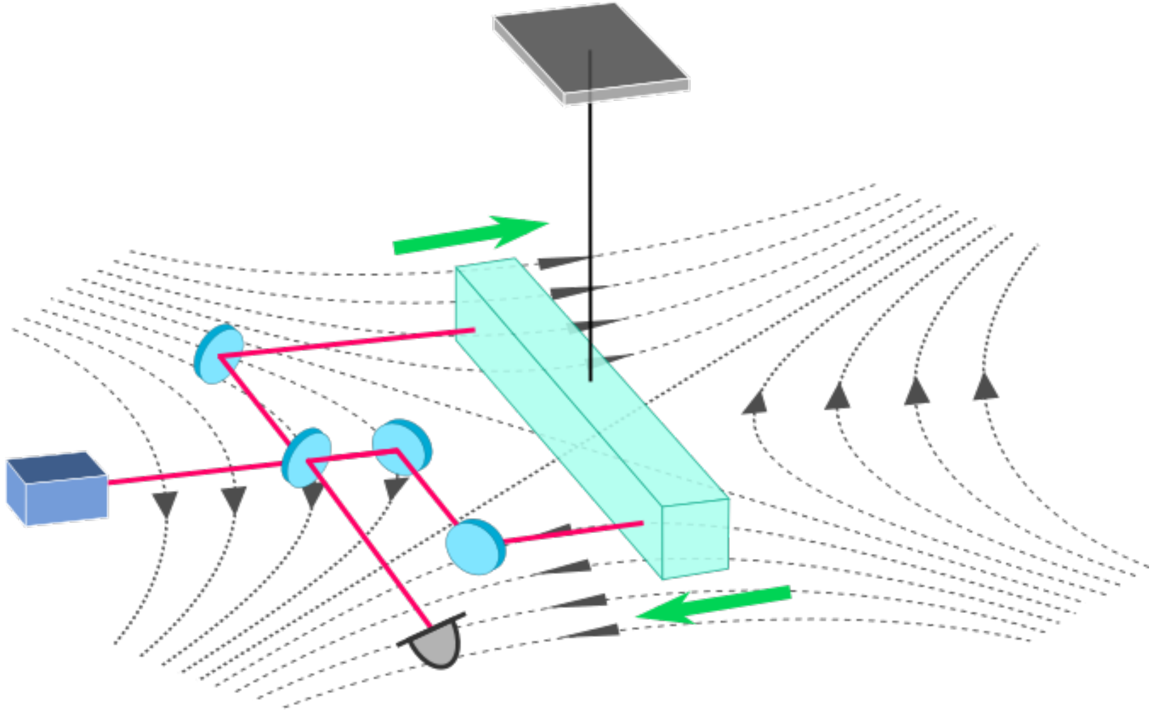
Report on TOBA experiment and future prospect (TOBA実験の報告と今後)

Shimoda Tomofumi

Ando Lab. midterm seminar (26 Apr. 2017)

Contents

- about TOBA experiment
- next tasks about seismic cross-coupling noise
- other tasks



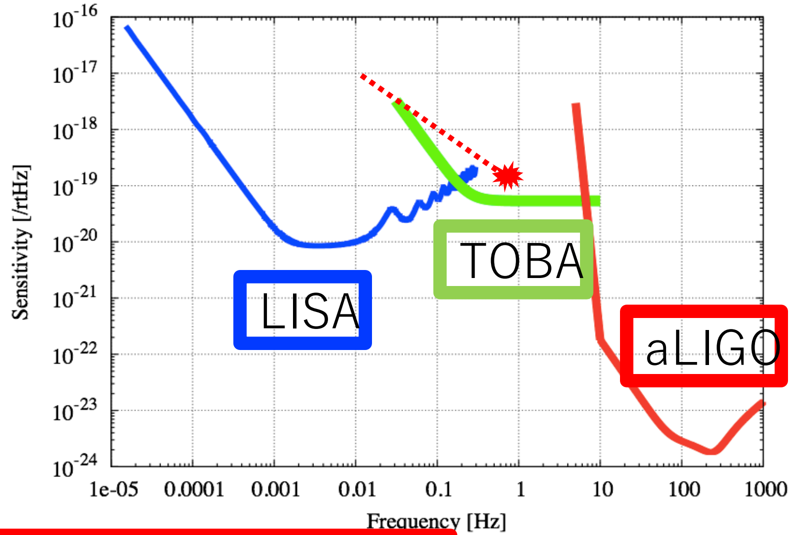
TOBA experiment

Motivation

- Torsion pendulum : **<u>low resonant frequncy(~mHz)</u>**

- Low-frequency gravitational wave (~0.1Hz)
  - Intermediate Mass Black Hole (IMBH) merger
  - Stochastic graviational wave background

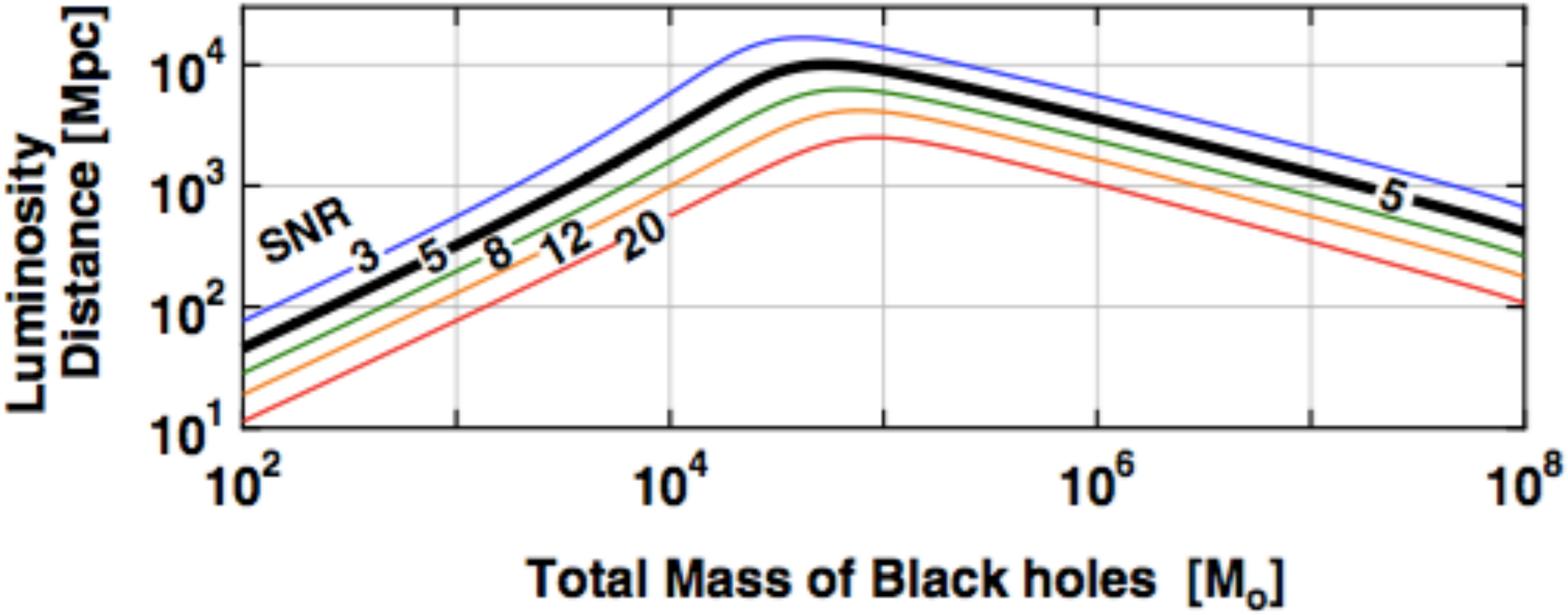
- Graviaty-gradiometer
  - Newtonian noise
  - Earthquake early alert



target sensitivity : 10^{-19} /rtHz @0.1Hz

Gravitational wave : IMBH merger

- IMBH : $10^2 < M/M_{sun} < 10^6$

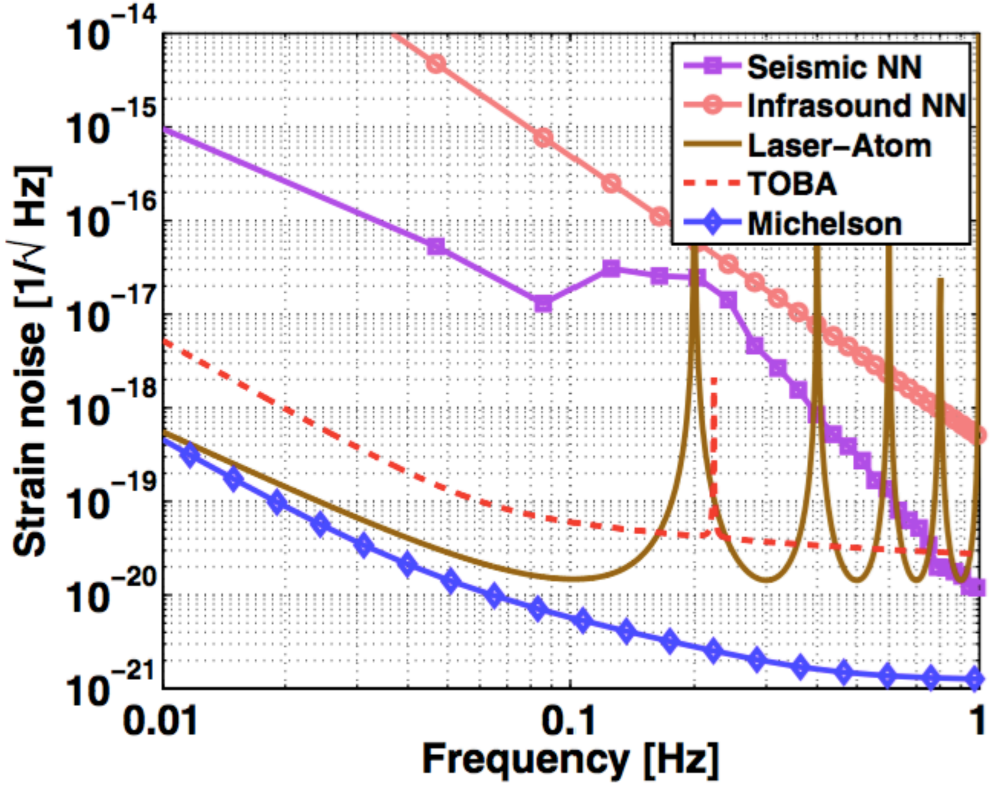


PhysRevLett. 105.161101

observable ~10Gpc ⇒ few events/yr (?)

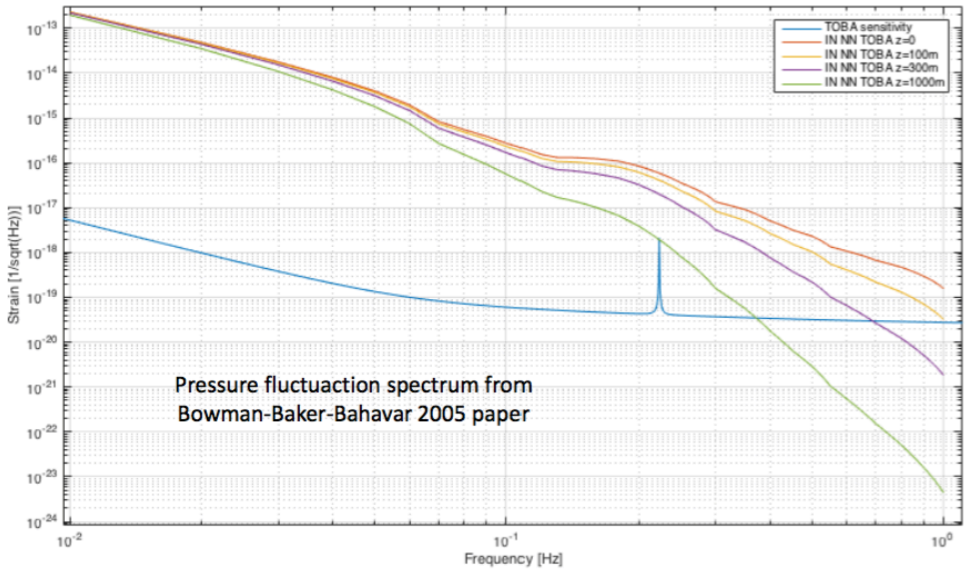
Gravity-gradiometer

- Newtonian noise
  - fluctuation of newtonian gravity from ground and atmosphere
  - can be a dominant noise in third-generation GW detector (ET, …)



(J.Harms et al., 2013)

～10^{-15} /rtHz @0.1Hz



(by Donatella Fiorucci)

Current phase of TOBA

- Phase-I,II ⇒ **Phase-III** ⇒ Final
- target sensitivity : 10^{-15} /rtHz @0.1Hz

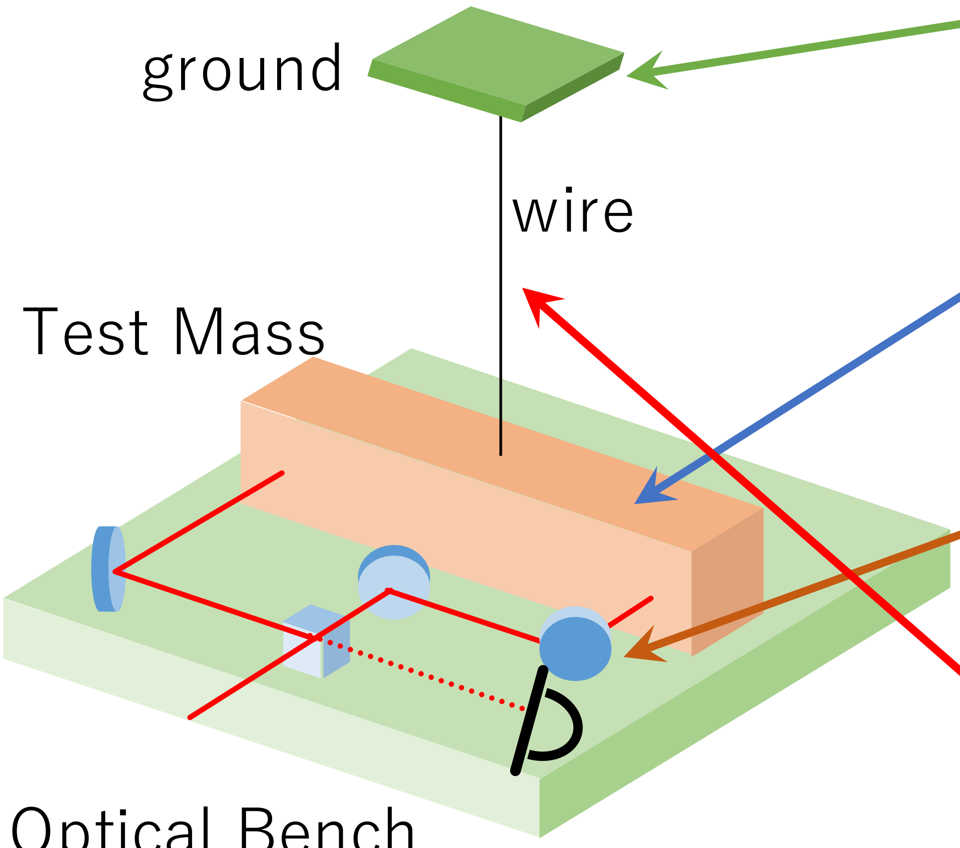
	Phase-I	Phase-II	**Phase-III**	Final
構成	超伝導磁気浮上 20cm試験マス	ワイヤ懸架 24cm試験マス	ワイヤ懸架 30cm試験マス **低温**	ワイヤ懸架 10m試験マス 低温
感度	10^{-8} /$Hz^{1/2}$ @0.1Hz	10^{-10} /$Hz^{1/2}$ @5Hz	**10^{-15} /$Hz^{1/2}$ @0.1Hz**	10^{-19} /$Hz^{1/2}$ @0.1Hz
	原理実証		**雑音低減実証**	本格観測

