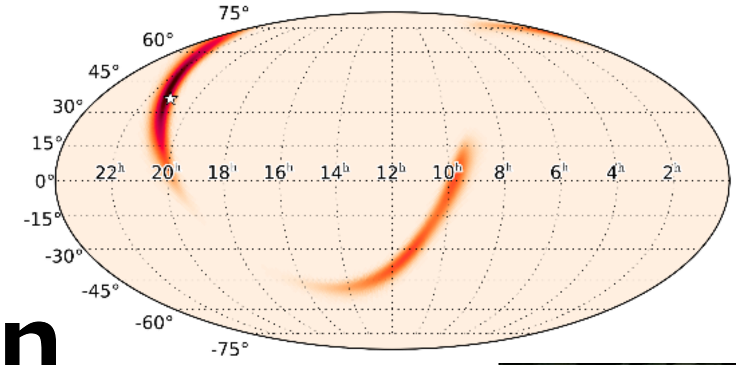
Development of
a low frequency vibration isolation system for KAGRA,
and study of the localization of coalescing binaries
with a hierarchical network of gravitational wave detectors.

Master's thesis defense
35-156218
Yoshinori Fujii

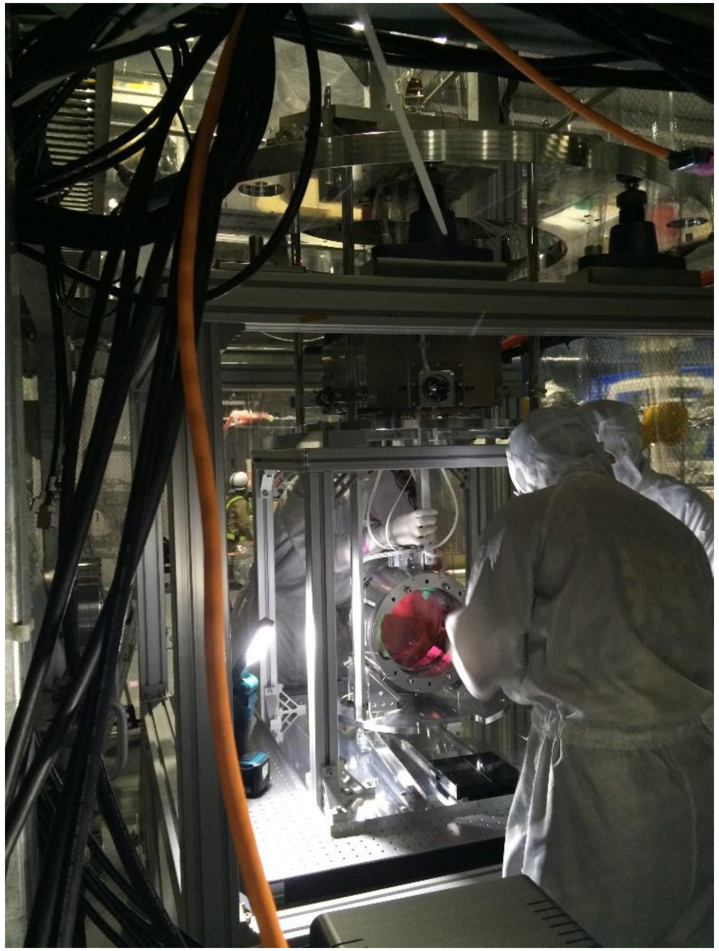
Contents



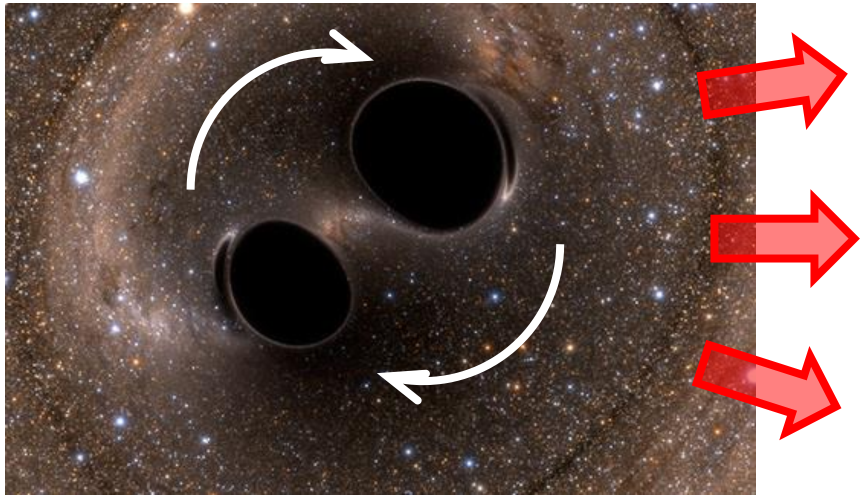
1. Source localization

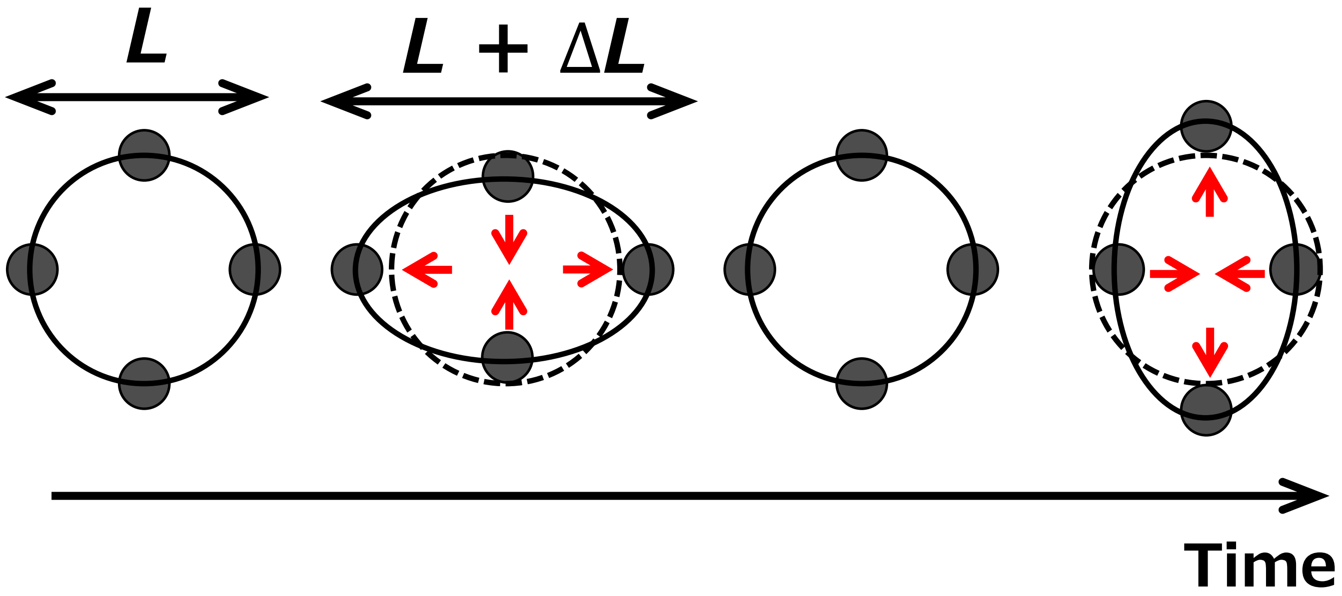
↓

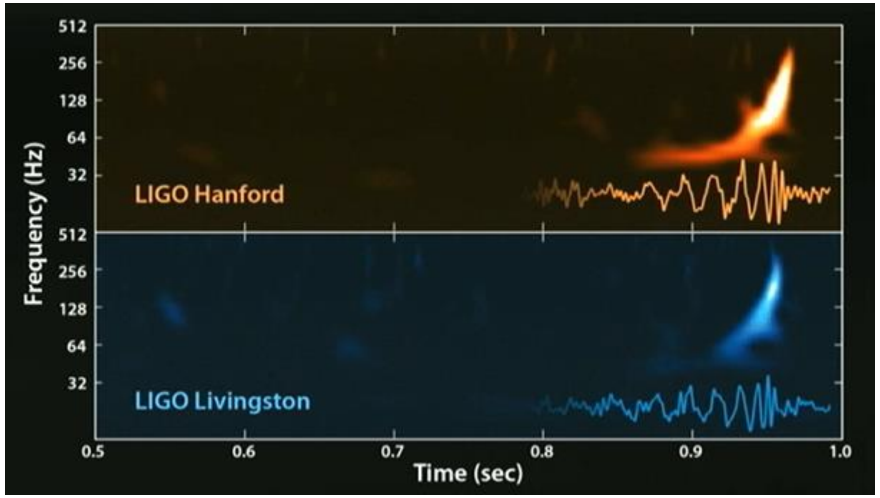
2. Detector development



Gravitational wave



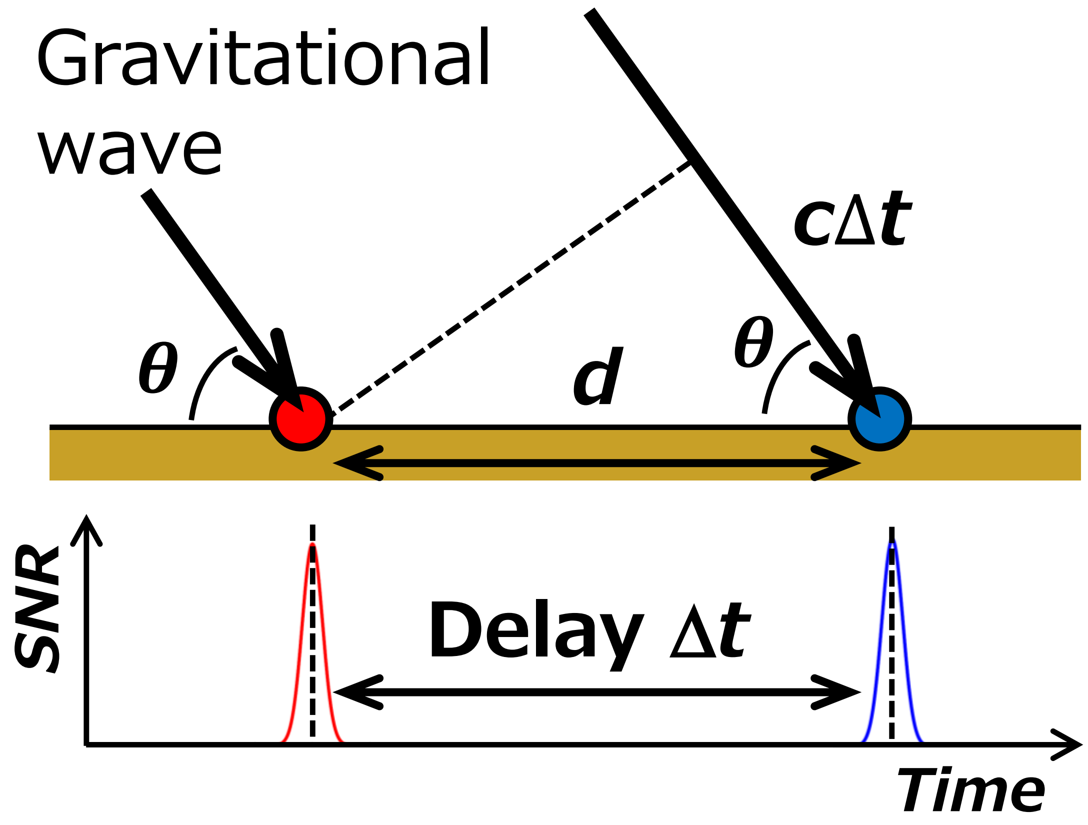




First detection! done!

→ New astronomy!

From where?



Time delay → Localization

$\Delta t \longrightarrow \theta$

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

From where?

1) Only a few detectors
→ × **Continuous observation**

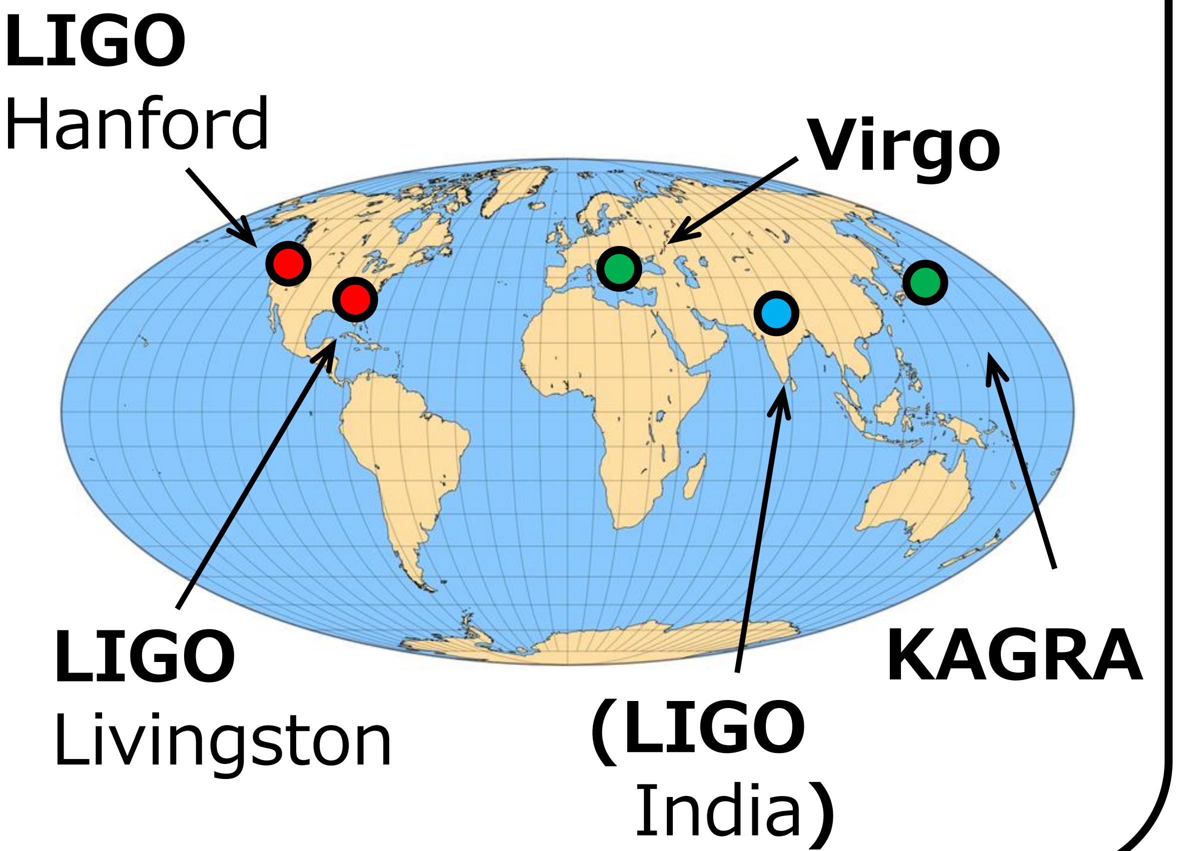
2) Only 2~3 detectors
→ **Blind spots**

From where?

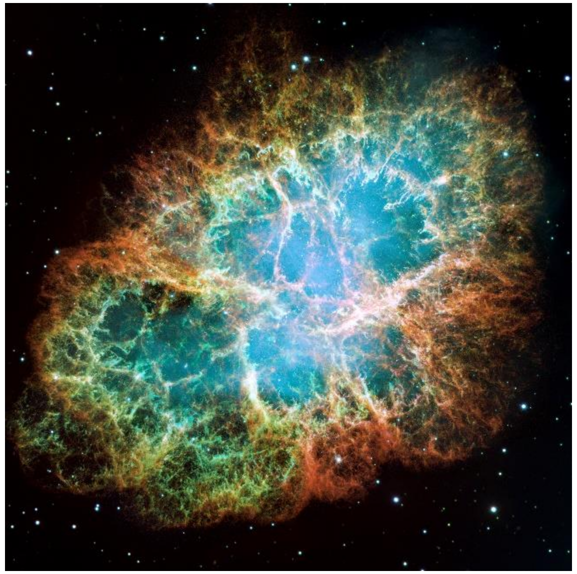
1) Only a few detectors
→ ✕ **Continuous observation**

2) Only 2~3 detectors
→ **Blind spots**

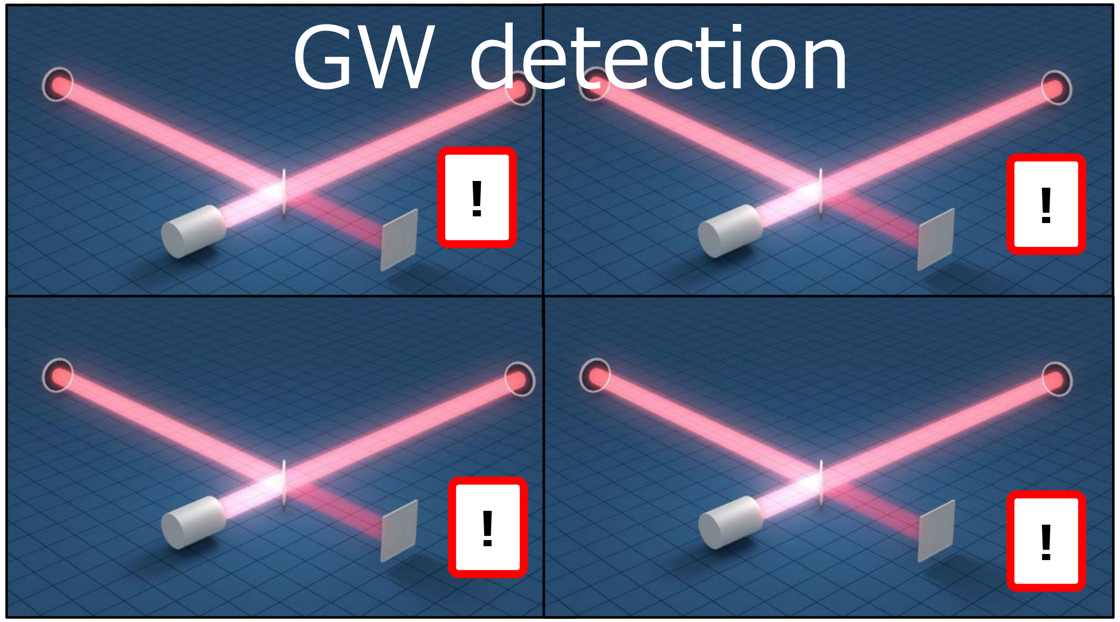
Source localization
→ **Several detectors!**



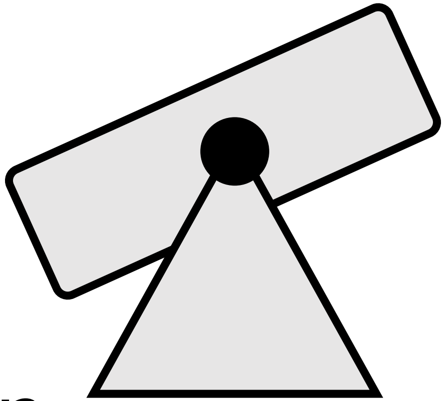
For EM and ν follow-up observation:



Source localization:
more precise is better.



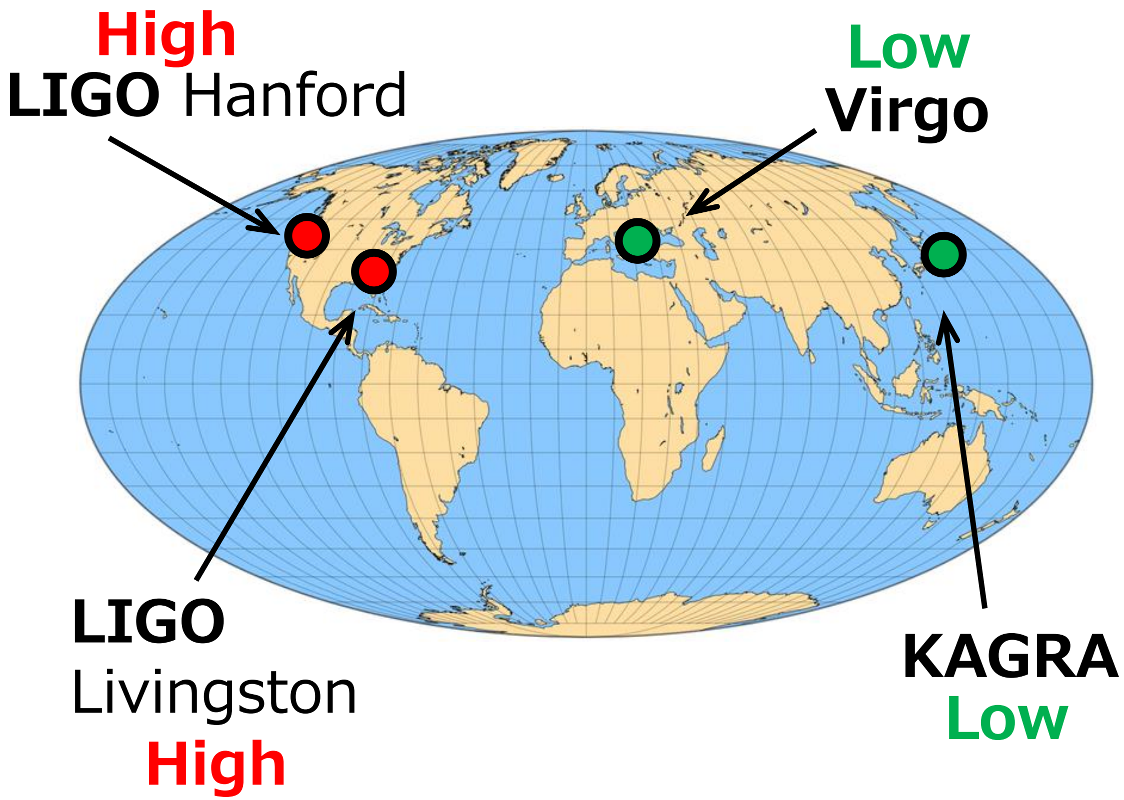
GW localization



EM and ν follow-up

We have different sensitivities.. OK?

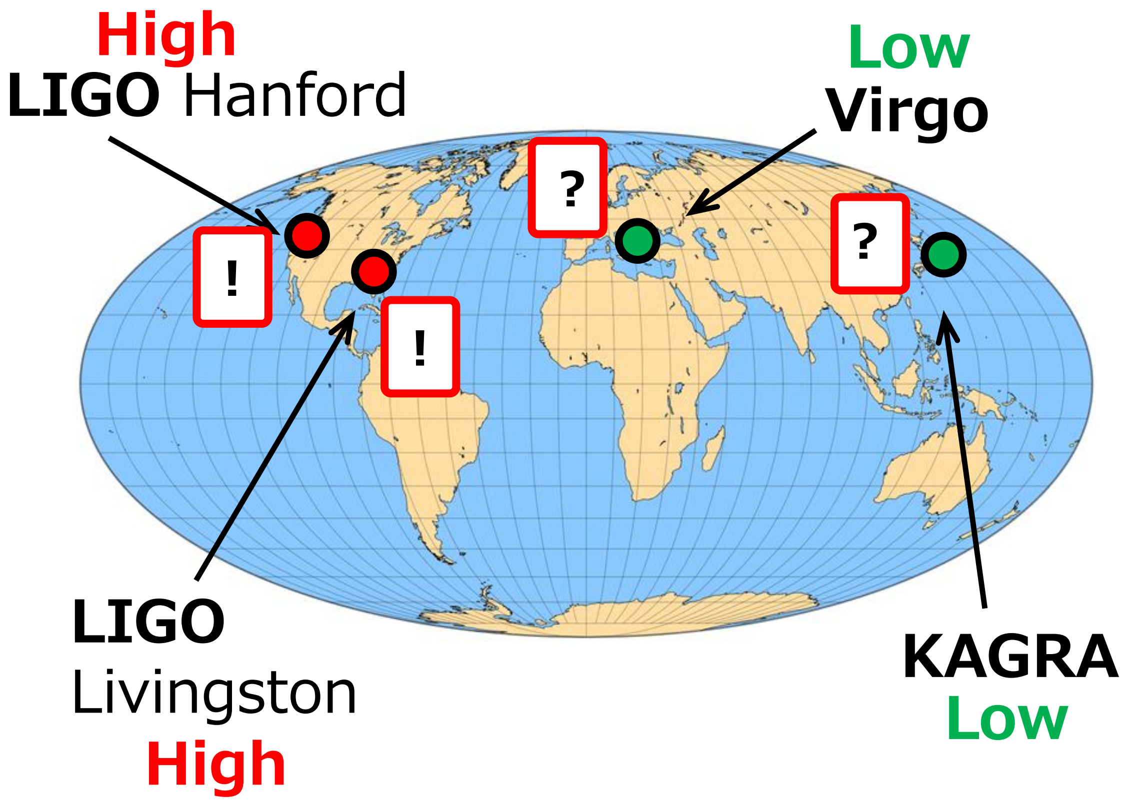
Ex.) SNR > 5 → detection



(Expected situation)

We have different sensitivities.. OK?

Ex.) SNR > 5 → detection



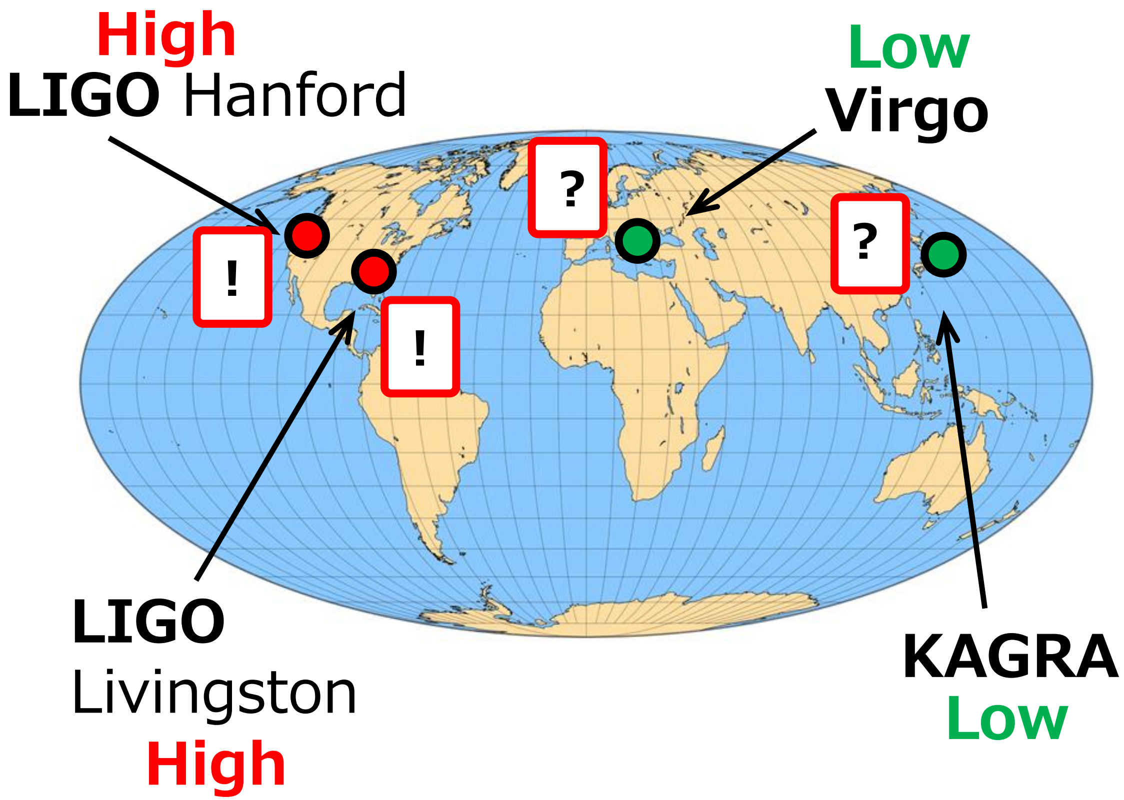
(Expected situation)

1) Triple (or more) coincidence
→ Rare

2) Localization
→ Not Precise

We have different sensitivities.. OK?

