Angular Sensor for TOBA and my future plans

M2 Yuki Miyazaki

Contents

- about TOBA
- coupled wave front sensor
  - merits and demerits
- What is done so far

I made too much slides..
Sorry for fast speaking..

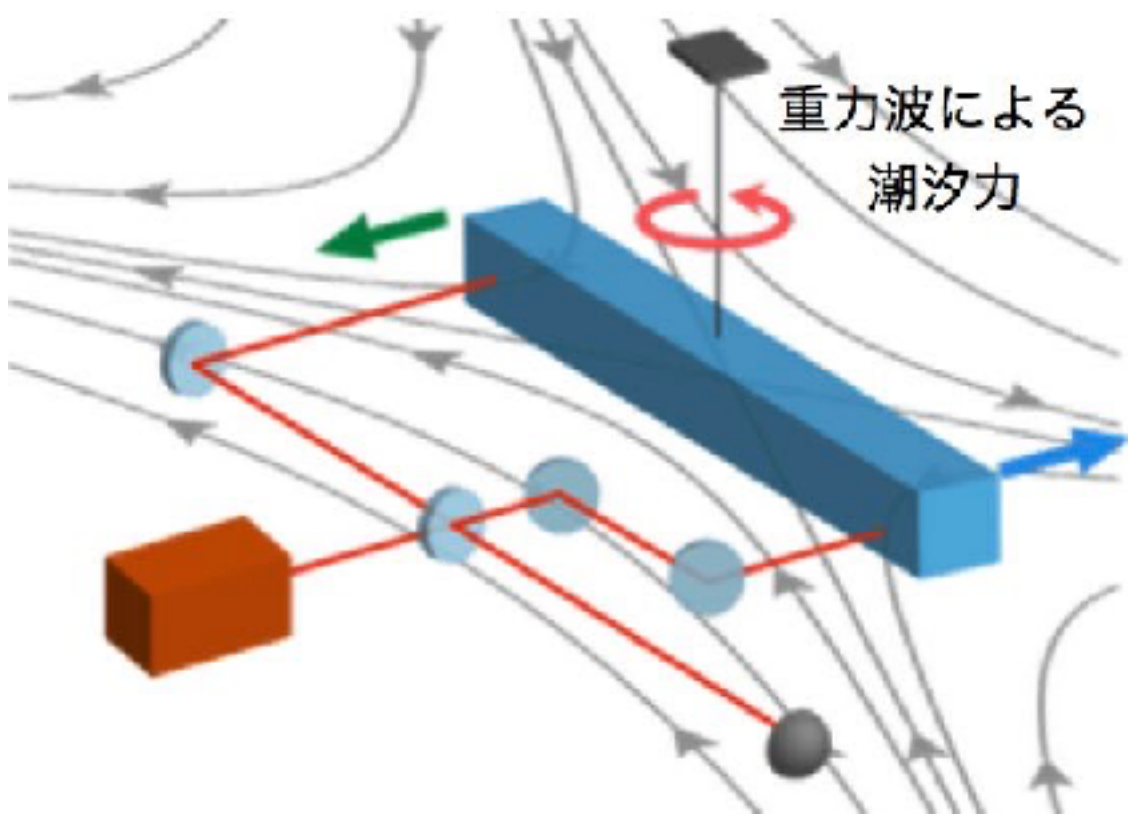
- What I want to study with the coupled WFS (For M Thesis)
  - demonstration test (confirm its principle)
  - check its characteristics
  - obtain good sensitivity

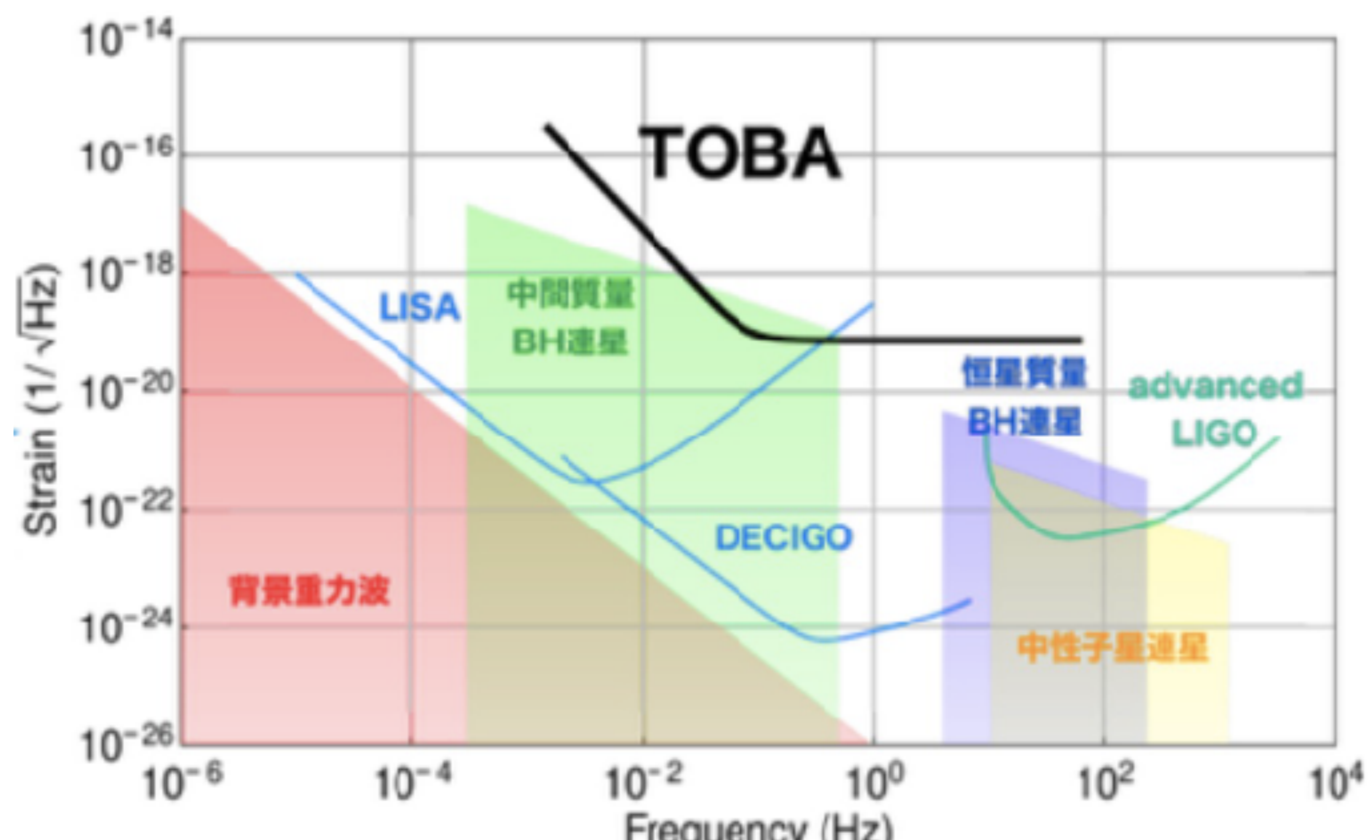
- Summary

TOBA (TOrsion-Bar Antenna)

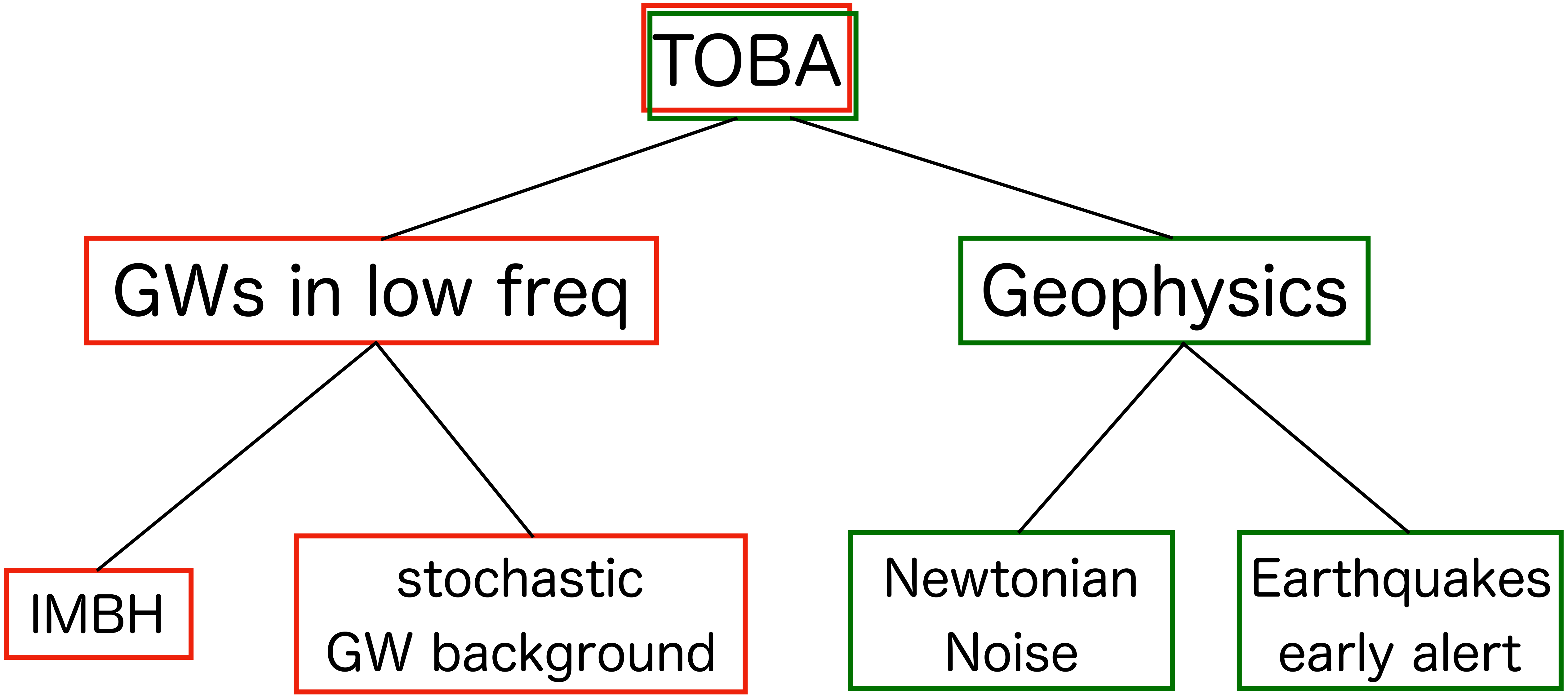
- TOBA: a gravitational wave detector using torsion pendulums
- It rotates when GWs come
- Its resonant freq of Yaw rotation: ~mHz

  → It has good sensitivity at low freq
- Goal sensitivity: $h \sim 10^{-19} / \sqrt{\mathrm{Hz}}$ @ $0.1\ \mathrm{Hz}$ (Final TOBA)





Targets of TOBA

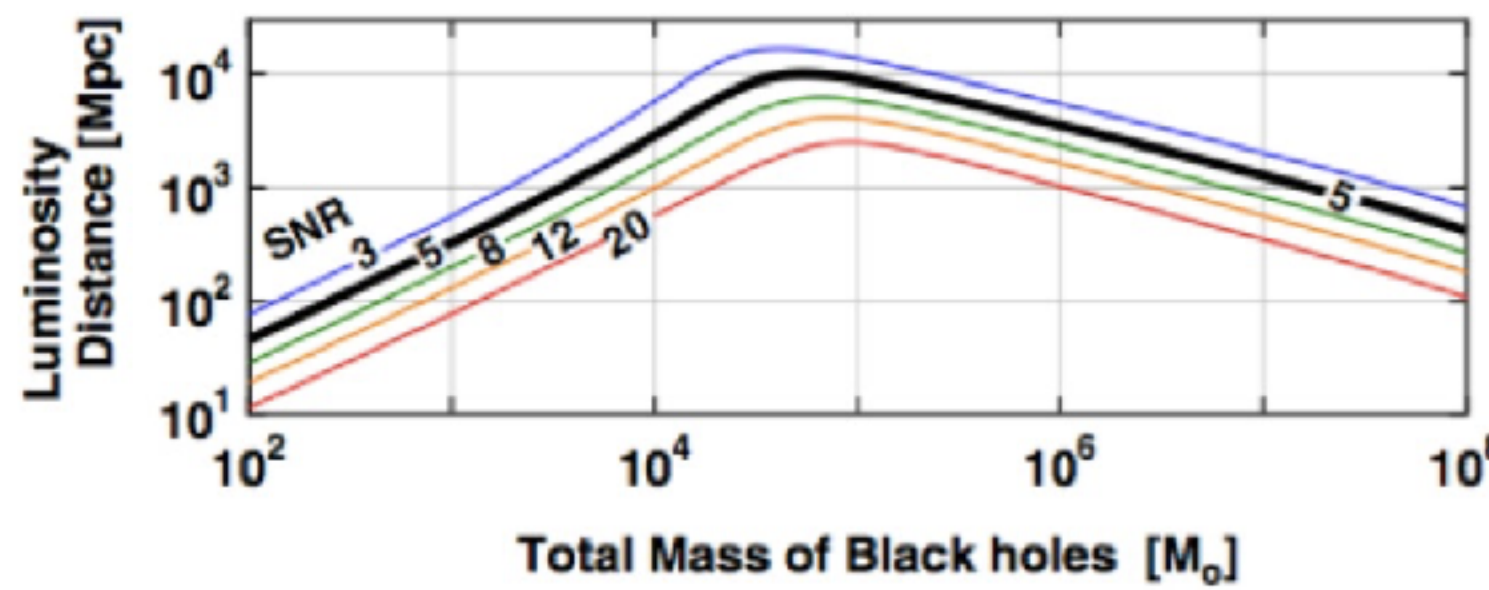


Targets of TOBA

GWs in low freq

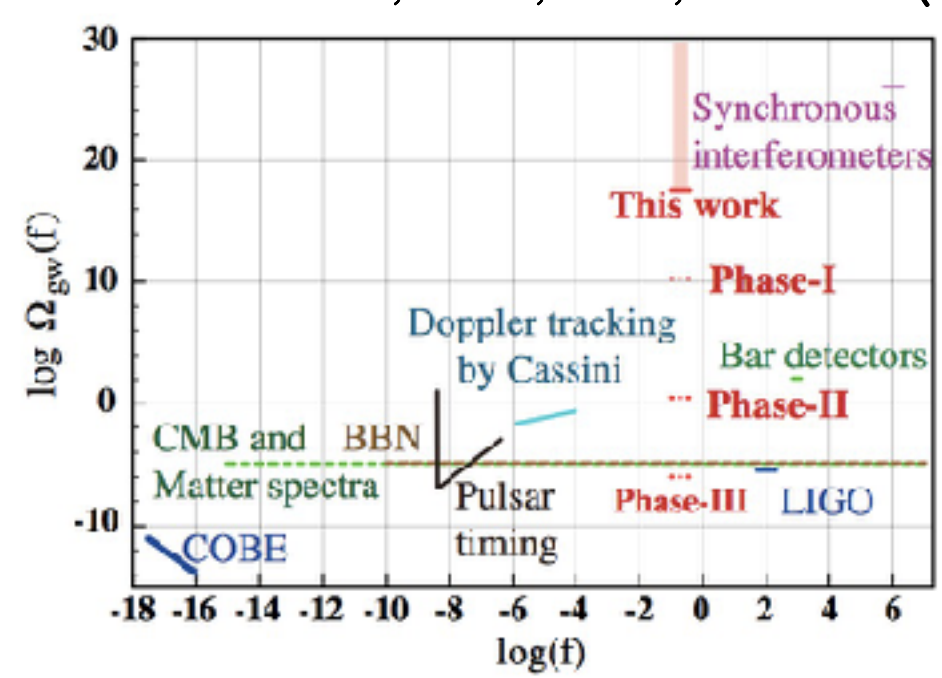
- Intermediate mass blackholes (~10^5 M_{sun})

M. Ando et al., PRL, 105, 161101(2010)



- Stochastic GW background
  - Big Bang Nucleosynthesis ~information for element ratio
  - give knowledge for early universe

K. Ishidoshiro et al., PRL, 106, 161101(2011)

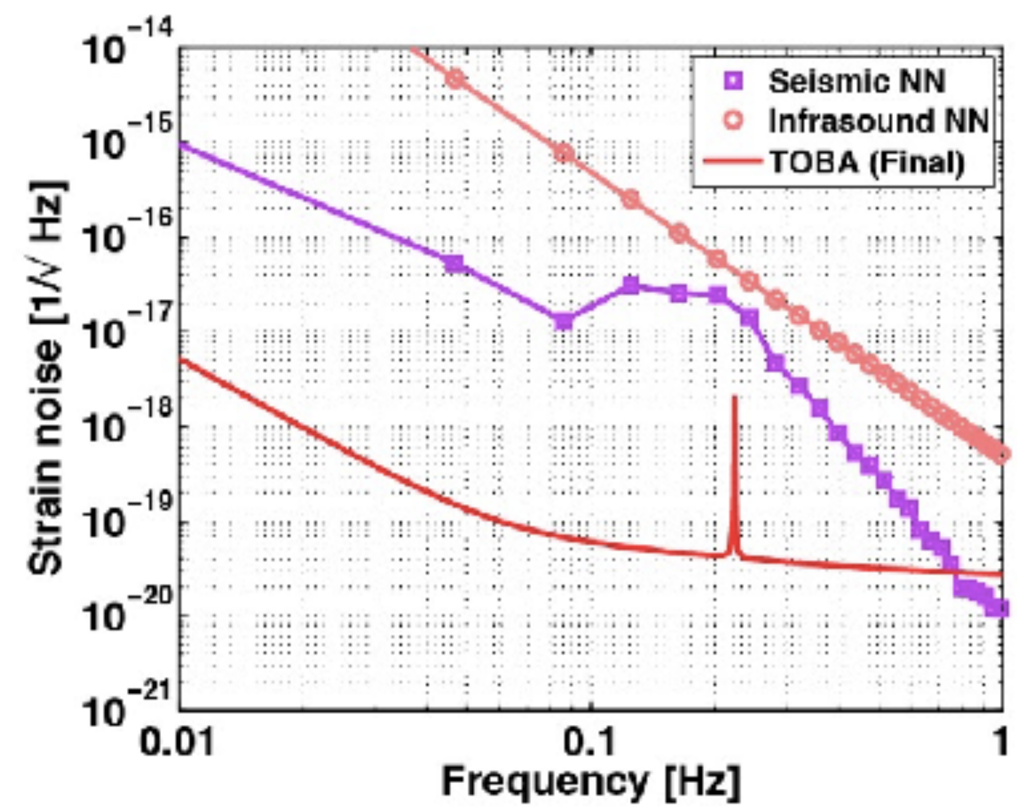


Targets of TOBA

Geophysics

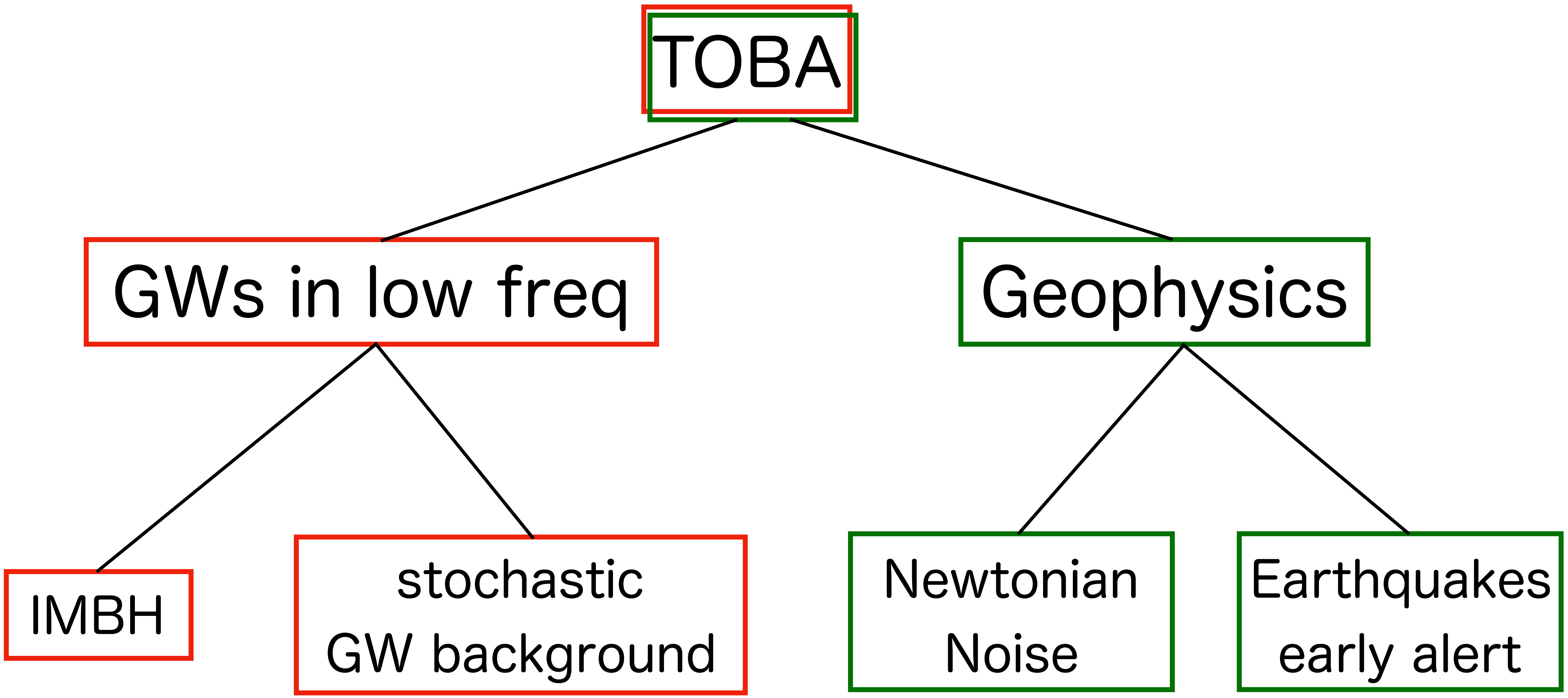
- Newtonian noise
  - density perturbation of the ground and the atmosphere
  - It may limit sensitivity of 3G detectors

J.Harms et al., PRD, 88, 122003(2013)



- Early alert for earthquakes
  - M6.0 earthquakes are detectable in 10sec from 100km away

