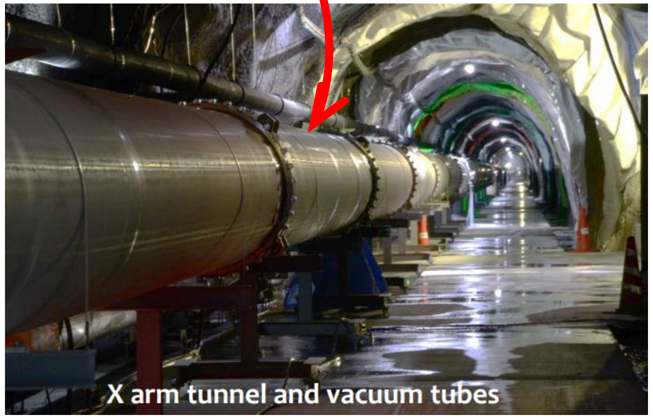
In particular, KAGRA.



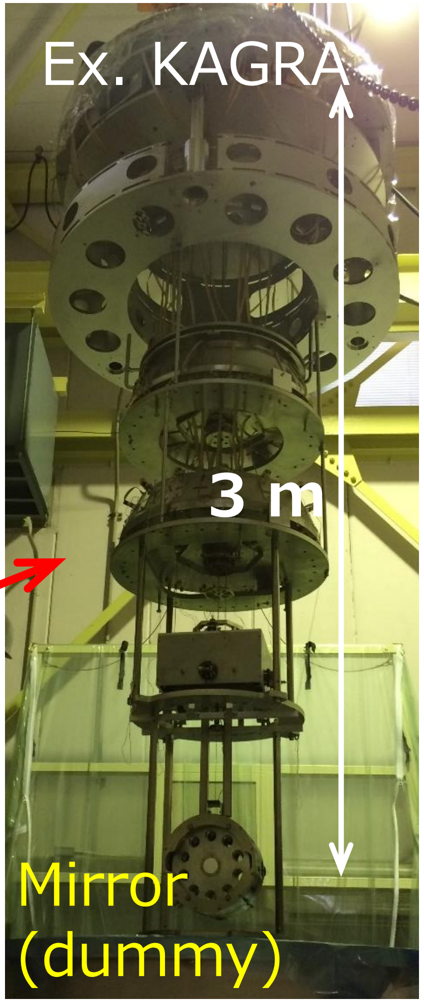
Gravitational wave detector



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



4) Suspended core optics



Detector noise

- Quantum noise
- Thermal noise

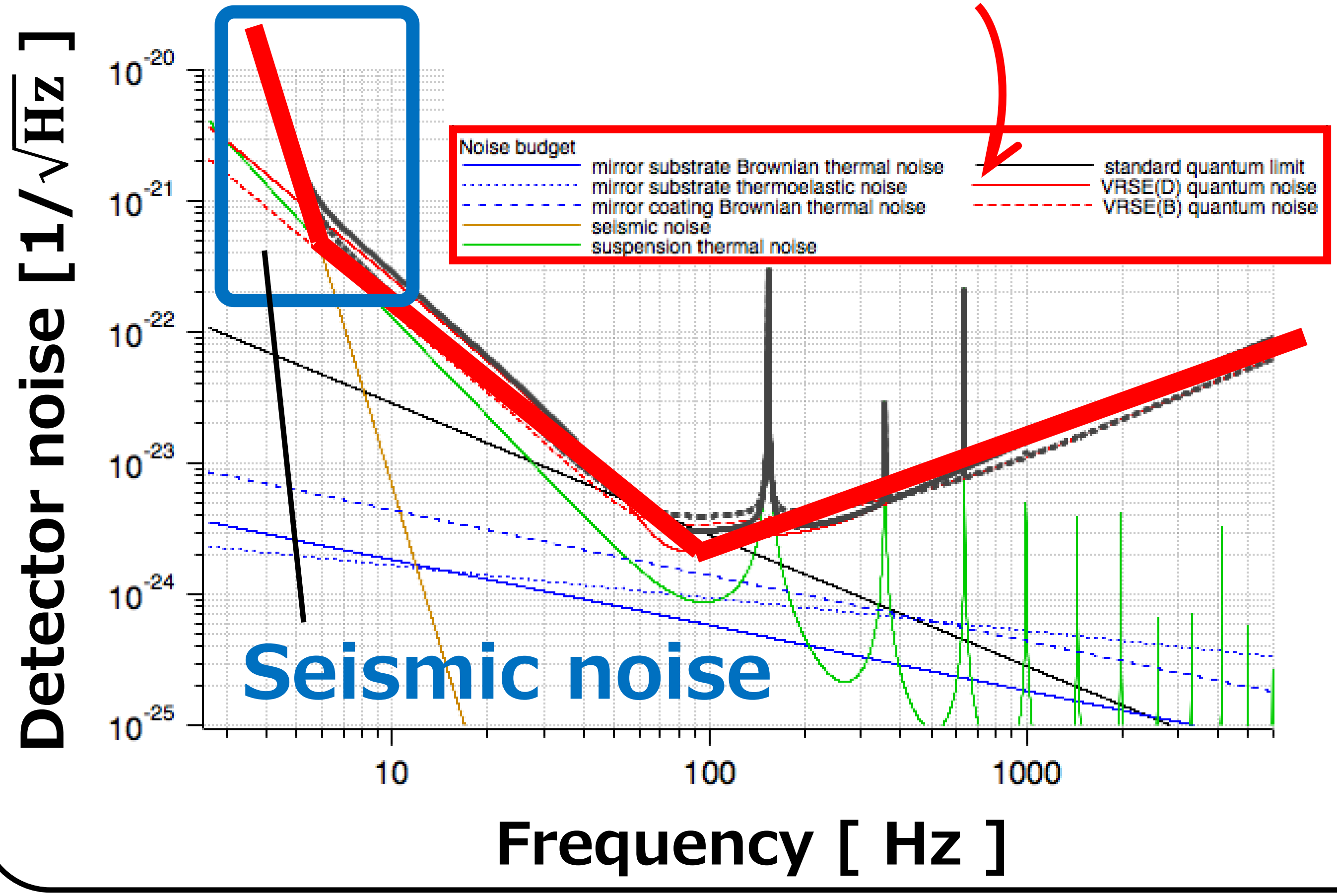
…

- **Seismic noise**

mirror oscillation

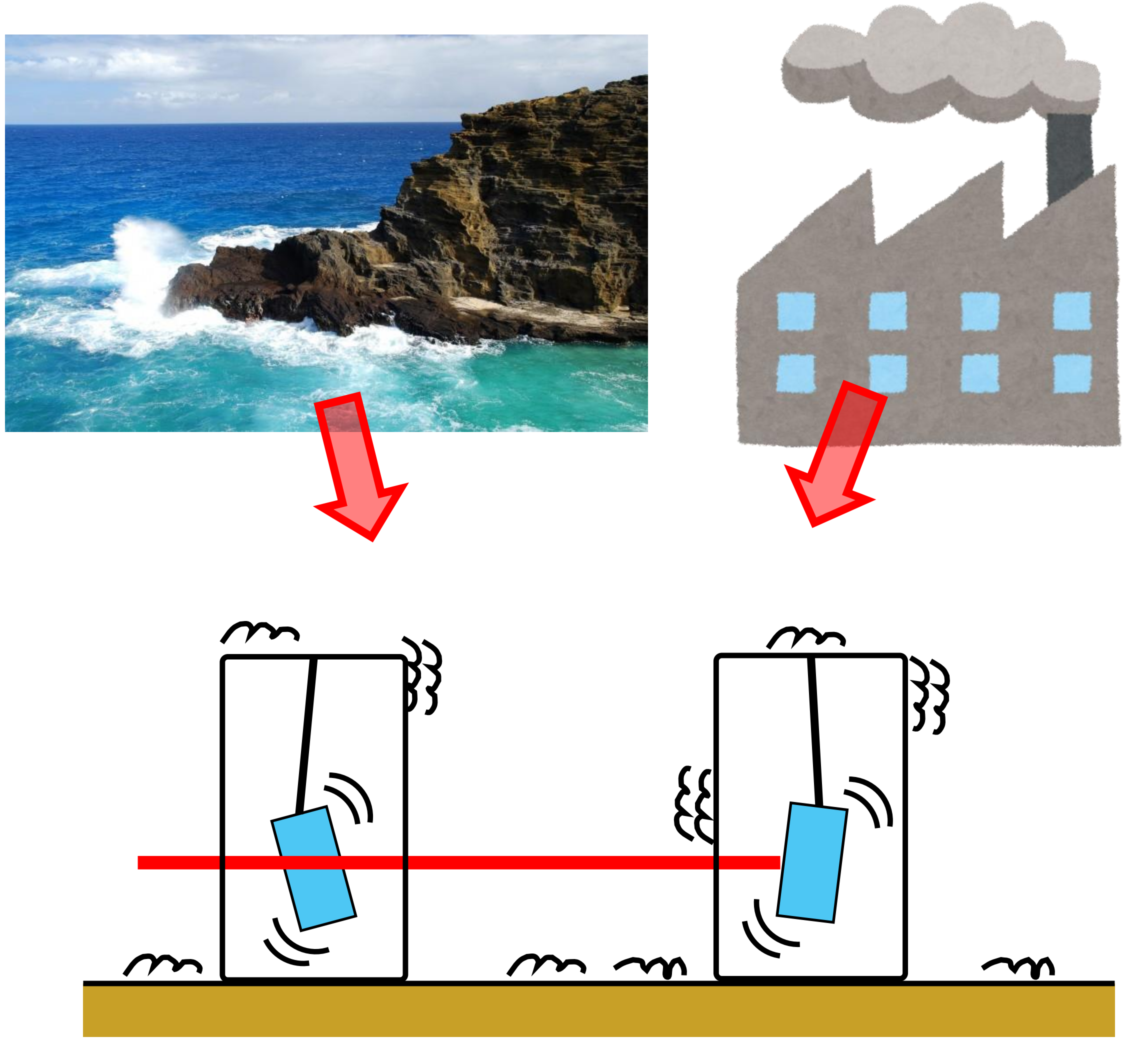
→ Necessary to suppress

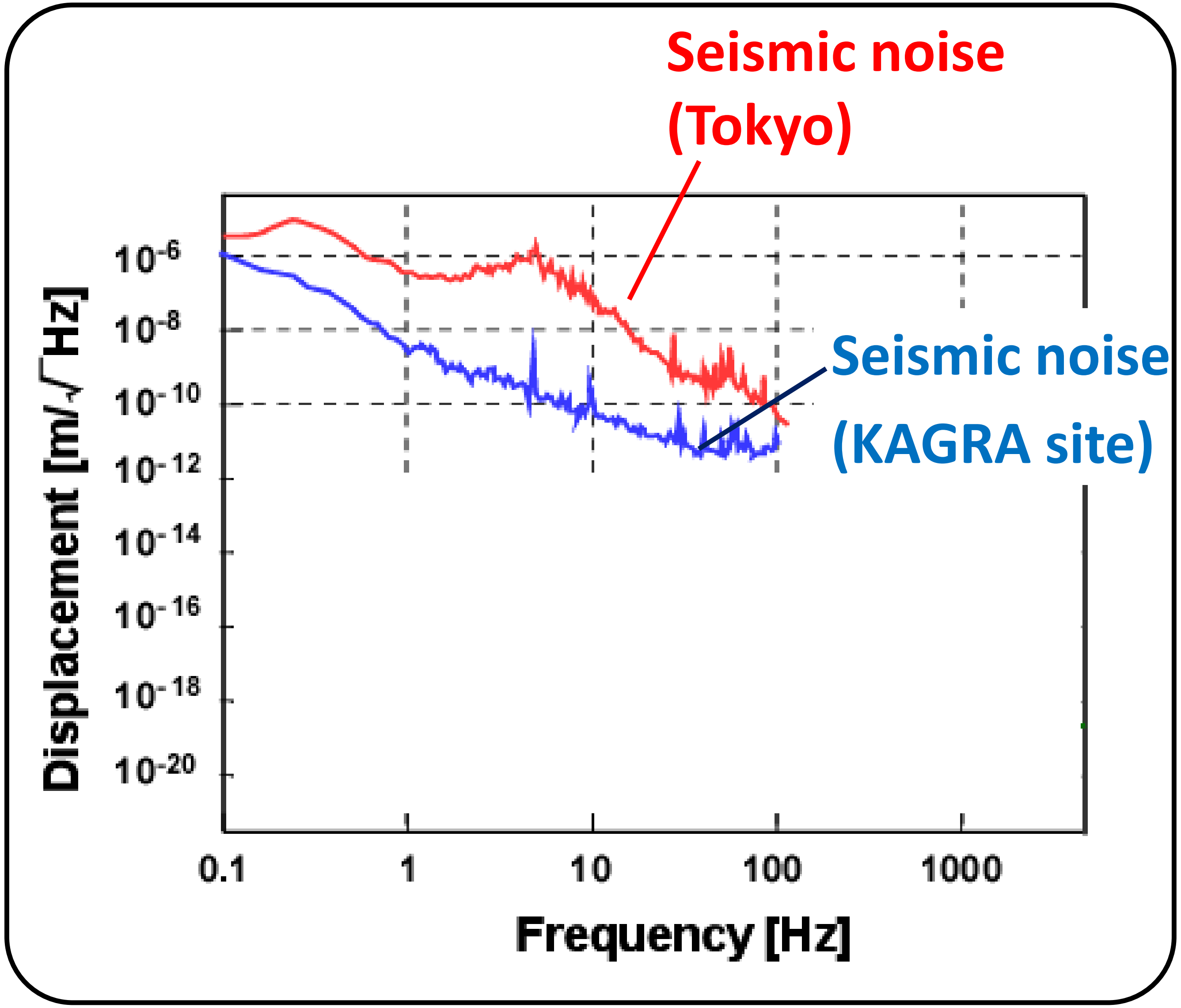
So many noise sources..