Ex.) SNR > 5 → detection



(Expected situation)

1) Triple (or more) coincidence
→ Rare

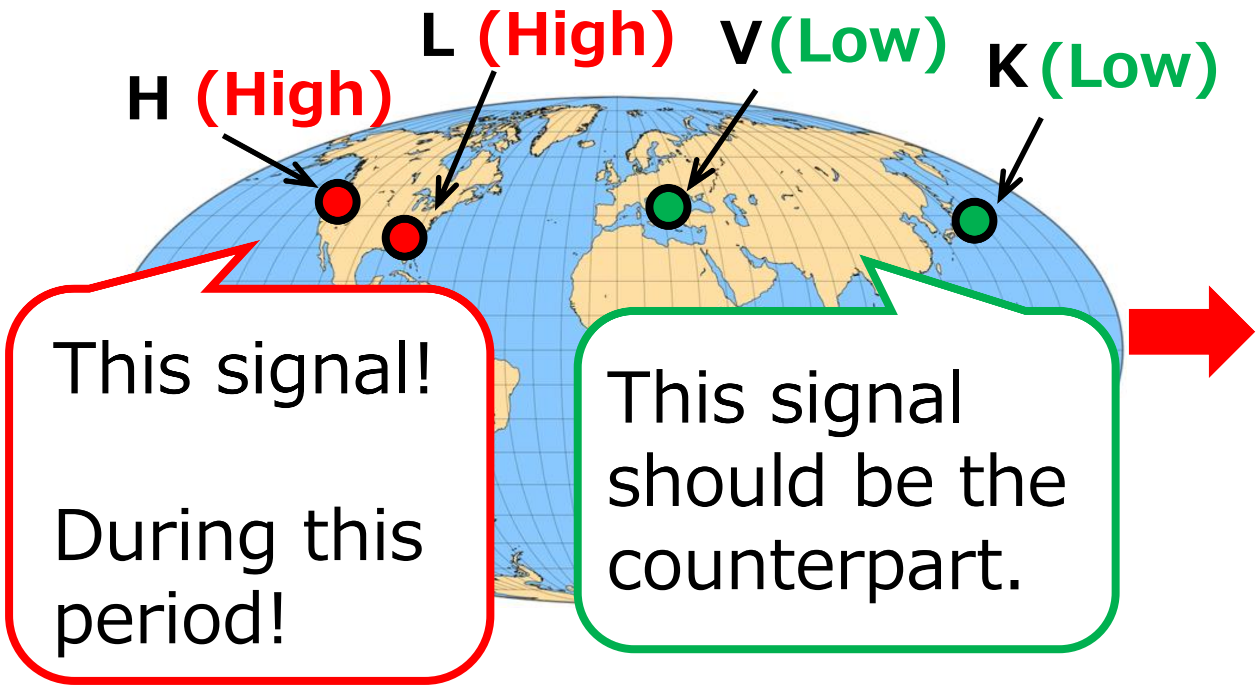
2) Localization
→ Not Precise

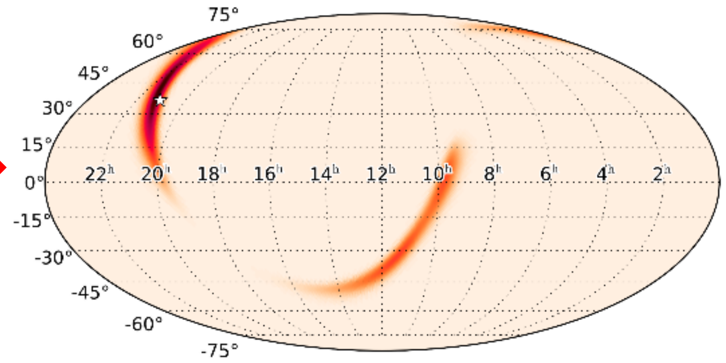
We have to establish a method for EM follow-up!

Hierarchical network search

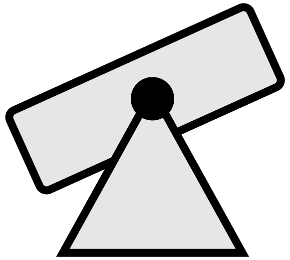
1) High/Low sensitivity → higher/lower SNR threshold

2) high sensitivity detector → low sensitivity detector





GW localization



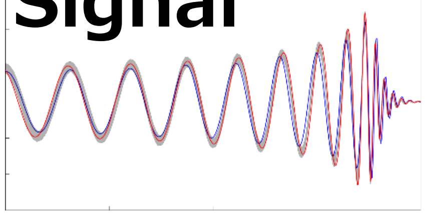
EM follow-up observation

Calculation setup / Assumption

1. GW-EM pipeline for GWs from CBC

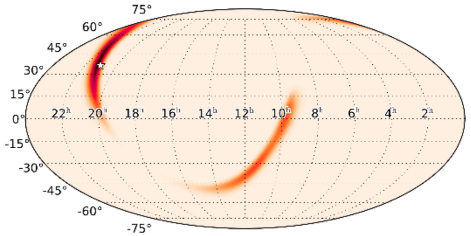
GW detectors → MBTA → BAYESTAR → EM telescopes

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 setup / Main flow 1

MBTA

248 Injection data

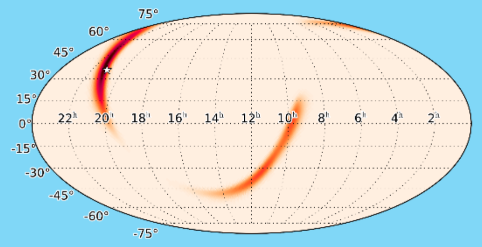
H
L
Existing measured data

V
Artificial data

(Random) or (true + δ)

Arrival timing, SNR, Phase.

BAYESTAR

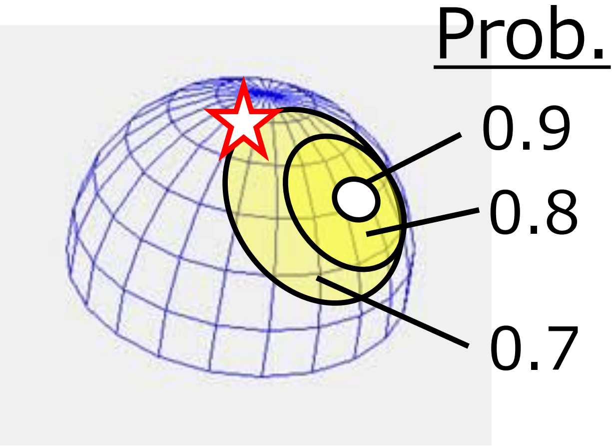


Localization performance

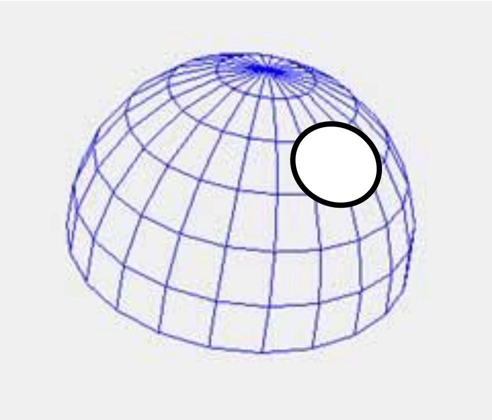
Calculation setup / Main flow 2

Localization performance

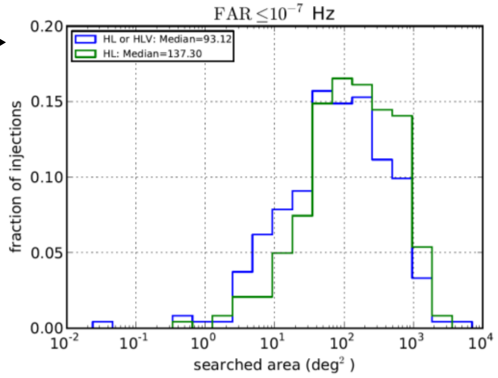
1) **Accuracy**
→ Searched area (deg^2)

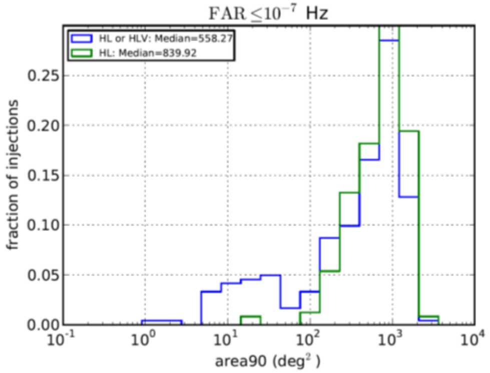


2) **Precision**
→ 90 % confidence area (deg^2)



Histograms from 248 events.

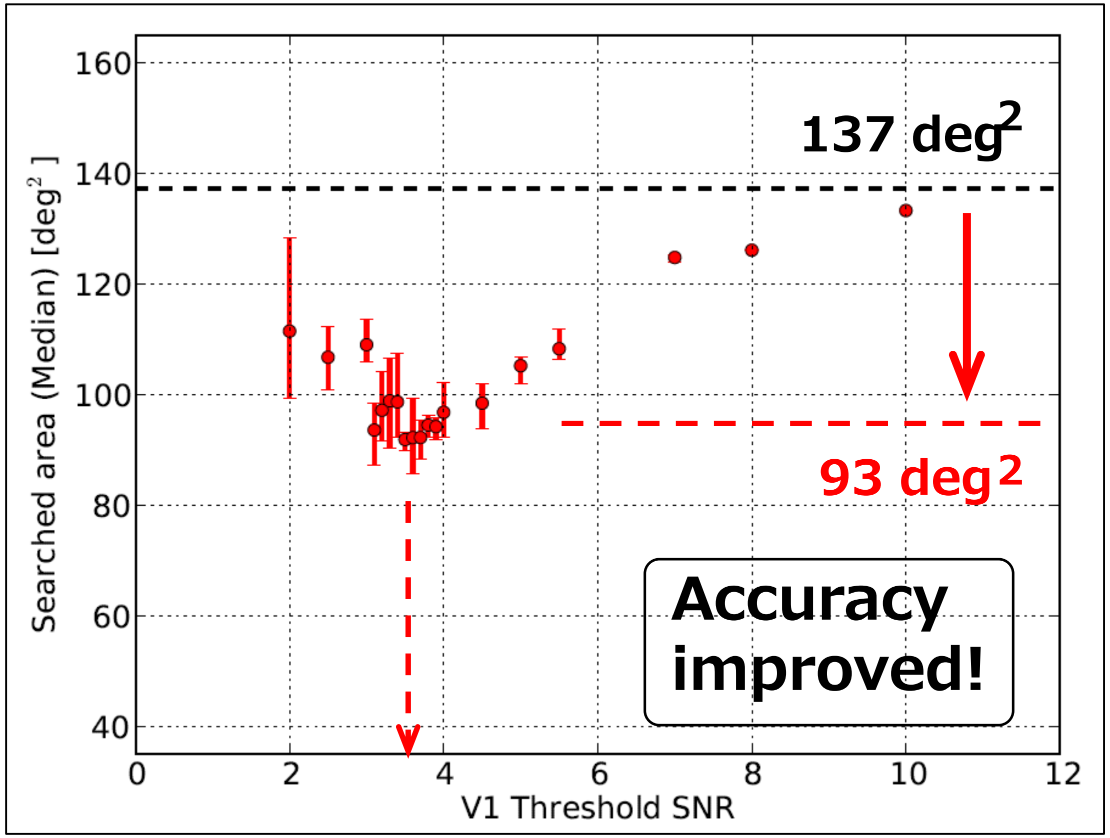


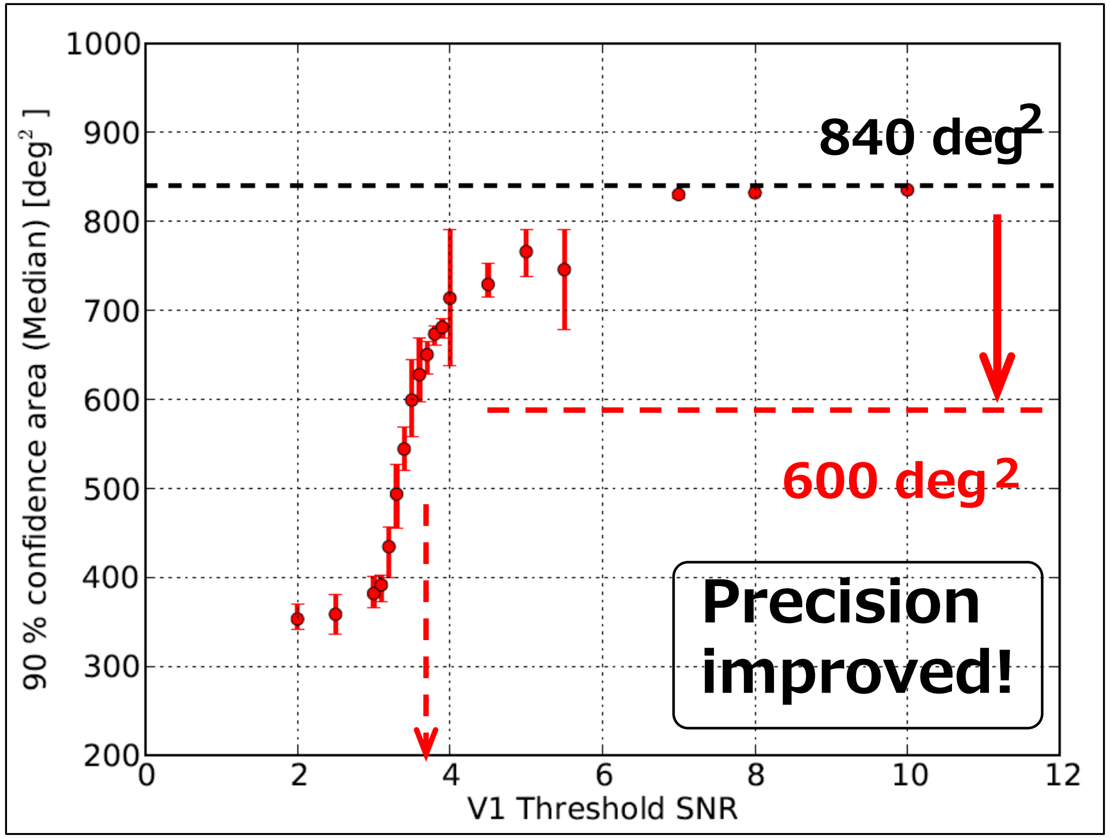


median values

Expected performance, HLV

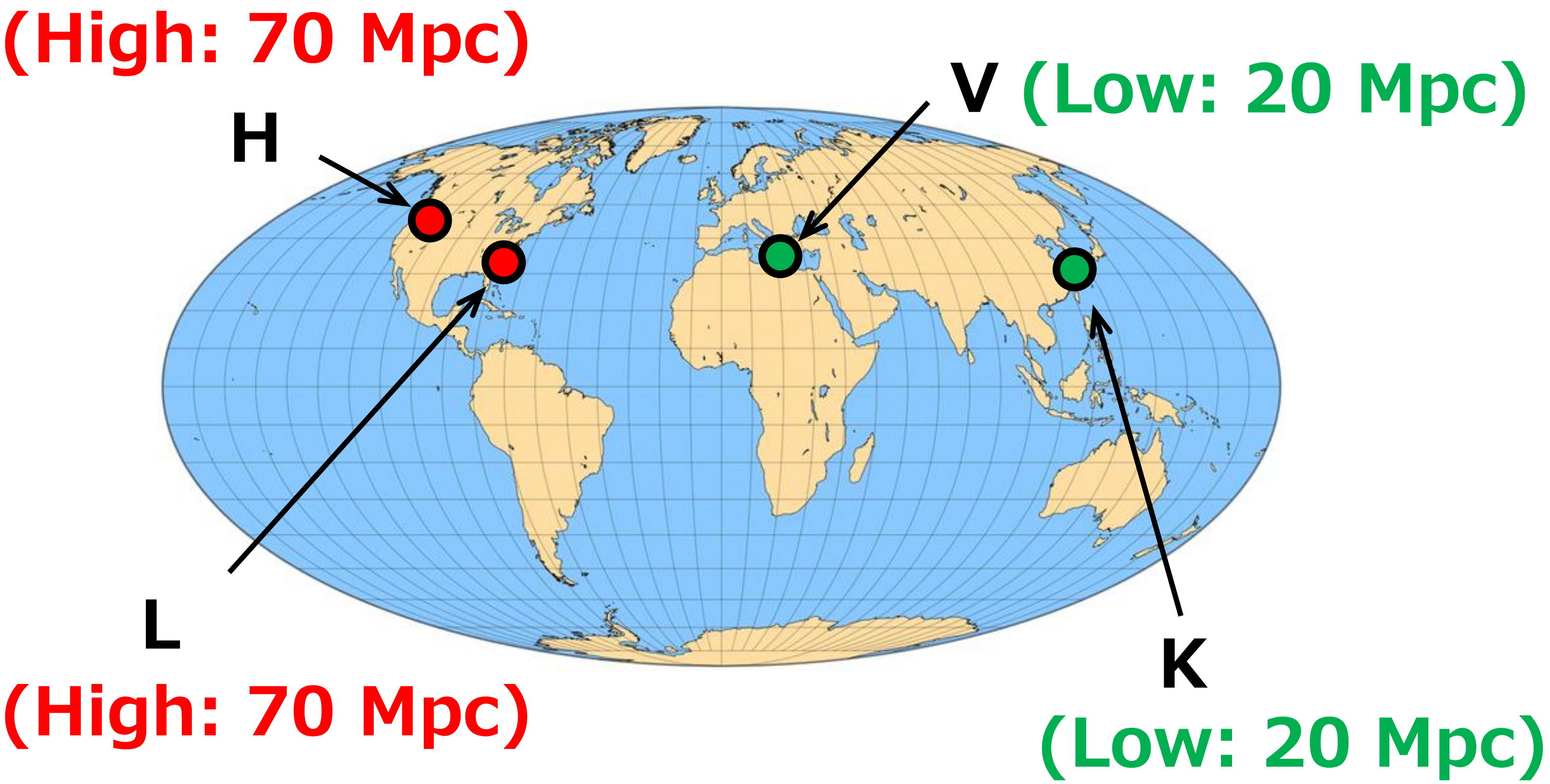
(SNR threshold for H, L = 5.)





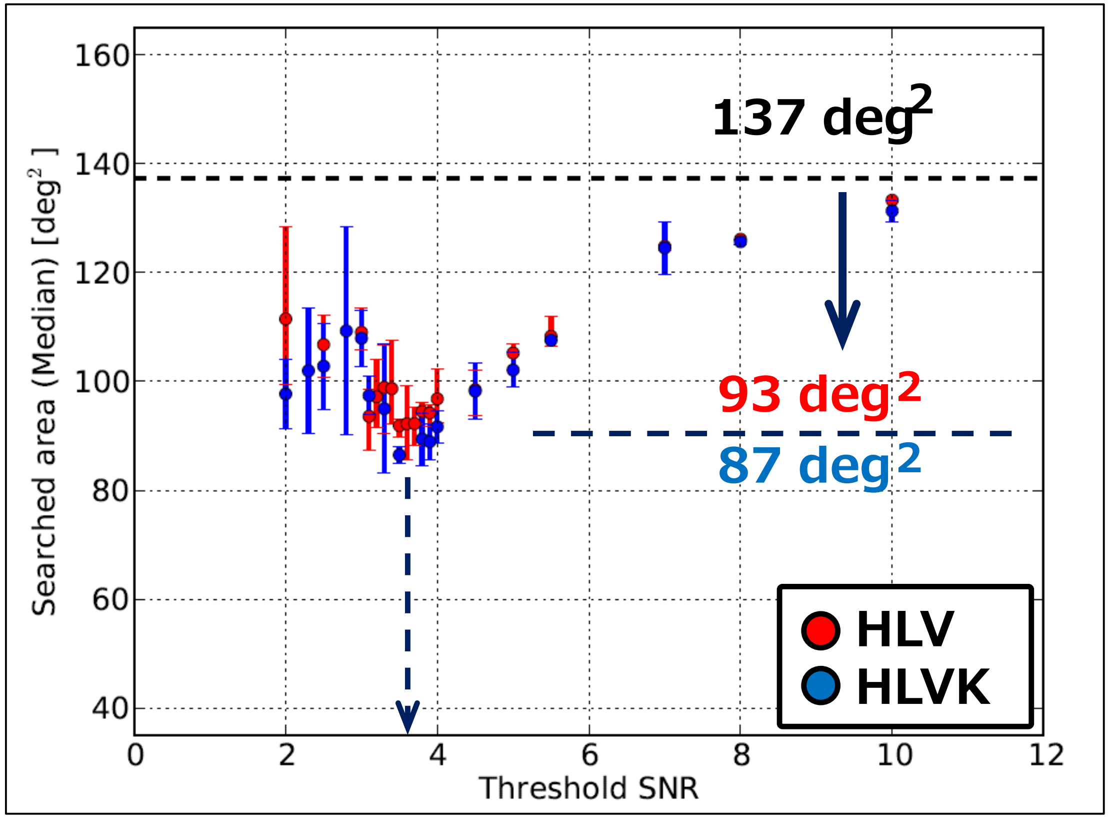
→ By including low sensitivity detectors,
errors on sky maps can be reduced by a factor of ~ 0.7.

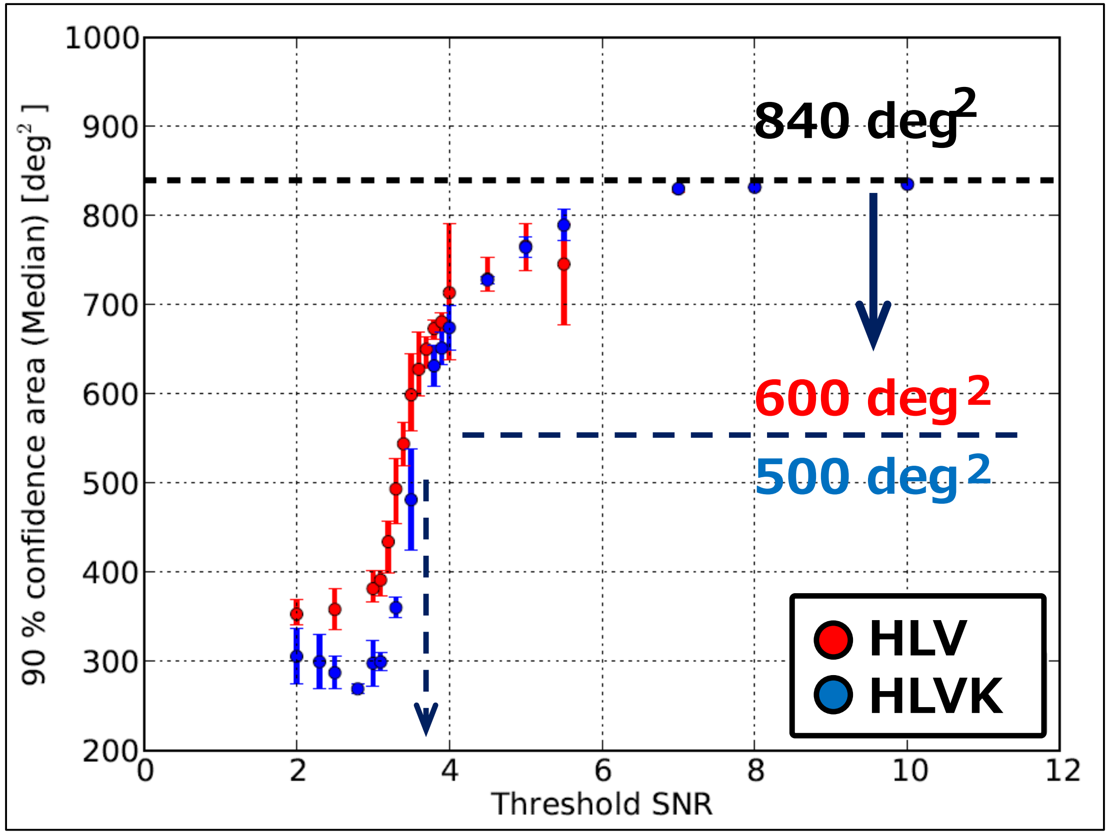
How about 4 detectors, HLVK?



Expected performance, HLVK

(SNR threshold for H, L = 5.)





Accuracy → Not so improved..
Precision → improved!

→ 4th detector contributes to EM follow-up!

More improvement → Necessary to improve sensitivity.