Targets of TOBA

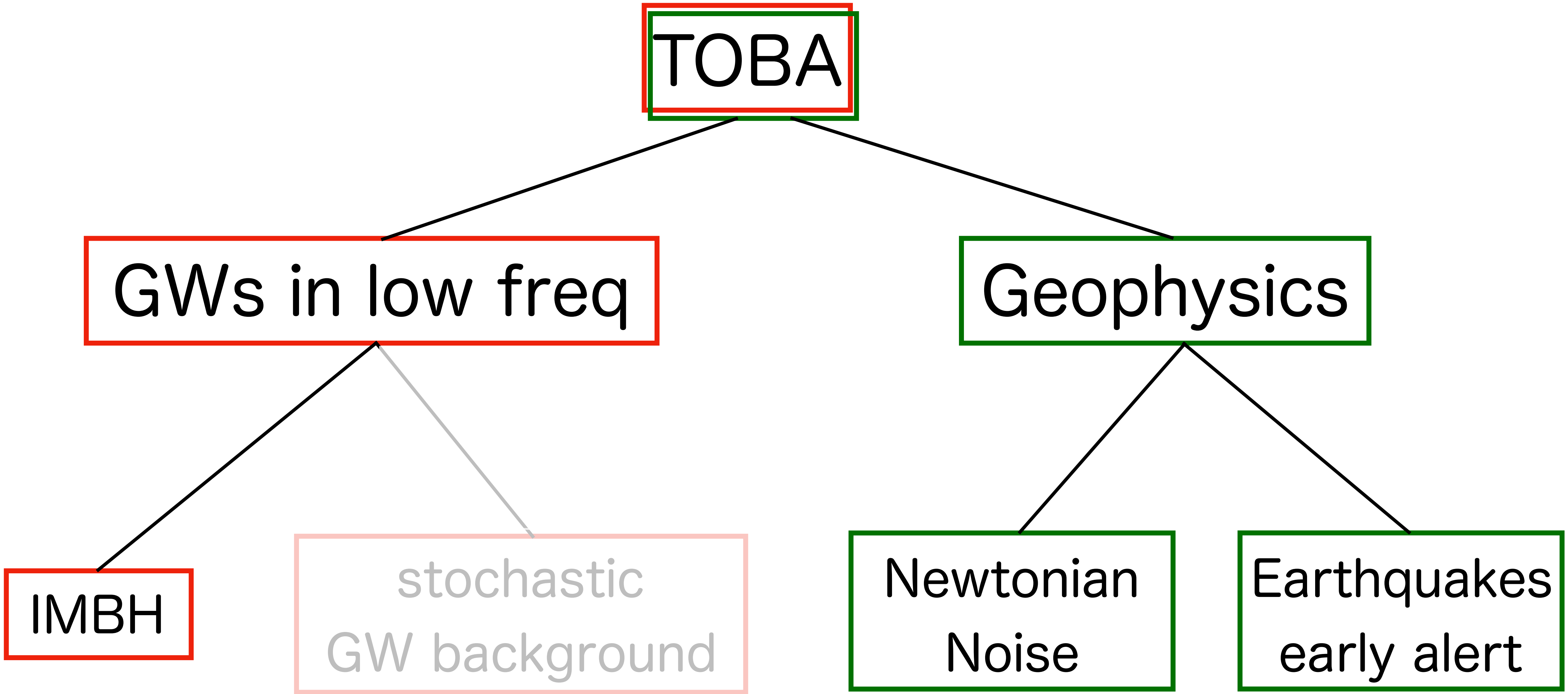


R&D plan

Phase-I	Phase-II	Phase-III	Final
Principle test		Prototype	Goal
• 10^{-8} /√Hz • ~20 cm test mass • room temperature		• 10^{-15} /√Hz • 35 cm test mass • cryogenic (4K)	• 10^{-19} /√Hz • 10 m test mass • cryogenic (4K)

Now: Development for Phase-III TOBA

Targets of Phase-III TOBA

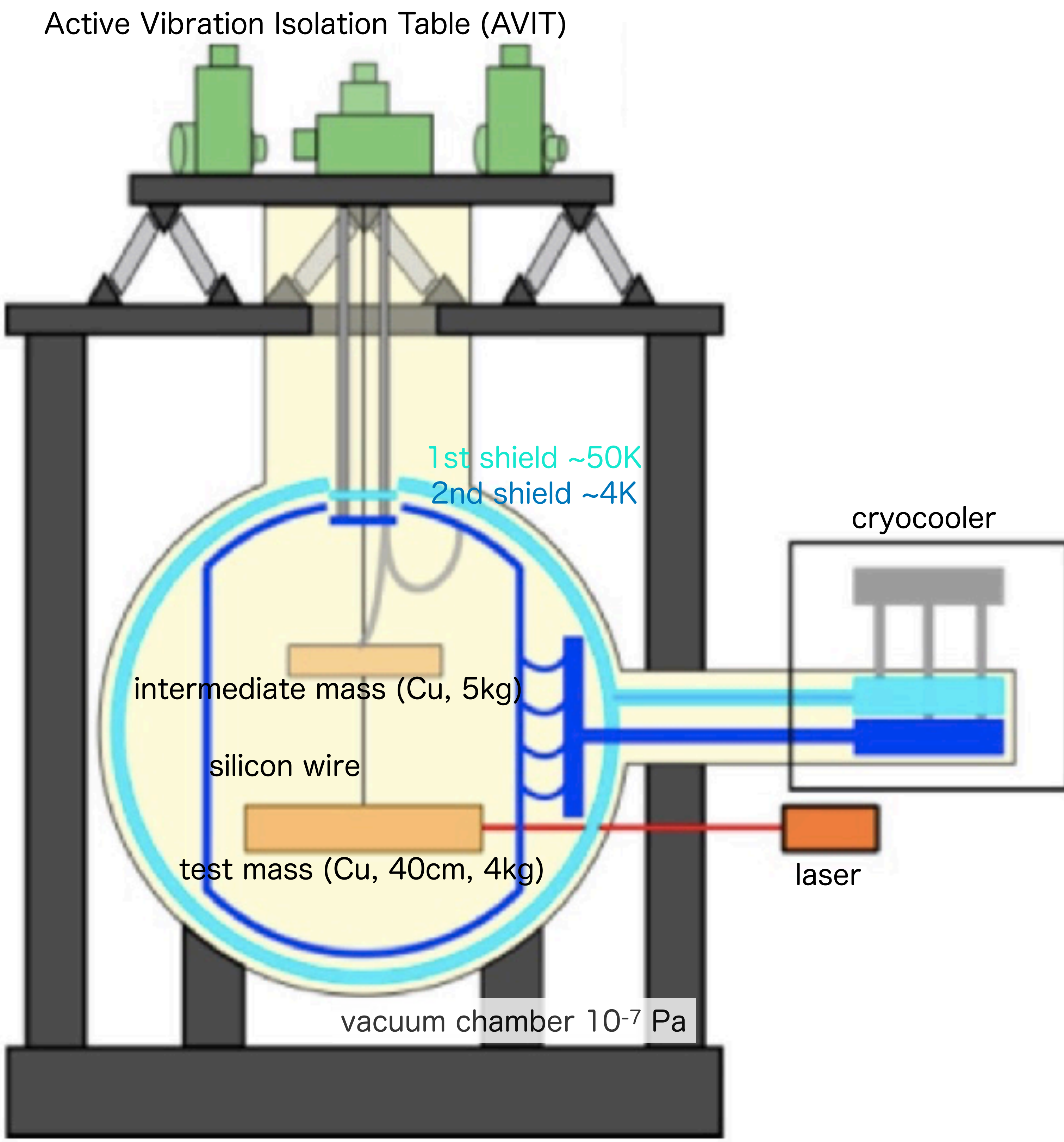


detectable event:
10^5 M_{sun}, 1 Mpc

- model testing
- checking reduction method

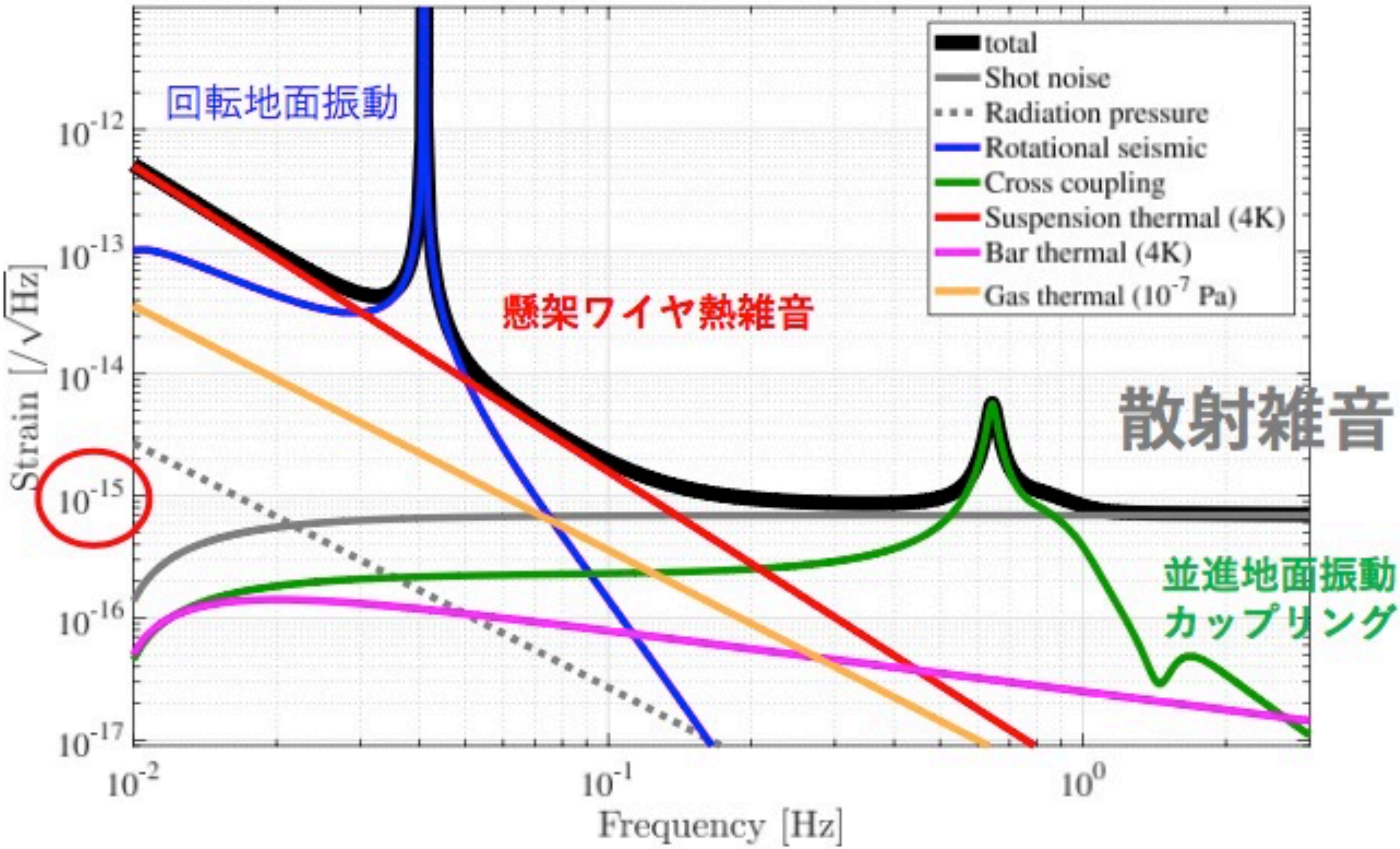
M7.0 earthquakes are detectable in 10sec from 100km away

Setup of Phase-III TOBA

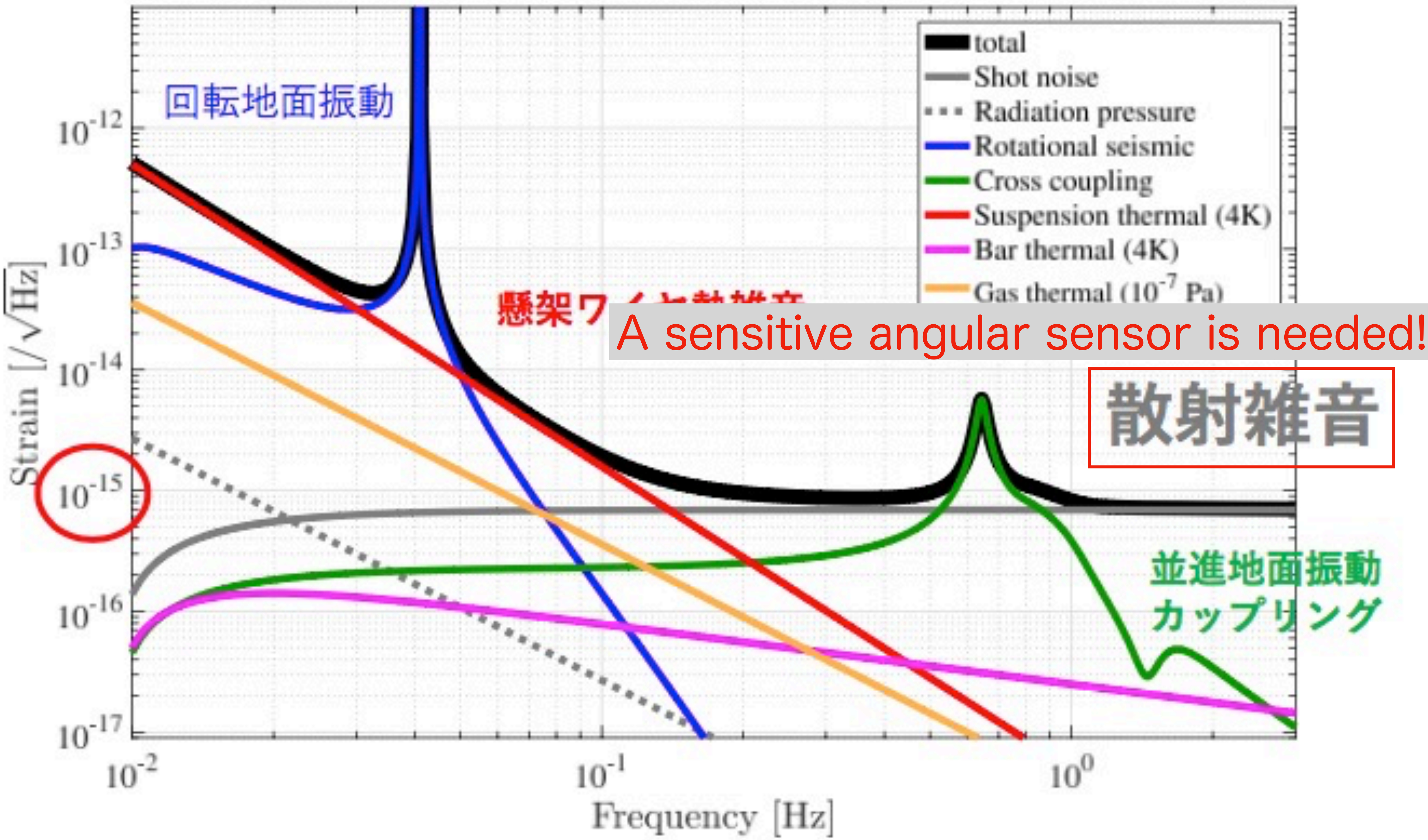


- 40 cm test mass
- cooling to 4K
- active vibration isolation
- new readout system

Design sensitivity

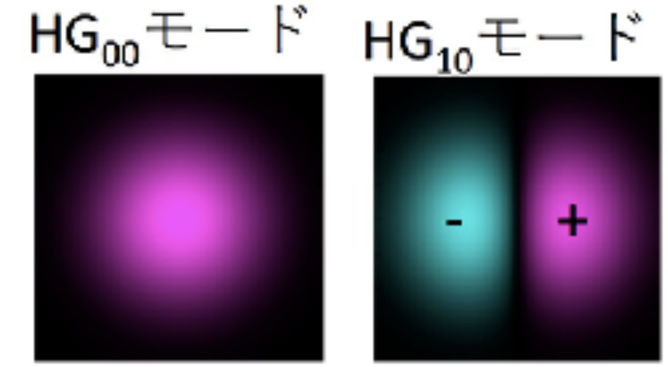


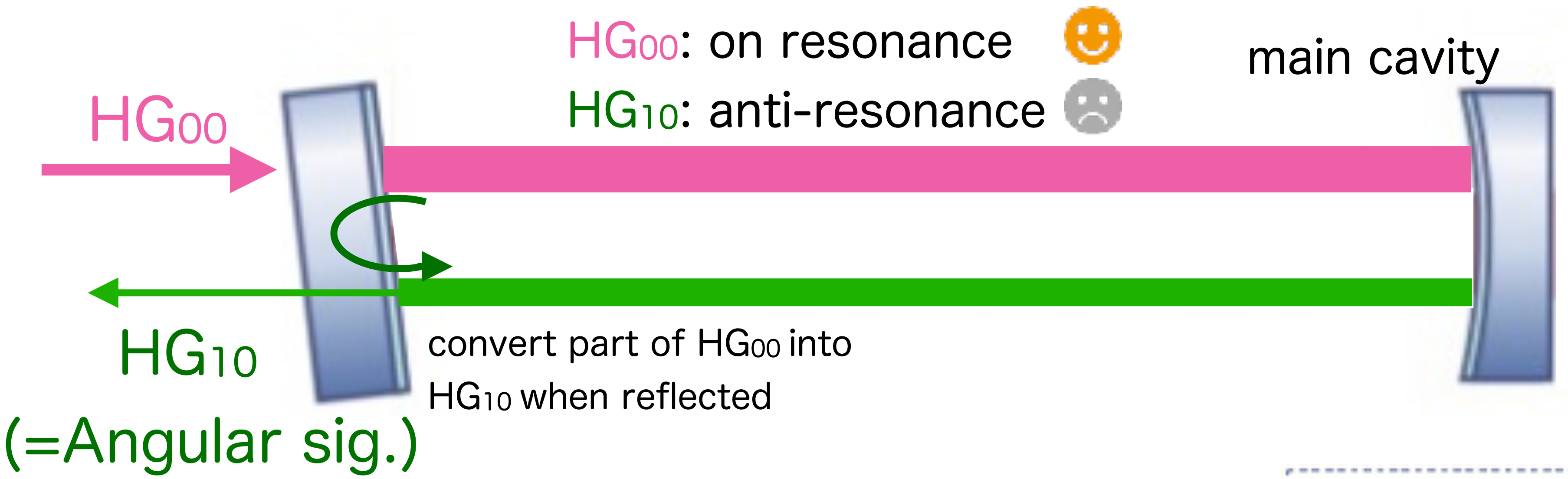
Design sensitivity



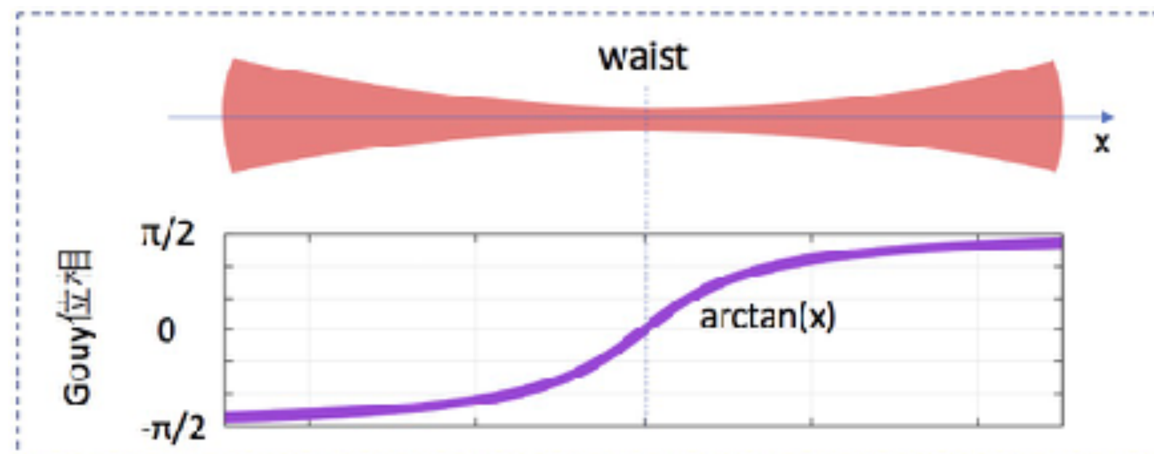
Conventional Wave Front Sensor

Angular sig. = HG_{10} mode created by tilted mirror





The phase HG_{00} and HG_{10} receives in a round trip differs. The phase shift is called Gouy phase.



In an ordinary cavity,
0<(round trip Gouy phase)<2π

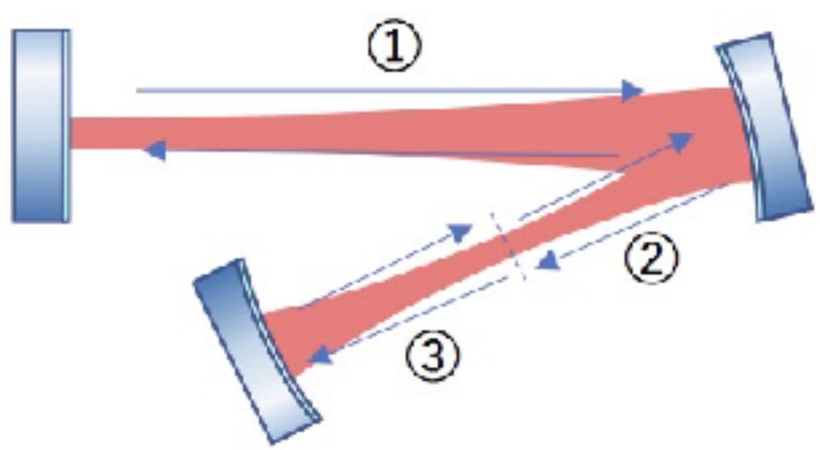
→ conventional one:
HG_{00} and HG_{10} cannot resonate simultaneously

Idea of sensitive sensors

00 and 10 can resonate simultaneously in the below sensors

① folded cavity (demonstration test was done by Shimoda-san)

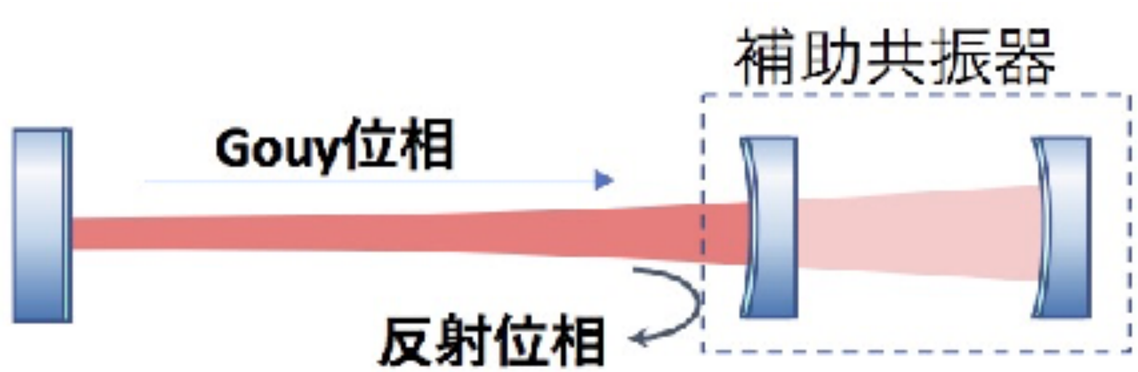
- make round Gouy phase 2π using curved mirrors



round Gouy phase
(①+②+③)×2 = 2π

② coupled cavity

- reflective phase compensates Gouy phase



round Gouy phase
+ reflective phase = 0

Idea of sensitive sensors

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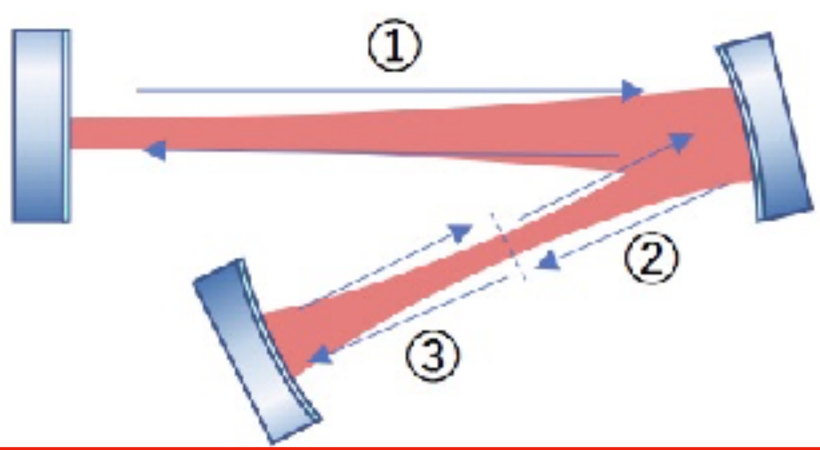

