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

Abstract:
Development of a low frequency vibration isolation system for KAGRA

KAGRA → Japanese interferometric large-scale gravitational wave detector.
→ now being developed underground in the Kamioka mine.

core optics → suspended by the so-called seismic attenuation system (SAS).
optic's position → actively controlled using sensors and actuators.

Content : This work verified a simulation tool for the active control system by using a KAGRA-SAS.
Conclusion: It was confirmed the simulation tool worked for designing active control systems.
By using the tool, active control systems for a KAGRA-SAS were designed.

Abstract:
Study of the localization of coalescing binaries with a hierarchical network of gravitational wave detectors.

In order to achieve source localization,
→ coincident observations by large-scale gravitational wave detectors

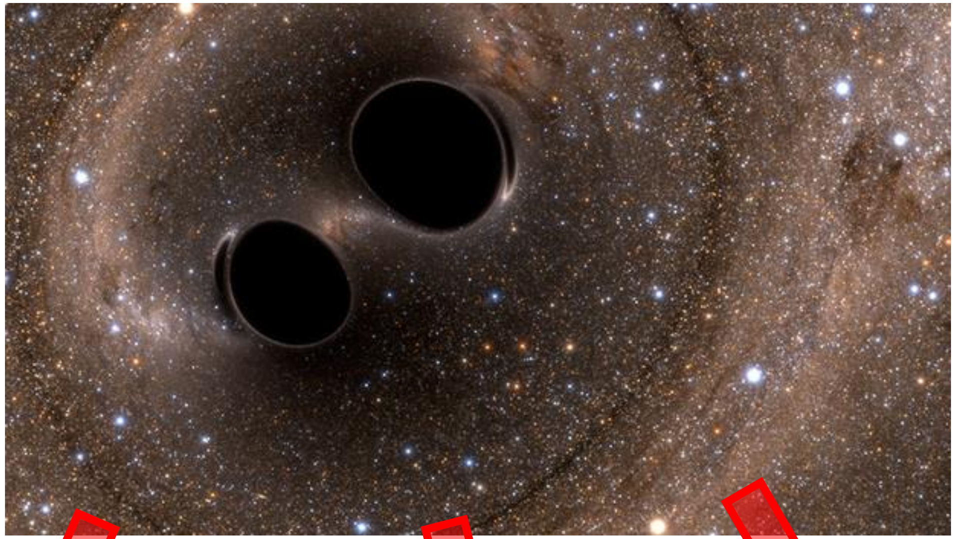
→ the sensitivities of those detectors can be different from each other.

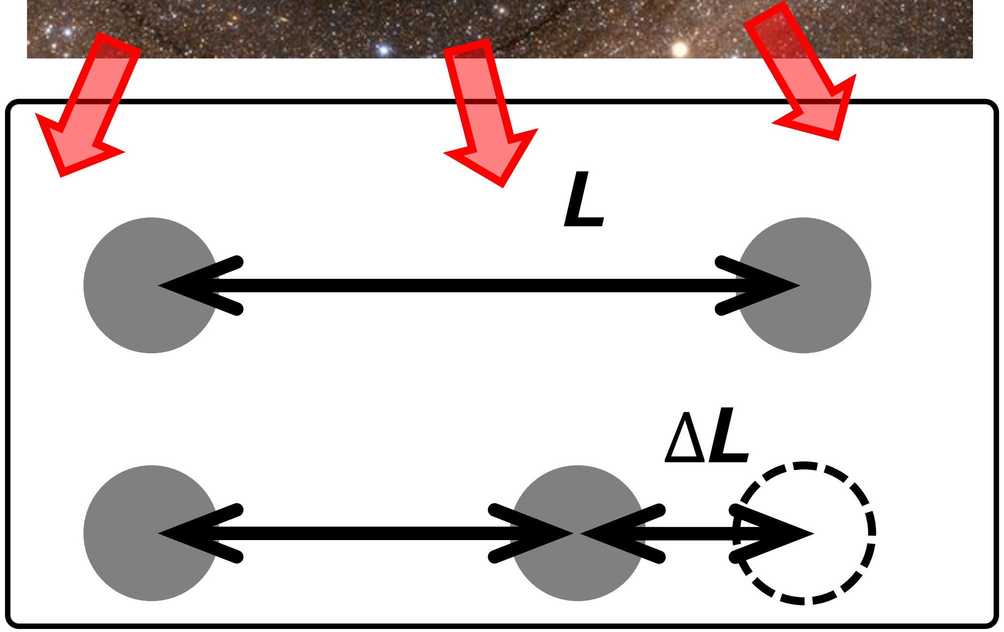
→ Necessary to construct a method
to effectively use the less sensitive detectors' information.

Content : This work estimates performance of a hierarchical network search to deal with this situation.
Conclusion: This method can reduce the systematic error on a sky map probability by a factor of 0.7.

Contents

Introduction / Gravitational wave and its detection



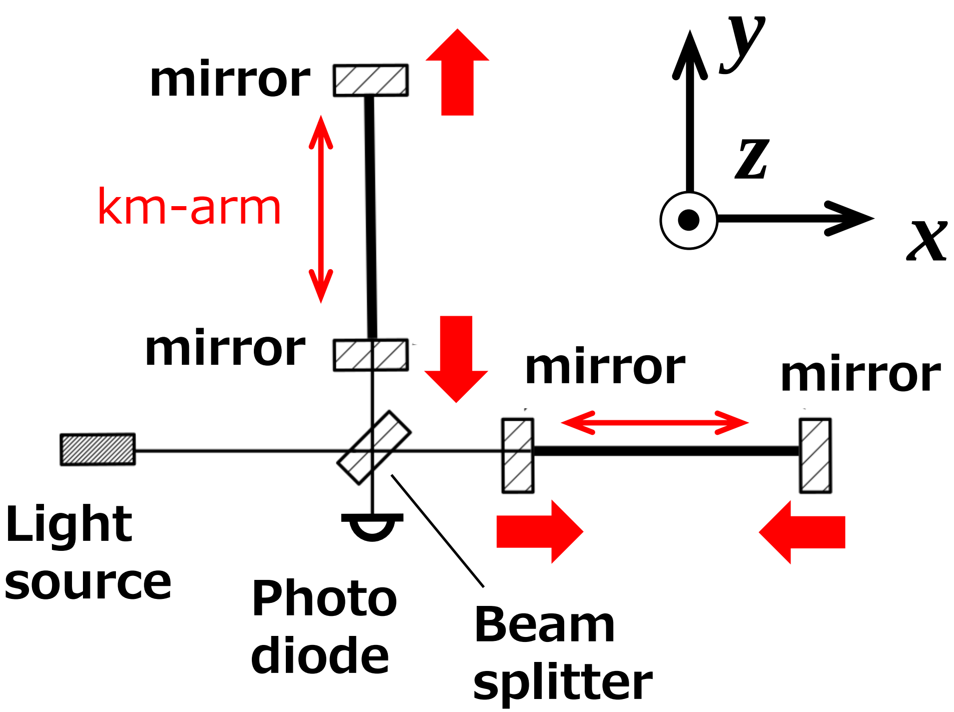


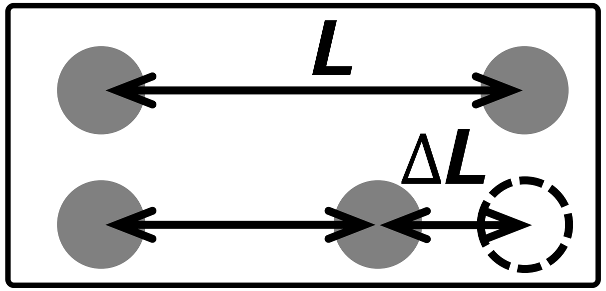
Gravitational wave:
- It is a distortion of spacetime
- GW propagates at the speed of light
- Its typical amplitude h on the earth
  → $h \sim \Delta L/L \sim 10^{-21}$

Observable gravitational wave sources:
- compact binary coalescence
- supernovae
- spinning of pulsars
- ..

First direct detection was achieved in 2015 from coalescing binary black hole system.
→ GW astronomy is starting.

Introduction / Gravitational wave and its detection





Interferometric GW detectors:

1) Based on Michelson interferometer
→ To measure distortion due to GWs.

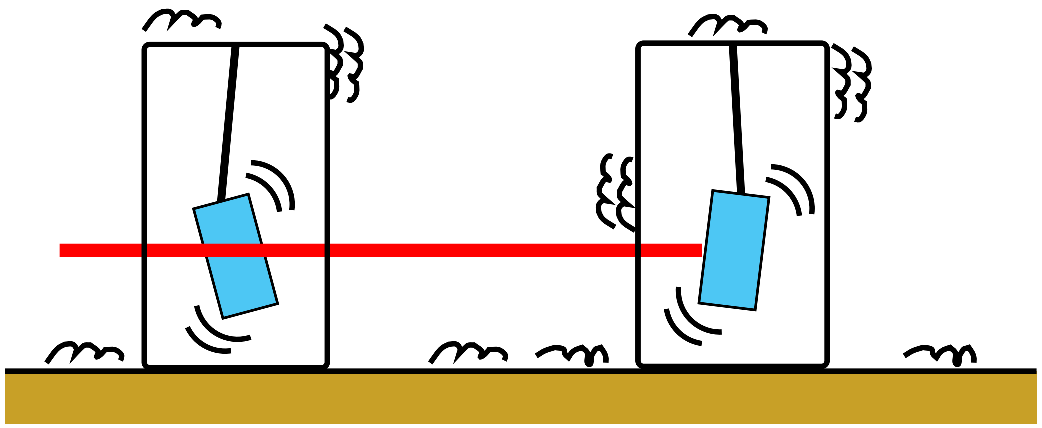
2) km-arm Fabry-Perot cavities
→ To expand optical pass length.
(L largen → ΔL largen)

3) Suspended core optics
→ To let them move as free particles.
→ To isolate optics from external vibration.

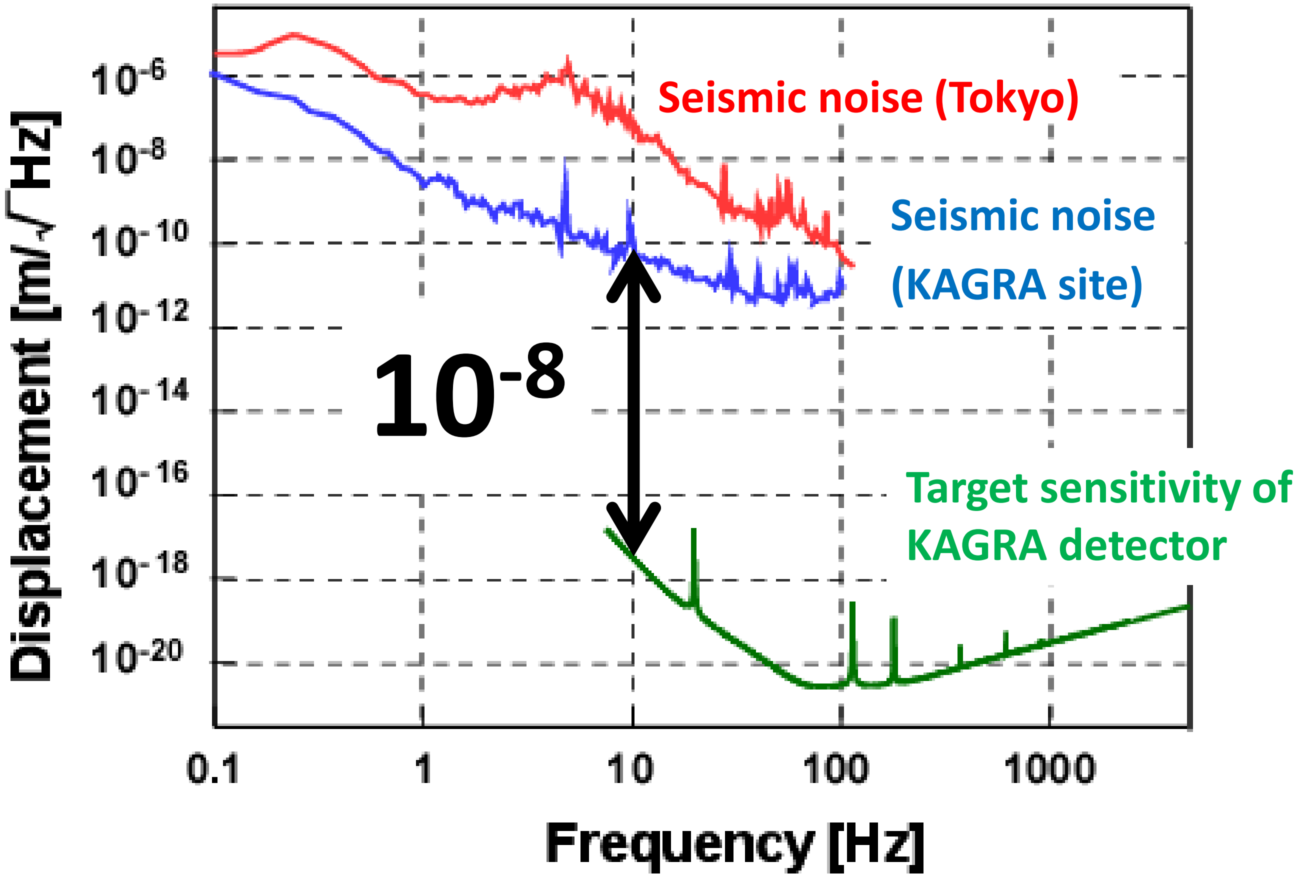
Contents

Vibration isolation system / Seismic noise

- Ground vibration changes the optical path length continuously and randomly.
  → **Seismic noise**



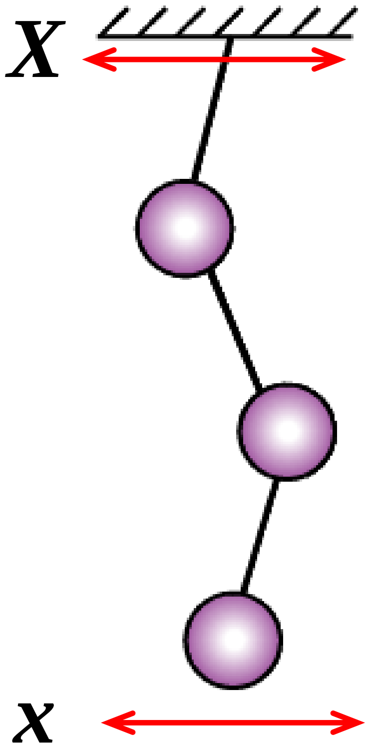
Spectrum density:
seismic vibration vs.
target sensitivity of KAGRA detector →

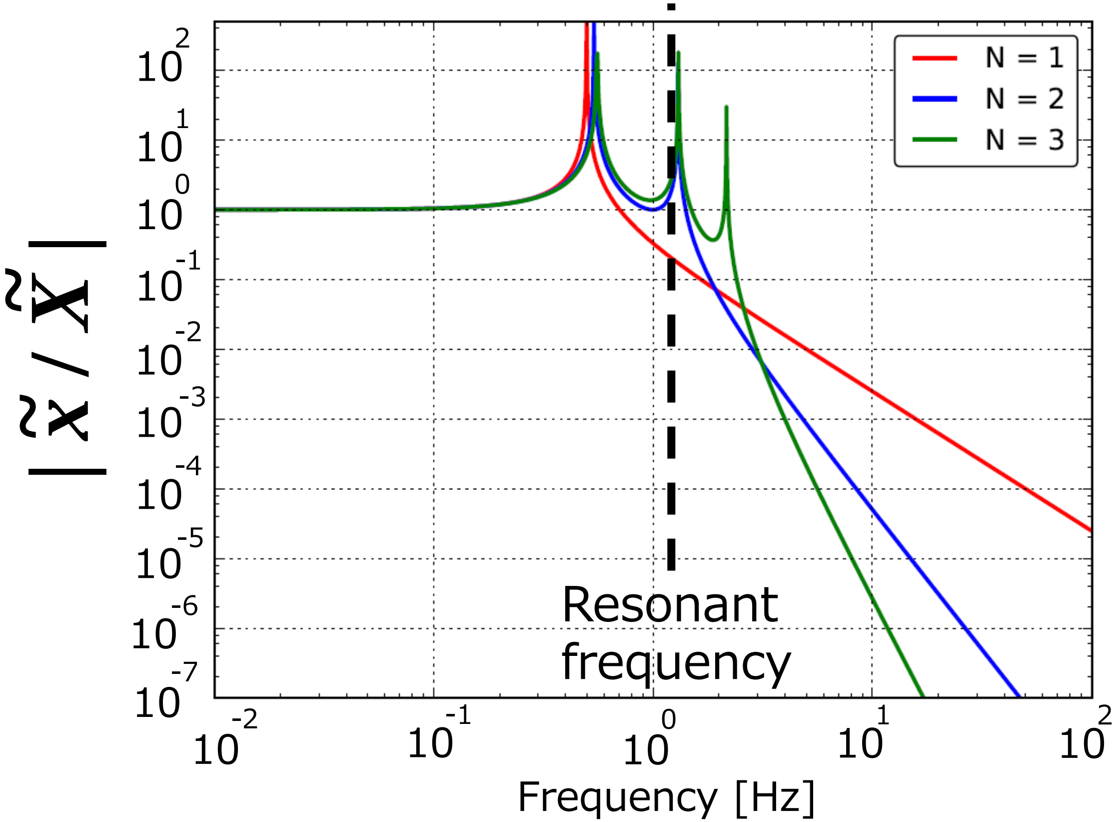


Necessary to attenuate the vibration on order of 8 ~ 10.

Vibration isolation system / Vibration attenuation

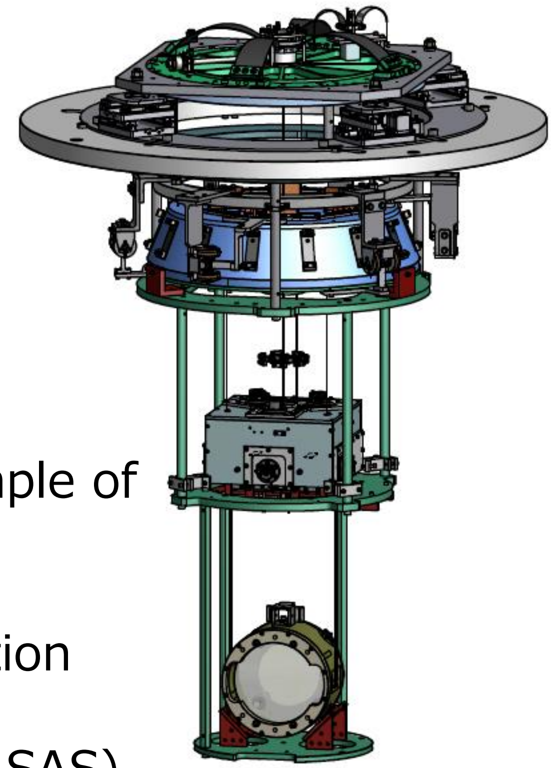
- Pendulum system attenuates vibration at high frequencies.
- Multi-pendulum system realizes stronger attenuation performance.





Displacement of N-th stage mass compared to ground motion.

An example of KAGRA Seismic Attenuation System (KAGRA-SAS)

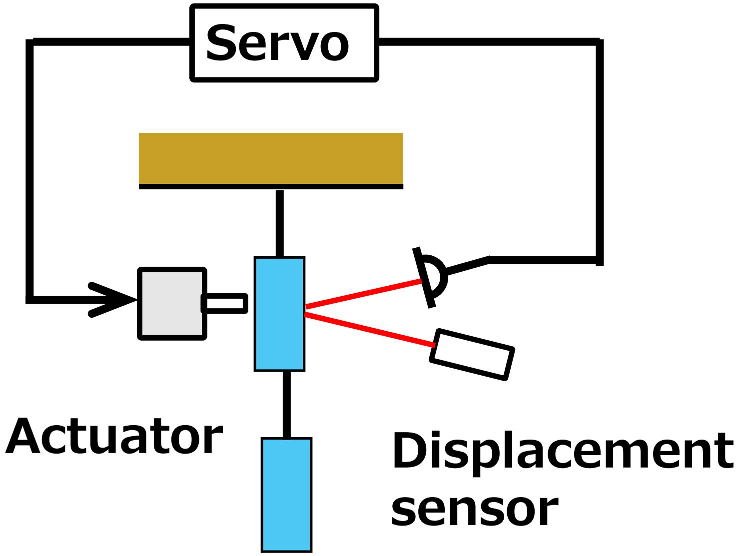


Vibration isolation system / damping system & drift compensation

- Suspended optics vibrate at low frequency **due to mechanical resonances, drifts**.
  → For stable interferometer operation, such vibration should be suppressed.

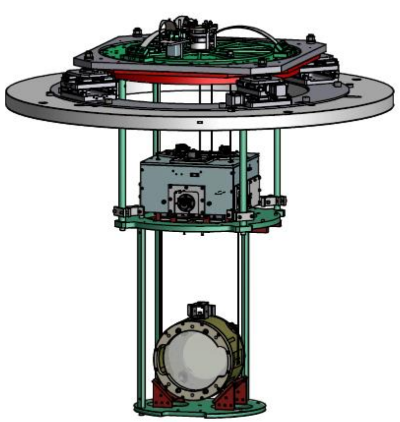
- This low frequency vibration is suppressed
  by **active control system** using sensors and actuators.
  → Servo system should be designed
  so that the sensor and actuator noises
  do not vibrates the optics so much.

  Ex. If sensor noise > actual displacement
  → control system causes optic vibration.

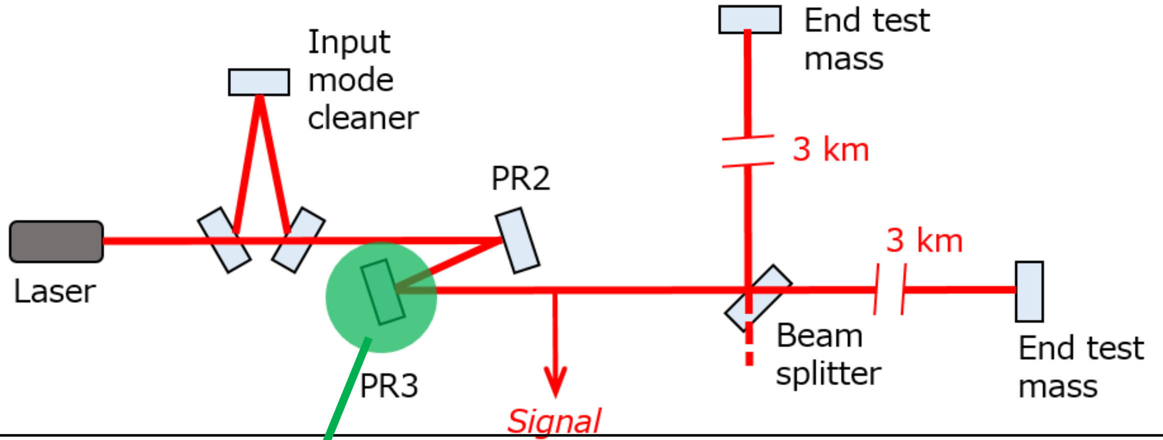


Vibration isolation system / Designing control system

- For designing the active control system
  → a simulation tool based on 3D rigid-body model.
    → This tool was tested only once so far.
      → This work tested the simulation tool
        by using a simple KAGRA-SAS.