Summary 1

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

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

Accuracy: 137 deg^2 → 93 deg^2

Precision: 840 deg^2 → 600 deg^2

→ ***Low sensitivity detector can contribute!***

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

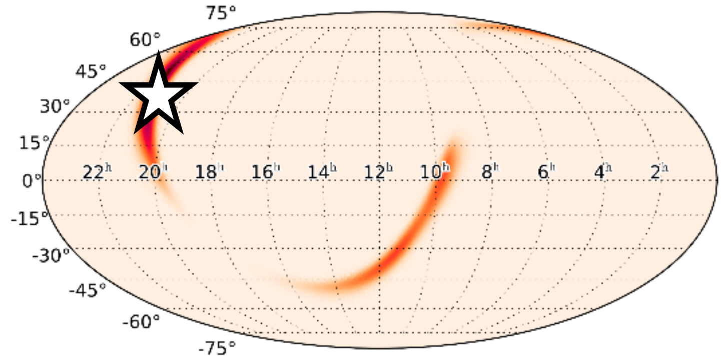
Accuracy: 137 deg^2 → 87 deg^2

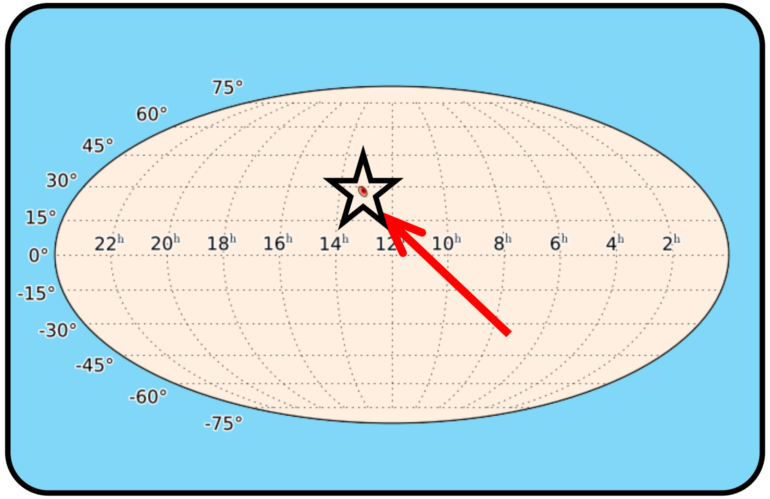
Precision: 840 deg^2 → 500 deg^2

→ ***4th detector contributes! → useful for EM follow-up!***

Source localization → detector development

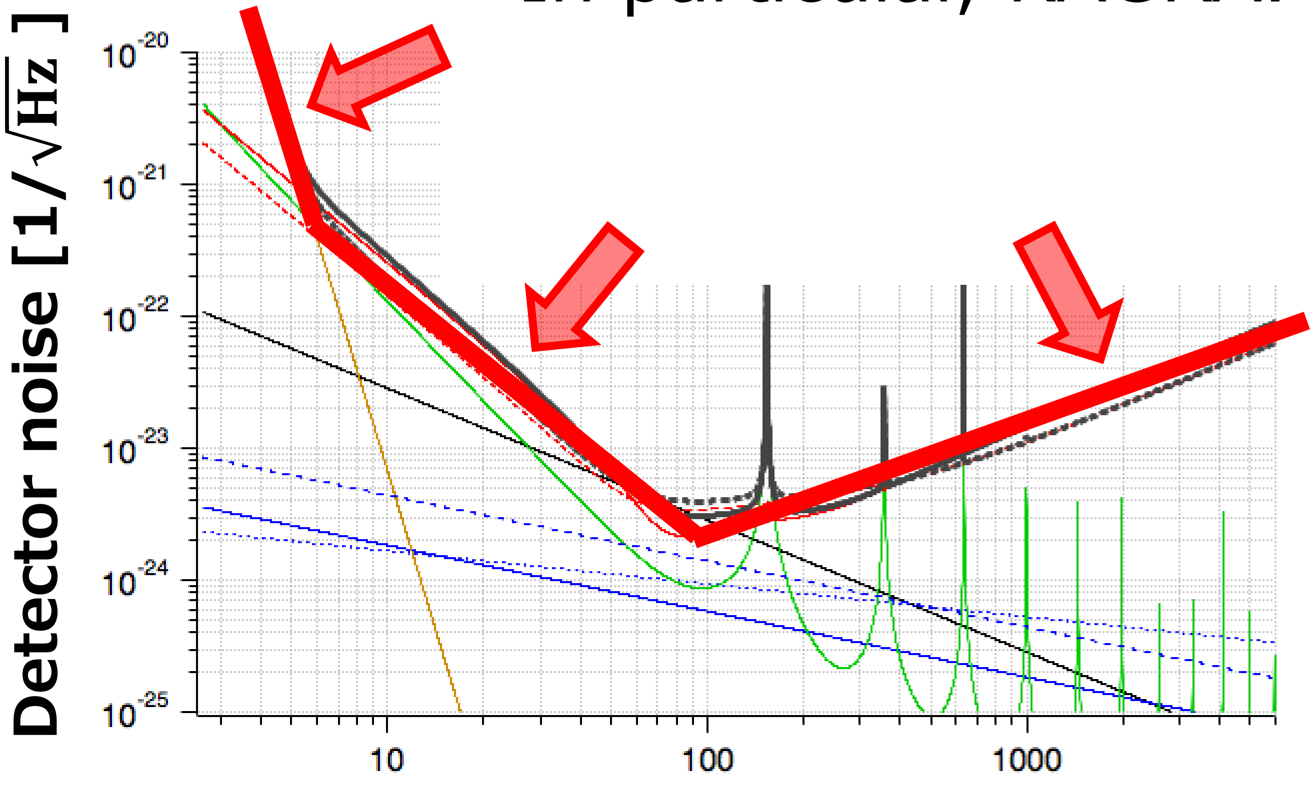
We want ..



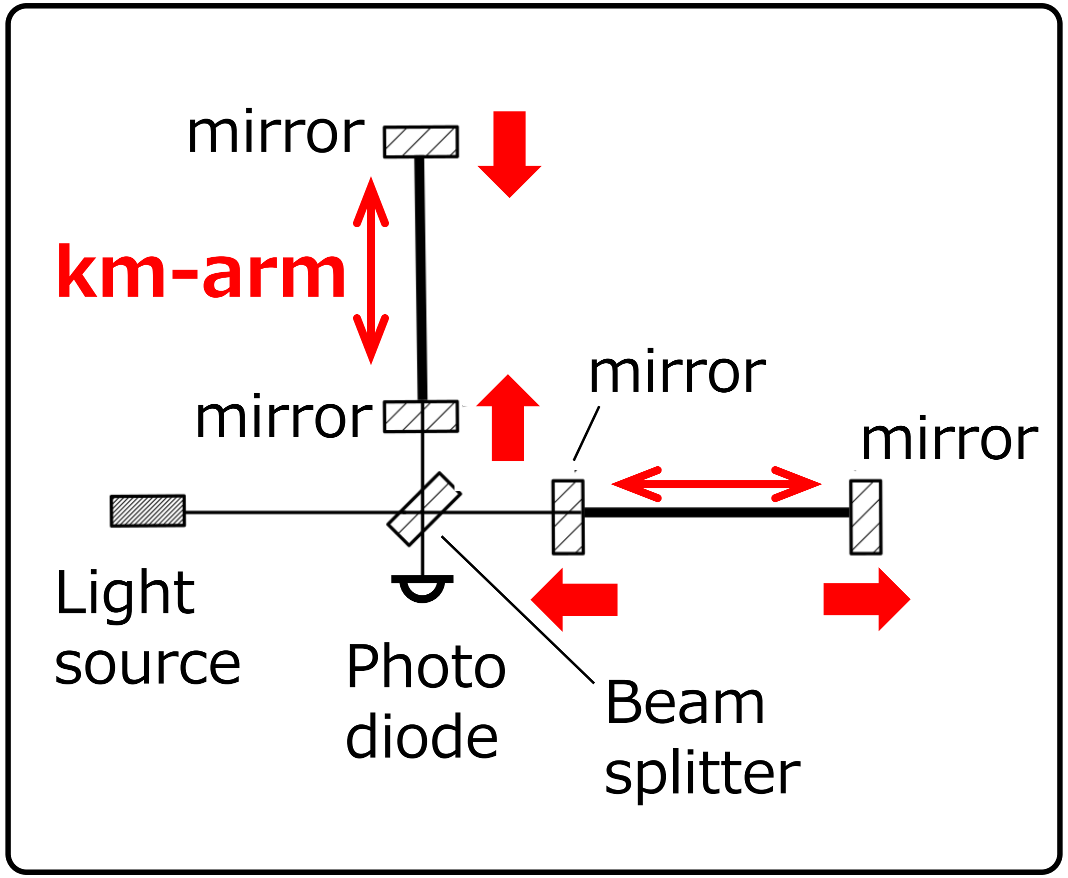


Necessary to improve sensitivity!

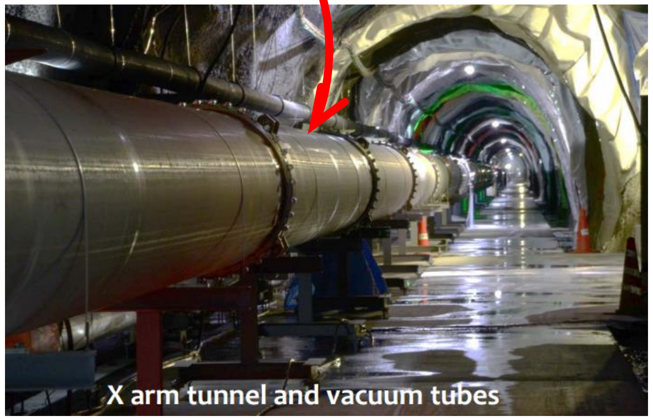
In particular, KAGRA.



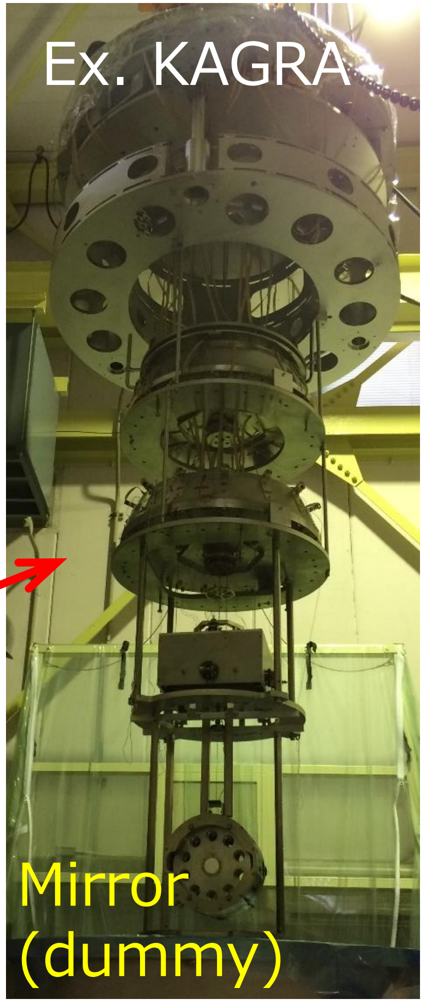
Gravitational wave detector



1) Michelson-based interferometer
2) Optical cavities
3) km-arm



4) Suspended core optics



Detector noise

- Quantum noise
- Thermal noise

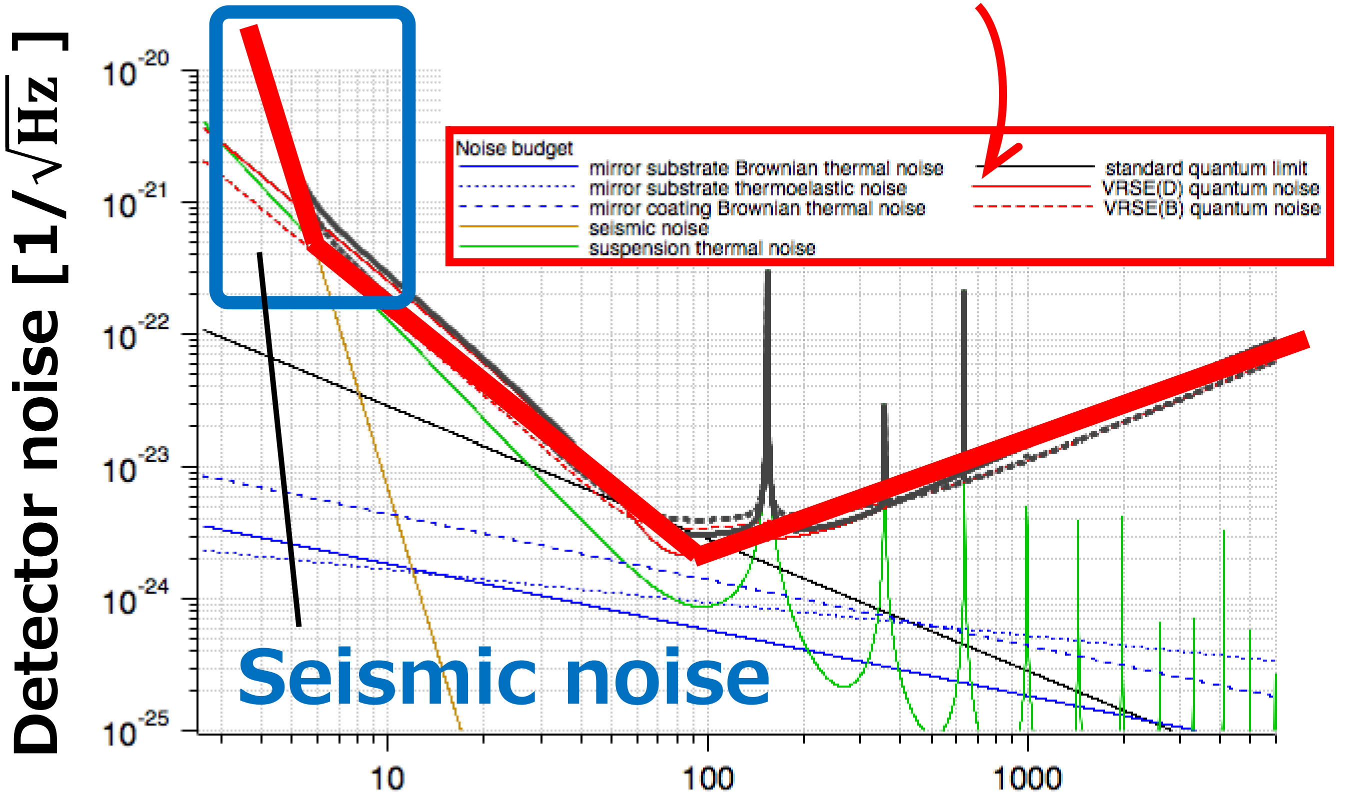
…

- **Seismic noise**

mirror vibration

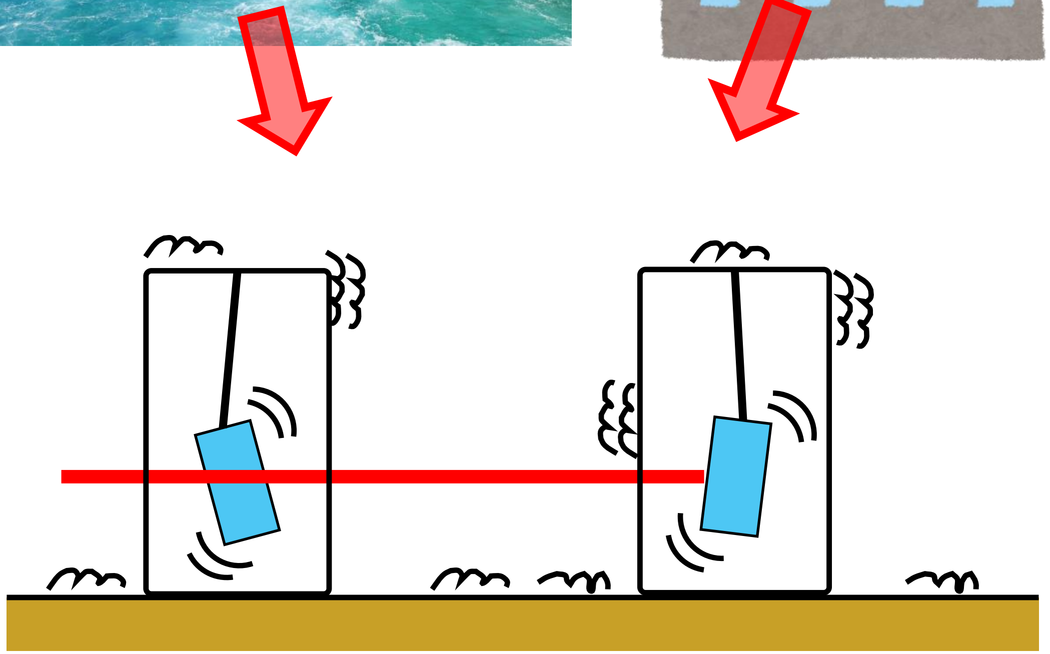
→ Necessary to suppress

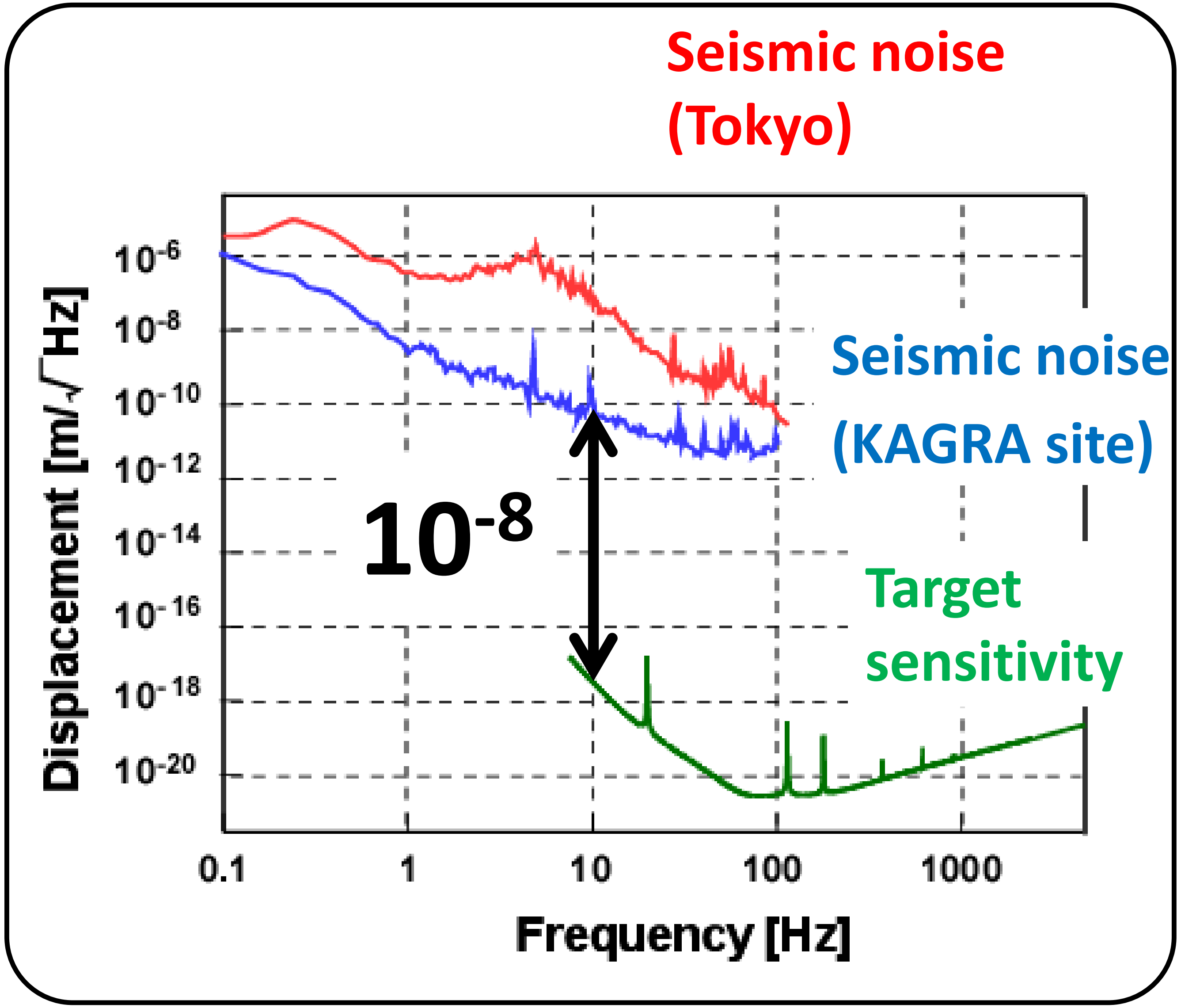
So many noise sources..



