Current status and future plans of LSRC, optomechanics, and B-L dark matter experiments

Kentaro Komori

Mid-term report 2023/04/24

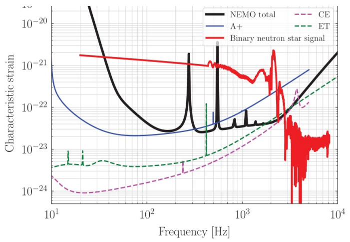
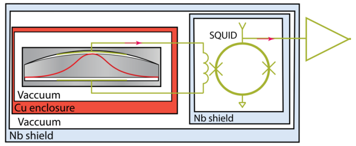
Contents

- Main contents
  - Long SRC

- Sub contents
  - Optomechanical torsion pendulum
  - B-L dark matter

Motivation

➢High frequency GWs

Frequency	~kHz	Above kHz
Science	• Equation of state of NS • Sky localization • Pulsar ellipticity • Harmonics of BBH ringdown	• Merger of primordial BHs • BH supper radiance • Phase transition in the early Universe
Detector	Conventional large detector • NEMO • LIGO-HF • KAGRA-HF 	New-type • Levitated sensors • Bulk acoustic wave • Interferometer 

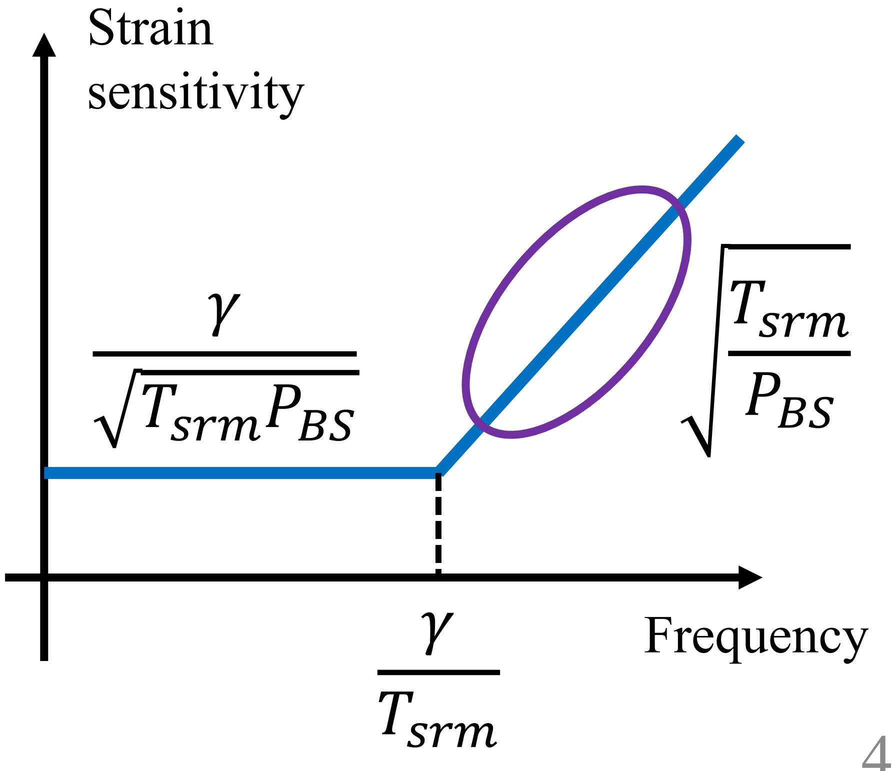
PASA 37, e047 (2020)

PRL 127, 071102 (2021)

Advantages of HF measurement

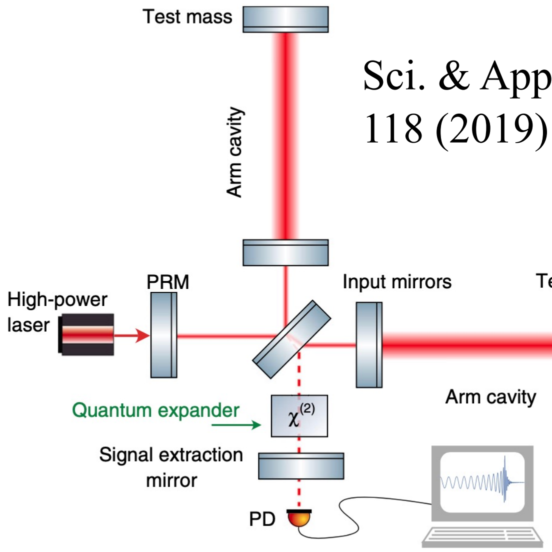
- Only shot noise, no displacement noises
  - Simple suspension is accepted
  - No couplings from other degrees of freedom