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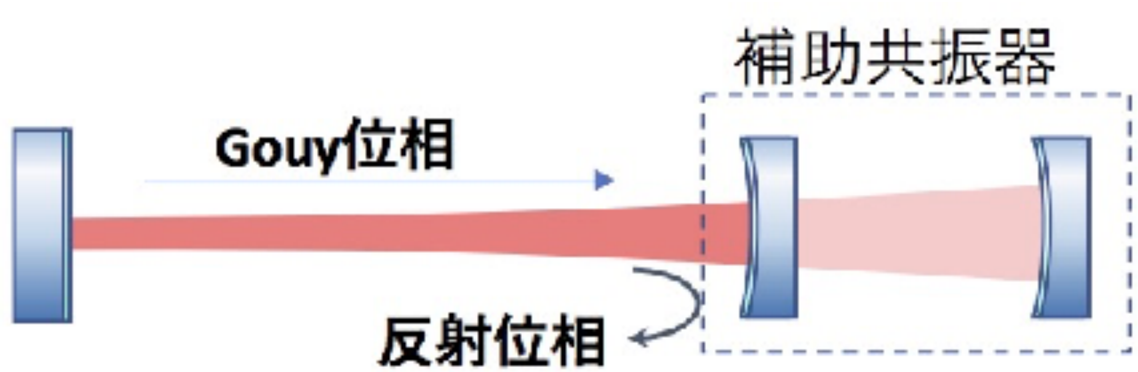
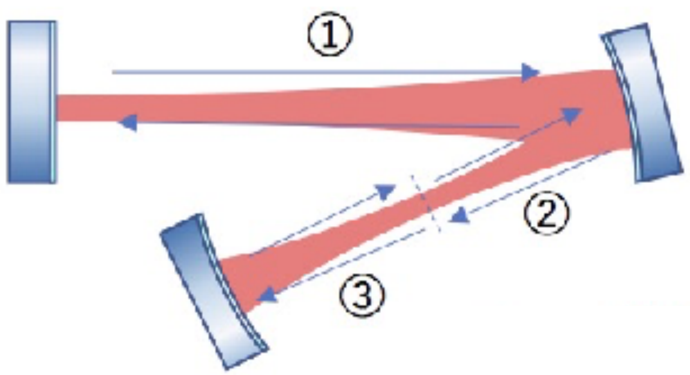


round Gouy phase
\+ reflective phase = 0

Folded cavity

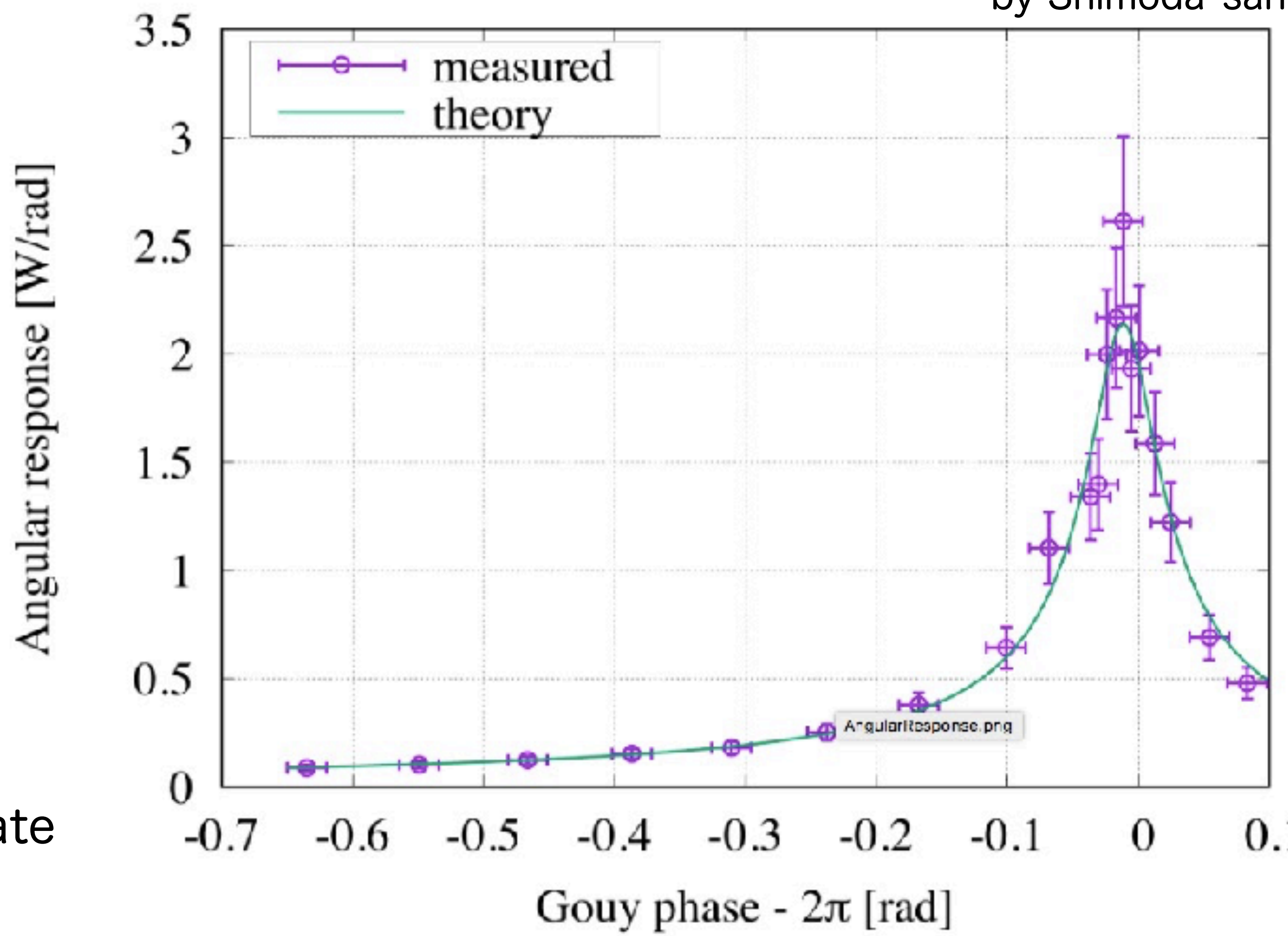
① folded cavity (demonstration test was done by Shimoda-san)

- make round Gouy phase 2π using curved mirrors



round Gouy phase
(①+②+③)×2 = 2π

by Shimoda-san



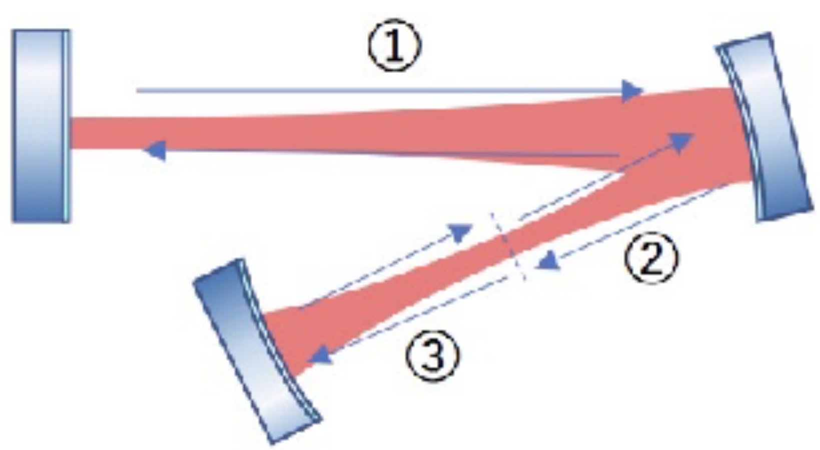
Changing cav length, confirmed the angular signal is amplified when 00 and 10 modes resonate simultaneously.

Idea of sensitive sensors

00 and 10 can resonate simultaneously in the below sensors

① folded cavity (demonstration test was done by Shimoda-san)

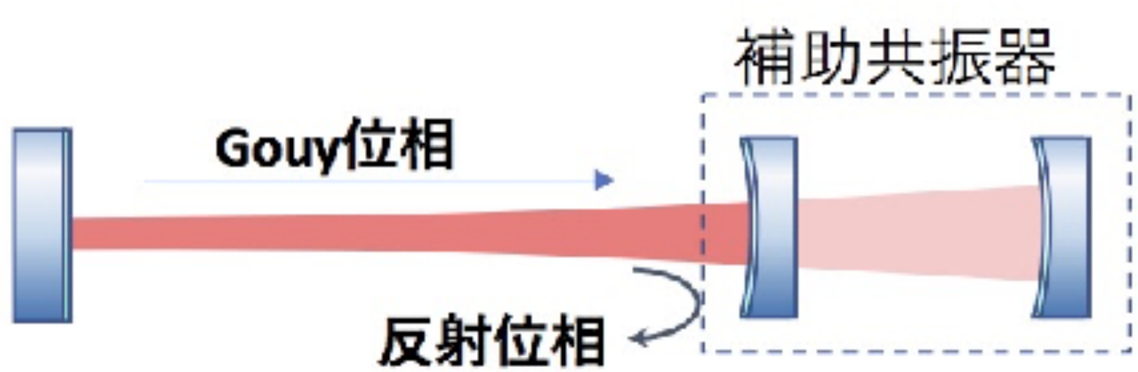
- make round Gouy phase 2π using curved mirrors



round Gouy phase
(①+②+③)×2 = 2π

② coupled cavity

- reflective phase compensates Gouy phase

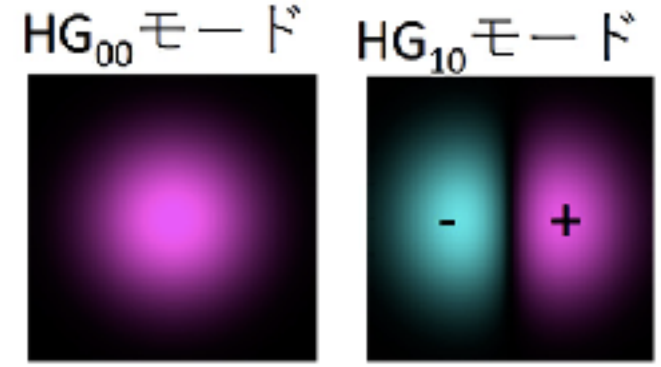


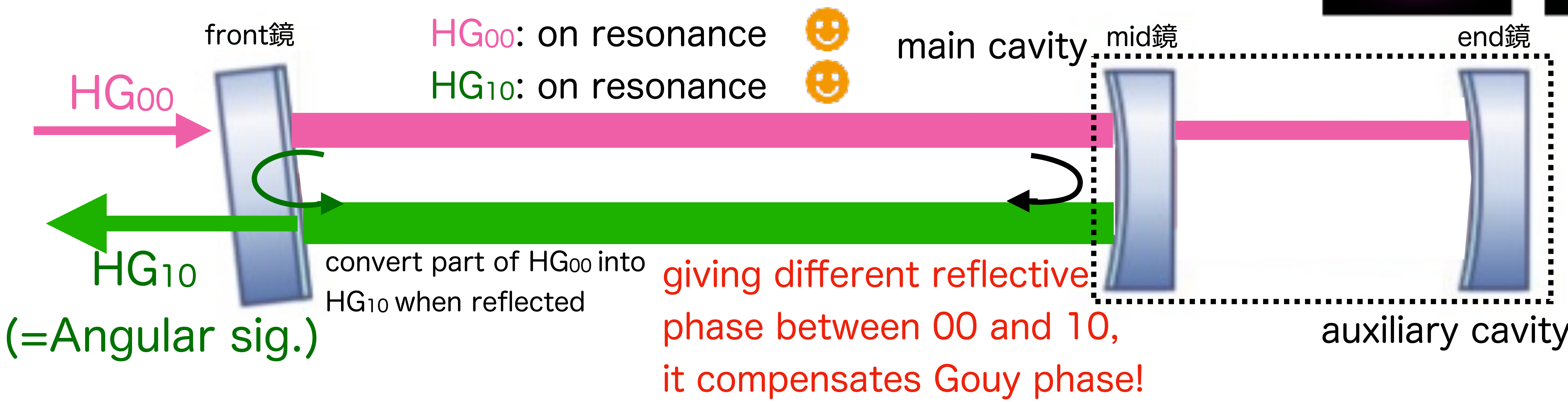
On going

round Gouy phase
+ reflective phase = 0

Coupled Wave Front Sensor

Angular sig. = HG_{10} mode created by tilted mirror





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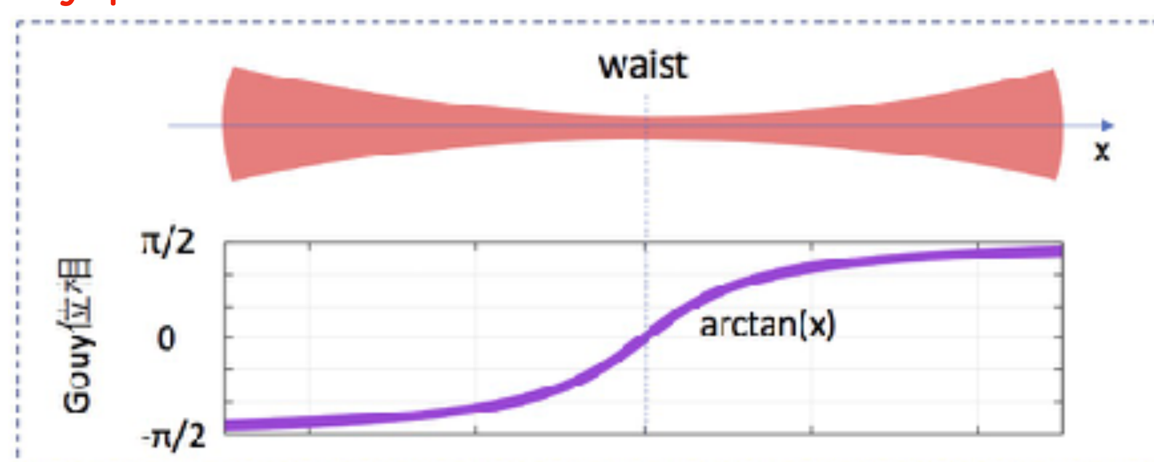


→ improved one:

HG_{00} and HG_{10} CAN resonate simultaneously

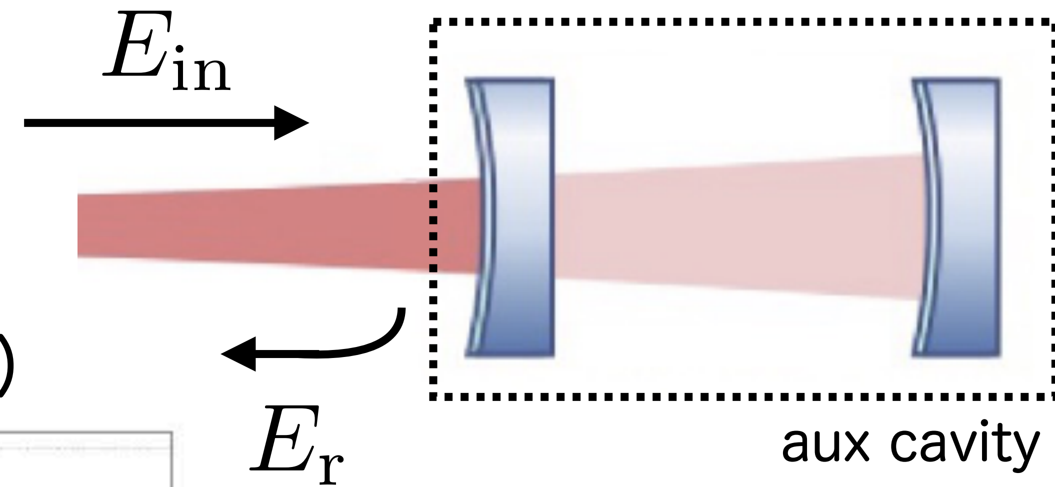
In an ordinary cavity,

0<(round trip Gouy phase)<2π

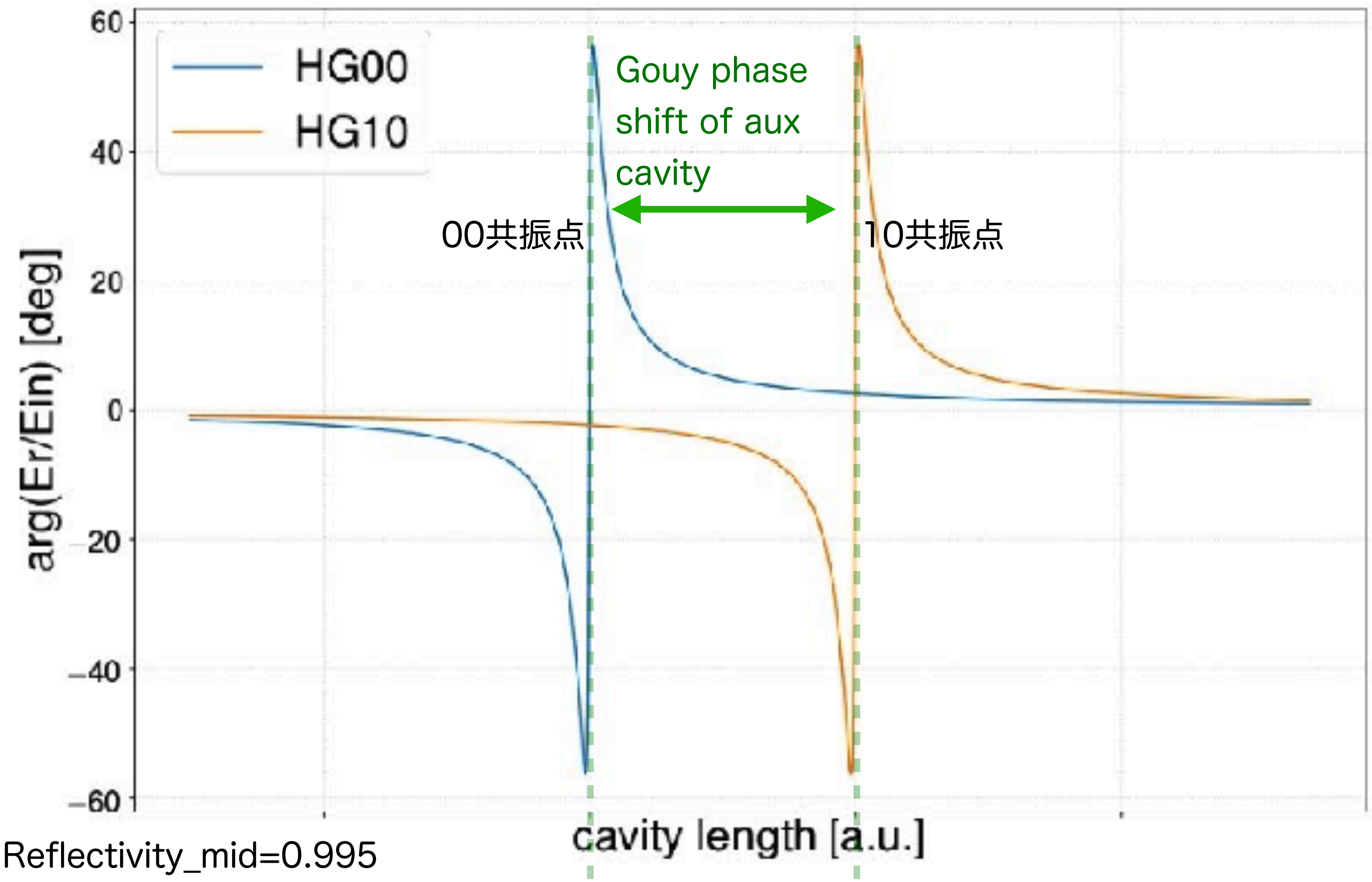
phase compensation by using a cavity

(complex) reflectivity of a cavity

$$= E_{\mathrm{r}}/E_{\mathrm{in}}$$



$\arg(E_{\mathrm{r}}/E_{\mathrm{in}})$ (=reflective phase)



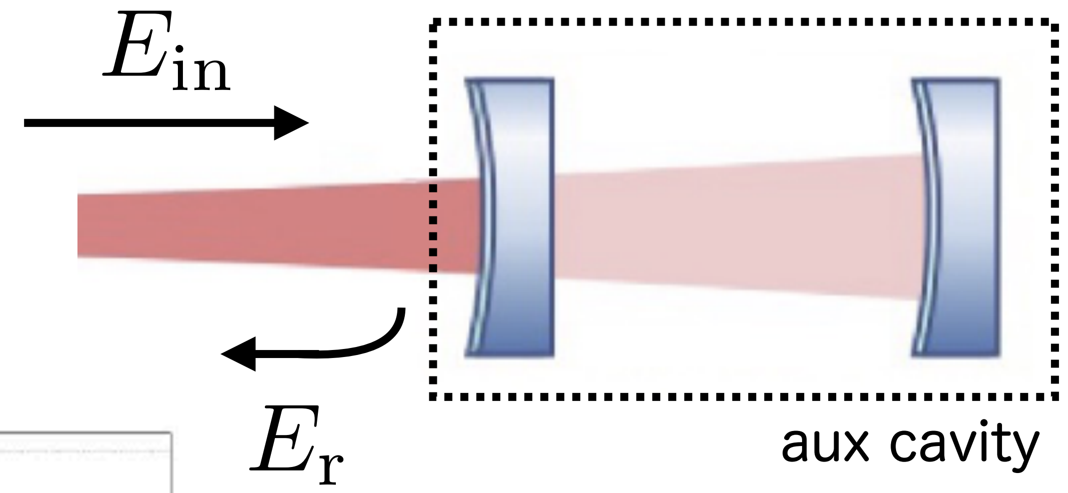
<u>give different reflective phase between HG_{00} and HG_{10} when reflected by the auxiliary cavity</u>

Reflectivity_mid=0.995
Reflectivity_end=0.994
Gouy_main=20deg, Gouy_auxiliary=5.6deg