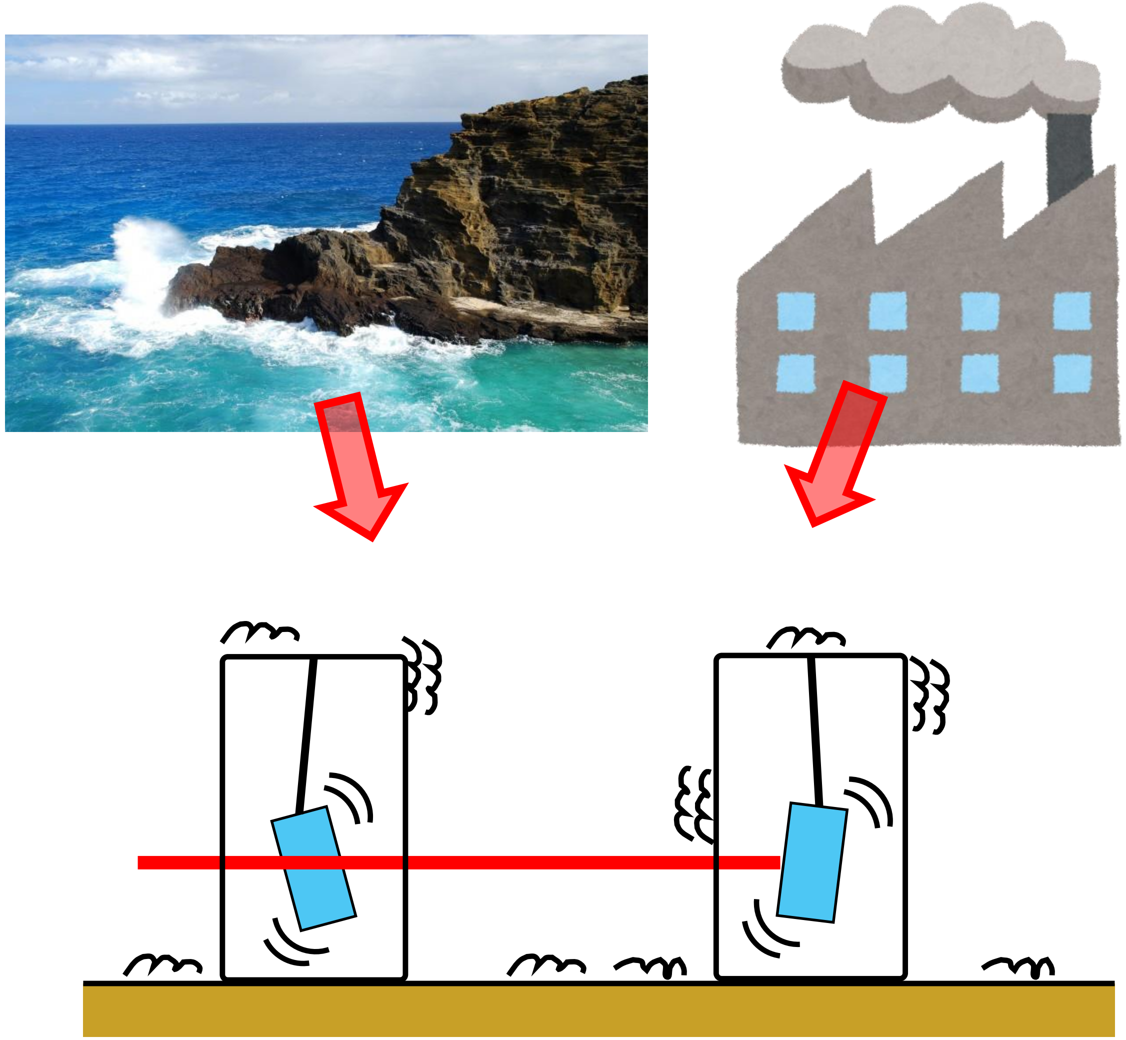
In case of KAGRA

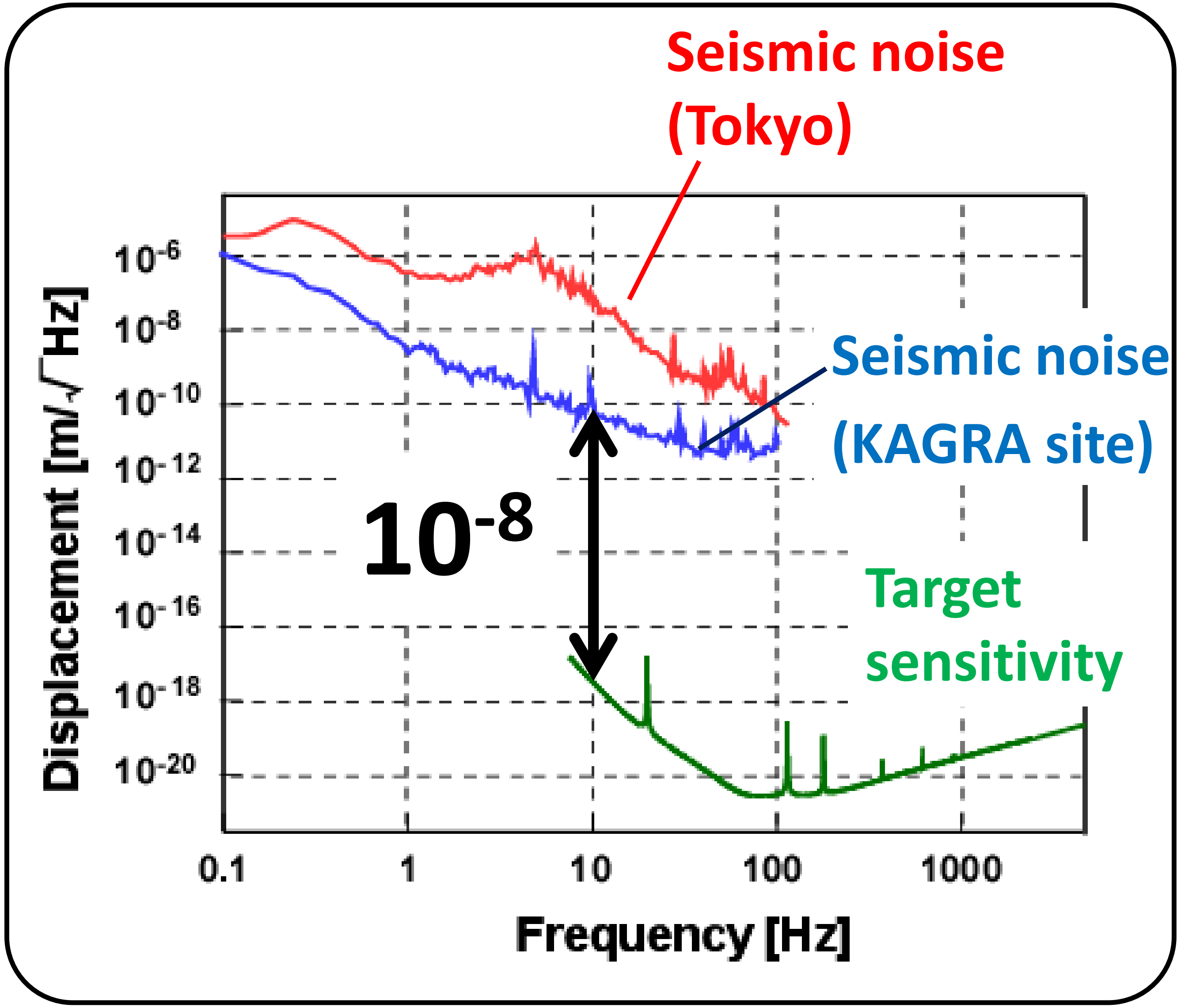
Seismic noise



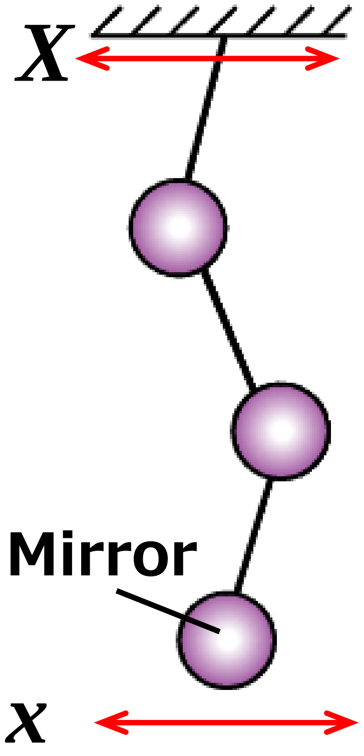


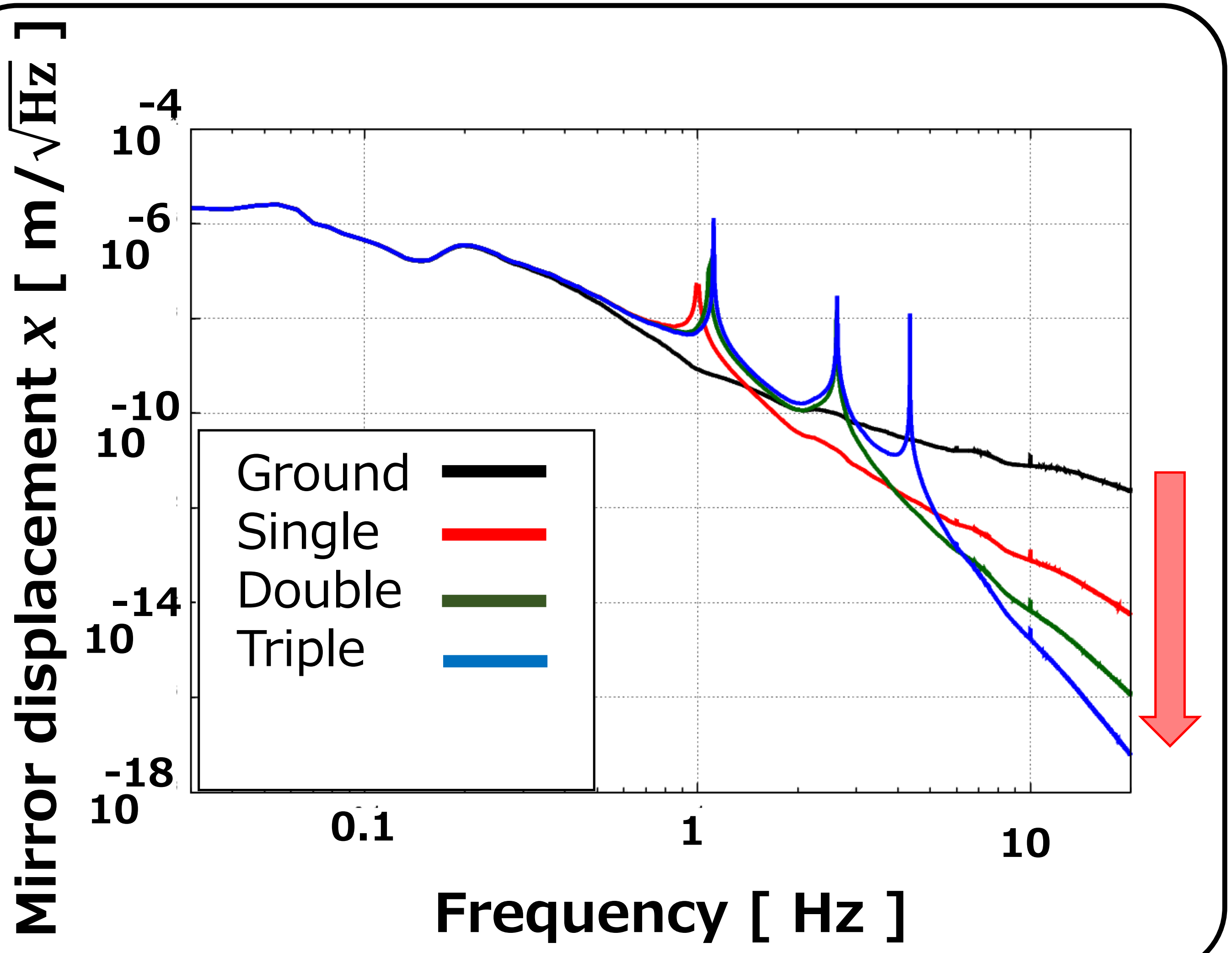
Seismic noise



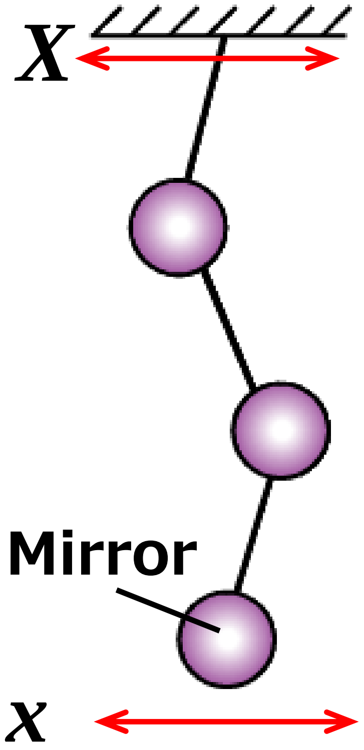


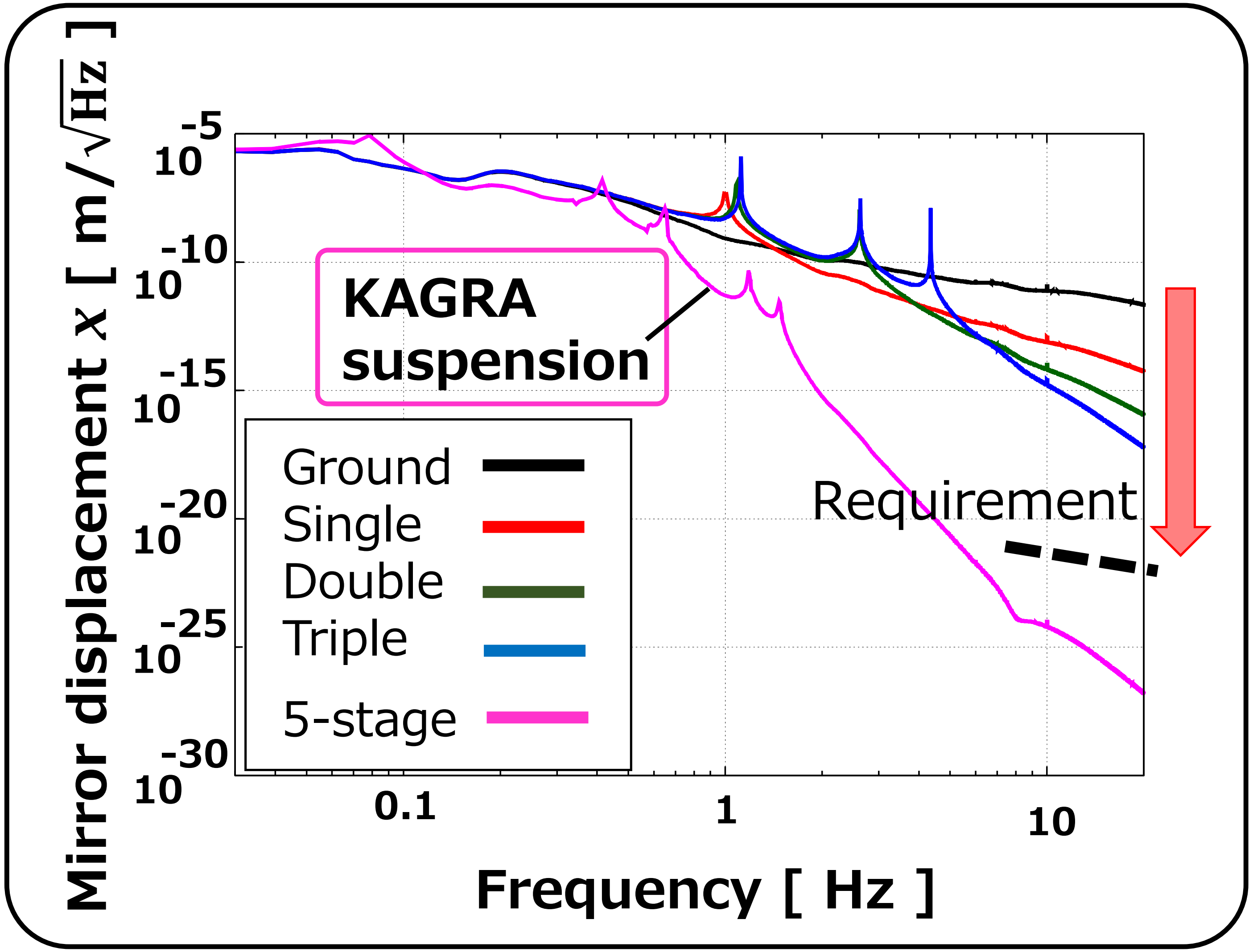
Seismic attenuation

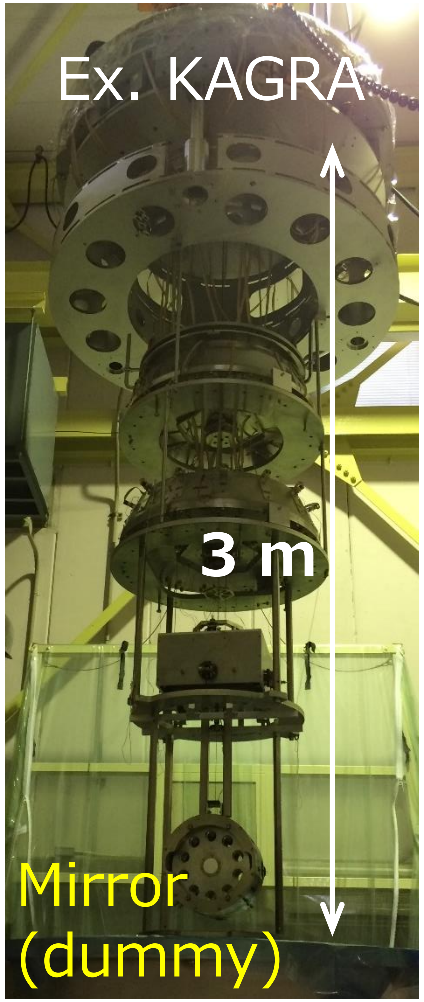




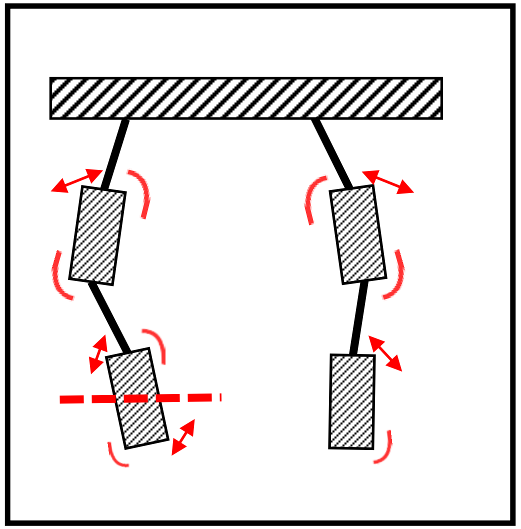
Seismic attenuation







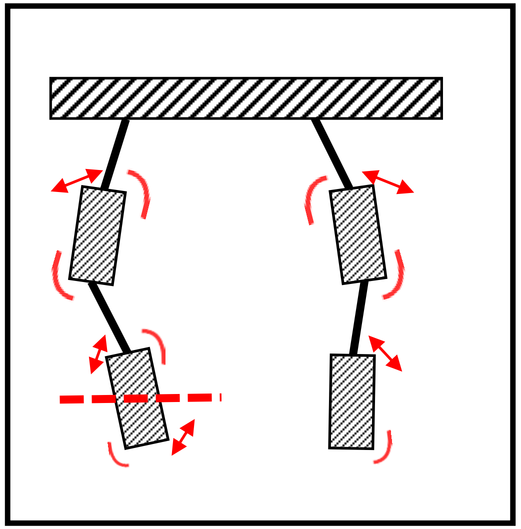
Resonance damping



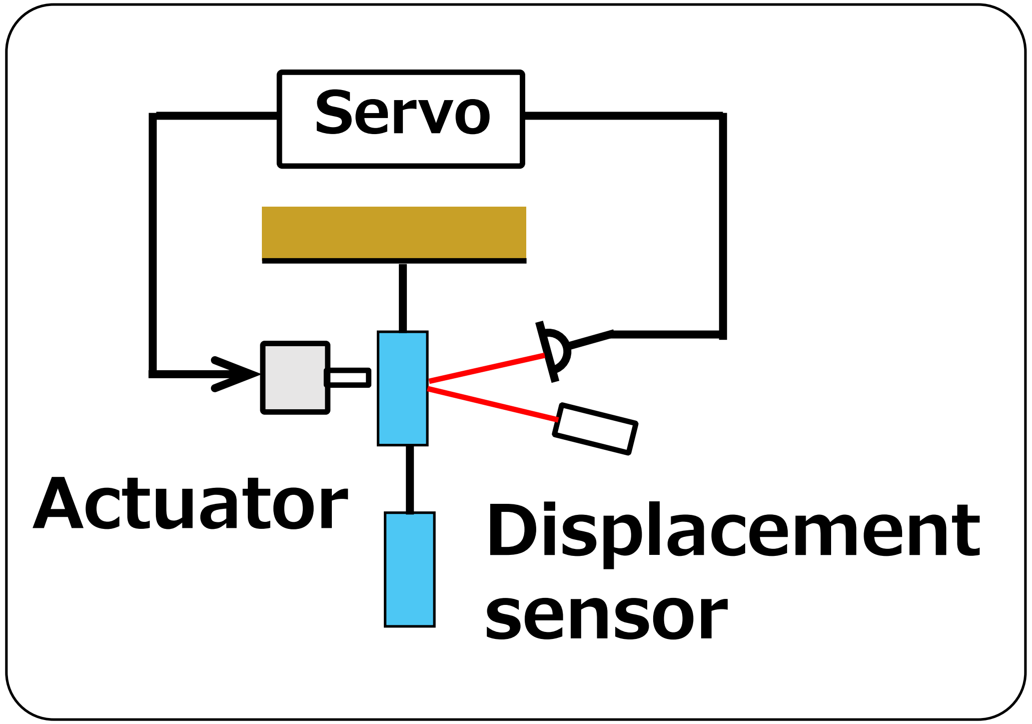
Starting interferometer operation

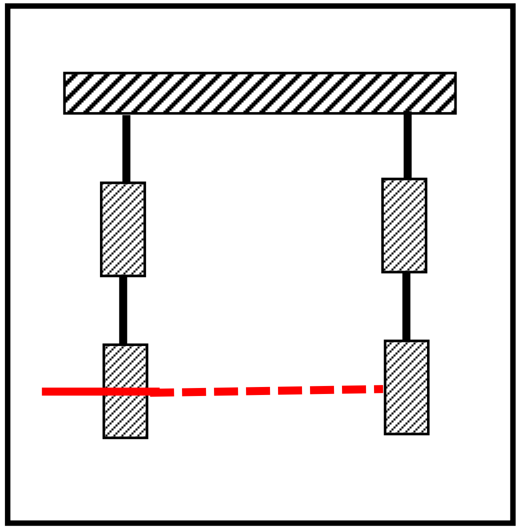
Resonance damping

→ *Active control*



~~Starting interferometer operation~~



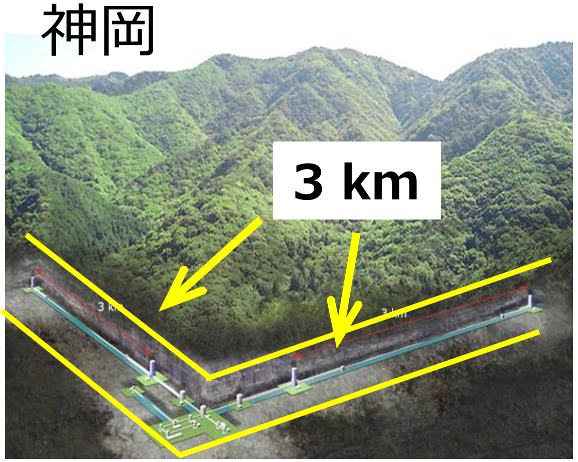


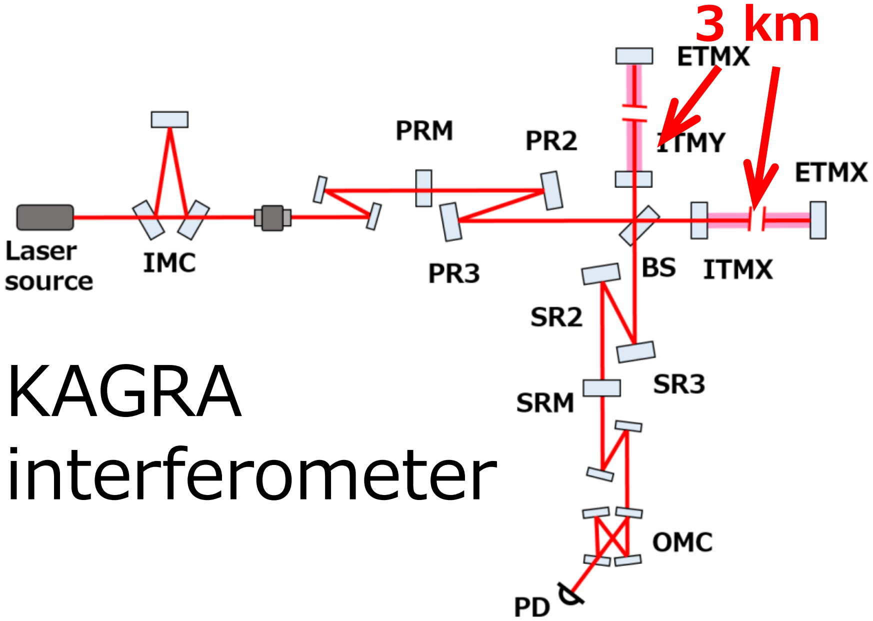
Stable interferometer operation

KAGRA project

KAGRA detector

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





KAGRA interferometer

KAGRA project

KAGRA detector

1) Japanese detector
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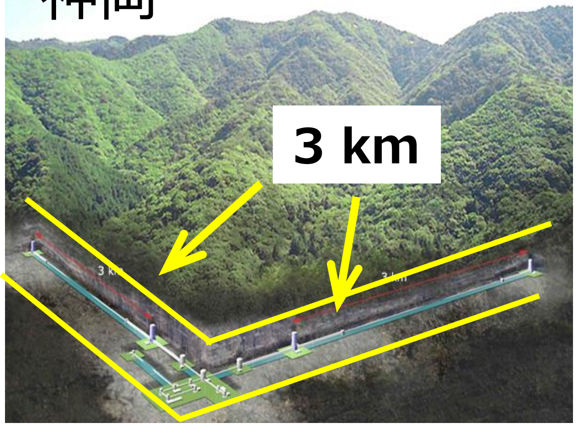
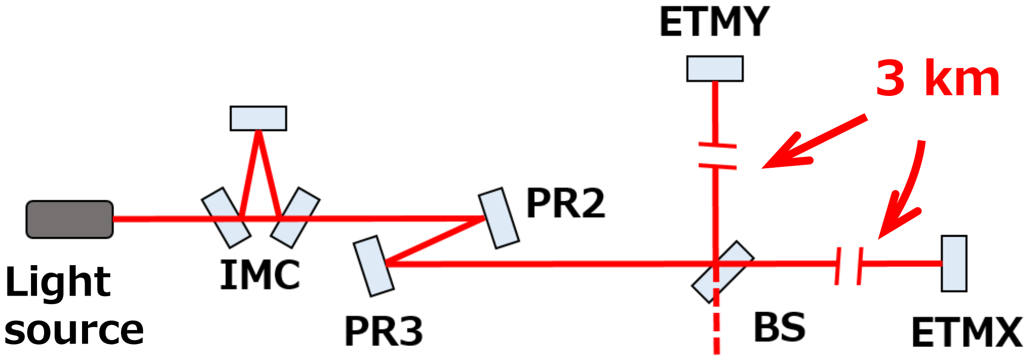
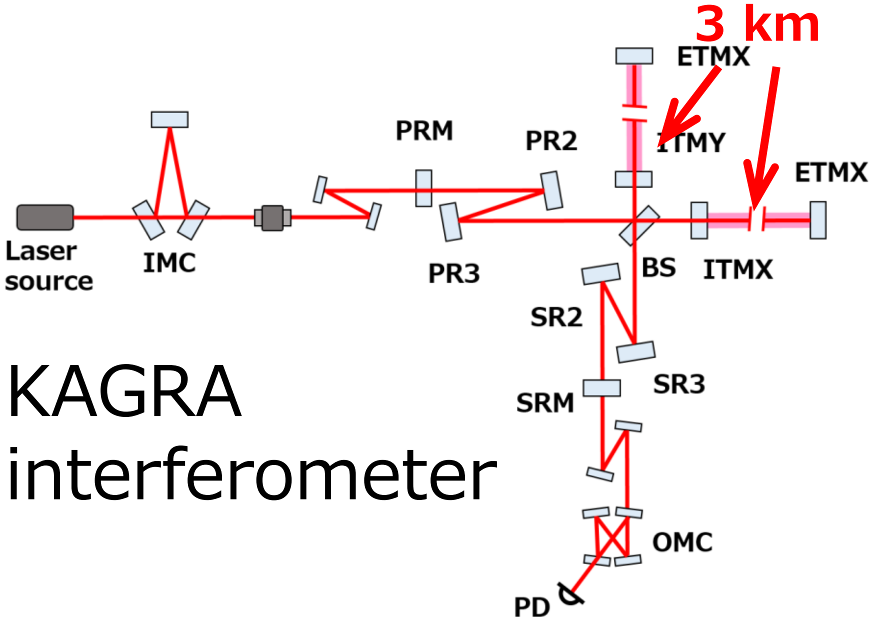
神岡



iKAGRA

1) test run in 2016
2) Simple interferometer



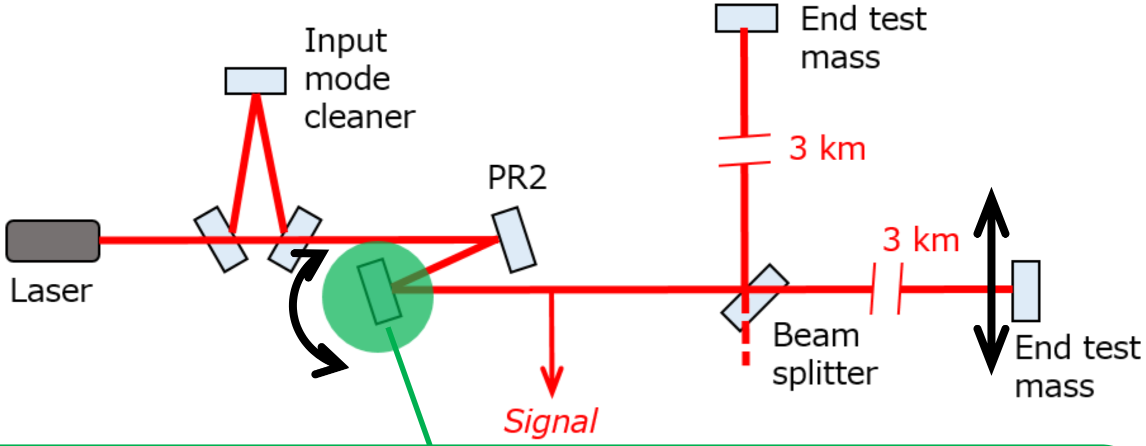


KAGRA interferometer

iKAGRA suspension development

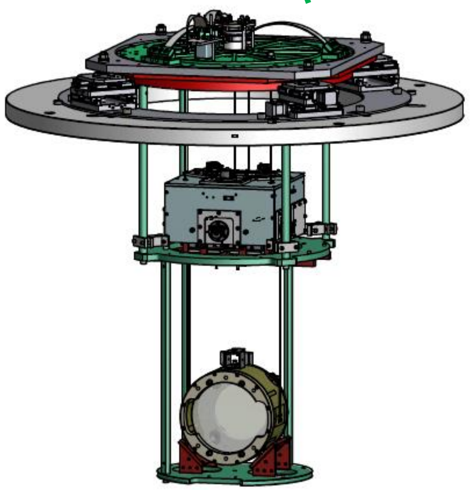
Development work:

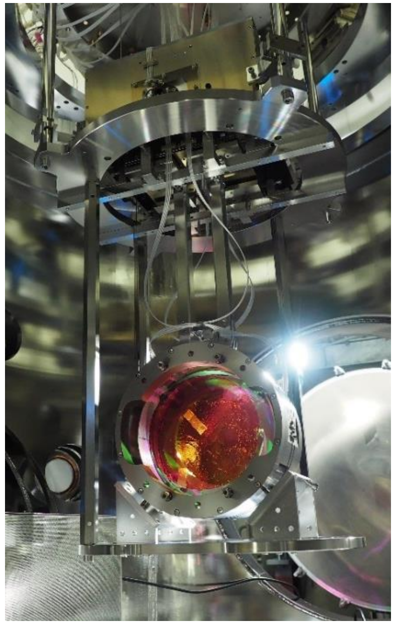
1) Assembly
2) Measurement
3) Upgrade for final phase



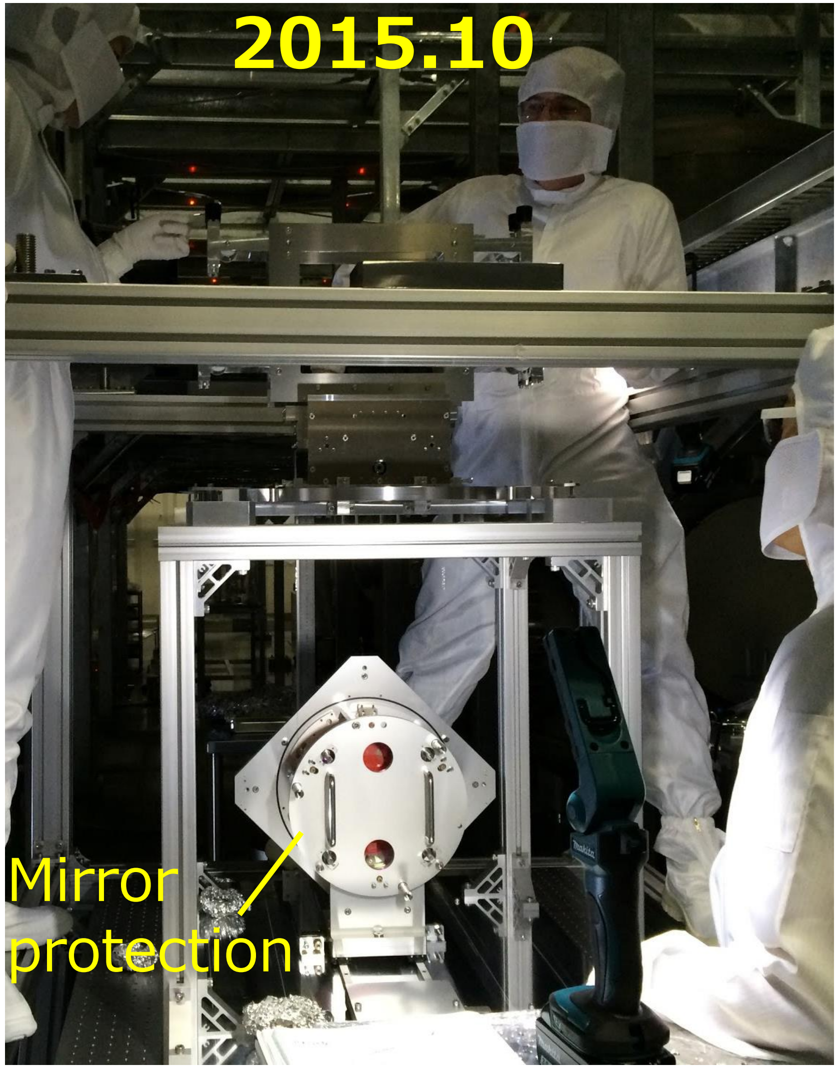
iKAGRA suspension:

Alignment mirror of iKAGRA
for initial alignment
for stable operation.