懸架系変更

now here

大型化, ハイパワー化

Main noise sources in TOBA



✓Seismic noise
- reduce cross-coupling

my task

✓Magnetic noise
- develop coil-coil actuator

✓Sensor noise
- develop monolithic optics

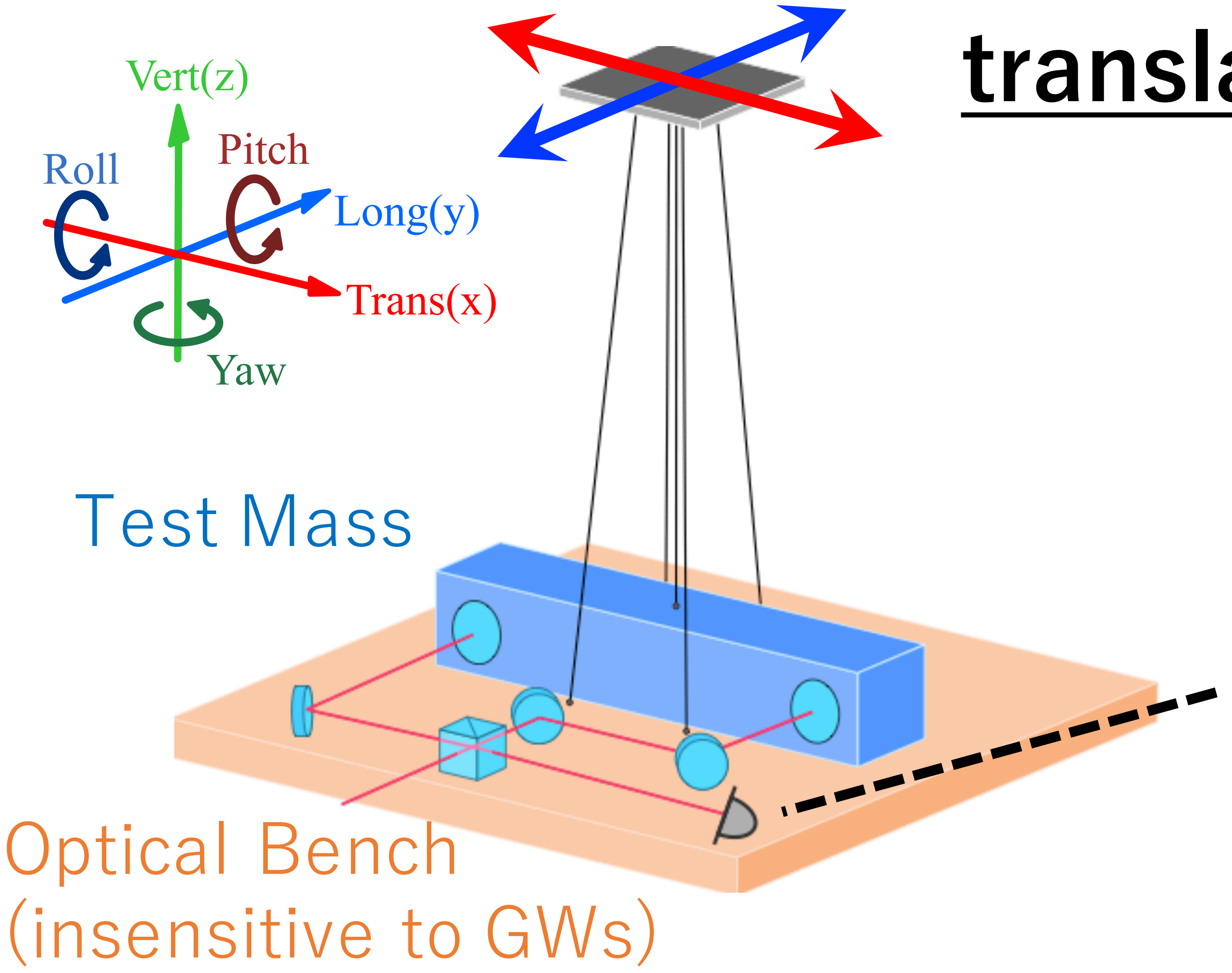
有冨

✓Suspension thermal noise
- develop high-Q wire / cryogenic

Ching Pin

Seismic cross-coupling noise

Seismic cross-coupling noise



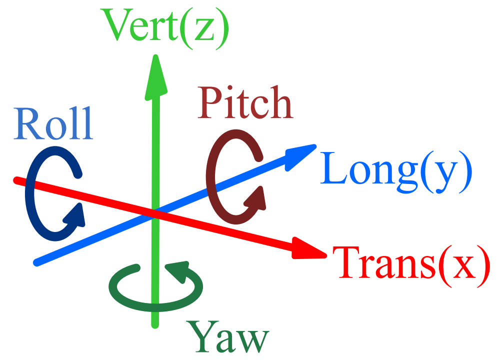
translation of the ground

Cross-coupling

YAW rotational signal
(interferometer output)

requirement: $< 10^{-10}$ **rad/m**

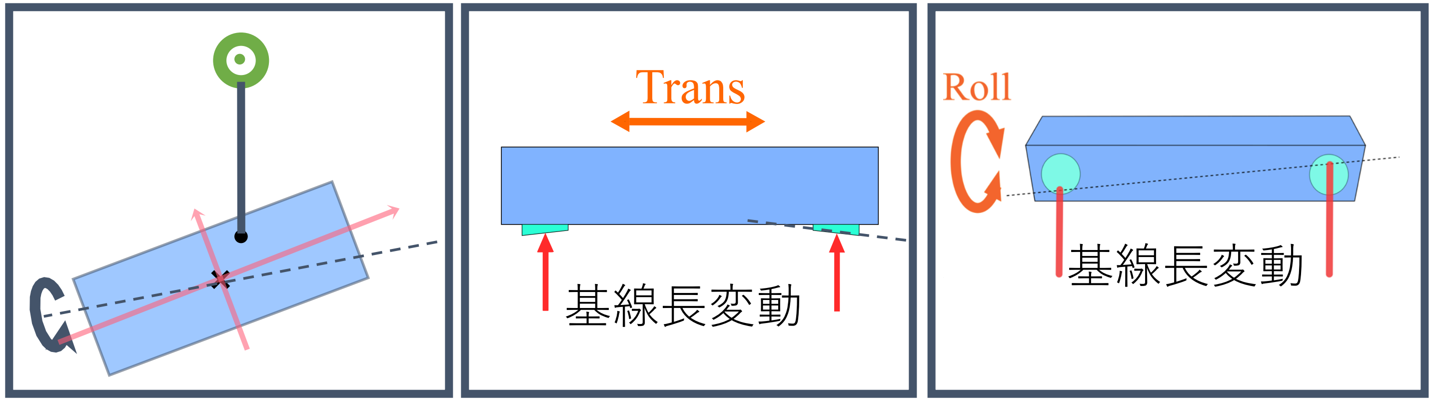
What is done



- find coupling routes and transfer functions
- measure coupling transter functions <u>(from Long,Trans)</u>
- demonstrate reduction <u>(from Long,Trans)</u>

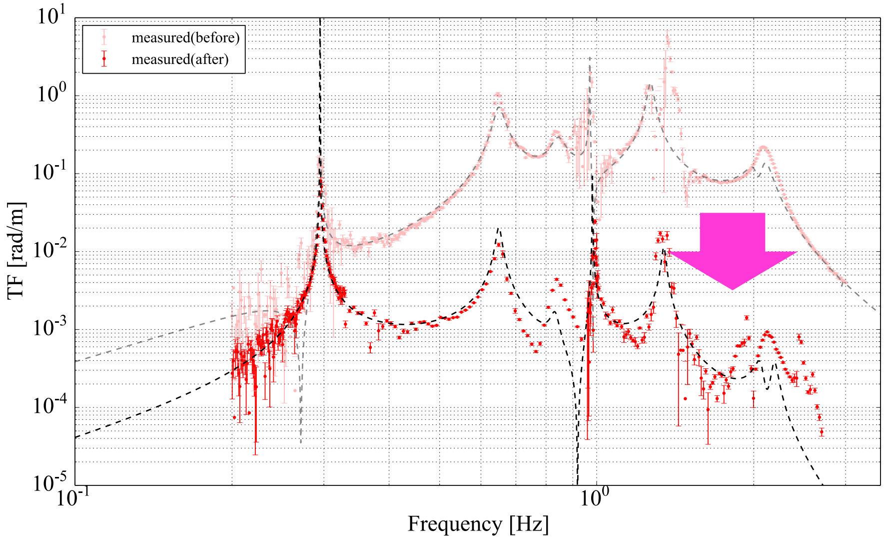
Coupling routes

(1)重心-懸架点ズレ　(2)鏡面の傾き　(3)ビームスポット高さズレ

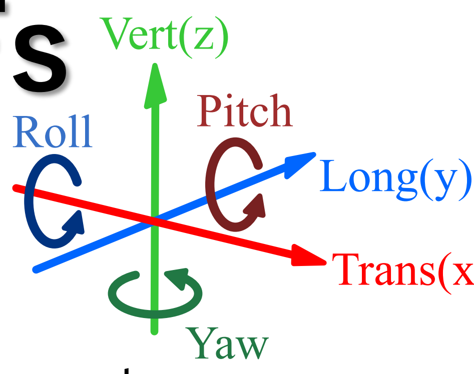


(Coupling) = (tilt) × (Roll,Pitch,...)

measure & reduce

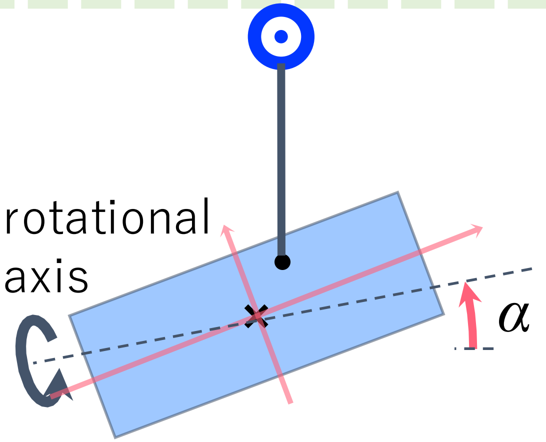


What is done : coupling routes & TFs



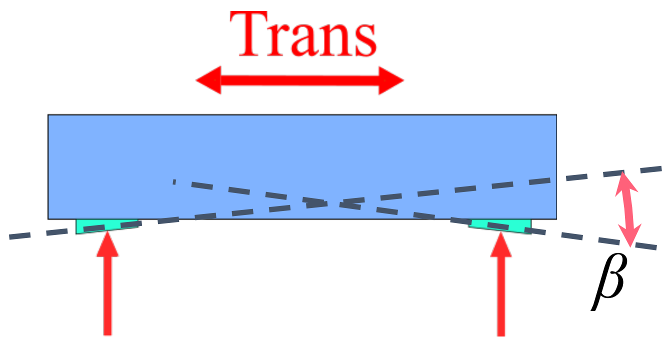
- find coupling routes & transfer functions

tilt of rotational axis



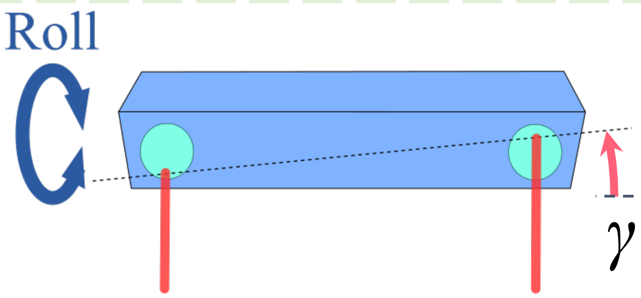
(coupling) $= \boxed{\alpha \times (\text{Roll})}$

tilt of mirror



$\boxed{\beta \times (\text{Trans}, \text{Vert}, \text{Pitch})}$

tilt of beamspots



$\boxed{\gamma \times (\text{Roll})}$

- there is also nonlinear transfer

linear coupling

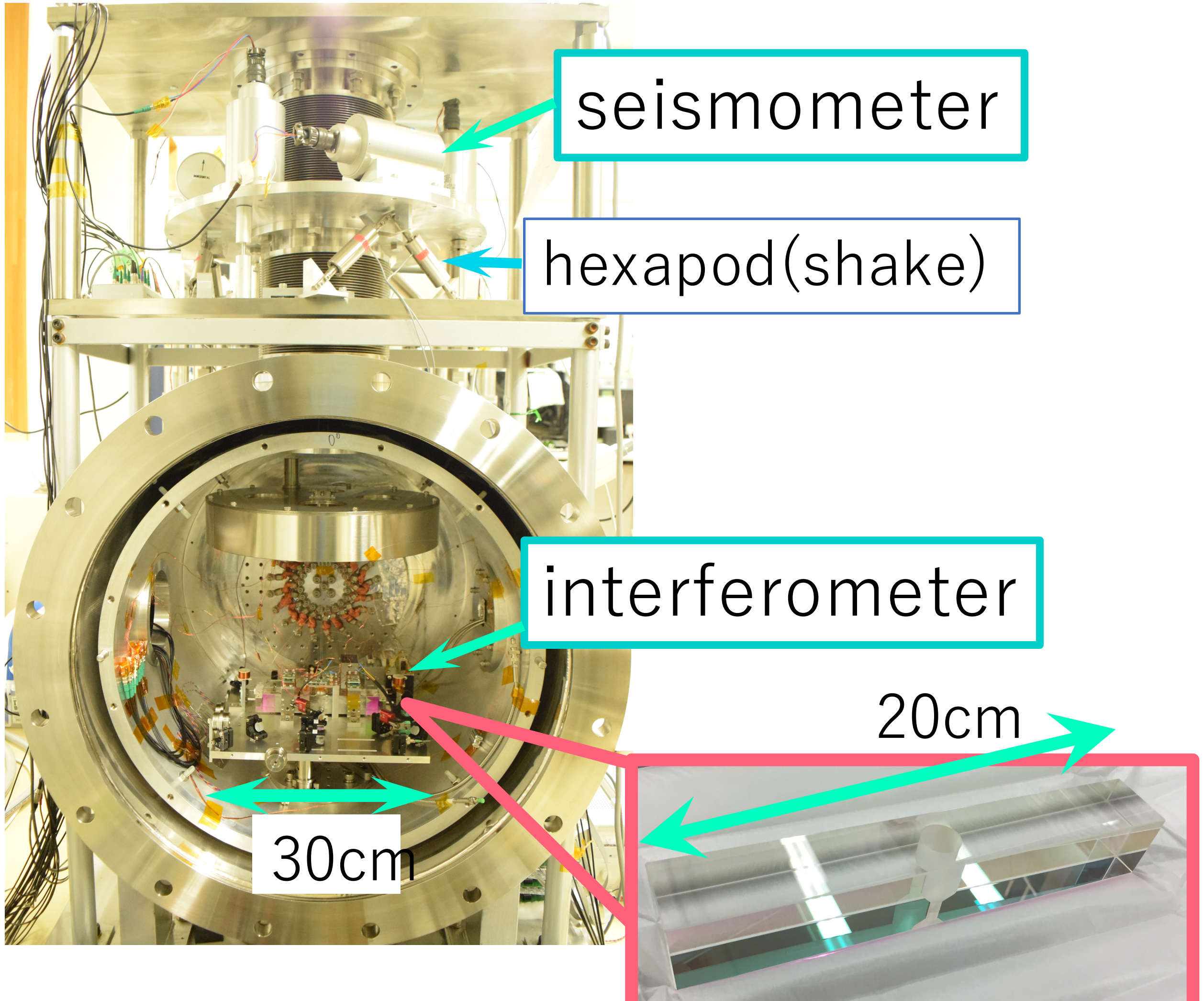
(Yaw) = (tilt) × (Roll)

