Fast localization of coalescing binaries with gravitational wave detectors

and

Low frequency vibration isolation for KAGRA

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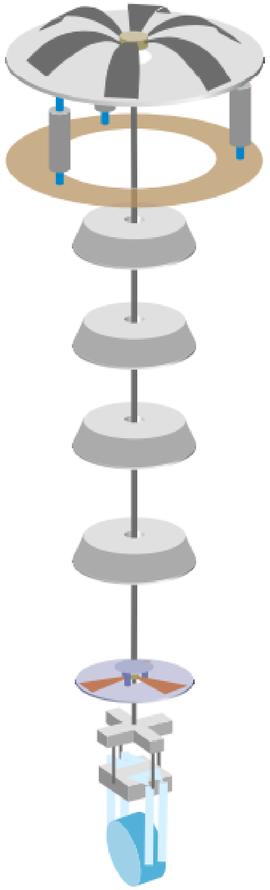
U. of Tokyo, NAOJ



Abstract

1. Expected fast localization performance with current network
   by one template search with hierarchical approach
   using heterogeneous HLV-, HLK- and HLVK-network
   * got impact of adding new detectors to the network
   * got required sensitivity of the less sensitive detector.

2. Local control system for KAGRA Type-A suspension
   aiming more robust interferometer operation
   * confirmed the control system satisfied the requirements
     for acquiring interferometer lock.

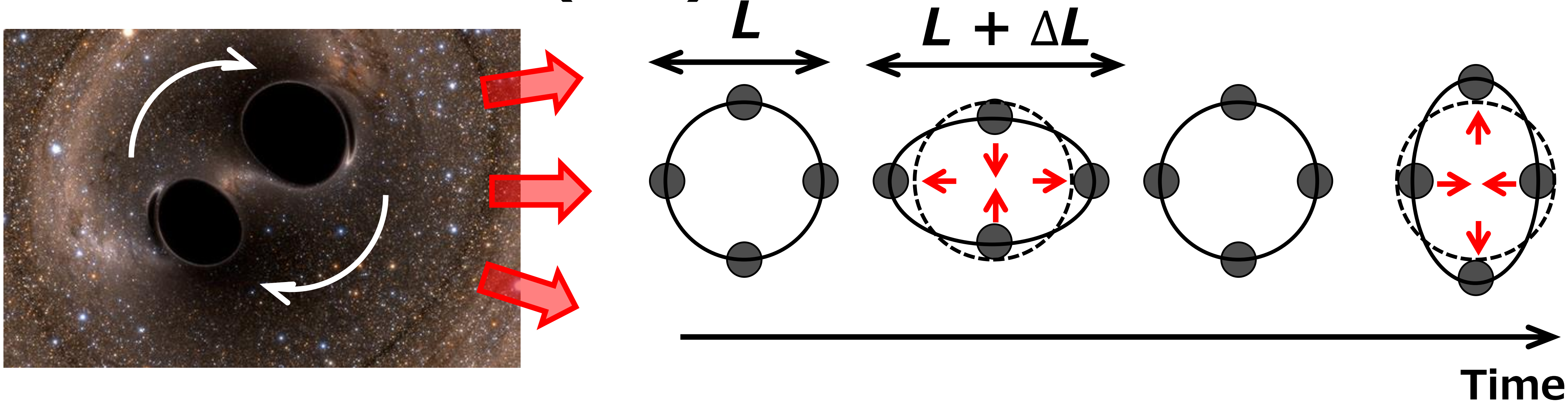
Thesis contents

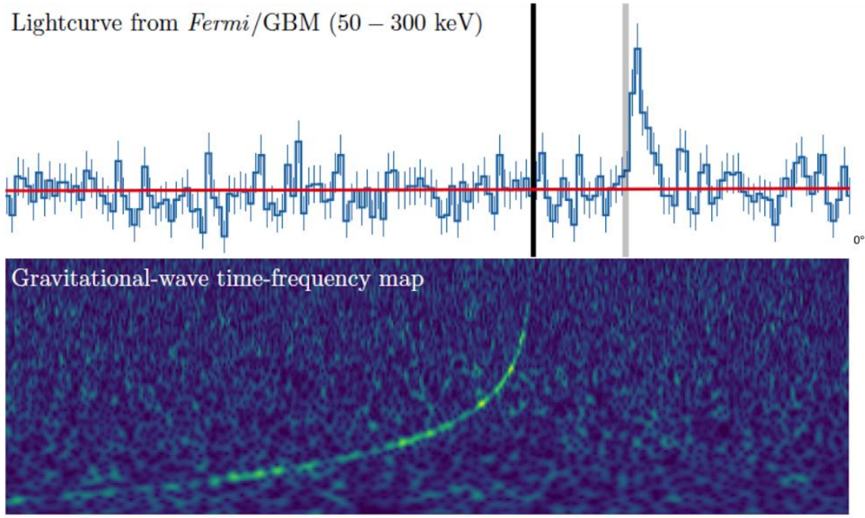
My main research

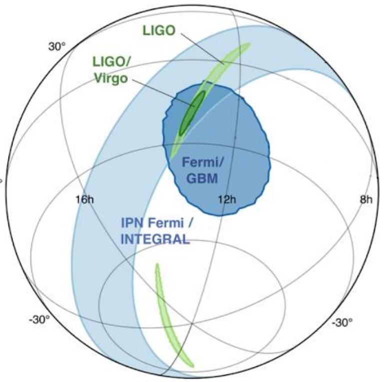
→ Fast localization simulation with current network

→ TypeA suspension controls toward lock acquisition

Gravitational wave (GW):





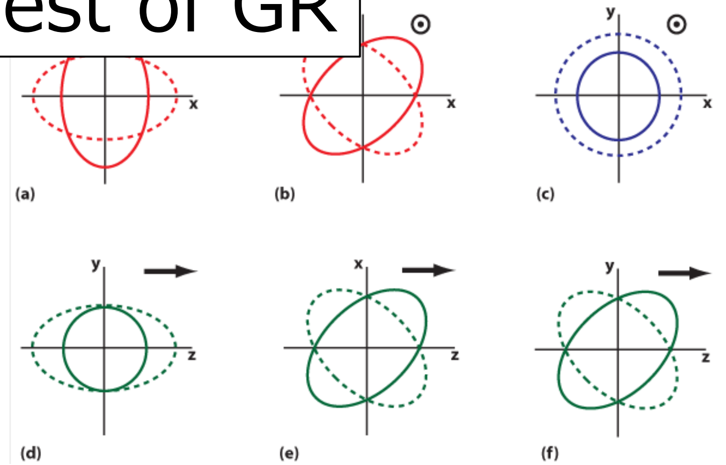


* First BNS detection & EM-follow up

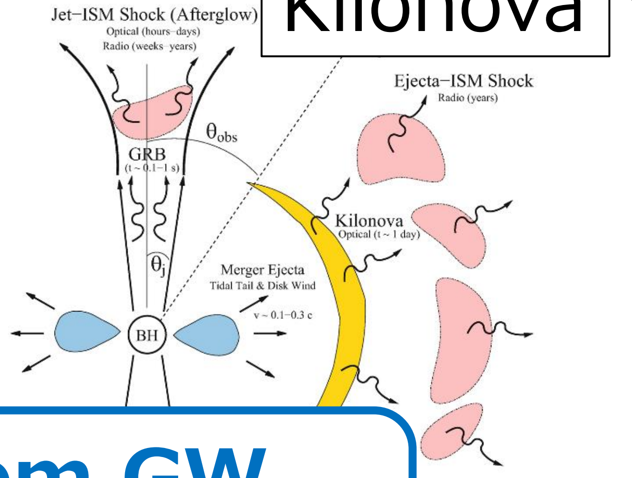
→ **Era of Multi-messenger astronomy**

Motivation to search for GWs:

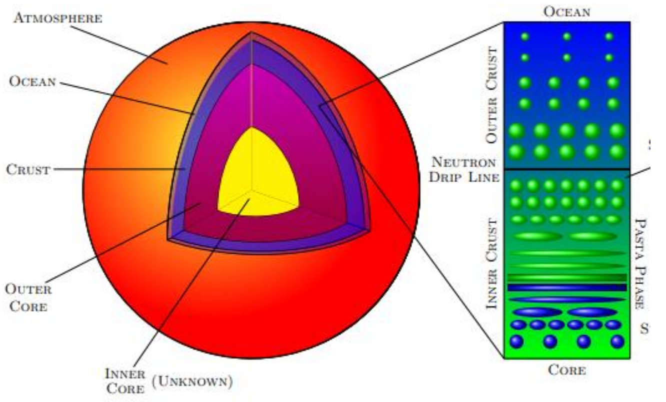
Test of GR



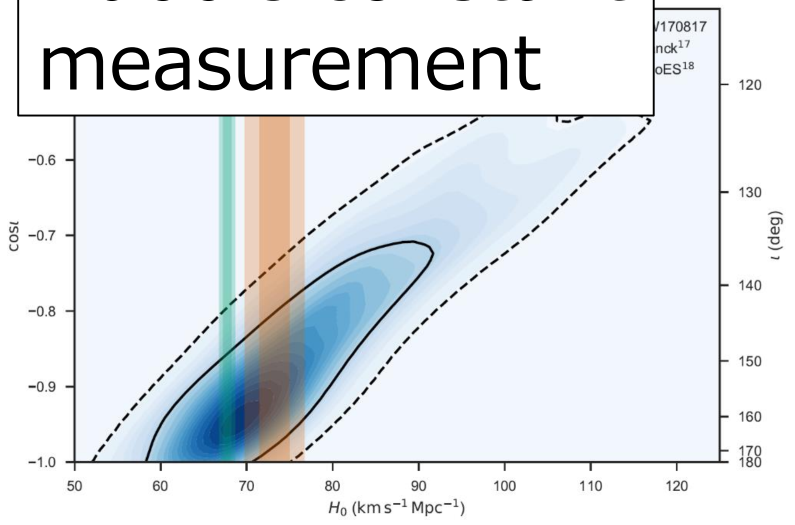
Kilonova



Neutron Star interior

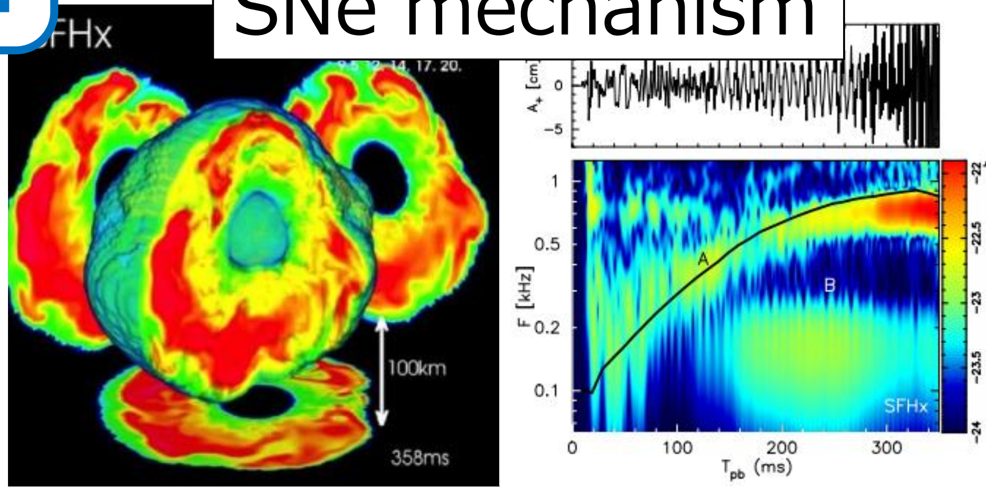


Hubble constant measurement



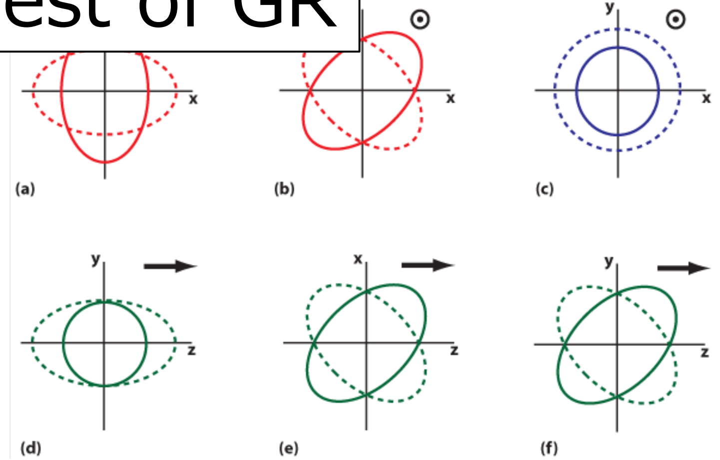
From GW observation

SNe mechanism

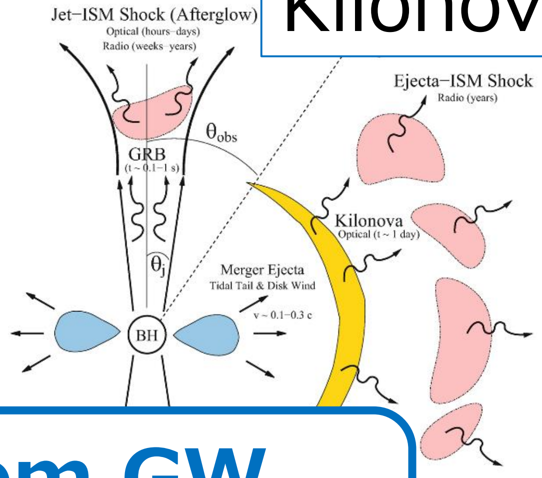


Motivation to search for GWs:

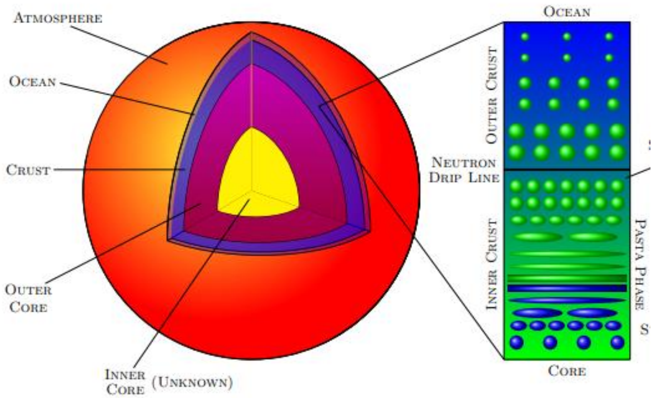
Test of GR



Kilonova

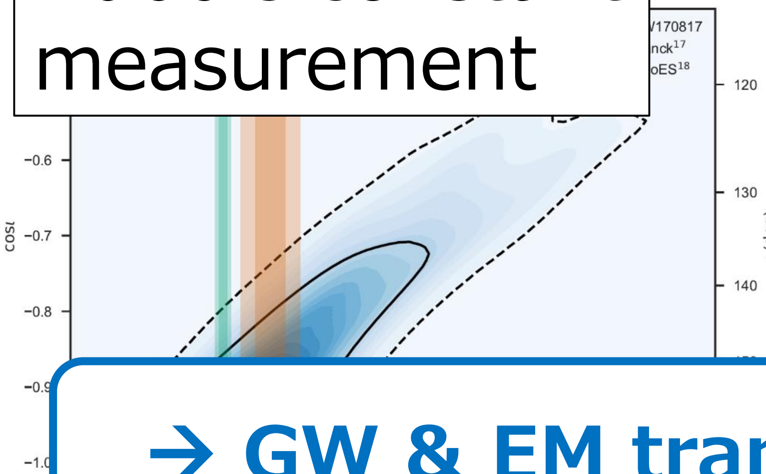


Neutron Star interior

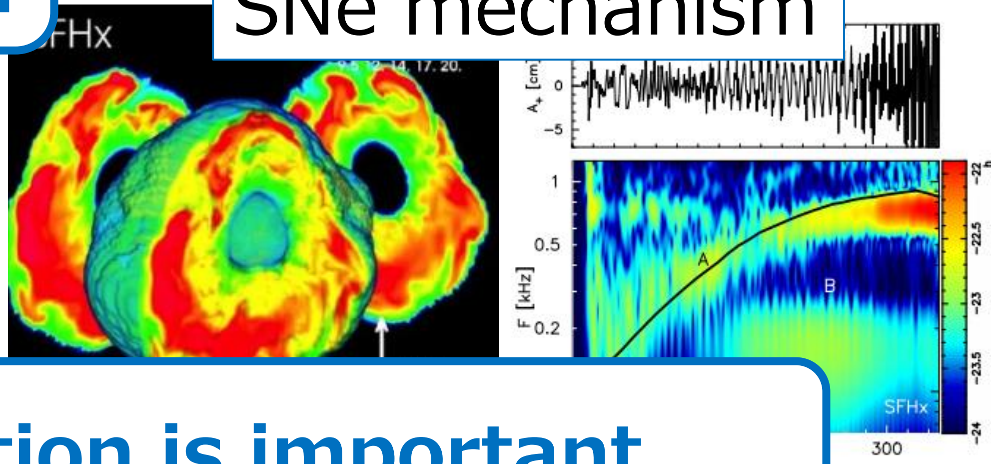


From GW observation

Hubble constant measurement



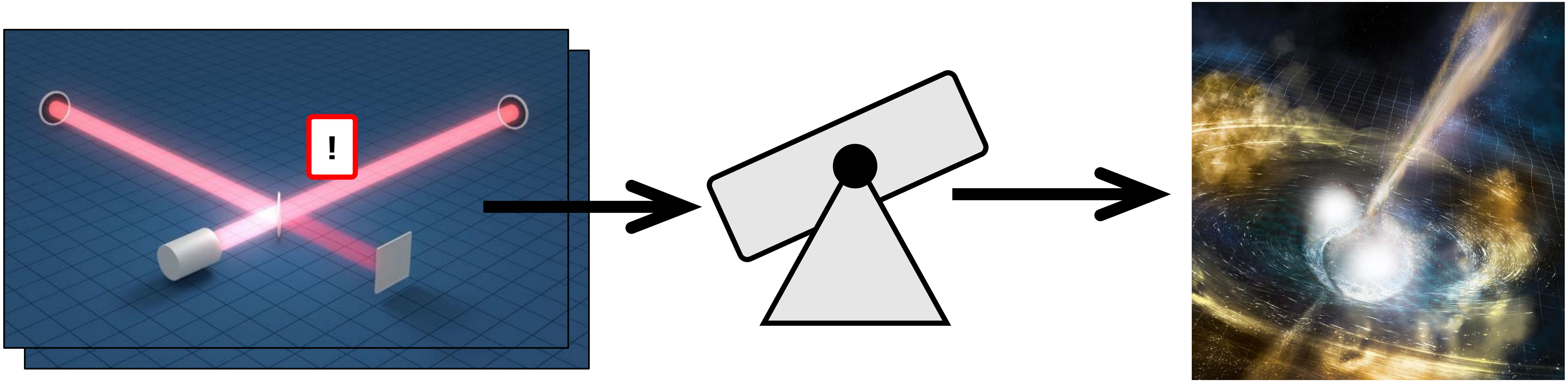
SNe mechanism



→ GW & EM transient observation is important.

For effective EM-follow up observation

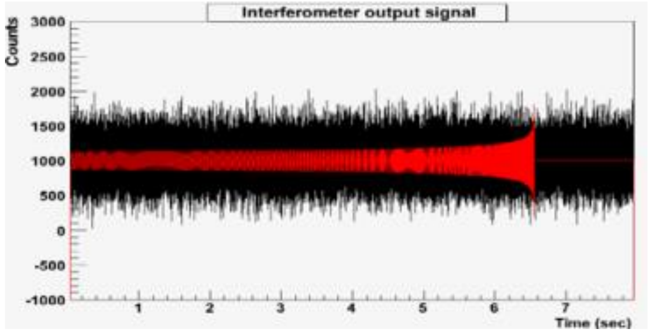
→ Fast source localization



How GW signal analyzed:

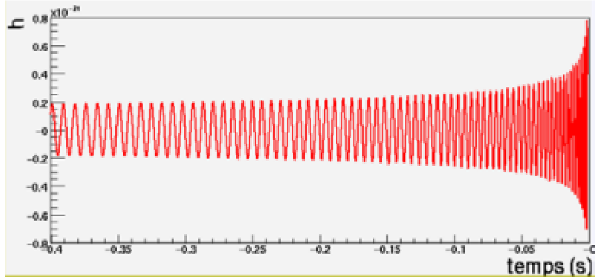
→ Matched filtering, for

Detector output

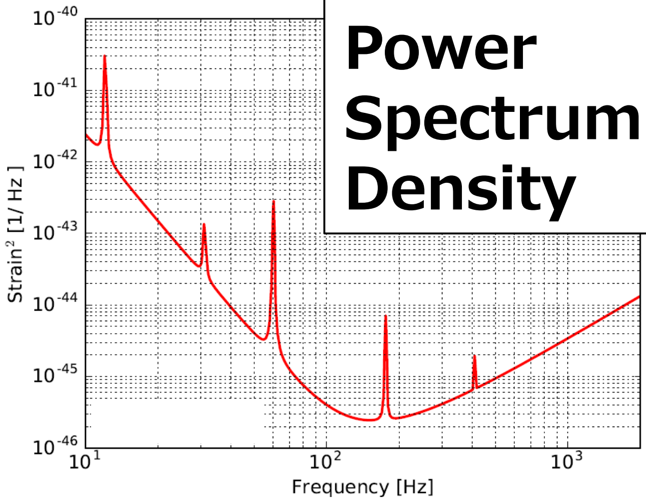


⊗

Template

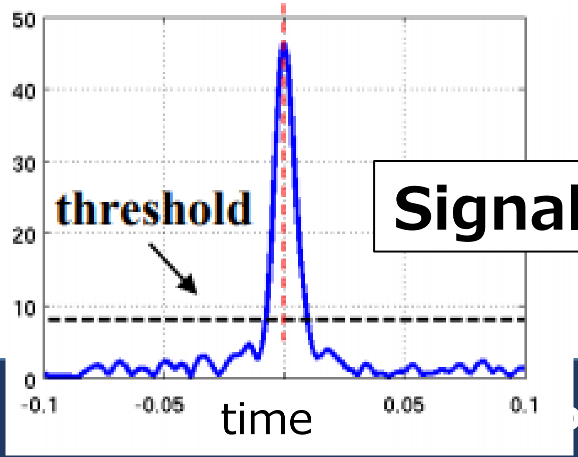


/



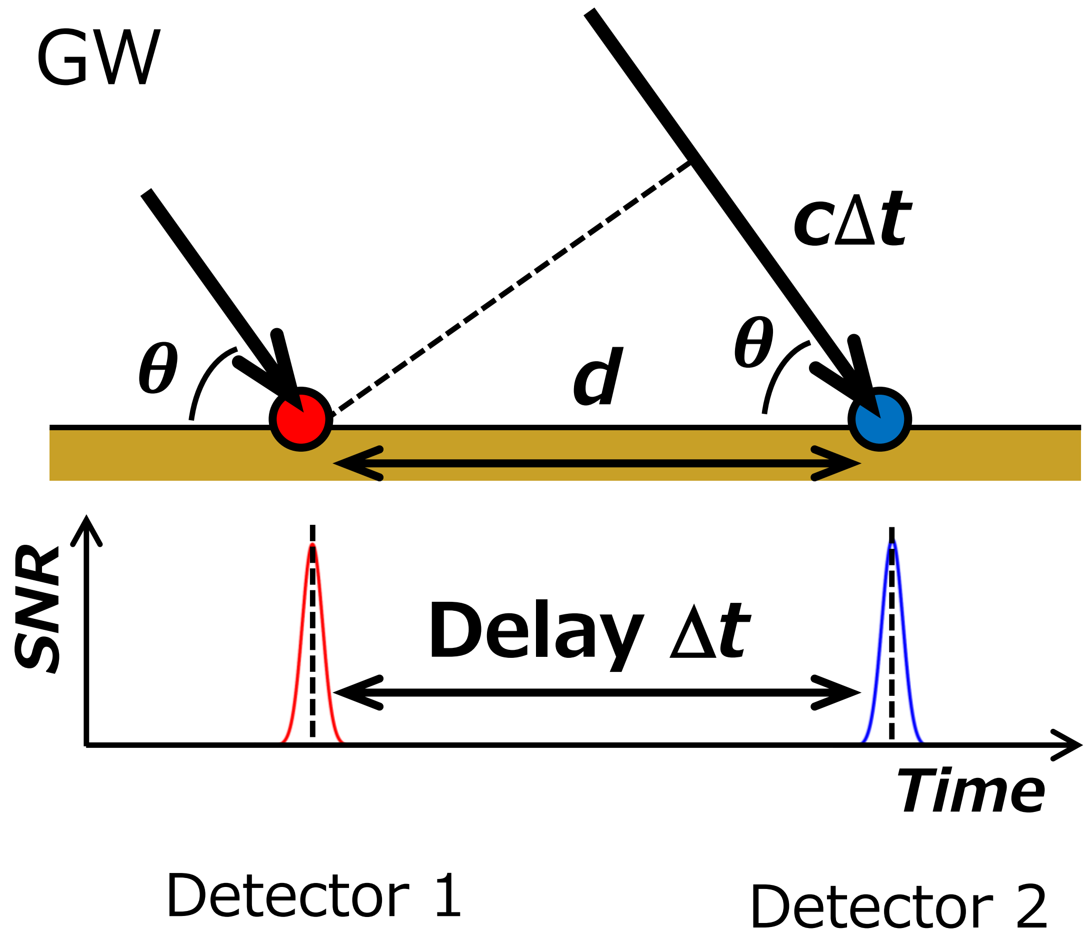
Noise Power Spectrum Density

→

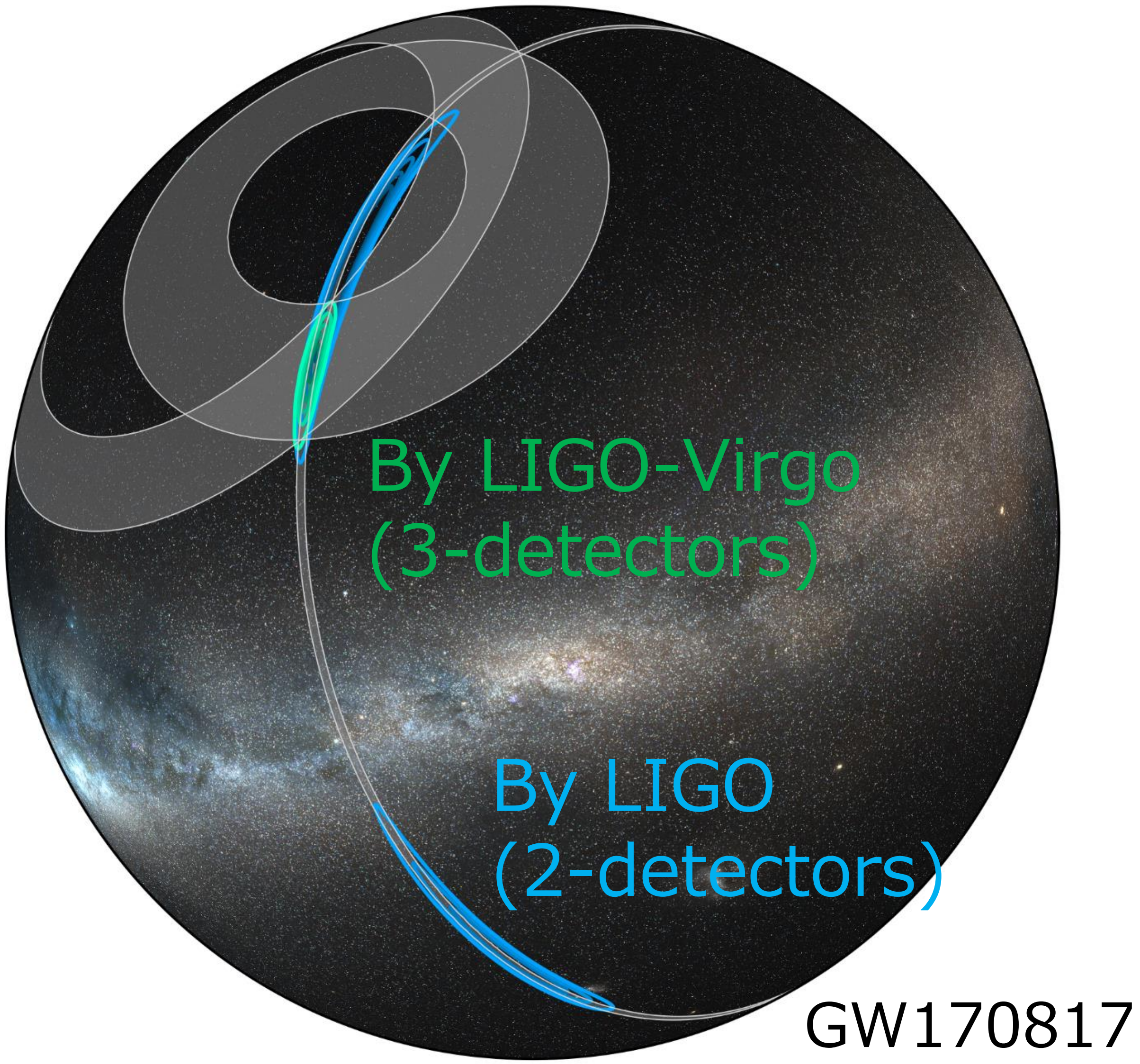


Signal-to-Noise ratio

How source localized:



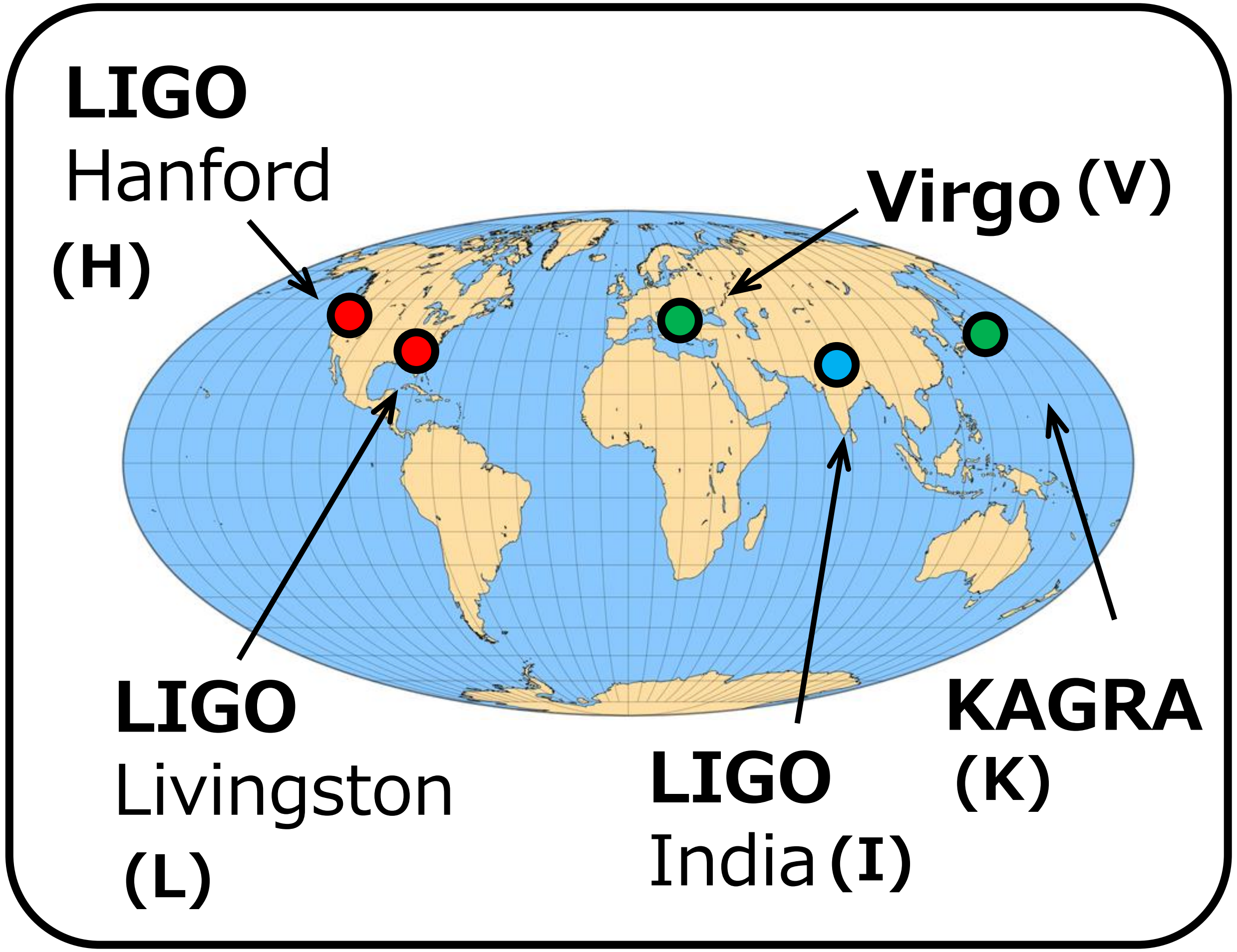
By 3-detector network :



Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

For more precise localization

→ detector network is necessary



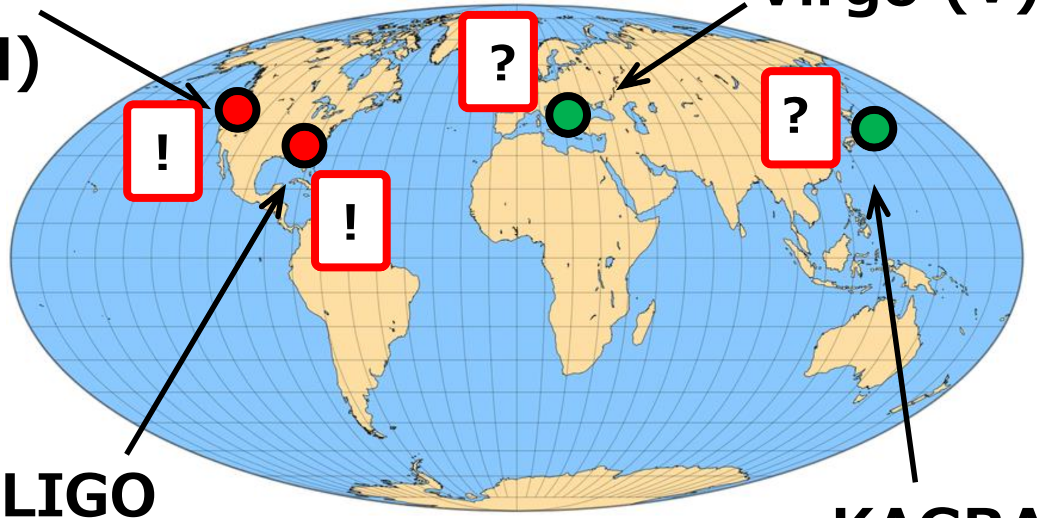
The network helps:

* better localization
* better sky coverage
* to extract GW polarization
* higher network duty cycle

Thesis contents

My main research

In heterogeneous network:



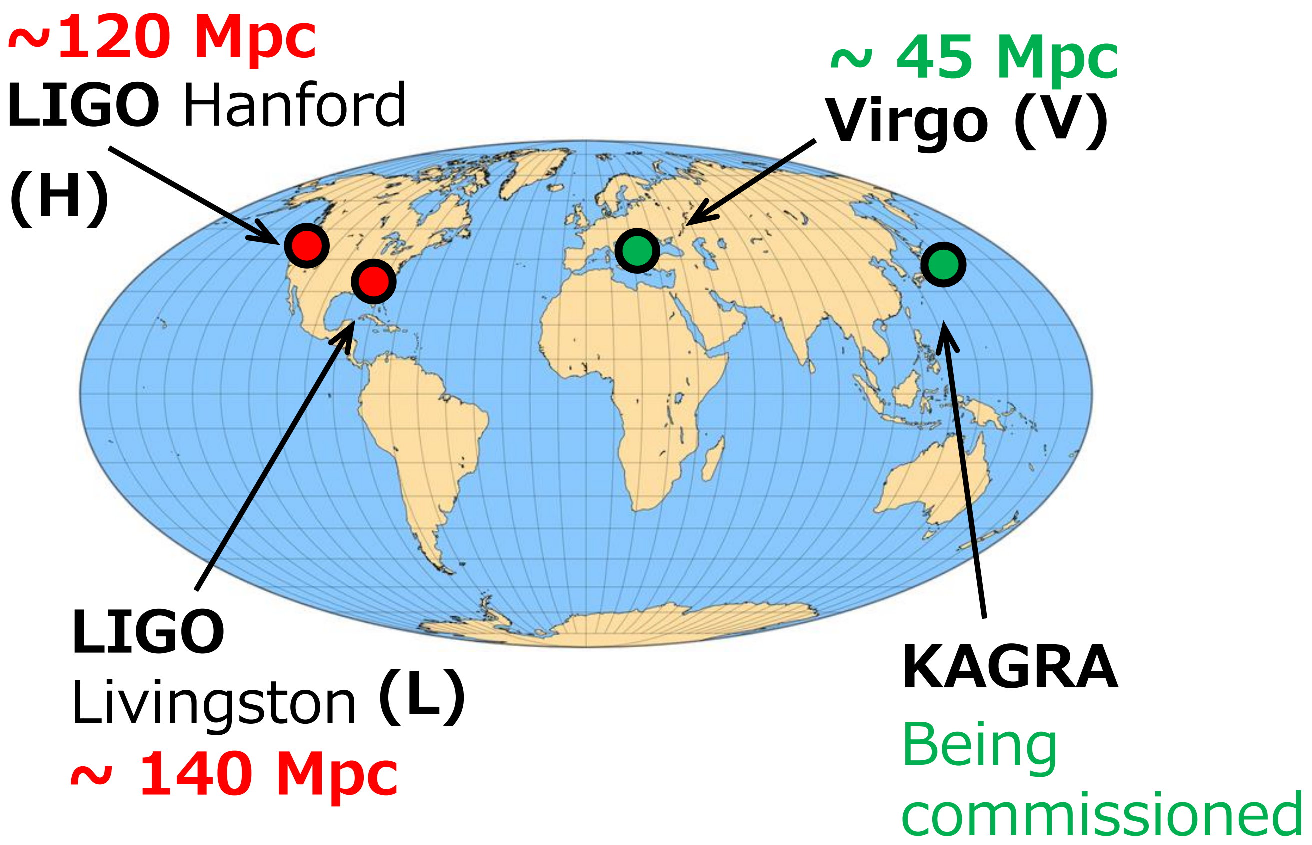
(At the beginning)

Ex.) SNR > SNRth → detection

→ Triple (or more) coincidences
→ Hardly happens

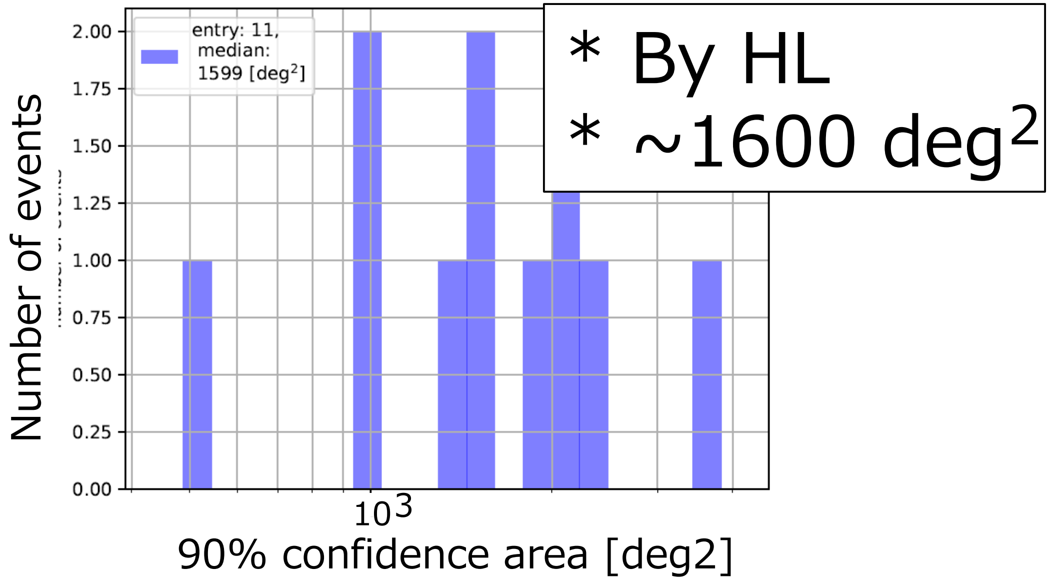
→ Not good for EM-follow up

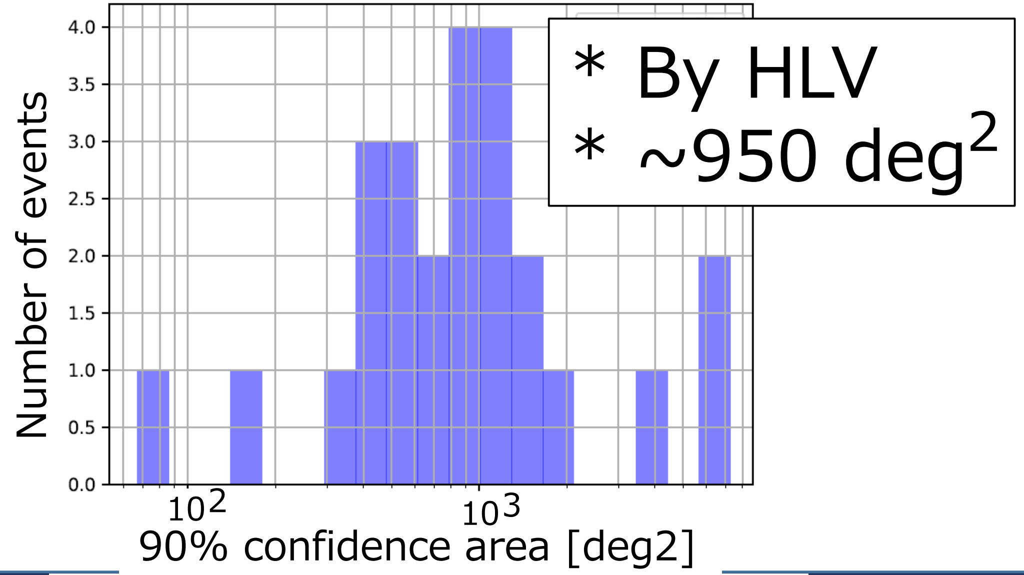
In the real life in O3:



[ref] https://summary.ligo.org/~detchar/summary/O3a/

Size of localized area (detected)





[ref] https://gracedb.ligo.org/superevents/public/O3/

Demanded for EM-follow up:

As an example:

* For kilonova search with BlackGEM

→ **2.7 deg^2 / 5 min**
(for 23rd Magnitude)

[ref] https://link.springer.com/chapter/10.1007/978-3-319-10488-1_5

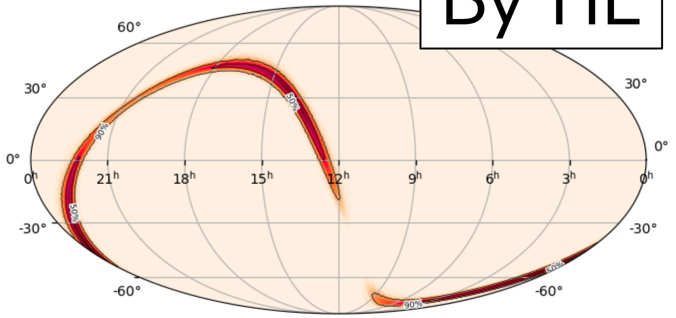
https://astro.ru.nl/blackgem/

For 1600 deg^2, it will take ~50 hrs.

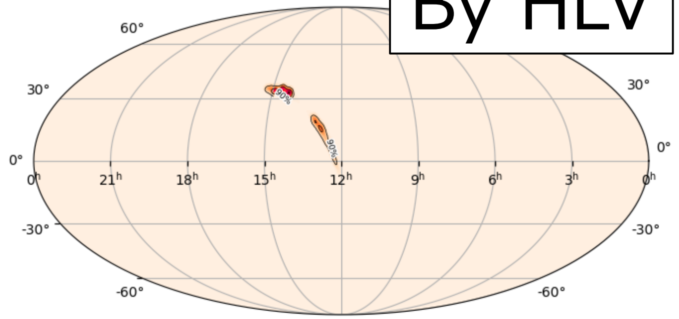
↓

To complete < 9 hrs (one night)
→ < 300 deg^2

By HL

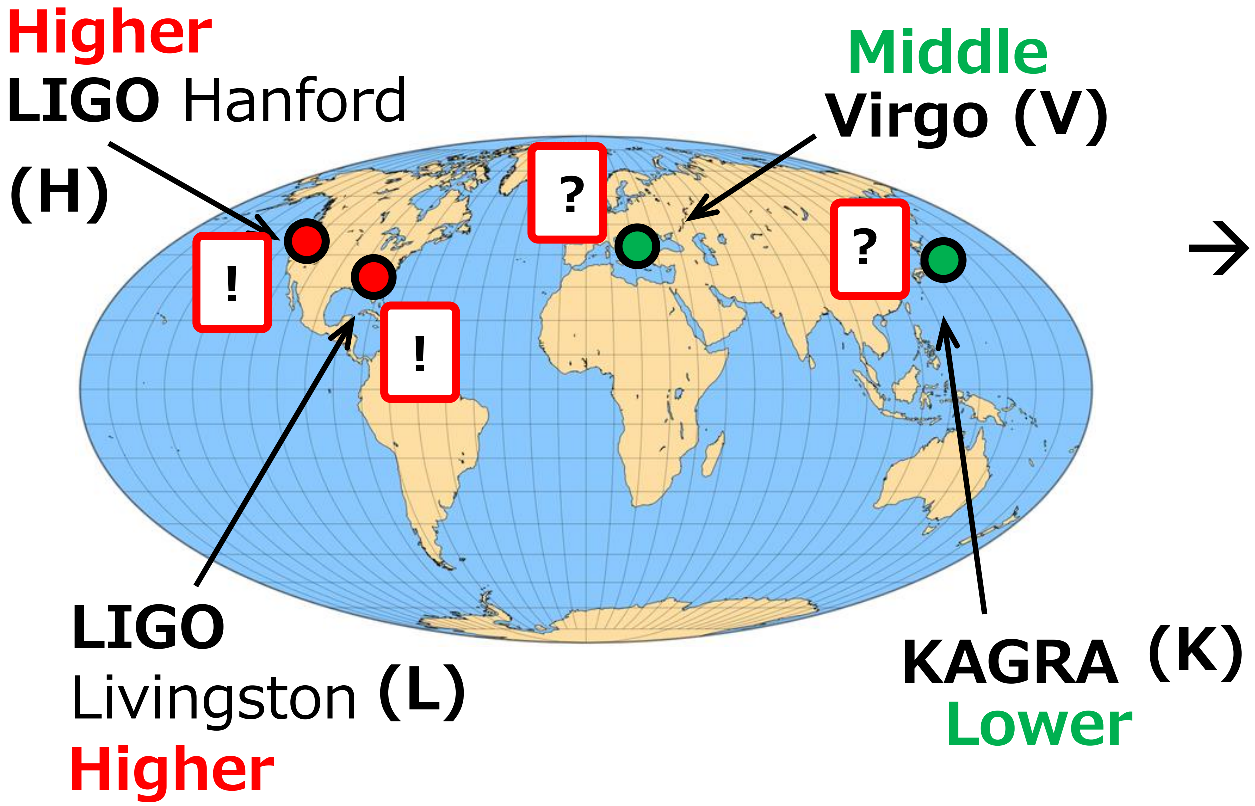


By HLV



[ref] https://gracedb.ligo.org/superevents/public/O3/

In heterogeneous network:



(At the beginning)

Ex.) SNR > SNRth → detection

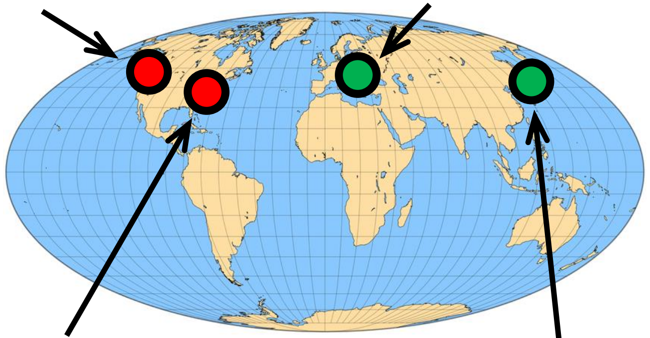
→ * Set a lower threshold,

* as long as not too many background triggers.

Hierarchical approach

Higher sensitivity
LIGO Hanford **(H)**

Middle sensitivity
Virgo (V)



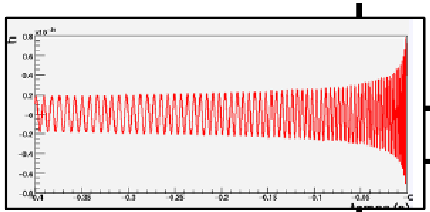
Higher sensitivity
LIGO Livingston **(L)**

Lower sensitivity
KAGRA (K)

(At the beginning)

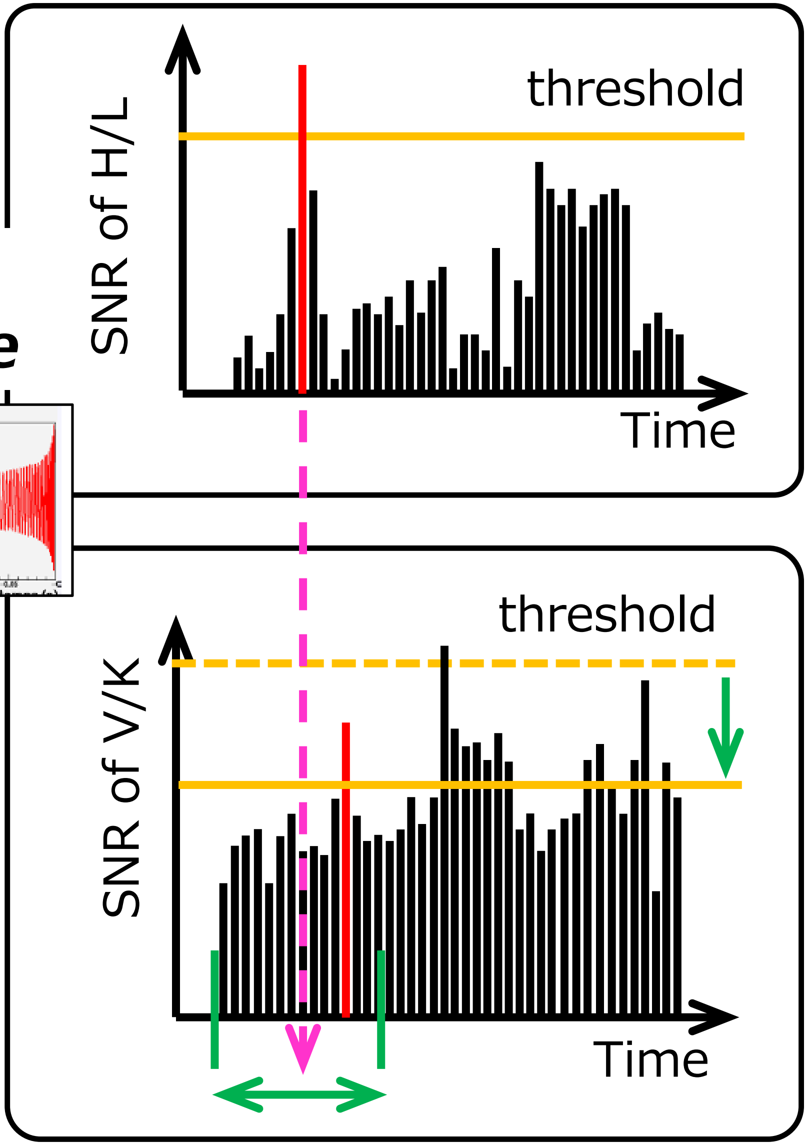
Sub network by higher sensitive detectors find candidate event.

One template



Less sensitive detectors are added into network with

1. lower SNR threshold,
2. same template,
3. a small window around time of double coincidences.



Hierarchical approach in fast localization

With LIGO-Virgo / LIGO-KAGRA / LIGO-Virgo-KAGRA network:

→ **Expected performance?**

→ **Required detector sensitivity?**

→ **Optimal SNR threshold?**

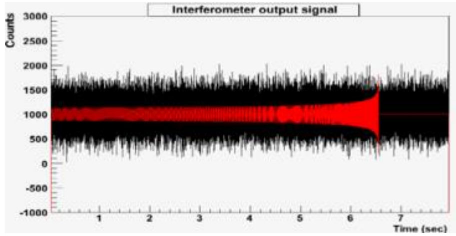
Calculation set up:

1. GW-EM pipeline (for GWs from CBC)

Matched filtering — Sky map

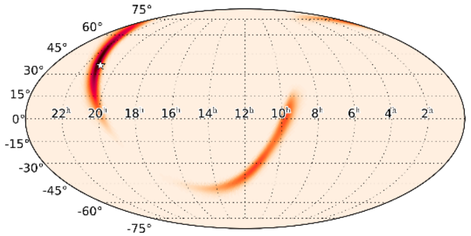
→ GW detector → MBTA → BAYESTAR → EM telescopes

Signal



Event info:
SNR,
arrival time,
etc.

Sky map probability



2. Two LIGOs (54 Mpc), Virgo, KAGRA (< 54 Mpc)

Higher sensitivity × 2 & Lower sensitivity (× 2)

Main flow:

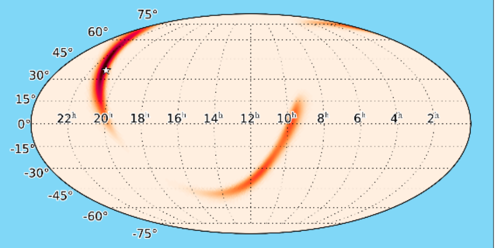
MBTA

H
L
V
K

1. Time of arrival,
2. SNR,
3. Phase,
4. Noise PSD

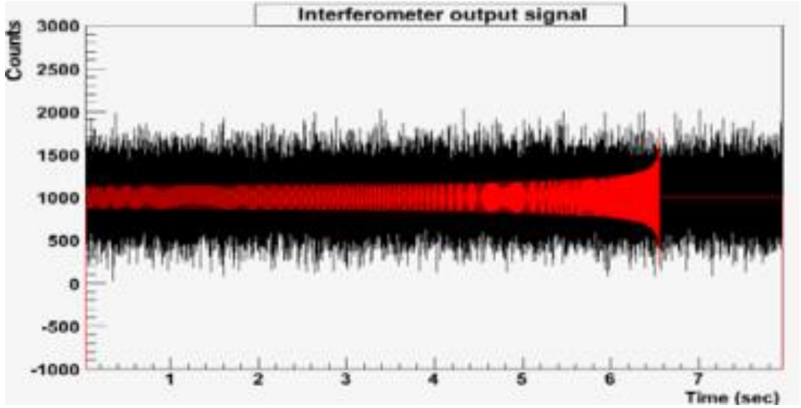
BAYESTAR

(HL or HLV ..)



Sky map probability

Injections

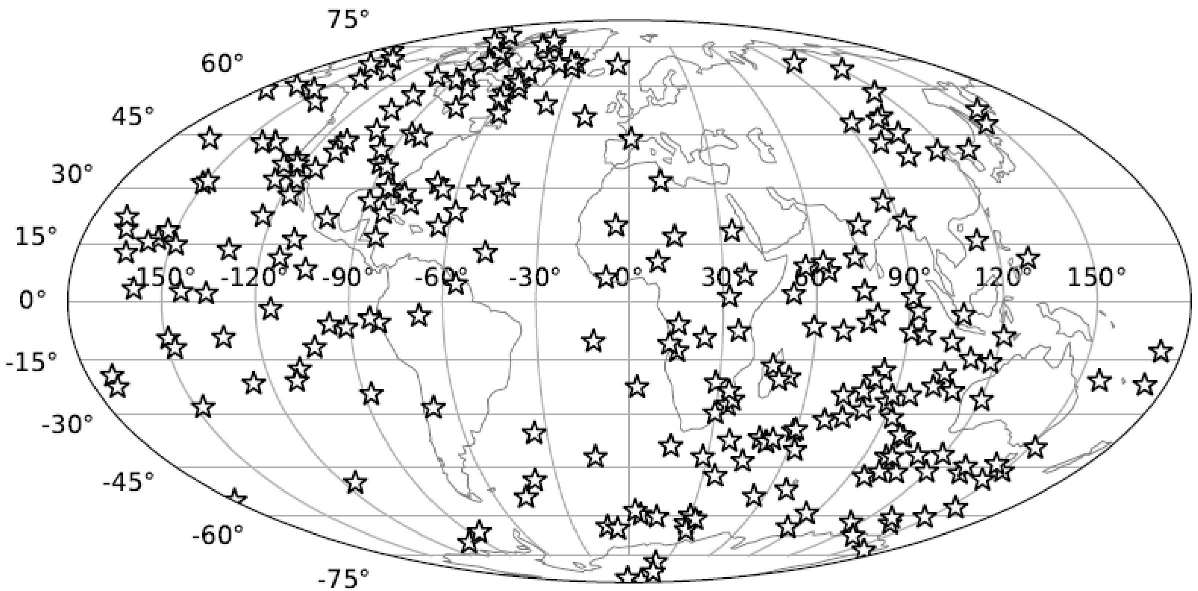


Main flow:

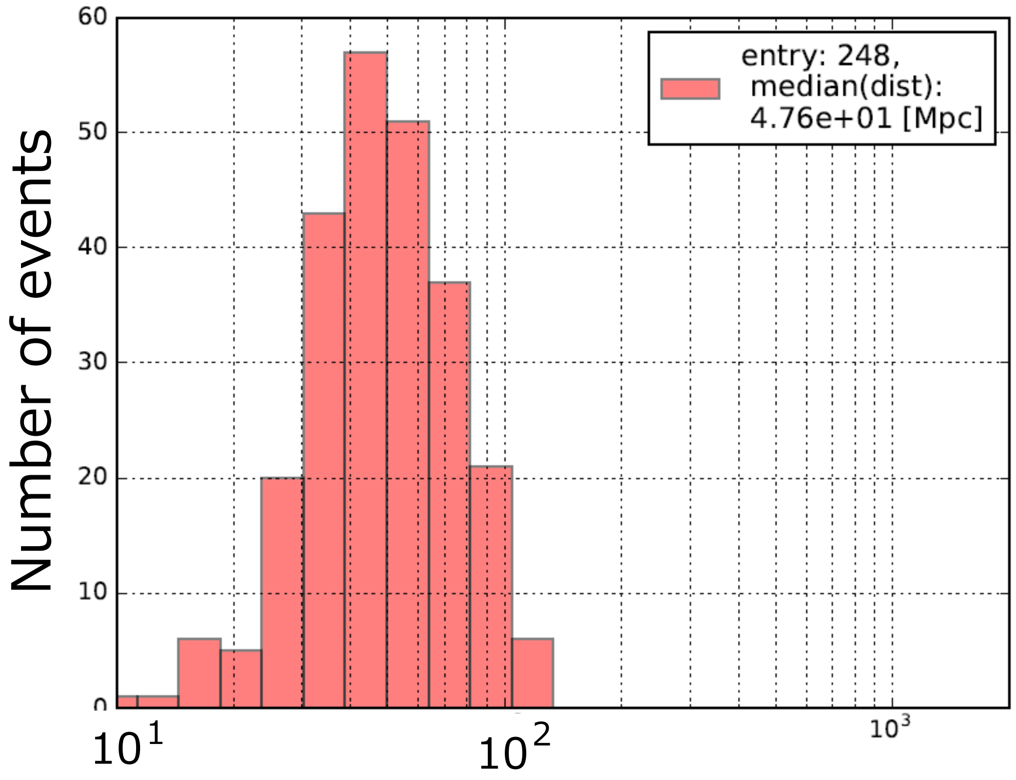
H 1. Time of arrival,

L

Injections (number of events: 248)



Orientation



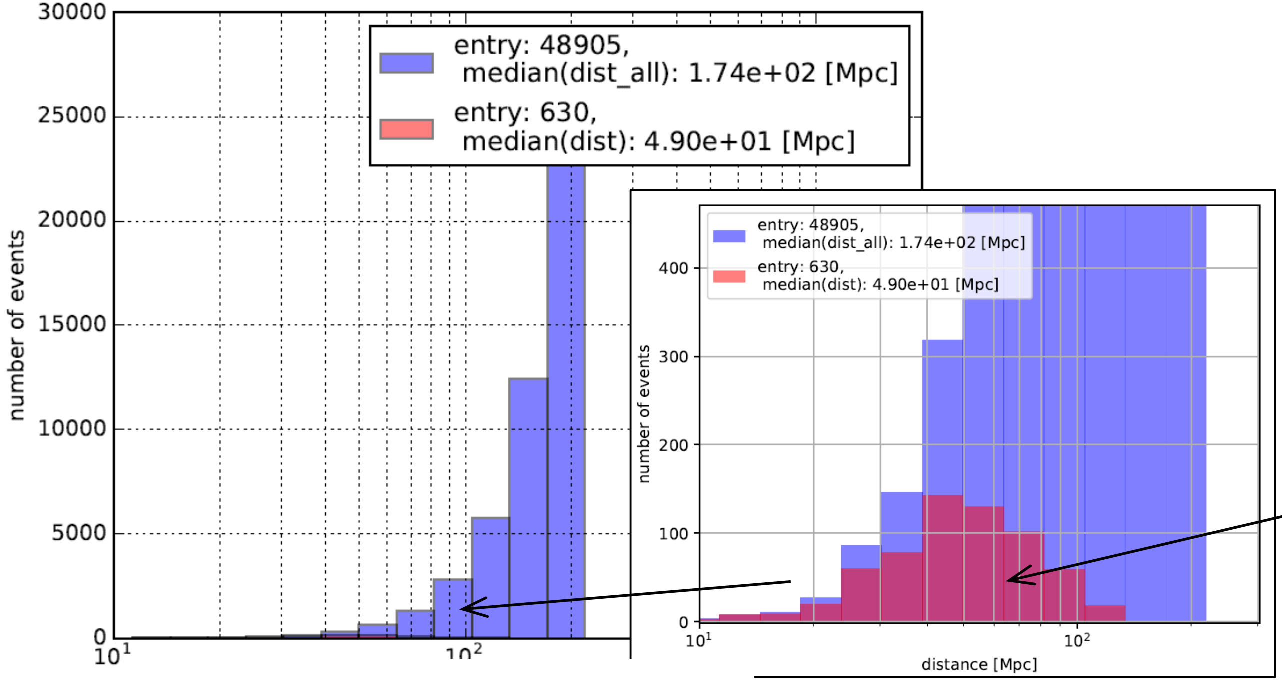
Distance [Mpc]

More correctly:

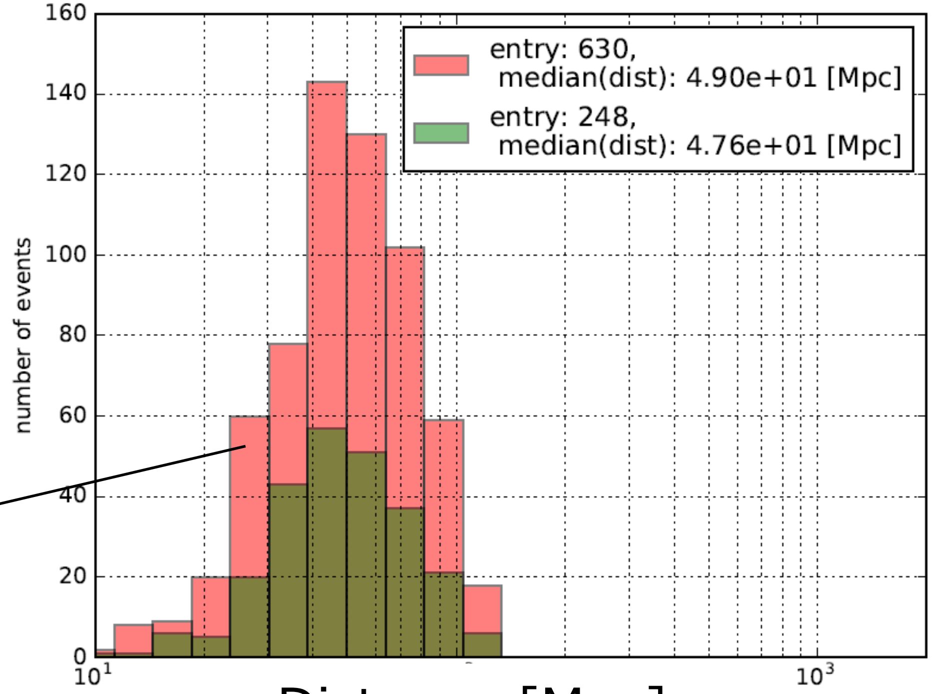
Injections (number of events: 248)

* Reuse of other calculation [ref]:

All injections
Random, isotropic
(48905 events)
→
Events detected
by HL
(630 events)
→
Randomly selected
events
(248 events)



Distance [Mpc]



Distance [Mpc]

[ref] https://www.ligo.org/scientists/first2years/

Main flow:

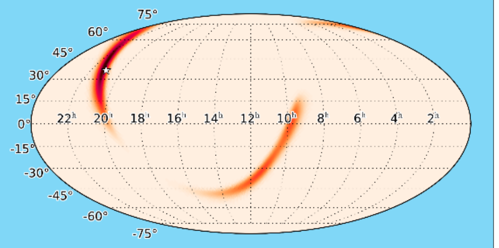
→ MBTA →

H
L
V
K

1. Time of arrival,
2. SNR,
3. Phase,
4. Noise PSD

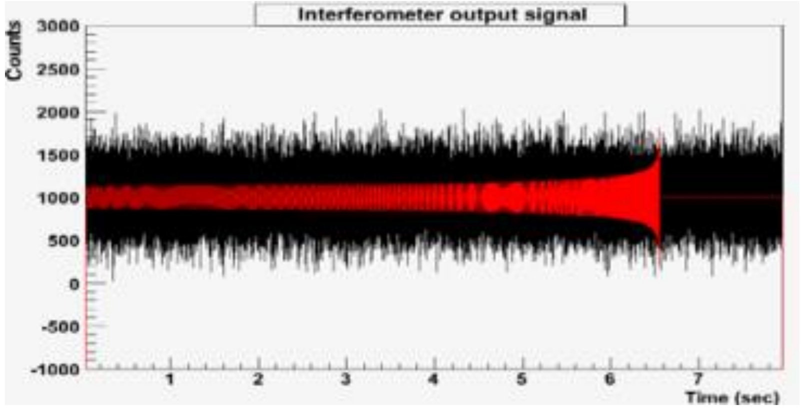
→ BAYESTAR →

(HL or HLV ..)



Sky map probability →

Injections



Main flow:

248 Injections

MBTA

H L — **Analyzed data**

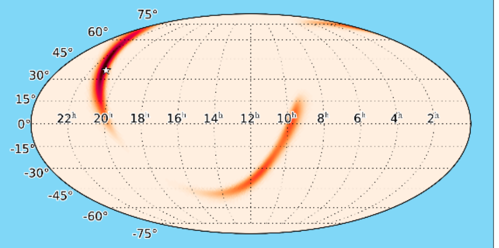
V K — **Artificial data**

Time of arrival,
SNR,
Phase,
Noise PSD.

from here

BAYESTAR

(HL or HLV ..)



Sky map probability

In order to save computational cost

How artificial V/K triggers generated:

Noise event:

$$\begin{bmatrix} \text{SNR} \\ \text{Time} \\ \text{phase} \end{bmatrix} = \begin{bmatrix} \text{Random number from } \textbf{background trigger} \text{ dsit.} \\ \text{Time\_}_{\text{LIGO}} + \text{ Random number from } \textbf{uniform} \text{ dist.} \\ \text{Random number from } \textbf{uniform} \text{ dist.} \end{bmatrix}$$

Injection event:

$$\begin{bmatrix} \text{SNR} \\ \text{Time} \\ \text{phase} \end{bmatrix} = \begin{bmatrix} \text{Expected} \end{bmatrix} + \begin{bmatrix} \text{Random number} \\ \text{from } \textbf{Gaussian} \text{ dist.} \end{bmatrix}$$

Main flow:

248 Injections

MBTA

H

L

Analyzed data

V

K

Artificial data

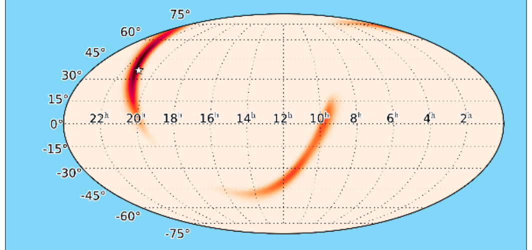
Time of arrival,
SNR,
Phase,
Noise PSD.

from here

BAYESTAR

HL or
HLVnoise or
HLVinjection ..

Generate coincident triggers



Sky map probability

How coincident triggers generated?

* Using **SNR threshold** & **False-Alarm-Probability (FAP)**

→ Even though ($SNR > SNR_{th}$), not everything is injection.

In LIGO-Virgo network case (With P_V = random [0 : 1]):

($SNR_V > SNR_{th}$) and ($p_V > FAP$) → $HLV_{injection}$

($SNR_V < SNR_{th}$) and ($p_V > FAP$) → HL

($p_V < FAP$) → HLV_{noise}

Main flow:

248 Injections

MBTA

H
L
Analyzed data

V
K
Artificial data

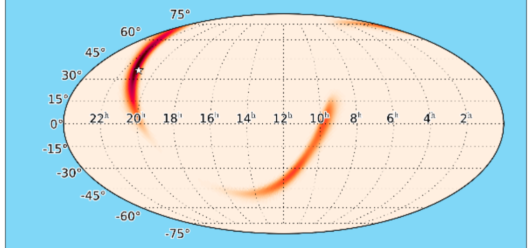
Time of arrival,
SNR,
Phase,
Noise PSD.

from here

BAYESTAR

HL or
HLVnoise or
HLVinjection ..

Generate coincident triggers

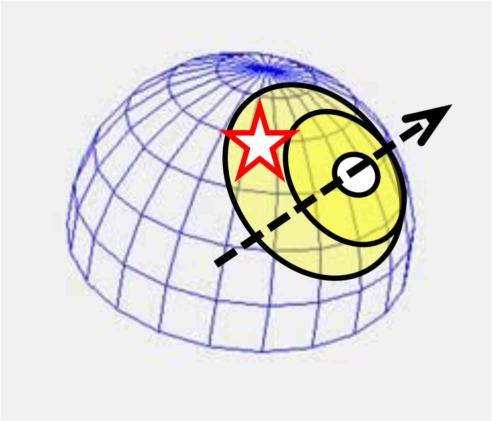


Sky map probability

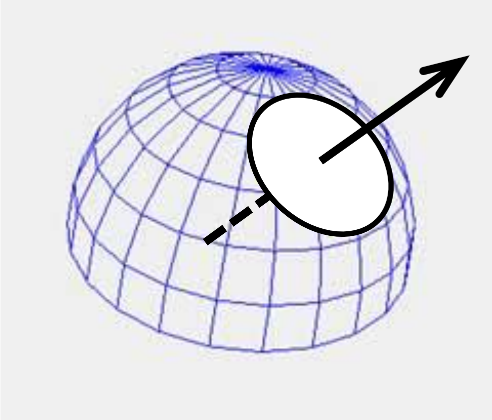
Main flow:

Localization performance

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



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

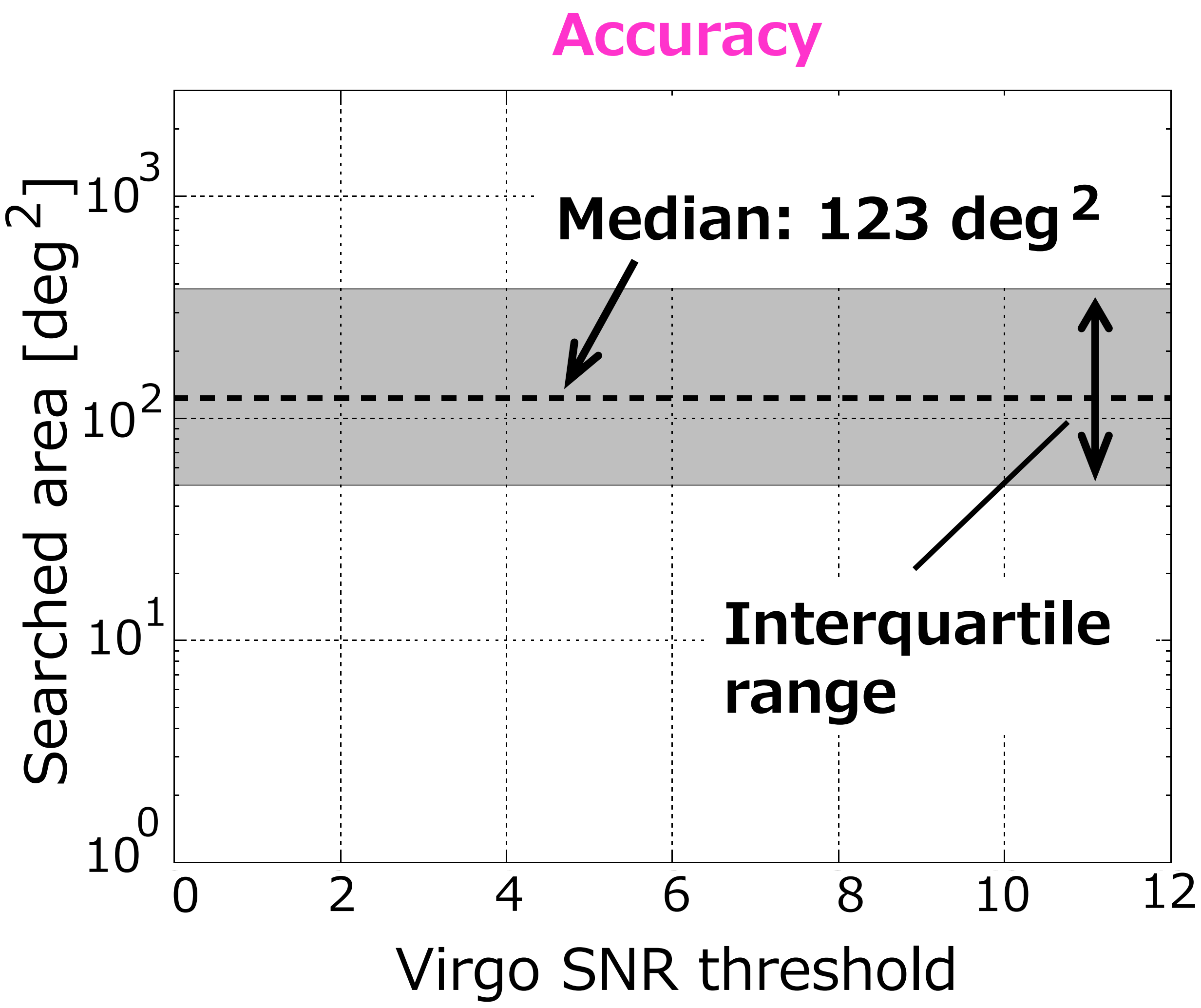


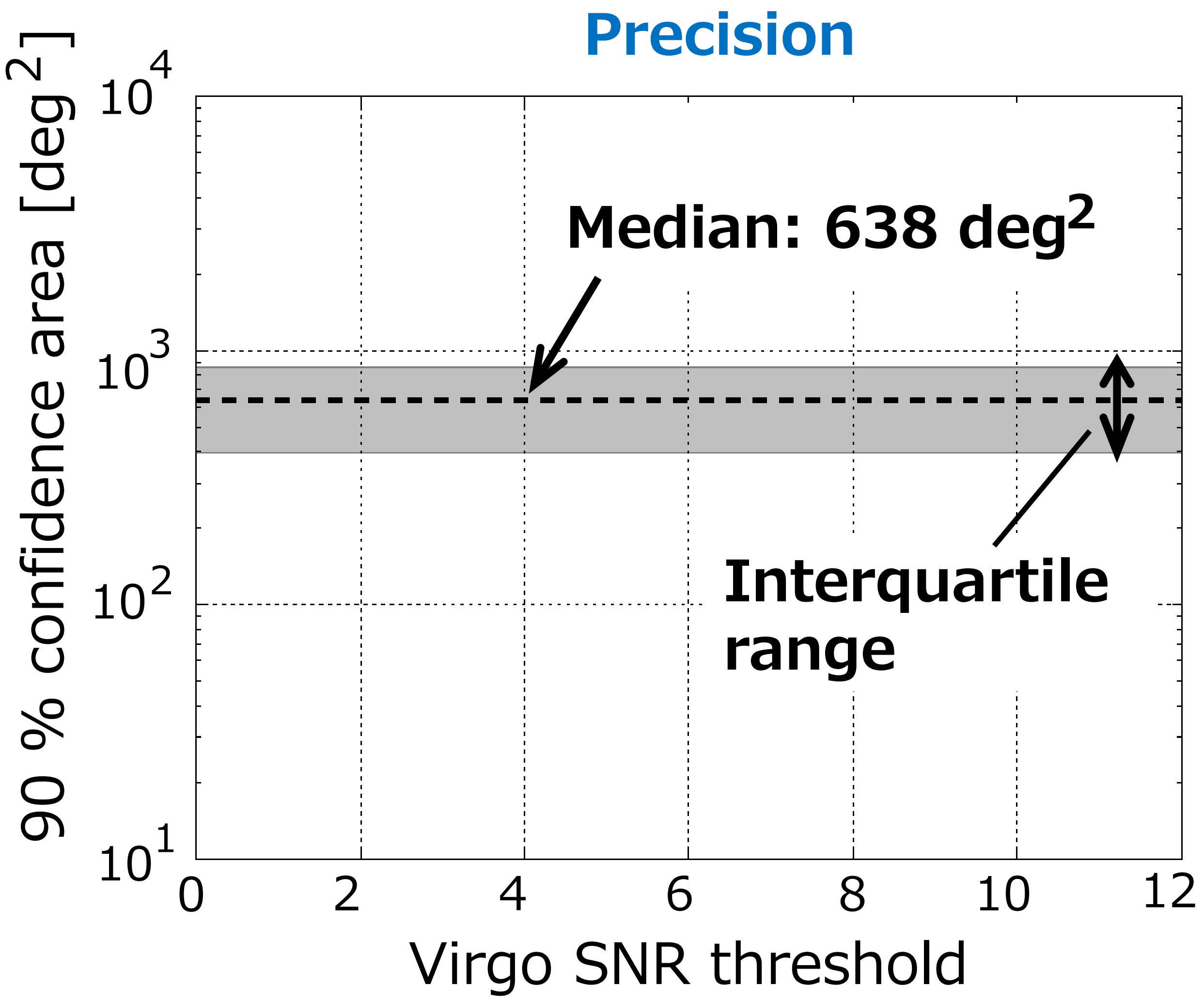
For both, ***smaller*** *is* ***better.***

Median values for 248 events

Performance (HL):

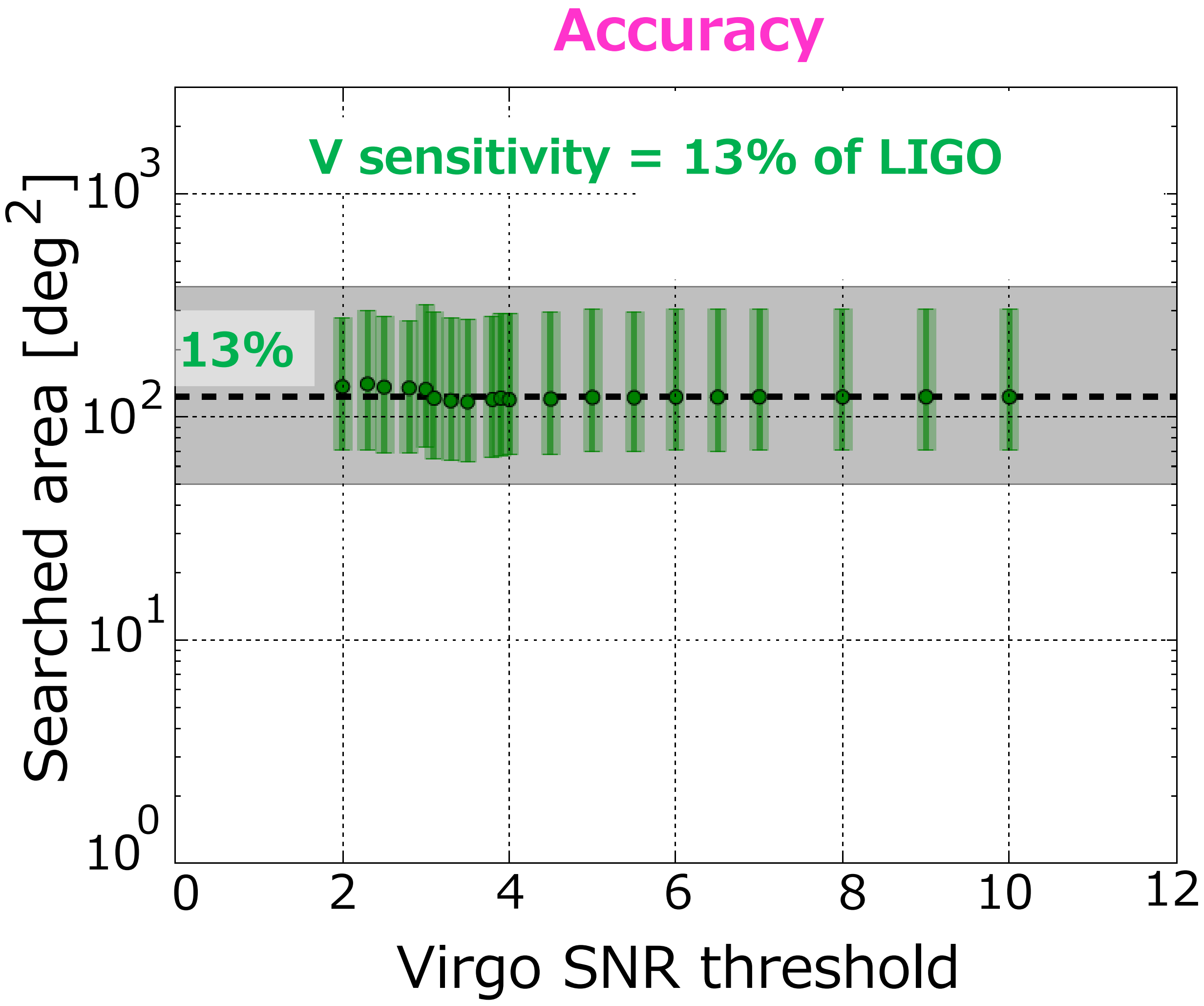
(SNR threshold for H, L = 5., 5.)