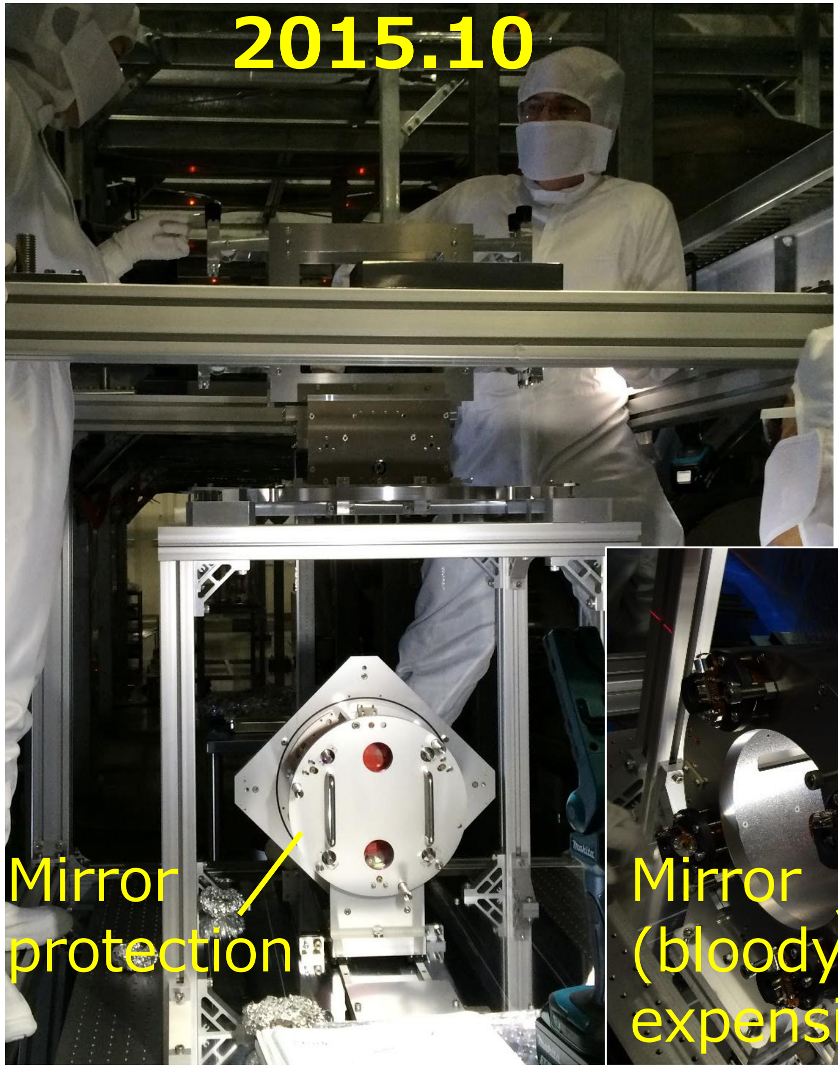


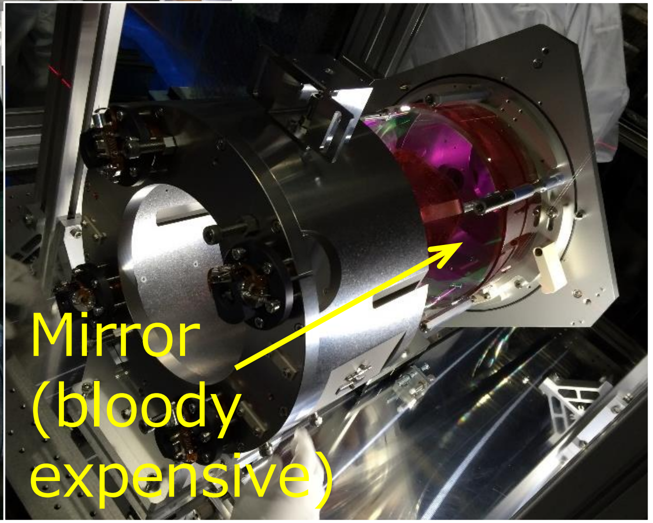


Assembly

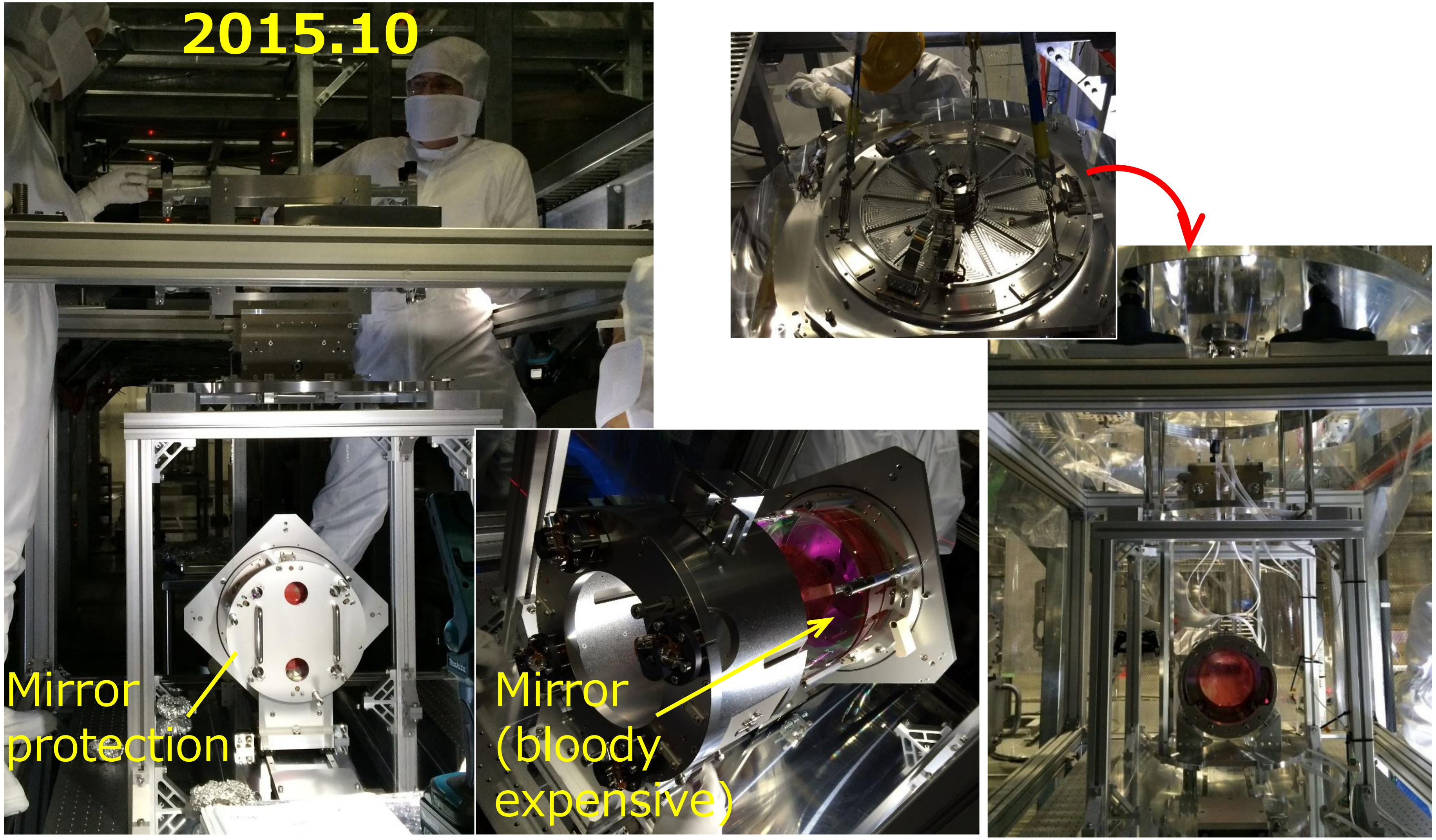


Assembly

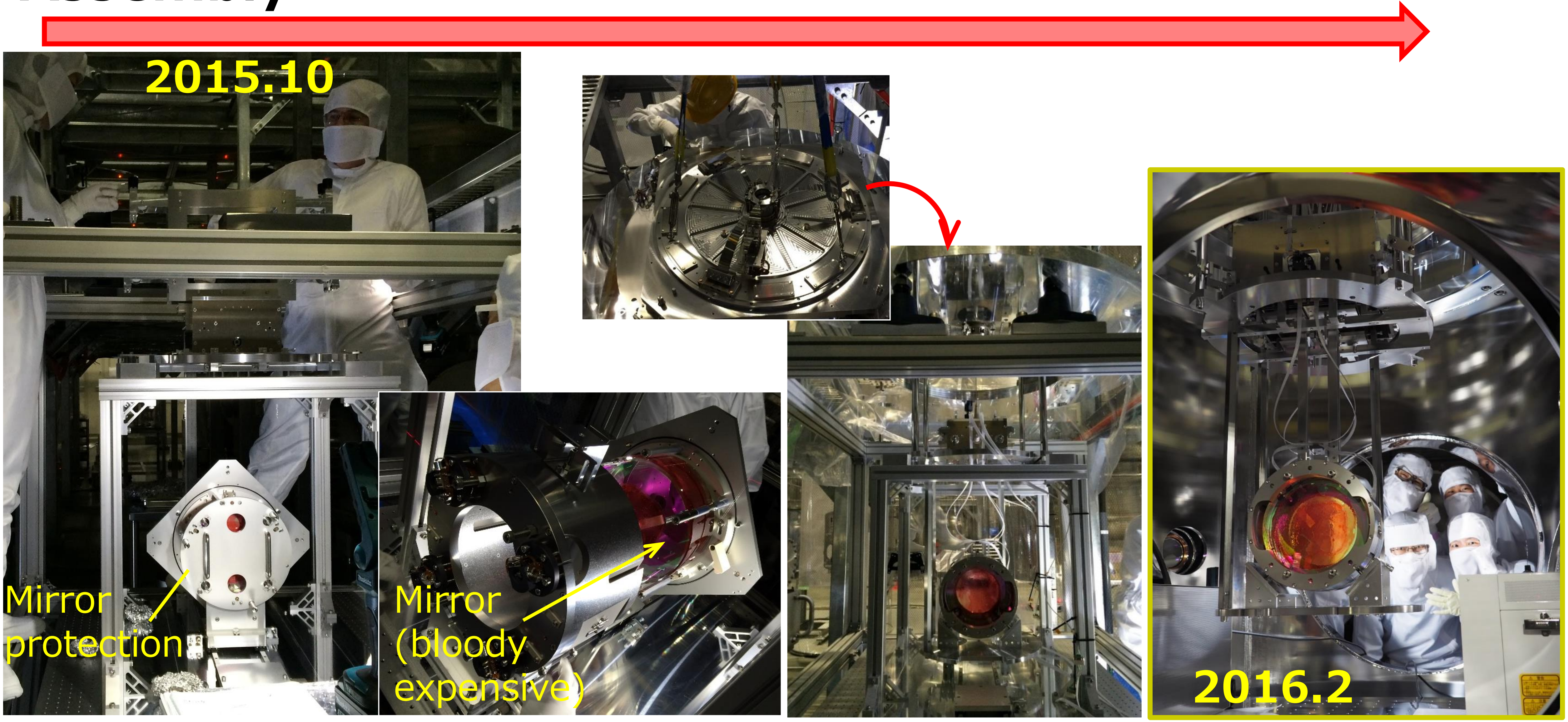




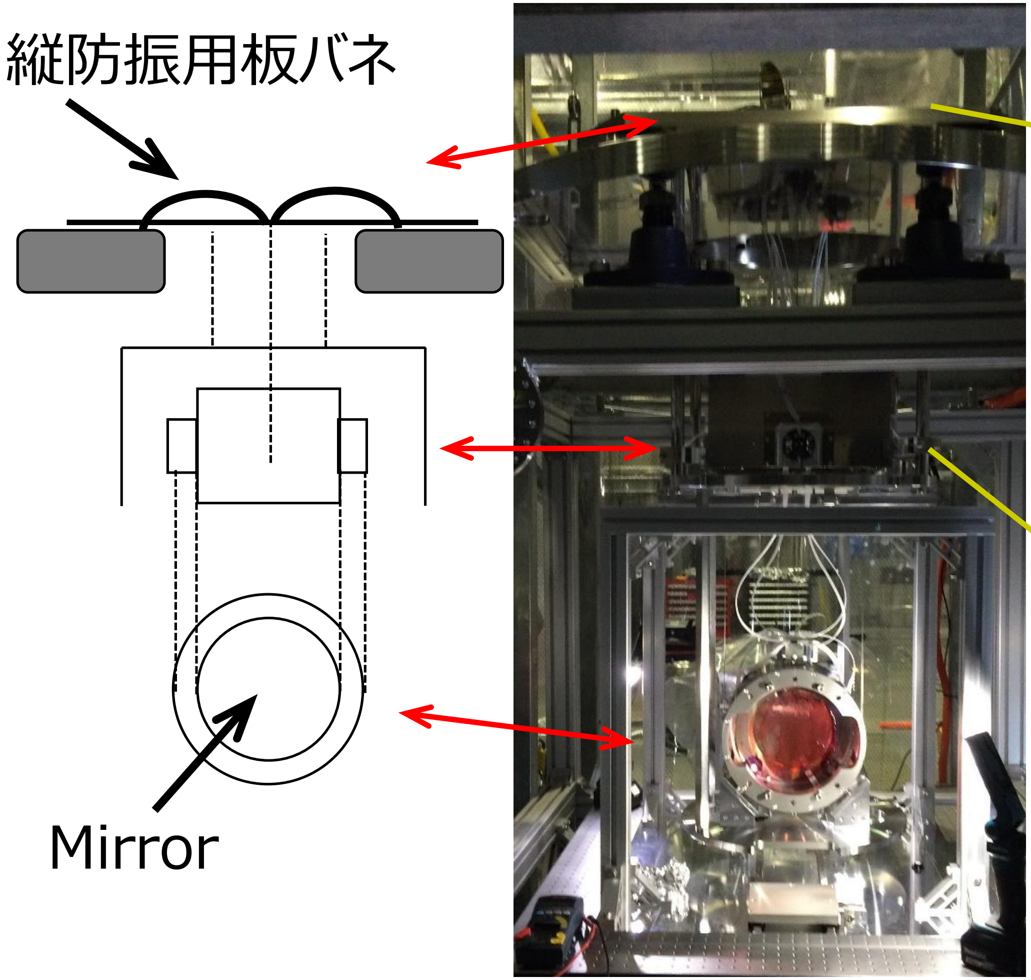
Assembly



Assembly

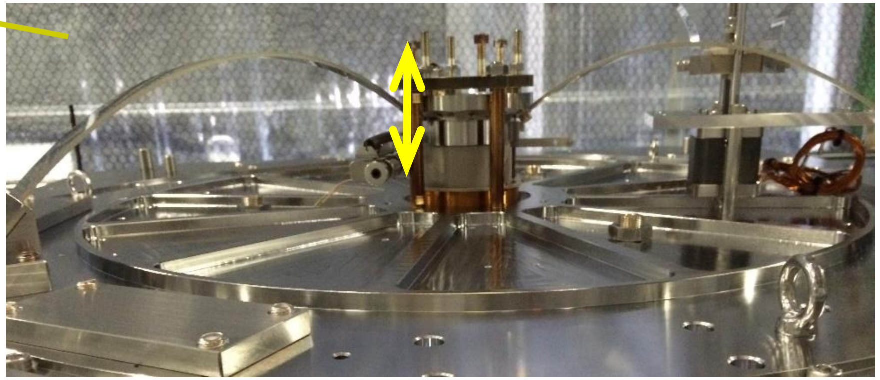


Sensors and actuators

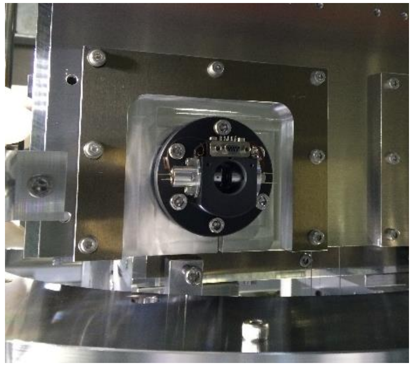


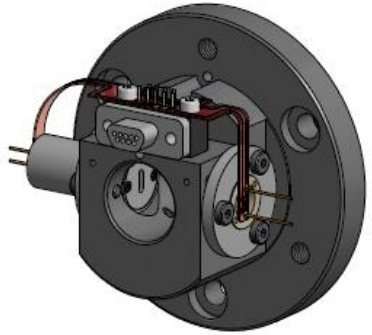
iKAGRA-PR3 SAS

Displacement sensor and coil-magnet actuator 1

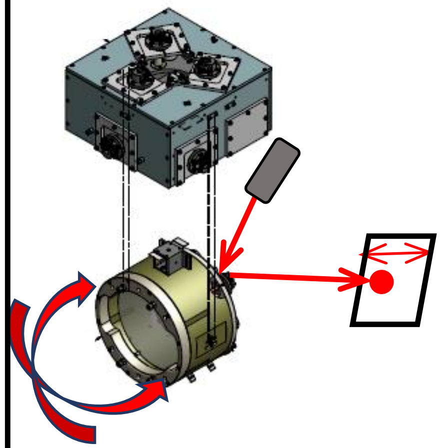


Displacement sensor and coil-magnet actuator 2



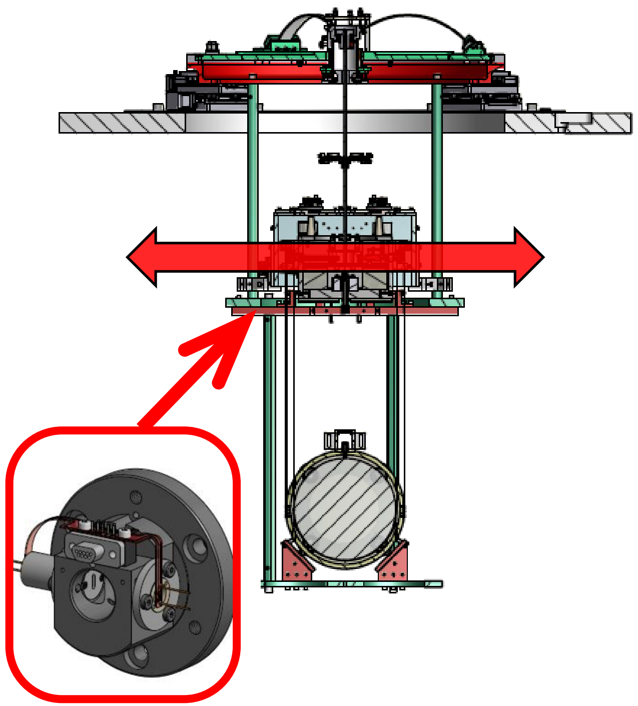


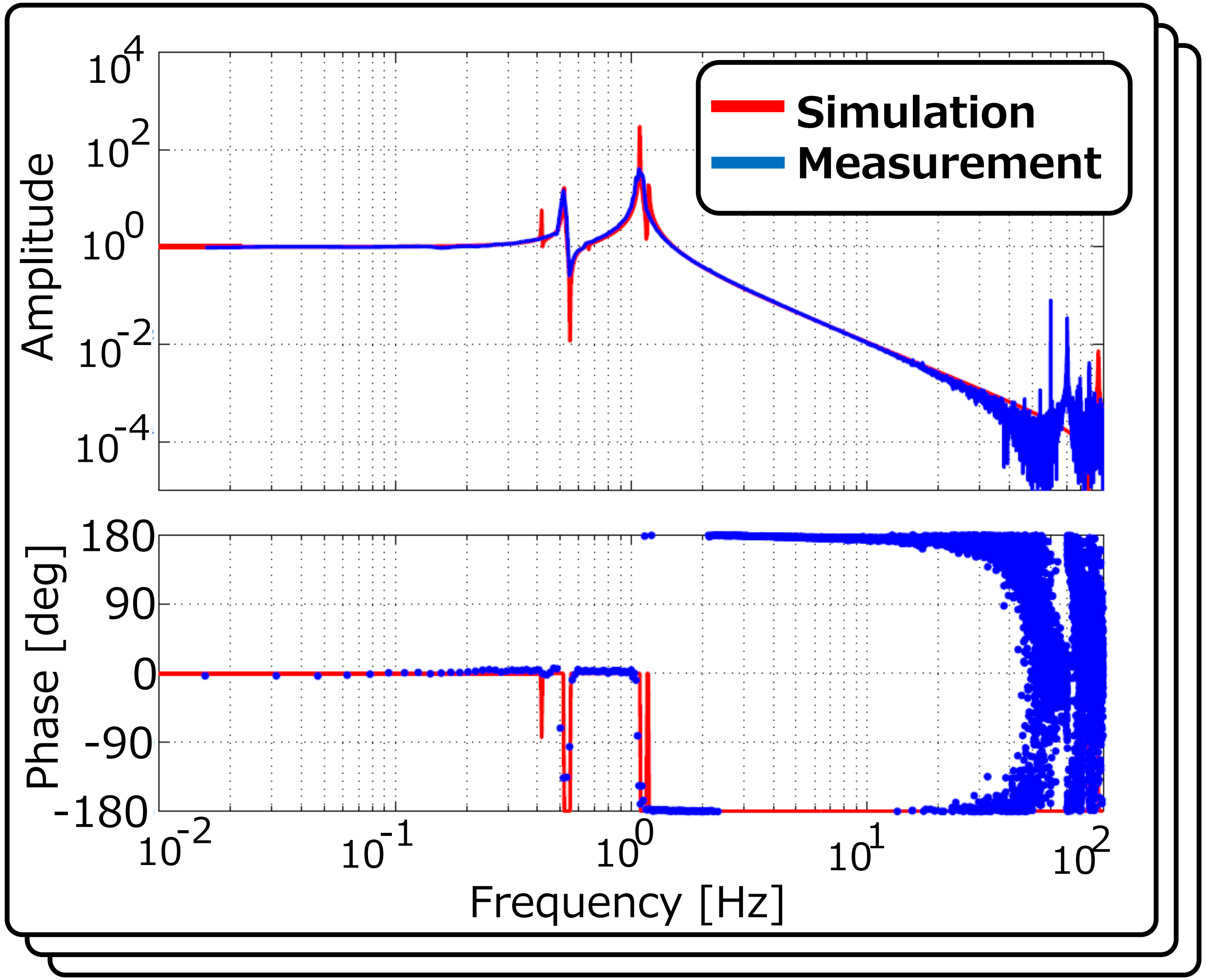
Angular sensor



1. Frequency response

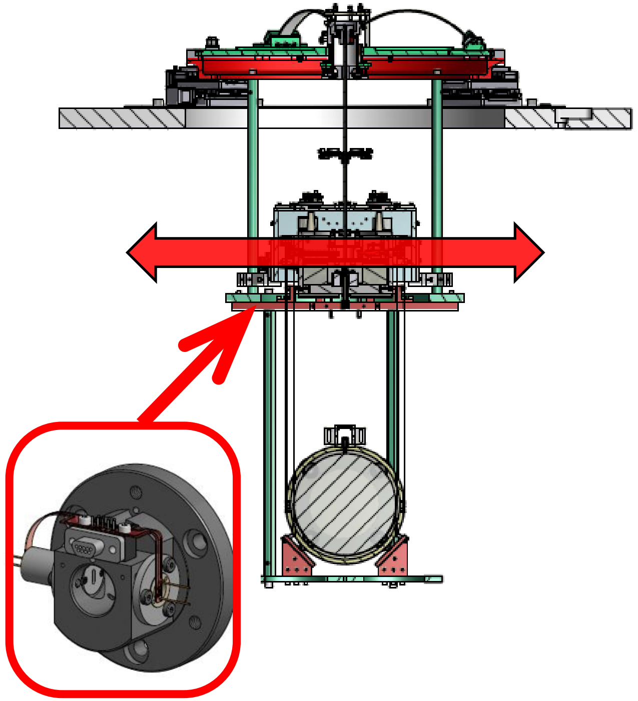
For each Components:

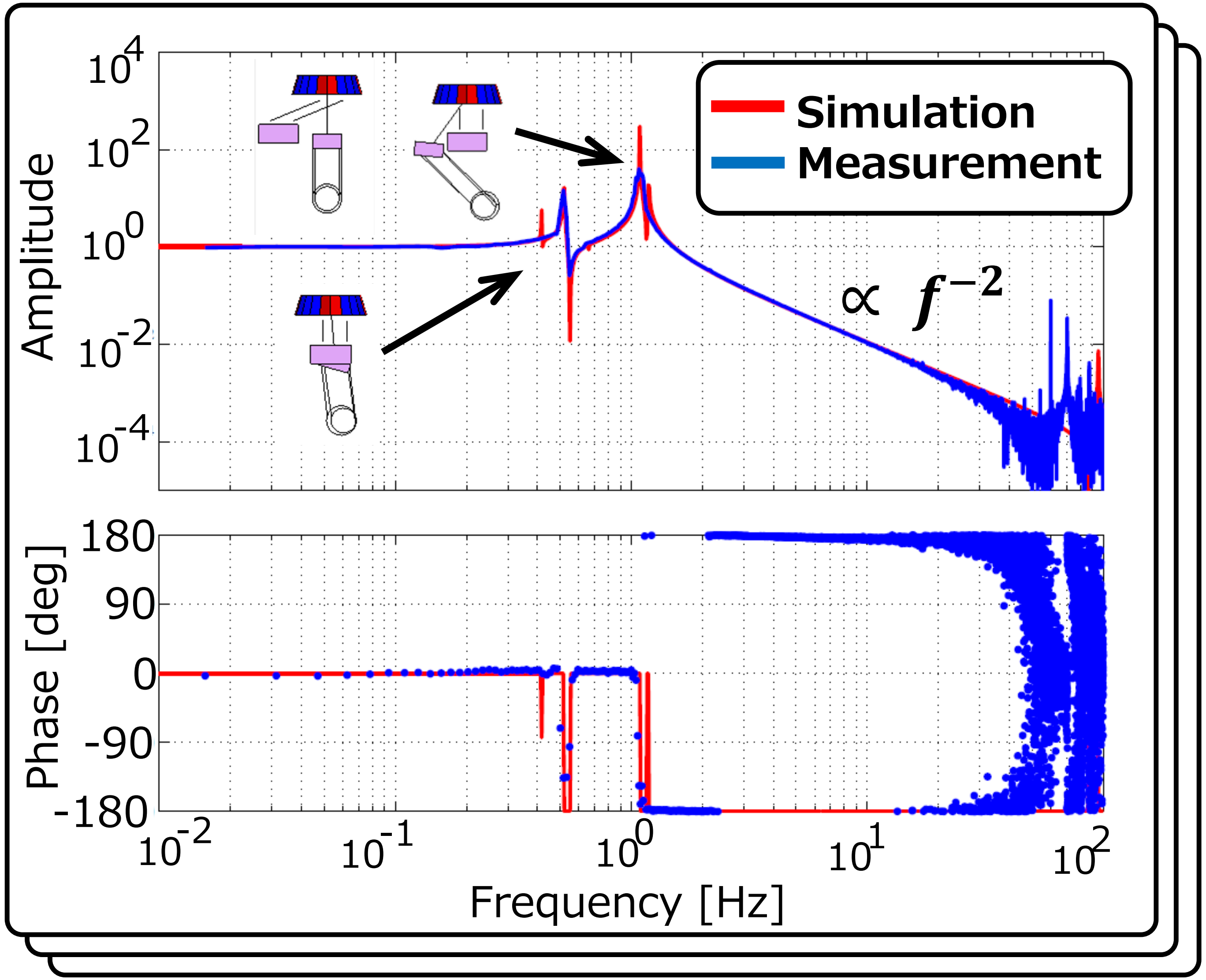




1. Frequency response

For each Components:



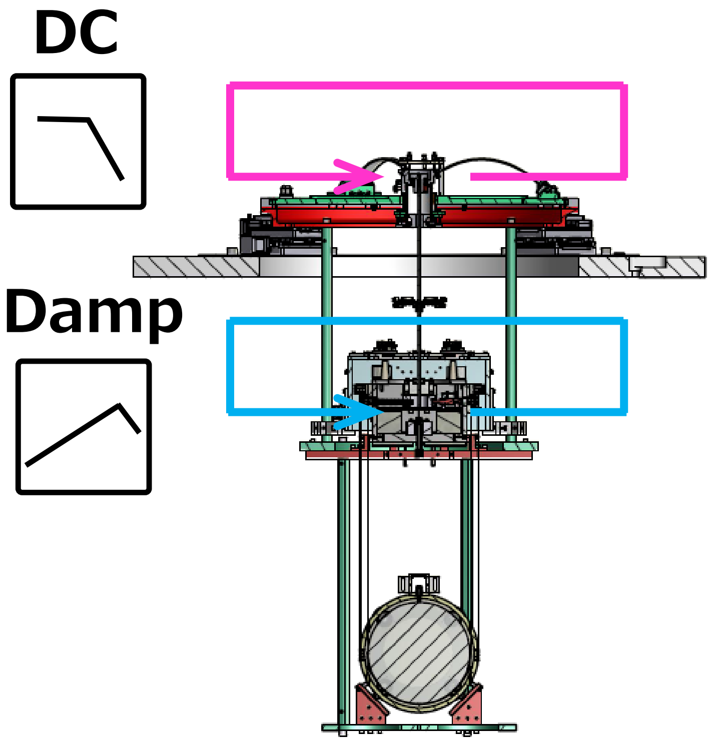


1) Pendulum

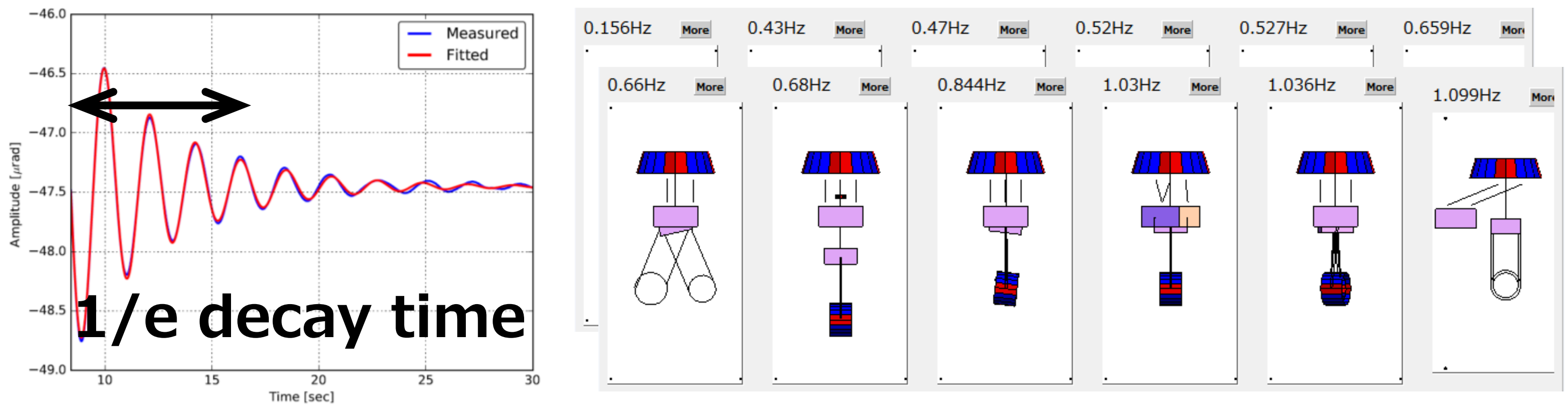
2) Simulation

→ Consistent measurement

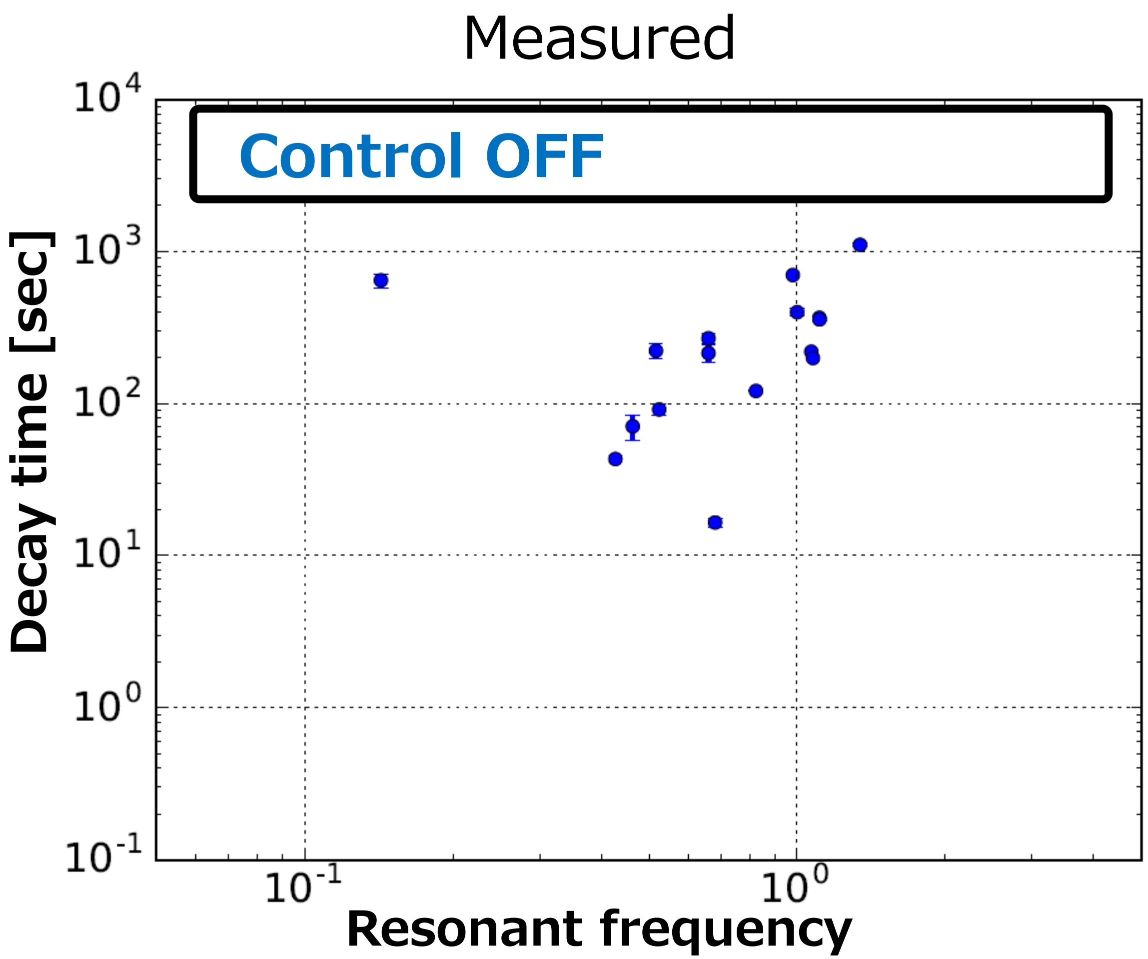
2. Damping time

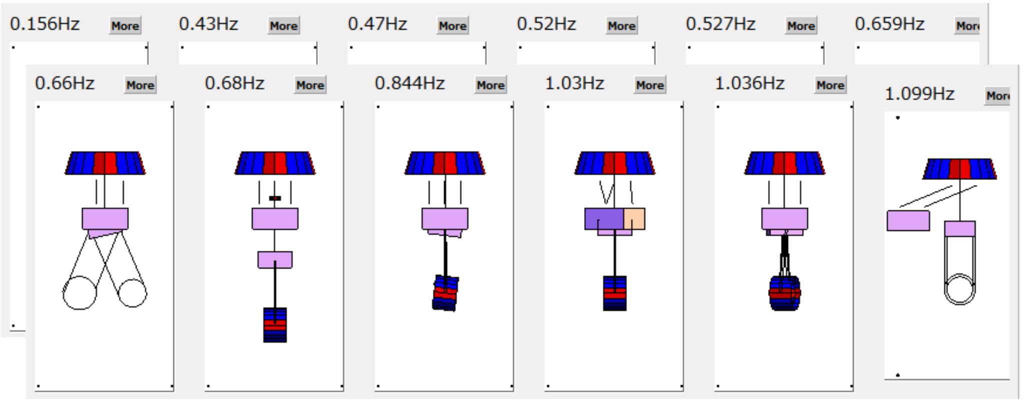


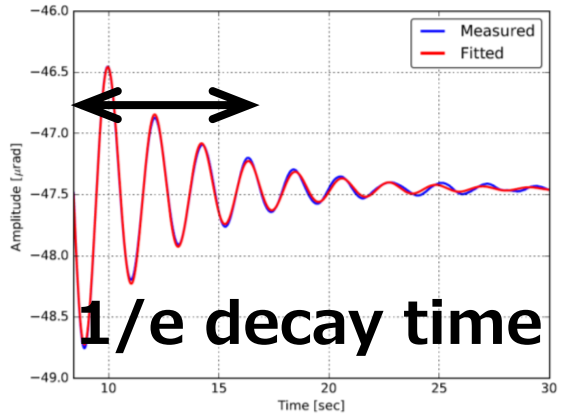
For damping resonances



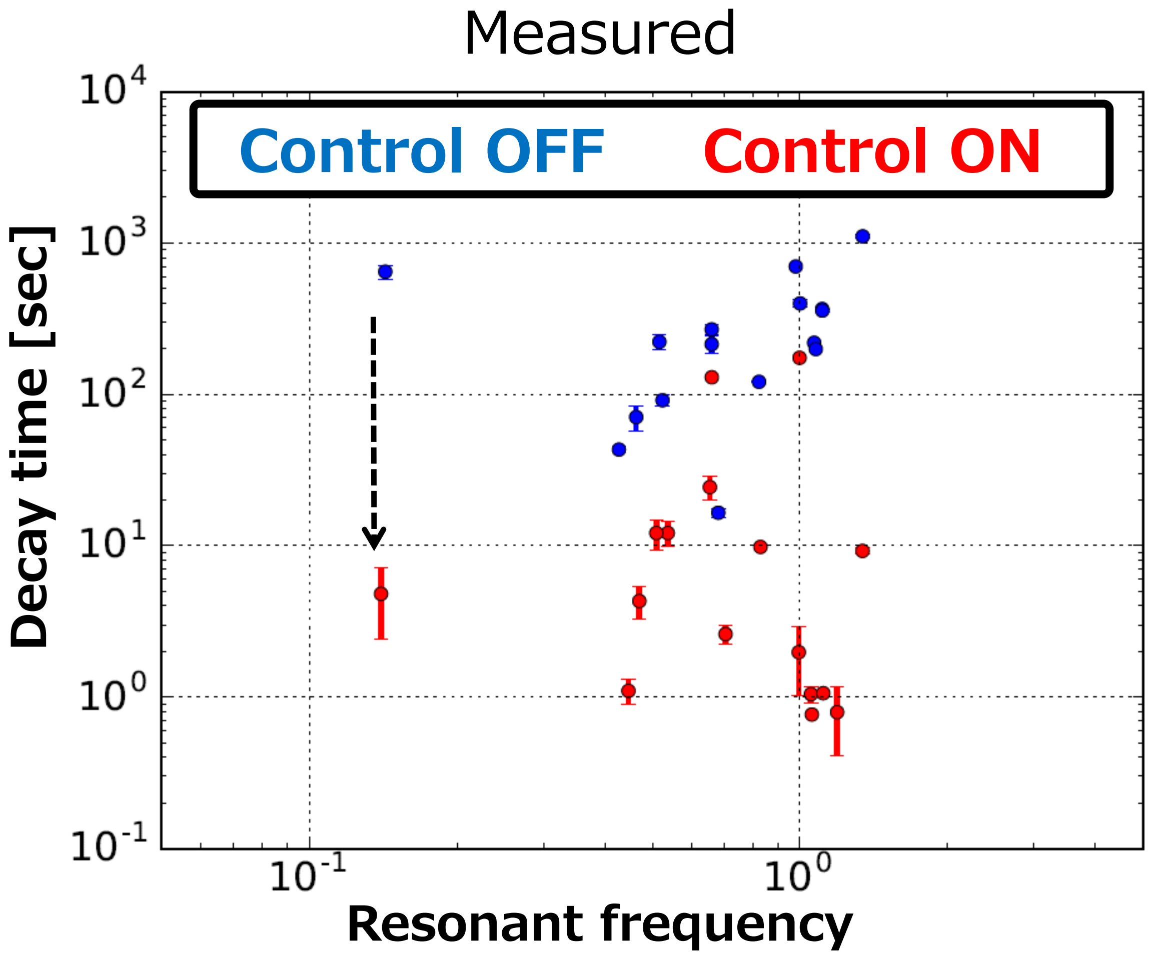
2. Damping time without damping

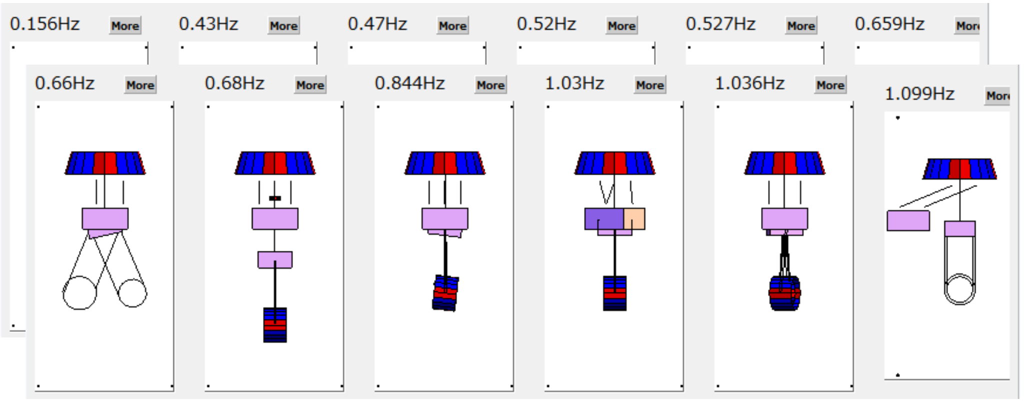


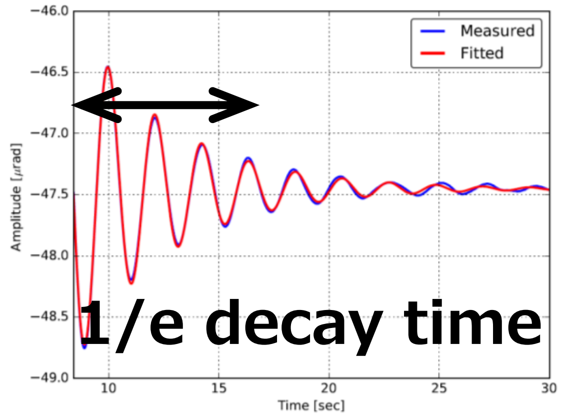




2. Damping time with damping

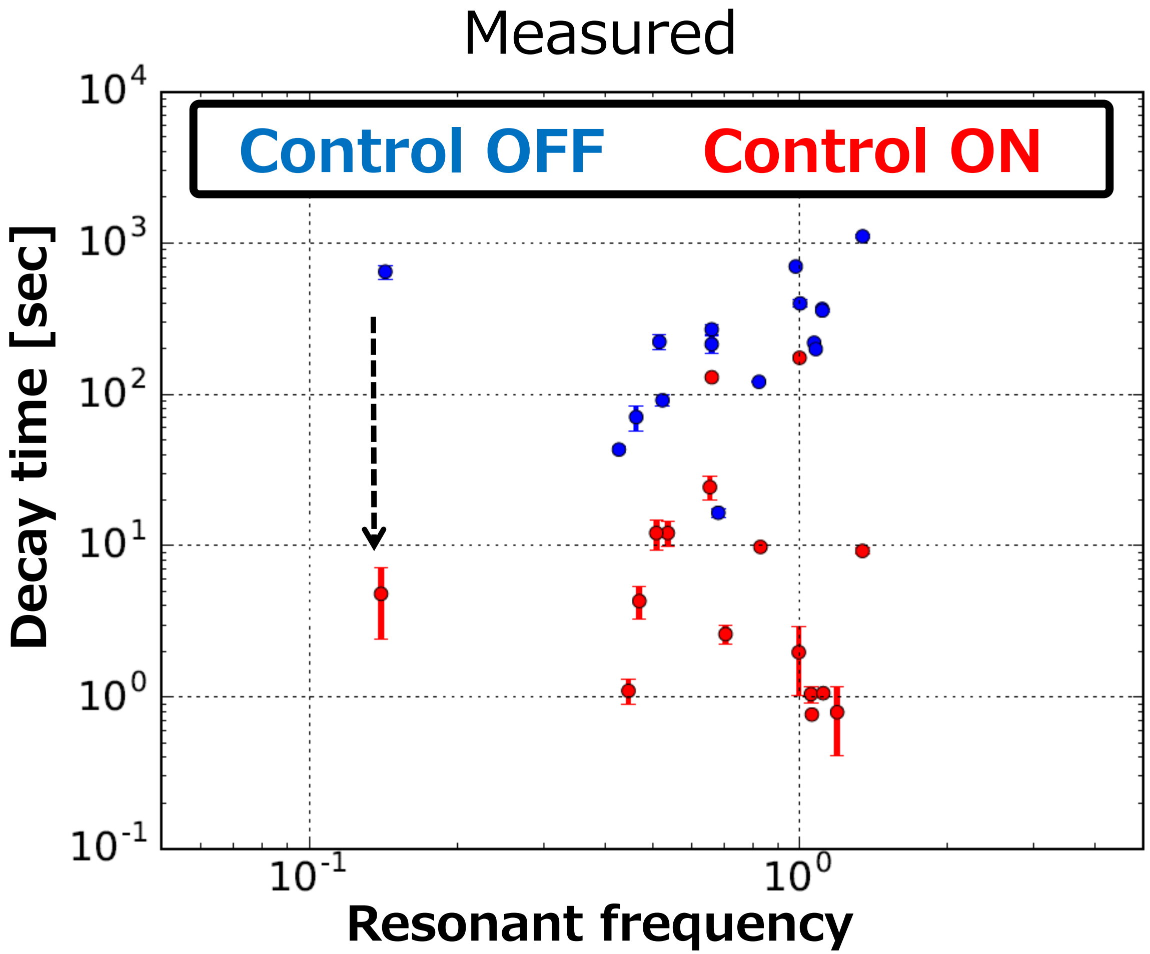


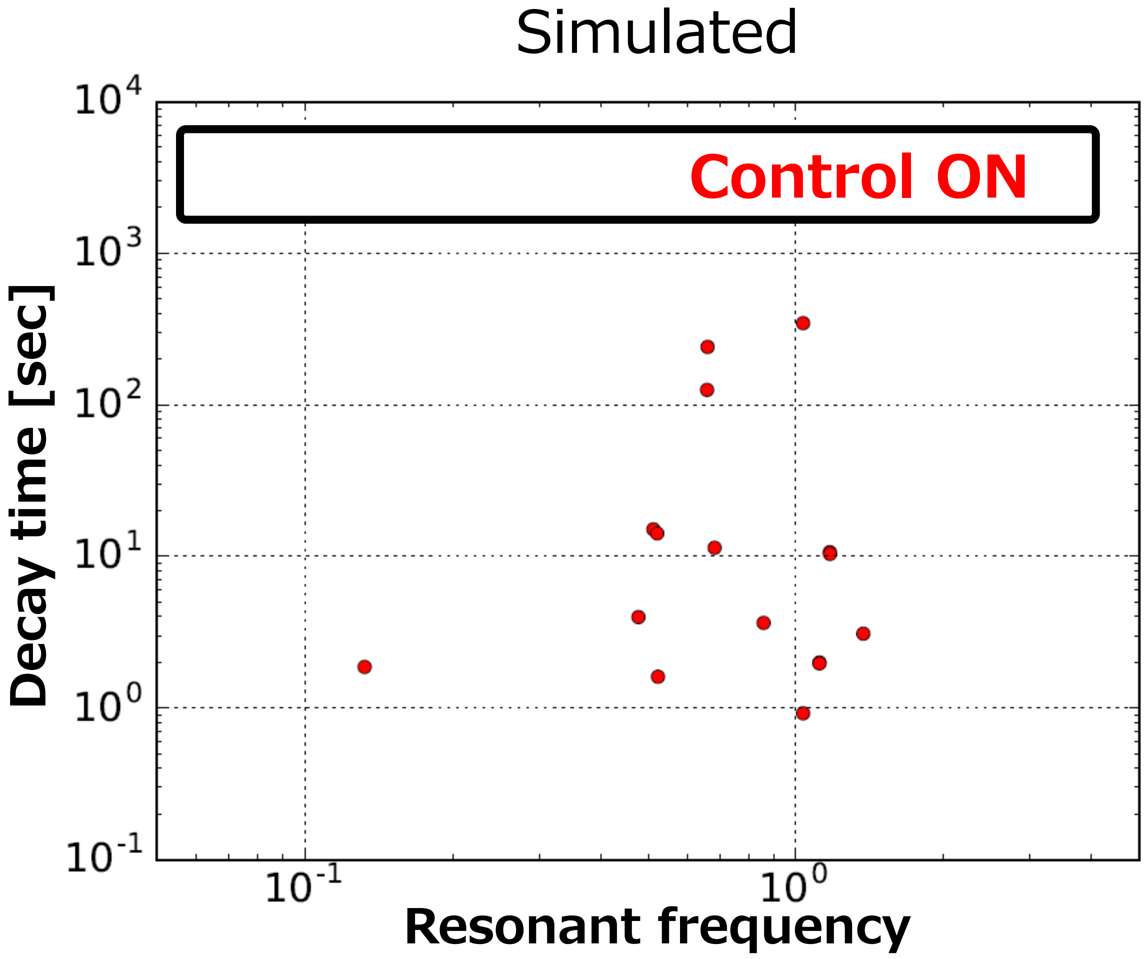




Resonances → damped

2. Damping time with damping

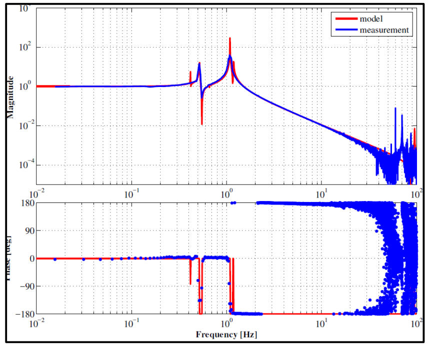




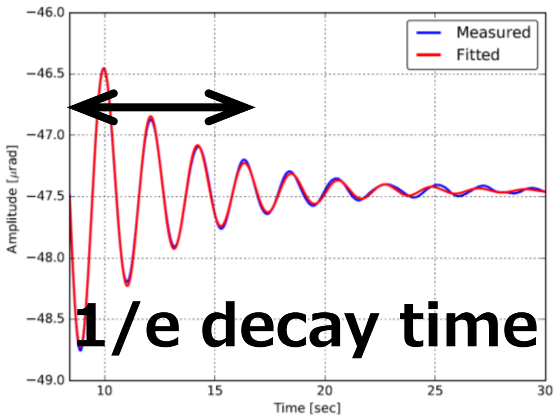
Simulation → consistent with measurement

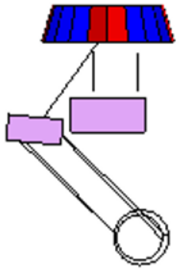
Measurement:

1. Frequency response



2. Damping time





Each component
→ *Pendulum*

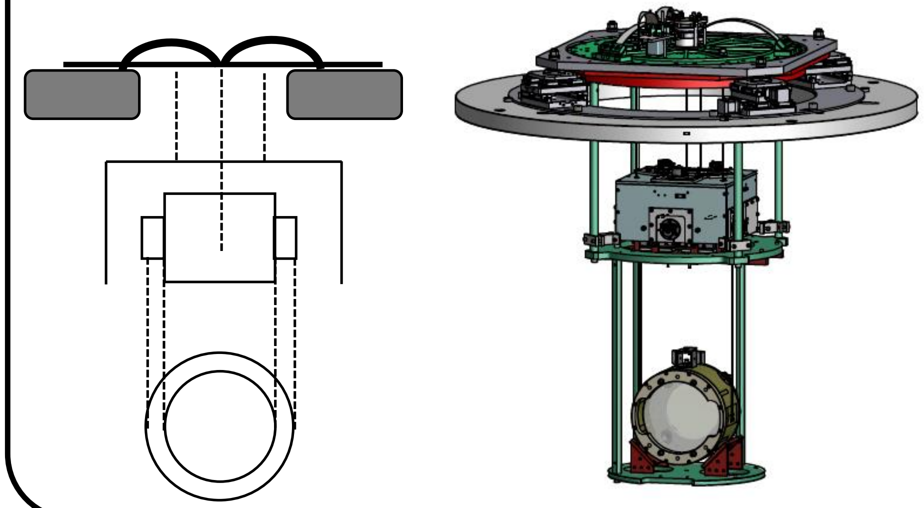
Resonances
→ *Damped*

Simulation
→ *Consistent with measurement*

Upgrade: iKAGRA → final KAGRA

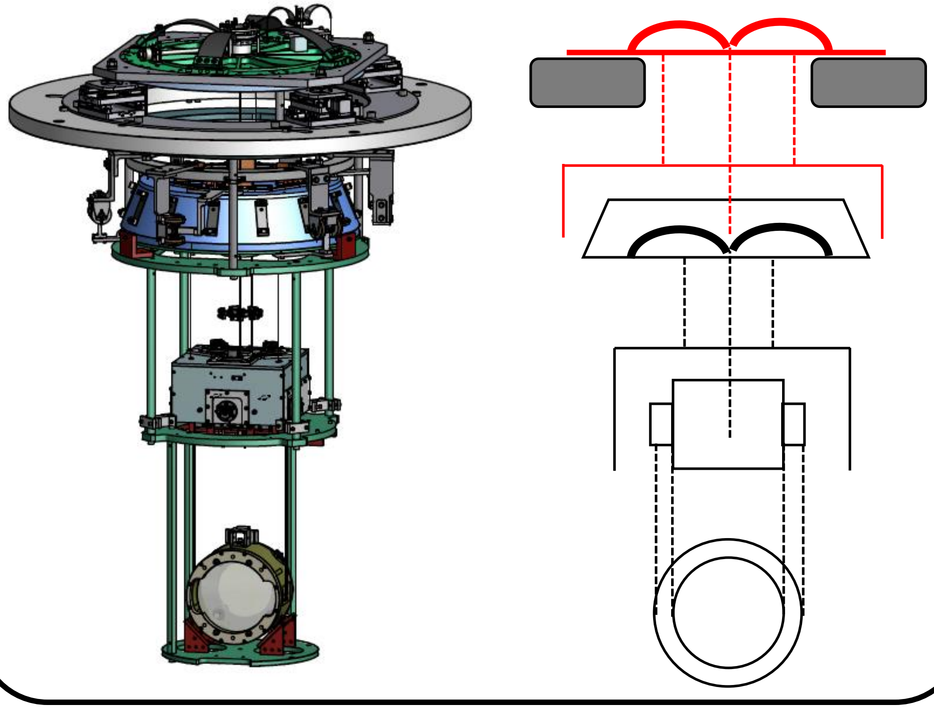
In order to meet final requirements:

Initial phase



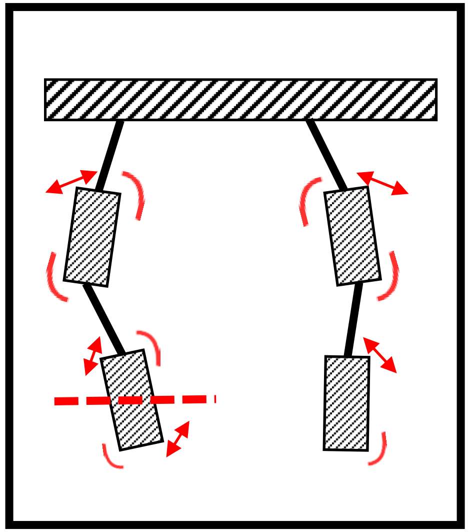
Add one more stage

Final phase



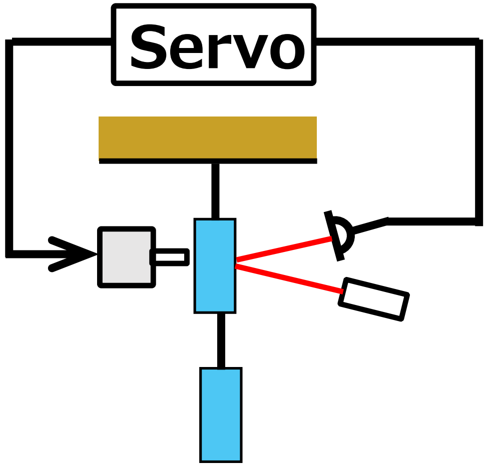
→ Design active control systems.

Steps for observation

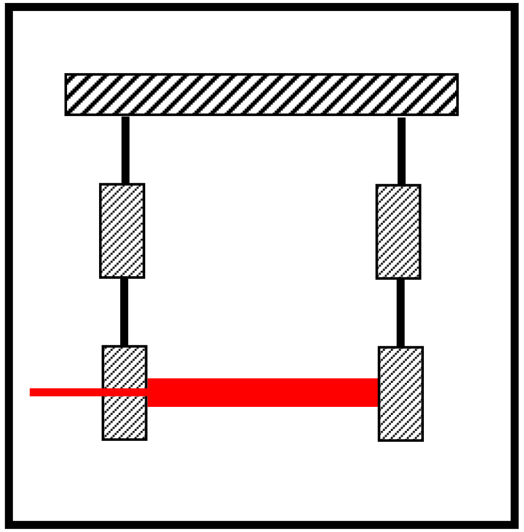


Free swinging

Calm-down phase

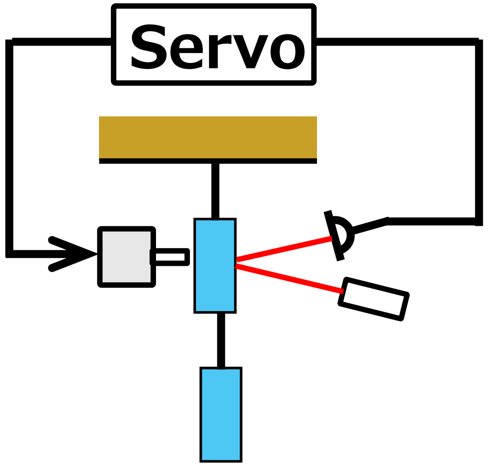


All stages → Damping



Interferometer Lock

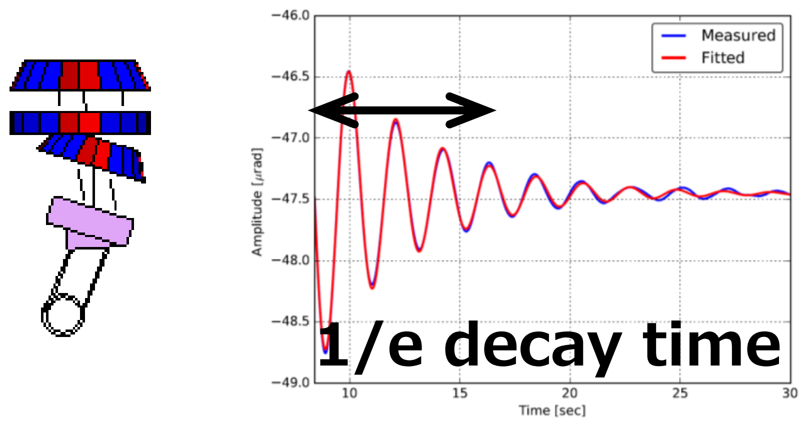
Observation phase



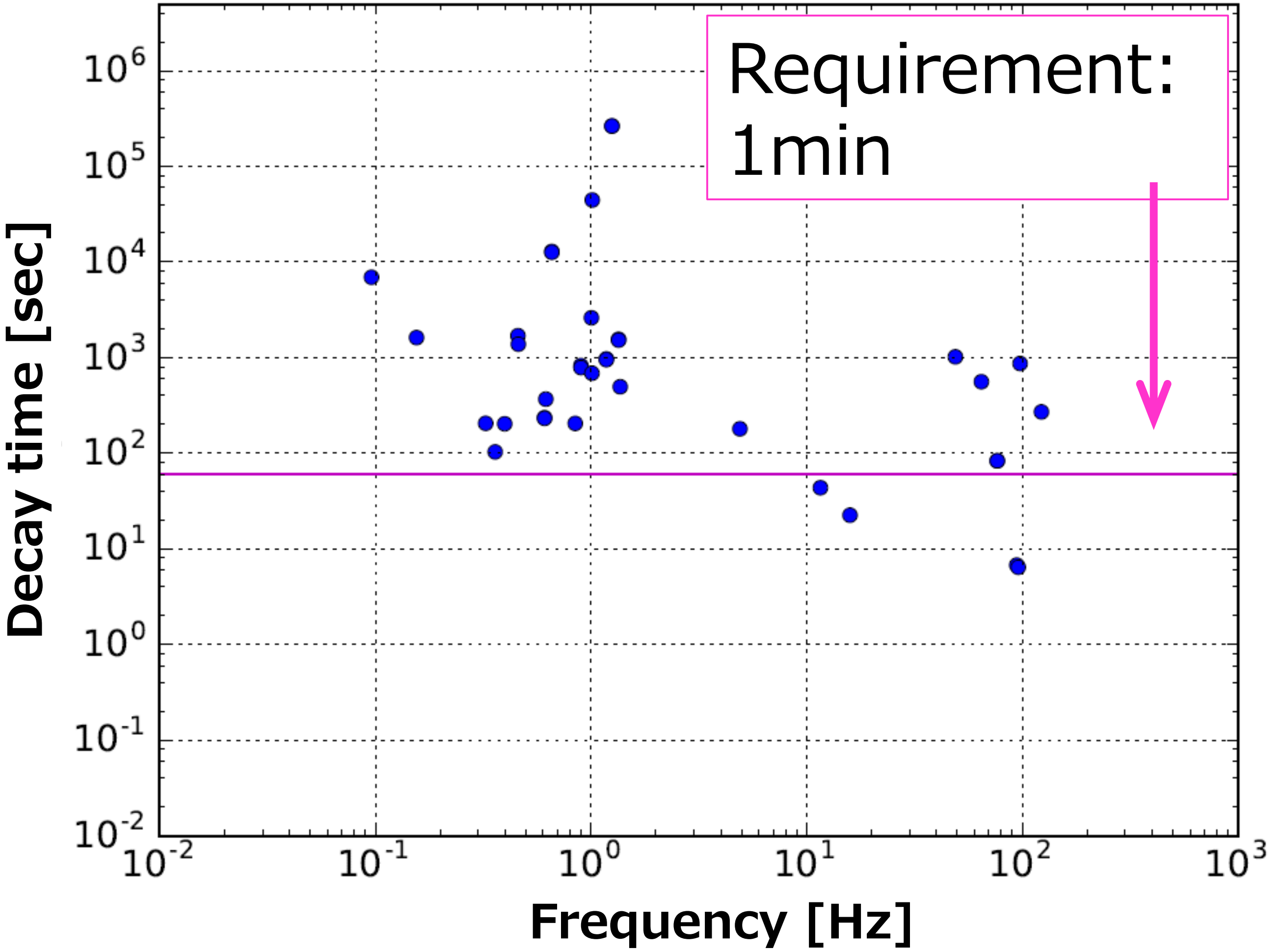
Upper stage → Damping

Lower stage → Alignment

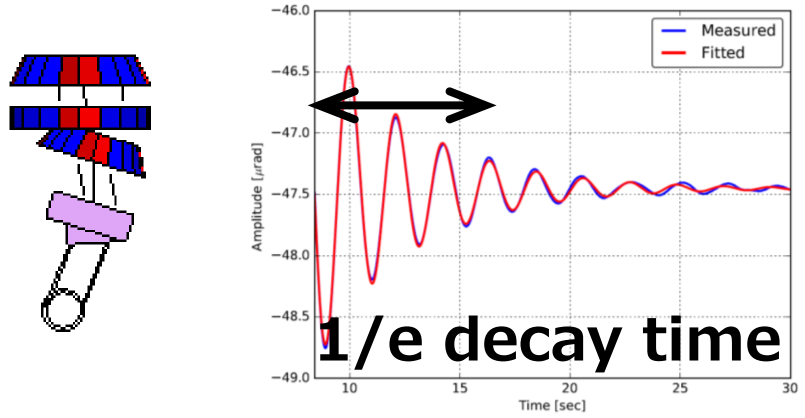
Clam-down phase:
Suppress large disturbance