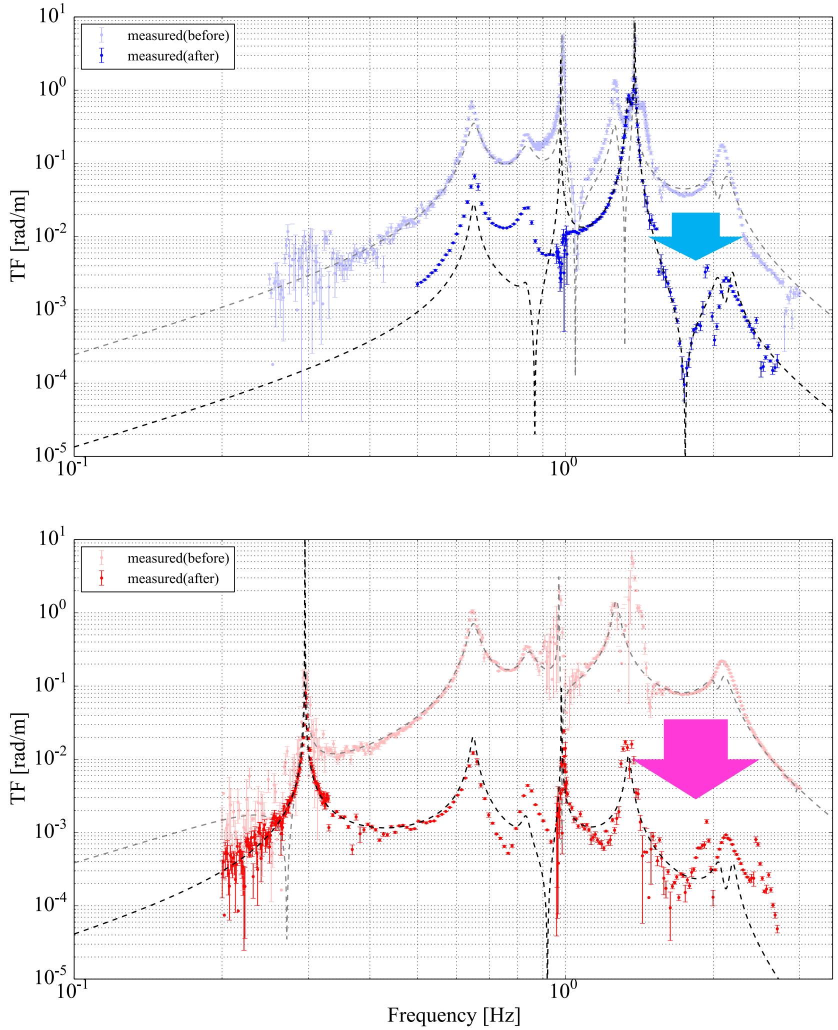
nonlinear

(Yaw) = (Pitch) × (Roll)

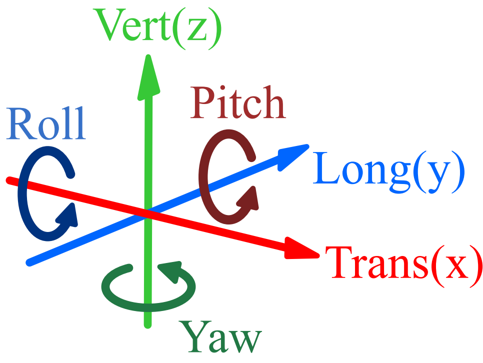
What is done : measurement & reduction

- measured and reduced (from Long, Trans only)





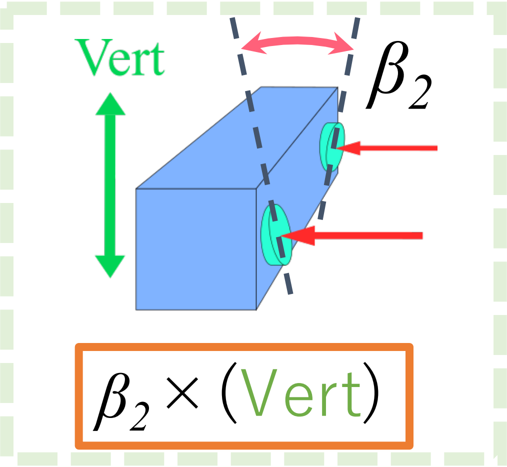
Achievements



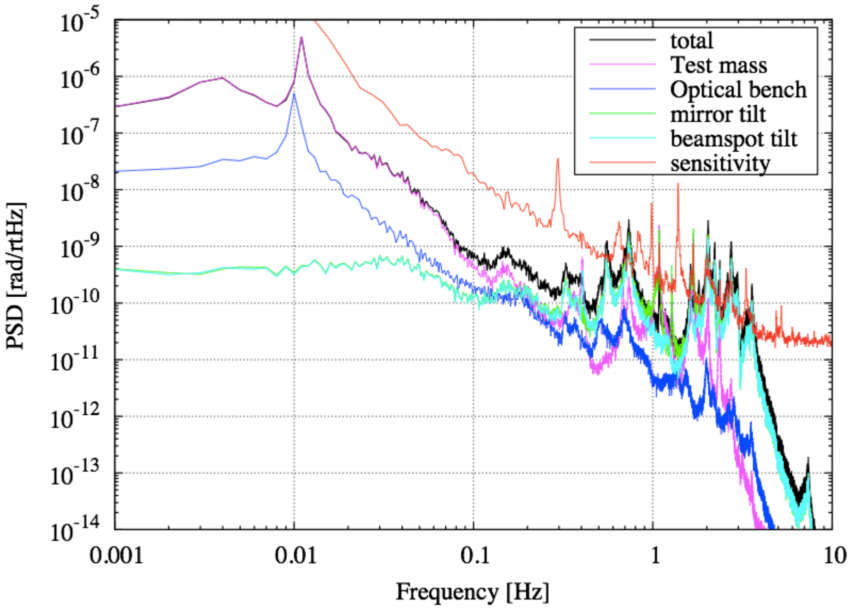
	horizontal (Long,Trans)	vertical (Vert)	nonlinear coupling	others
theoretical analysis	○	○(?)	○	△
measurement	○	△	△	-
reduction	△ (not enough)	-	-	-

Next tasks about cross-coupling

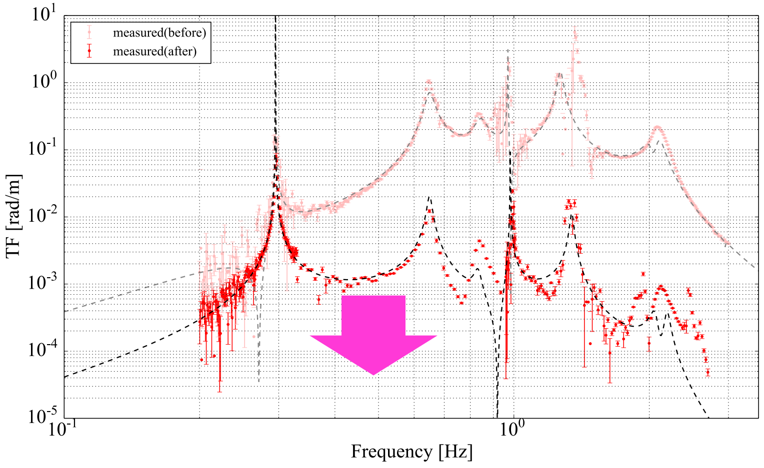
① measure and analyze cross-coupling from Vert
② measure nonlinear coupling
③ reduce cross-coupling from Long,Trans more
④ calculate about other coupling routes



coupling from VERT



nonlinear coupling



reduce more

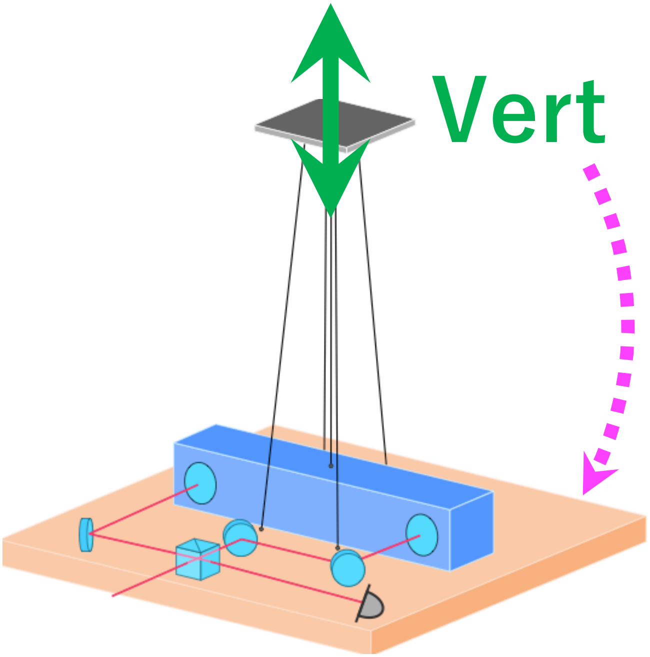
Next tasks about cross-coupling

① measure and analyze cross-coupling from Vert

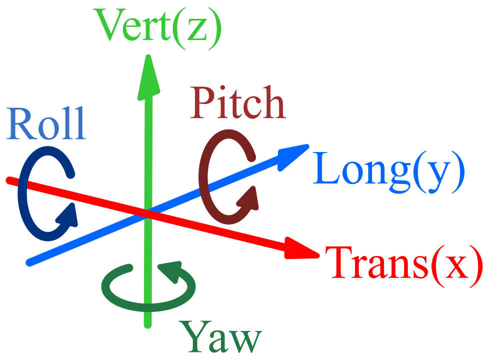
② measure nonlinear coupling

③ reduce cross-coupling from Long,Trans more

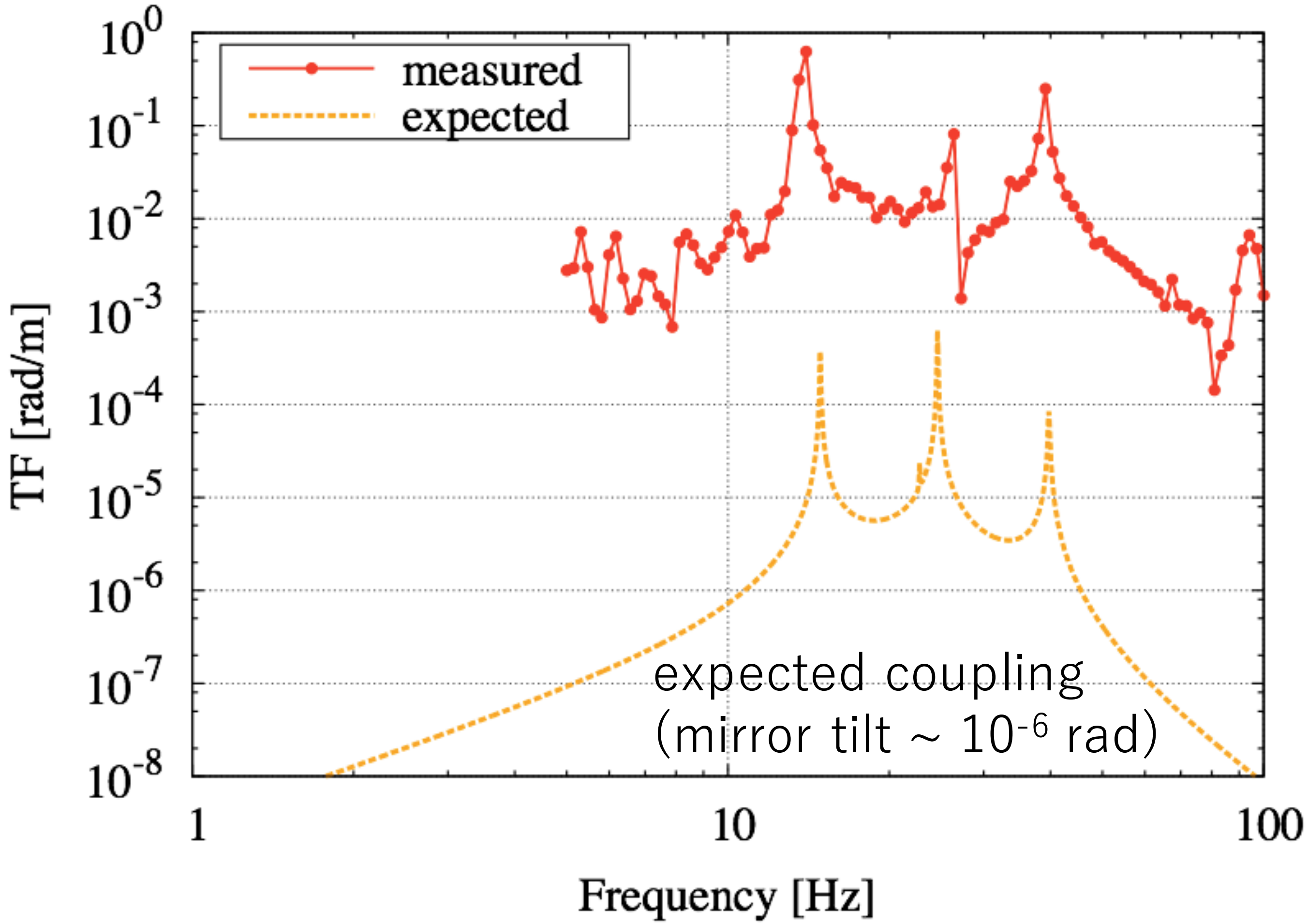
④ calculate about other coupling routes



①Cross-coupling from VERT



- measurement test with Takano-kun



✓ Much higher than expected

✓ Shape of the measured transfer function disagrees with theory

Further analysis is required

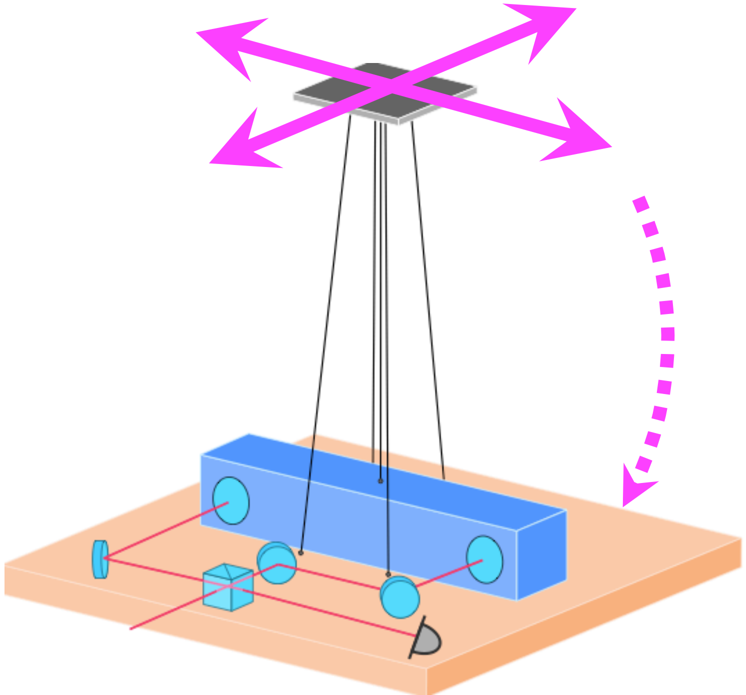
・**identify coupling route**

Next tasks about cross-coupling

② measure nonlinear coupling

③ reduce cross-coupling from Long,Trans more

④ calculate about other coupling routes



②Nonlinear coupling

- Coupling by nonlinear transfer

linear coupling

(**Yaw**) = (**tilt**) × (**Roll**)

