



中央研究院
Academia Sinica



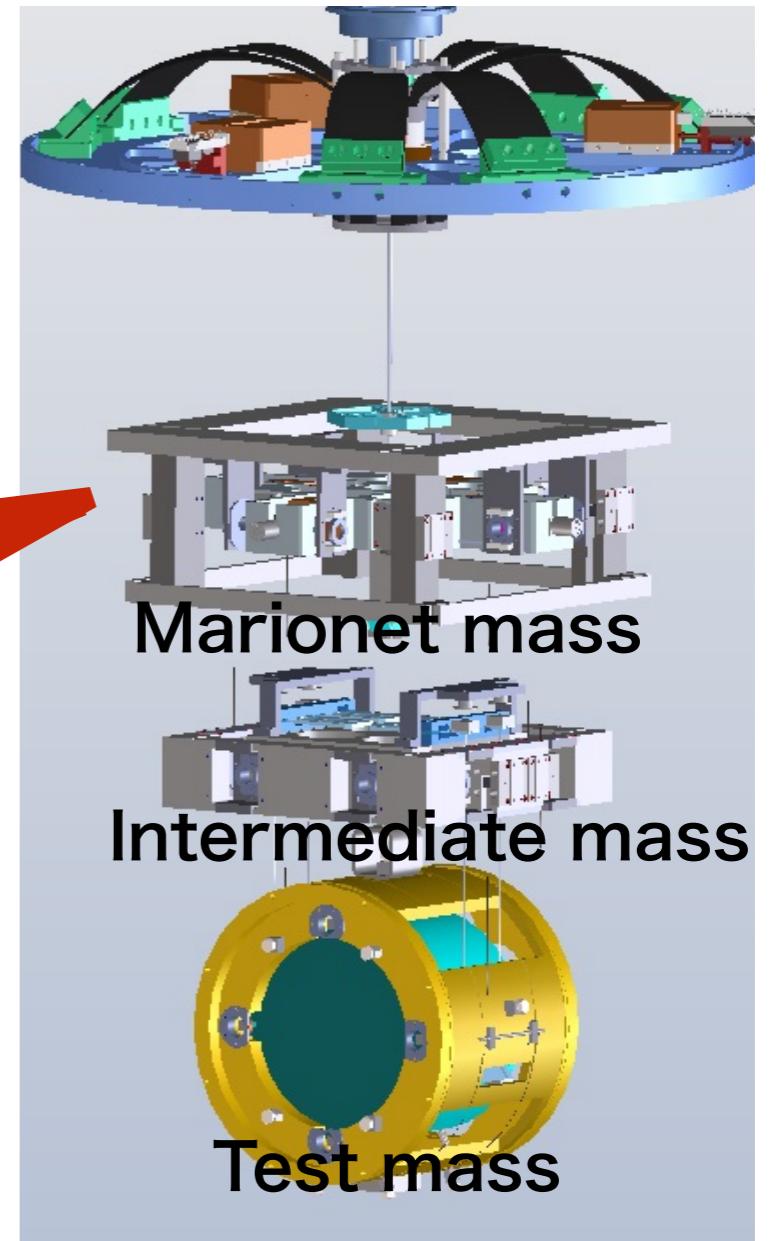
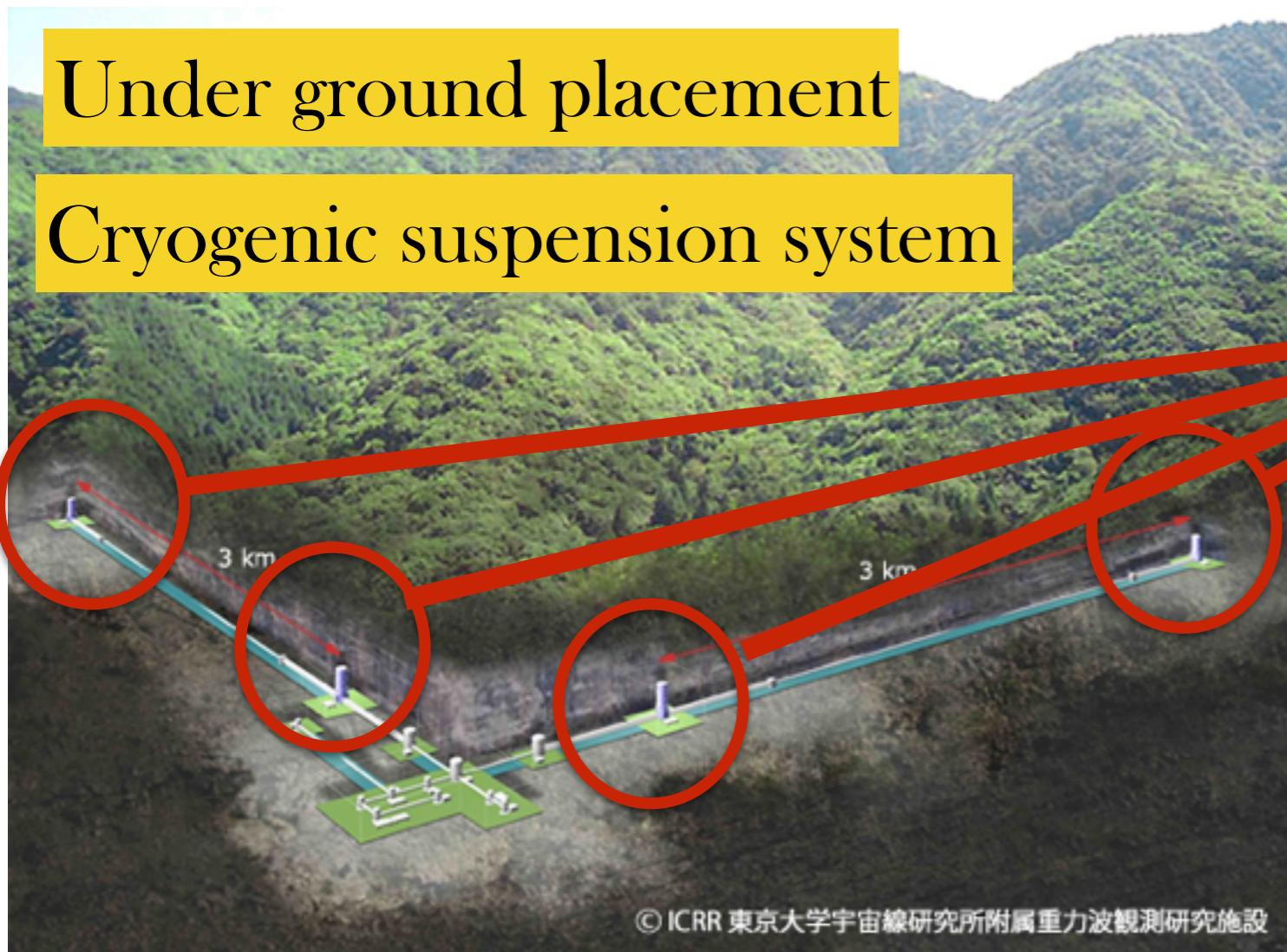
KAGRA calibration and waveform accuracy

Academia Sinica / KEK
Yuki Inoue
on behalf of KAGRA collaboration

Outline

- Introduction
- KAGRA photon calibrator
- Calibration Interferometer
- Relative Cross-calibration between LVK
- Absolute Cross-calibration between LVK
- Summary

Introduction of KAGRA

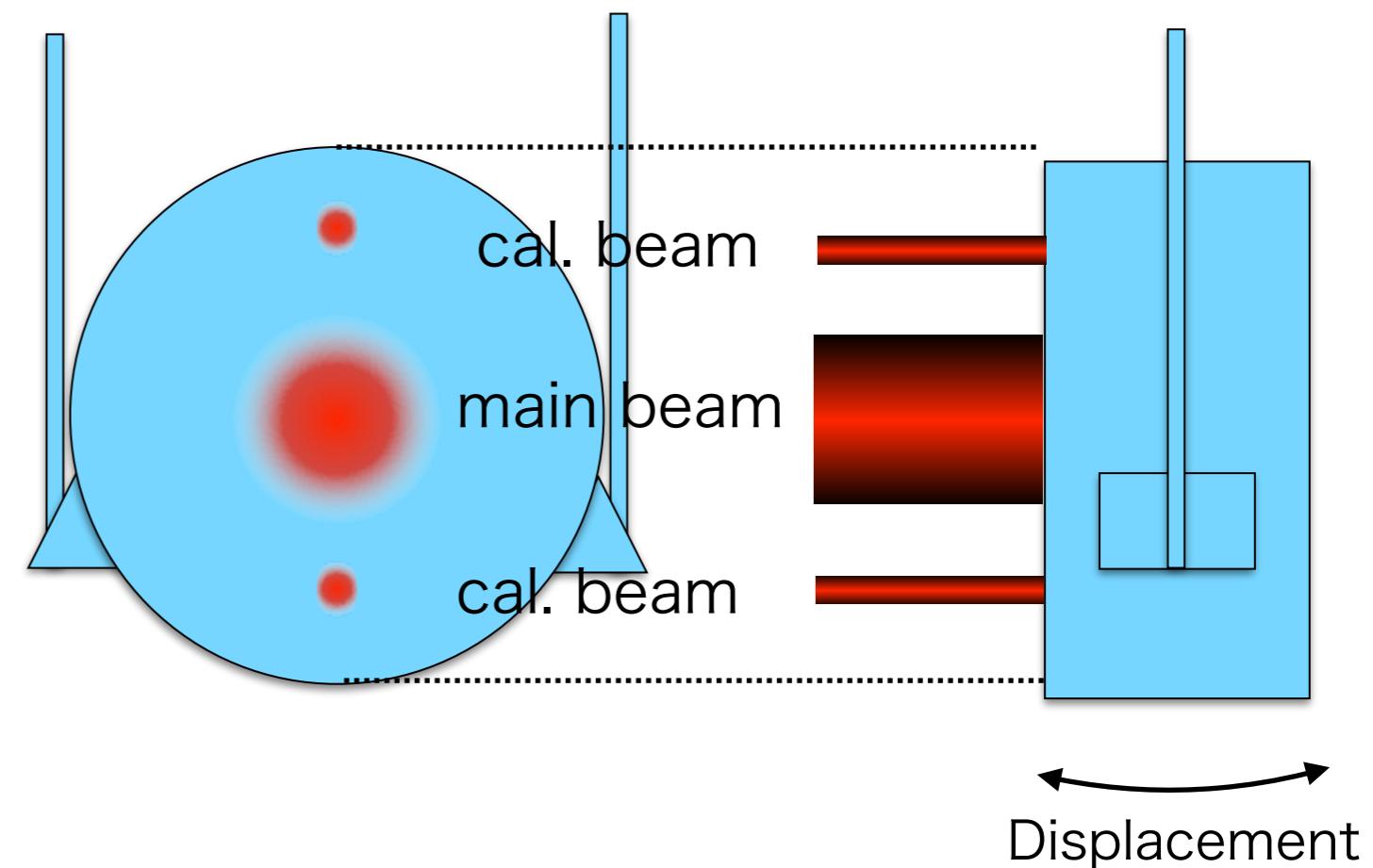


KAGRA is currently installing the instruments to start the full operation at 2020. The error of calibration and reconstruction propagate to waveform error. If the reconstructed $h(t)$ of LIGO, Virgo and KAGRA include bias, we misestimate the GW parameters.

“Detector bias”

KAGRA photon calibrator

- Technologically established in LIGO.
- 20W laser
- Modulate laser power
- Assuming free mass motion
- Calibrating absolute laser power in NIST



$$dx = \frac{2P \cos \theta}{c} s(f) \left(1 + \frac{M}{I} \vec{a} \cdot \vec{b} \right)$$

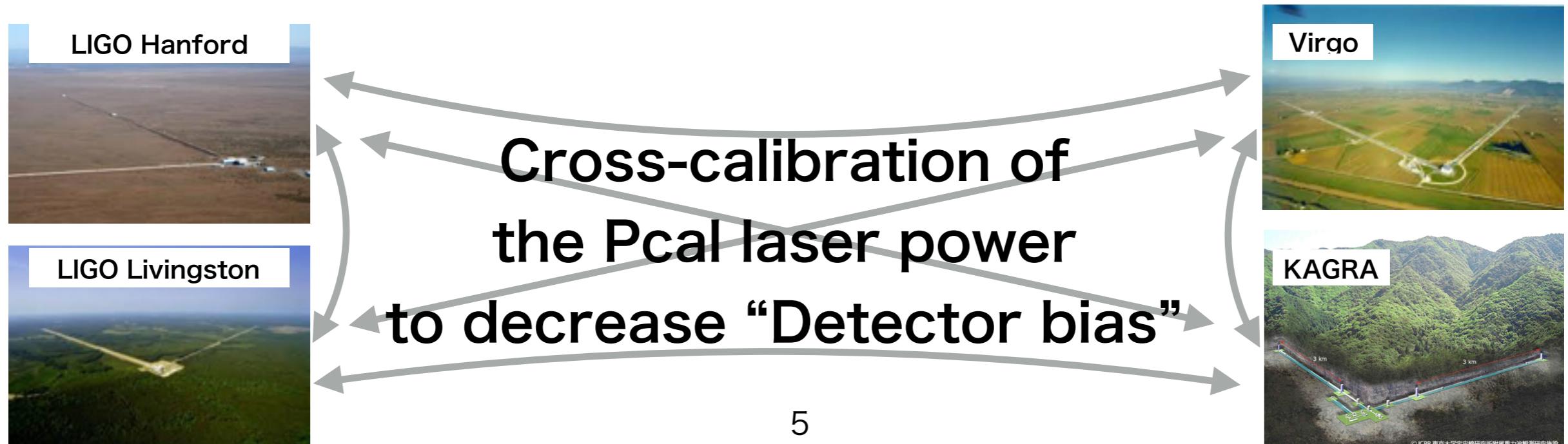
Force Transfer function Geometrical factor

$$\text{Free mass motion: } s(f) = \frac{1}{M\omega^2}$$

We can calibrate the absolute displacement through the absolute laser power.

Calibration for LVK global observation

1. Calibrating response function of each interferometer
 - Impact on e.g. CBC parameter estimation
2. Cross-calibration of relative GW amplitudes of LVK through laser powers of photon calibrator
 - Impact on e.g. source localization
3. Absolute calibration of GW amplitude through the absolute power calibration of photon calibrators
 - Impact on e.g. source distance



Calibration for LVK global observation

1. Calibrating response function of each interferometer

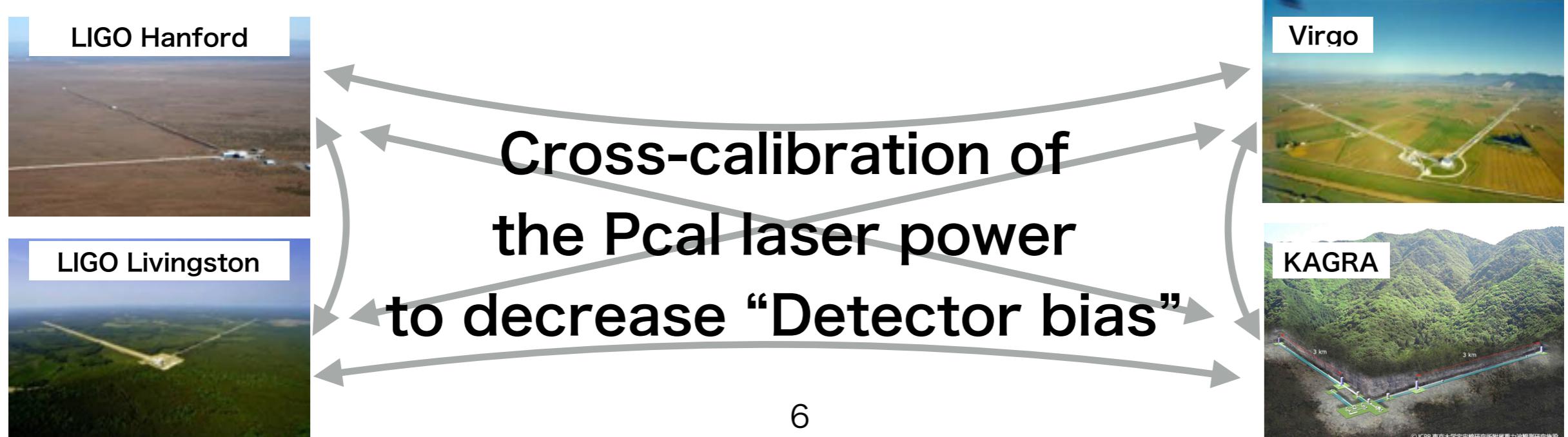
- Impact on e.g. CBC parameter estimation