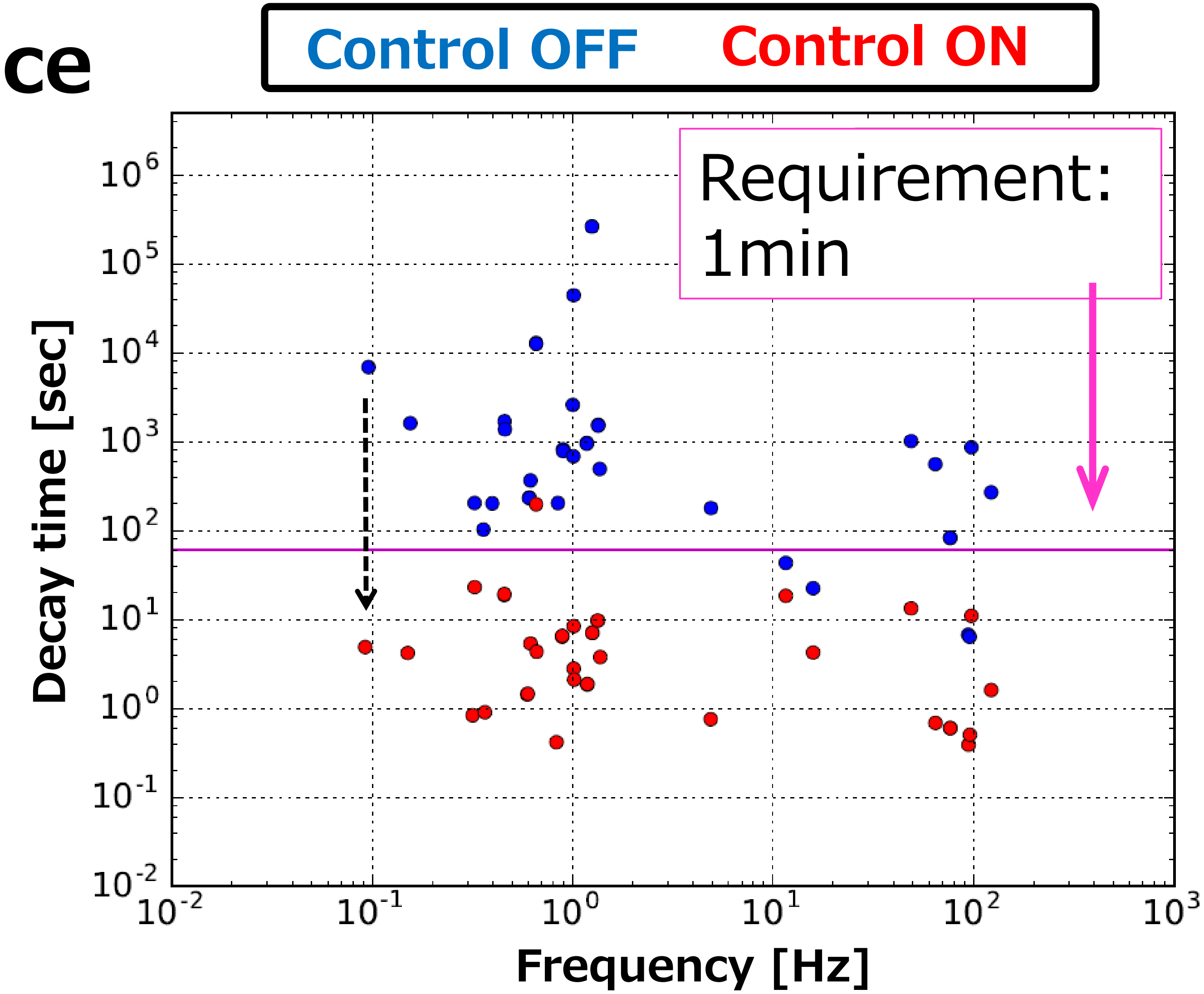


Control OFF

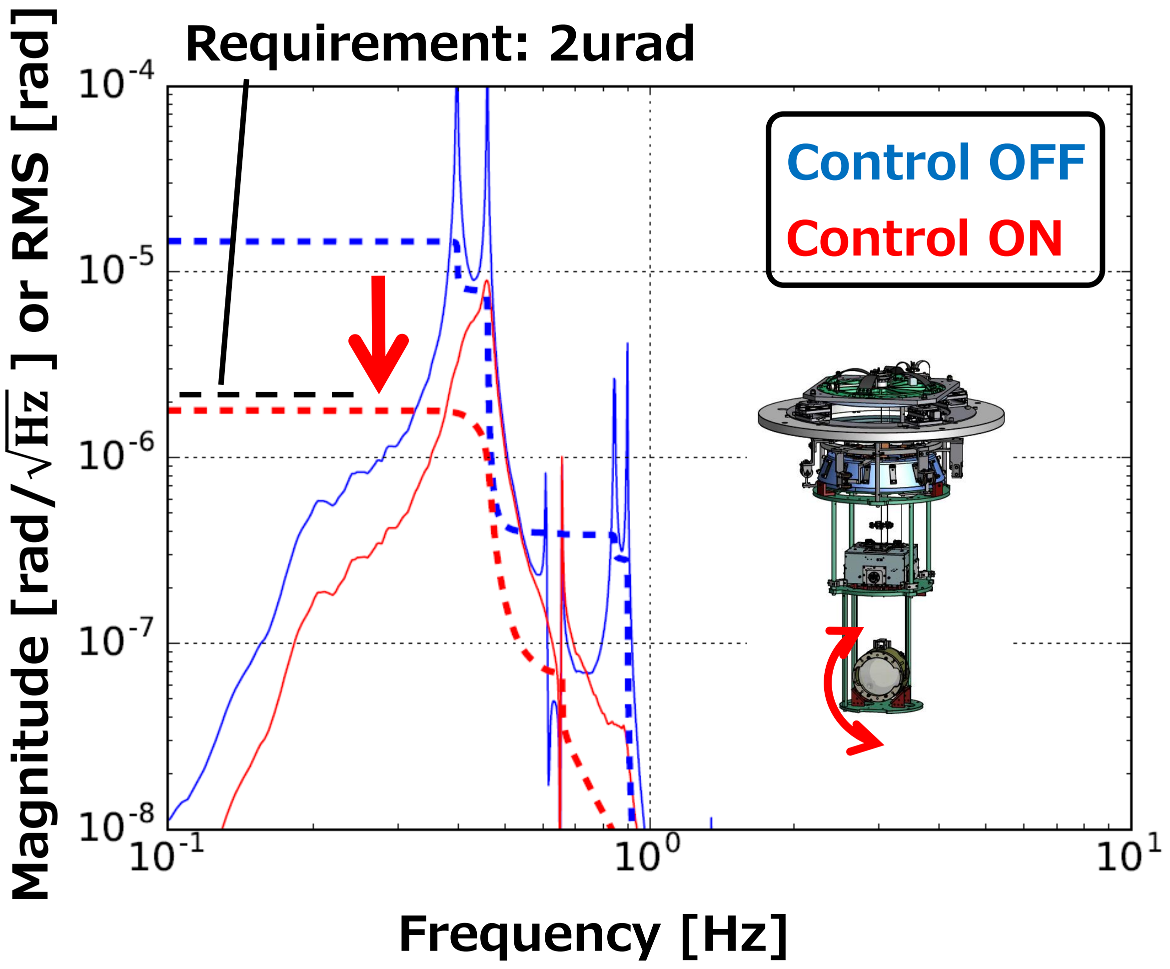


Clam-down phase:
Suppress large disturbance

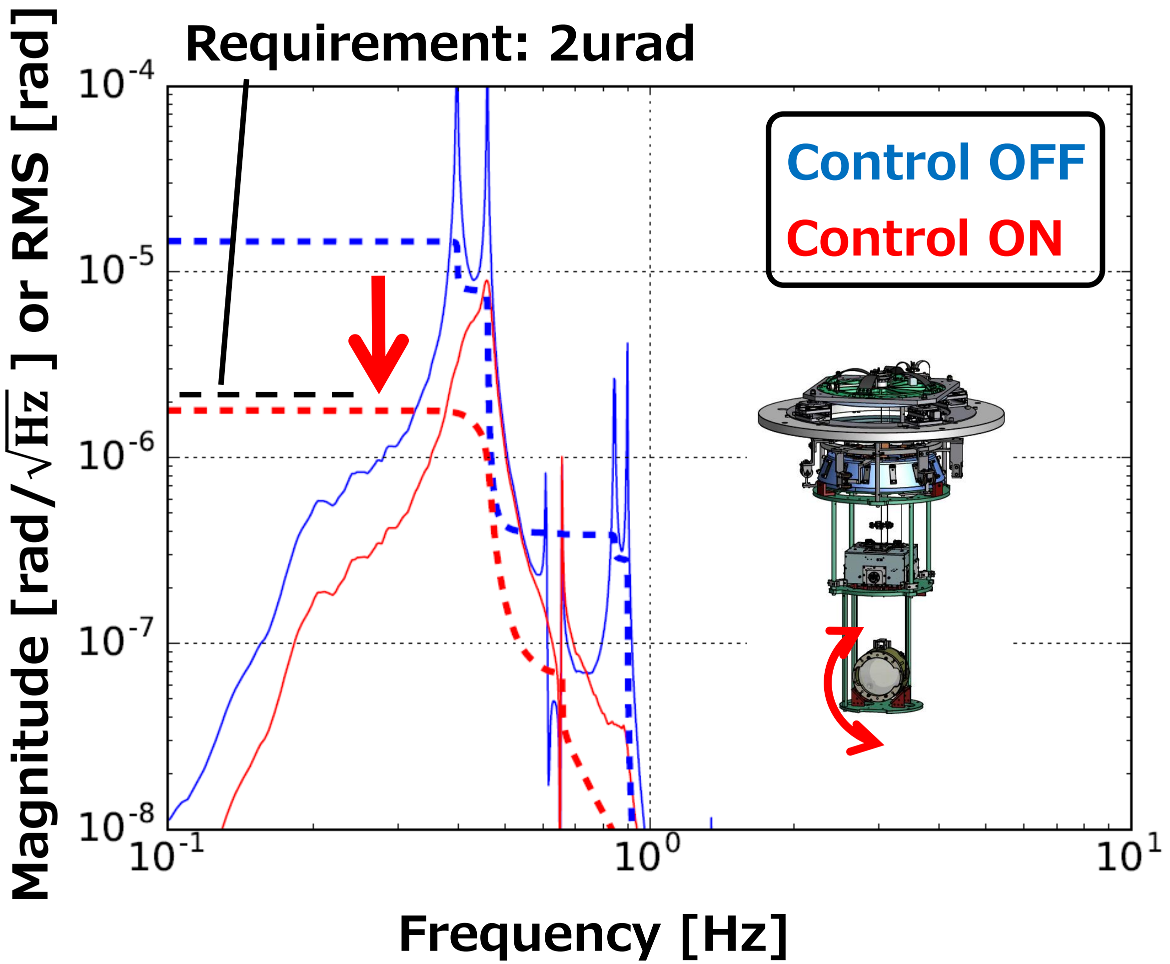


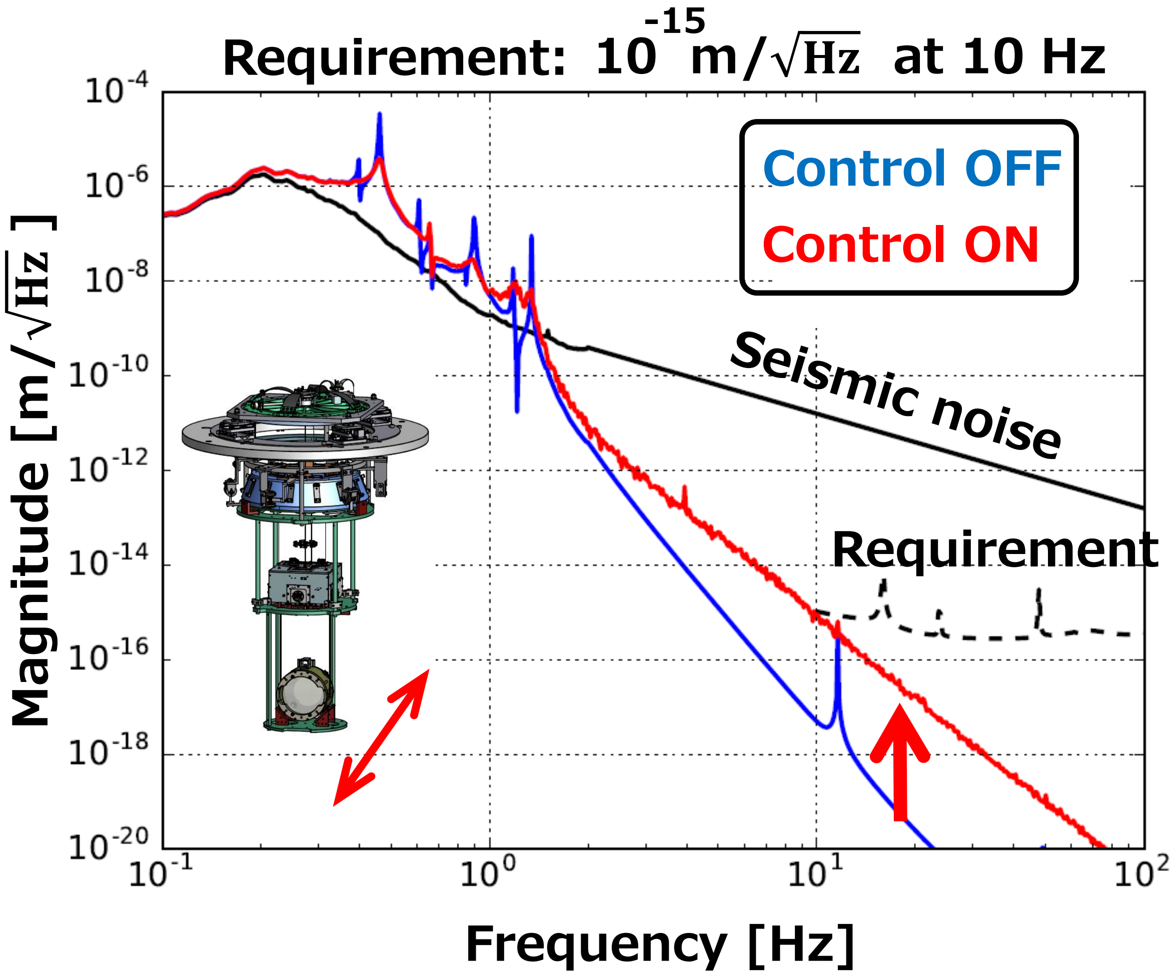


Observation phase:
Suppress RMS (Root Mean Square) & control noise



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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→ ***Clam-down phase: resonances → damped.***
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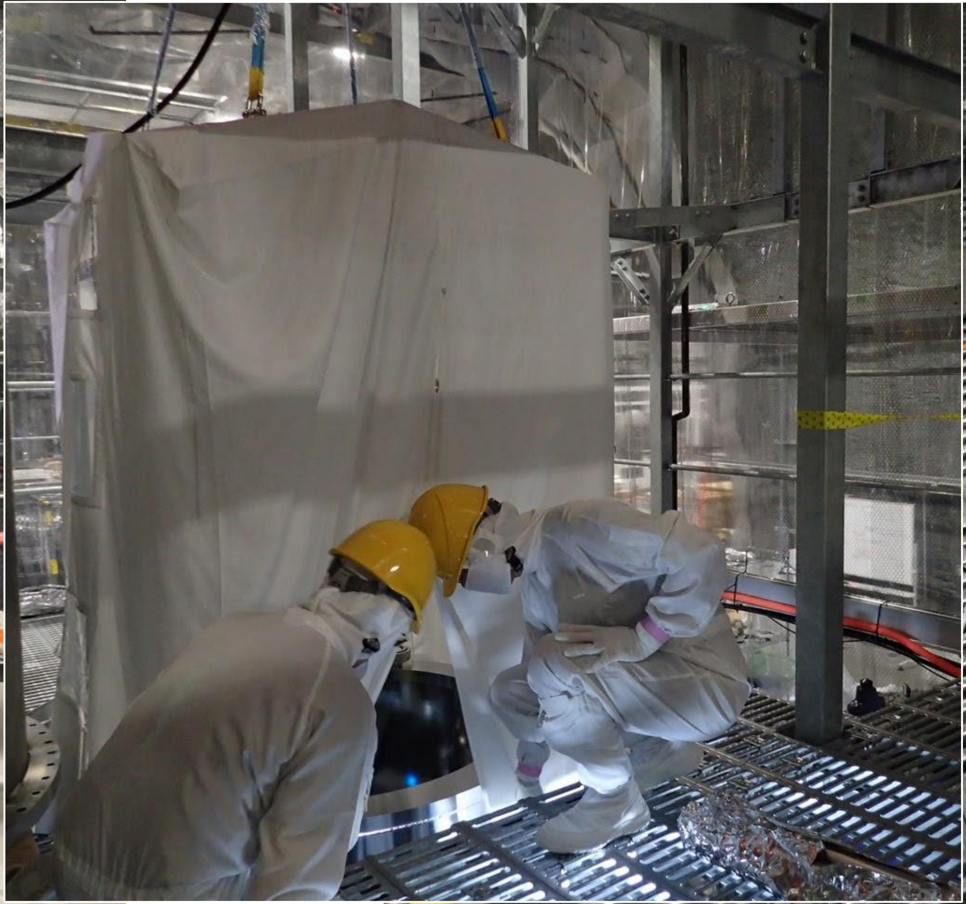
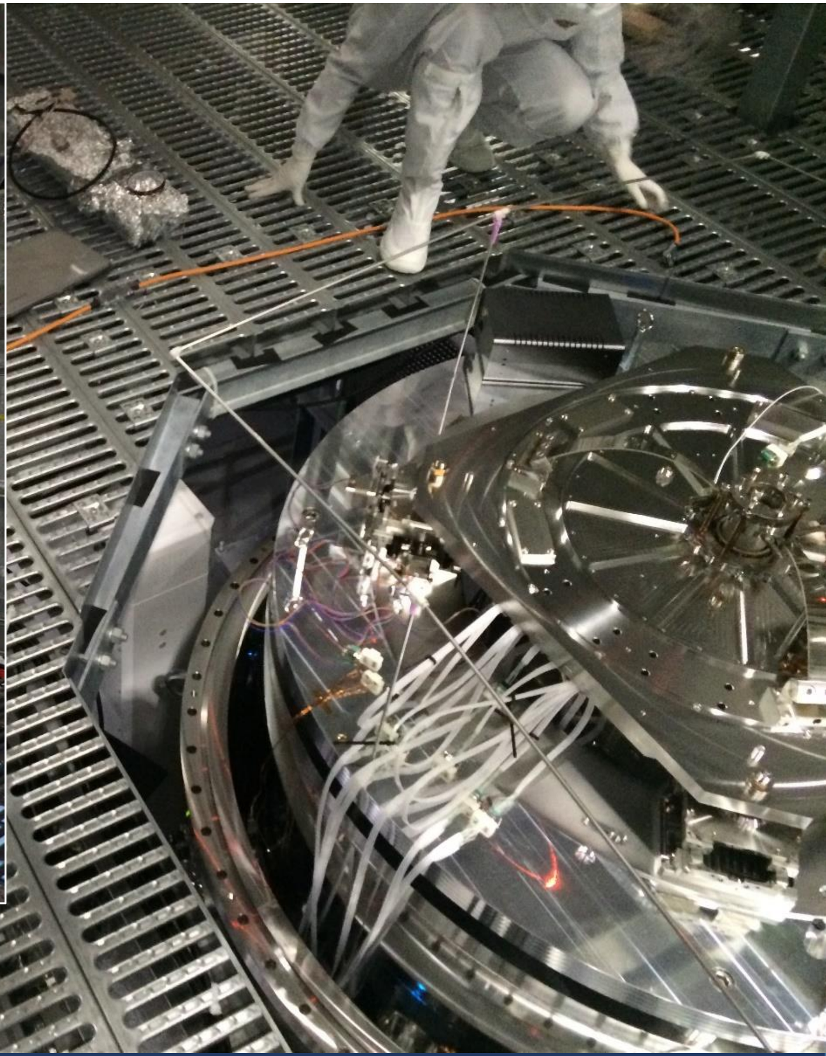
Back up

Modern NINJAs in the Kamioka mine.





Summary

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A localization with hierarchical network is demonstrated.
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1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
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→ ***Clam-down phase: resonances → damped.***
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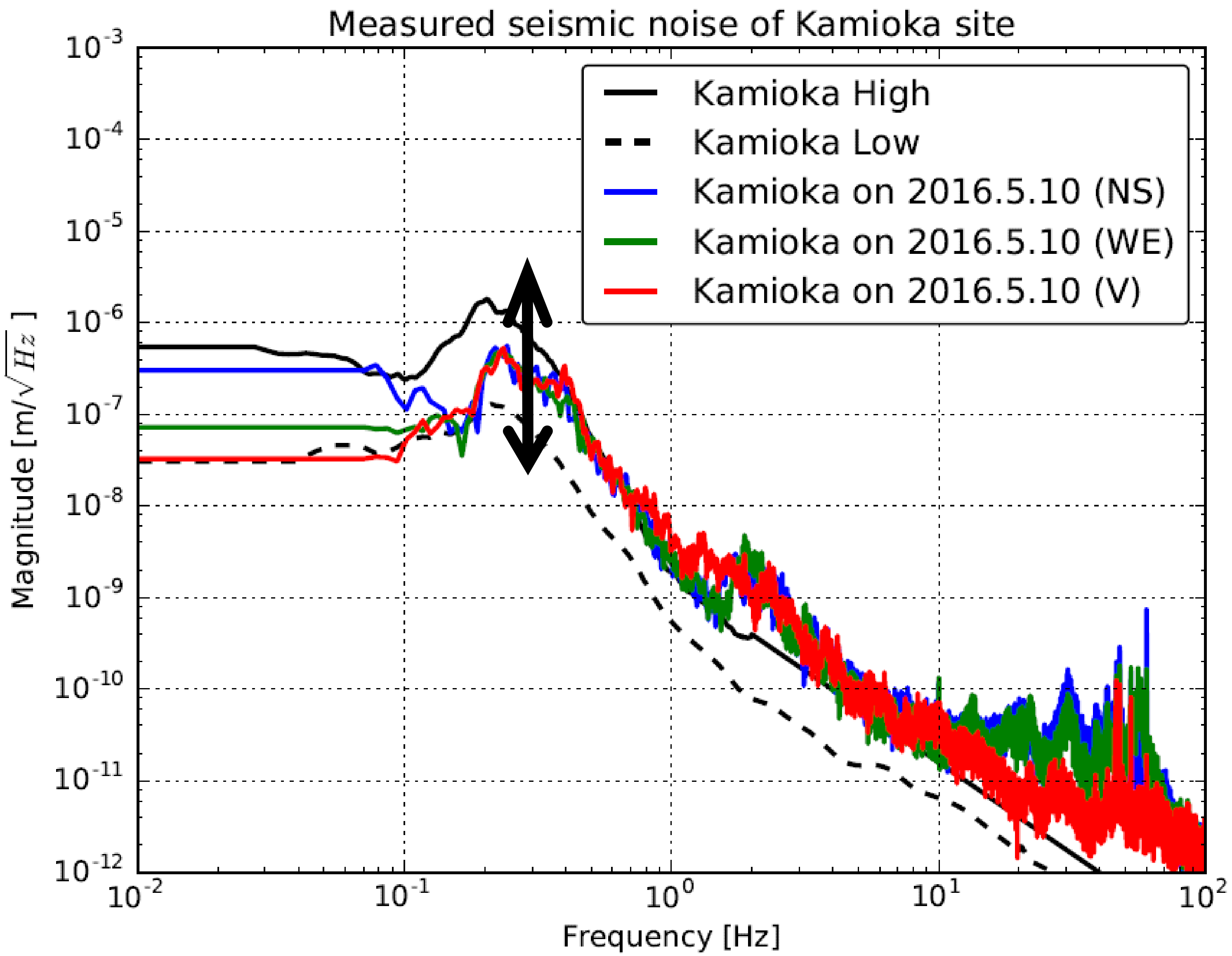
Seismic noise of Kamioka (on 2016.5.10)

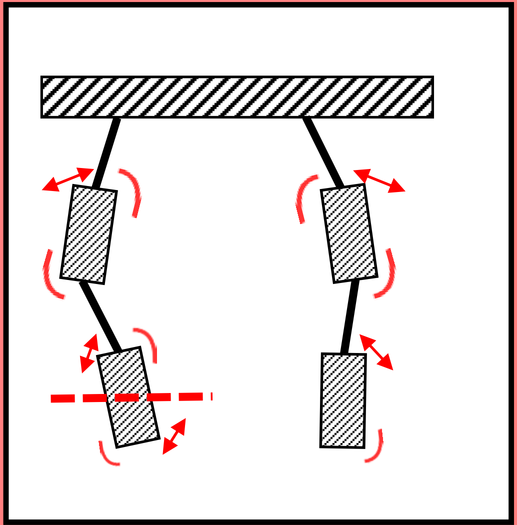


seismic noise was measured on 2016.5.10.

PR3 measurement was conducted on 2016.5.24.