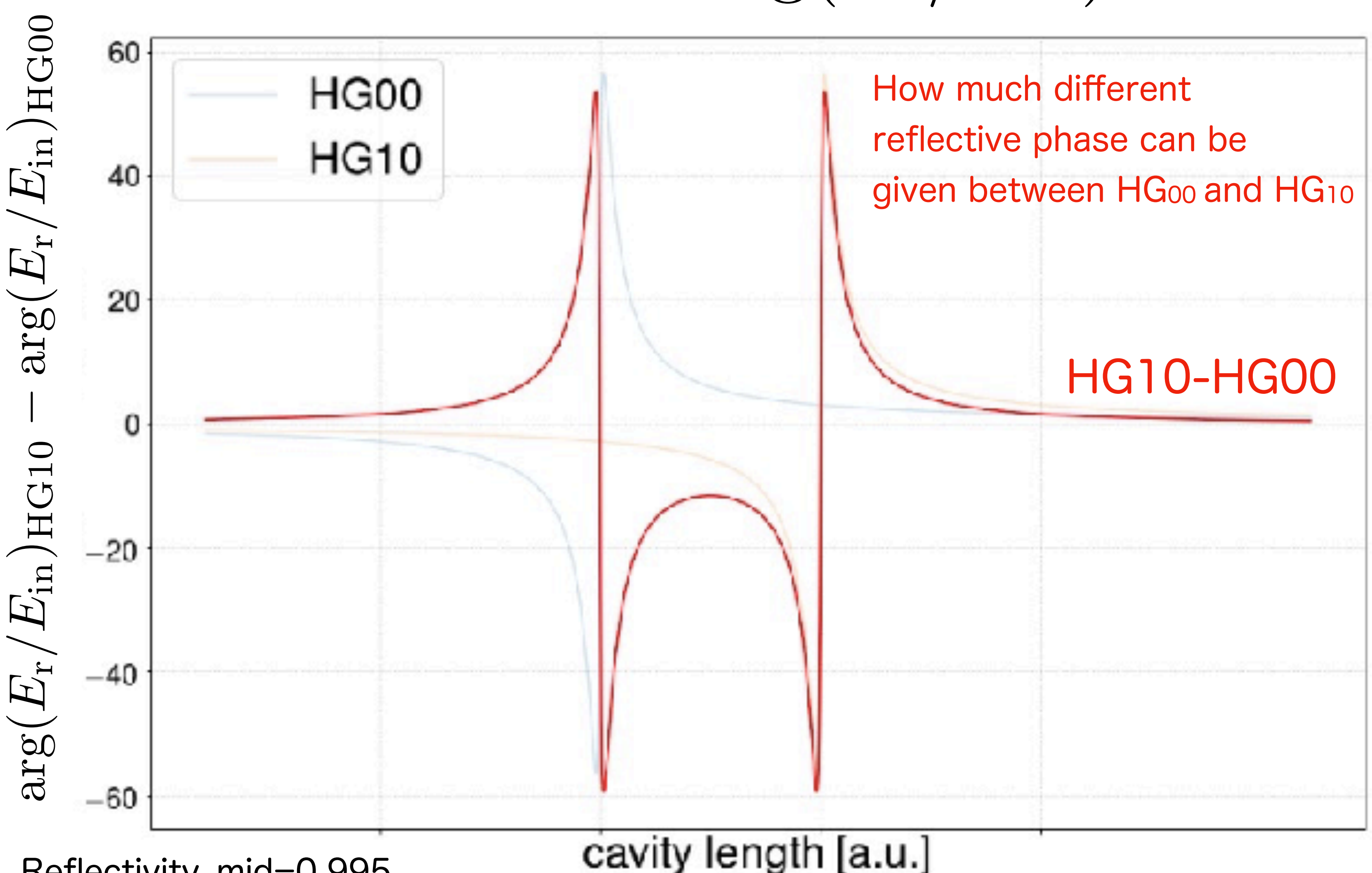
phase compensation by using a cavity

(complex) reflectivity of a cavity

$= E_r / E_{in}$



difference of $\arg(E_r / E_{in})$



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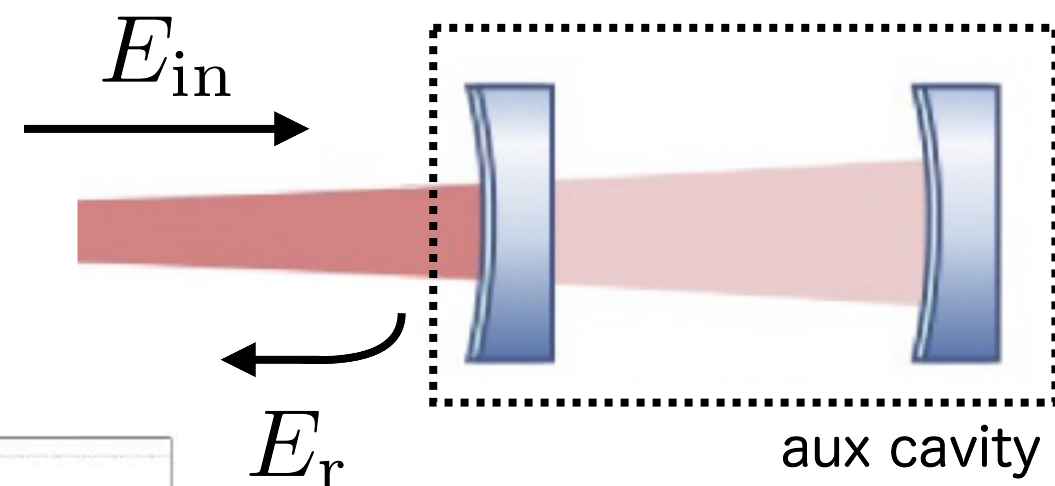

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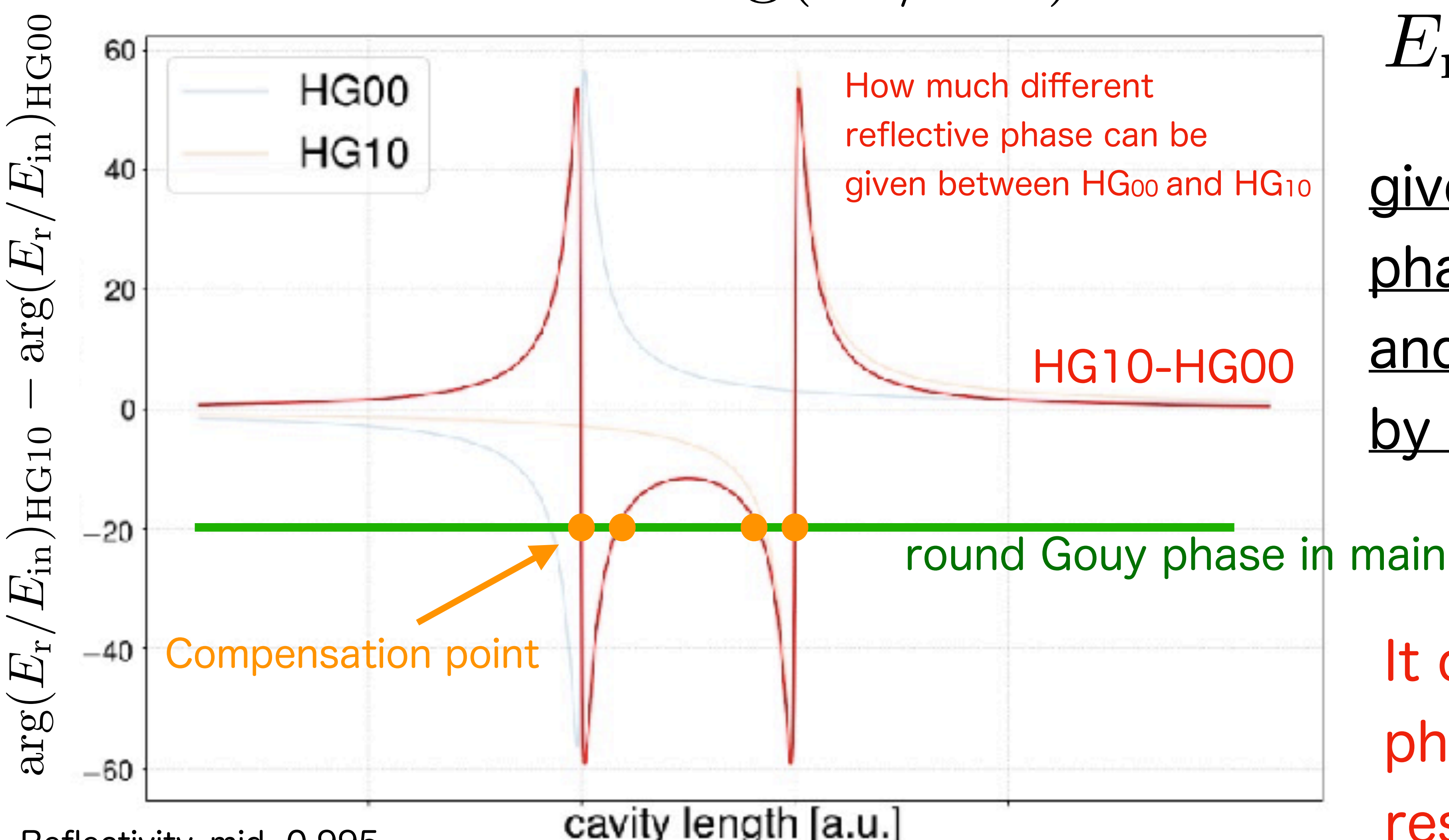


Reflectivity_mid=0.995
Reflectivity_end=0.994
Gouy_main=20deg, Gouy_auxiliary=5.6deg

<u>give different reflective phase between HG_{00} and HG_{10} when reflected by the auxiliary cavity</u>

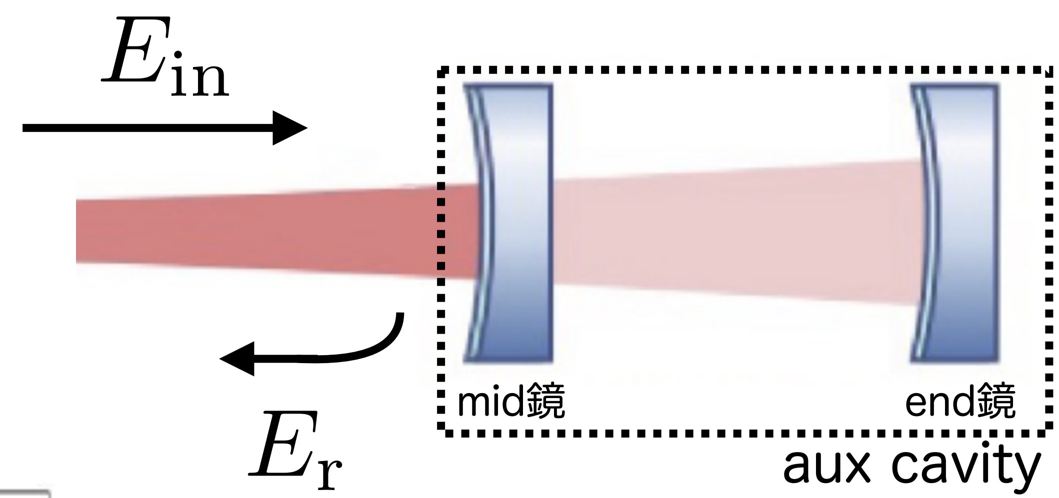
↓

It can compensate Gouy phase shift and HG_{10} can be resonated simultaneously

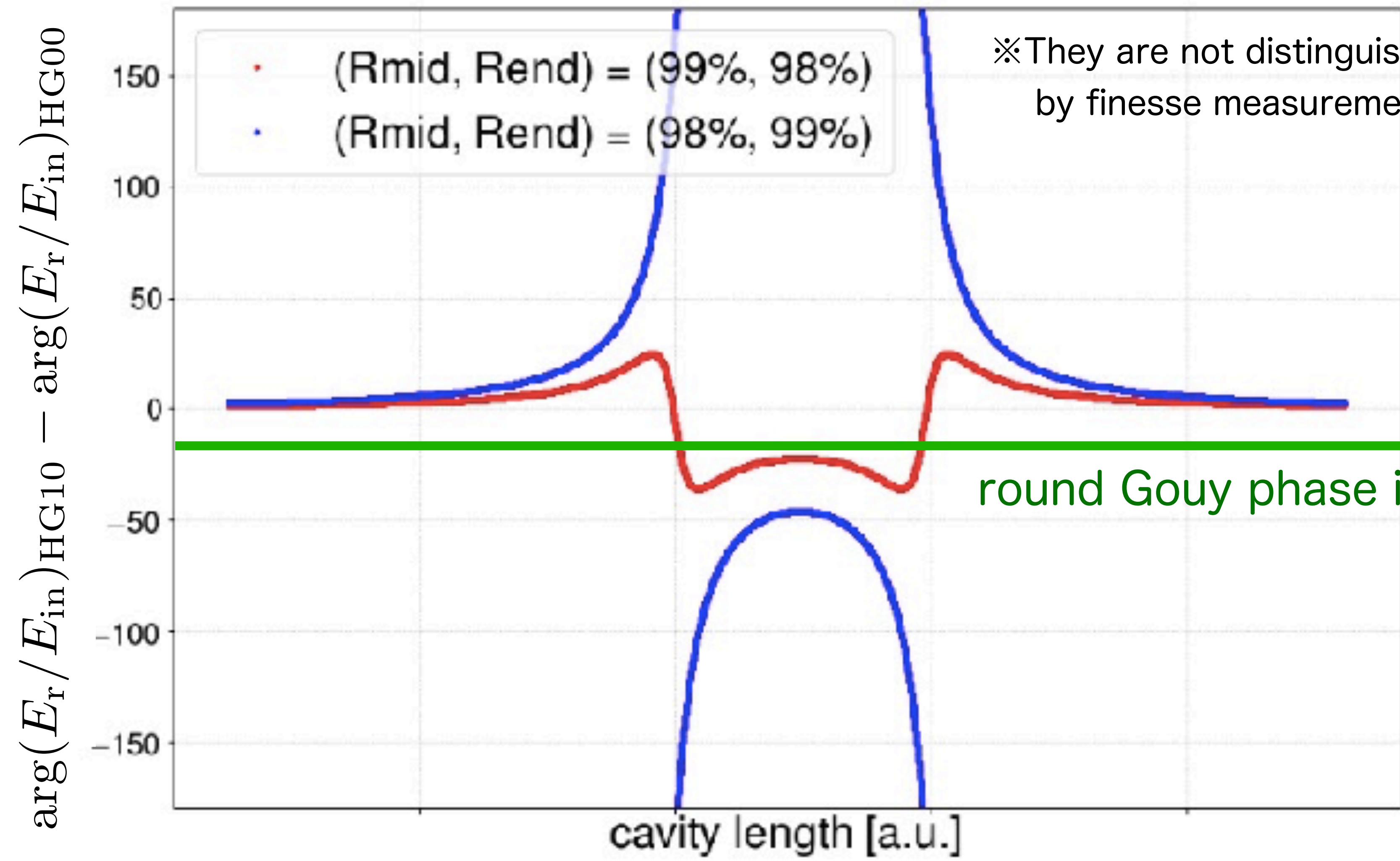
Bad case: cannot compensate Gouy phase

(complex) reflectivity of a cavity

$= E_r / E_{in}$



difference of $\arg(E_r / E_{in})$



※They are not distinguished by finesse measurement

depending on the reflectivity of 2 mirrors which composed of aux cavity, Gouy phase is not compensated.

↓

Angular signal (10mode) is not amplified well

Gouy_main=6.7deg, Gouy_auxiliary=5.6deg

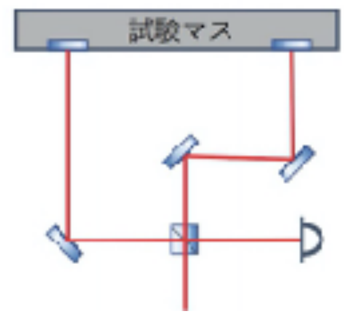
Contents

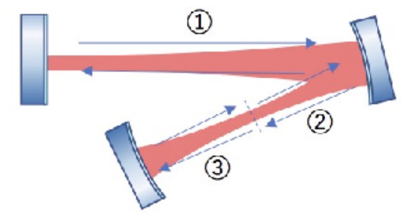
- about TOBA
- coupled wave front sensor
  - merits and demerits　(overview)
- What is done so far

- What I want to study with the coupled WFS (For M Thesis)
  - demonstration test (confirm its principle)
  - check its characteristics
  - obtain good sensitivity

- Summary

merits and demerits





	Michelson interferometer	folded WFS	coupled WFS
shot noise	🙂 30cm bar	🙂 1mm beam, finesse 300	
frequency noise	☹️	🙂	🙂
trans-coupling	☹️	🙂	🙂
thermal noise	🙂	☹️	☹️
linear range	☹️	🙂	🙂
beam jitter	😐 ?	🙂 → 😐 ?	🙂 → 😐 ?
shrink in cryo	🙂	☹️	🙂
control/operation	🙂	🙂	☹️

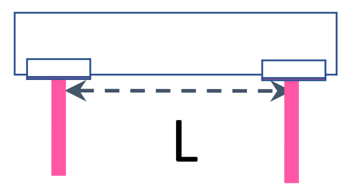
I will talk this issue later

low shot noise

- ⇔ high angular response (almost same as MI)

Michelson(P_{in}:input power, L:bar length)

$$\sim\ P_{in}\frac{L}{\lambda}\ \ [\mathrm{W/rad}]$$



new WFS(w:beam radius, F:finesse)

$$\sim\ P_{in}\frac{w}{\lambda}F\ \ [\mathrm{W/rad}]$$

new WFS with 1mm beam
& finesse 300
⇔ MI with 30cm bar

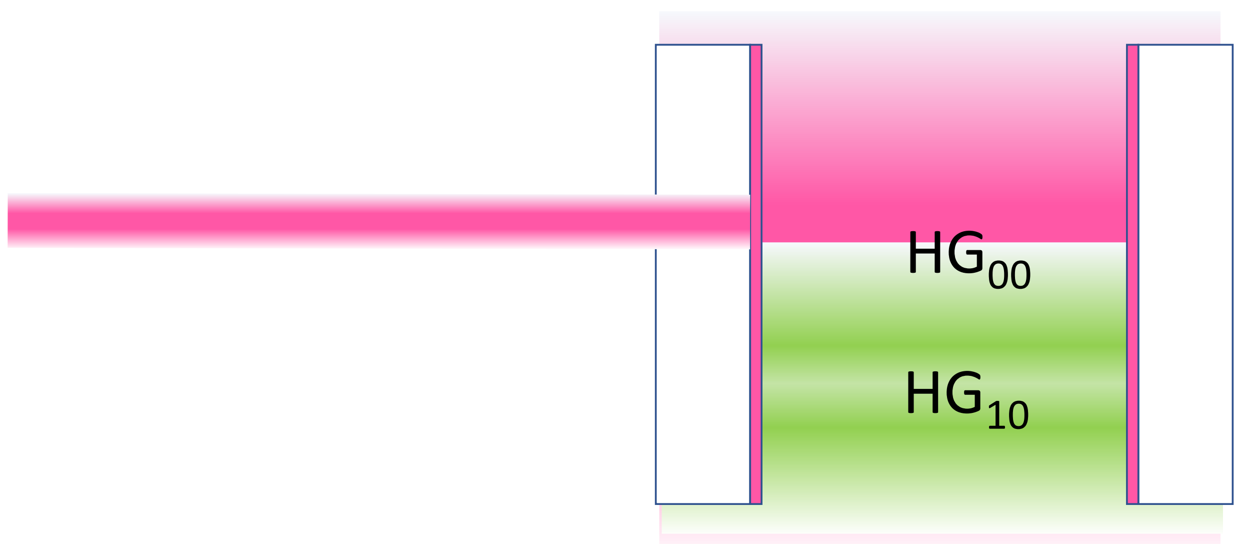
- same as MI shot noise level

～ 10^{-15} rad/rtHz

(from Shimoda-san's slides)

no(low) frequency noise ☺

- no frequency noise in wave front sensor



- (spatial nonuniformity of frequency fluctuation can be noise ...?)

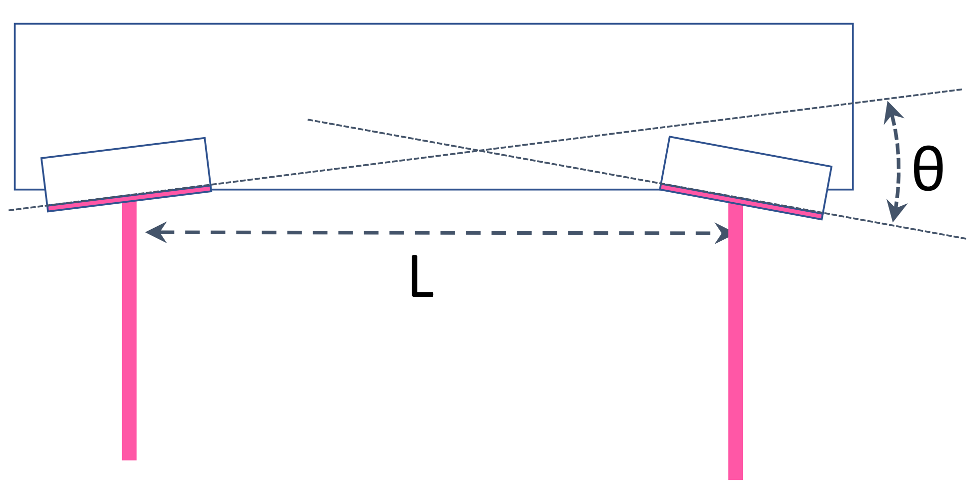
(from Shimoda-san's slides)

small trans-coupling(?)

than Michelson interferometers

- making flatness is easier in smaller scale
- especially this is good point for large bars (L>50cm) which are difficult to make flatness between both ends

Michelson interferometer



~ bar size (~m)

WFS

~ beam size (~mm)

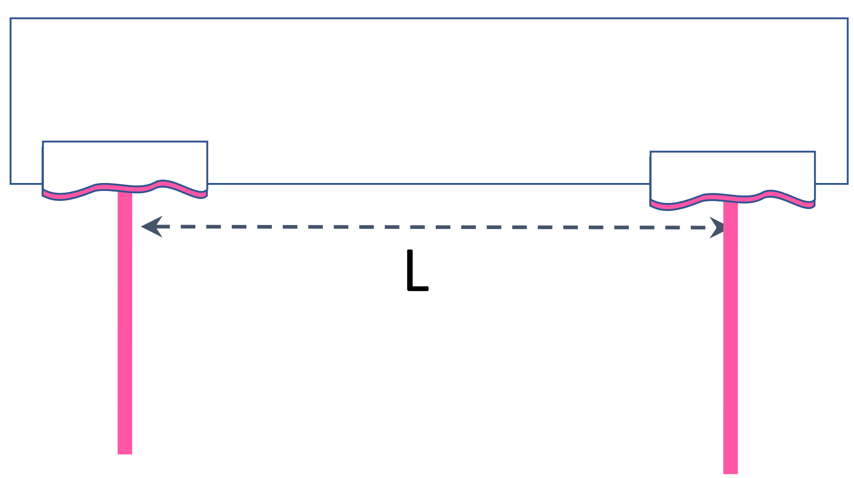
(from Shimoda-san's slides)

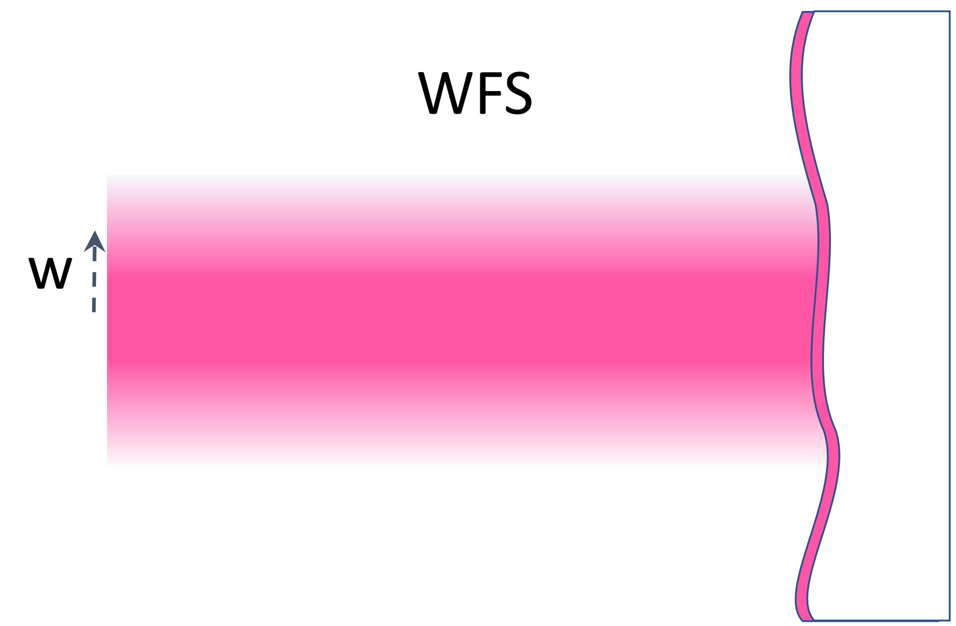
higher thermal brownian

than Michelson interferometers

- higher by (bar length) / (beam diameter)