2. Cross-calibration of relative GW amplitudes of LVK through laser powers of photon calibrator

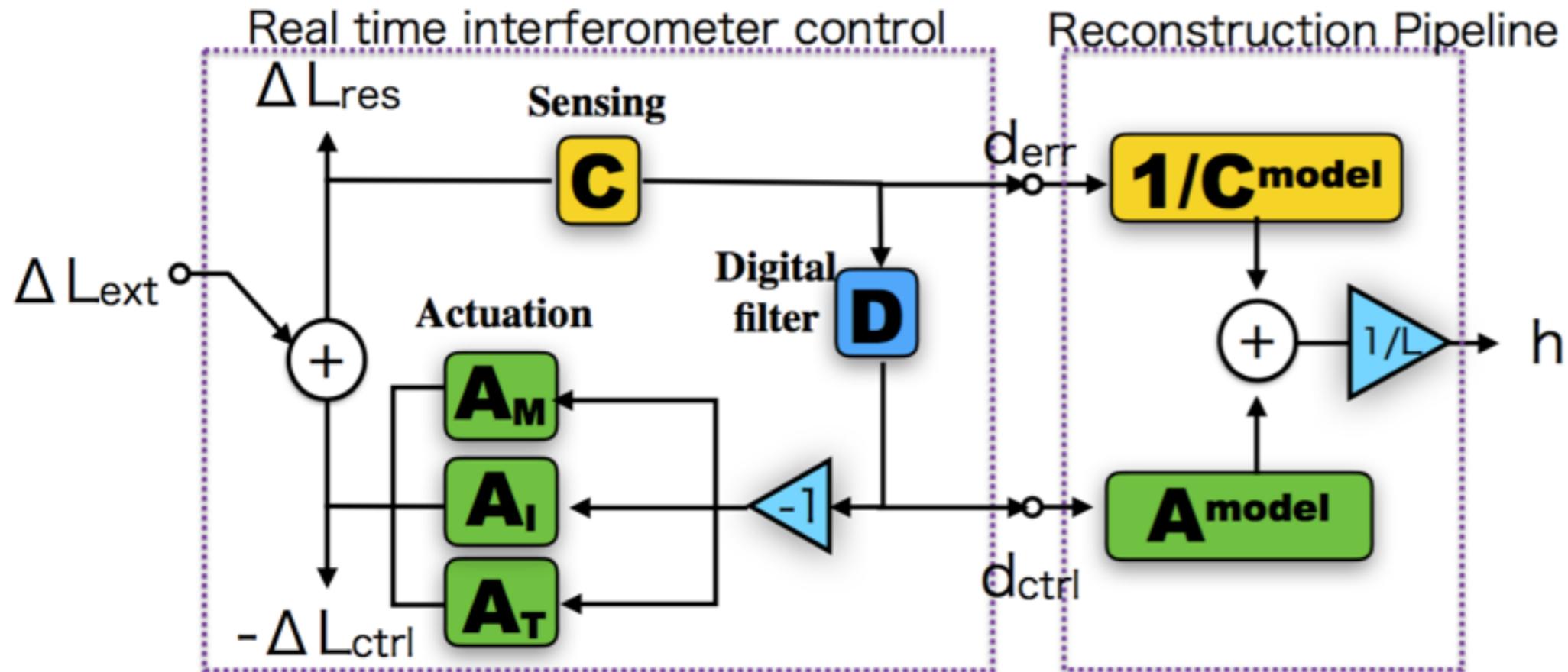
- Impact on e.g. source localization

3. Absolute calibration of GW amplitude through the absolute power calibration of photon calibrators

- Impact on e.g. source distance



KAGRA Feedback loop model



We reconstruct $h(t)$ by modeling time-dependent Sensing and Actuation factor

C^{model}

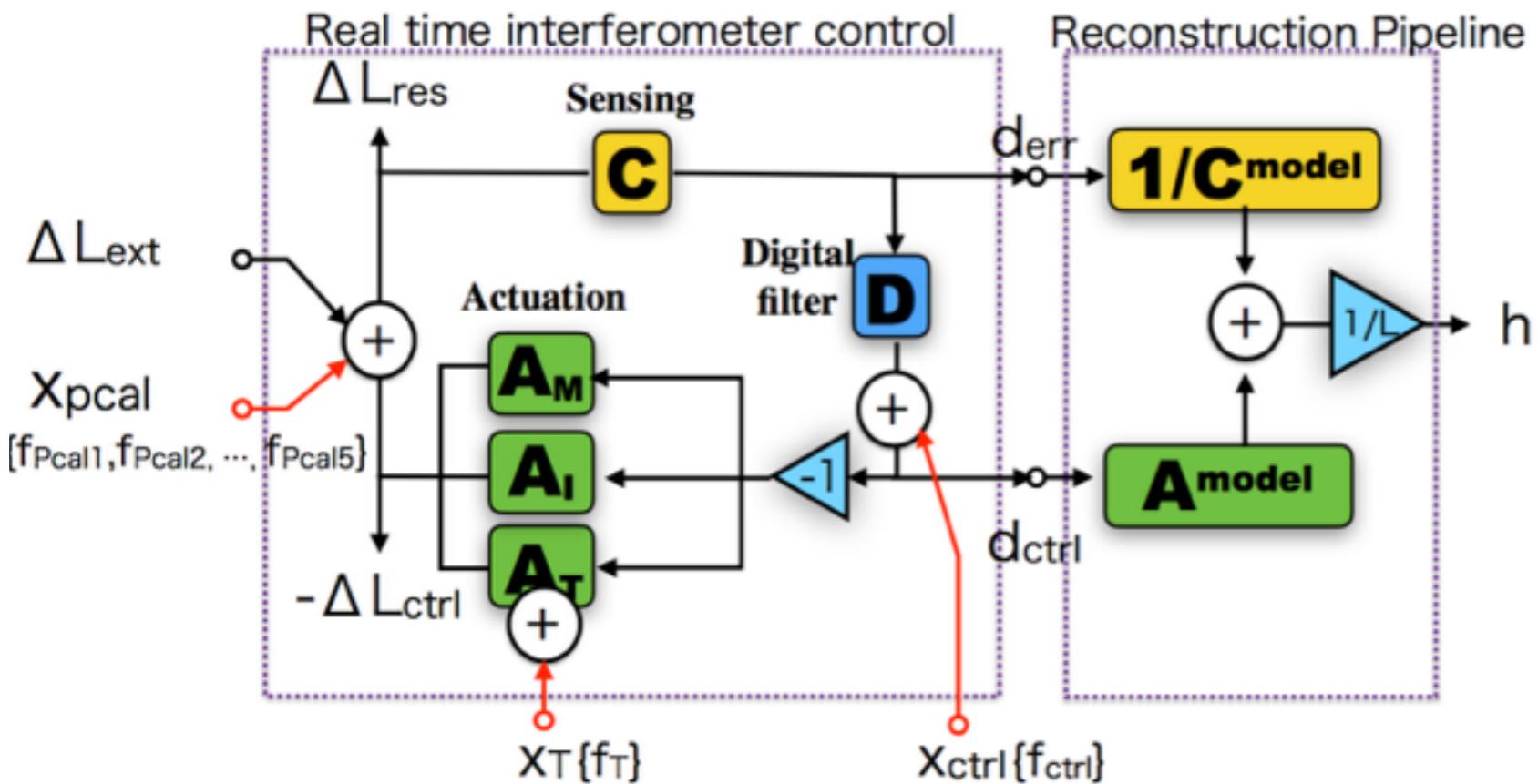
$$: C(f, t) = \frac{\kappa_C(t)}{1 + if/f_C(t)} Q(f) \equiv P(f, t)Q(f).$$

A^{model}

$$: A(f, t) = \kappa_M(t)A_{M,0}(f) + \kappa_I(t)A_{I,0}(f) + \kappa_T(t)A_{T,0}(f)$$

$$h(t) = \frac{\Delta L_{\text{ext}}(t)}{L} = C^{-1} * d_{\text{err}}(t)/L + A * d_{\text{ctrl}}(t)/L$$

KAGRA Feedback loop model



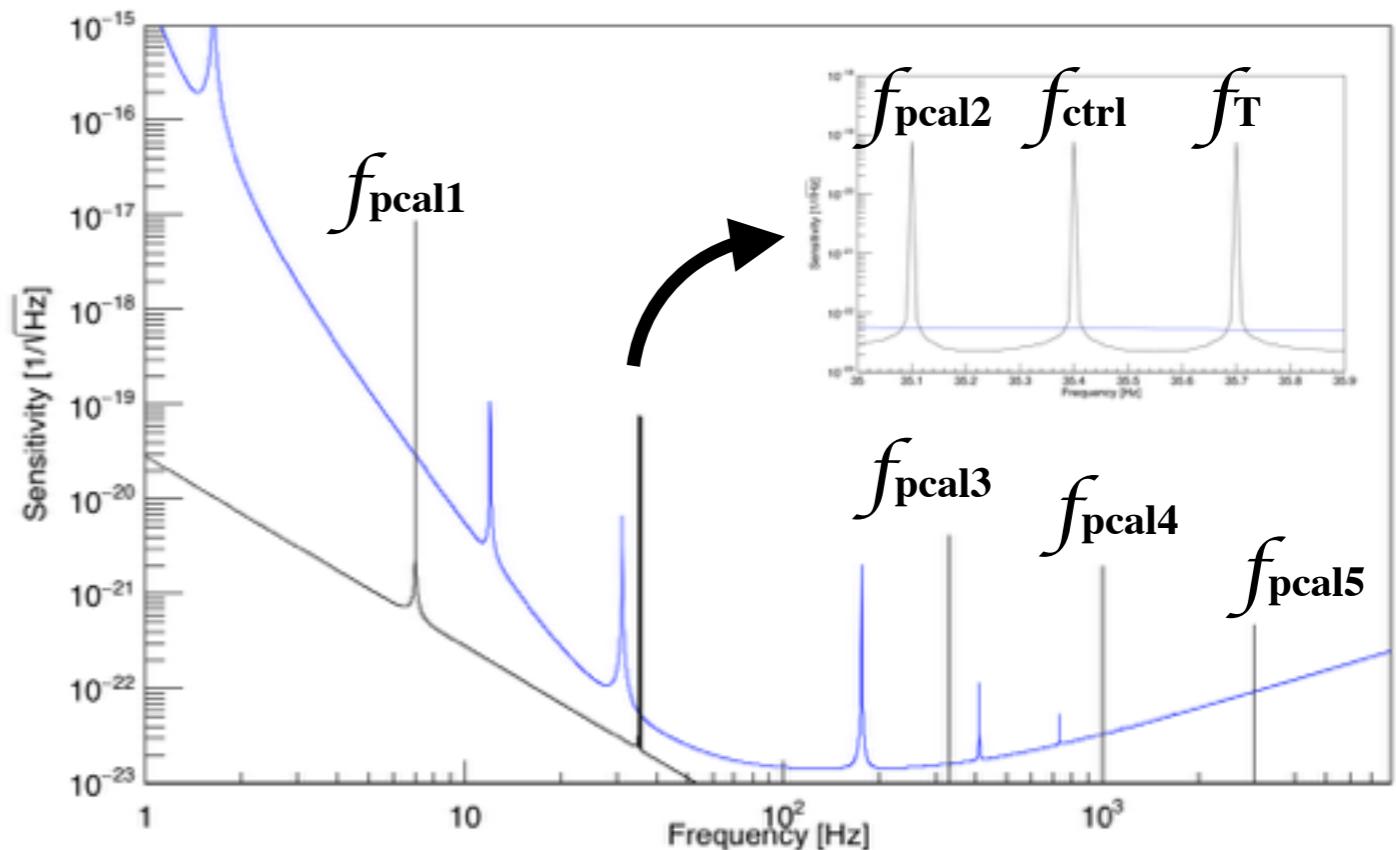
Line name	Cal.	Frequenc
Xpcal	$f_{\text{pcal}1}$	~7Hz
	$f_{\text{pcal}2}$	35Hz
	$f_{\text{pcal}3}$	~330Hz
	$f_{\text{pcal}4}$	~1000Hz
	$f_{\text{pcal}5}$	~3000Hz
Xctrl	f_{ctrl}	~35Hz
XT	f_T	~35Hz