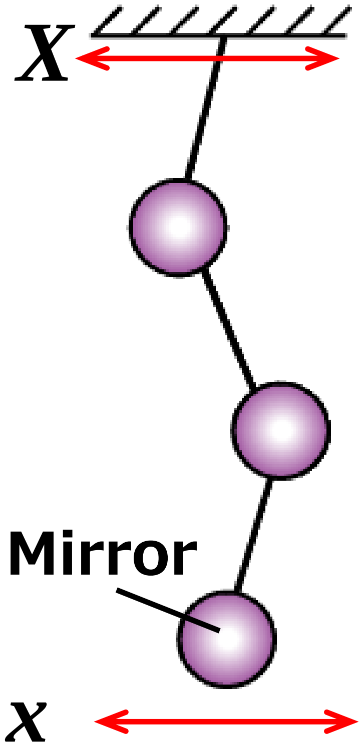
In case of KAGRA

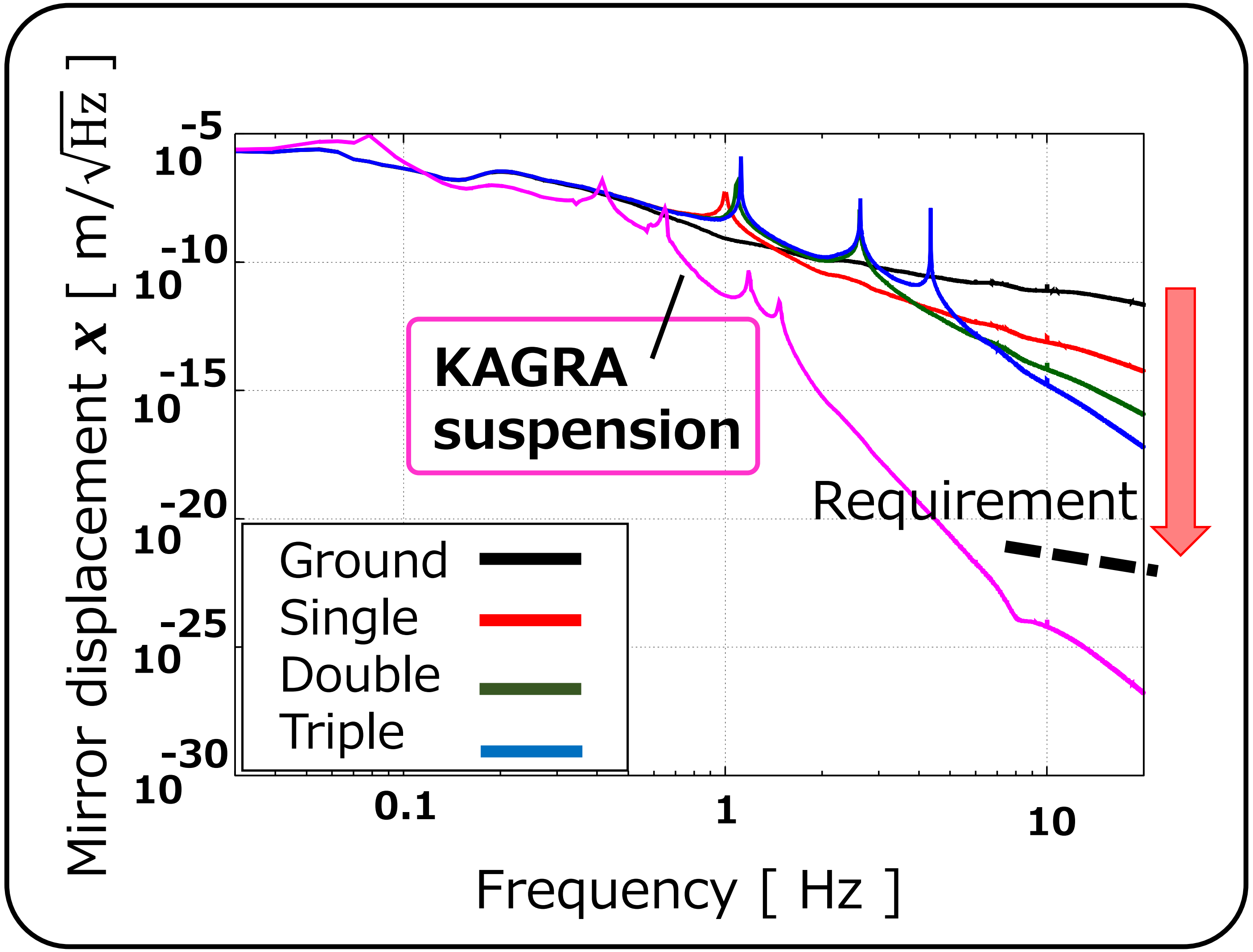
Seismic noise

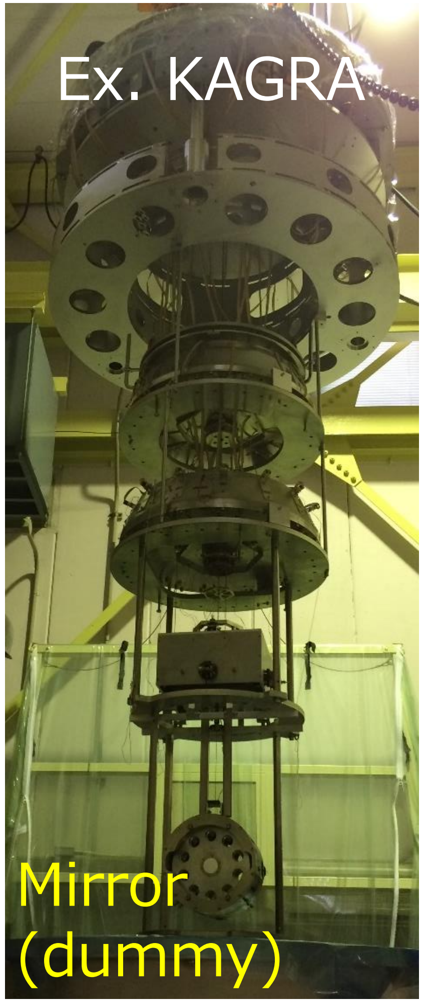




Seismic attenuation

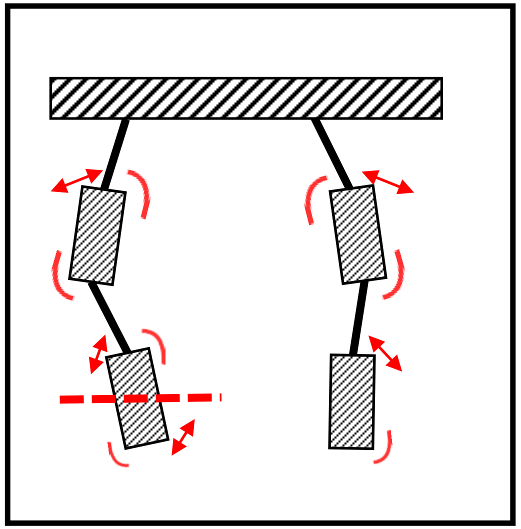




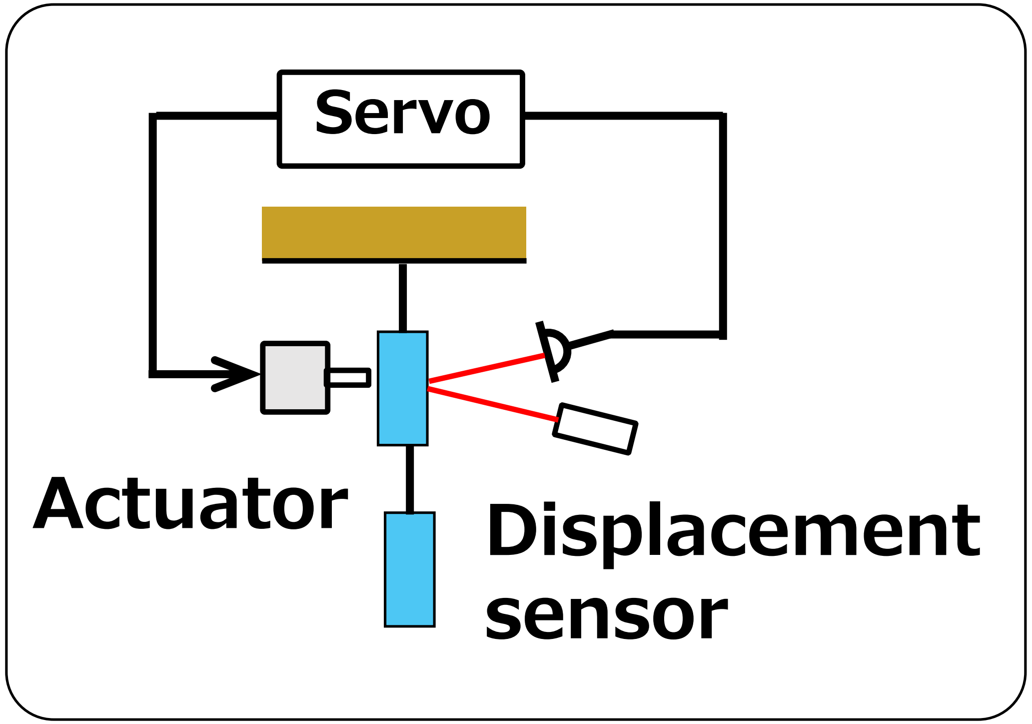


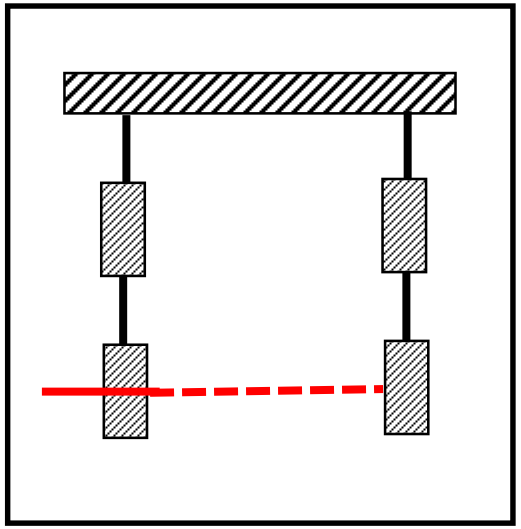
Resonance damping & drift compensation

→ *Active control*



Starting interferometer operation





Stable interferometer operation

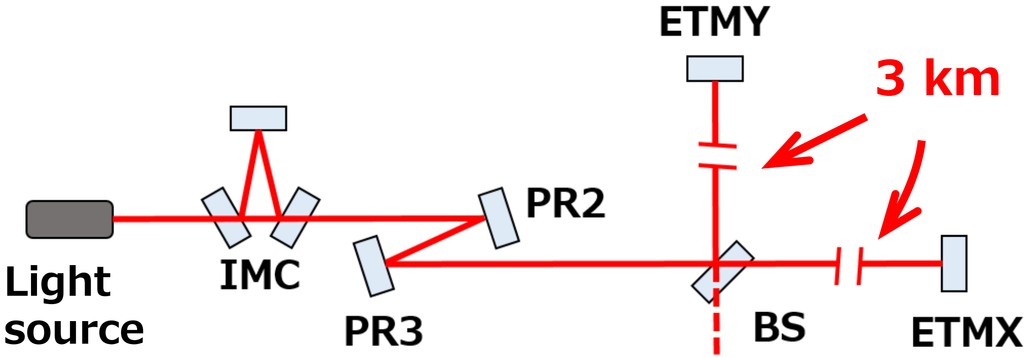
KAGRA project

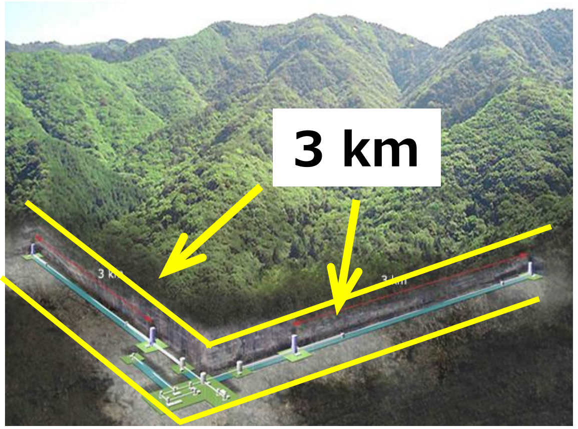
KAGRA

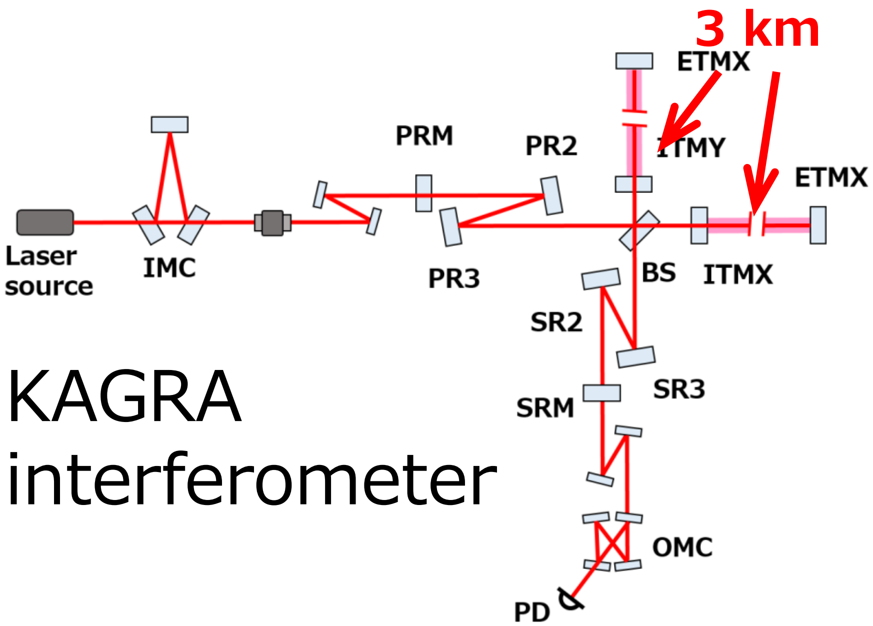
1) Japanese detector
2) now being developed
3) underground

iKAGRA

1) test run in 2016
2) Simple interferometer





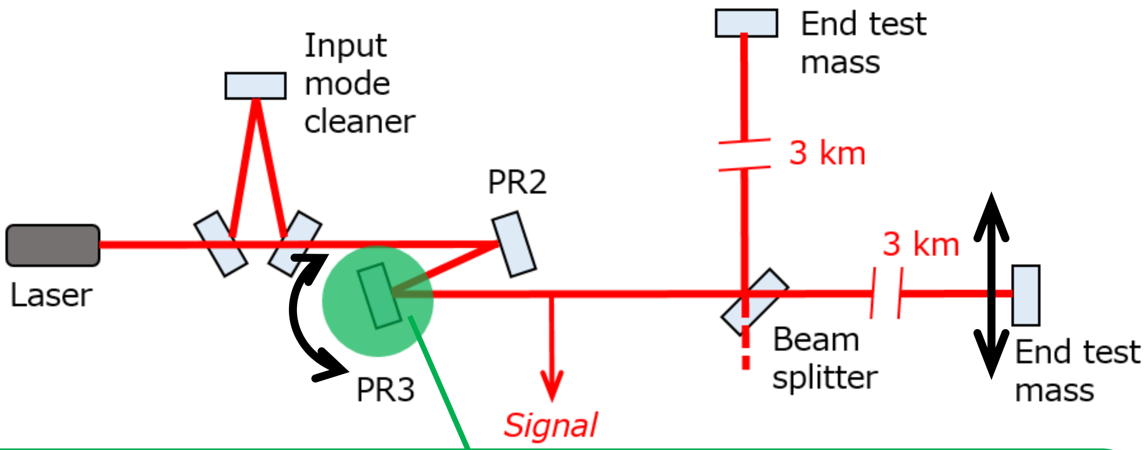


KAGRA interferometer

KAGRA suspension development

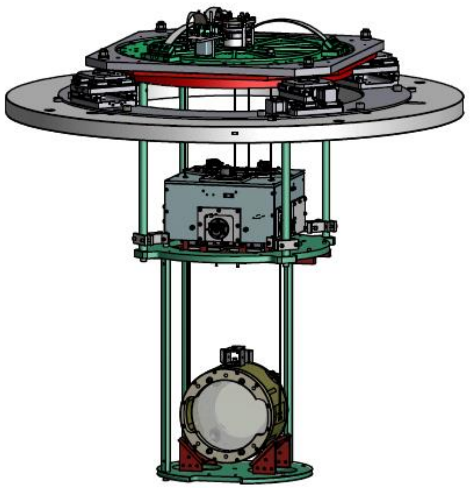
iKAGRA-PR3 work:

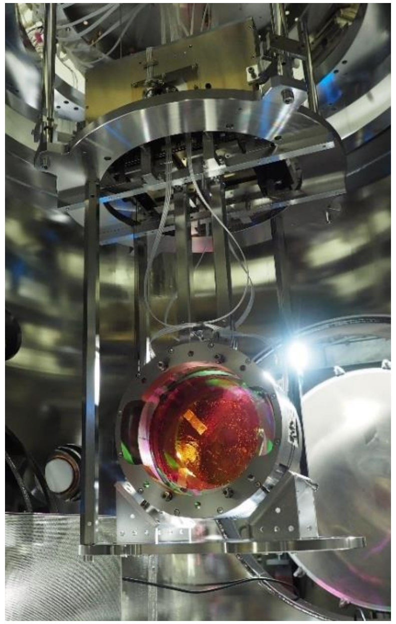
1) Assembly
2) Performance test
3) Upgrading for KAGRA



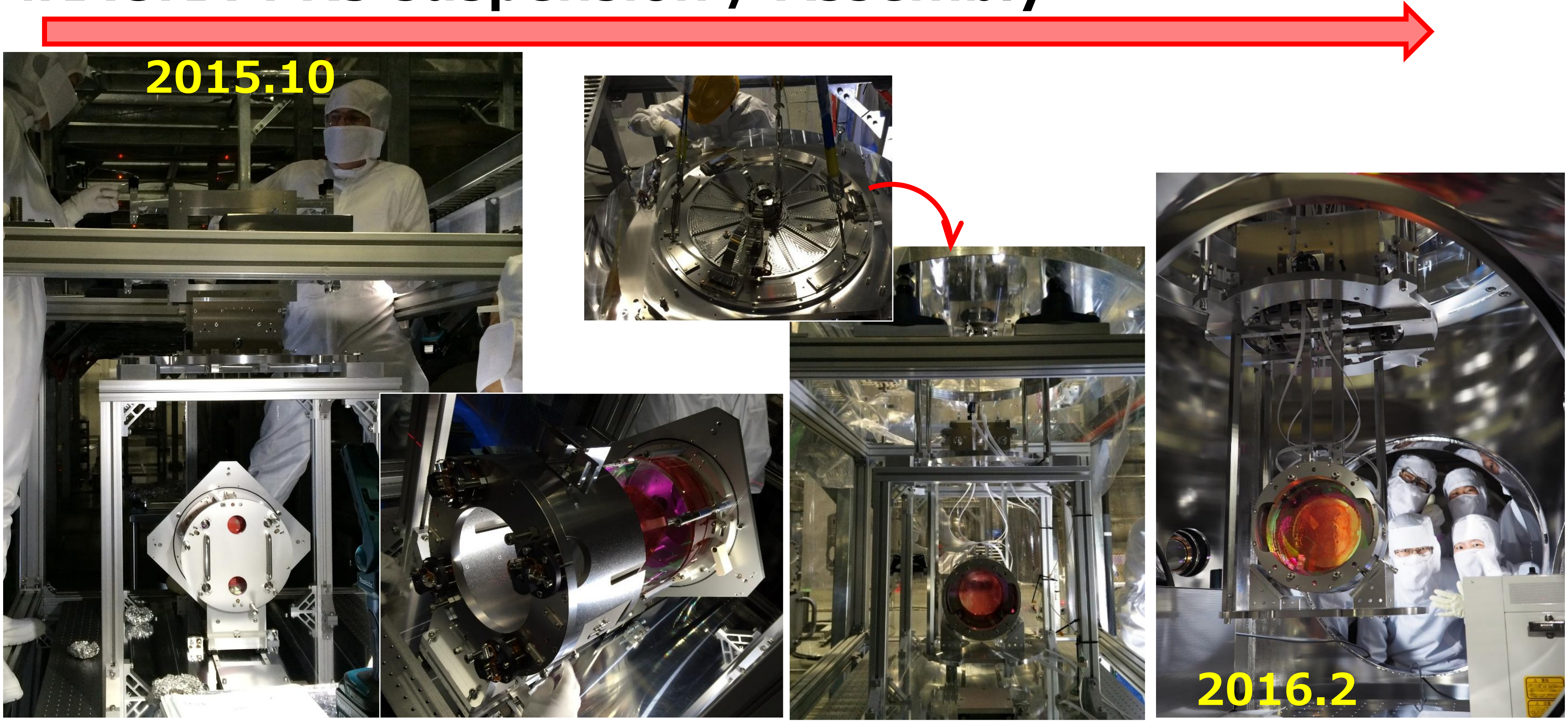
iKAGRA-PR3 suspension:

Alignment mirror of iKAGRA
for initial alignment
for stable operation.

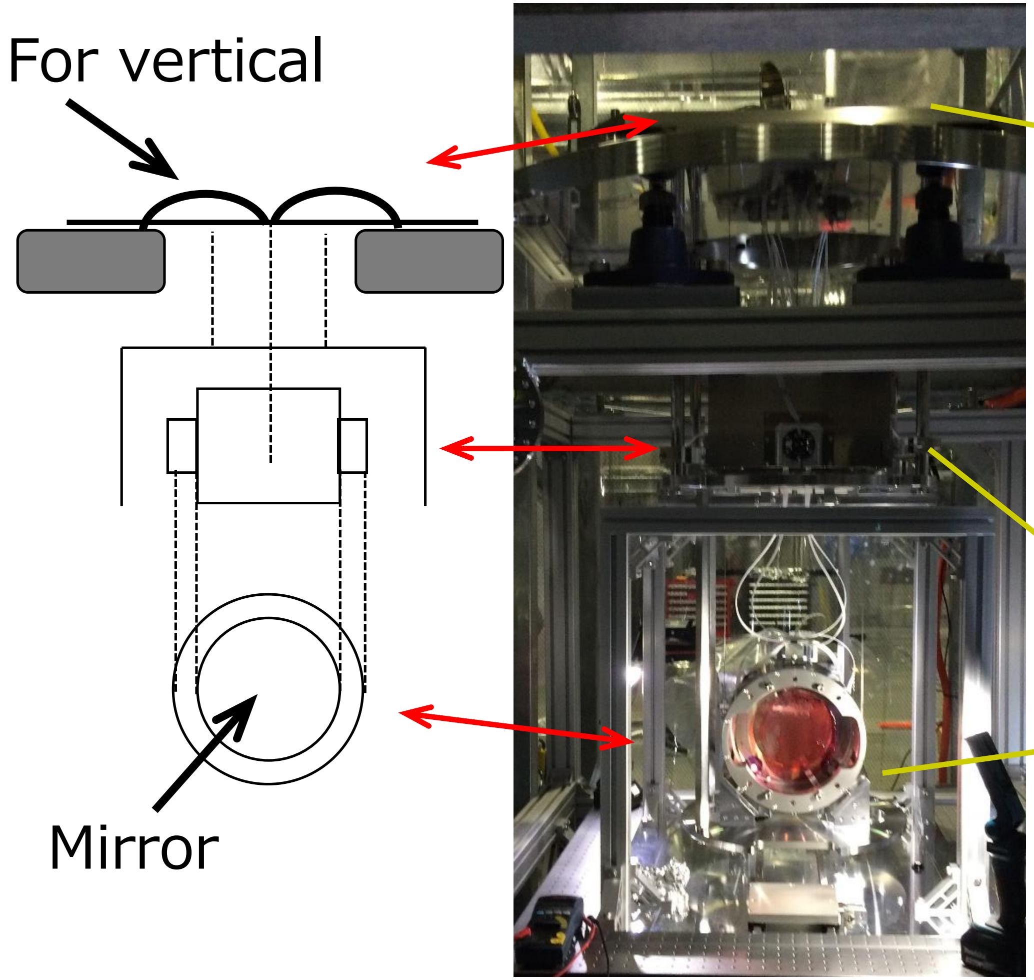




iKAGRA-PR3 suspension / Assembly

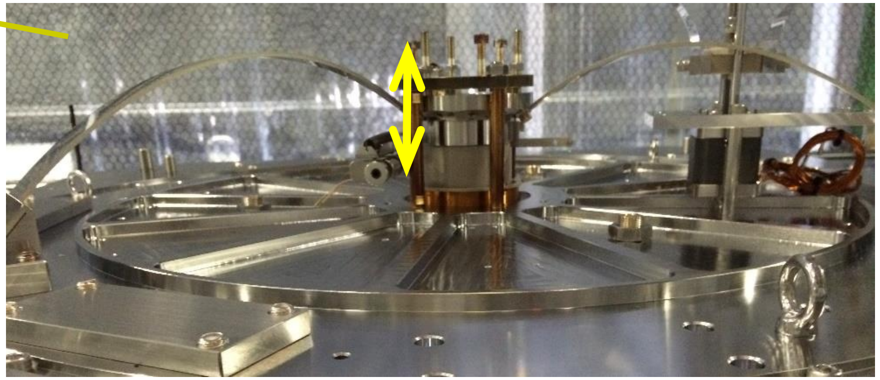


iKAGRA-PR3 suspension / Sensors and actuators

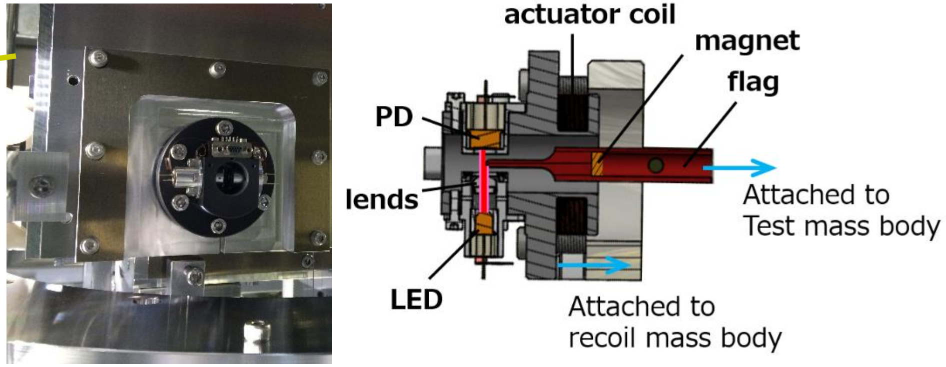


iKAGRA-PR3 SAS

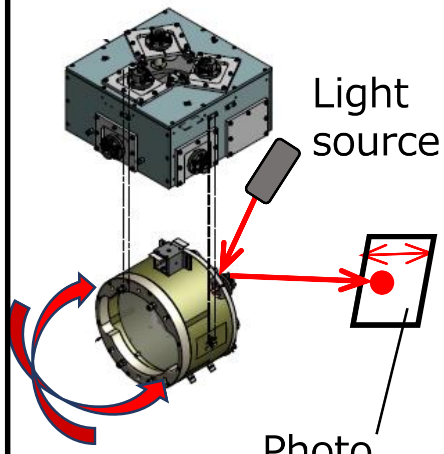
Displacement sensor and coil-magnet actuator 1



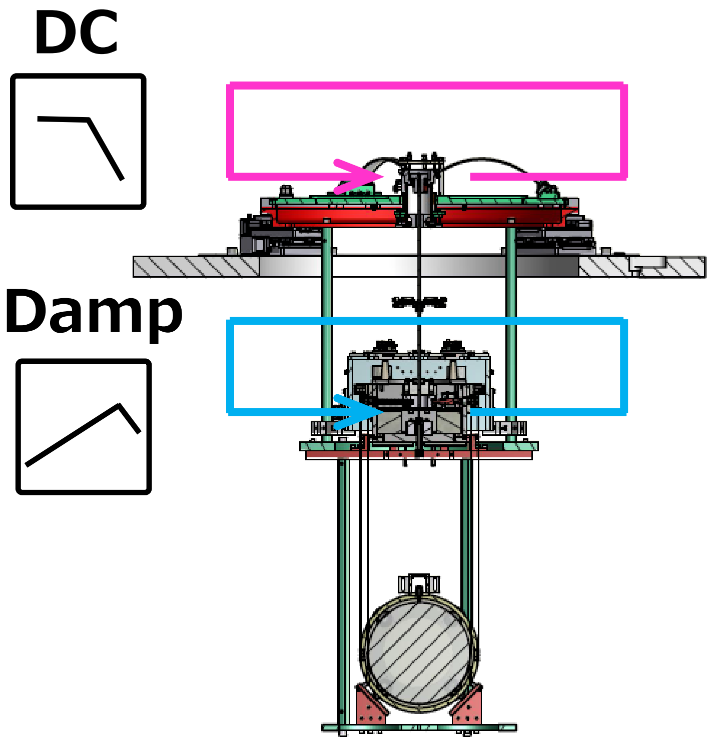
Displacement sensor and coil-magnet actuator 2



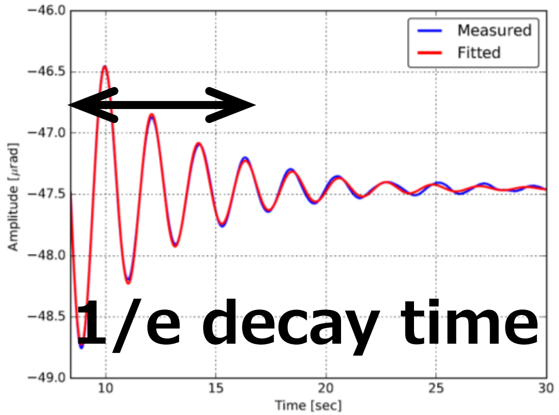
Angular sensor

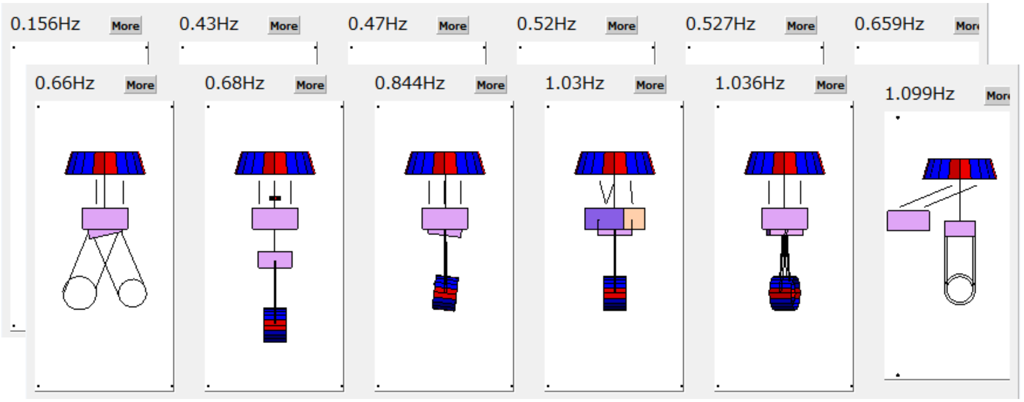


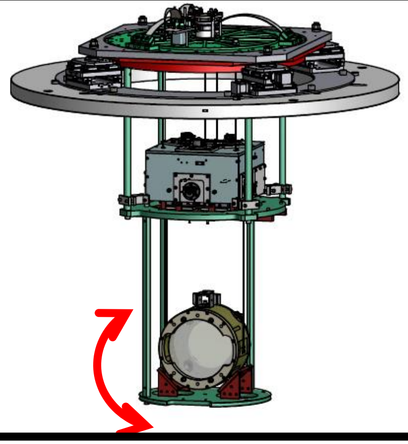
Performance test / Measurement vs. simulation