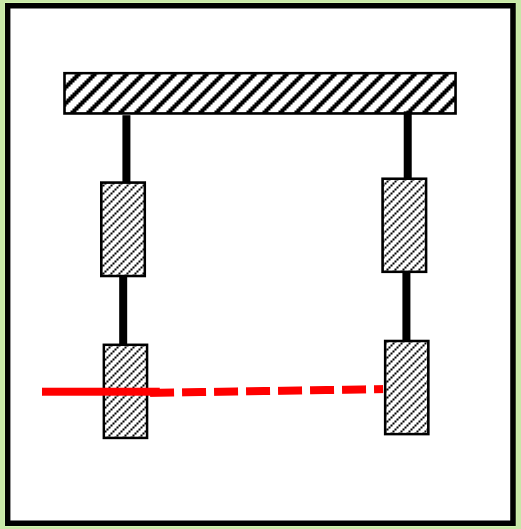
Designing active control system / Control phase

1. Calm-down phase



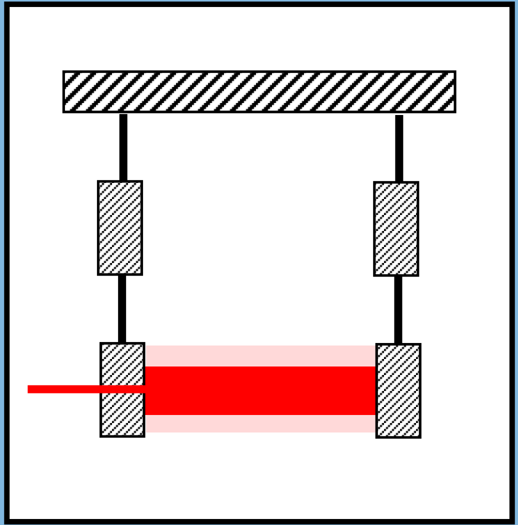
Suppress
large disturbance

2. Lock-acquisition phase



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

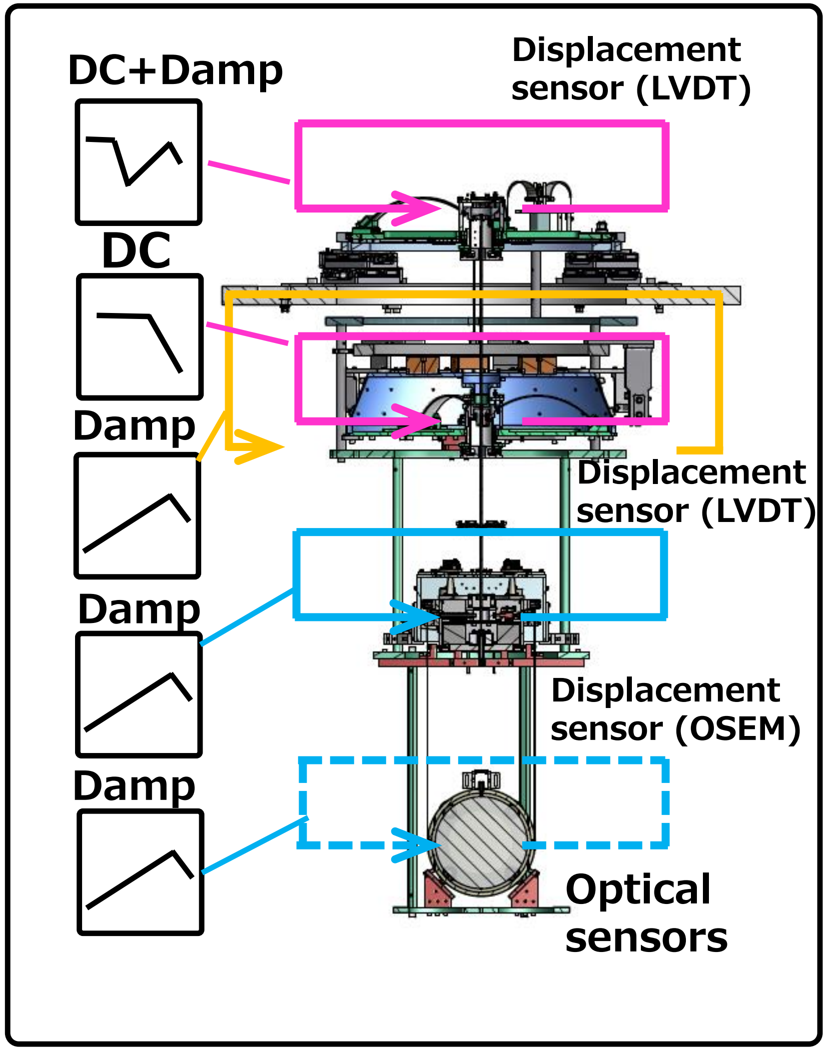
3. Observation phase



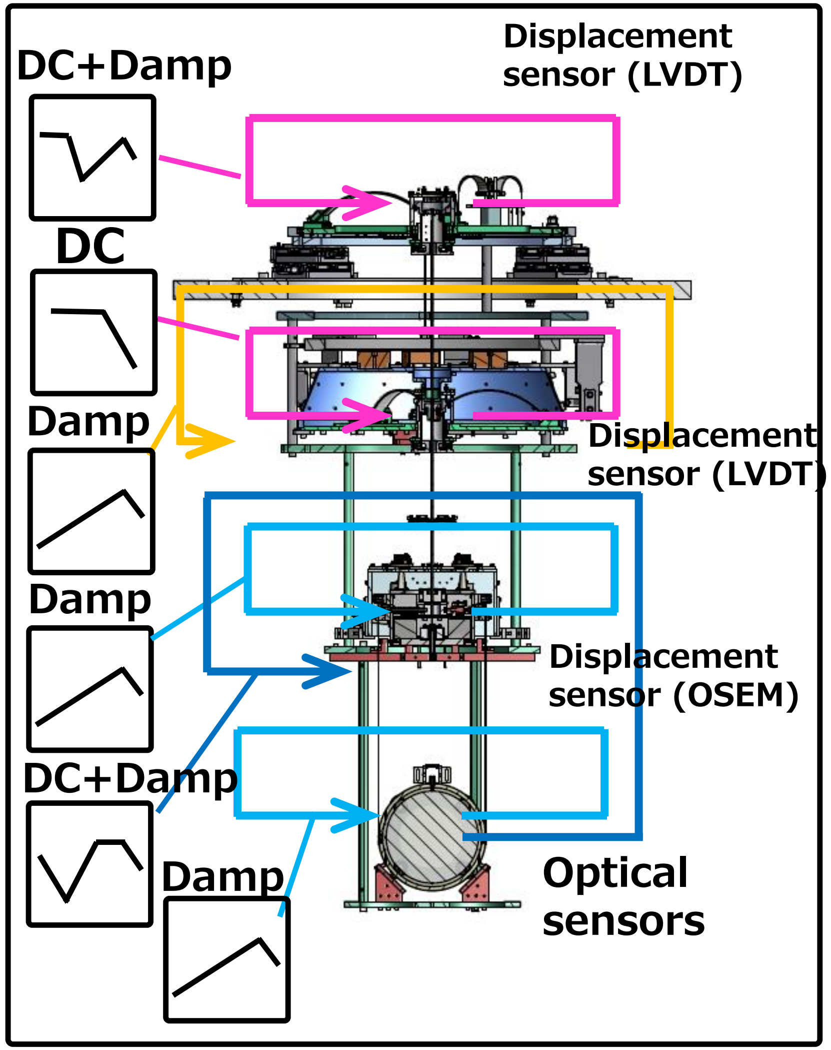
Keep position
with low noise
control

Designing active control system / Type-Bp SAS

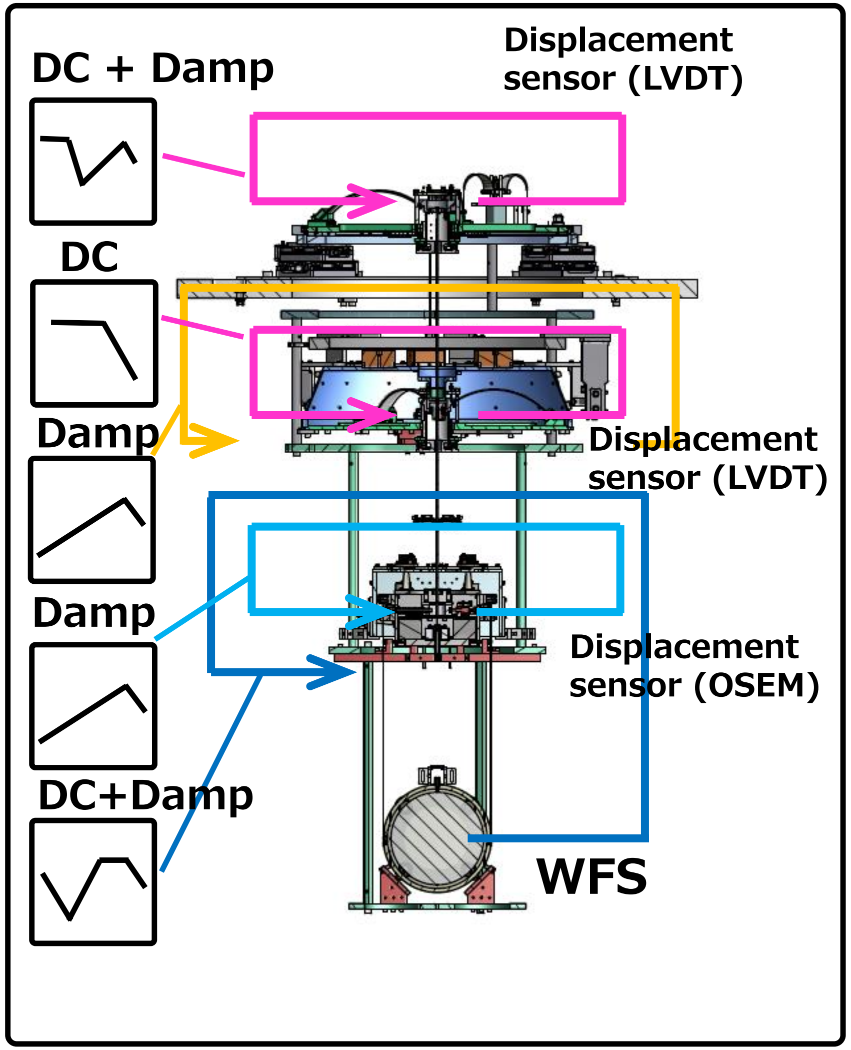
1. Calm-down phase



2. Lock-acquisition phase

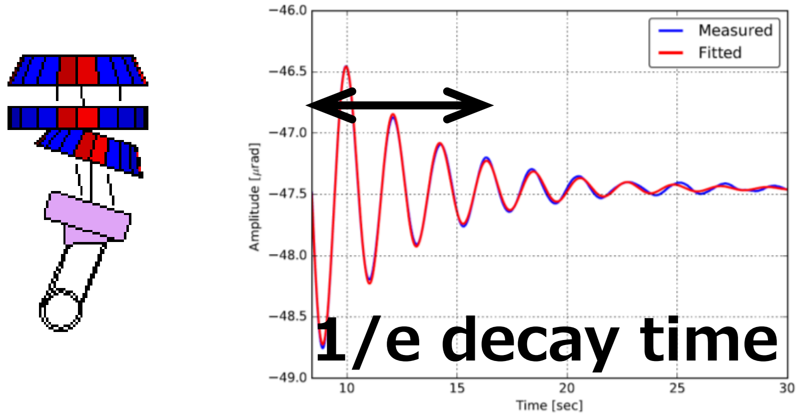


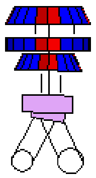
3. Observation phase



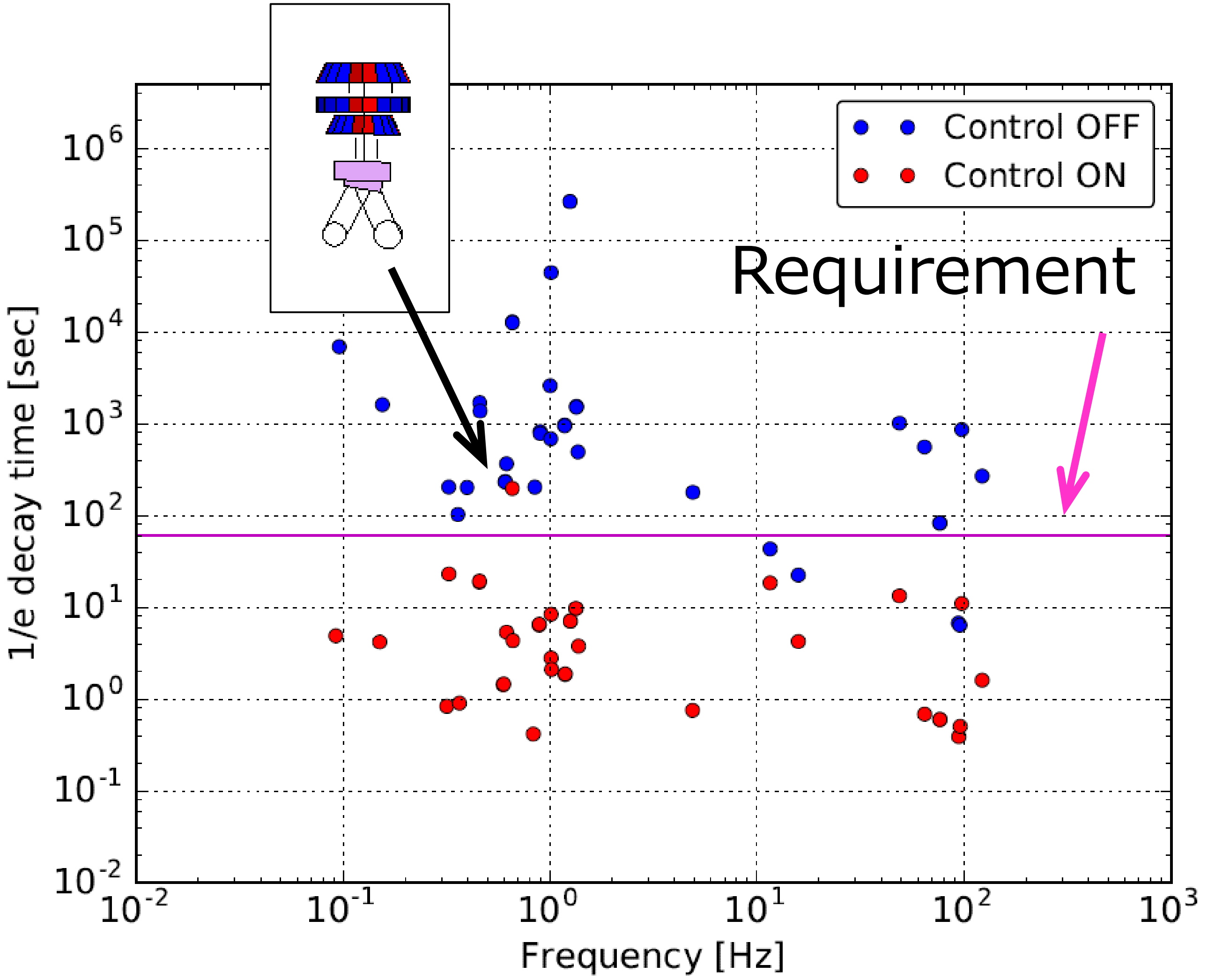
Designing active control system 1

Calm-down phase:
Suppress large disturbance



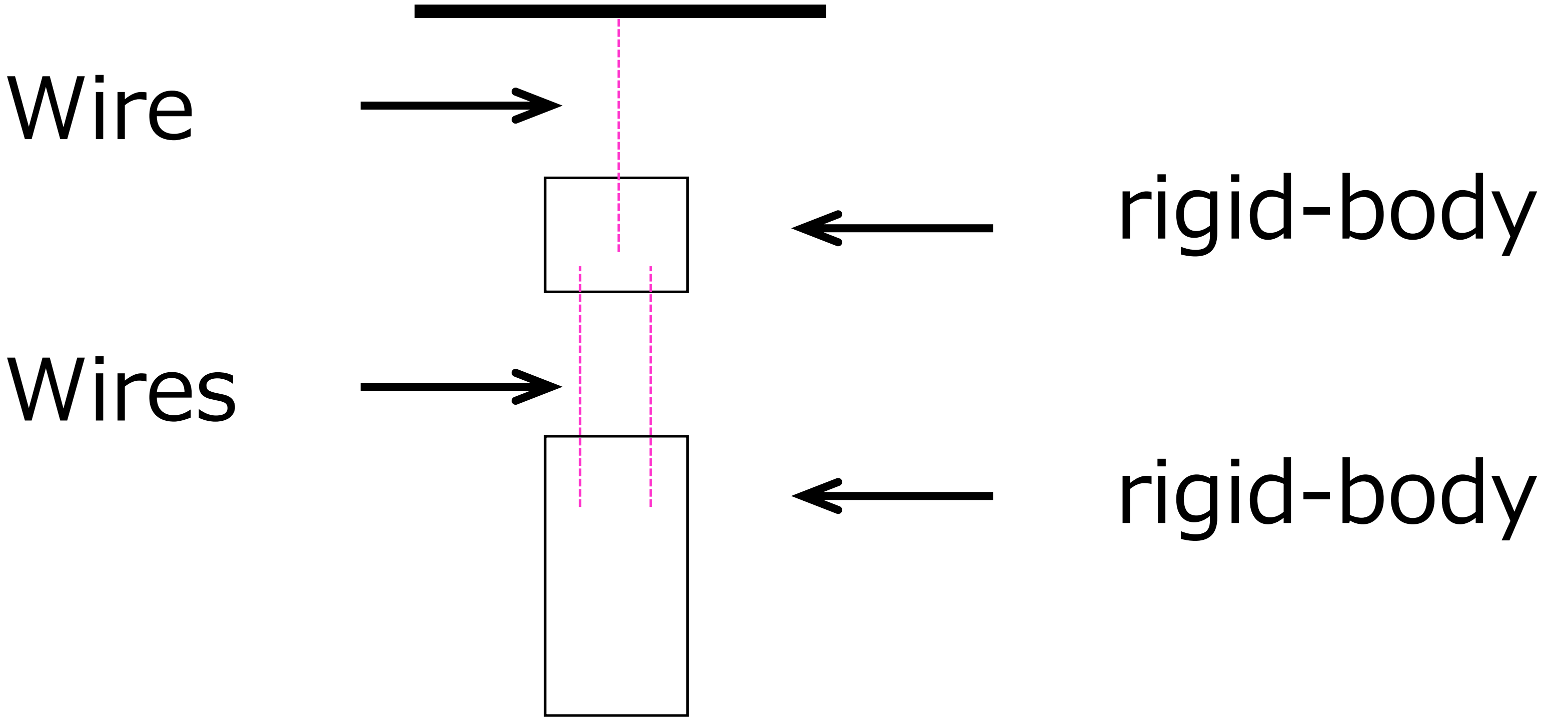


Not disturb operation
→ No problem.

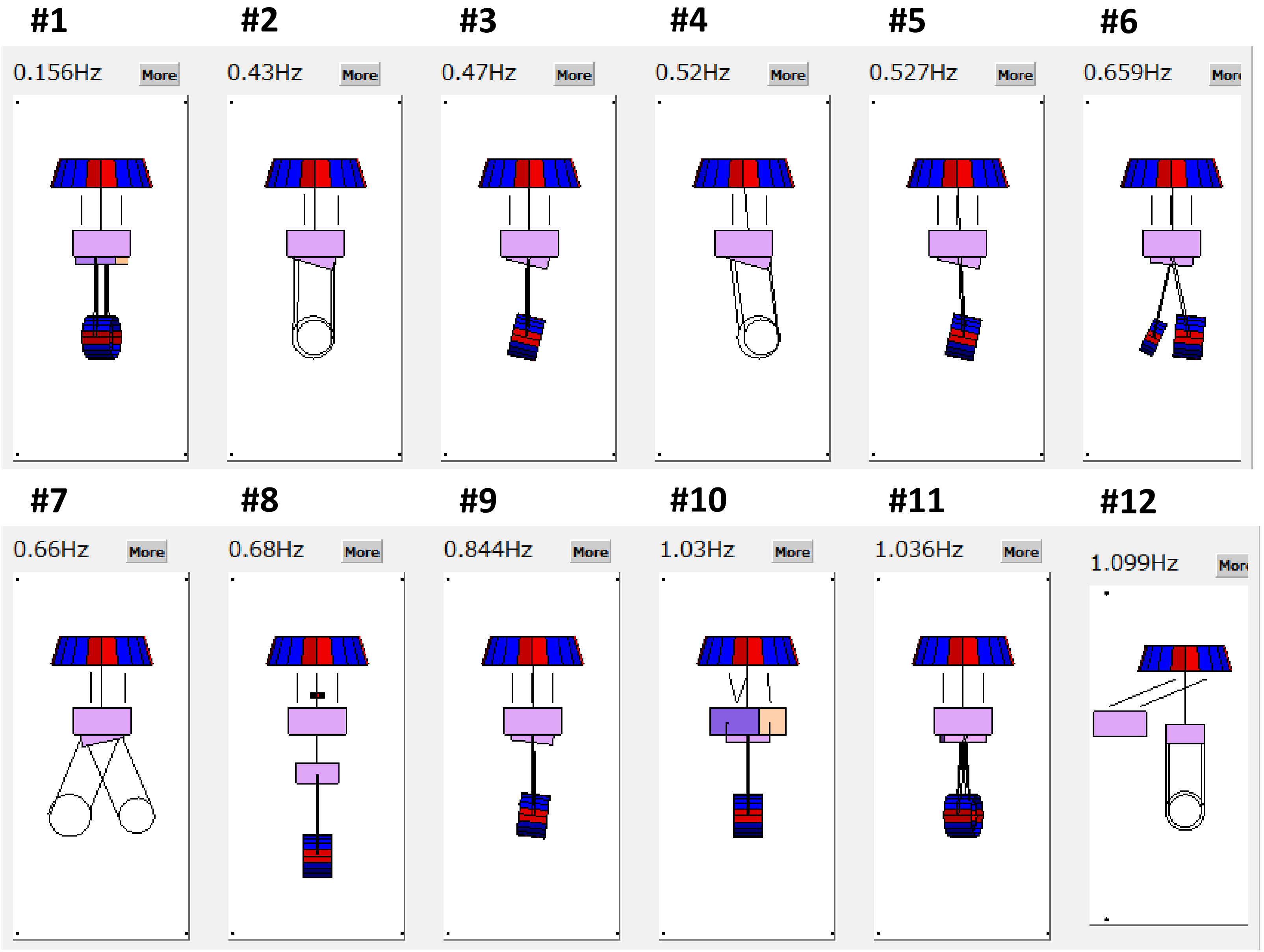


(if all sensors available)