To solve, we inject calibration line to feed back loop

X_{pcal} : Photon Calibrator

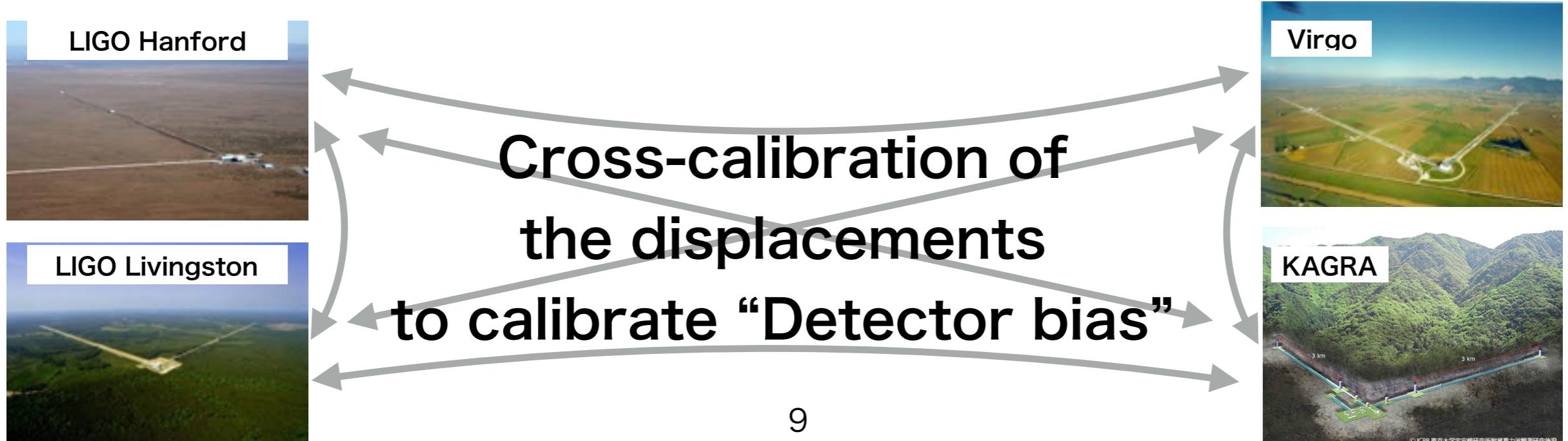
X_T : Coil magnet actuator

X_{ctrl} : Software



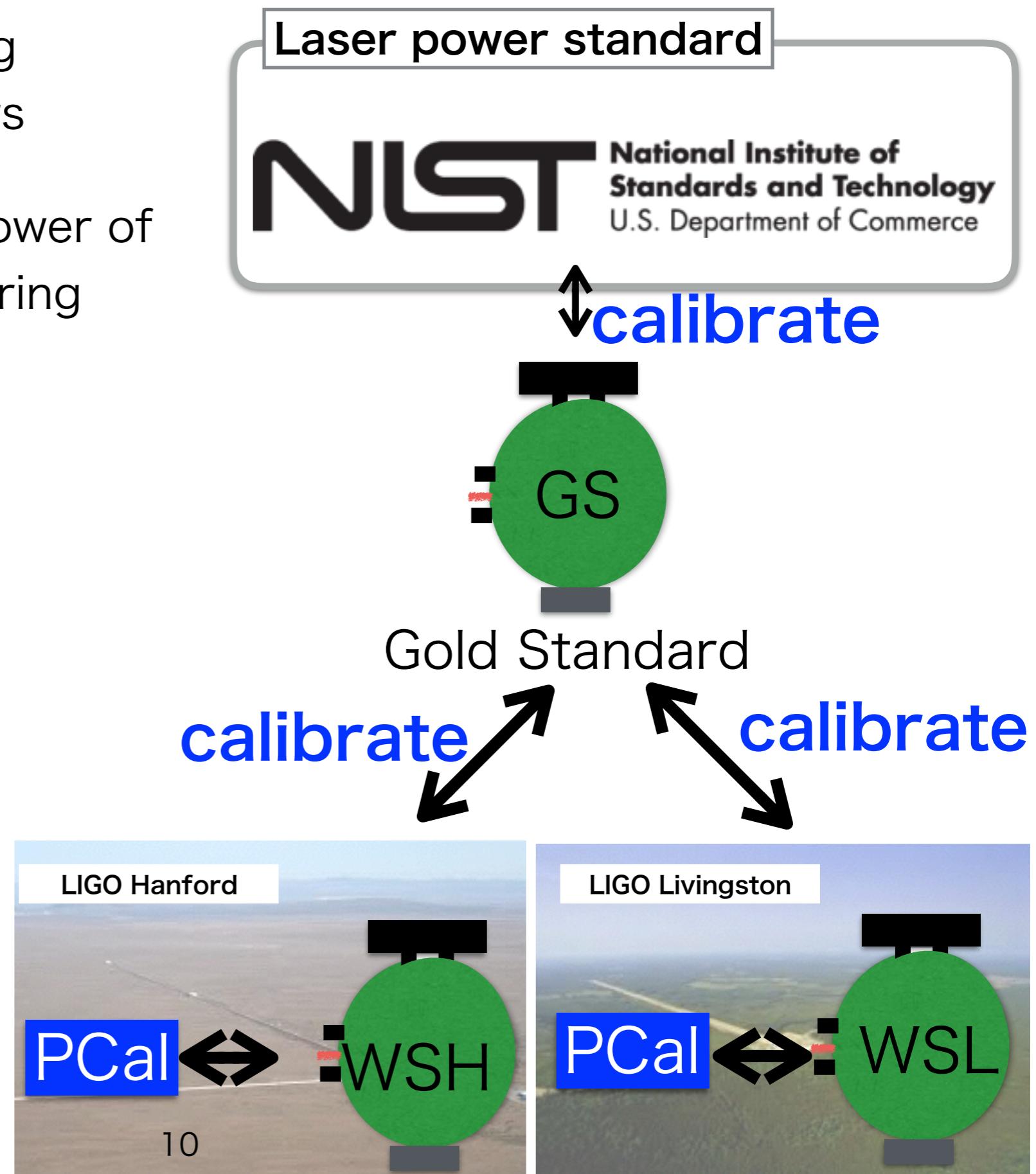
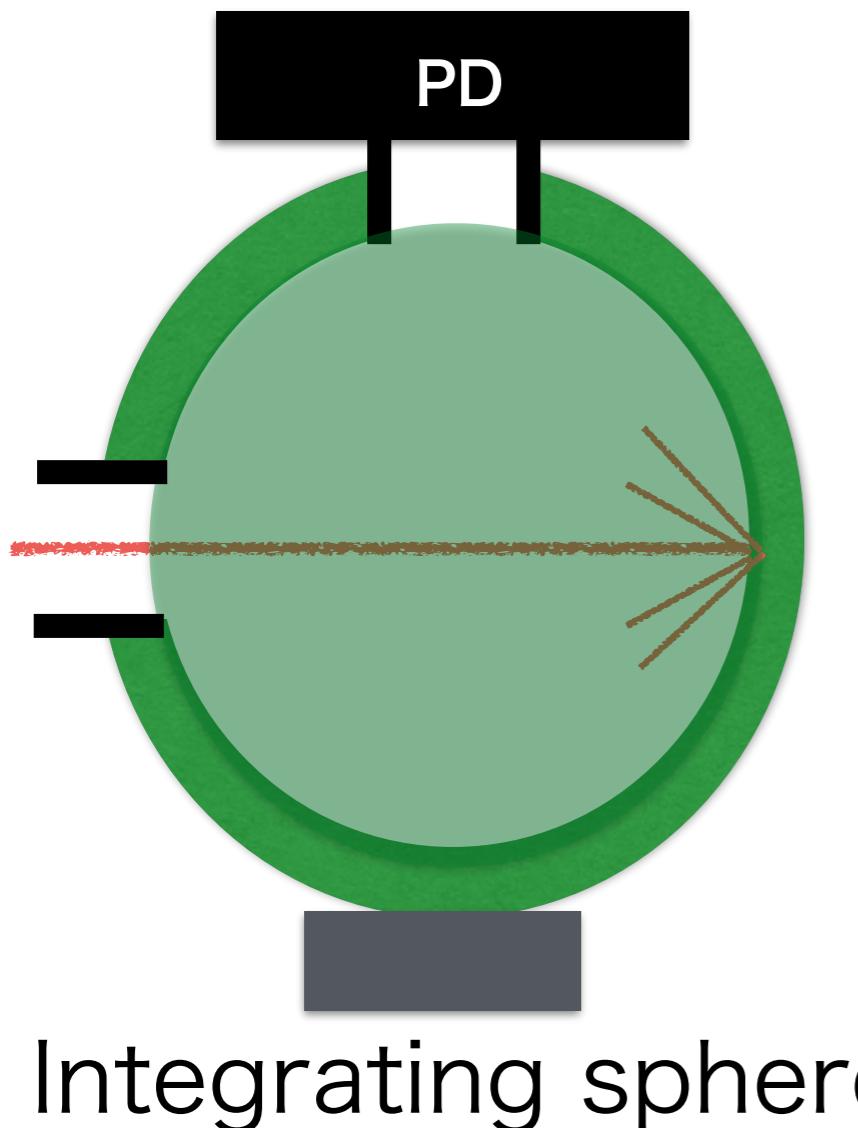
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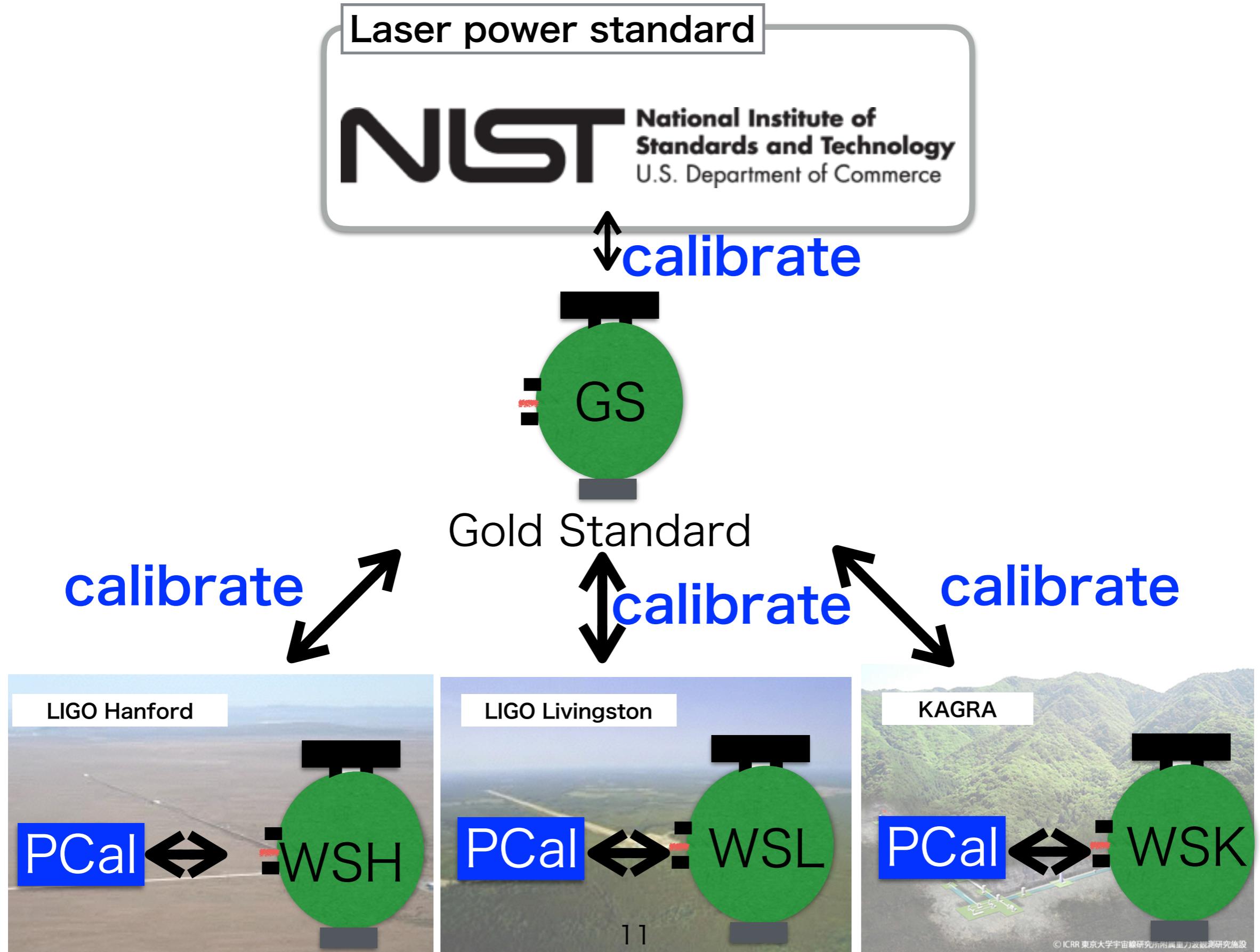


Calibration standard (Previous study in LIGO)

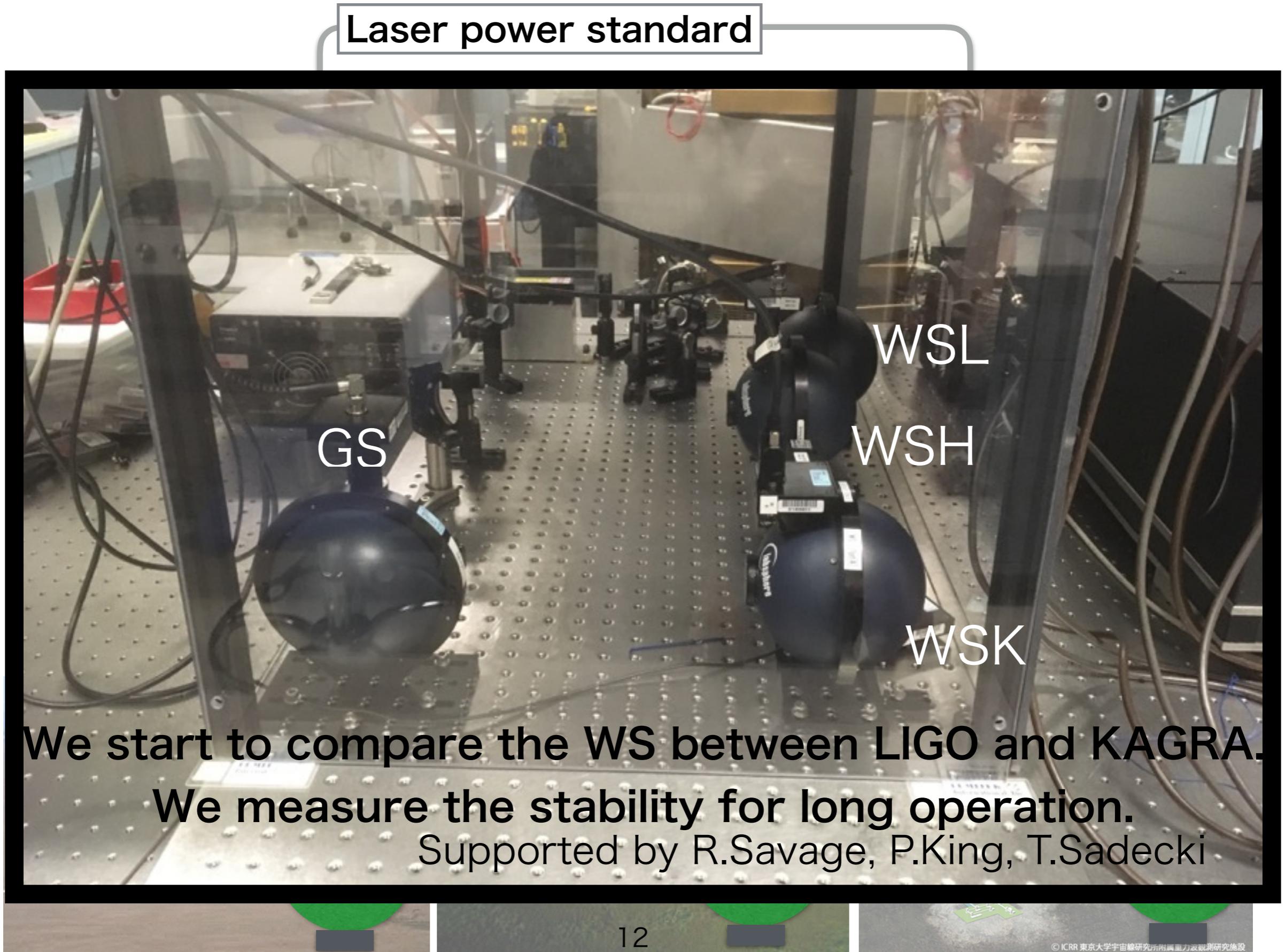
- LIGO prepare the Integrating spheres and photo detectors
- Calibrating absolute laser power of Photon calibrator by comparing response of detector



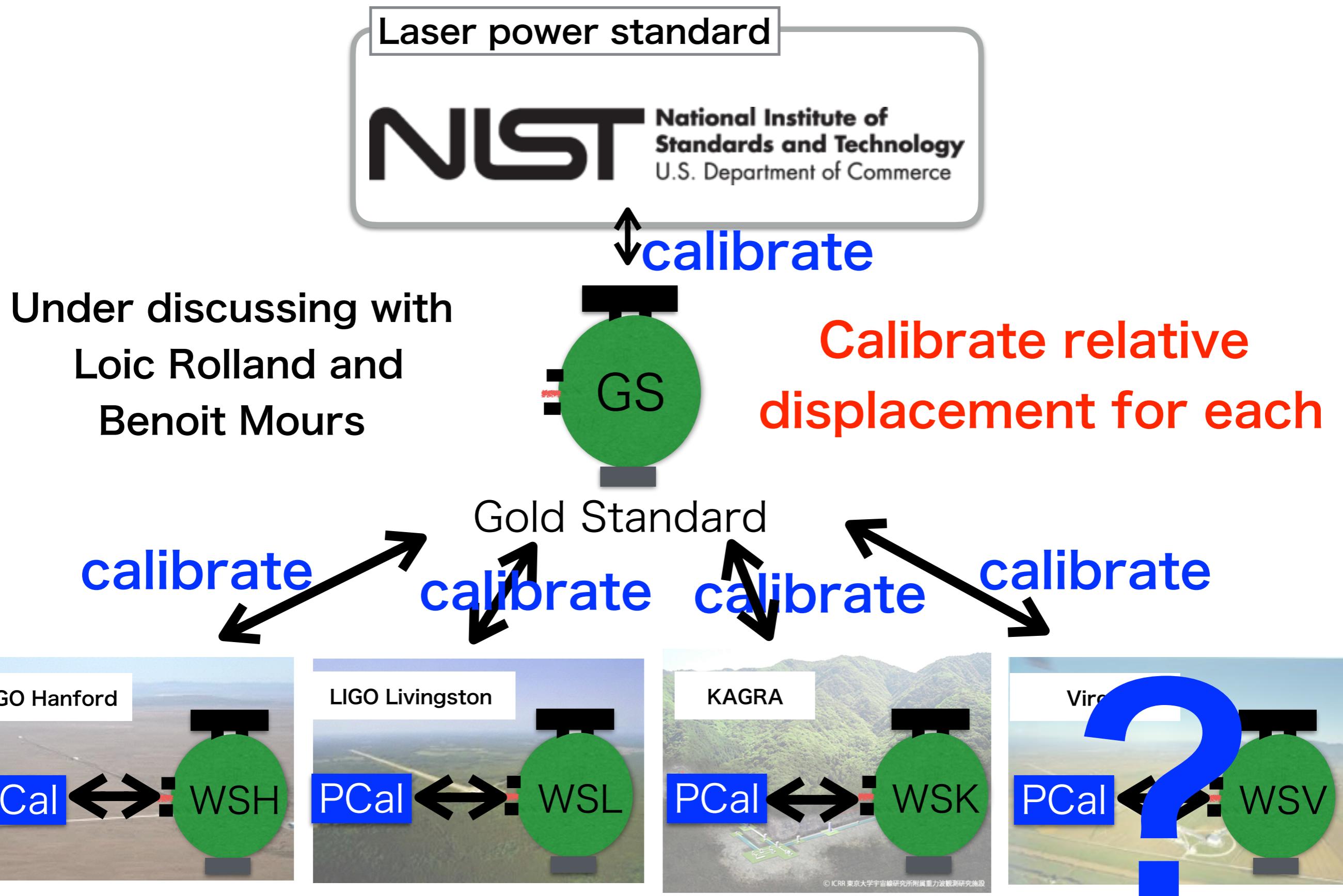
Calibration standard (Current status)