- Good sensitivity even with shorter arms
  - Longer arm and higher finesse (lower arm cavity pole) are better for the bucket sensitivity
  - It is hard to achieve good sensitivities above the bandwidth of the interferometer
  - Shorter interferometers can achieve better sensitivity than longer ones



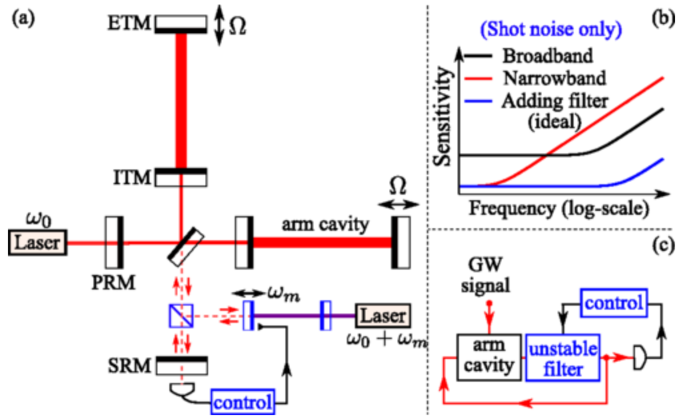
Method

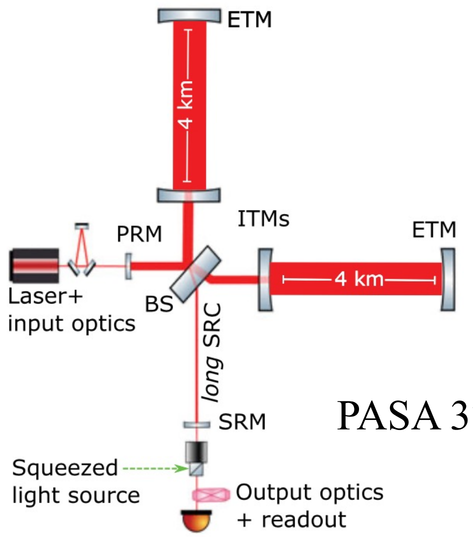
- ➤Quantum expander
  - Nonlinear crystal in SRC
- ➤Unstable optomechanical filter
  - Low-temperature high-Q mechanical oscillator
- ➤Long signal recycling cavity
  - Another space for the long cavity



Sci. & App. 8, 118 (2019)

PRL 115, 211104 (2015)





PASA 37, e047 (2020)

Sensitivity calculation

- Quantum noise

PRD 64, 042006 (2001) “BC paper” PRD 65, 022002 (2001) “KLMTV paper”

$$S_h = \frac{h_{SQL}^2}{2}\left(\mathcal{K} + \frac{1}{\mathcal{K}}\right) \qquad S_{h,shot} = \frac{h_{SQL}^2}{2\mathcal{K}} \qquad \mathcal{K} = \left(\frac{\omega_{SQL}}{\omega}\right)^2 K(\omega)$$

Radiation pressure noise

h_{SQL}^2: SQL sensitivity

SRM amplitude reflectivity

Conventional $$\frac{1}{K(\omega)} = 1 + \frac{(1-r)^2}{(1+r)^2\gamma^2}\omega^2 \qquad (L_{src} \to 0)$$

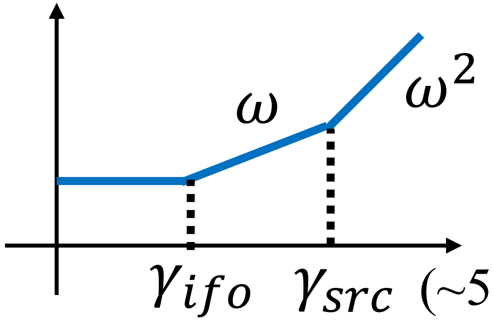
Arm cavity line width

Non-zero SRC length $$\frac{1}{K(\omega)} = 1 + \frac{(1-r)^2 - 8rL_{src}\gamma/c}{(1+r)^2\gamma^2}\omega^2 + \frac{4rL_{src}^2/c^2}{(1+r)^2\gamma^2}\omega^4$$

Amplitude sensitivity

➢ Short SRC

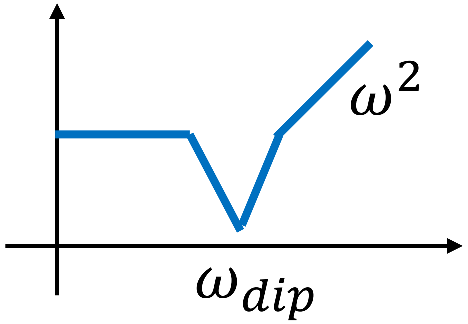
- $\omega < \gamma_{ifo}$: flat
- $\gamma_{ifo} < \omega < \gamma_{src}$: $\sqrt{S_h} \propto \omega$
- $\gamma_{src} < \omega$: $\sqrt{S_h} \propto \omega^2$ (through two cavities)