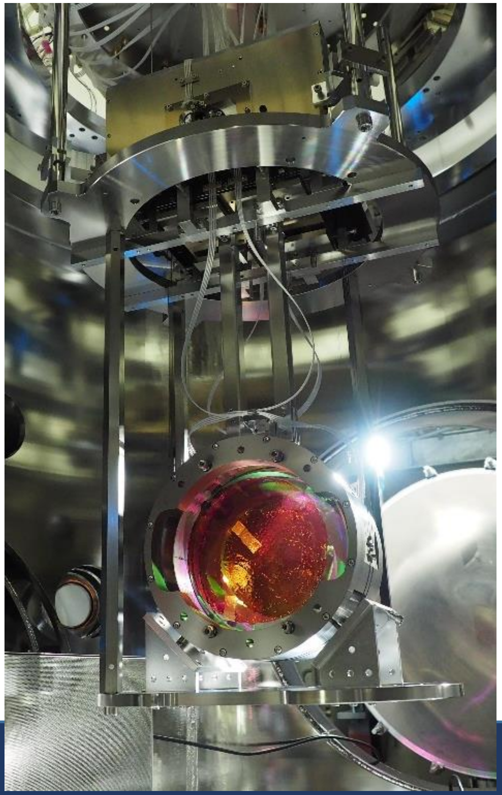


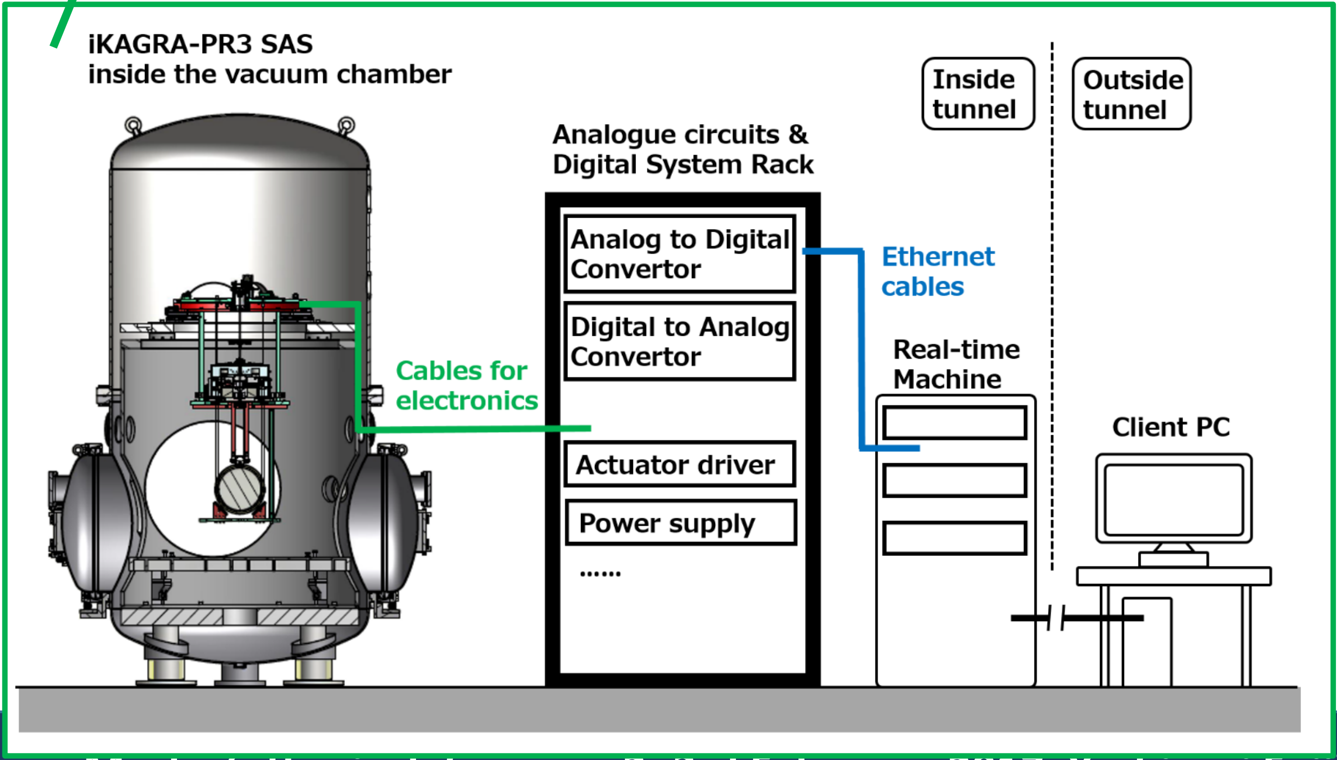
Verification of simulation performance / iKAGRA-PR3 SAS



iKAGRA:
→ test run in 2016
→ Michelson configuration

PR3 mirror:
→ steering mirror
(in iKAGRA)

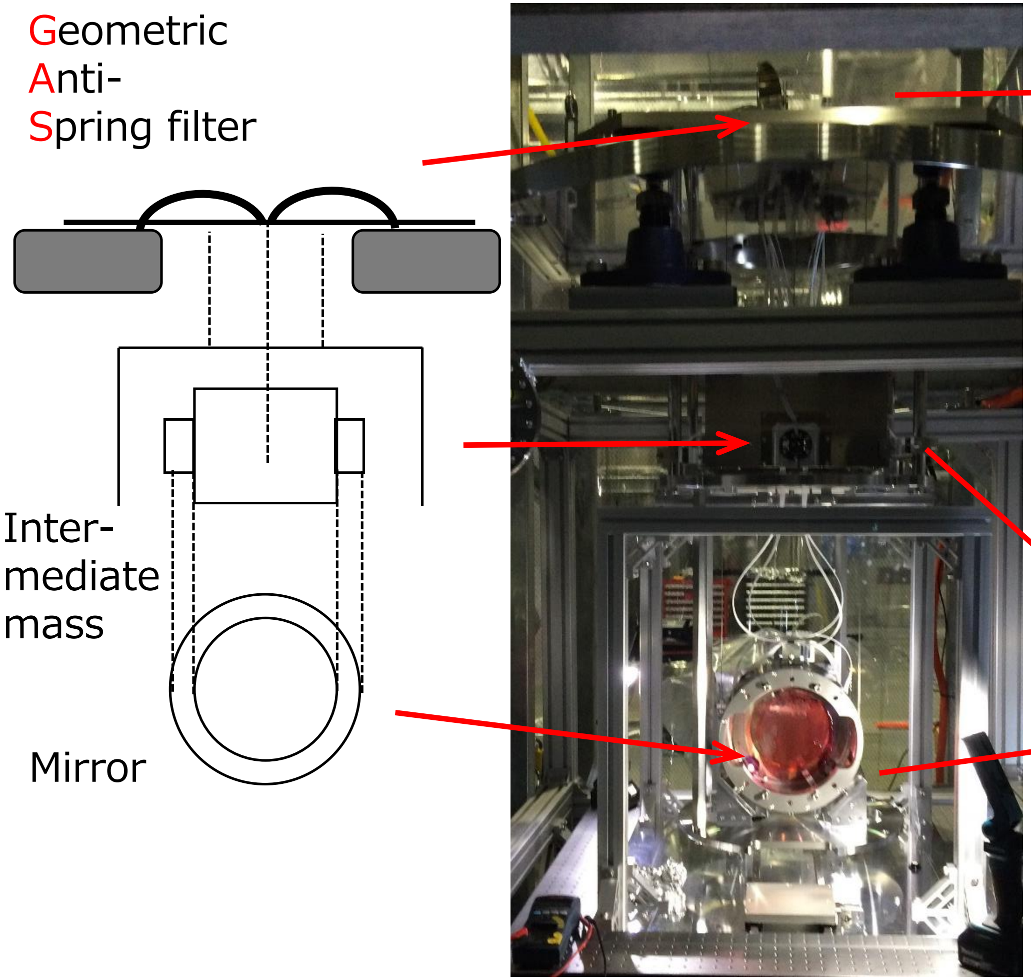




iKAGRA-PR3 SAS:

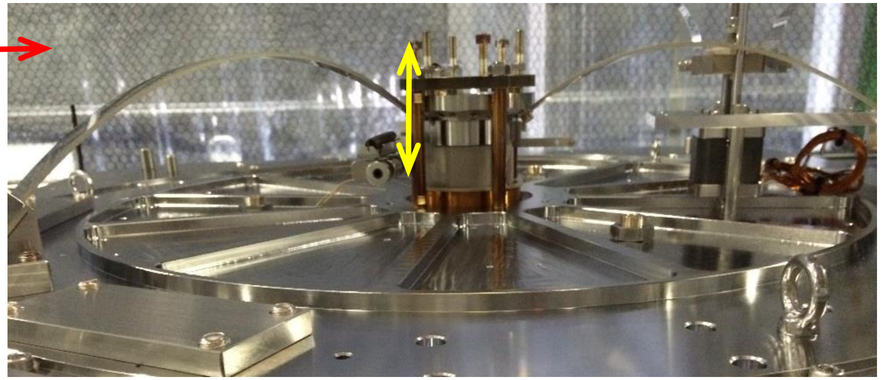
→ First KAGRA-SAS installed at KAGRA site
→ 2 stage pendulum
→ Controlled by digital system

Verification of simulation performance / Sensors and actuators



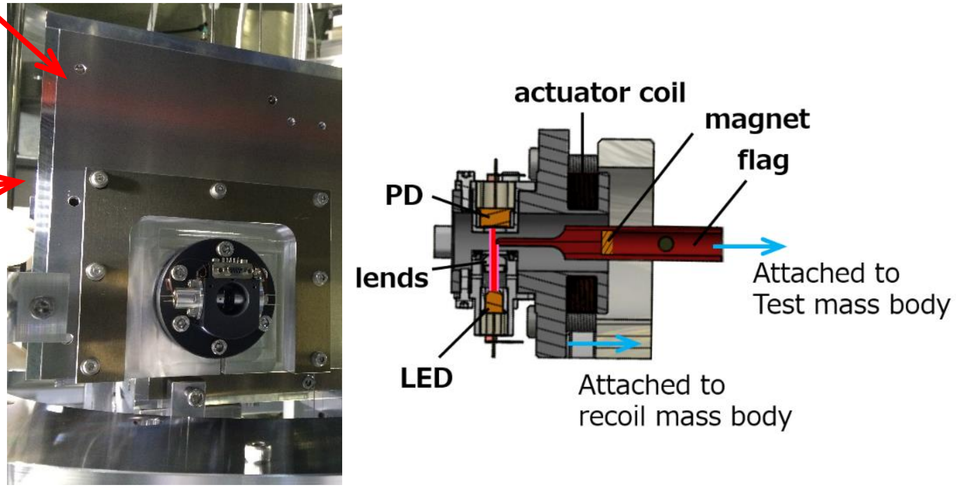
iKAGRA-PR3 SAS

LVDT (Linear Variable Differential Transducer)
and coil-magnet actuator



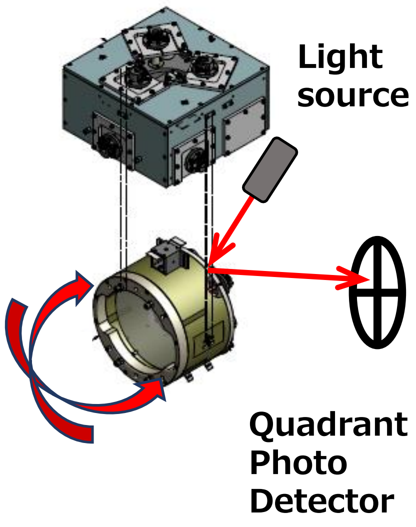
For GAS-filter's drift compensation control

OSEM (Optical Sensor and Electro-Magnetic actuator)



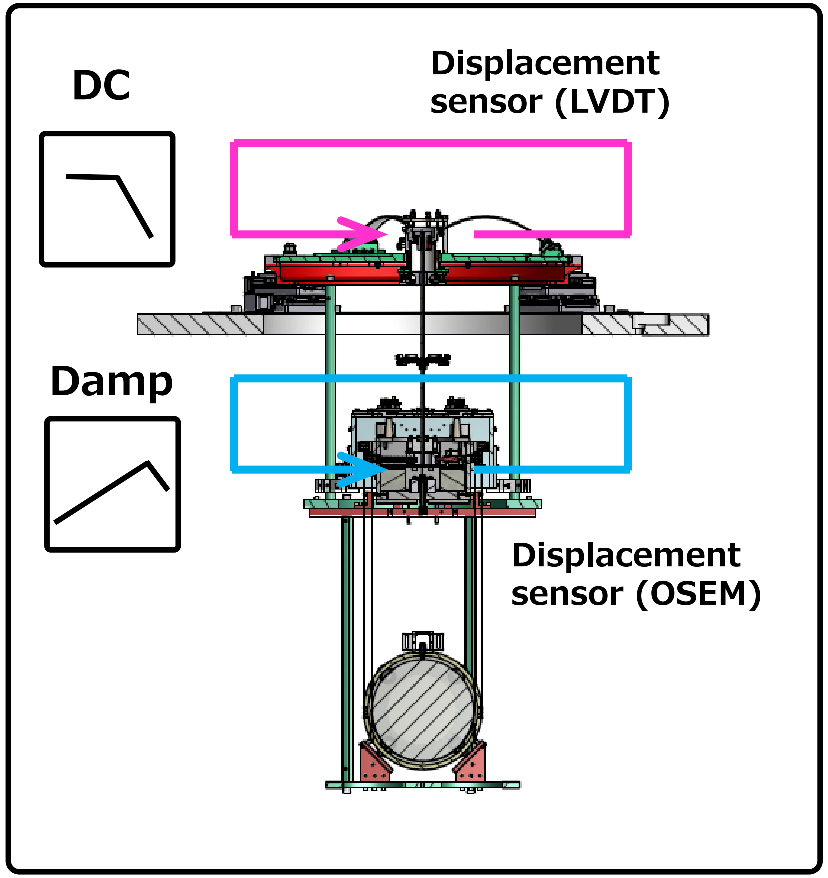
For resonance mode damping of the mirror

OpLev (Optical Lever)



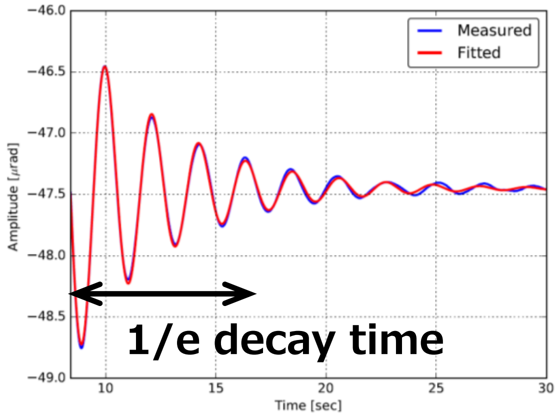
For alignment of the mirror

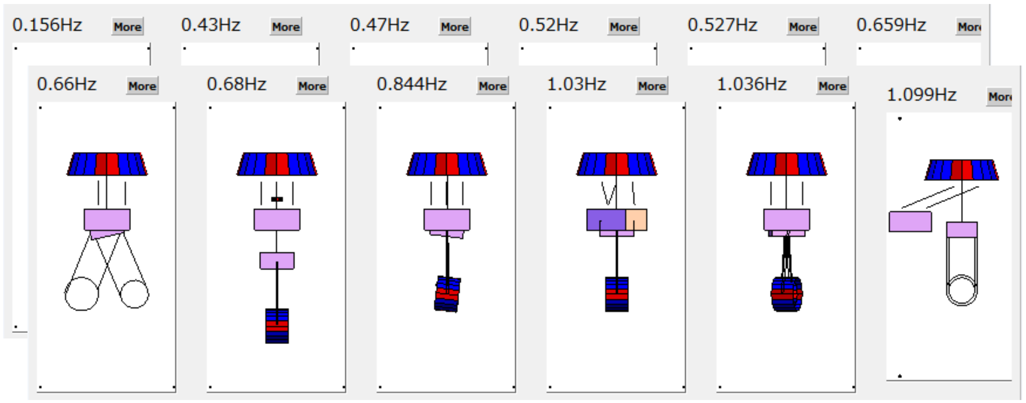
Verification of simulation performance / Active control performance