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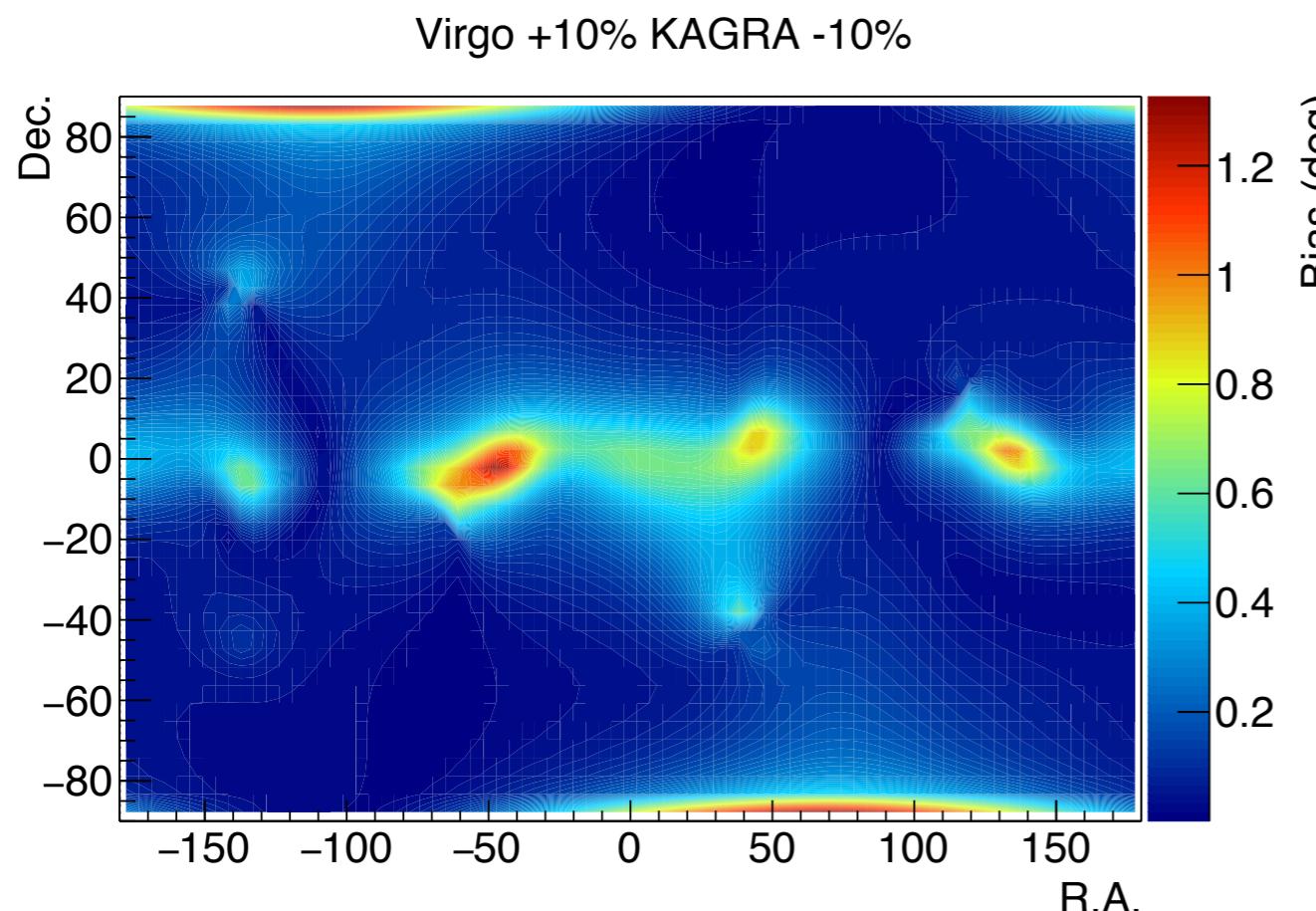
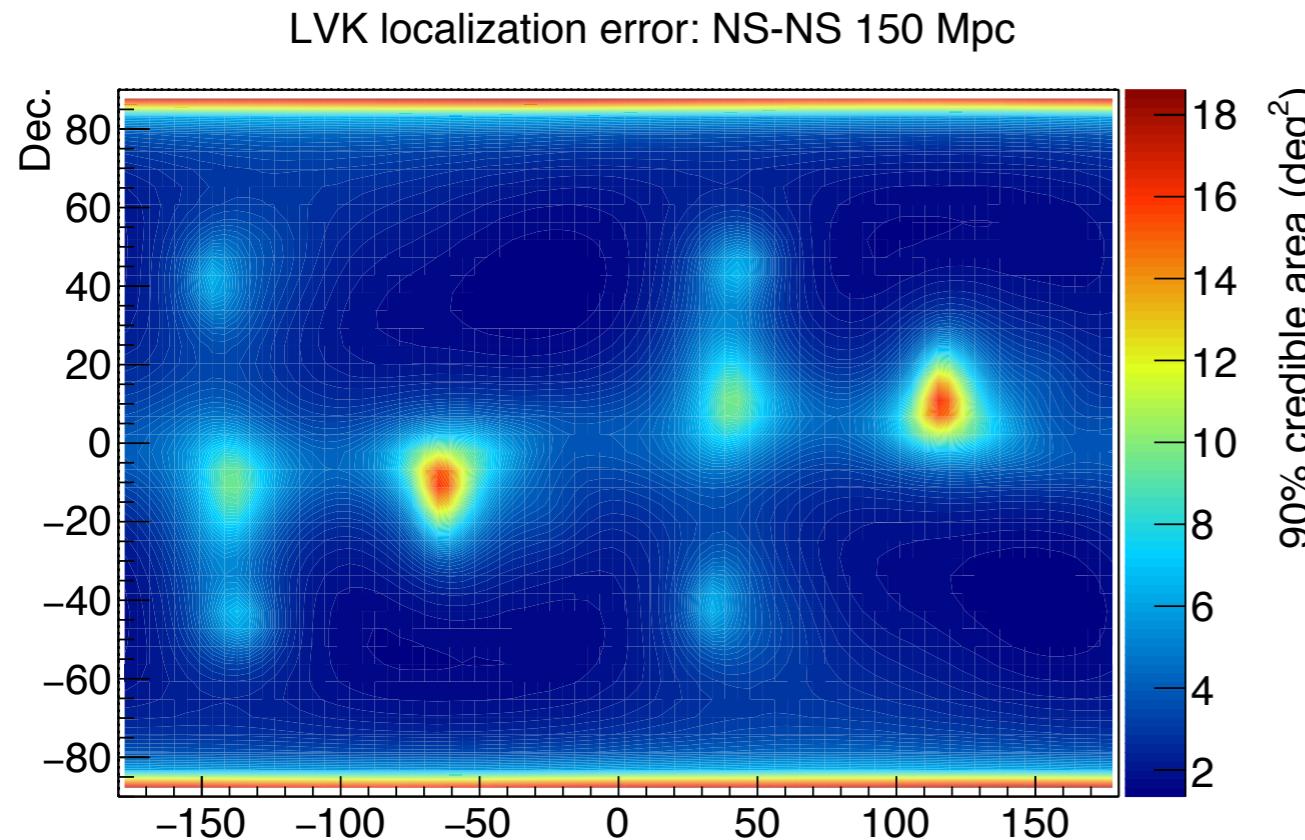


Calibration standard (Future)



Localization

Analysis method adopted from arxiv1606.00953

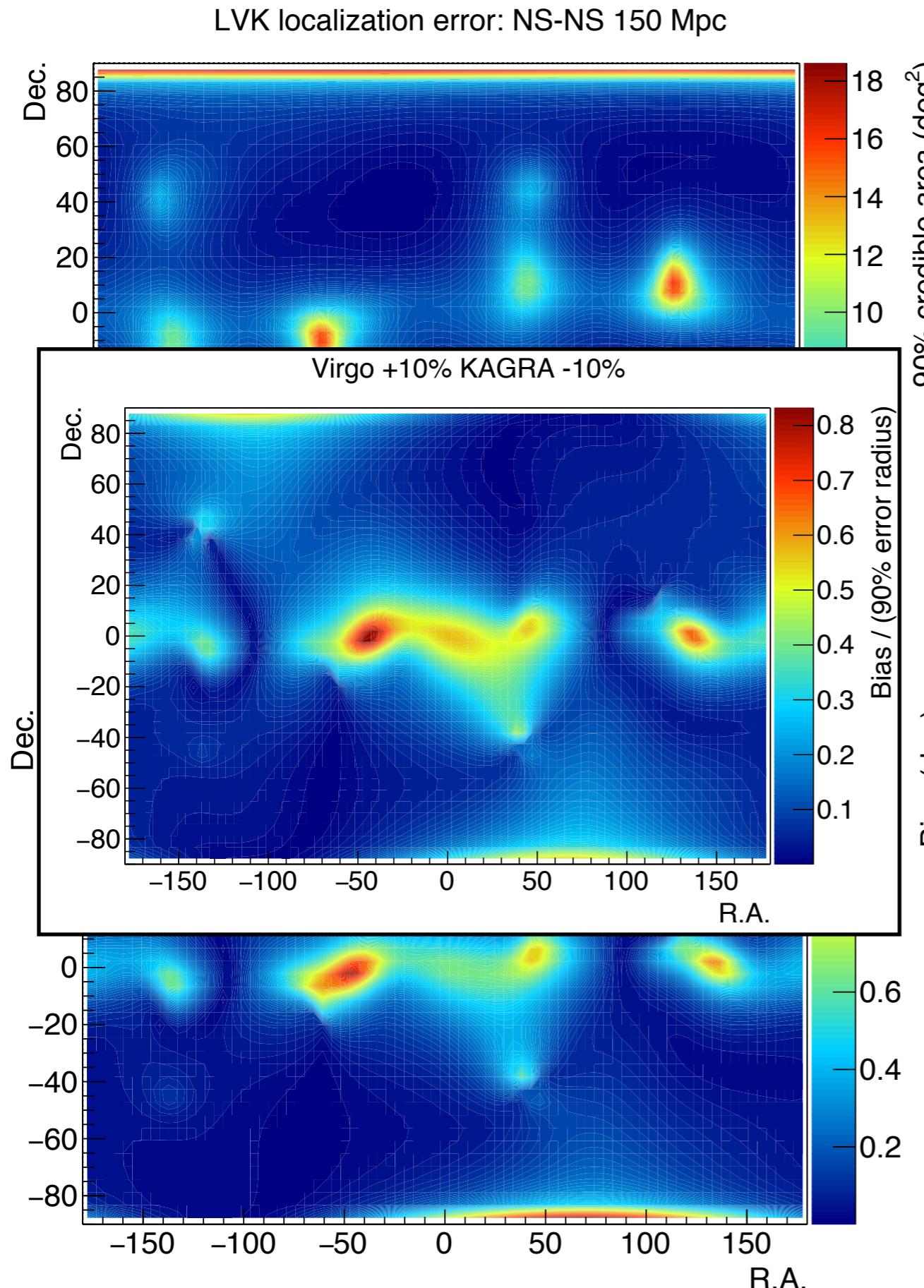


- LHO,LLO,Virgo,KAGRA
- 1.4-1.4 BNS
- 150Mpc
- LHO,LLO: no bias
- Virgo: +10%
- KAGRA: -10%

bias of up to 1.2 deg
(large bias in weaker
combined antenna region)

Localization

Analysis method adopted from arxiv1606.00953

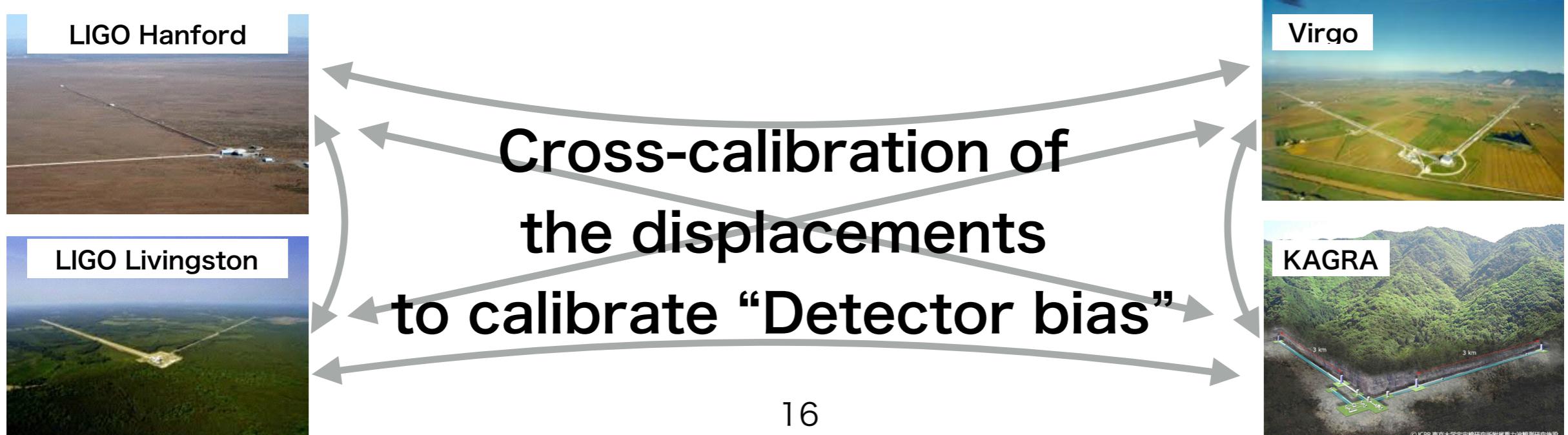


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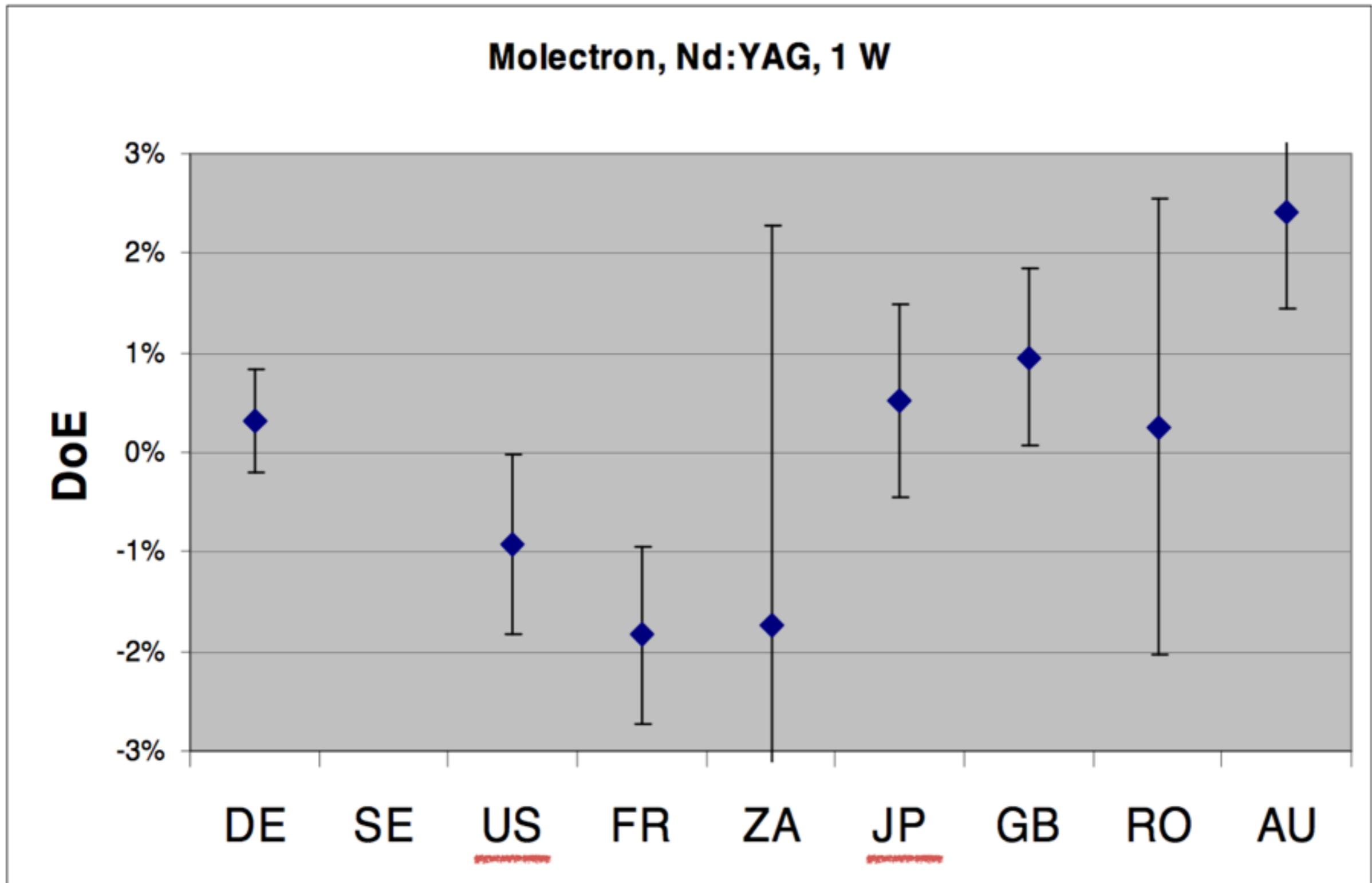
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Calibration for LVK global observation