(~500 kHz in aLIGO)

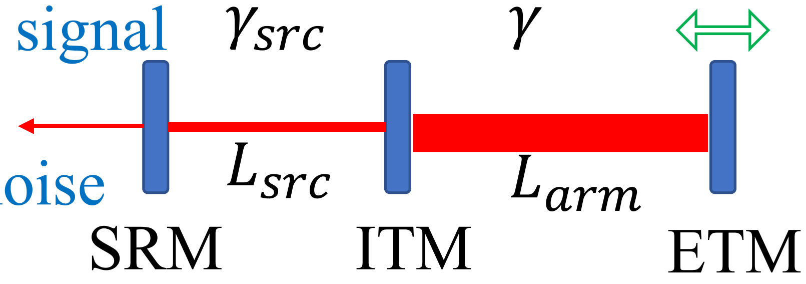
➢ Long SRC

- $\omega < \omega_{dip}$: flat
- $\omega_{dip} < \omega$: $\sqrt{S_h} \propto \omega^2$



positive | negative

Enhanced signal v.s. flat shot noise



Non-zero SRC length

$$\frac{1}{K(\omega)} = 1 + \frac{(1-r)^2 - 8rL_{src}\gamma/c}{(1+r)^2\gamma^2}\omega^2 + \frac{4rL_{src}^2/c^2}{(1+r)^2\gamma^2}\omega^4$$

Dip in the sensitivity

- The negative ω^2 term causes the dip when $L_{src} > T_{srm}^2 L_{arm}/(8T_i)$

Dip frequency: $f_{dip} = \frac{c}{8\pi}\sqrt{\frac{T_i}{L_{arm}L_{src}}}$

~kHz with km-scale arm

~MHz at table-top scale

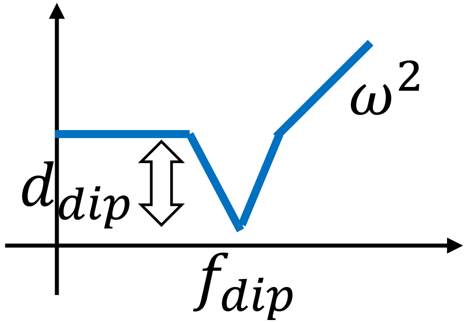
Depth: $d_{dip} = \frac{T_{srm}}{2}\sqrt{\frac{L_{arm}}{T_i L_{src}}}$