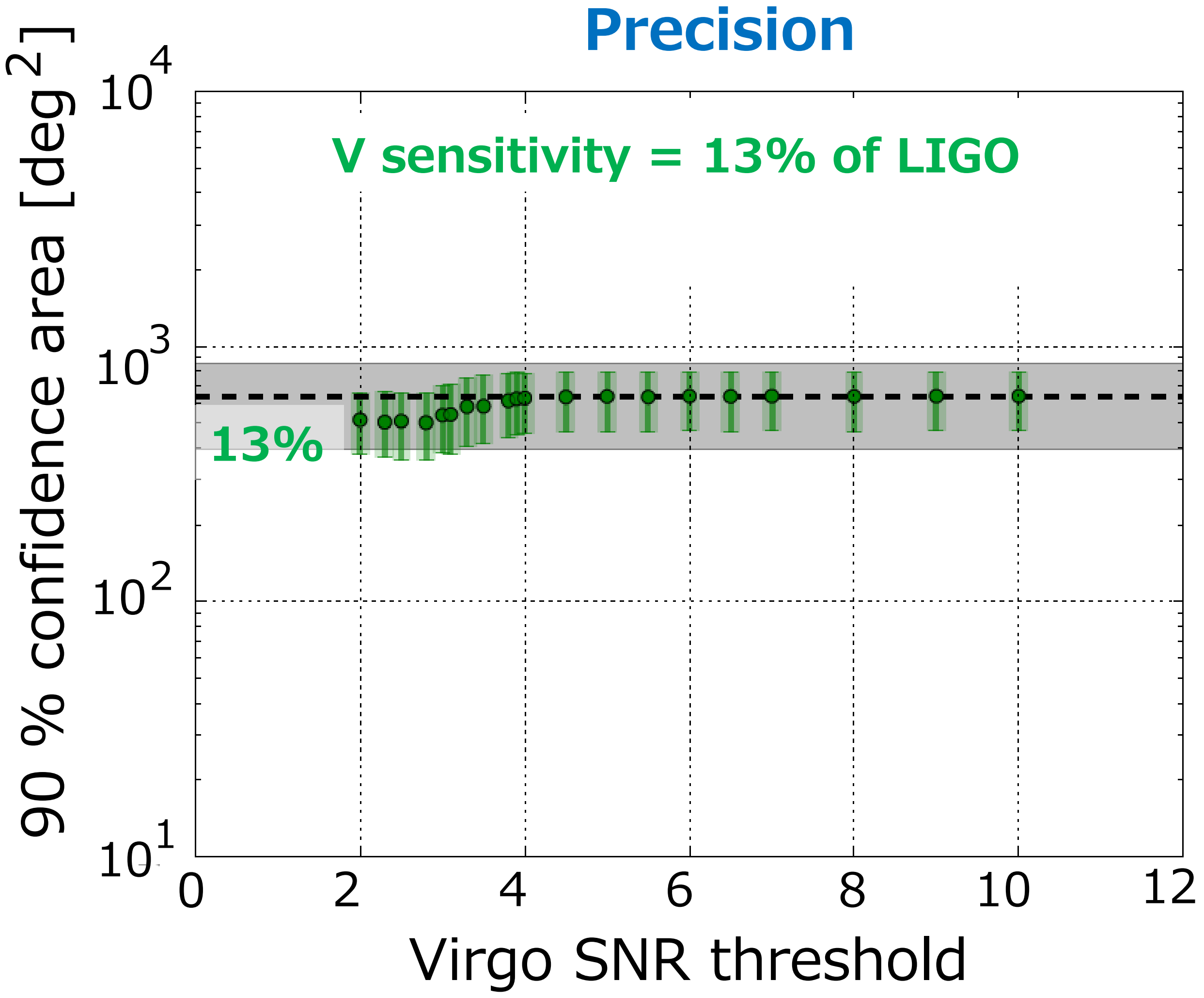




Performance (HLV):

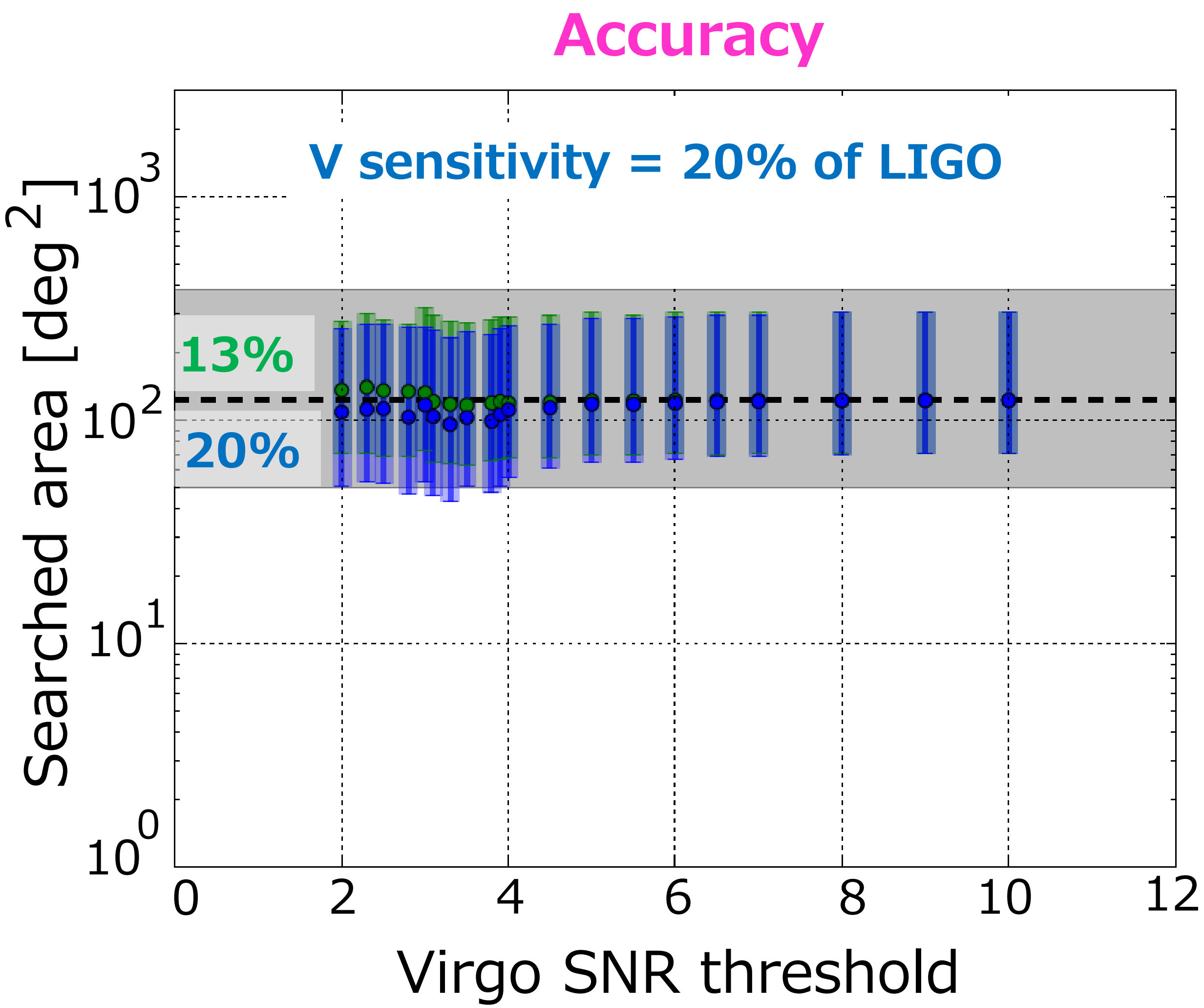
(SNR threshold for H, L = 5., 5.)

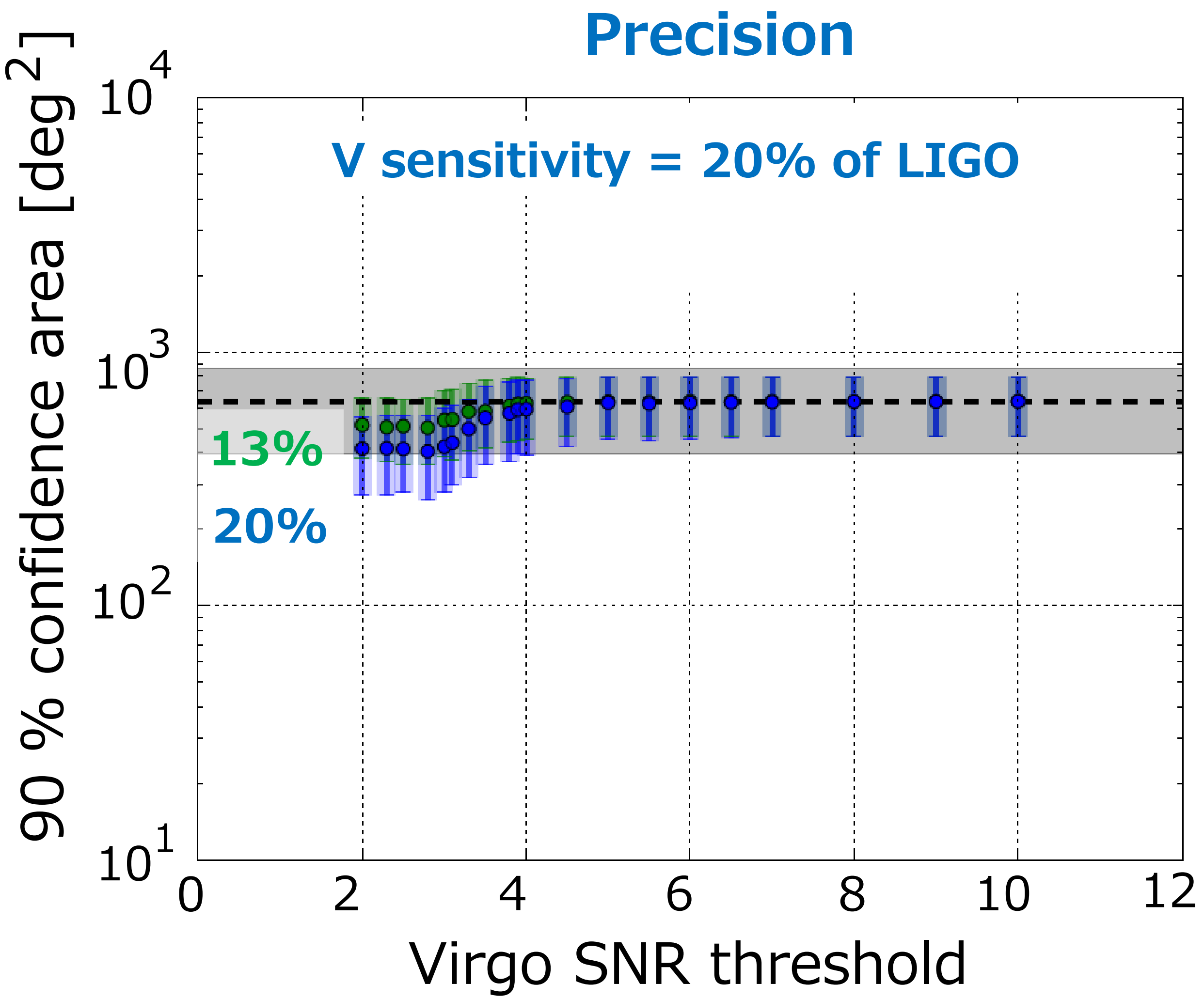




Performance (HLV):

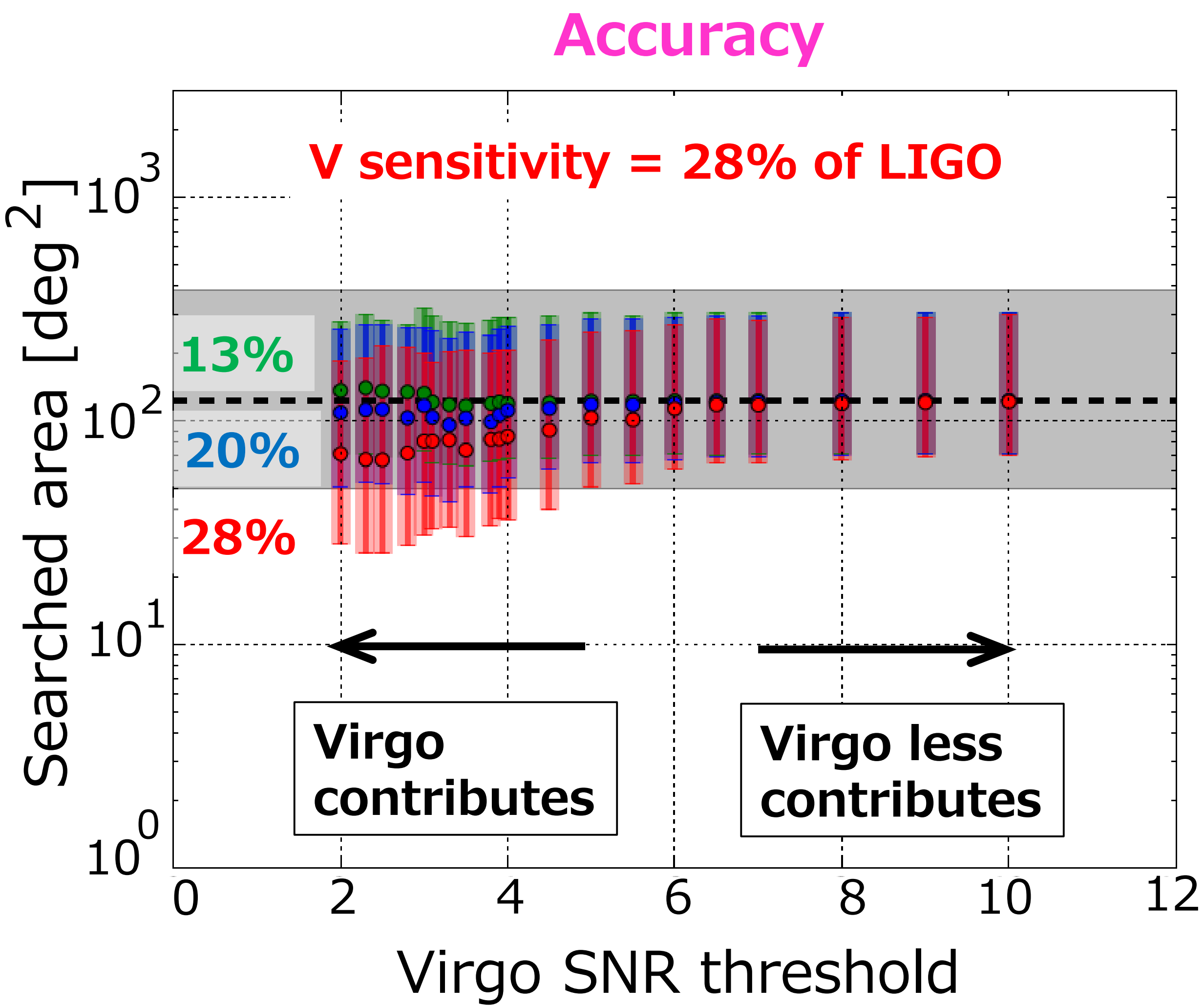
(SNR threshold for H, L = 5., 5.)

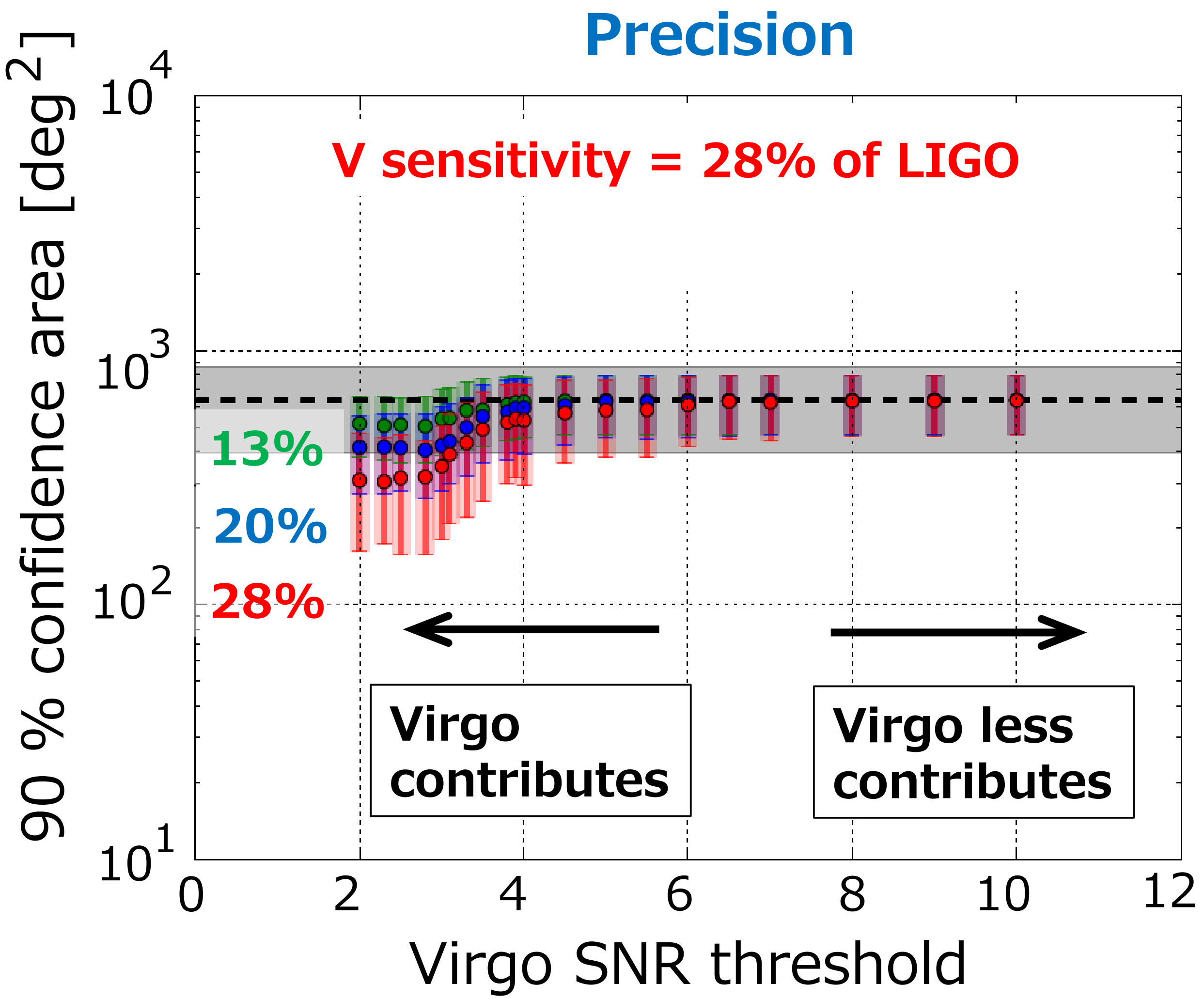




Performance (HLV):

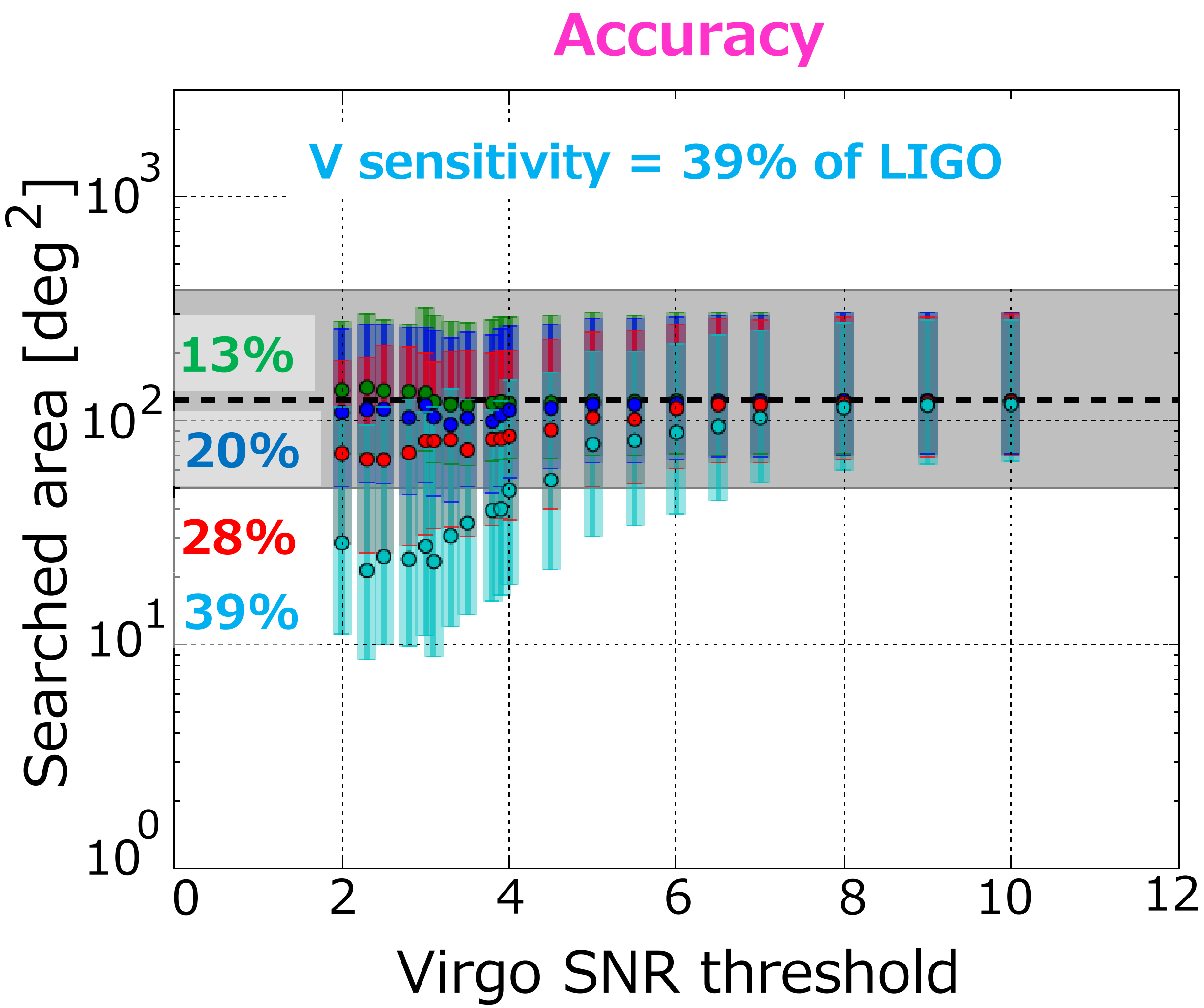
(SNR threshold for H, L = 5., 5.)

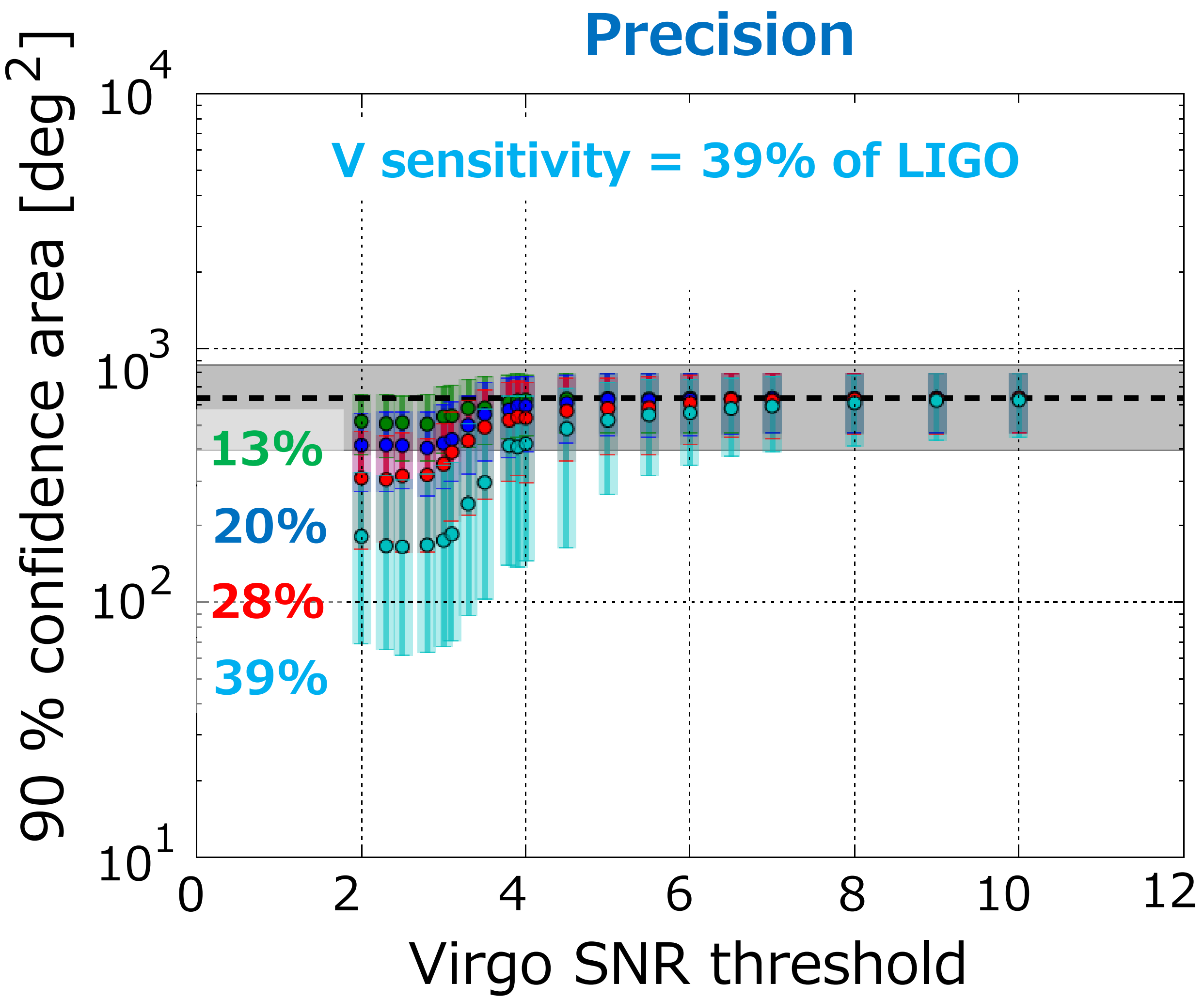




Performance (HLV):

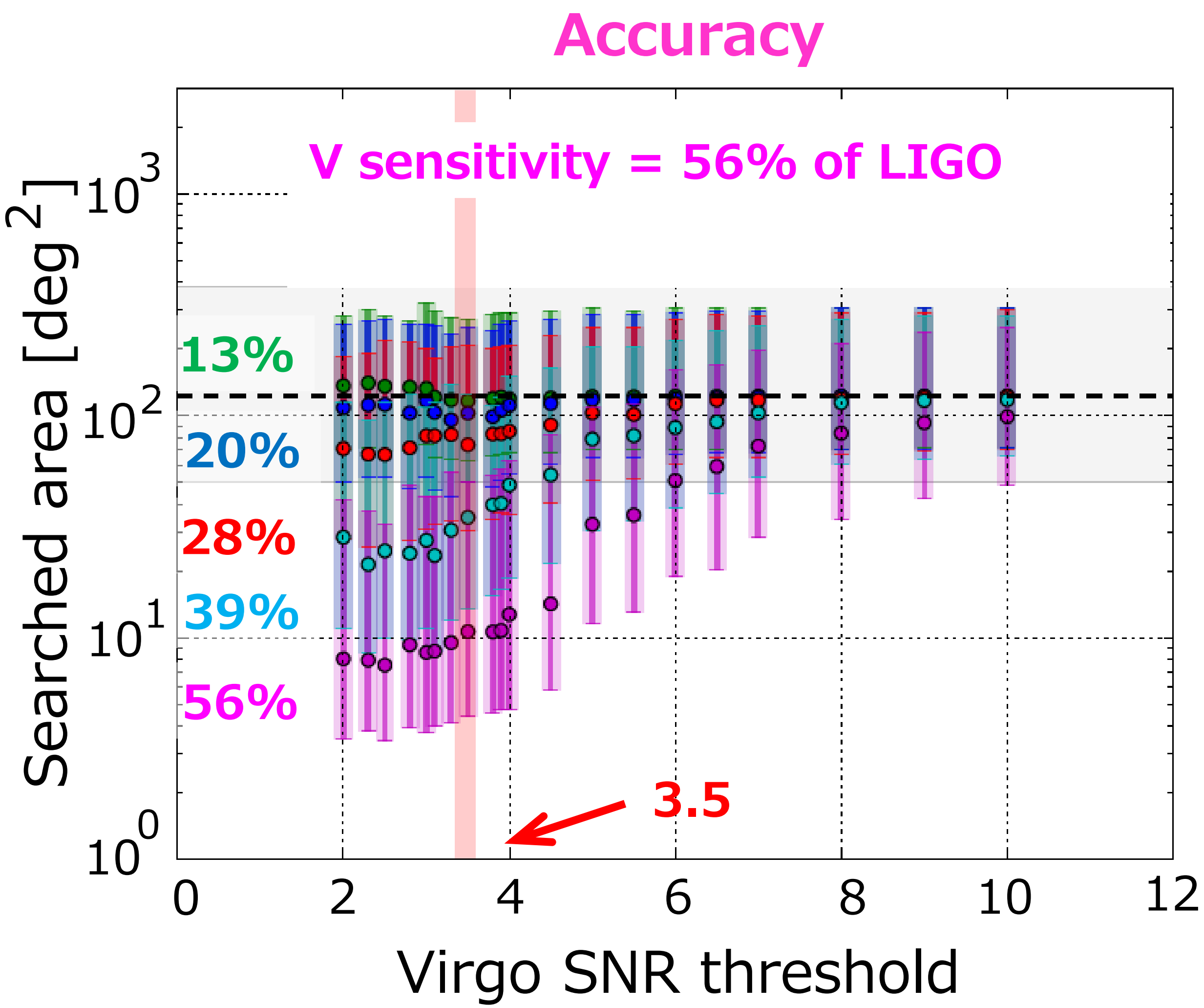
(SNR threshold for H, L = 5., 5.)

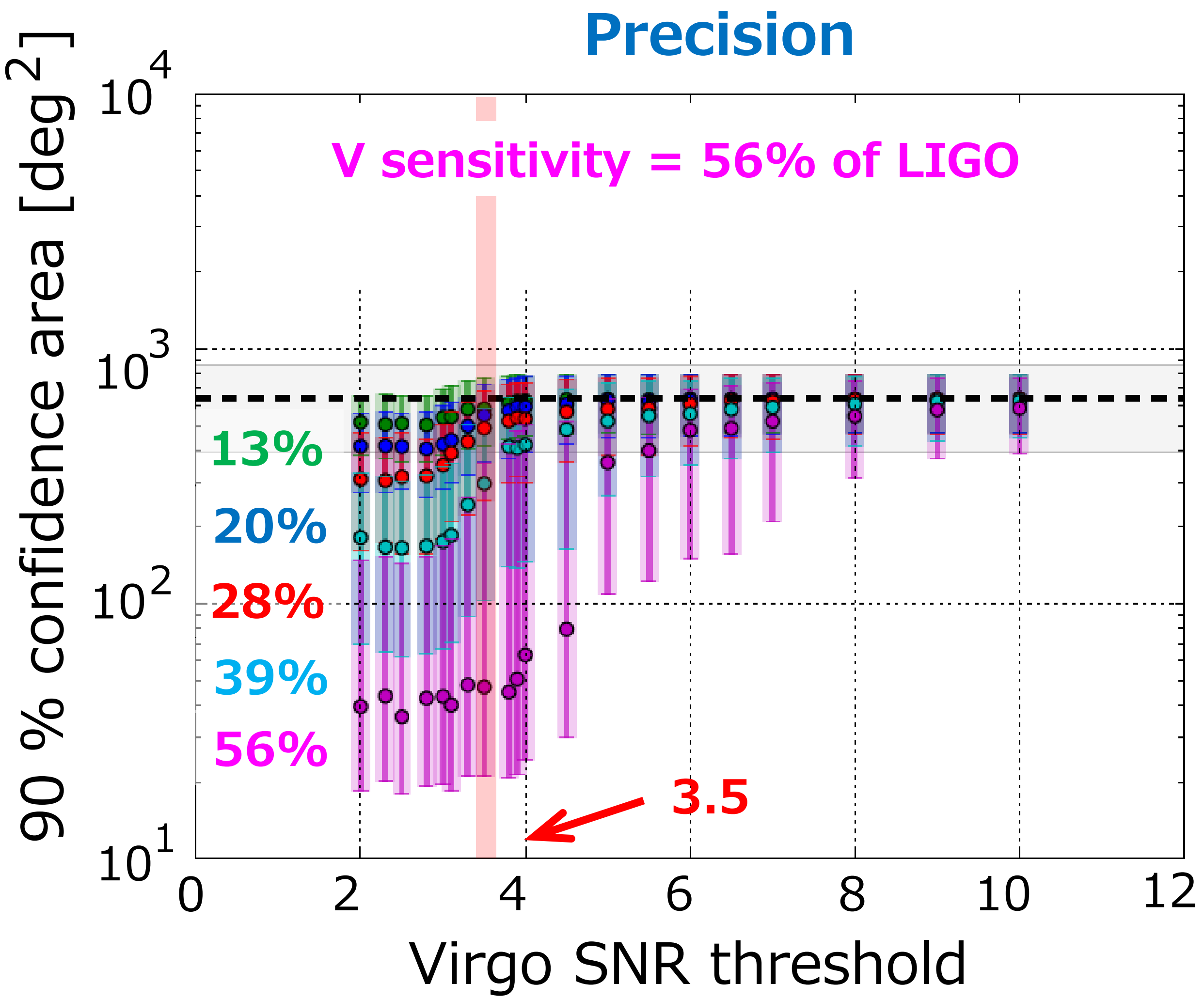




Performance (HLV):

(SNR threshold for H, L = 5., 5.)

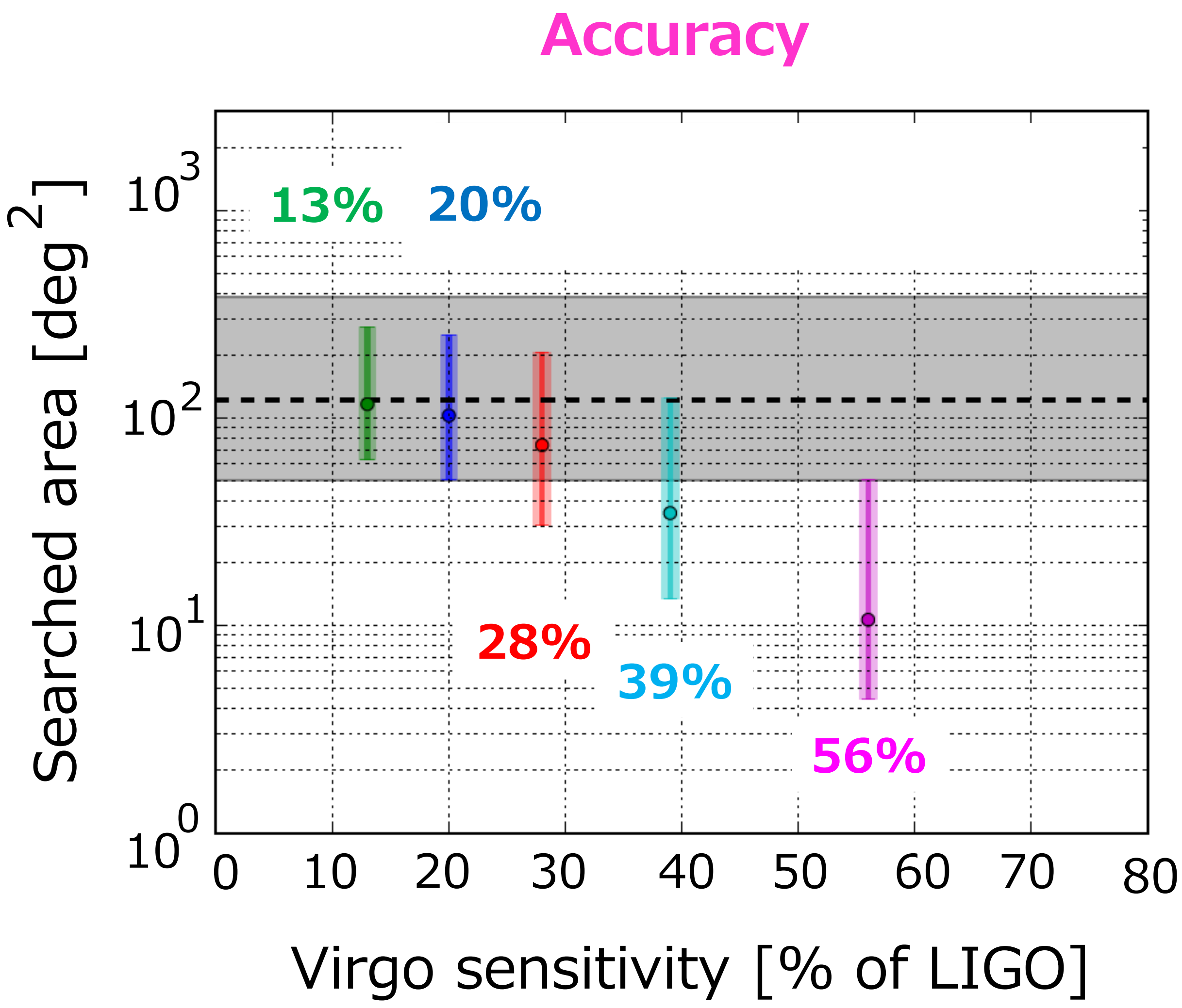


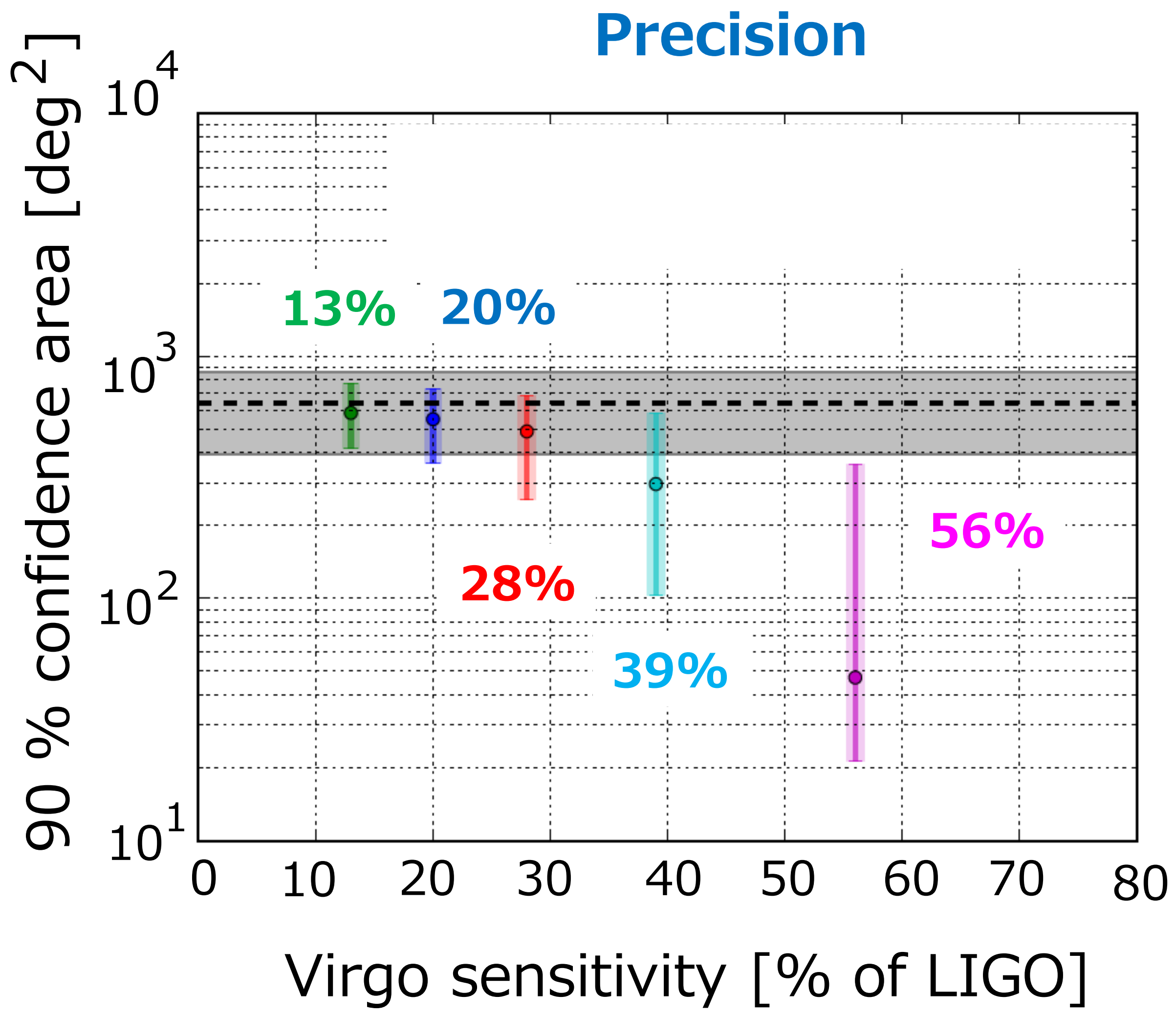


At low SNR threshold, performance becomes worse due to noise triggers.

V SNR threshold = ~3.5

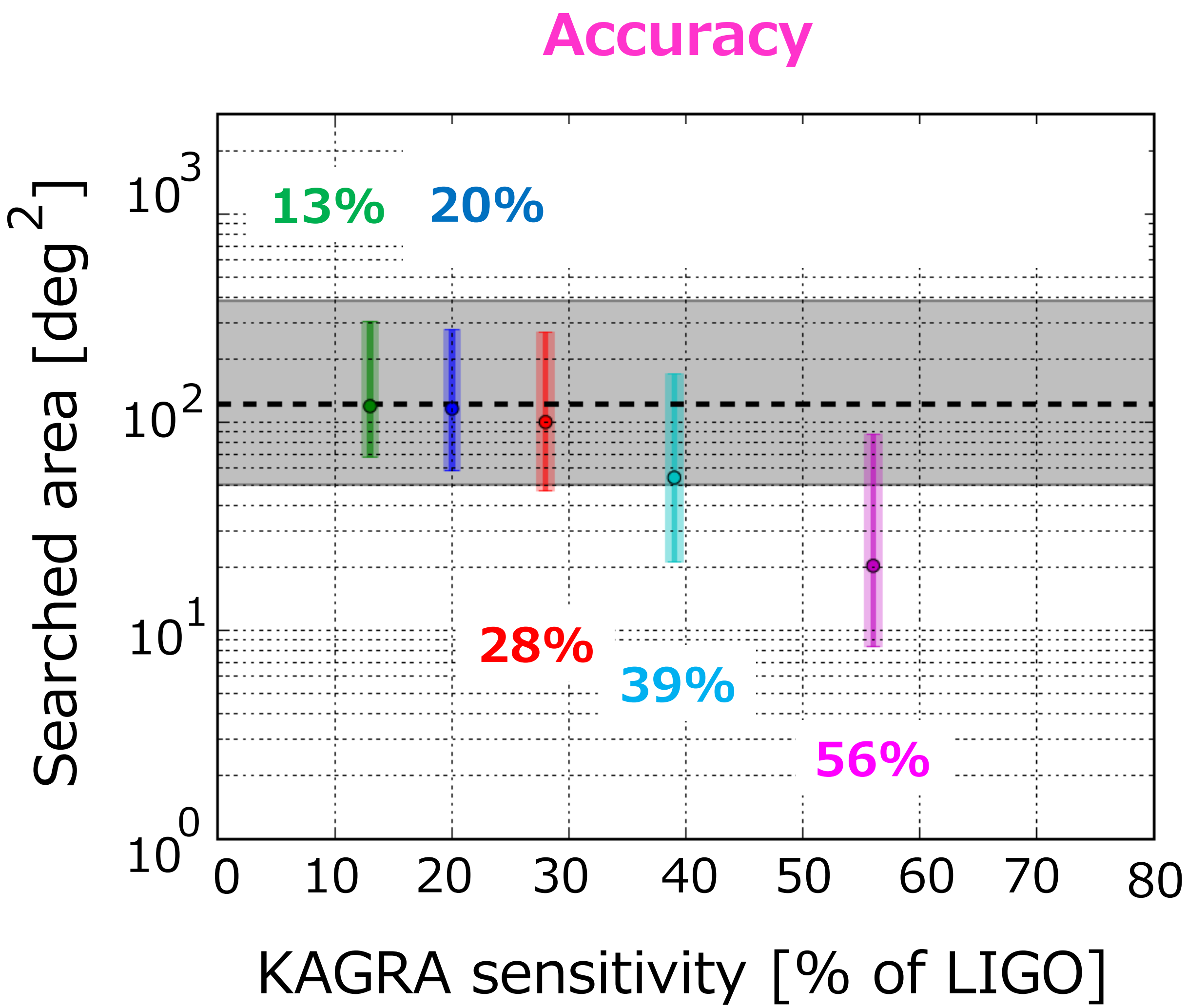
Performance (HLV): **(SNR threshold for H, L, V = 5, 5, 3.5)**

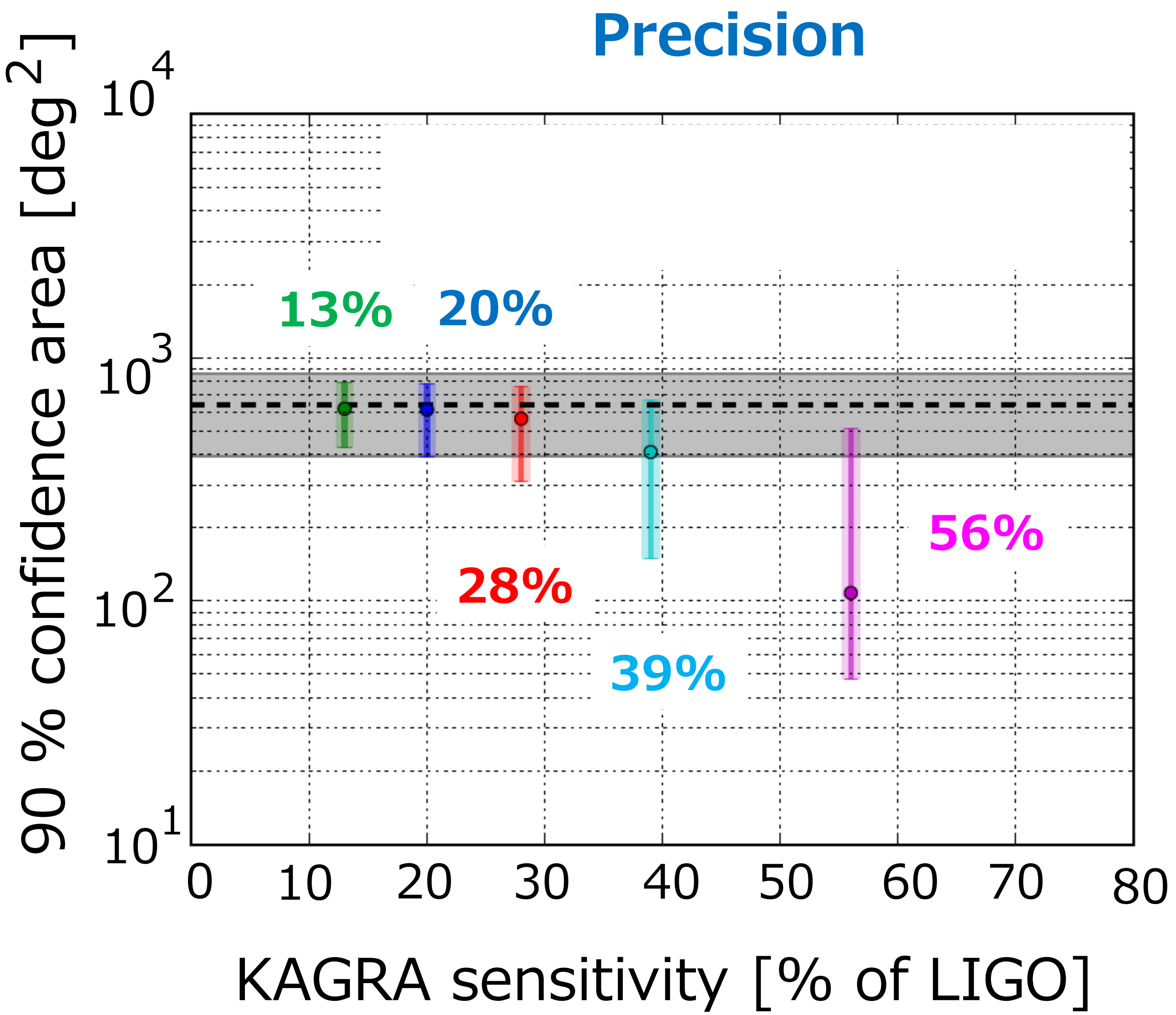




Required: Virgo sensitivity > 20% of LIGO

Performance (HLK): (SNR threshold for H, L, K = 5, 5, 3.5)





Required: KAGRA sensitivity > 28% of LIGO

Hierarchical approach by 4-detector network

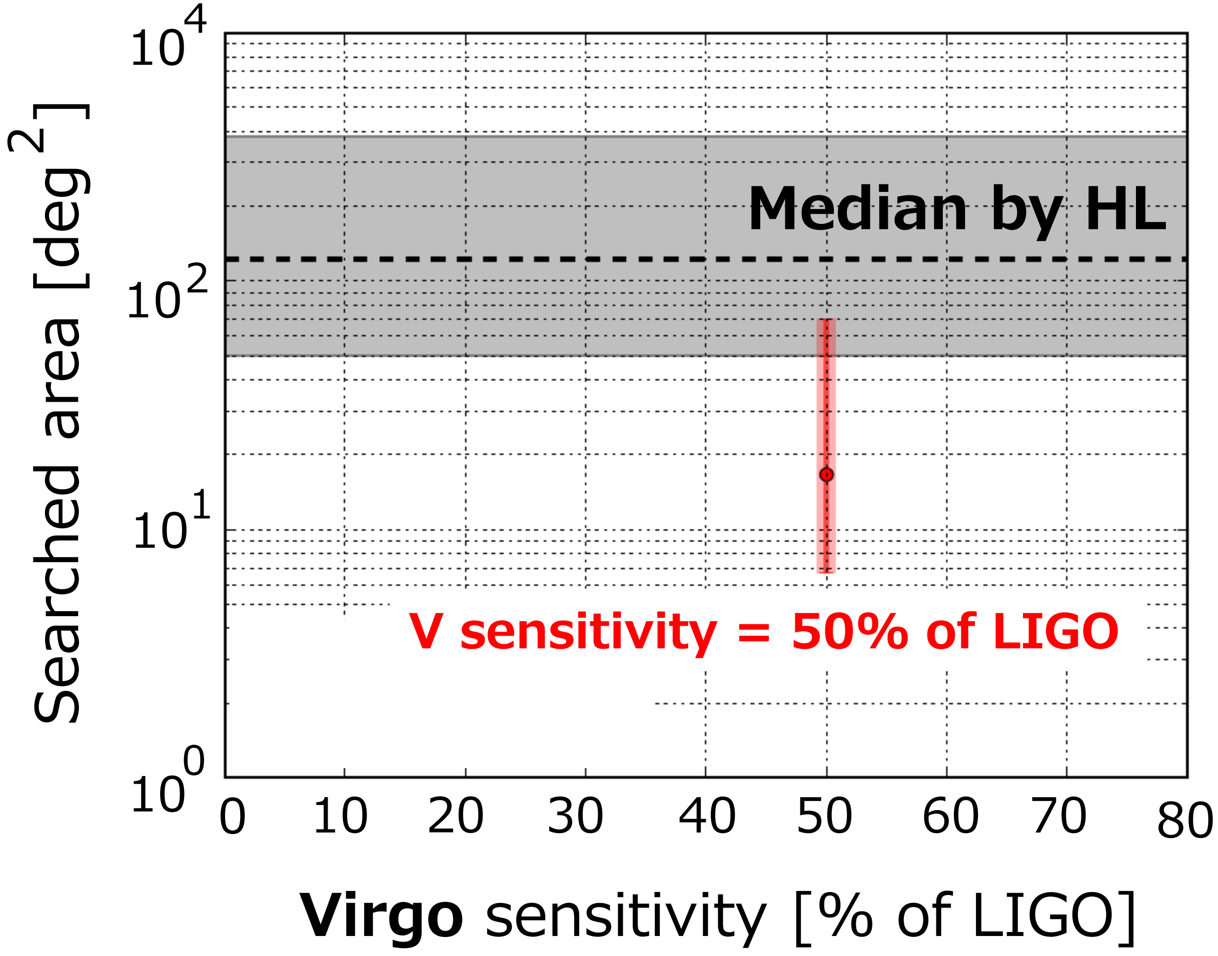
Assuming that:

1. Relative sensitivity
   H : L : V = 1 : 1 : 0.5

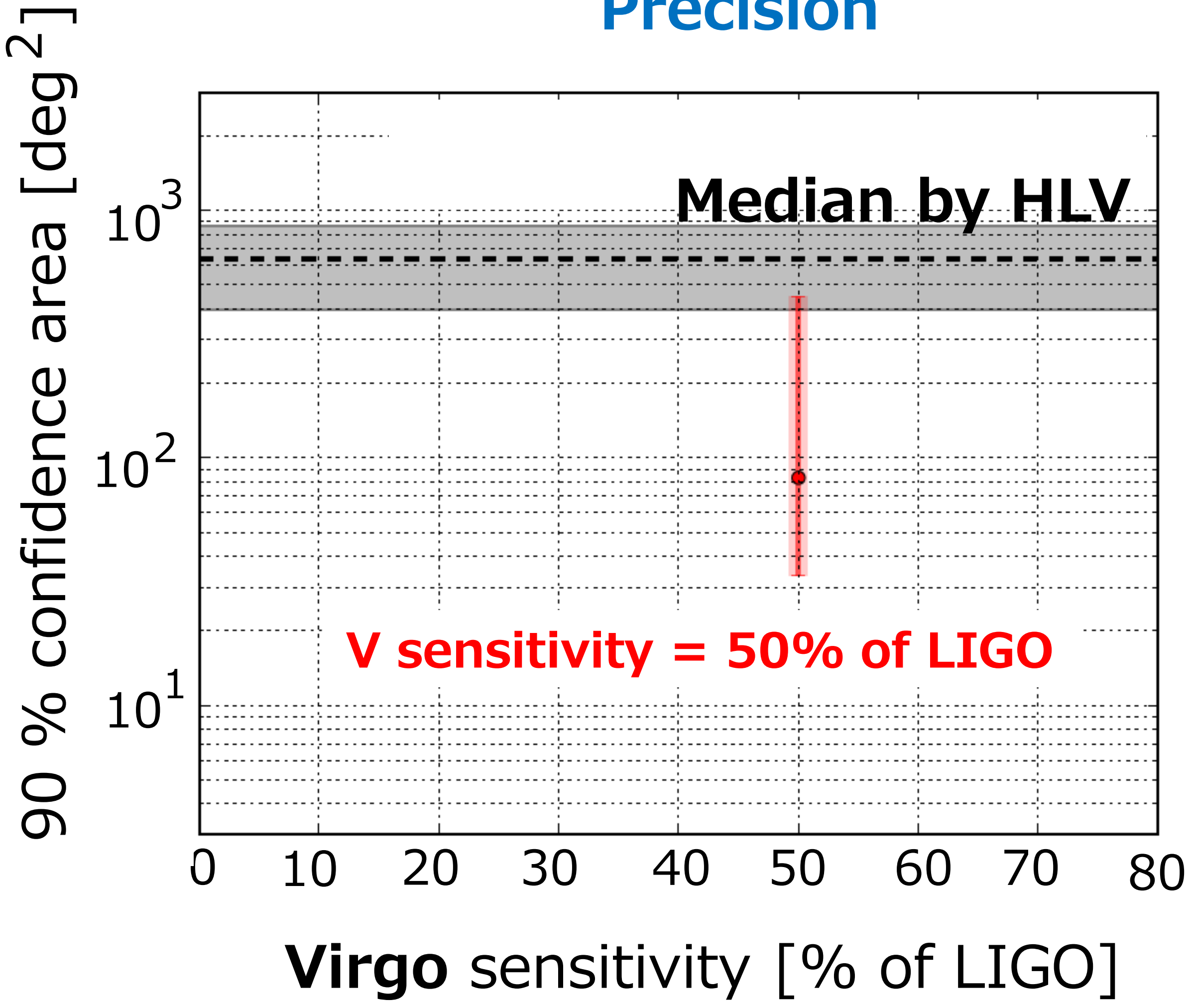
2. SNR threshold
   H : L : V = 5 : 5 : 3.5

Performance (HLV): (SNR threshold for H, L, V = 5, 5, 3.5)

Accuracy

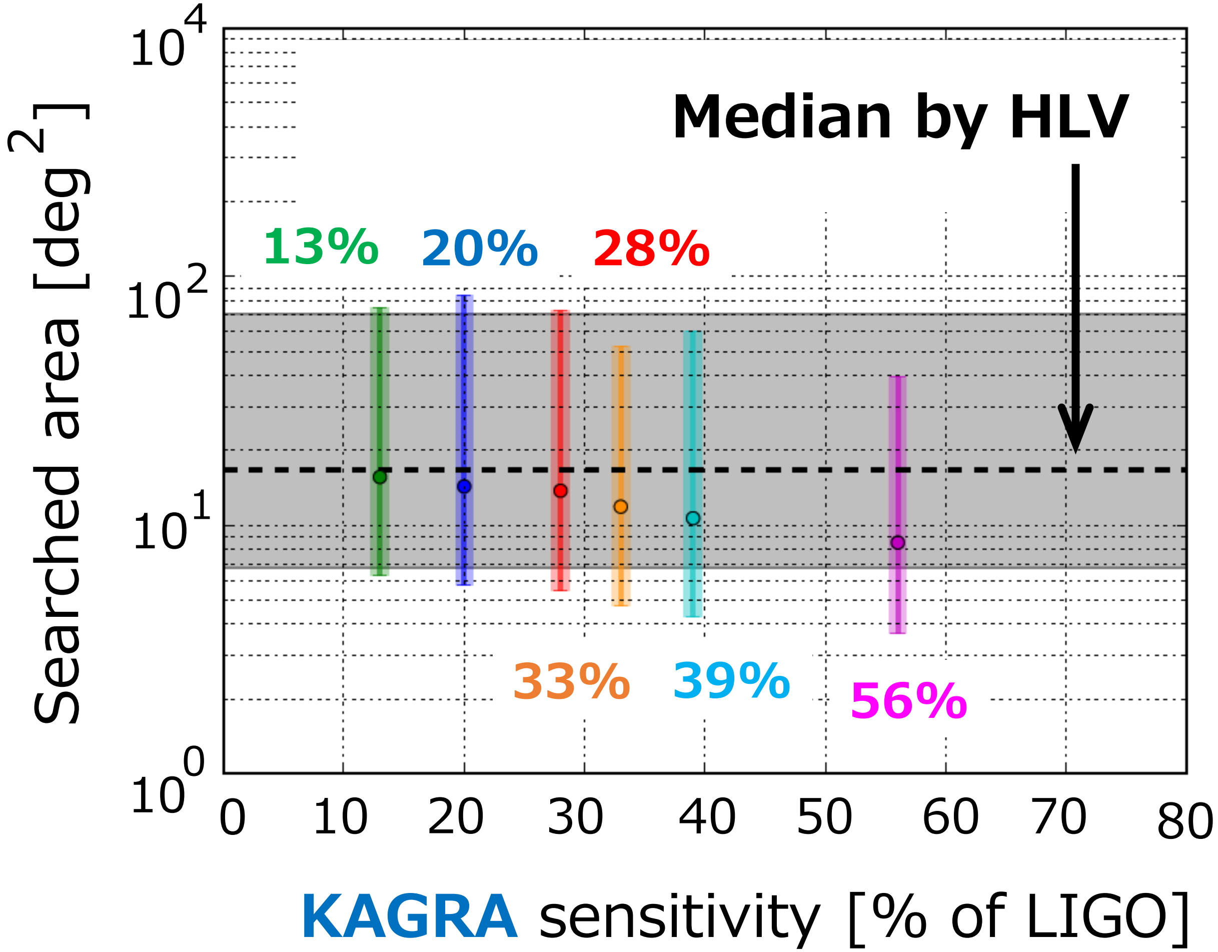


Precision

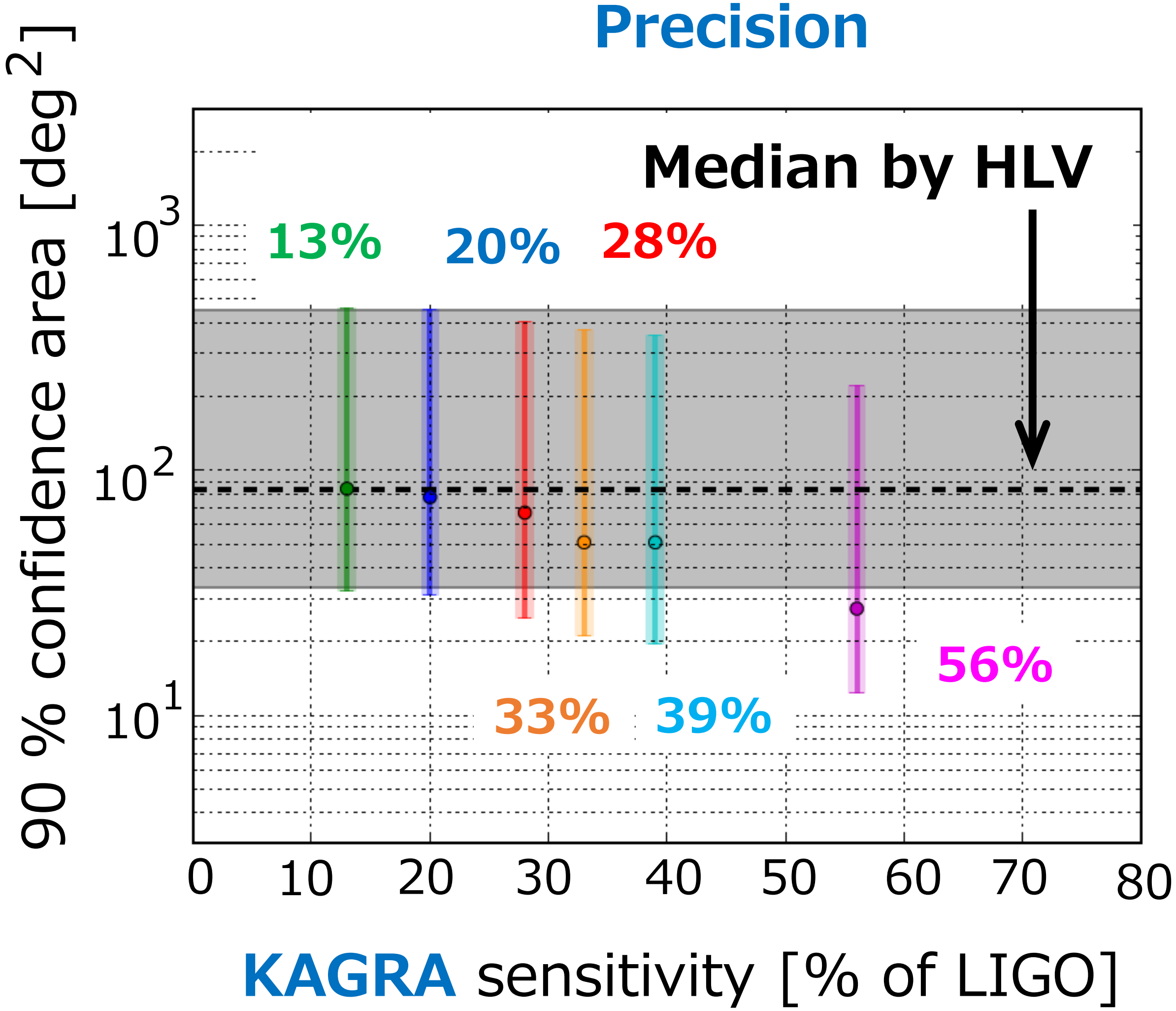


Performance (HLVK): (SNR threshold for H, L, V, K = 5, 5, 3.5, 3.5)

Accuracy



Precision



Required: KAGRA sensitivity > 28% of LIGO

Summary of the hierarchical approach

* Required detector sensitivity at SNR threshold 3.5:

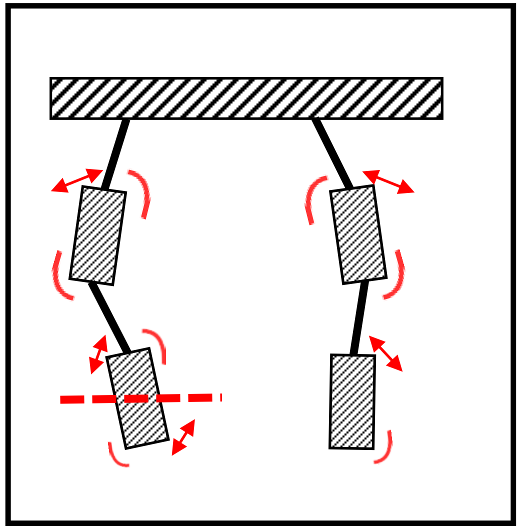
	Relative sensitivity
• **HLV-network:**	Virgo sensitivity > 0.2 * LIGO
• **HLK-network:**	KAGRA sensitivity > 0.28 * LIGO
• **HLVK-network:**	KAGRA sensitivity > 0.28 * LIGO

→ **This hierarchical approach will improve the fast localization in the heterogeneous network.**

As more practical aspect,
higher network duty cycle → key for EM follow up

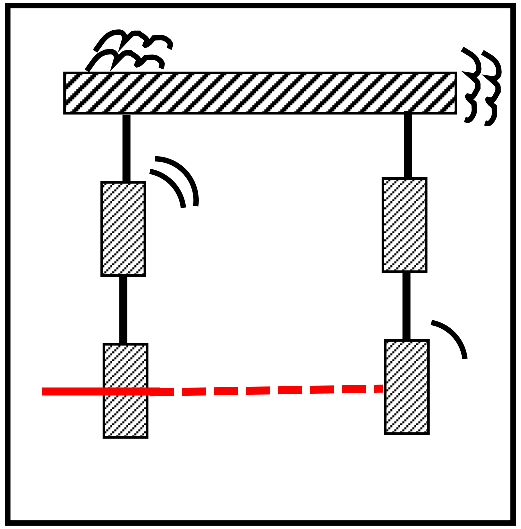
→ <u>Robust operation of fourth detector</u>

Cannot operate interferometer



→

Demanded for stable operation



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My main research

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5. Suspension control design
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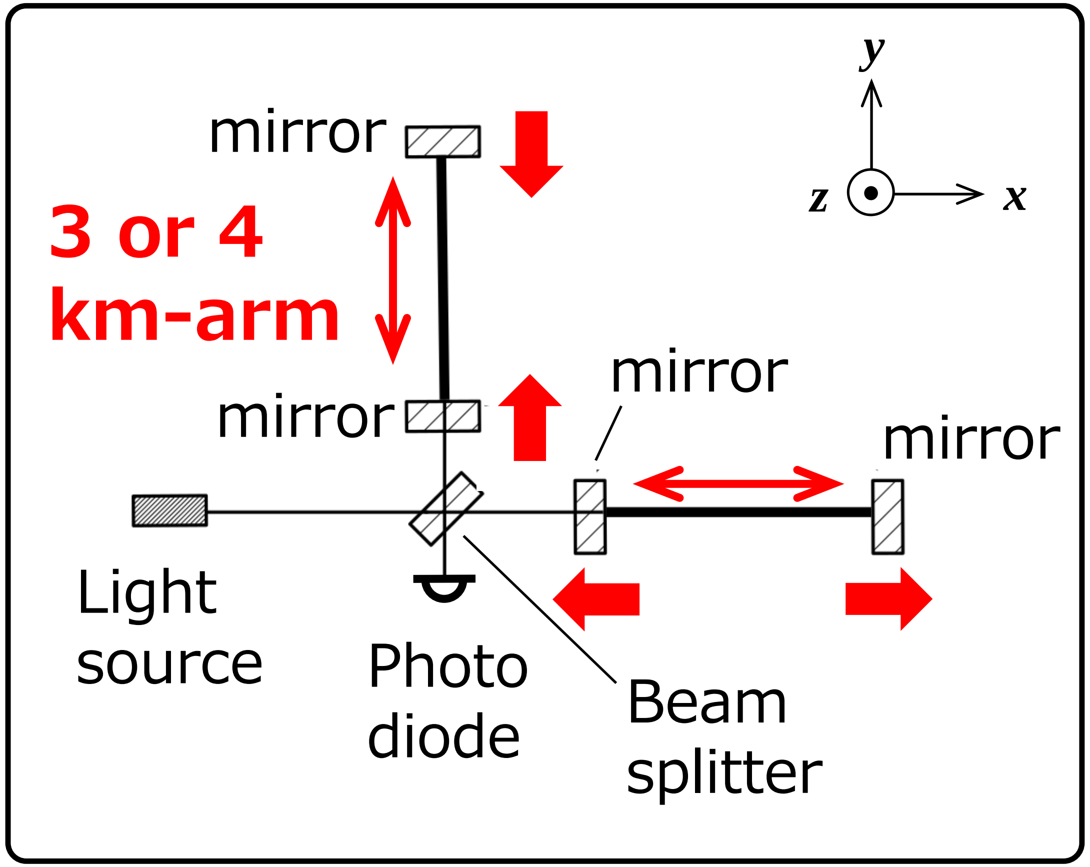
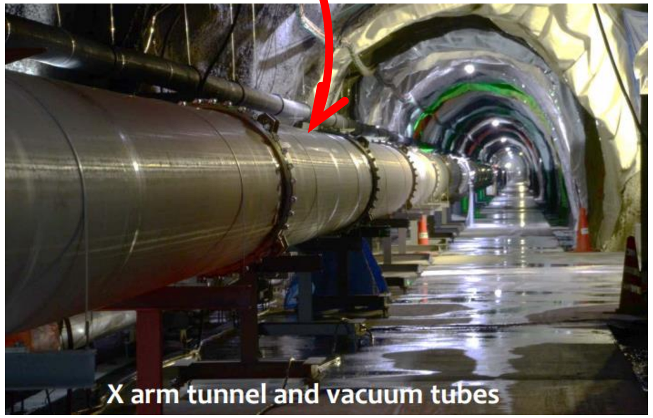
7. Summary

→ Type-A suspension controls toward lock acquisition

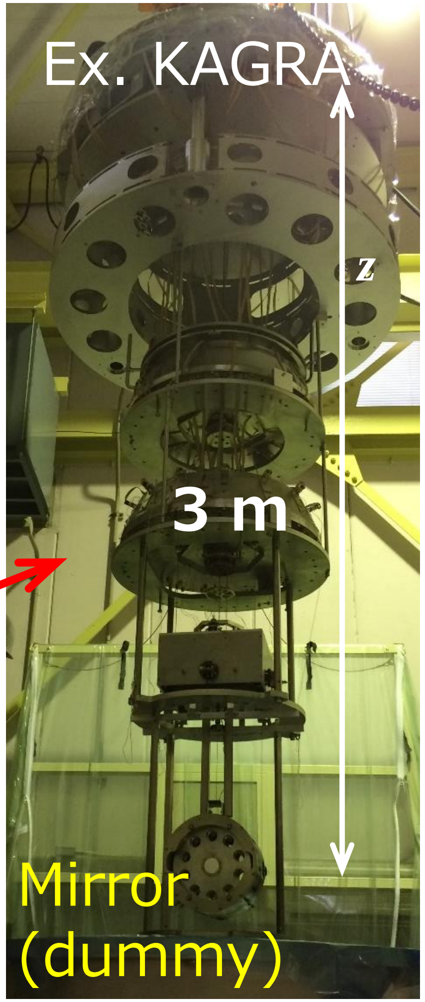
GW detector & suspension



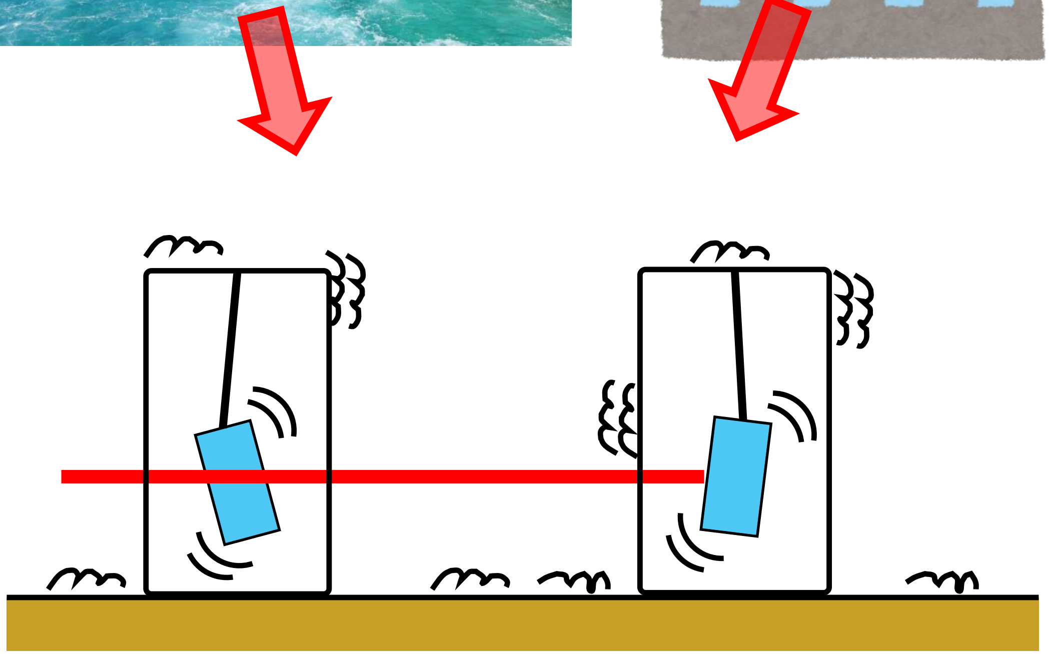
1) Michelson-based interferometer
2) Fabry-Perot cavities
3) 3 or 4 km-arm



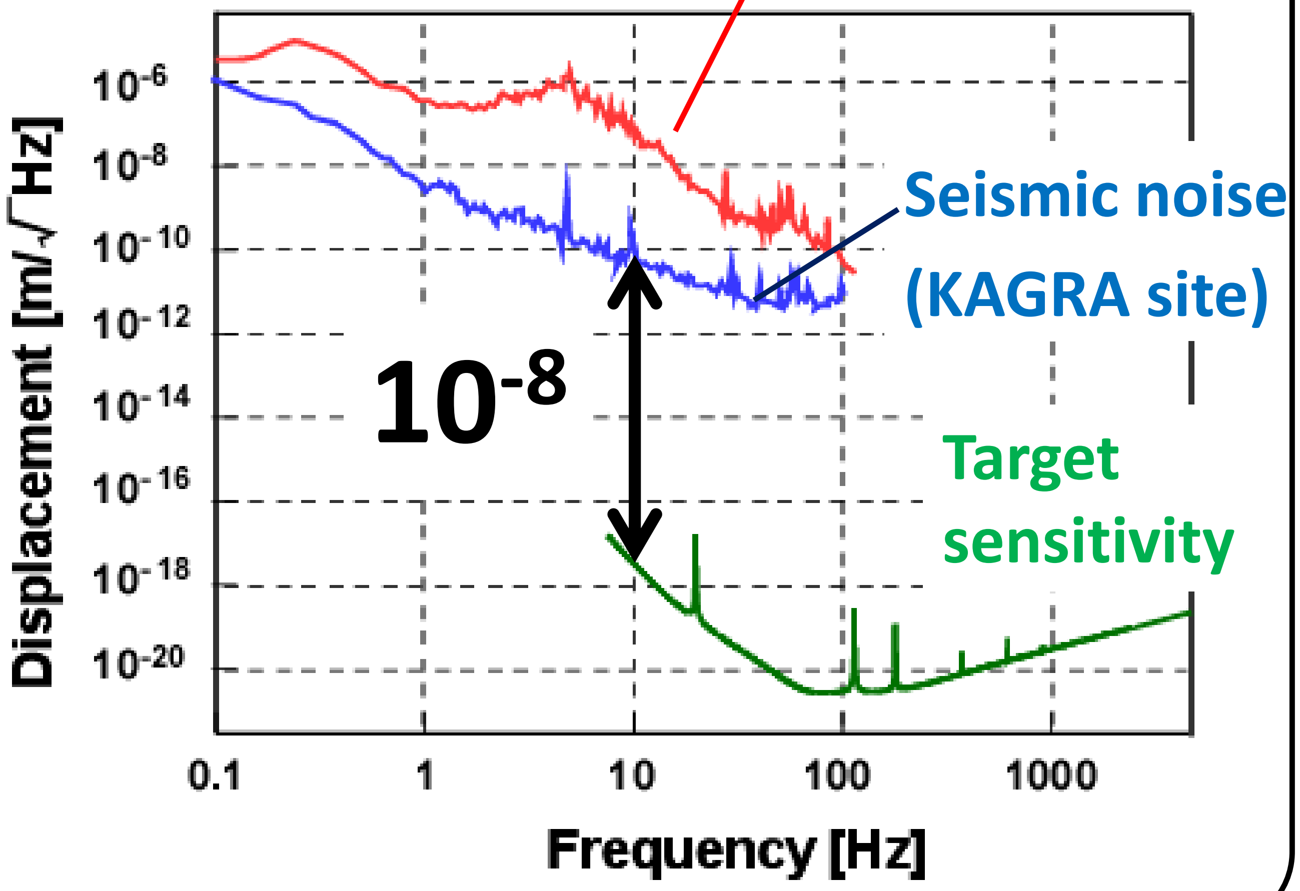
4) Suspended core optics



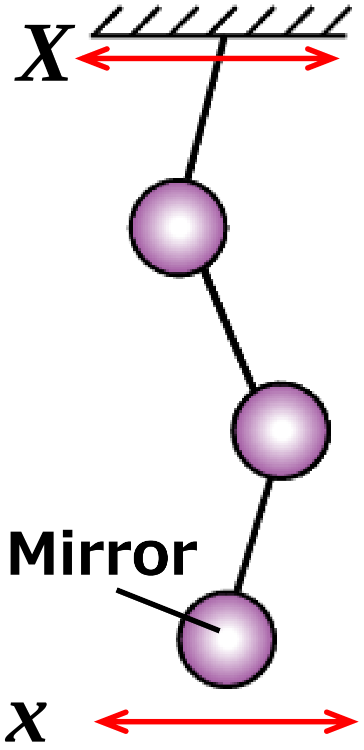
Why pendulum?

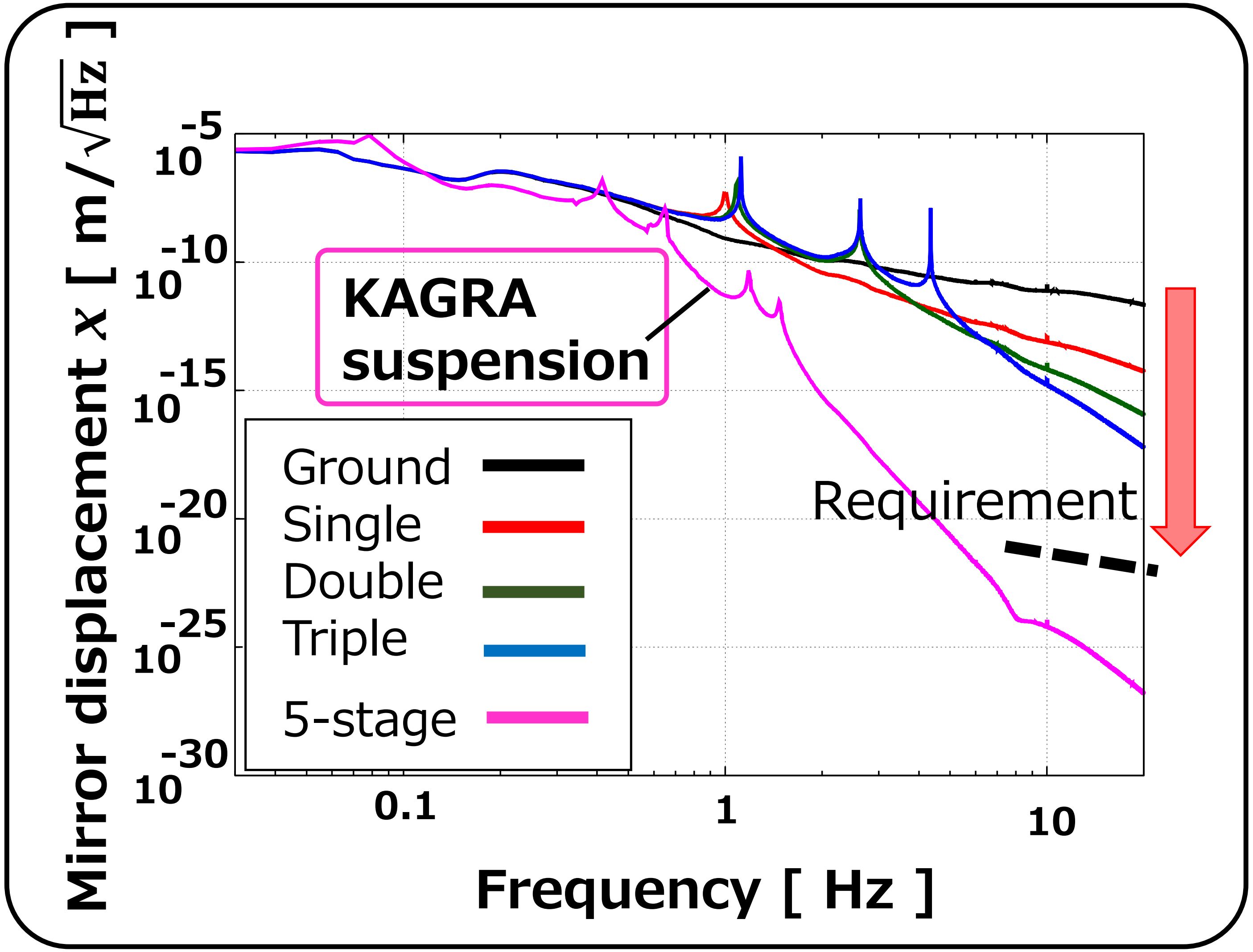


→ To treat seismic noise

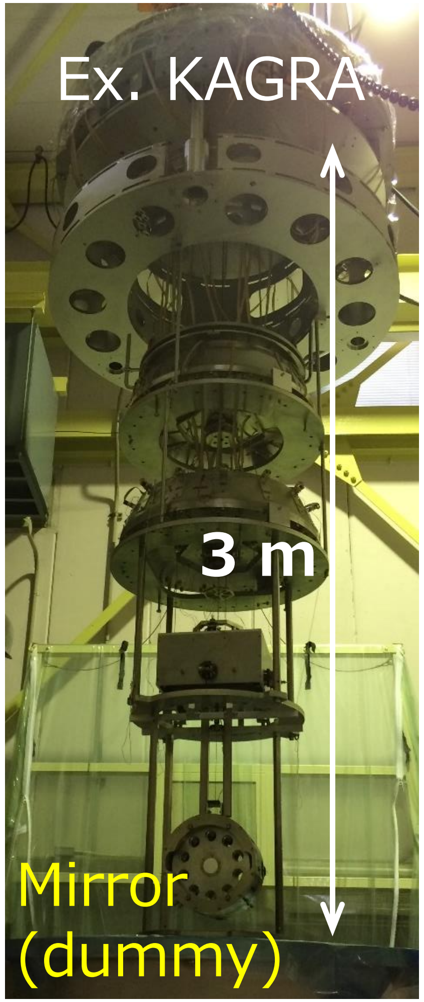


Seismic noise attenuation → pendulum





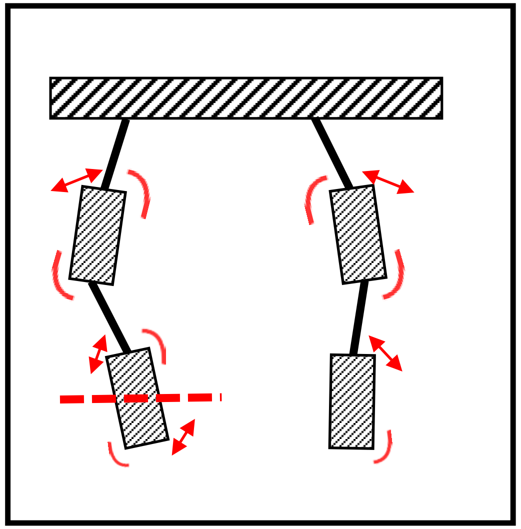
(BS/SRs-suspension case)

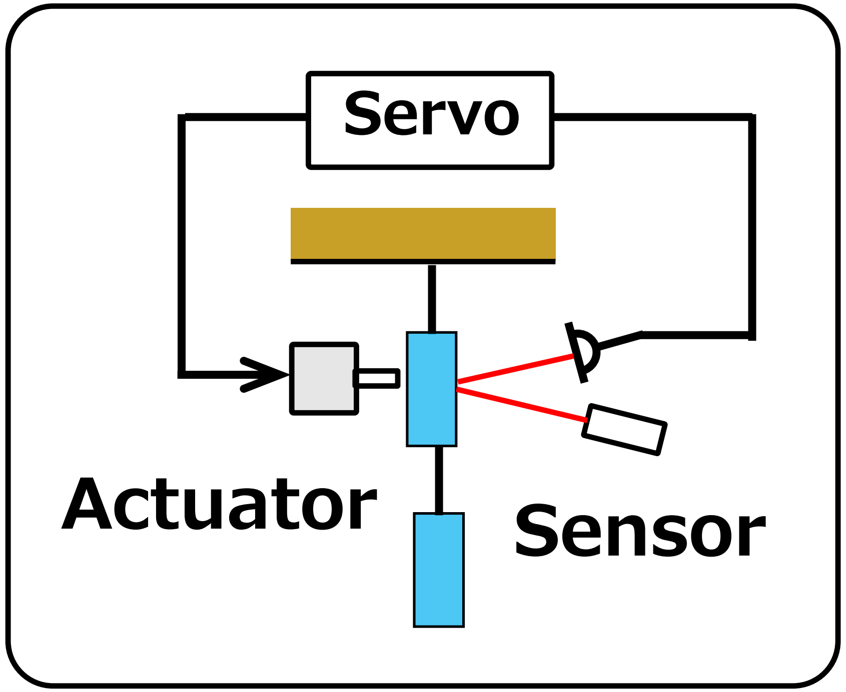


Resonant damping / Mirror Alignment: necessary

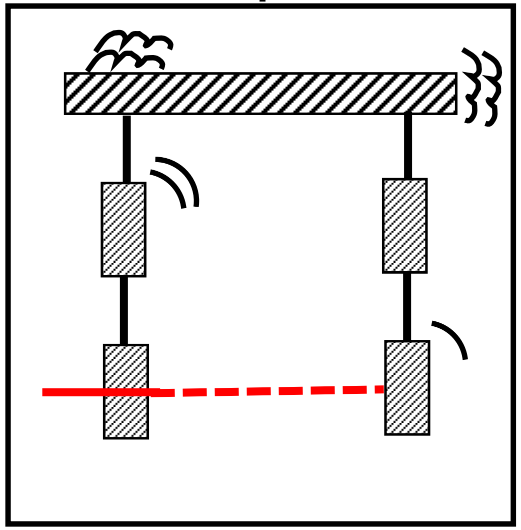
→ Control system

Cannot operate interferometer





Demanded for stable operation



* DAMP resonances.
* Don't care the controls noise.