Test 1: damping performance
→ 1/e decay time for each resonances



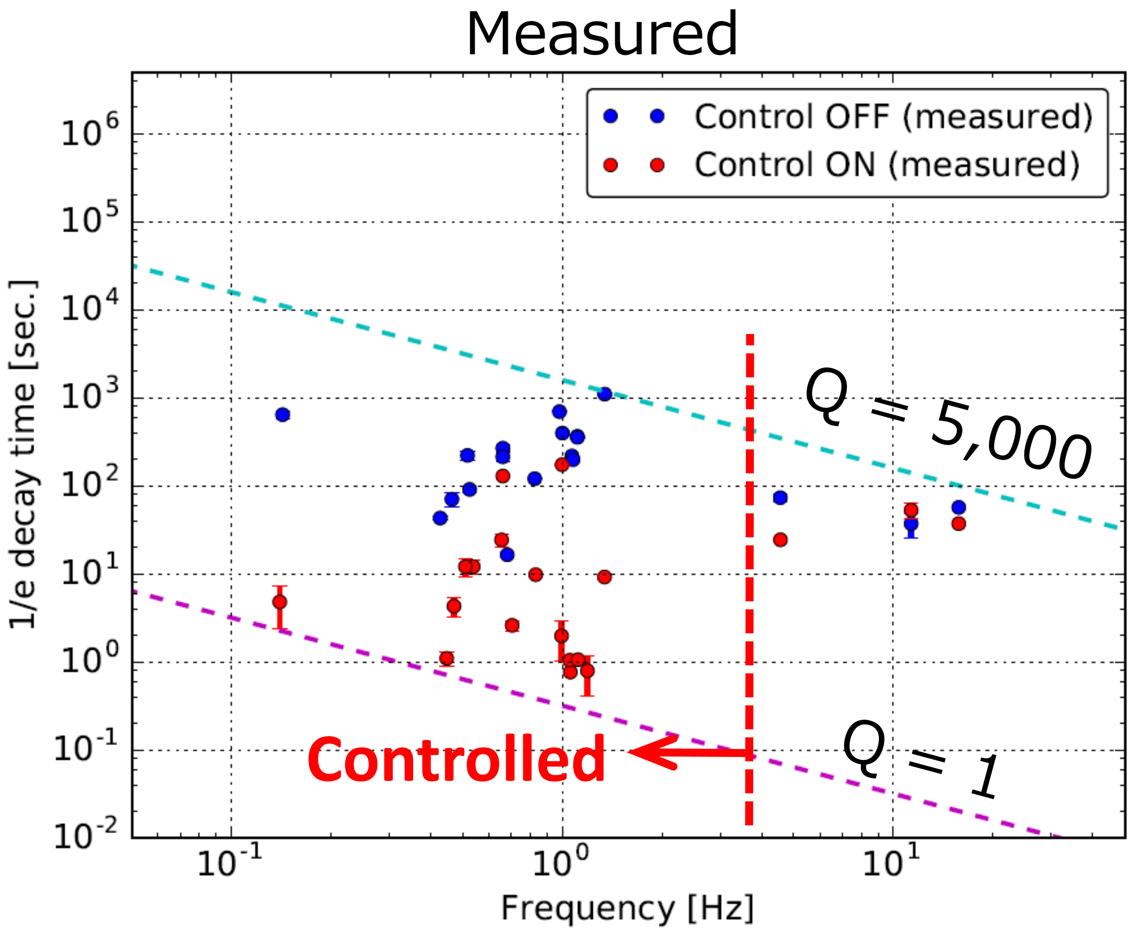


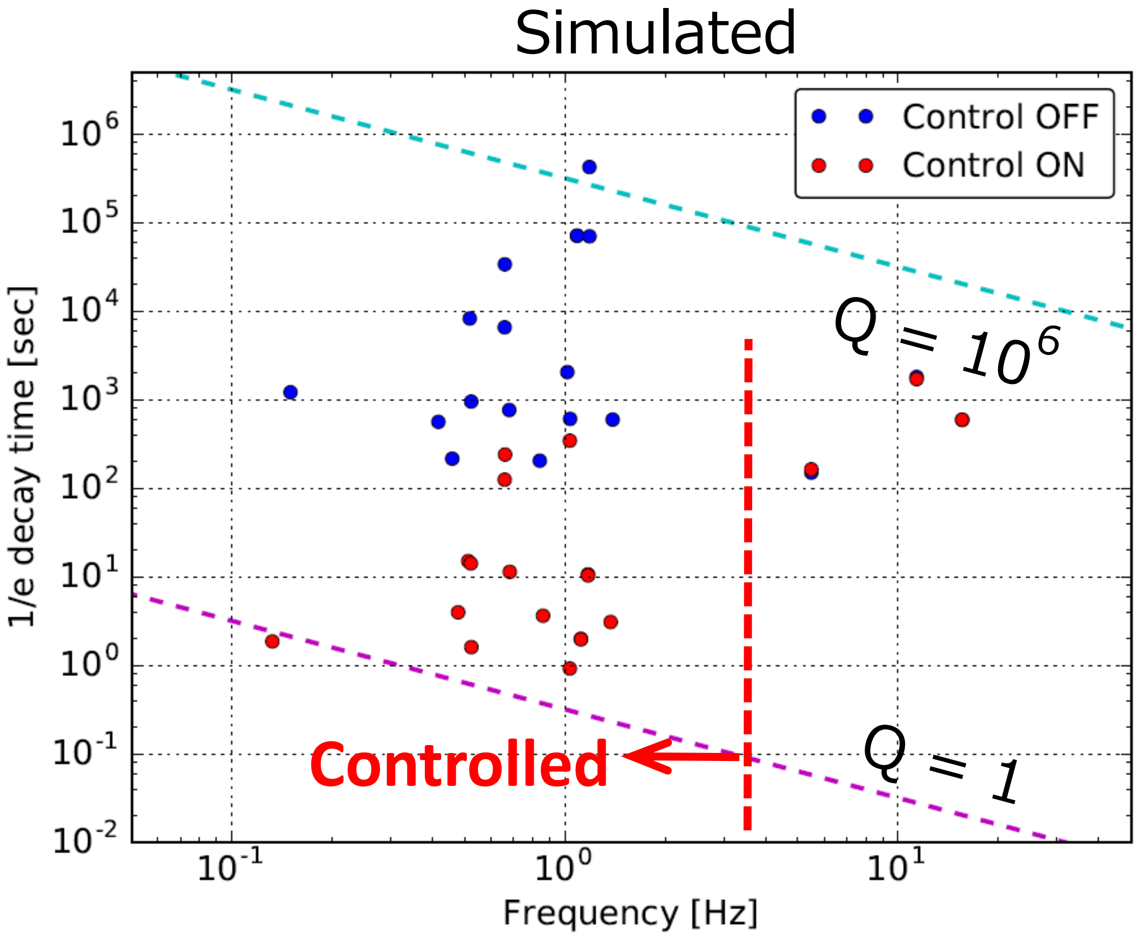


Test 2:
Residual vibration estimation

Performance test 1

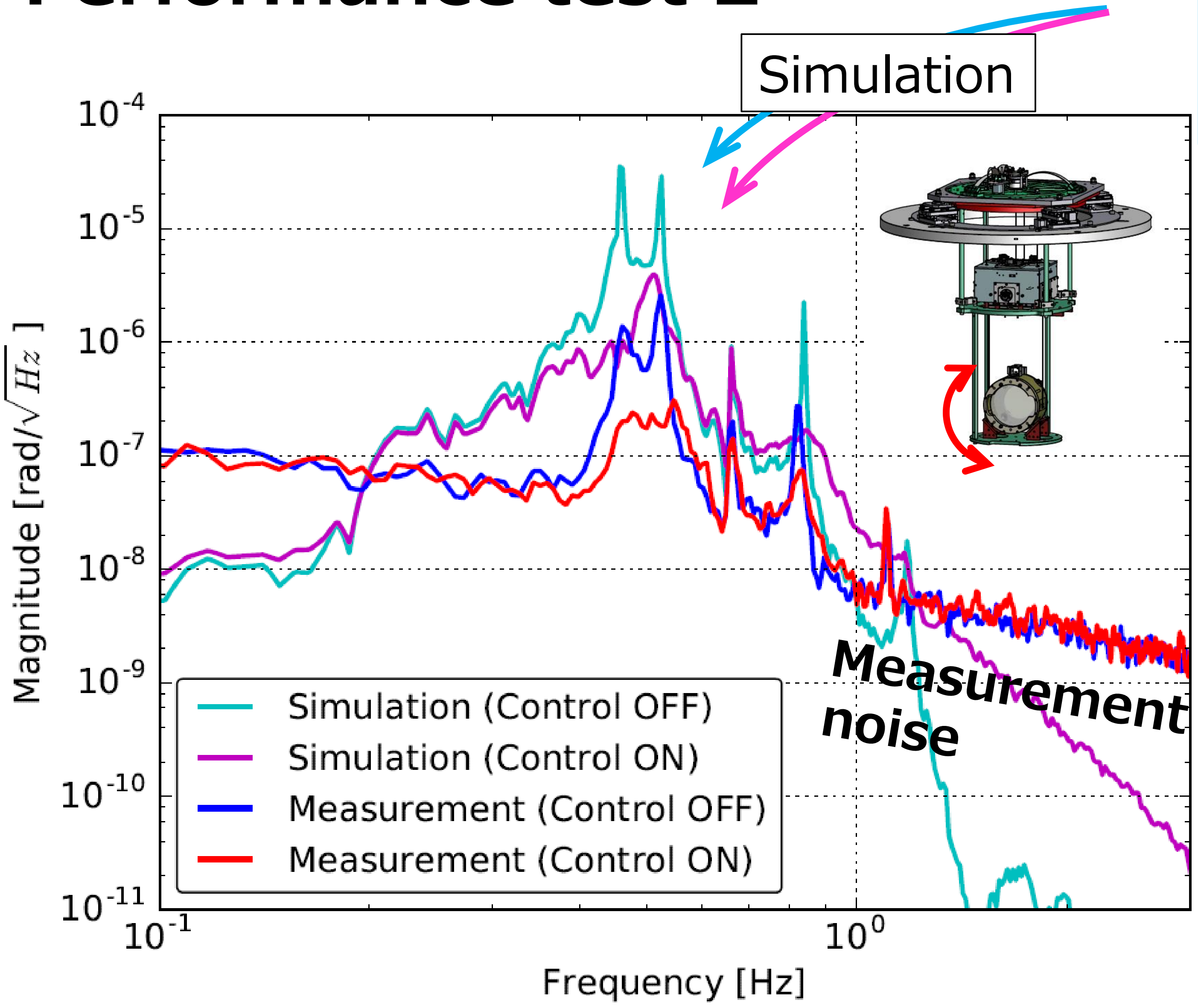
(Q: Quality factor)





1) Control OFF → Necessary to feedback measurement.
2) Control ON → Consistent.

Performance test 2



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

Simulation — Measurement

Uncertainty ~1 order

Suspension point shift?

Lower seismic motion?

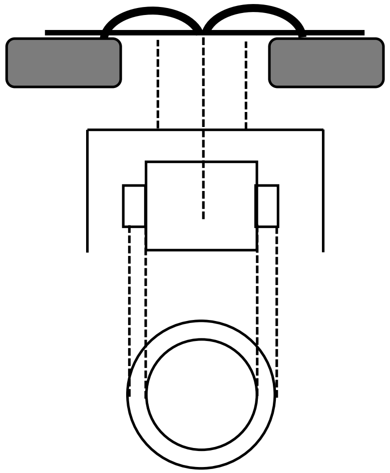
→ Uncertainty ≲ 1 order
→ For designing, calculate using high seismic noise.

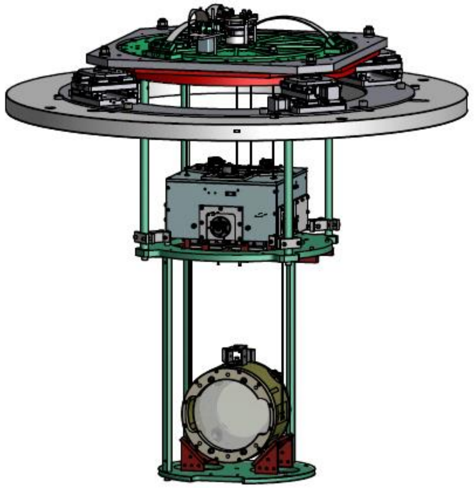
Upgrading for KAGRA

iKAGRA-PR3 SAS → Type-Bp SAS
In order to meet KAGRA requirement.

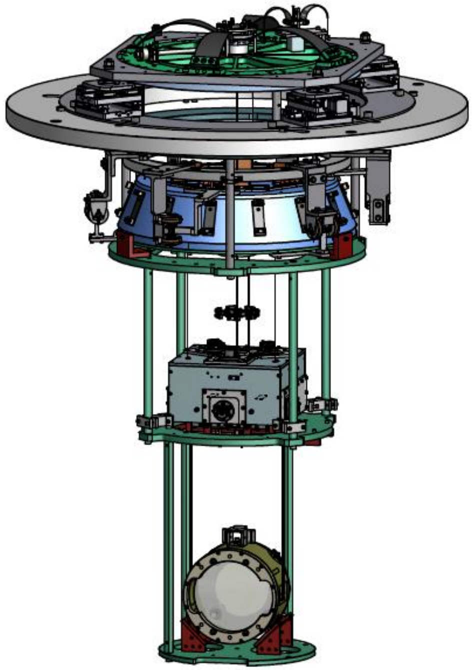
Design
active control systems.

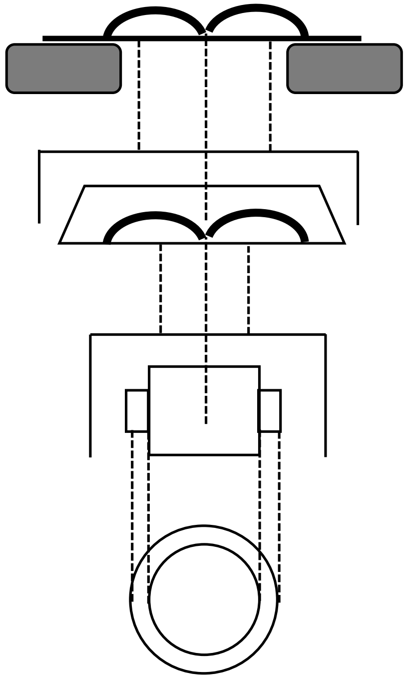
iKAGRA-PR3 SAS



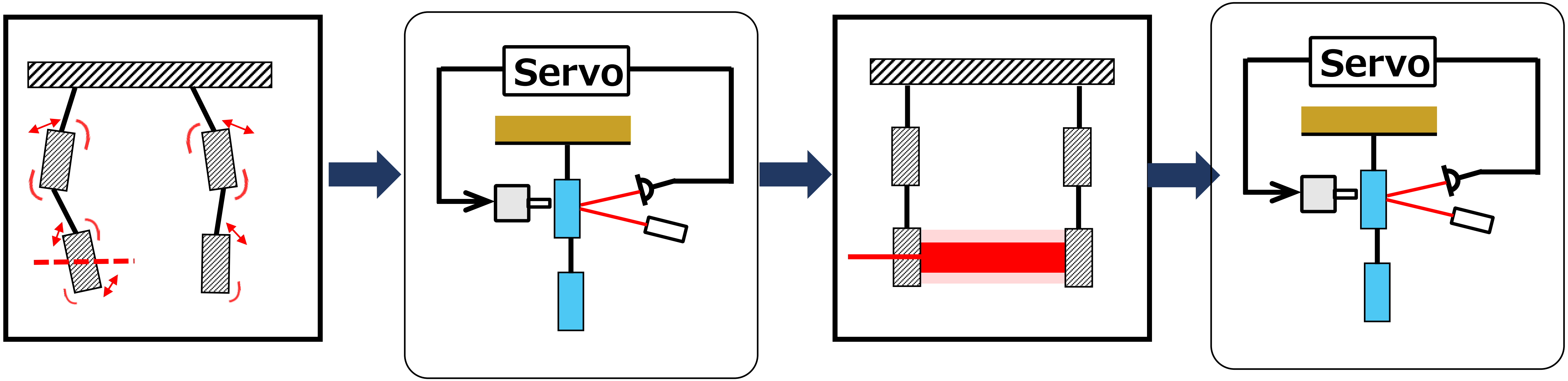


Type-Bp SAS





Designing active control system

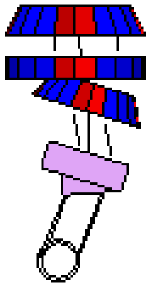


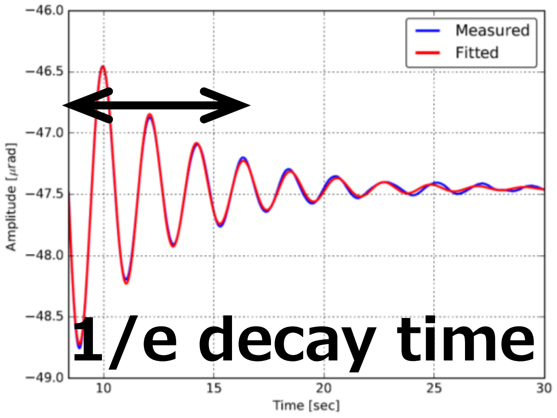
Calm-down phase

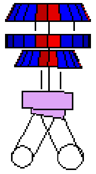
Observation phase

Designing active control system 1

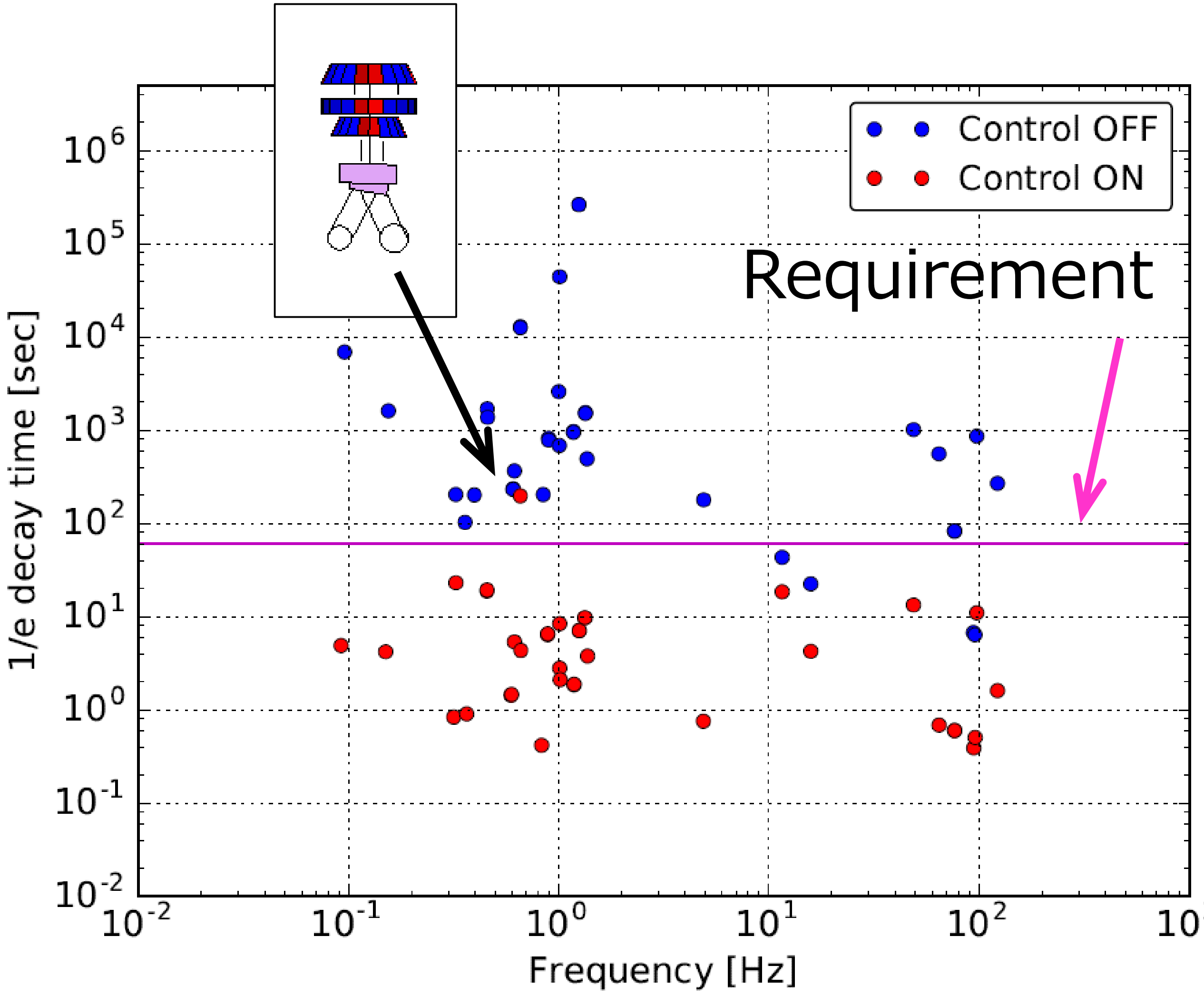
Calm-down phase:
Suppress large disturbance







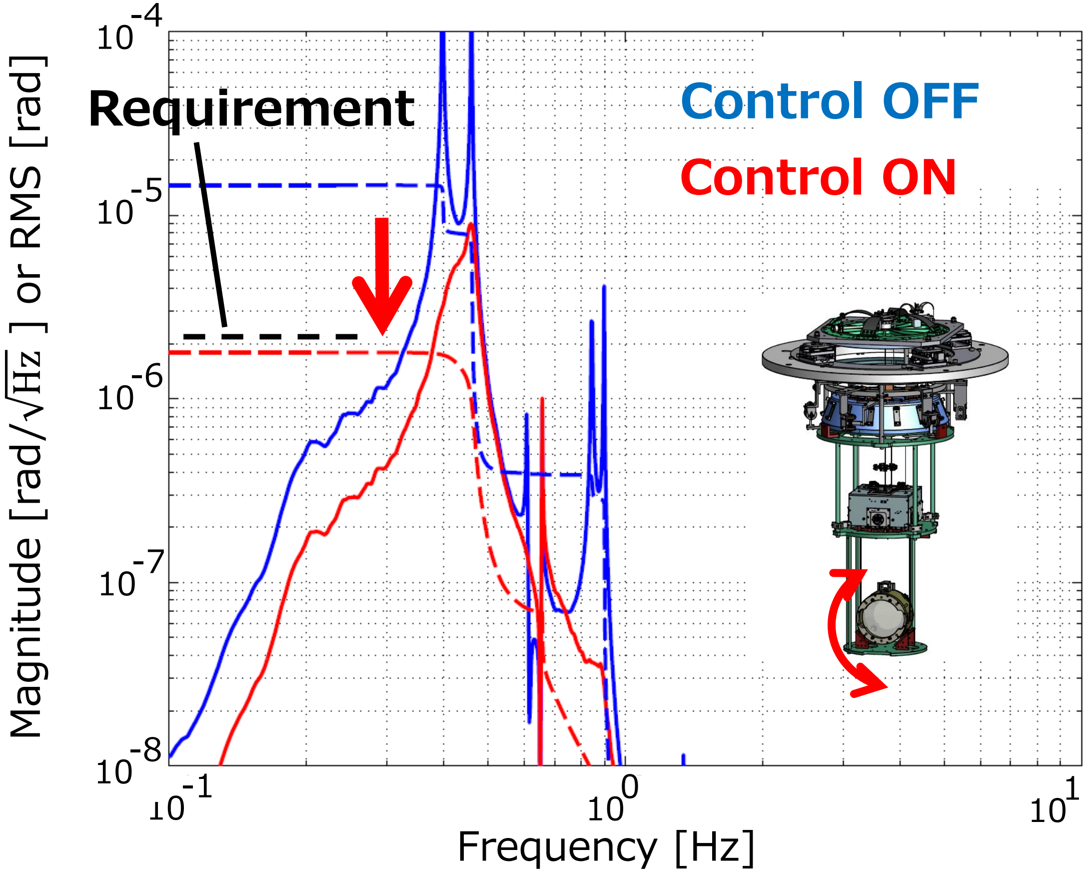
Not disturb operation
→ No problem.

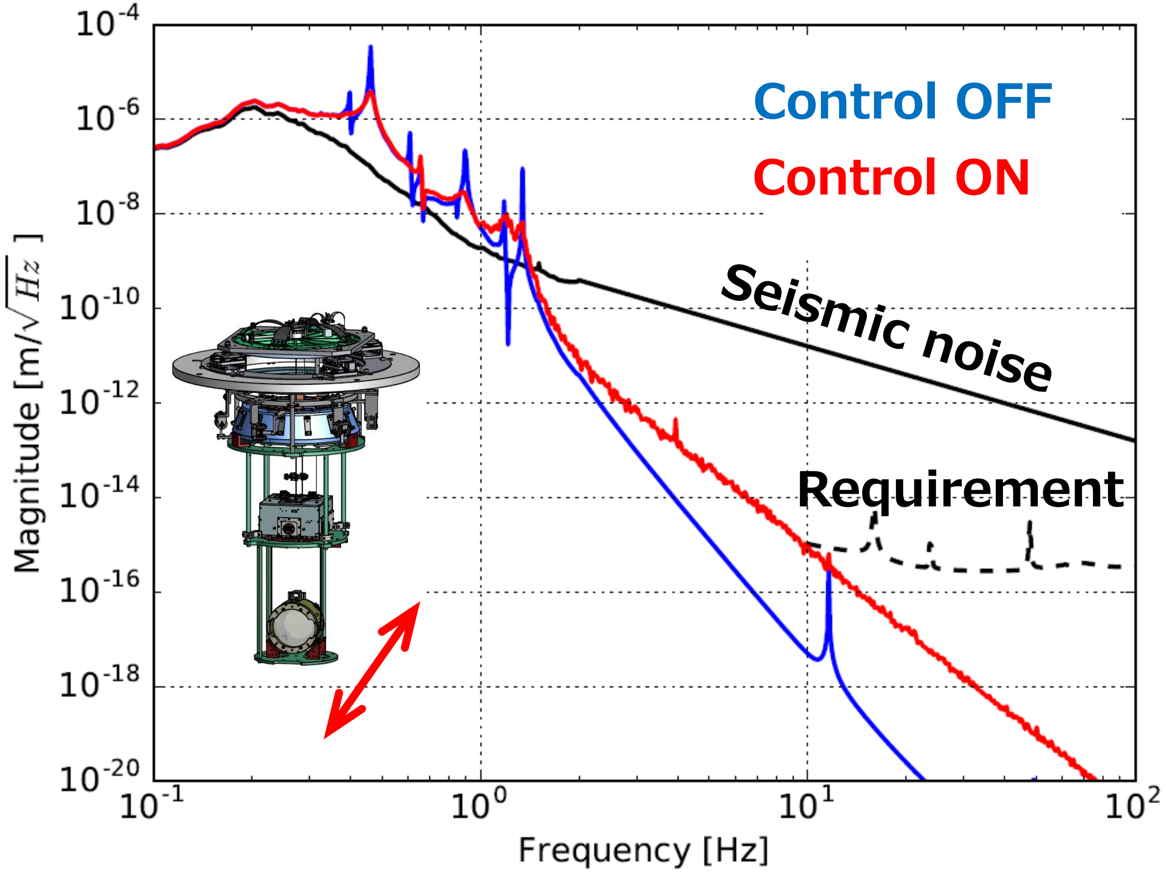


(if all sensors available)

Designing active control system 2

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 gives reasonable prediction.***

3) Active control system for a KAGRA-SAS is designed.
   → ***Next: implement into actual suspensions.***