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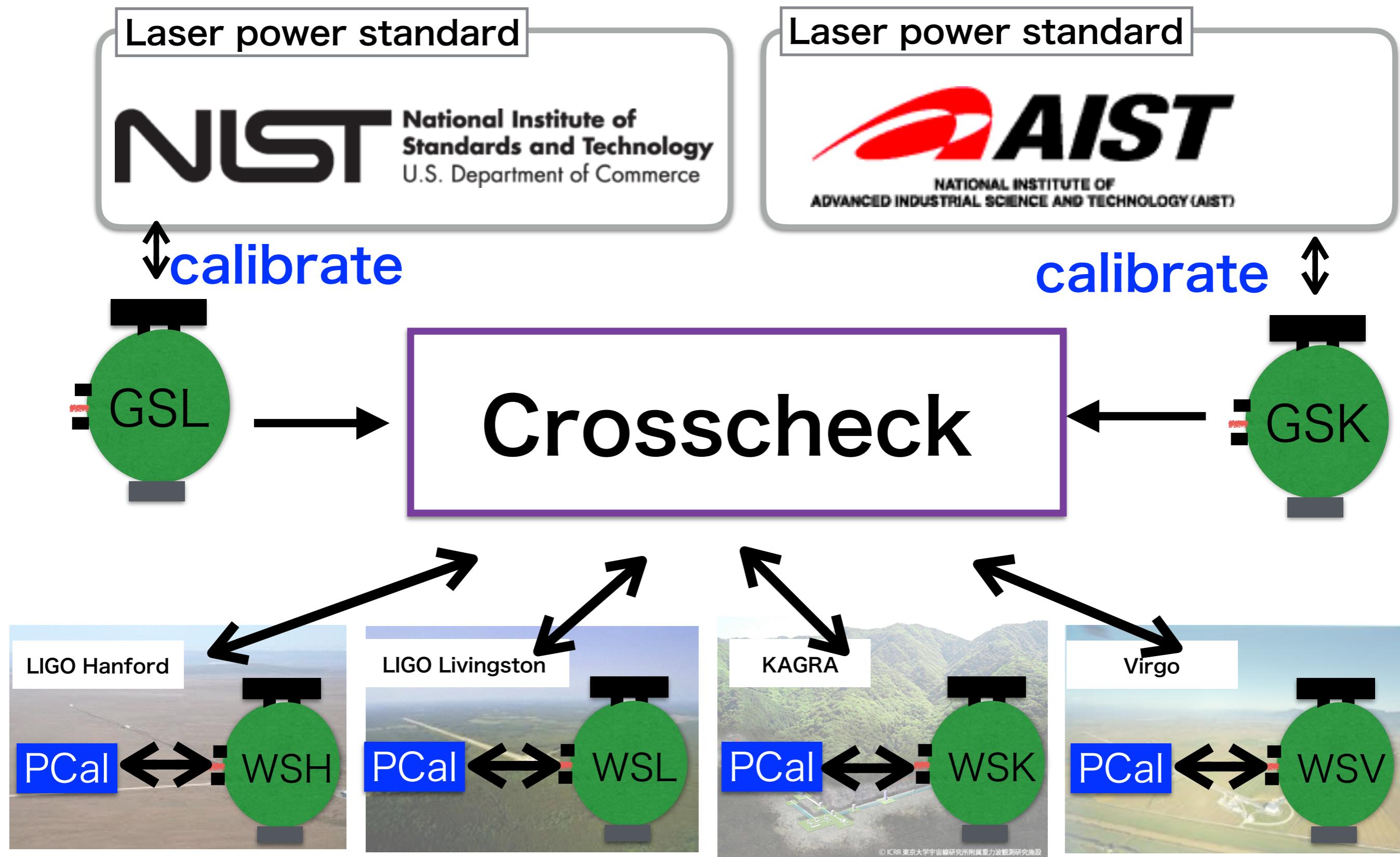


Comparison of absolute power of laser power standard



Power standard also have uncertainty

Calibration standard (More future)

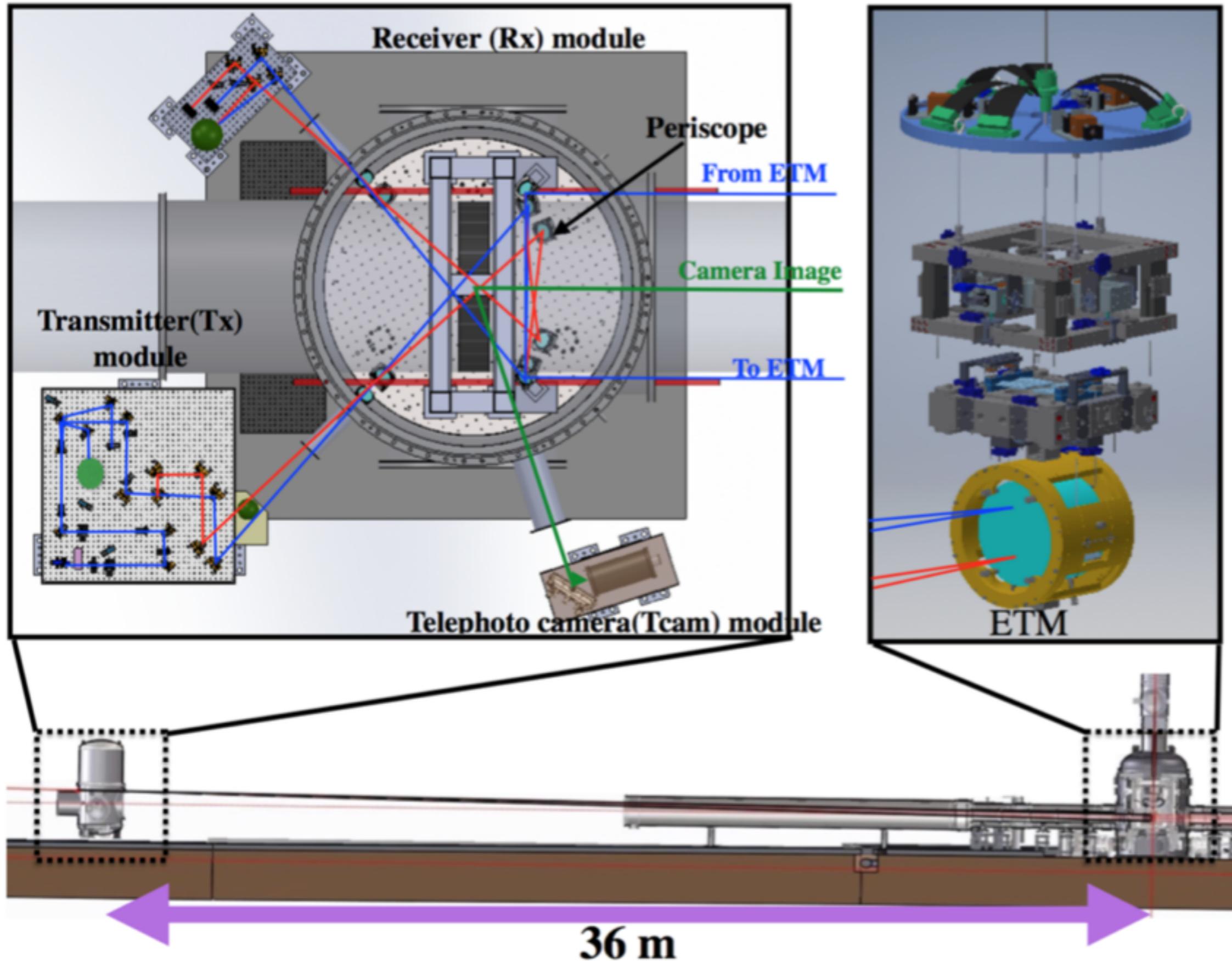


We plan to make GSK for crosschecking

Summary

- KAGRA is currently installing the instruments to start the full operation at 2020.
- KAGRA will employ the photon calibrator to calibrate the distance of the test masses.
- We are studying the calibration for LVK global observation.
- We start the cross-calibration of photon calibrator between LIGO and KAGRA.
- We want to start the cross-calibration study in LVK observation network.

Overview of Photon calibrator



We finish the design ! We will install all the system in 2018 Apr.

Specification of Photon Calibrator

	KAGRA	advanced LIGO	advanced Virgo
Mirror material	Sapphire	Silica	Silica
Mirror mass	22.8 kg	42 kg	40 kg
Mirror diameter	220 mm	340 mm	350 mm
Mirror thickness	150 mm	200 mm	200 mm
Distance of Pcal from ETM	36 m	8 m	1.5 m
Pcal laser power	20 W	2W	3 W
Laser frequency	1047 nm	1047 nm	1047 nm
Incident angle	0.72 deg	8.75 deg	30 deg

1. 20W High power laser

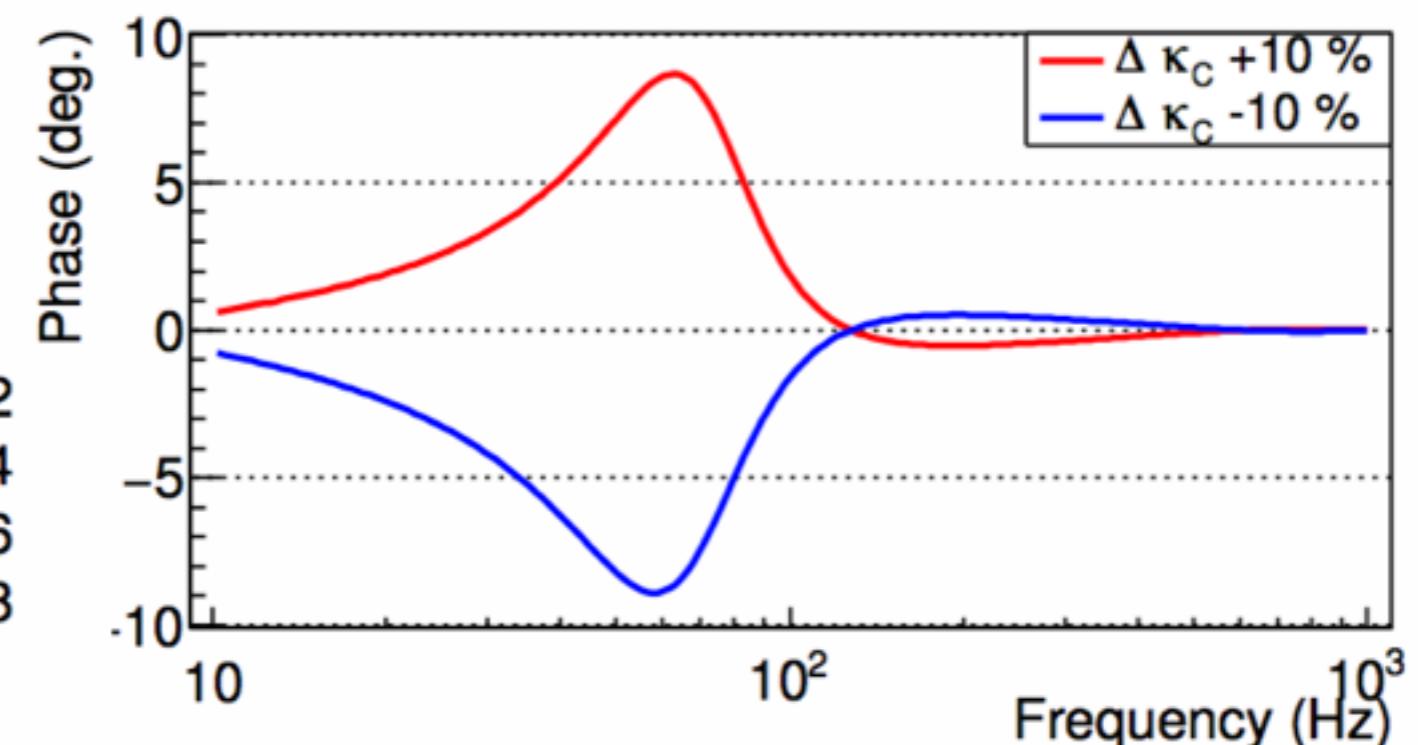
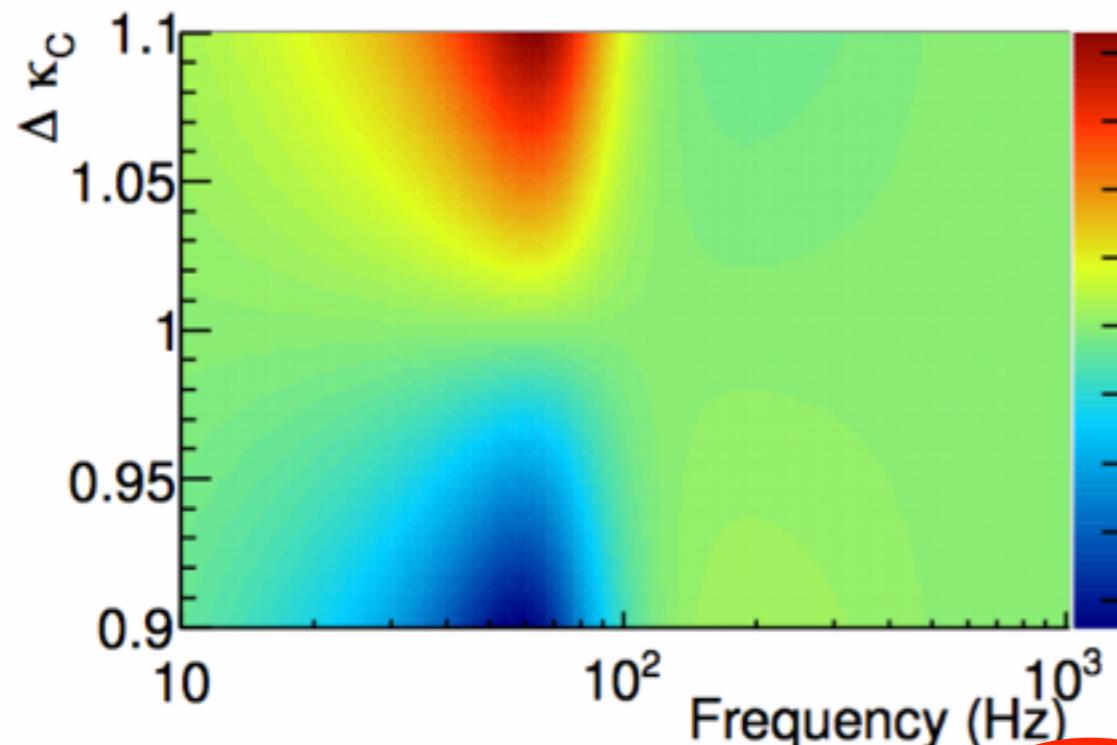
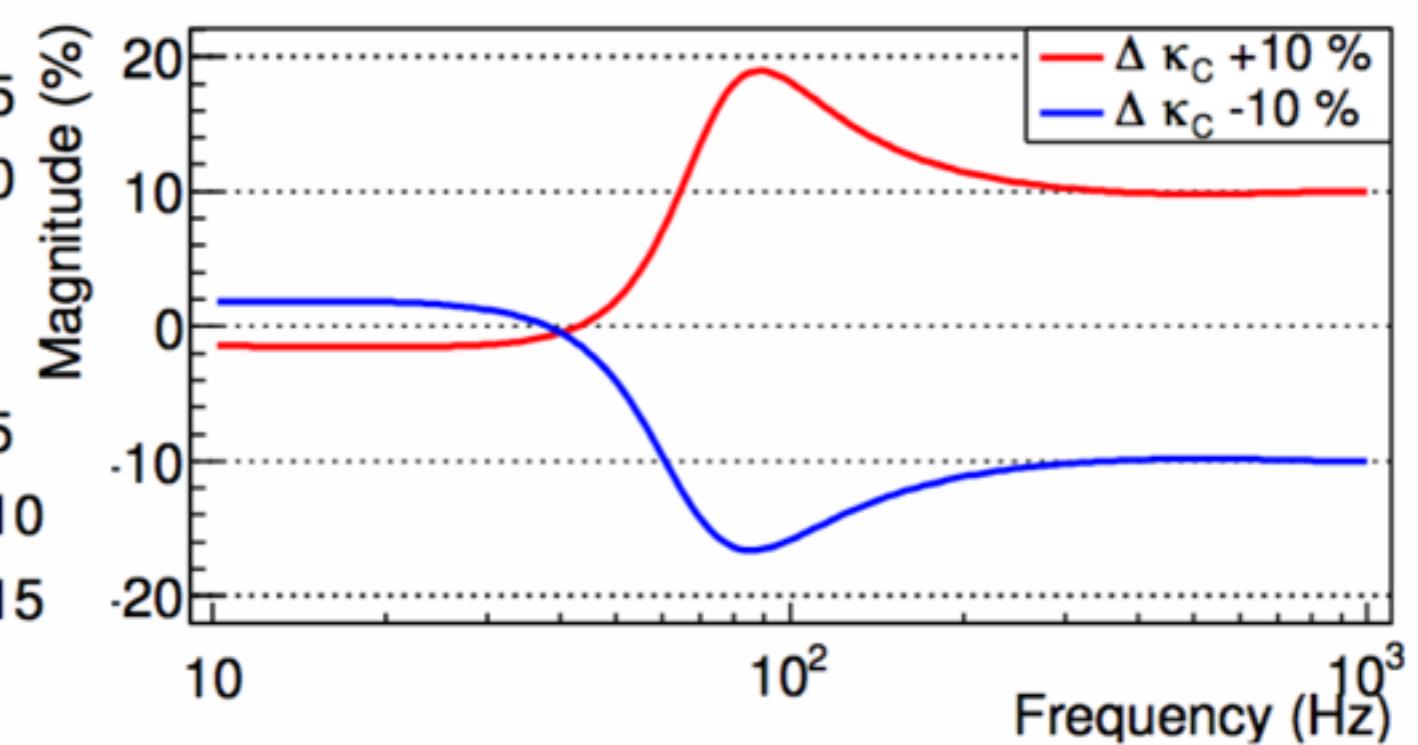
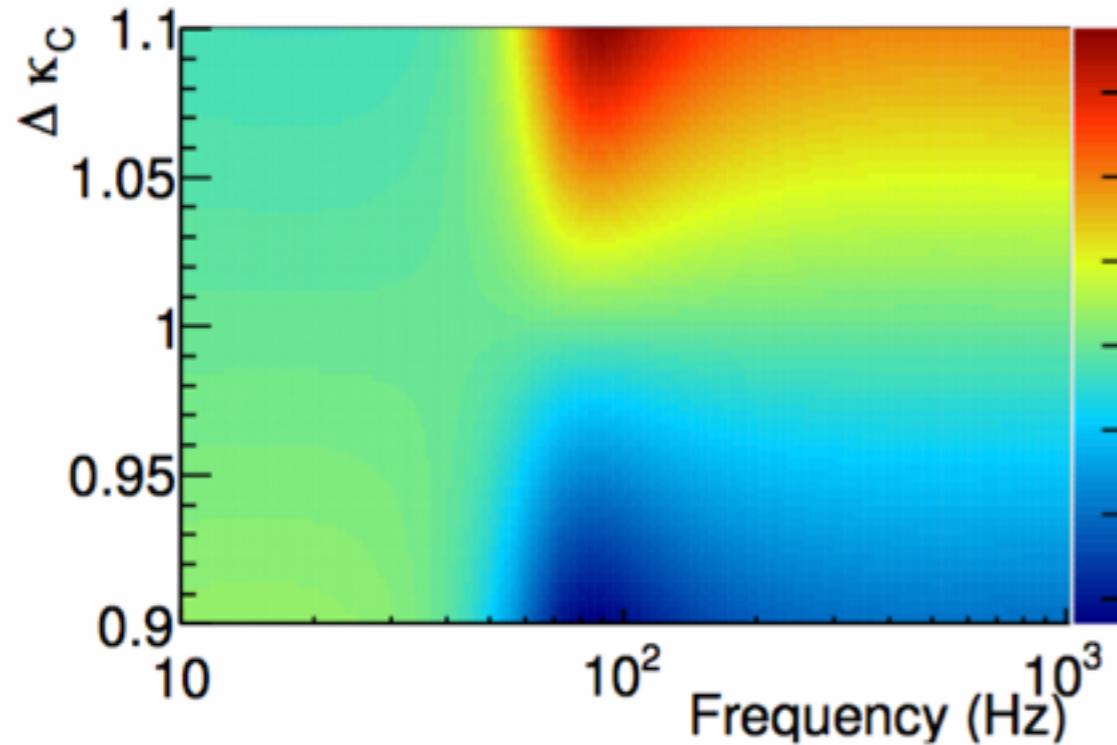
-We can inject the calibration line at the high frequency using high power laser