* Freeze the mirrors
(* Keep low noise)

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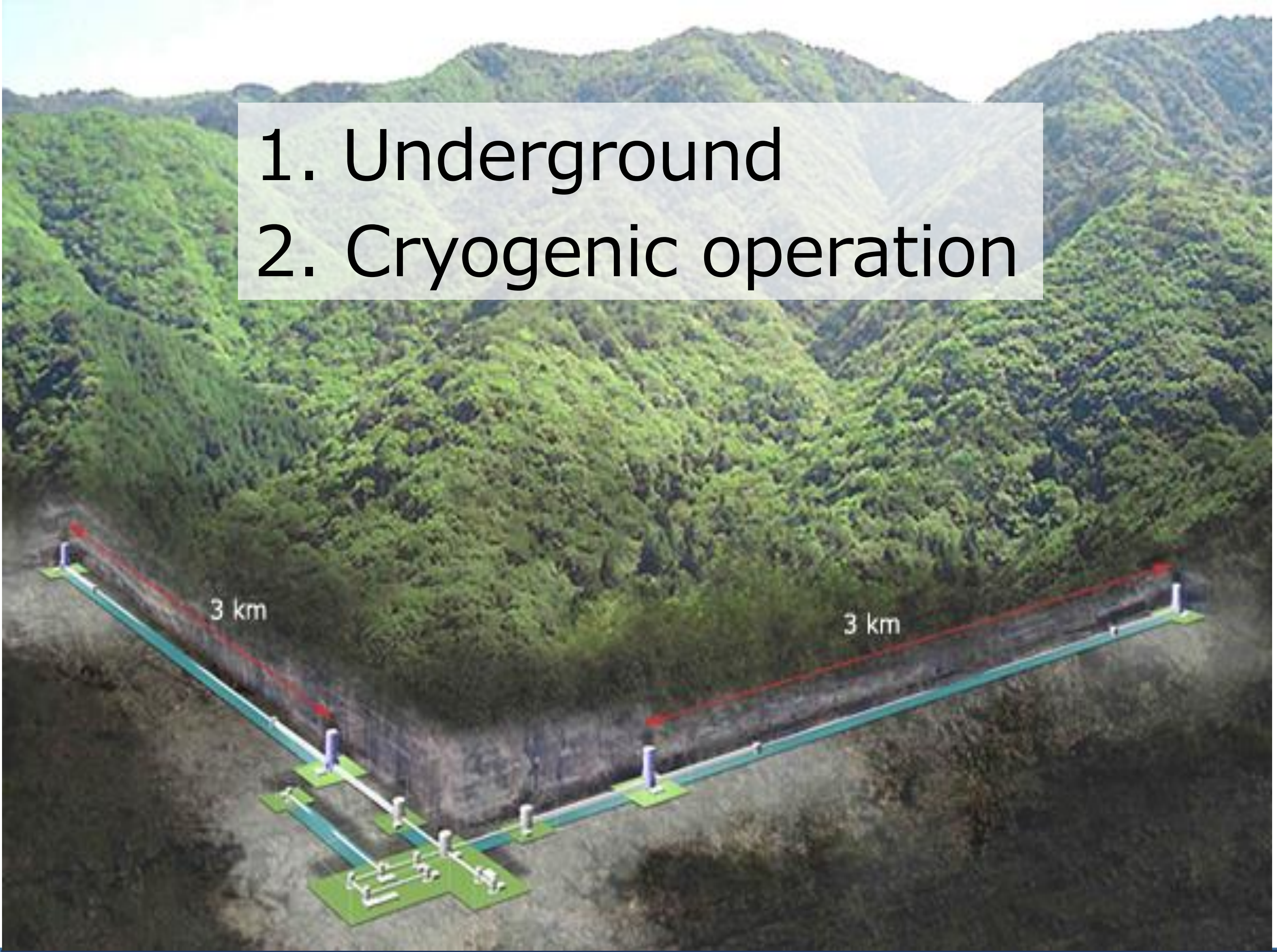
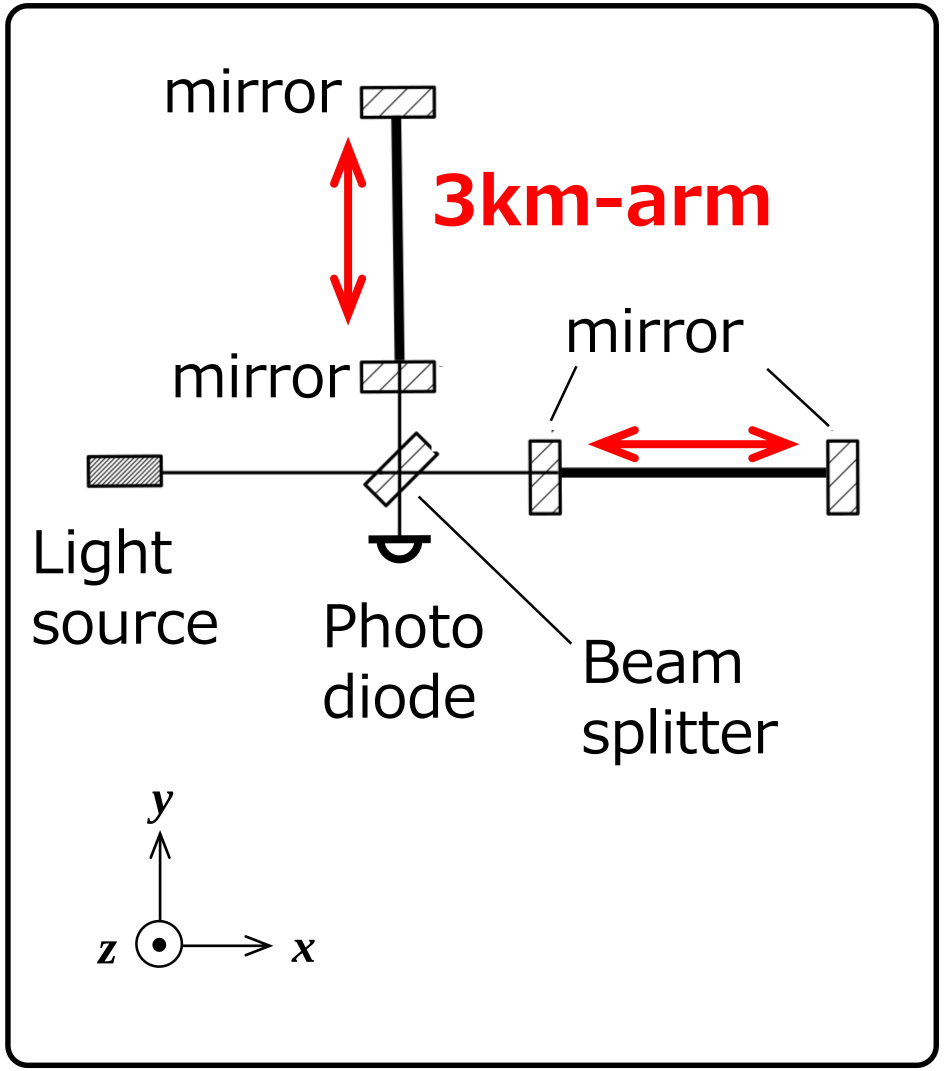
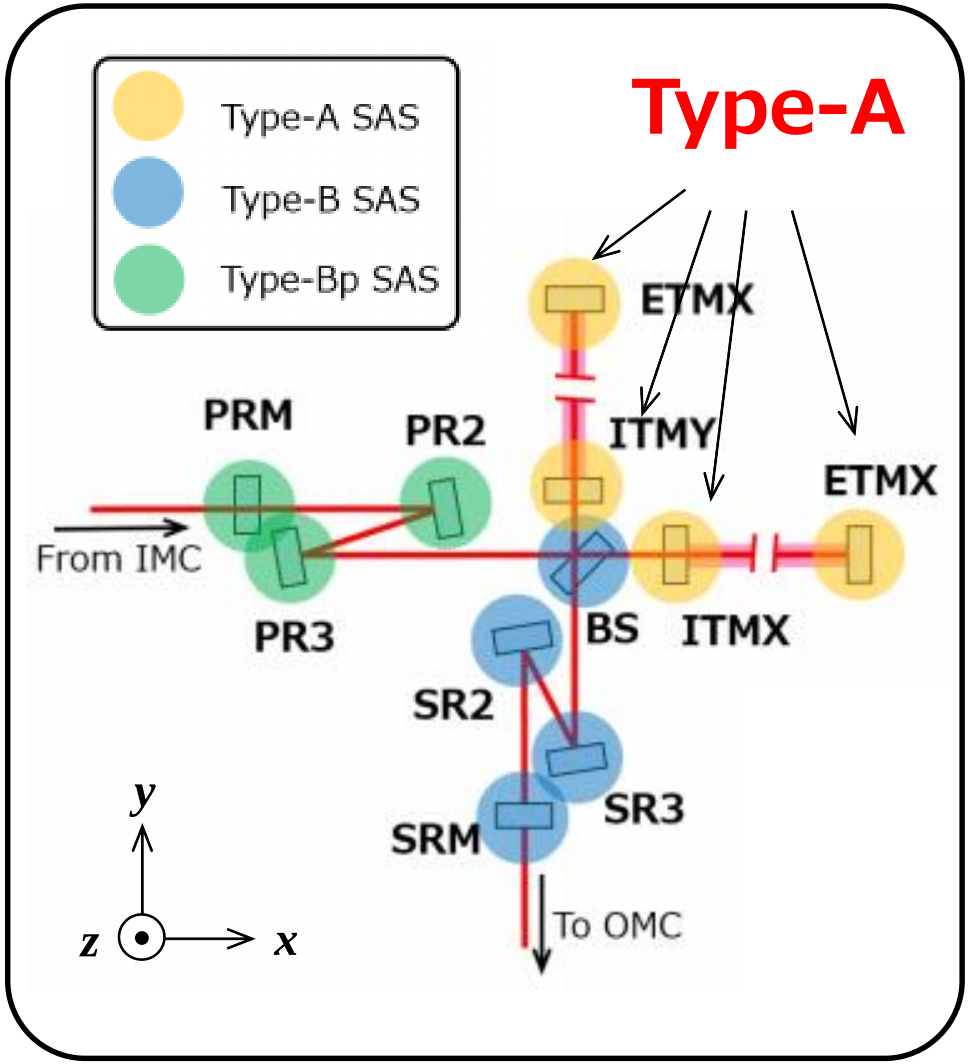
→ TypeA suspension controls toward lock acquisition

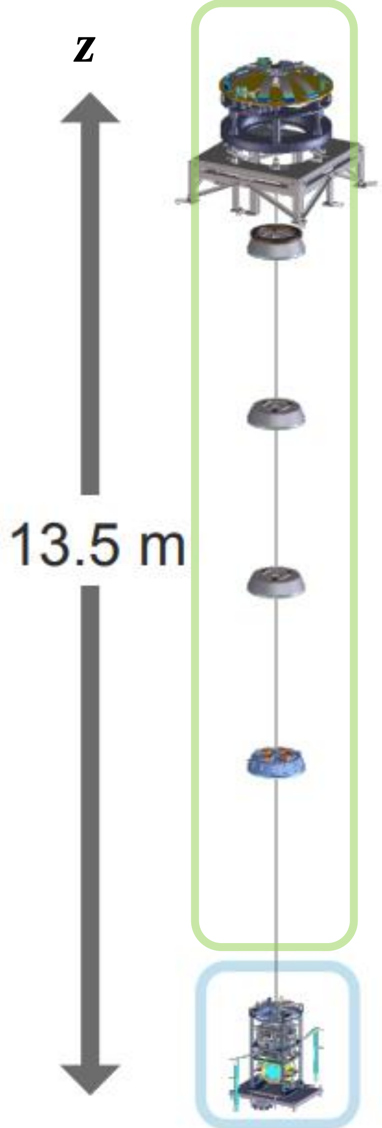
KAGRA detector





Then what's Type-A?

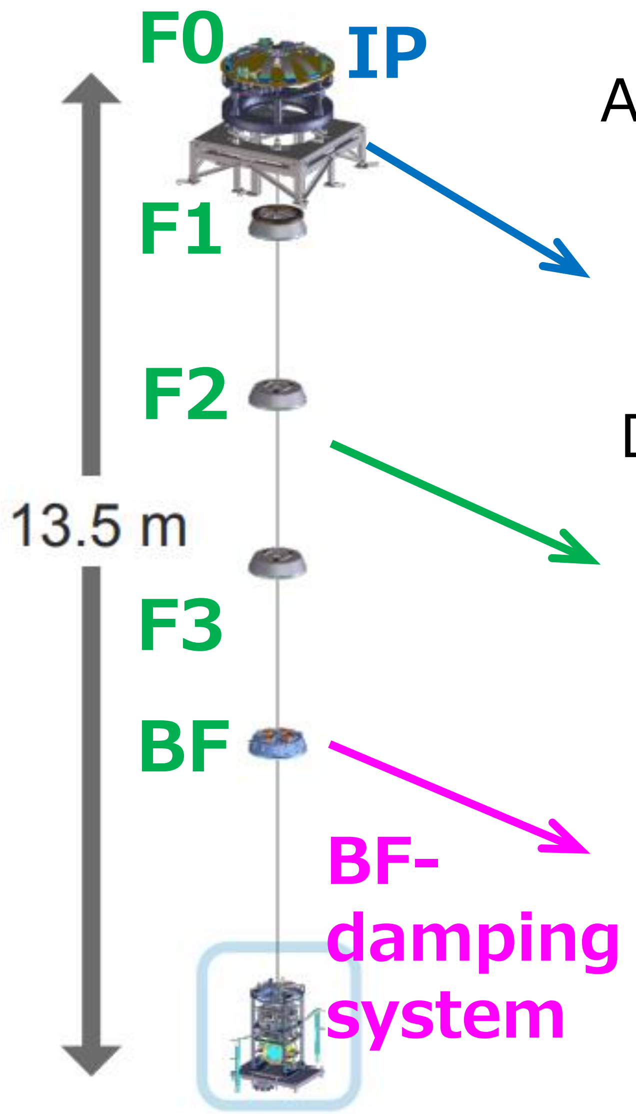


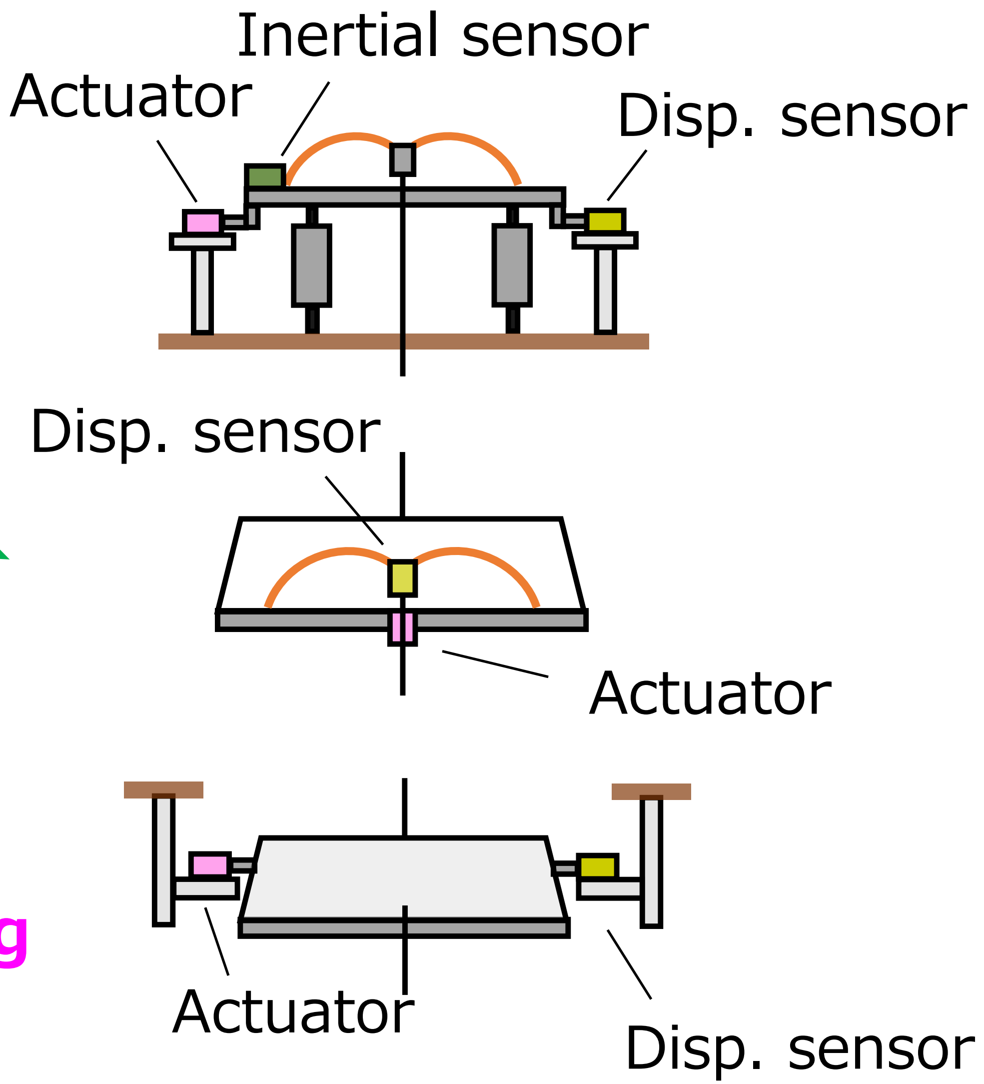


→ **The longest suspension in KAGRA**

- Upper 5 stages: room-temperature
- Lower 4 stages: cryogenic-temperature

Components of Type-A suspension



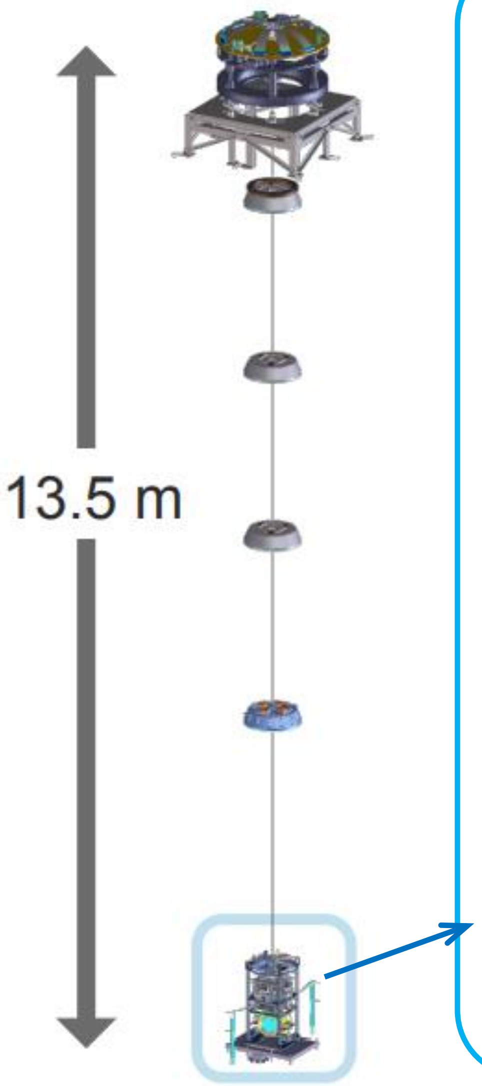


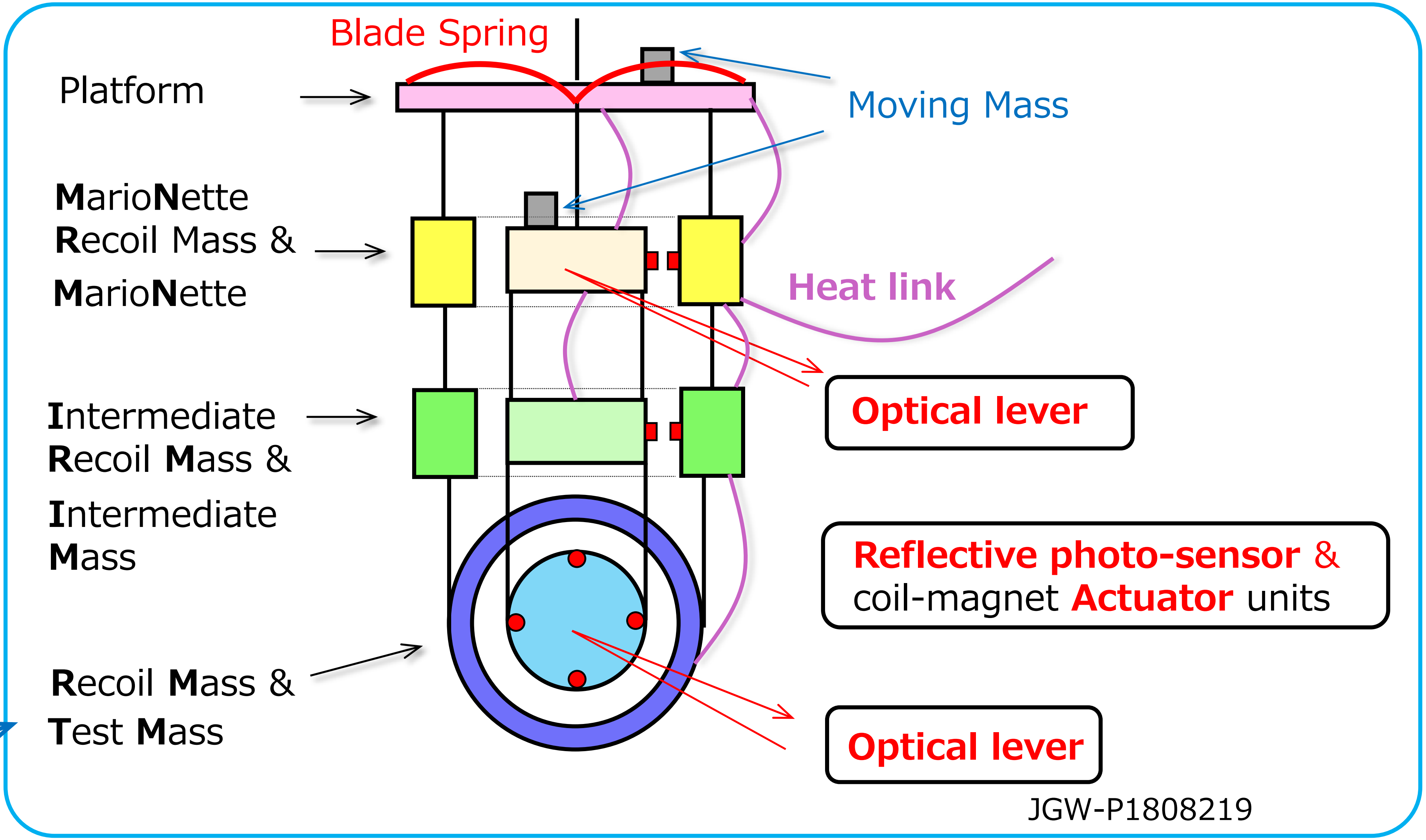
* Inverted pendulum (IP)
f_{IP}: ~70 mHz

* Geometric Anti-Spring (GAS) filter
f_{GAS}: ~0.4Hz

* BF-damping system

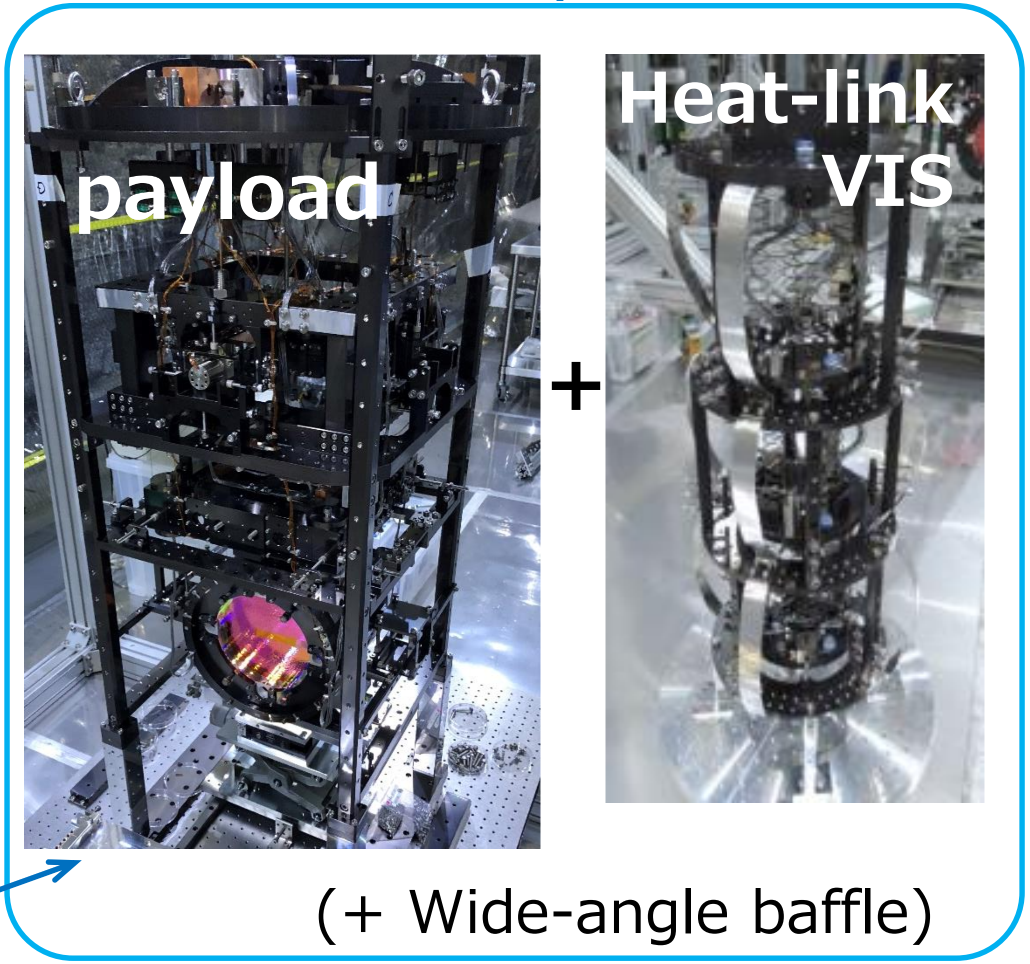
Details of cryogenic payload



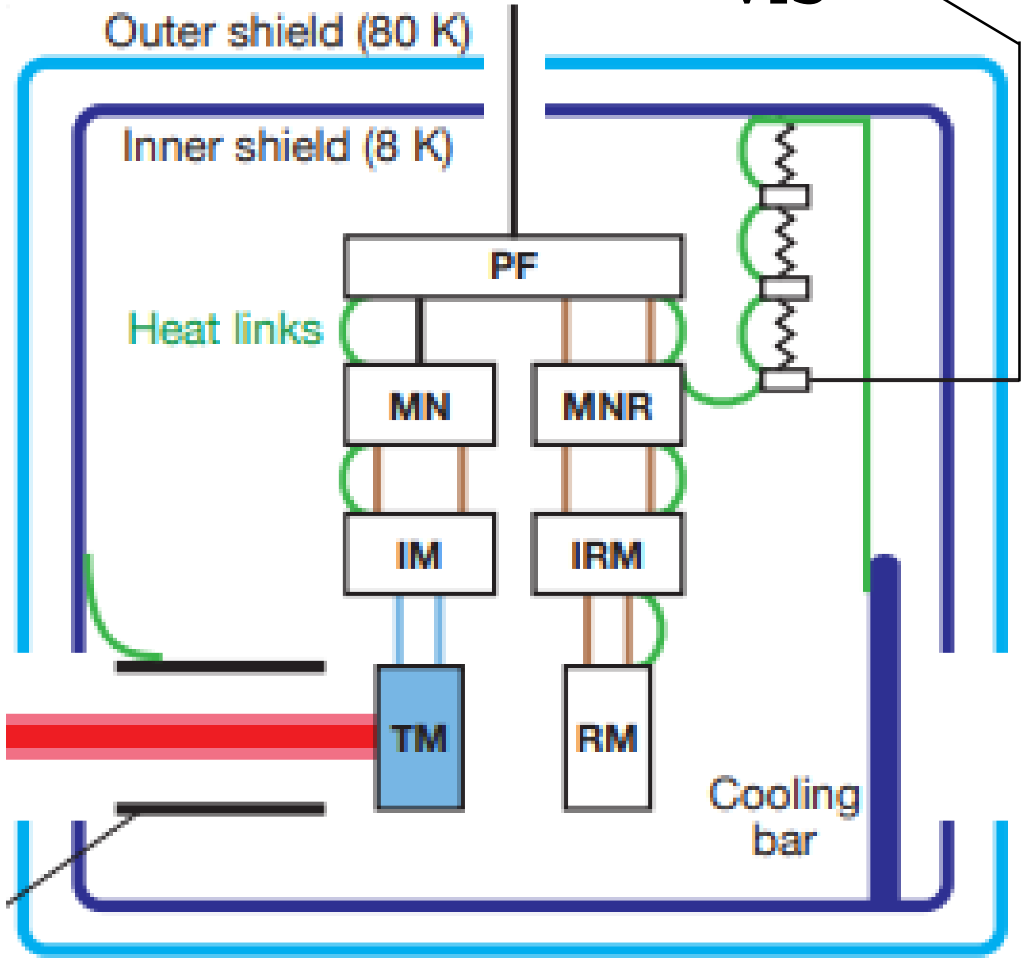


And, the cryogenic part

Inside cryostat



Heat-link
VIS



JGW-P1809347

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→ TypeA suspension controls toward lock acquisition

What already done & not done for Type-A:

Mechanical system

Basic designing

suspension system:
[T. Sekiguchi internal doc.(2014)]+

cryogenic system:
[D. Chen PhD thesis(2015)+

Installation & characterization

room-temp. part:
[K. Otutomi PhD (2019)]

cryogenic temp. part:
[T. Yamada master's(2018)]
[CQG **36** (2019) 165008]+

Data acq. system & digital system
[PTEP (2018) 013F01]+

Room-temp. part

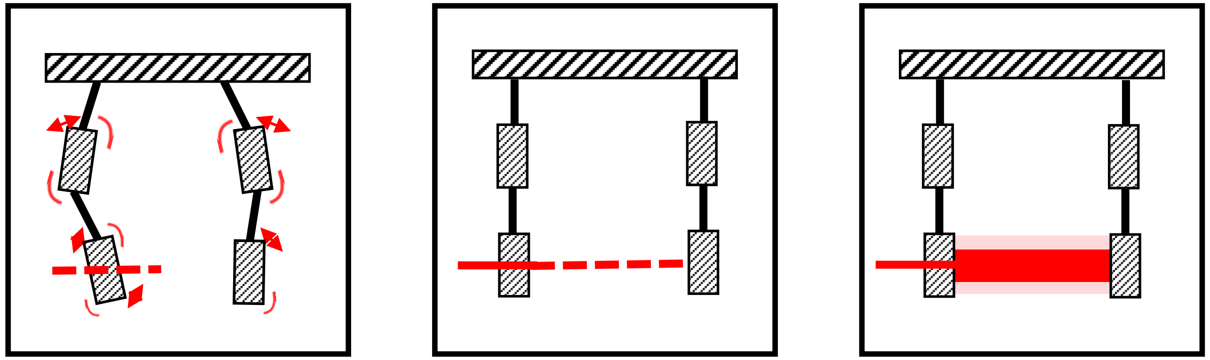
Cryogenic-temp. part

Basic mechanical-system development
→ Already finished.

What already done & not done for Type-A:

Local control system

Designing & Performance test



Calm-down **Lock-acq.** **Observation**

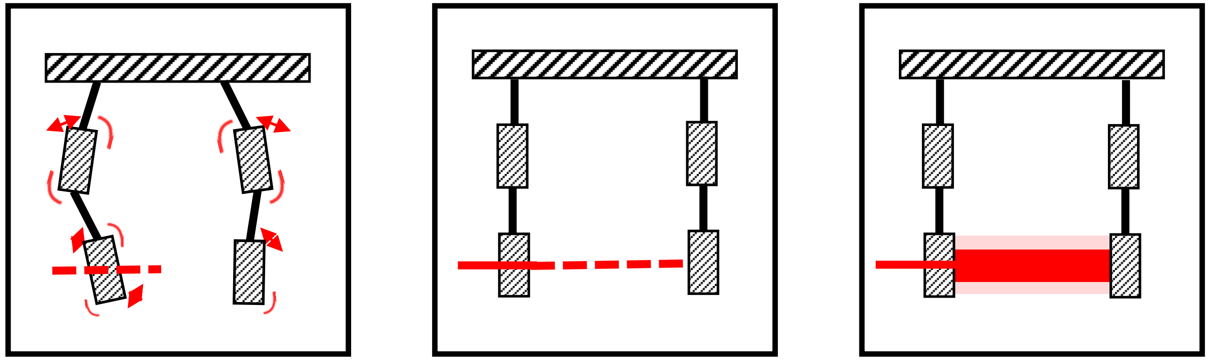
With room-temp. part:
[K. Otutomi PhD (2019)] (*1)

(*1) for arm-cavity lock.

What already done & not done for Type-A:

Local control system

Designing & Performance test



Calm-down **Lock-acq.** **Observation**

With room-temp. part:
[K. Otutomi PhD (2019)] (*1)

With full Type-A:
→ Not done so far.

My main research

(*1) for arm-cavity lock.

Goal:

To construct local control system toward lock acquisition with full Type-A.

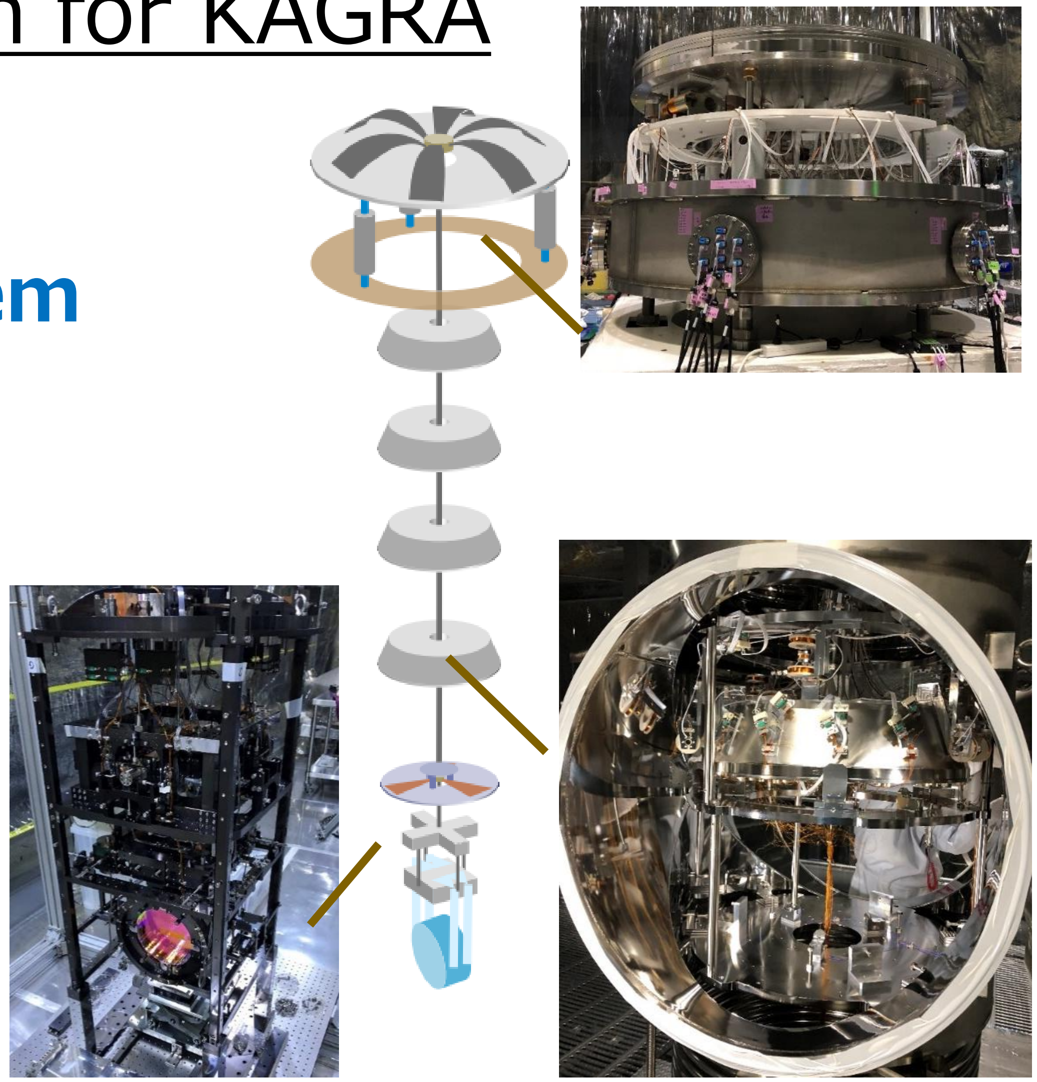
* Control system in observation:
→ global control is demanded in addition.
→ out of this scope.

Targets
of low frequency vibration isolation for KAGRA

1. To construct local control system toward interferometer lock

→ Resonance damping
→ Mirror residual suppression

2. To confirm that the system satisfies the requirements



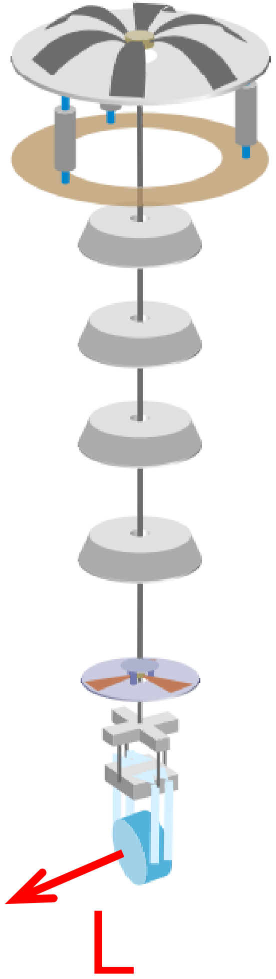
Overview of performance tests:

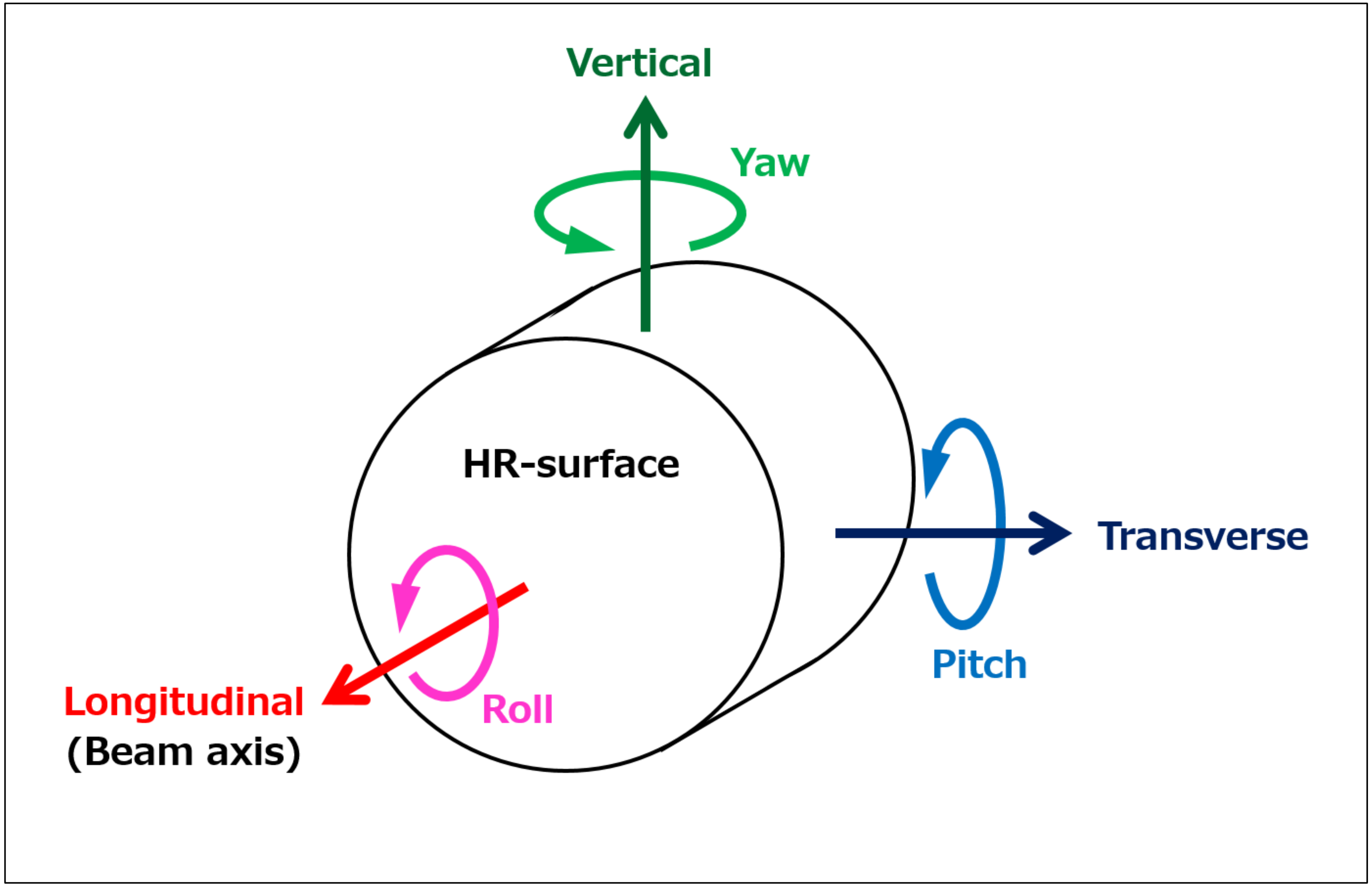
1. Mechanical system characterization

2. Resonance damping

3. Mirror residual suppression

Axis definition:





1. Mechanical system characterization:

- **Target:** Confirm the system has characteristics of pendulum
- **Measurement:** Frequency responses from actuators to sensors

---

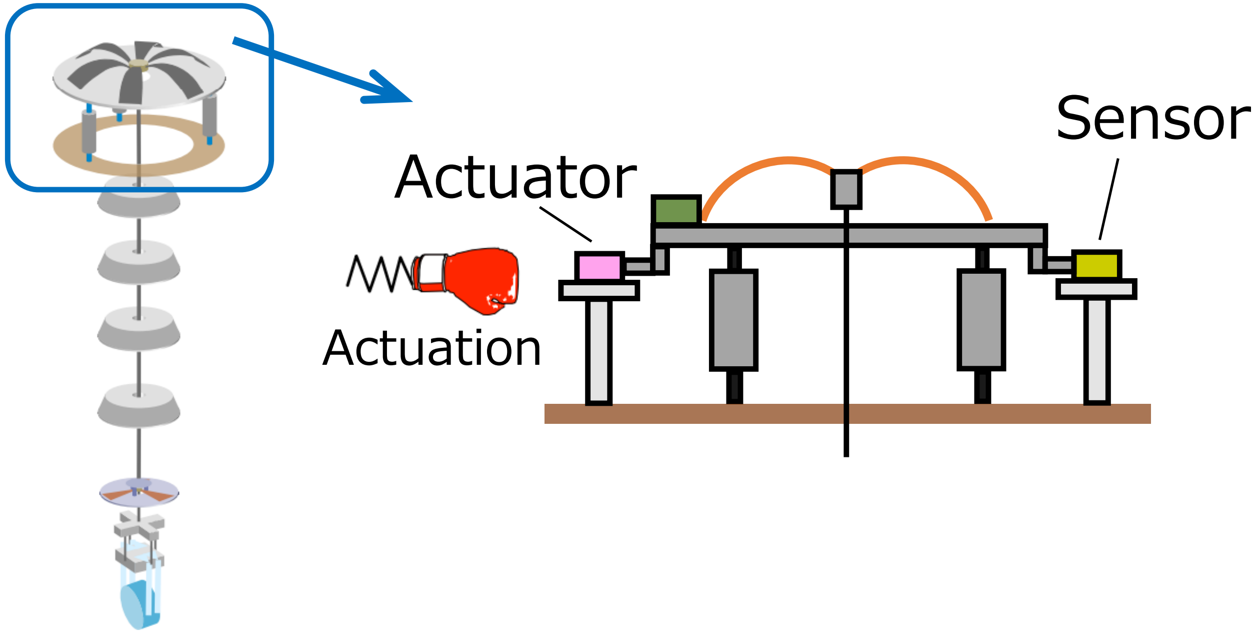
→ **For preparation of test 2 & test 3.**

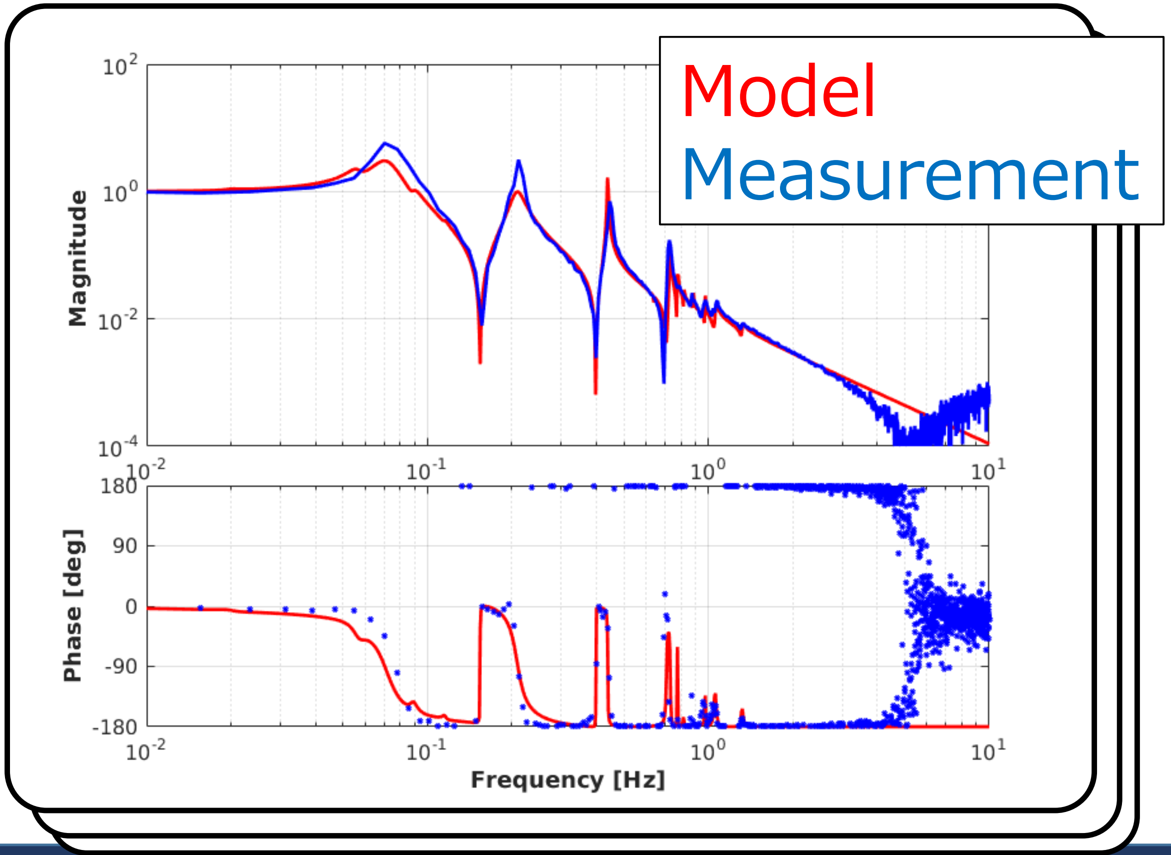
→ compared to 3D-rigod-body simulation

1. Mechanical system characterization:

- **Target:** Confirm the system has characteristics of pendulum
- **Measurement:** Frequency responses from actuators to sensors

*** By each component**

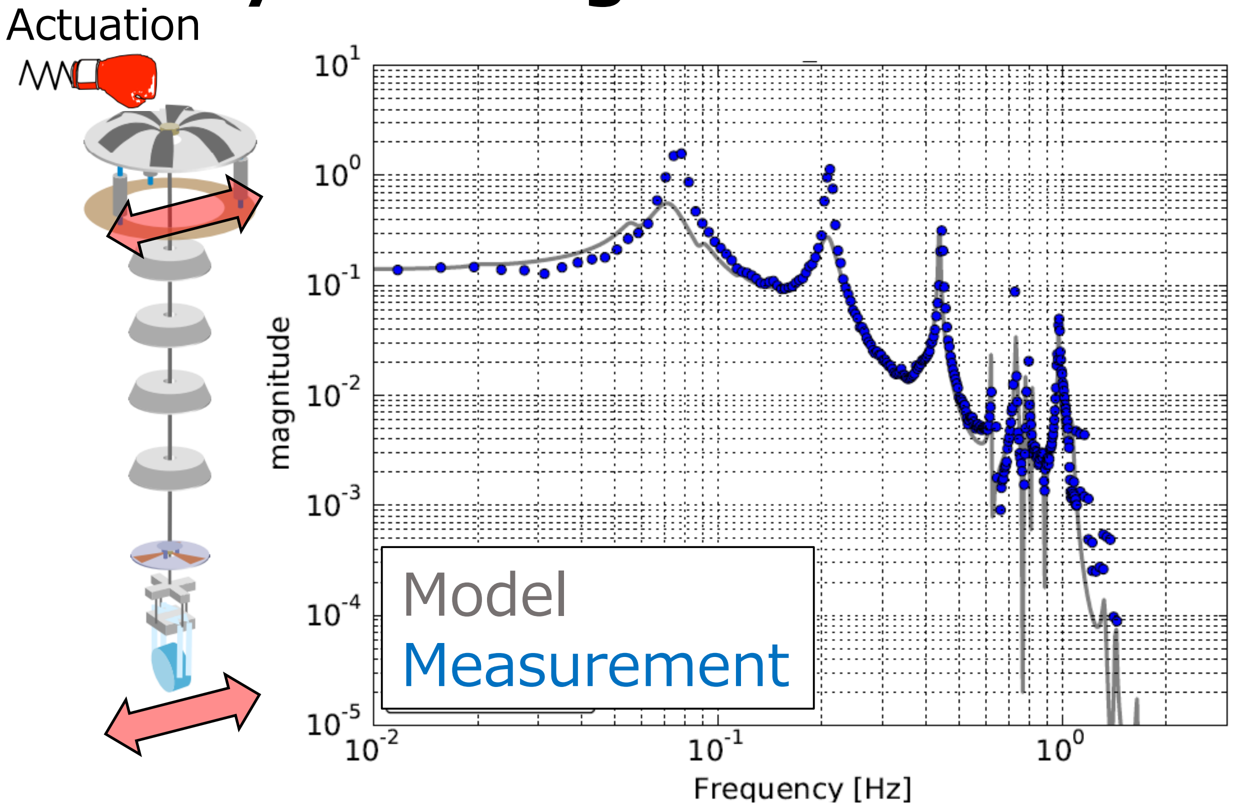


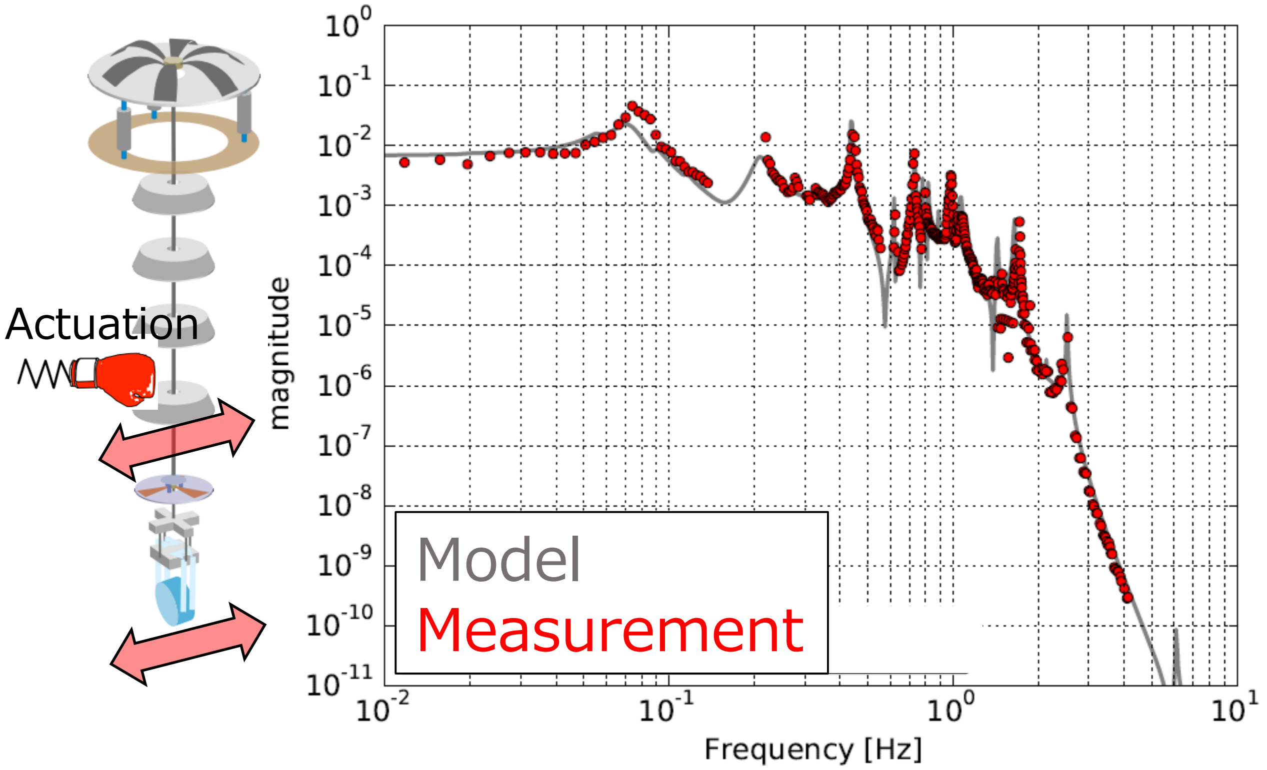


1. Mechanical system characterization:

*** By checking vibration isolation** (from actuator)

For higher frequency



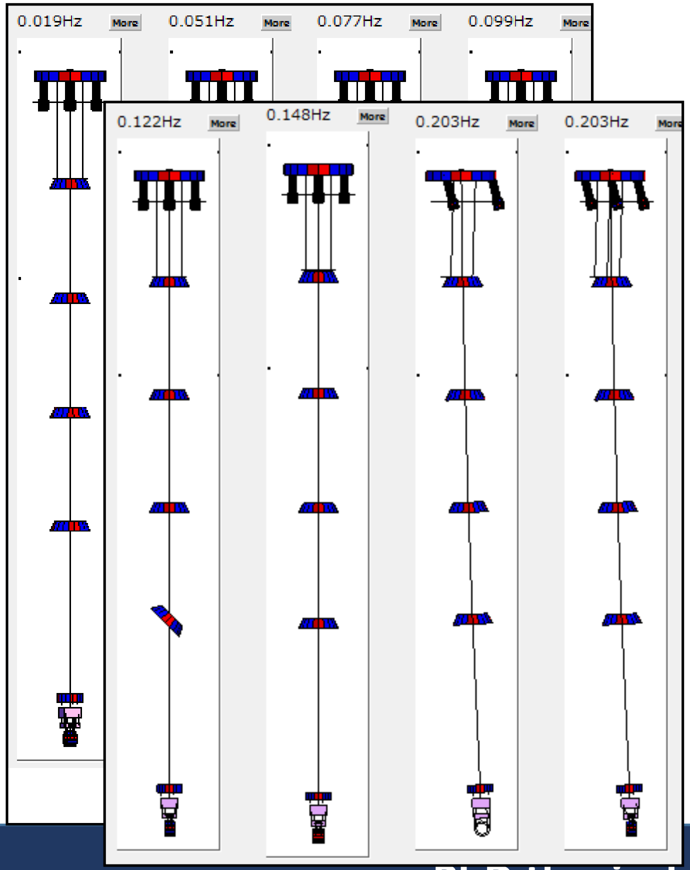


→ Type-A suspension has characteristics of pendulum up to 4.2 Hz.

→ discrepancy at 1.1 Hz to 1.5 Hz is worth to investigate for the further step.

2. Resonance damping:

- **Target:** Confirm the control system damps all the resonances which disturbs the lock acquisition, within 1/e decay time of 1 min.



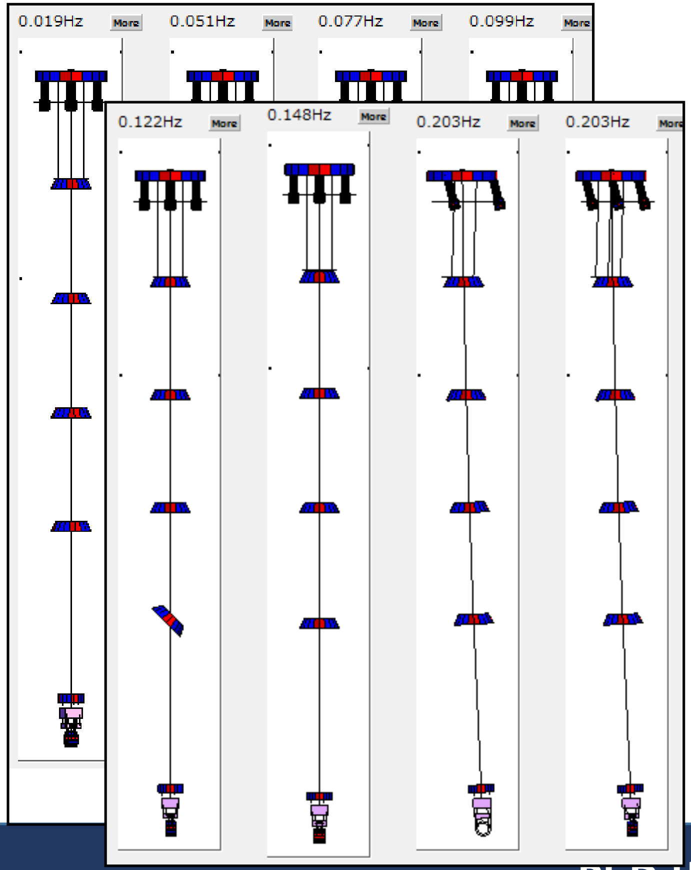
Number of resonances:

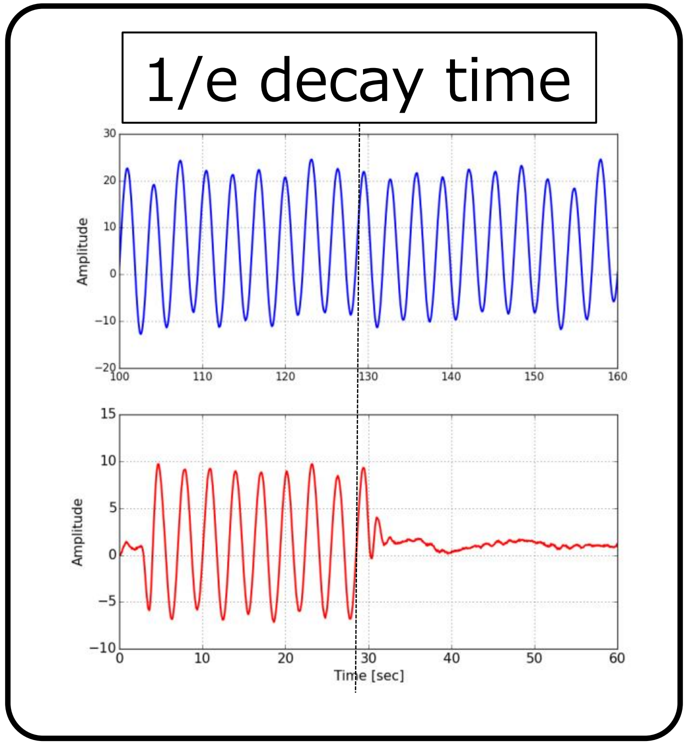
Assuming rigid-bodies
→ 75 modes

From sensor & actuator availability
Measured:
→ For 53 modes

2. Resonance damping:

- **Target:** Confirm the control system damps all the resonances which disturbs the lock acquisition, within 1min.
- **Measurement:** 1/e decay time constant of each resonant mode



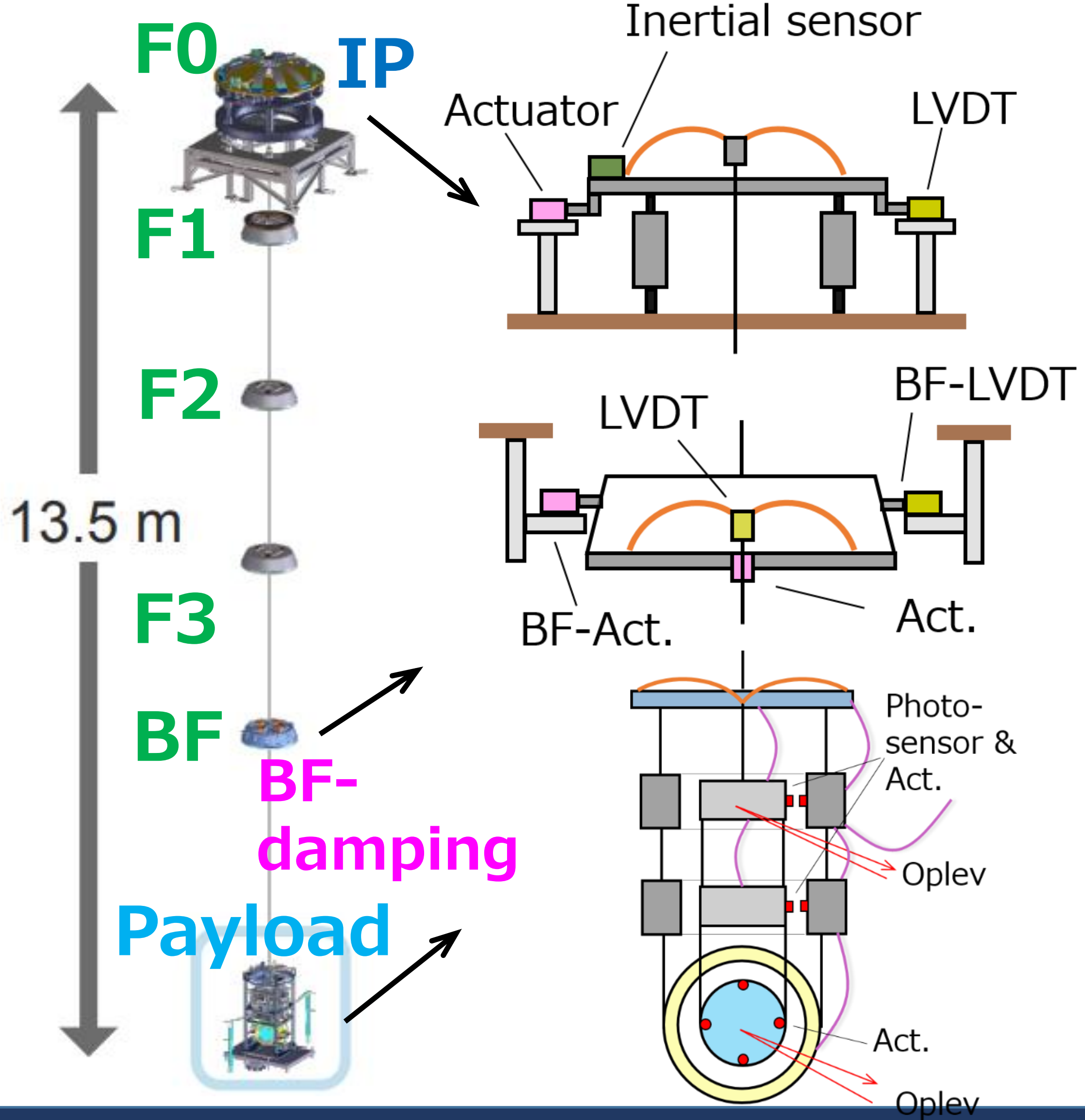


* Excite the mode one by one,

by sending a sinusoidal signal to implemented actuators.

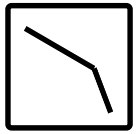
2. Resonance damping:

Control system for damping with disp. sensors



Room-temperature part:

DC+Damp

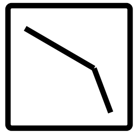


DC

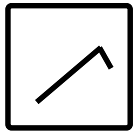
IP / GAS / BF-Yaw

* Pendulum mode damping
* drift compensation

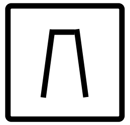
Cryogenic part:



DC



Damp

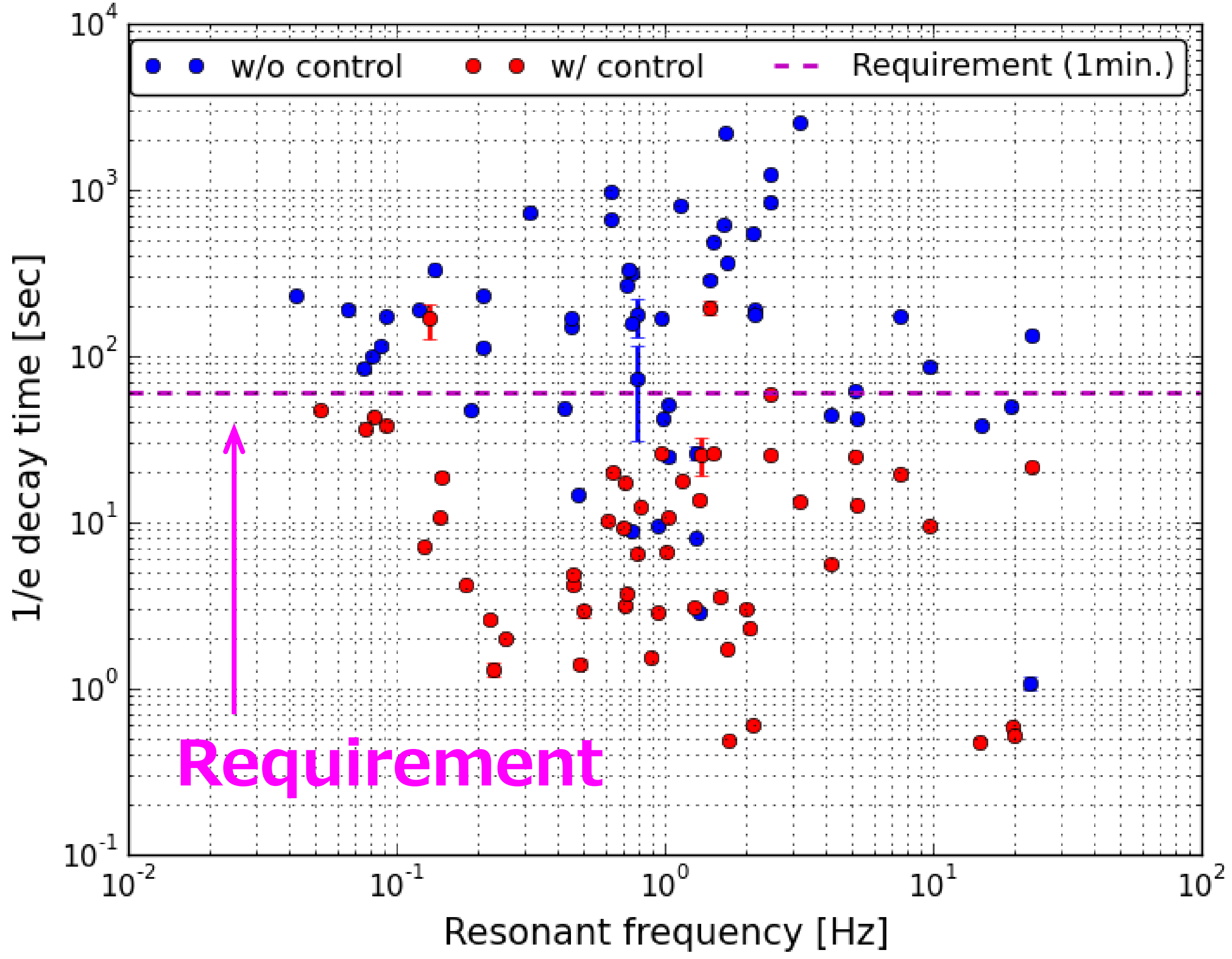


Band-pass damping

Payload

* Internal mode damping
* Mirror alignment
* drift compensation

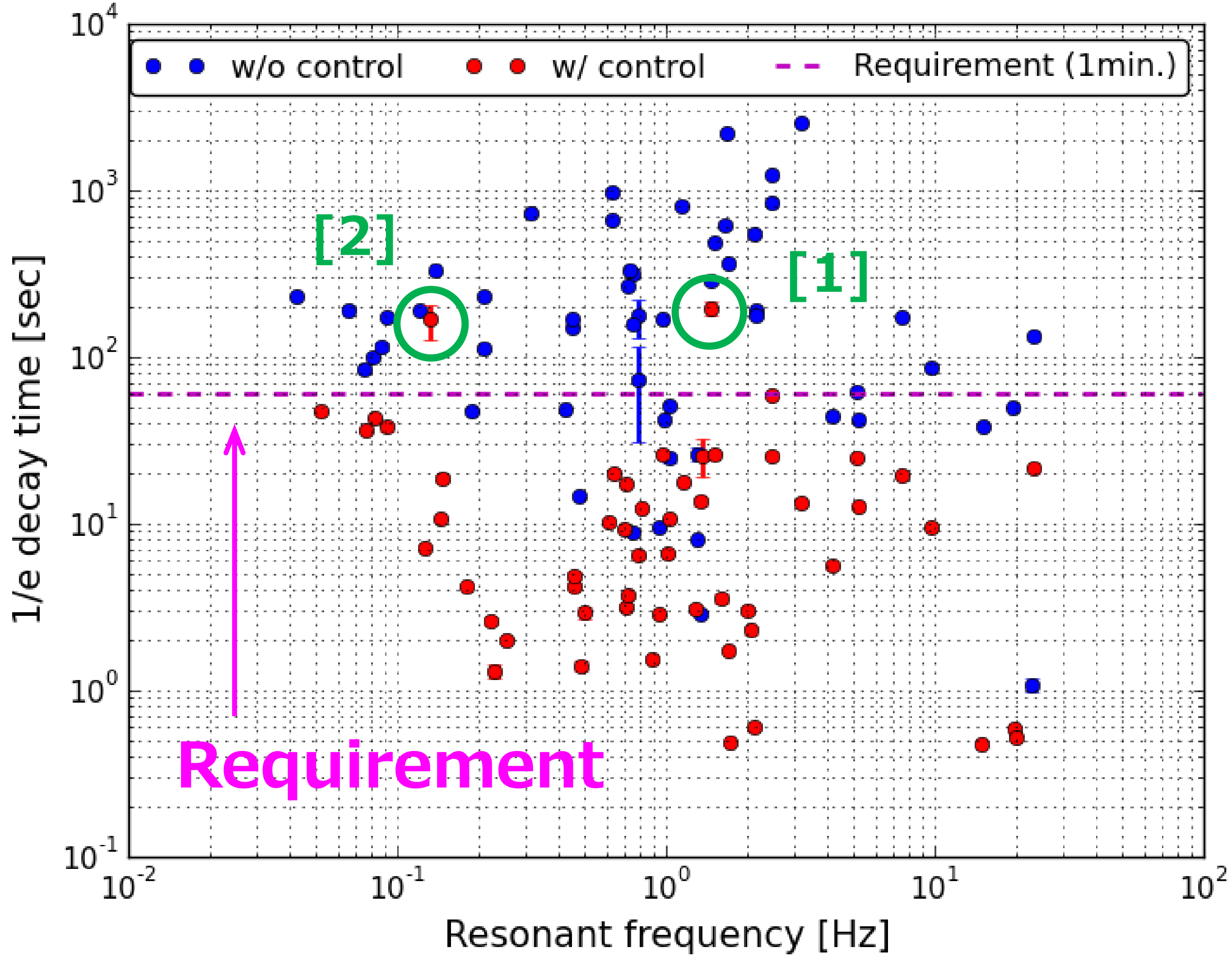
2. Resonance damping:



w/o control

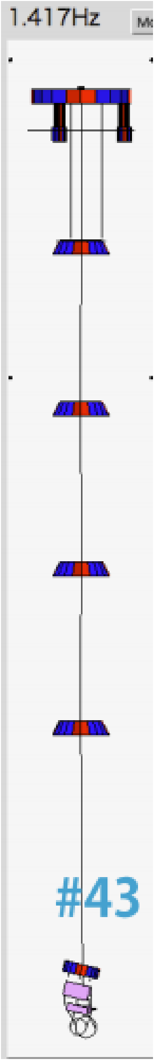
w/ control

2. Resonance damping:



[1] #43: **1.5Hz**
Roll / Trans. motion
→ Not disturbs the lock acquisition.

[2] 0.14Hz
unknown Yaw motion
→ The model w/o heat-link system failed to predict.



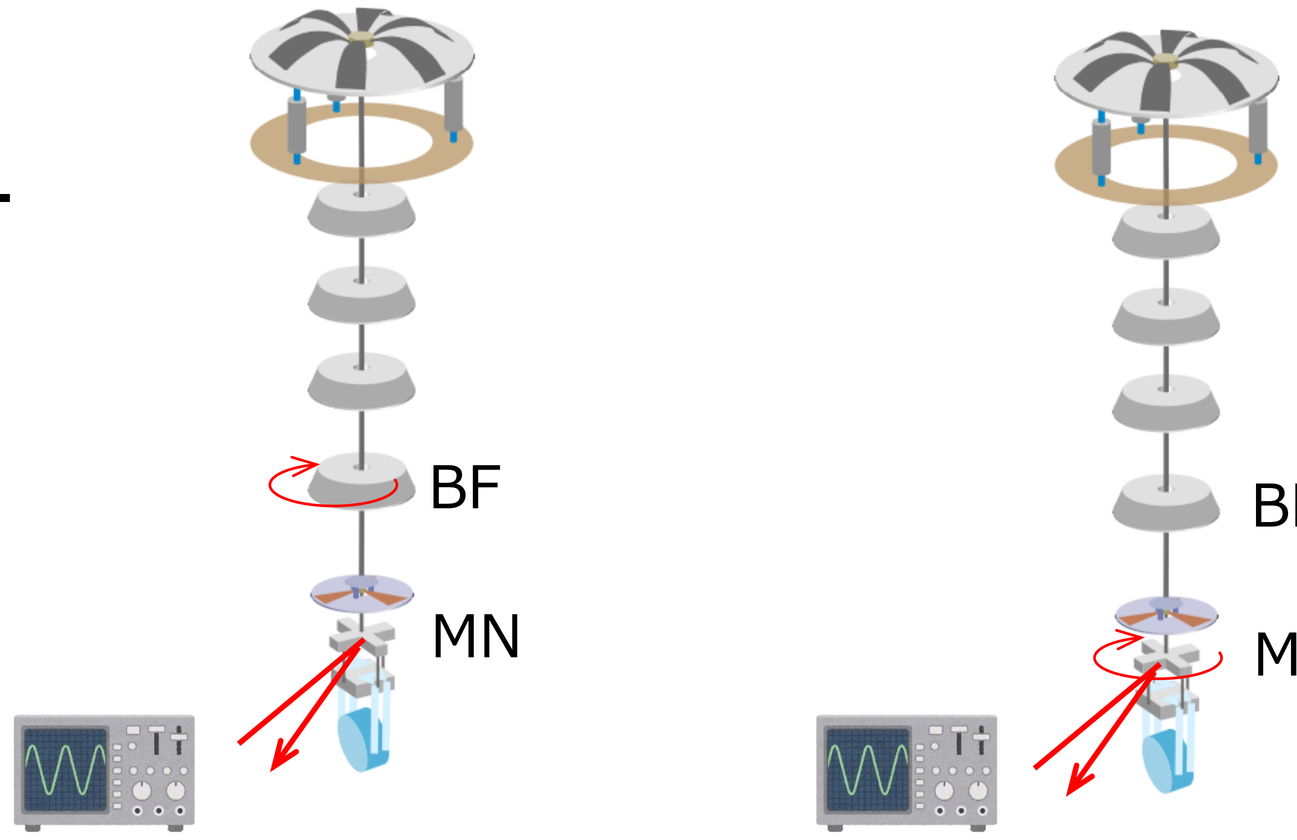
2. Resonance damping:

[2] 0.14Hz

→ will be excited when BF-stage actuated.

Also, for lock acquisition: only payload is controlled.

→ Hardly excited at lock loss.



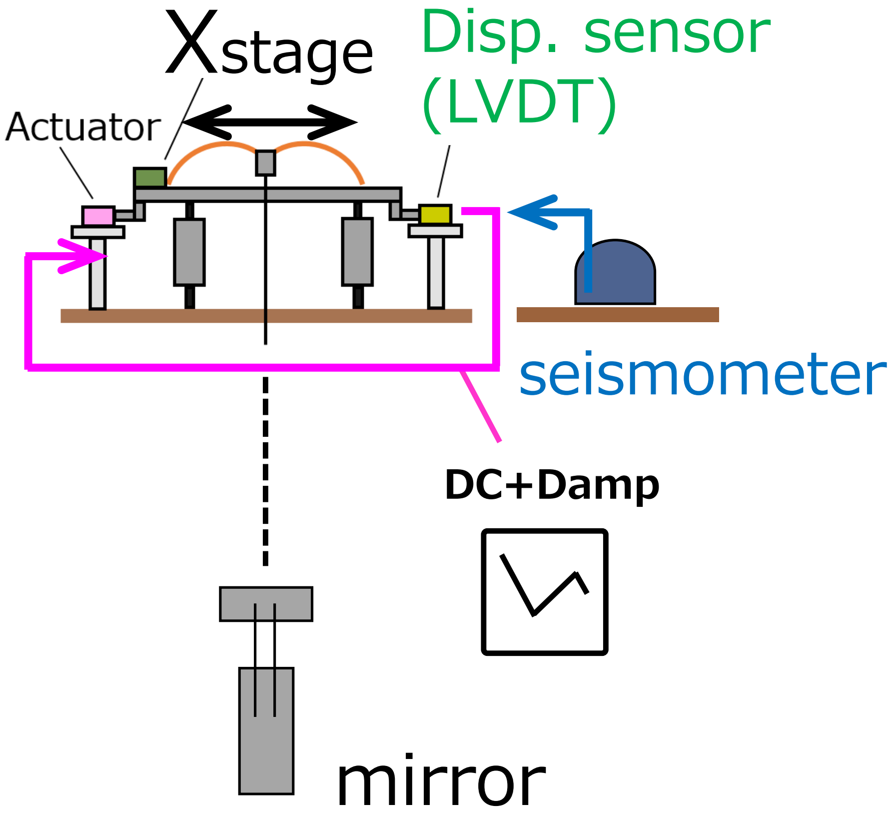
→ Observed in TM

→ Not observed in TM

→ The control system damped all the resonances which disturbs the lock acquisition **for the lock-recovery mode**.