<u>**nonlinear transfer**</u>

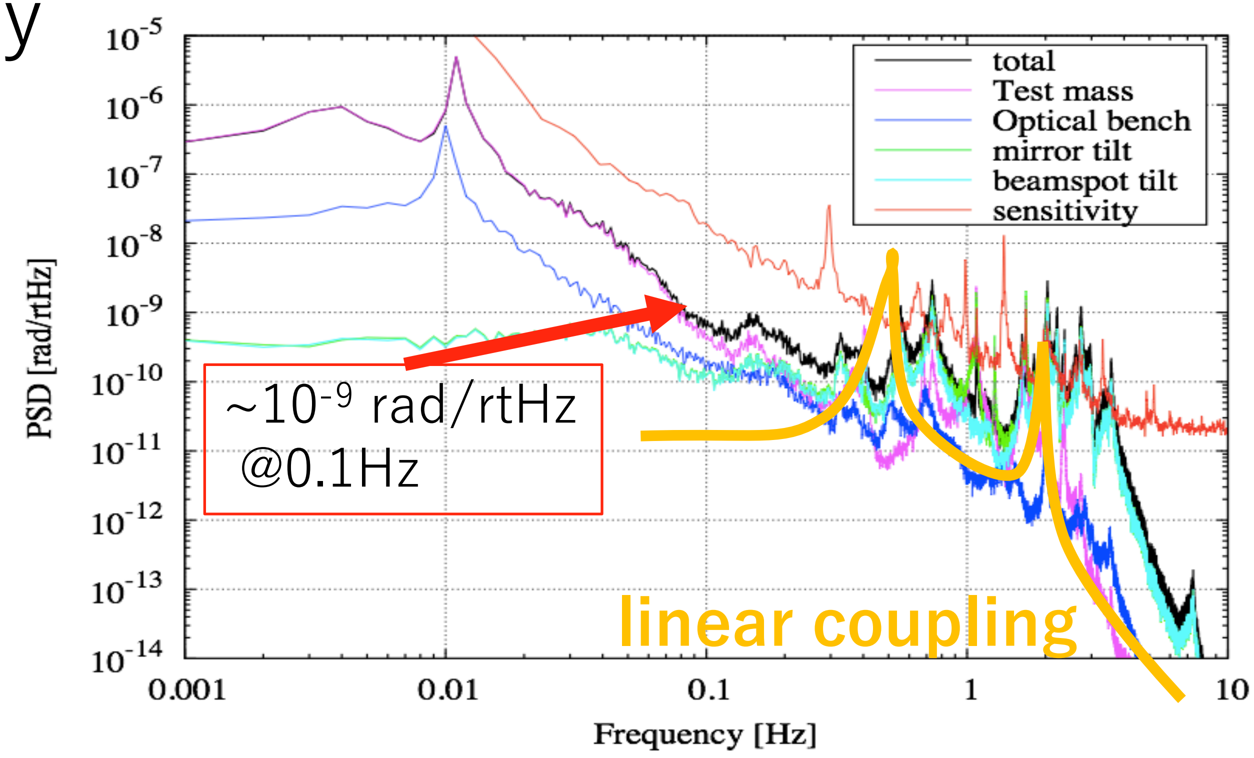
(**Yaw**) = (**Pitch**) × (**Roll**)

(time-dependent tilt)

- already calculated theoretically
- dominant at low frequency
  (⇔linear coupling : ~1Hz)

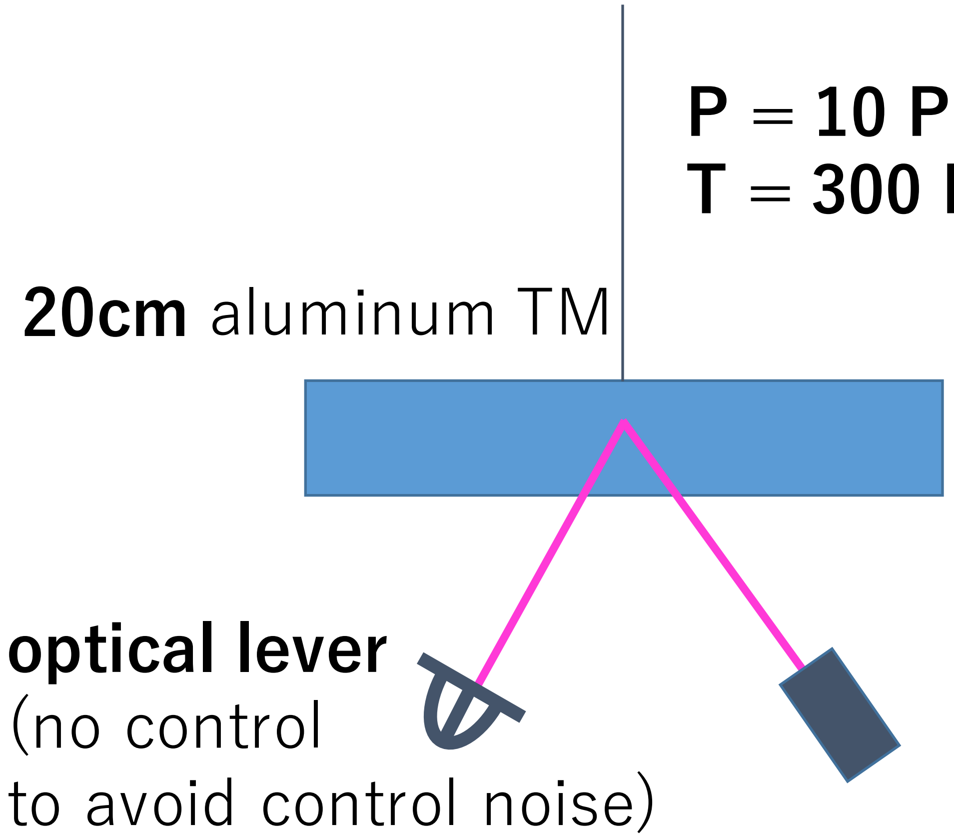
⇒ **also important for other experiments**

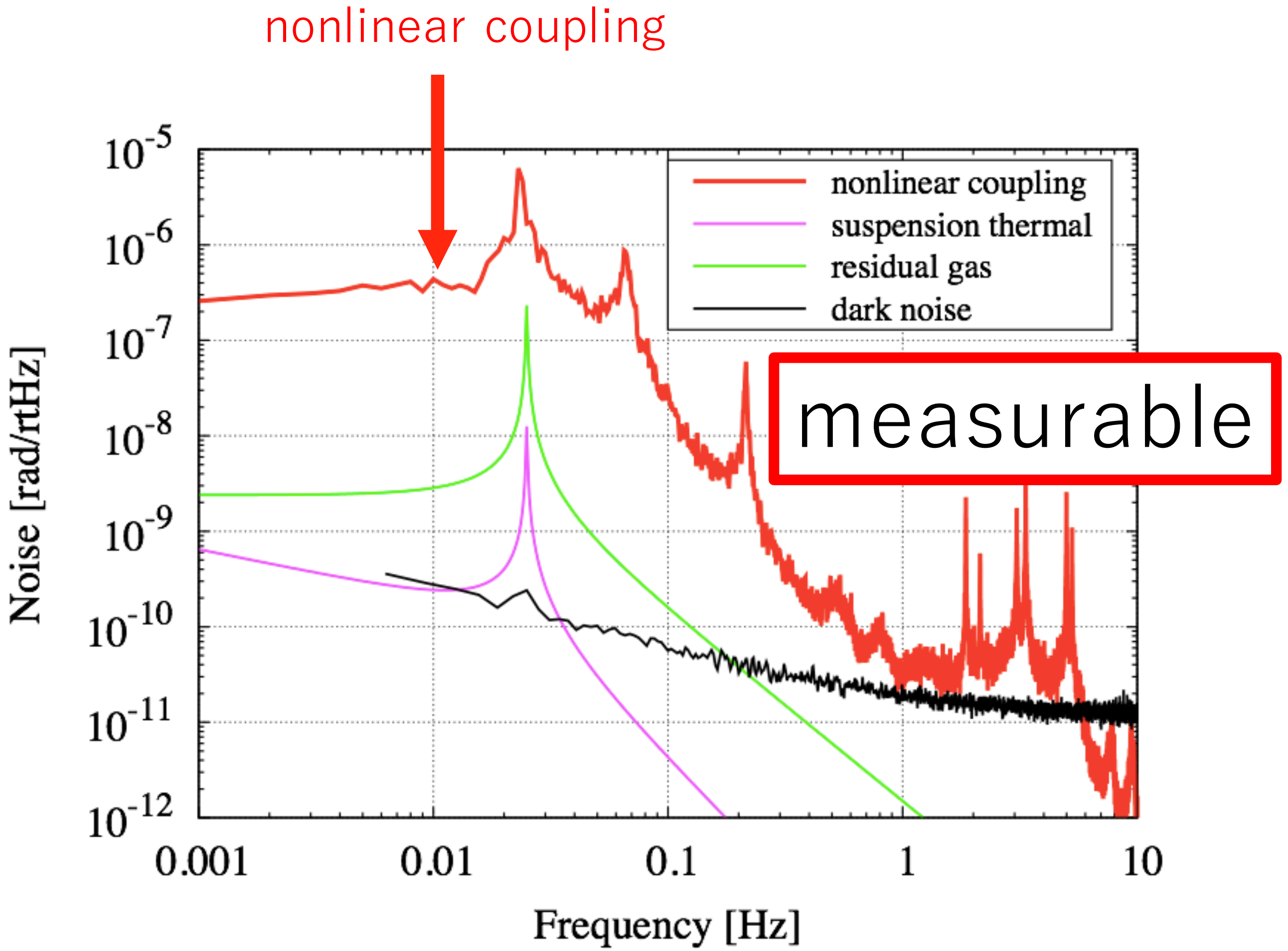
(inverse-square law, ...)



Measurement experiment

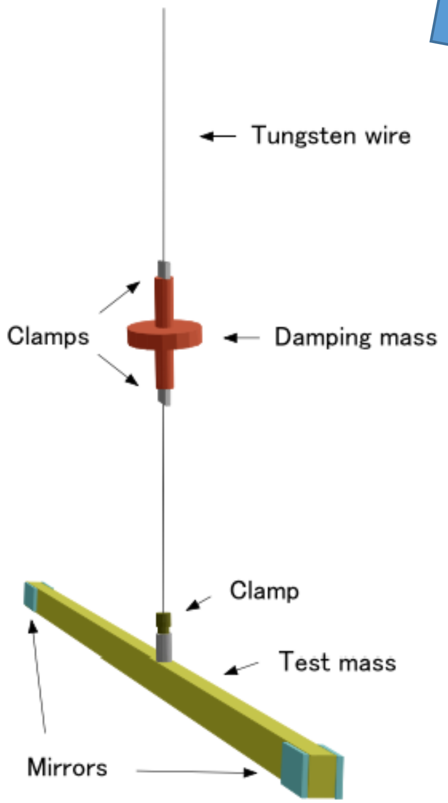
- measurable by very simple experiment

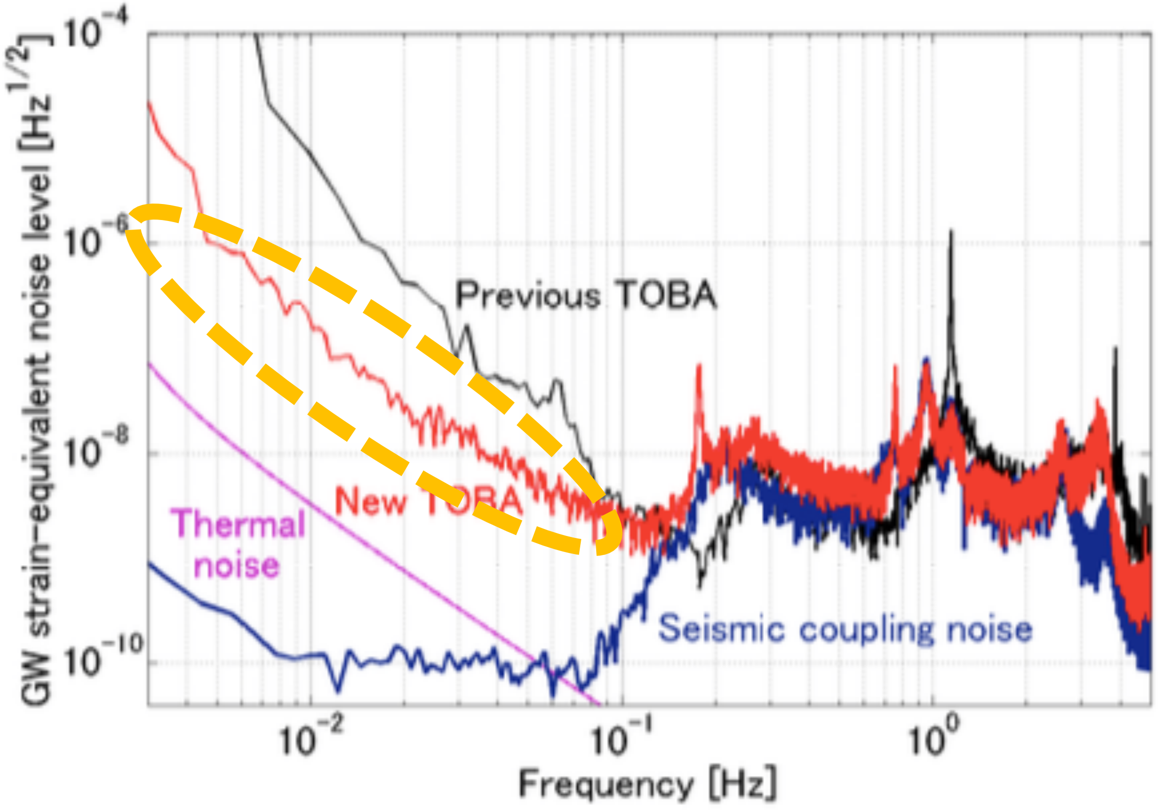




Okada-san's TOBA

- Nonlinear coupling was already observed?
  - 40cm test mass
  - quadrature interferometer (no control)