Michelson interferometer





noise ~ (fluctuation) / L

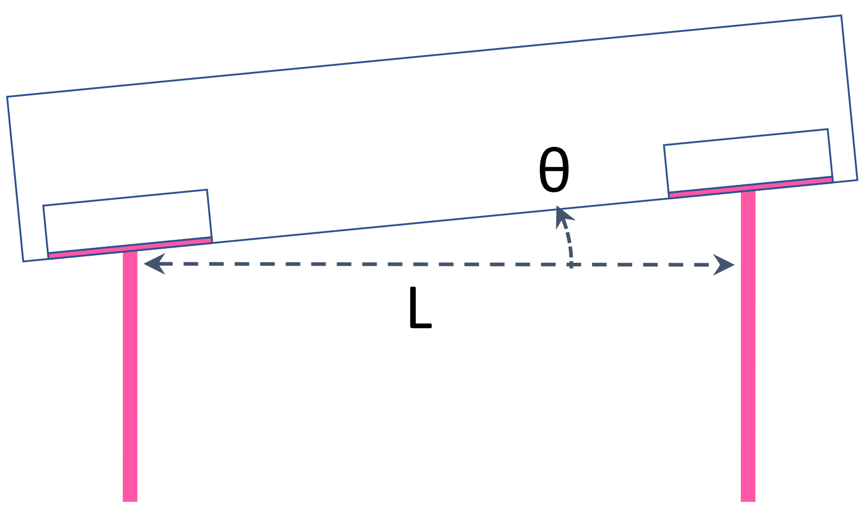
noise ~ (fluctuation) / w

(from Shimoda-san's slides)

large linear range

than Michelson interferometers

- roughly larger by (bar length) / (beam diamerer)



$\theta < \lambda/L \sim$ 1urad

$\theta < \lambda/w \sim$ 0.1mrad

- less(no) angular control is required ⇔ less(no) actuator noise
- (practically, range of PD should be considered)

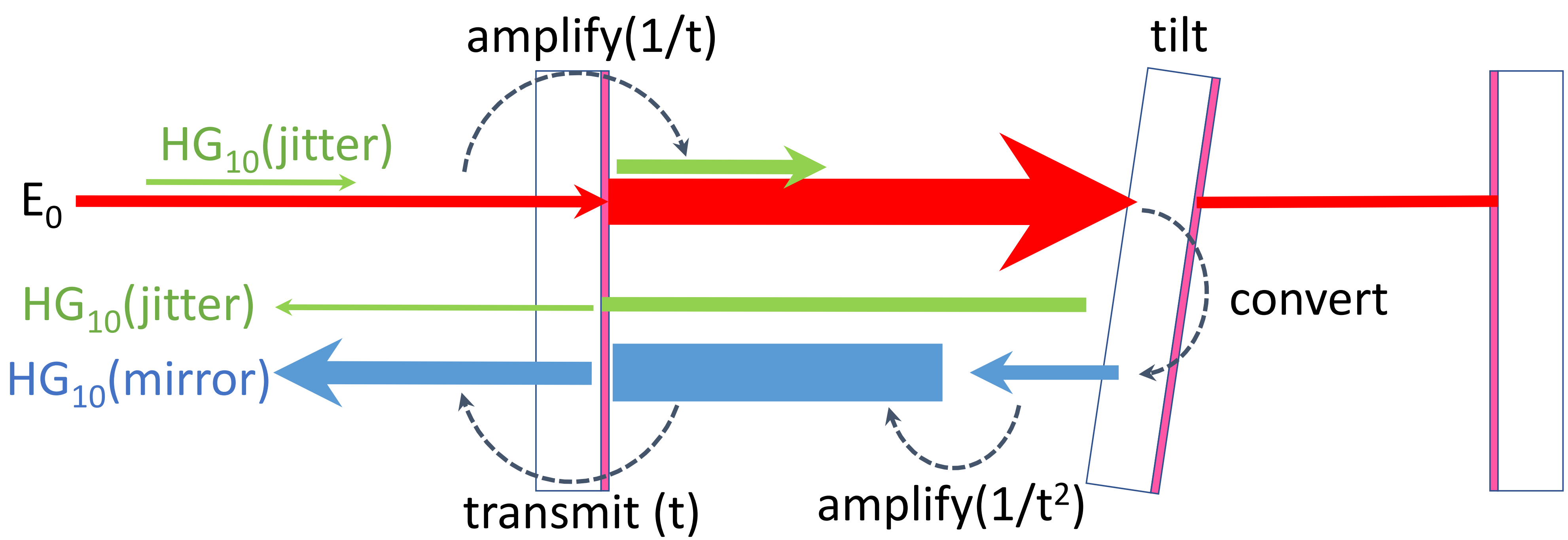
(from Shimoda-san's slides)

low beam jitter noise

than conventional WFSs

☺

- suppressed by finesse of 00 mode



beam jitter θ_{jitter} : generate HG_{10} outside the cavity

$\Rightarrow E_{10,jitter} = E_0 \times \theta_{jitter} \times 1/t \times t$

(amplify) (transmit)

cavity mirror tilt θ_{mir} : generate HG_{10} inside the cavity

$\Rightarrow E_{10,mirror} = E_0 \times 1/t \times \theta_{mir} \times 1/t^2 \times t$

(amplify) (amplify) (transmit)

$E_{10,jitter} \sim t^2 \times E_{10,mirror}$

$(\sim E_{10,mirror} / F)$

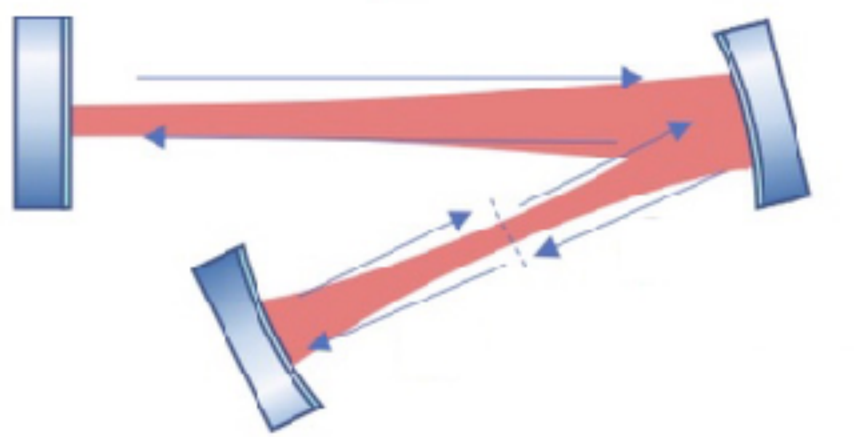
(from Shimoda-san's slides)

shrink in cryogenic

When putting the WFS into a cryogenic, the system may shrink. (I don't know how much)

→ initial adjustment in cryogenic is needed

folded cavity



- need to adjust the cavity length about Rayleigh range (~ 1m)

coupled cavity

- need to adjust the cavity length about wave length (~ 1um)

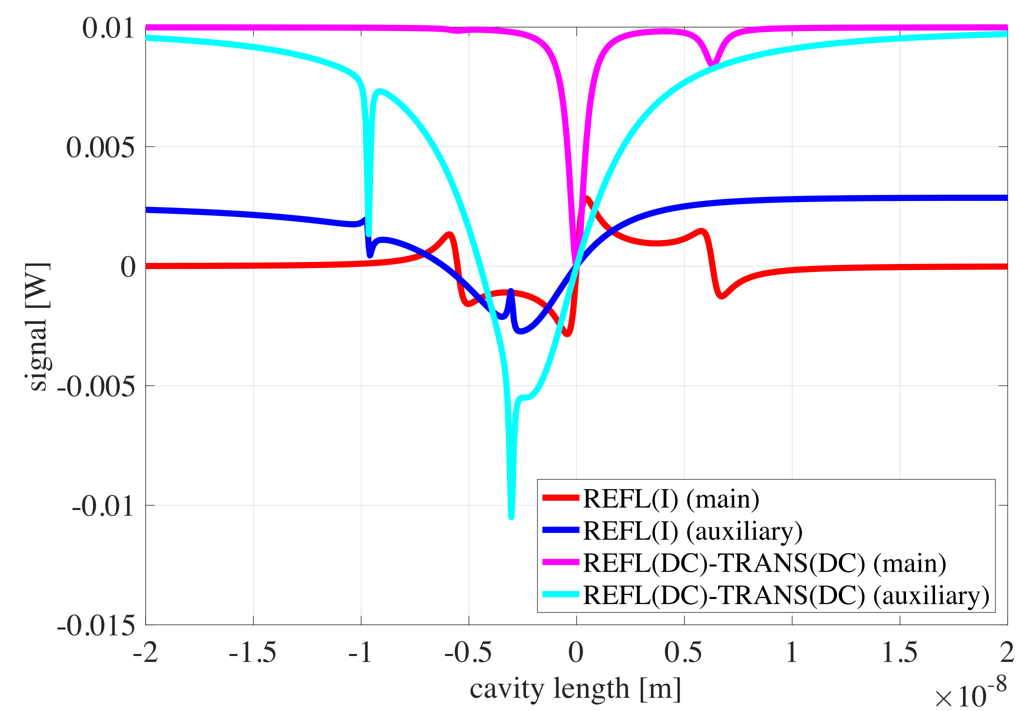
difficulty of control/operation ☹

signal separation

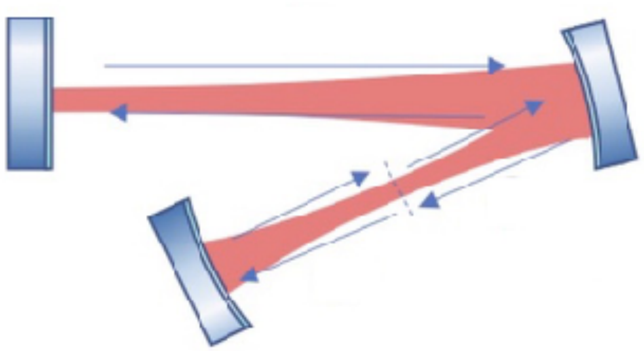
- control of 2 DoF is much difficult

- not bad

(R_{front} = 99% ,
R_{mid} = 99.95% ,
R_{end} = 99.9%)



On the other hand,

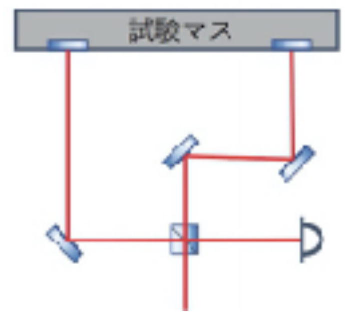


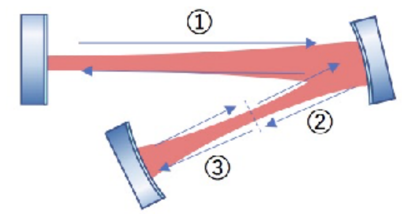
- folded cavity has only 1 DoF.

sensing matrix	main cavity	auxiliary cavity
PDH signal (refl)	1 —	0.09 —
DC signal (refl-trans)	0 —	1 —

(from Shimoda-san's slides)

merits and demerits





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thermal noise	😊	☹	☹
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control/operation	😊	😊	☹

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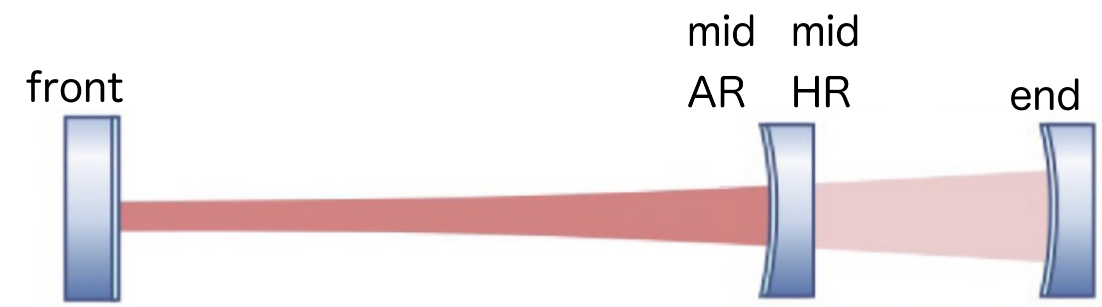
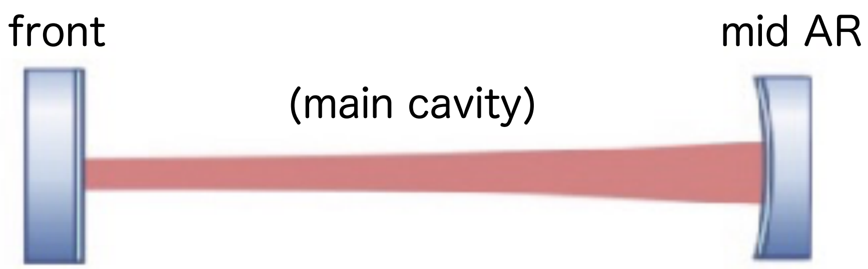
reflectivity measurement

reflective phase and finesse are important

→ reflectivity is to be measured value

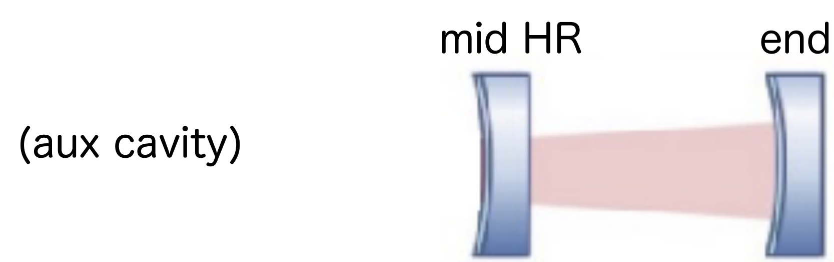
there are 4 reflectivity





finesse

506 +/- 68
(503)

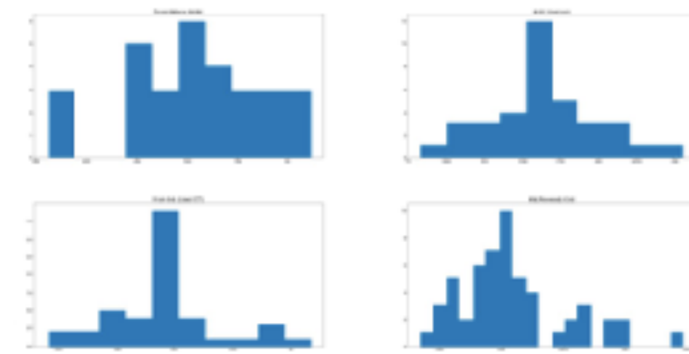


1625 +/- 346
(4189)

481 +/- 94
(571)

2177 +/- 875
(1795)

histogram of measured finesse



(see log p=2303)

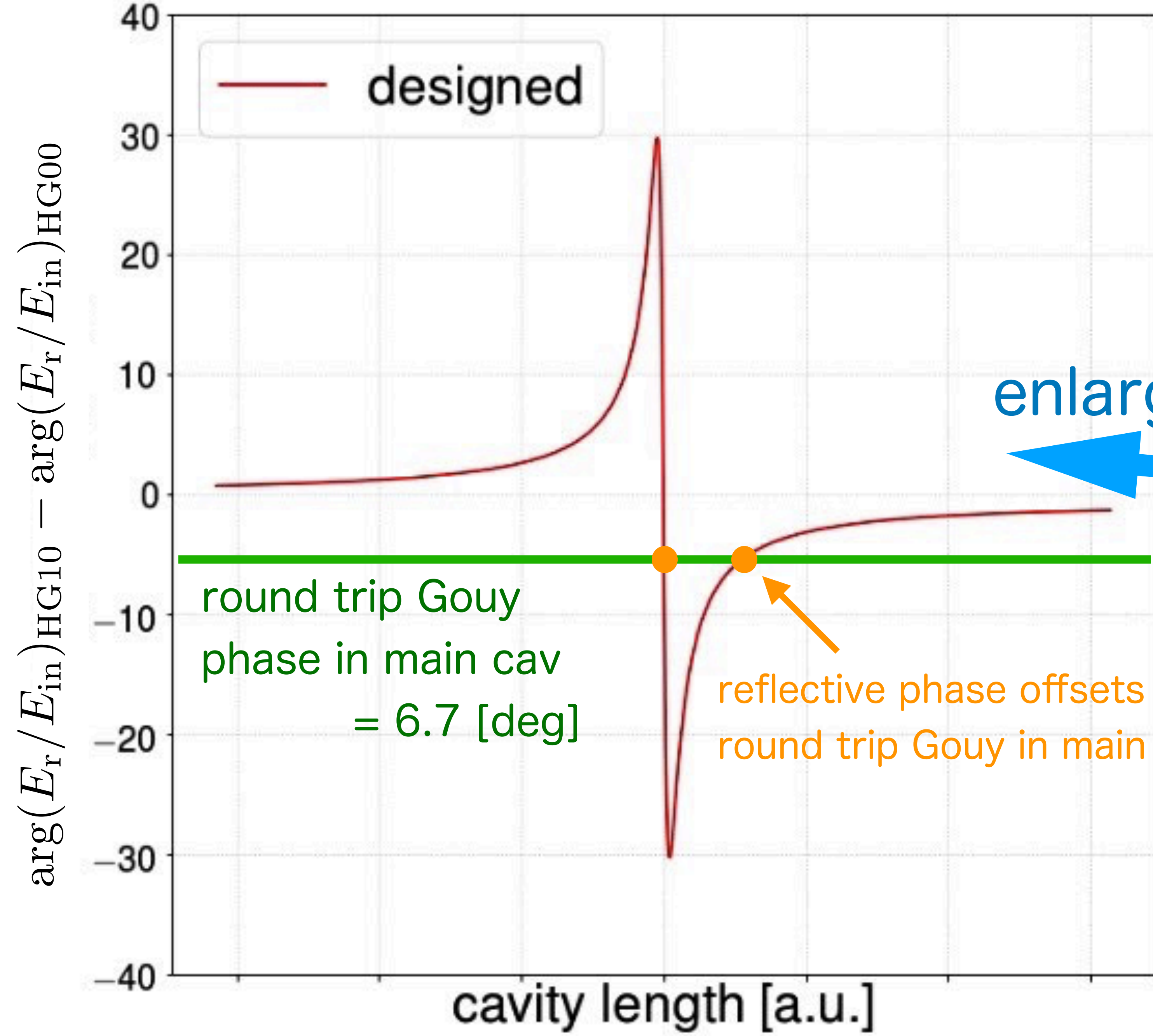
Results:

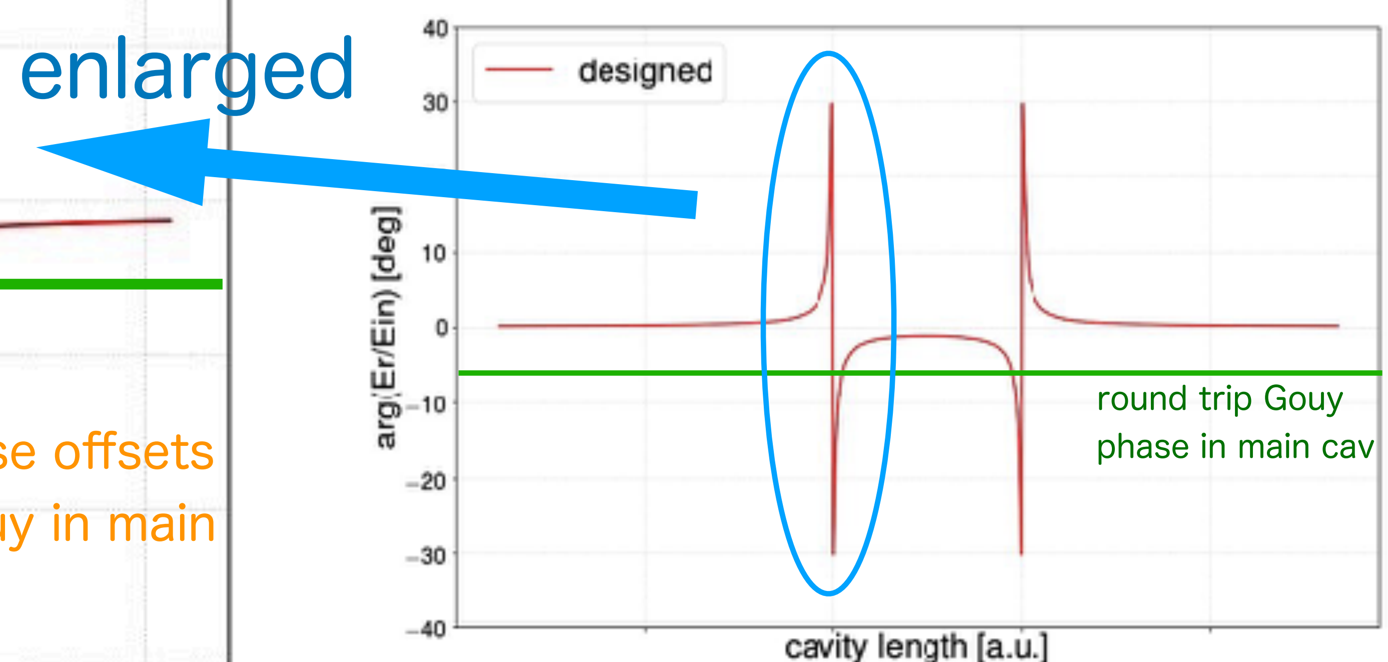
R_front = 98.87 +/- 0.16 % (99%)
R_end = 99.82 +/- 0.16 % (99.9%)
R_midAR = 99.88 +/- 0.16 % (99.75%)
R_midHR = 99.79 +/- 0.18 % (99.95%)
ARloss = -0.09 +/- 0.31 %

statistical error is big

reflectivity measurement

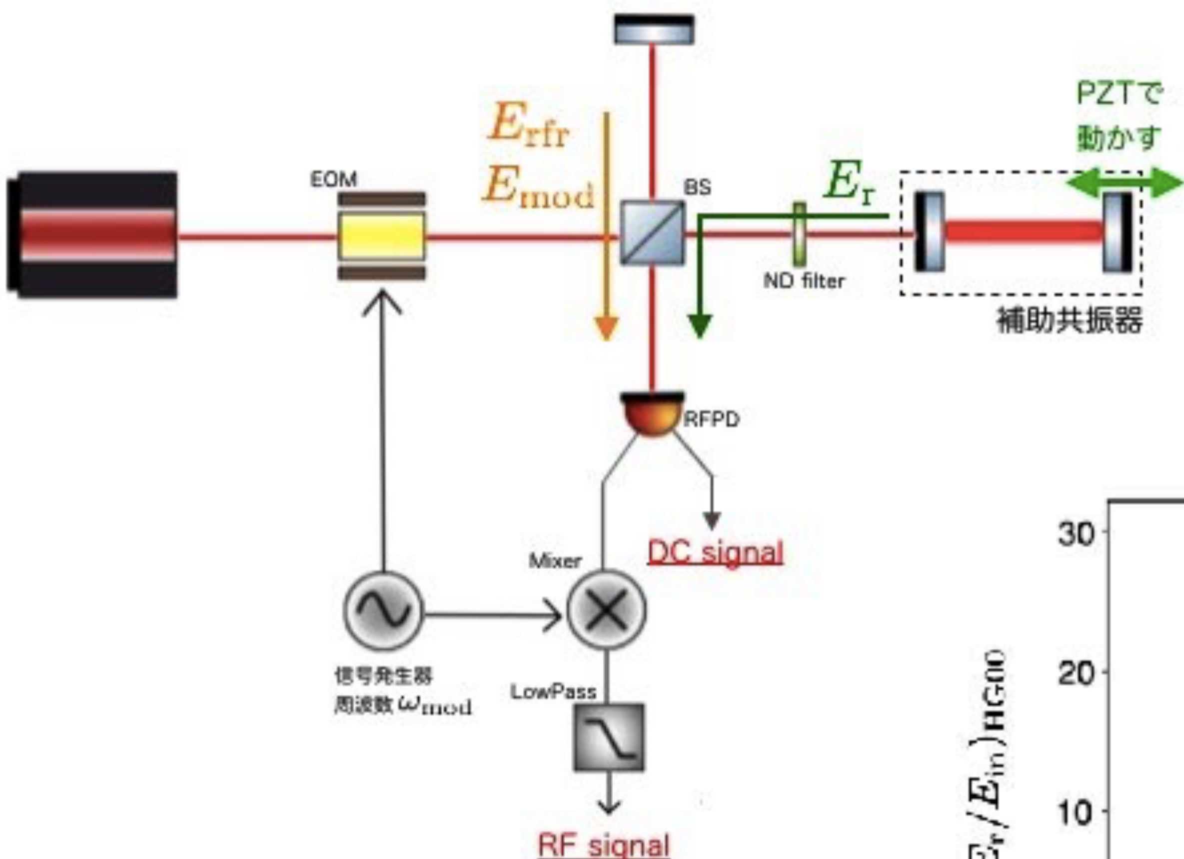
Designed reflectivity:

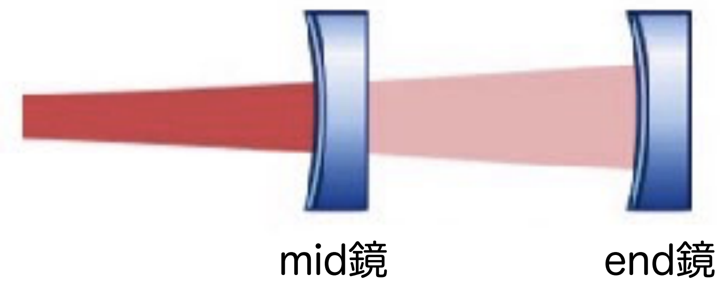




Reflectivity_front=0.99
Reflectivity_mid=0.9995
Reflectivity_end=0.999
Gouy_main=6.7deg, Gouy_auxiliary=5.6deg

reflectivity measurement





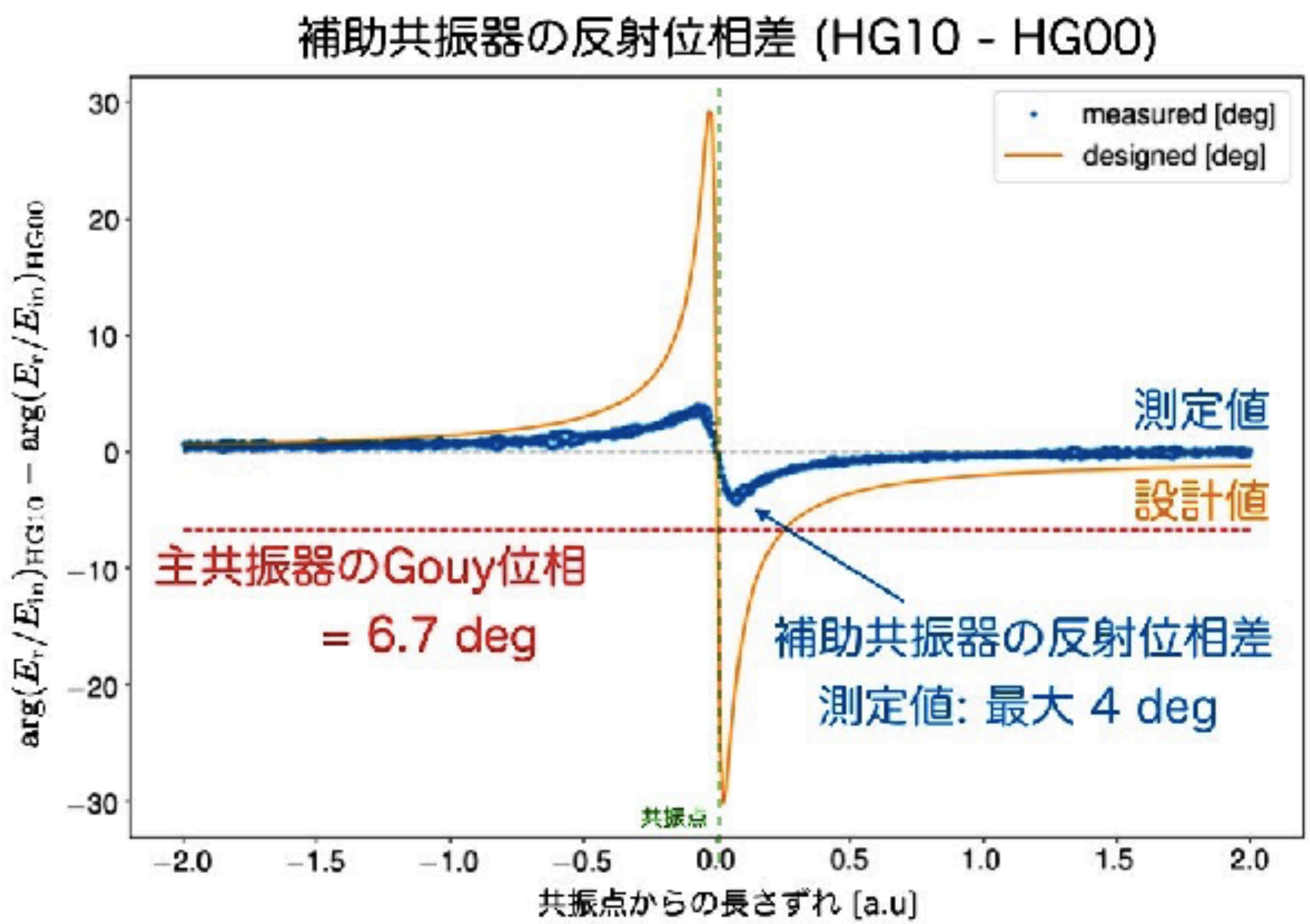
$$R_{mid} = 99.97(2)\%$$

$$R_{end} = 99.5(2)\%$$ 小

The result is consistent with finesse measurement

$$2 - (R_{mid} + R_{end}) = 0.39(8)\%$$

(design: 0.15%)



Contents

- about TOBA
- coupled wave front sensor
  - merits and demerits
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  - demonstration test (confirm its principle)
  - check its characteristics
  - obtain good sensitivity

- Summary

Future Plans

- demonstration test (confirm its principle)
  - confirm the amplification of angular signal
  - compare with theoretical one
  - check its characteristics
    - frequency noise
    - beam jitter

- construct a new (semi-monolithic) system
  - trans-rotational coupling
  - performance test in cryogenic
  - obtain good sensitivity
    - reduce jitter noise
    - other technical noises

Future Plans

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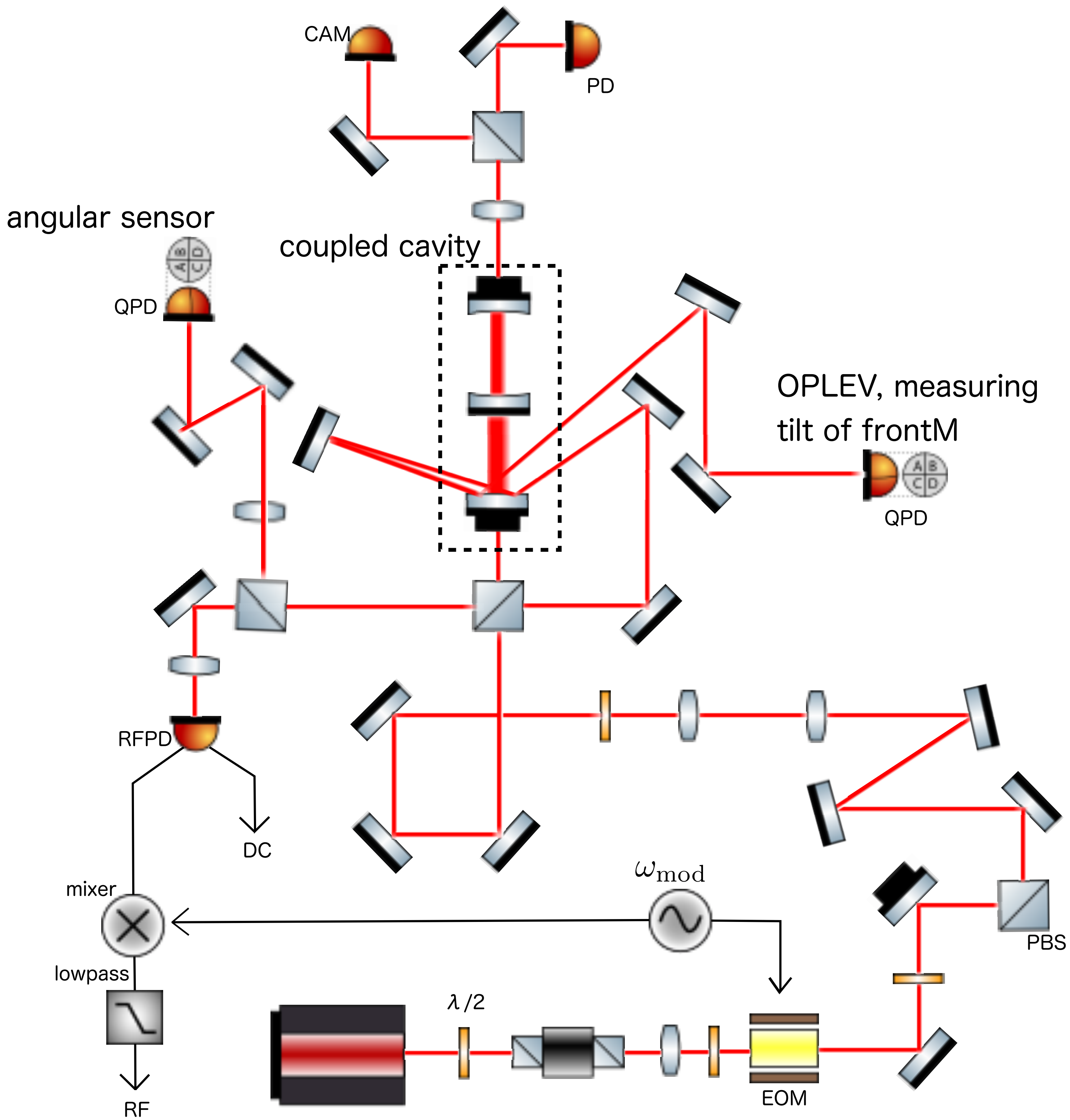
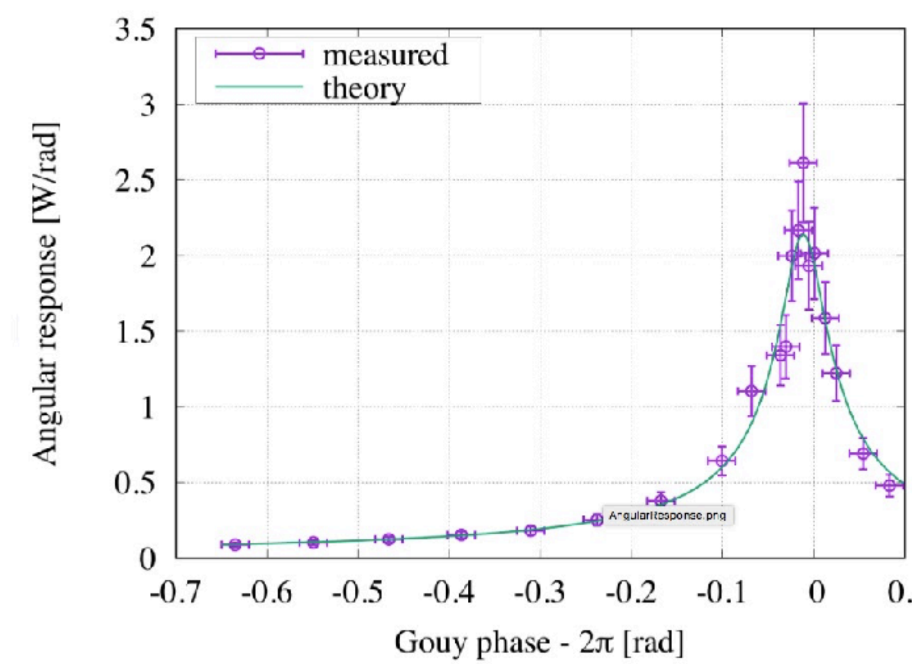
demonstration test

- confirm the amplification of angular signal
- compare with theoretical one



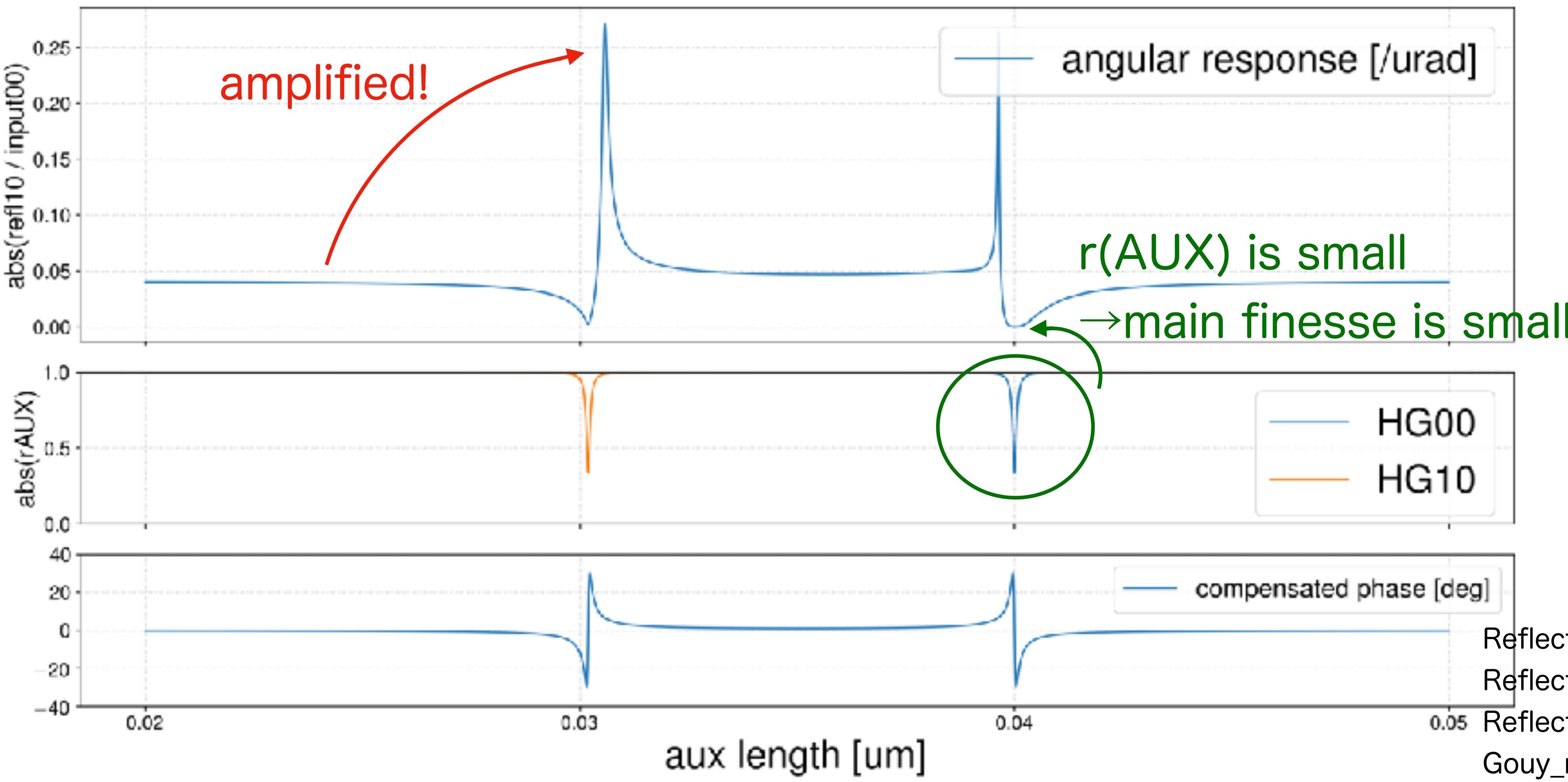
Example:
confirming the amplification of
Folded cavity by Shimoda-san



demonstration test

- confirm the amplification of angular signal
- compare with theoretical one

How much the angular signal(HG10) is generated. (main:locked, front:tilted(1urad), end:sweep)



Reflectivity_front=0.99
Reflectivity_mid=0.9995
Reflectivity_end=0.999
Gouy_main=6.7deg
Gouy_auxiliary=5.6deg

demonstration test

- confirm the amplification of angular signal
- compare with theoretical one

What to do to confirm the amplification of angular signal:

- increase reflectivity of (end) mirror
- control 3 mirrors
- sweep endM while main cav locked

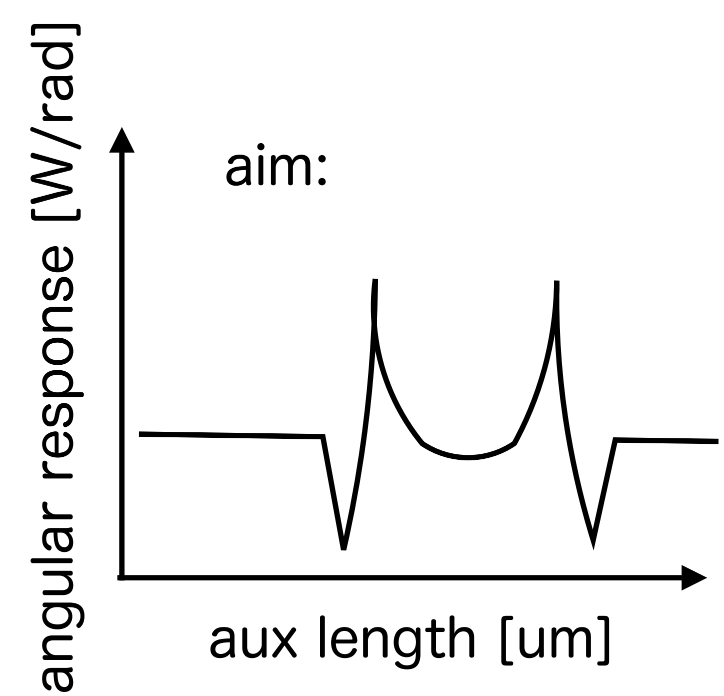
- calibrate efficiency of PZT on endM
- calibrate OPLEV [rad/V]
- measure DC/RF efficiency of QPD
  → obtain angular response [W/rad]

QPD receives

$$E_{00} + (\alpha + i\beta)E_{10}$$

α: translational → DC

β: rotational → RF

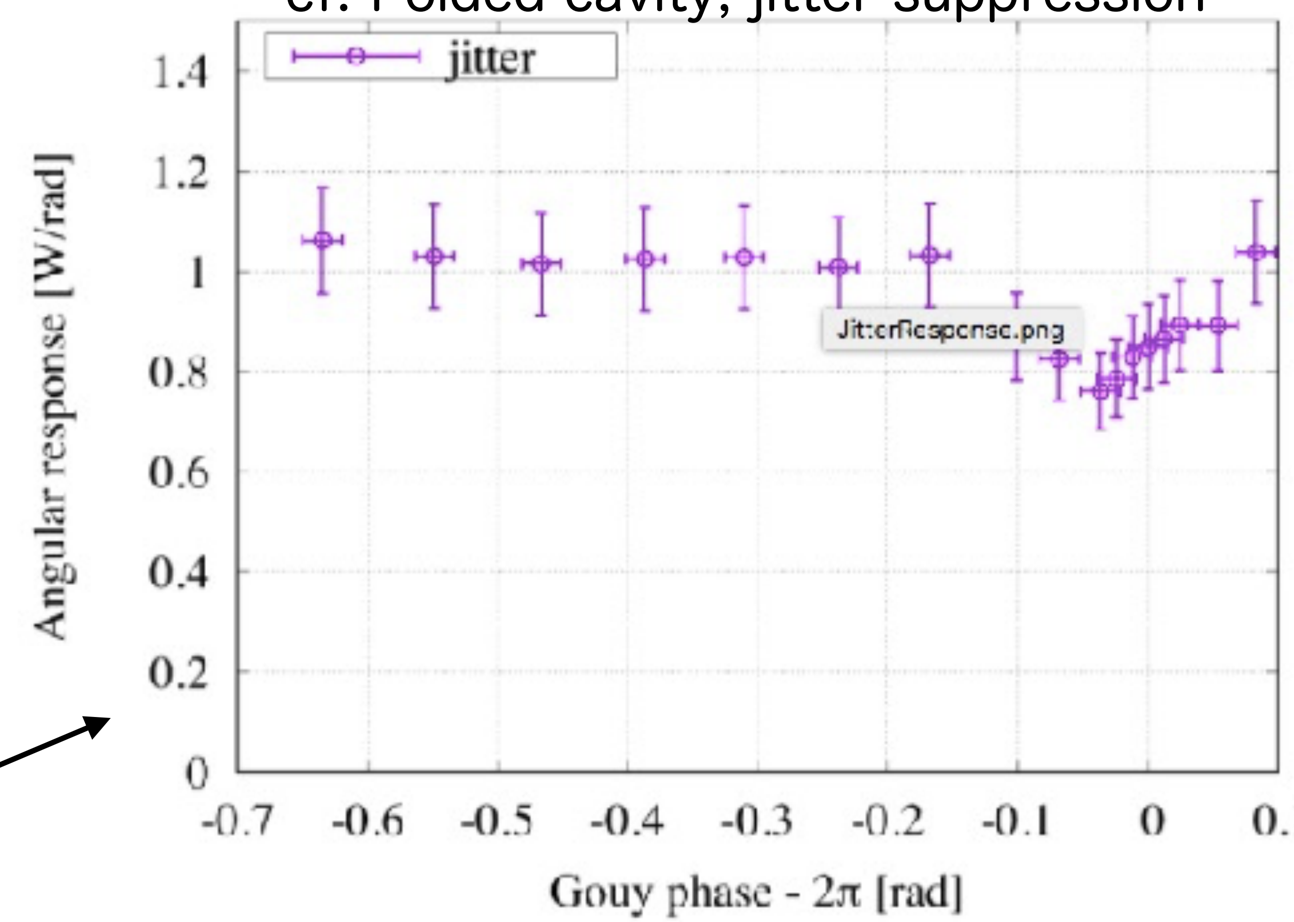


demonstration test

- check its characteristics
  - frequency noise
  - beam jitter

- test merits of the coupled cavity
  - no/low frequency noise
    injecting signal to EOM,
    check angular response doesn't change
  - suppress beam jitter
    shaking PZT on a mirror
    in front of the cavity,
    check angular response
    doesn't change

cf. Folded cavity, jitter suppression



ref: response to beam jitter for Folded cavity by Shimoda-san

Future Plans

- demonstration test (confirm its principle)
  - confirm the amplification of angular signal
  - compare with theoretical one
  - check its characteristics
    - frequency noise
    - beam jitter