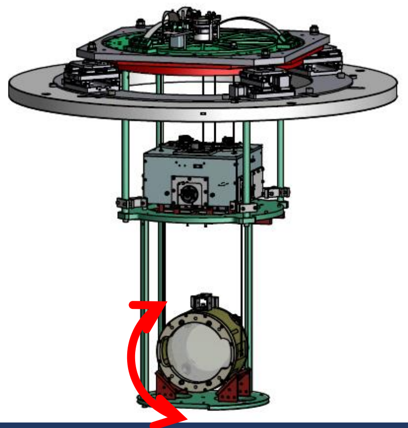
Implemented control loops

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

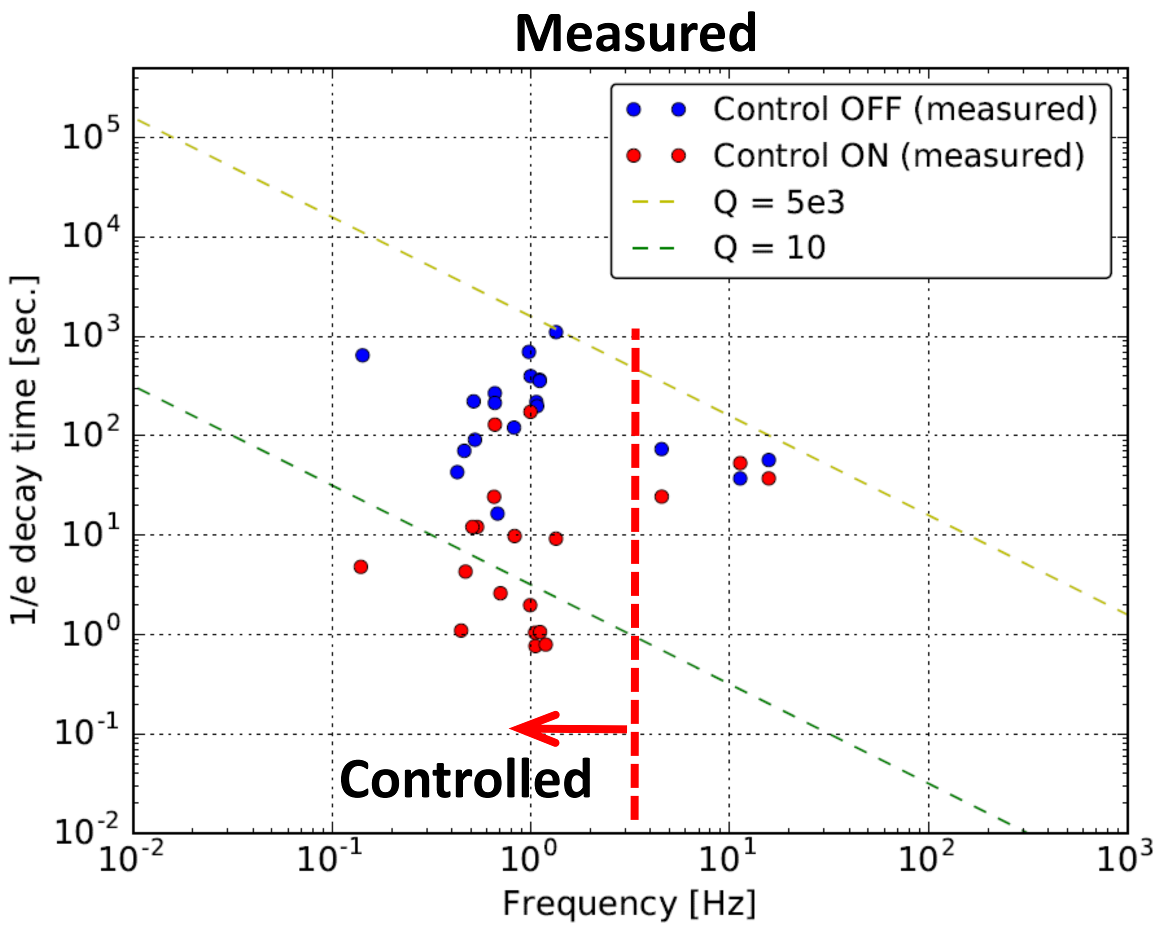


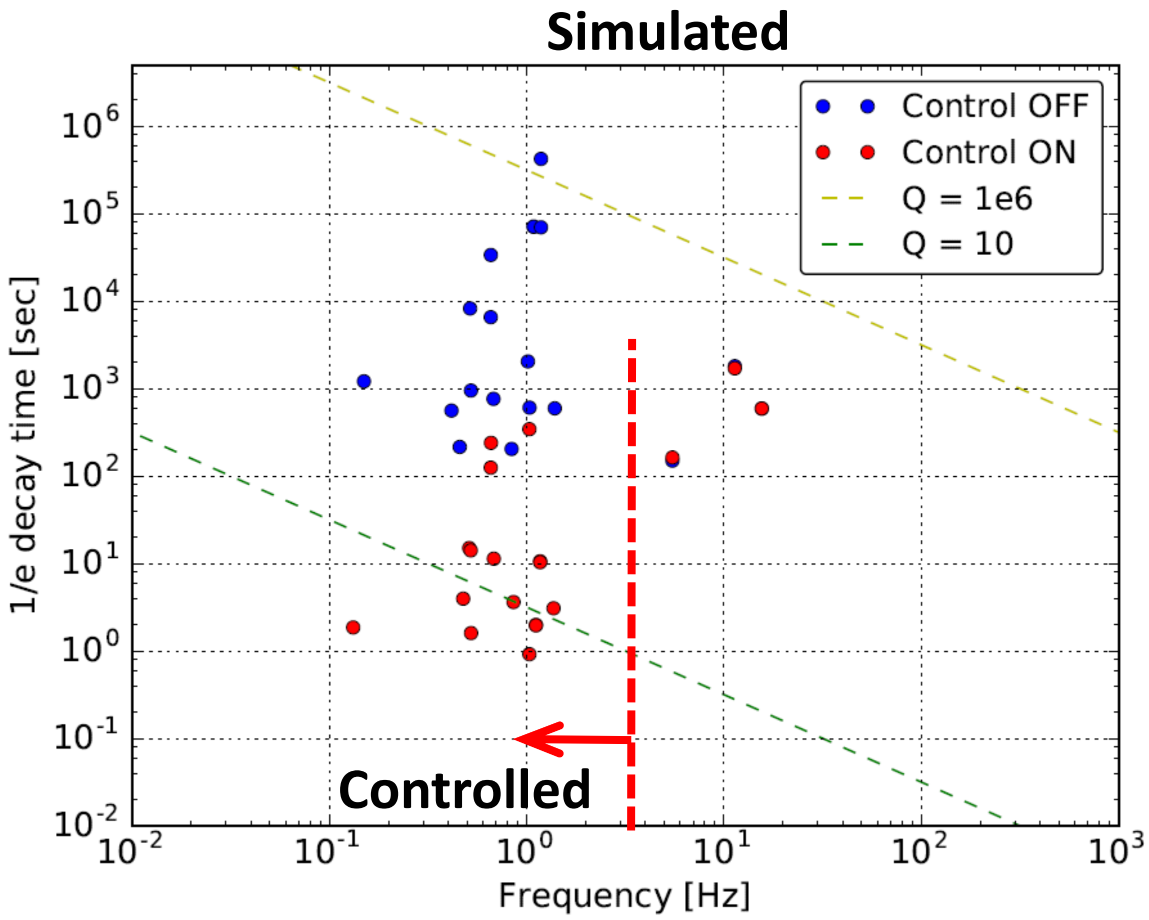


Test 2: Rseidual vibration estimation



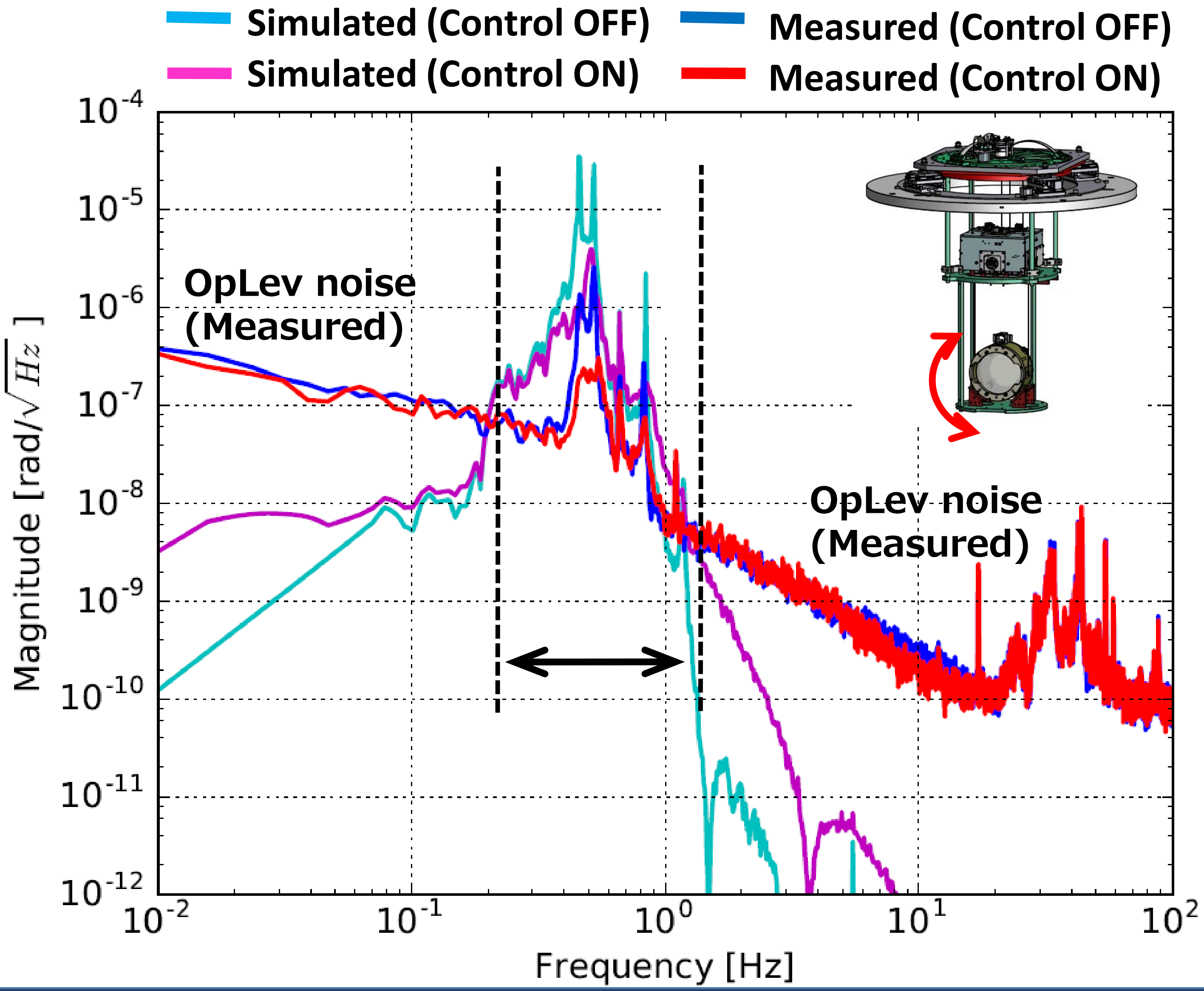
Verification of simulation performance /Test 1: damping performance





1) Without control → simulation has large uncertainties. →
2) With controls → prediction is consistent with actual system.

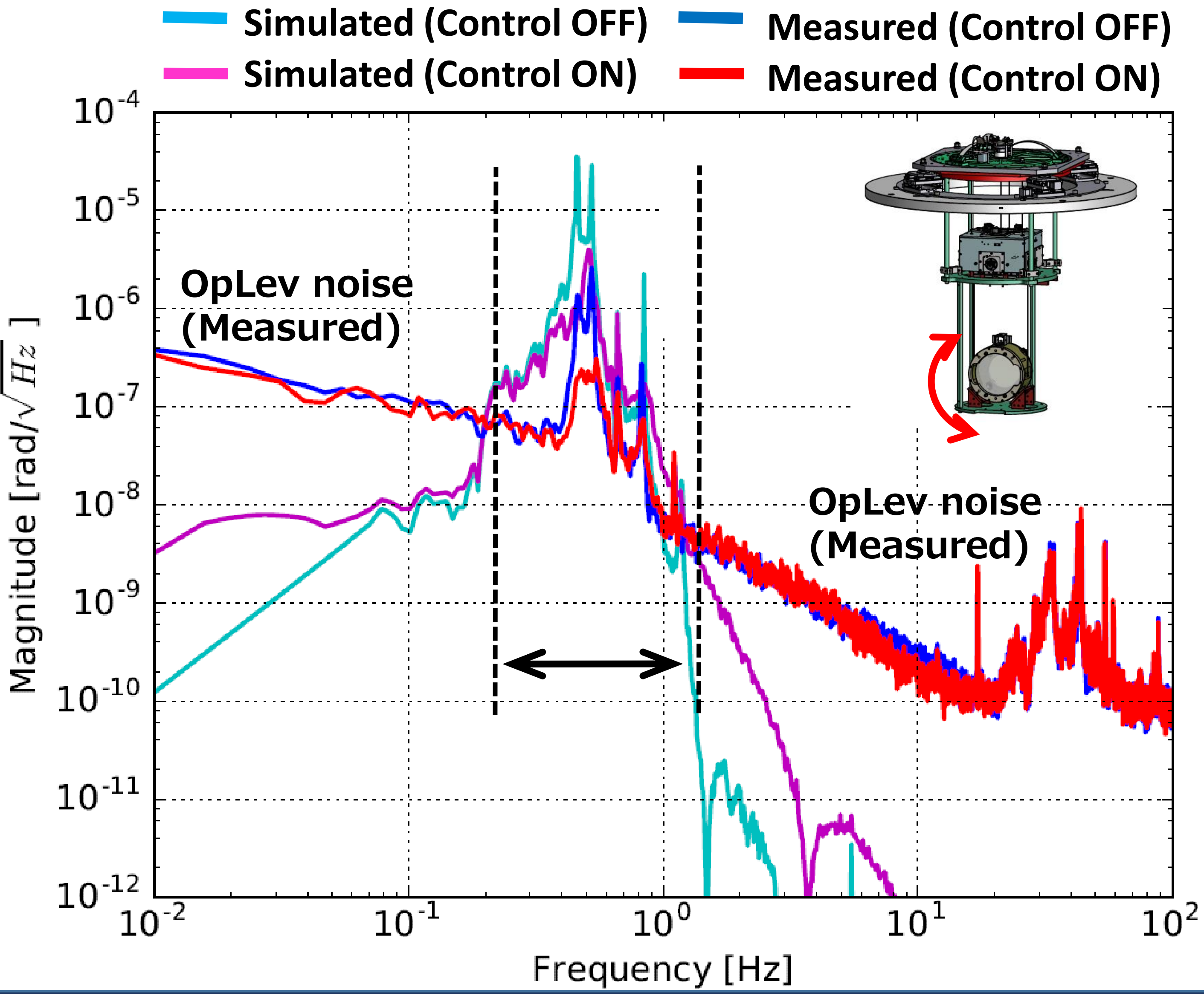
Verification of simulation performance / Test 2: Residual vibration



- Measured seismic vibration at KAGRA site is implemented into the simulation.
- Measured by optical lever
- From ~ 0.2 Hz to ~1 Hz:

1) Resonant frequency → well fitted.
2) Simulation spectra → consistent with measurement.
3) Q factor, without control → Simulation $\gtrsim$ measurement
4) Background spectra → simulation $\not\approx$ measurement → should be considered: seismic noise, hanging condition.

Verification of simulation performance / Test 2: Residual vibration



For further precise prediction:
→ real-time seismic vibration,
hanging condition,
should be considered.

If a calculation
- with large Q factors and
- large seismic noise
meets requirements on active control system, it should be met in actual system.

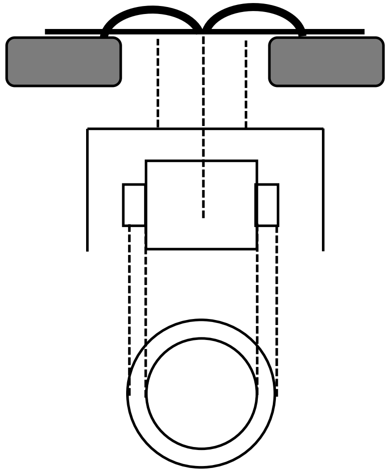
→ This simulation tool works for designing active control system.

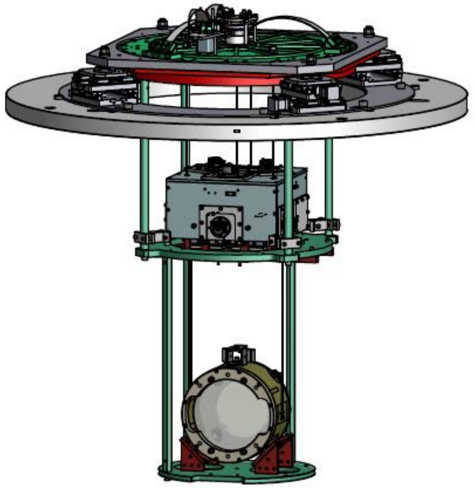
Designing active control system / Type-Bp SAS

iKAGRA-PR3 SAS → upgraded into Type-Bp SAS
- In order to meet KAGRA requirement.
- three type-Bp SAS will be installed.

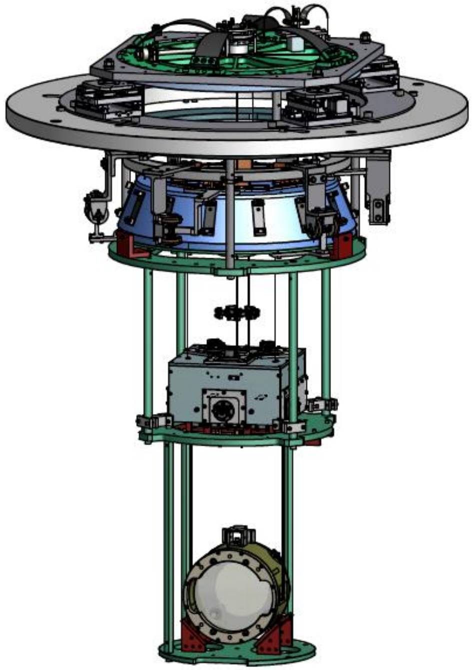
This work designed the active control systems by using the simulation tool.

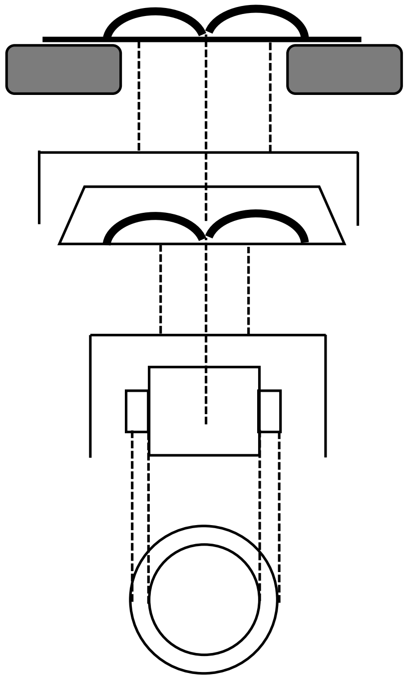
iKAGRA-PR3 SAS





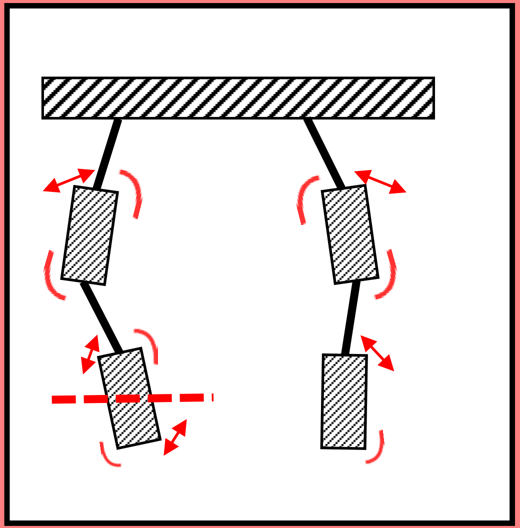
Type-Bp SAS





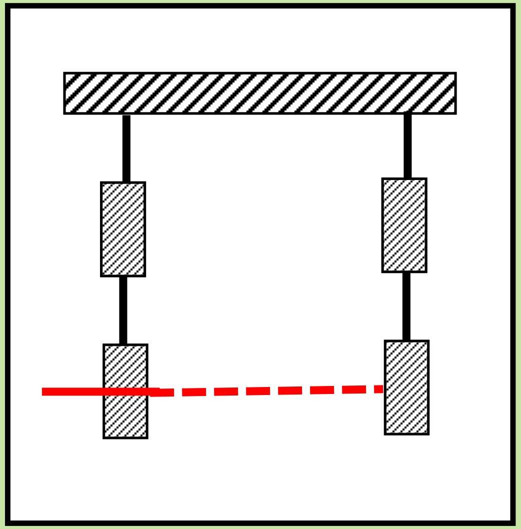
Designing active control system / Control phase

1. Calm-down phase



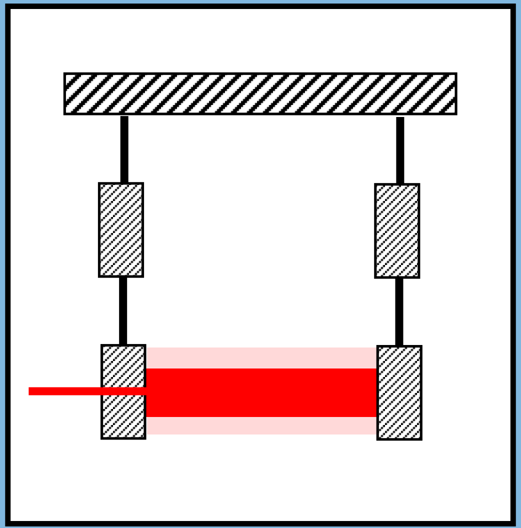
Suppress
large disturbance

2. Lock-acquisition phase



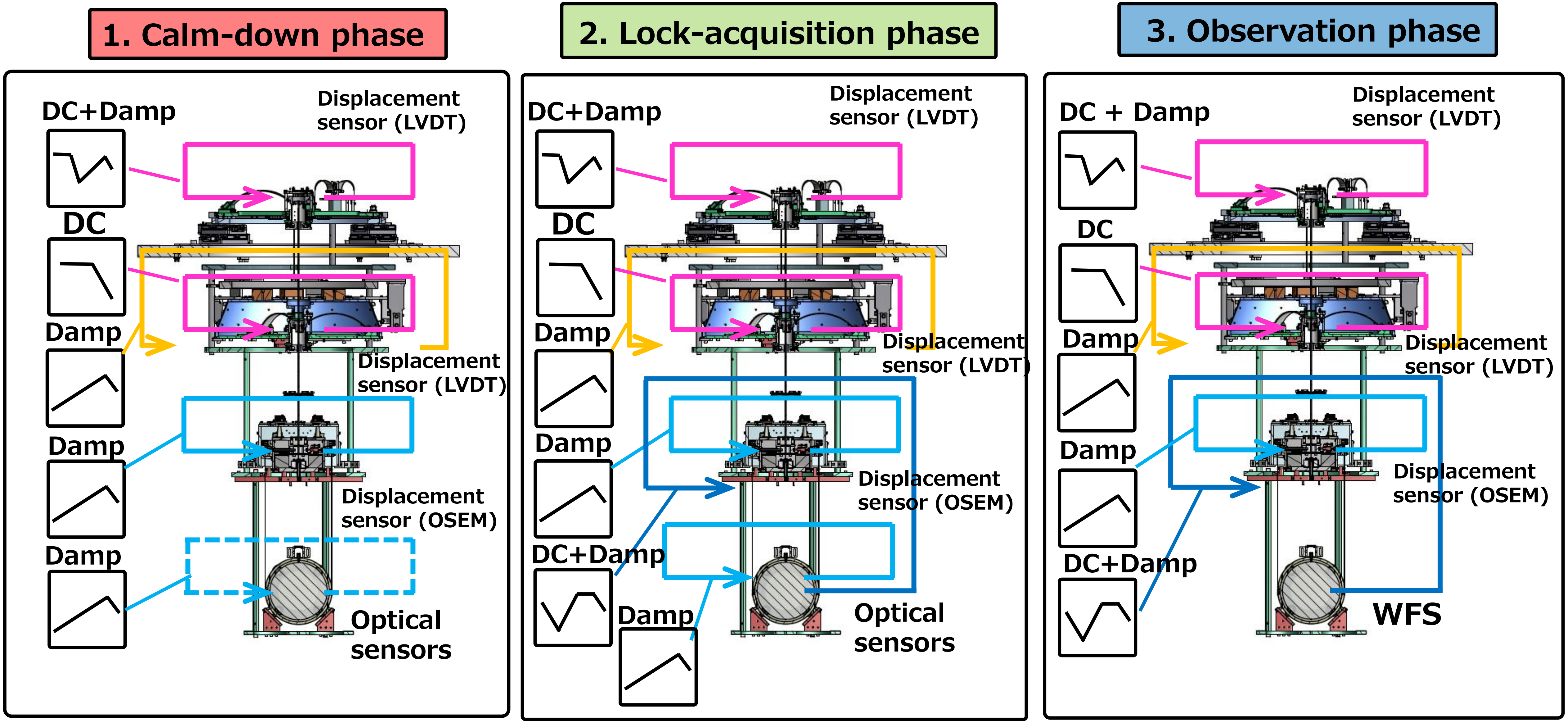
Reduce RMS velocity
RMS angle
(Root-Mean-Square)

3. Observation phase



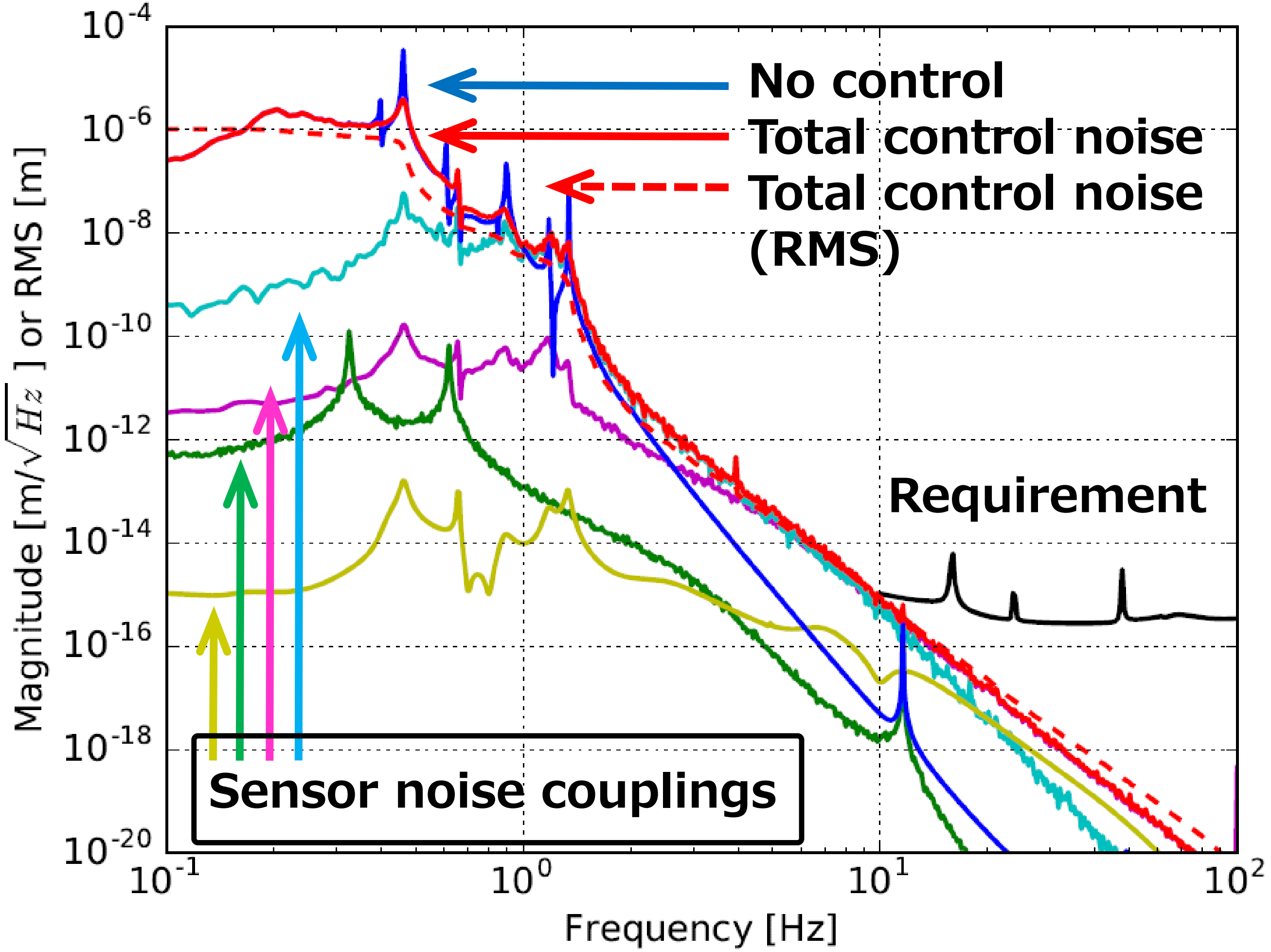
Keep position
with low noise
control

Designing active control system / Type-Bp SAS



Designing active control system / Type-Bp SAS

Ex. **3. Observation phase**



- Expected sensor noise couplings into mirror displacement fluctuation:

→ This control system was designed in order to meet requirements:

1) **Sensor noise coupling < 10^{-15} m/$\sqrt{Hz}$** in detection band (>10 Hz)

2) **Suppress RMS values**

Summary

1) A simulation tool for active control system is tested by using a KAGRA-SAS.
2) It is confirmed the simulation tool works for designing active control systems.