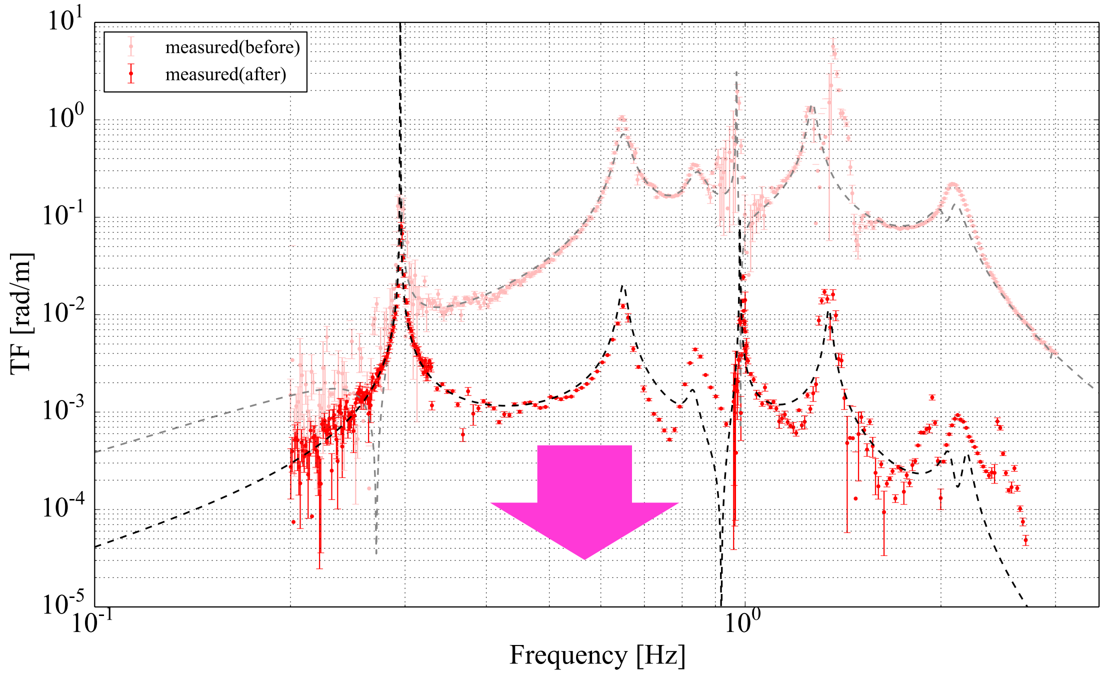


岡田さん資料より

Next tasks about cross-coupling

③ reduce cross-coupling from Long,Trans more

④ calculate about other coupling routes



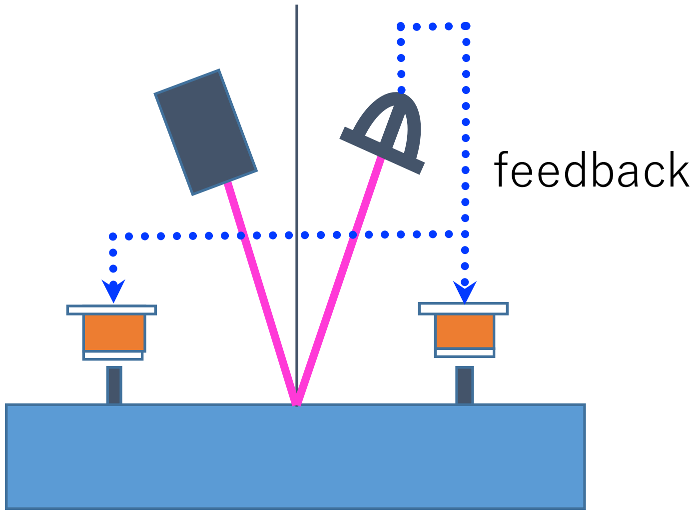
③more reduction for Long/Trans

- achieved tilt : ～10^{-4} **rad**

adjust by counter weight

RMS amplitude : ～10^{-5} rad

control Pitch/Roll vibration



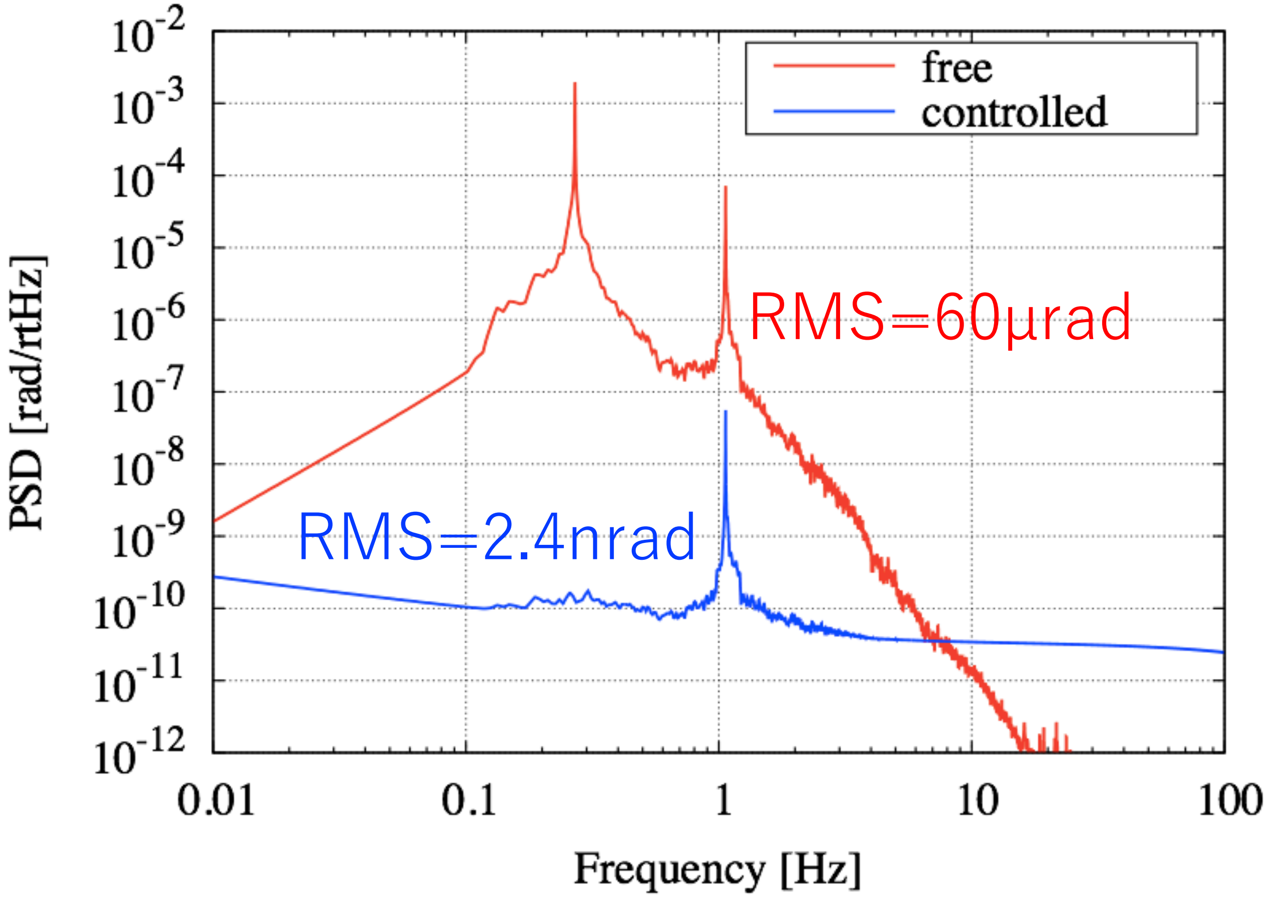
✓ install tilt sensor
  - Optical lever will be enough

✓ decoupling
  - Not to degrade sensitivity

- requirement : ～10^{-9} **rad**

Tilt control with optical lever

- simulation including sensor/actuator noise



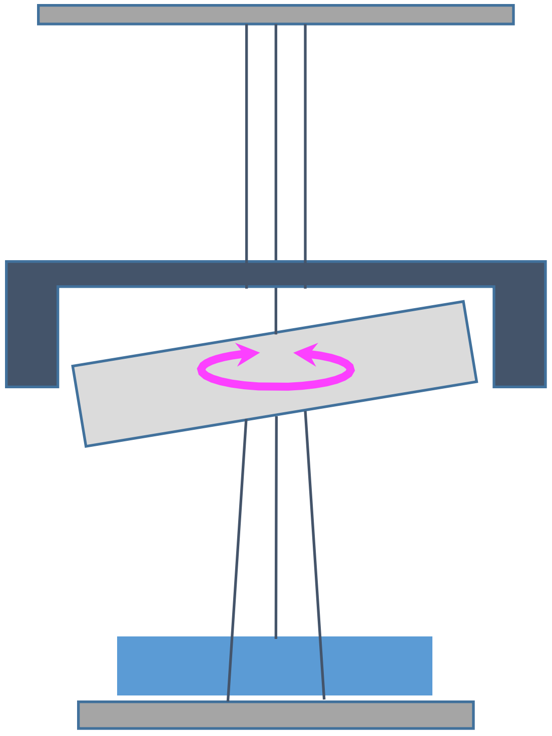
Next tasks about cross-coupling

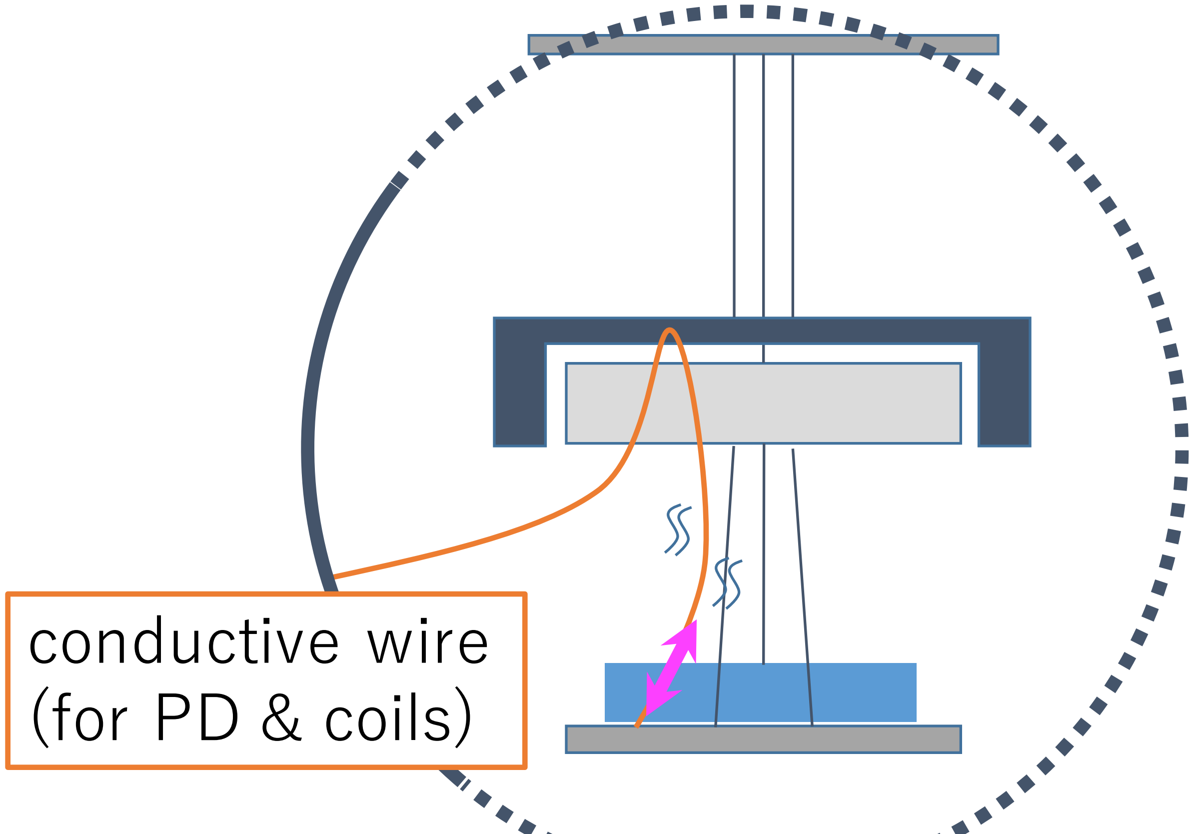
④ calculate about other coupling routes

④ other coupling routes

- asymmetry of **intermediate mass**
- (transfer via **conductive wires**)

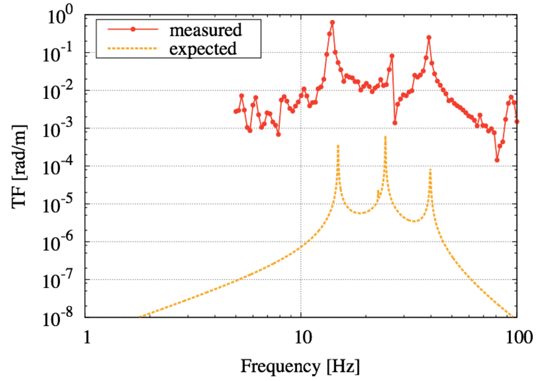
calculate



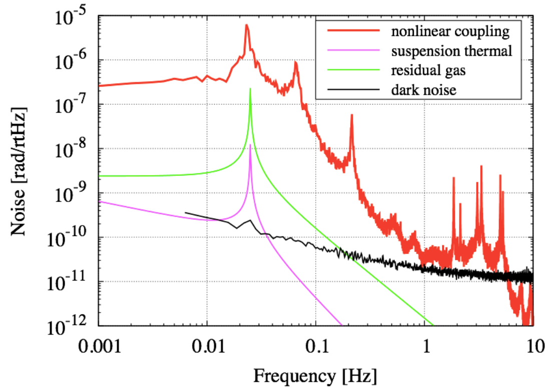


Summary of tasks about cross-coupling

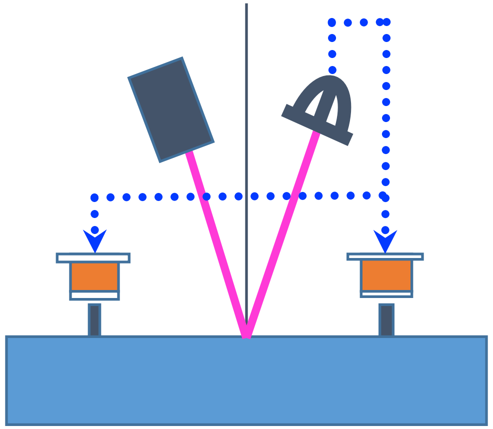
✓cross-coupling from Vert
- identify coupling route
  (already measured but disagree with theory)