Summary

1. Source localization

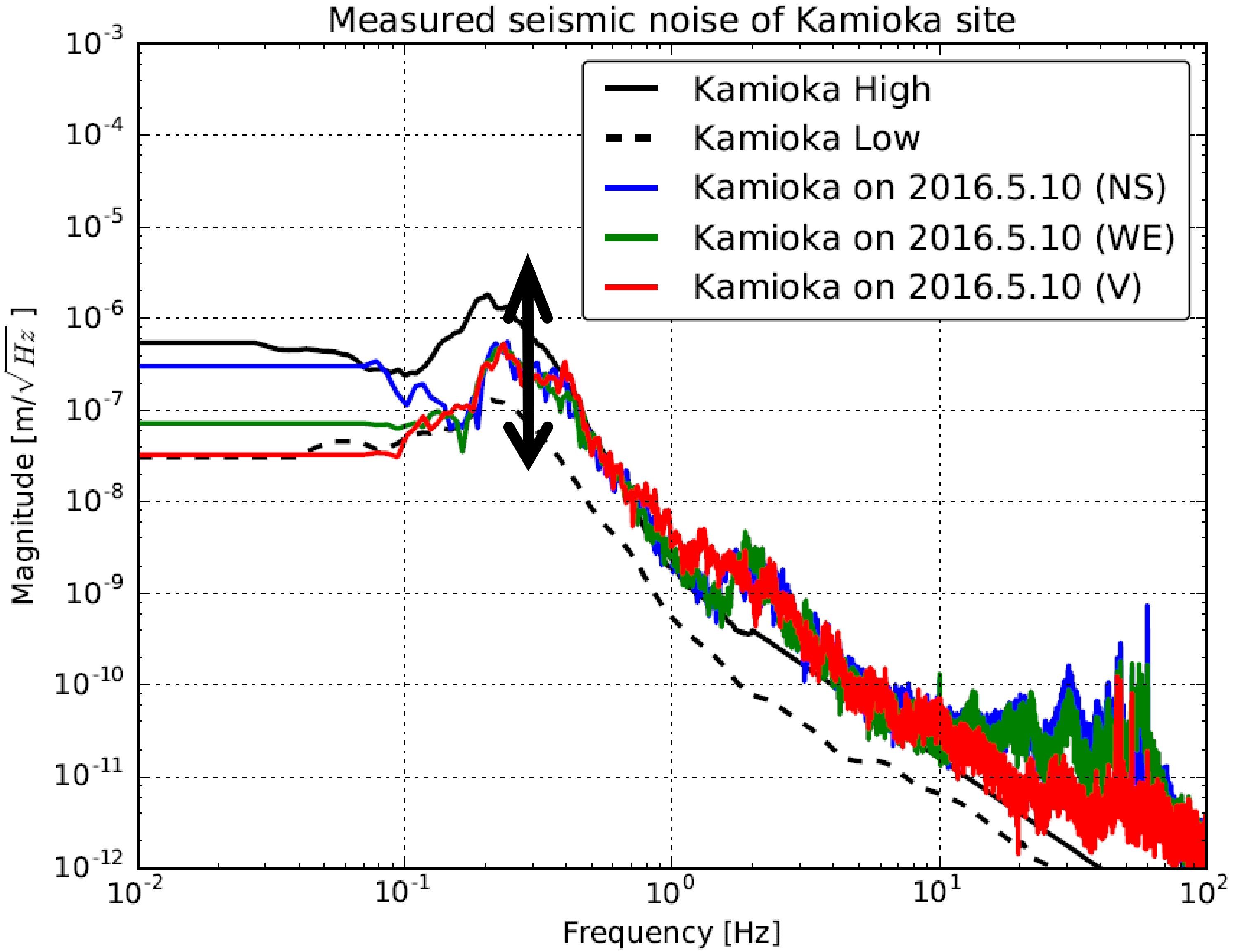
A localization with hierarchical network is demonstrated.
→ ***Low sensitivity detector can contribute.***
→ ***4th detector contributes.*** → ***useful for EM follow-up.***

2. Detector development

1) iKAGRA-PR3 suspension was assembled for iKAGRA operation.
2) Its performance were tested.
→ ***Simulation gives reasonable prediction.***
3) Active control system for a KAGRA-SAS is designed.
→ ***Next: implement into KAGRA suspensions.***

Back up

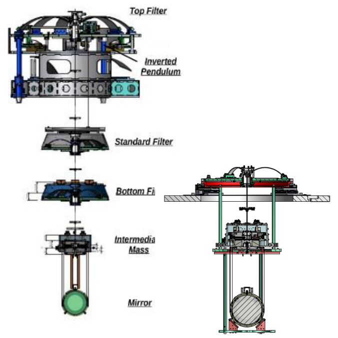
Seismic noise of Kamioka (on 2016.5.10)



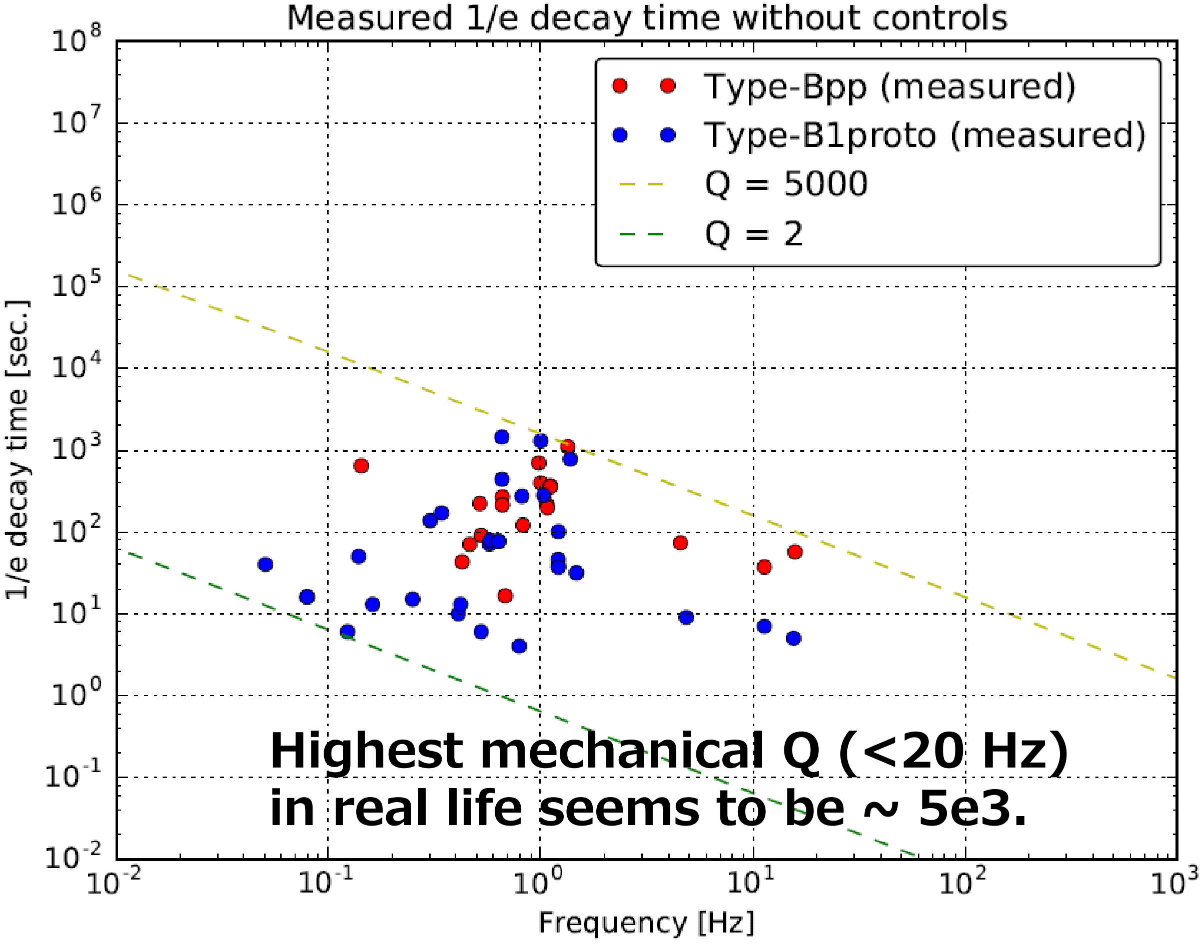
seismic noise was measured on 2016.5.10.

PR3 measurement was conducted on 2016.5.24.

Mechanical Q factor of free swinging : Type-B1proto vs. Type-Bpp

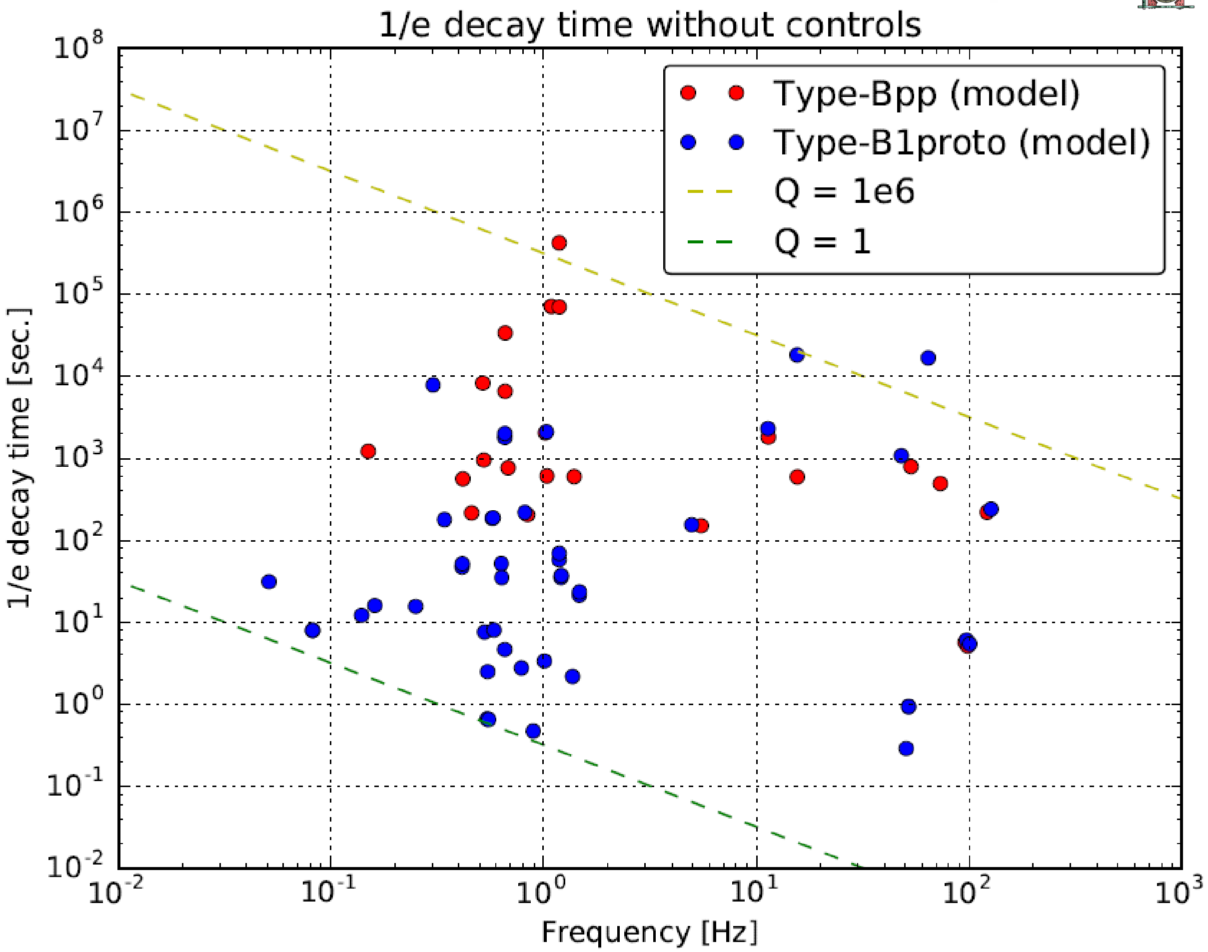


Measured



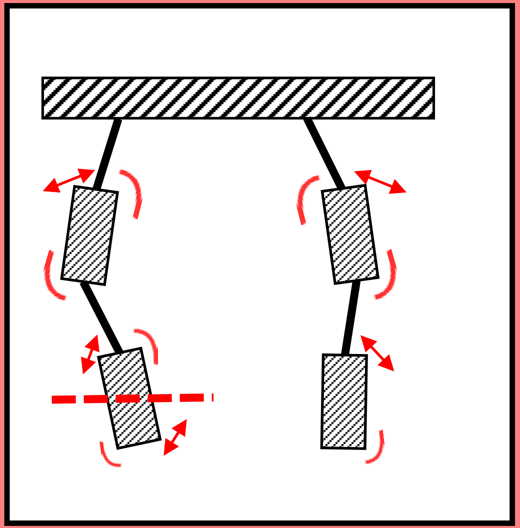
Highest mechanical Q (<20 Hz) in real life seems to be ~ 5e3.

Model



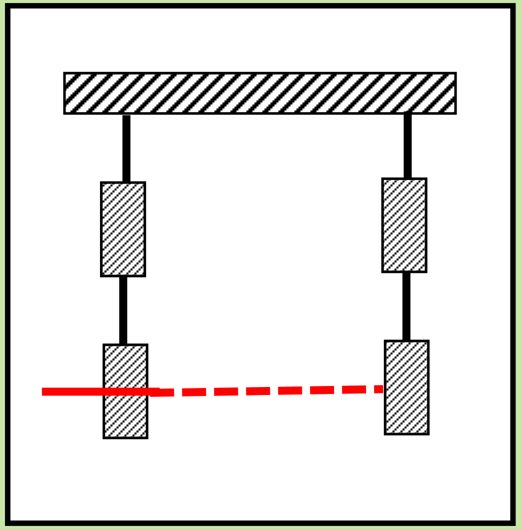
Designing active control system / Control phase

1. Calm-down phase



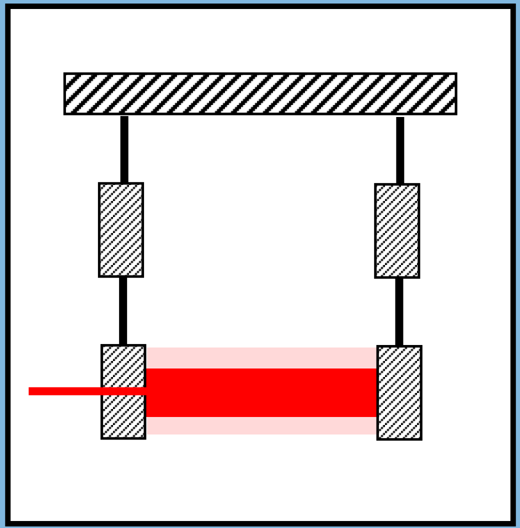
Suppress
large disturbance

2. Lock-acquisition phase



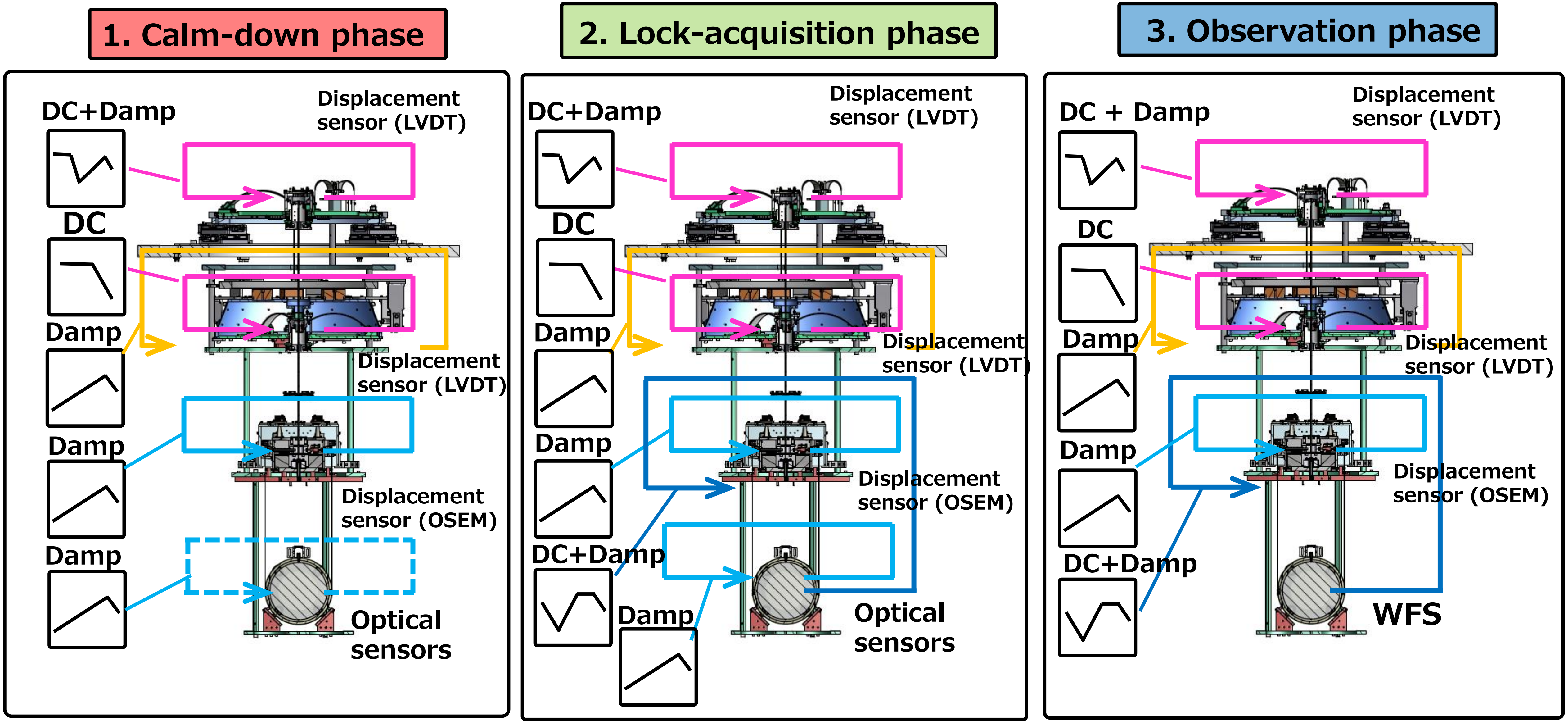
Reduce RMS velocity
RMS angle
(Root-Mean-Square)

3. Observation phase

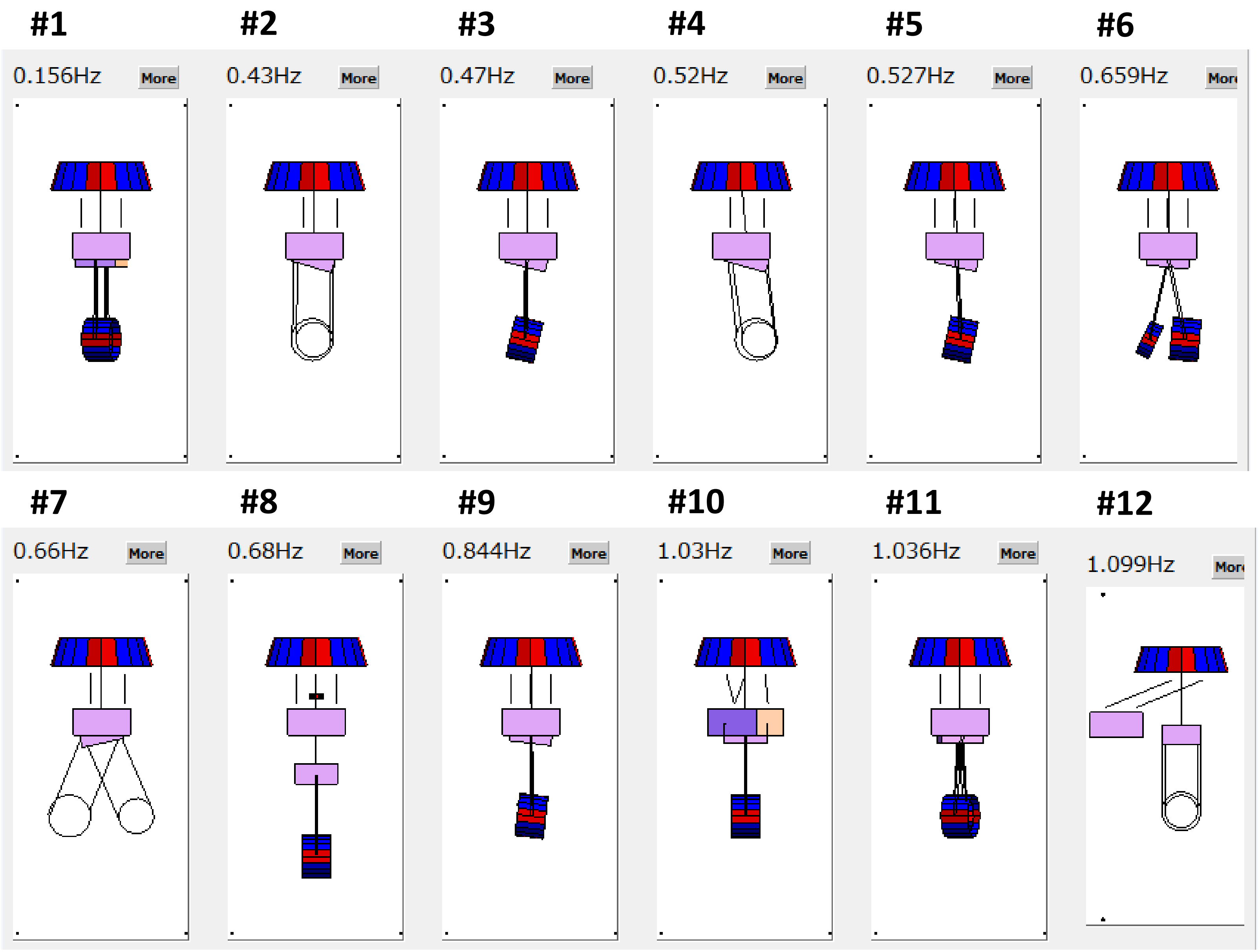


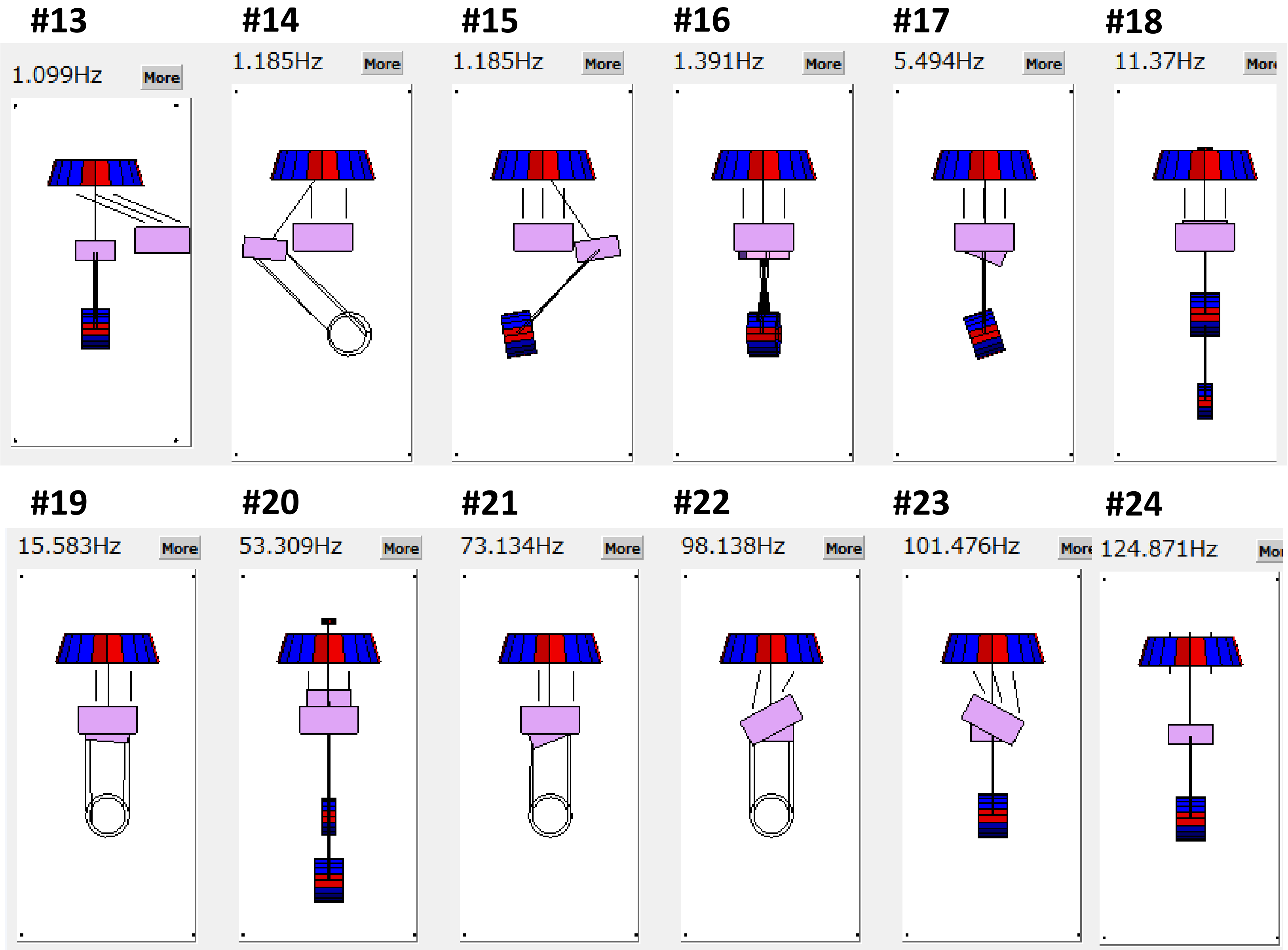
Keep position
with low noise
control

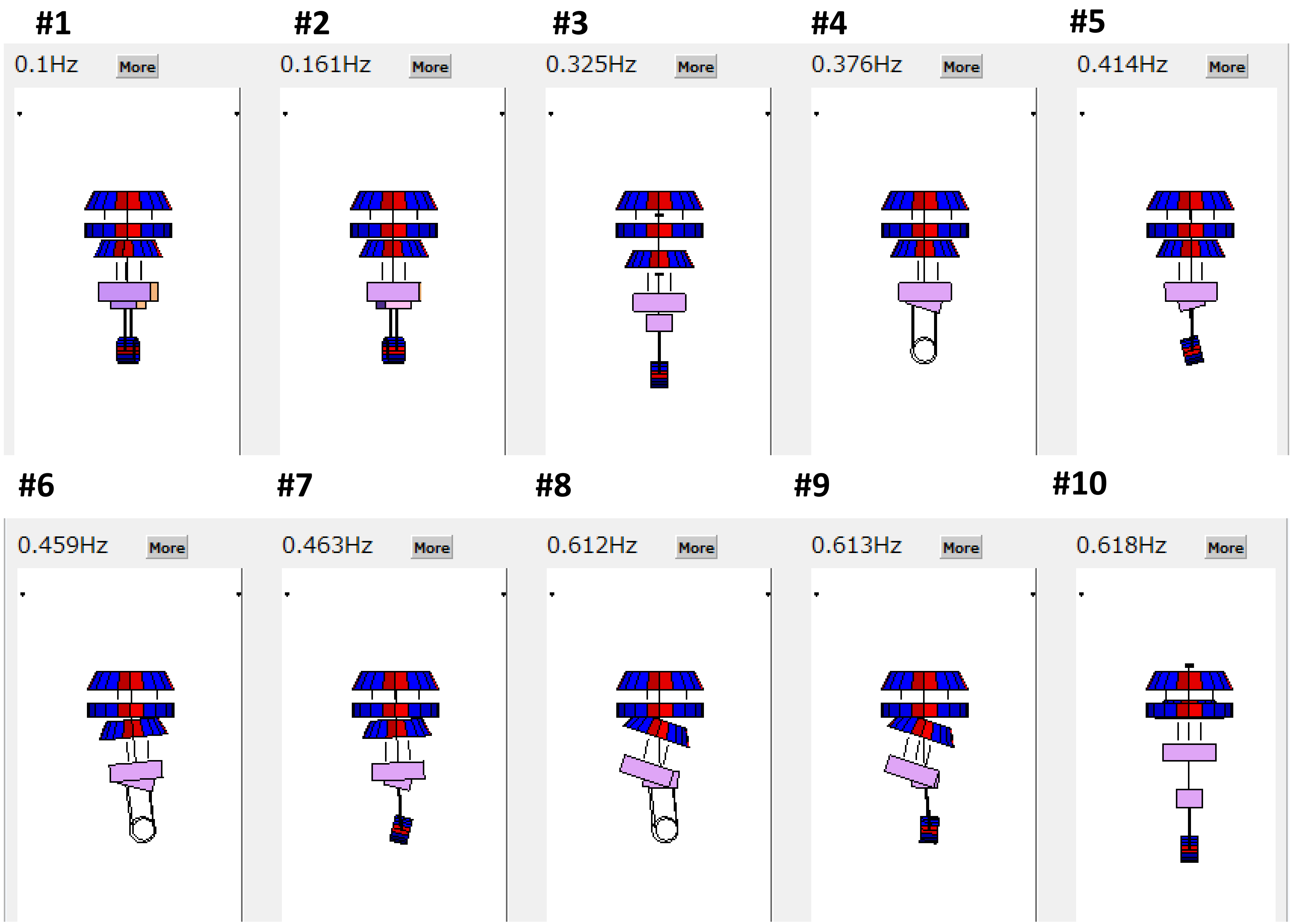
Designing active control system / Type-Bp SAS