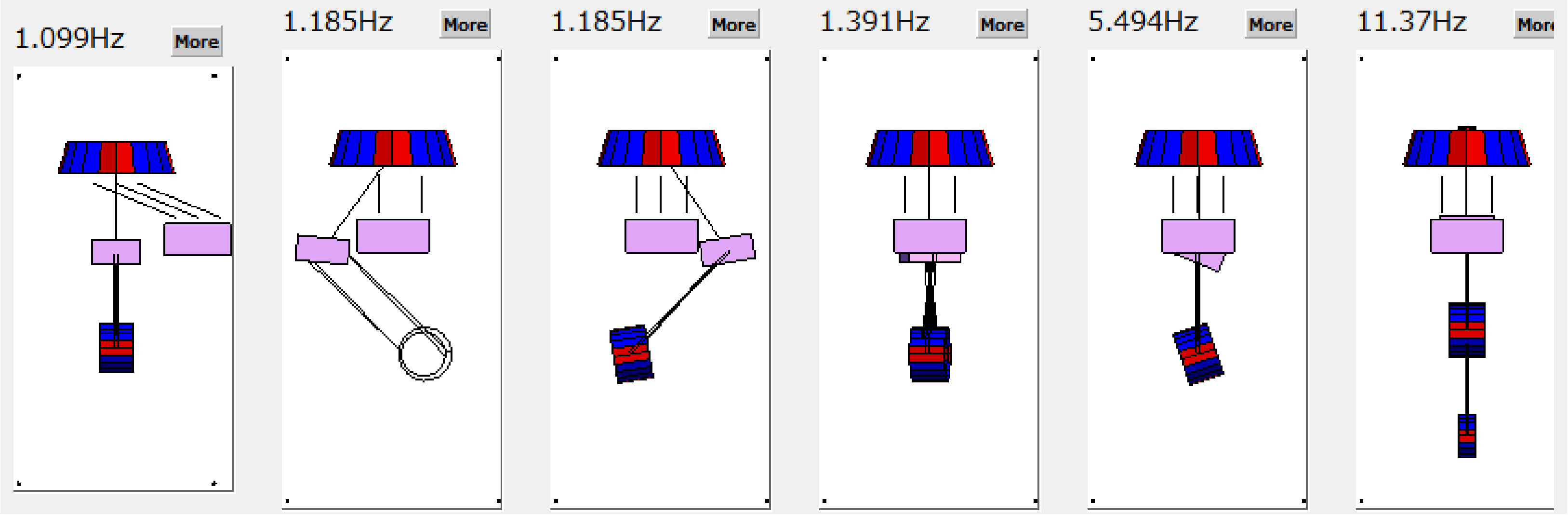
Simulation model: Based on rigid-body



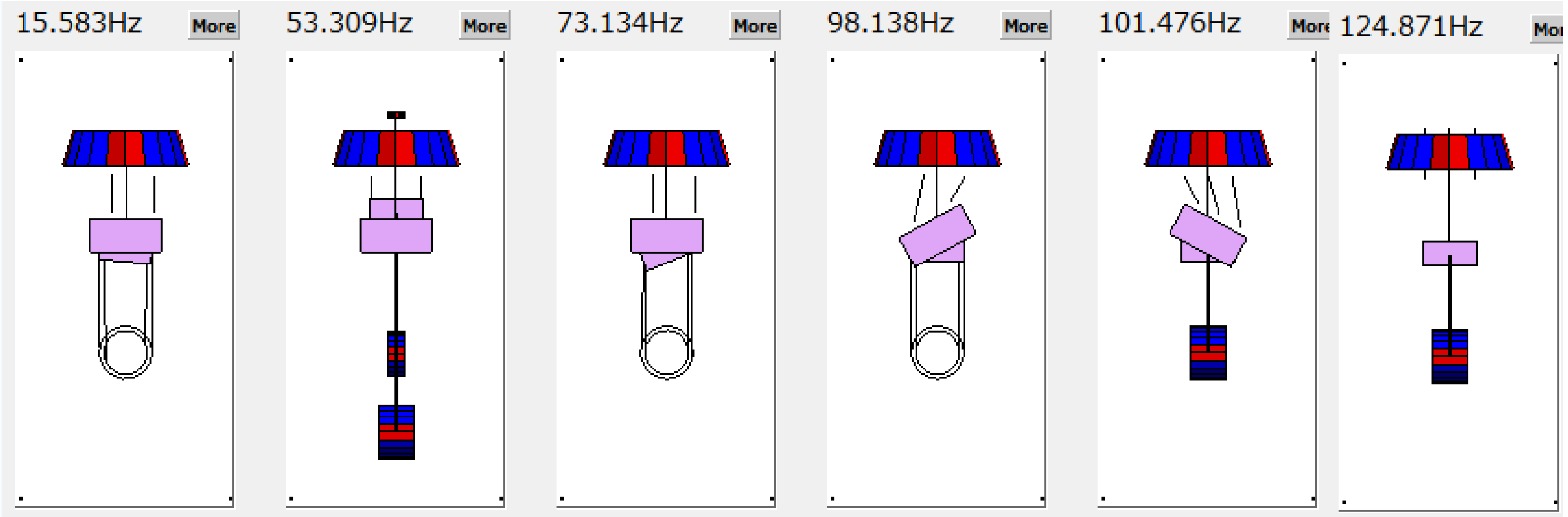
TypeBpp SAS
Eigen mode List : 24 modes

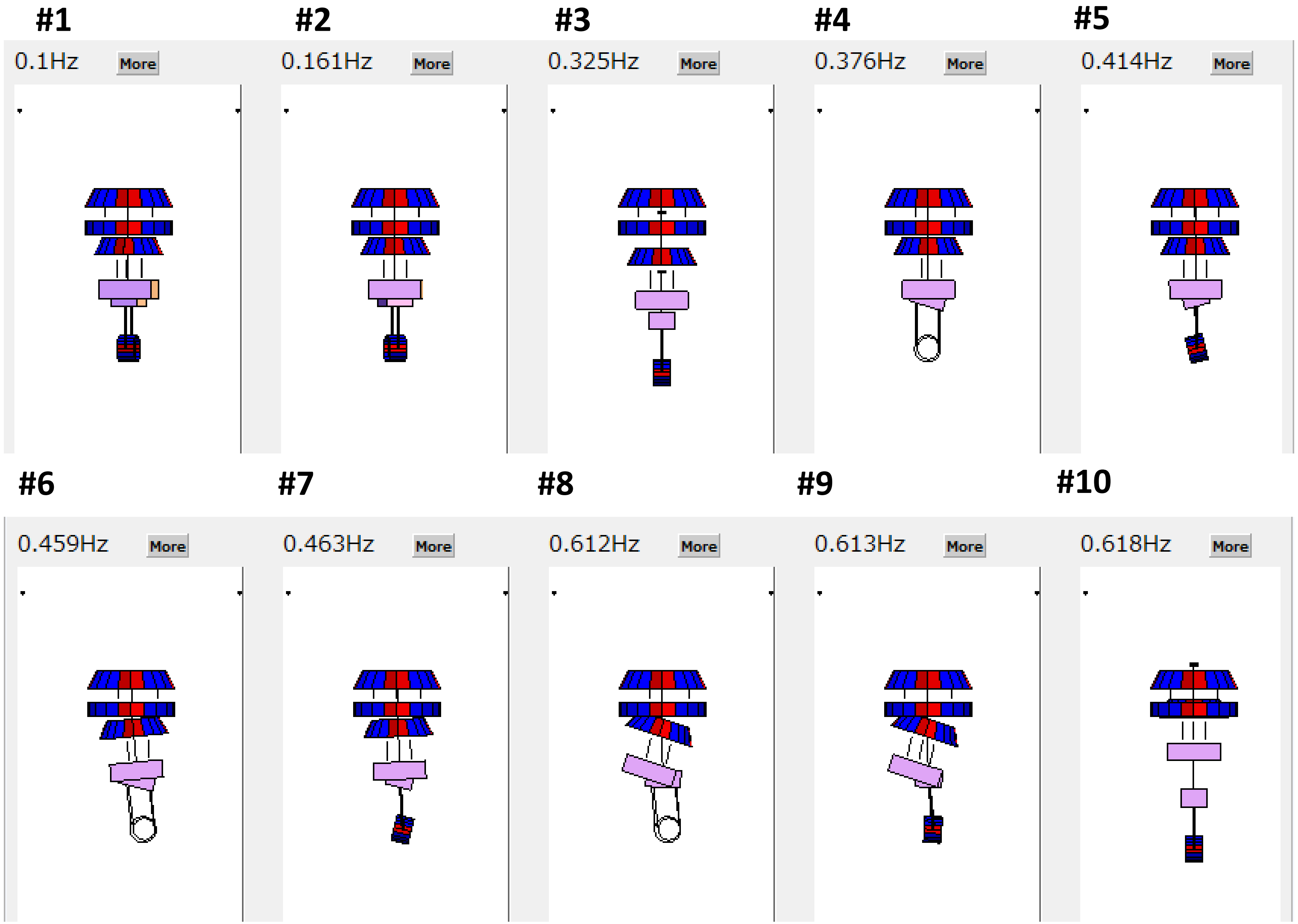


#13 #14 #15 #16 #17 #18

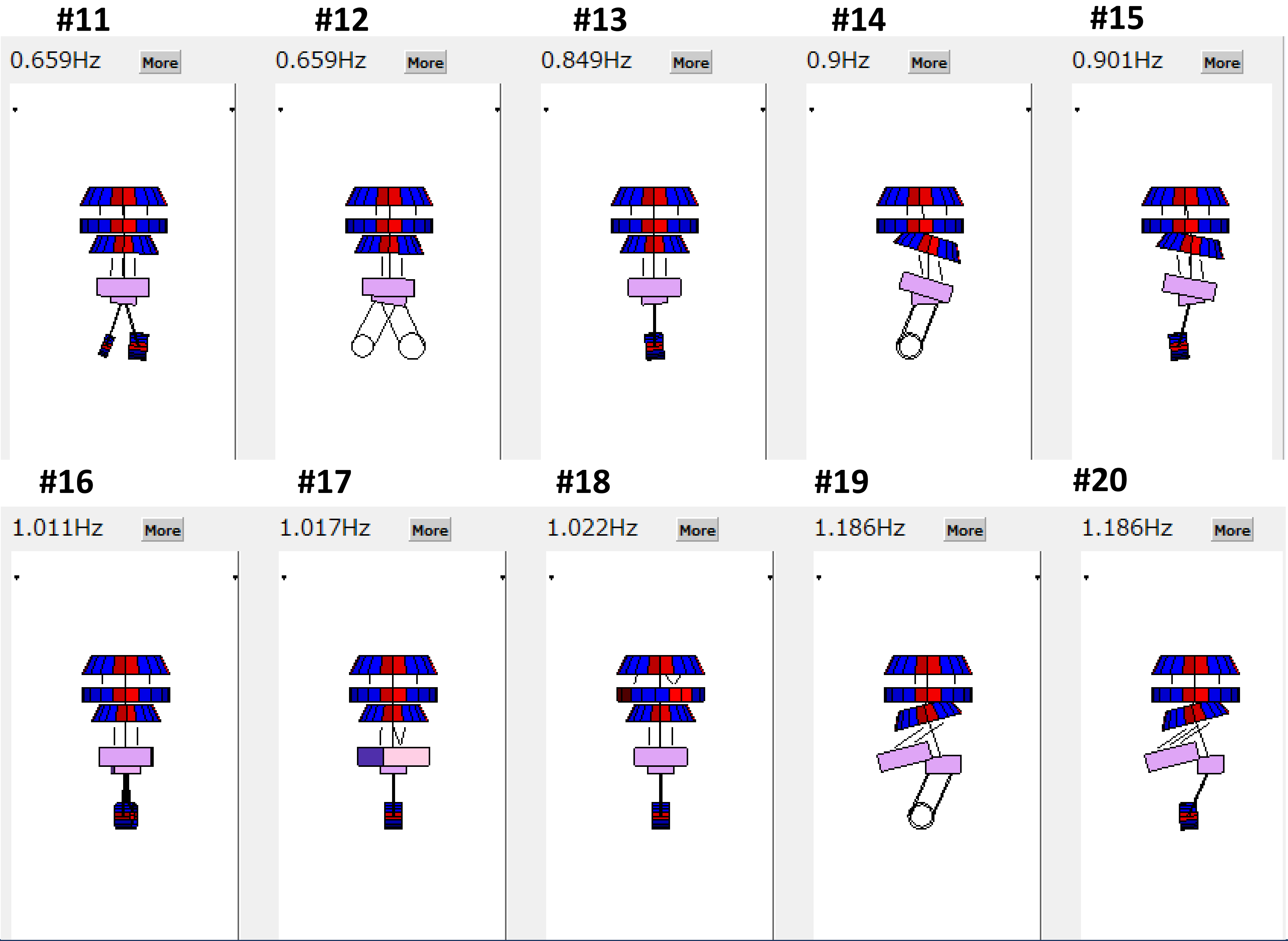


#19 #20 #21 #22 #23 #24

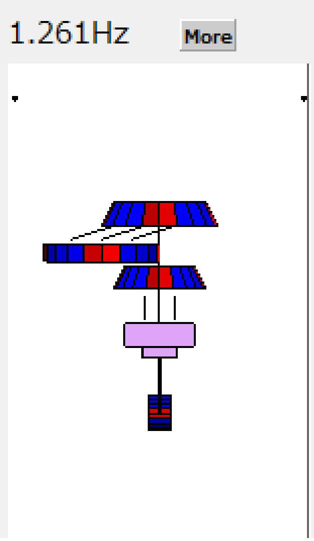




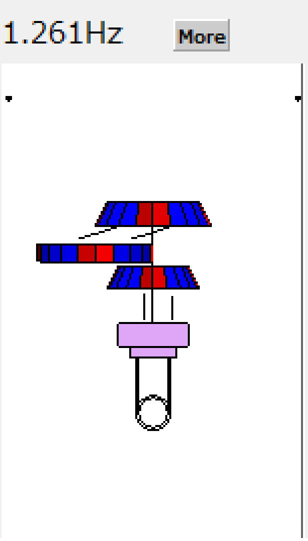
TypeBp SAS
Eigen mode List : 36 modes


#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



#22



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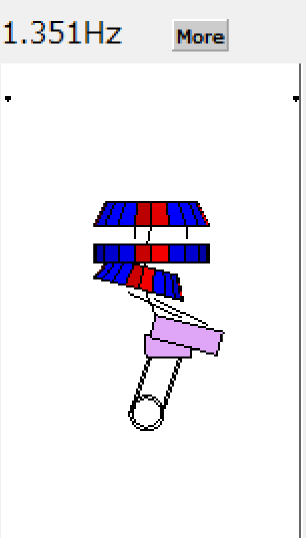
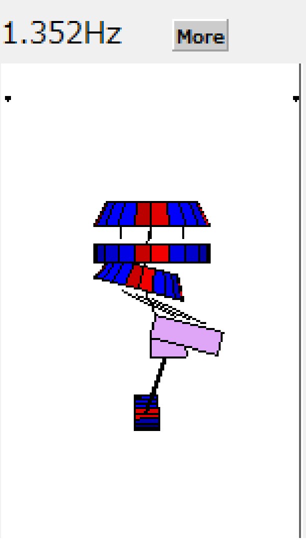
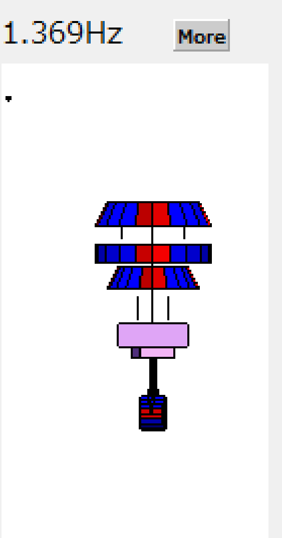


#24



#25



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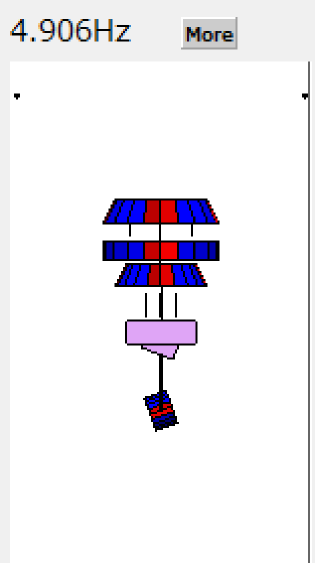

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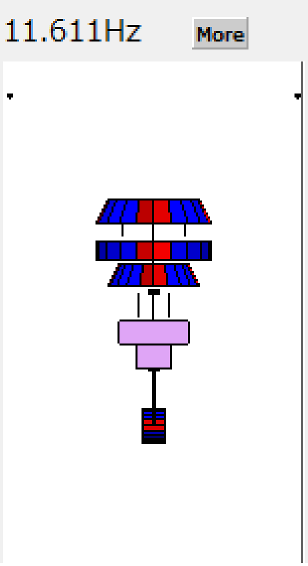
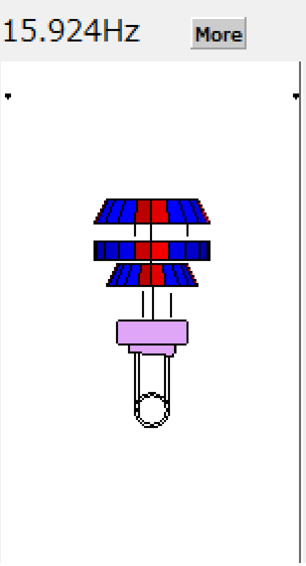
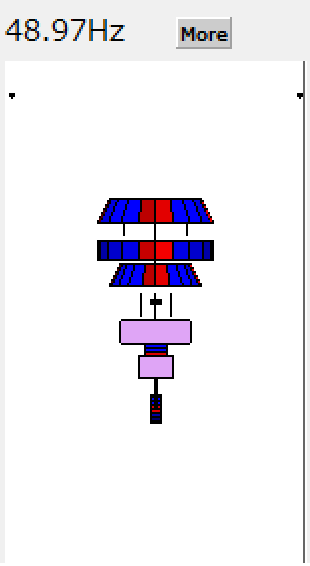


#28



#29



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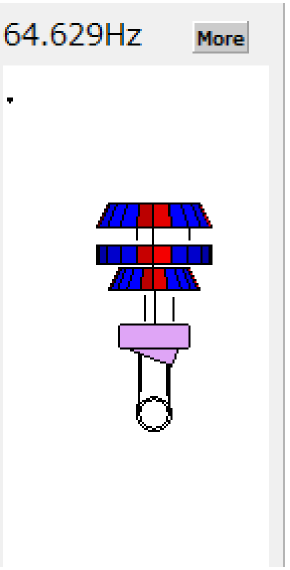
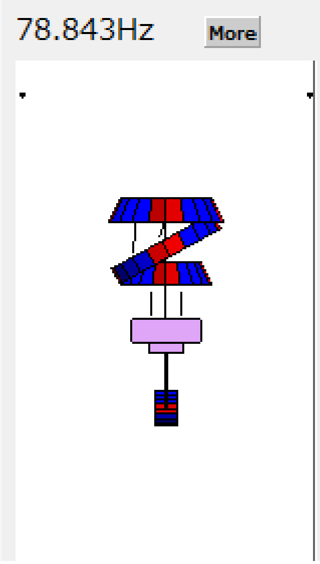


#31



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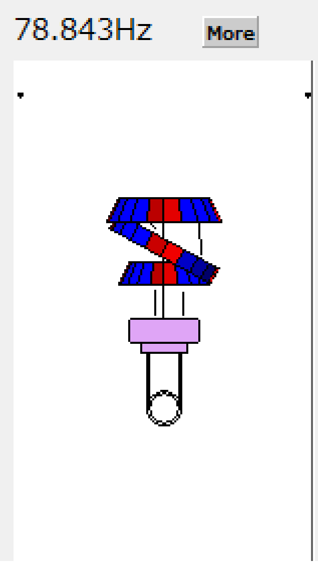
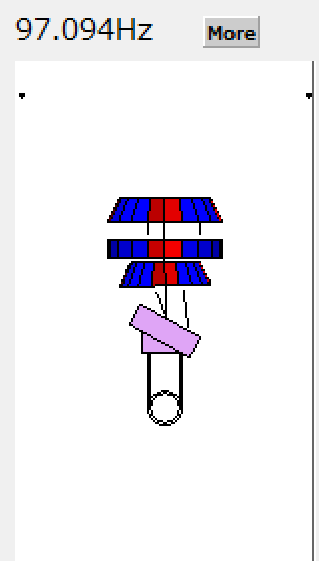
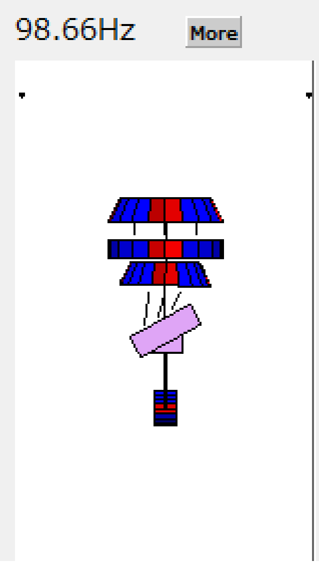


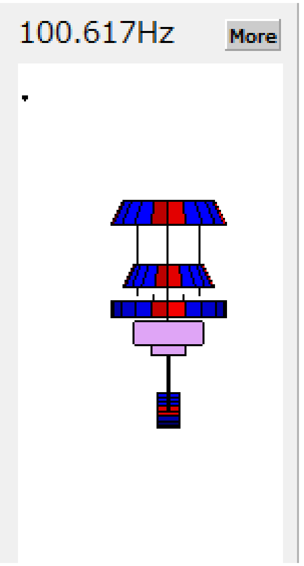
#33



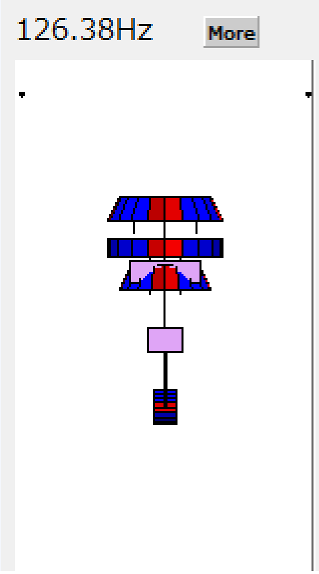
#34

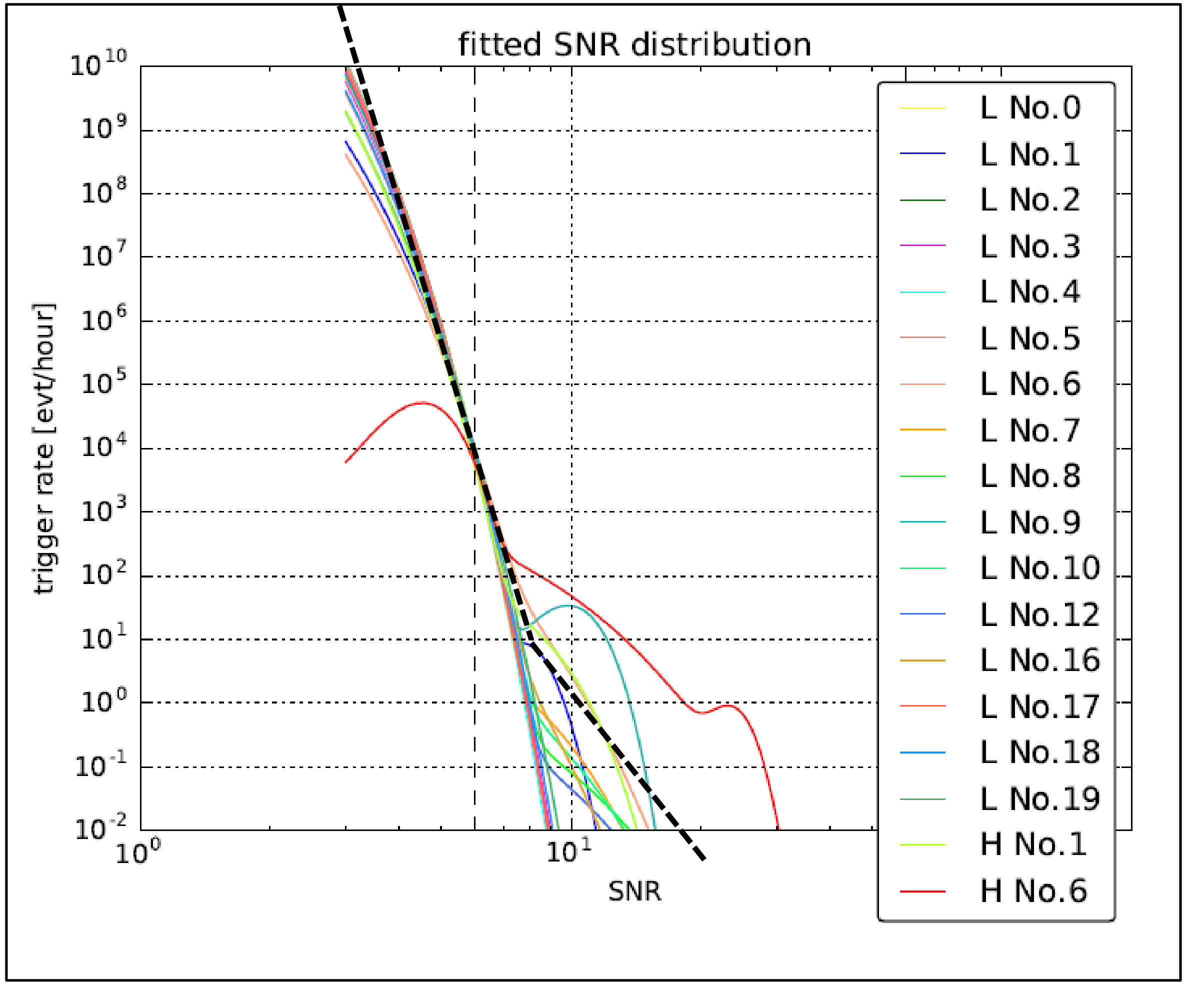


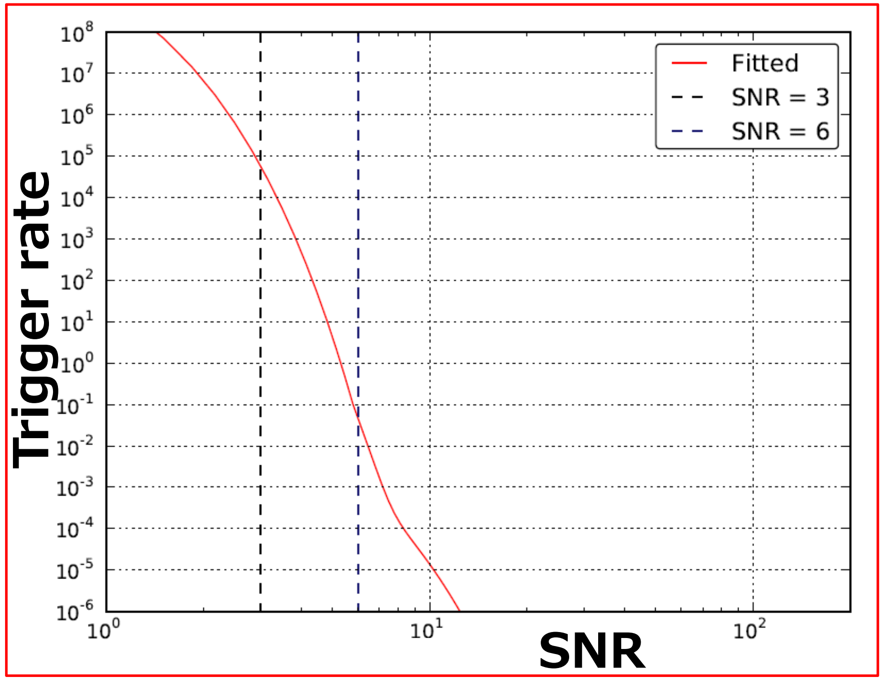
#35



#36

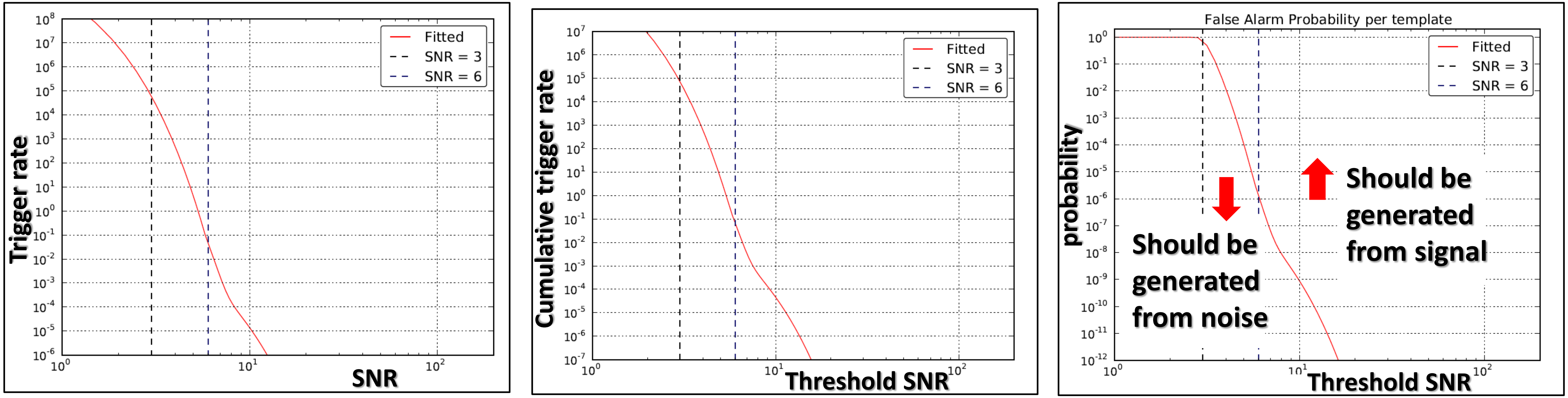



fitted SNR distribution
trigger rate [evt/hour]
SNR
L No.0
L No.1
L No.2
L No.3
L No.4
L No.5
L No.6
L No.7
L No.8
L No.9
L No.10
L No.12
L No.16
L No.17
L No.18
L No.19
H No.1
H No.6


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)

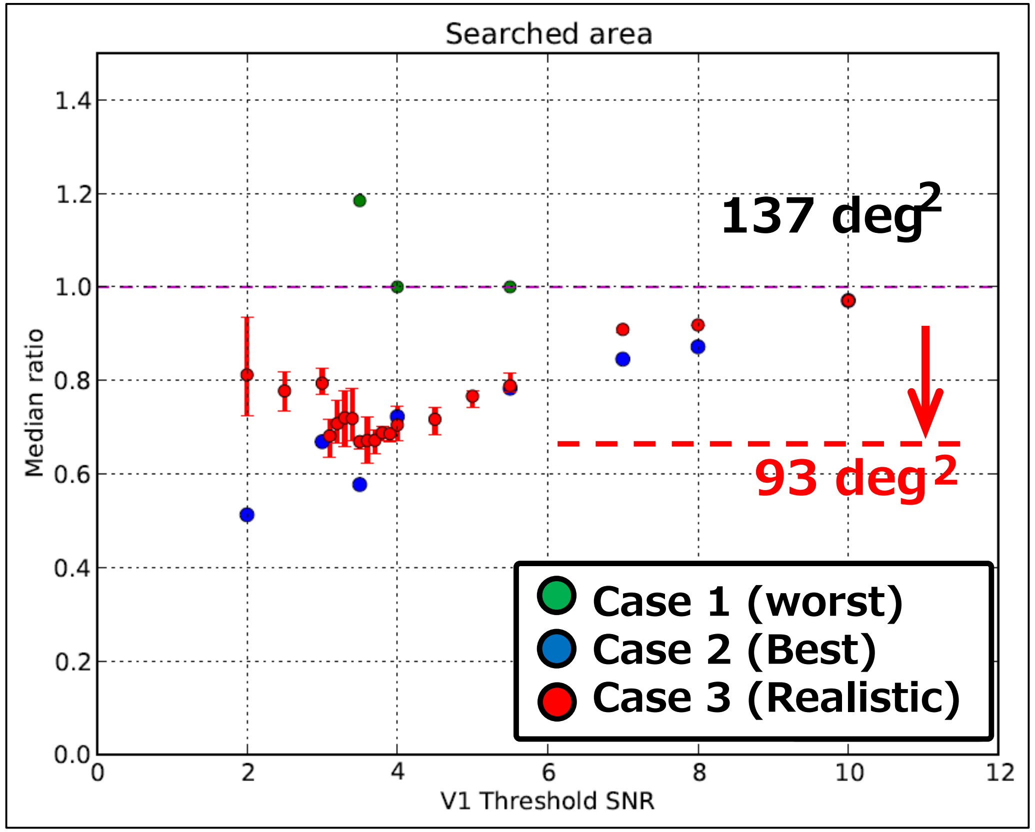


FAP = $1 - \exp(-R \times T)$

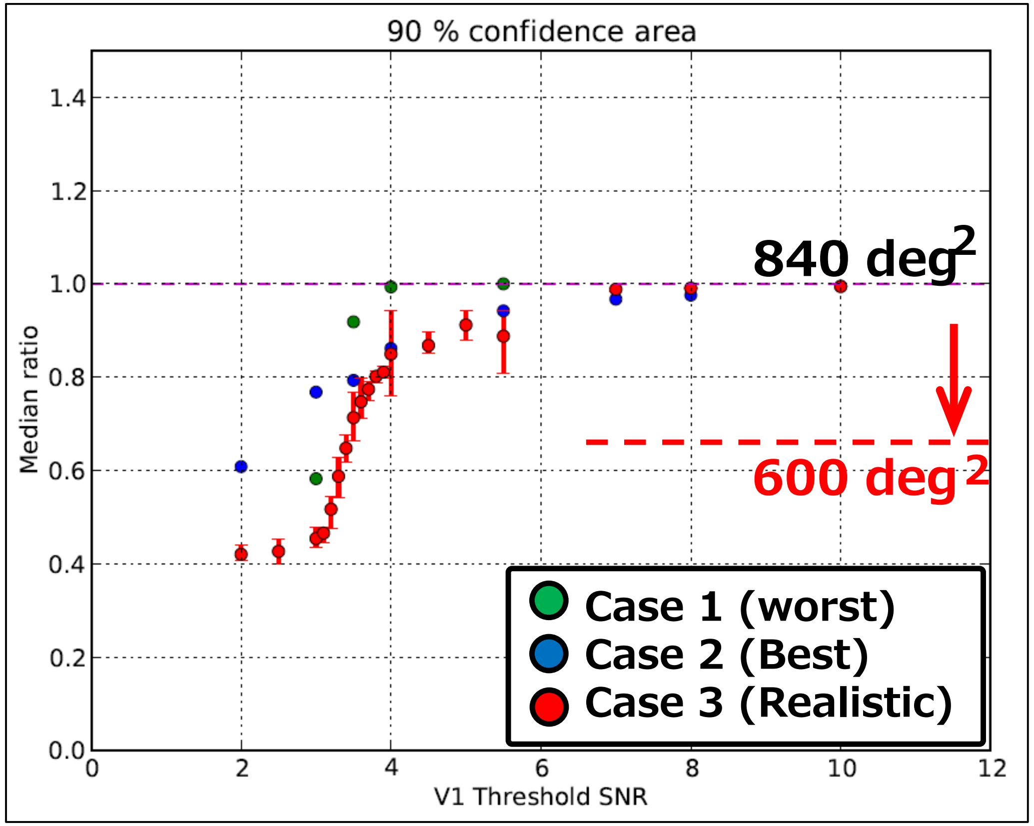
R = cumulative rate of background triggers per template, above a given threshold, per template,

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

Optimization of Virgo threshold :

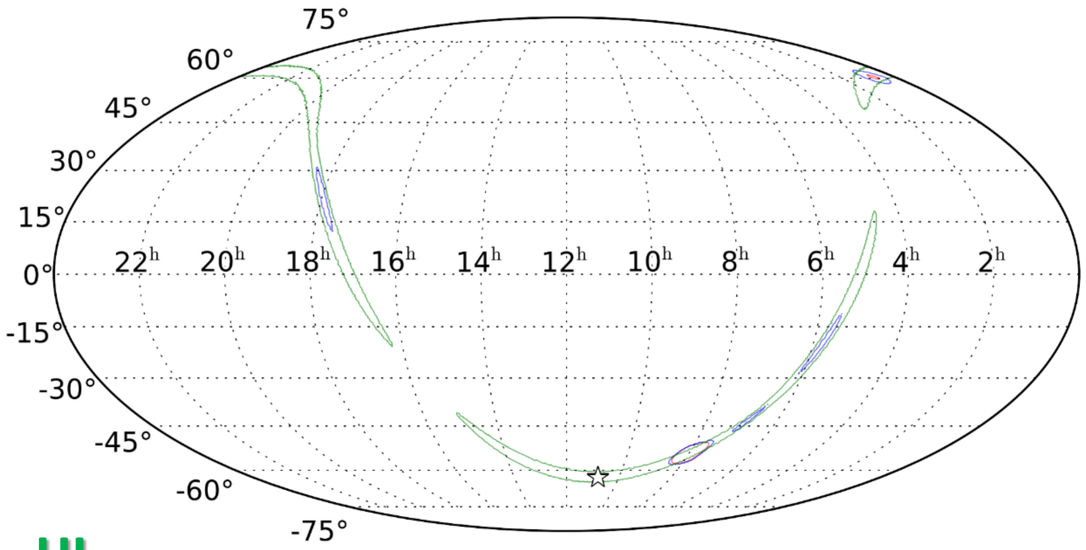


SNR threshold for H, L = 5.

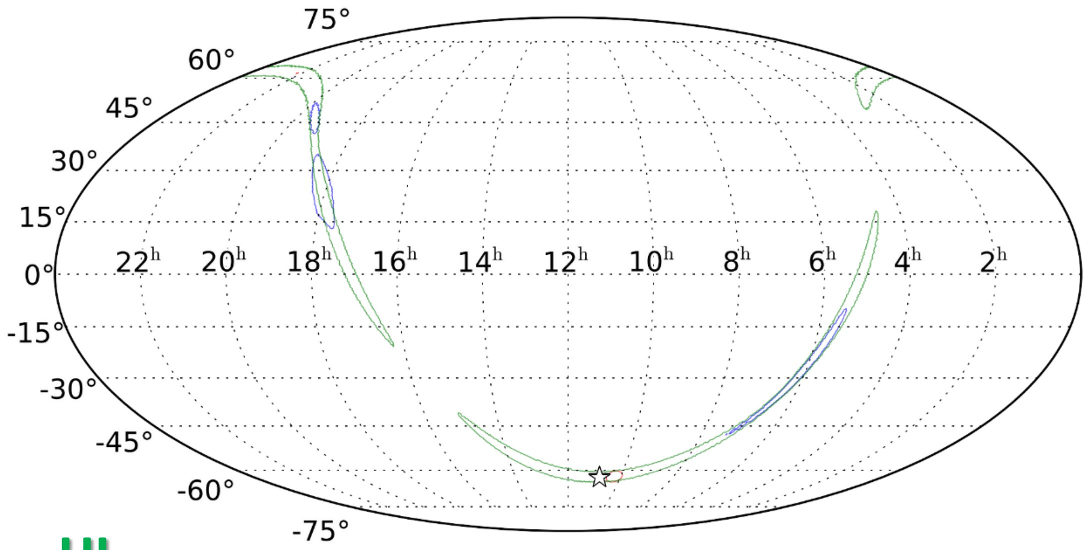


SNR threshold for H, L = 5.