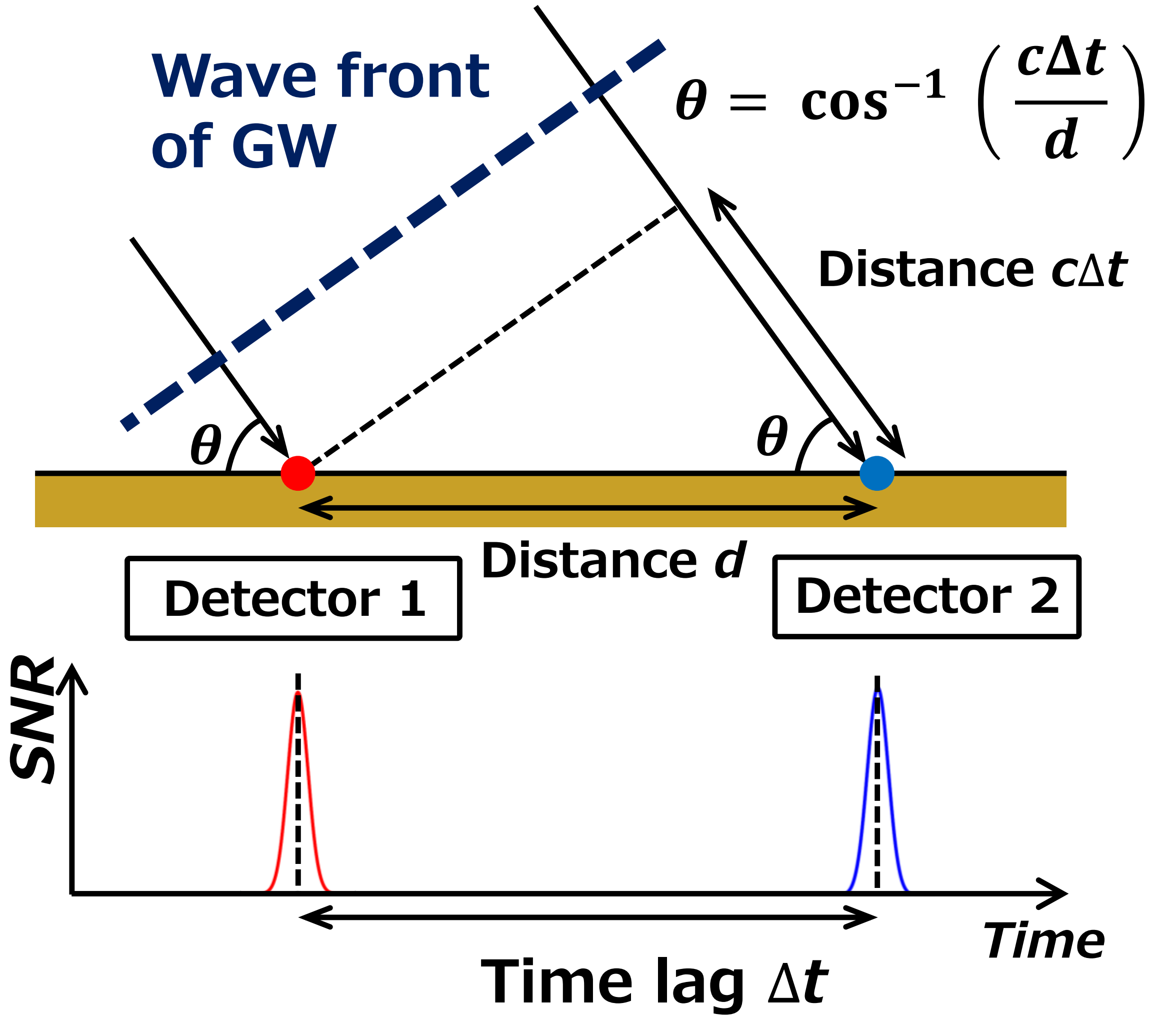
3)Active control system for a KAGRA-SAS is designed by using the tool.

Future work

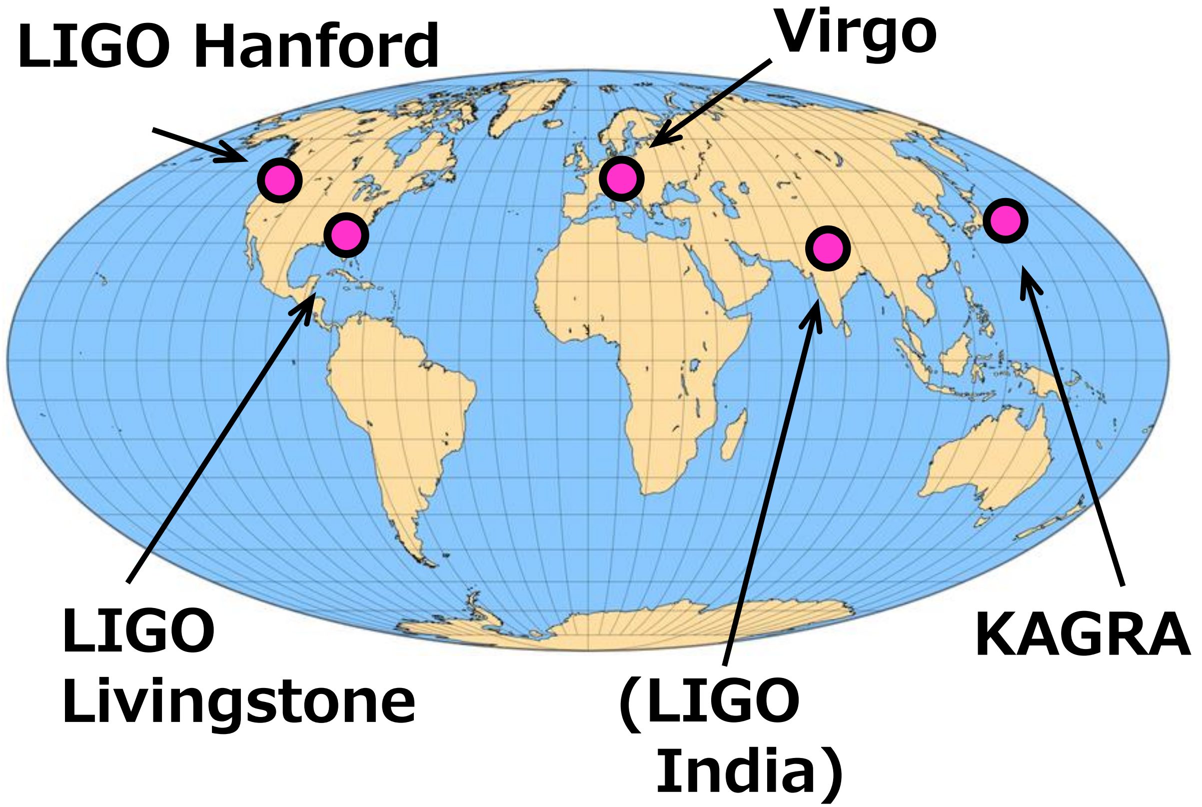
1) Investigate mechanical responses of KAGRA-SAS
2) Implement the designed active control systems into assembled type-Bp SAS.

Contents

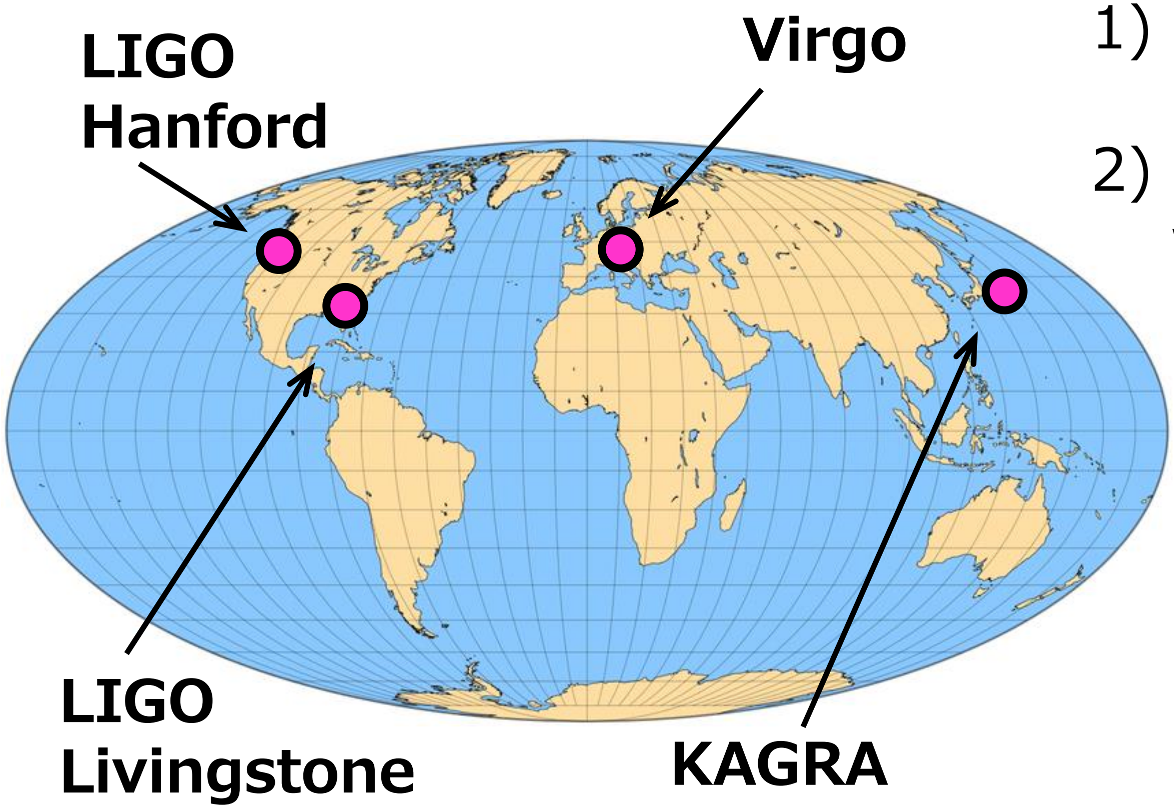
Source localization by GW detectors



Source localization:
1) Array and coincident observation
2) Triangulation using time lags.



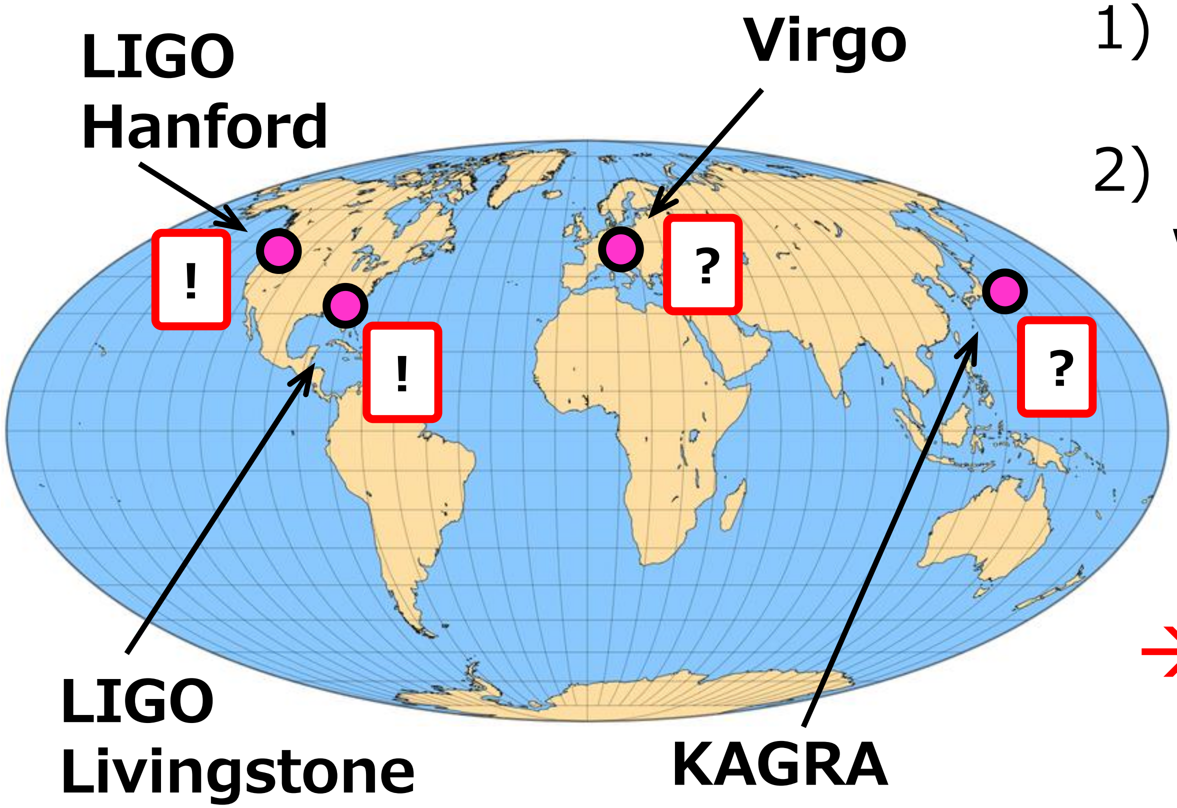
Network search by GW detectors with different sensitivities



1) For source localization → coincident search.

2) How does a network by GW detectors with different sensitivities look like?

Network search by GW detectors with different sensitivities



(Ex. Current expected situation)

1) For source localization → coincident search.

2) How does a network by GW detectors with different sensitivities look like?

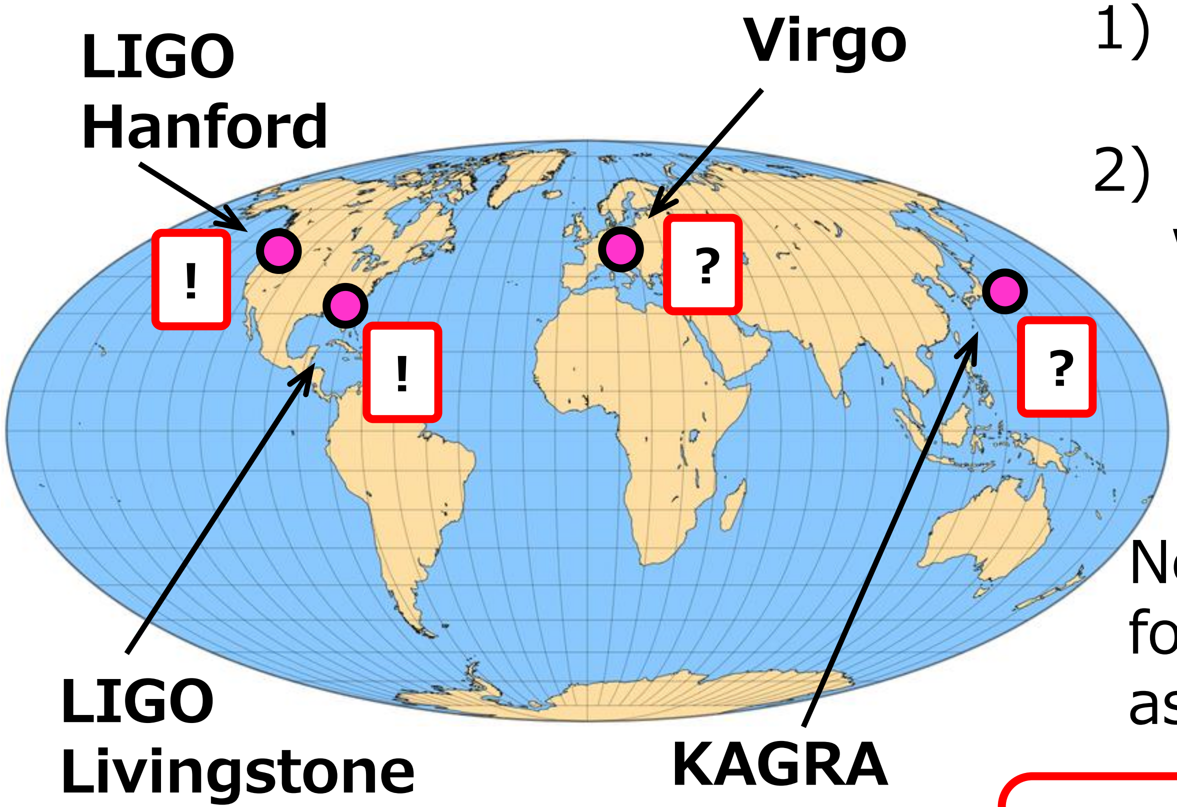
→ Triple (or more) coincidence are rare.
→ Hardly localized.

(If all the threshold are same.)

→ Not suitable for rapid localization, EM follow-up observation.

But this situation should happen, in coming years.

Network search by GW detectors with different sensitivities



(Ex. Current expected situation)

1) For source localization → coincident search.

2) How does a network by GW detectors with different sensitivities look like?

→ Triple (or more) coincidence are rare.
→ Hardly localized.

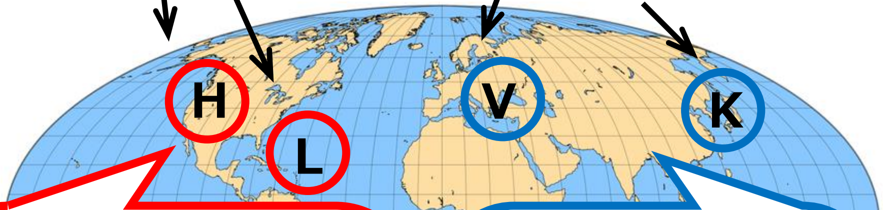
Necessary to set lower SNR thresholds for low sensitivity detectors as long as not too many background triggers.

How about including less sensitive detectors,
1. with low threshold,
2. only when we analyze triggers from high sensitivity detectors' coincidences?

Hierarchical network search

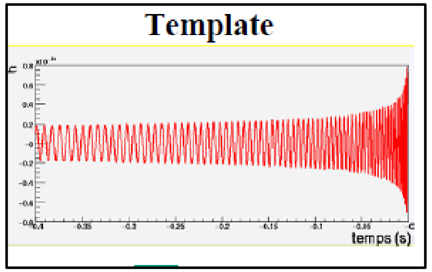
High sensitivity detectors

Low sensitivity detectors
(With low SNR thresholds)



This Template!

During this period!

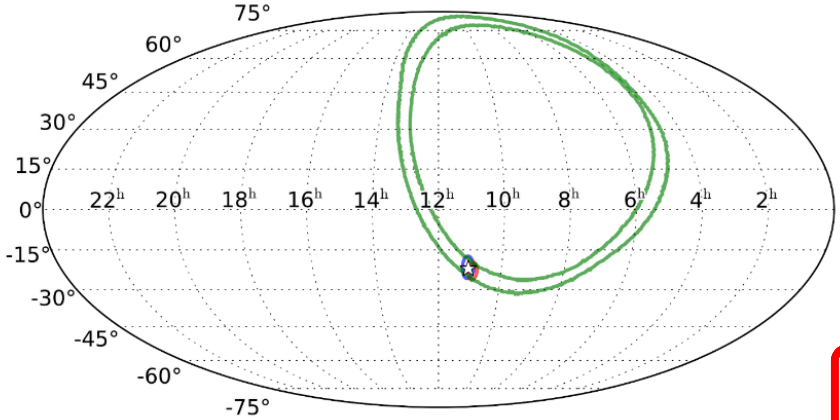


This trigger should be the counterpart.

These are the recorded SNR, arrival timing, phase.

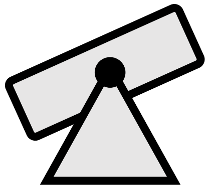
(Ex. Current expected situation)

Sky map probability



Combine 3 (or more) detectors' information

EM follow-up observation



Send alarm to EM partners

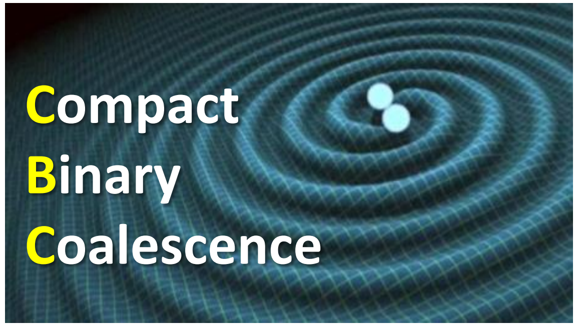
Goal of this Part:
Estimate localization performance by this approach.

Calculation setup / 3 detector network by HLV

Assumption

1. Implementing a GW-EM pipeline for GWs from CBC
2. Two LIGOs (70 Mpc), Virgo (20 Mpc)

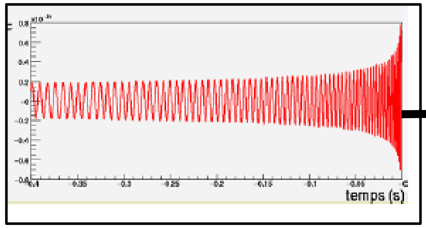
High sensitivity   Low sensitivity



GW-EM pipeline for GWs from CBC

GW detectors → MBTA → BAYESTAR → EM telescopes

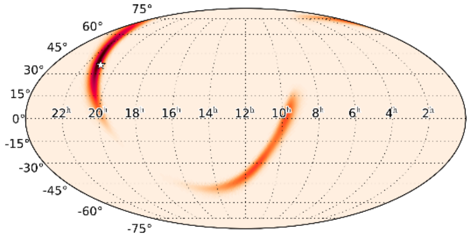
- GW detectors: GW data production
- MBTA: Identification of candidate GW events
- BAYESTAR: Sky localization
- EM telescopes: EM follow-up observations



→

SNR,
arrival time,
phase, mass,
FAR, etc,
par event

→



Calculation setup / 3 detector network by HLV

Main flow

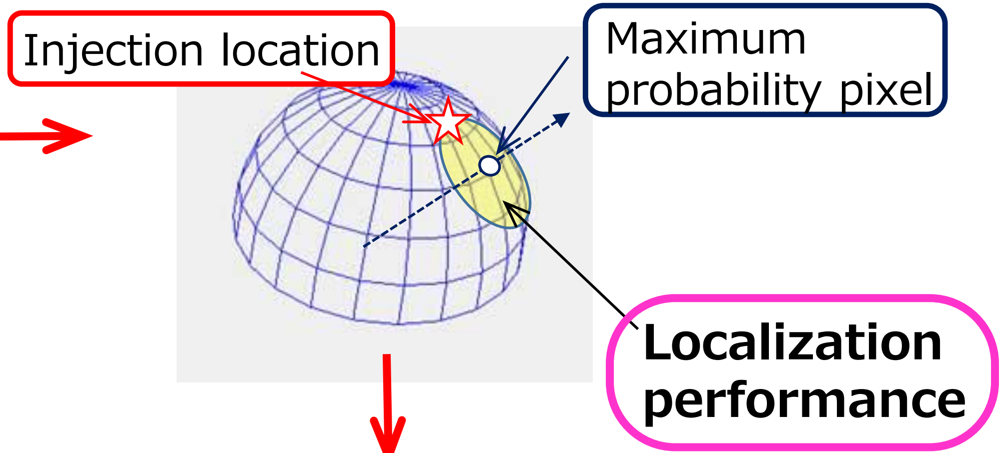
1. Prepare 248 sets of HL MBTA triggers from MDC.
2. Transform HL MBTA triggers to HL or HLV triggers (***SNR***, ***arrival timing***, ***phase*** from each detector).
3. Generate sky maps with BAYESTAR.