- construct a new (semi-monolithic) system
  - trans-rotational coupling
  - performance test in cryogenic
  - obtain good sensitivity
    - reduce jitter noise
    - other technical noises

Future Plans

I also want to check/do

- trans-rotational coupling
- performance in cryogenic
- obtain good sensitivity

put the frontM on a stage and translate it (→ trans-rotational coupling)

construct a small system and put it into cryogenic (→ performance in cryogenic)

	Michelson interferometer	folded WFS	coupled WFS
shot noise	🙂 30cm bar	🙂 1mm beam, finesse 300	
frequency noise	☹️	🙂	🙂
trans-coupling	☹️	🙂	🙂
thermal noise	🙂	☹️	☹️
linear range	☹️	🙂	🙂
beam jitter	😐?	🙂 → 😐?	🙂 → 😐 ?
stability in cryo	🙂	☹️	🙂
control/operation	🙂	🙂	☹️

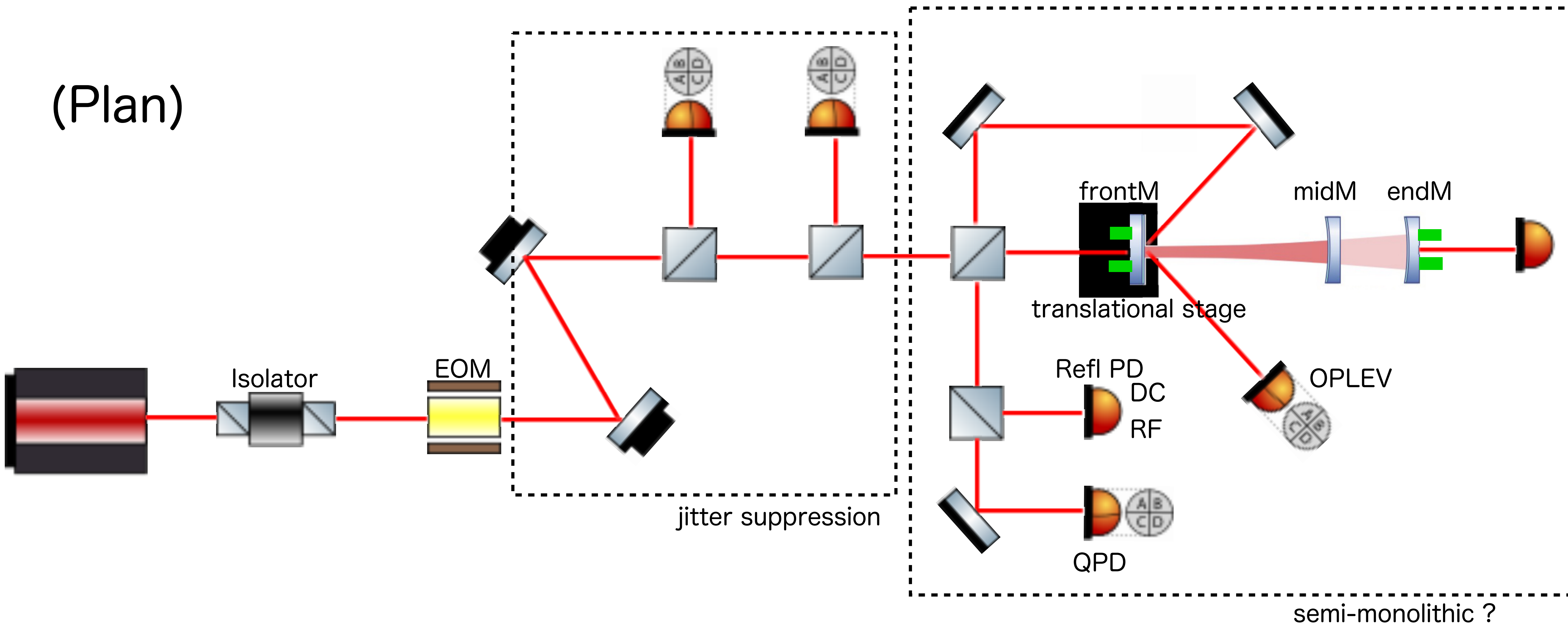
I will talk this issue later

Future Plans

I also want to check/do

- trans-rotational coupling ← put the frontM on a stage and translate it
- performance in cryogenic ← construct a small system and put it into cryogenic
- obtain good sensitivity

(Plan)



Future Plans

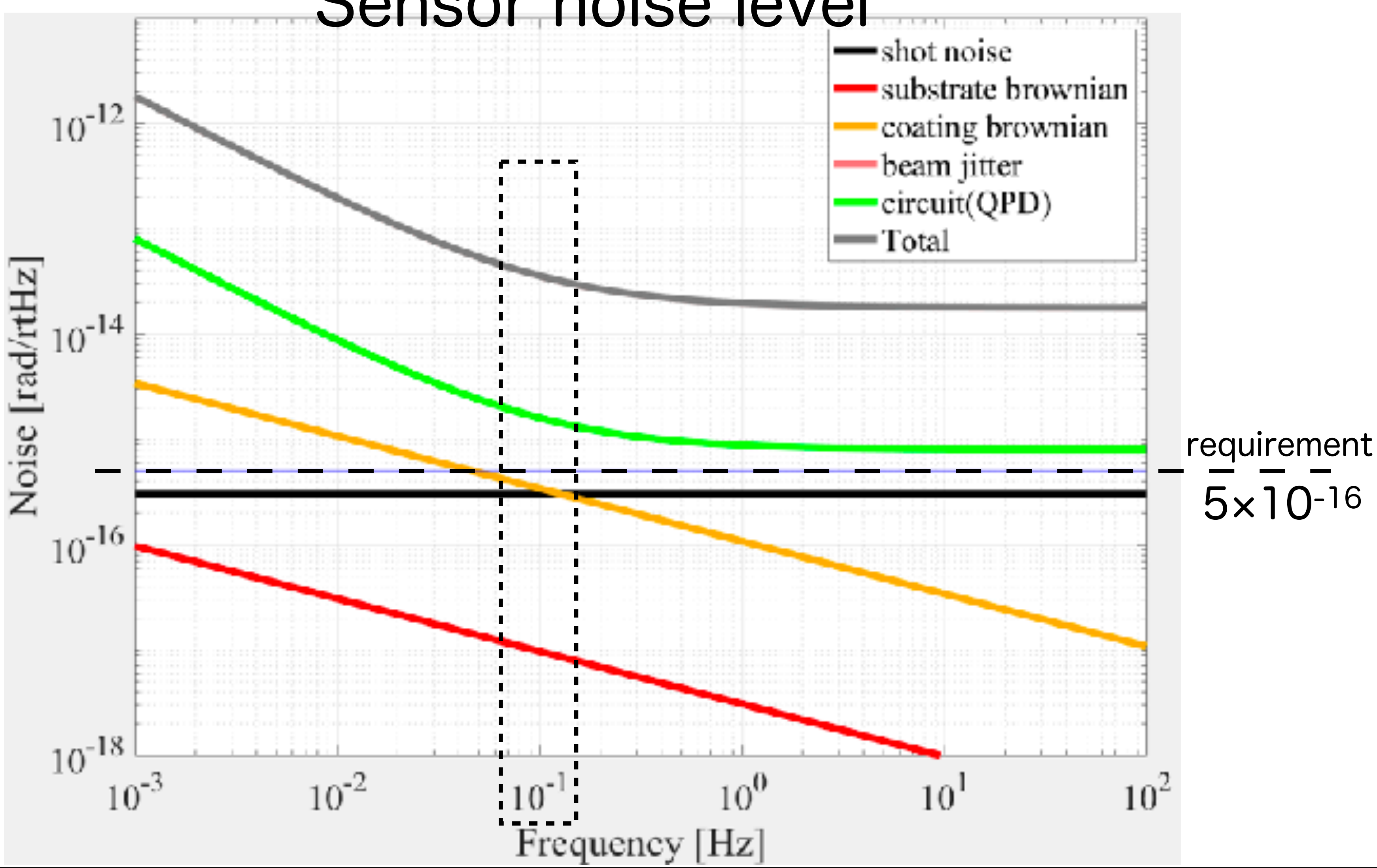
I also want to check/do

- trans-rotational coupling
- performance in cryogenic
- obtain good sensitivity

put the frontM on a stage and translate it

construct a small system and put it into cryogenic

Sensor noise level

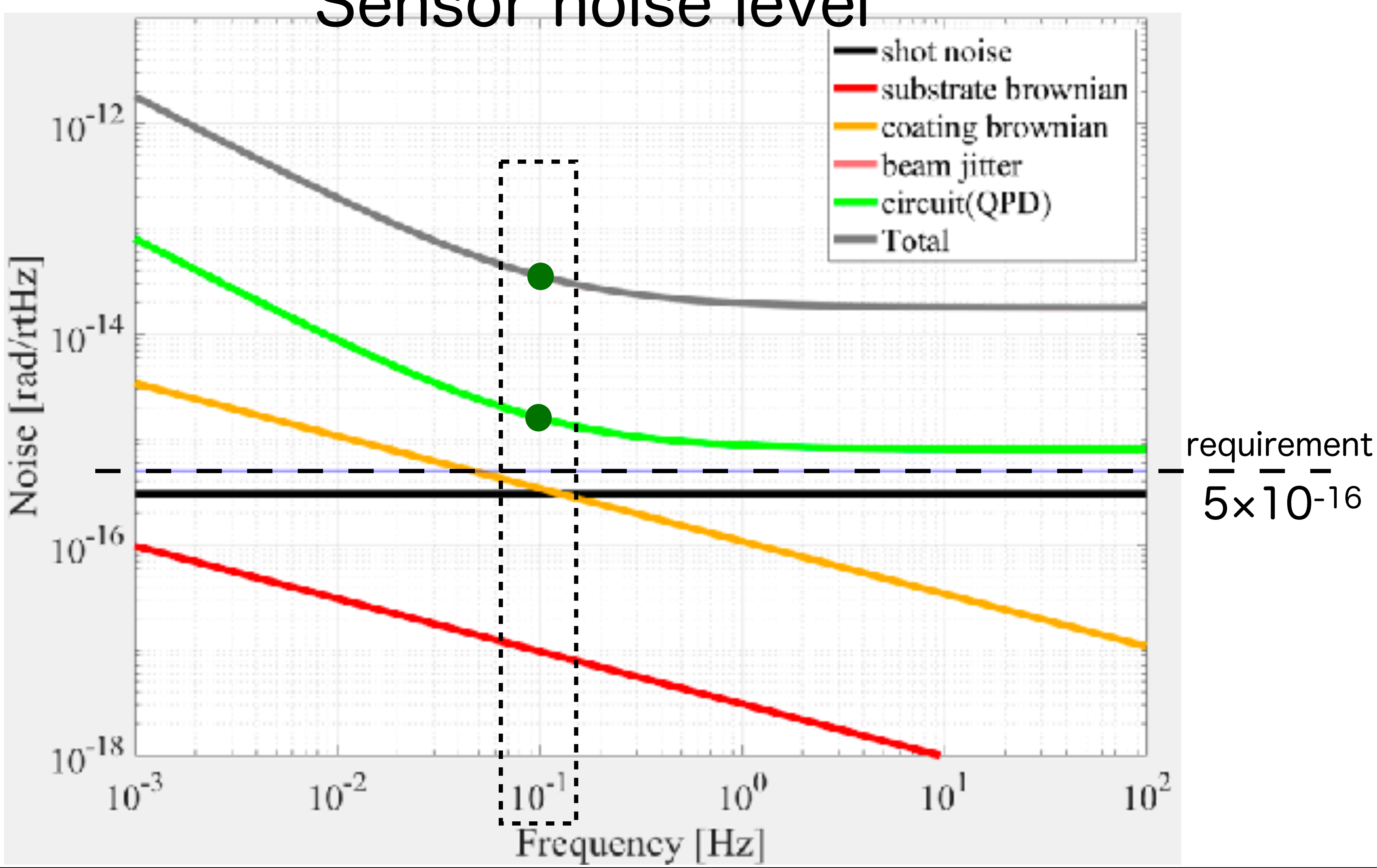


wavelength: 1064nm
beam radius: 3.5mm
beam power: 50mW
cavity length: ~10cm
finesse main cavity:
620 (00 mode)
210 (10 mode)
temperature: 4K
substrate: sapphire
substrate loss: 10^{-8}
coating loss: 10^{-3}

To achieve good sensitivity

- shot noise — OK
- thermal noise — OK
- beam jitter noise — factor: 100
- QPD noise — factor: 3

Sensor noise level



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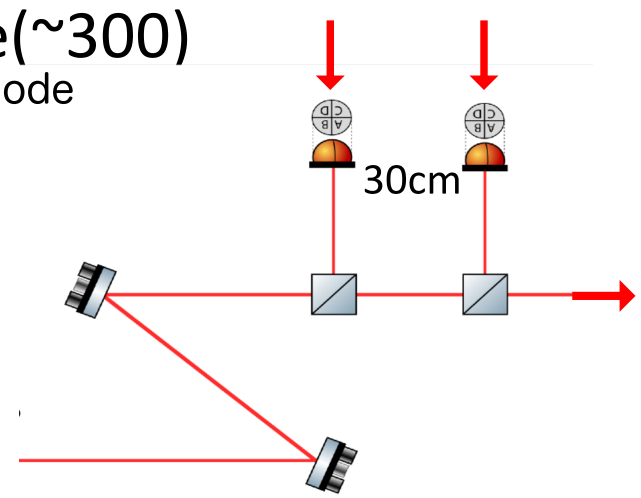
beam jitter noise suppression

- beam jitter noise factor: 100

(from Shimoda-san)

jitter suppression

- QPD noise : ~ 10^{-7} V/rtHz @0.1Hz
- position sensitivity of QPD (w=0.4mm) : ~ 30 V/mm
  → position sensing noise : 3×10^{-12} m/rtHz
- measure beam center at two points (separated by 30cm)
  → angular jitter : 10^{-11} rad/rtHz
- jitter noise is suppressed by finesse(~300) of 00mode
  → 3×10^{-14} rad/rtHz



How to suppress:

1. set distance between QPDs much bigger (~1m?)

beam jitter noise suppression

- beam jitter noise factor: 100

(from Shimoda-san)

jitter suppression

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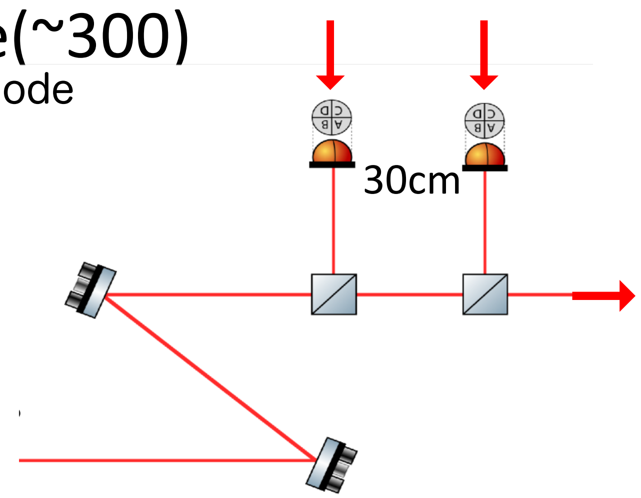

How to suppress:

1. set distance between QPDs much bigger (~1m?)
2. suppress QPD noise
   current problem:
   - cannot increase sensing gain due to saturation of OPamp

   solution:
   - use RF (not DC) ?
   - take difference between output electricity (not voltage) of QPD devices ?

beam jitter noise suppression

- beam jitter noise factor: 100

(from Shimoda-san)

jitter suppression

- QPD noise : ~ 10^{-7} V/rtHz @0.1Hz
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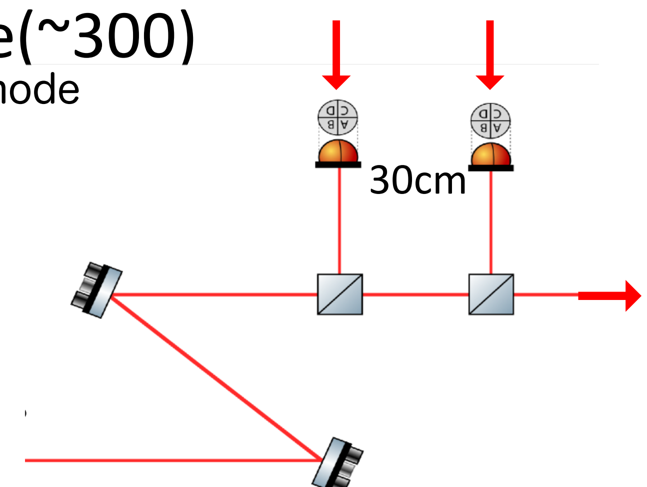
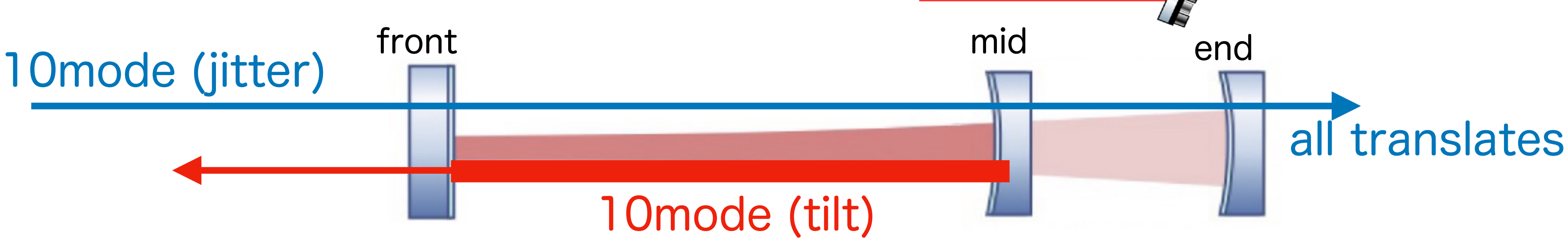




How to suppress:

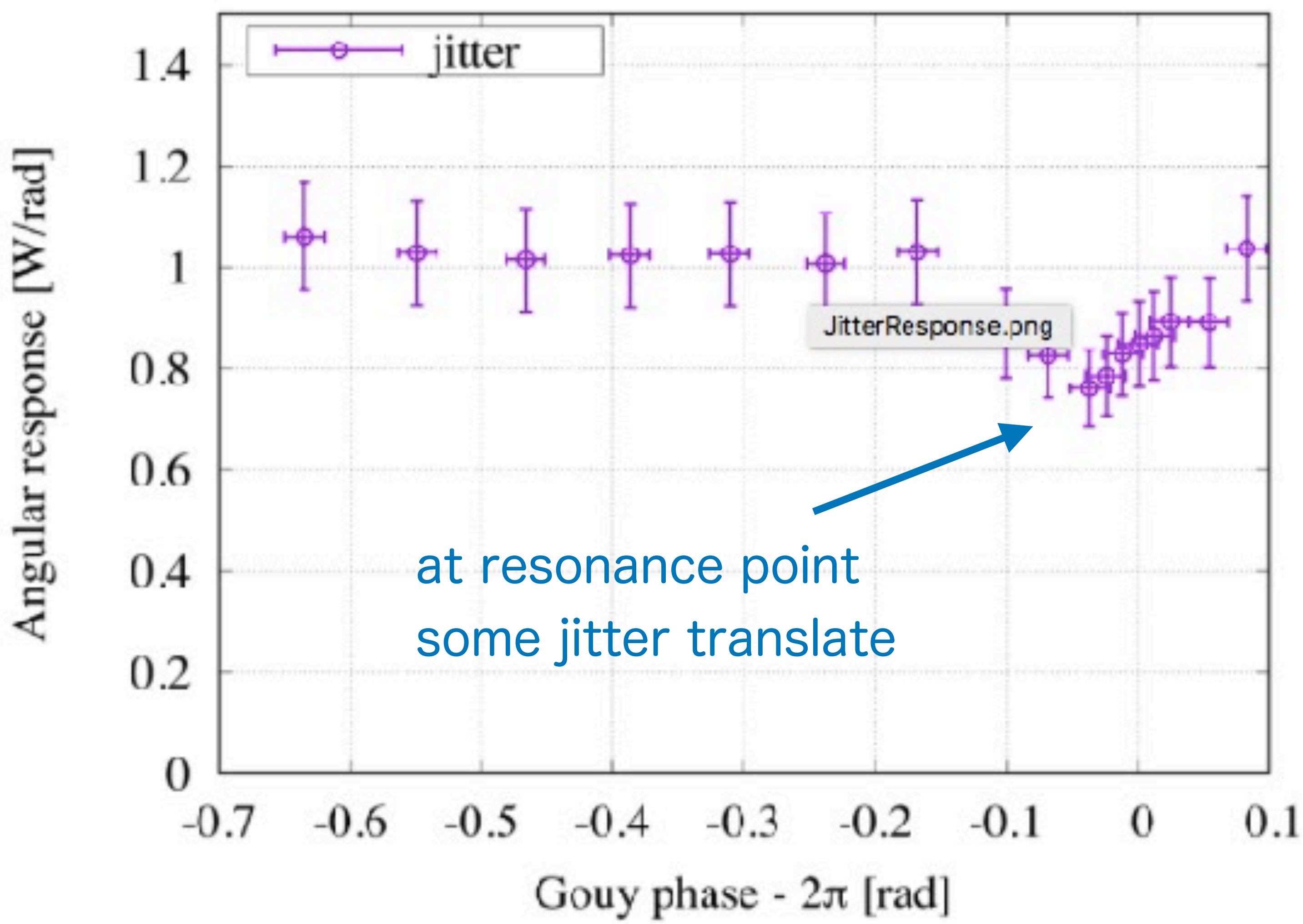
1. set distance between QPDs much bigger (~1m?)
2. suppress QPD noise
   current problem:
   - cannot increase sensing gain due to saturation of OPamp
   solution:
   - use RF (not DC) ?
   - take difference between output <u>electricity</u> (not voltage) of QPD devices ?
3. make the cavity critical coupling for 10mode
   → input 10mode does not reflect

beam jitter noise suppression

- beam jitter noise   factor: 100

Folded cavity demonstration by Shimoda-san

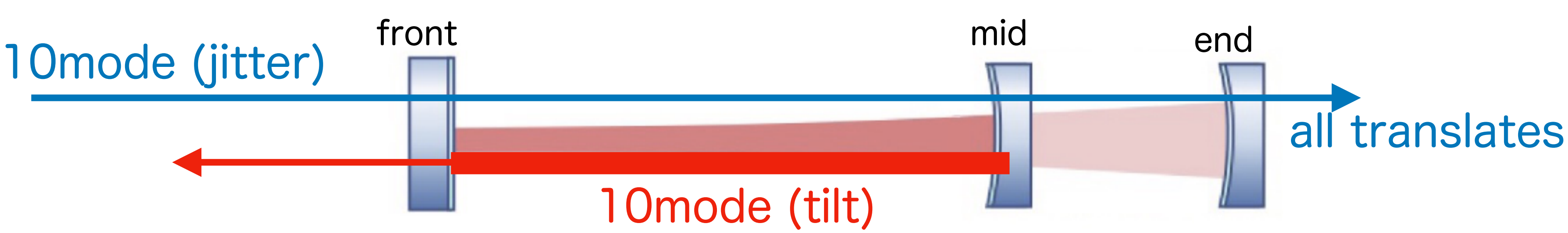
Angular response while making beam jitter