3. Mirror residual suppression:

- **Target:** Suppress the mirror residual velocity & displacement
- **Measurement:** Frequency response from ground to mirror

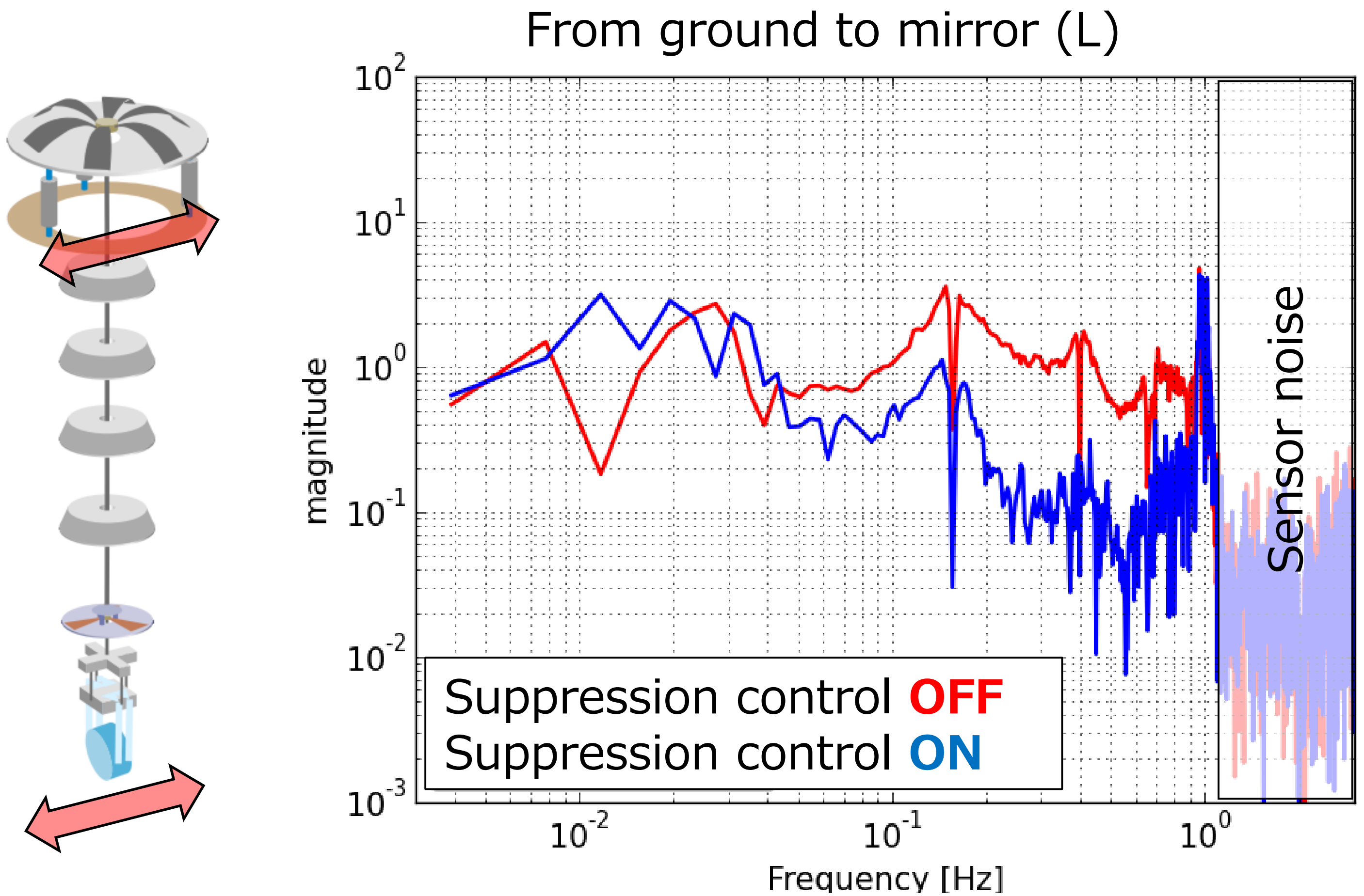


$$X^{virtual}_{sensor} = \left[\, \underbrace{X_{stage} - X_{ground}}_{\text{Displacement sensor signal}} + \underbrace{X^{seis}_{ground}}_{\text{Seismomter signal}} \,\right]$$

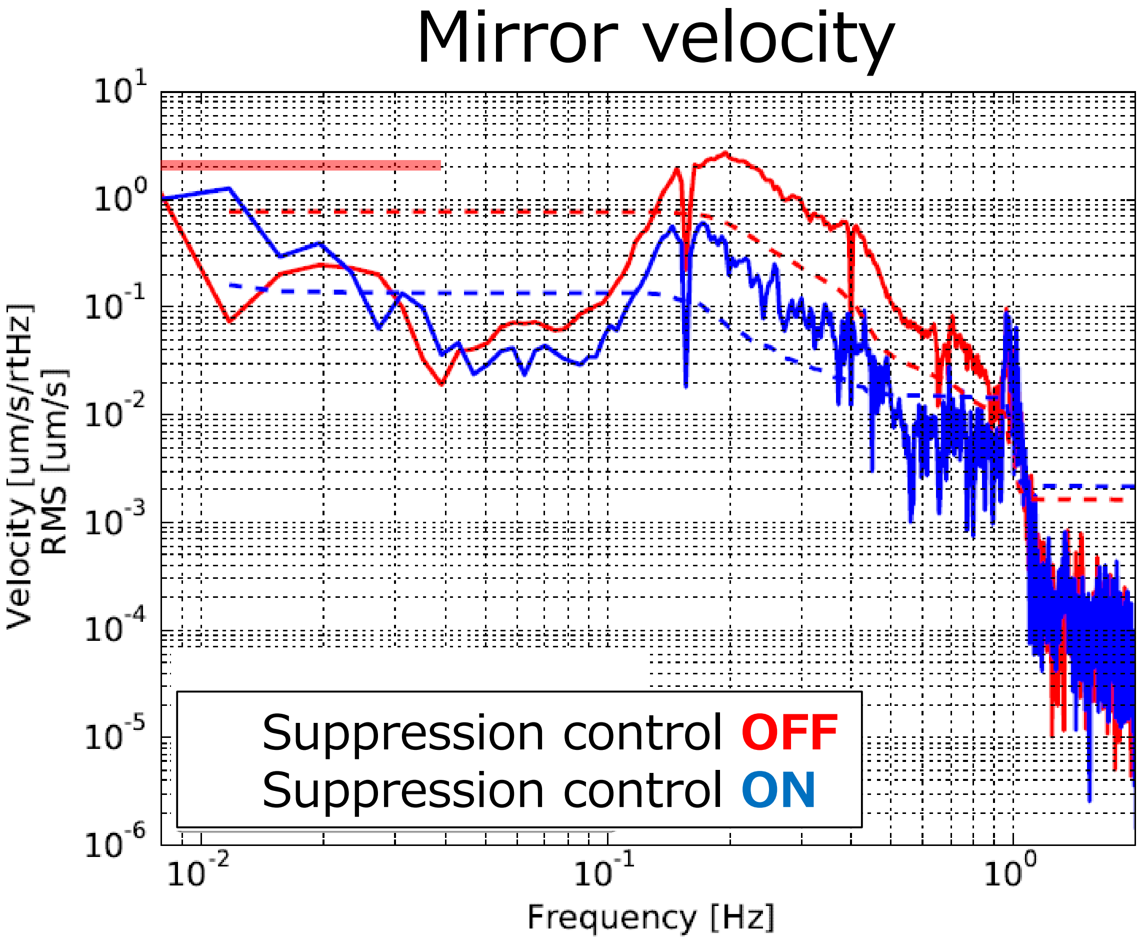
→ Cut the seismic noise injection via disp. sensor. (→ sensor correction)

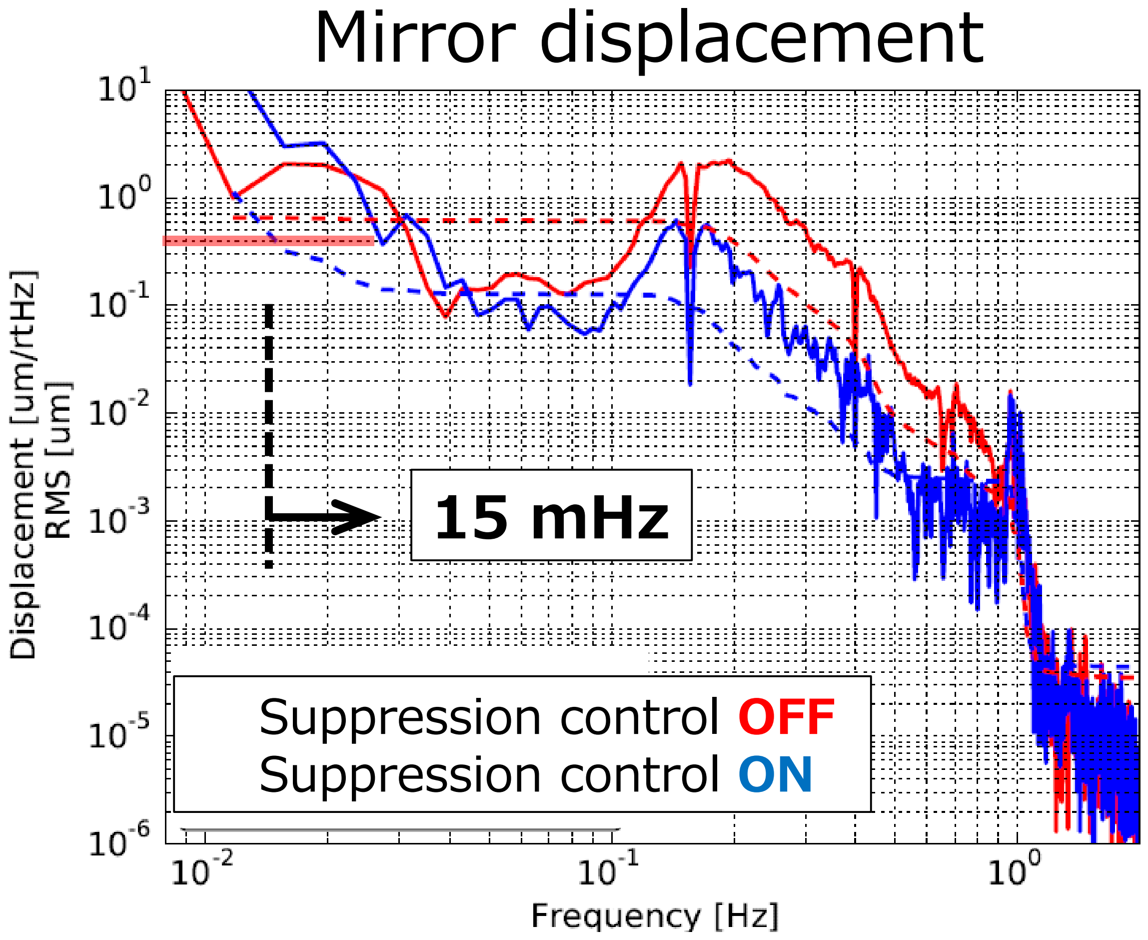
3. Mirror residual suppression:

* Frequency response from ground to mirror



3. Mirror residual suppression (w/ 90%tile seismic motion)





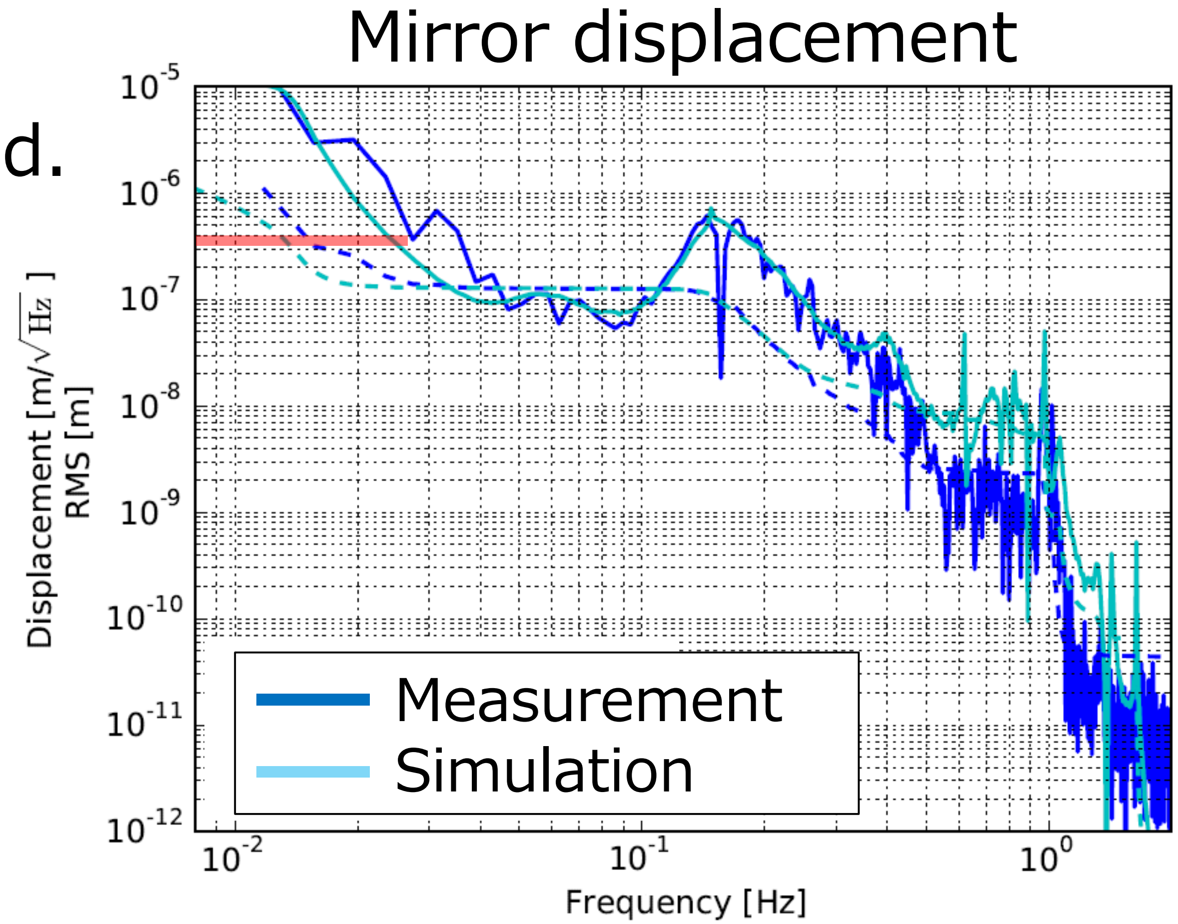
→ The control system locally suppresses the residual and satisfies the requirement in the time scale of 1 min.

3. Mirror residual suppression (w/ 90%tile seismic motion)

* Measurement agrees with simulation. → works as designed.

* Performance at < 15 mHz:
→ due to noise coupling from seismometers.
→ For further stabilization,
1. local seismometer corr. system (with tilt-meter), or
2. global control with interferometer signal

is necessary.



→ Local control system toward lock acquisition has constructed.

Summary of performance test of local control system:

1. Mechanical system characterization
   → Type-A suspension has characteristics of pendulum up to 4.2Hz.
     → the unexpected frequency response (→ further investigation).

2. Resonance damping
   → The installed damping control system damped all the resonances which disturbs the lock acquisition for the lock-recovery mode.

3. Mirror residual suppression
   → The control system locally suppresses the residuals enough and satisfies the requirement in the time scale of 1 min.

→ KAGRA Type-A full suspension is firstly controlled.

Summary of this work:

1. Fast localization simulation with current network

→ demonstrated that:
Search with hierarchical approach will be most useful when adding new, less sensitive detectors to the network, as they are undergoing commissioning.

2. TypeA suspension controls toward lock acquisition

→ Constructed local control system for KAGRA Type-A suspension.
→ Confirmed that the implemented system satisfies requirements for acquiring interferometer lock.

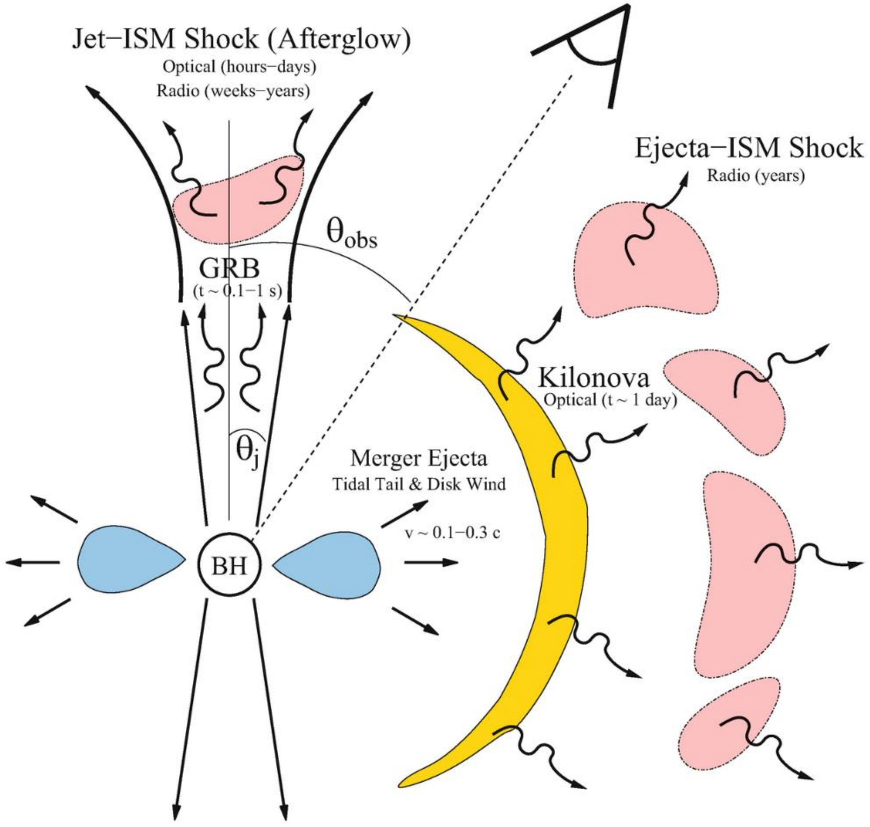
→ This contributes to KAGRA joining to the network as the 4th detector.

Backups

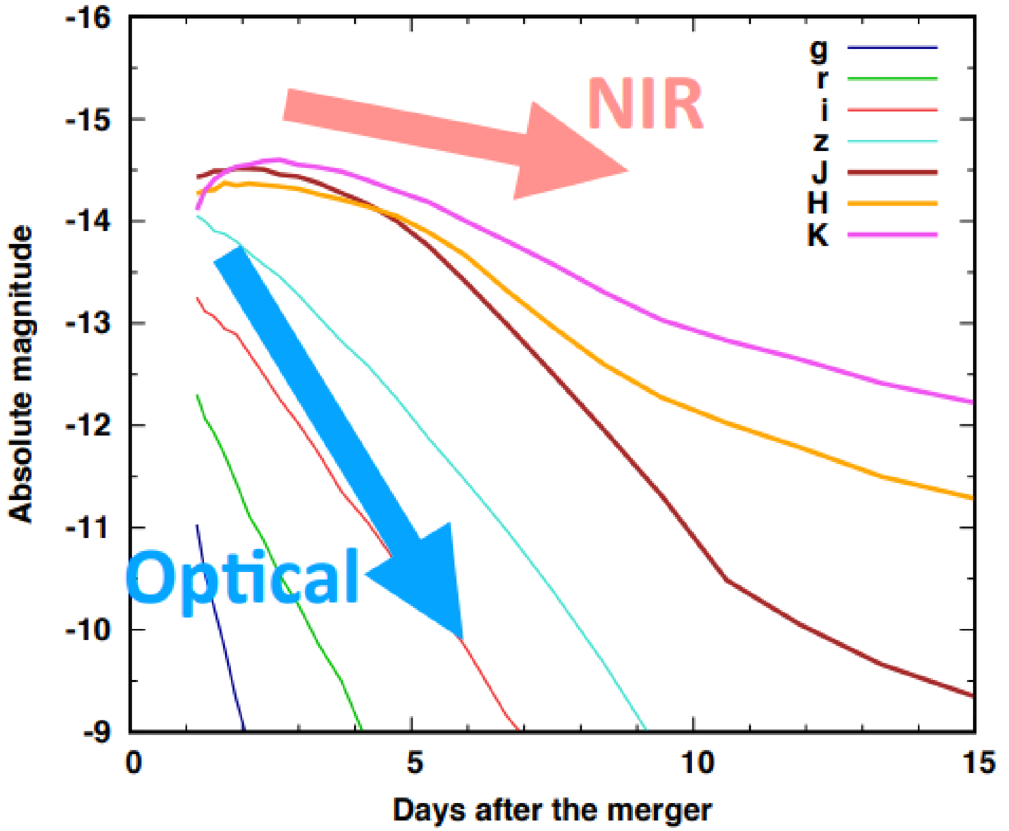
Note: fast localization

Kilonova: Electromagnetic emission powered by radioactive decays of r-process nuclei, given by ejected material from neutron star mergers.

[ref] https://iopscience.iop.org/article/10.3847/1538-4357/aaa0cb/pdf



Metzger & Berger 2012

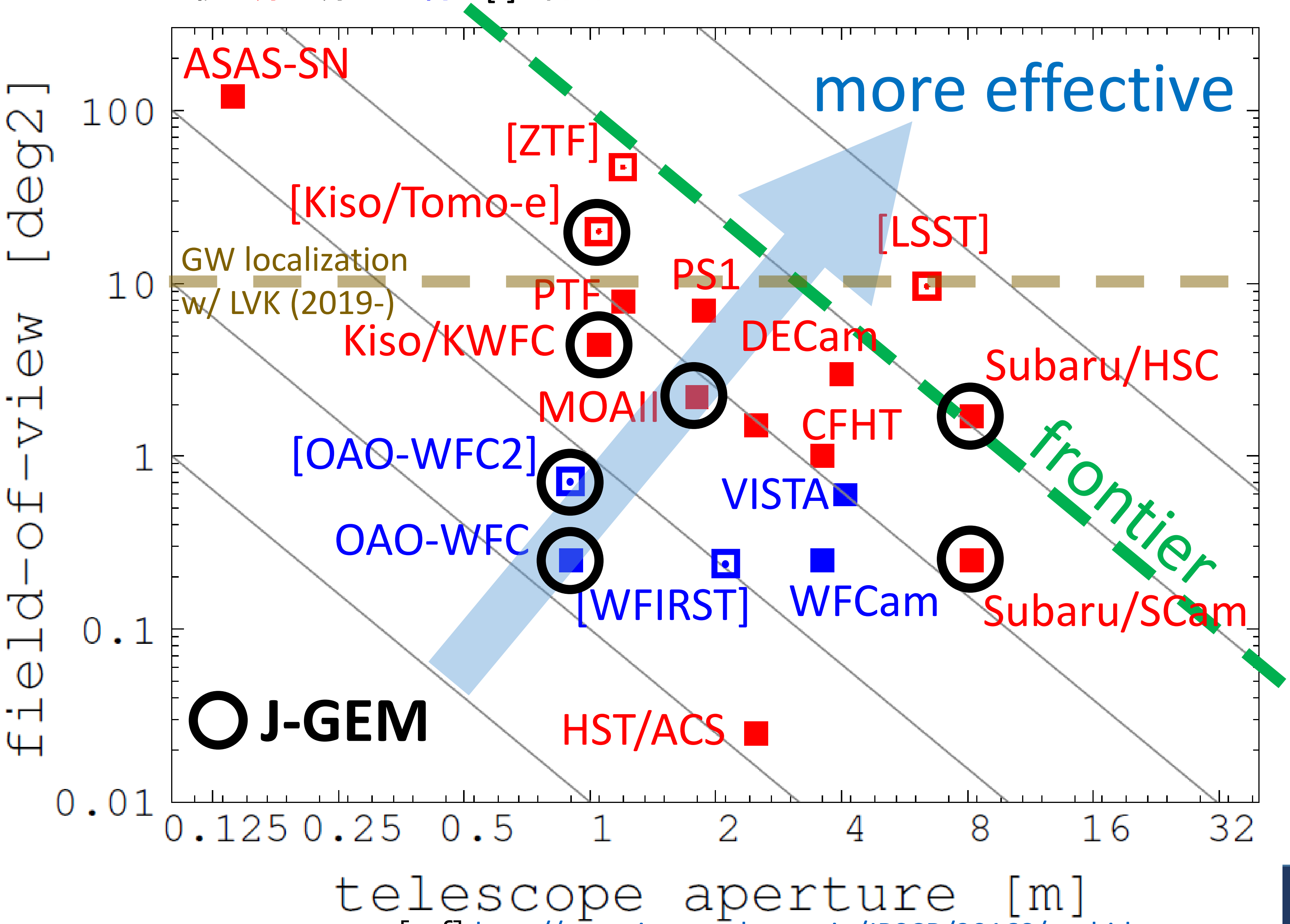


http://www.icehap.chiba-u.jp/activity/180326MultiMessenger/3-26/tanaka_20180326.pdf

FOV vs. Area by GWs

世界の可視近赤外広視野望遠鏡・装置

可視：赤　赤外：青　[ ]：将来計画



[ref] http://www.icrr.u-tokyo.ac.jp/JPSCR/2016S/yoshida.pptx

Detector response:

The signal (I)

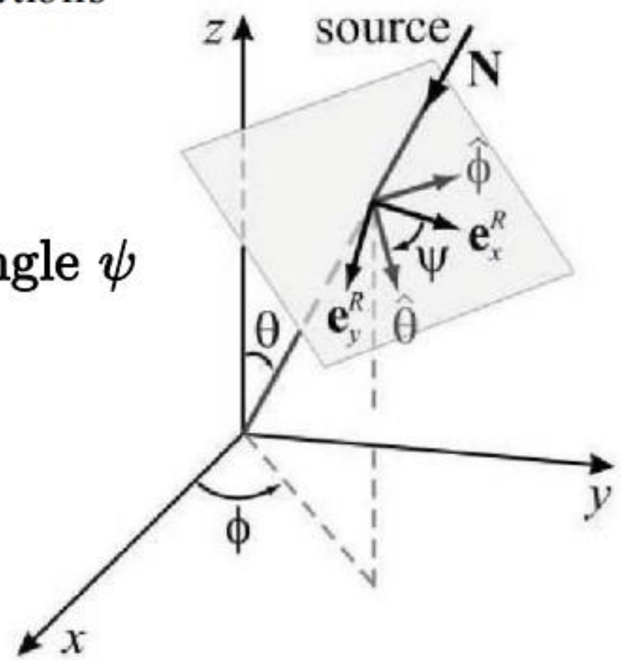
Signal sensed by detector is a combination of two polarizations

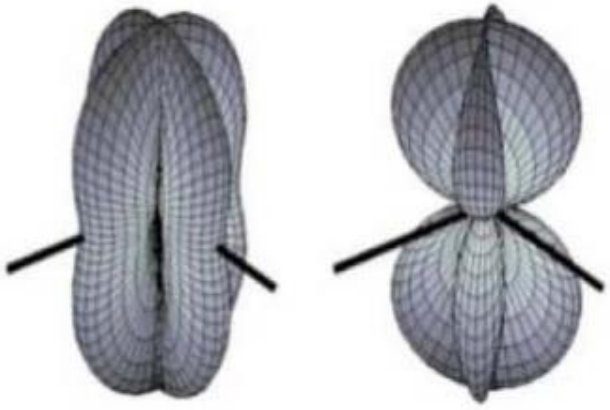
$$h(t) = F_+(\theta,\phi,\psi)\ h_+(t) + F_\times(\theta,\phi,\psi)\ h_\times(t)$$

F_+ and $F_\times$: detector response functions
depend on sky location (θ,ϕ) and polarization angle ψ

$$F_+ = -\tfrac{1}{2}(1+\cos^2\theta)\cos 2\phi\cos 2\psi - \cos\theta\sin 2\phi\sin 2\psi$$

$$F_\times = \tfrac{1}{2}(1+\cos^2\theta)\cos 2\phi\sin 2\psi - \cos\theta\sin 2\phi\cos 2\psi$$



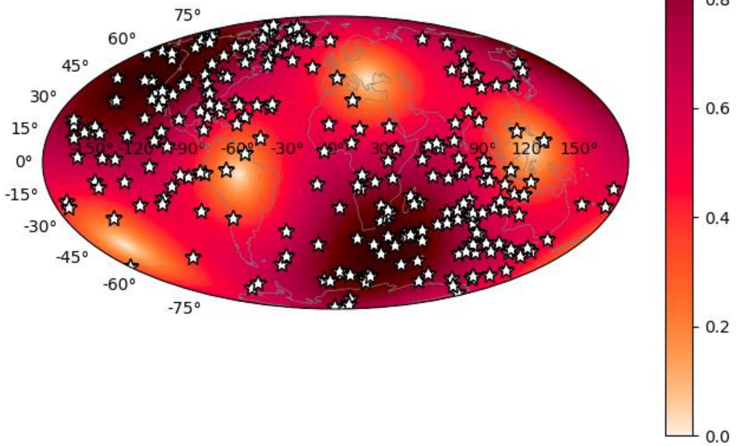


F_+ and $F_\times$ can be approximated as constant over length of CBC signals in ground based detectors

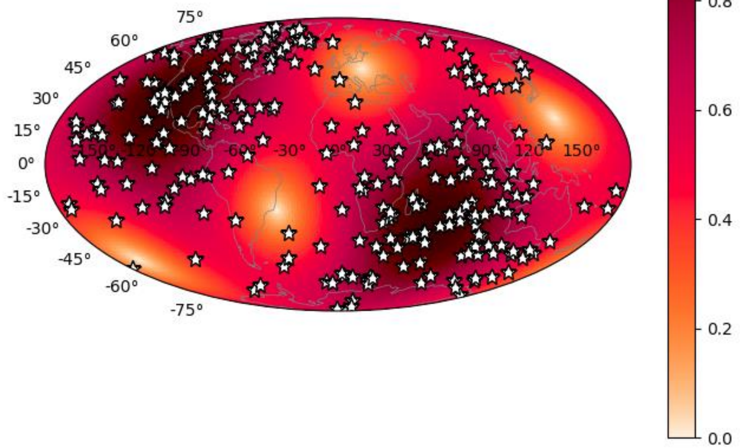
Ref: http://old.apctp.org/conferences/2011/NRG2011/NRGPDF/CBC_DA_Korean_School_2011.pdf

Antenna pattern & source position

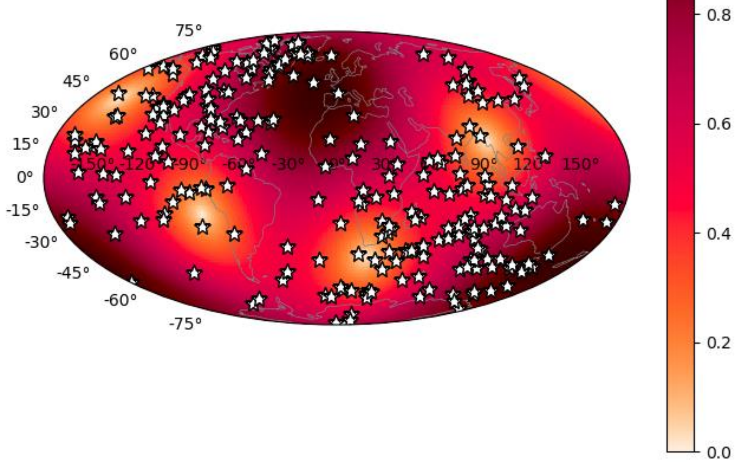
LIGO Hanford



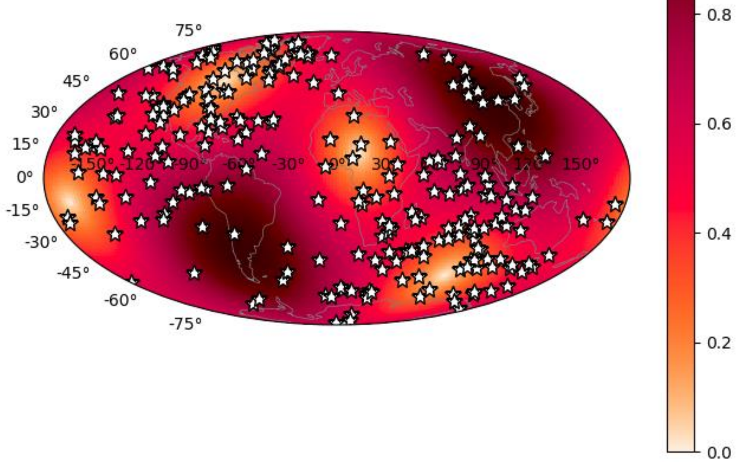
LIGO Livingston



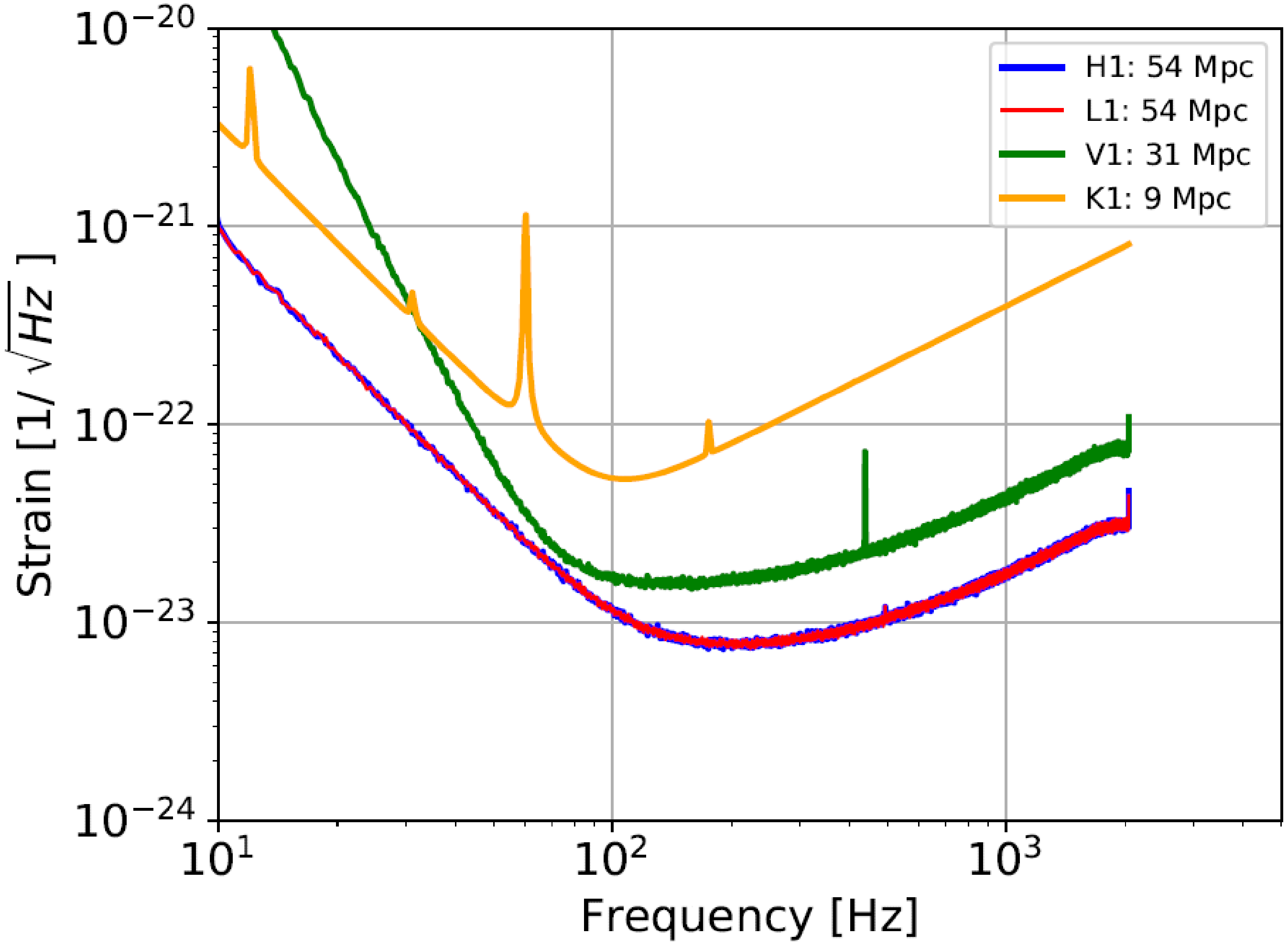
Virgo



KAGRA



Assumed noise curves:



- For V/K, the curves are scaled.

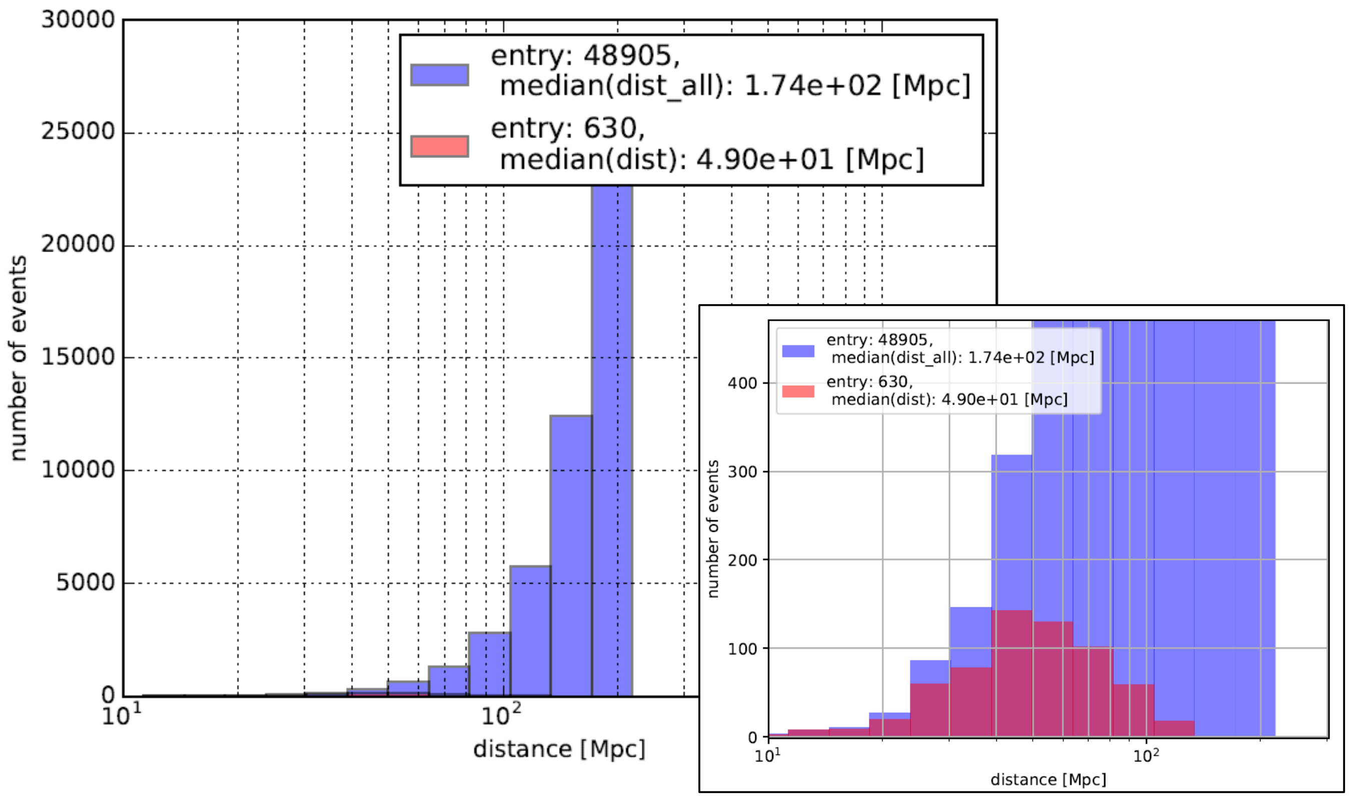
How the inputs obtained?: 2015 scenario in [1] vs. 2016sim

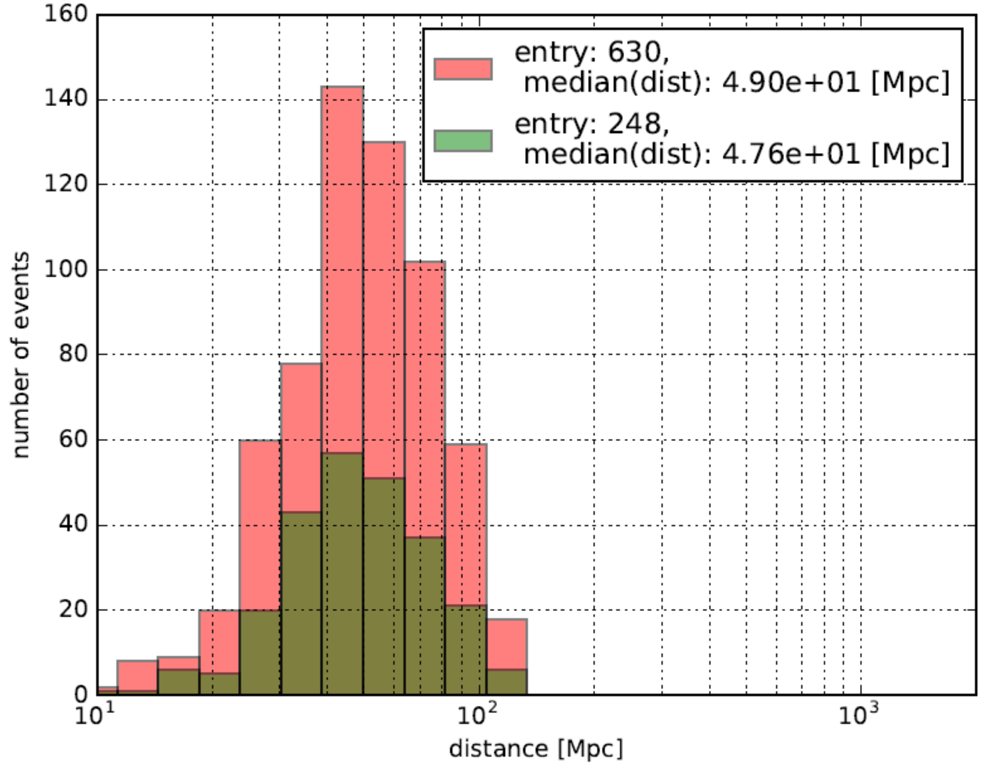
* Configuration (number of events)

Randomly selected in order to save computational cost.

* All injections (48905) ⟶ * Found events (630) ⟶ * Used in simulation (248)

2 events missed



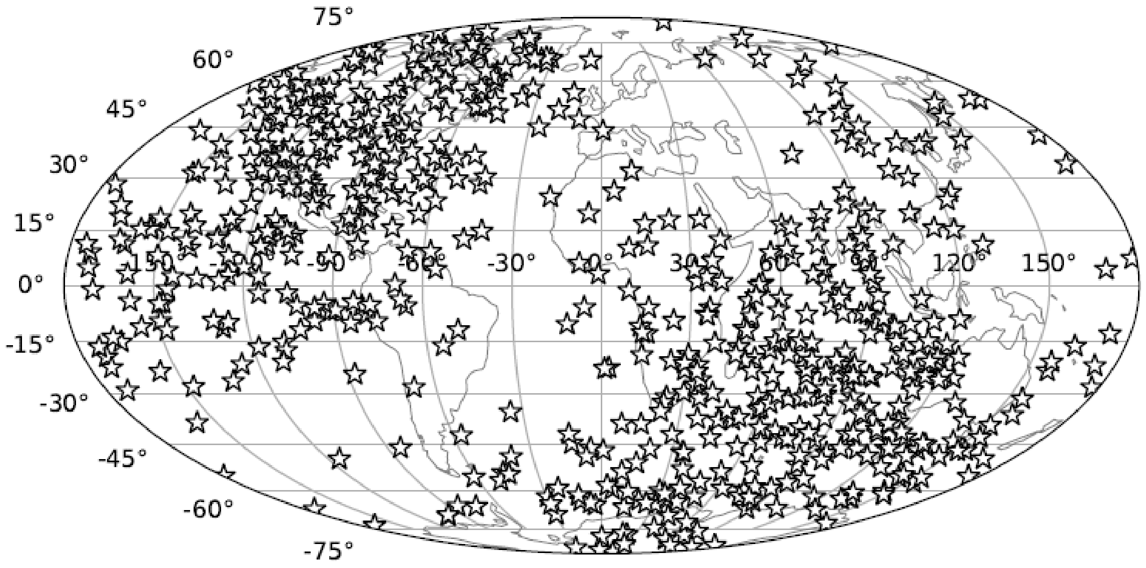


[1] https://www.ligo.org/scientists/first2years/

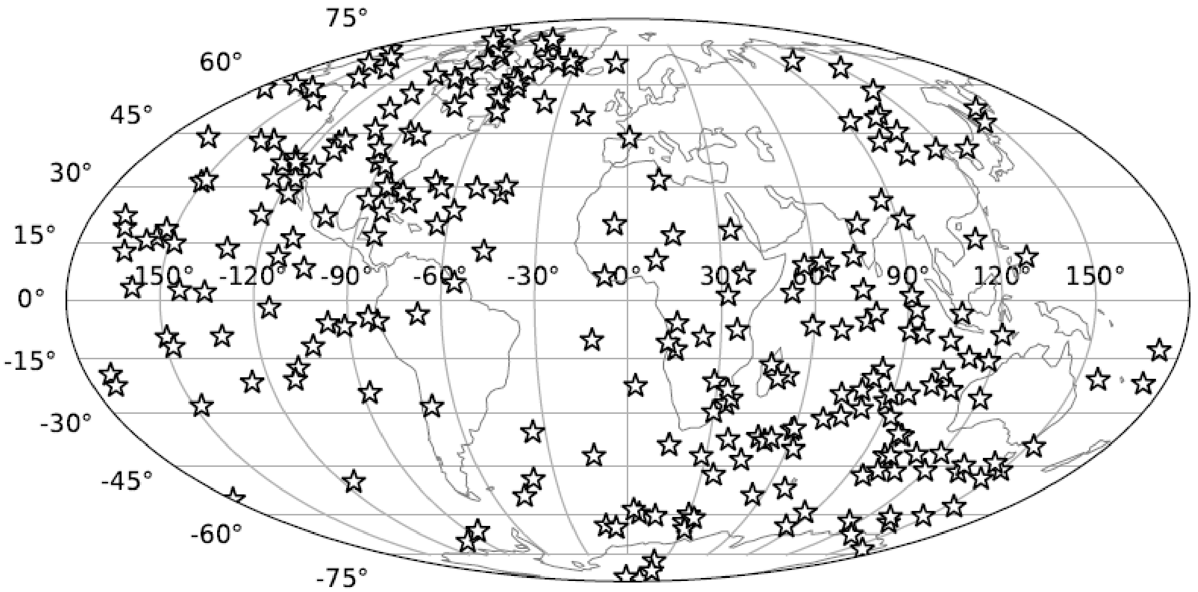
How the inputs obtained?:

In 2015 scenario in [1]

* Found events (630)



* Used events (248)



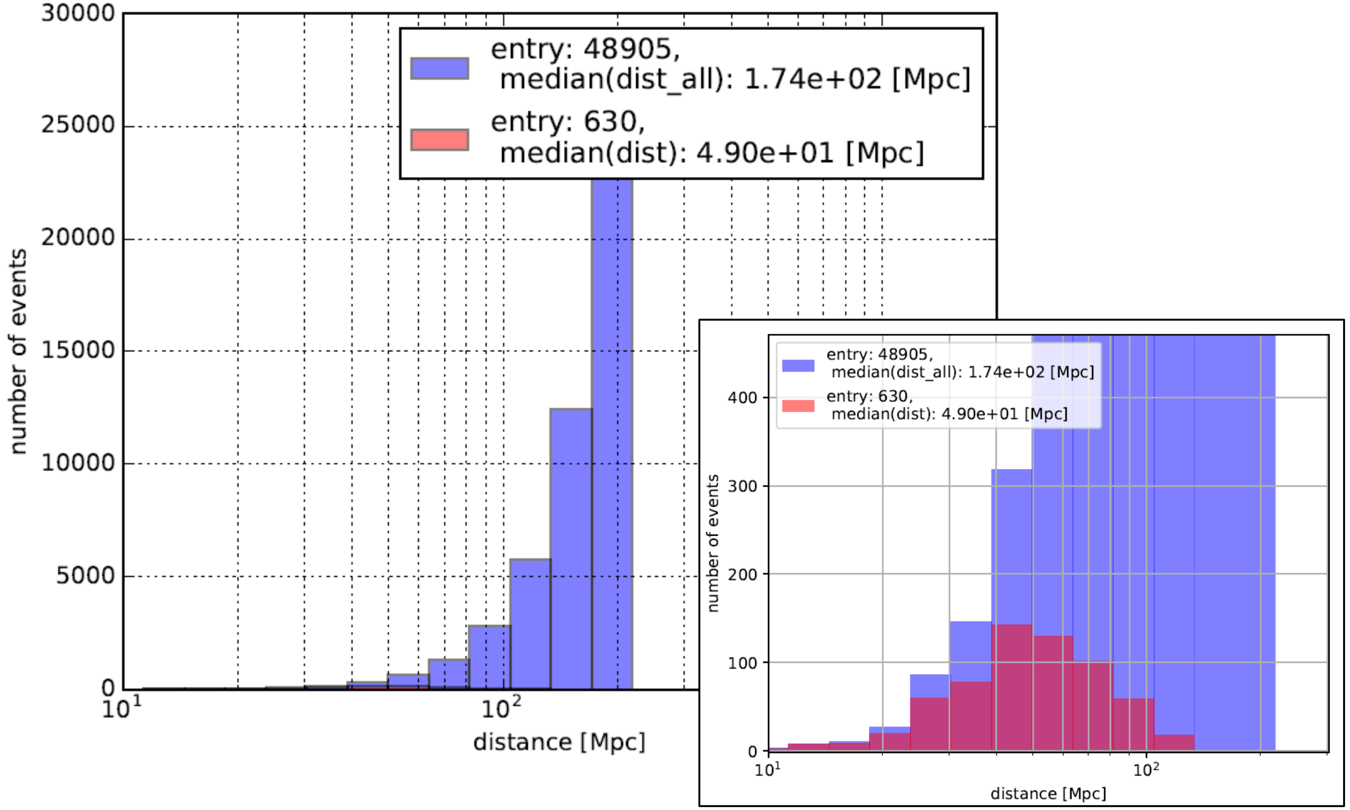
Reference: the inputs:

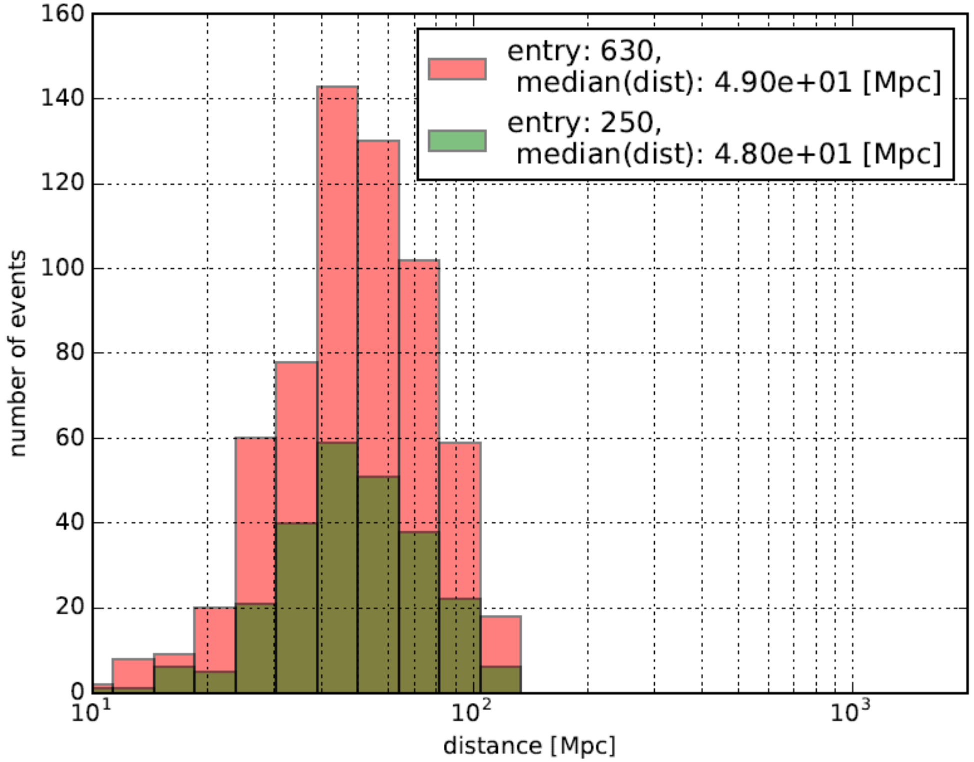
In 2015 scenario in [1]

* Configuration (number of events)

Randomly selected in order to save computational cost.

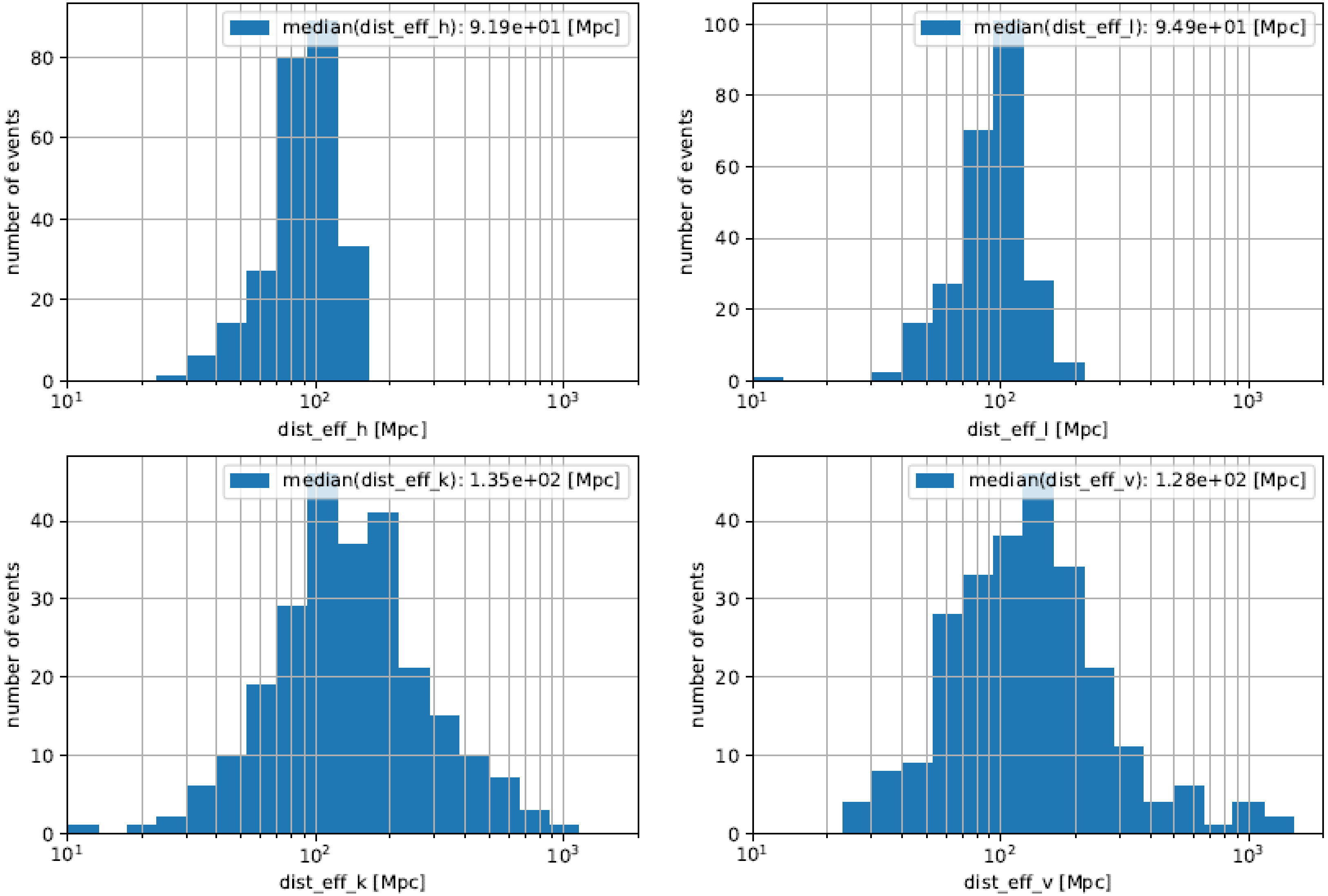
* All injections (48905) → * Found events (630) → * Used in simulation (250)





[1] https://www.ligo.org/scientists/first2years/

Effective distances of the injections:



Expected SNR, ρ:

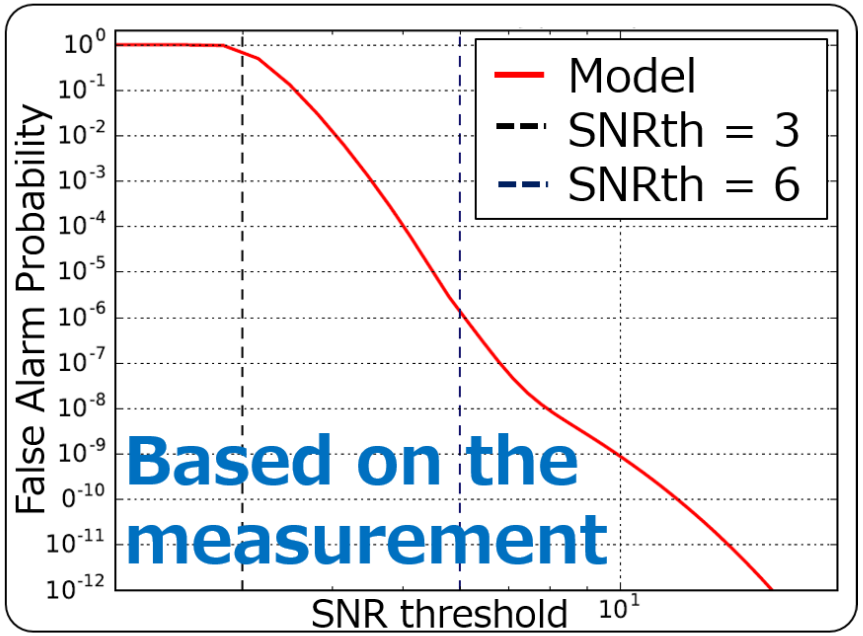
$$\rho = \frac{8 * 2.26 * R\_det}{D\_eff}$$

Generating & mixing artificial V triggers

2. Mixing HLV triggers

p = random [0:1]
$FAP = FAP(SNR)$ or FAP(SNRth)

$p<FAP$ → HLV_r
$p>FAP$ & $SNR>$SNRth → HLV_i
$p>FAP$ & $SNR<$SNRth → HL



Generating & mixing artificial V triggers

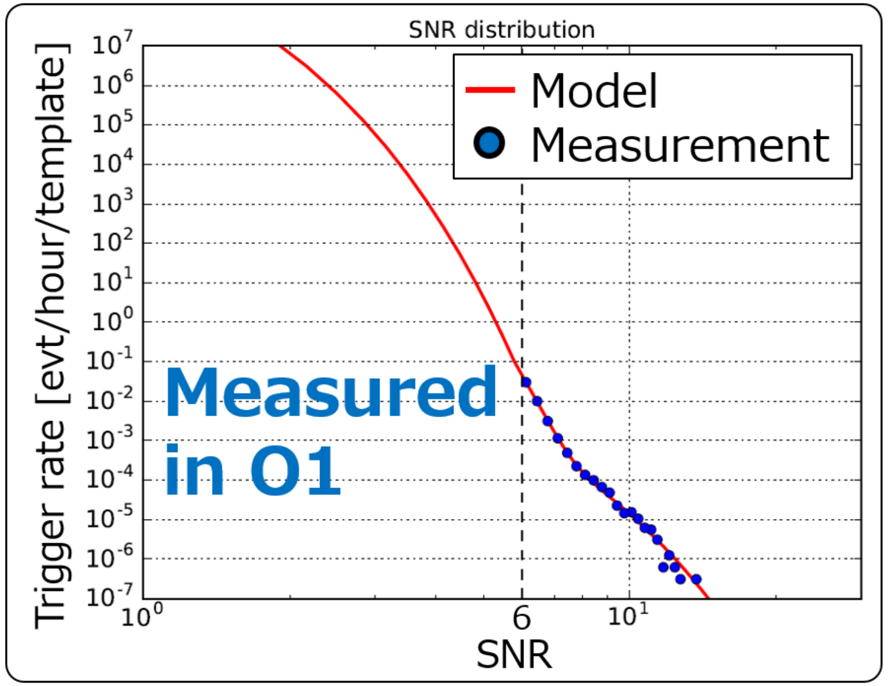
1. Generating V triggers

V_r : V trigger based on random parameters

SNR = random following measurement ←

Time = t_{H1} or t_{L1} + random [-35ms:35ms]

Phase = random $[0:2\pi]$



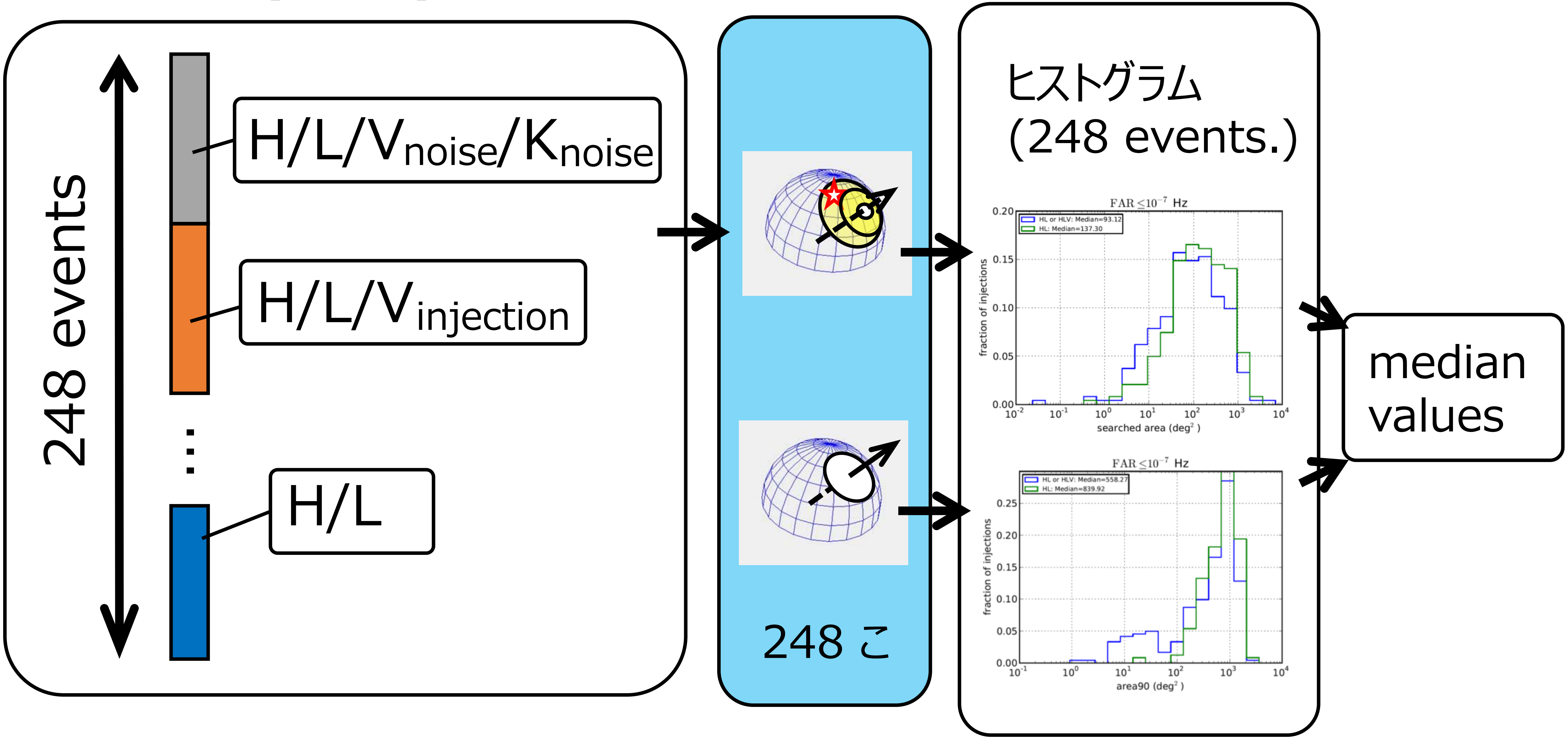
V_i : V trigger based on injection parameters

SNR = metadata + Gauss(0,1)

Time = metadata + Gauss(0,0.66 ms*$\frac{6}{\mathrm{SNR}}$)

Phase = metadata + Gauss(0,0.25 rad)

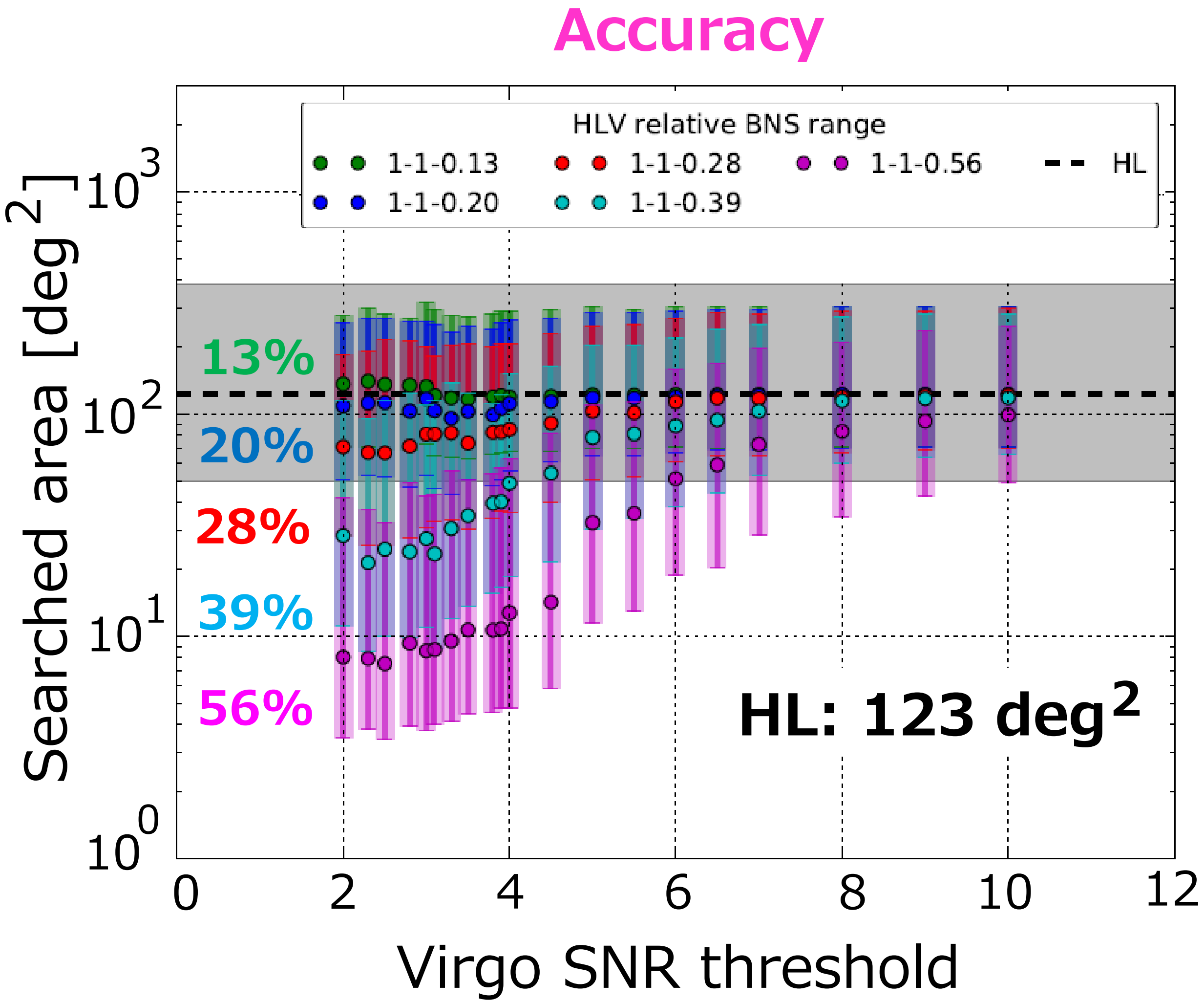
計算の流れ(まとめ)

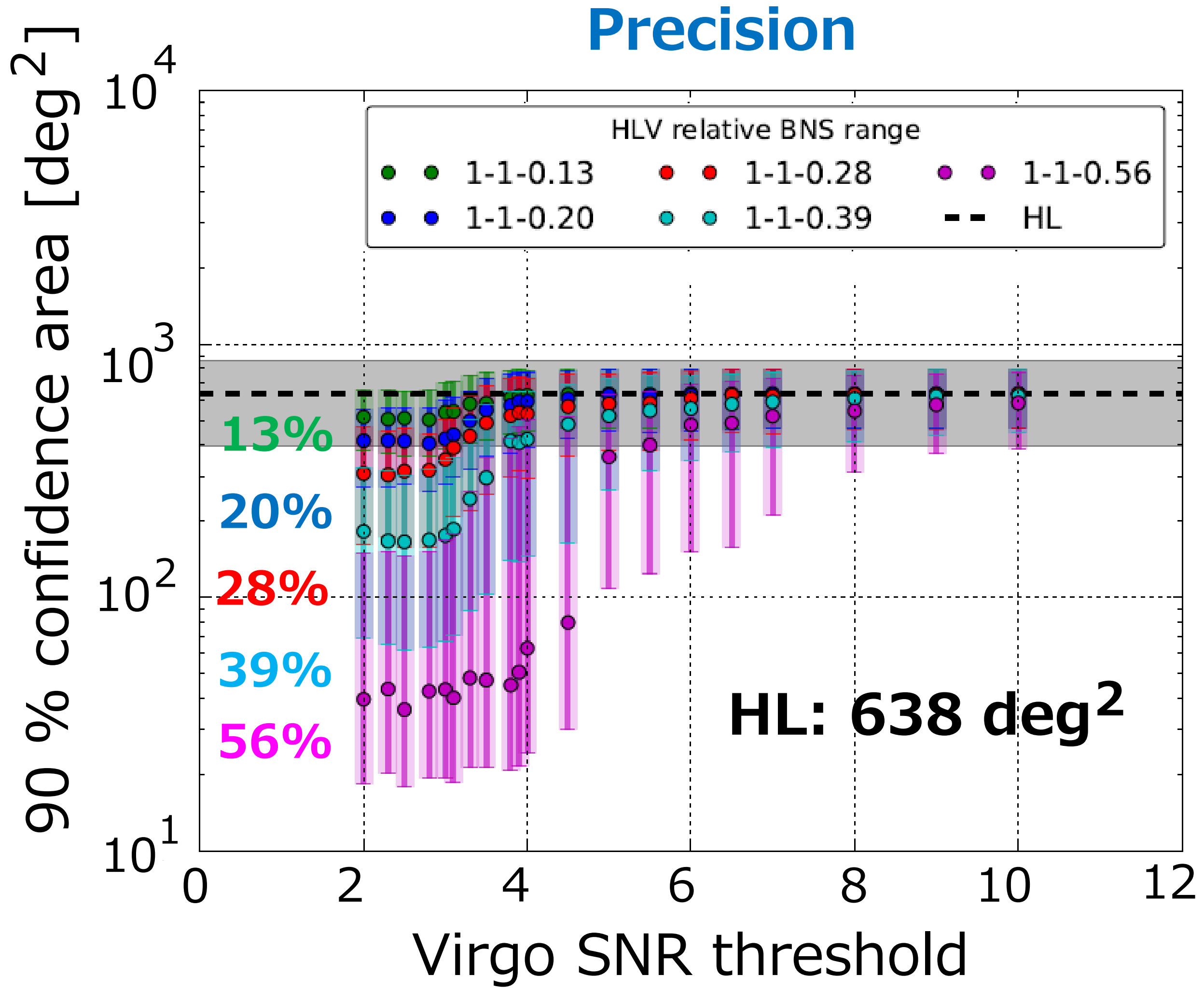


248 events
H/L/Vnoise/Knoise
H/L/Vinjection
H/L
248 こ
ヒストグラム
(248 events.)
FAR ≤10^-7 Hz
HL or HLV: Median=93.12
HL: Median=137.30
fraction of injections
searched area (deg²)
FAR ≤10^-7 Hz
HL or HLV: Median=558.27
HL: Median=839.92
fraction of injections
area90 (deg²)
median values

Performance (HLV):

(SNR threshold for H, L = 5.)

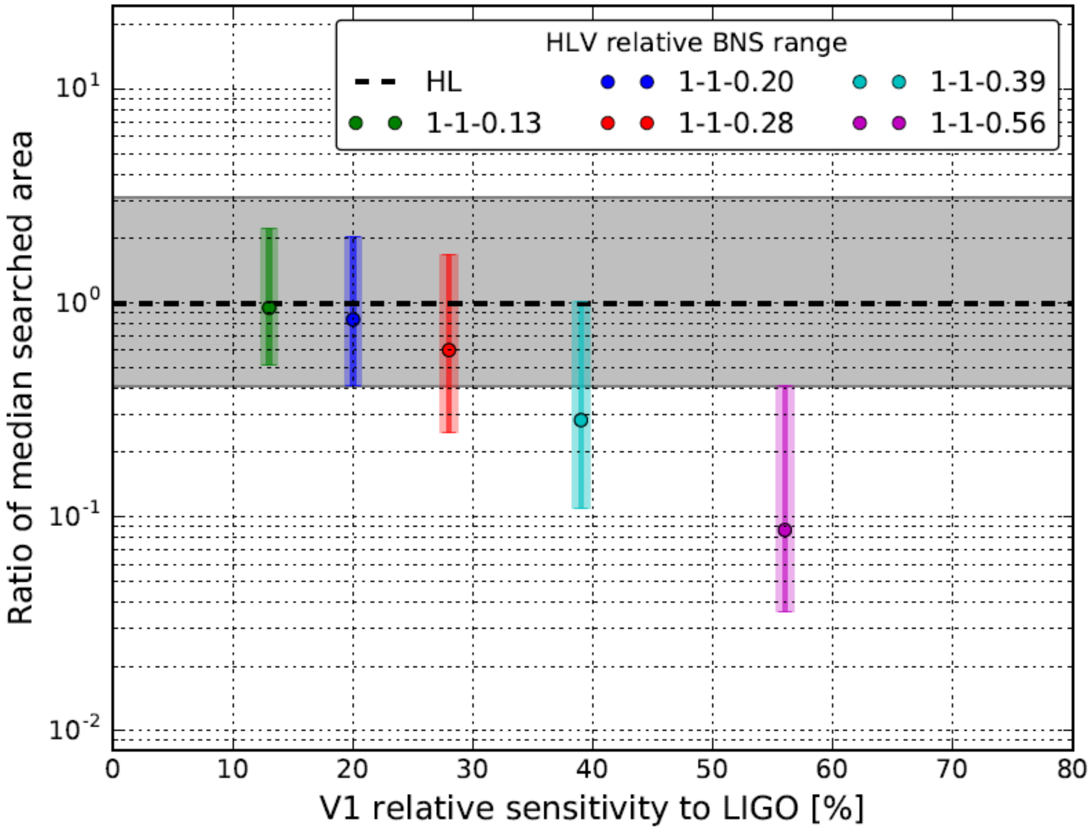


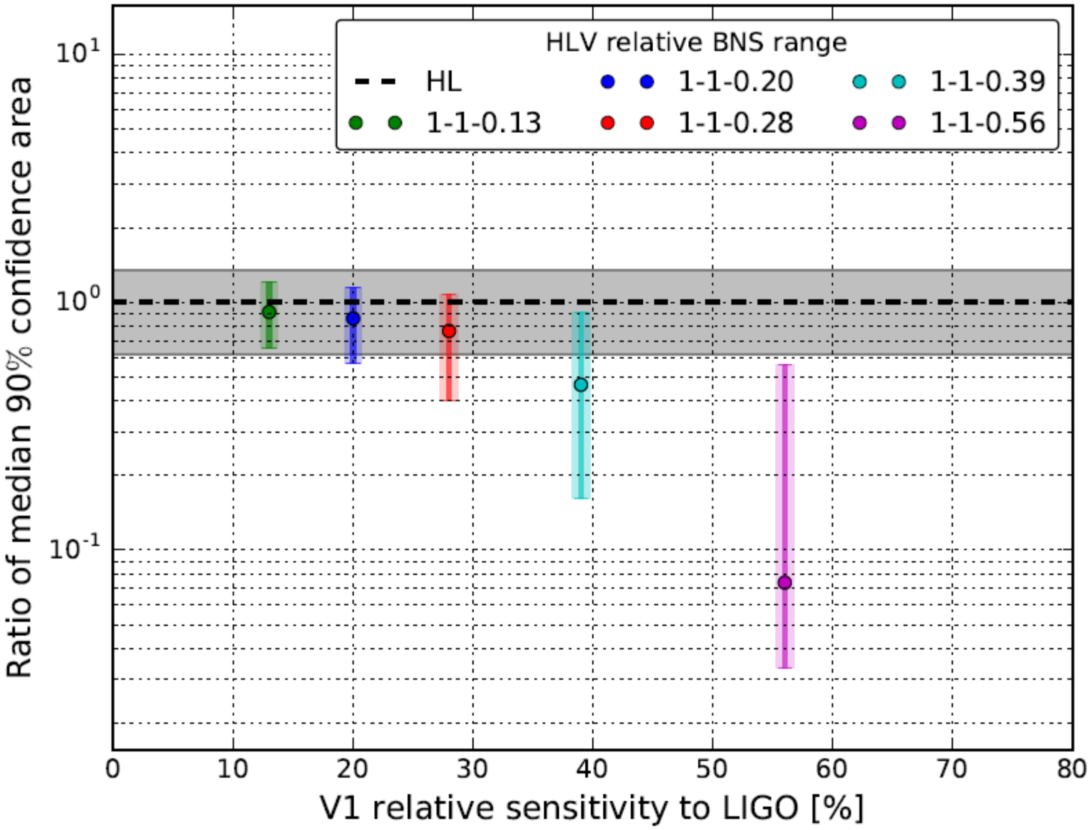


Performance of HL- vs. HLV-hierarchical-network:

RnageH : RangeL = 54 : 54 (Mpc)

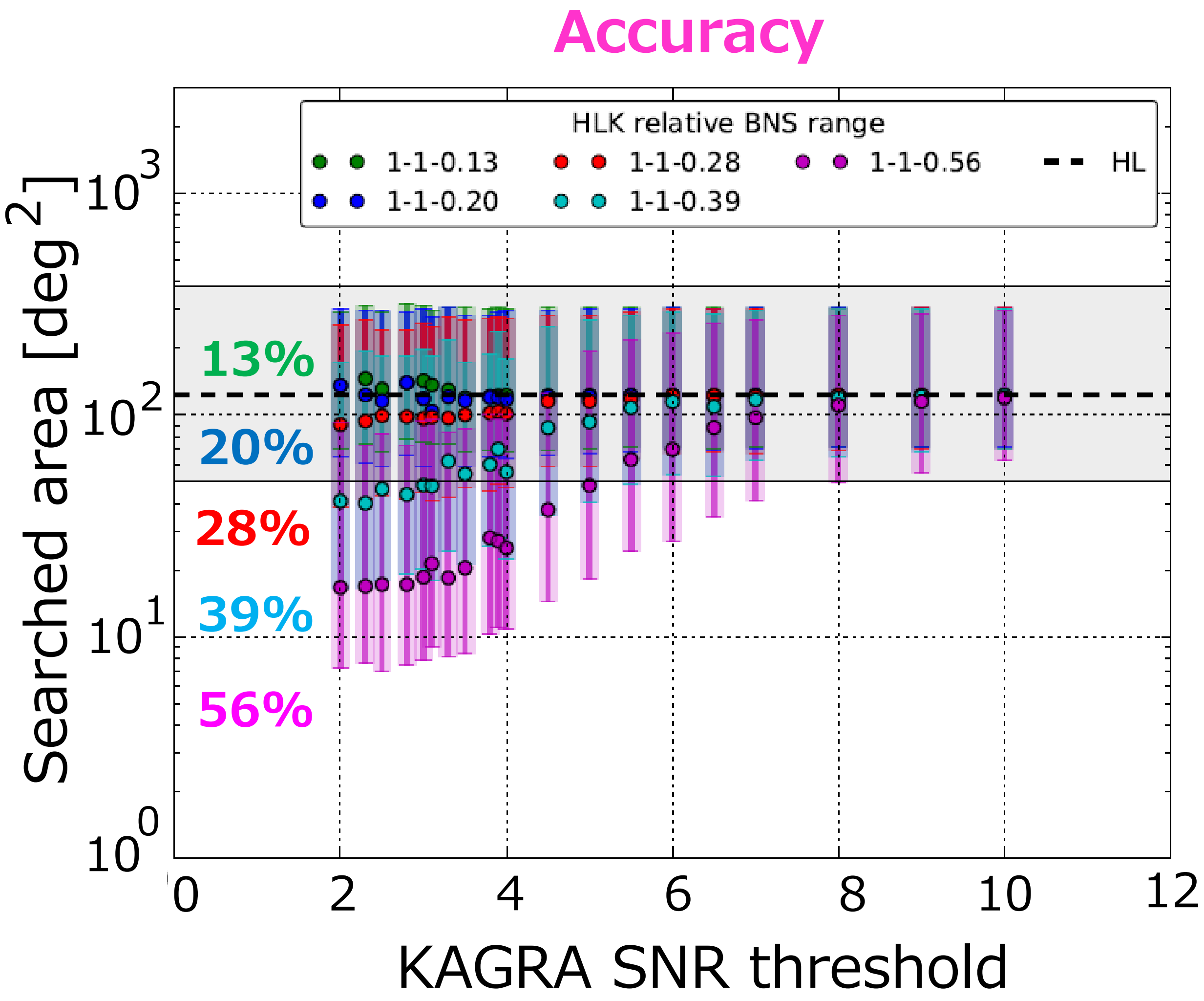
H1th : L1th : V1th = 5 : 5 : 3.5

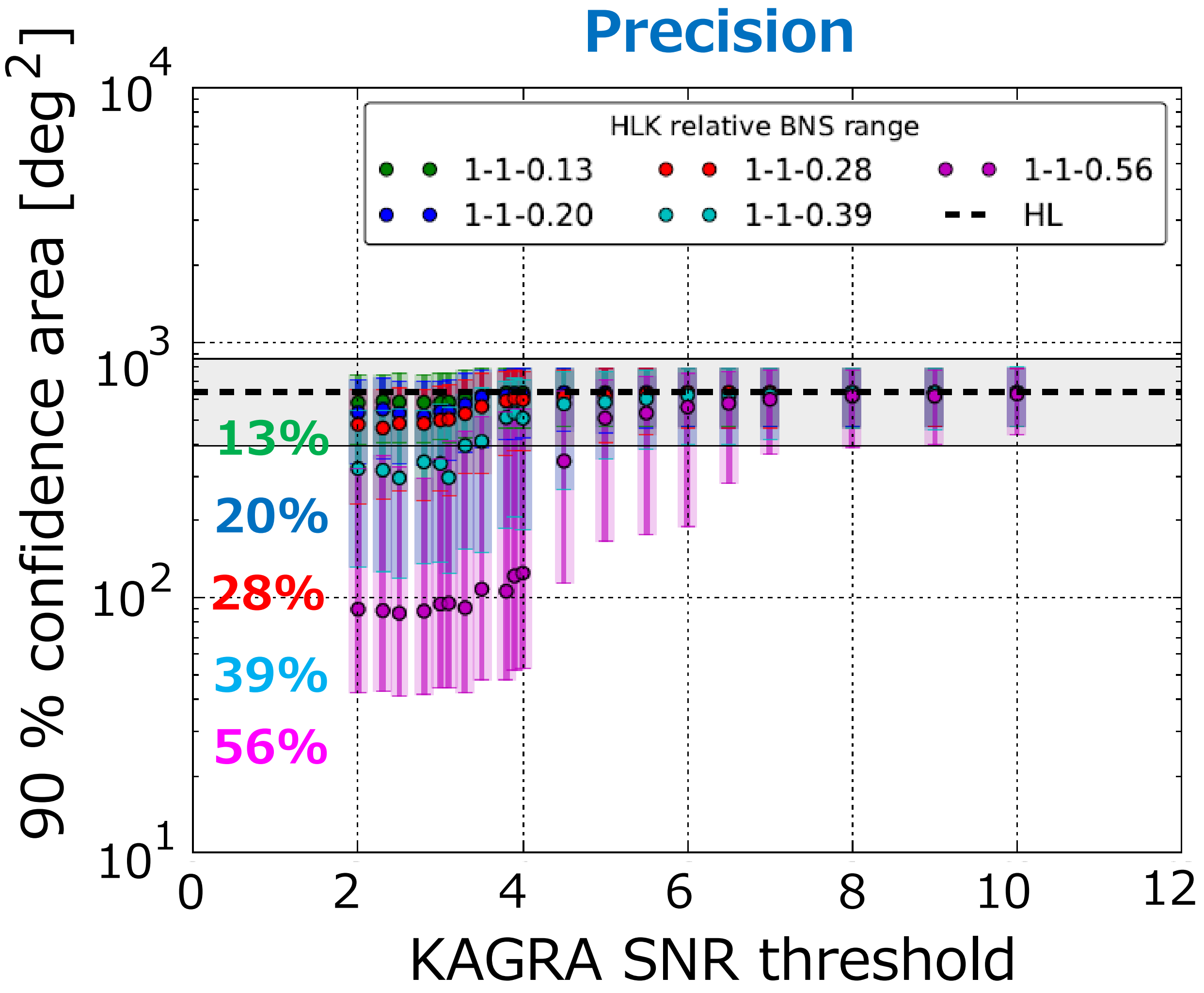




Performance (HLK):

(SNR threshold for H, L = 5.)