2. Advantage of high frequency observation

-We can attenuate the elastic deformation at the high frequency due to the rigid material of sapphire

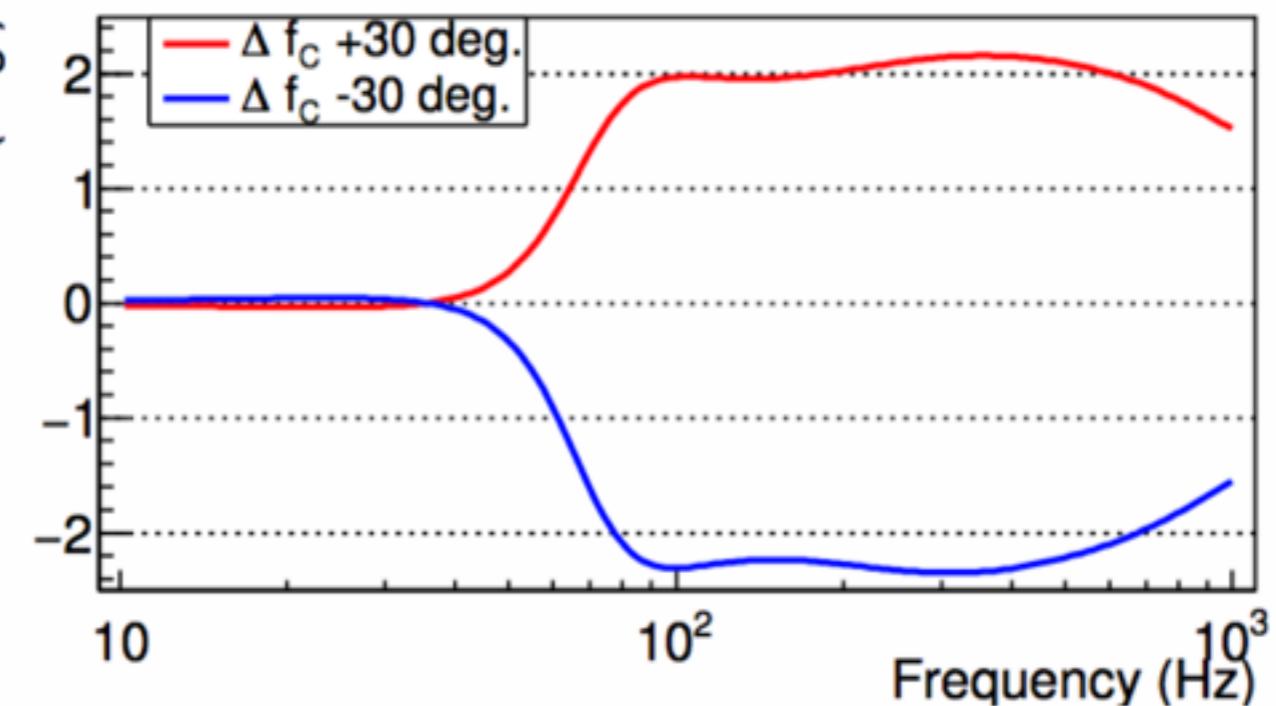
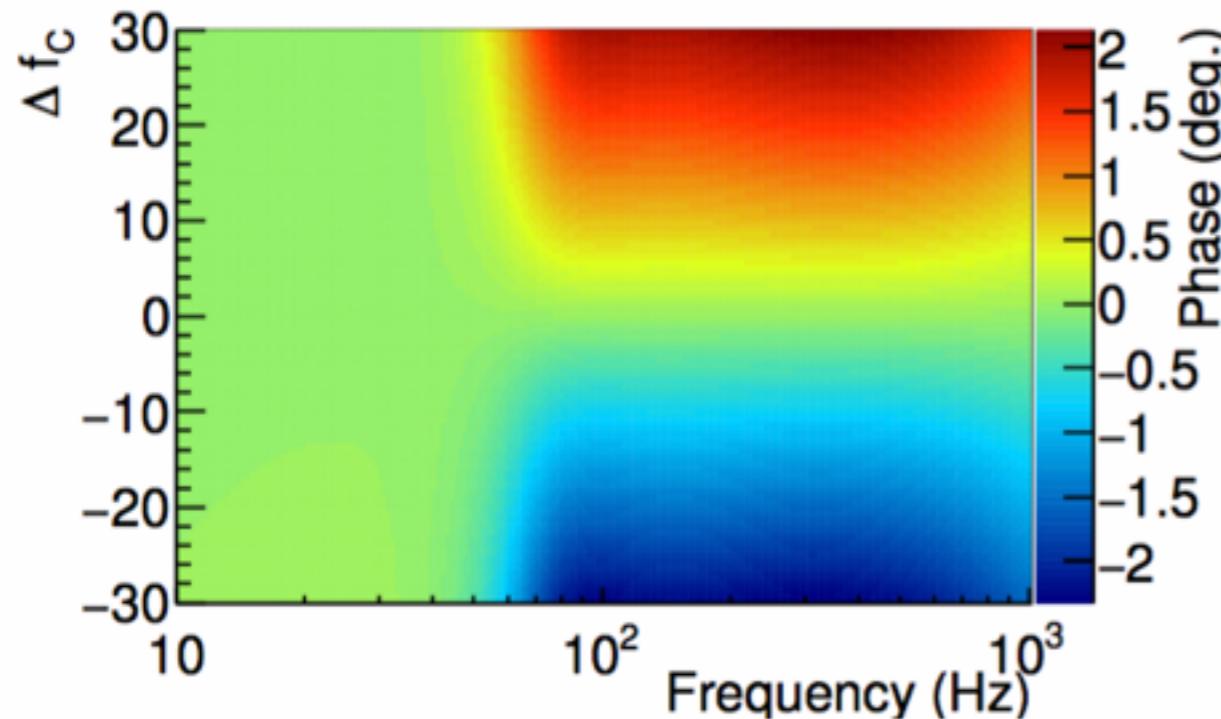
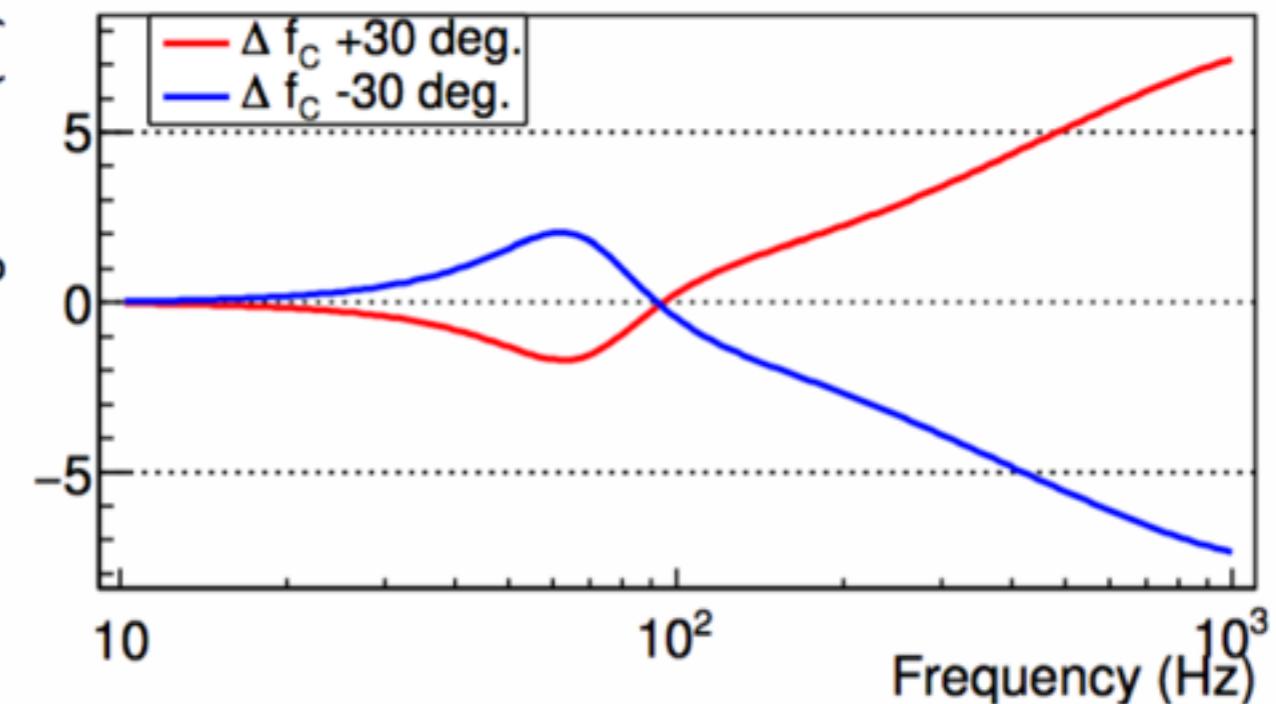
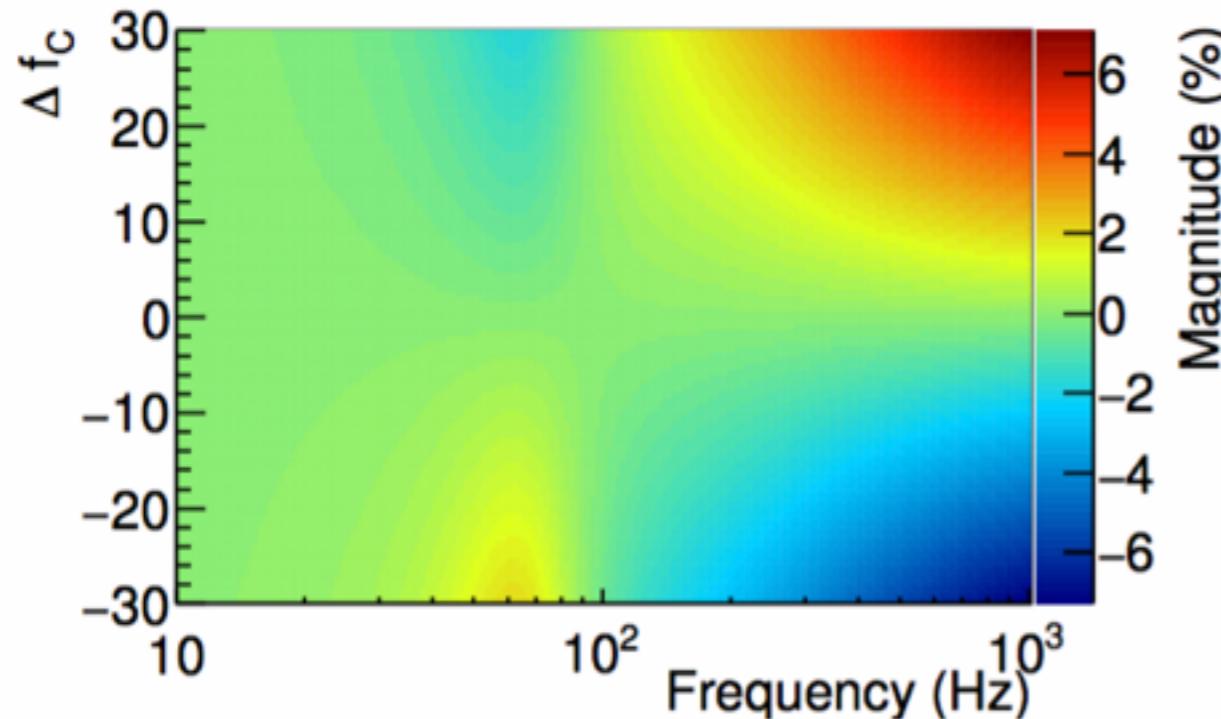
Optical gain