✓Nonlinear coupling
- measurement experiment
  with simple torsion pendulum



✓reduce cross-coupling from Long,Trans more
- control Pitch/Roll vibration
  (install tilt sensor, decoupling)



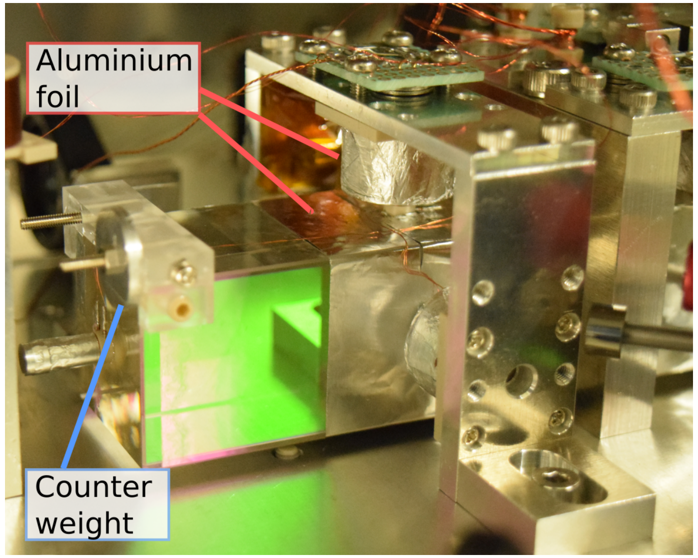
✓calculate about other coupling routes
- intermediate mass, conductive wire, etc...

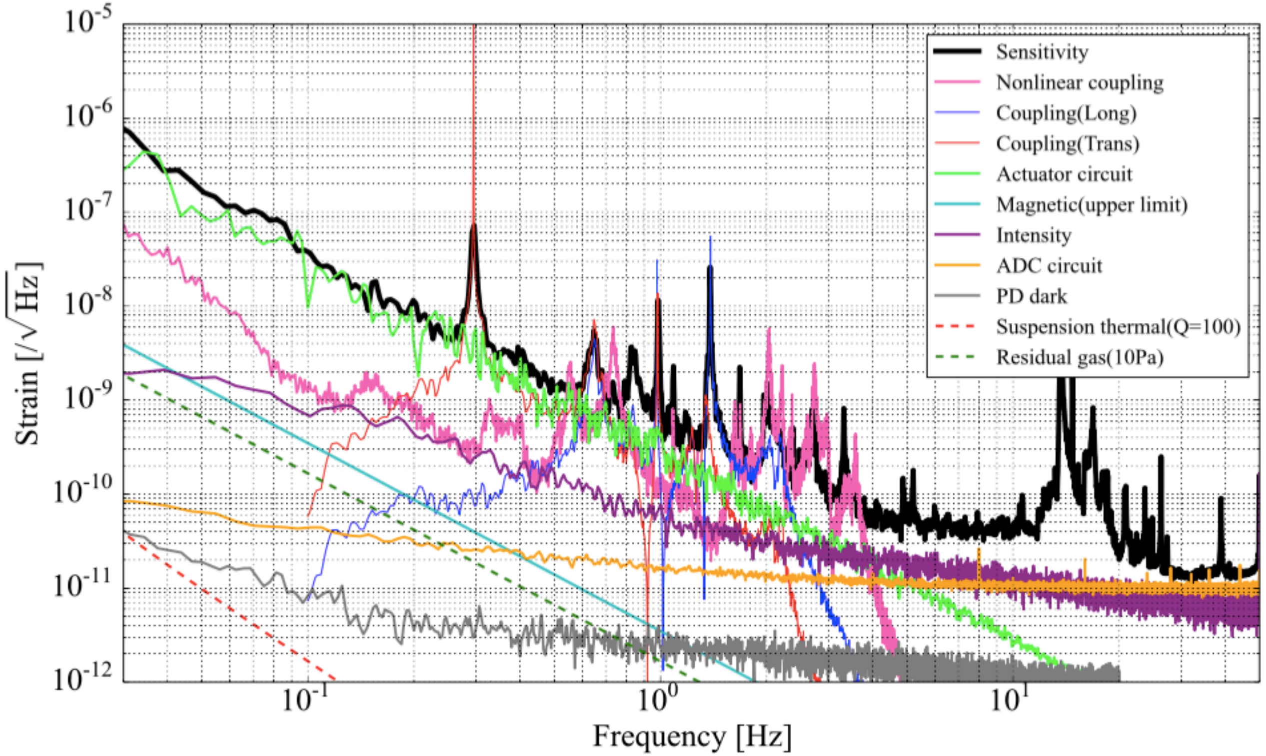
Other problems

Problems

- How to improve the sensitivity
  - noise source around 0.1Hz is not completely identified

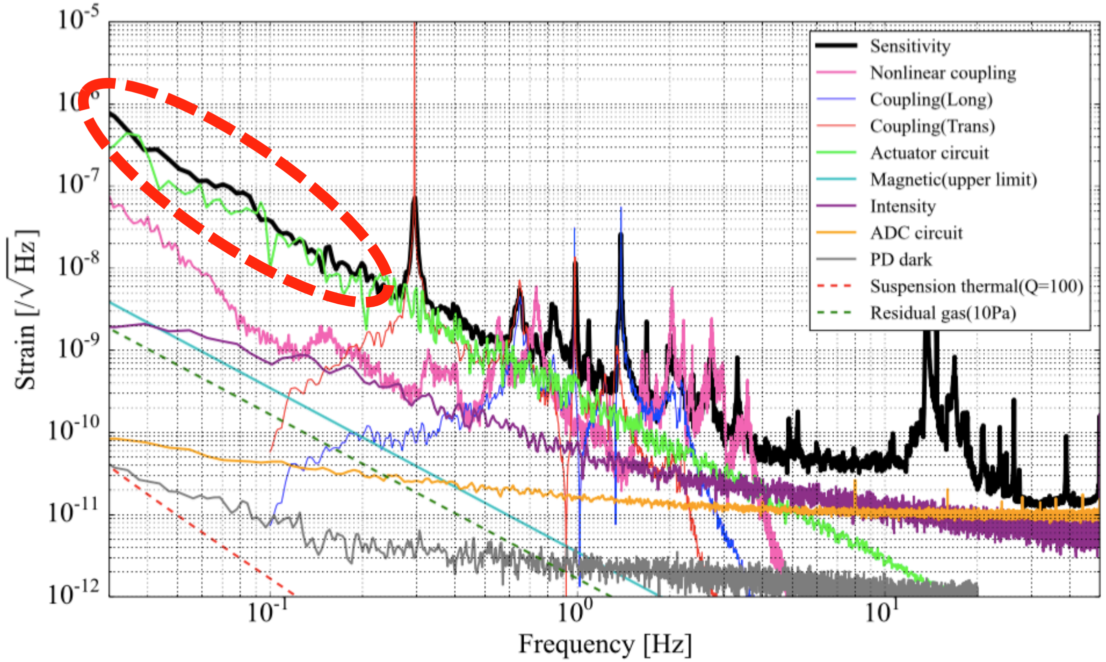
- technical issues
  - electrostatic force

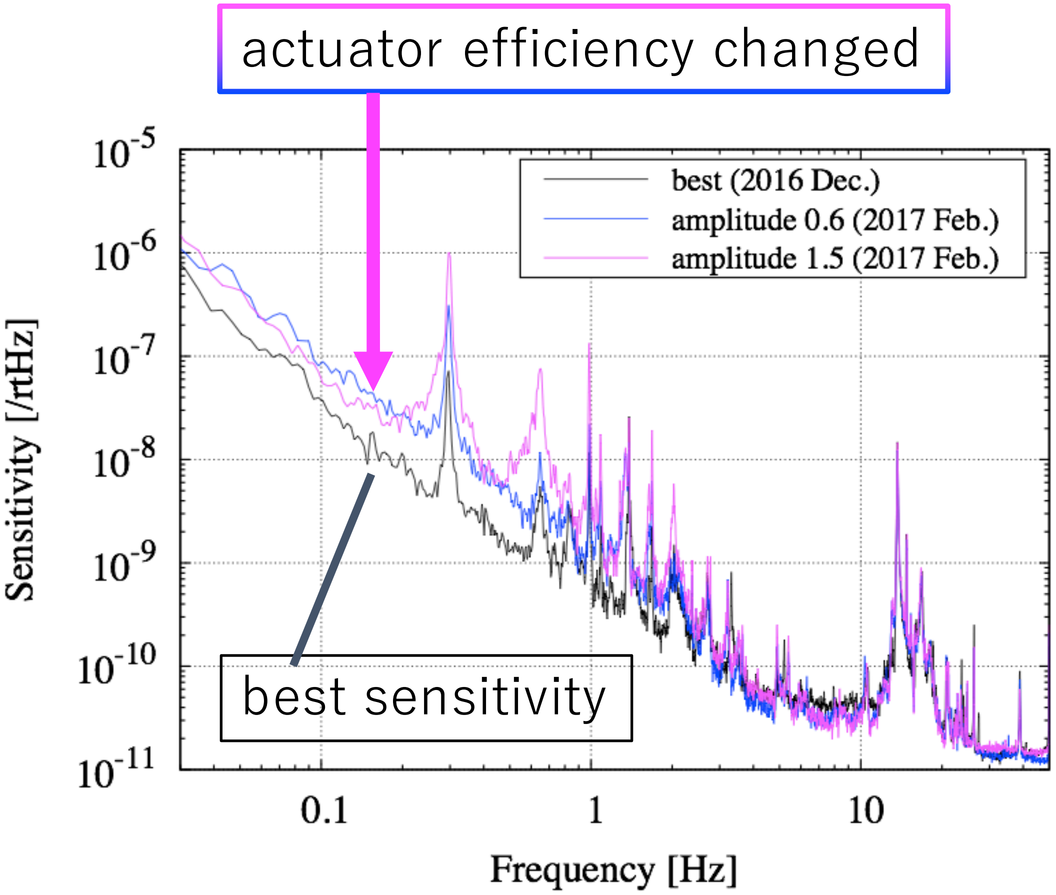




Noise around 0.1Hz

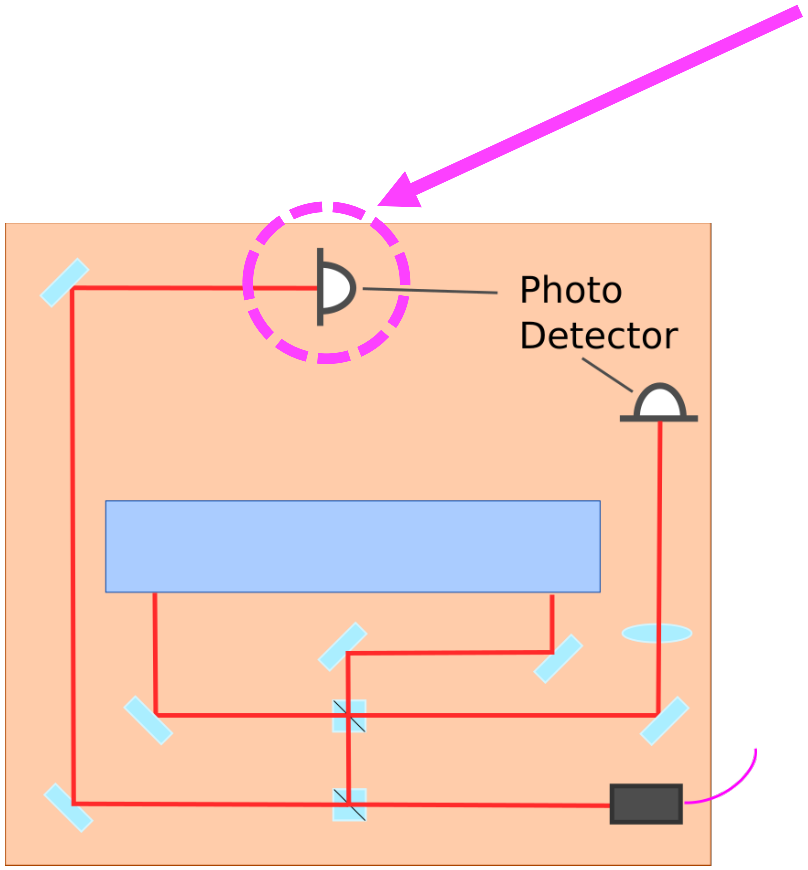
- Not only actuator noise

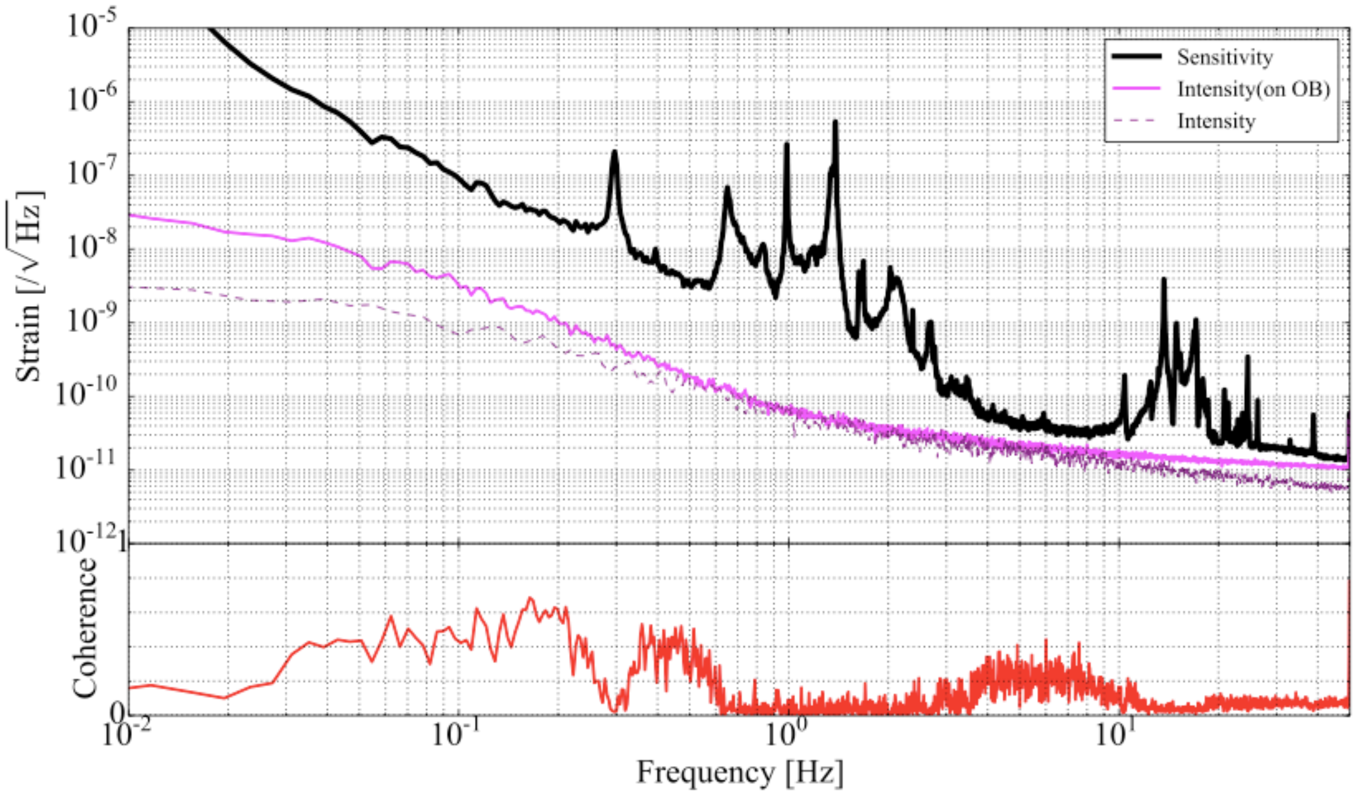




Scattering?