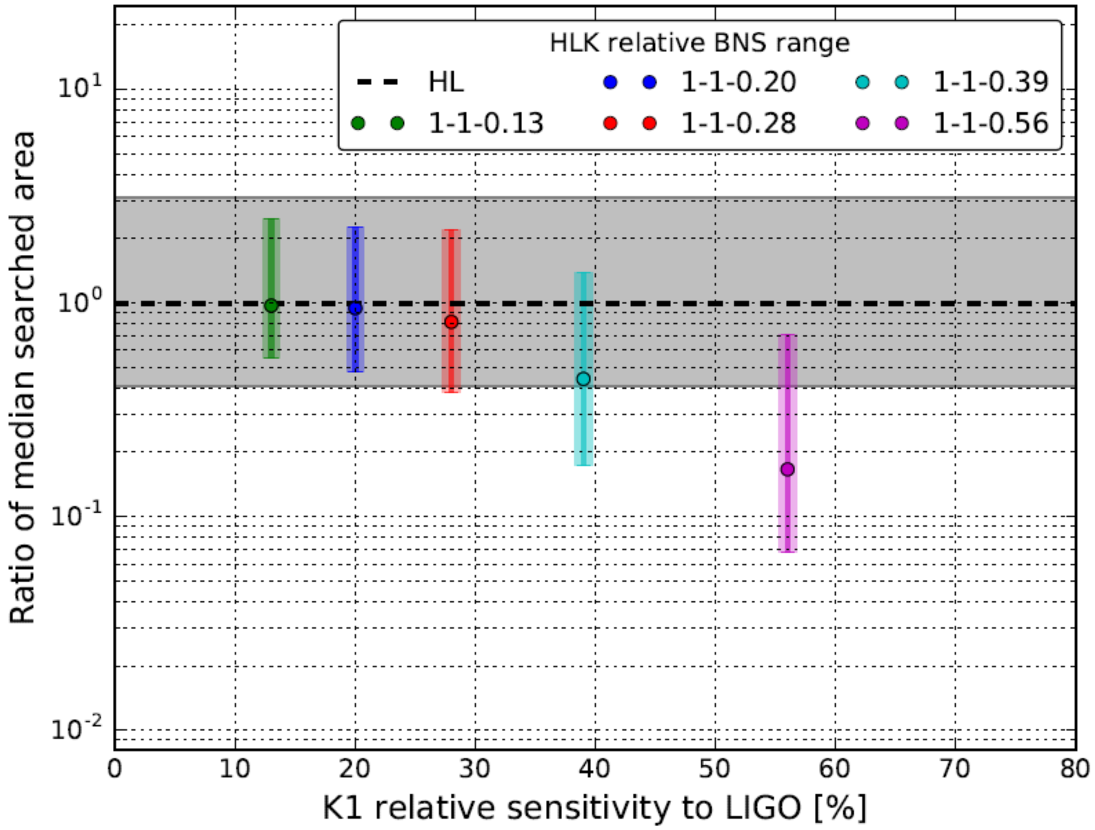


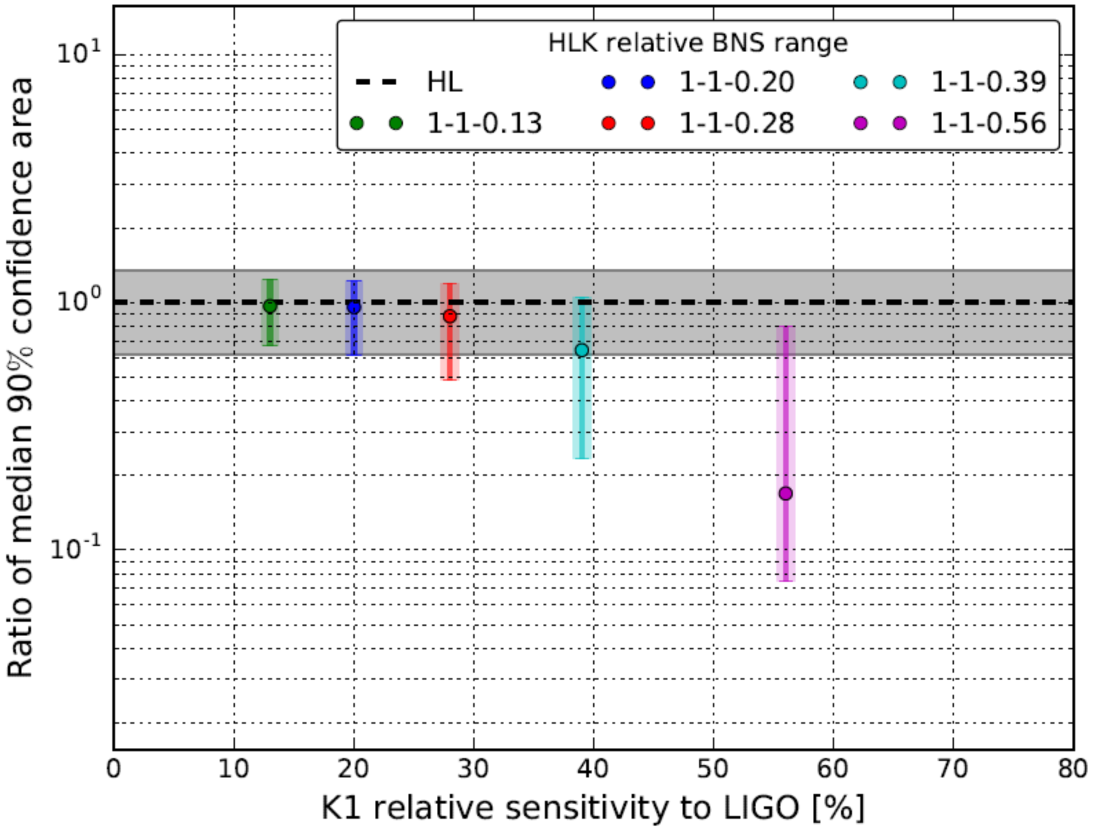
Relative sensitivity = (1, 1, >0.28), SNR threshold = (5, 5, ~3.5)
→ **becomes improved**

Performance of HL- vs. HLK-hierarchical-network:

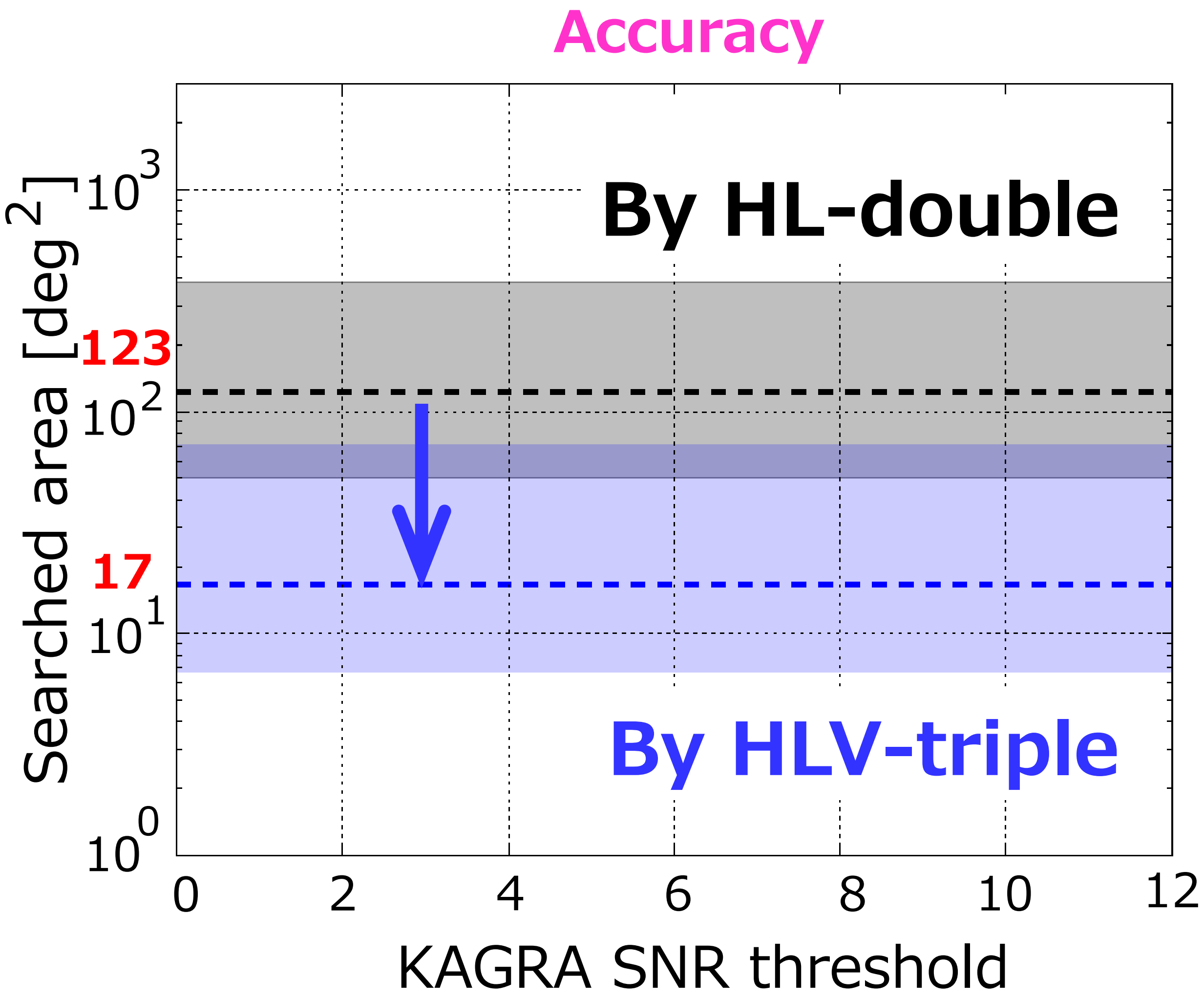
RnageH : RangeL = 54 : 54 (Mpc)

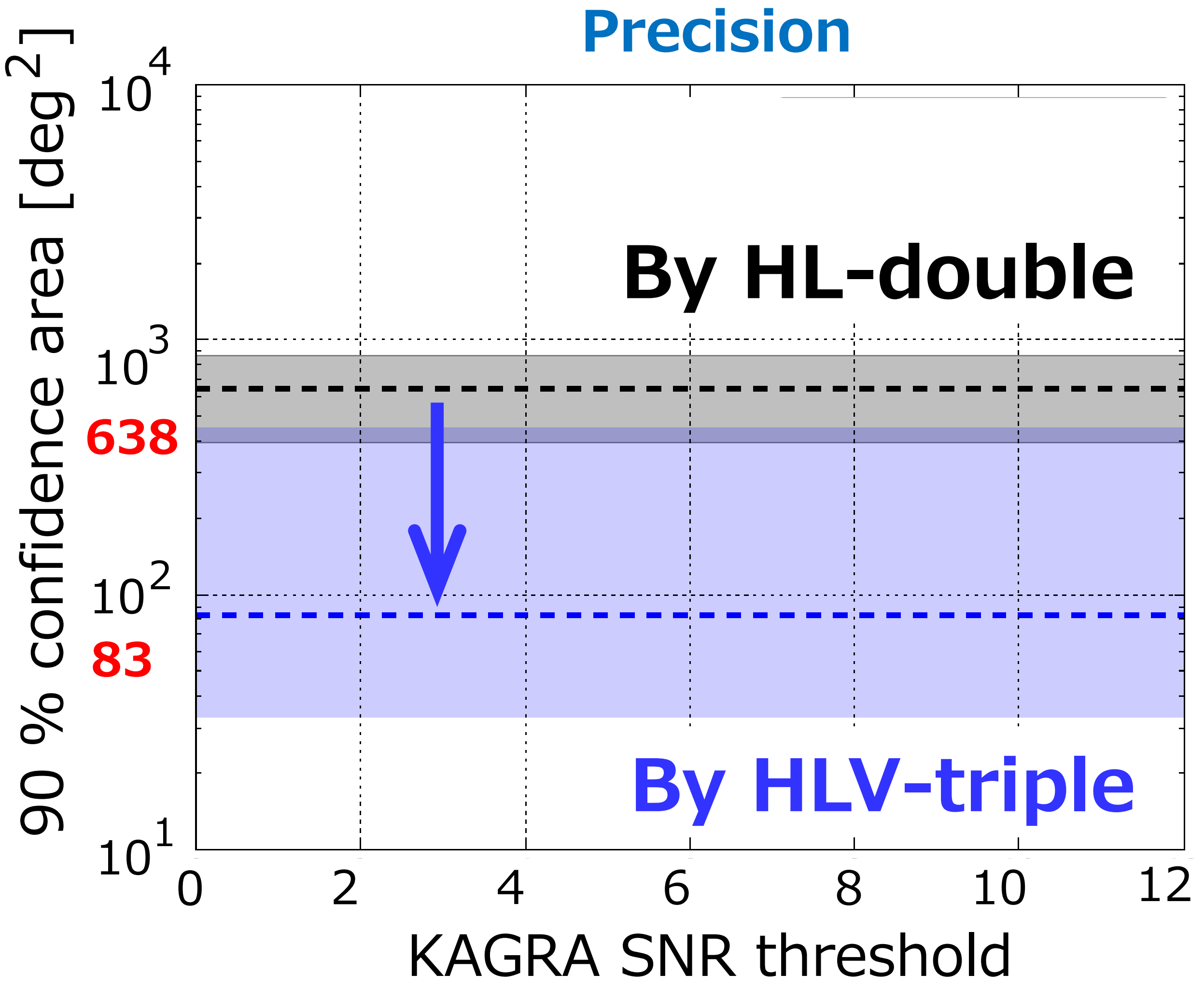
H1th : L1th : K1th = 5 : 5 : 3.5





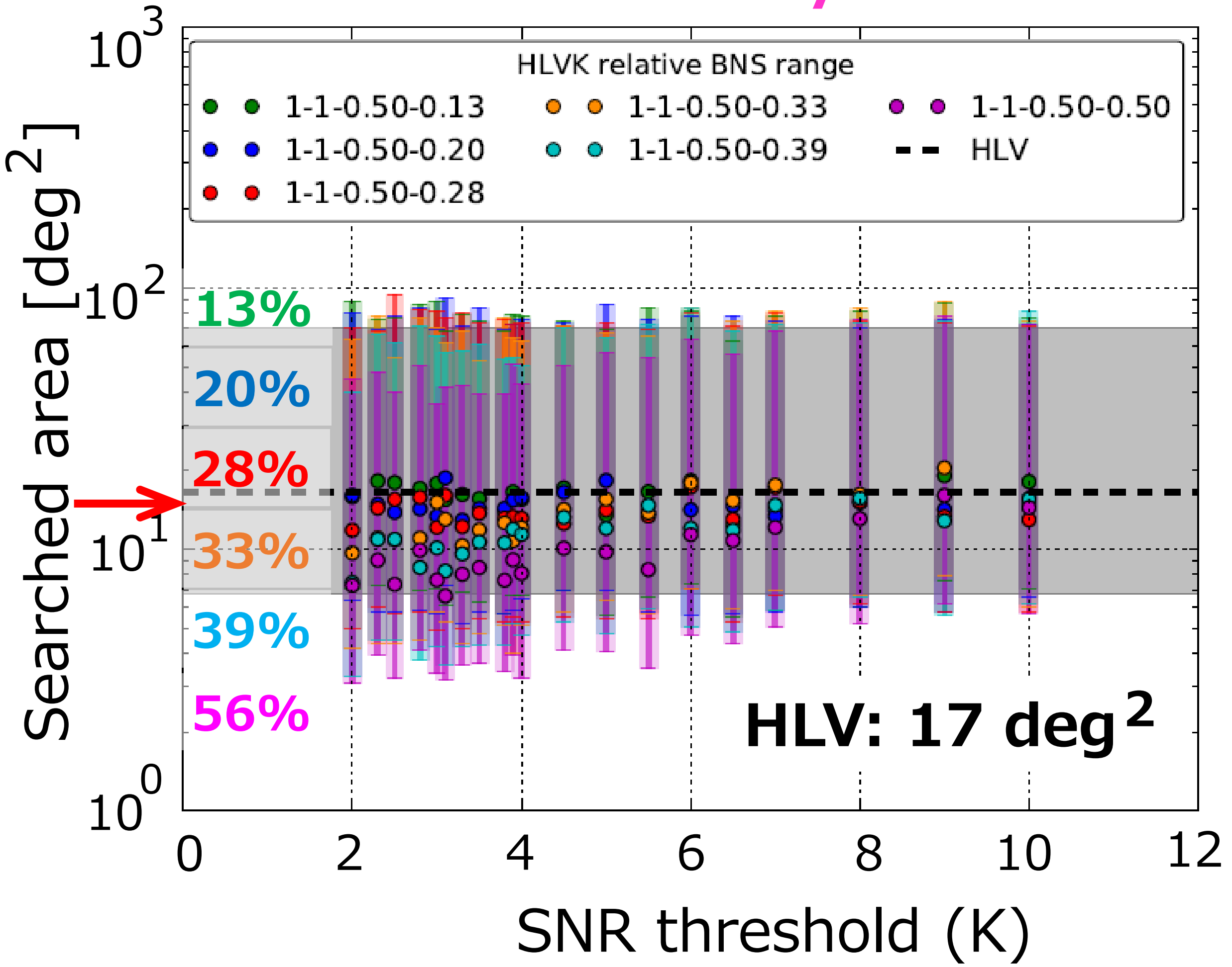
Performance (HL vs. HLV): **(SNR threshold for H, L, V = 5, 5, 3.5)**



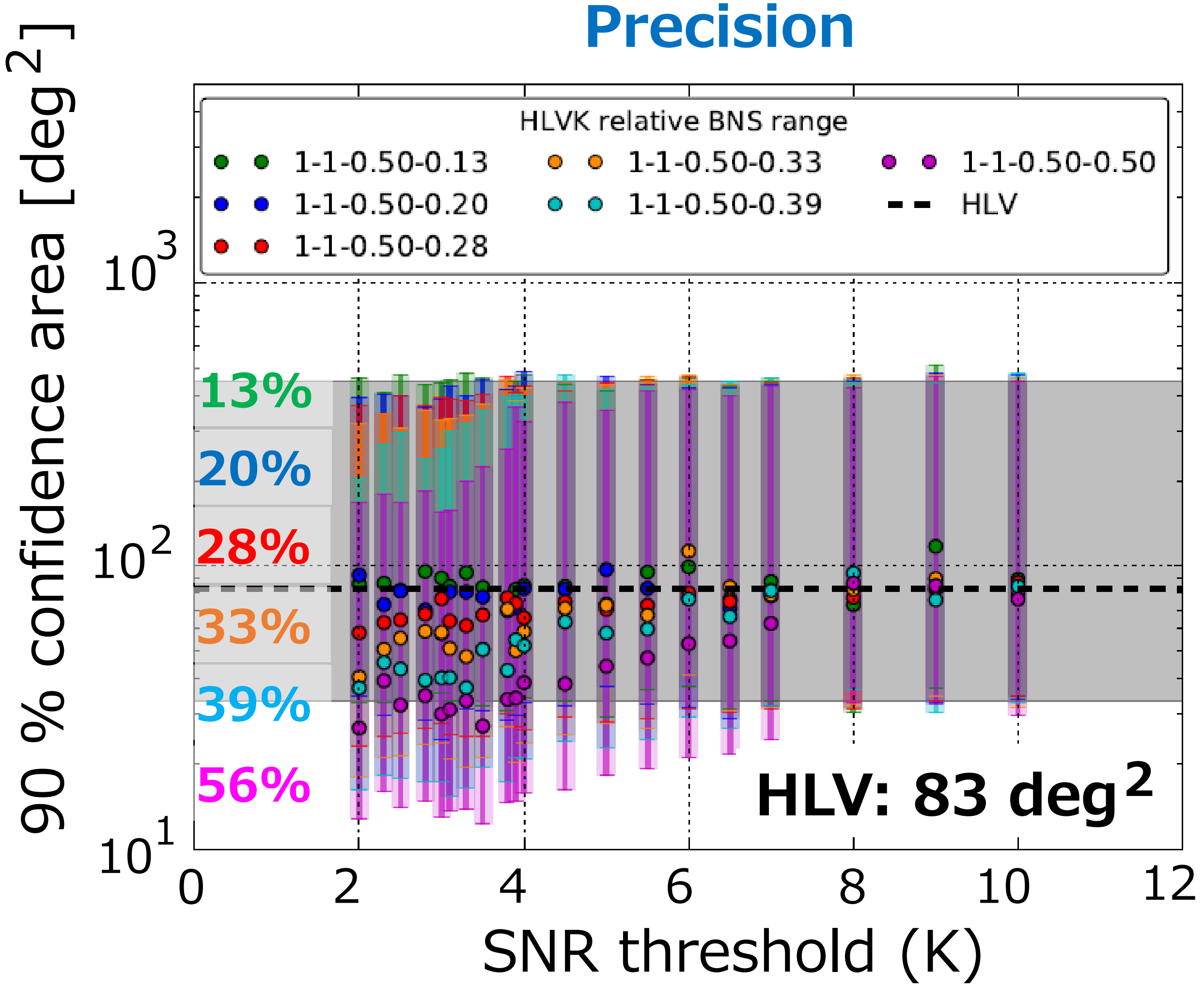


Performance (HLVK): (SNR threshold for H, L, V = 5, 5, 3.5)

Accuracy



Precision

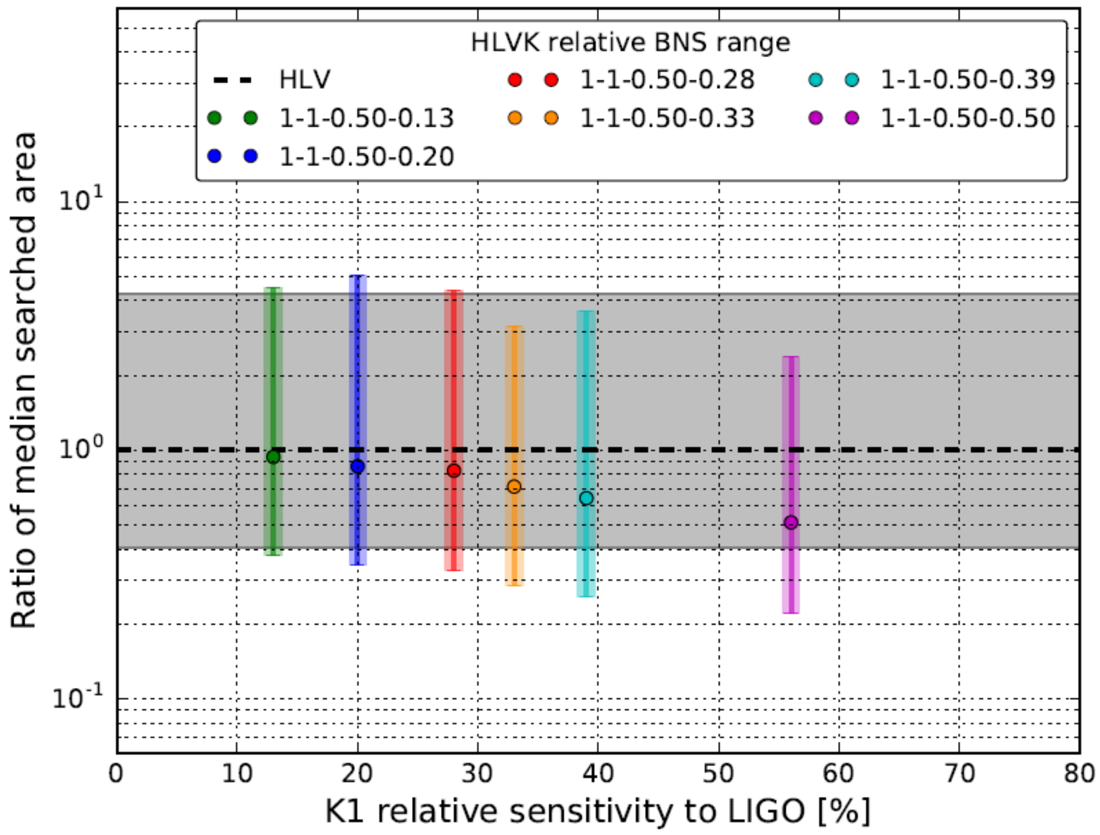


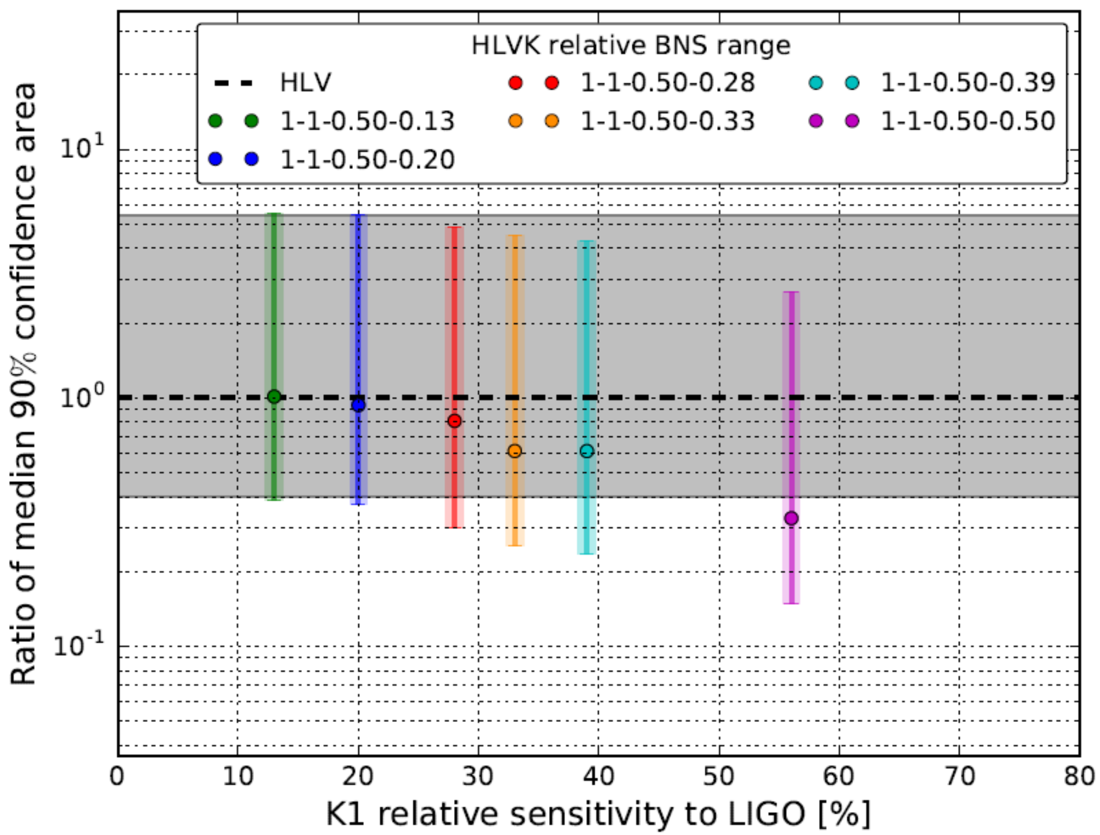
Relative sensitivity = (1, 1, >0.3), SNR threshold = (5, 5, ~3.5)
→ **Effectively improved**

Performance of HL- vs. HLK-hierarchical-network:

RnageH : RangeL : RangeV = 54 : 54 : 27 (Mpc)

H1th : L1th : V1th : K1th = 5 : 5 : 3.5 : 3.5





Summary of the hierarchical approach

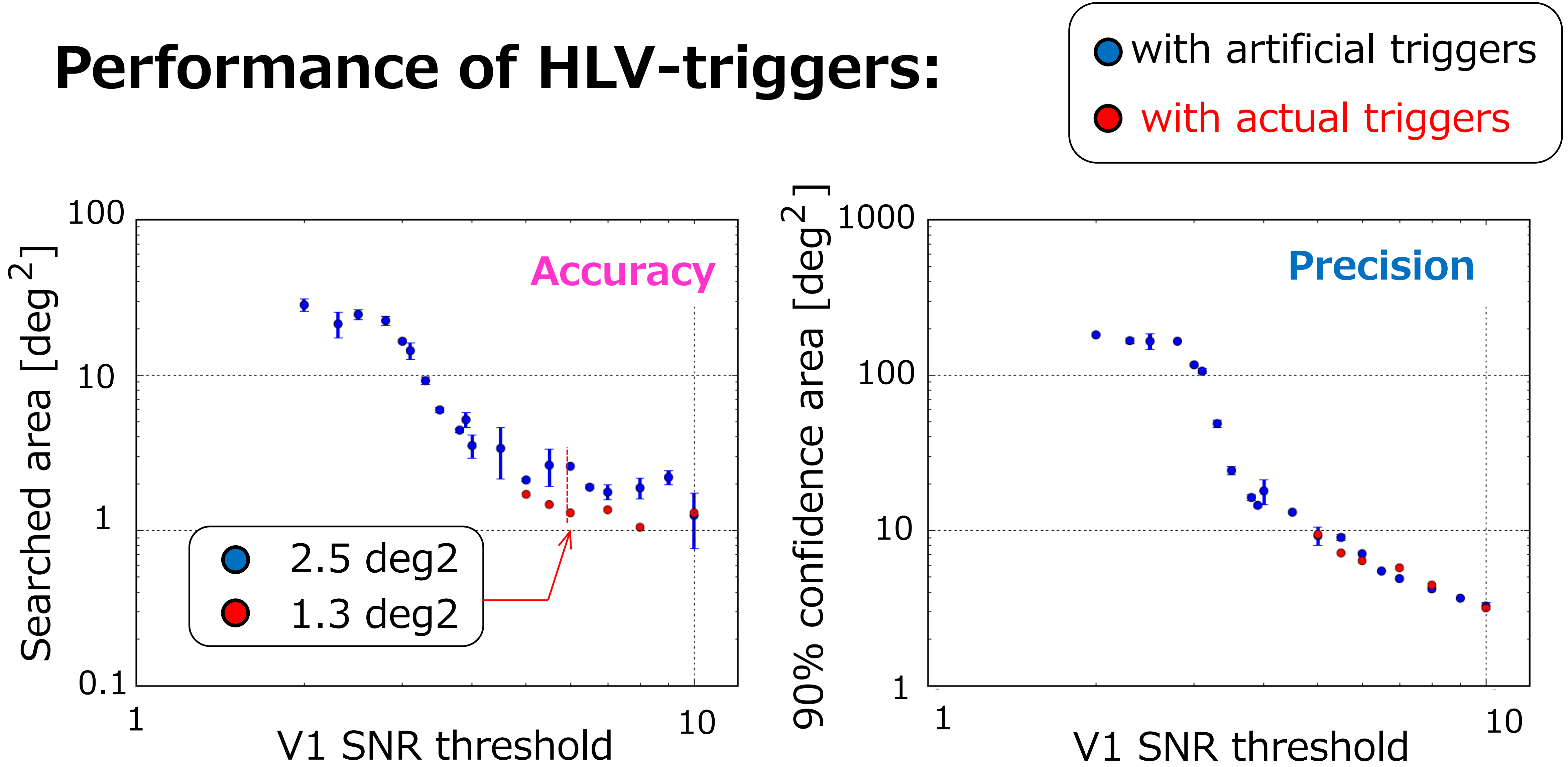
* Required detector sensitivity & optimal SNR threshold?

Add plot

	Relative sensitivity	SNR threshold
• **HLV-network:**	(1, 1, >0.2)	(5, 5, ~3.5)
• **HLK-network:**	(1, 1, >0.28)	(5, 5, ~3.5)
• **HLVK-network:**	(1, 1, 0.5, >0.3),	(5, 5, 3.5, ~3.5)

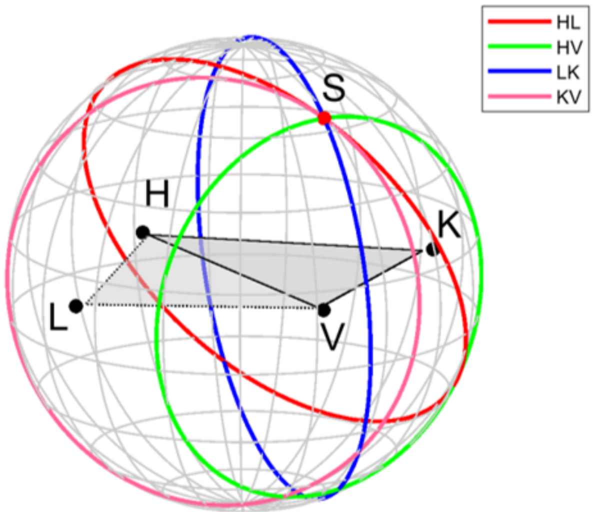
→ **This hierarchical approach will improve the fast localization in the heterogeneous network.**

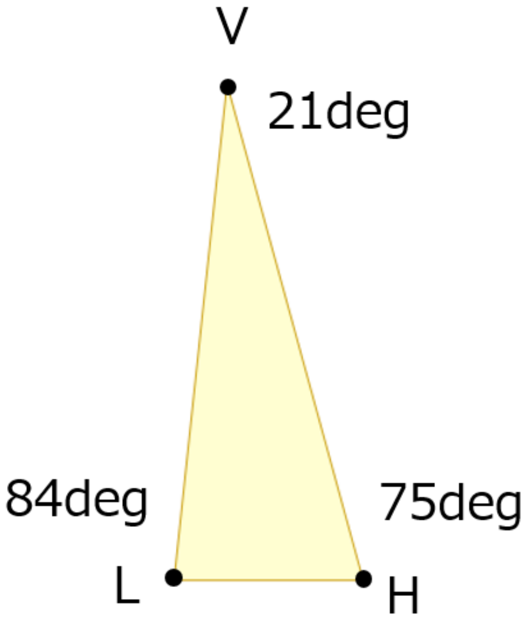
Performance of HLV-triggers:

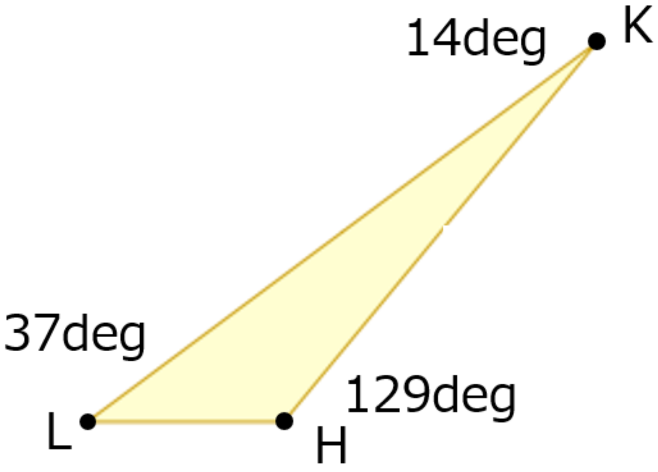


今回のシミュレーション → 実際の解析結果とコンシステント

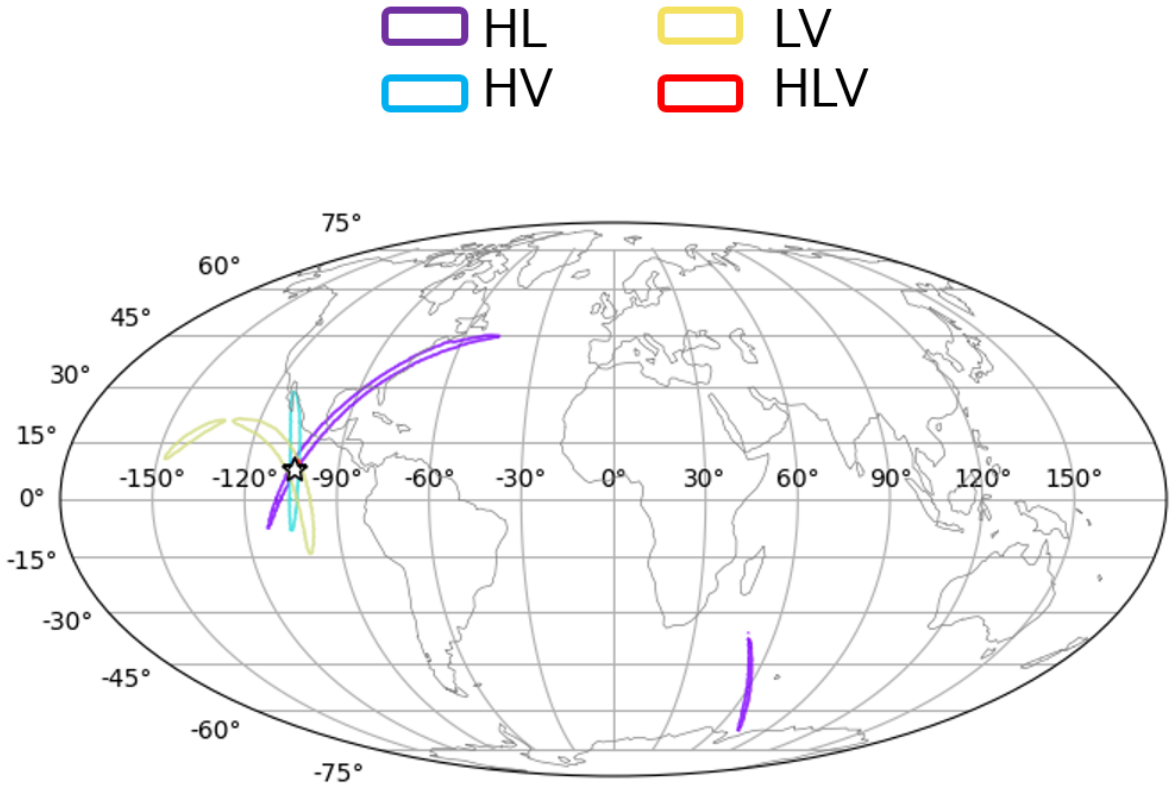
Difference: from geometry

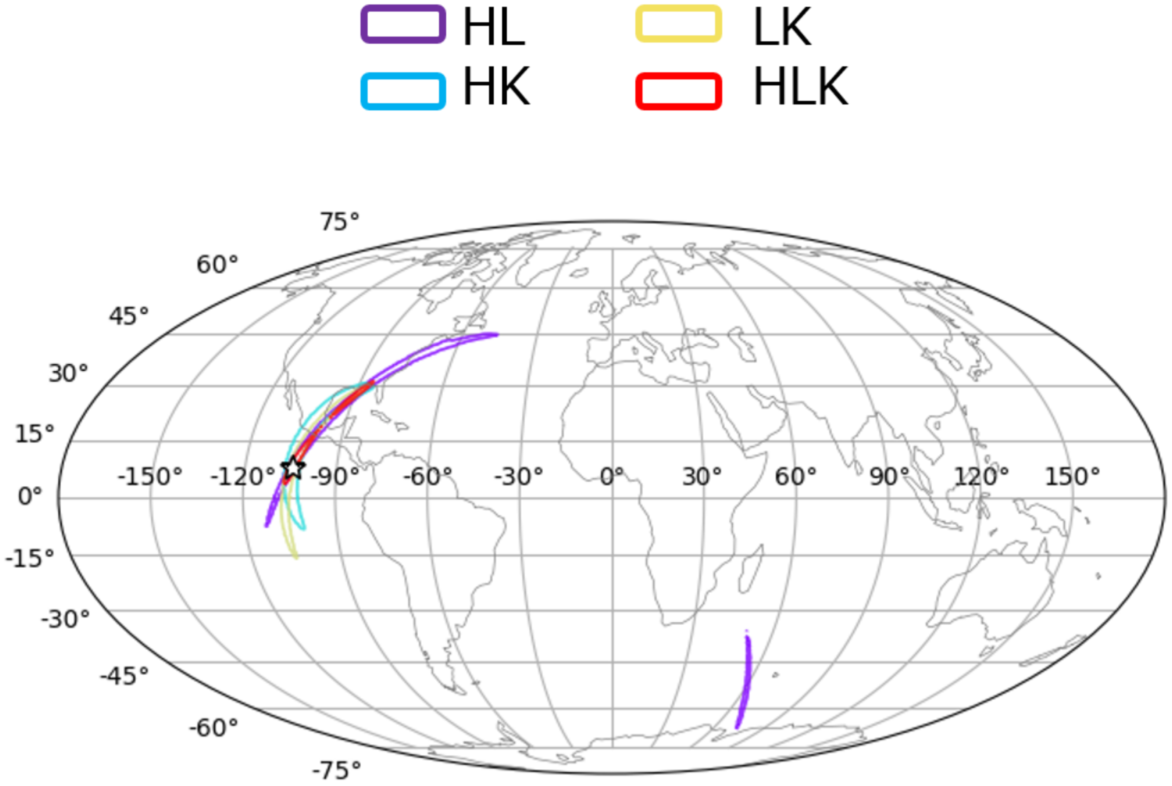






Difference: from geometry





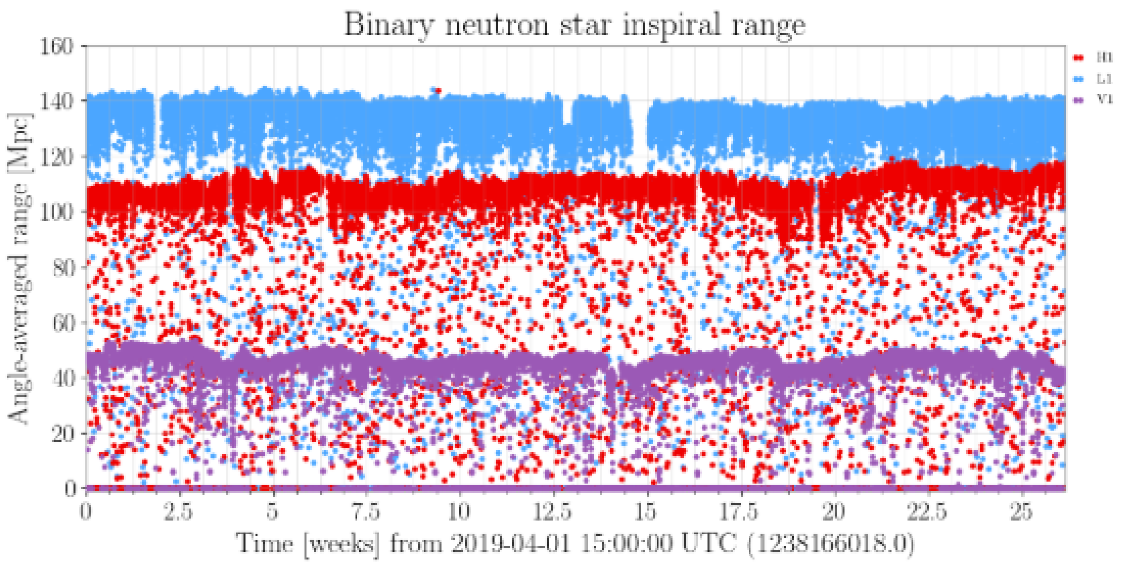
Actual duty cycle:

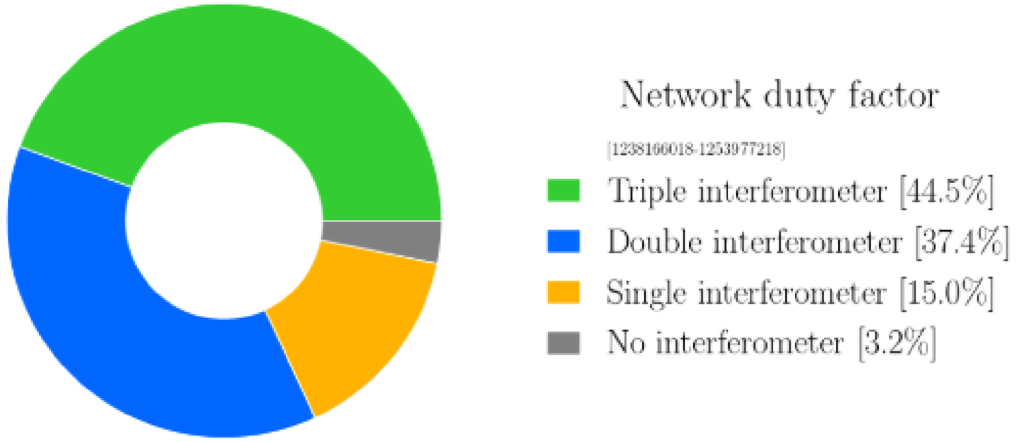
Table 1 Percentage of time during the first and second observing runs that the aLIGO and AdV detectors spent in different operating modes as recorded by the on-duty operator. Since several factors may influence detector operation at any given time, there is a certain subjectivity to the assignments. Maintenance includes a planned 4-h weekly period ($\sim$ 2.4% of the total), and unplanned corrective maintenance to deal with equipment or hardware failures. Coincident operation of the aLIGO detectors occurred $\sim$ 43% of the time in O1 and $\sim$ 46% in O2. After joining O2 on August 1 2017 AdV operated with a duty factor of approximately 85% until the end of the run on August 25 2017.

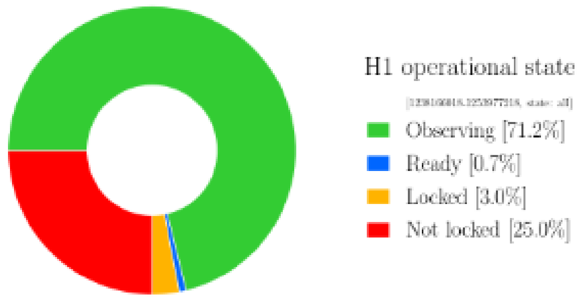
		O1		O2		
		Hanford	Livingston	Hanford	Livingston	Virgo
Operating mode %	Observing	64.6	57.4	65.3	61.8	85.1
	Locking	17.9	16.1	8.0	11.7	3.1
	Environmental	9.7	19.8	5.8	10.1	5.6
	Maintenance	4.4	4.9	5.4	6.0	3.1
	Commissioning	2.9	1.6	3.4	4.7	1.1
	Planned engineering	0.1	0.0	11.9	5.5	–
	Other	0.4	0.2	0.2	0.2	2.0

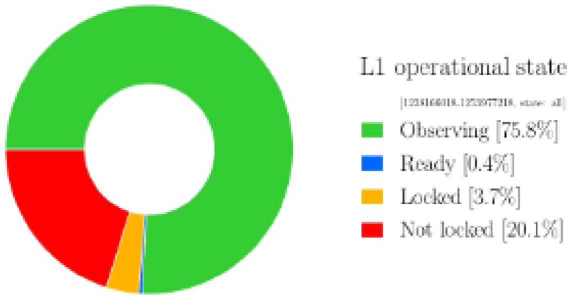
Actual performance of online detectors:

https://summary.ligo.org/~detchar/summary/O3a/



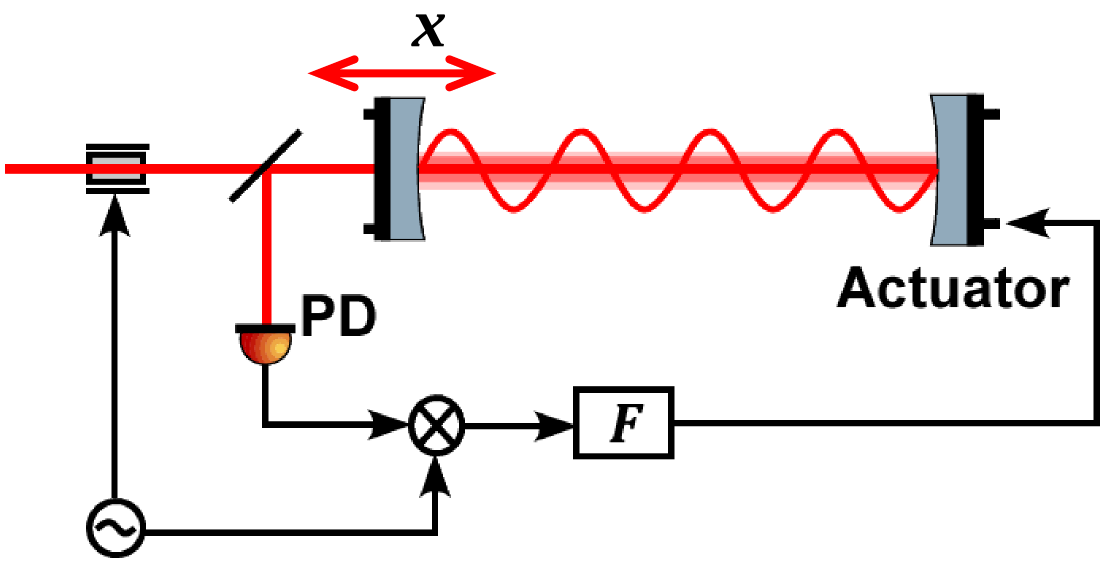




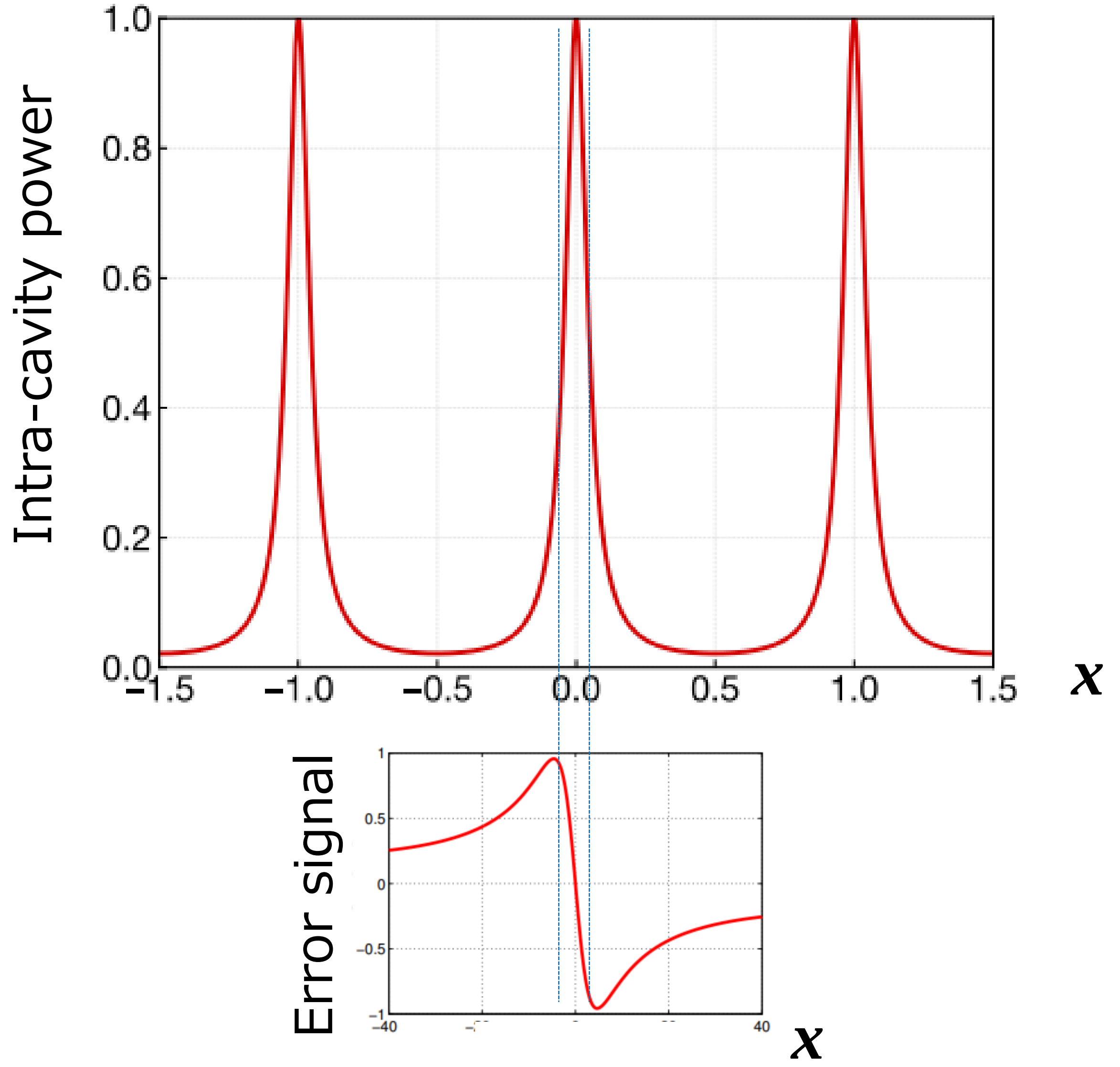


Interferometer locking:

Pound-Drever-hall (PDH) technique:

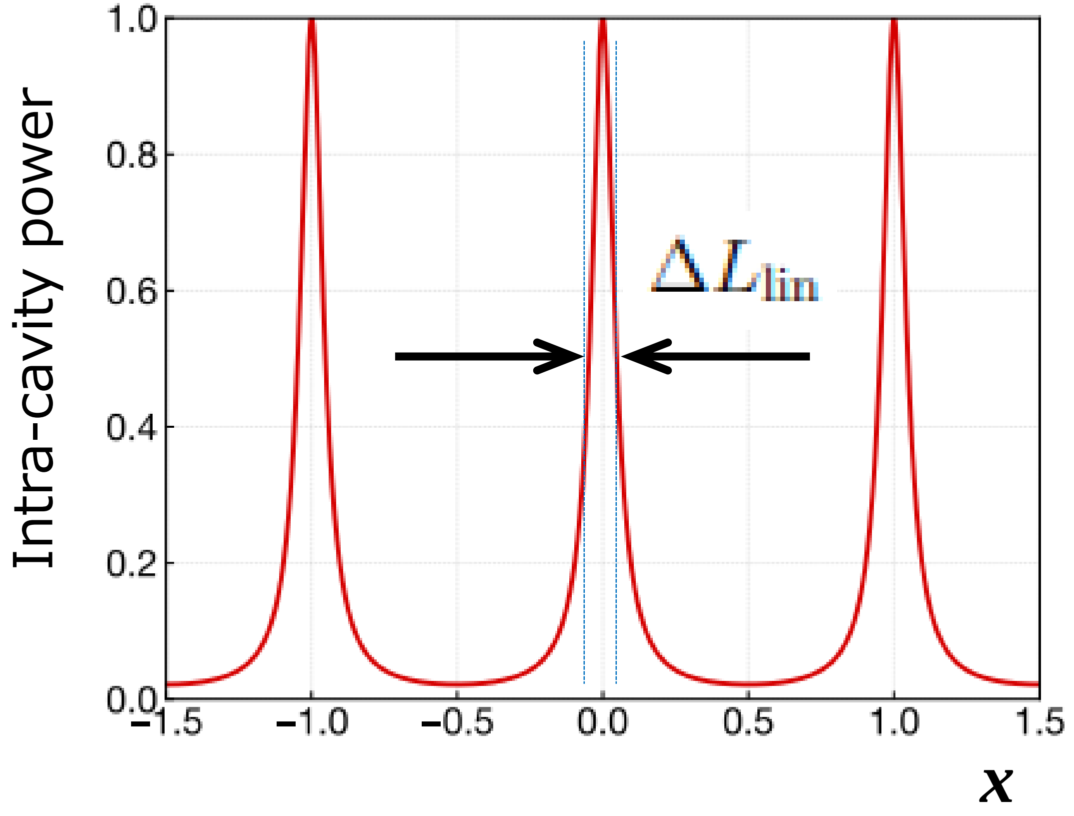


[ref] https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=4739

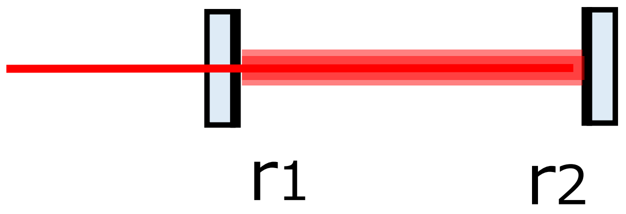


Feedback control only works within linewidth (FWHM).

Cavity linewidth:



$$\Delta L_{\mathrm{lin}} = \frac{\lambda}{2\mathcal{F}}. \qquad \left(\mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}.\right)$$



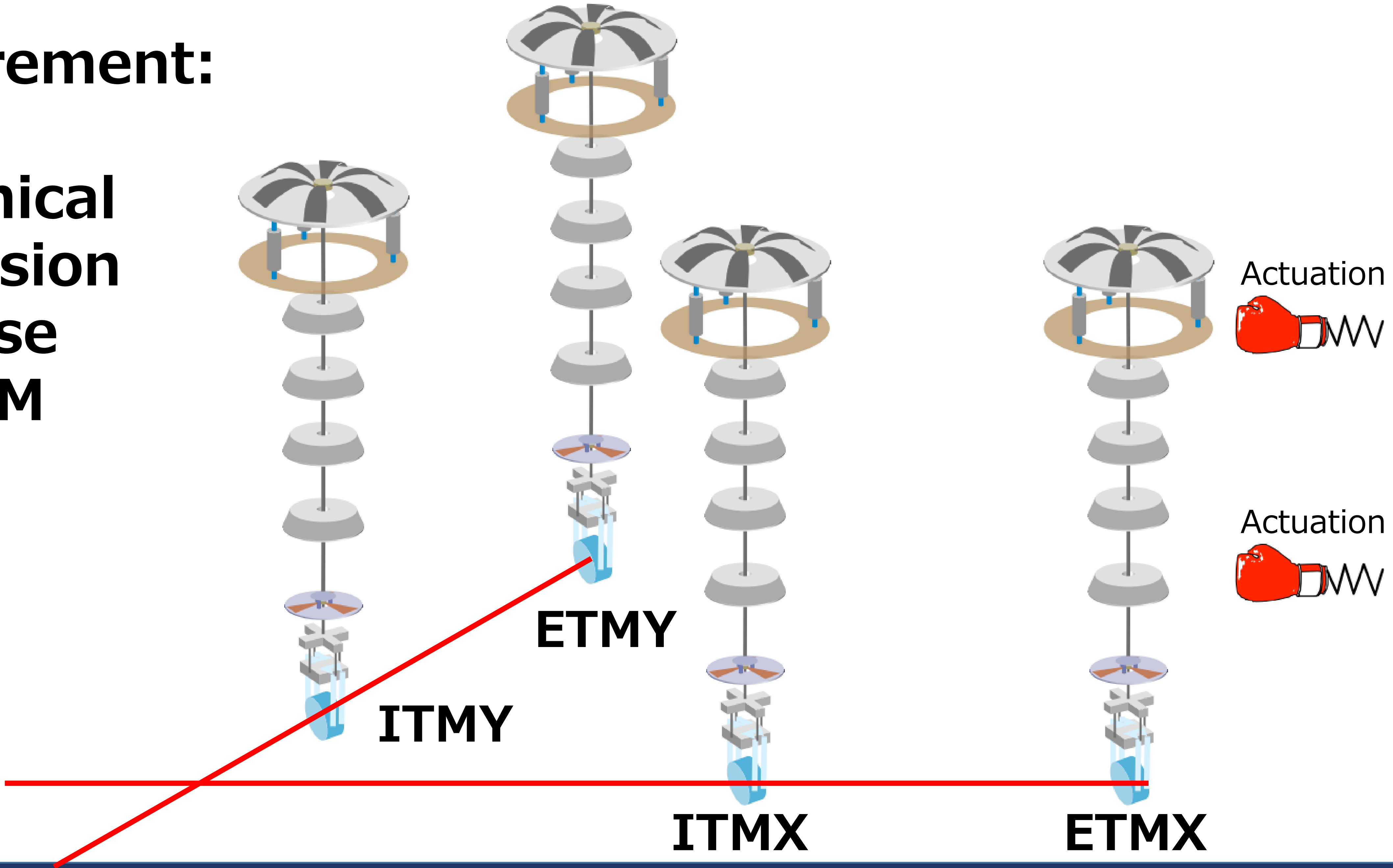
wb*del_L_lin = (2*pi*UGF)*lumbda/2/F

DoFs	UGF [Hz]	Finessse	lambda [nm]	wb*del_L_lin [um/s]	del_L_lin [nm]
ARM_IR		1550	1064		0.34
ARM_GR	10e3	50	532	334	53.24
MICH	50 for BS	1	1064	167	226
PRCL	50 for PRM	57	1064	2.93	9.33
SRCL	50 for SRM	38	1064	4.398	14

Note: verification of suspension performance

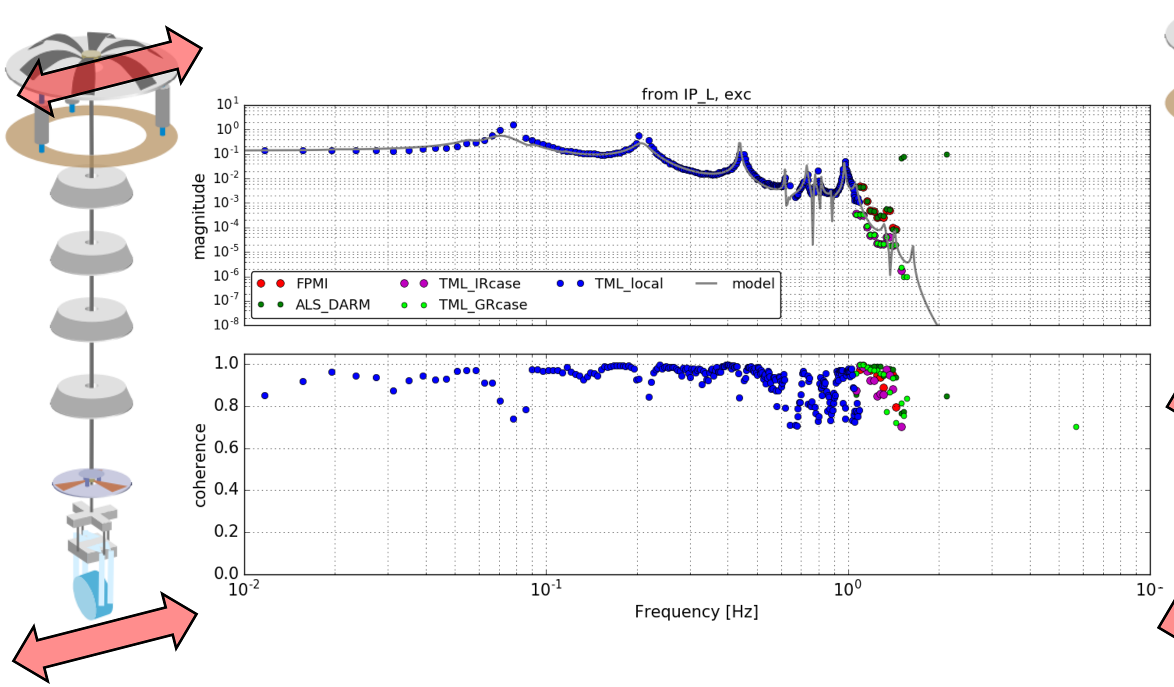
Measurement:

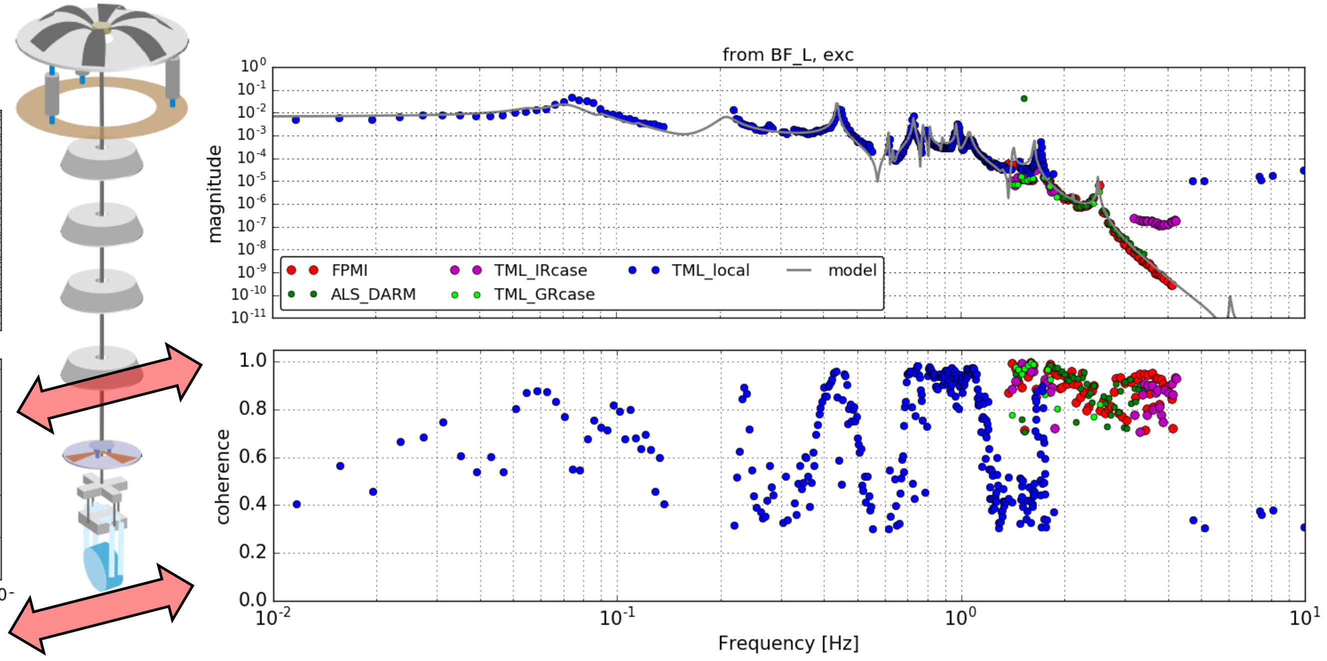
Mechanical suspension response to DARM



1. Mechanical system characterization:

* By checking vibration isolation

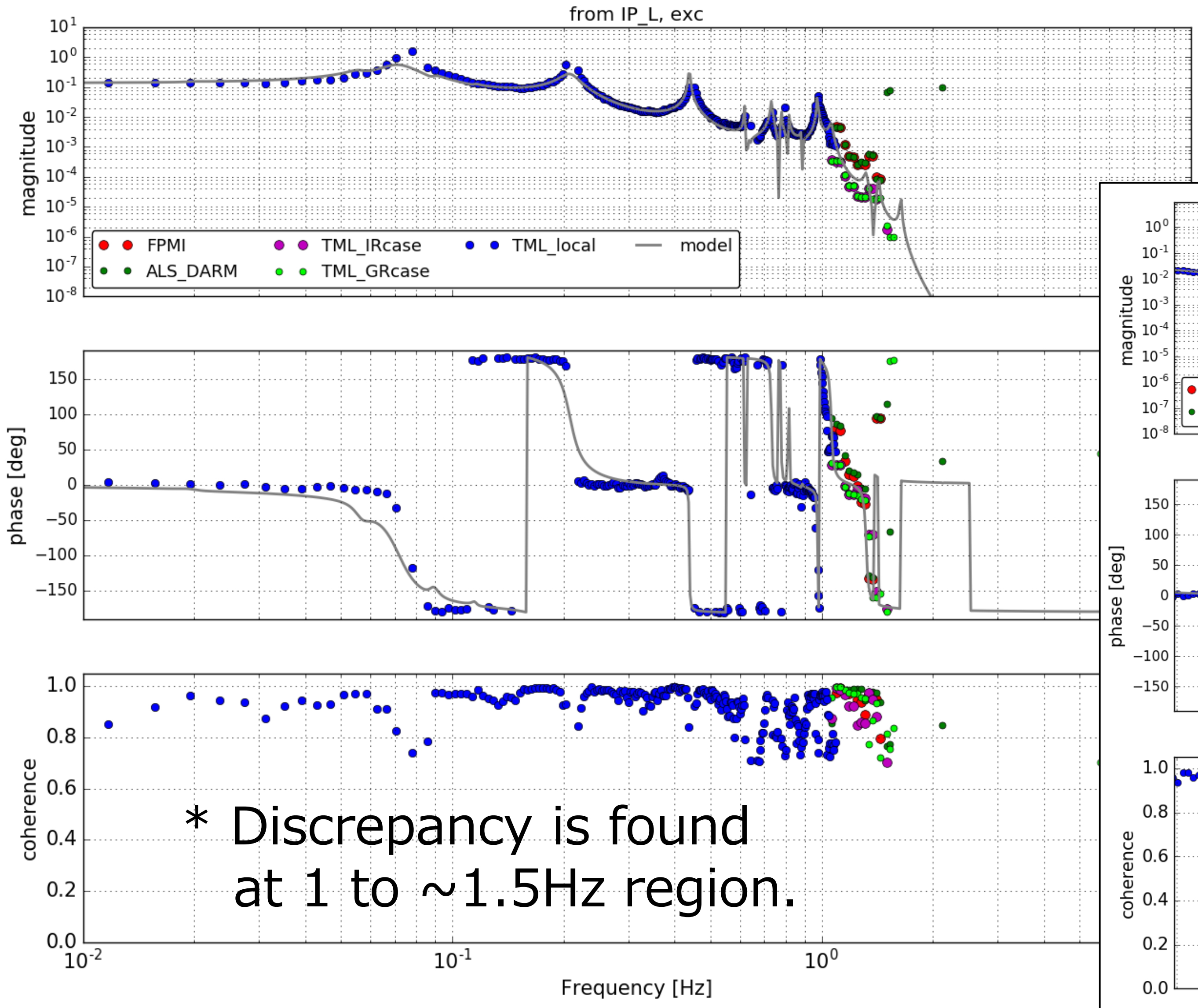




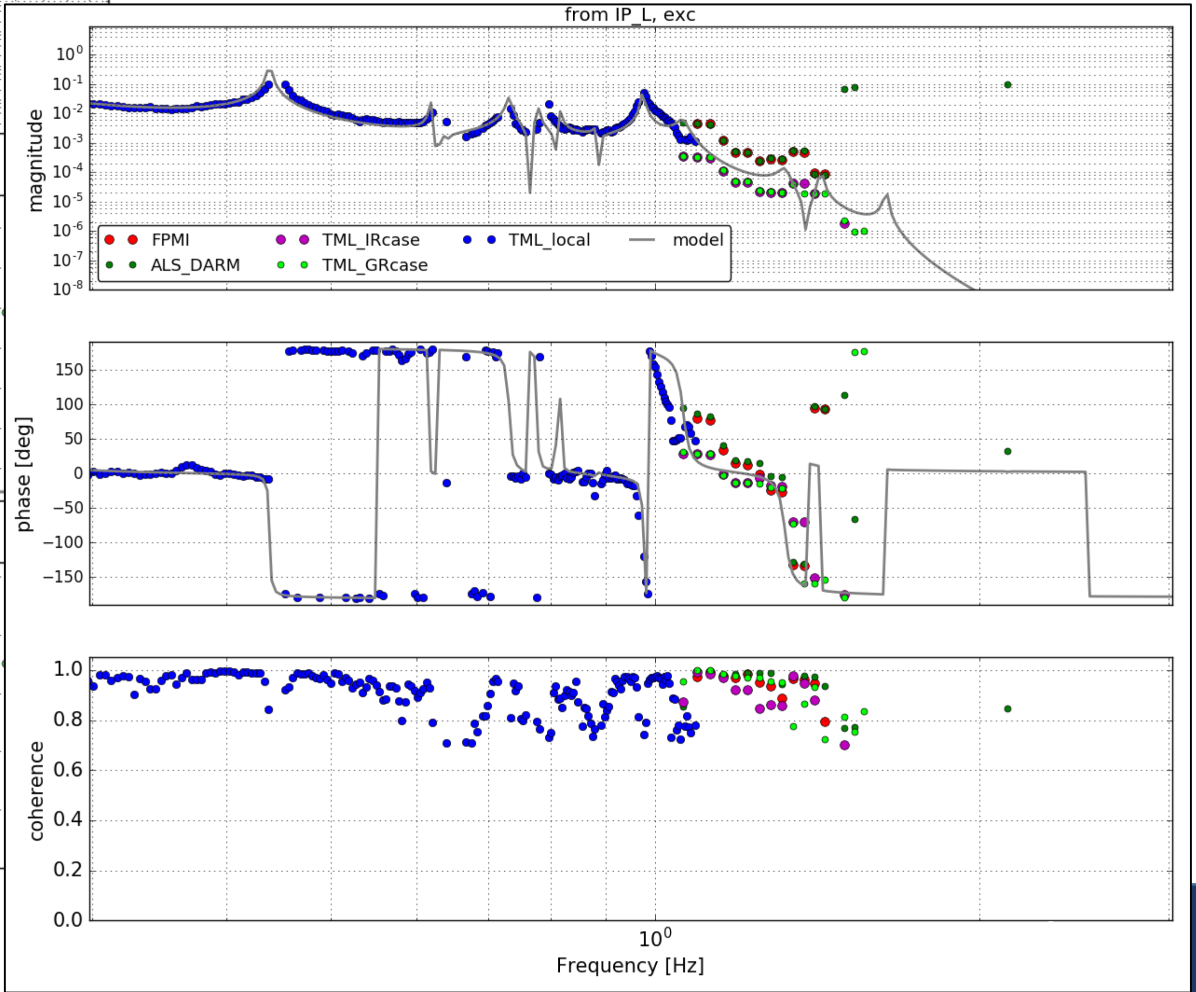
→ Type-A suspension has characteristics of pendulum up to 4 Hz.

→ discrepancy at 1 Hz to 1.5 Hz is worth to investigate for further improvement.

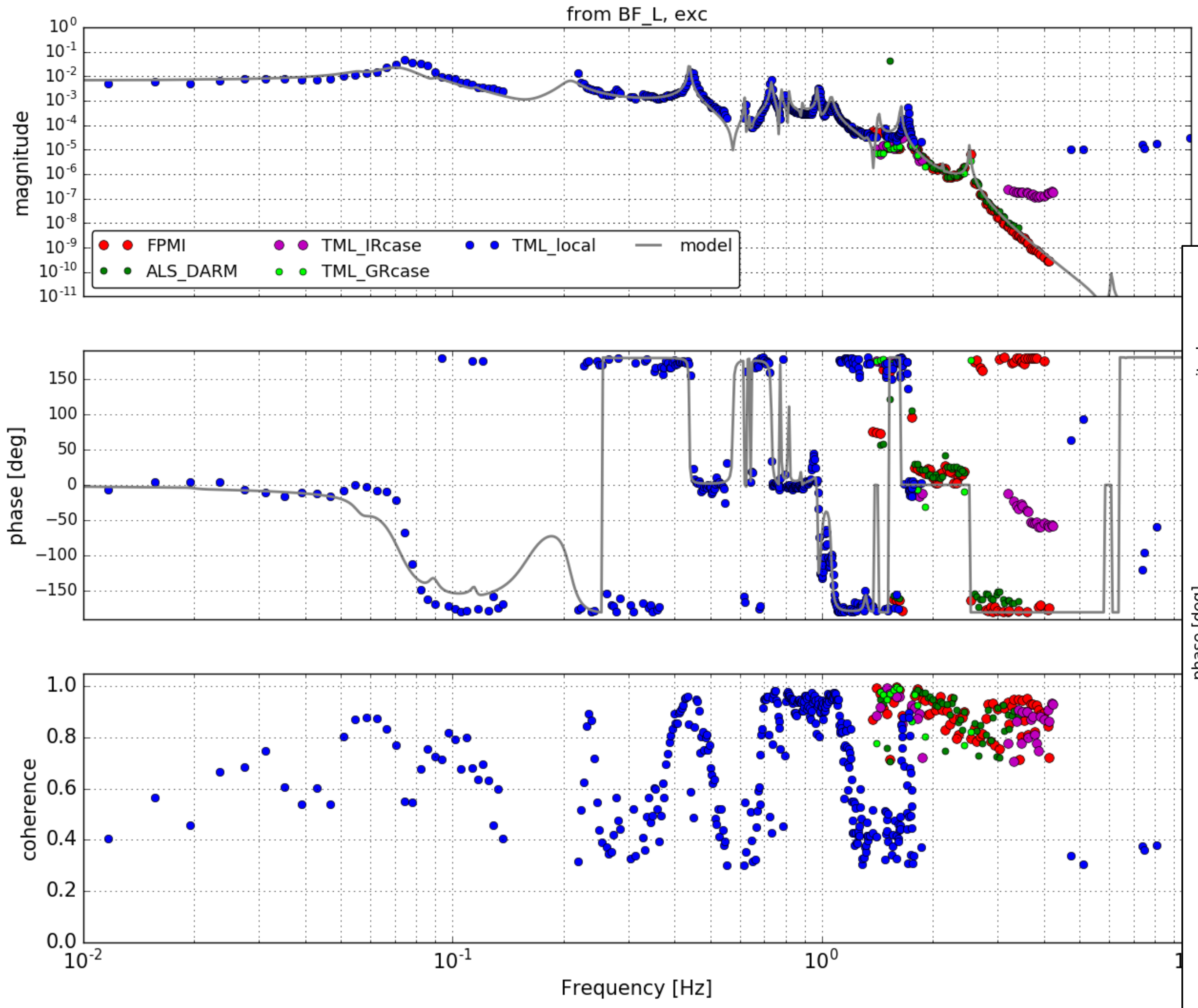
Results: force transfer functions, from IPL



* Discrepancy is found
at 1 to ~1.5Hz region.

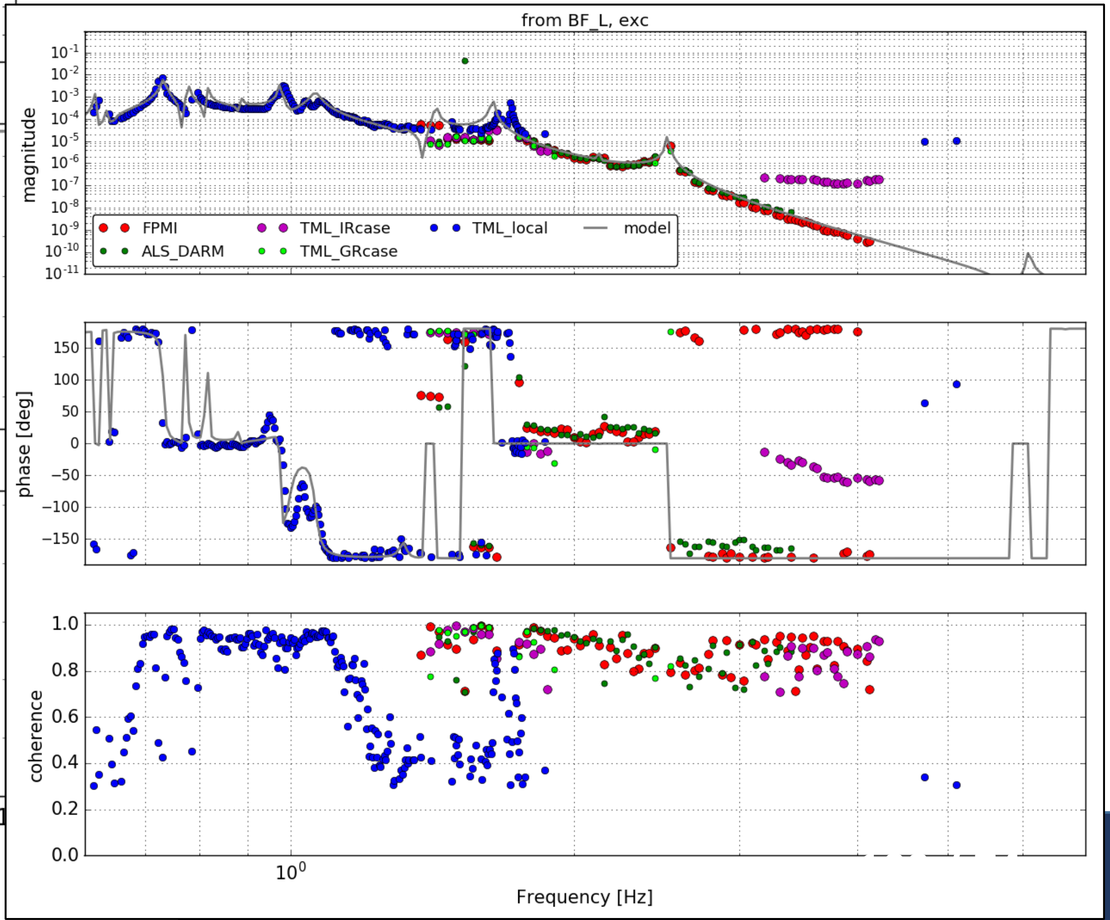


Results: force transfer functions, from BFL

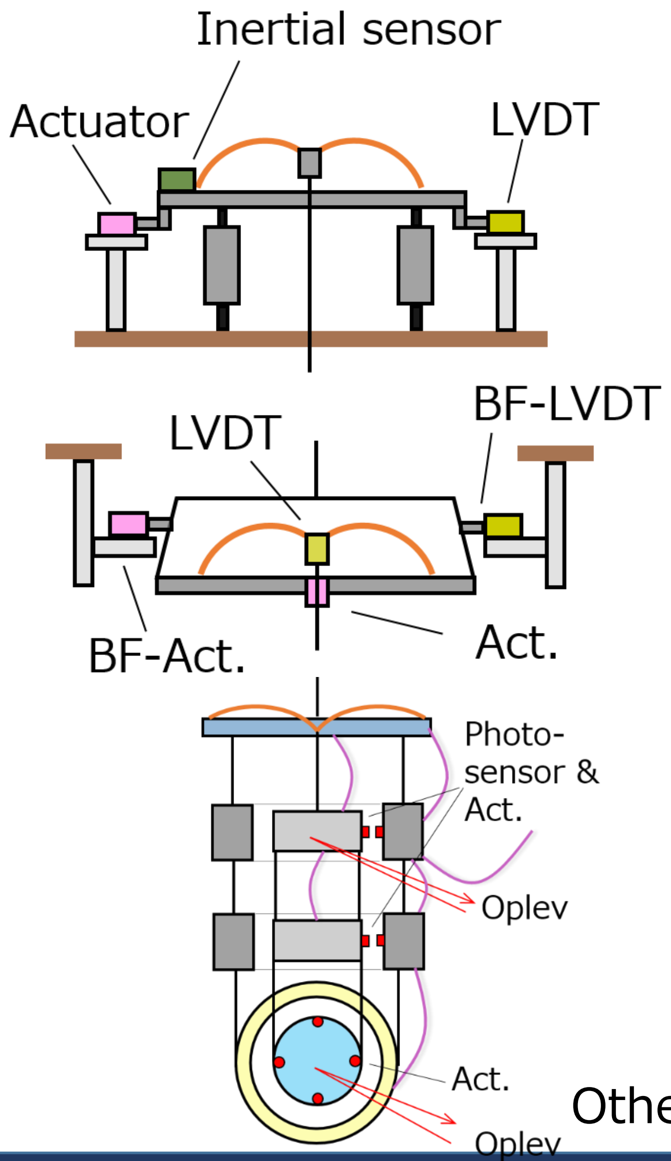


The transfer function up to 4Hz agree with the model.

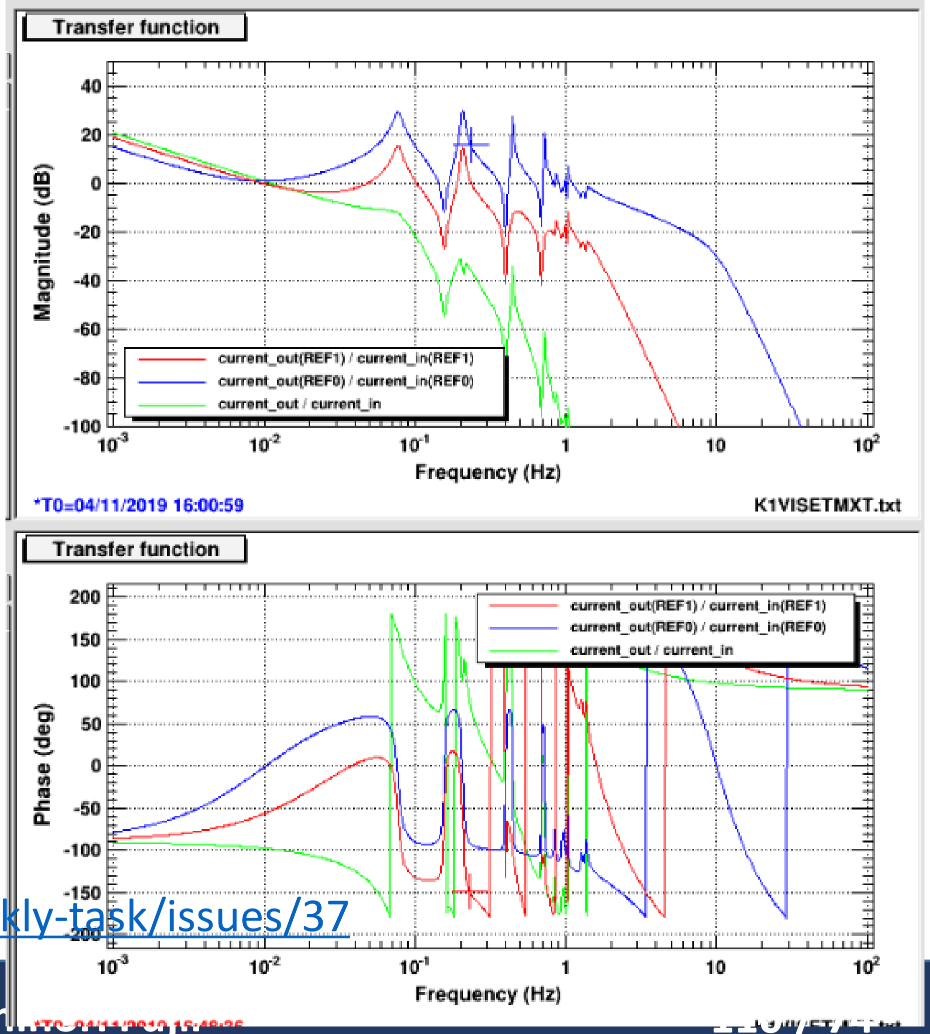
~~Except for 1-1.5Hz band.~~



Settings for the measurement w/o controls:

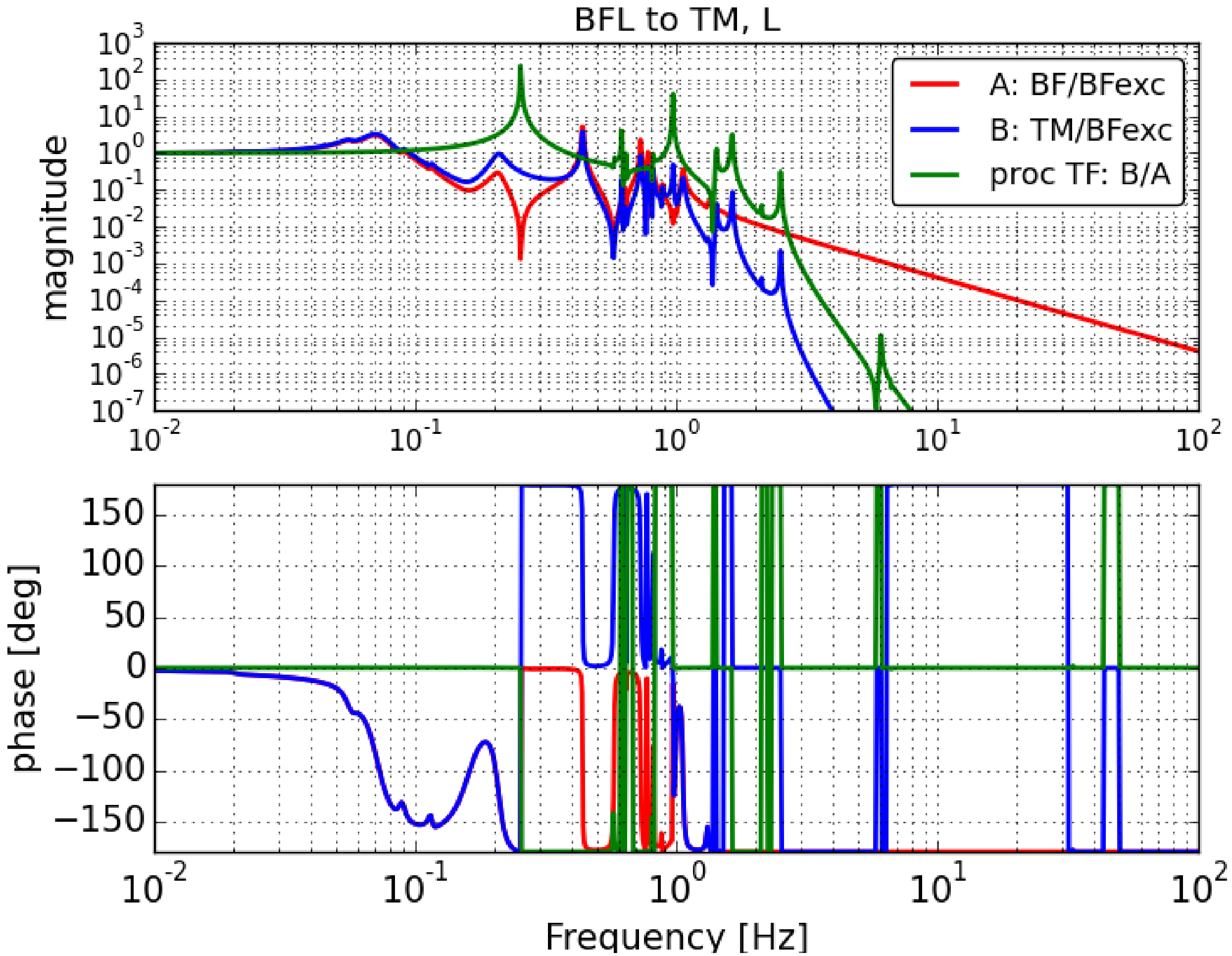


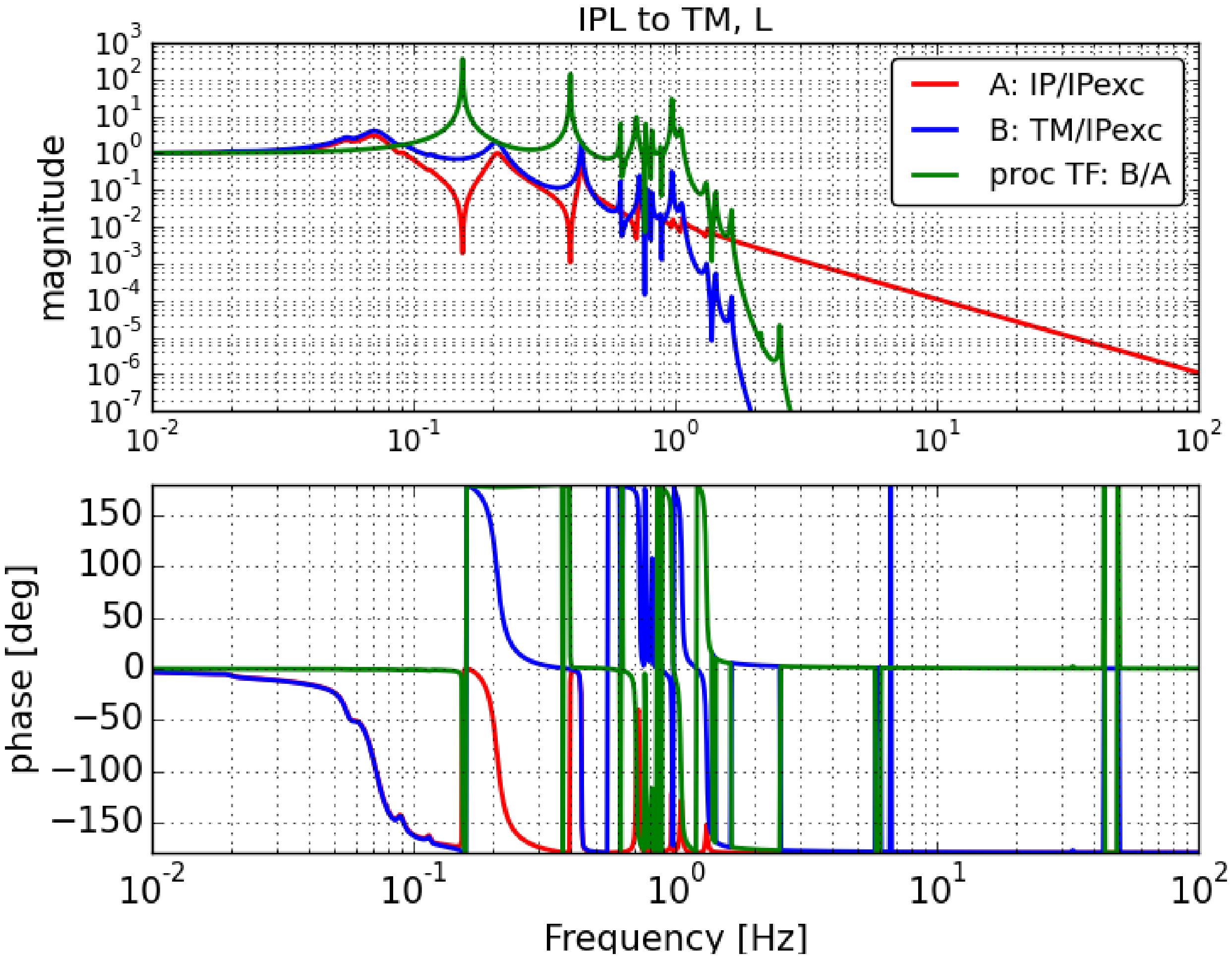
With Tower-damped state,
- ordinal L-loop (blue) was opened at IP satge.
- instead,
  - green curve loop was used for the ALS_DARM measurement,
  - red curve loop was used for the FPMI_DARM measurement.