GW detectors → MBTA → BAYESTAR →

GW data production

Identification of candidate GW events

Sky localization



1. Prepare 248 existing MBTA outputs from HL coincidences. → 2. Transform HL into HLV coincidences.

3. Construct sky maps and investigate localization performance.

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)

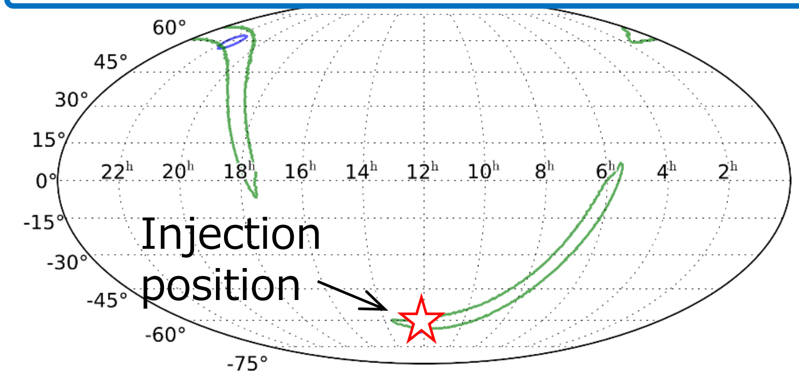
Case 1: worst case
HL+Vr, or HL
(Based on ***FAP***)

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)

Calculation setup / 3 detector network by HLV

Step 1: Plot sky map probability



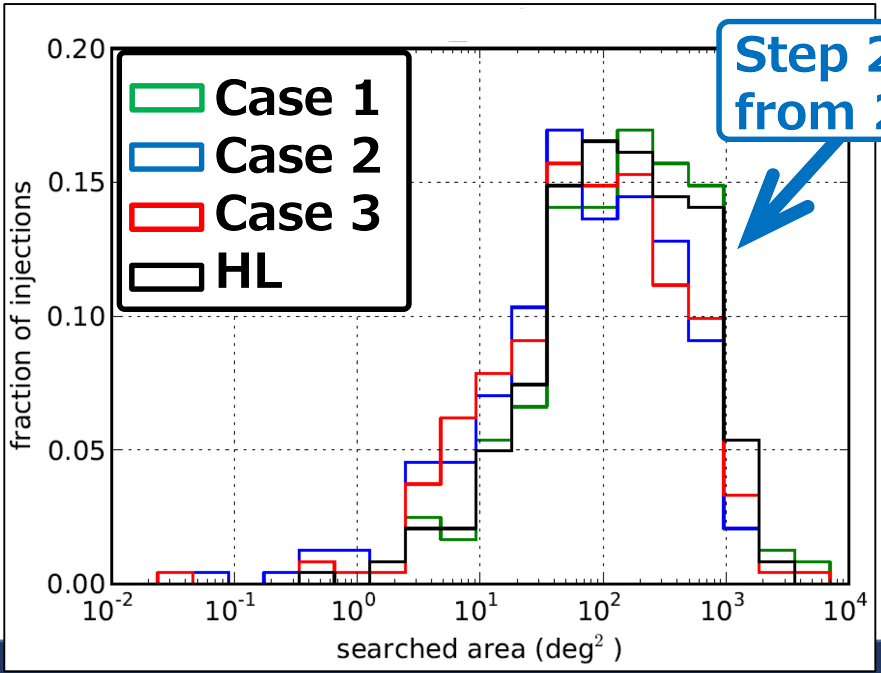
Localization performance:

1) Searched area (deg²)

→ Difference between injection position and prediction.

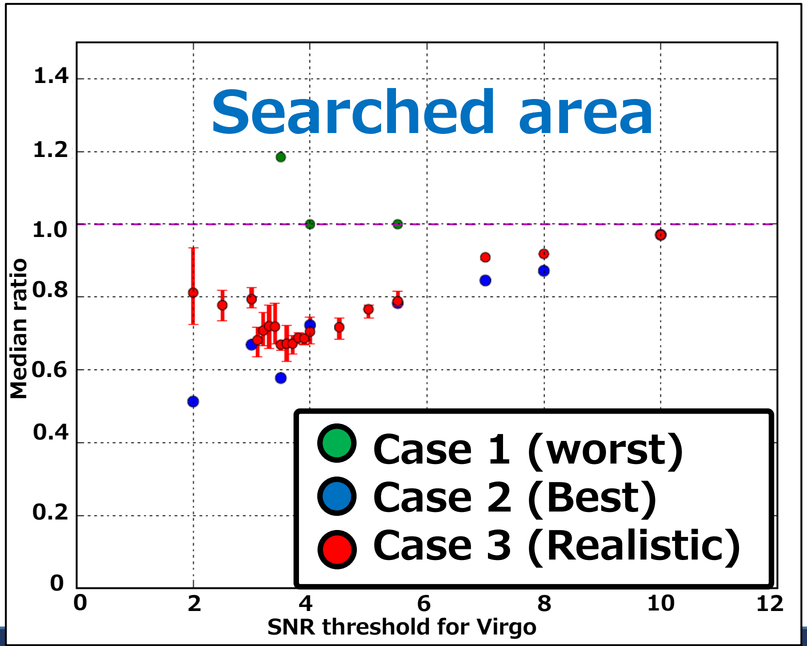
2) 90 % confidence area (deg²)

→ How spread/concentrated the map is.

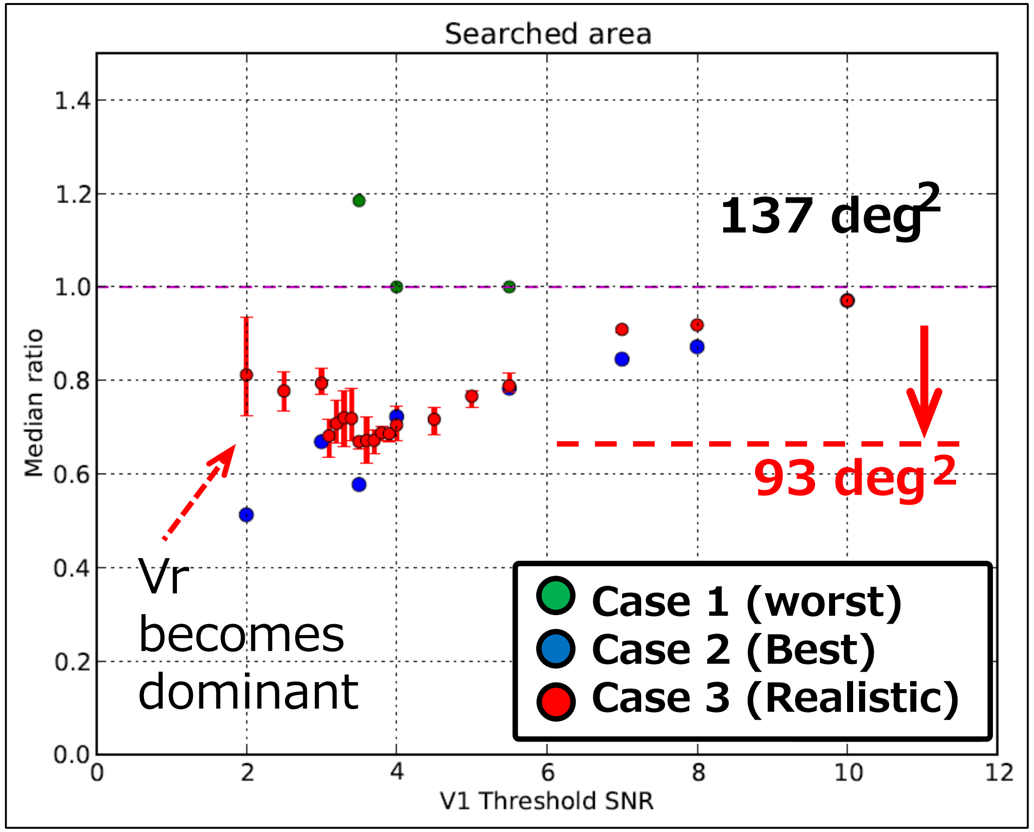


Step 2: Collect these values from 250 events

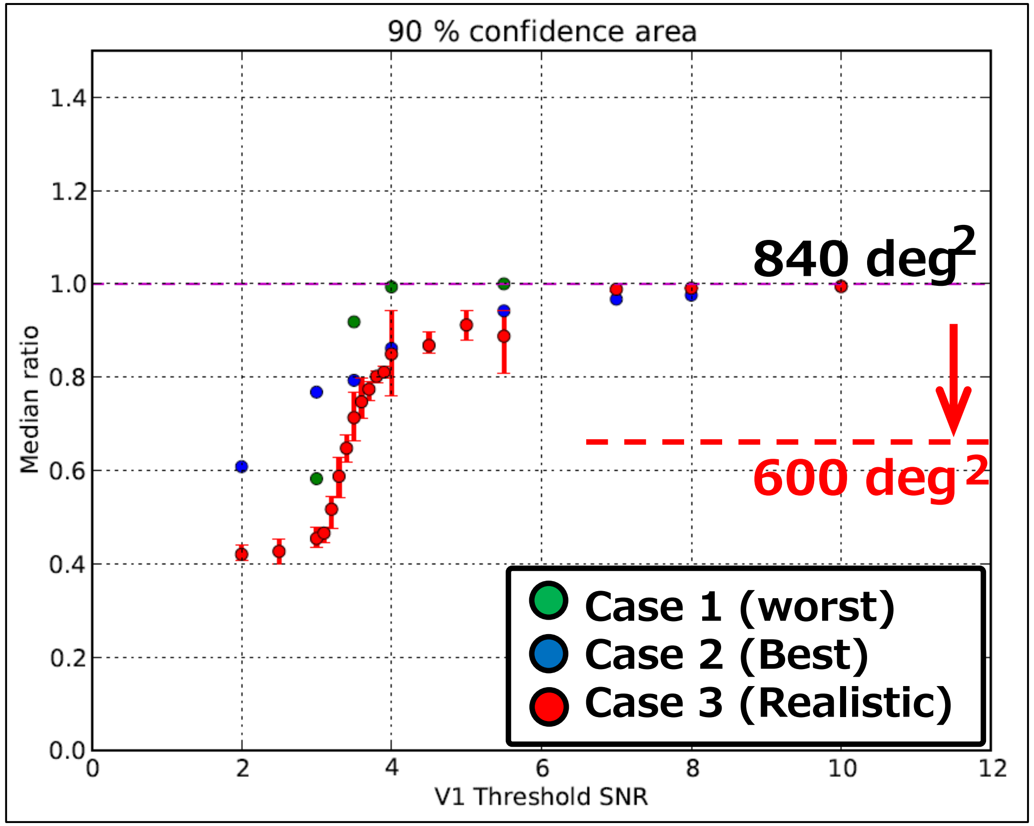
Step 3: Collect median values by changing *SNR*th for Virgo detector



Expected localization performance / by HLV



SNR threshold for H, L = 5.



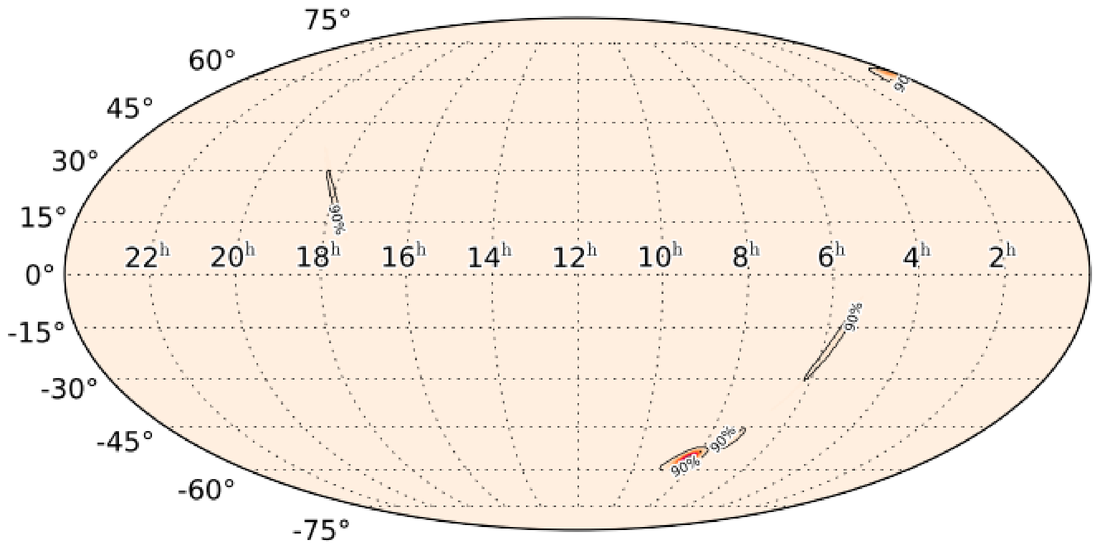
SNR threshold for H, L = 5.

In case 3:
1) Searched area (accuracy) is improved.
2) Prediction becomes more concentrated.

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

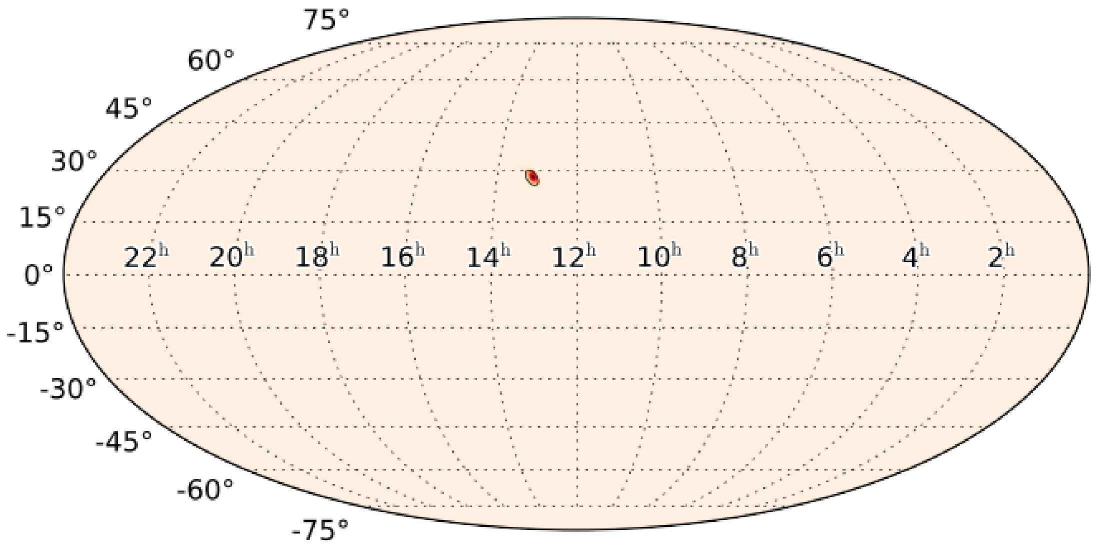
Expected localization performance / by HLV

HL+Vrandom



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

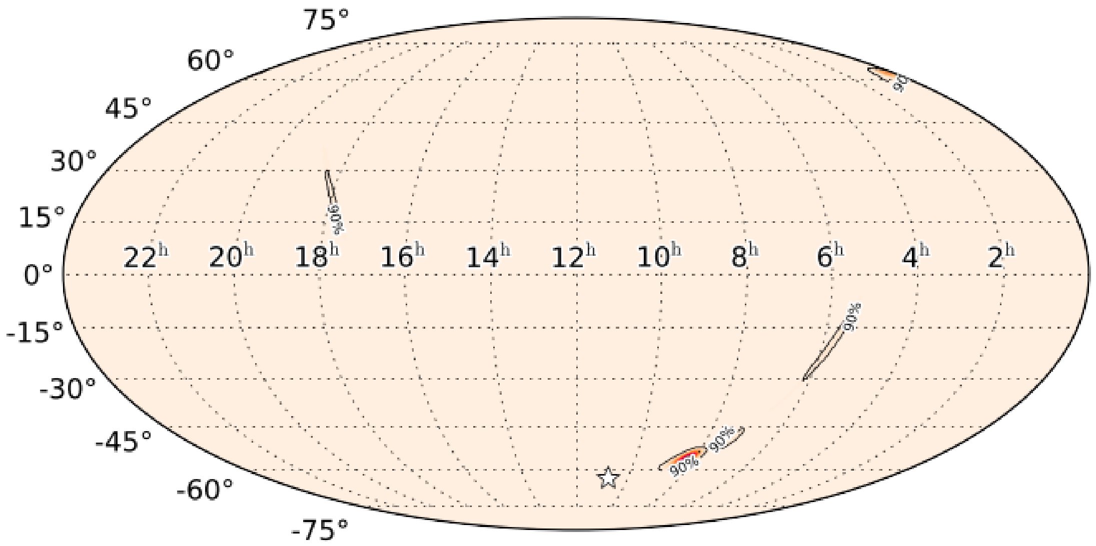
HL+Vinjection



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

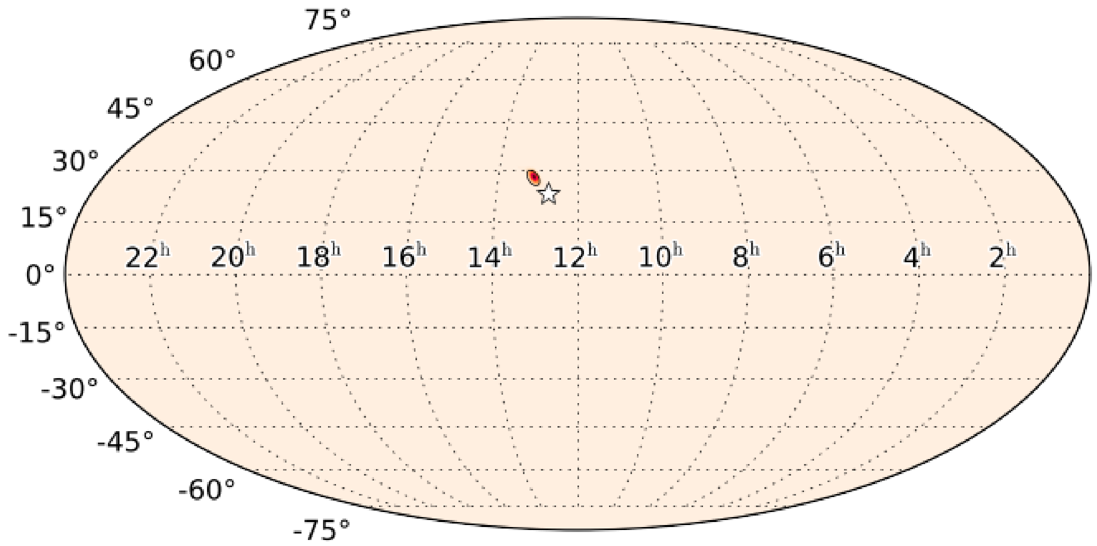
Expected localization performance / by HLV

HL+Vrandom



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

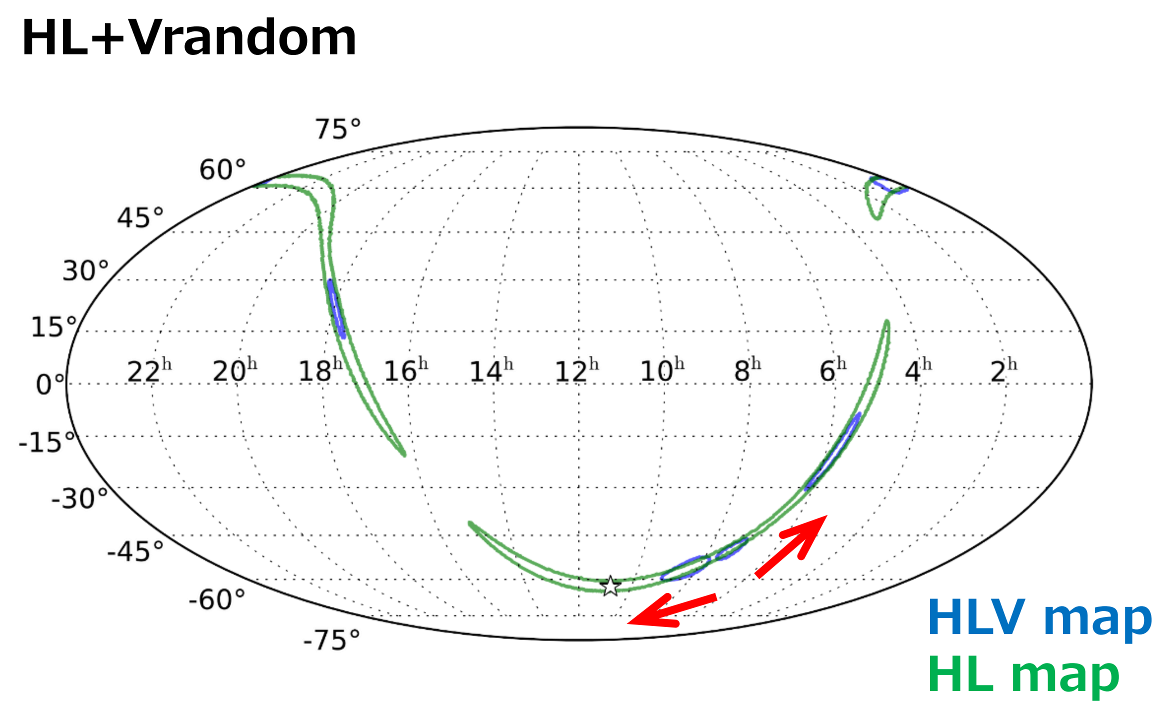
HL+Vinjection

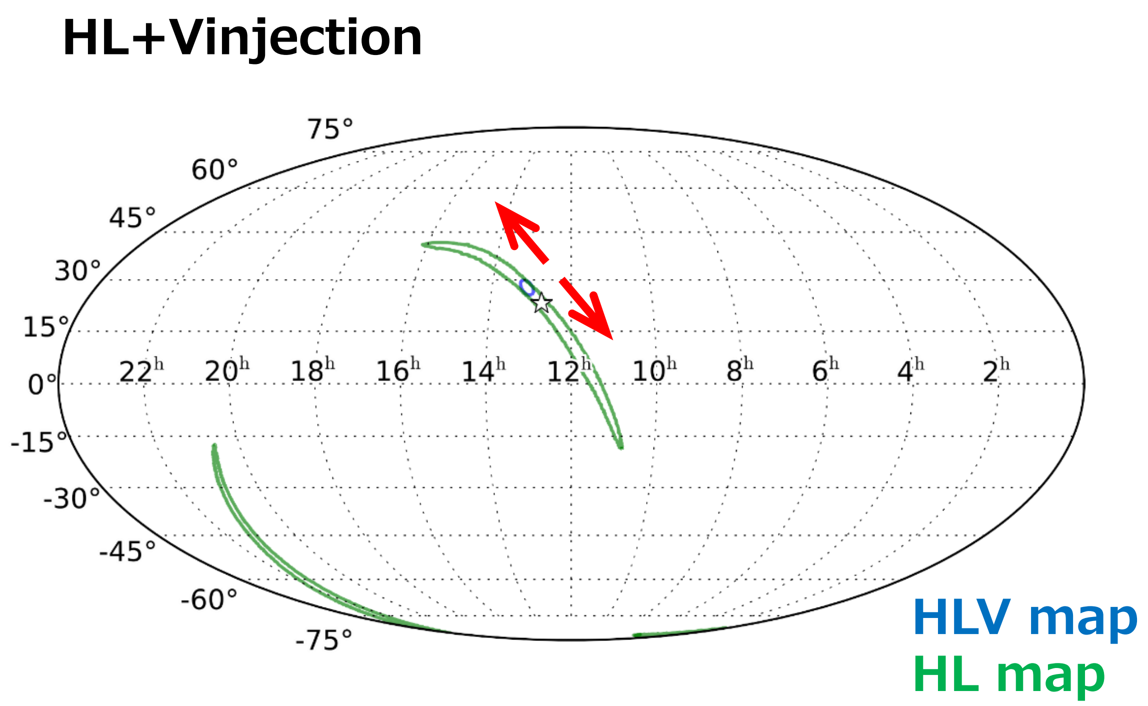


SNR (H)	SNR (L)	SNR(V)
16.5	17.1	3.9

- 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.

Summary

1) A fast localization with hierarchical network is demonstrated.
→ In network by 3 GW detectors (70 Mpc, 70Mpc, and 20Mpc),

→ By using this method, the systematic error on the sky map can be reduced, compared to HL double coincidence search.

→ the performance will be optimized when Virgo threshold is set at ~3.5.

2) It is confirmed this hierarchical network is useful for low sensitivity detectors.