Original work in LIGO D.Tuyenbayev 2017



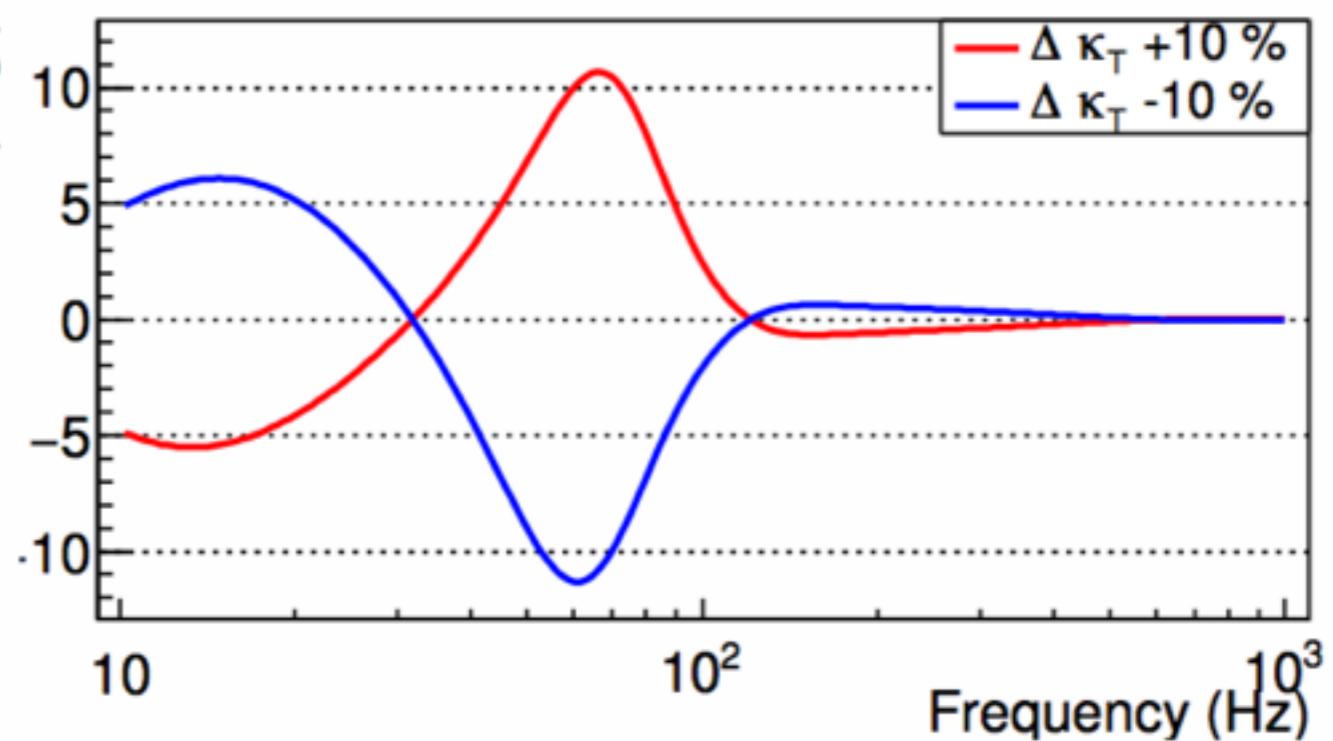
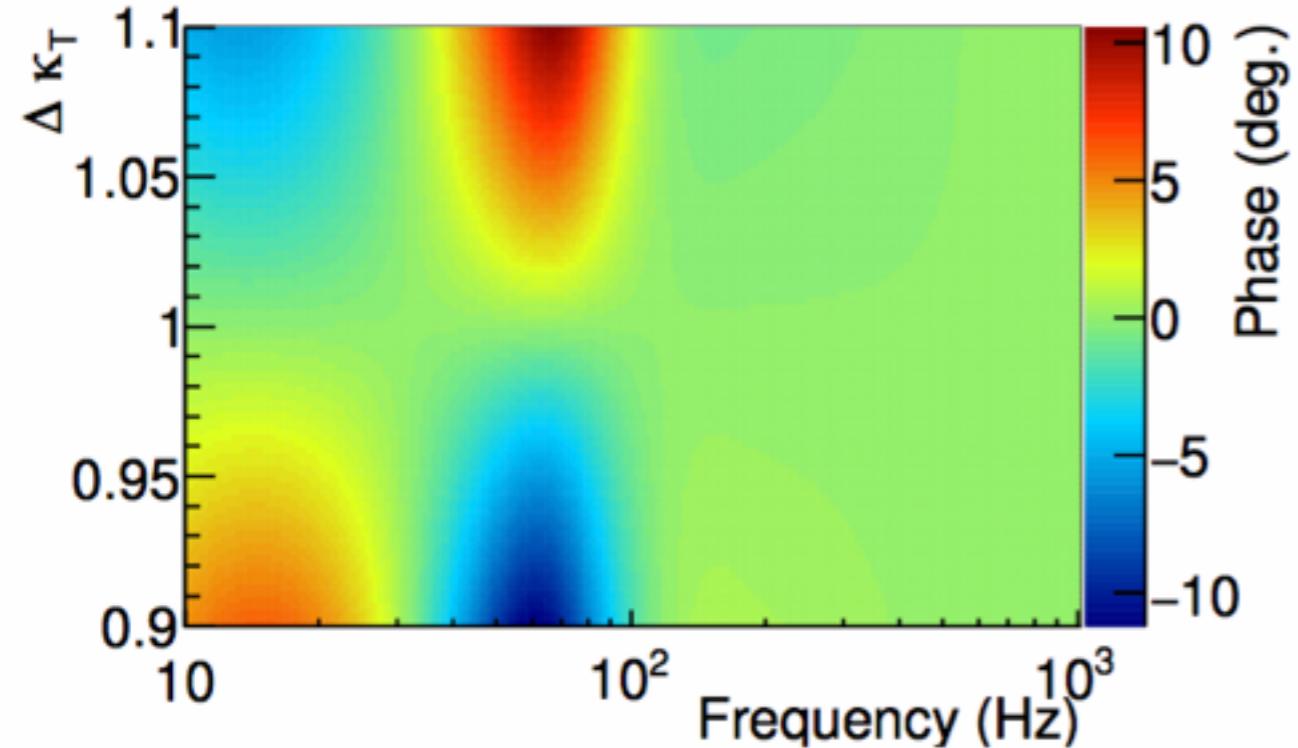
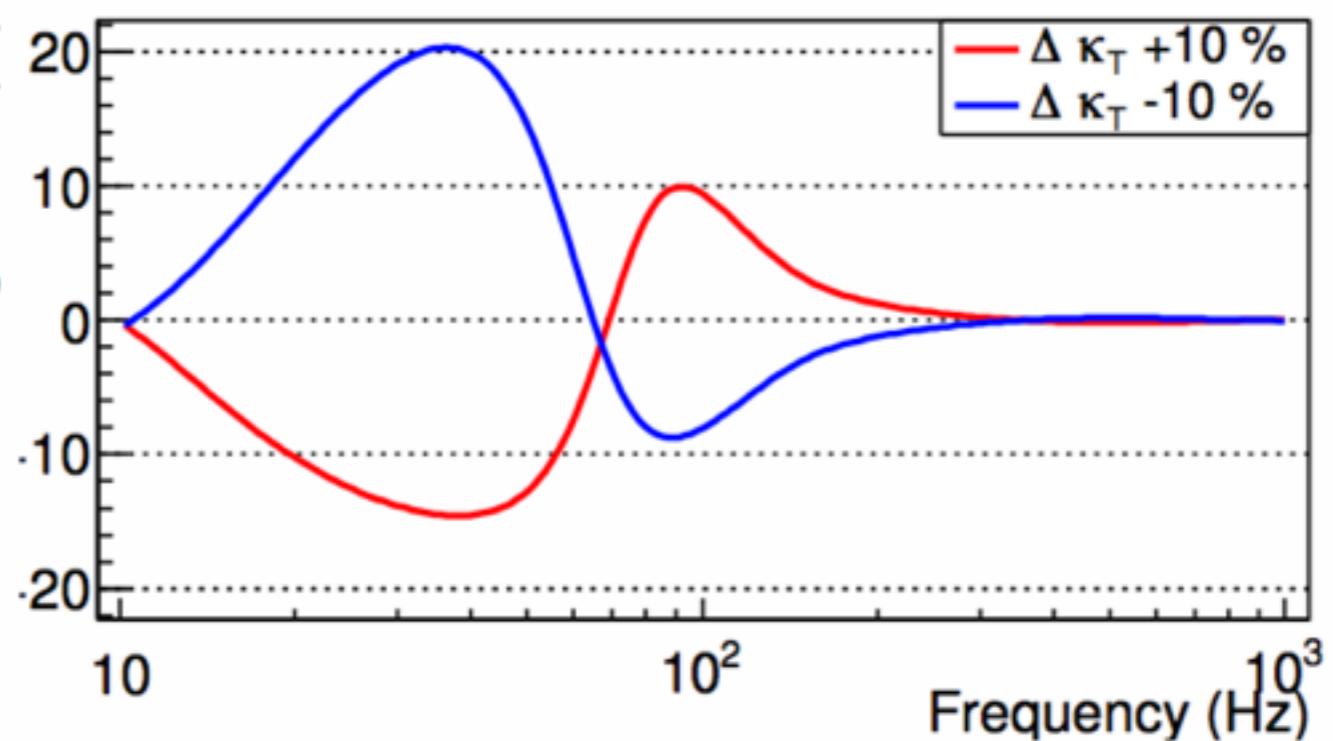
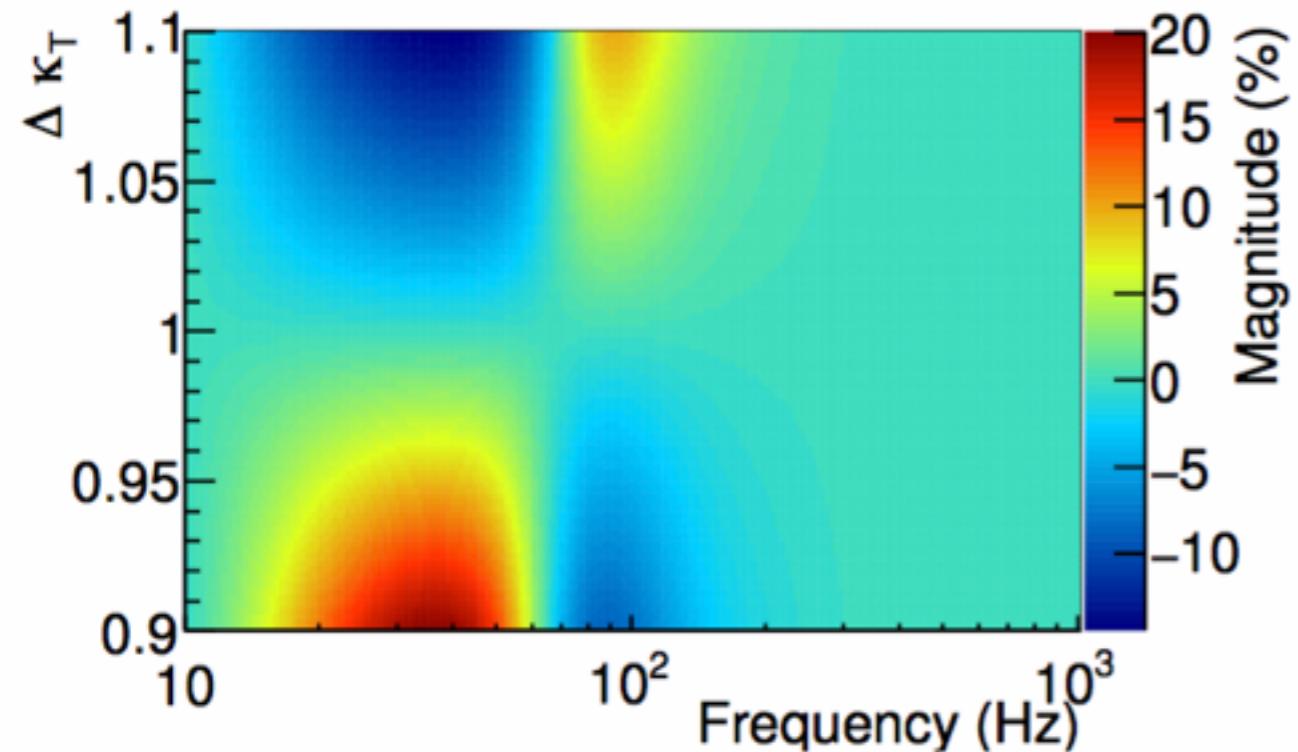
$$C(f, t) = \frac{\kappa_C(t)}{1 + i f / f_C(t)} Q(f) \equiv P(f, t) Q(f).$$

Cavity pole frequency



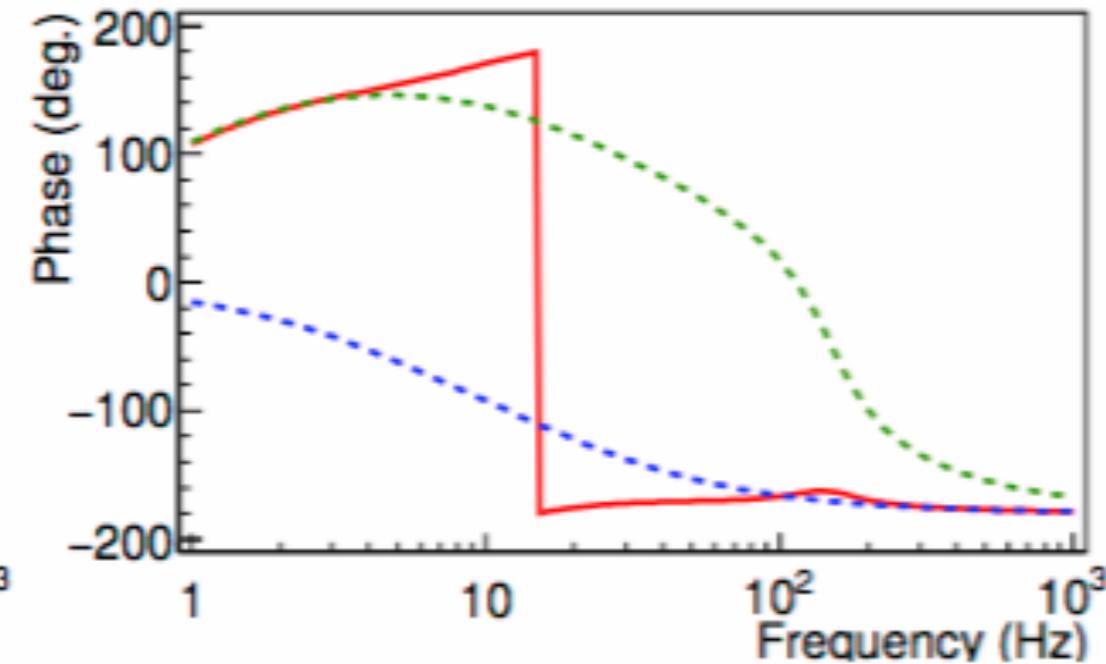
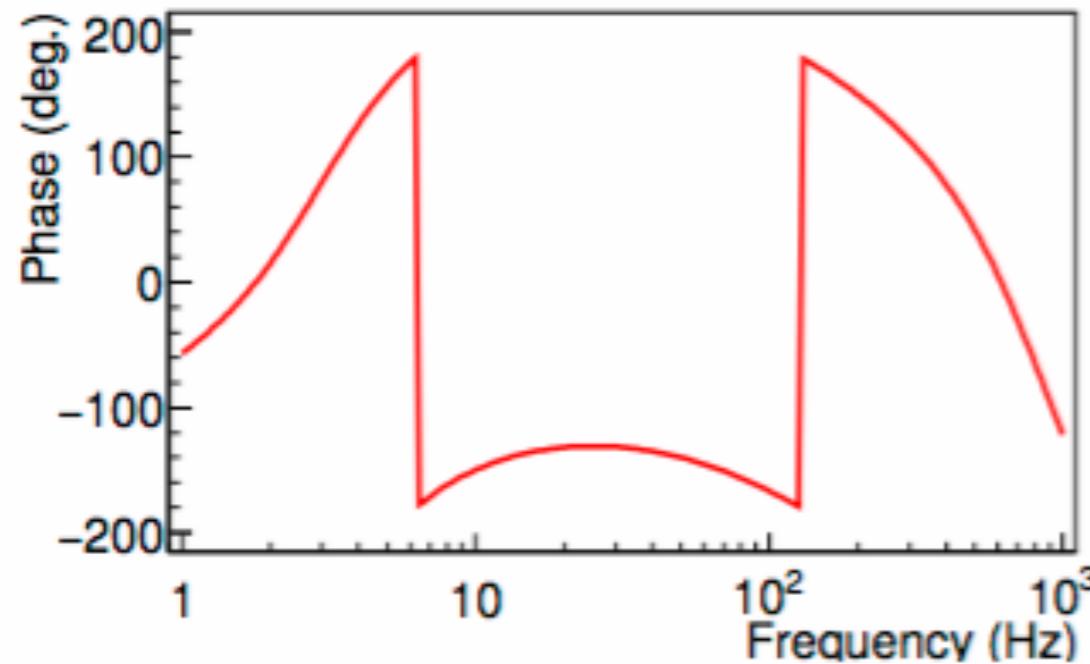
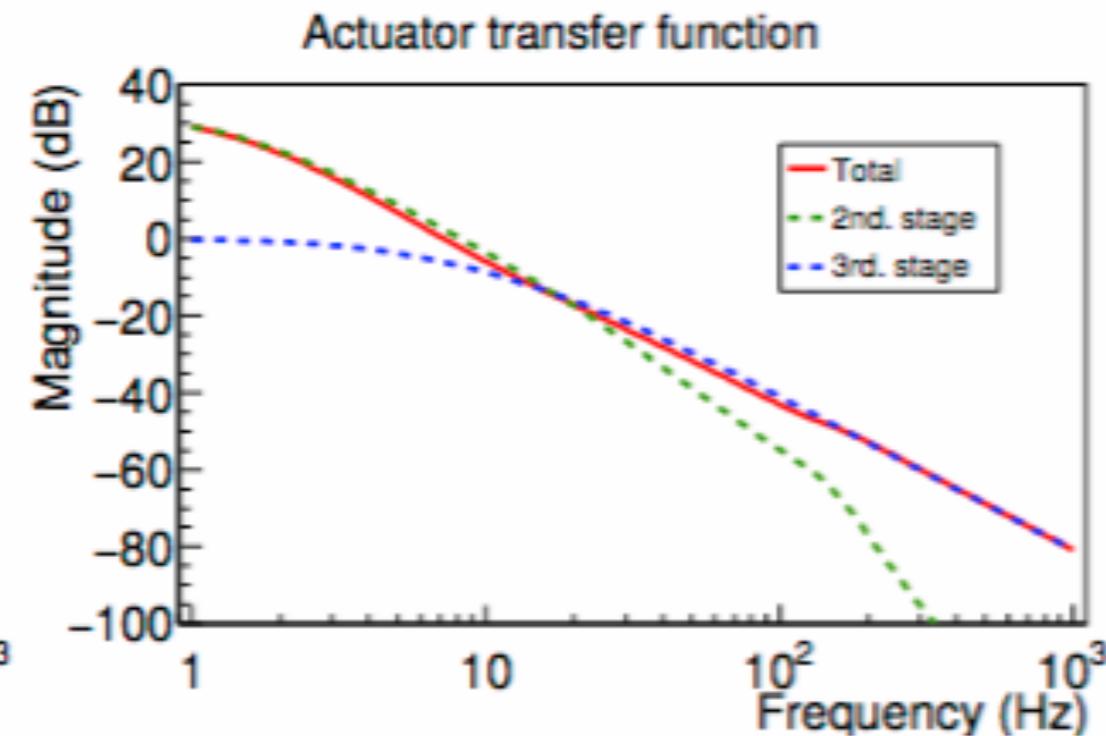
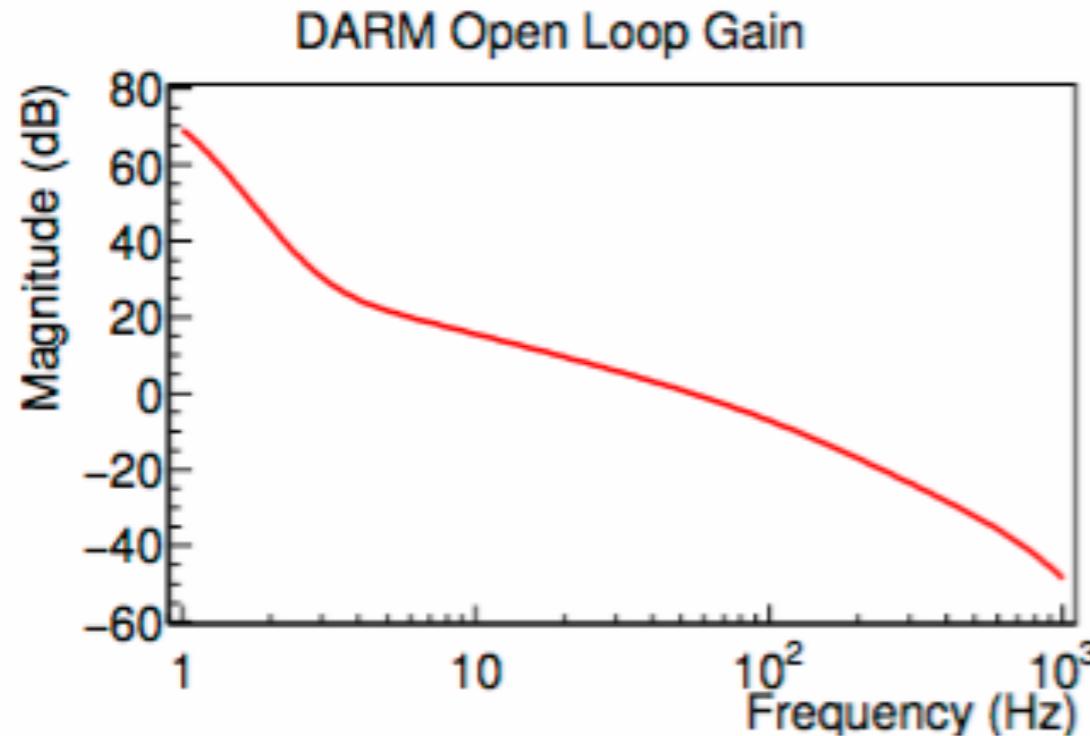
$$C(f, t) = \frac{\kappa_C(t)}{1 + i f / f_C(t)} Q(f) \equiv P(f, t) Q(f).$$