How to suppress:

1. set distance between QPDs much bigger (~1m?)
2. suppress QPD noise
   current problem:
   - cannot increase sensing gain due to saturation of OPamp

   solution:
   - use RF (not DC) ?
   - take difference between output <u>electricity</u> (not voltage) of QPD devices ?
3. make main-cavity critical coupling for 10mode
   → input 10mode does not reflect



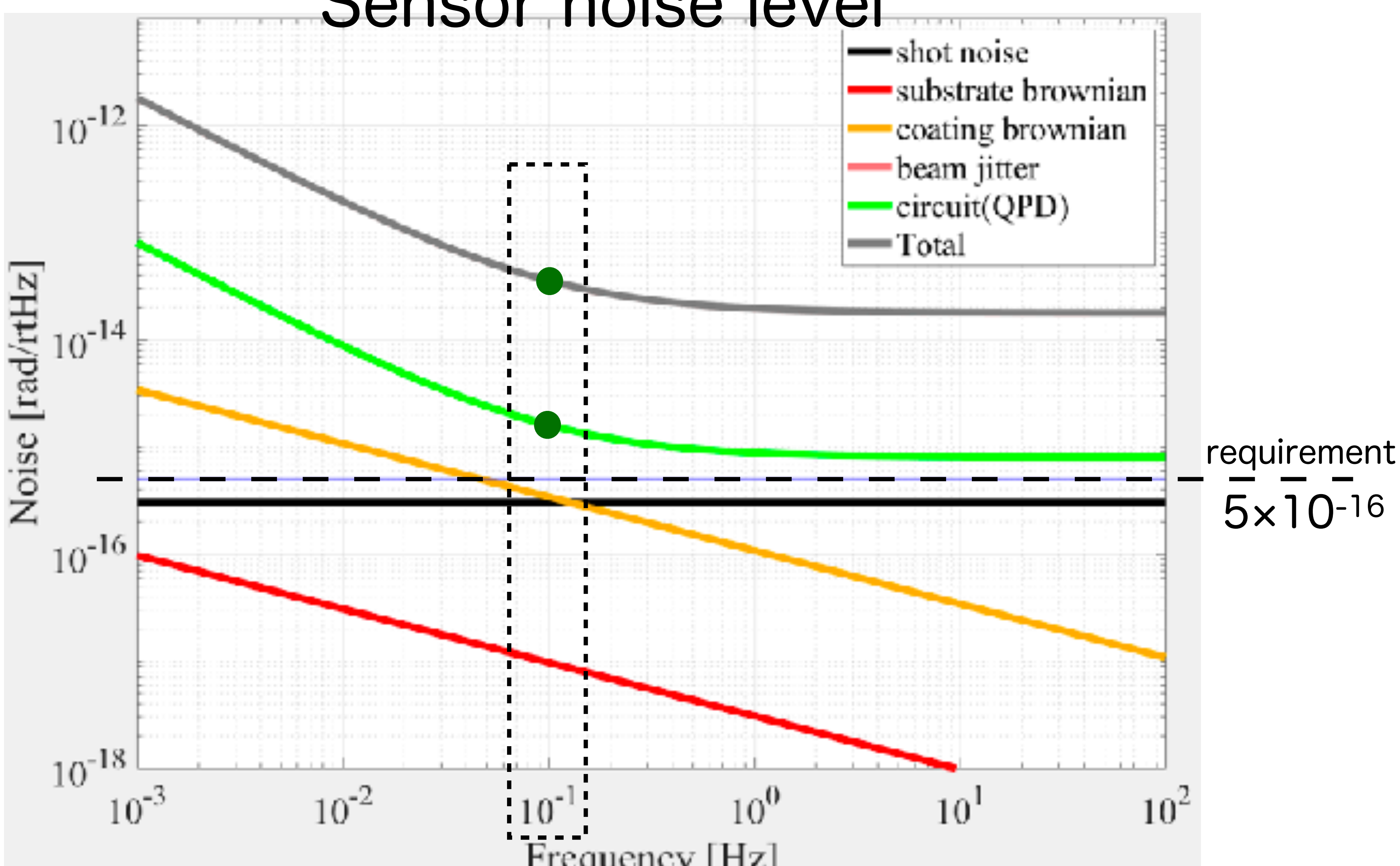
➡ Need fine tune

To achieve good sensitivity

- shot noise — OK
- thermal noise — OK
- beam jitter noise — factor: 100
- QPD noise — factor: 3 ←

As I told in about beam jitter noise, "taking difference between output electricity (not voltage) of QPD devices" and increase QPD gain may solve the problem.

Sensor noise level



wavelength: 1064nm
beam radius: 3.5mm
beam power: 50mW
cavity length: ~10cm
finesse main cavity:
620 (00 mode)
210 (10 mode)
temperature: 4K
substrate: sapphire
substrate loss: 10^{-8}
coating loss: 10^{-3}

Future Plans

- demonstration test (confirm its principle)
  - confirm the amplification of angular signal
  - compare with theoretical one
  - check its characteristics
    - frequency noise
    - beam jitter

- construct a new (semi-monolithic) system
  - trans-rotational coupling
  - performance test in cryogenic
  - obtain good sensitivity
    - reduce jitter noise
    - other technical noises

schedule

I took too much time
to deal with trivial things

until today | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 1 | 2 | 3

demonstration test

- 10 amplification
- check its characteristics

write thesis

design & order

construct the setup

- jitter suppression system
  - 10 amplification
  - check its characteristics
    - improve sensitivity
      - cryo test?

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- Summary

Summary

- Phase-III TOBA is on going
- a sensitive angular sensor "coupled cavity" is designed
- its demonstration and operation are have to be checked

- What I want to study with the coupled WFS (For M Thesis)
    - demonstration test (confirm its principle)
    - check its characteristics
    - obtain good sensitivity

(The preparation of this seminar was good opportunity for me to find what I have/want to do. Although the way is tough, I will do my best.)

End.

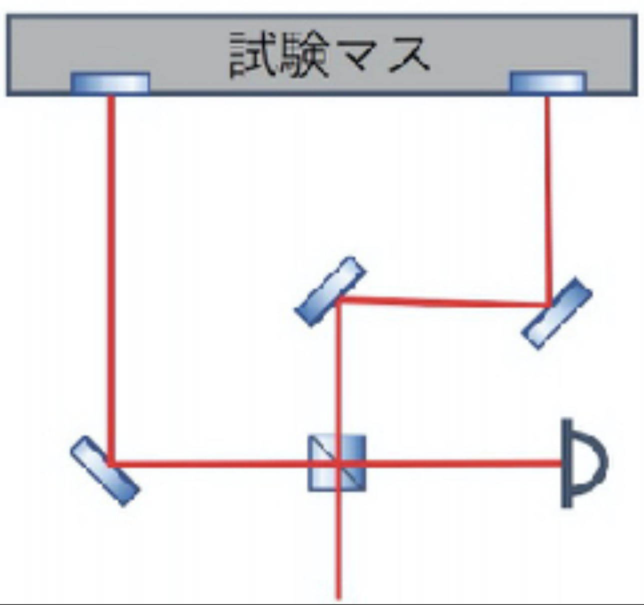
ゴミ箱

Angular sensors for TOBA

Required sensitivity: 5×10^{-16} rad/√Hz @0.1Hz (phase-III)

Previous study:

Michelson Interferometer

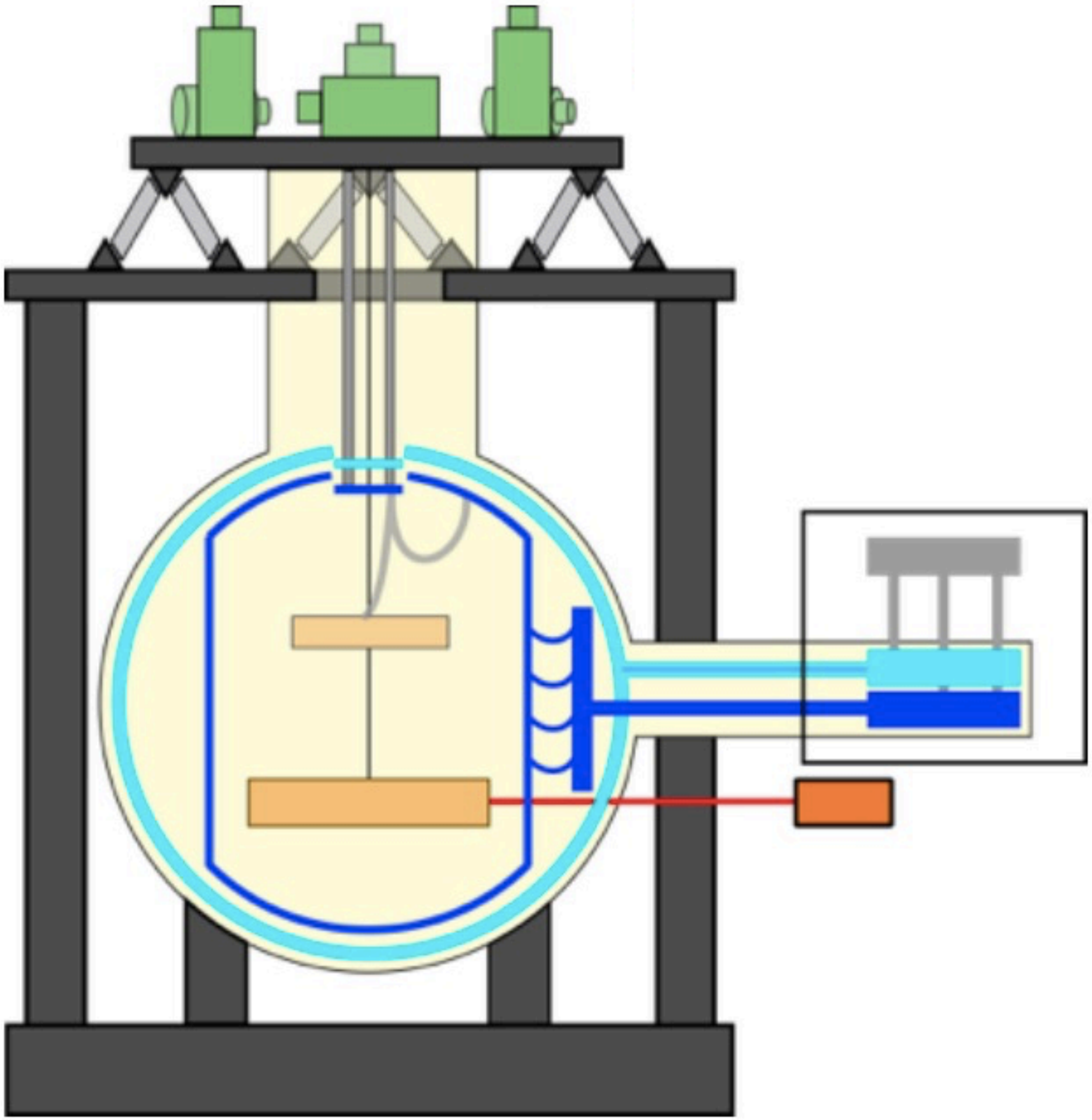


Conventional
Wave front sensor

New sensor:

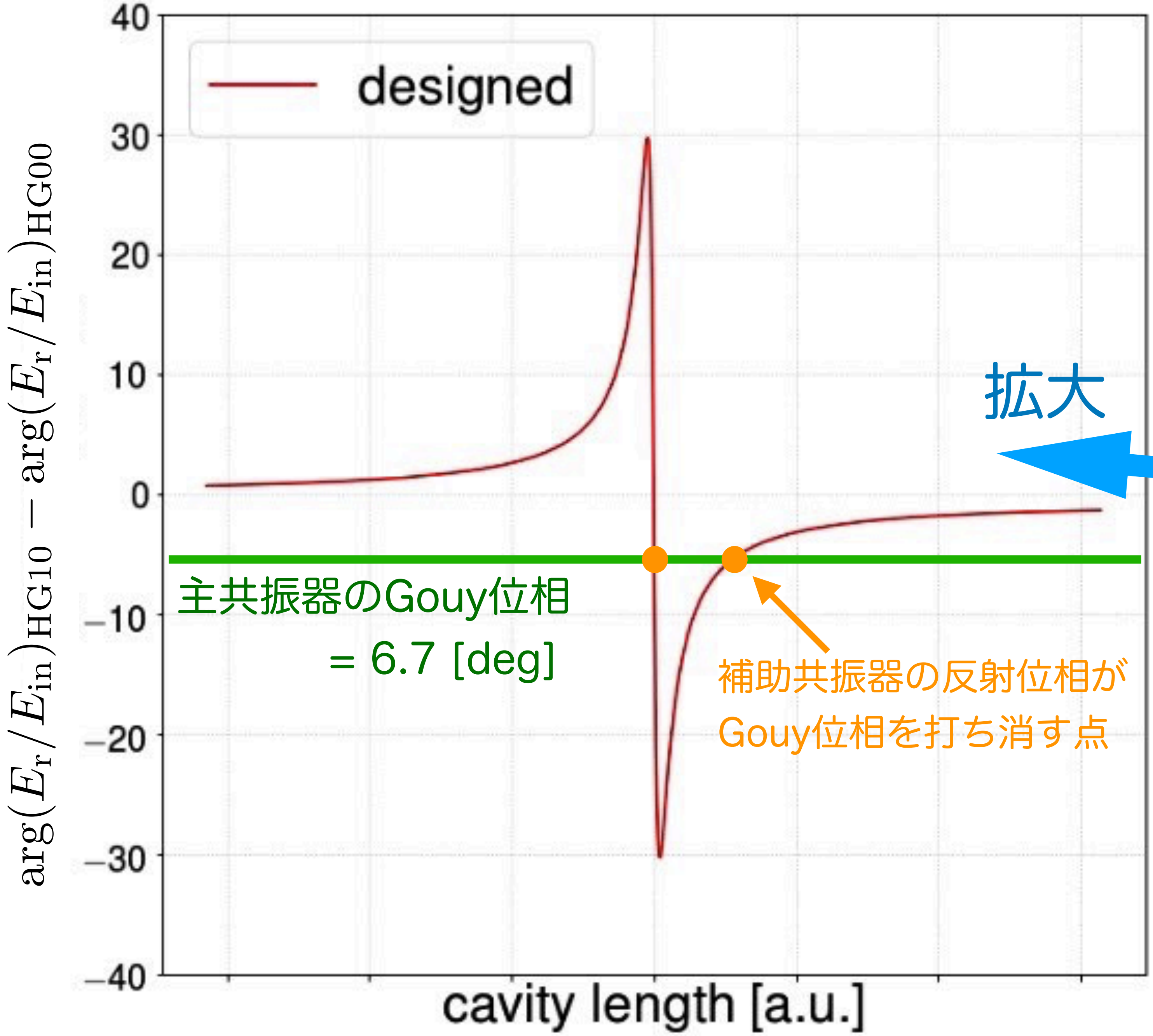
Improved wave front sensor

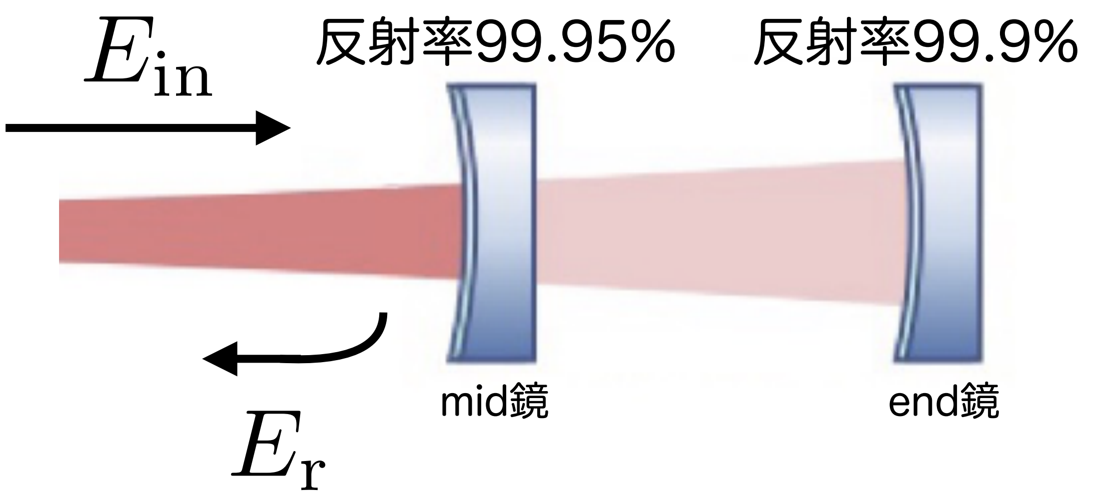
	Michelson Interferometer	Conventional Wave front sensor	Improved wave front sensor
Sensitivity		Angular signal is small	Angular signal is amplified
Trans-Rotation coupling	Difficult to put distant mirrors in parallel		



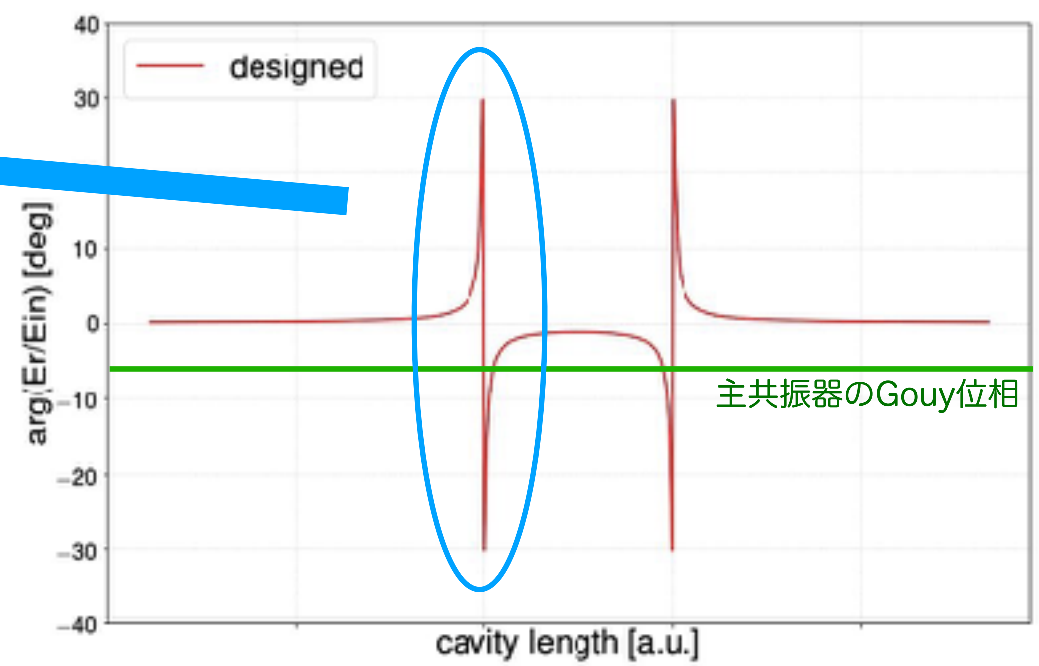
反射位相の設計値

$\arg(E_r/E_{in})$ の差 (=反射位相の差)





拡大



Reflectivity_mid=0.9995
Reflectivity_end=0.999
Gouy_main=6.7deg, Gouy_auxiliary=5.6deg

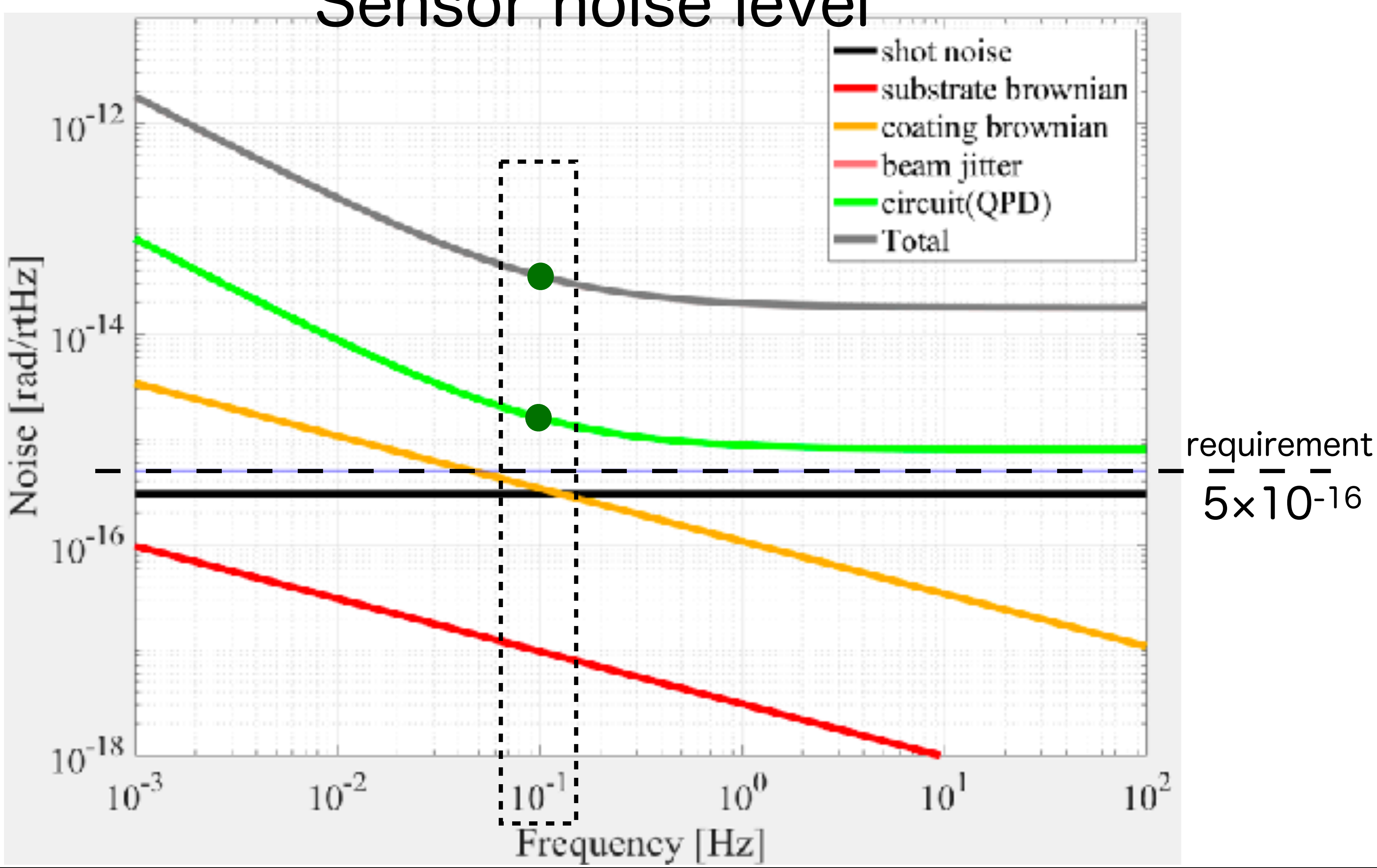
実際に反射位相を測定して、角度信号を増幅できるか確認

To achieve good sensitivity

- shot noise — OK — $\propto w^{-1}$
- beam jitter noise — factor: 100
- QPD noise — factor: 3
- thermal noise — OK

Angular response is proportional to beam power and beam radius. So setting beam radius to 3.5mm seems good, but the change also affects Rayleigh range (and Gouy phase), so fine tune is needed. (Not done yet)

Sensor noise level



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