Future work

1) Investigation of performance by two detectors with different sensitivities.
2) More theoretical prediction of optimal SNR threshold

Summary

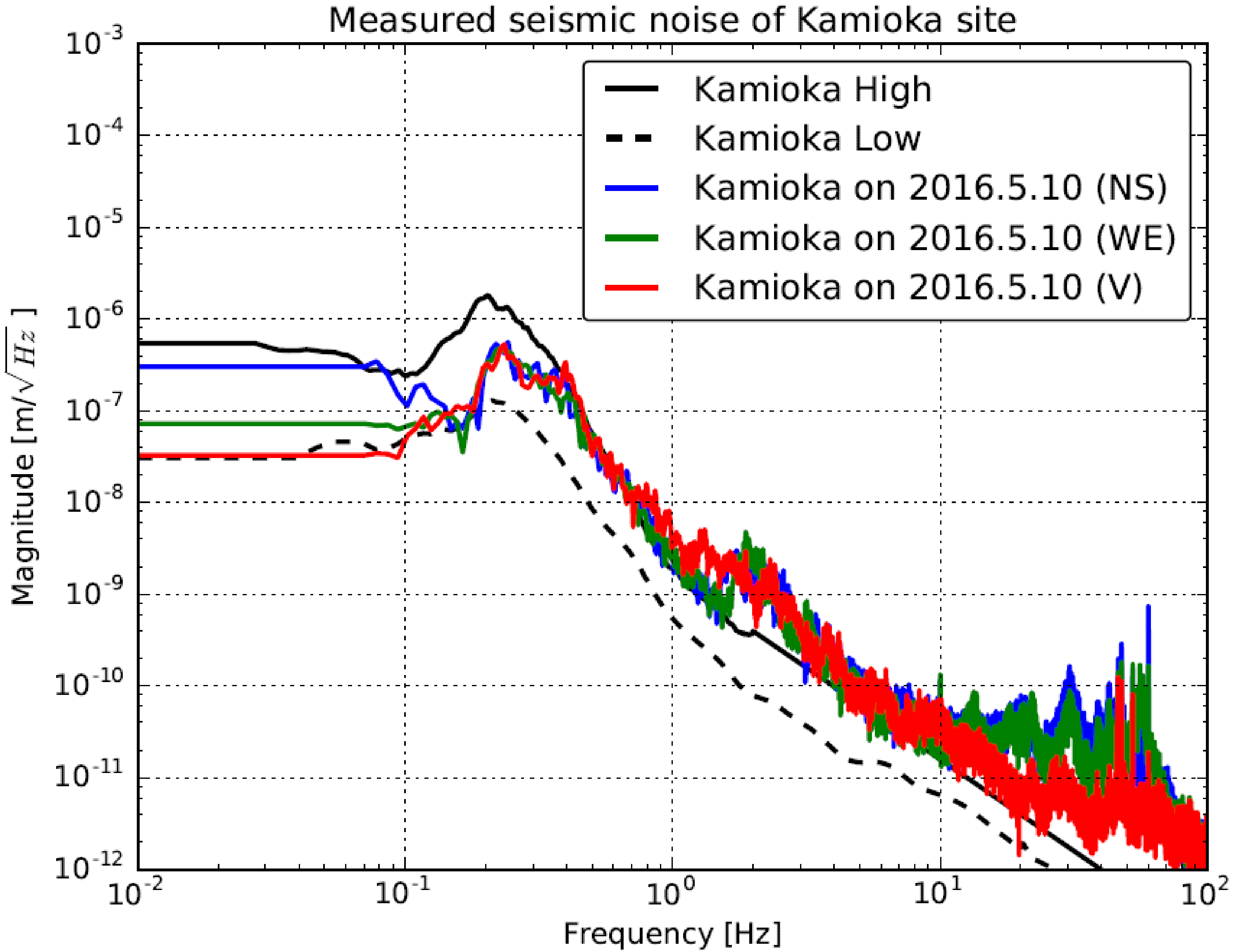
Part 2:
- A simulation tool for active control system was verified by using iKAGRA-PR3 SAS.
- It is confirmed the simulation tool works for designing active control systems.
- Active control system for a KAGRA-SAS is designed by using the tool.

Part 3:
- Localization performance with a hierarchical network search is demonstrated
- It is confirmed this method can effectively use of low sensitivity detectors.

Thank you for your attention.

Back up

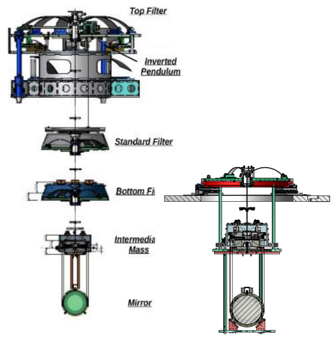
Seismic noise of Kamioka (on 2016.5.10)



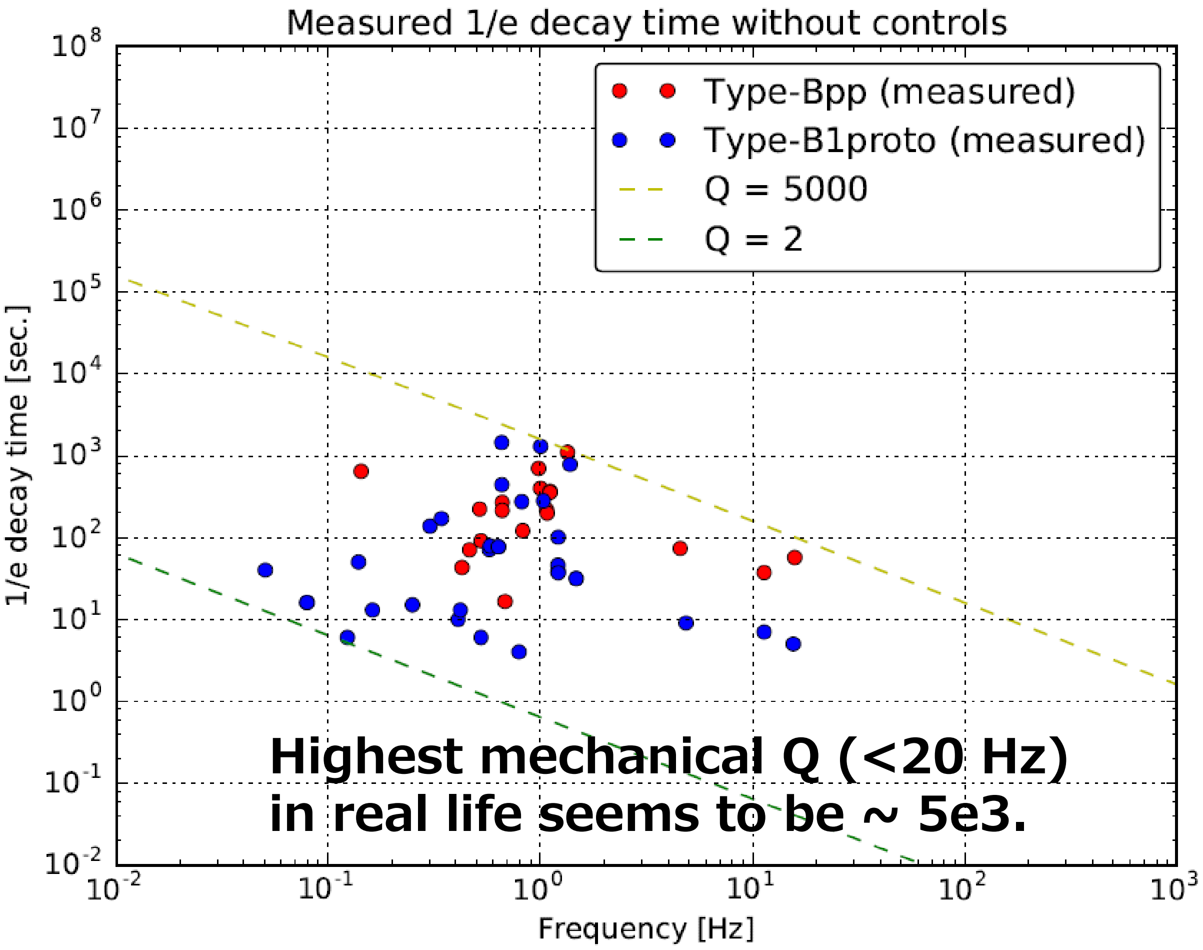
In following calculation, seismic noise measured on 2016.5.10 is considered (blue one).

cf.)
Following measurement was done on 2016.5.24.

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

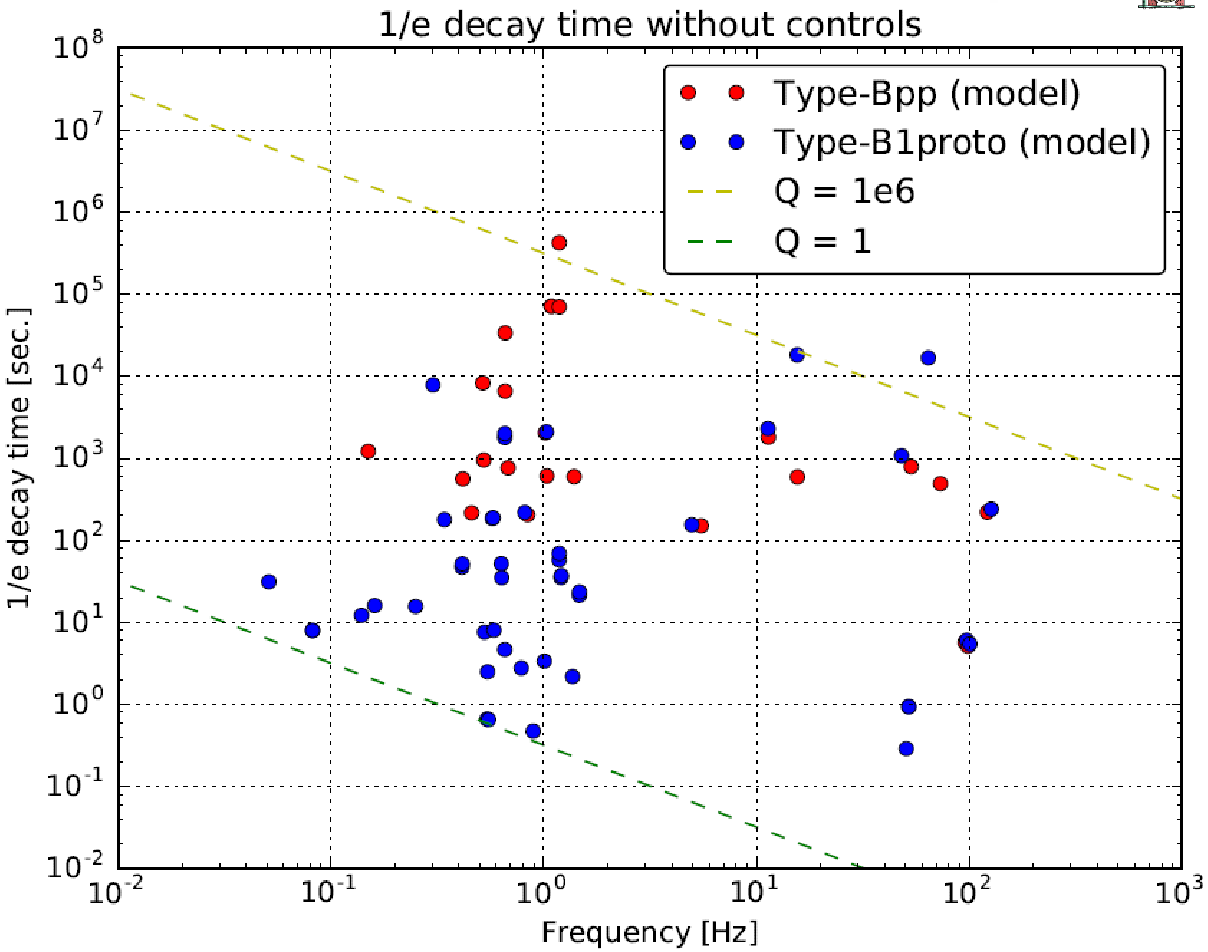


Measured

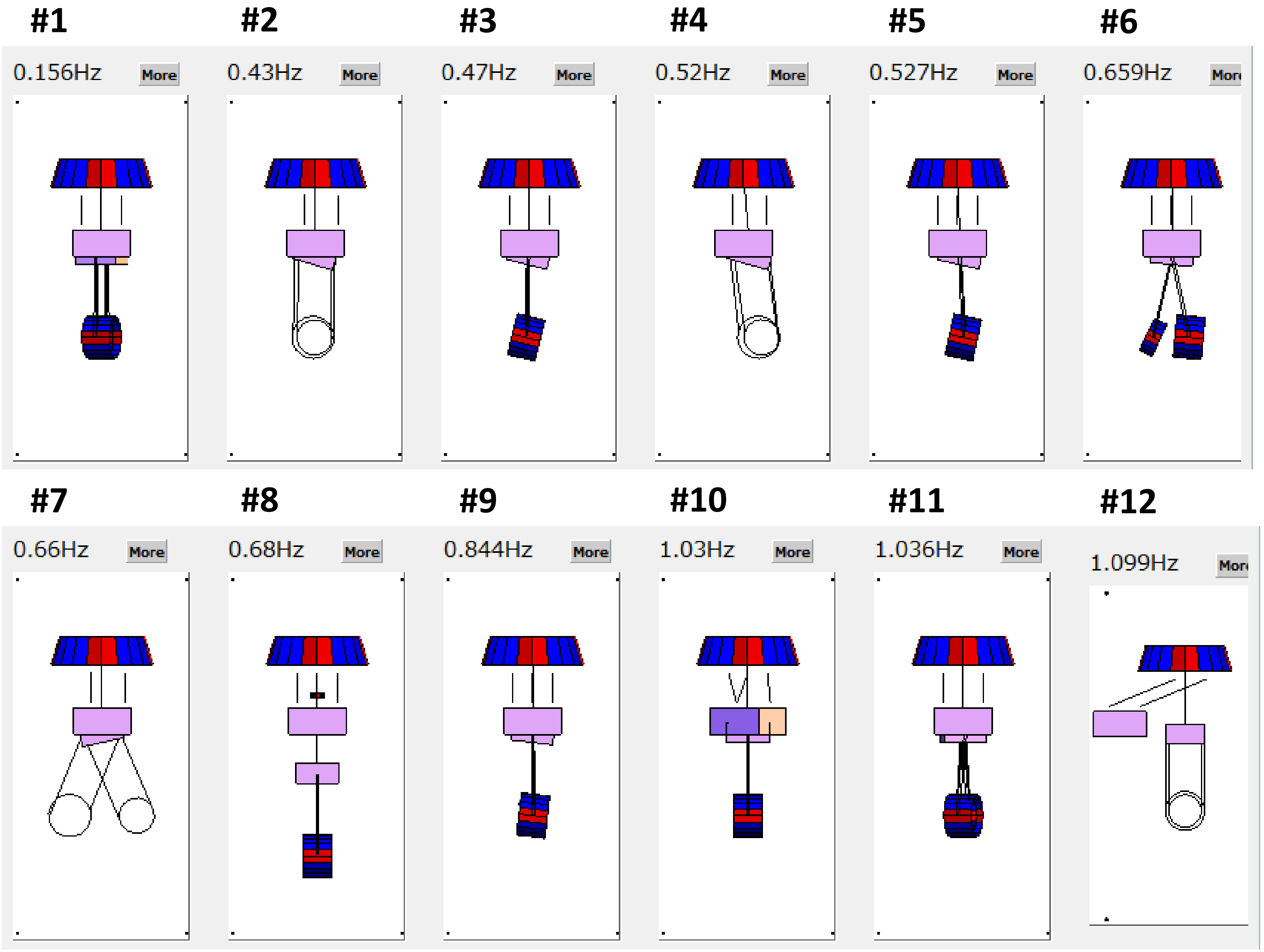


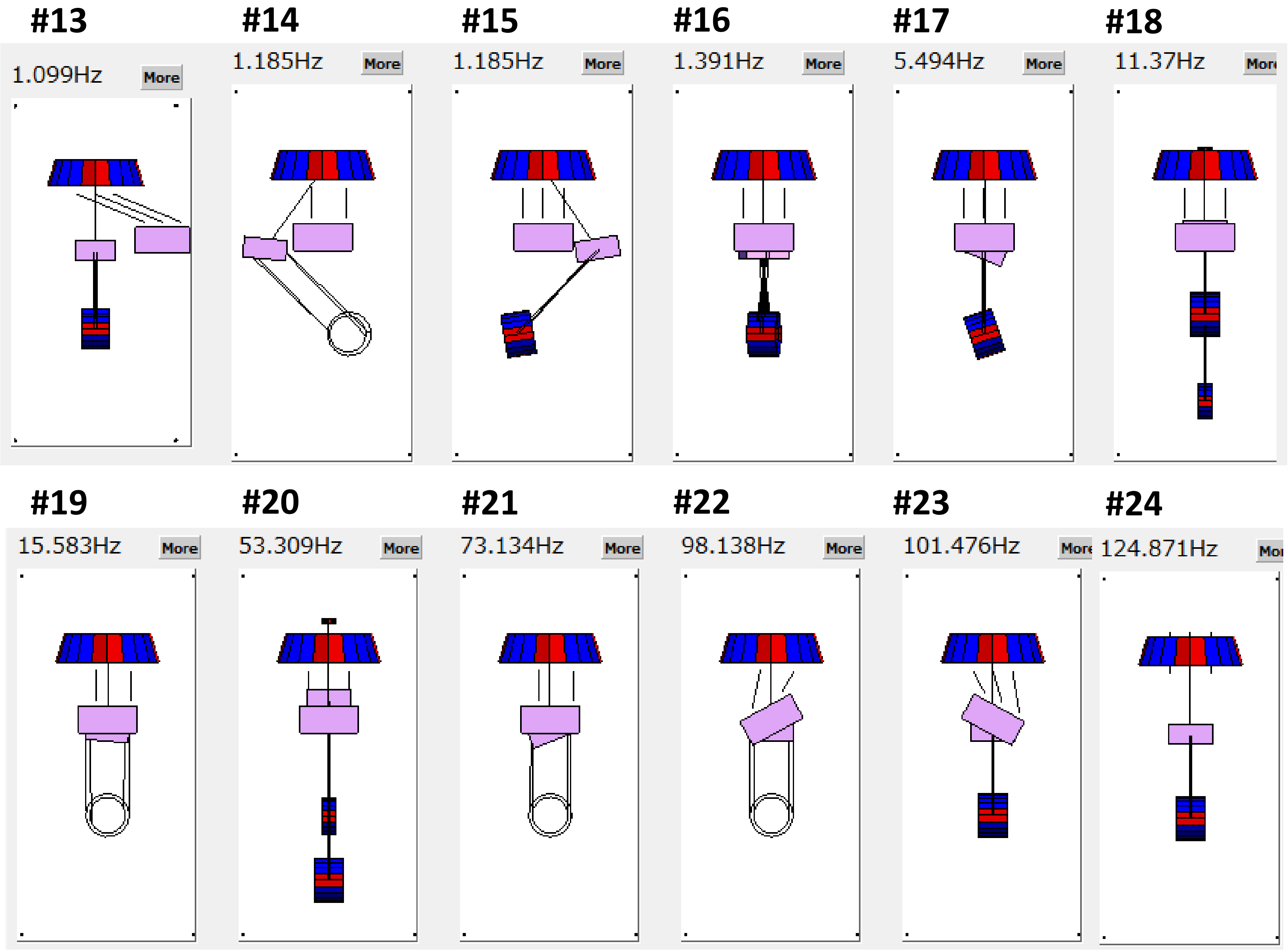
Highest mechanical Q (<20 Hz) in real life seems to be ~ 5e3.