Actuation of test mass



$$A(f, t) = \kappa_M(t) A_{M,0}(f) + \kappa_I(t) A_{I,0}(f) + \kappa_T(t) A_{T,0}(f)$$

Open loop transfer function



We calculate the error propagation from each time-dependent parameters to ΔL by assuming these transfer function.

Schedule

2020 Full operation

~3% response function error

(Photon calibrator, Free swinging Michelson)

2019 Fabry-Perot interferometer

~5% response function error

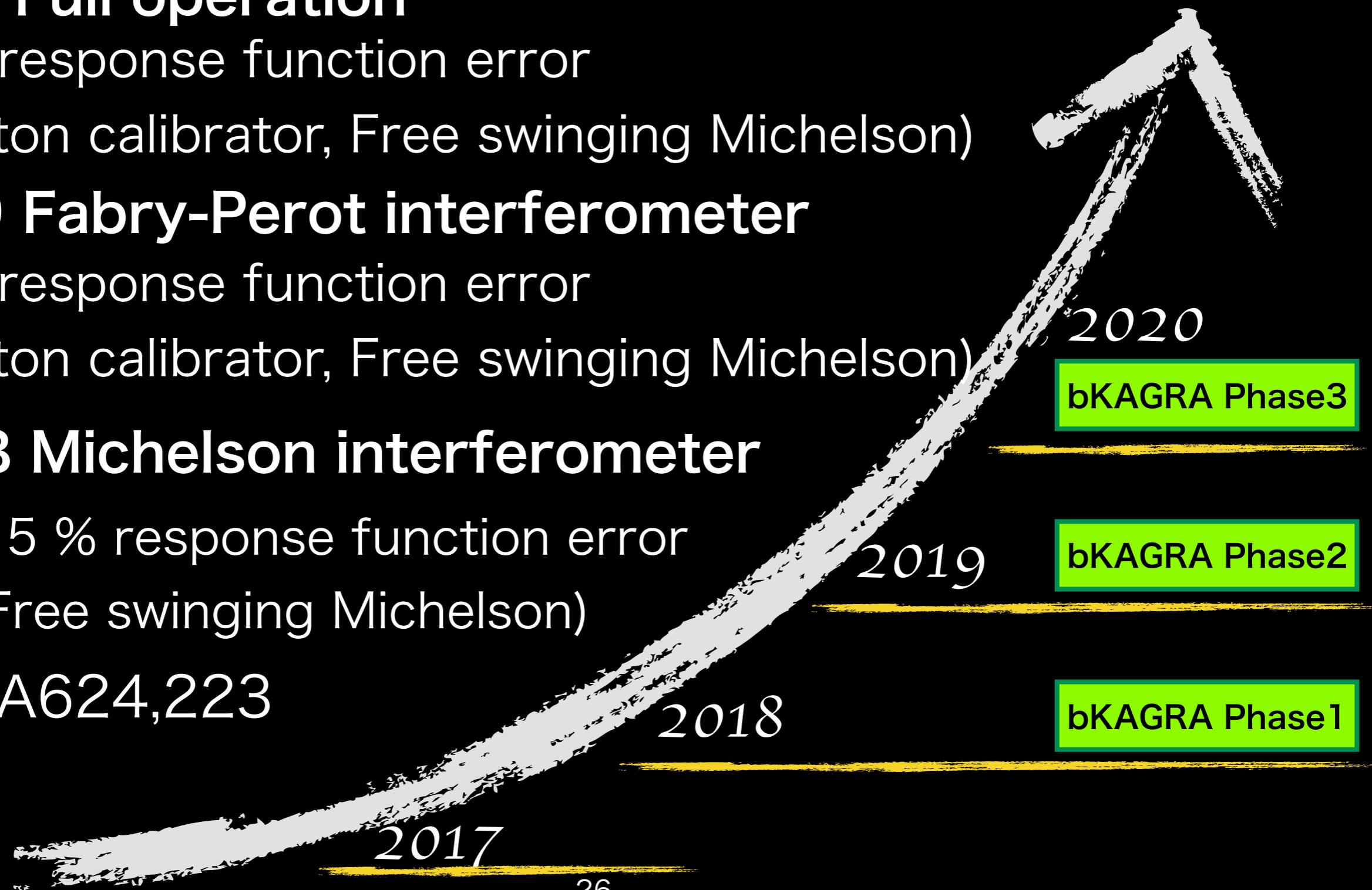
(Photon calibrator, Free swinging Michelson)

2018 Michelson interferometer

~10-15 % response function error

(Free swinging Michelson)

NIMA624,223



Requirement from analysis

Amplitude

- Neutron star binary (Parameter estimation)
- High z event (Cosmology)
- Localization (follow-up observation)

Phase

- Localization (follow-up observation)

Gold-plated event

- High S/N >30 event; GR test
- Supernova event in our galaxy

We propose to set a requirement of 3%

Error Budget of LIGO Pcal

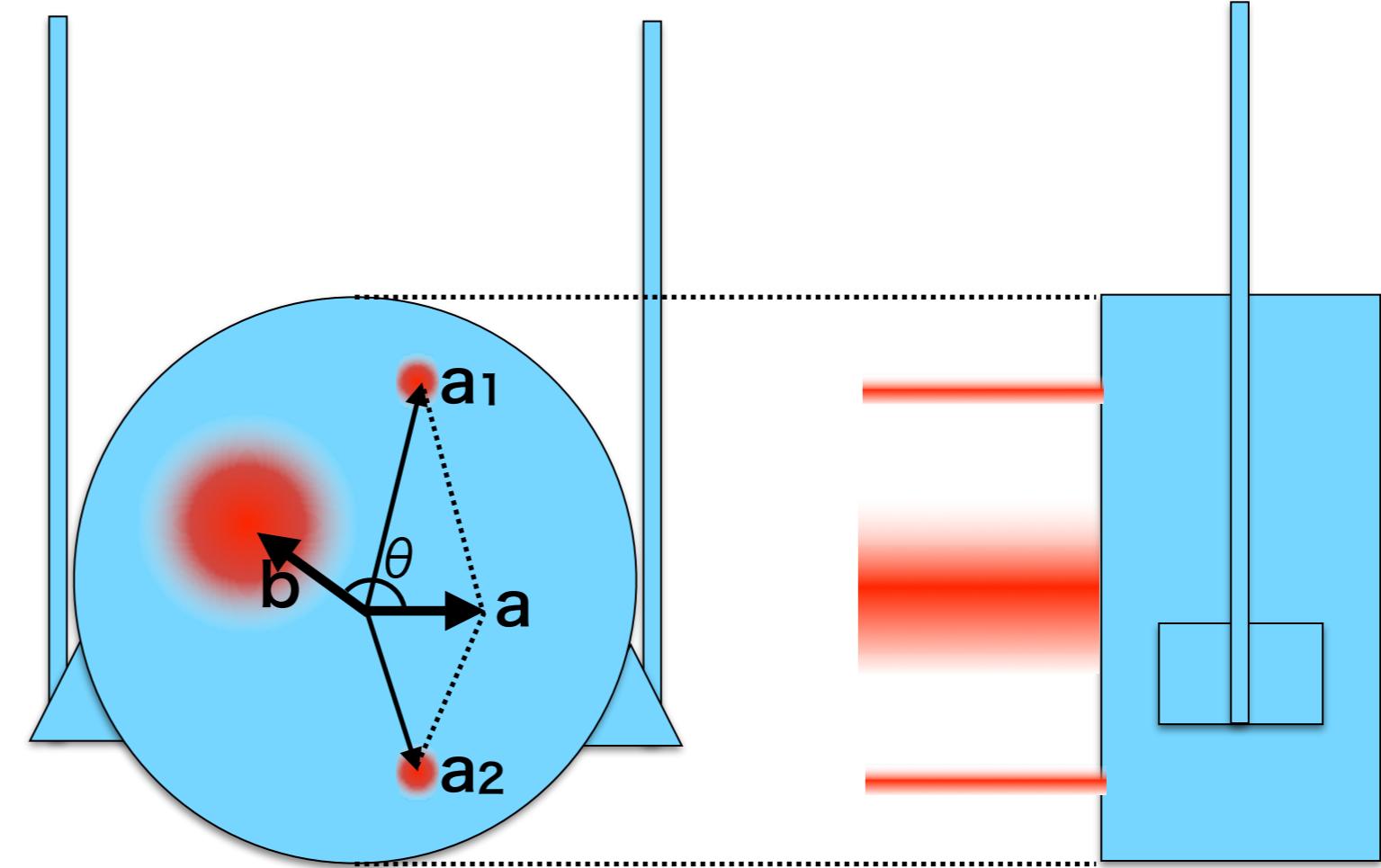
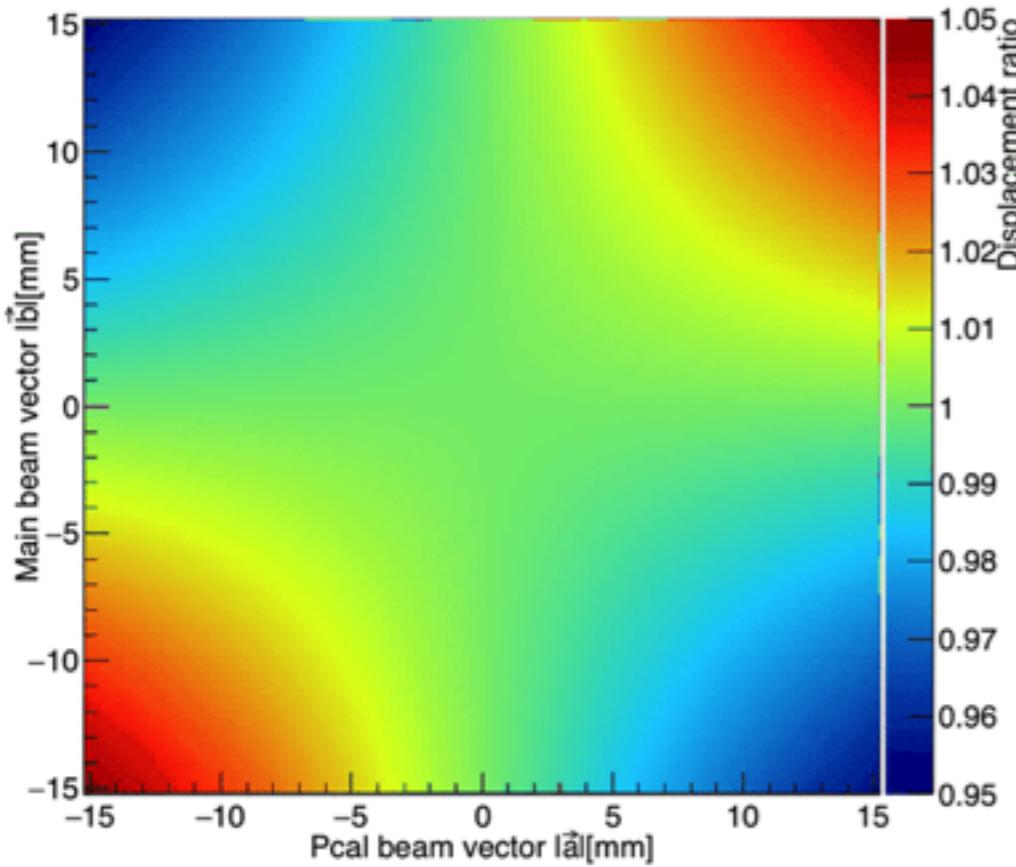
Parameter	uncertainty
Laser power	0.57%
Angle	0.007%
Mass of test	0.005%
Rotation	0.40%
Total	0.75%

Absolute Transfer
force function Rotation

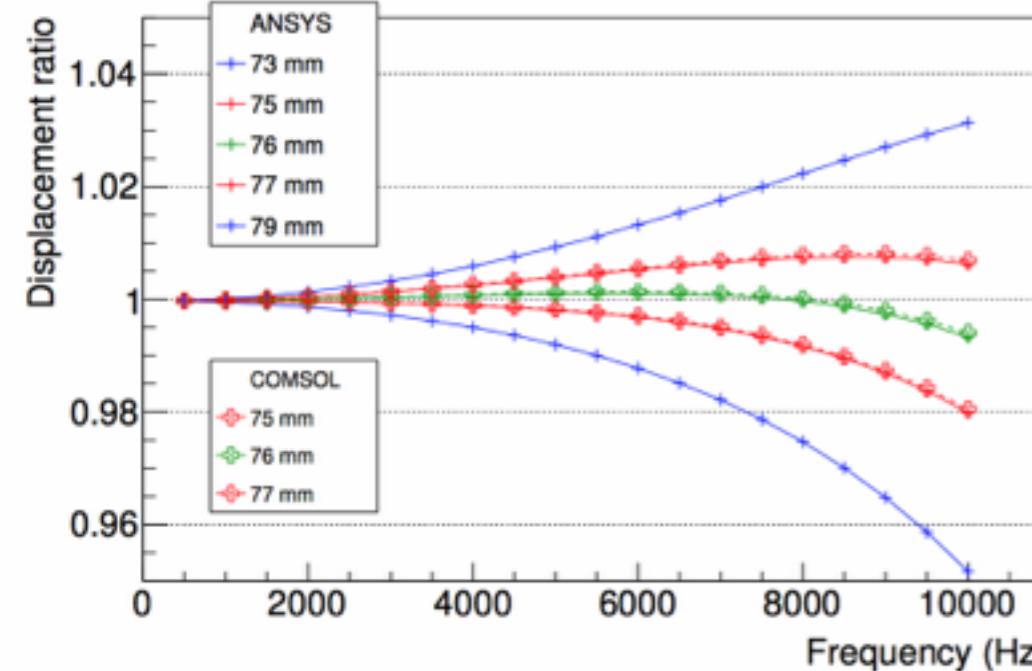
$$\delta x = \frac{\Delta P}{c} \cos \theta [s(f)] \left(1 + \frac{M}{I} \vec{a} \cdot \vec{b} \right)$$

Systematic error of beam position

Angle=0.0deg



KAGRA ETM



1. Rotation effect

$$1 + M/I \cdot \mathbf{a} \cdot \mathbf{b}$$

2. Elastic deformation effect

$$\int D(x,y;f) W(x,y) dx dy / s(f)$$