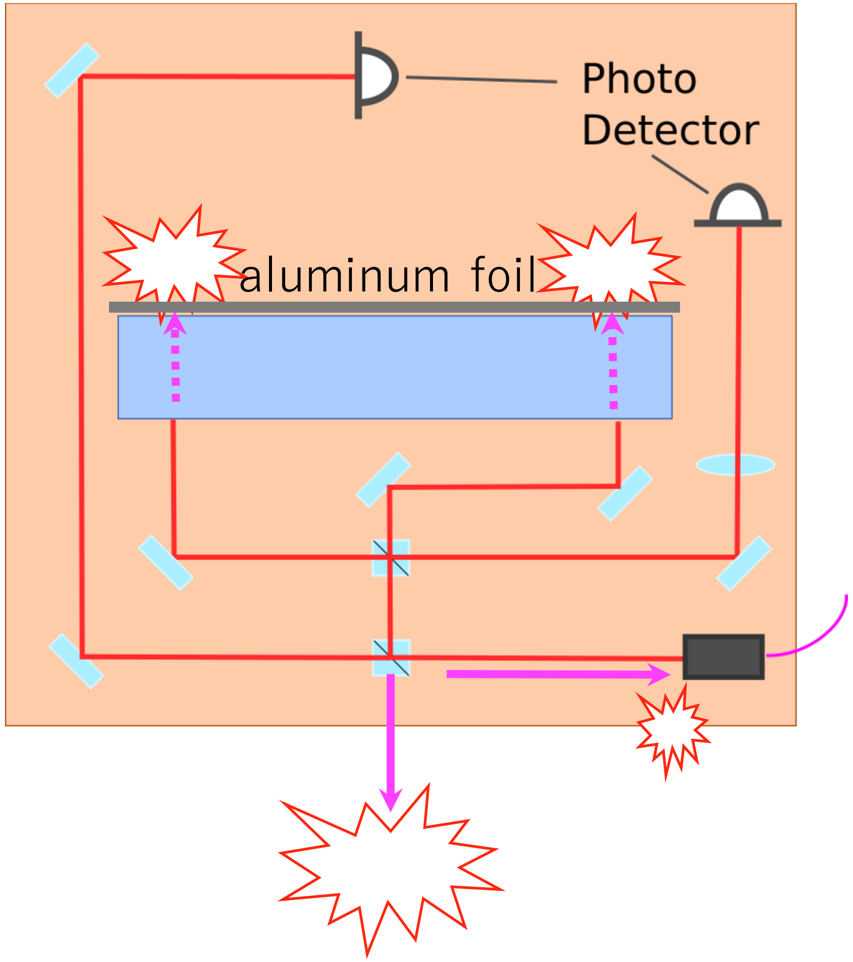
- Coherence with intensity monitor PD

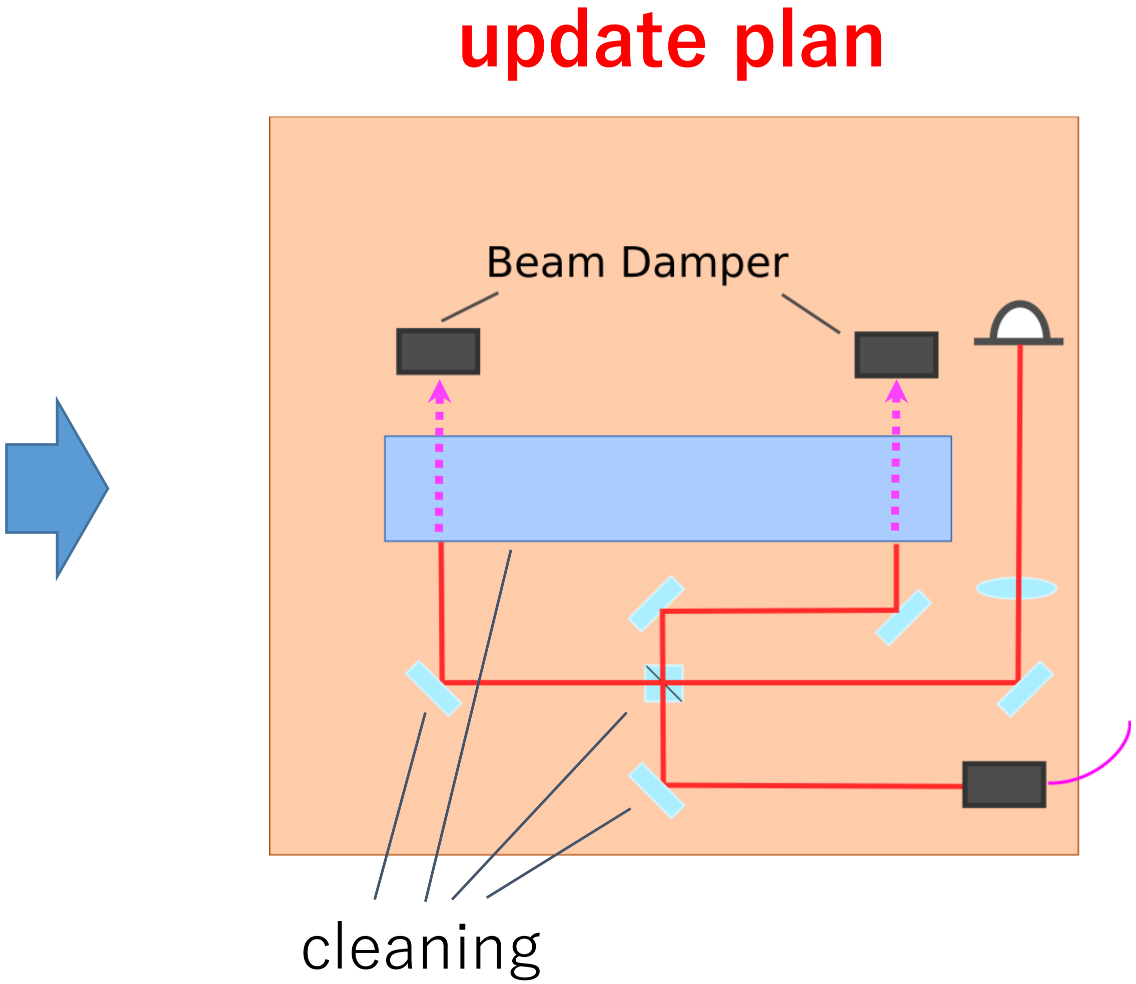




Reduce scattering

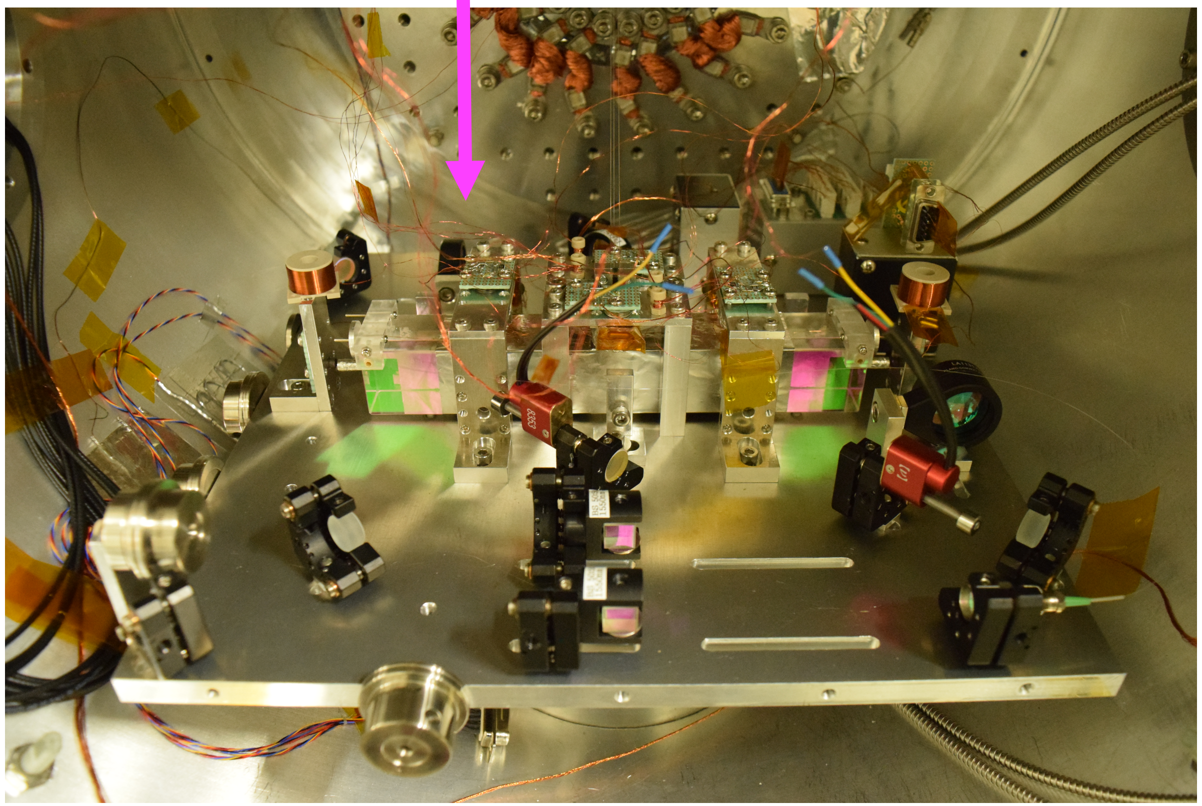
- Current setup is terrible

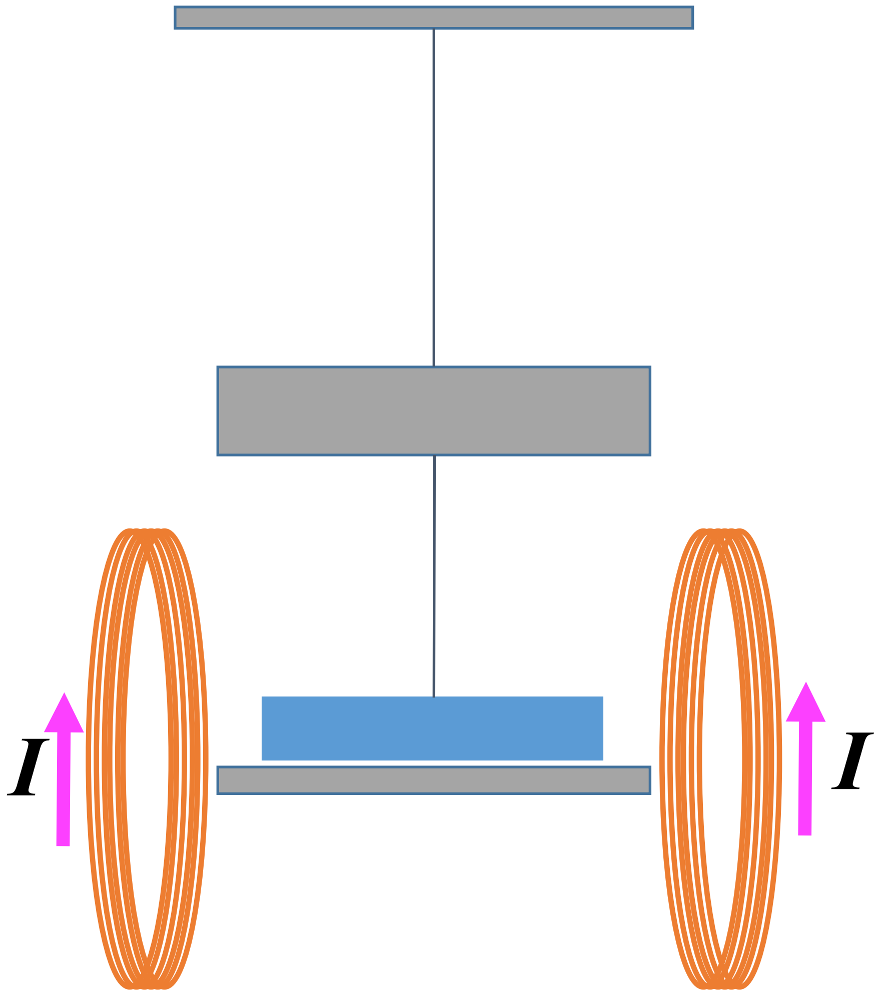




Other noise sources

- magnetic noise of Optical Bench
    - many components on the bench



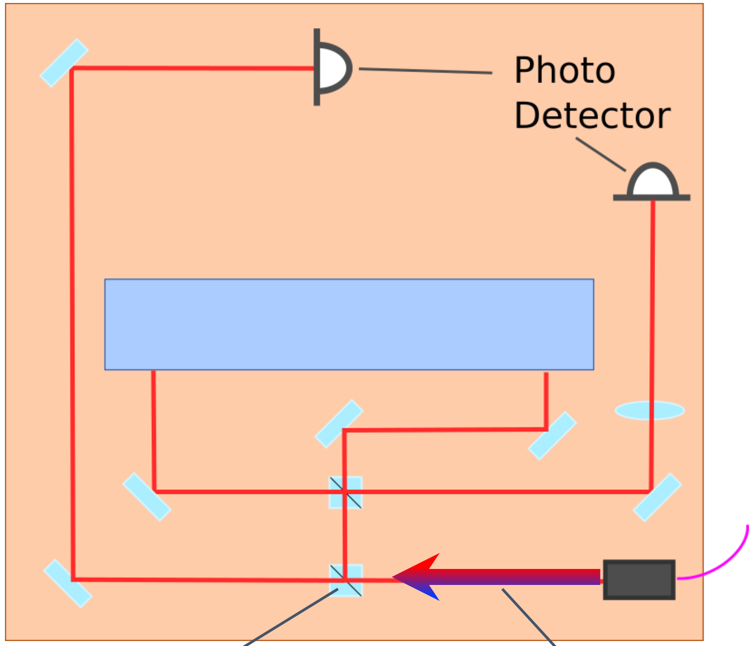


measure response with Helmholtz coils

Other noise sources

- fluctuation of polarization

  ⇒ fluctuation of input power and visibility of interferometer



polarization fluctuating

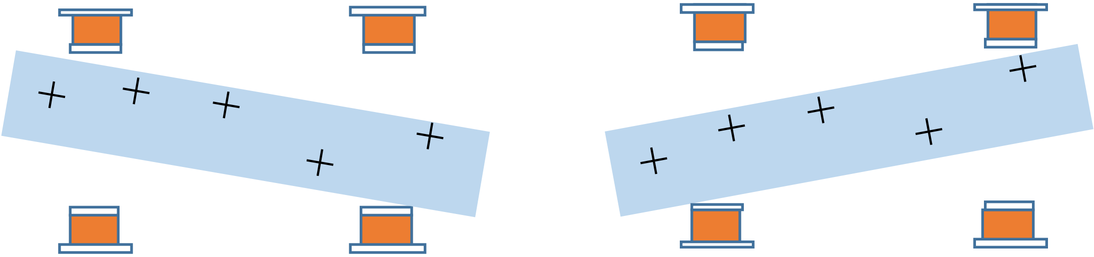
BS (have a little dependence on polarization)