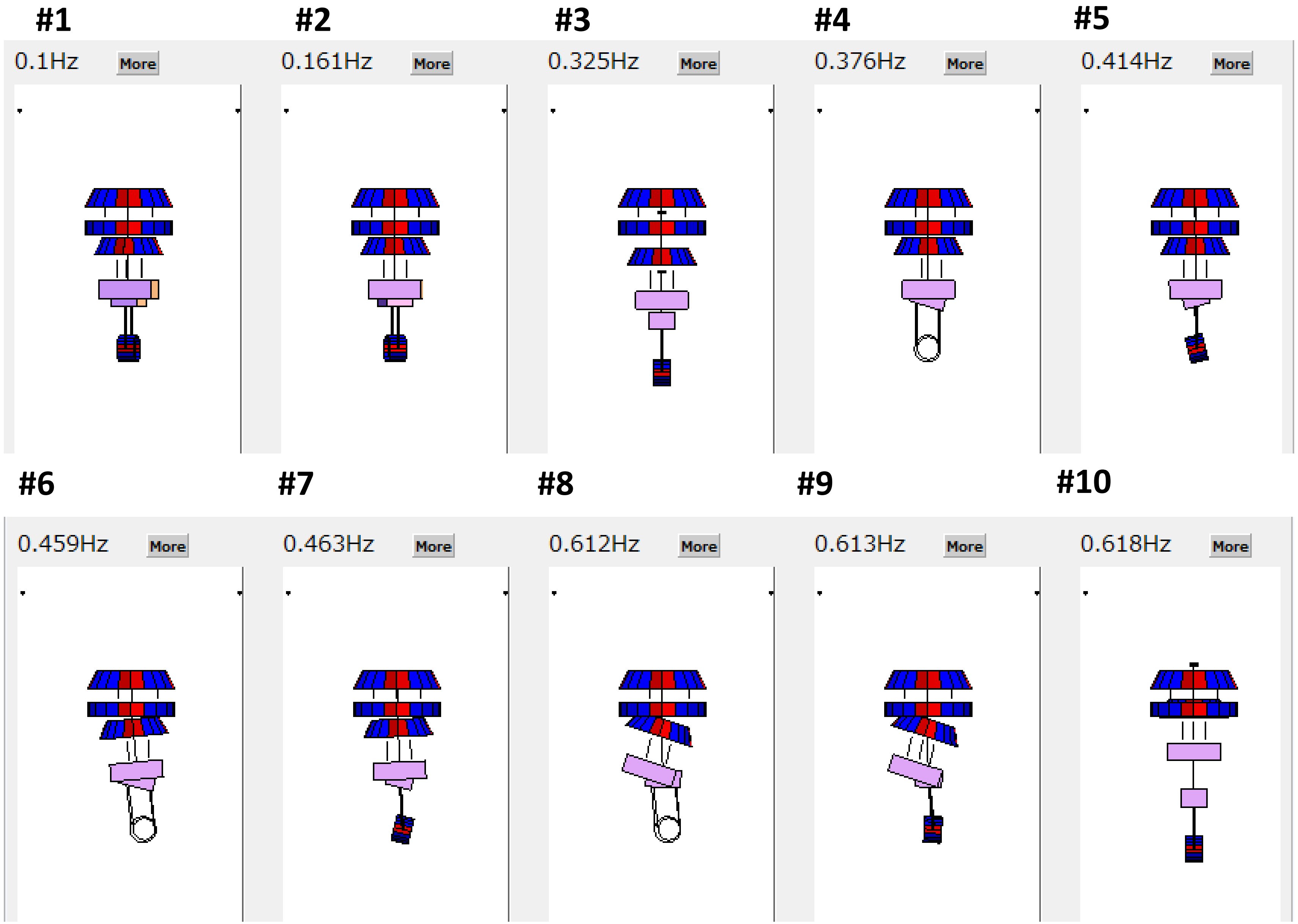
Model



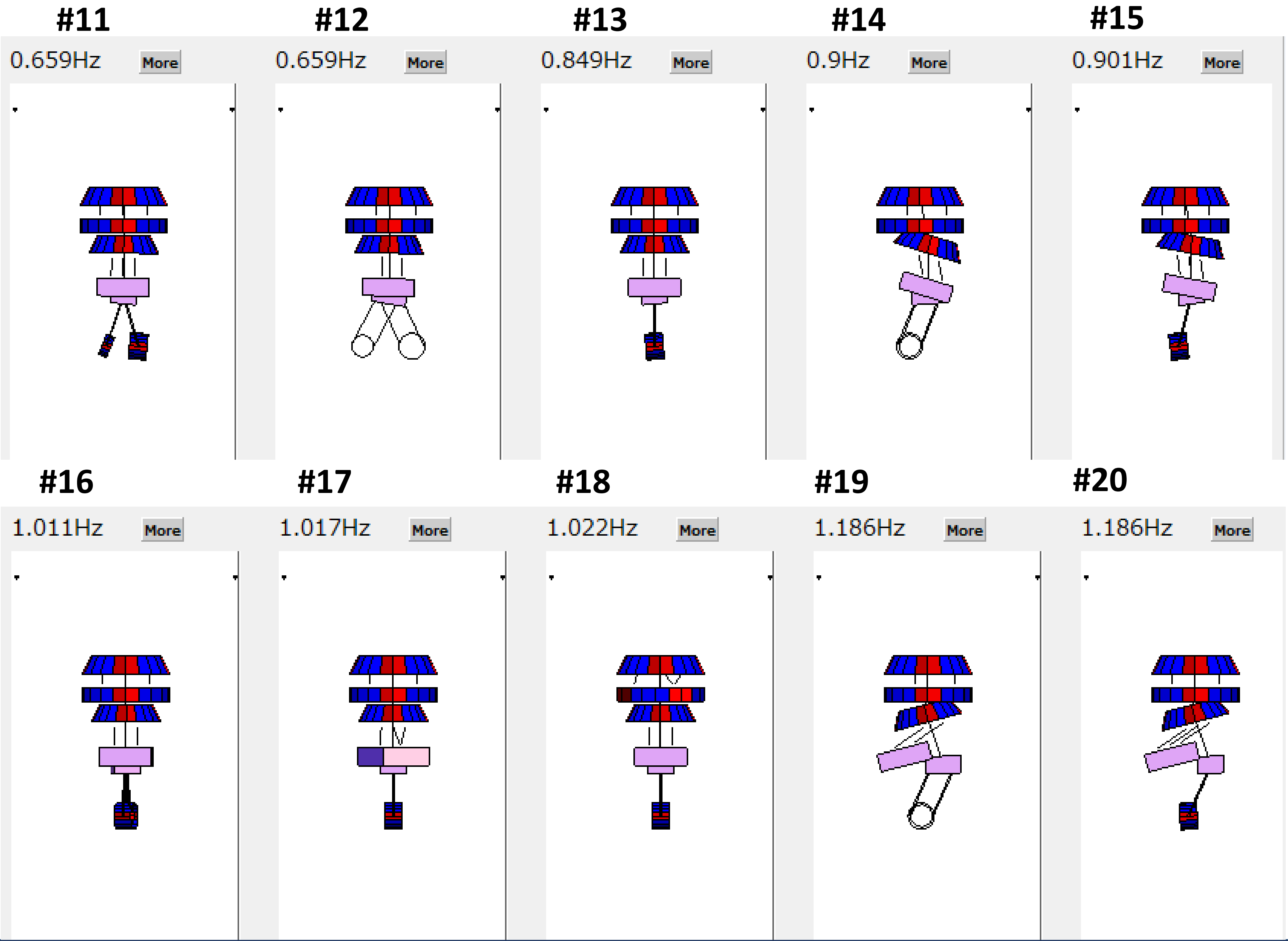
TypeBpp SAS
Eigen mode List : 24 modes

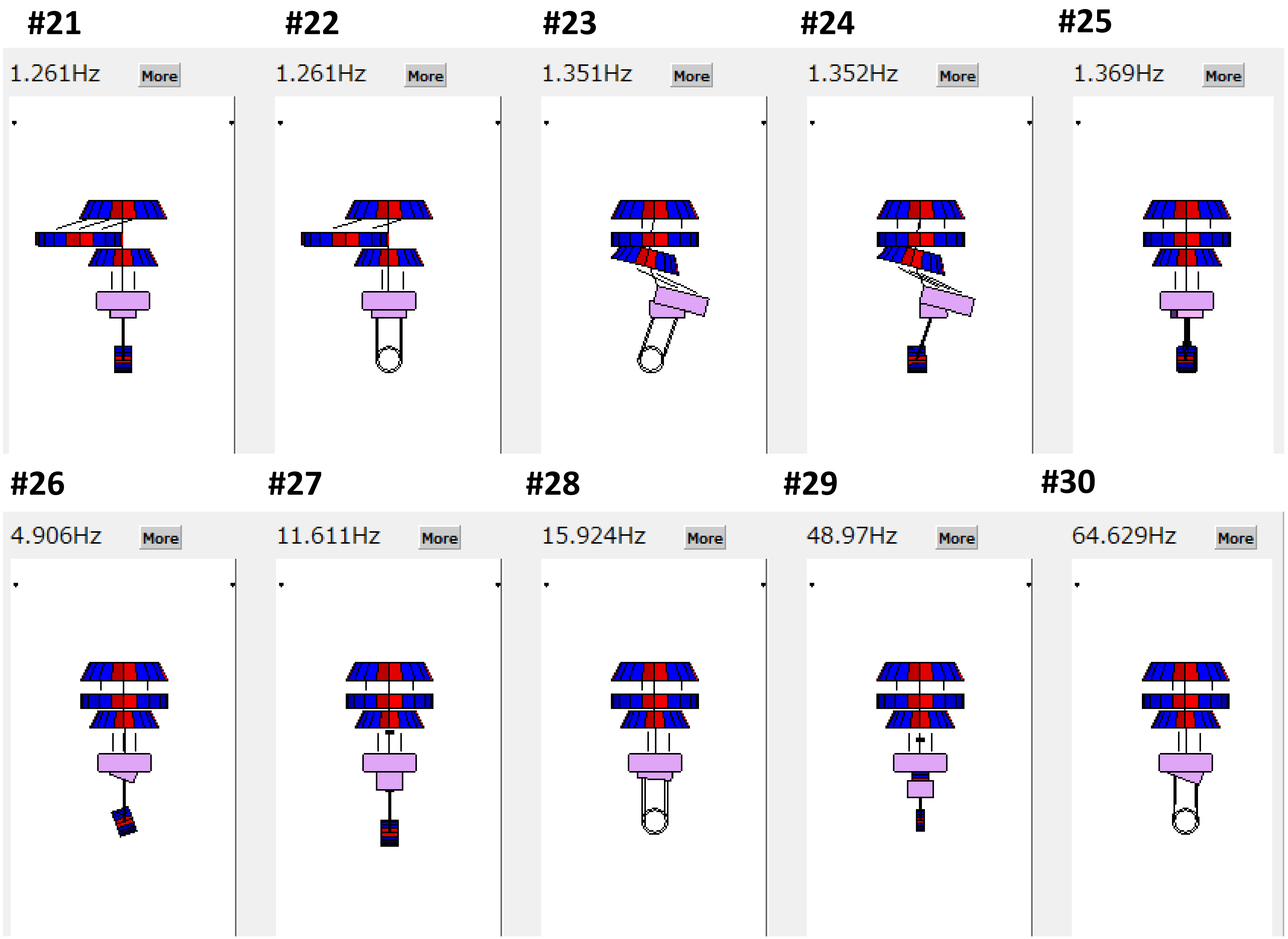



#13
1.099Hz
More
#14
1.185Hz
More
#15
1.185Hz
More
#16
1.391Hz
More
#17
5.494Hz
More
#18
11.37Hz
#19
15.583Hz
More
#20
53.309Hz
More
#21
73.134Hz
More
#22
98.138Hz
More
#23
101.476Hz
More
#24
124.871Hz

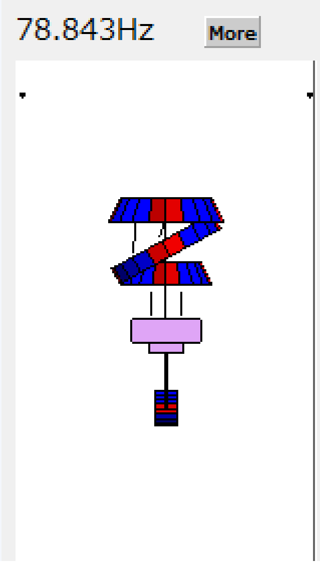


TypeBp SAS
Eigen mode List : 36 modes

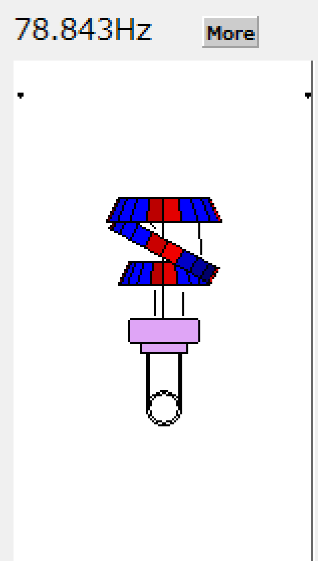

#11
0.659Hz
More
#12
0.659Hz
More
#13
0.849Hz
More
#14
0.9Hz
More
#15
0.901Hz
More
#16
1.011Hz
More
#17
1.017Hz
More
#18
1.022Hz
More
#19
1.186Hz
More
#20
1.186Hz
More


#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

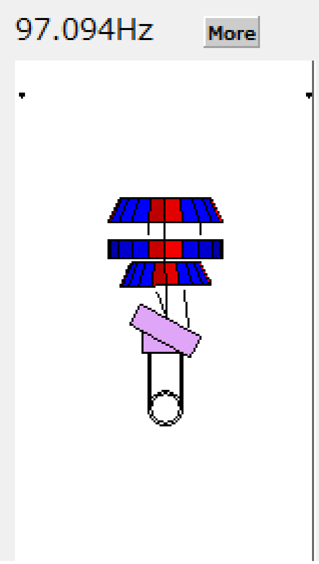
#31



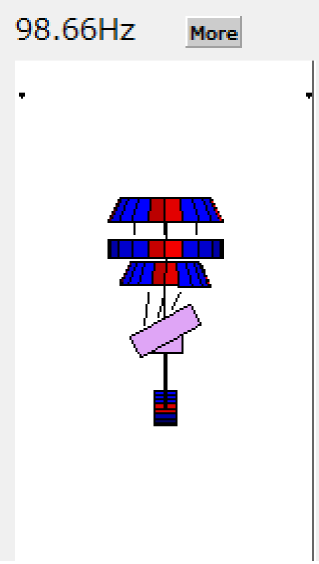
#32



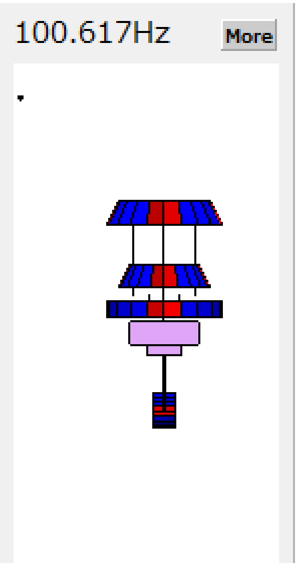
#33



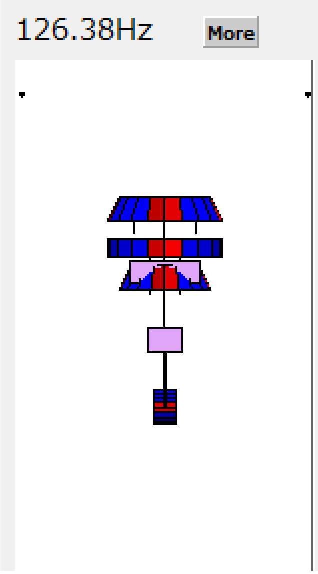
#34



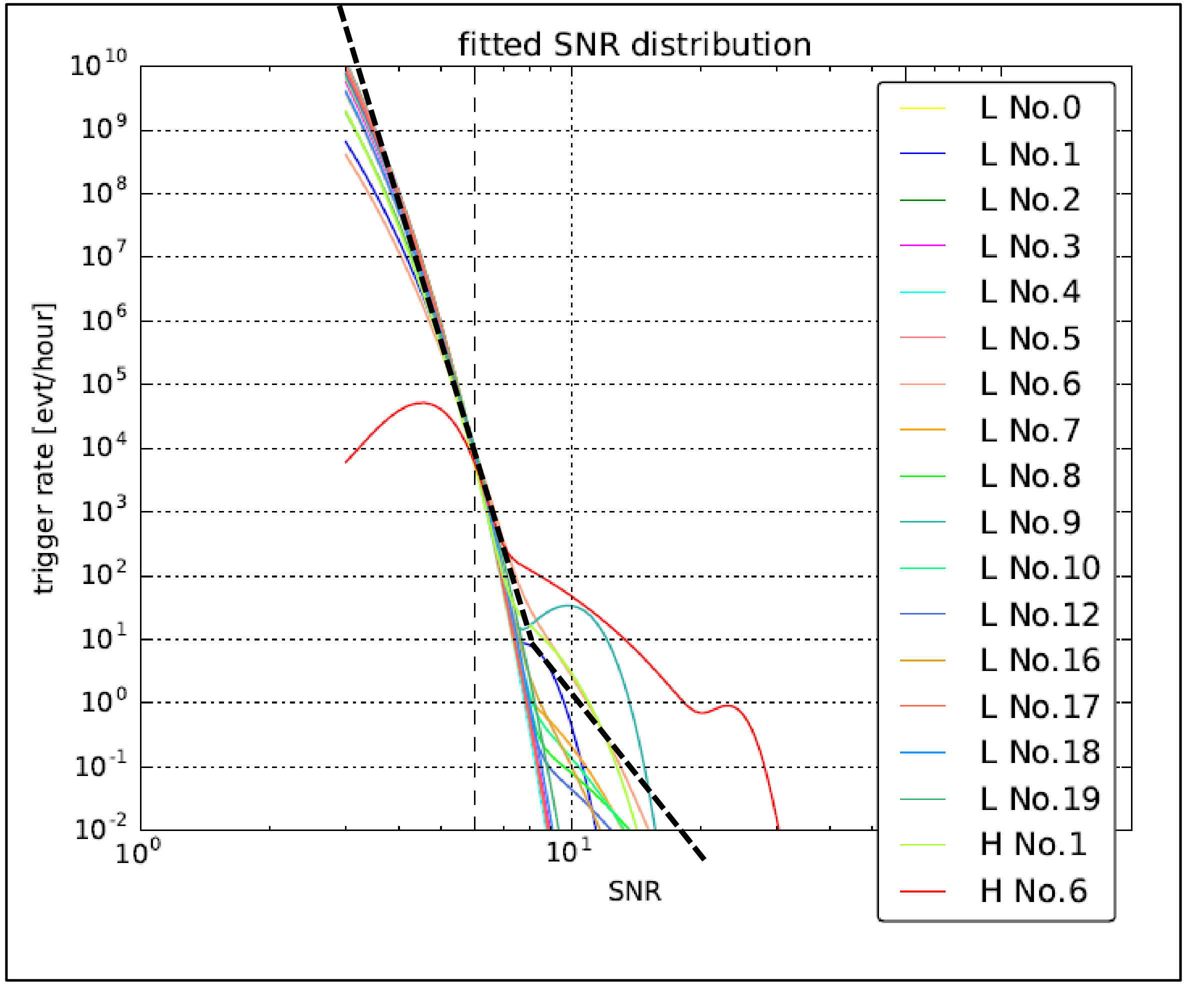
#35

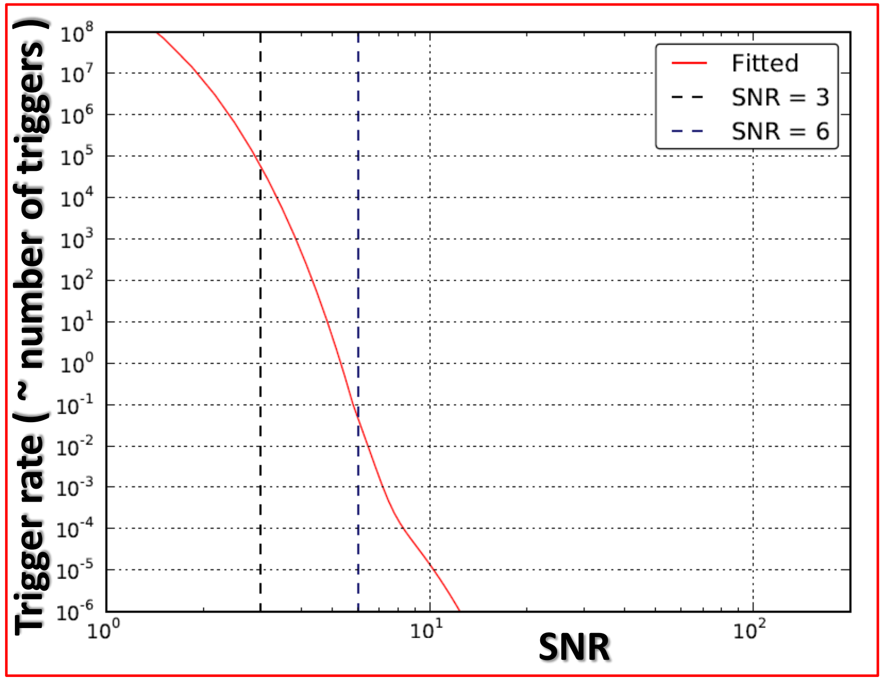


#36



Calculation setup : How to generate SNR, arrival timing, phase of the V1

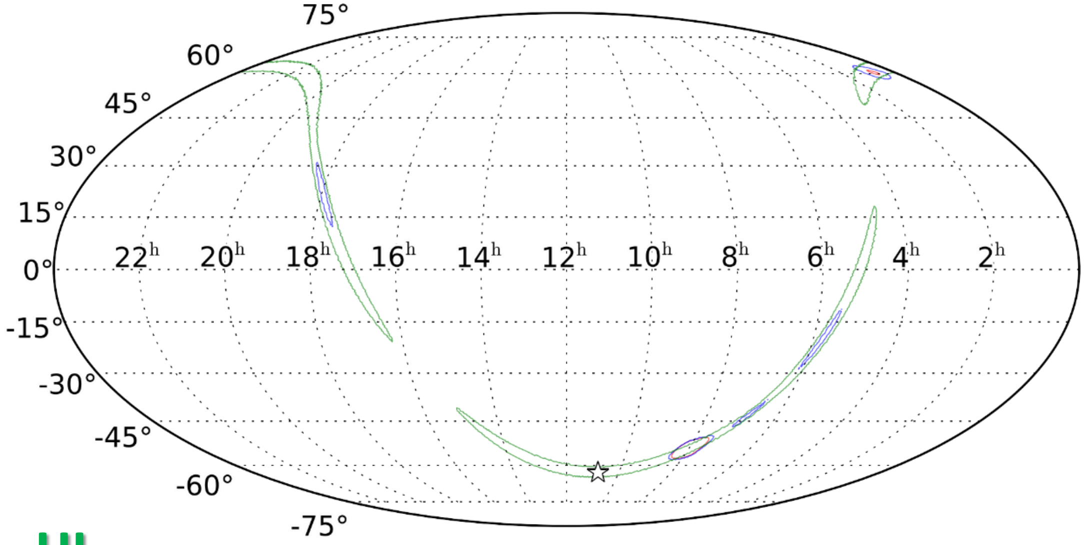




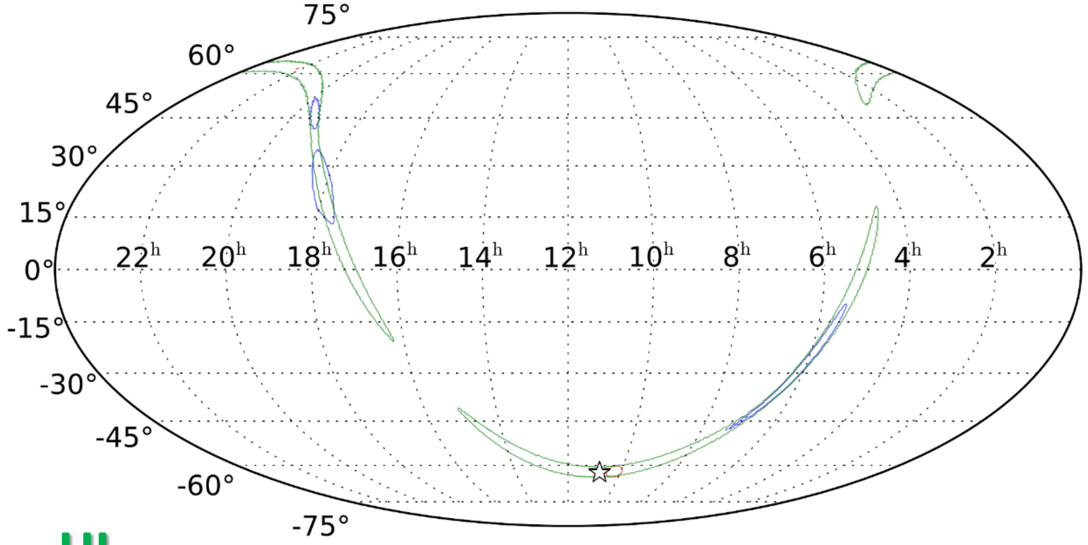
Plot SNR distribution from ~ about 20 hours data

→ Choose typical curve ("quiet")

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



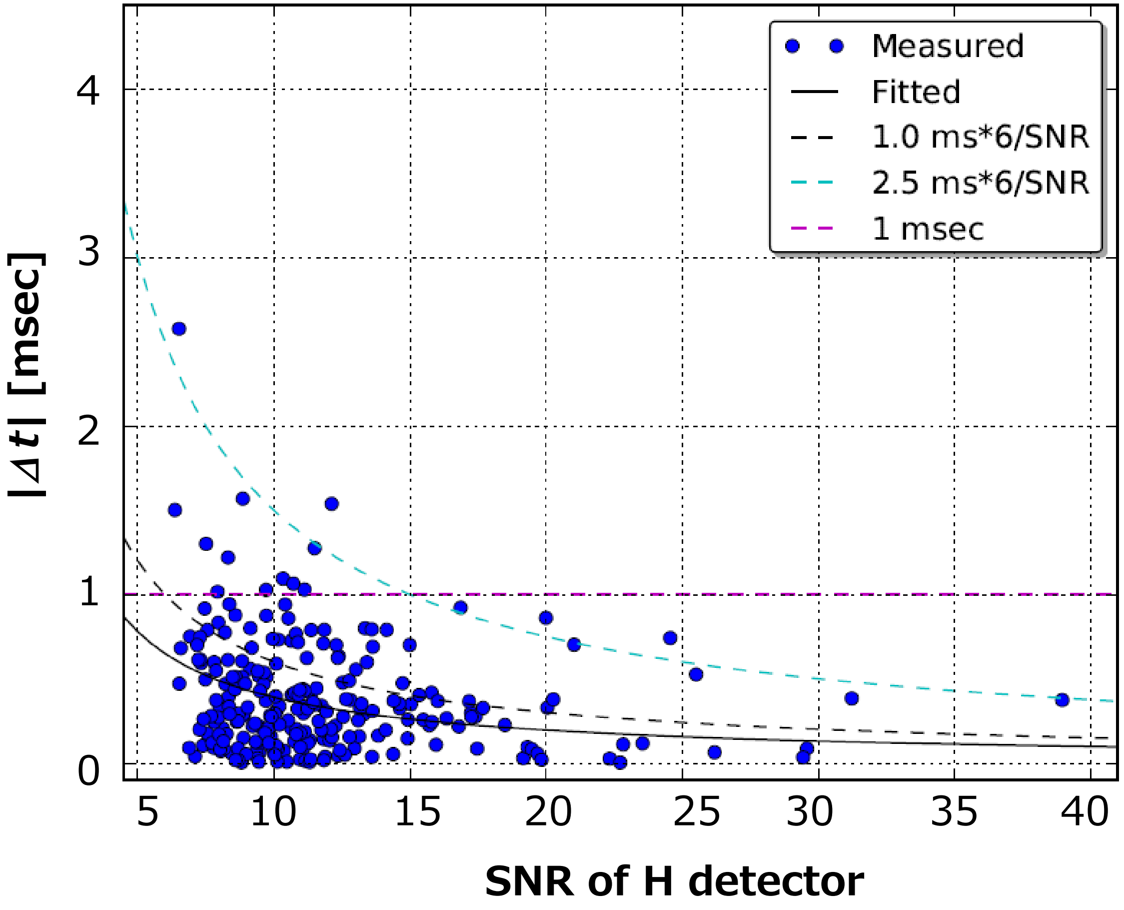
HL
HL + Vrandom
HL + Vrandom + Krandom



HL
HL + Vinj
HL + Vinj + Kinj

For further accuracy improvement:

Measured uncertainties on arrival time vs. SNR.