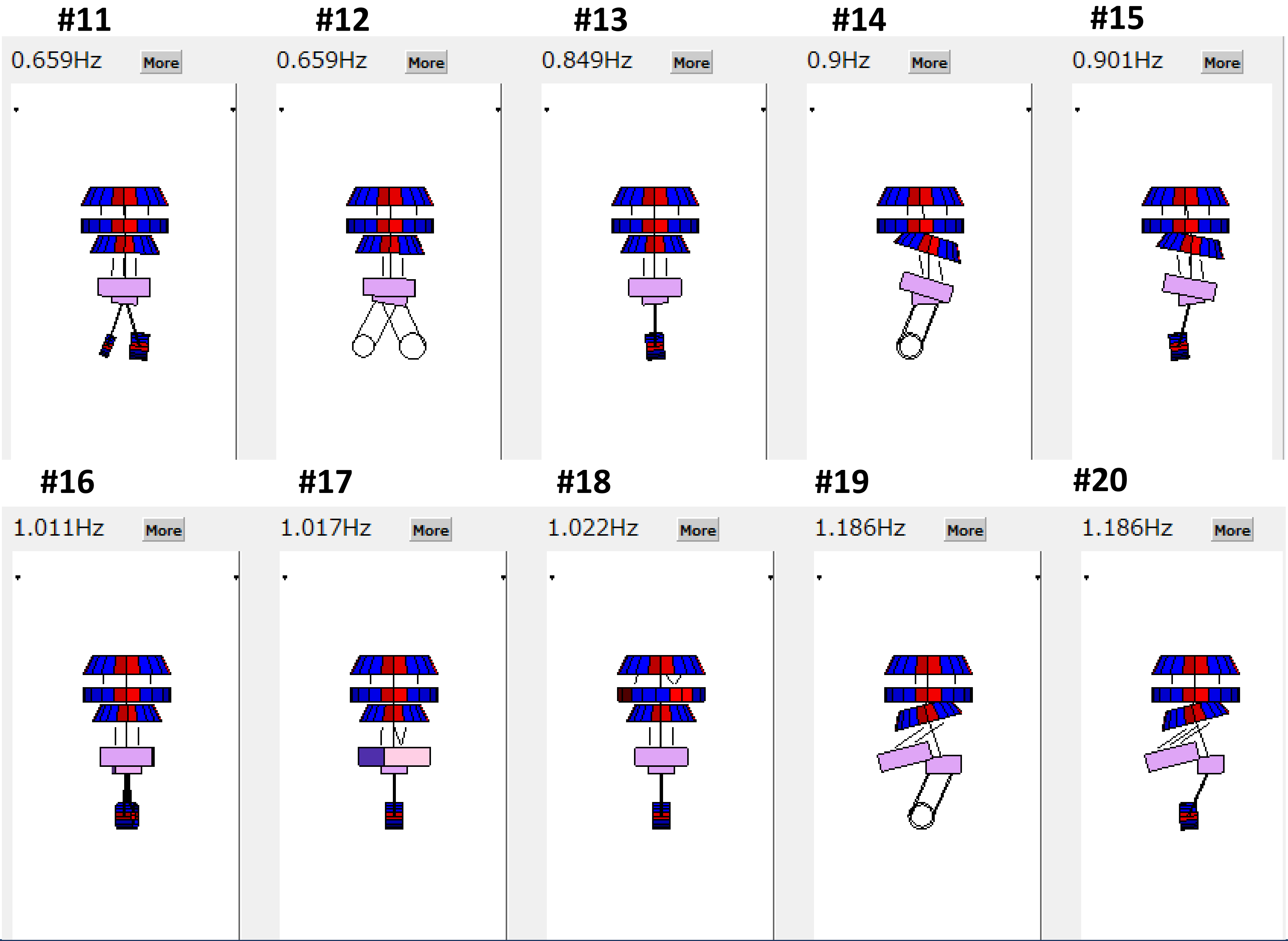
TypeBpp SAS
Eigen mode List : 24 modes



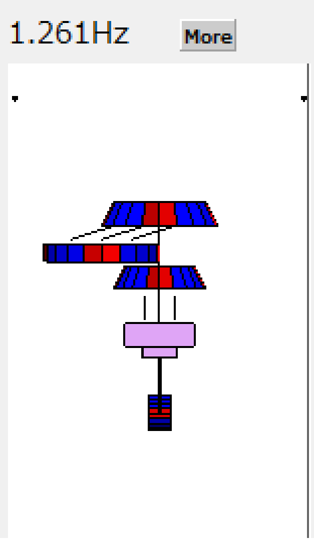

#13
1.099Hz
More
#14
1.185Hz
More
#15
1.185Hz
More
#16
1.391Hz
More
#17
5.494Hz
More
#18
11.37Hz
#19
15.583Hz
More
#20
53.309Hz
More
#21
73.134Hz
More
#22
98.138Hz
More
#23
101.476Hz
#24
124.871Hz



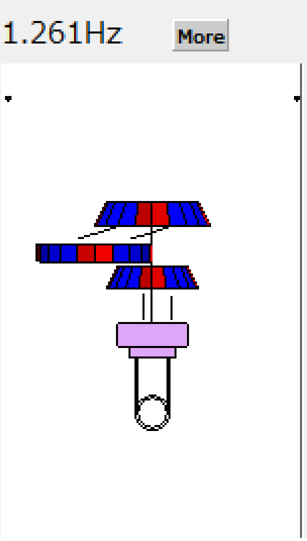
TypeBp SAS
Eigen mode List : 36 modes


#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



#22



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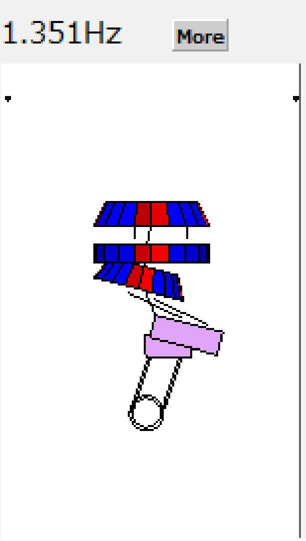
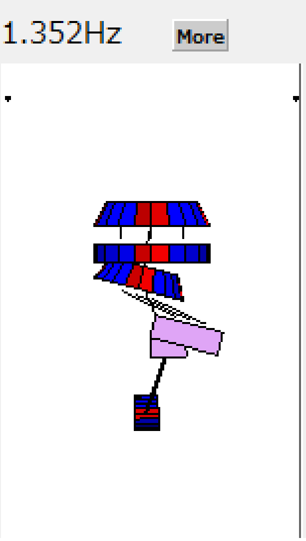
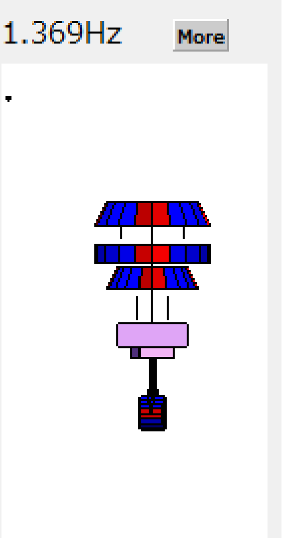


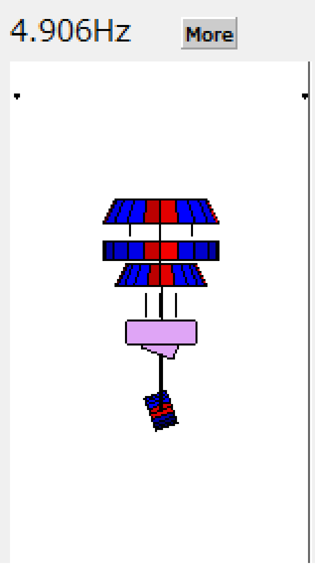
#24



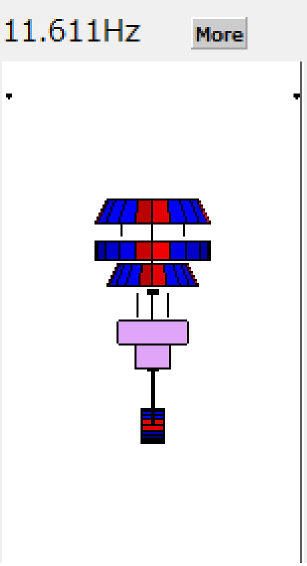
#25



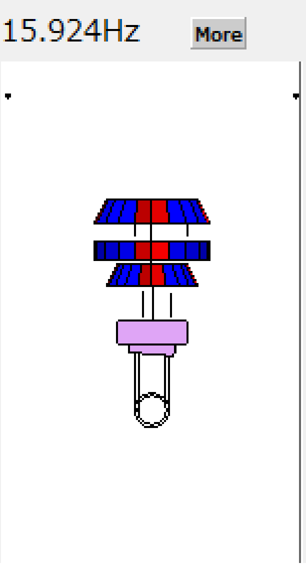
#26



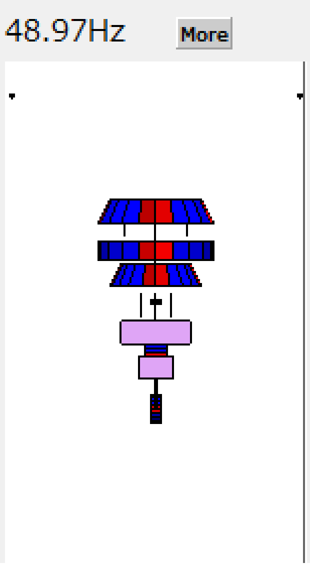
#27



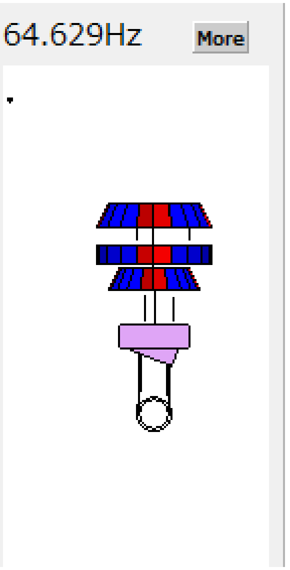
#28



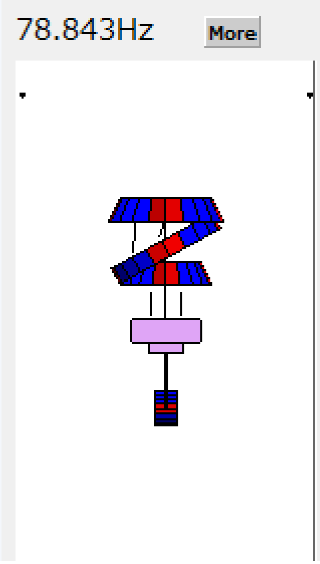
#29



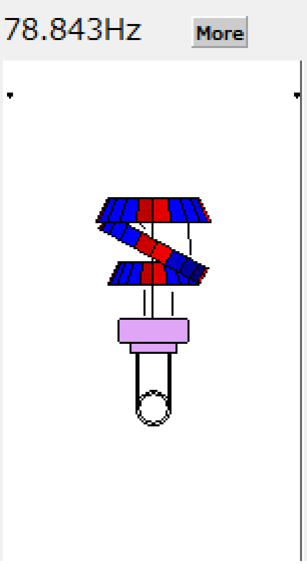
#30



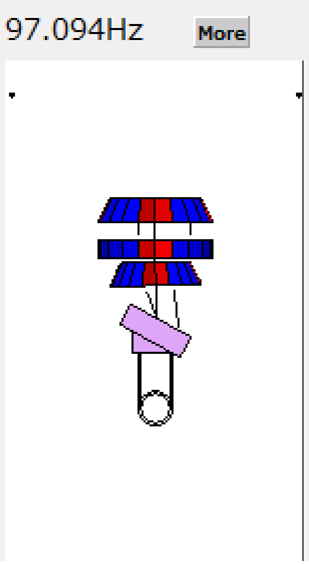
#31



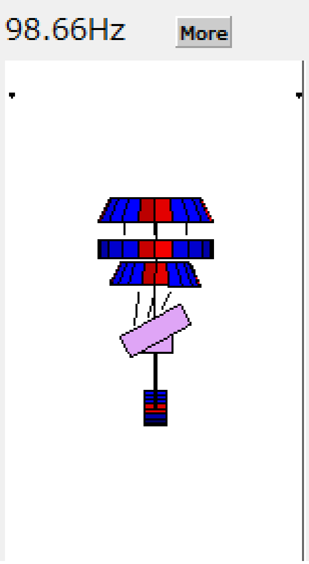
#32



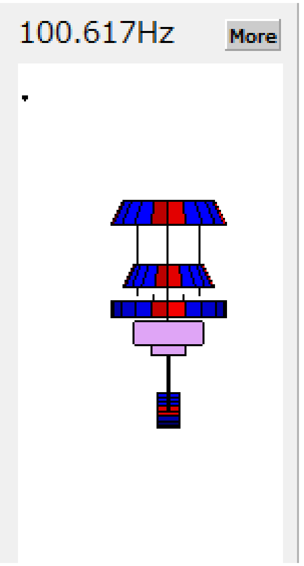
#33



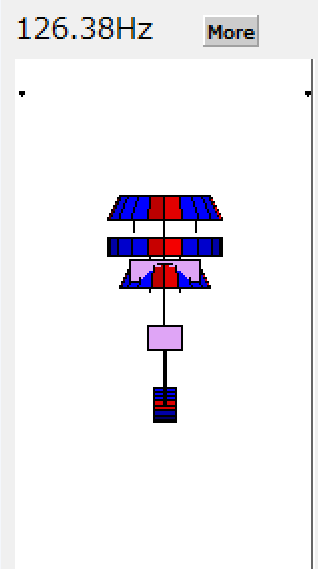
#34

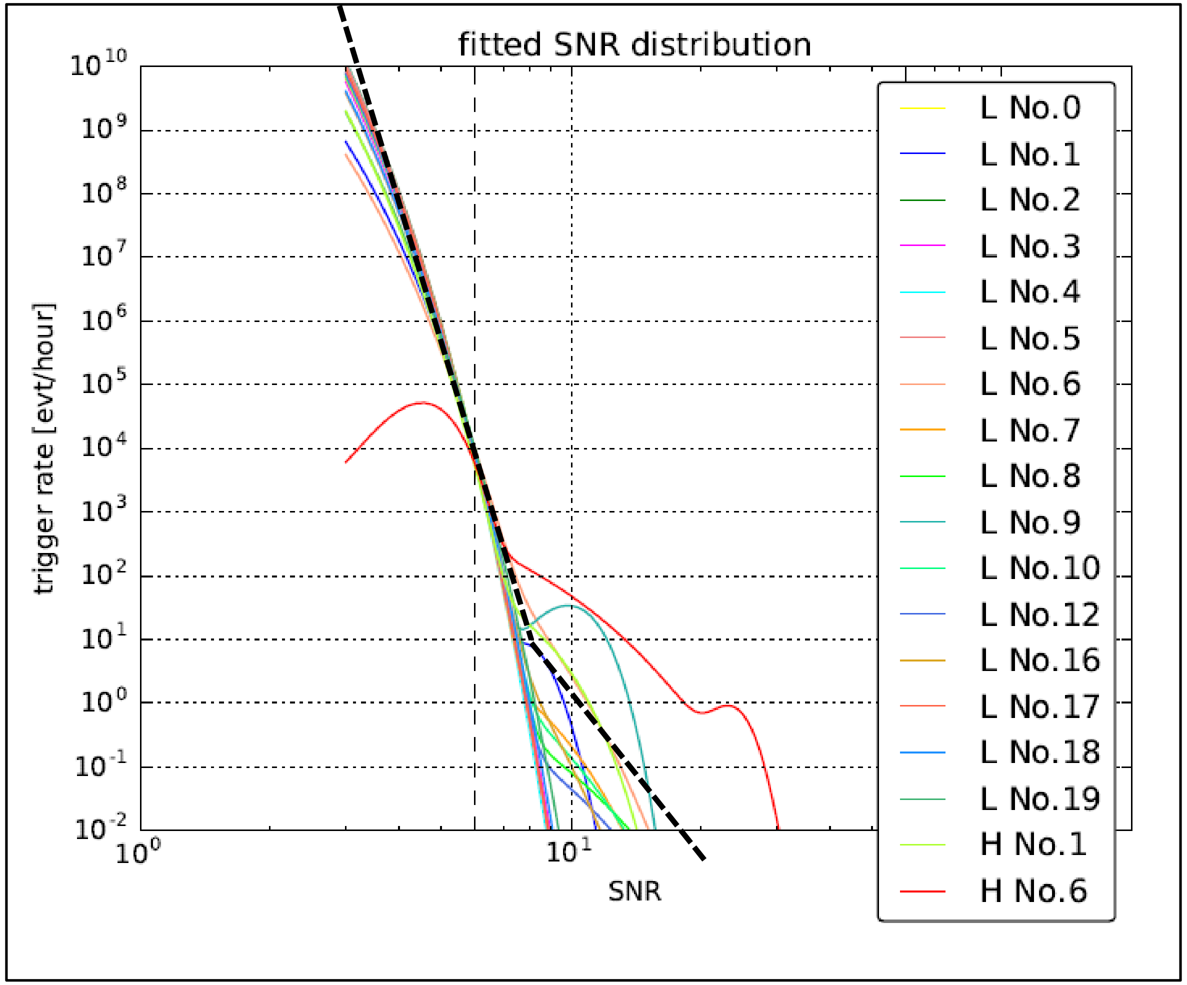


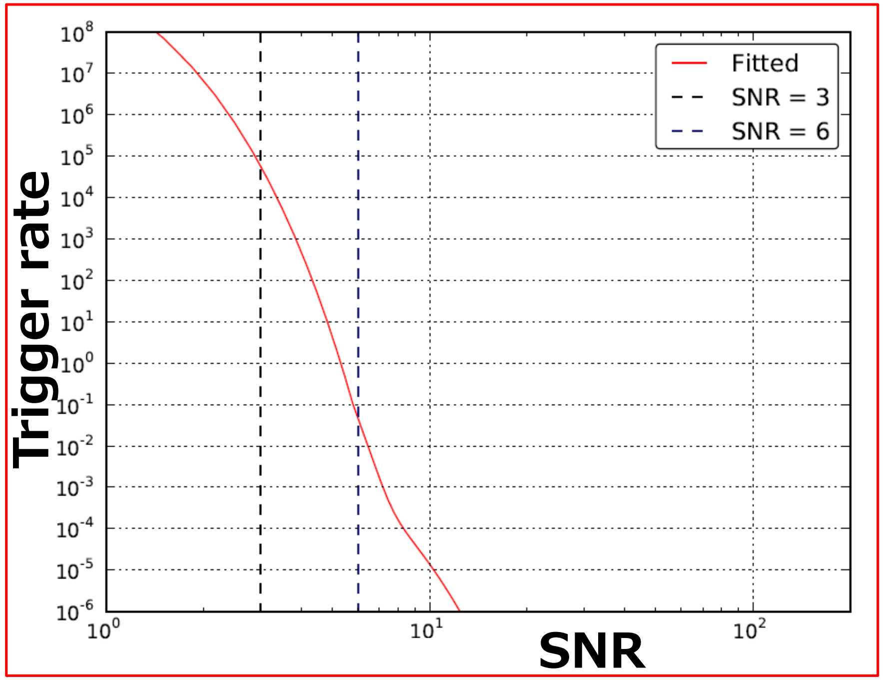
#35



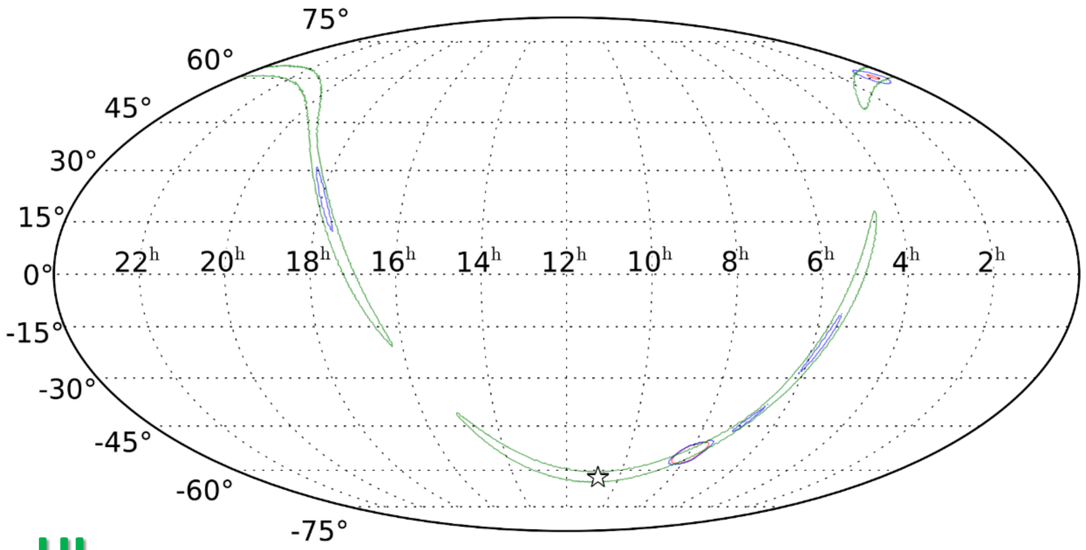
#36



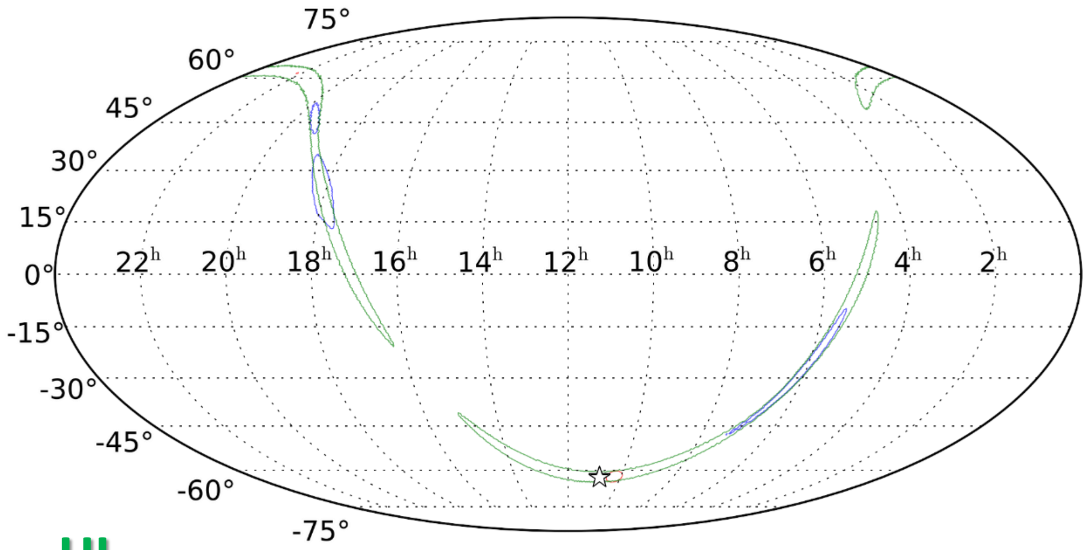

fitted SNR distribution
trigger rate [evt/hour]
SNR
L No.0
L No.1
L No.2
L No.3
L No.4
L No.5
L No.6
L No.7
L No.8
L No.9
L No.10
L No.12
L No.16
L No.17
L No.18
L No.19
H No.1
H No.6


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)

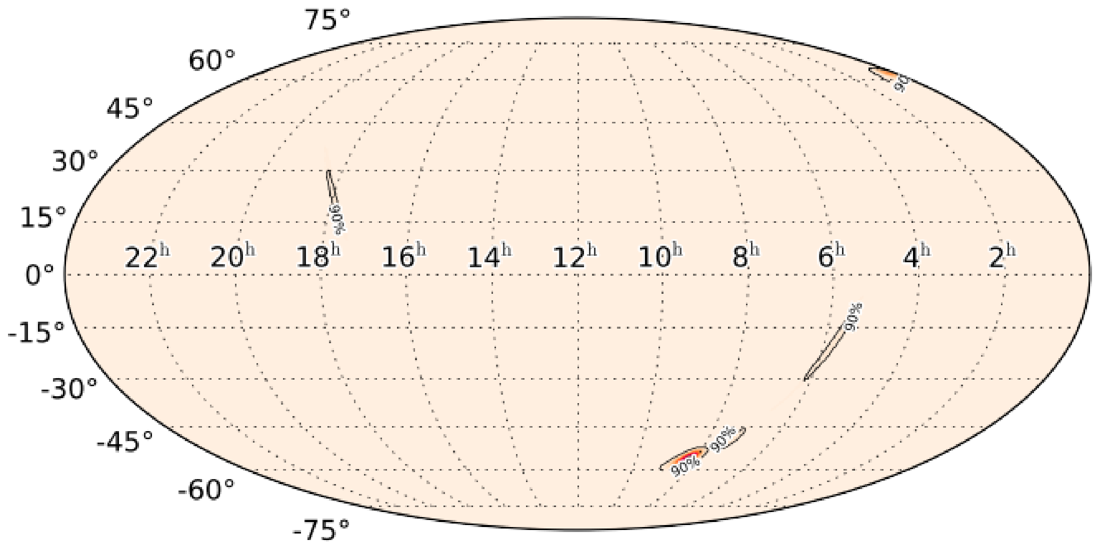
Case 1: worst case
HL+Vr, or HL
(Based on ***FAP***)

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)