Other ref: https://github.com/YoshinoriFujii/Weekly-task/issues/37

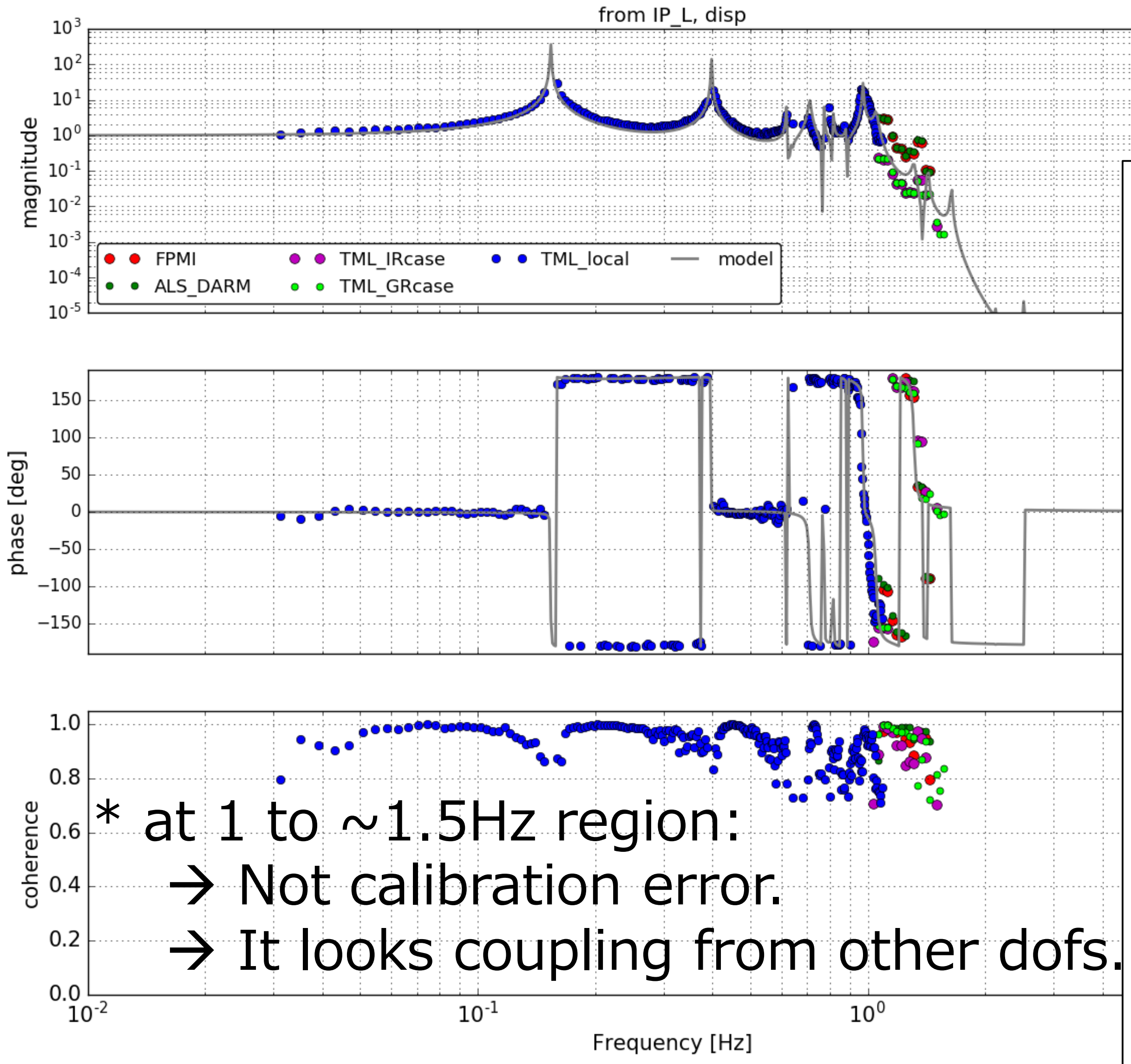
Simulation models:



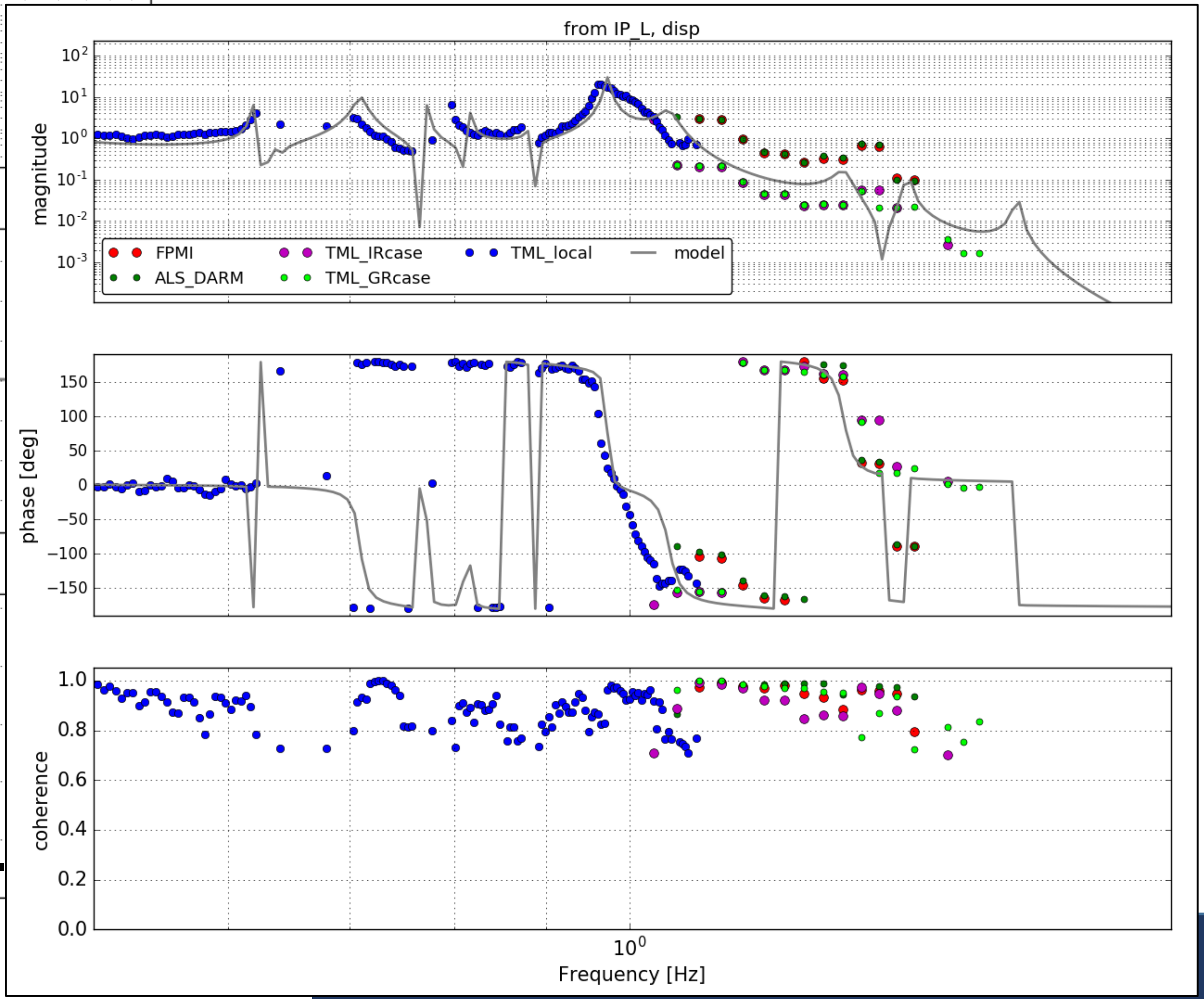


Results: displacement transfer functions, from IPL

It seems that model have to be tuned at 1 to ~1.5Hz region.



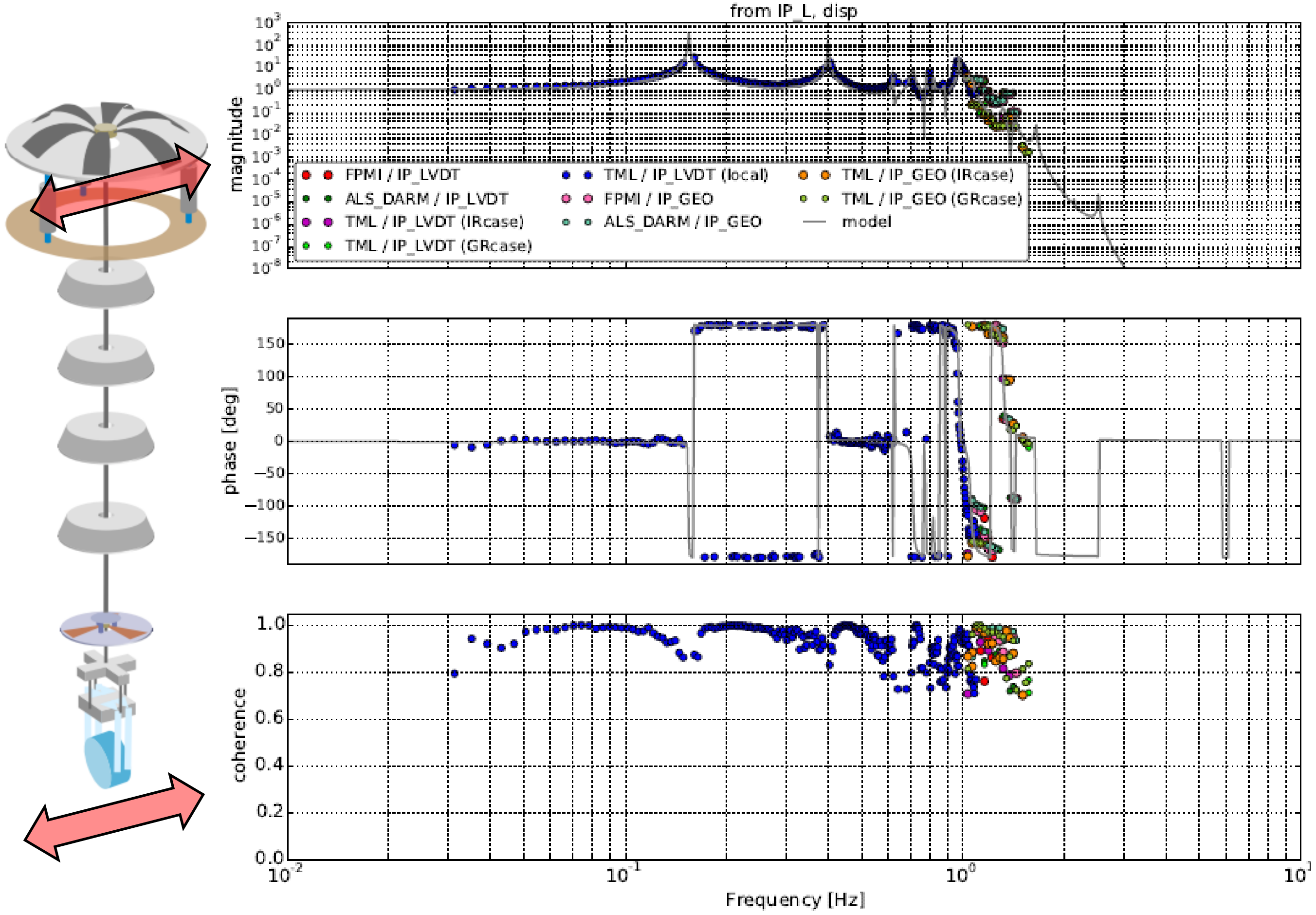
* at 1 to ~1.5Hz region:
 → Not calibration error.
 → It looks coupling from other dofs.

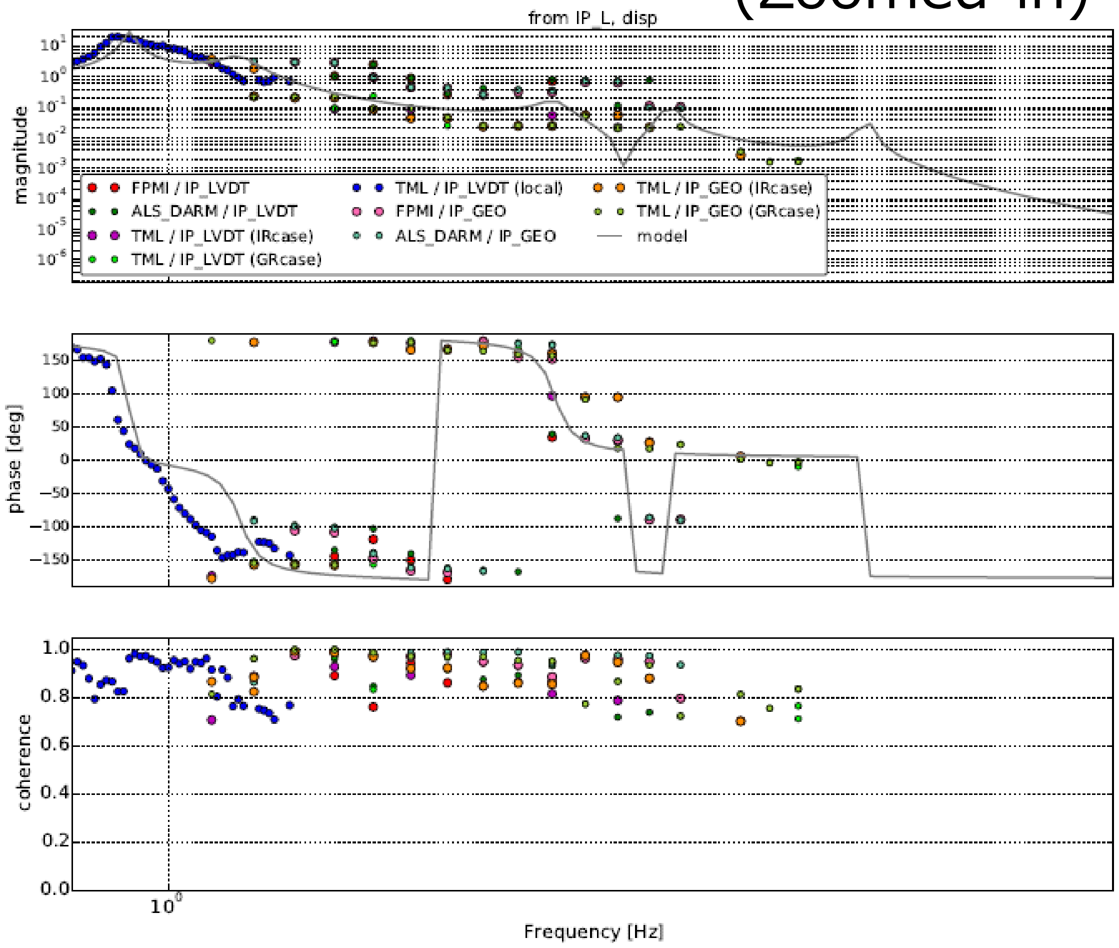


Results: displacement transfer functions, from IPL

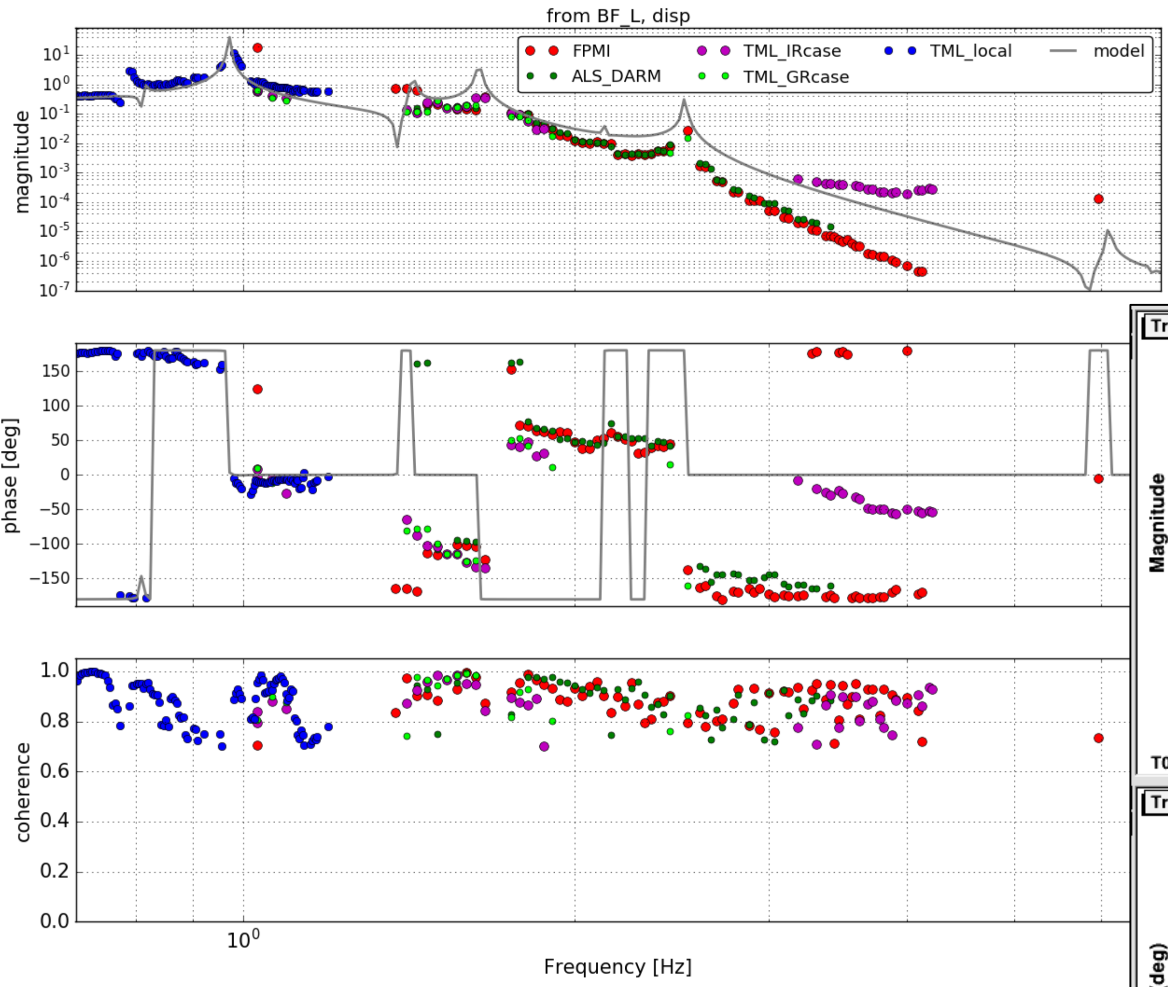
* Including IP(geo) signal.

(Zoomed-in)

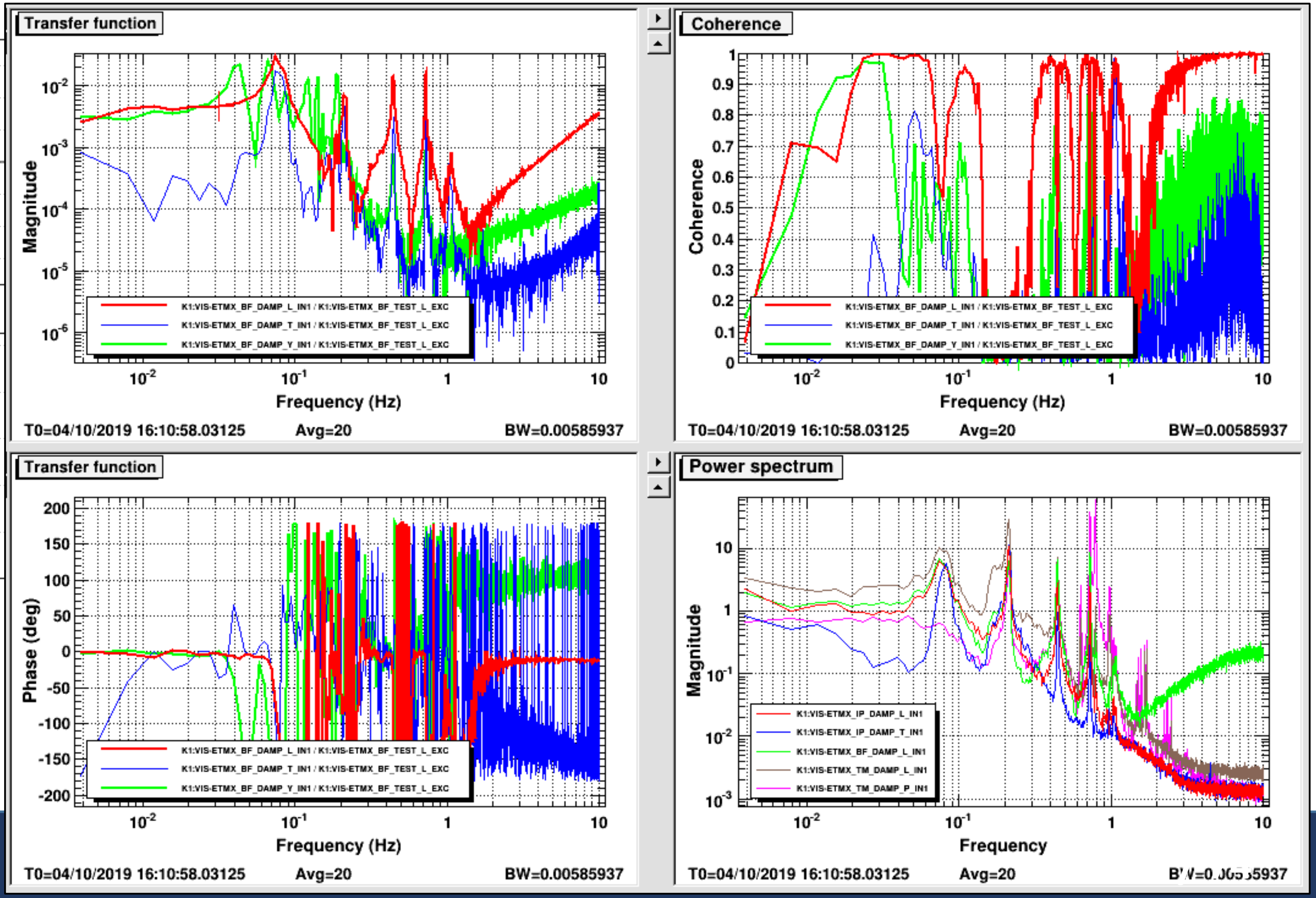




Results: displacement transfer functions, from BFL

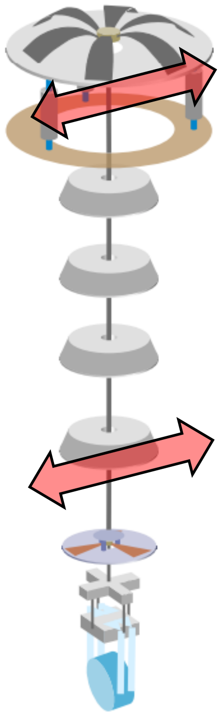


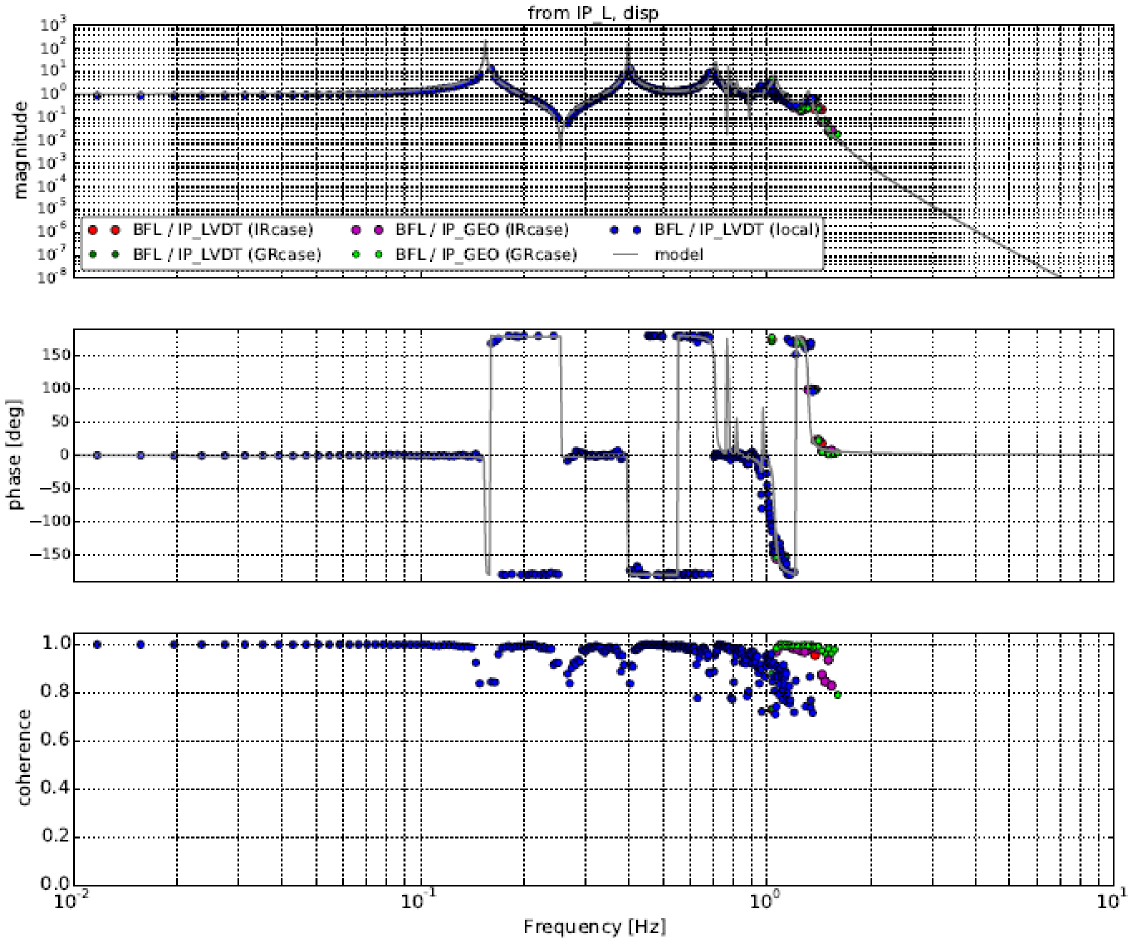
It seems that the discrepancy comes from the issue of LVDT, the direct sensor-actuator coupling.



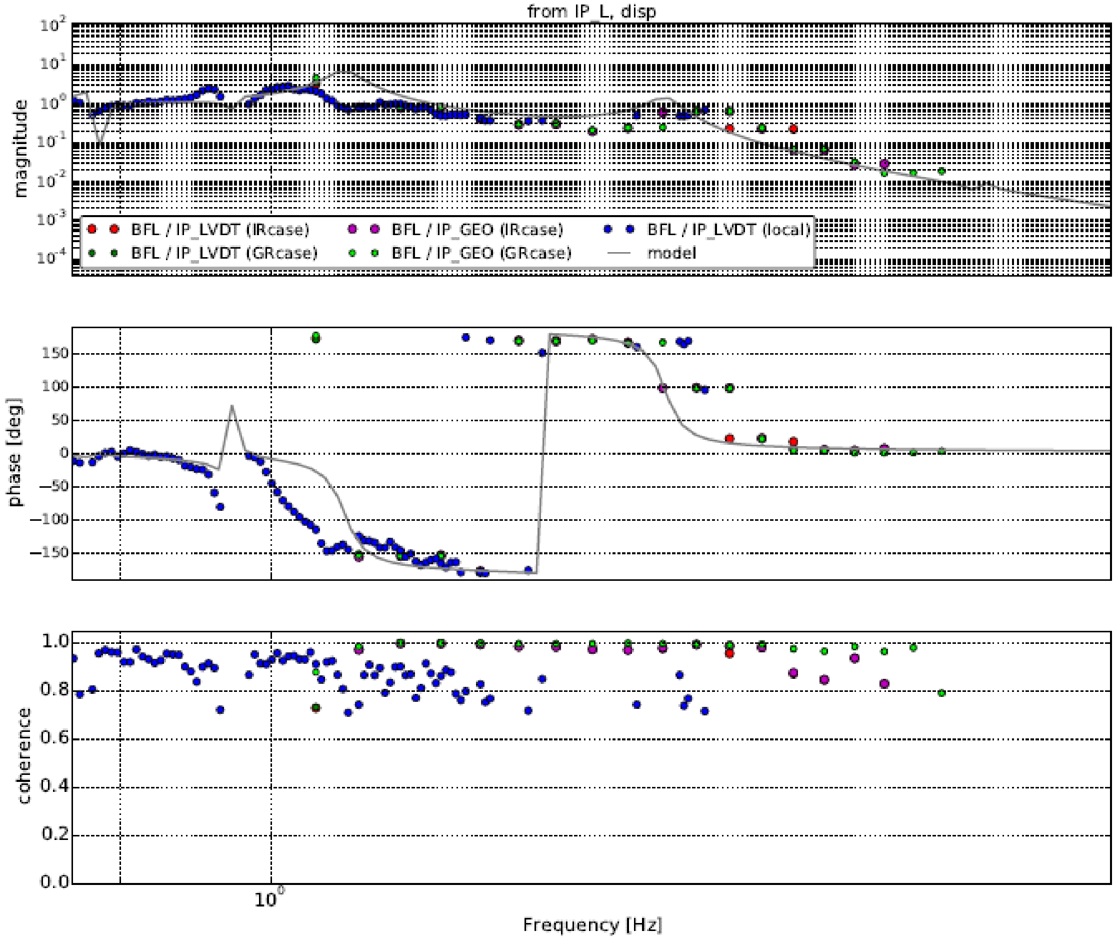
→ Not reliable.

Results: displacement transfer functions, from IPL to BFL





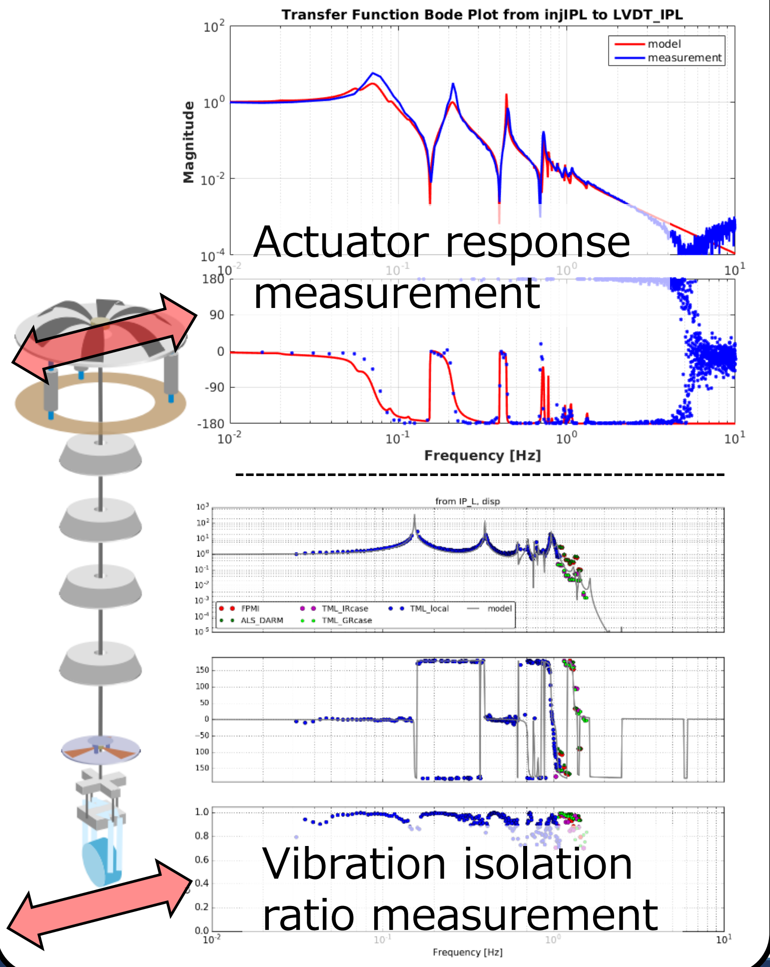
Including IP(geo) signal.



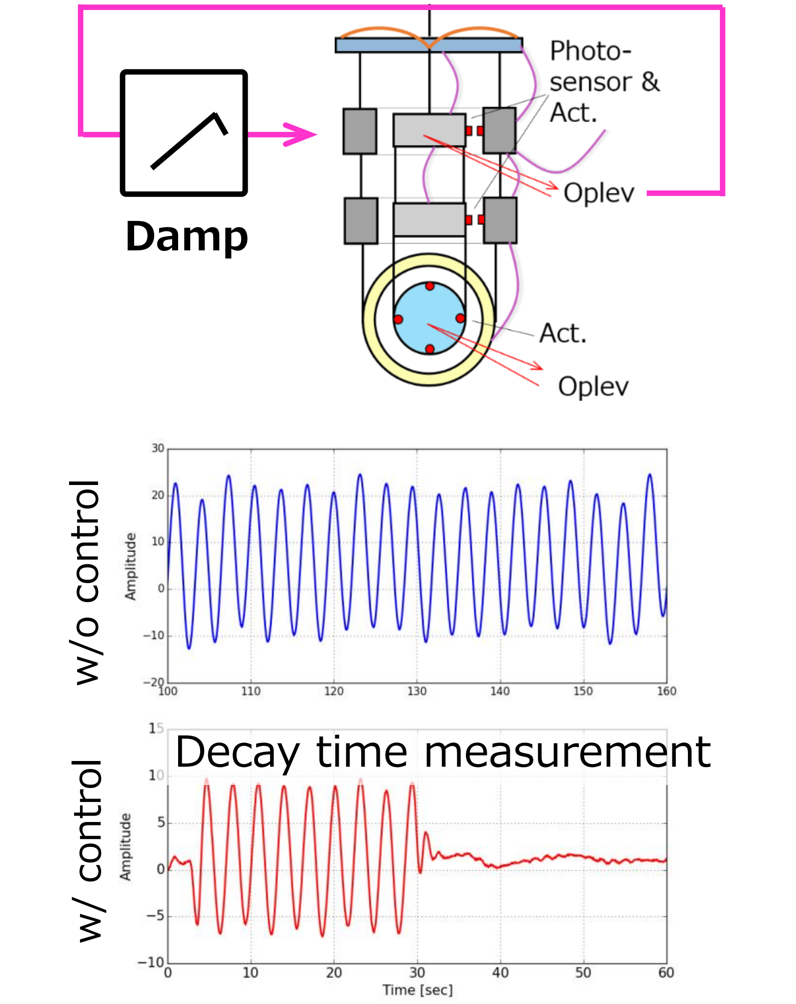
Notes: Resonance damping

My work: Constructing controls toward interferometer lock

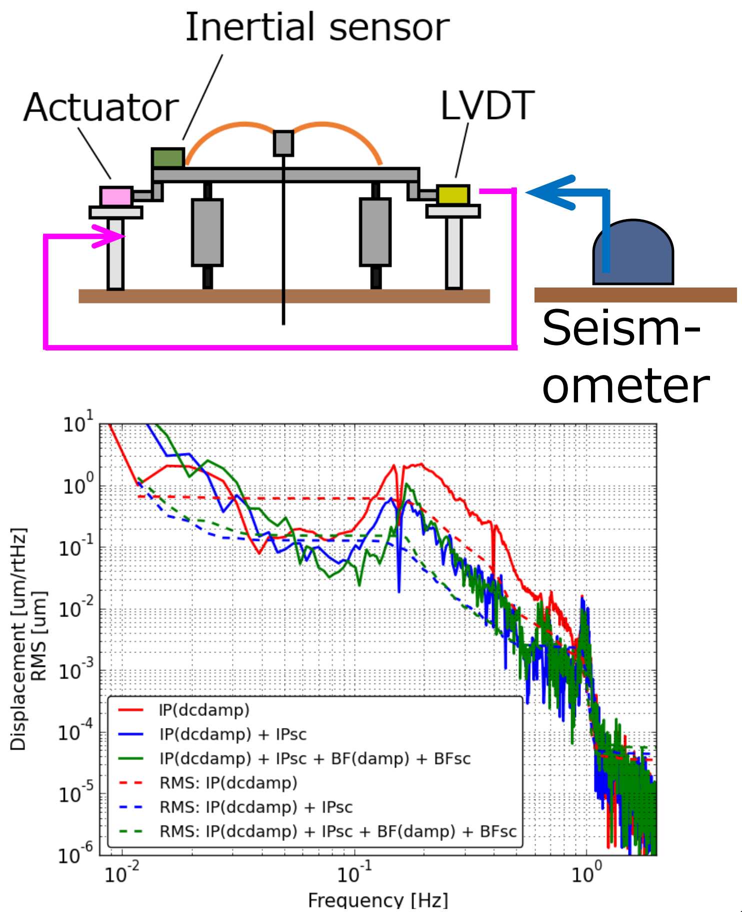
1. Mechanical system characterization



2. Resonance damping

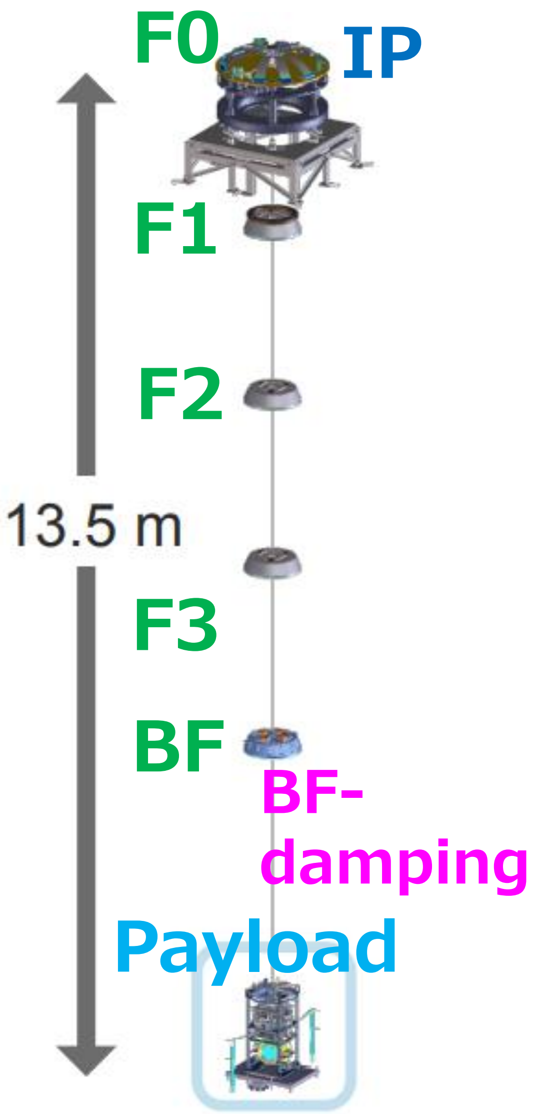


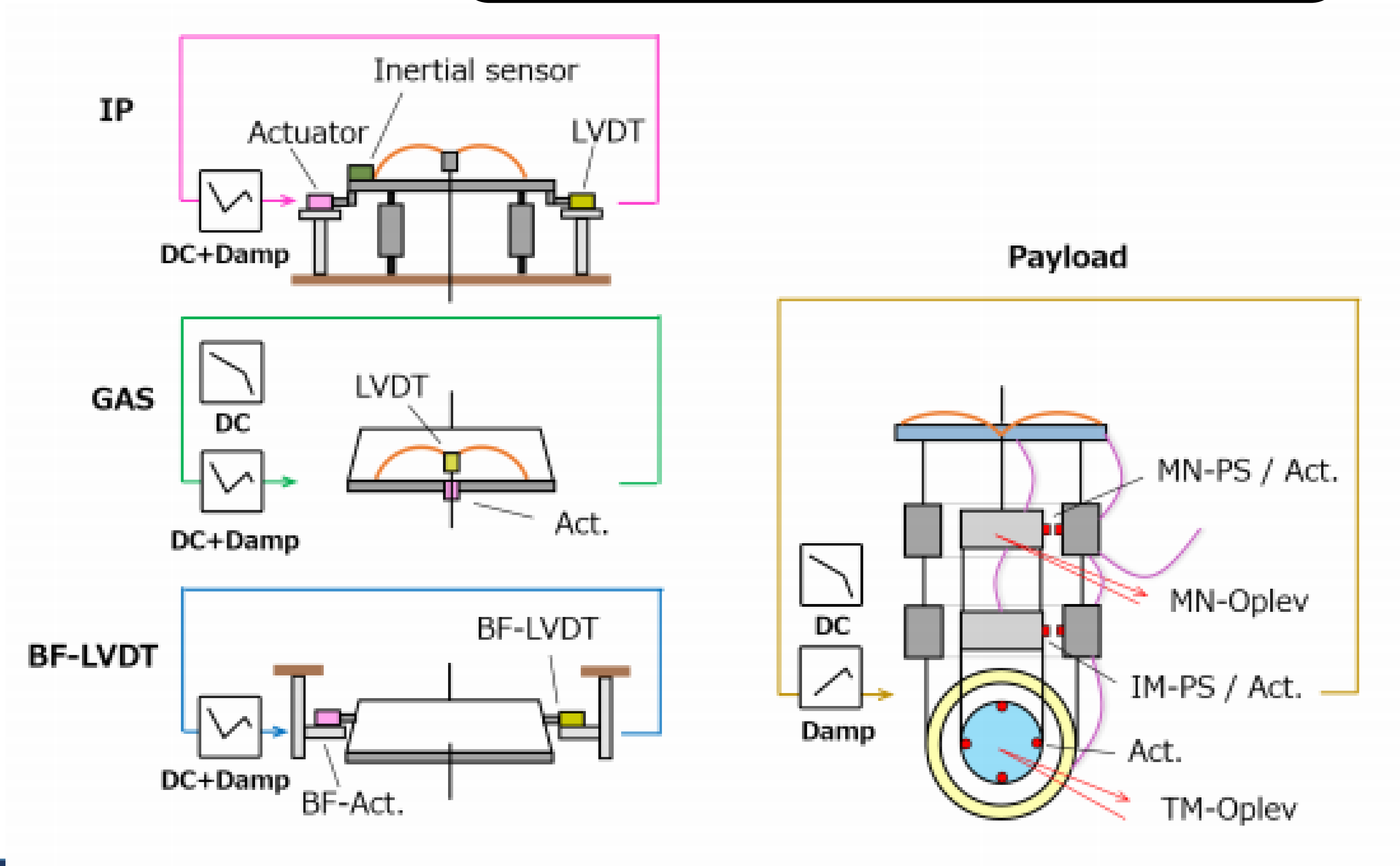
3. Mirror residual suppression



2. Resonance damping:

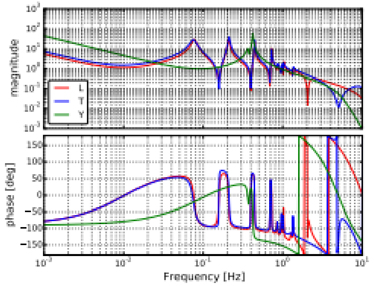
Control system for damping with disp. sensors



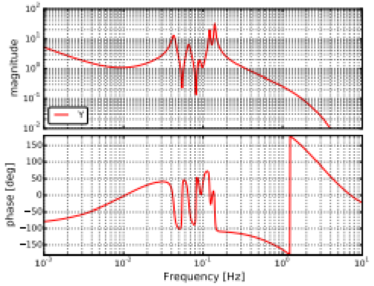


2. Resonance damping:

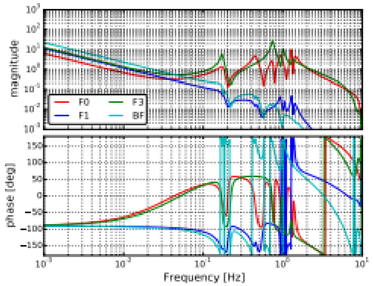
Open loop transfer functions for Control system for damping with disp. sensors



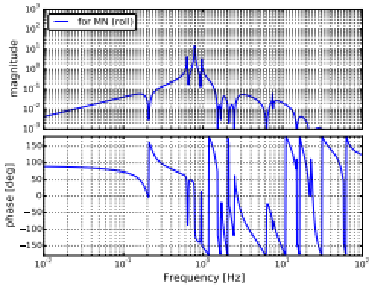
(a) IP loops in L, T and Y dof.



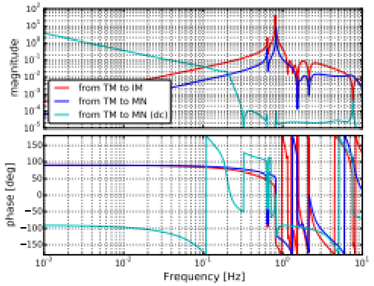
(b) BF loops in Y dof.



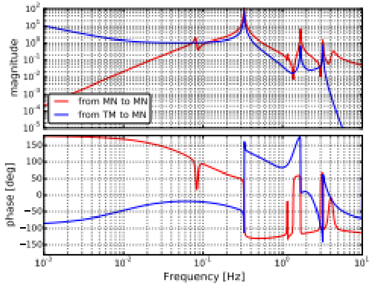
(c) F0, F1, F3 and BF GAS loops.



(d) Payload loops in R dof.

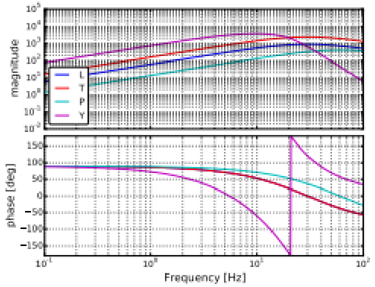


(e) Payload loops in P dof.

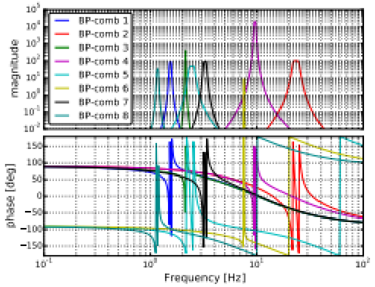


(f) Payload loops in Y dof.

Figure 6.12: Open loop transfer functions of the implemented servo filters for the calm-down phase.



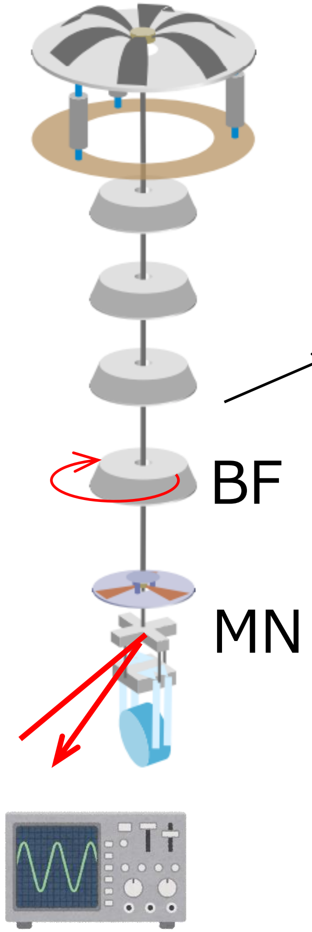
(a) PS loop filters at MN-stage in L, T, P and Y dof.

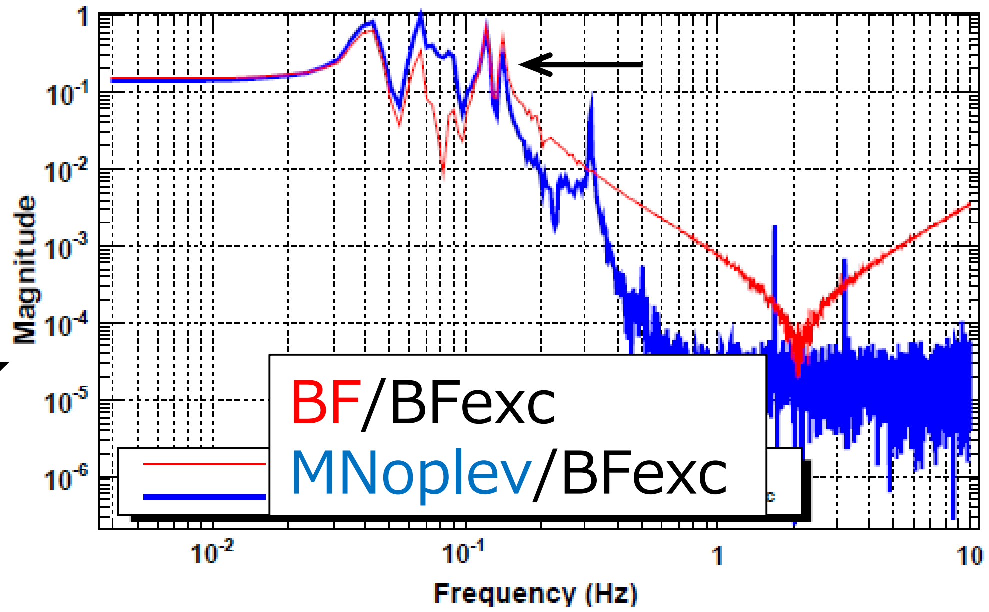


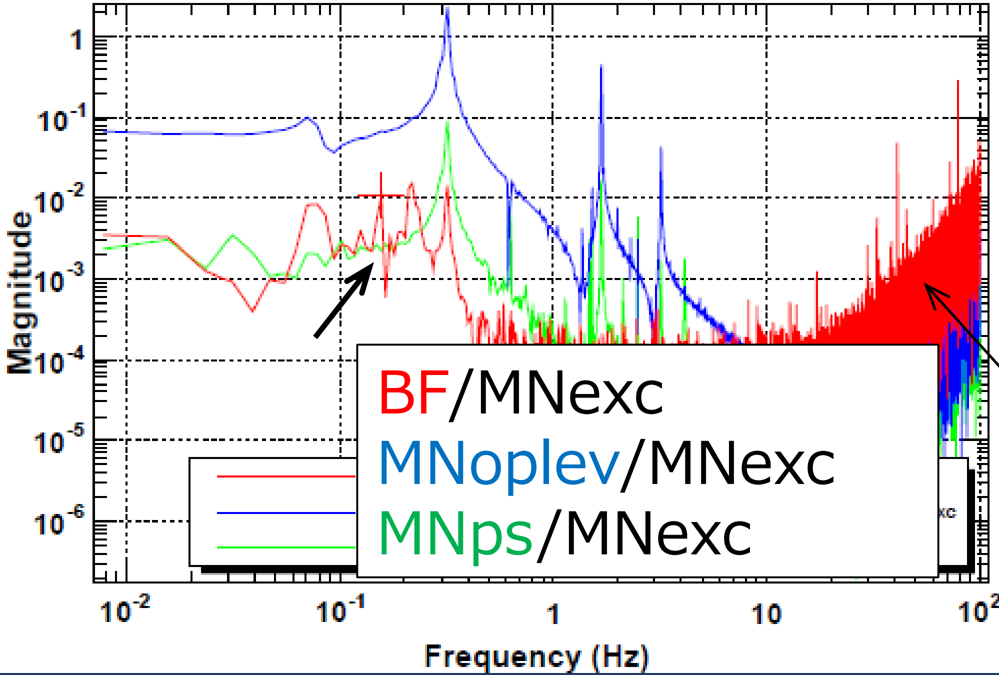
(b) Implemented band-pass comb filters.

Figure 6.13: Implemented servo filters in addition to the ones in Table 6.1.

So, is this unknown Yaw mode problematic for the target?





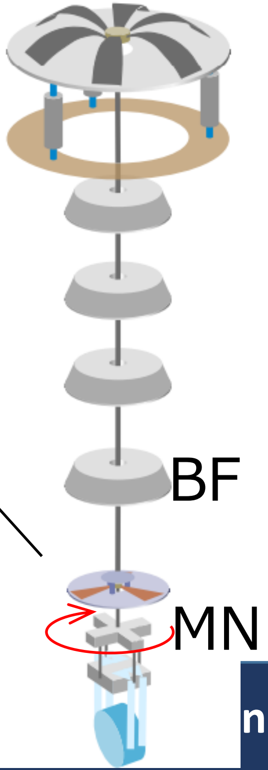


→ No for now, at leaset.
for (current) lock-recovery.

* When noise injected at **BF**-stage:
→ The mode looks exited.

* When noise injected at **MN**-stage:
→ Not (clearly) exited in TM-chain.

* The decay time ~3min.



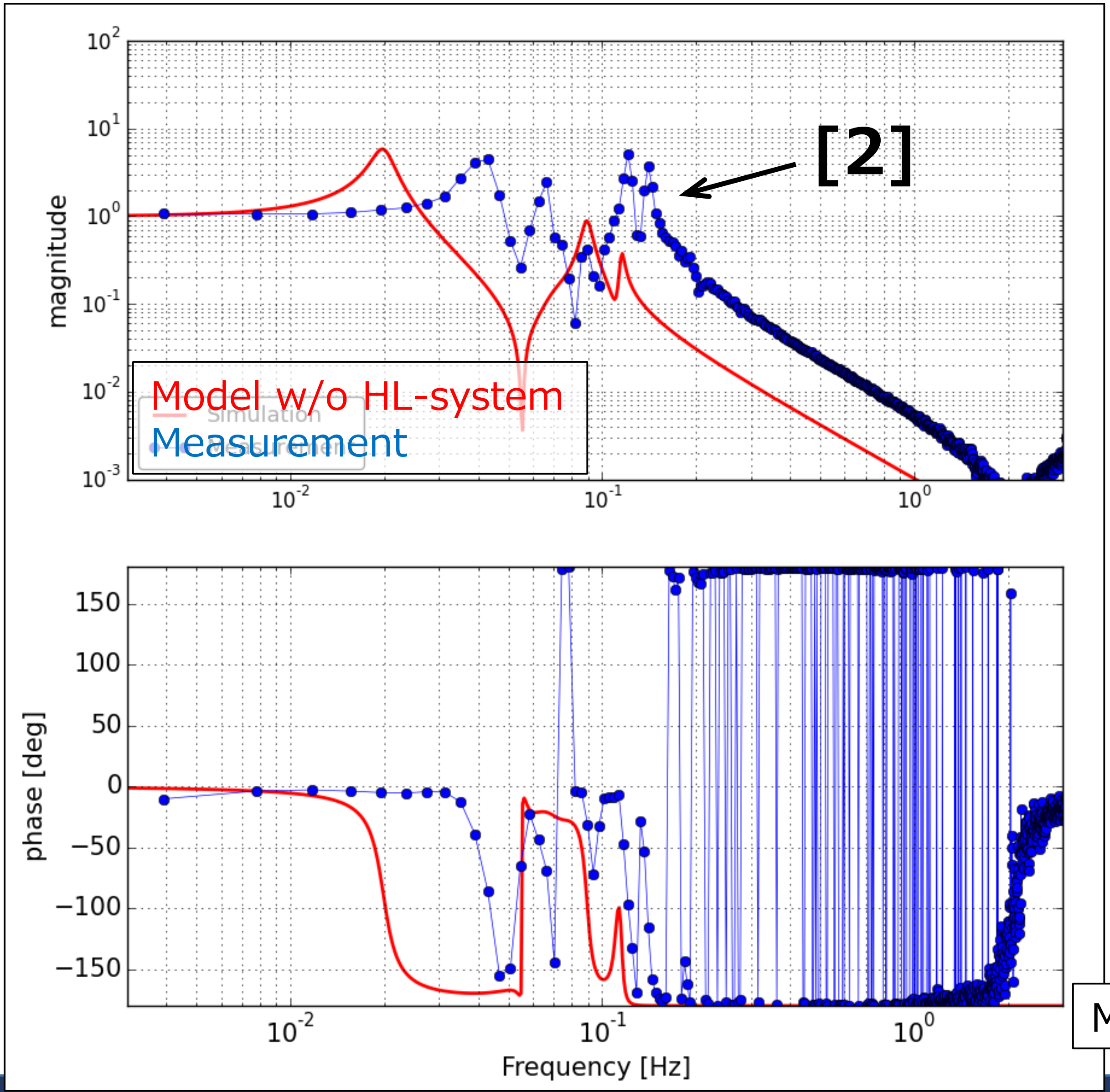
Summary of this work:

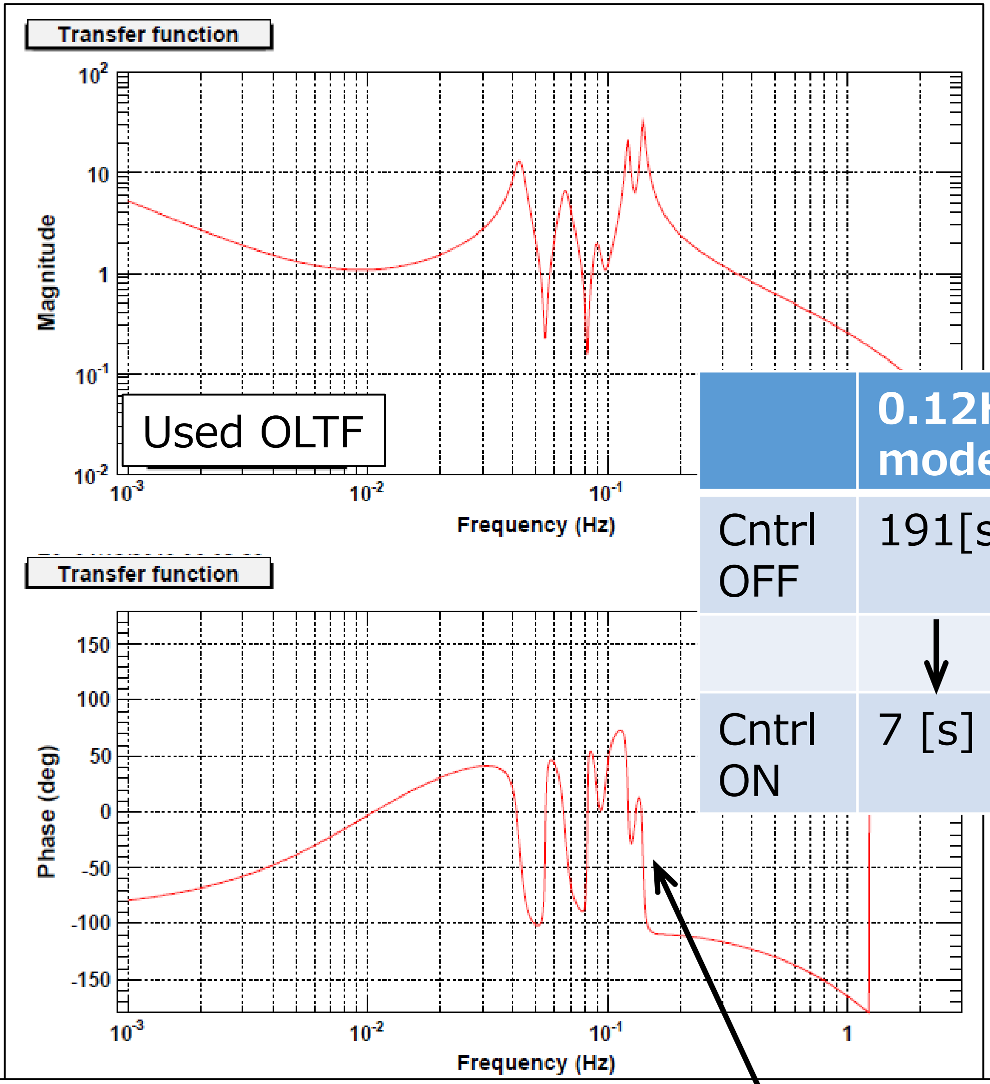
-- The installed damping control system damped all the resonances which disturbs the lock acquisition **for the lock-recovery mode**.

-- exception: one mode
  -- This mode looks from HL-system
  -- This would be problematic when upper stages are used for the global controls. → Further improvement

-- In this work, the payload damping system is constructed mainly with the optical levers (relatively small linear range).
  -- better to utilize Photo-sensors more effectively.

unknown Yaw mode [2]?

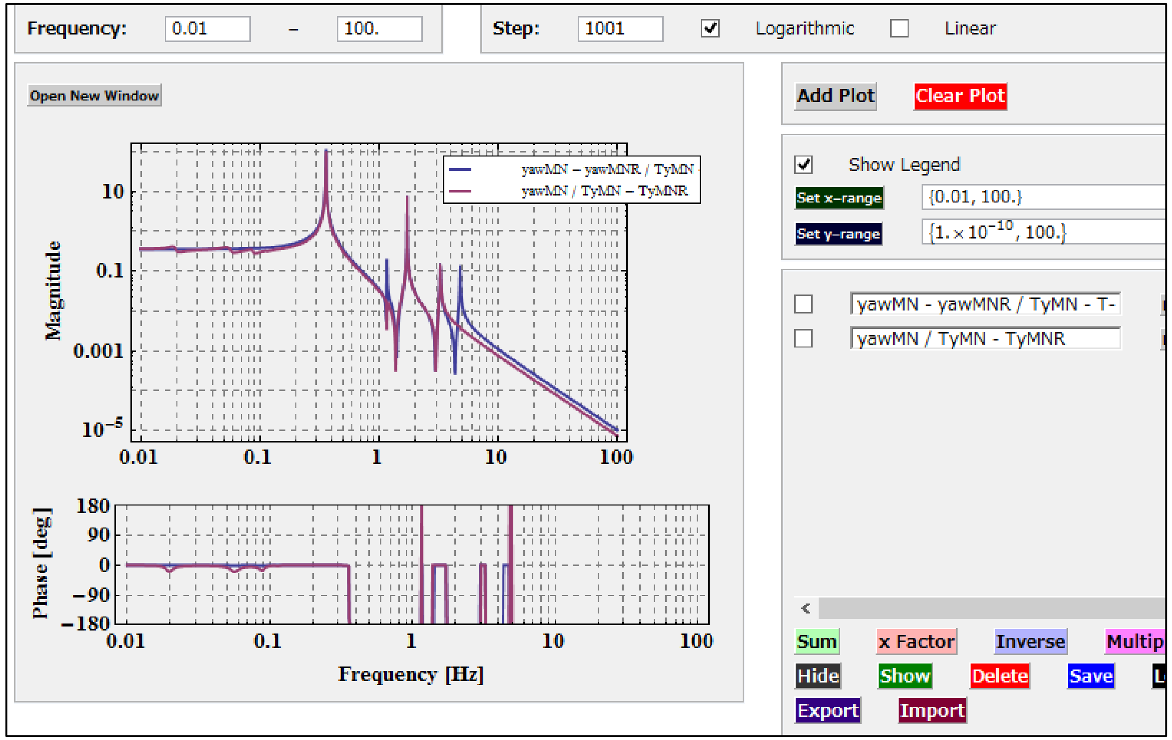




	0.12Hz mode	0.14Hz mode
Cntrl OFF	191[s]	330 [s]
	↓	↓
Cntrl ON	7 [s]	180 [s]

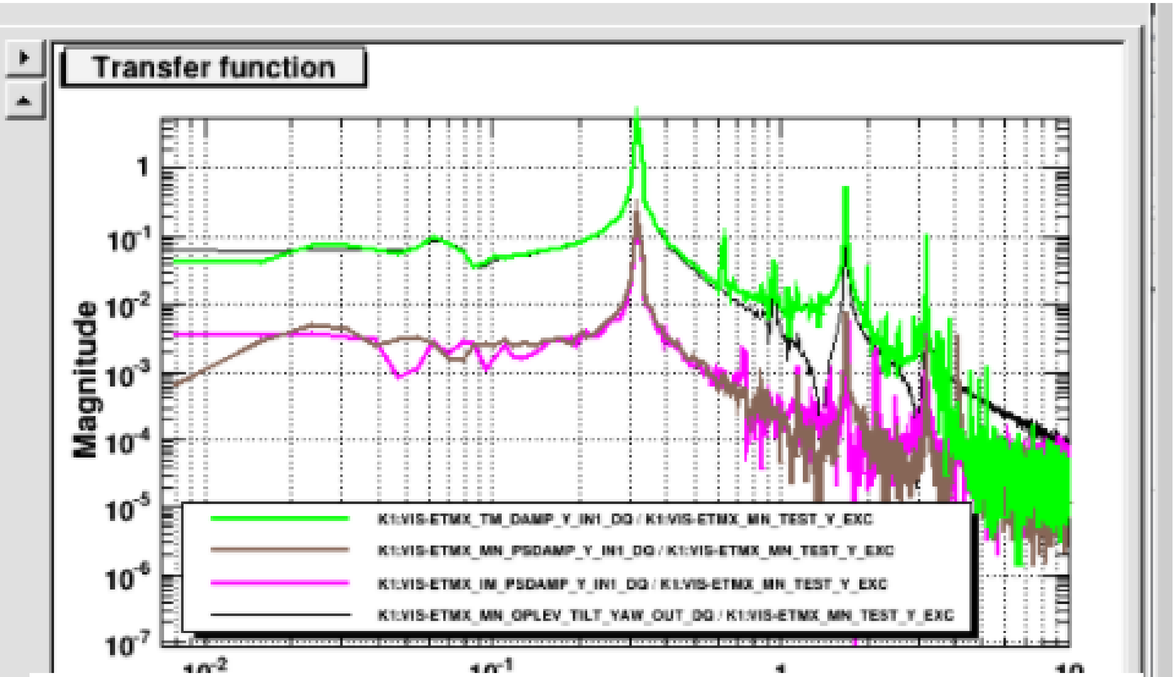
More finely tuned phase compensation might work

Photo-sensor inter-calibration



* According to a simulation,
the following force TFs should
have same DC gain
(since RM-chain is still enough
compared to TM-chain it seemed).

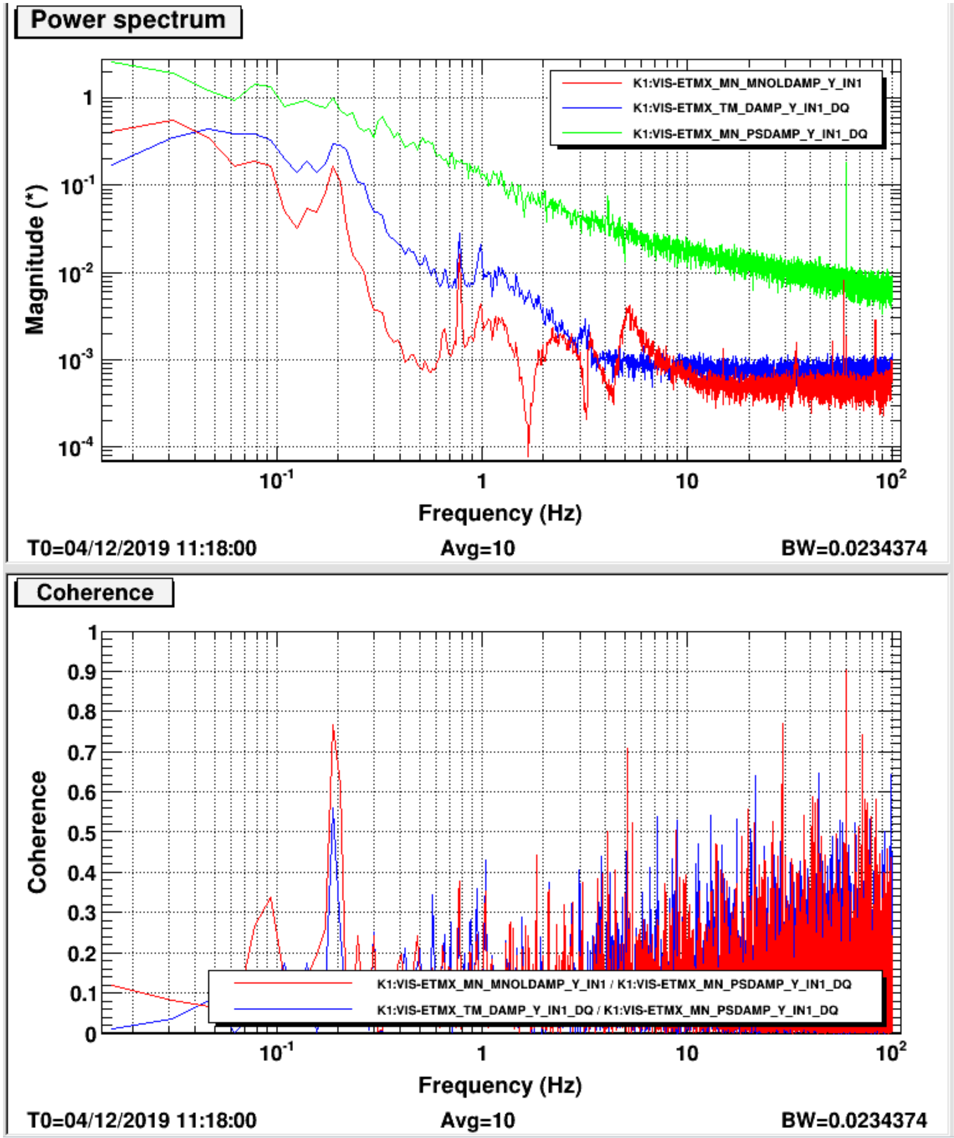
MN(Y)ps/MN(Y)exc and
MN(Y)oplev/MN(Y)exc



(current PSDAMP_IN) * ~20 → urad

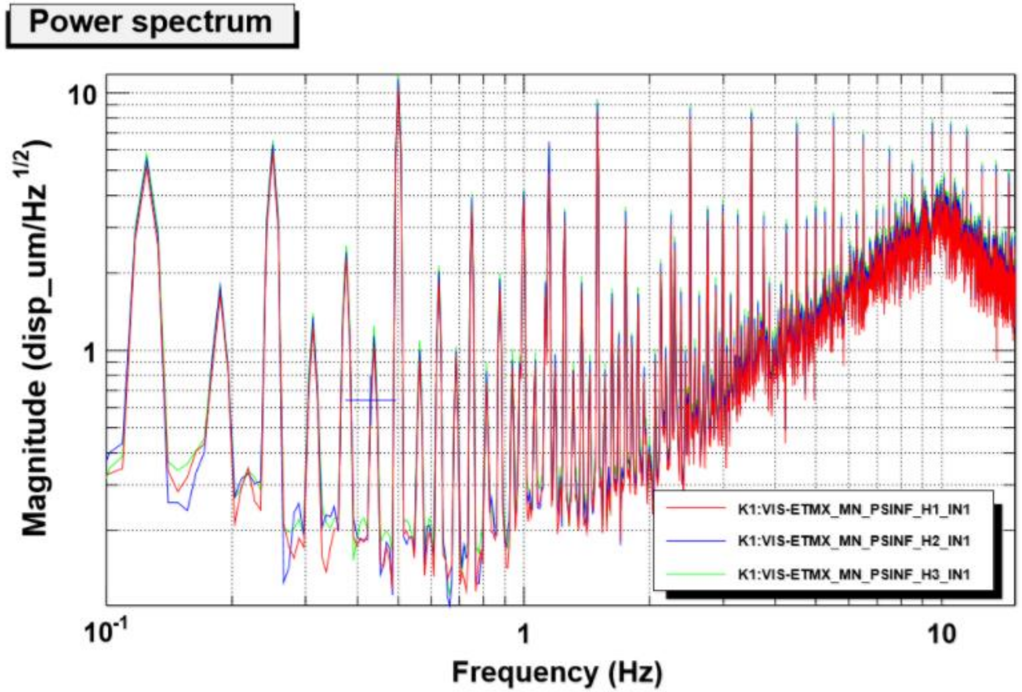
Photo-sensor inter-calibration

[urad/rtHz]



* Spectra w/ the calibration factor.
* Might be too large (a bit) though, direction looks okay.

Roughly estimated

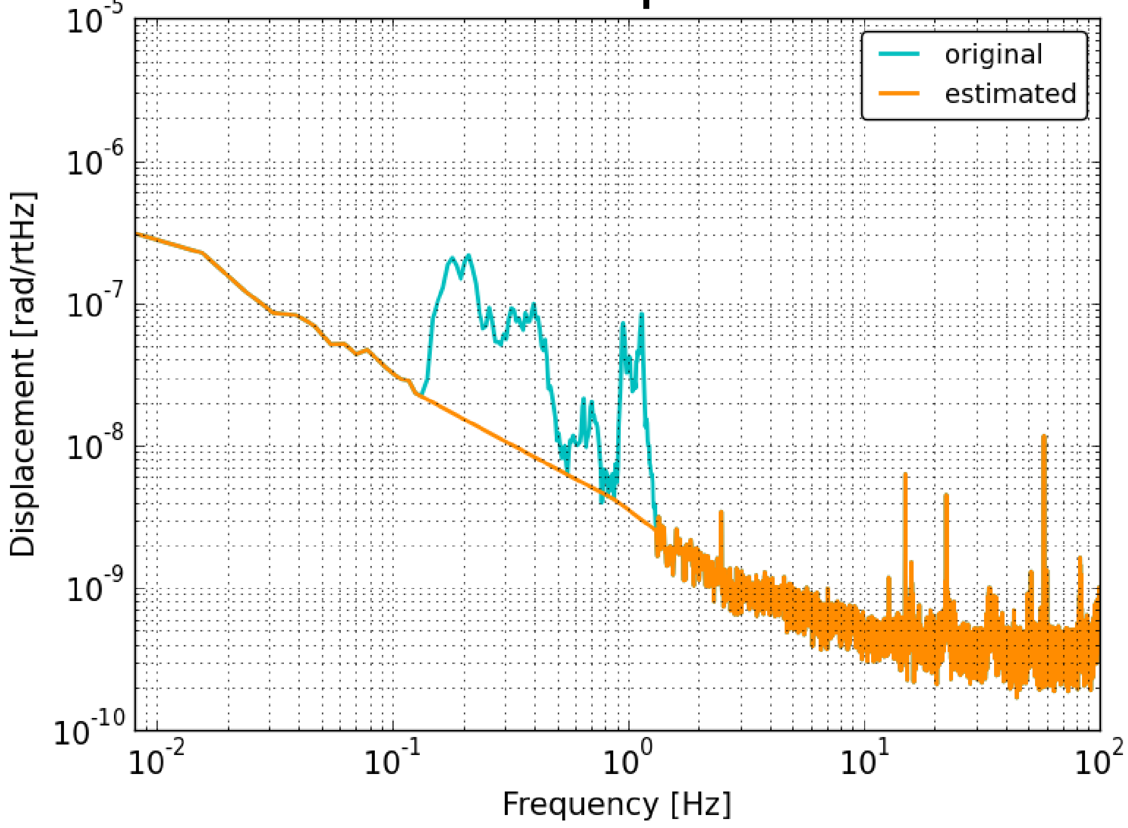


* We have to keep in mind that the PS in ETMX becomes sometimes crazy though.