Relation between timing error and SNR

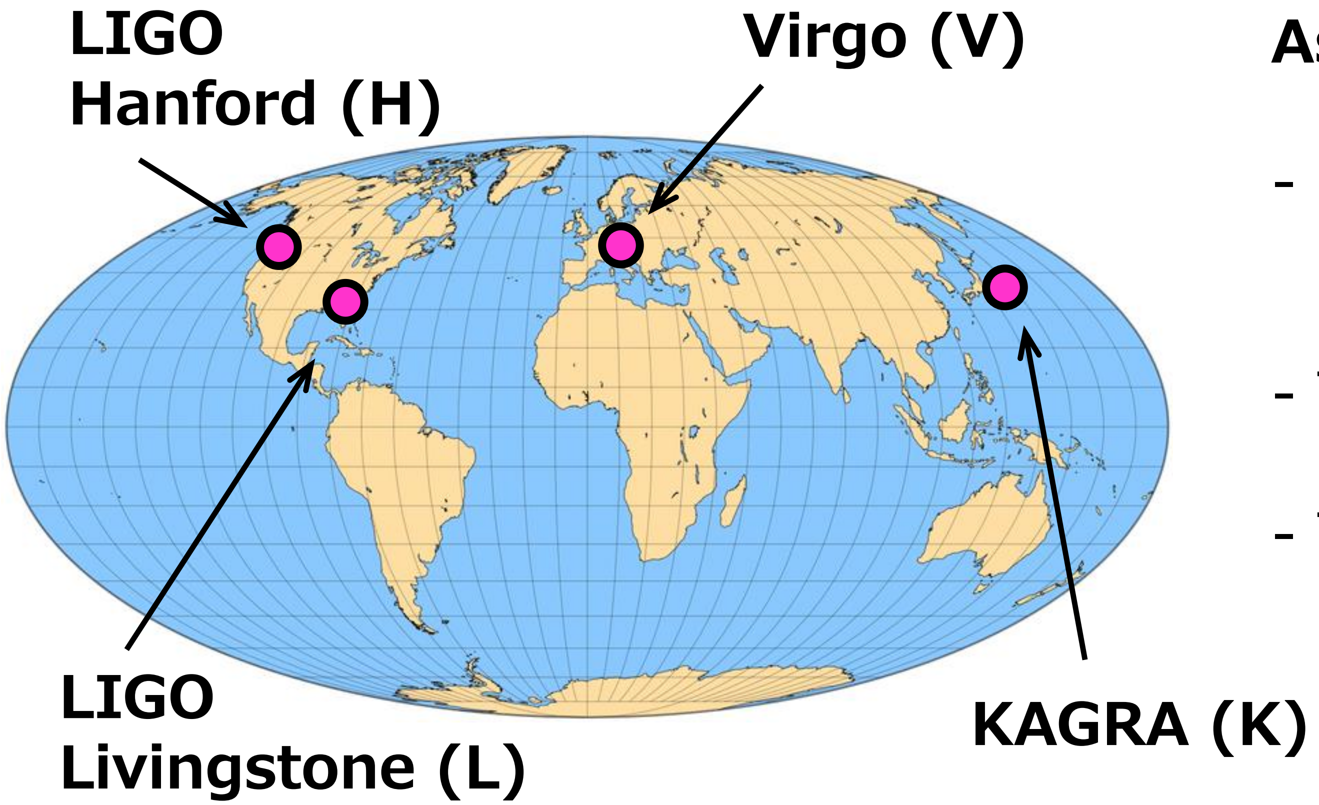
Detected arrival timing has some uncertainties Δt due to:
1) calibration uncertainty
2) discrepancies of templates.
and so on.

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.

How about this hierarchical network by 4 detectors, HLVK?



Assumption

- Implementing a GW-EM pipeline for GWs from CBC

- Two high sensitivity detectors **LIGOs (70 Mpc)**,
- Two low sensitivity detectors **Virgo (20 Mpc), KAGRA (20 Mpc)**

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 = *t*H1 or *t*L1
+ random [-35ms:35ms]
Phase = random $[0:2\pi]$

V1 trigger based on injection parameters : Vi, Ki

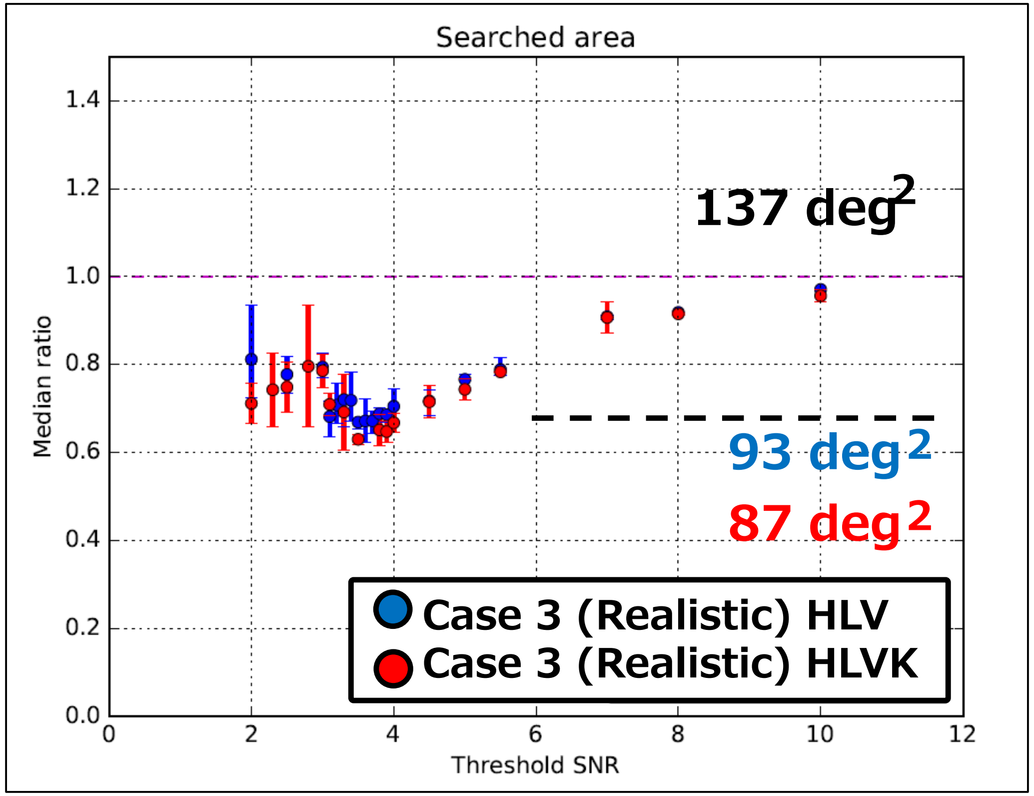
SNR = metadata + Gauss(0,1)
Timing = metadata
+ Gauss(0,0.66 ms*$\frac{6}{\mathrm{SNR}}$)
Phase = measured + Gauss(0,0.25 rad)

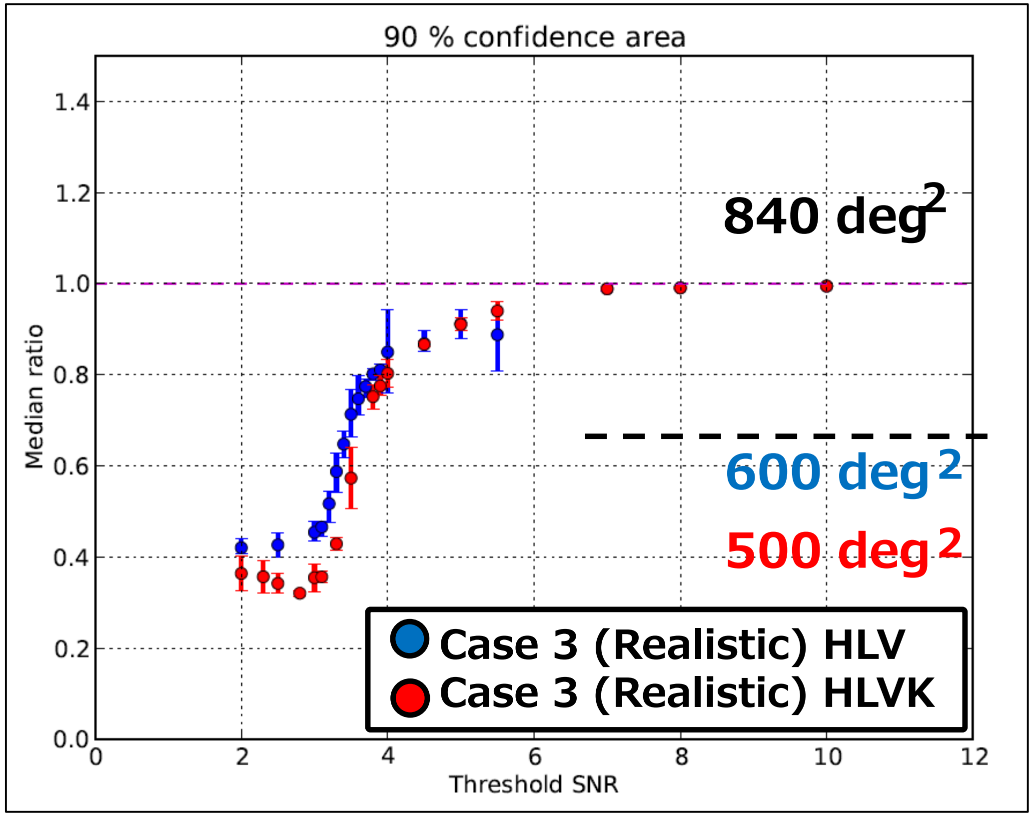
Case 1: worst case
HL+Vr, HL+Kr, HL+Vr+Kr or HL
(Based on ***FAP***)

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

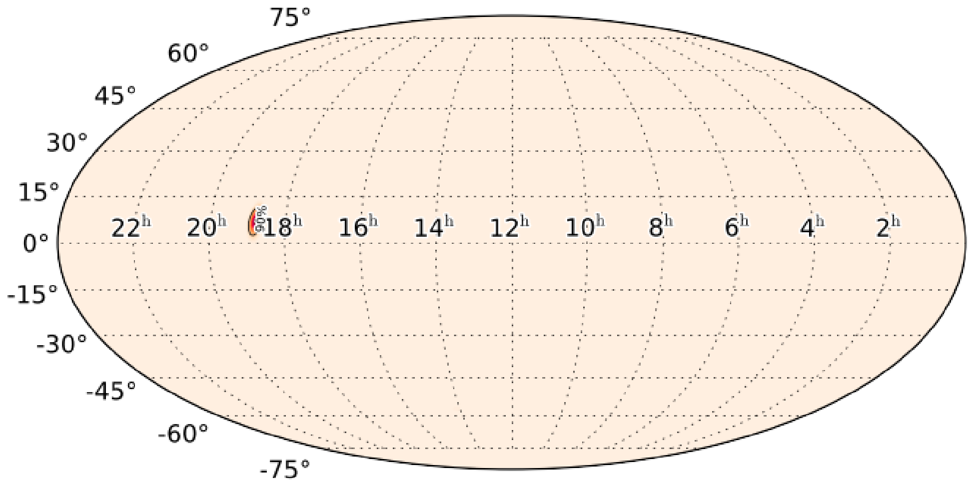




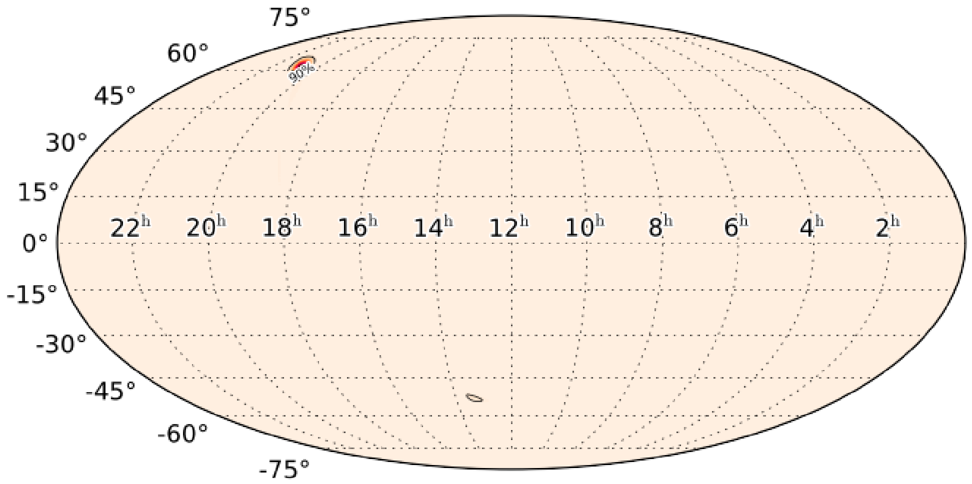
1) Accuracy (searched area) is so not improved since the timing error
2) In order to improve the accuracy of the map
   → Necessary to reduce timing error → Necessary to improve sensitivity of GW detectors.
3) Predicted area becomes more condensed.
   → By using low sensitivity detectors, systematic errors on sky maps can be reduced.

Expected localization performance / by HLVK

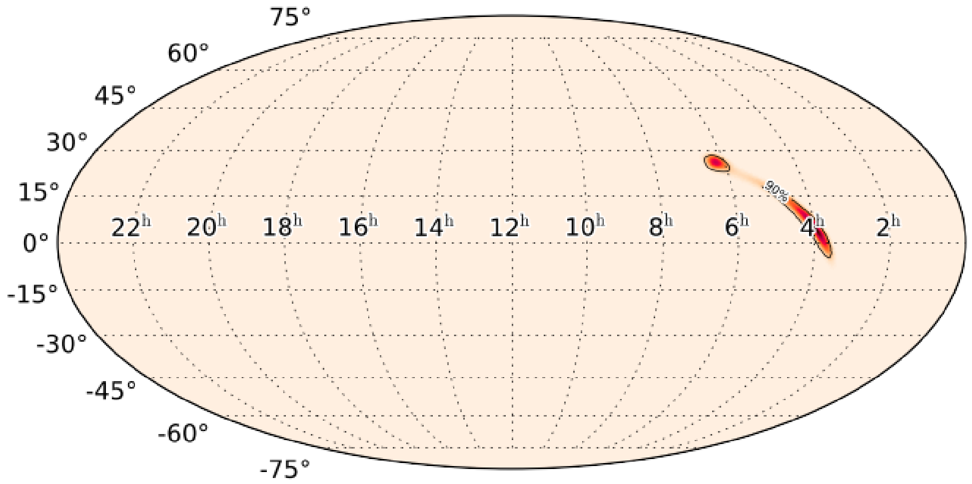
HL + Vi + Ki



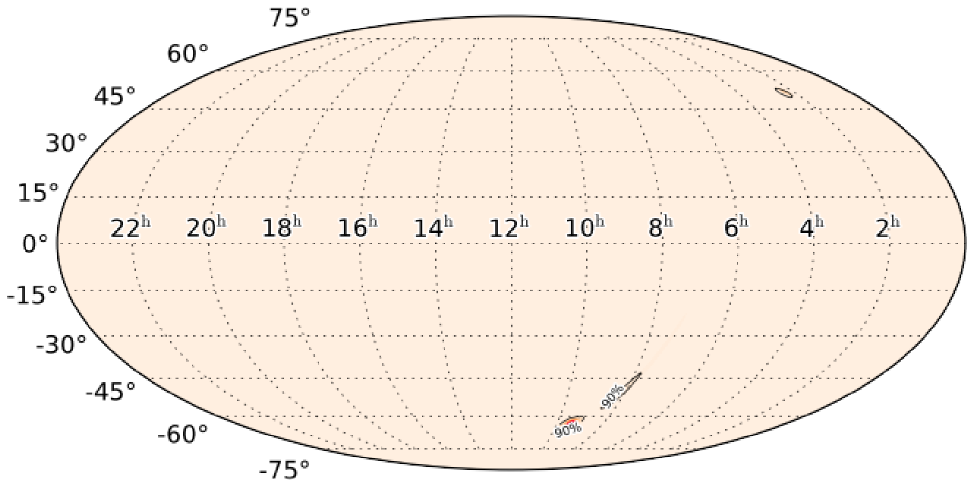
HL + Vr + Kr



HL + Vr + Ki

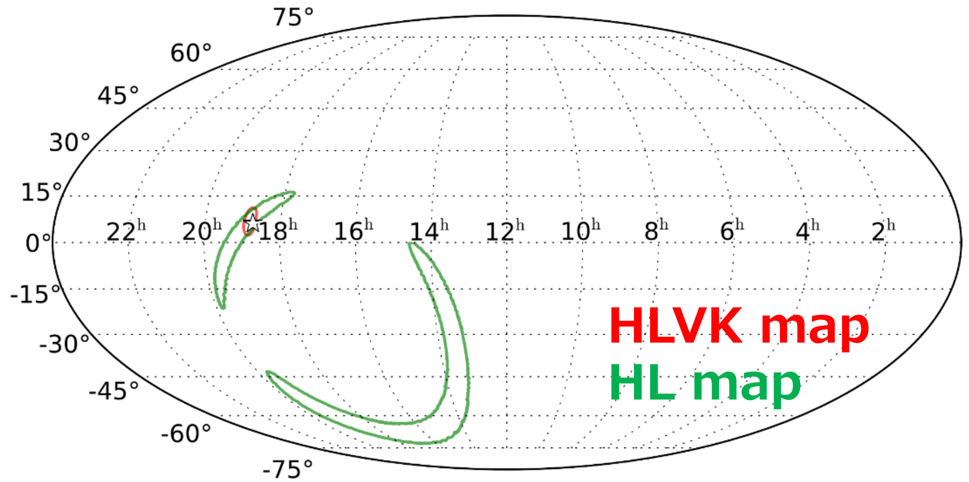


HL + Vi + Kr

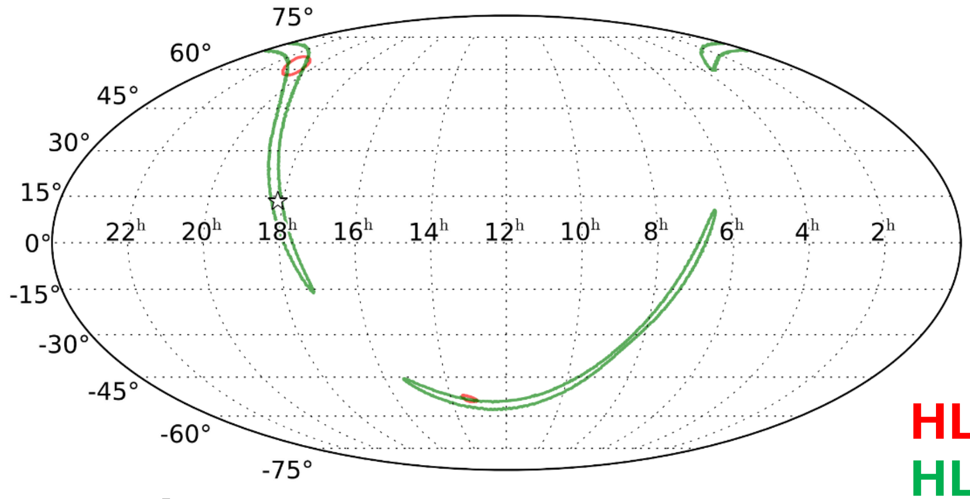


Expected localization performance / by HLVK

HL + Vi + Ki

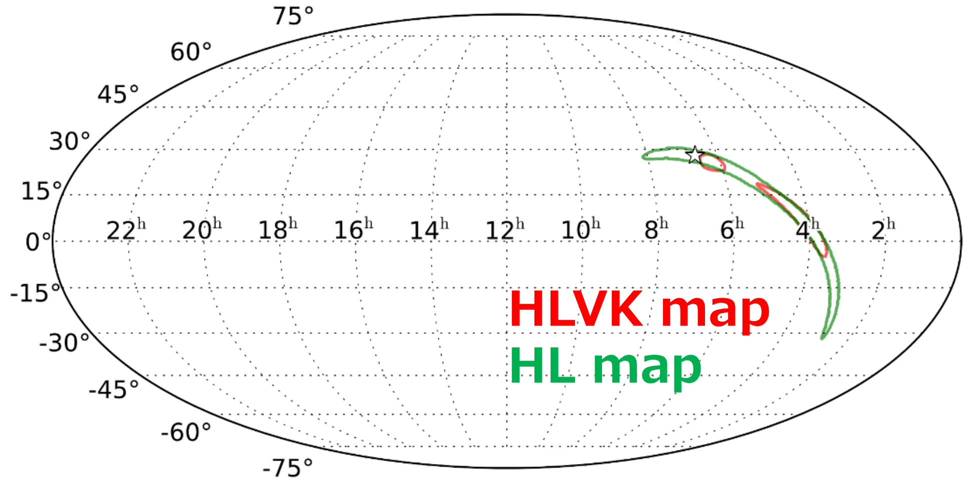


HL + Vr + Kr

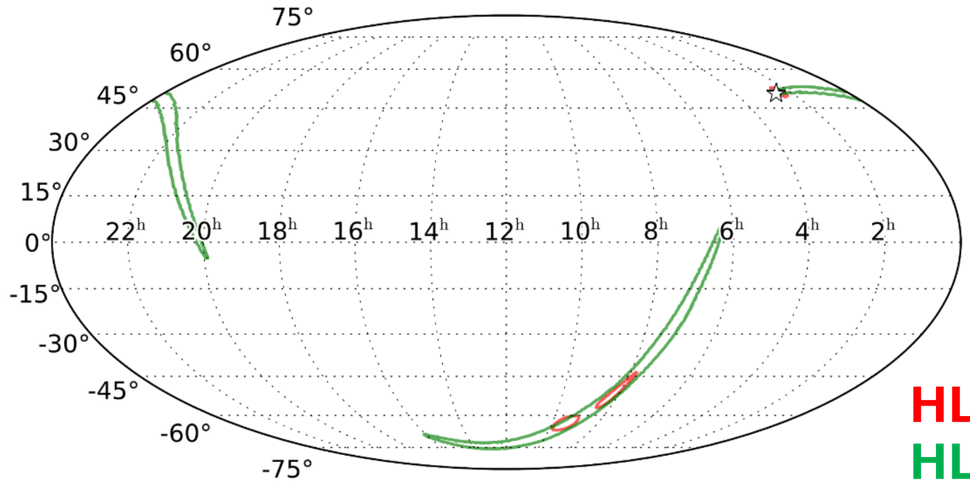


HLVK map
HL map

HL + Vr + Ki



HL + Vi + Kr



HLVK map
HL map