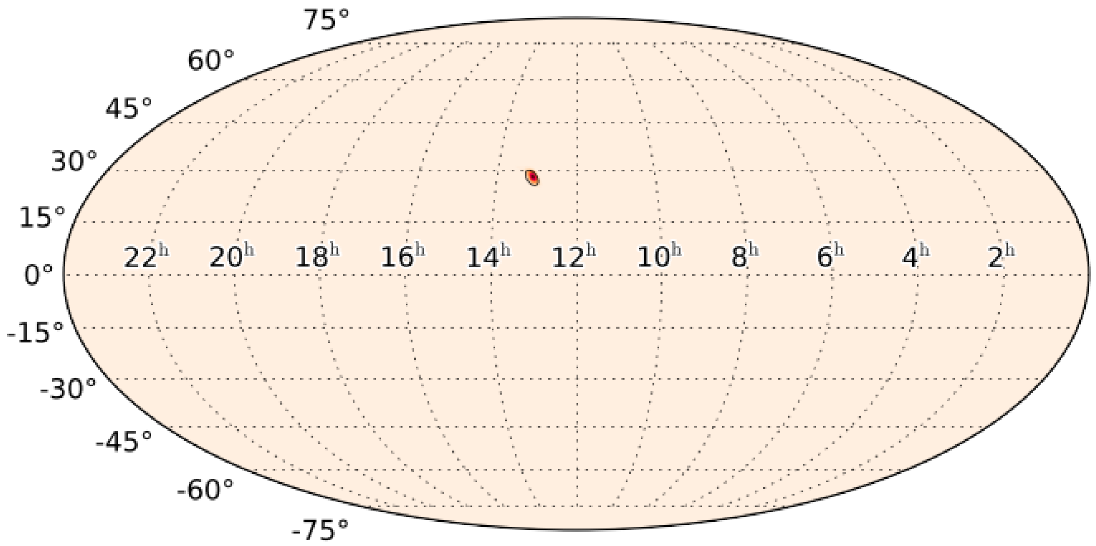
Expected localization performance / by HLV

HL+Vrandom



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

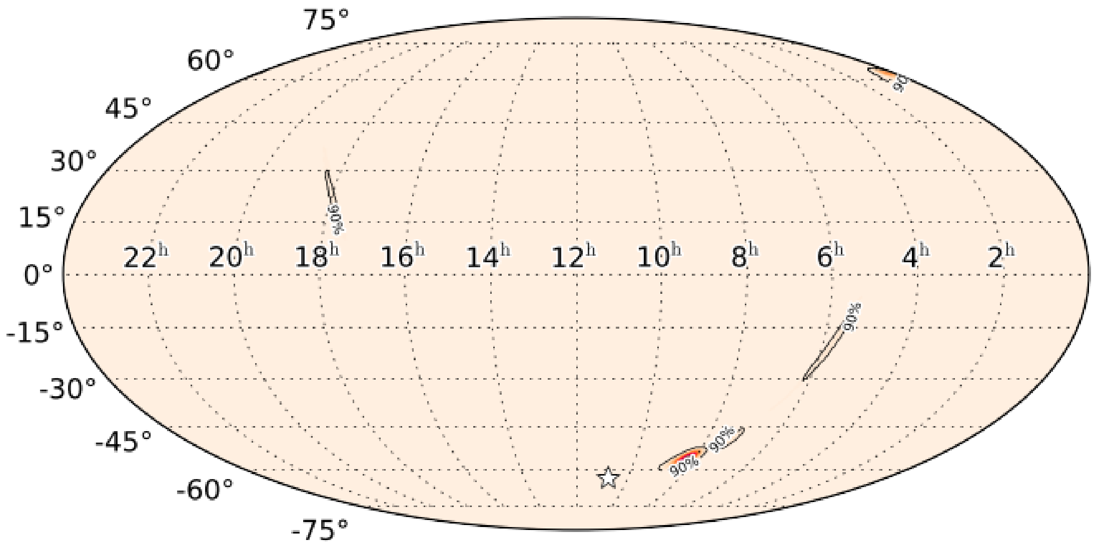
HL+Vinjection



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

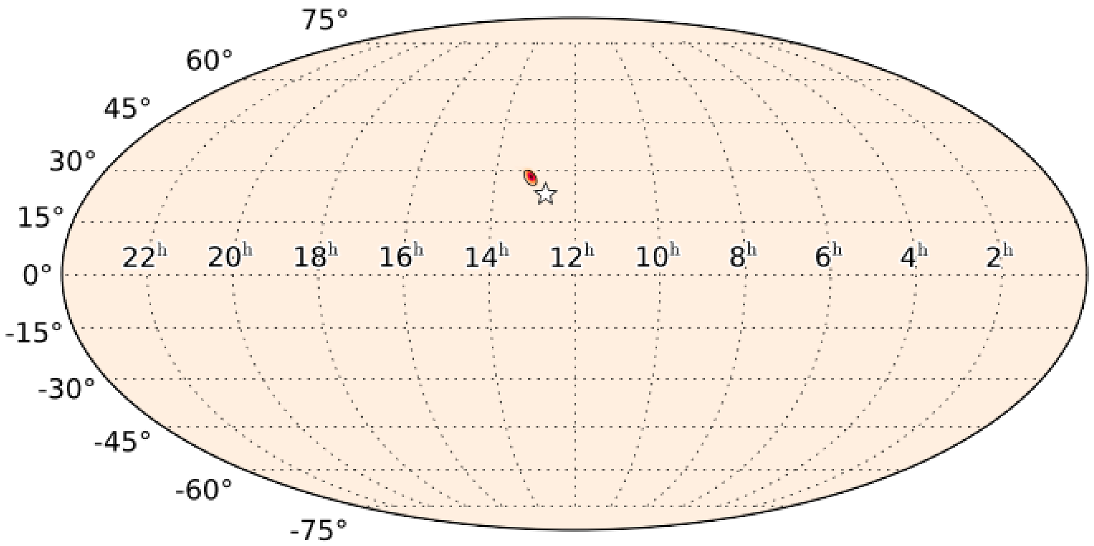
Expected localization performance / by HLV

HL+Vrandom



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

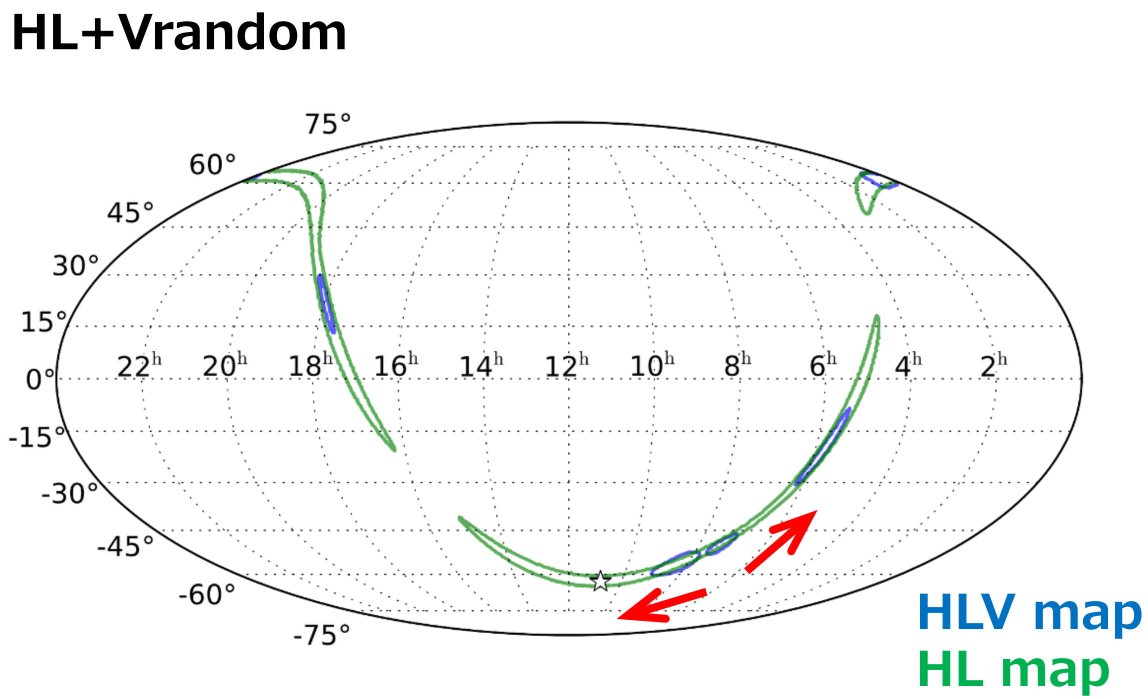
HL+Vinjection

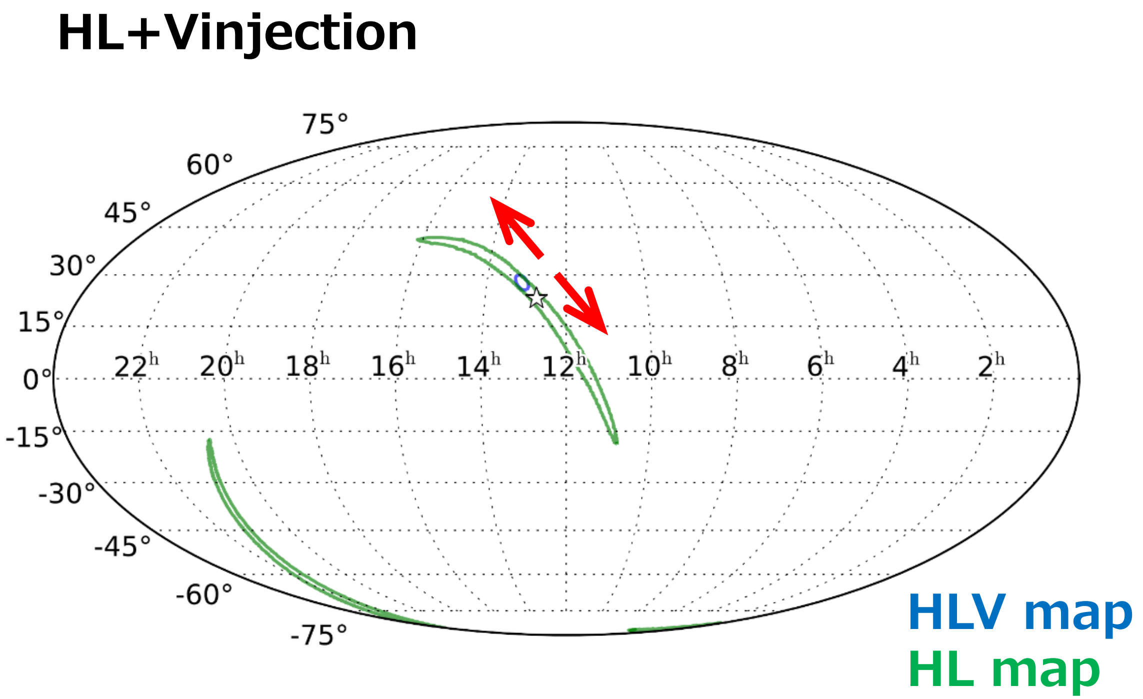


SNR (H)	SNR (L)	SNR(V)
16.5	17.1	3.9

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

Expected localization performance / by HLV

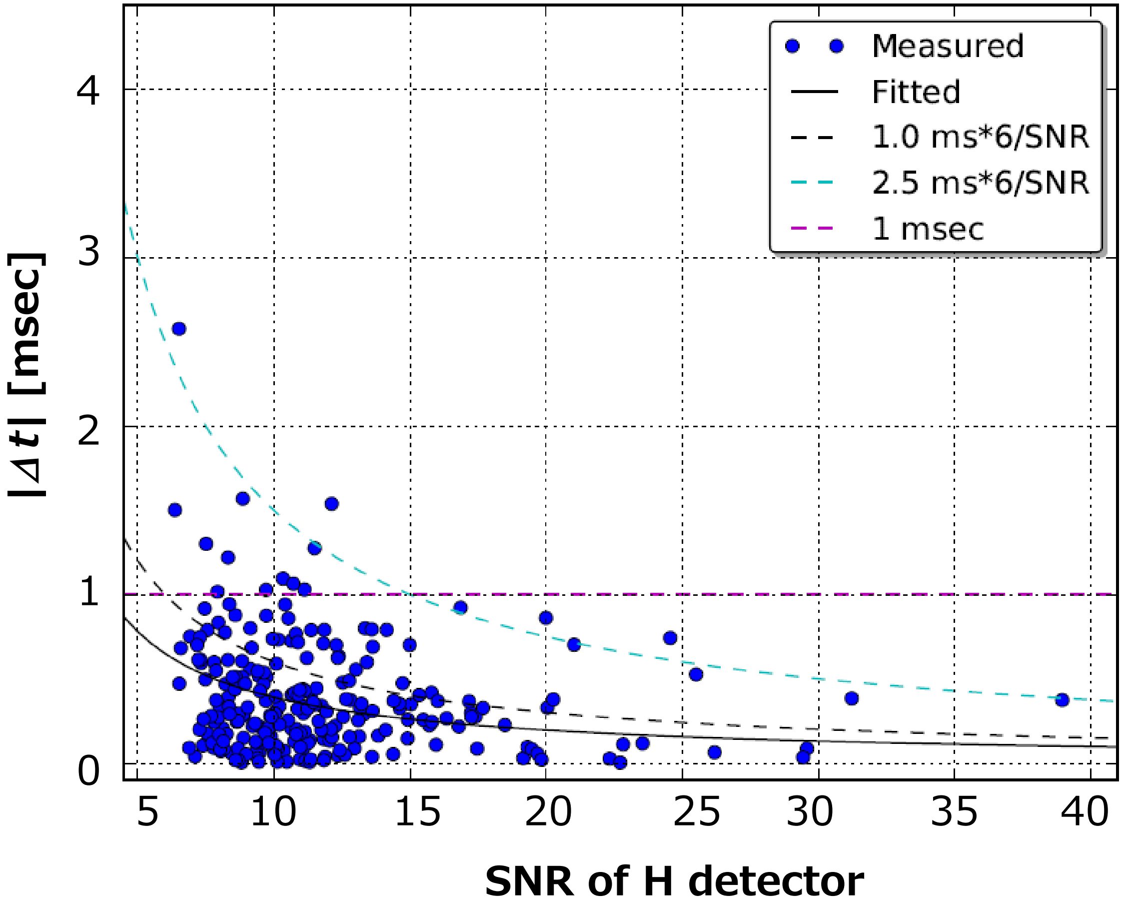




- In this hierarchical network search,
  HLV sky map → If there is no EM-counterpart in HLV map, **HL map**.
- It will be useful for GW-EM follow-up observation.

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)

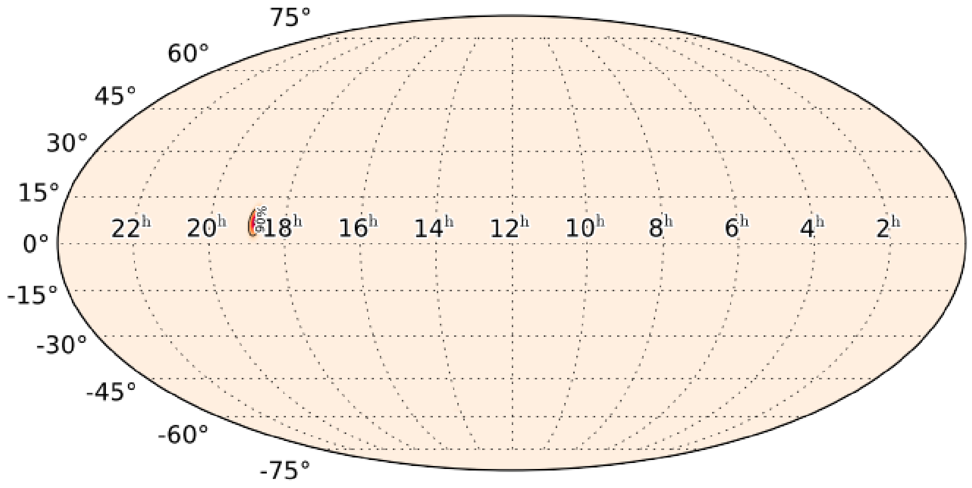
Case 1: worst case
HL+Vr, HL+Kr, HL+Vr+Kr or HL
(Based on ***FAP***)

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

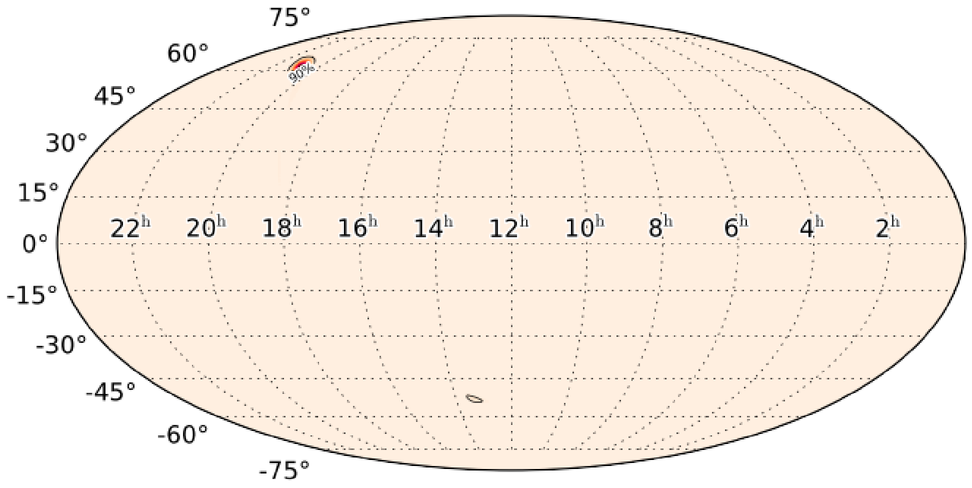
Case 3: Realistic case
HL+Vr, HL+Kr, HL+Vr+Kr,
HL+Vi, HL+Ki, HL+KVi+Ki,
HL+Vr+Ki, HL+ViKr, or HL
(Based on ***FAP*** and ***SNR***th)

Expected localization performance / by HLVK

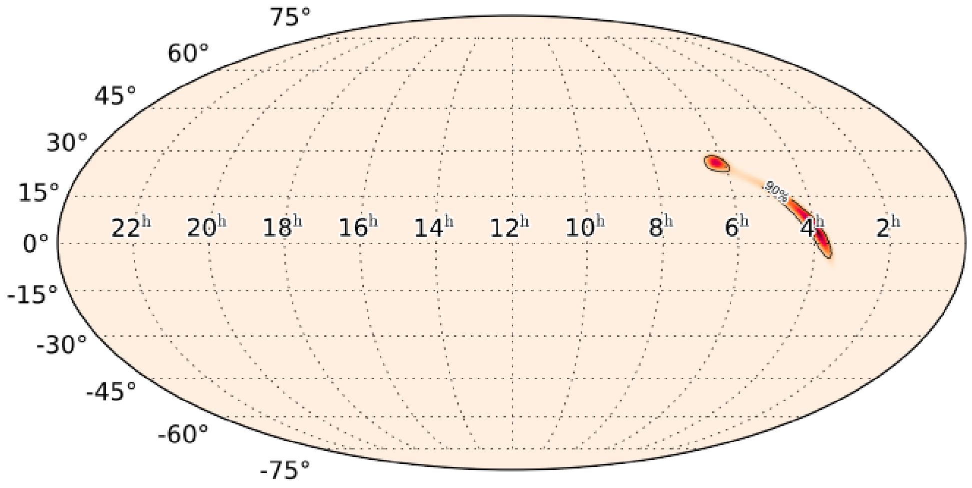
HL + Vi + Ki



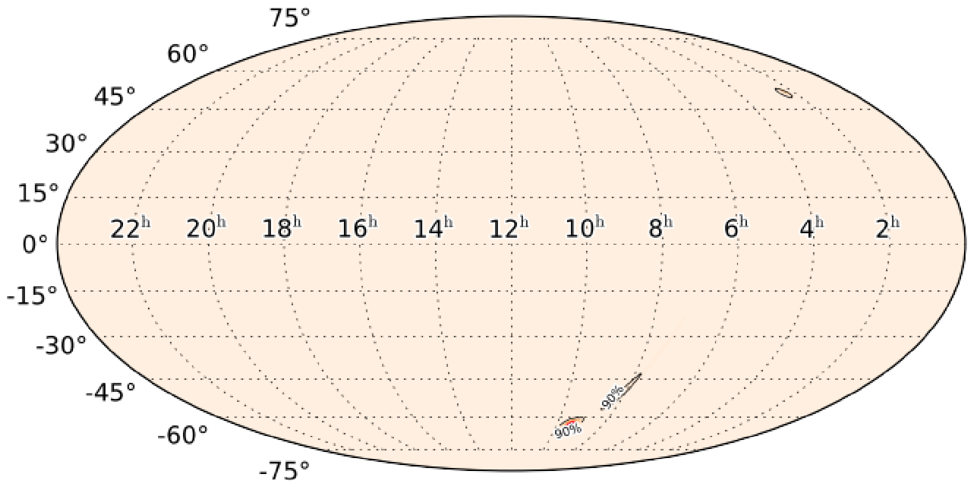
HL + Vr + Kr



HL + Vr + Ki

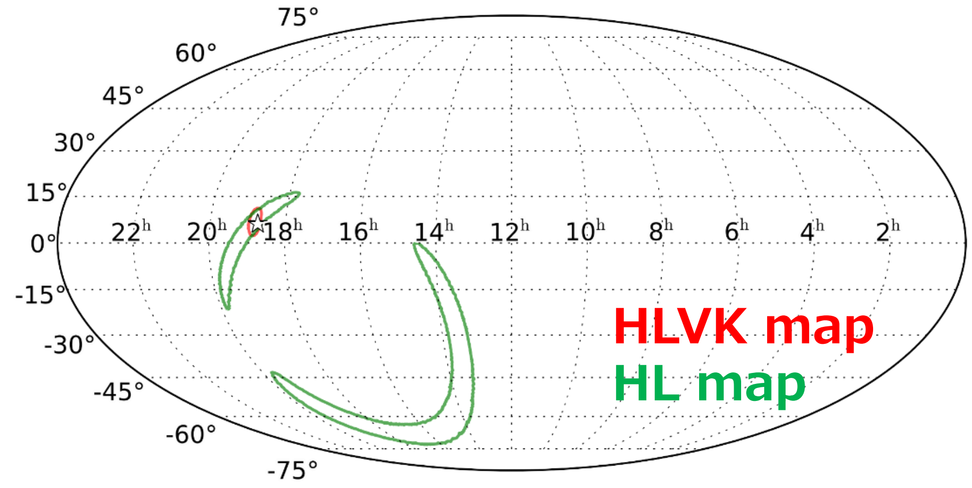


HL + Vi + Kr

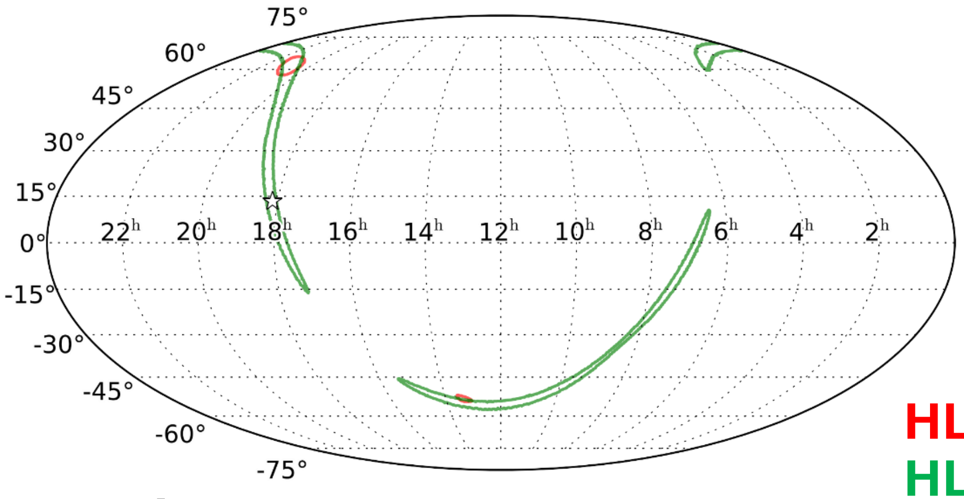


Expected localization performance / by HLVK

HL + Vi + Ki

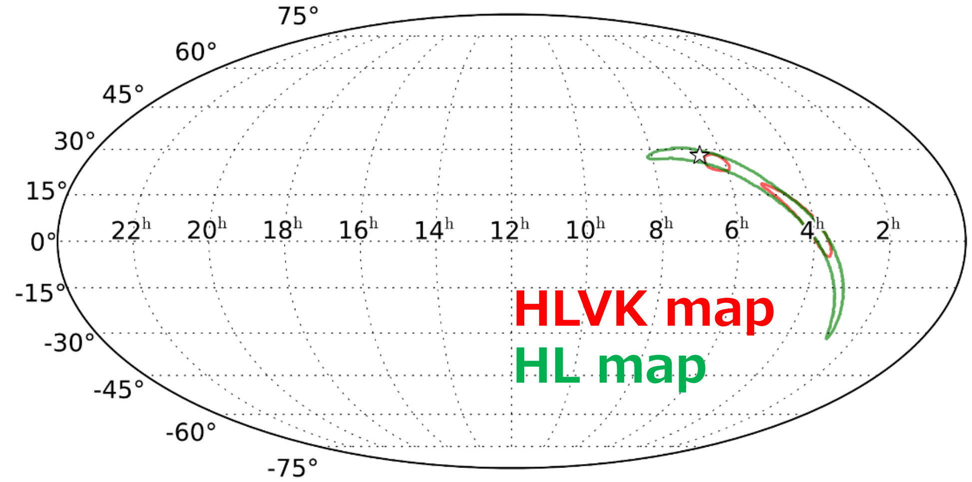


HL + Vr + Kr

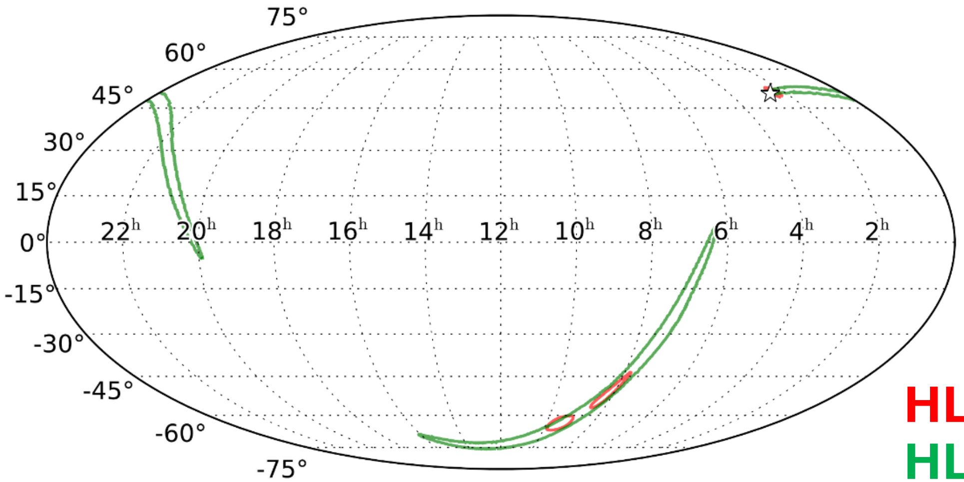


HLVK map
HL map

HL + Vr + Ki



HL + Vi + Kr



HLVK map
HL map