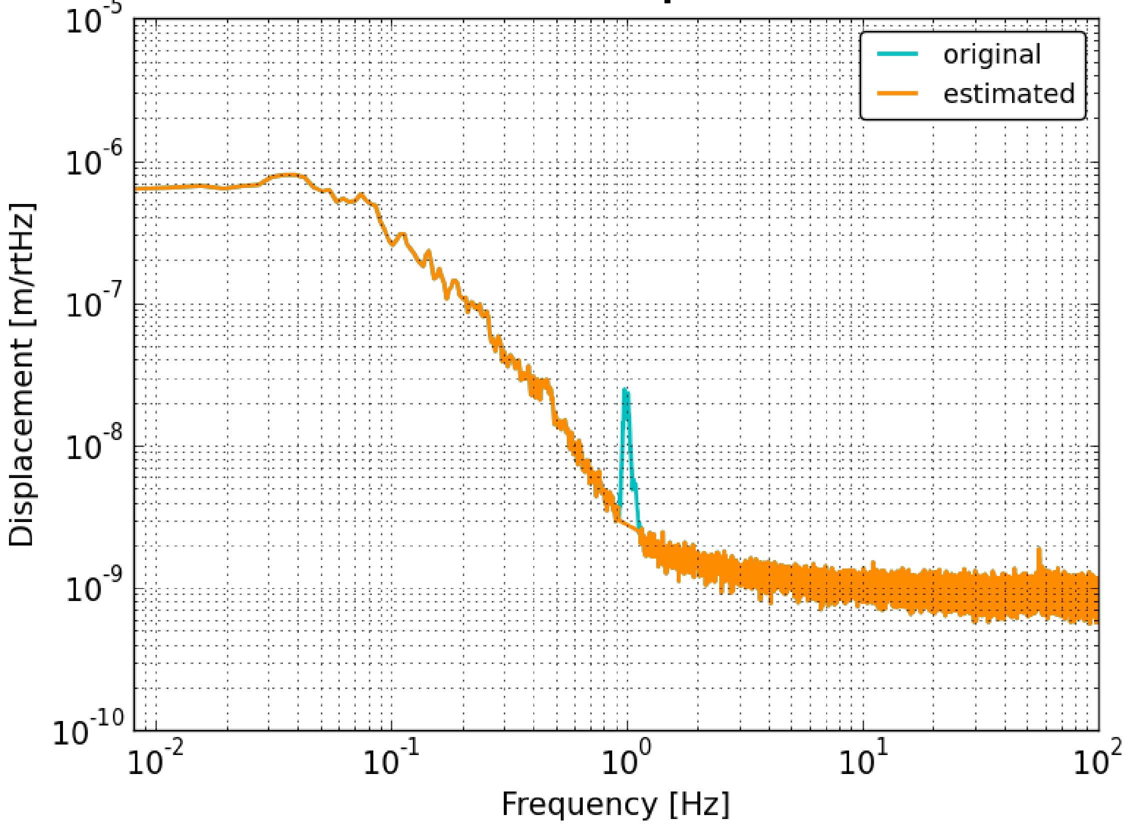
Optical lever noise floor:

* Obtained with interpolation: (~~Estimated~~ → interpolated)

MN-oplev

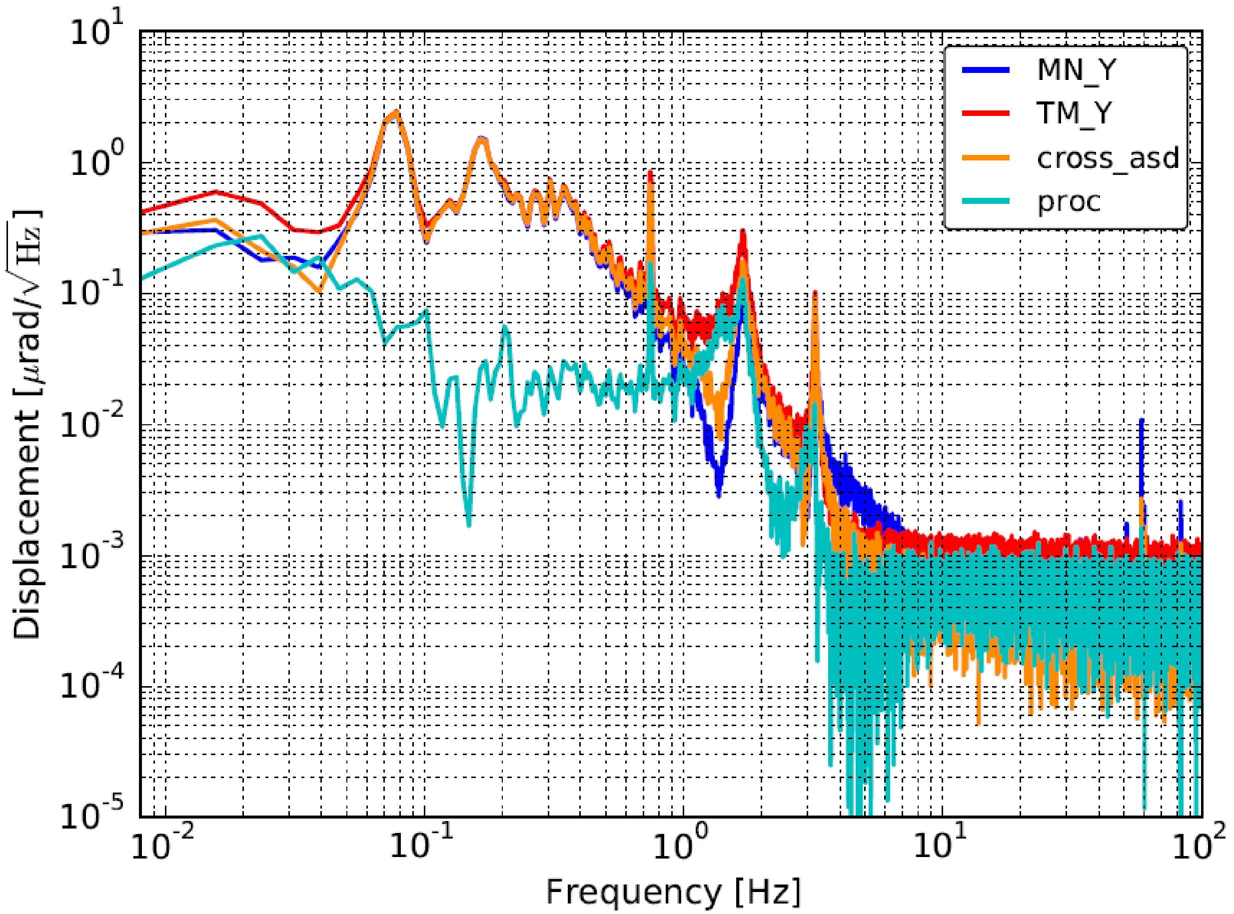


TM-L-oplev



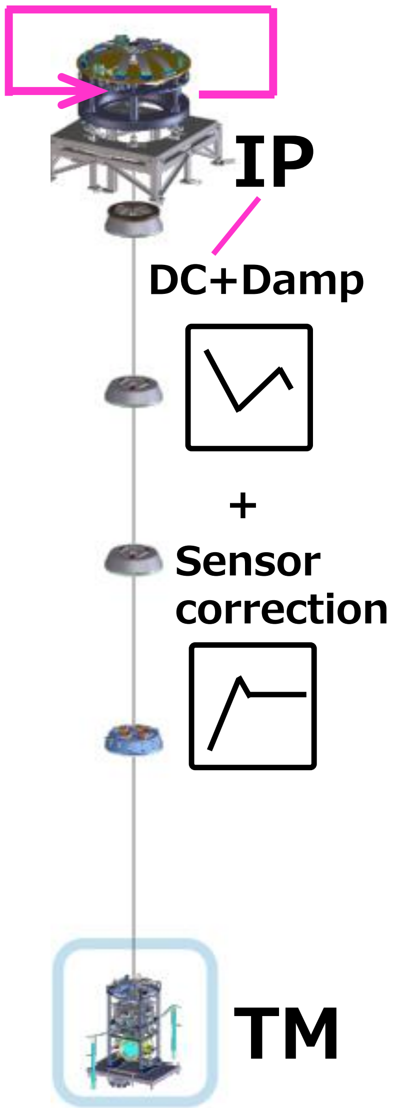
Optical lever noise floor:

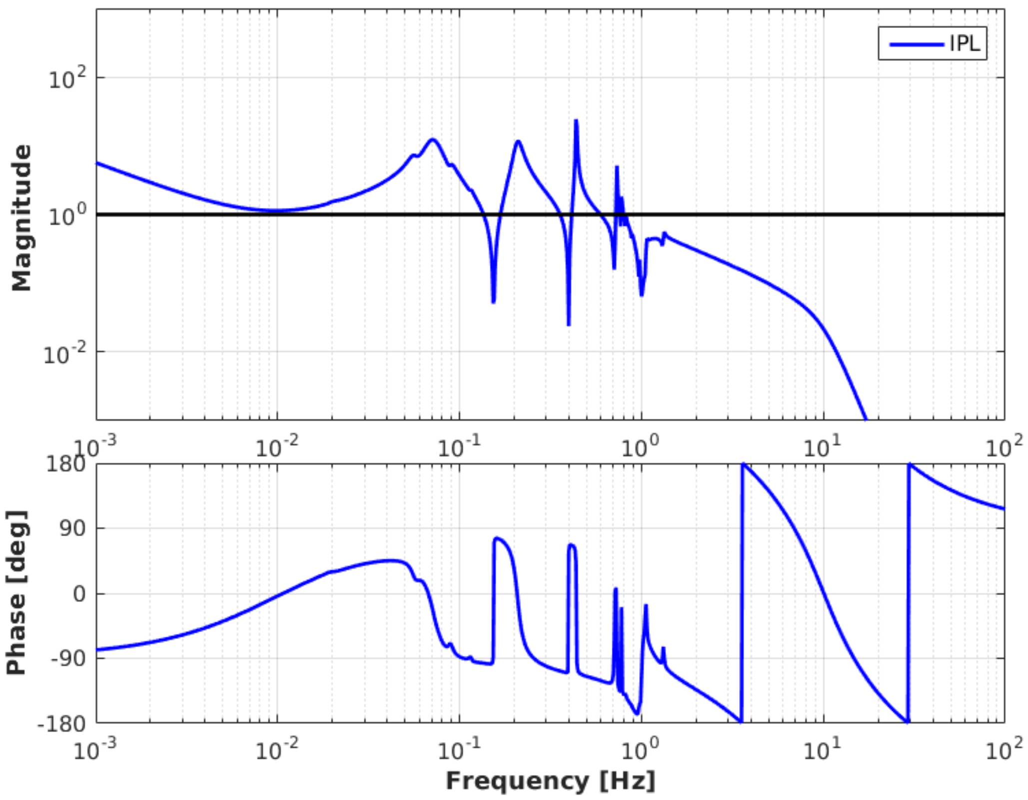
* Obtained with correlation analysis (TMY_ASD – MNY_cross_ASD):

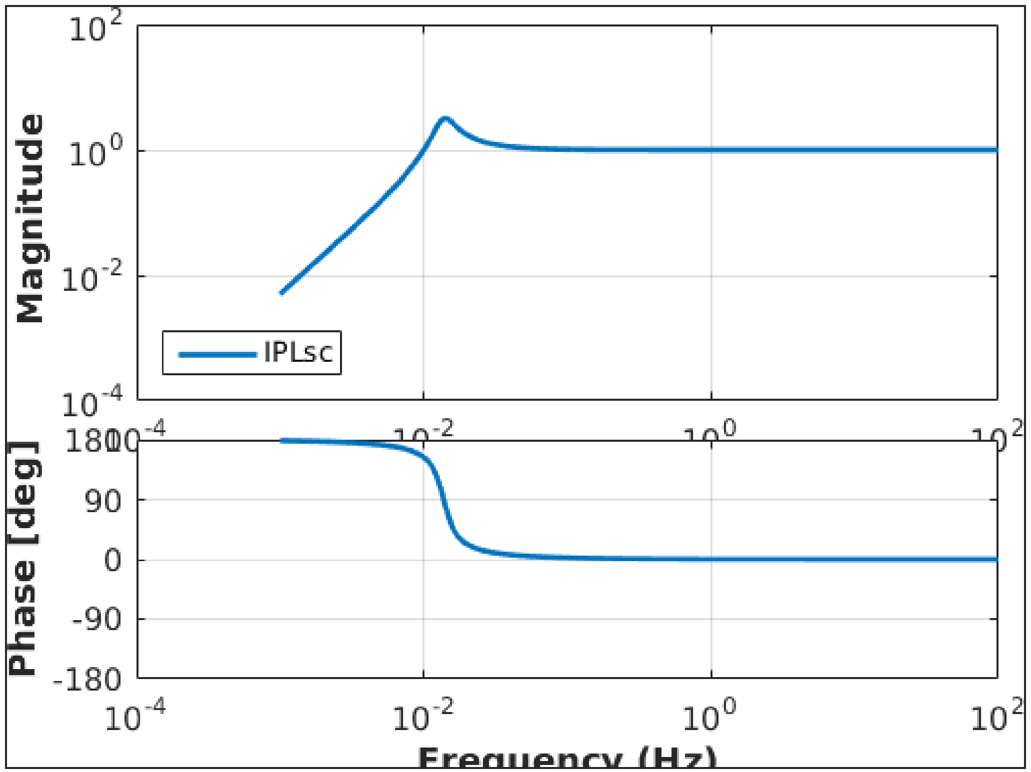


Notes: RMS suppression

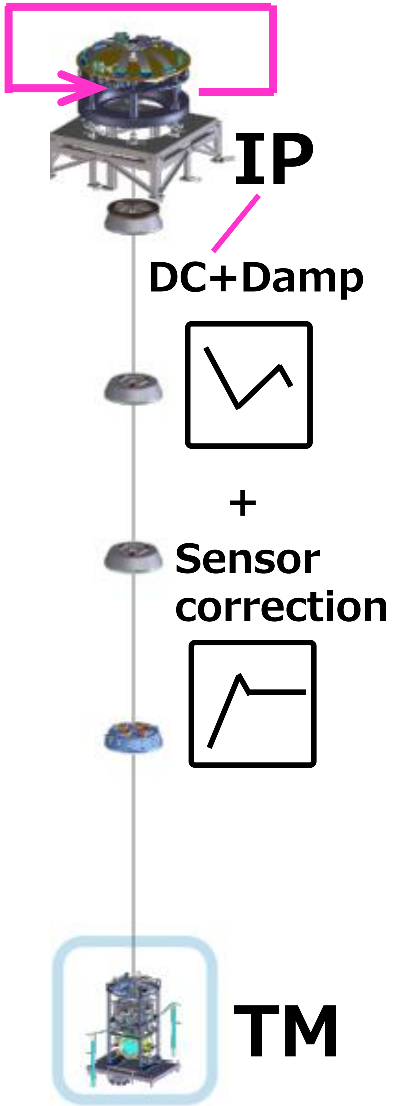
制御ループ at IP-stage:

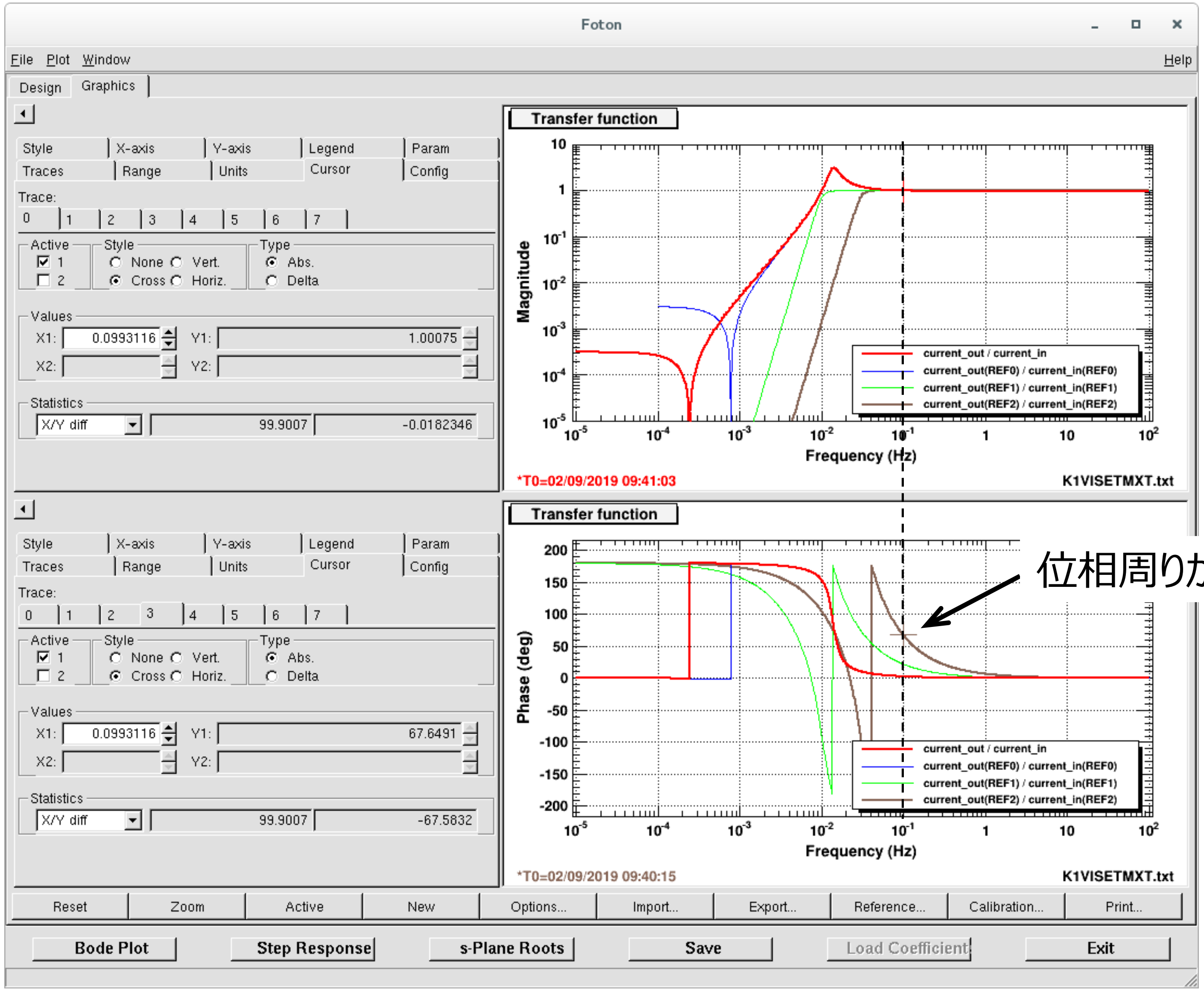






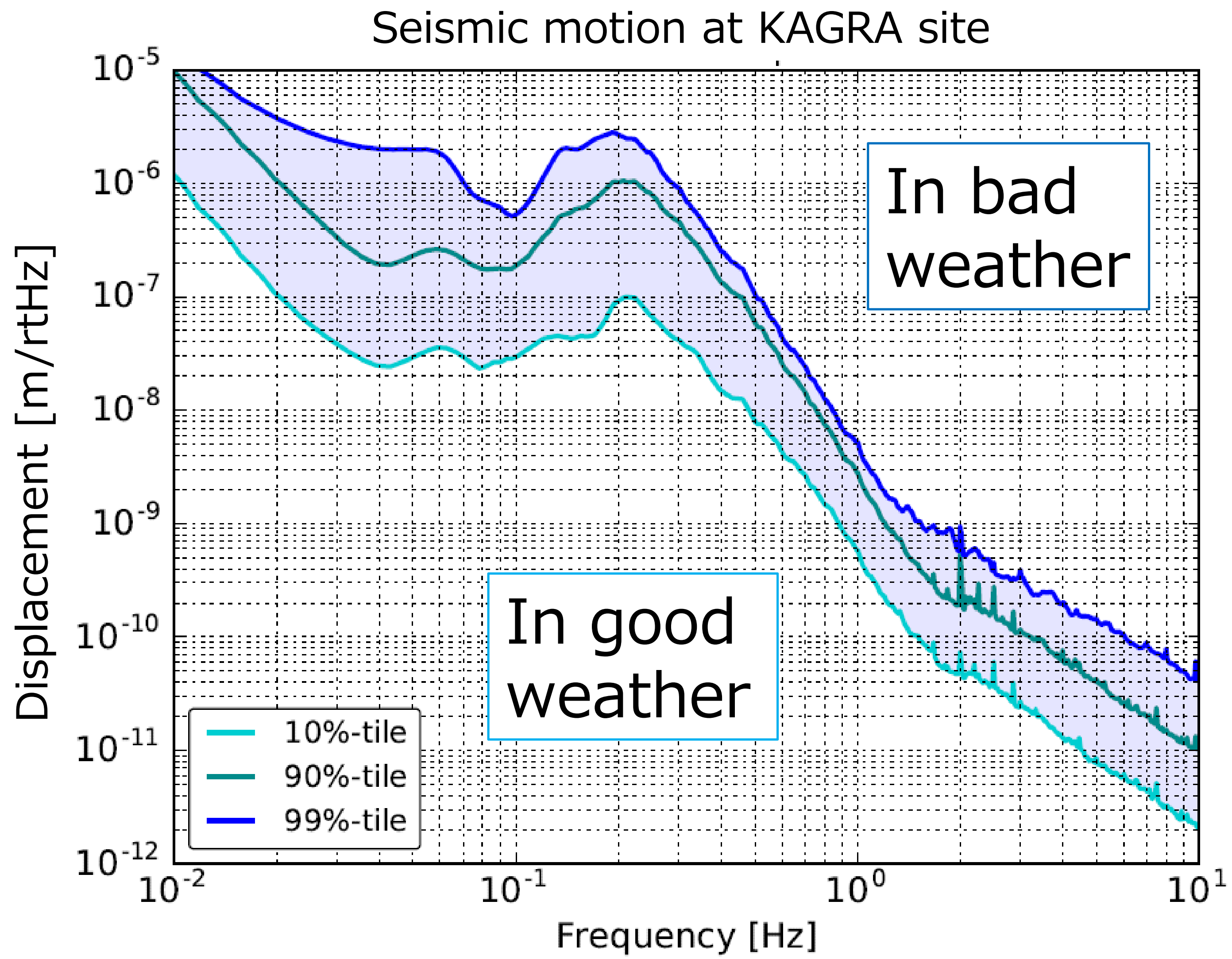
Sensor correction filter の検討



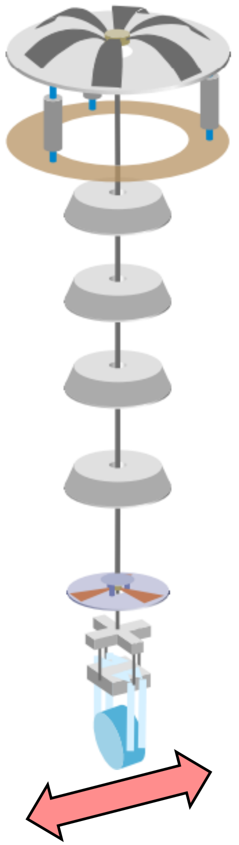


位相周りがなるべく少ないものを採用した。

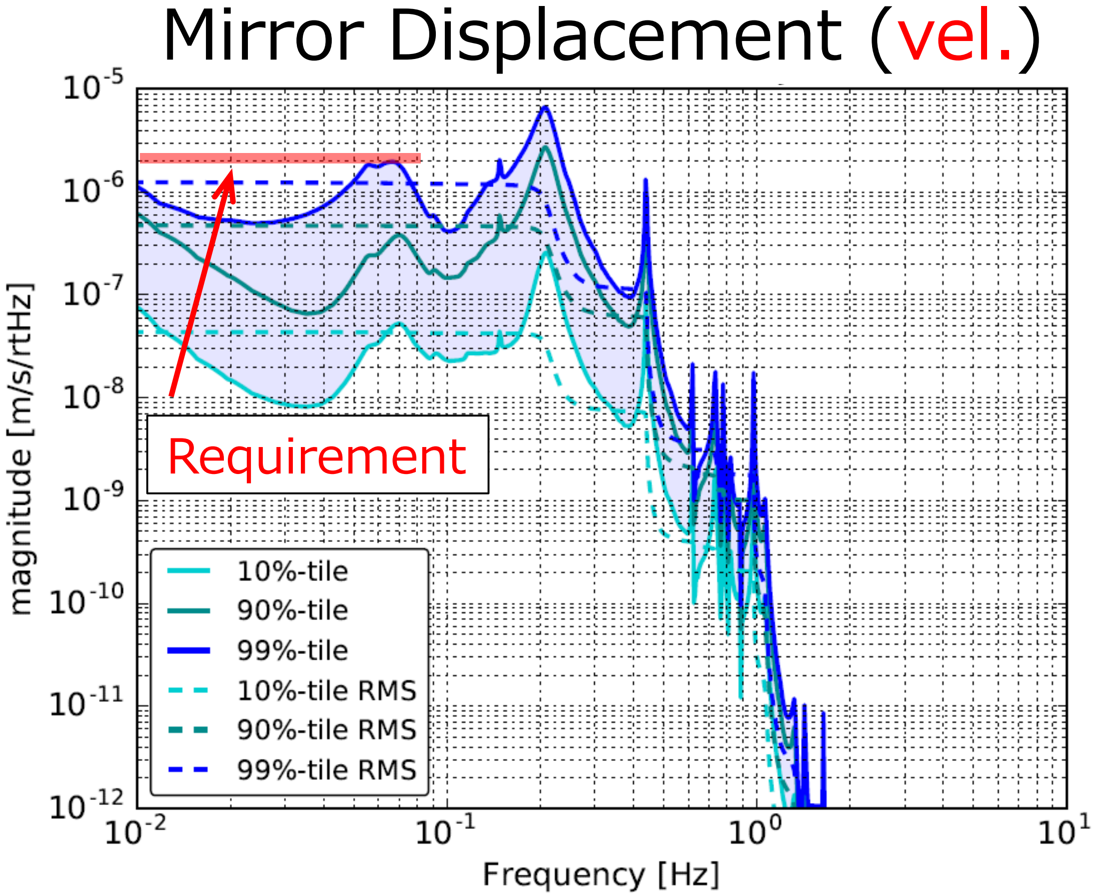
Ground motion at KAGRA site

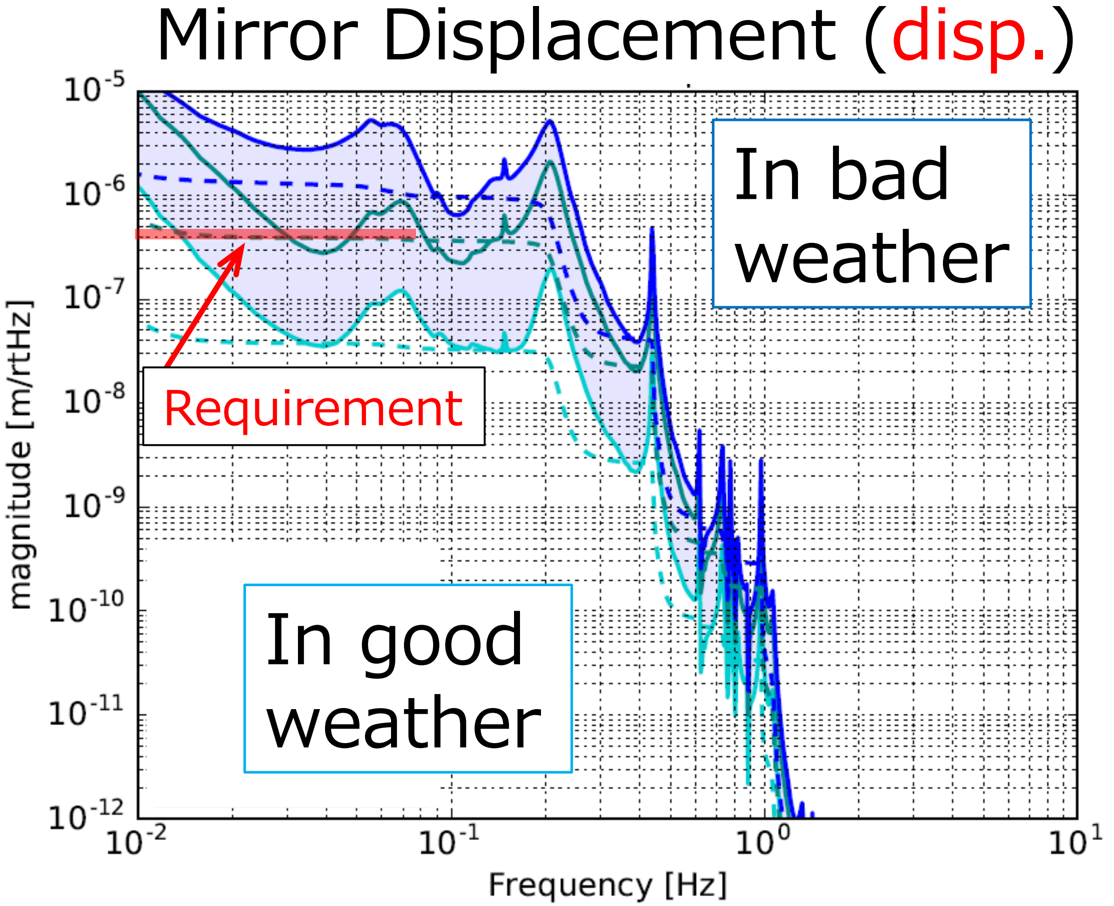


Suspension response at KAGRA site w/o control



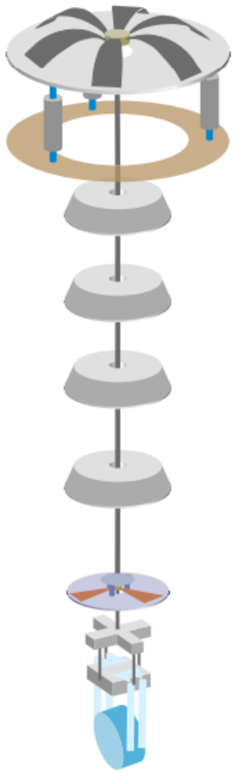
* Simulated mirror residual motion:



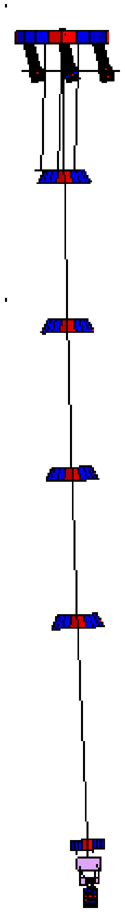


Ref: https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=10436

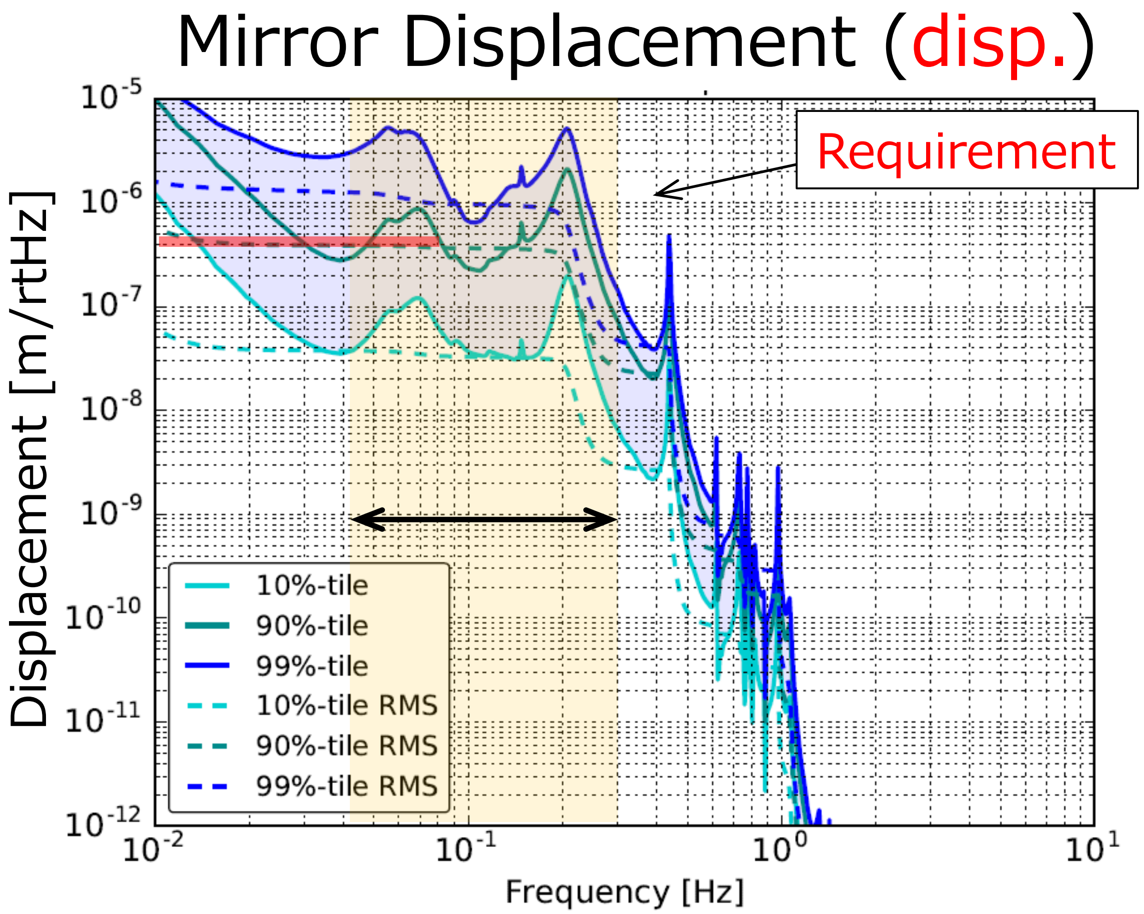
Suspension response at KAGRA site w/o control



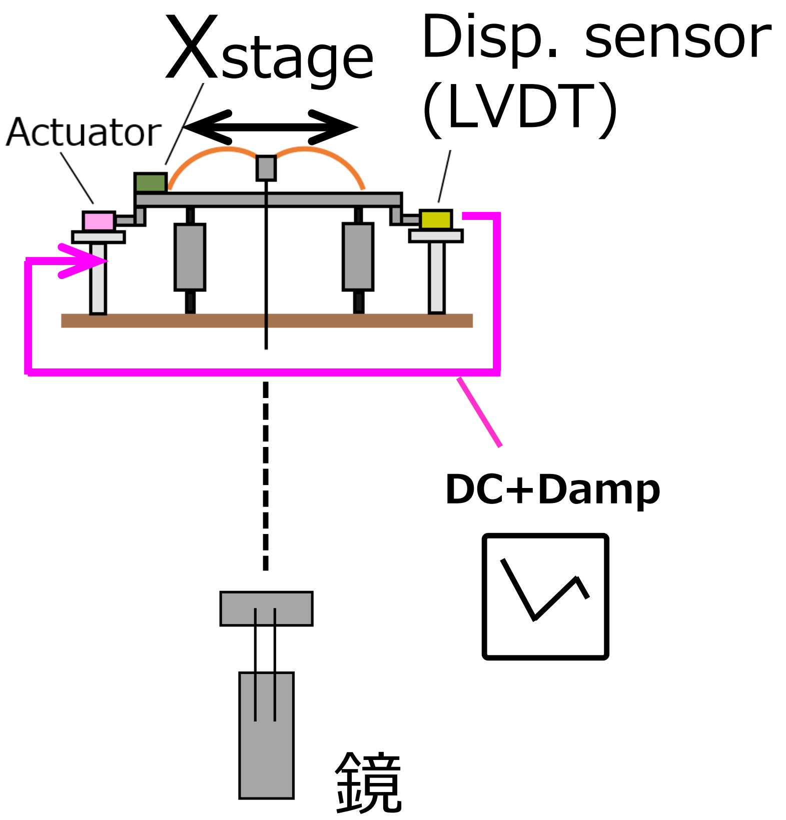
* In good weather
  → req. will be satisfied.
* In bad weather (especially in winter)
  → req. will not be satisfied
* Contribution to RMS is large in the band.
  → To be suppressed
  → at upper stage.

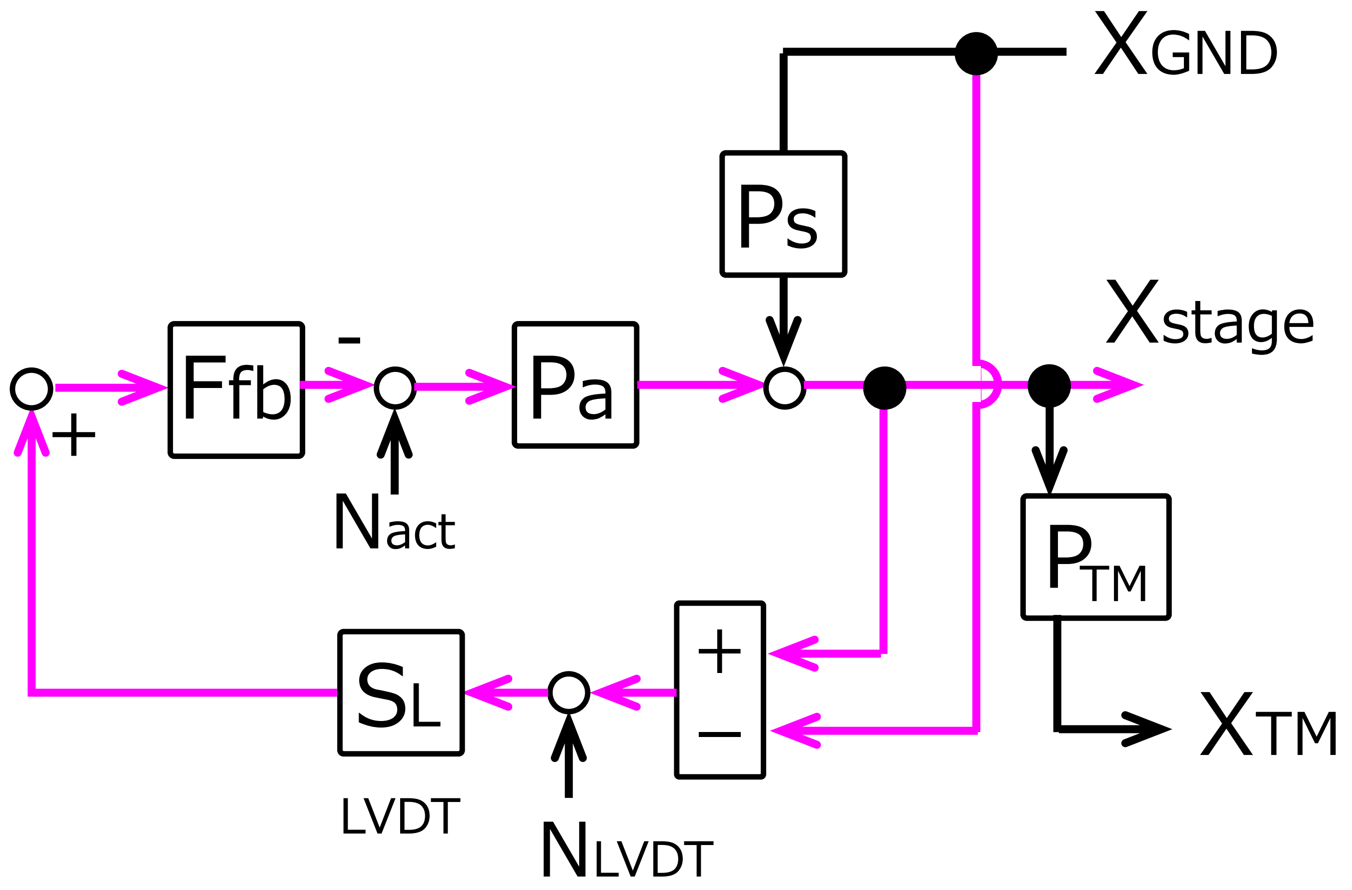


0.2 Hz mode



Control overview (in L):

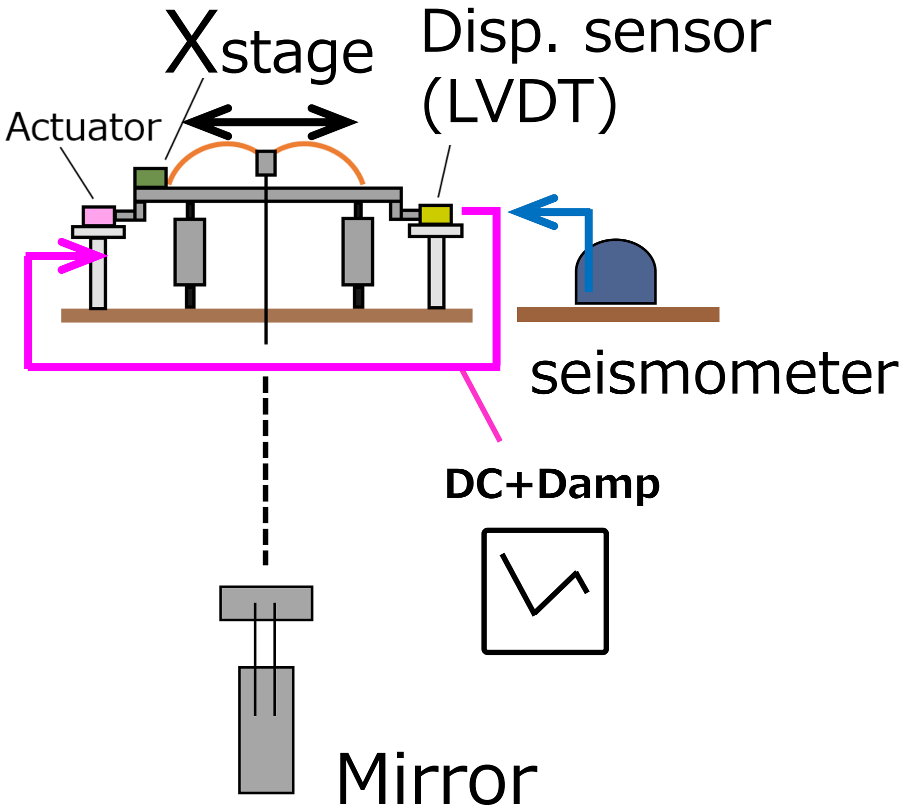


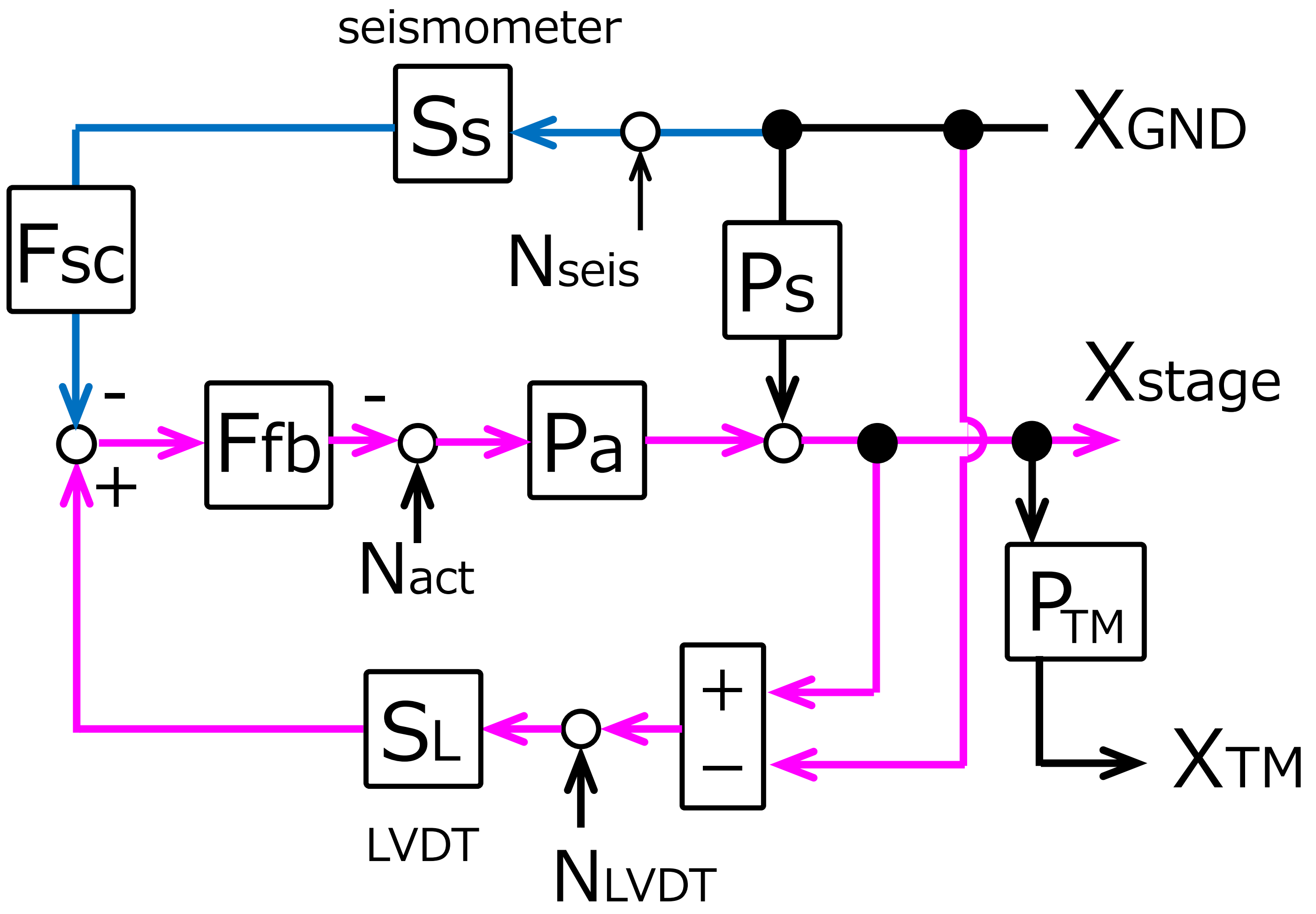


Disp. sensor uses:

$(X_{stage} - X_{GND}) \longrightarrow X_{stage} \sim X_{GND}$

Control overview (in L):

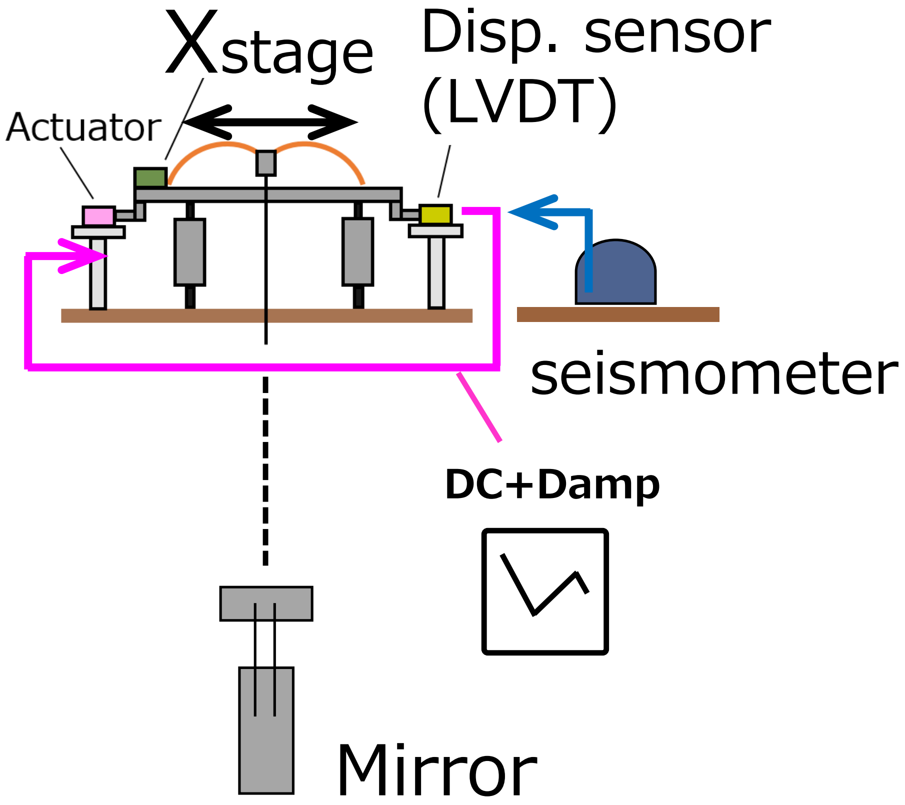


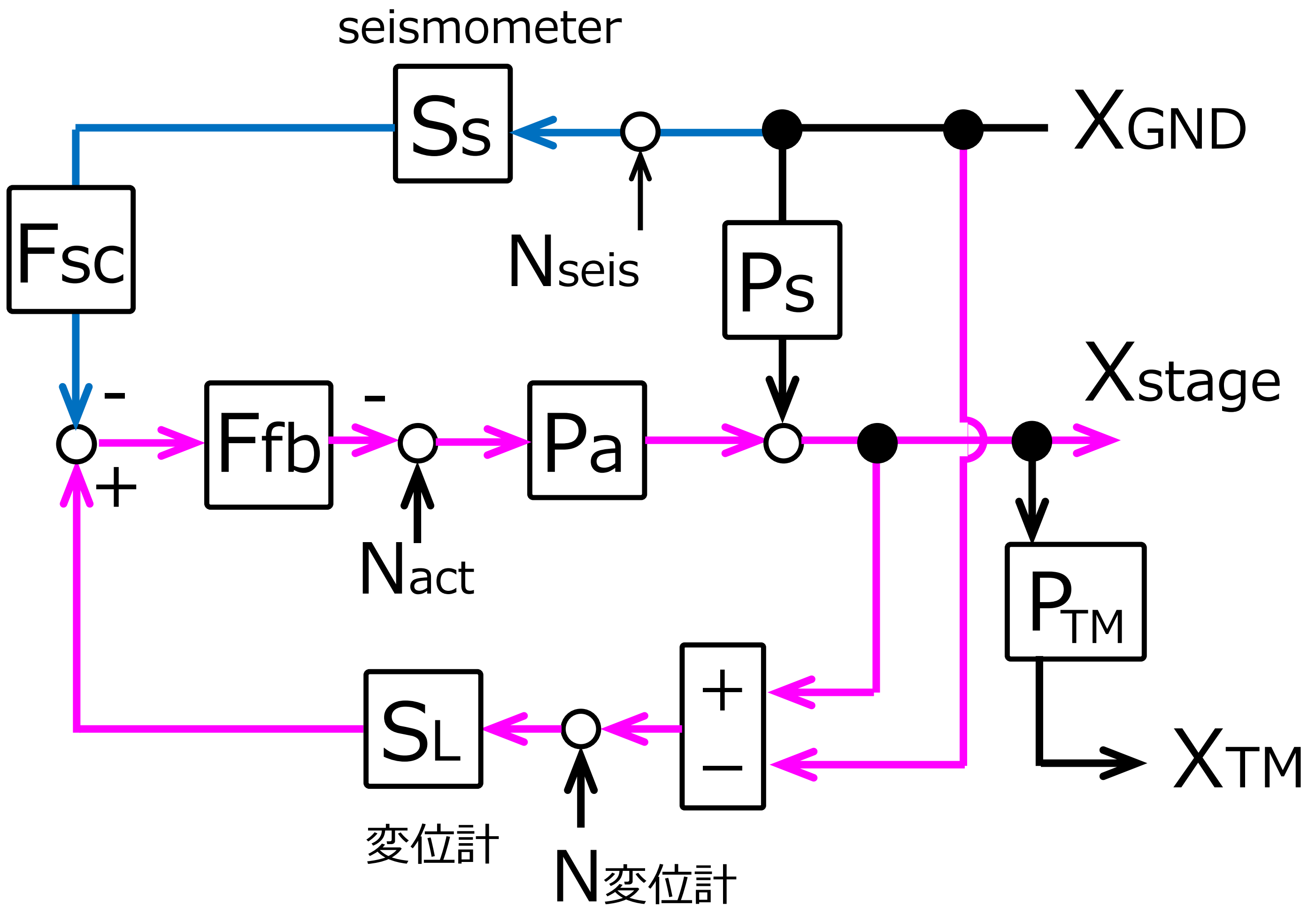


$$X_{stage} = \frac{1}{1+G}\left[G\left(1+F_{sc}\frac{S_S}{S_L}\right)+P_s\right]X_{GND}$$

$$(\,G = P_a\,F_{fb}\,S_L\,)$$

Control overview (in L):



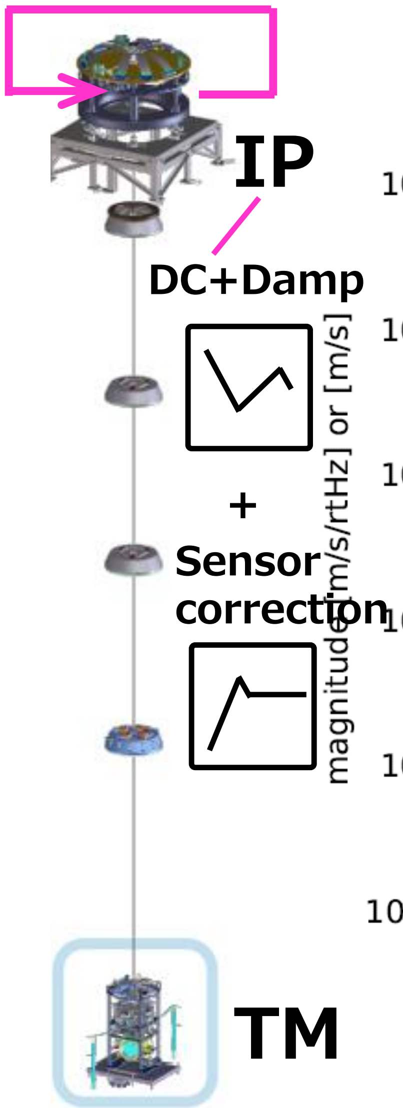


with Fsc = - SL/Ss:

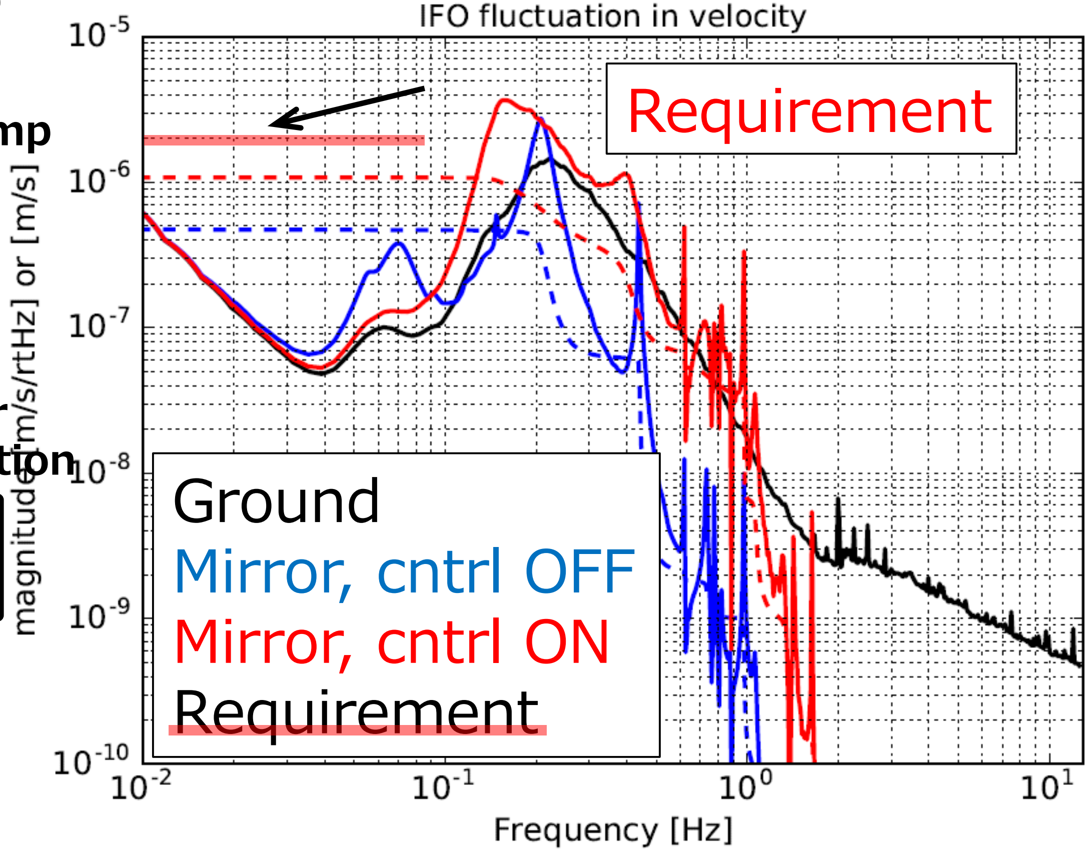
$$X_{stage} = \frac{1}{1+G}\left[G\left(1+F_{sc}\frac{S_S}{S_L}\right)+P_S\right]X_{GND}$$

Cut the seismic noise injection via LVDT
→ Sensor correction

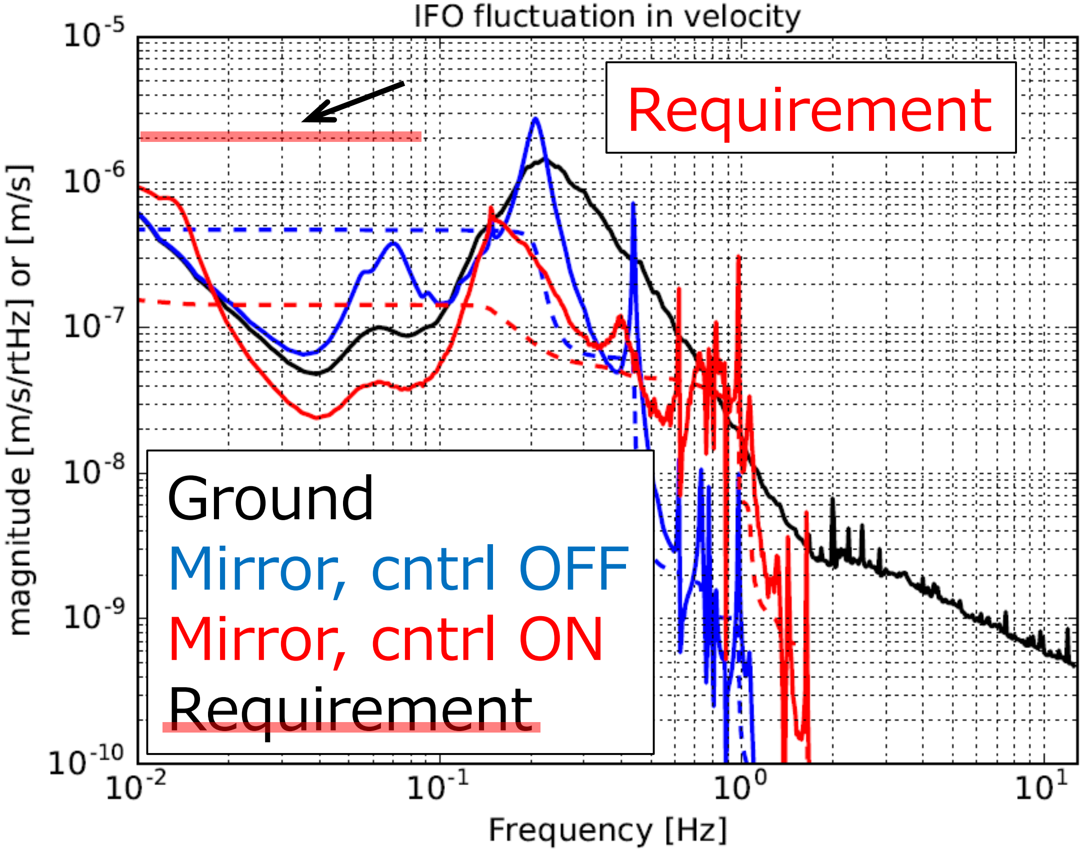
Simulation: mirror velocity w/ 90%tile seismic motion



Sensor correction **OFF**

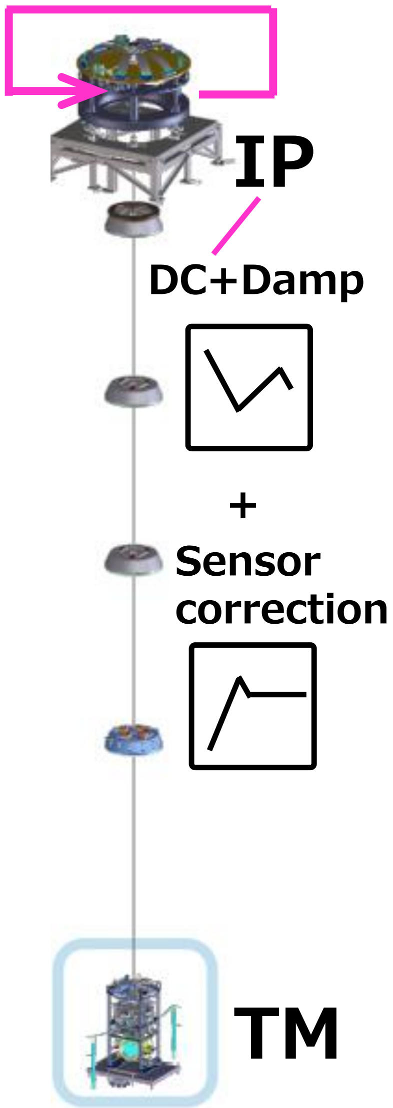


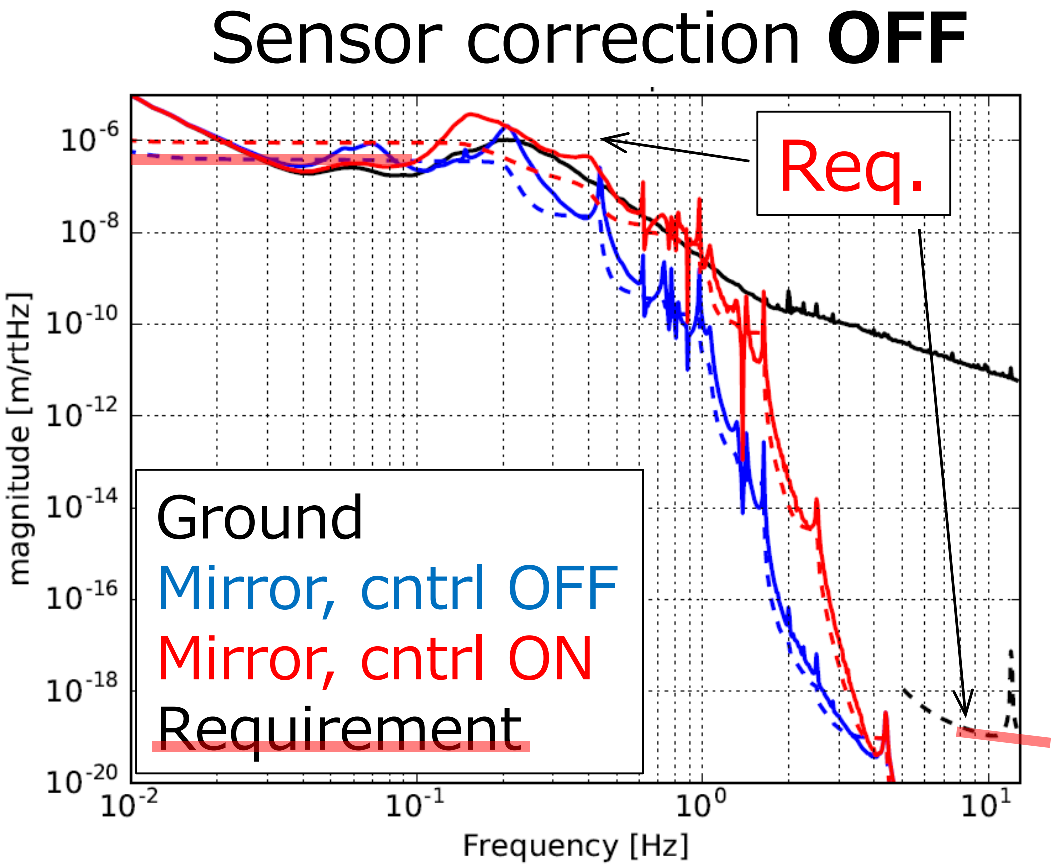
Sensor correction **ON**

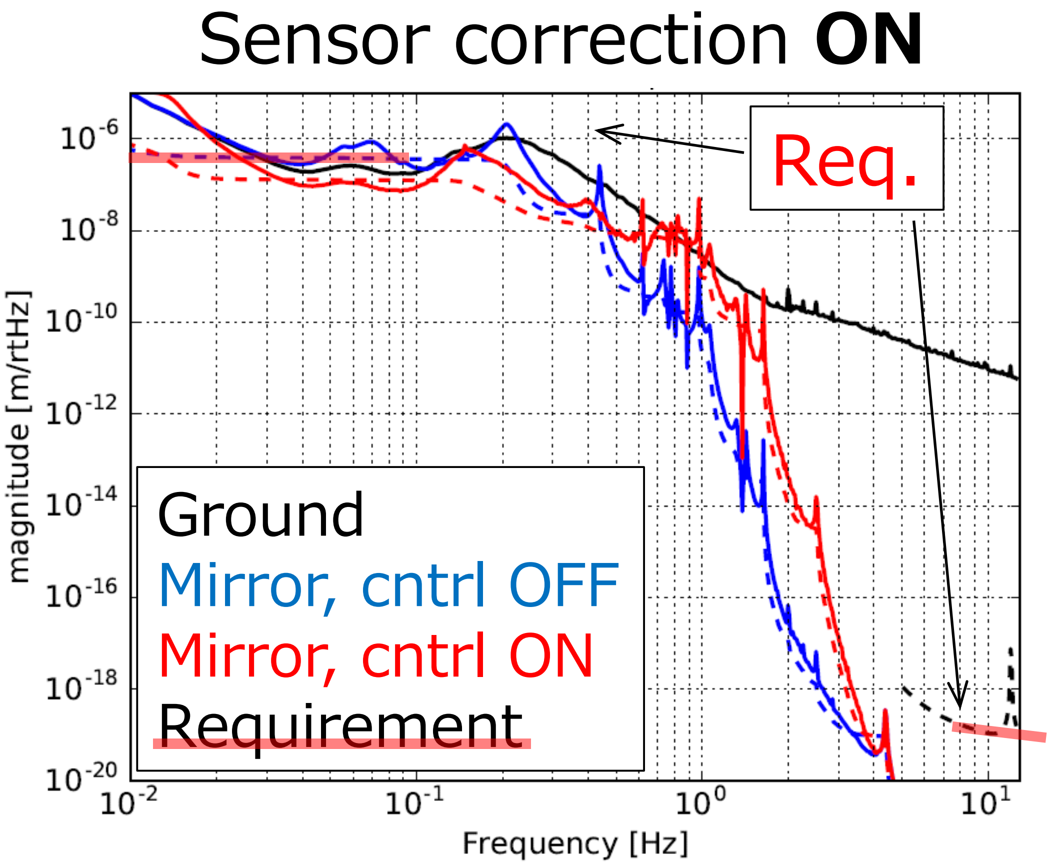


→ Sensor correction will satisfy requirement.

Simulation: mirror disp. w/ 90%tile seismic motion





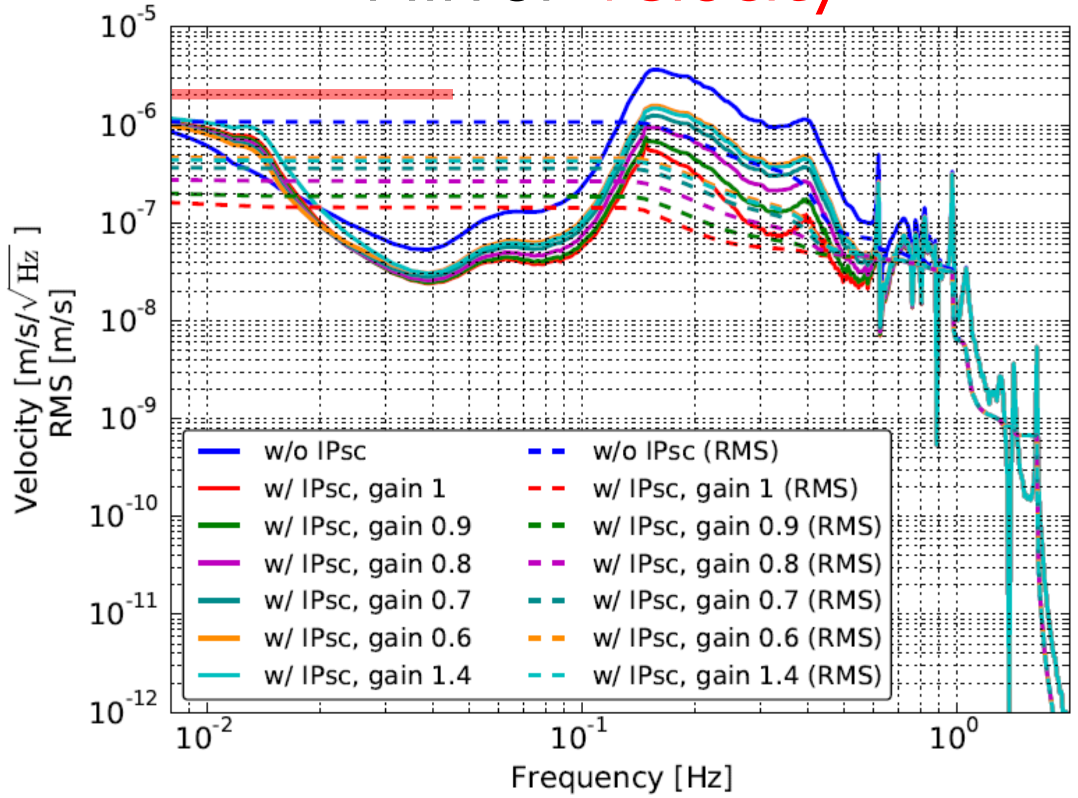


→ Sensor correction を用いて、要求値を満たせる。

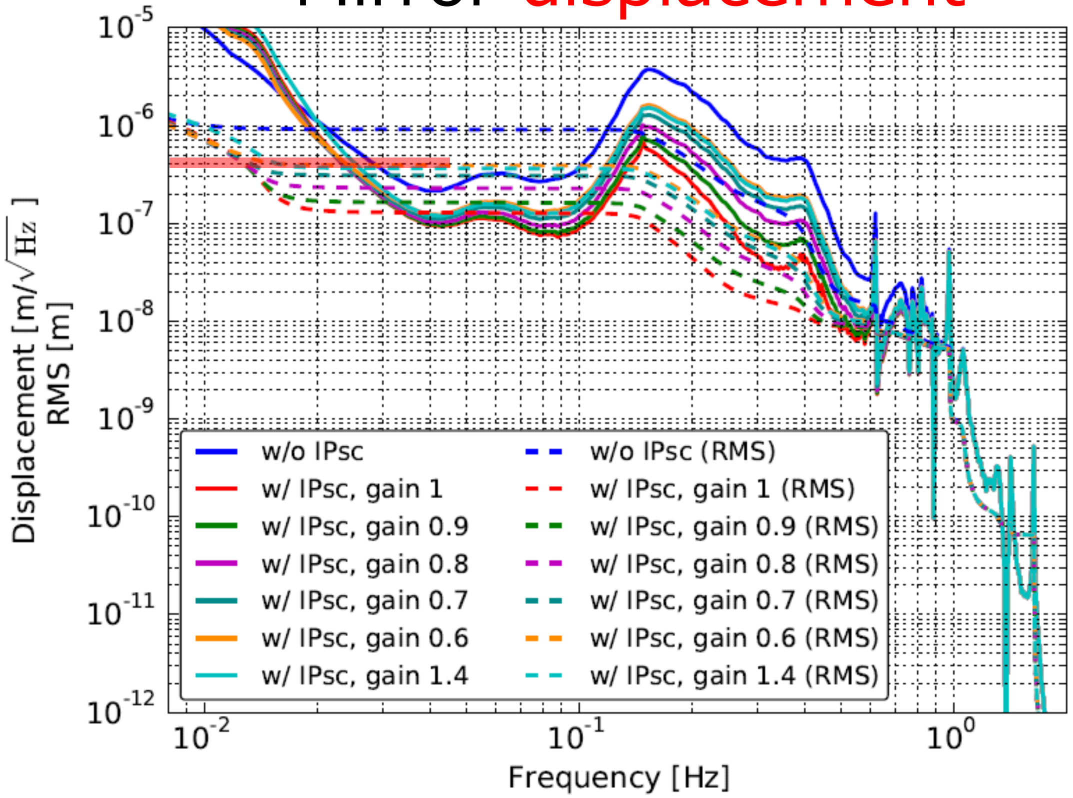
Simulation: mirror motion w/ 90%tile seismic motion

* Required precision of the inter-calibration:

Mirror velocity

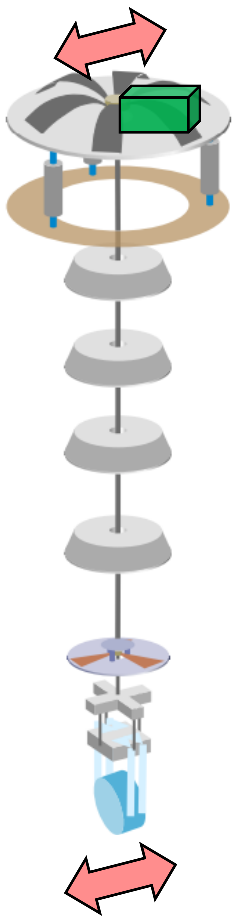


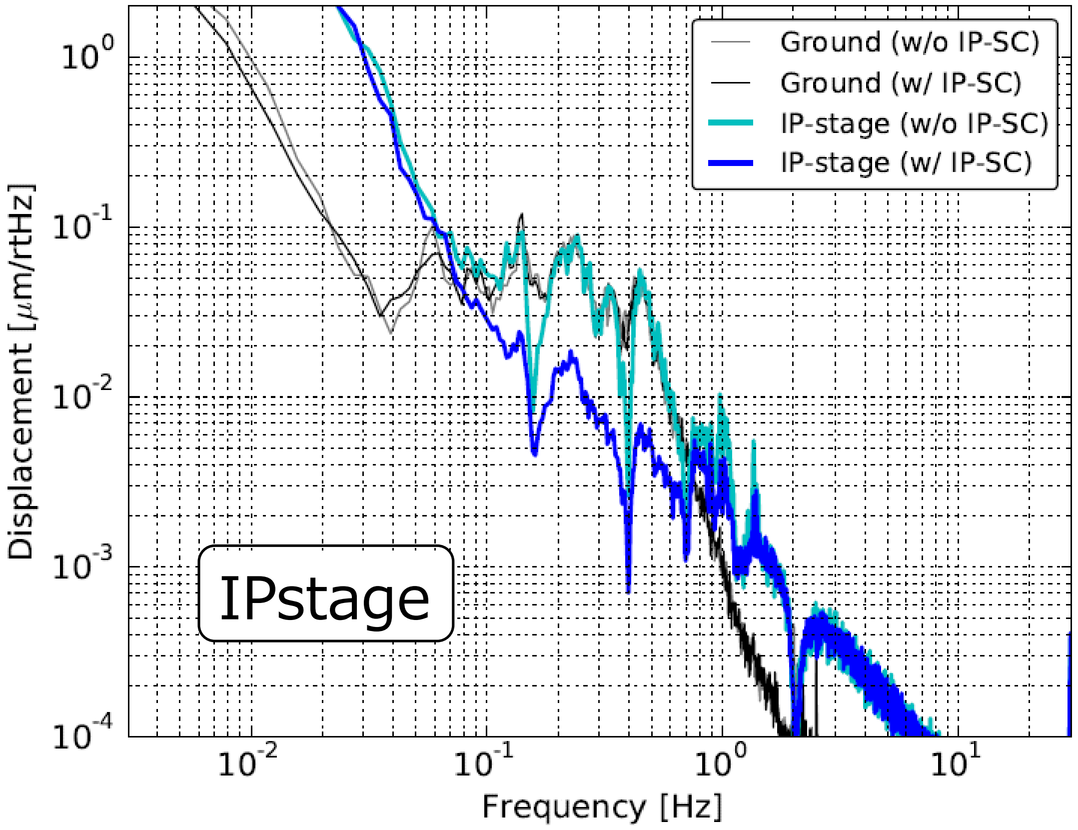
Mirror displacement

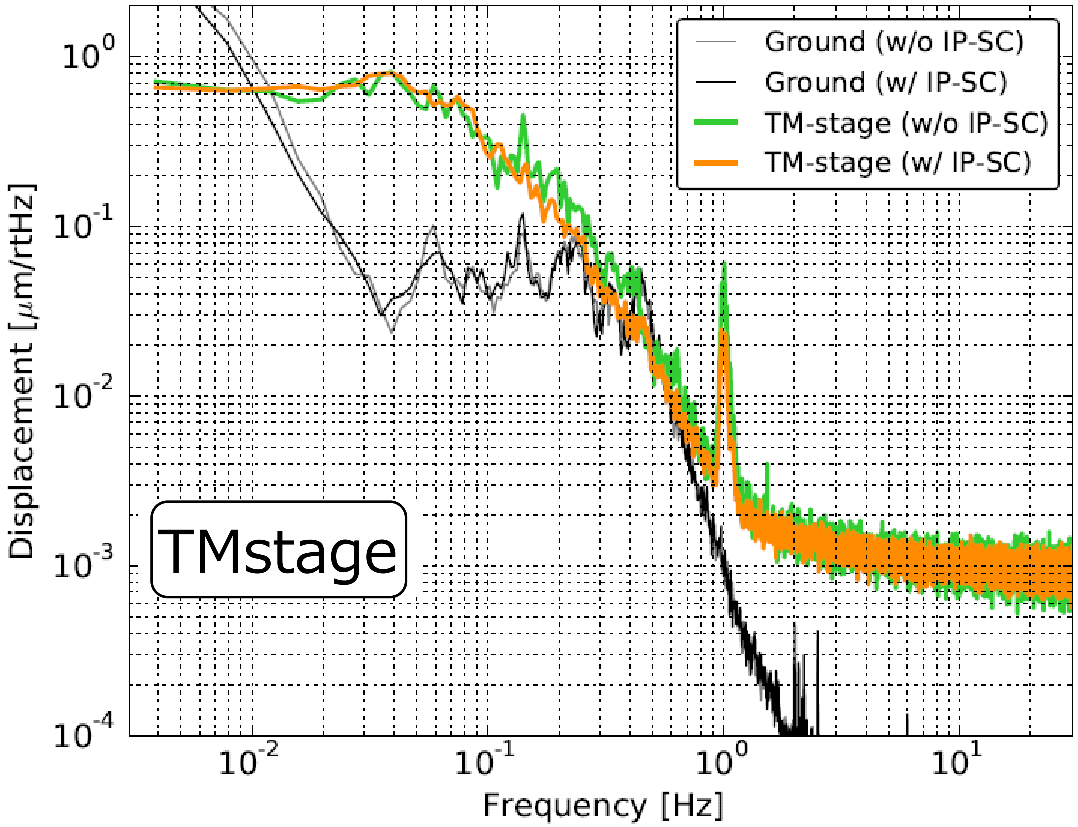


→ Necessary: seis/LVDT < 40% difference
→ Target: seis/LVDT < 10% difference

Improvement at IP- & TM-stage



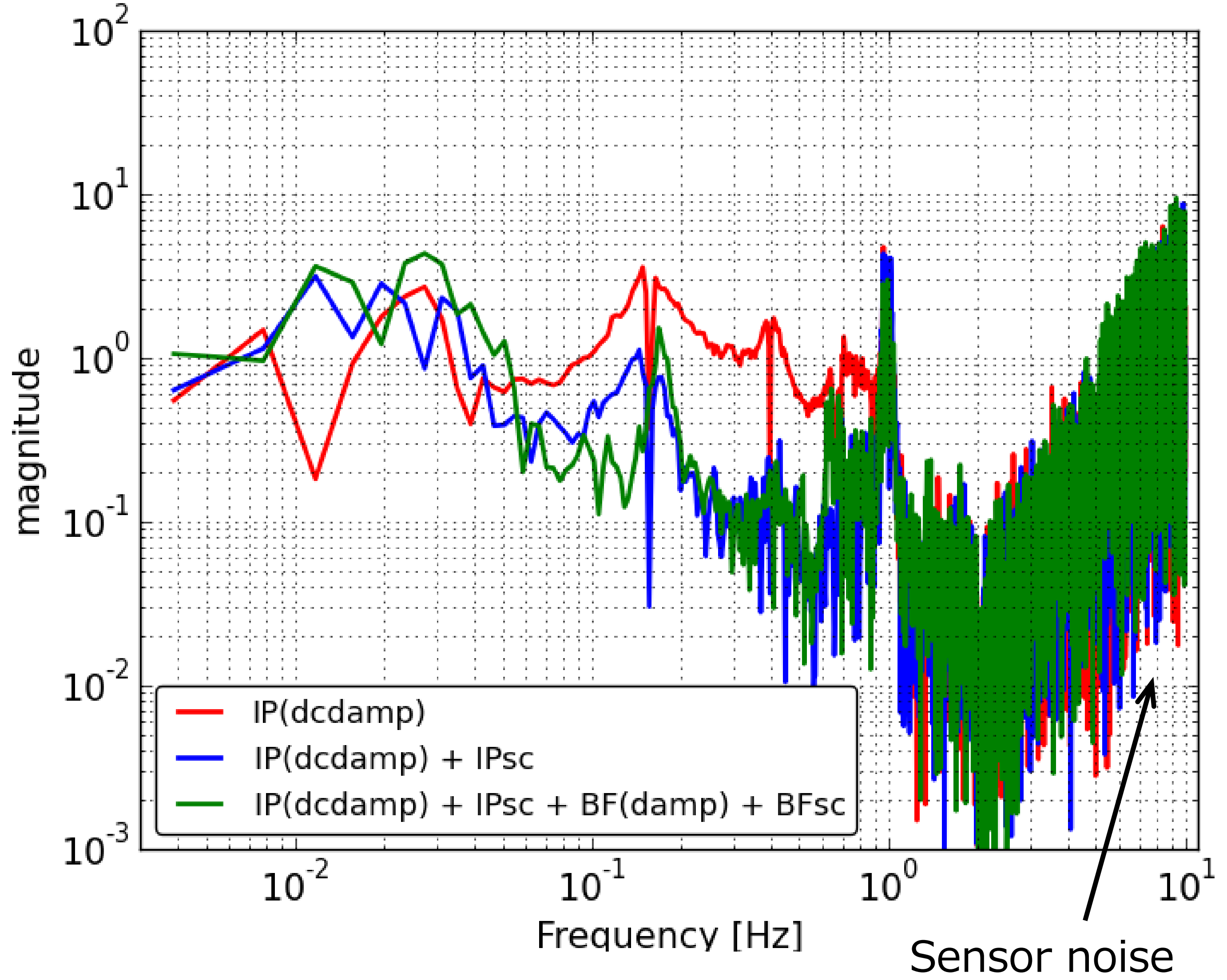




→ SC worked at 0.15 ~ 0.7Hz.

→ covered by TM oplev noise.

By combining (TML/IPL)*(IPL/GNDL)



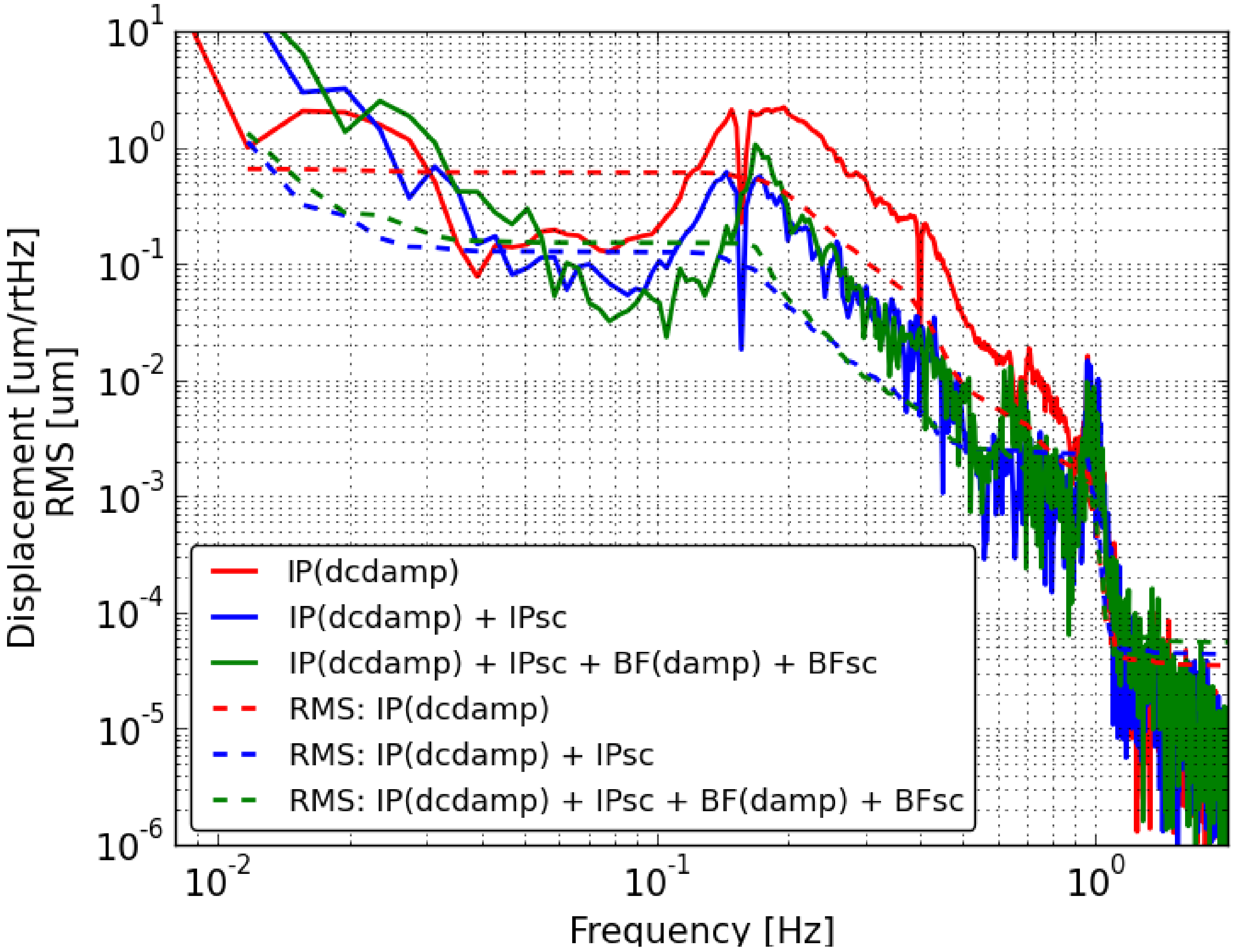
Displacement TF:
From GND to TML

(measured at ETMX)

Is notch real?
→ Not sure.
→ tilt coupling from Geophone
Or
→ Actual mechanical response

Whichever, the conclusion is same.