measure

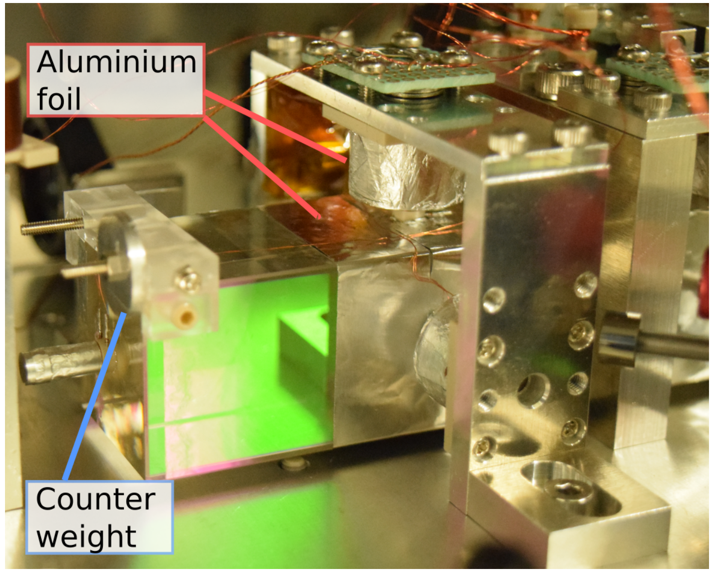
- fluctuation of polarization by using PBS
- polarization dependence of BS
- polarization dependence of interferometer visibility

Technical update : metal coating

- Metal coating for TM (and coils)
  - shield electrostatic force on TM
    (it makes the system unstable)



covered with aluminum foil

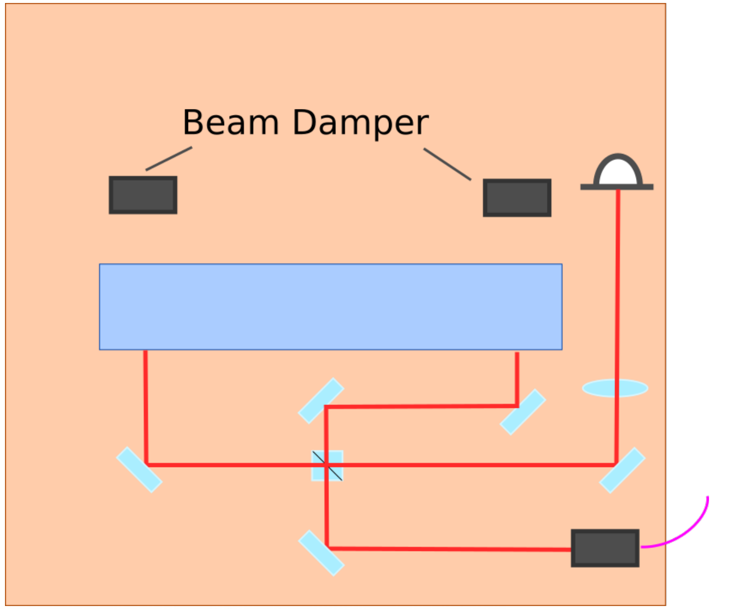


How much should it be shielded?
・as far as lock is stable?
・can it be a noise source?
 (Lorentz force etc...)

Summary of updates

- improve sensitivity around 0.1Hz
  - reduce scattering
  - investigate other noise sources

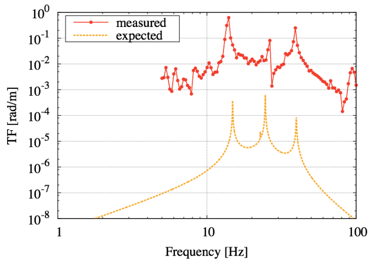
    (magnetic noise? fluctuation of polarization?)

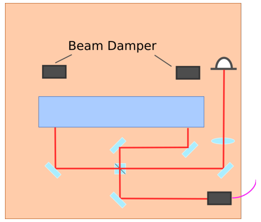


- Metal coating for TM and coils
  - shield electrostatic force

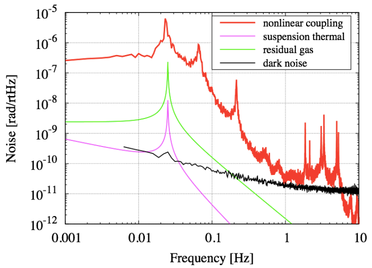
Total Plan about TOBA(rough)

- do some measurements with current setup for a while
  - coupling from VERT
  - scattering reduction
  - investigate other noise source





- calculation and other measurement at the same time
  - nonlinear coupling
  - other coupling routes



- renew the setup
  - metal coating for TM
  - install tilt sensors
  - (redesign the whole system?)

and so on...

Conclusion

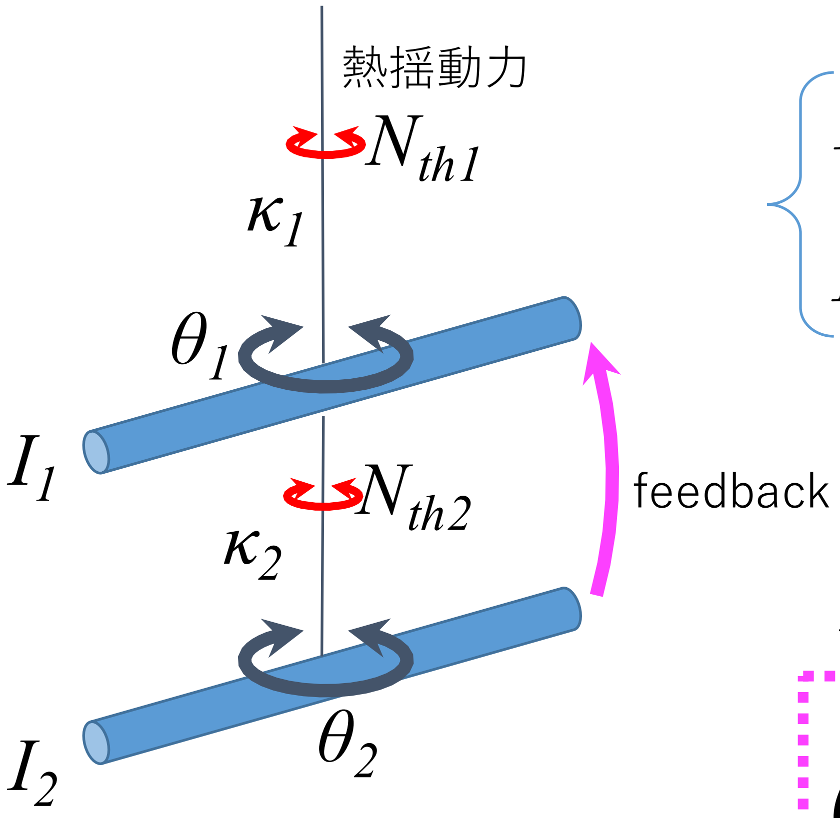
- We have many things to do

End

interesting experiment

Thermal noise reduction with SPI (by 安東さん)

- feedback relative motion(TM-IM) to intermediate mass(IM)



Eq. of motion

thermal torque of top/bottom wire

$$\begin{cases} I_1\ddot{\theta}_1 = -\kappa_1\theta_1 + \kappa_2(\theta_2-\theta_1) + N_{th1} - N_{th2} + \boxed{G(\theta_2-\theta_1)} \\ I_2\ddot{\theta}_2 = -\kappa_2(\theta_2-\theta_1) + N_{th2} \end{cases}$$

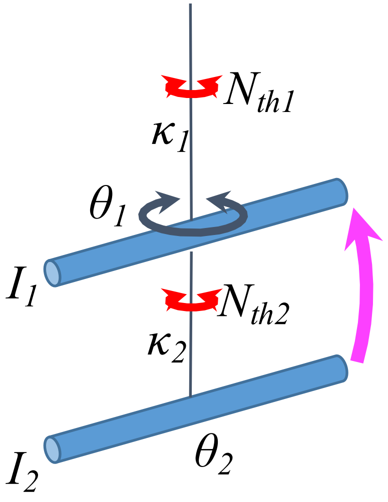
feedback torque

$$\tilde{D} = (\kappa_1+\kappa_2-I_1\omega^2+\tilde{G})(\kappa_2-I_2\omega^2) - \kappa_2(\kappa_2+\tilde{G})$$

$$\boxed{\tilde{\theta}_2 = \frac{\kappa_2}{\tilde{D}}\tilde{N}_{th1} + \frac{\kappa_1 - I_1\omega^2 + \tilde{G}}{\tilde{D}}\tilde{N}_{th2}}$$

Thermal noise suppression

- Thermal noise can be suppressed by tuning **G**



$$\tilde{D} = (\kappa_1 + \kappa_2 - I_1\omega^2 + \tilde{G})(\kappa_2 - I_2\omega^2) - \kappa_2(\kappa_2 + \tilde{G})$$

$$\tilde{\theta_2} = \frac{\kappa_2}{\tilde{D}}\tilde{N}_{th1} + \frac{\kappa_1 - I_1\omega^2 + \tilde{G}}{\tilde{D}}\tilde{N}_{th2}$$

(i) infinite **G**	0	$-\dfrac{1}{I_2\omega^2}$
(ii) tuned **G** (= - (κ_1 - $I_1\omega^2$))	$\dfrac{1}{\kappa_1 - (I_1 + I_2)\omega^2}$	0

N_{th1} : suppressed
N_{th2} : not changed

N_{th1} : increased
N_{th2} : broadband cancelled

Response to GW/Torque under control

- at high frequency (free mass region)

q_1, q_2 : quadrapole moment

	$\tilde{N}_{th1}$	$\tilde{N}_{th2}$	$\tilde{h}$	$\tilde{N}_{\mathrm{ext}}$
no control $\tilde{G}=0$	$\frac{\kappa_2}{I_1 I_2 \omega^4}$	$-\frac{1}{I_2\omega^2}$	$\frac{q_2}{2I_2}$	$-\frac{1}{I_2\omega^2}$
infinite gain $\tilde{G}=\infty$	0	$-\frac{1}{I_2\omega^2}$	$\frac{q_2}{2I_2}$	$-\frac{1}{I_2\omega^2}$
tuned gain $\tilde{G}=-(\kappa_1 - I_1\omega^2)$	$-\frac{1}{(I_1+I_2)\omega^2}$	0	$\frac{q_1+q_2}{2(I_1+I_2)}$	$-\frac{1}{(I_1+I_2)\omega^2}$

Response to GW/Torque under control

- increase(decrease) factors compared to the case without control at high frequency (free mass region)

	$\tilde{N}_{th1}$	$\tilde{N}_{th2}$	$\tilde{h}$	$\tilde{N}_{\mathrm{ext}}$
infinite gain $\tilde{G} = \infty$	0	1	1	1
tuned gain $\tilde{G} = -(\kappa_1 - I_1\omega^2)$	$\frac{I_1 I_2}{\kappa_2(I_1 + I_2)}\omega^2$	0	$\frac{q_1 + q_2}{q_2} \frac{I_2}{I_1 + I_2}$	$\frac{I_2}{I_1 + I_2}$

S/N can be improved?

- with practical thickness of wire : $\kappa \propto d^4 \propto m^2$

$$\tilde{N}_{th} = \sqrt{4k_B T \frac{\kappa\phi}{\omega}} \Rightarrow \begin{cases} \tilde{N}_{th1} \propto m_1 + m_2 \\ \tilde{N}_{th2} \propto m2 \end{cases}$$

	$\tilde{N}_{th1}$	$\tilde{N}_{th2}$	$\tilde{h}$	$\tilde{N}_{\mathrm{ext}}$
no control $\tilde{G} = 0$	$\frac{\kappa_2}{I_1 I_2 \omega^4}$	$\boxed{-\frac{1}{I_2\omega^2}}$	$\frac{q_2}{2I_2}$	$-\frac{1}{I_2\omega^2}$
tuned gain $\tilde{G} = -(\kappa_1 - I_1\omega^2)$	$\boxed{-\frac{1}{(I_1+I_2)\omega^2}}$	0	$\frac{q_1+q_2}{2(I_1+I_2)}$	$-\frac{1}{(I_1+I_2)\omega^2}$

$$\Rightarrow \quad \tilde{\theta}_{th}(G=0) \propto \frac{m_2}{I_2}, \quad \tilde{\theta}_{th}(\text{tuned}\, G) \propto \frac{m_1+m_2}{I_1+I_2}$$

Signal to Noise ratio

gravitational wave	external torque
$\tilde{h}/\tilde{\theta}_{th}$	$\tilde{\theta}_{\mathrm{ext}}/\tilde{\theta}_{th}$
$\boxed{\frac{q_2}{m_2} \downarrow \frac{q_1+q_2}{m_1+m_2}}$	$\boxed{\frac{1}{m_2} \downarrow \frac{1}{m_1+m_2}}$

S/N can be improved?

Signal to Noise ratio

gravitational wave

$$\tilde{h}/\tilde{\theta}_{th}$$

$$\boxed{\frac{q_2}{m_2} \downarrow \frac{q_1 + q_2}{m_1 + m_2}}$$

not change or decrease

external torque

$$\tilde{\theta}_{\mathrm{ext}}/\tilde{\theta}_{th}$$

$$\boxed{\frac{1}{m_2} \downarrow \frac{1}{m_1 + m_2}}$$

always decrease