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



HL
HL + Vrandom
HL + Vrandom + Krandom



HL
HL + Vinj
HL + Vinj + Kinj

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 [0:2π]

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)

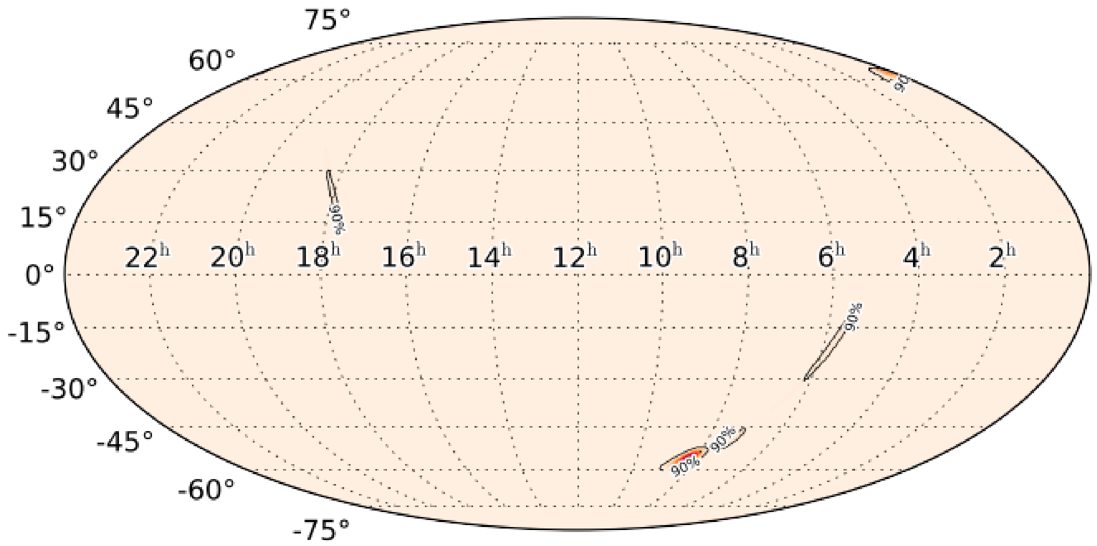
Case 1: worst case
HL+Vr, or HL
(Based on ***FAP***)

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)

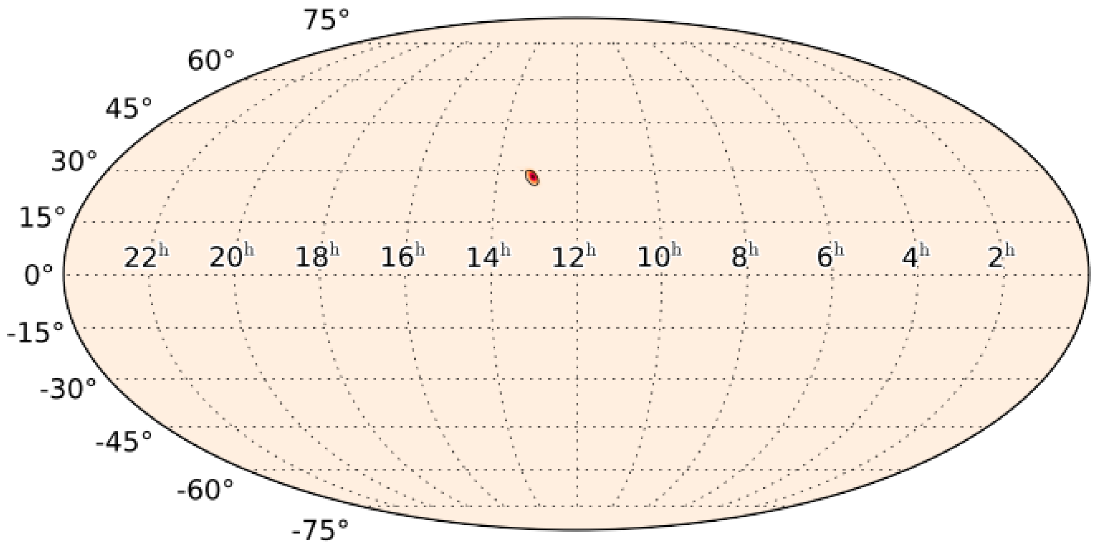
Expected localization performance / by HLV

HL+Vrandom



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

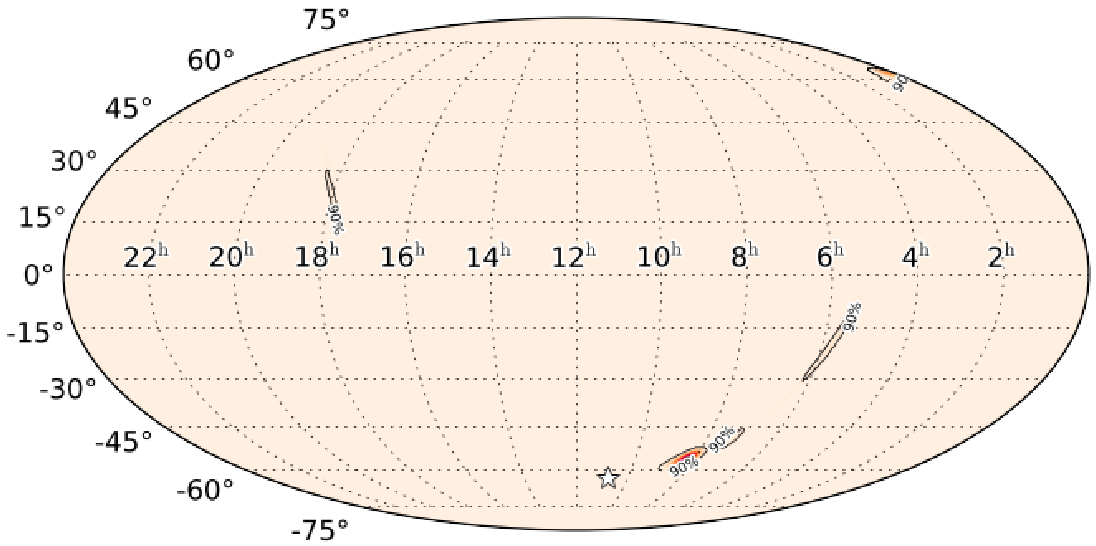
HL+Vinjection



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

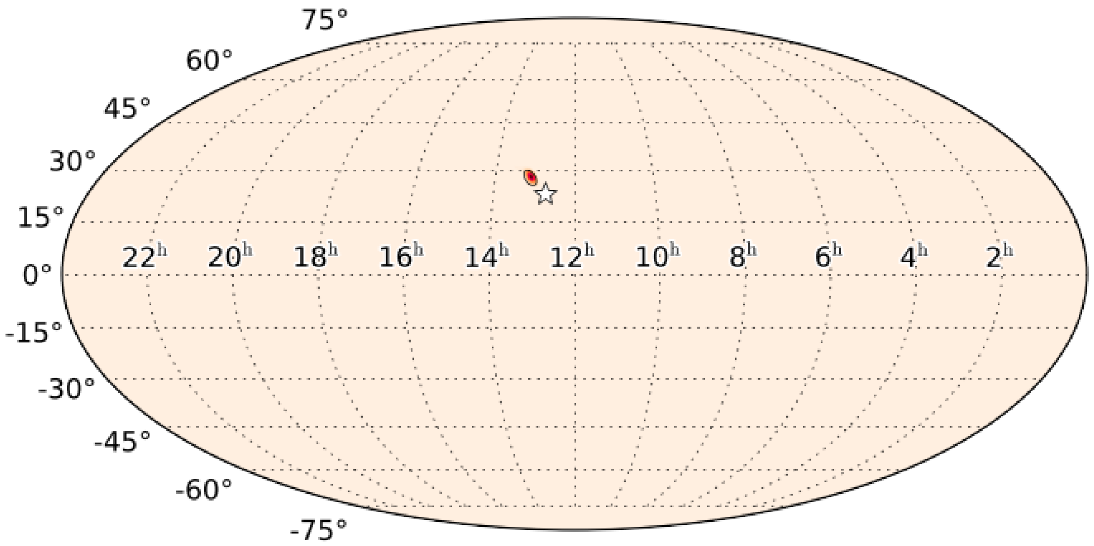
Expected localization performance / by HLV

HL+Vrandom



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

HL+Vinjection

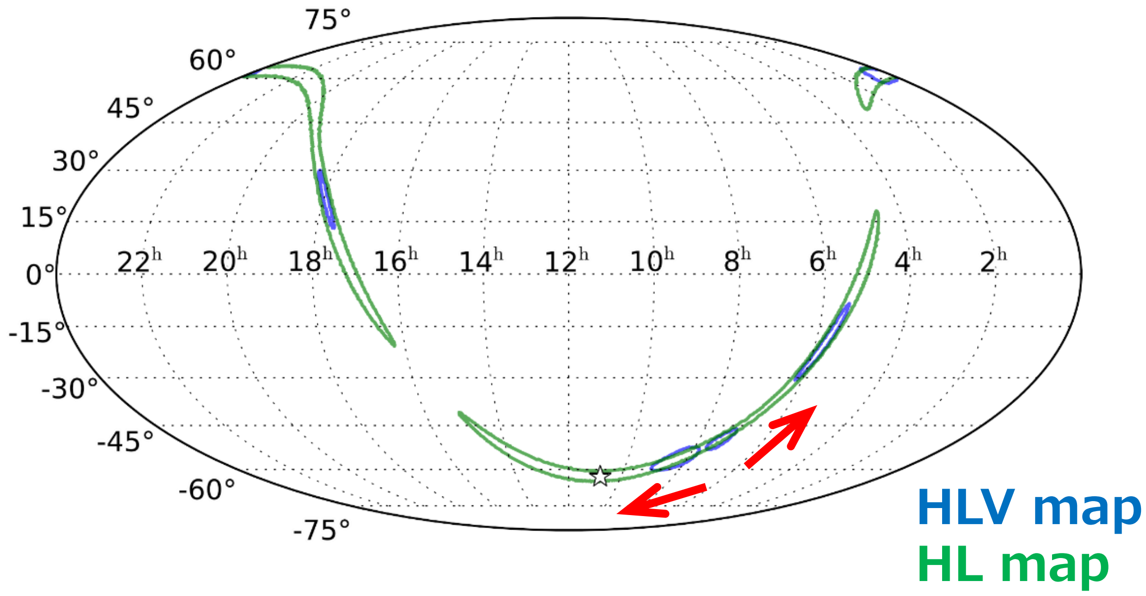


SNR (H)	SNR (L)	SNR(V)
16.5	17.1	3.9

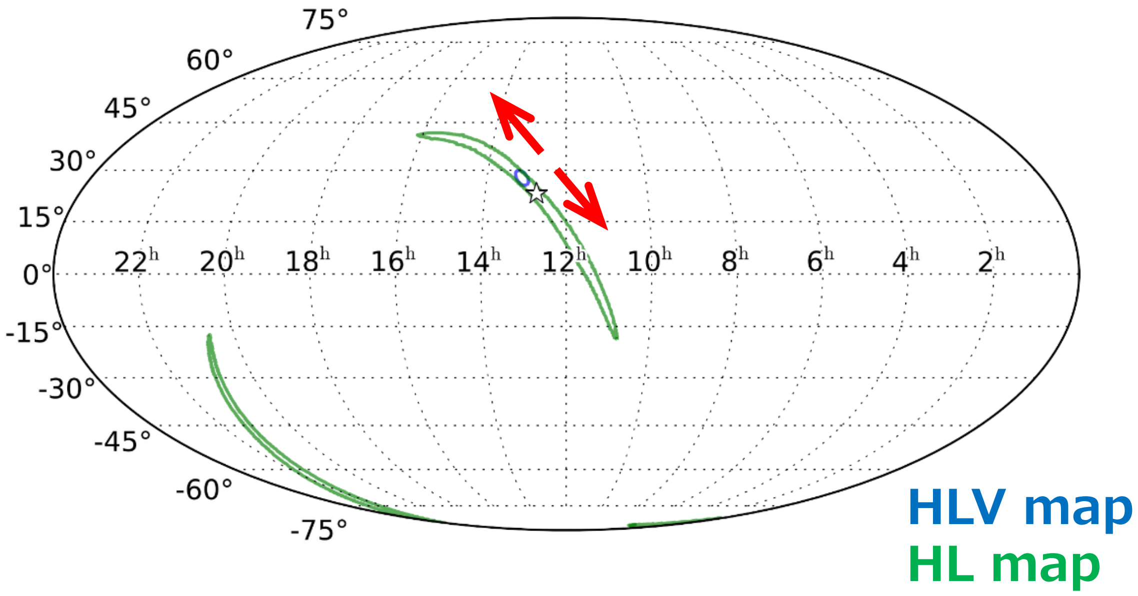
- Typical sky maps in this method
  → sometimes fail to predict the location within 90 % confidence area.

Expected localization performance / by HLV

HL+Vrandom



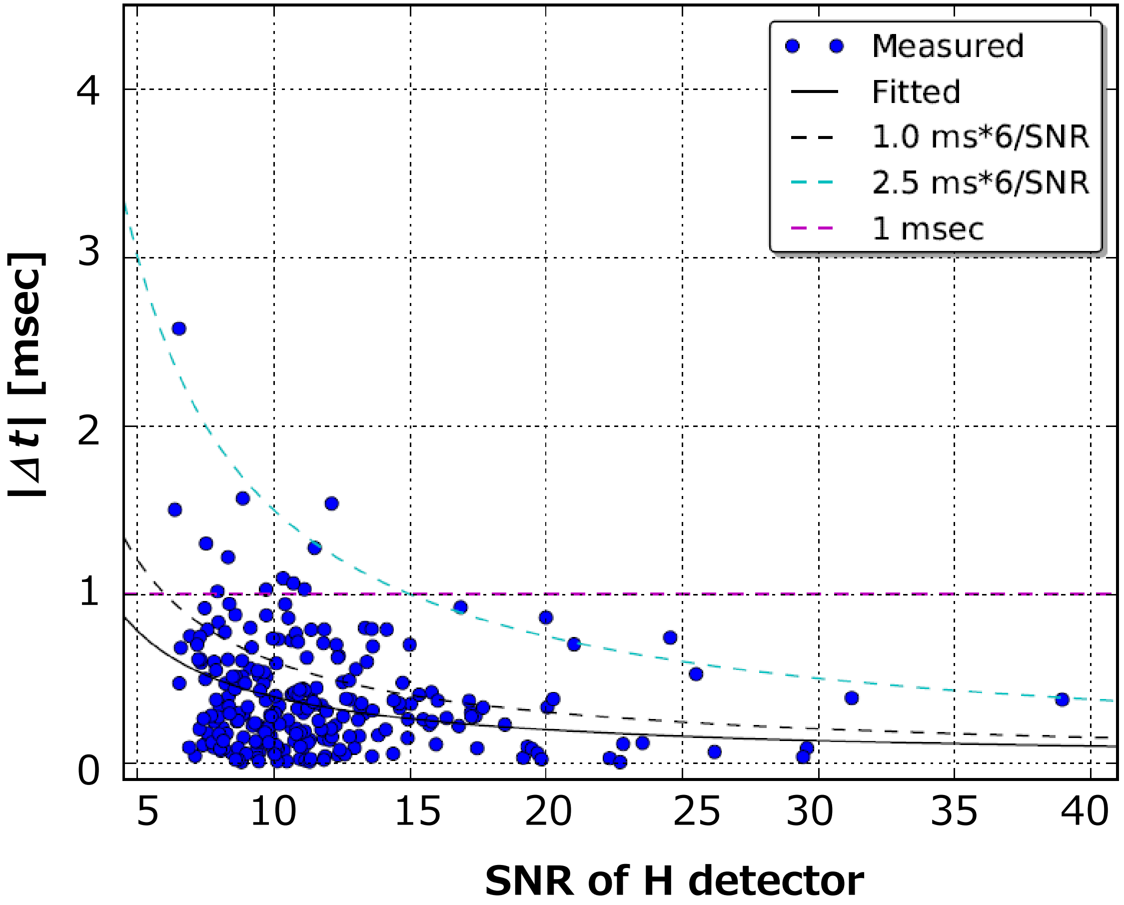
HL+Vinjection



- 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)

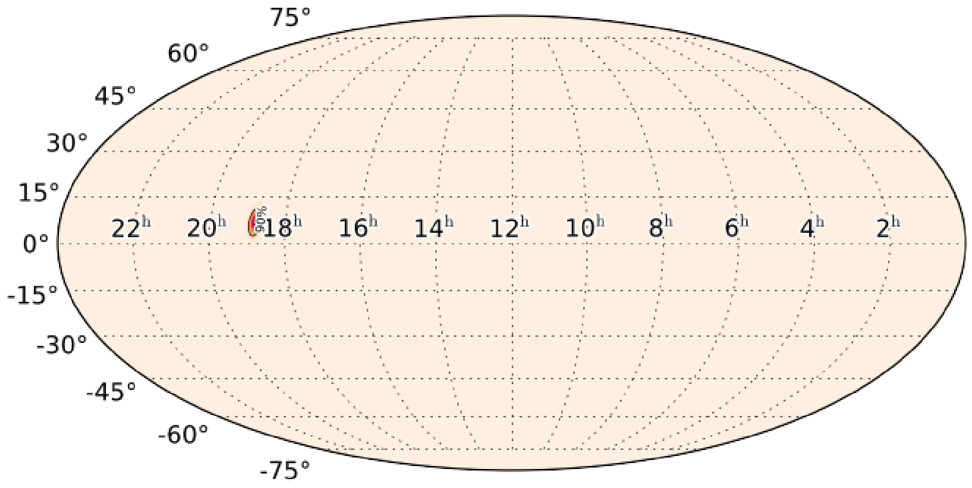
Case 1: worst case
HL+Vr, HL+Kr, HL+Vr+Kr or HL
(Based on ***FAP***)

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

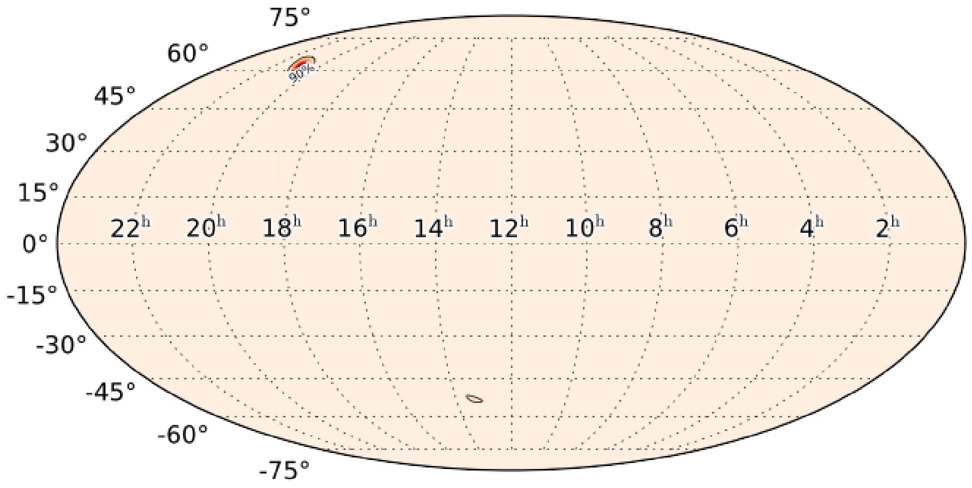
Case 3: Realistic case
HL+Vr, HL+Kr, HL+Vr+Kr,
HL+Vi, HL+Ki, HL+KVi+Ki,
HL+Vr+Ki, HL+ViKr, or HL
(Based on ***FAP*** and ***SNR***th)

Expected localization performance / by HLVK

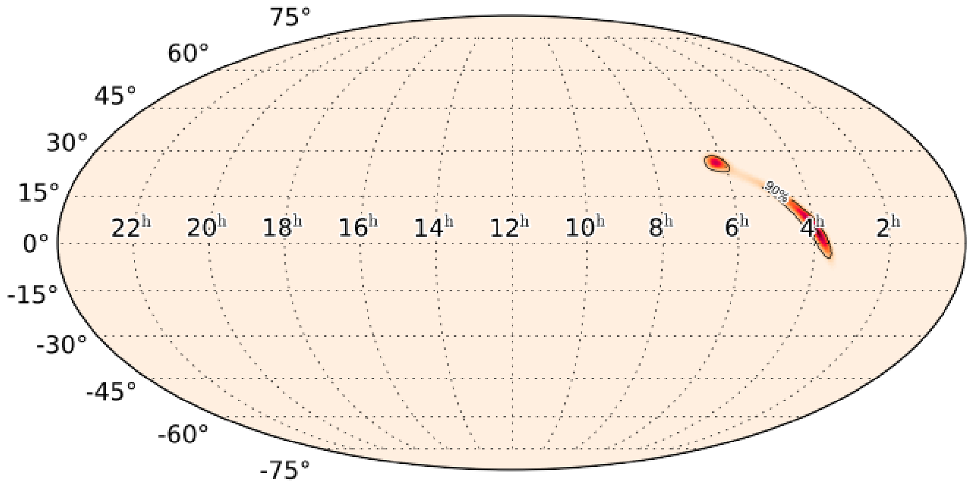
HL + Vi + Ki



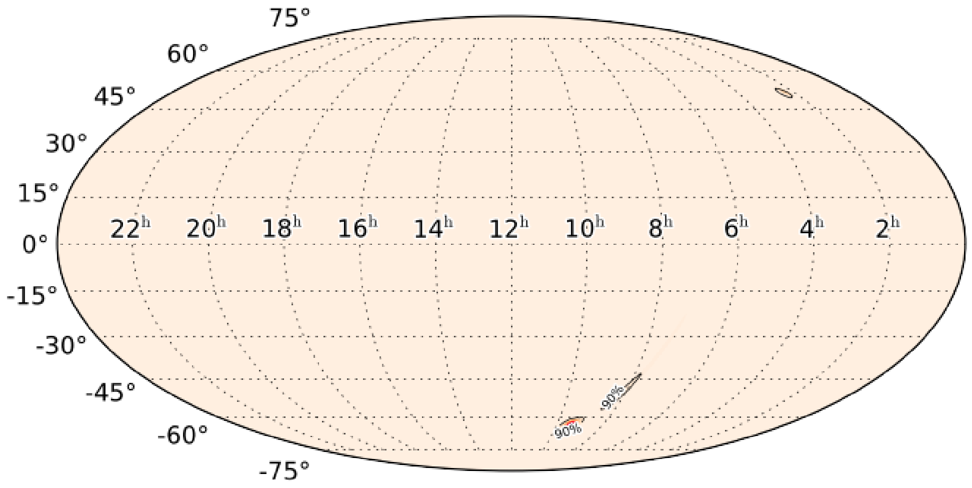
HL + Vr + Kr



HL + Vr + Ki

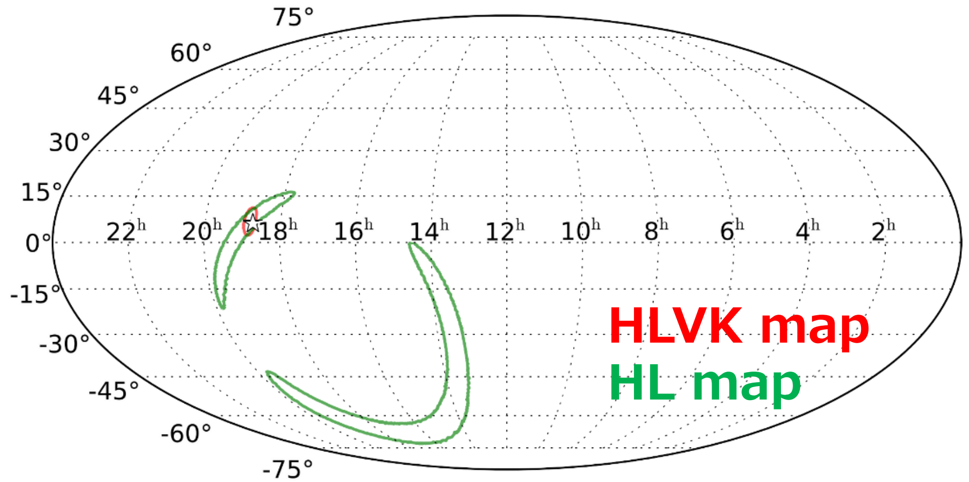


HL + Vi + Kr

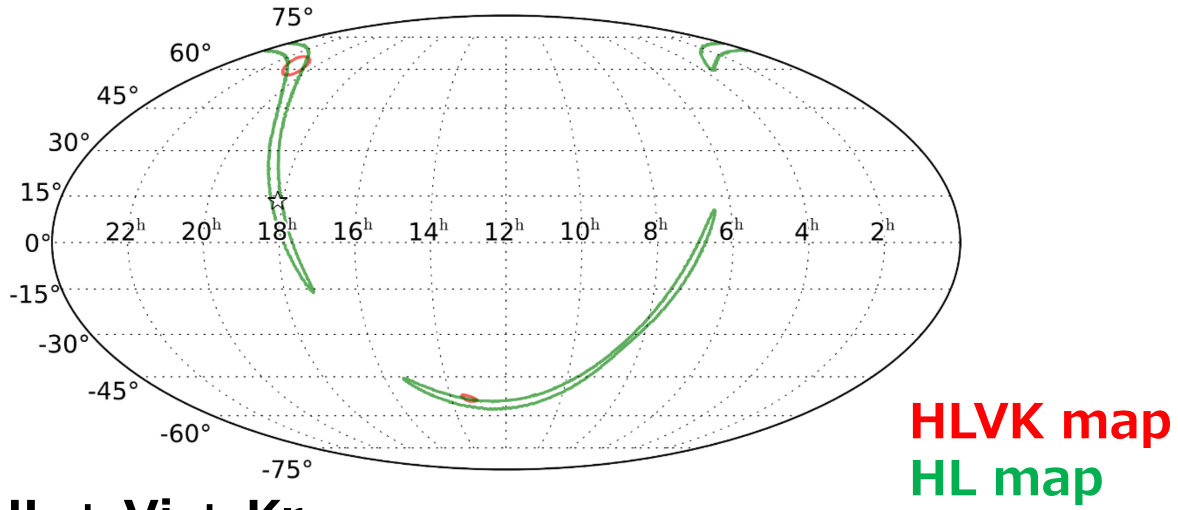


Expected localization performance / by HLVK

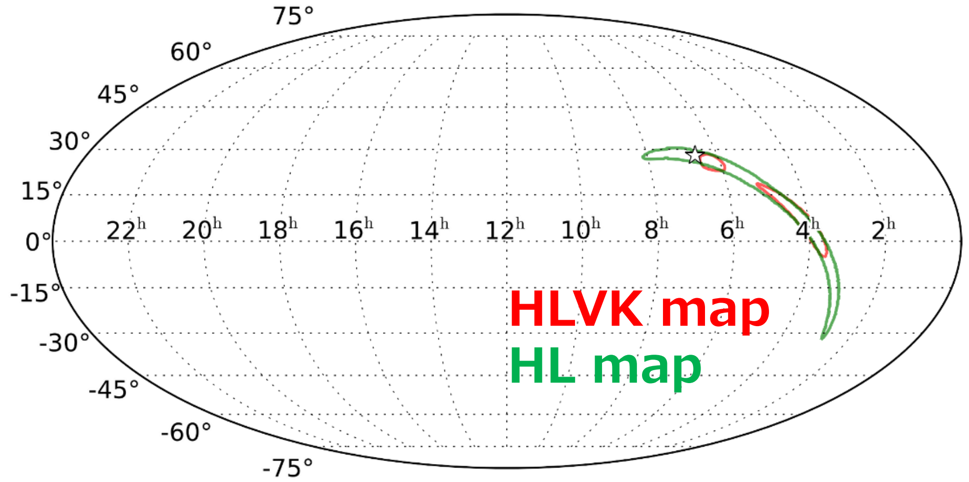
HL + Vi + Ki



HL + Vr + Kr



HL + Vr + Ki



HL + Vi + Kr