By combining (TML/IPL)*(IPL/GNDL)*(GNDL_model)



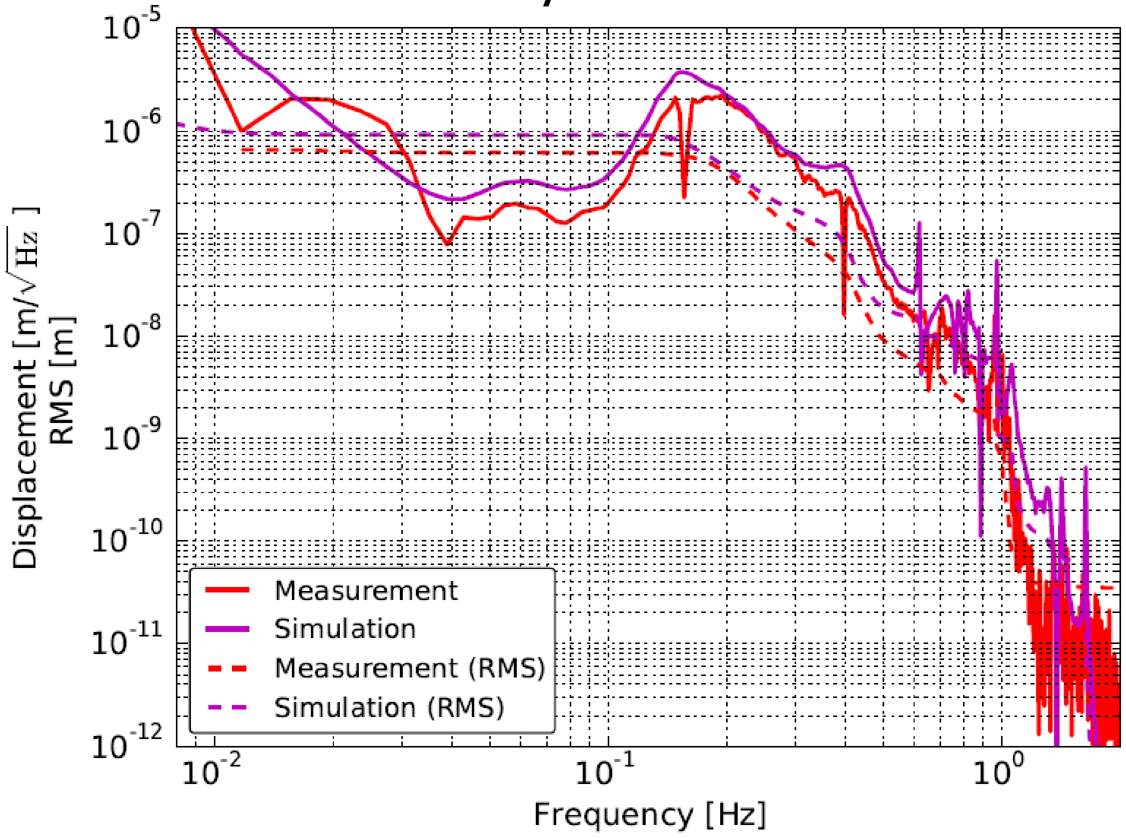
Disp. TF:

From GND to TML

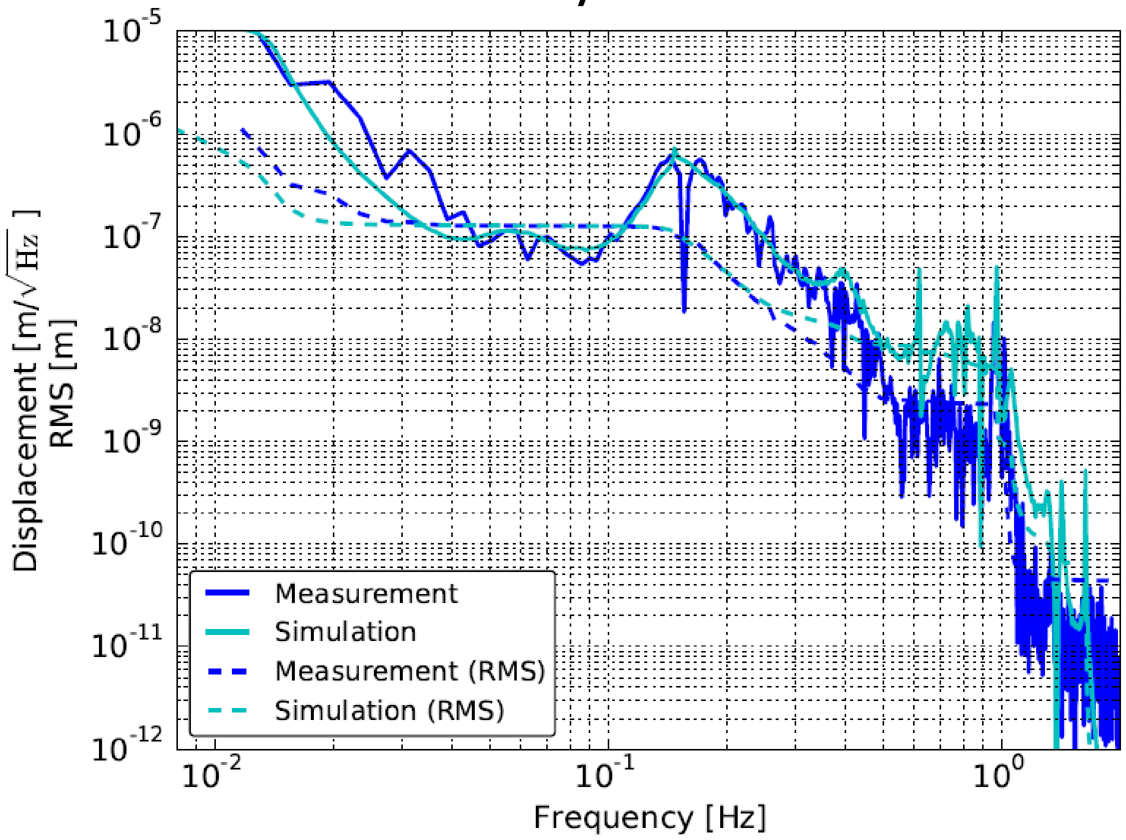
Comparison: simulation vs. measurement

* Mirror displacement w/ 90%tile seismic motion

w/o IPsc

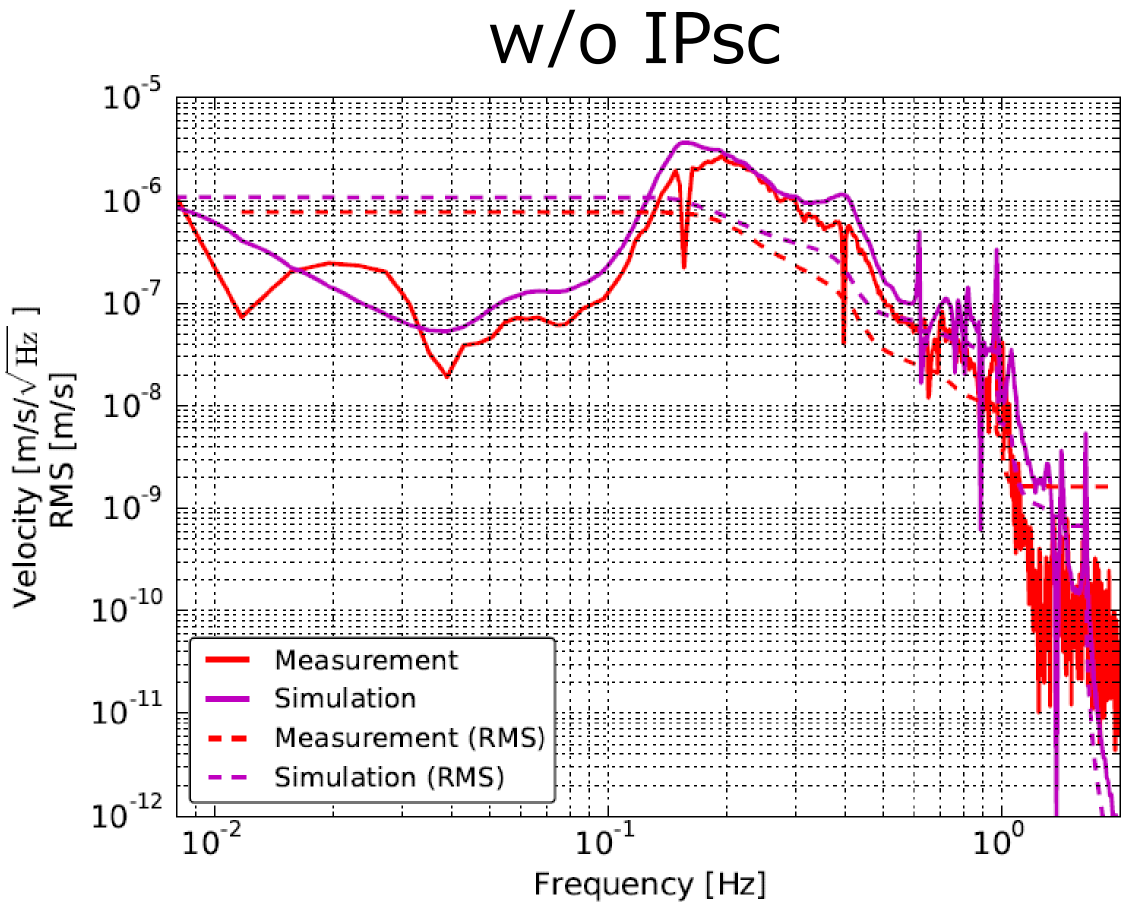


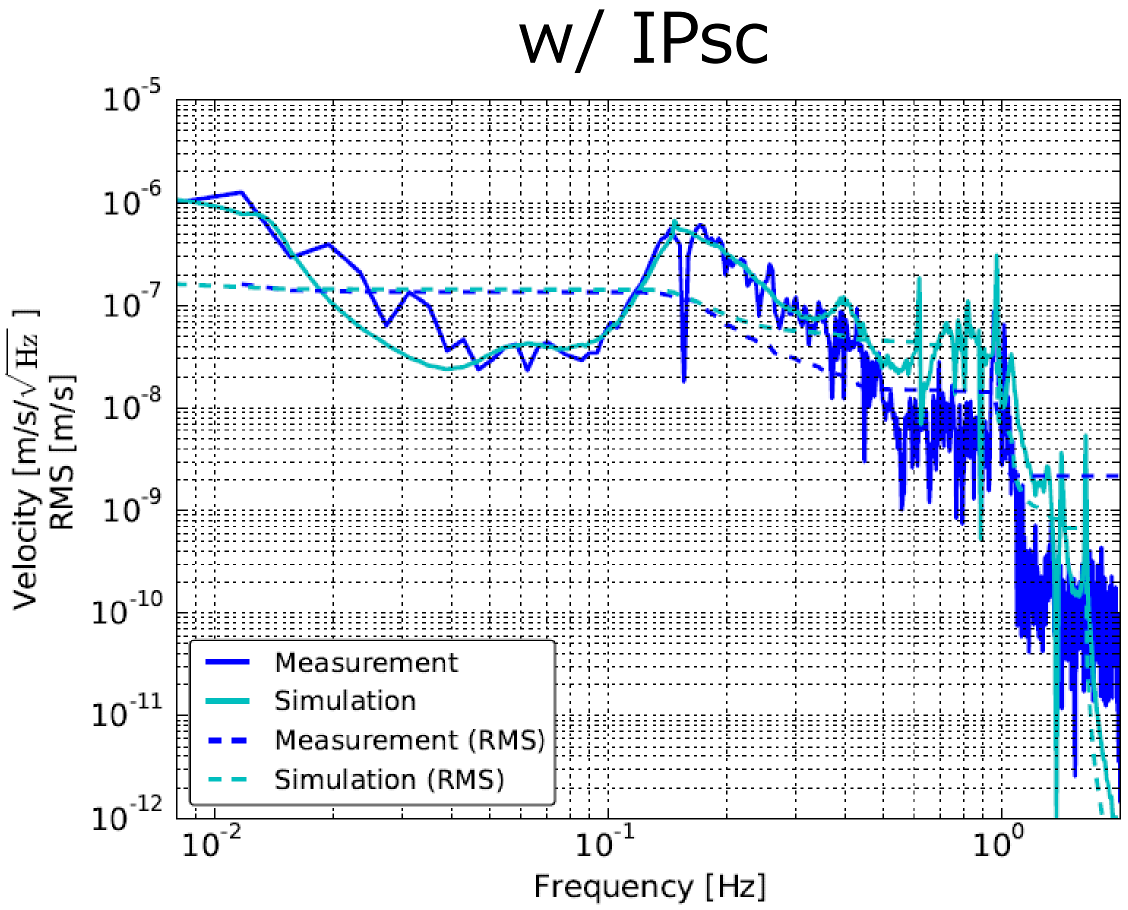
w/ IPsc



Comparison: simulation vs. measurement

* Mirror velocity w/ 90%tile seismic motion





3. Mirror residual suppression

* Options for further stabilization:

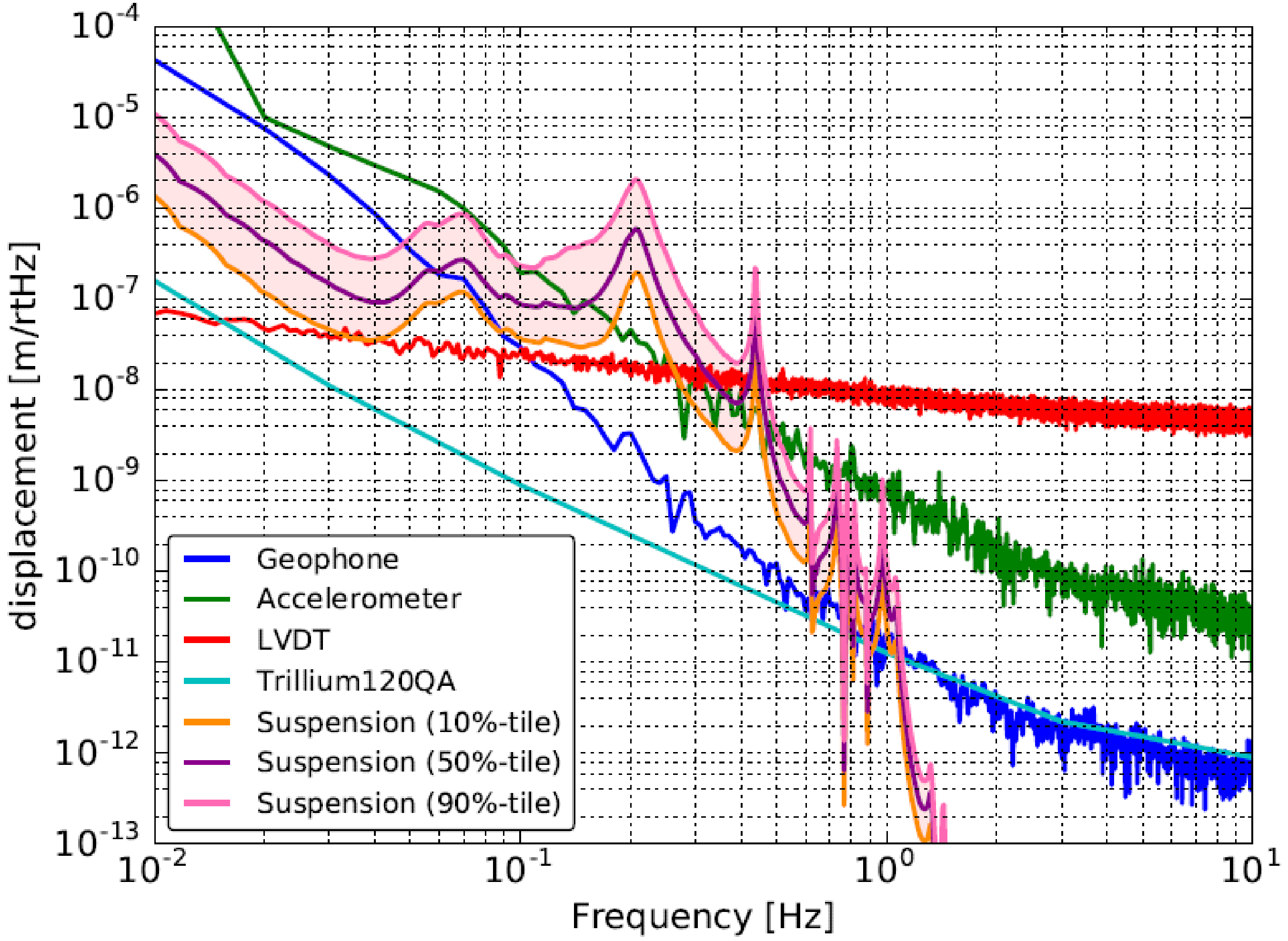
  * implement inertial damping system with sensitive inertial sensors.
    * For this, subtract tilt-signal from the inertial sensors with tilt-meter might be necessary.

  * locally subtract tilt-signal from seismometer with tilt-meter.

  * actuate the ETMs so that the their drifts follow that of ITMs with interferometer/cavity signal or strain-meter signal.

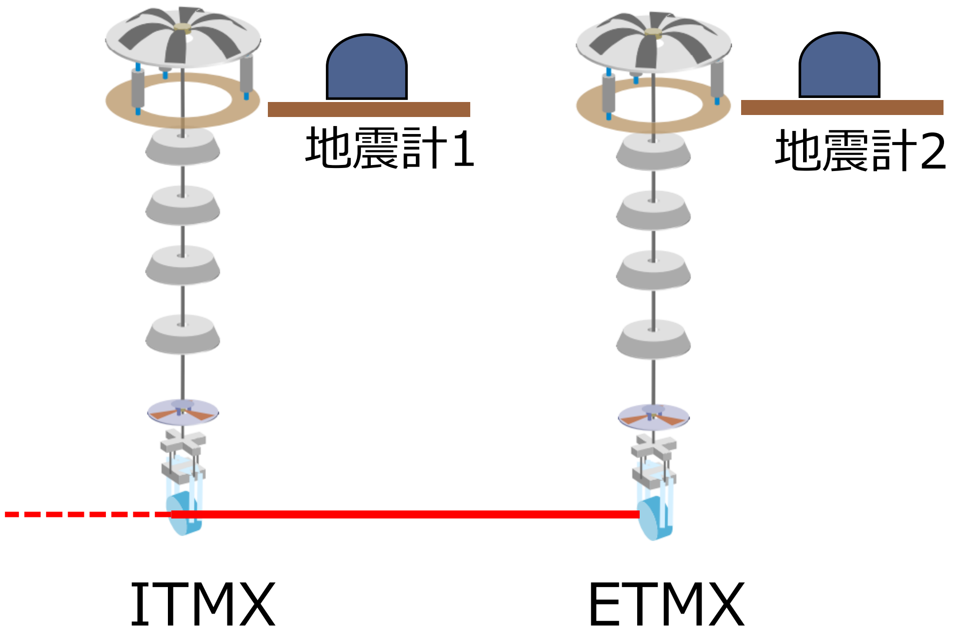
Sensor self-noise vs. mechanical response

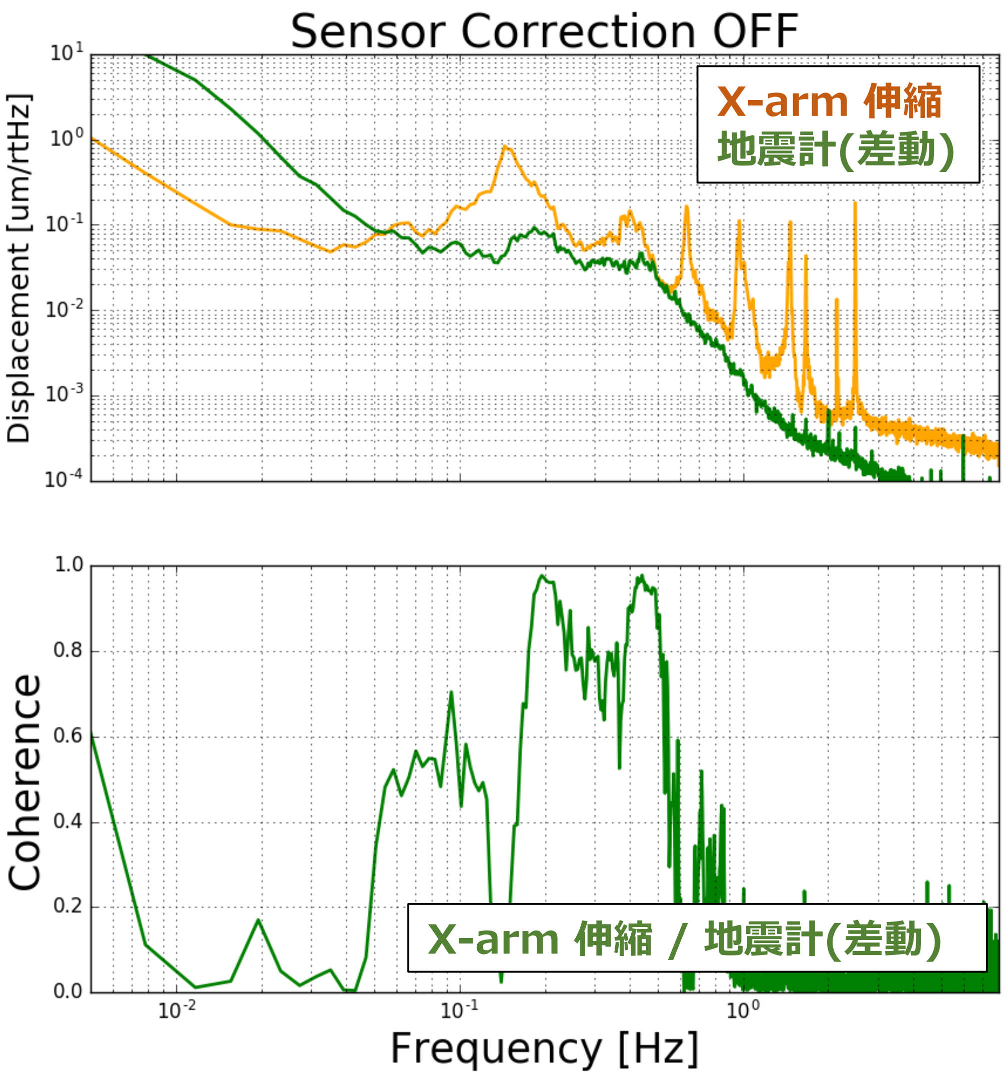
* w/ 10%tile, 50%tile and 90%tile seismic motion:



テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

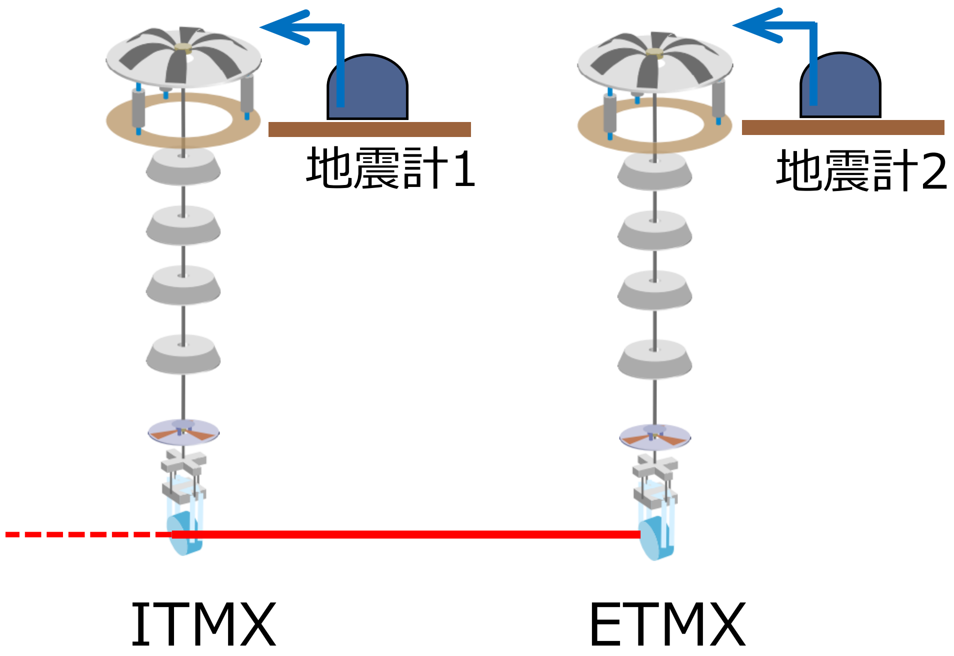
→ ETMX と ITMX に実装
  → 0.15 ~ 0.7 Hzにて同様な改善あり
→ X-arm (FP cavity) の共振器長の確認

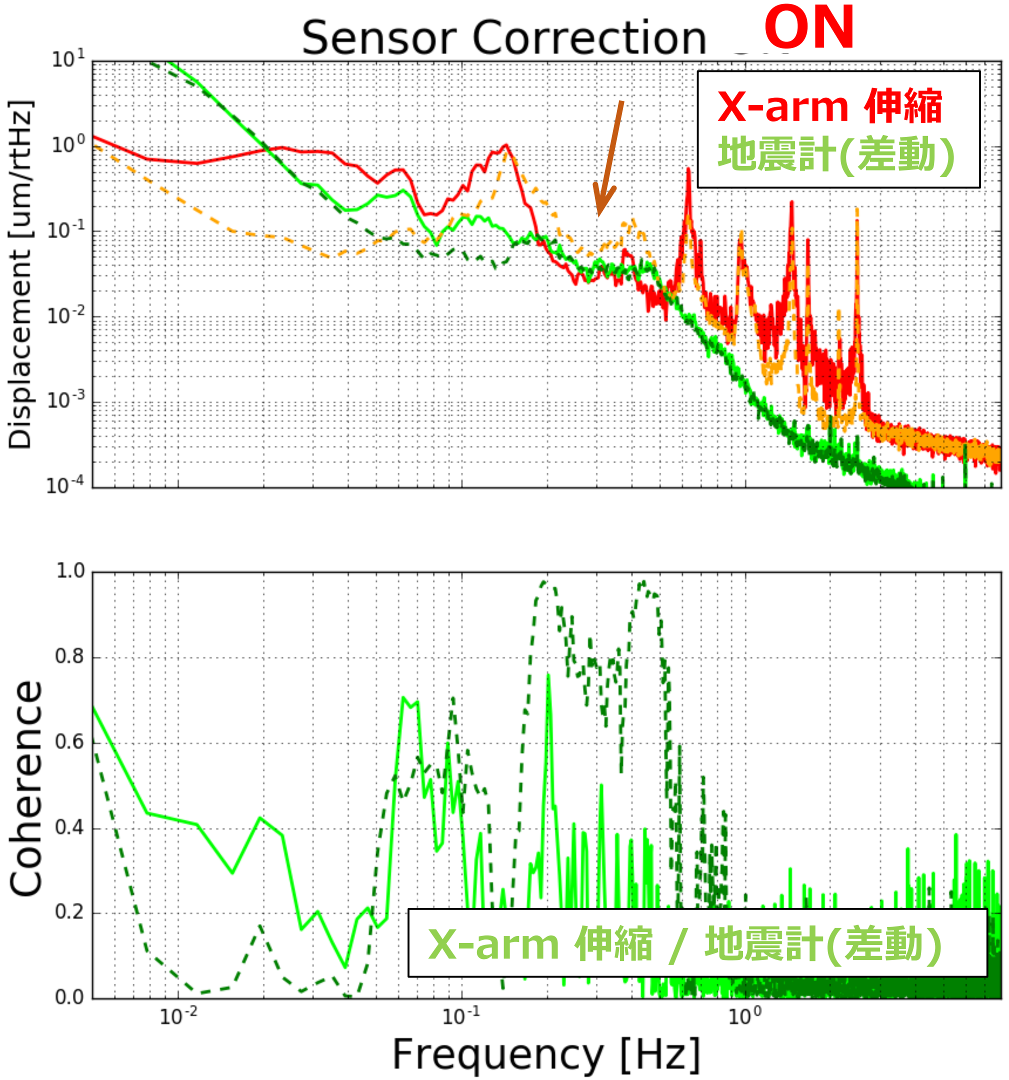




テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

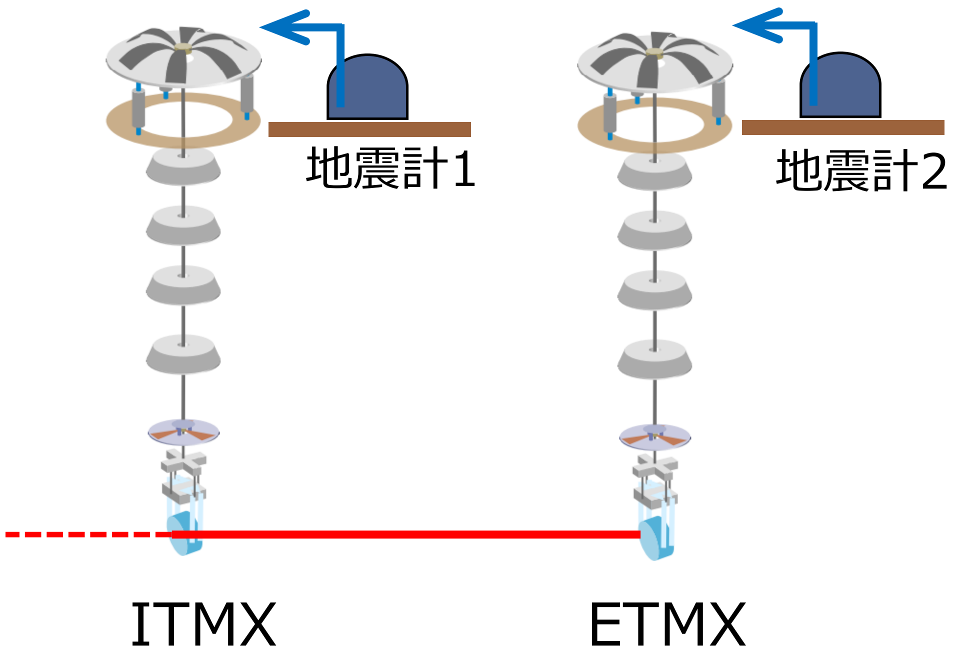
→ X-arm (FP cavity) の共振器長では



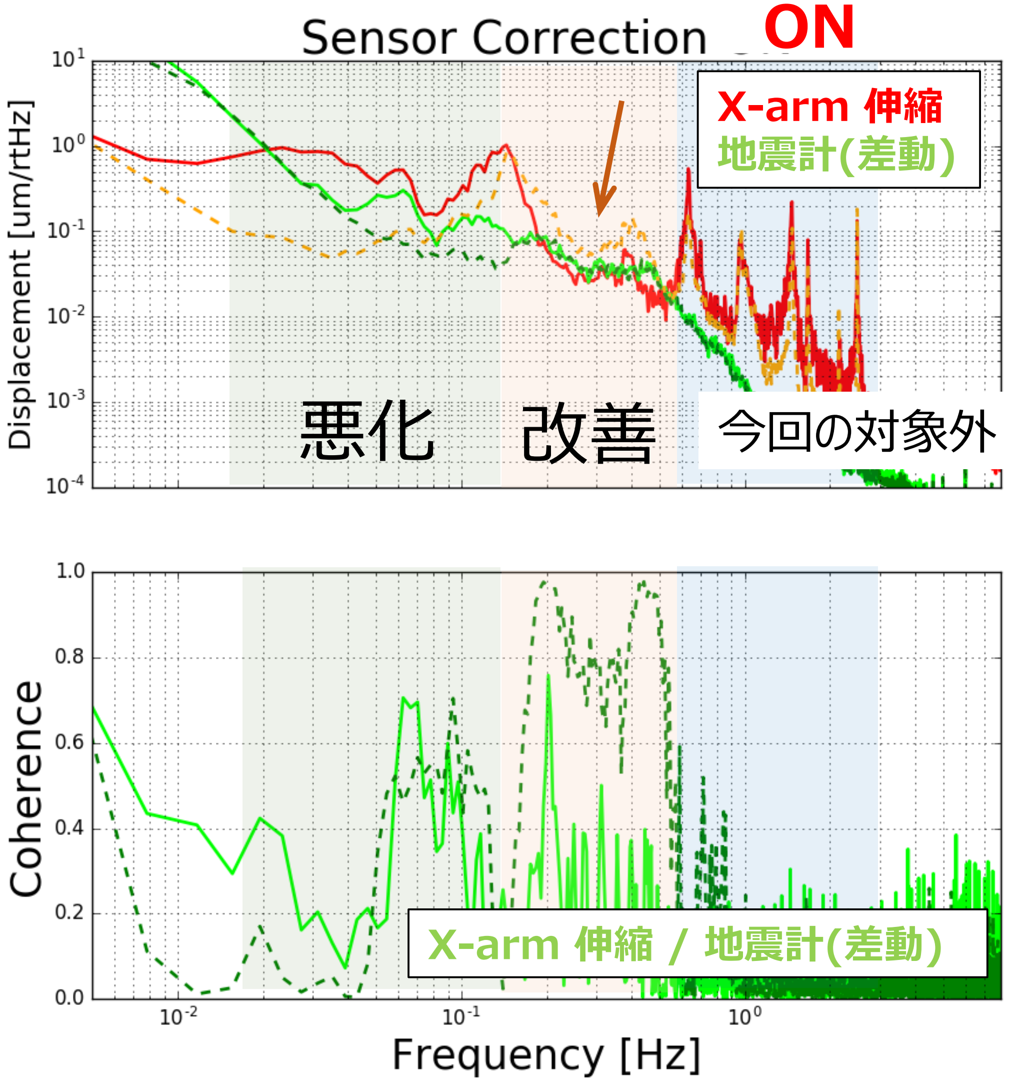


テスト実装: 2つのサスペンションのIP-stageに実装、Xarm で見ると

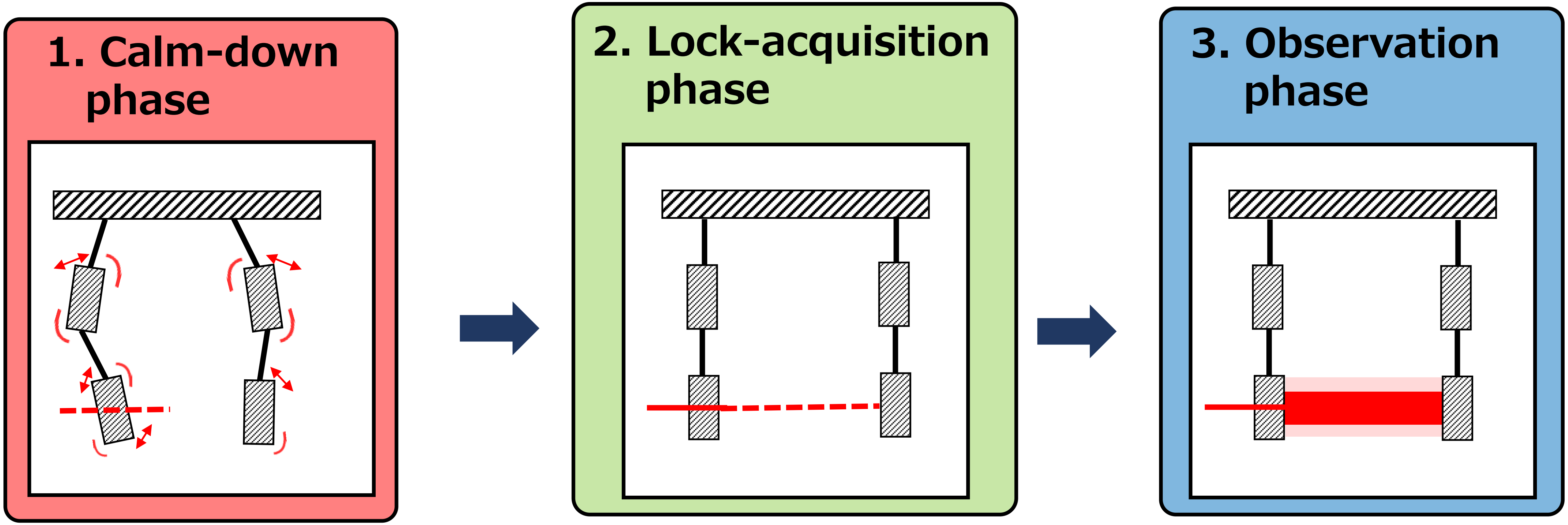
→ X-arm (FP cavity) の共振器長では



-- SC worked at 0.15 ~ 0.6Hz.
-- 低周波: 悪化
→ SC filterからの地震計の雑音の流入ほか
→ To be investigated.



Designing active control system / Control phase

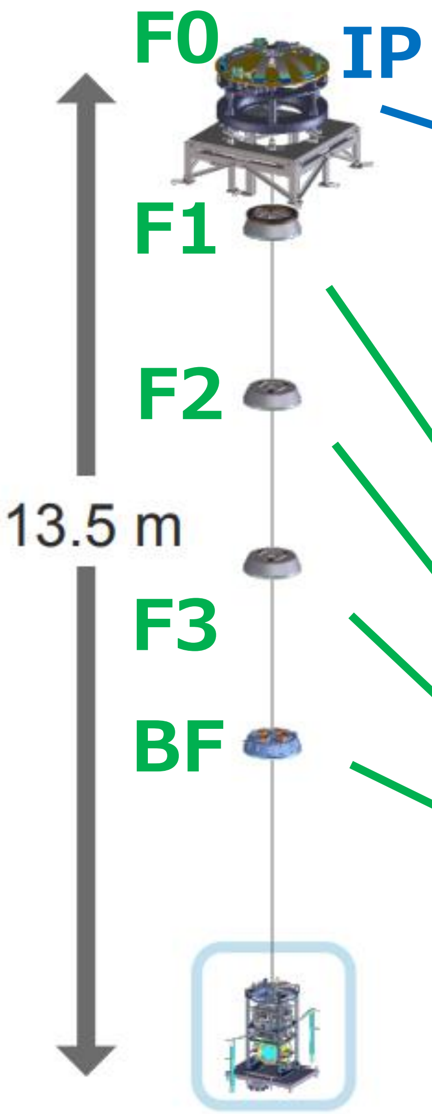


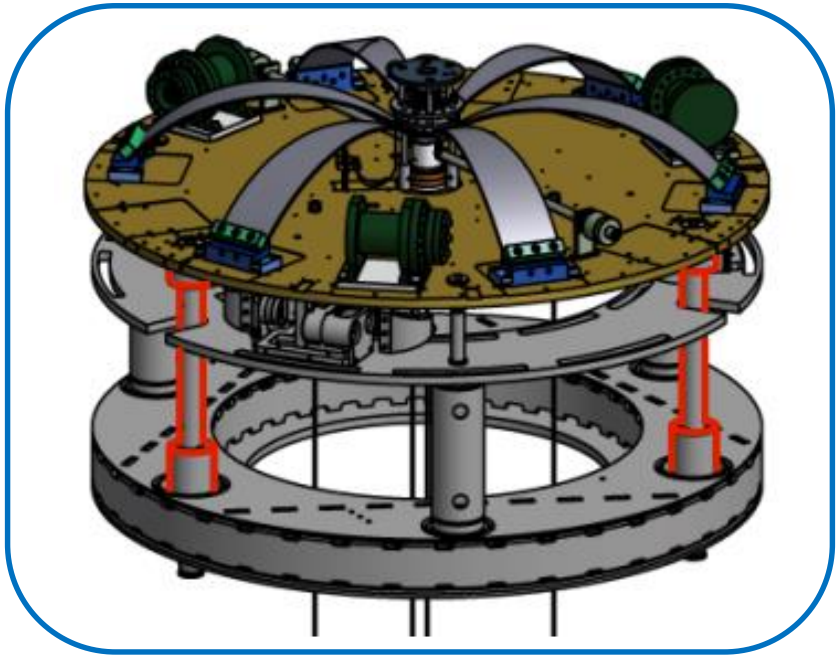
Suppress large disturbance

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

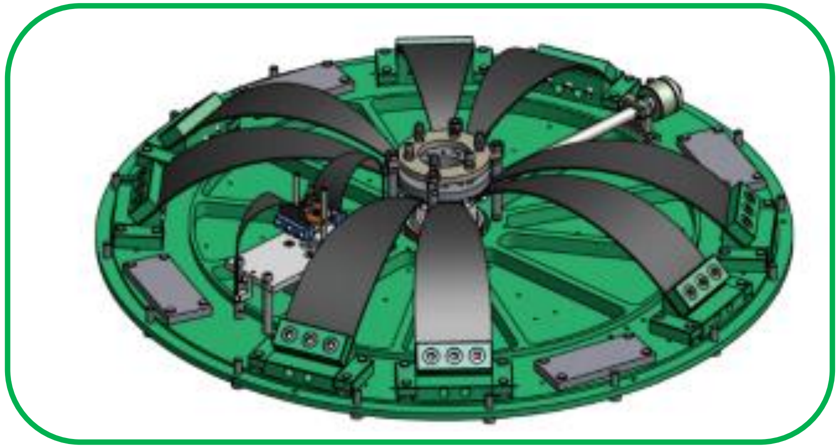
Keep position with low noise control

メイン鏡用の防振装置



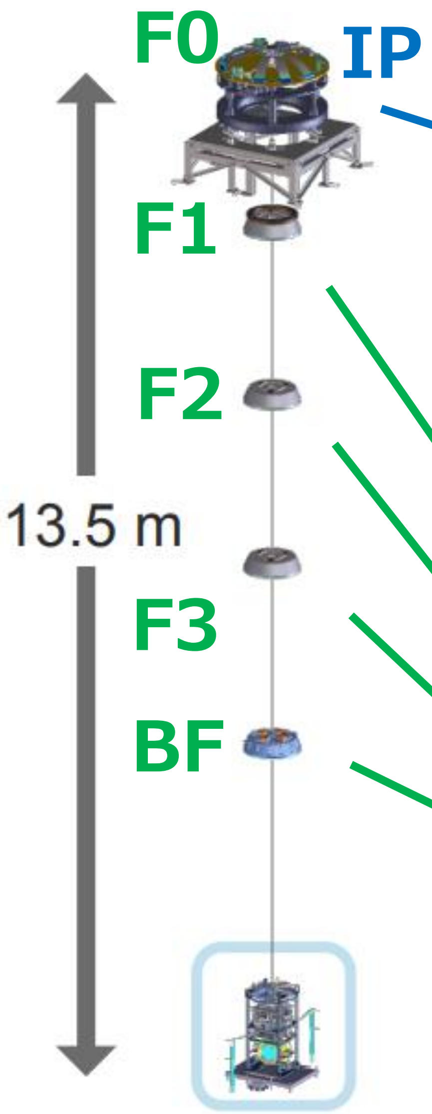


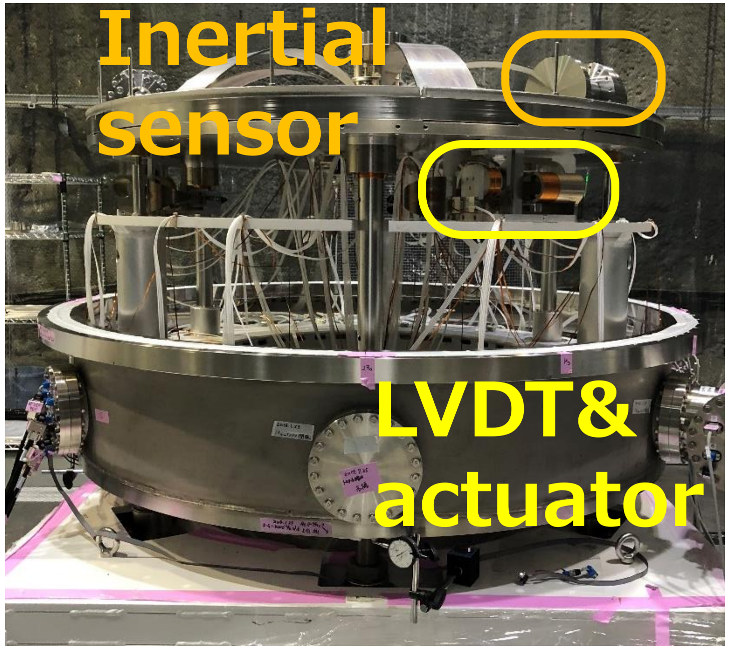
INVERTED PENDULUM
(~ 70 mHz)



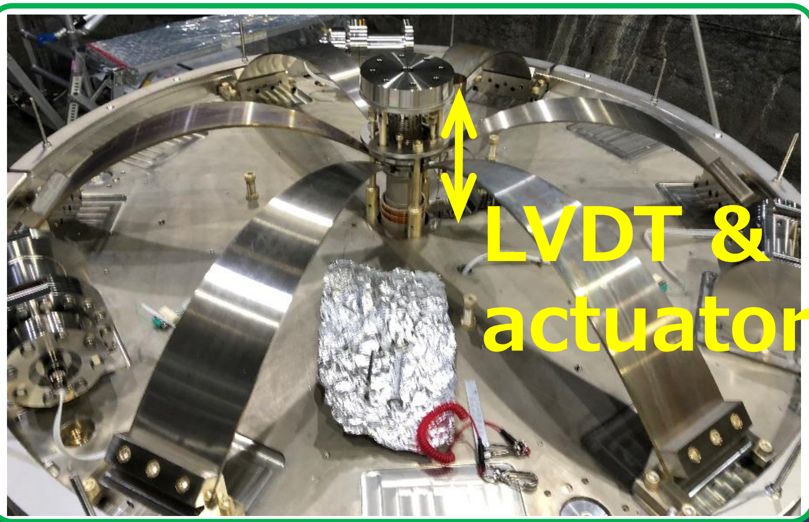
GEOMETRIC-ANTI SPRING
(~ 0.4 Hz)

メイン鏡用の防振装置





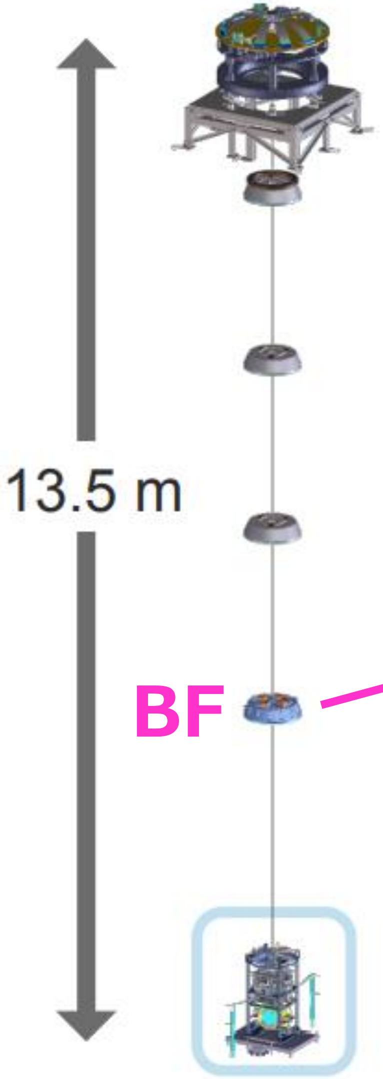
INVERTED PENDULUM
with 3 horizontal
-- LVDT & actuator units
-- inertial sensors



GEOMETRIC-ANTI SPRING
with 1 vertical
LVDT & actuator unit

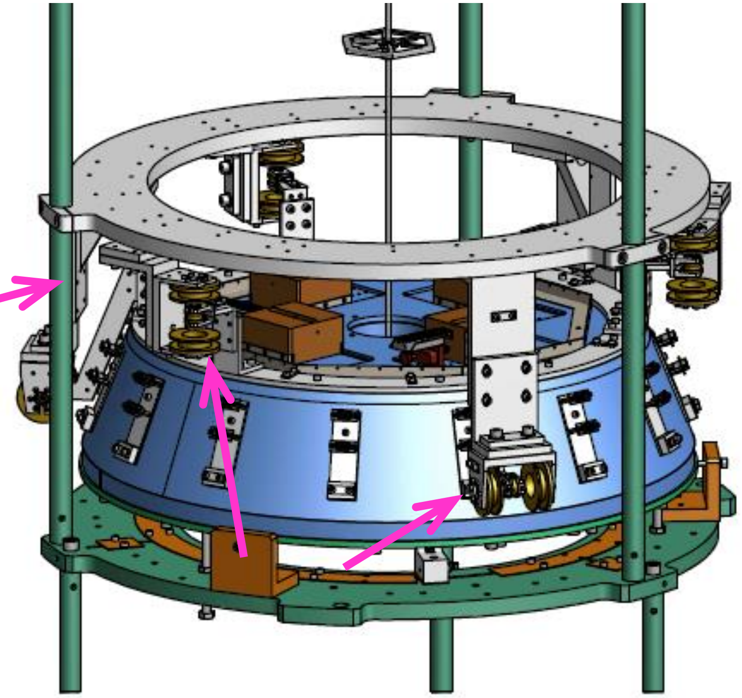
メイン鏡用の防振装置

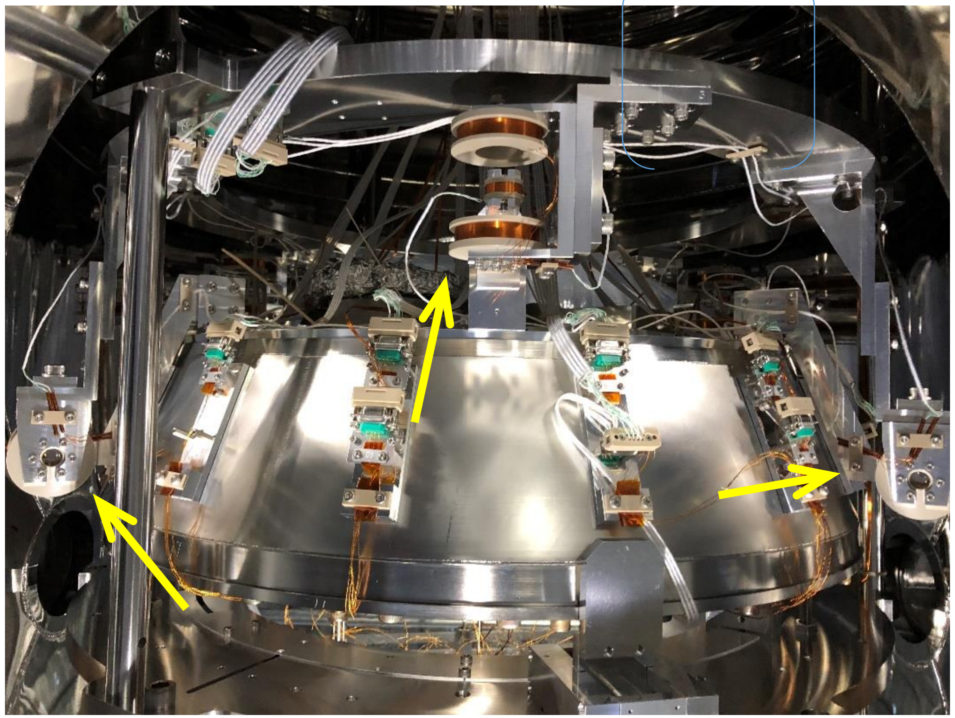
(イタリアのグループの協力のもと開発)



Bottom-Filter DAMPER

with 3 horizontal & 3 vertical LVDT & actuator units





Requirements, Type-A suspensions by YF

Table 5.2: Requirements on the Type-A suspension control. The column labeled as ref. describes the section which explains the reason of the requirements.

Items	Requirements	ref.
The calm-down phase		
$1/e$ decay time	< 1 min.	§ 5.1.2
RMS displacement (transverse, vertical)	< 0.1 mm	§ 5.1.6
The lock acquisition phase		
RMS velocity (longitudinal)	$< 2.0\ \mu$m/sec.	§ 5.1.3
RMS angle (pitch, yaw)	< 880 nrad	§ 5.1.4
RMS displacement (longitudinal)	$< 0.39\ \mu$m	§ 5.1.5
RMS displacement (transverse, vertical)	< 0.1 mm	§ 5.1.6
The observation phase		
Control noise at 10 Hz (longitudinal)	$< 8.0 \times 10^{-20}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$	§ 4.2
RMS displacement (longitudinal)	$< 0.39\ \mu$m	§ 5.1.5
RMS displacement (transverse, vertical)	< 0.1 mm	§ 5.1.6
RMS angle (pitch, yaw)	< 200 nrad	§ 5.1.4
DC angle drift (pitch, yaw)	< 400 nrad	§ 5.1.4

Requirements, Type-A suspensions by KO

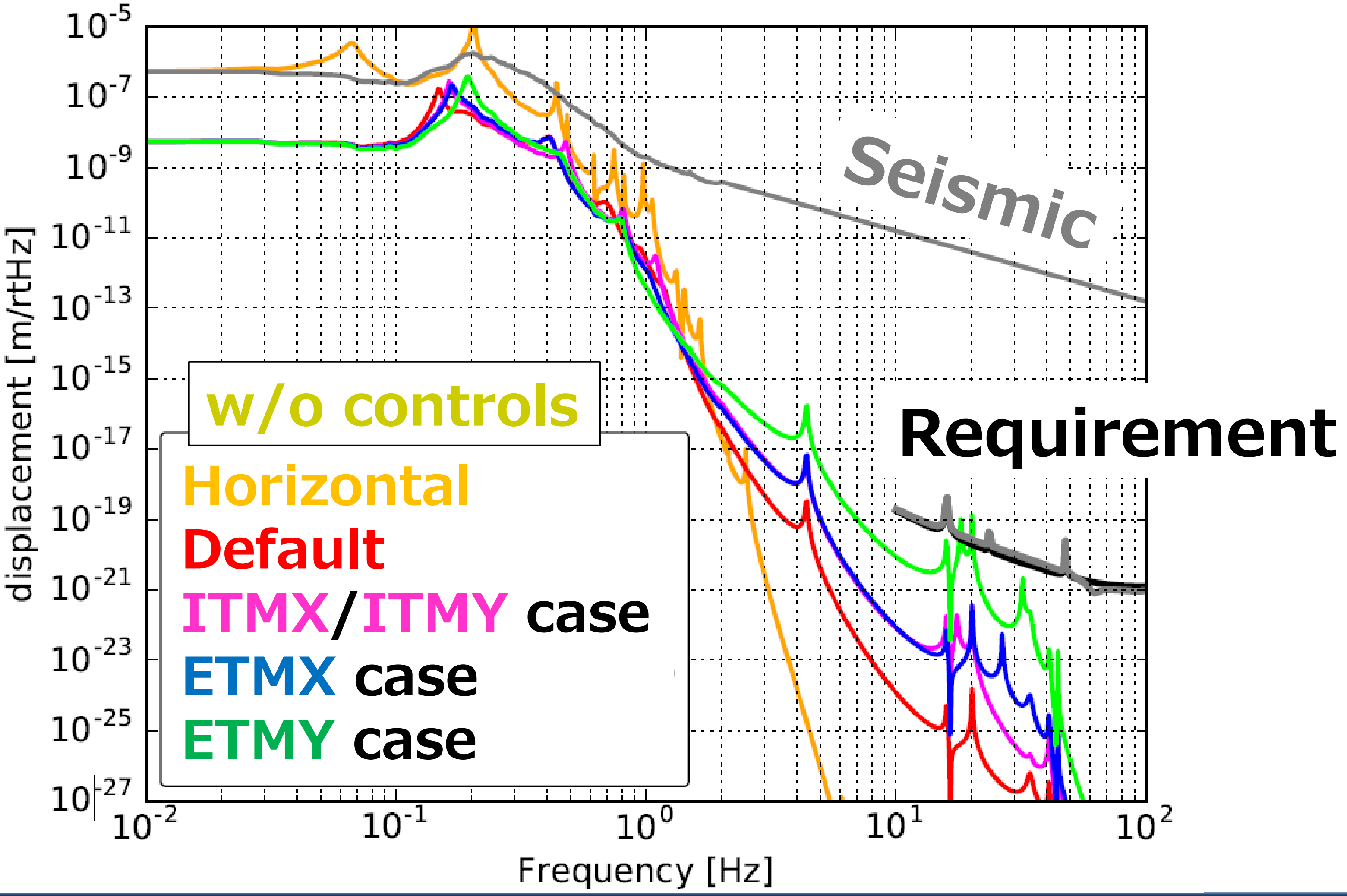
Calm-down phase		
Item	Requirement	For/Determined by
$1/e$ modal decay time	< 1 min	Quick recovery
RMS displacement (L)	$< 50\ \mu$m	Smooth transition to next phase
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	$< 50\ \mu$m	Smooth transition to next phase
Lock acquisition phase		
Item	Requirement	For/Determined by
RMS velocity (L)	$< 240\ \mu$m/s	Auxiliary laser locking
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 880 nrad	Optical gain degradation $< 5\%$
Observation phase		
Item	Requirement	For/Determined by
Displacement noise (L) @ 10 Hz	$< 8 \times 10^{-20}$ m/Hz$^{1/2}$	Sensitivity
Displacement noise (V) @ 10 Hz	$< 8 \times 10^{-18}$ m/Hz$^{1/2}$	Sensitivity (1% coupling to L)
RMS displacement (T, V)	< 0.1 mm	Miscentering
RMS angle (P, Y)	< 200 nrad	Beam spot fluctuation < 1 mm
DC drift (P, Y)	< 400 nrad/h	Sustainable lock for 1 day left

(P, Y) are set as 50 μm and 50 μrad, respectively [28]. The RMS displacement for the other translational DoFs (T, V) are required for another reason which is mentioned shortly later.

[ref] K. Okutomi PhD

Mechanical installation has done! HOWEVER ..

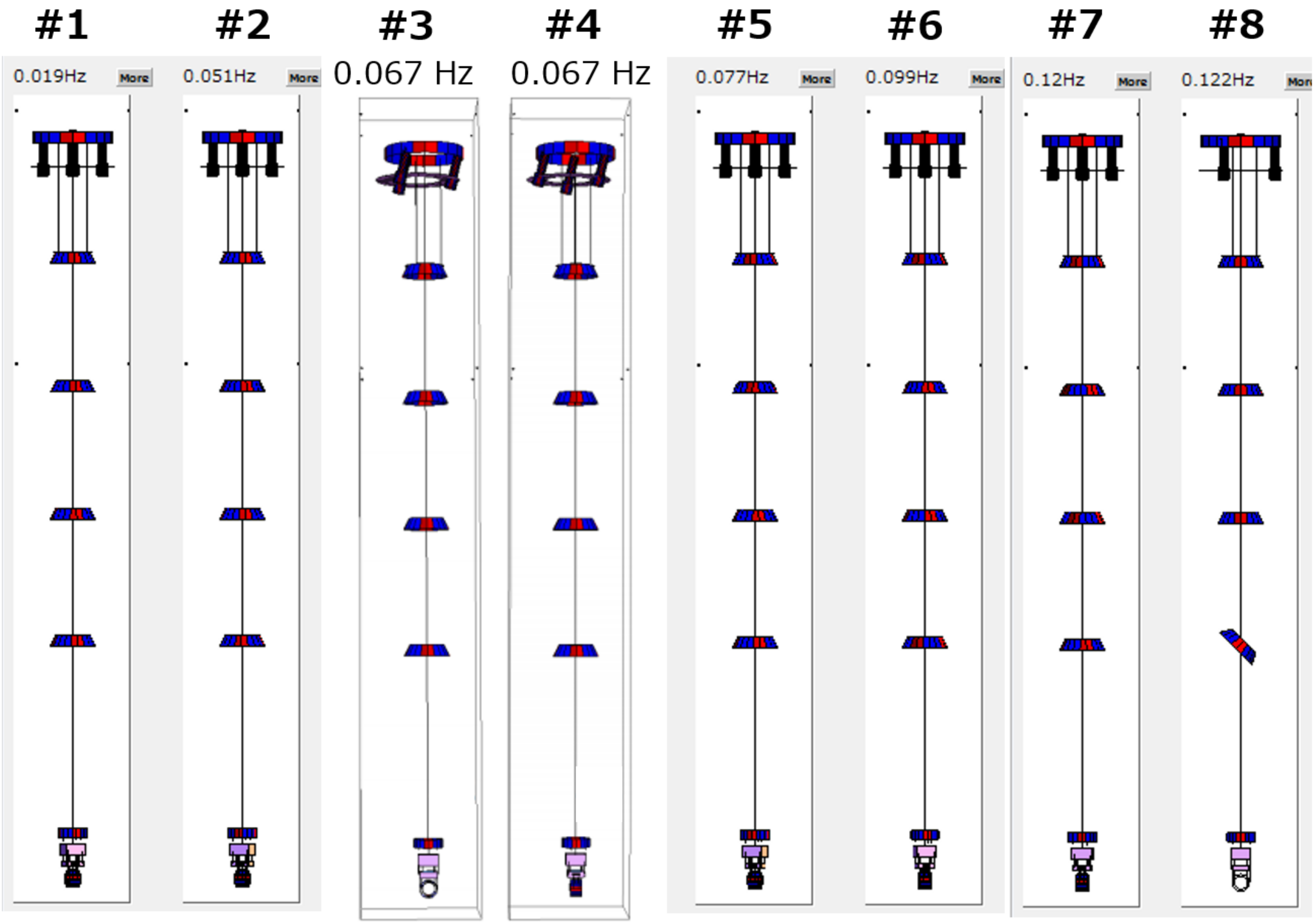
According to a simulation, assuming 1% coupling,



"acceptable
for the O3-run"

(should be)

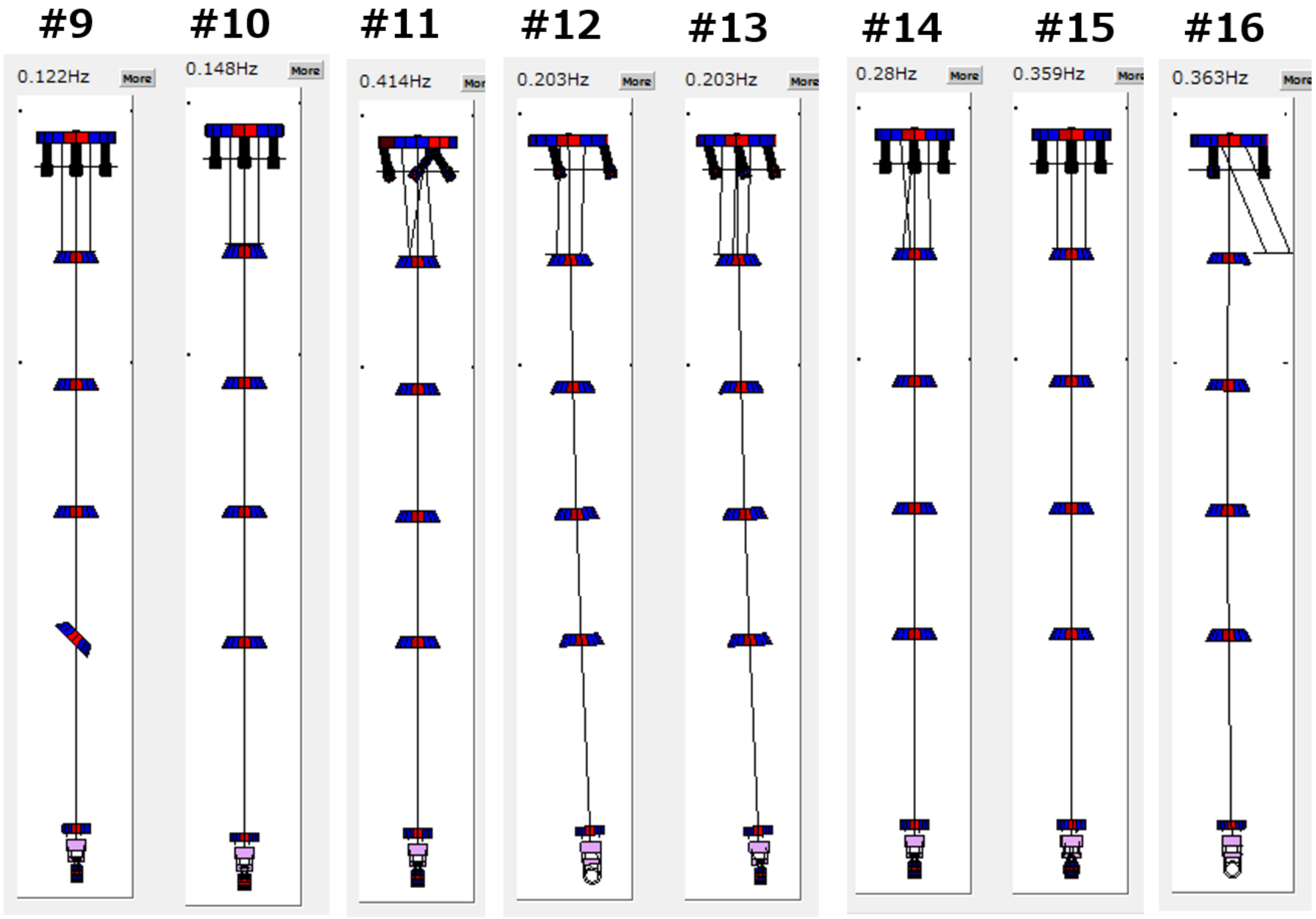
Note:
-- Modeled w/o Heat-links
-- params are not tuned.

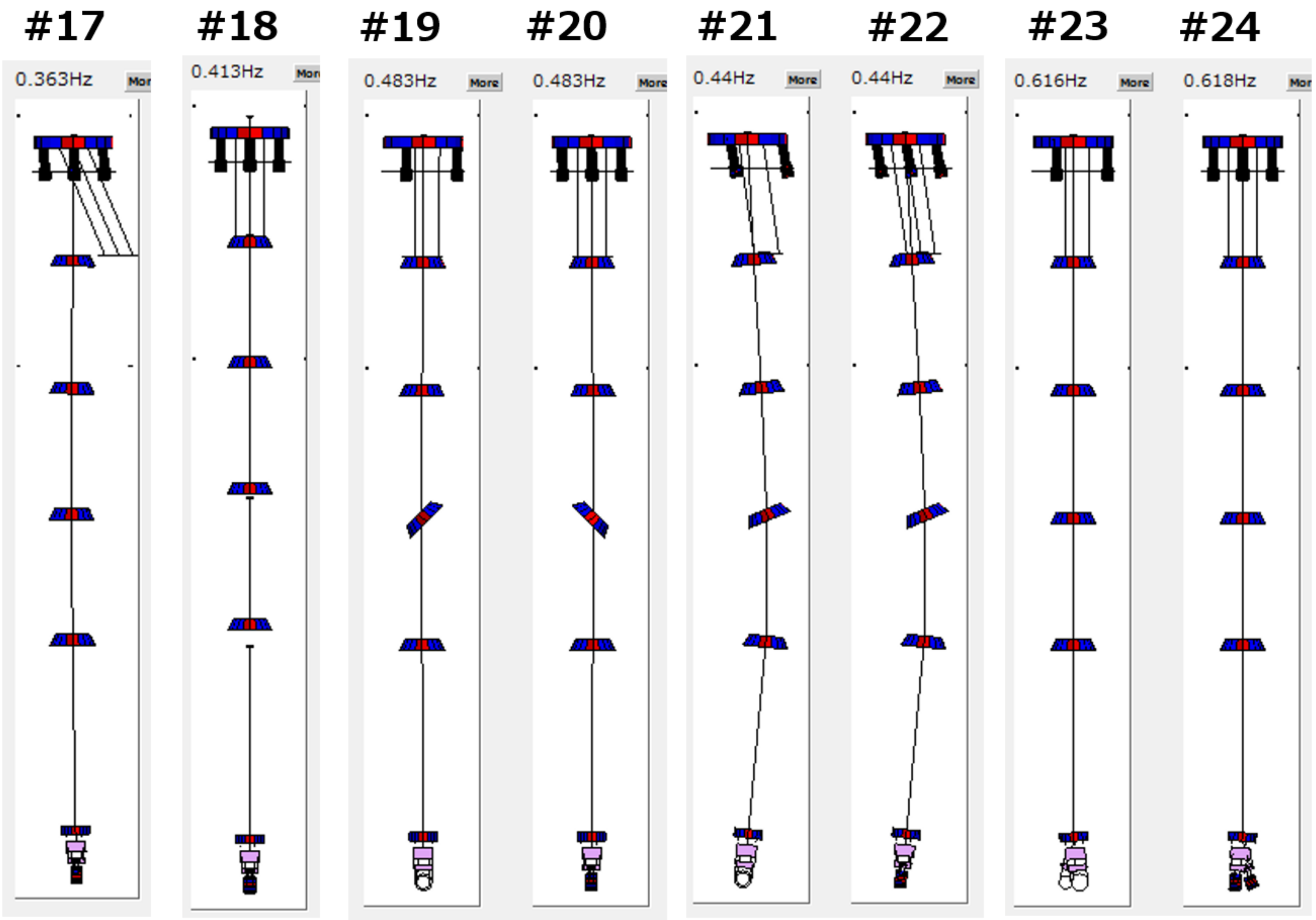


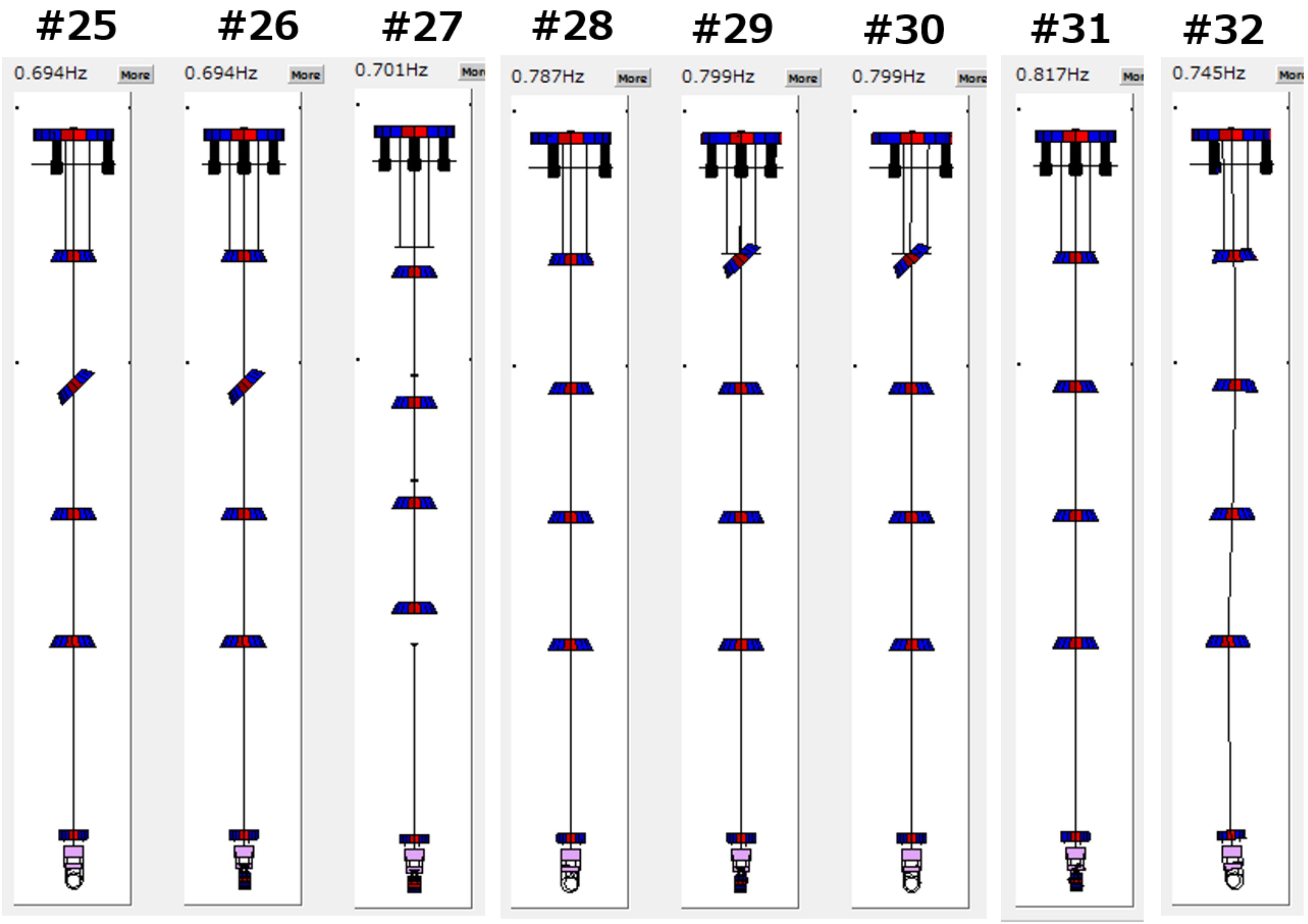
Type-A SAS,

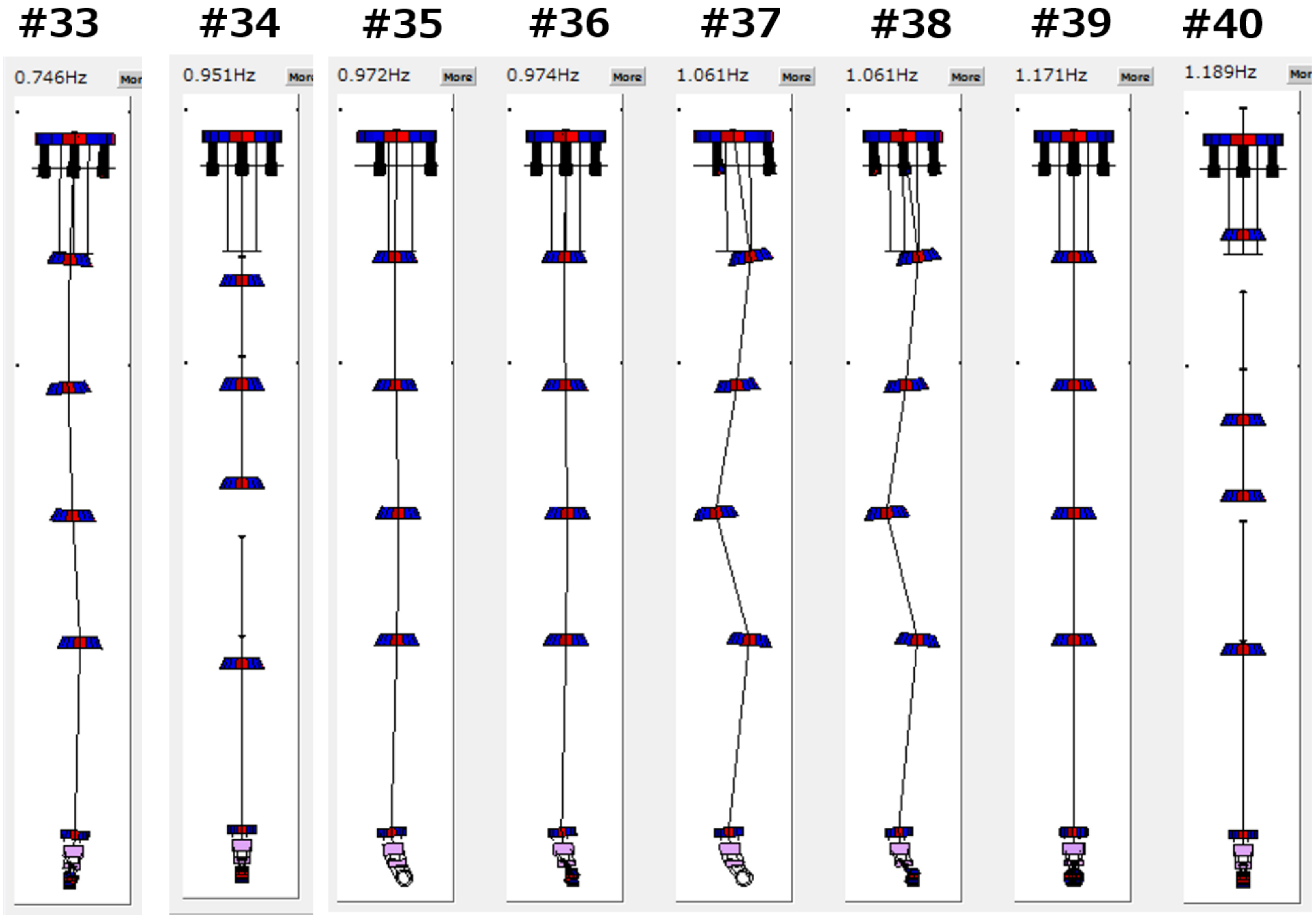
'TyrpeA180429_20K'

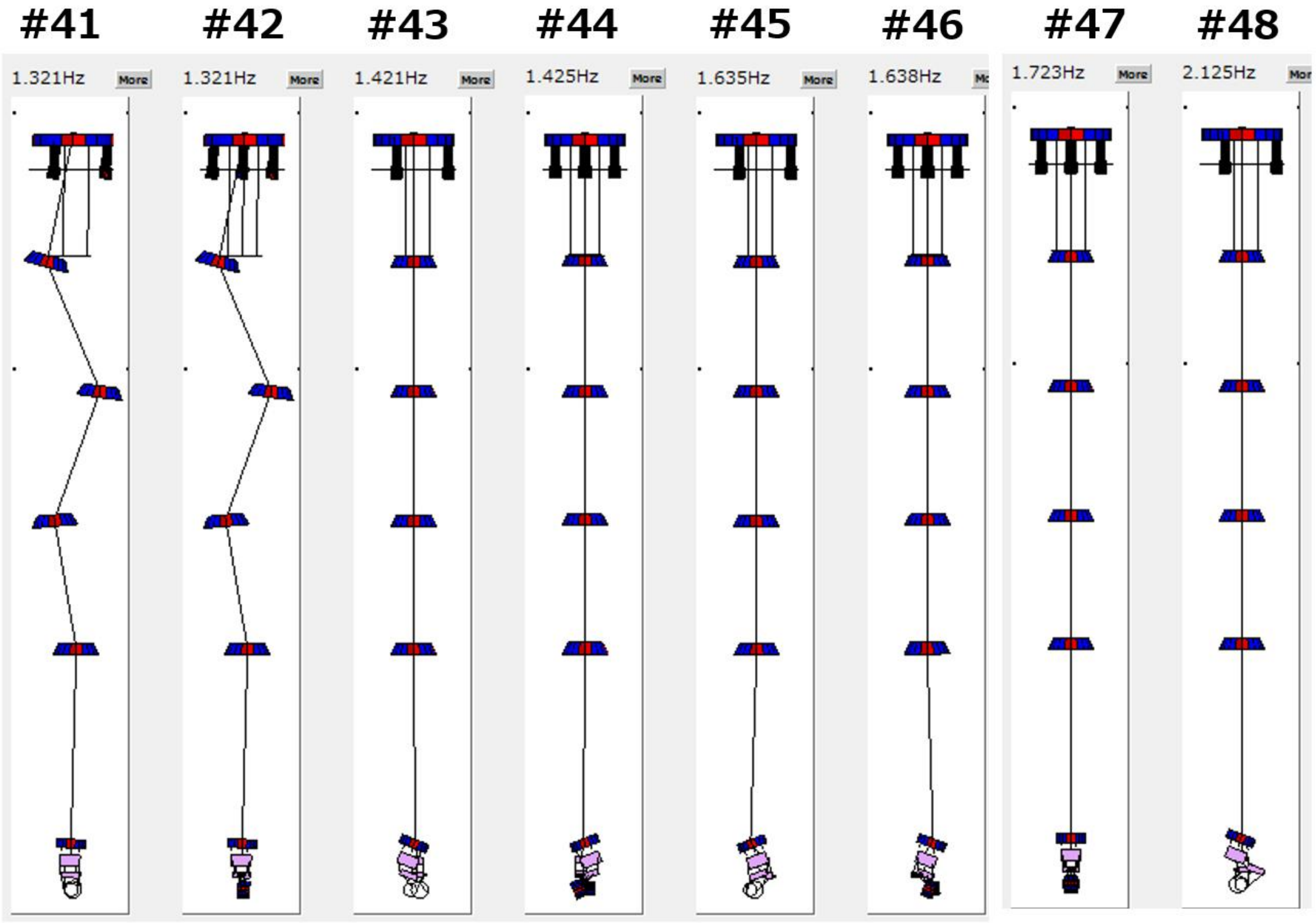
Eigen mode: 75 modes

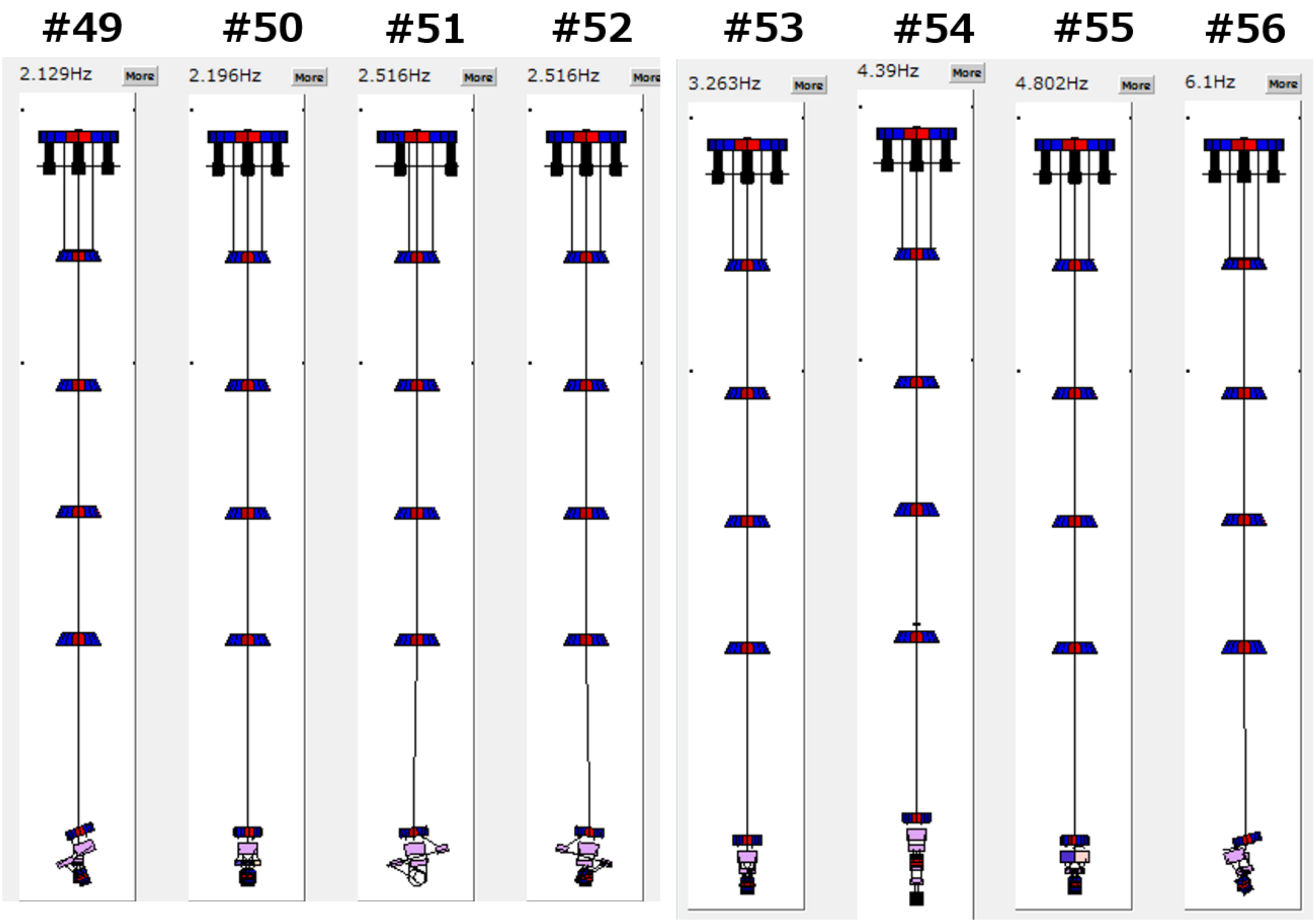

#9
0.122Hz
More
#10
0.148Hz
More
#11
0.414Hz
#12
0.203Hz
More
#13
0.203Hz
More
#14
0.28Hz
More
#15
0.359Hz
#16
0.363Hz

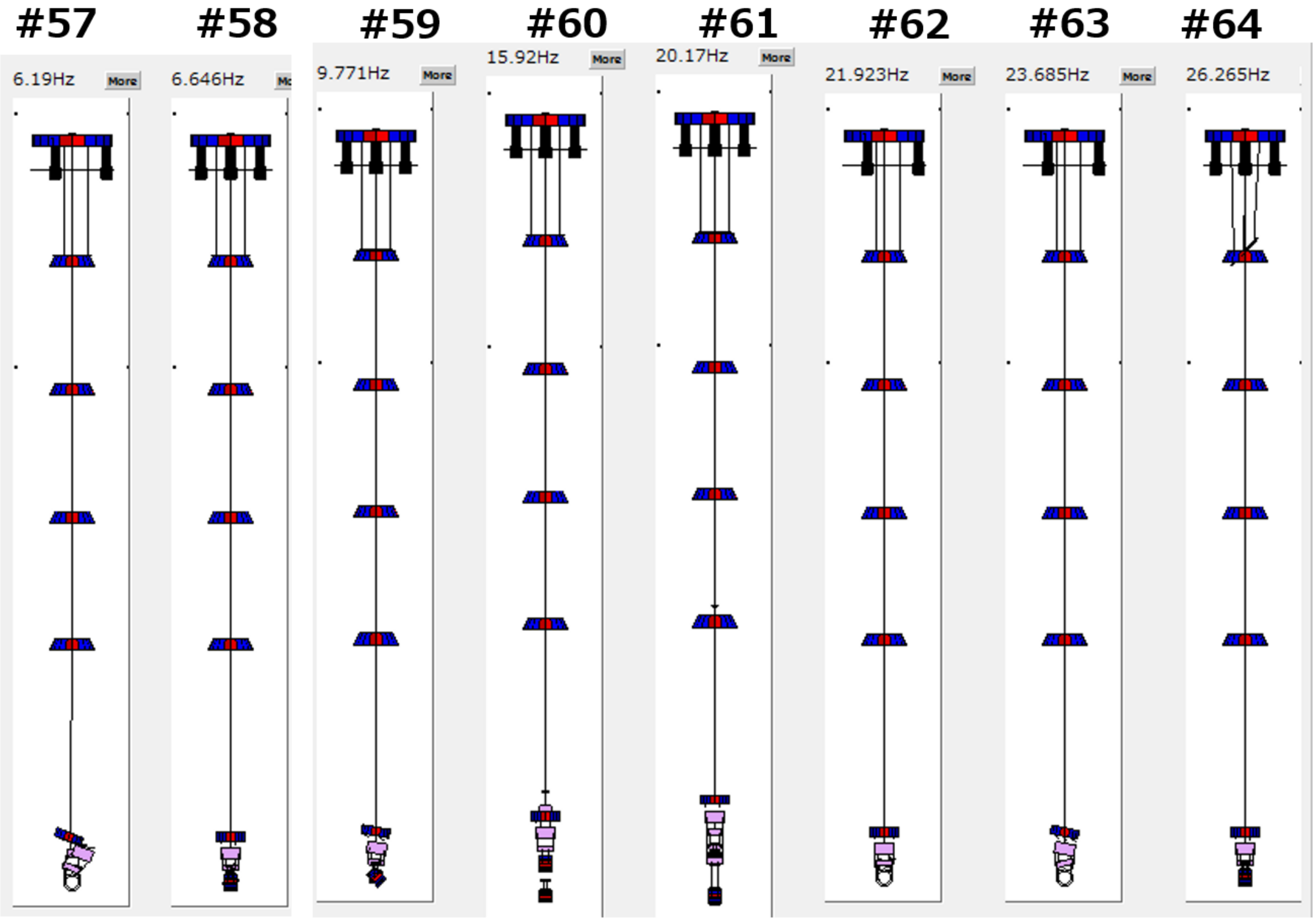

#17
#18
#19
#20
#21
#22
#23
#24
0.363Hz
0.413Hz
0.483Hz
0.483Hz
0.44Hz
0.44Hz
0.616Hz
0.618Hz


#25
0.694Hz
More
#26
0.694Hz
More
#27
0.701Hz
#28
0.787Hz
More
#29
0.799Hz
More
#30
0.799Hz
More
#31
0.817Hz
#32
0.745Hz

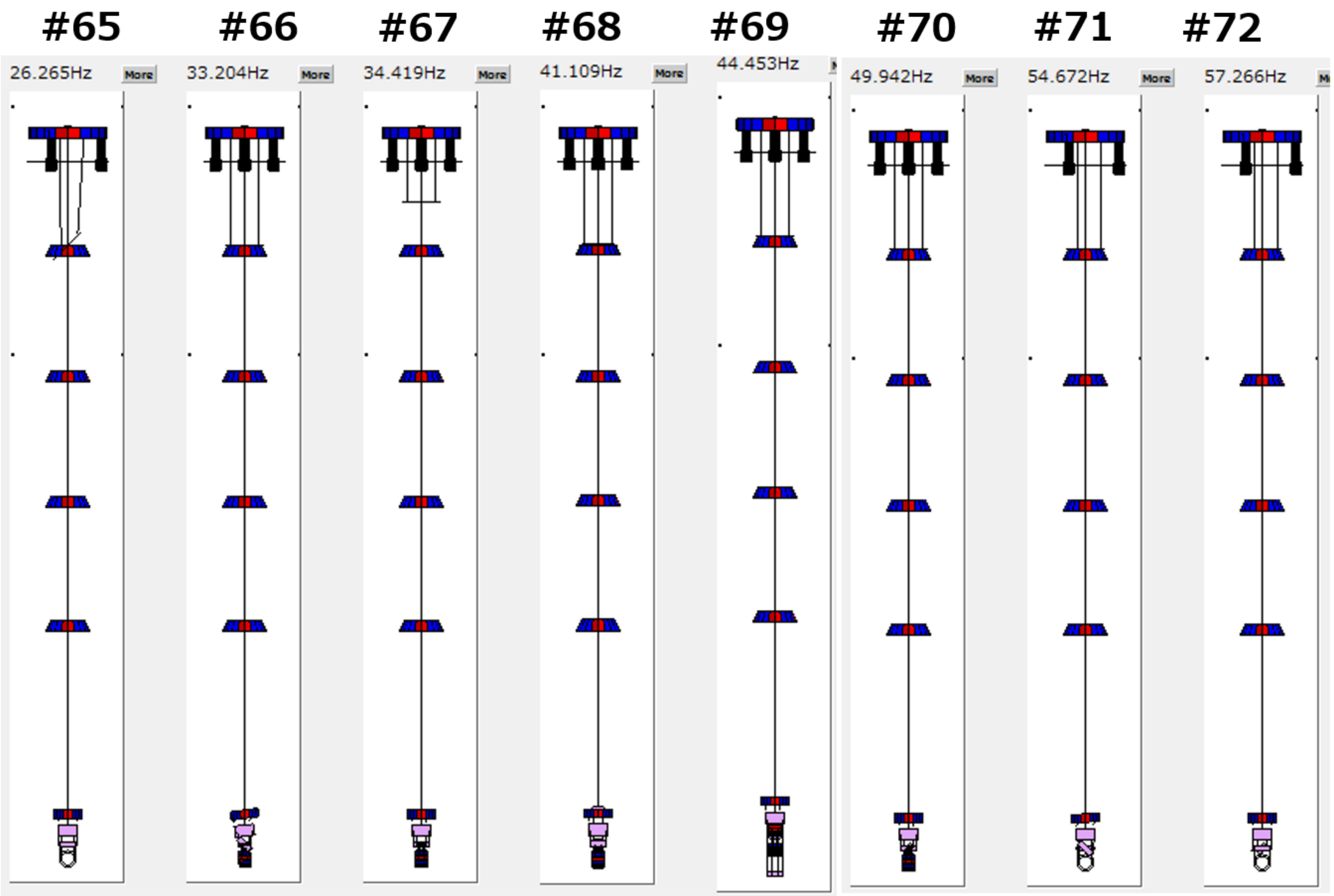

#33
0.746Hz
#34
0.951Hz
#35
0.972Hz
#36
0.974Hz
#37
1.061Hz
#38
1.061Hz
#39
1.171Hz
#40
1.189Hz


#41
#42
#43
#44
#45
#46
#47
#48
1.321Hz
1.321Hz
1.421Hz
1.425Hz
1.635Hz
1.638Hz
1.723Hz
2.125Hz


#49
2.129Hz
More
#50
2.196Hz
More
#51
2.516Hz
More
#52
2.516Hz
More
#53
3.263Hz
More
#54
4.39Hz
More
#55
4.802Hz
More
#56
6.1Hz
More



#57
6.19Hz
More
#58
6.646Hz
#59
9.771Hz
More
#60
15.92Hz
More
#61
20.17Hz
More
#62
21.923Hz
More
#63
23.685Hz
More
#64
26.265Hz


#65
#66
#67
#68
#69
#70
#71
#72
26.265Hz
More
33.204Hz
More
34.419Hz
More
41.109Hz
More
44.453Hz
49.942Hz
More
54.672Hz
More
57.266Hz

#73 #74 #75