T_{srm}: SRM transmissivity

T_i: ITM transmissivity

L_{arm}: Arm length

L_{src}: SRC length

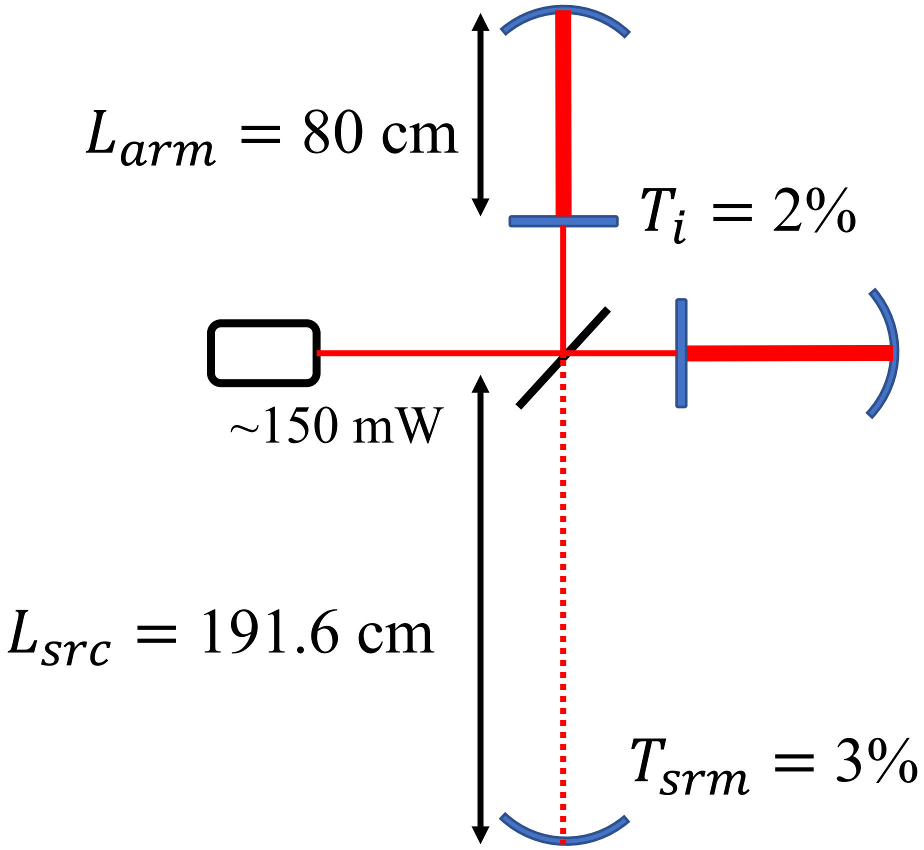


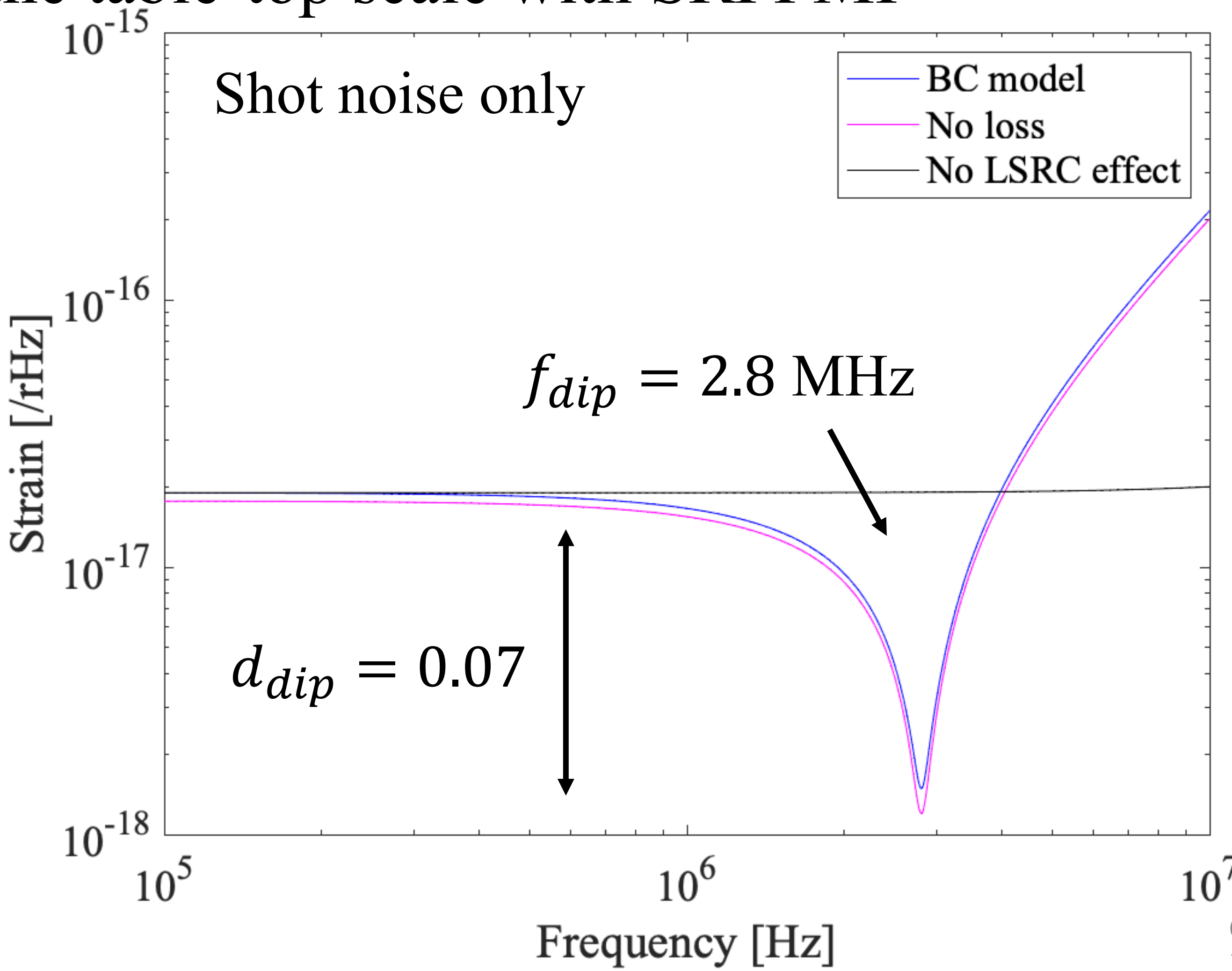
Non-zero SRC length

$$\frac{1}{K(\omega)} = 1 + \frac{(1-r)^2 - 8rL_{src}\gamma/c}{(1+r)^2\gamma^2}\omega^2 + \frac{4rL_{src}^2/c^2}{(1+r)^2\gamma^2}\omega^4$$

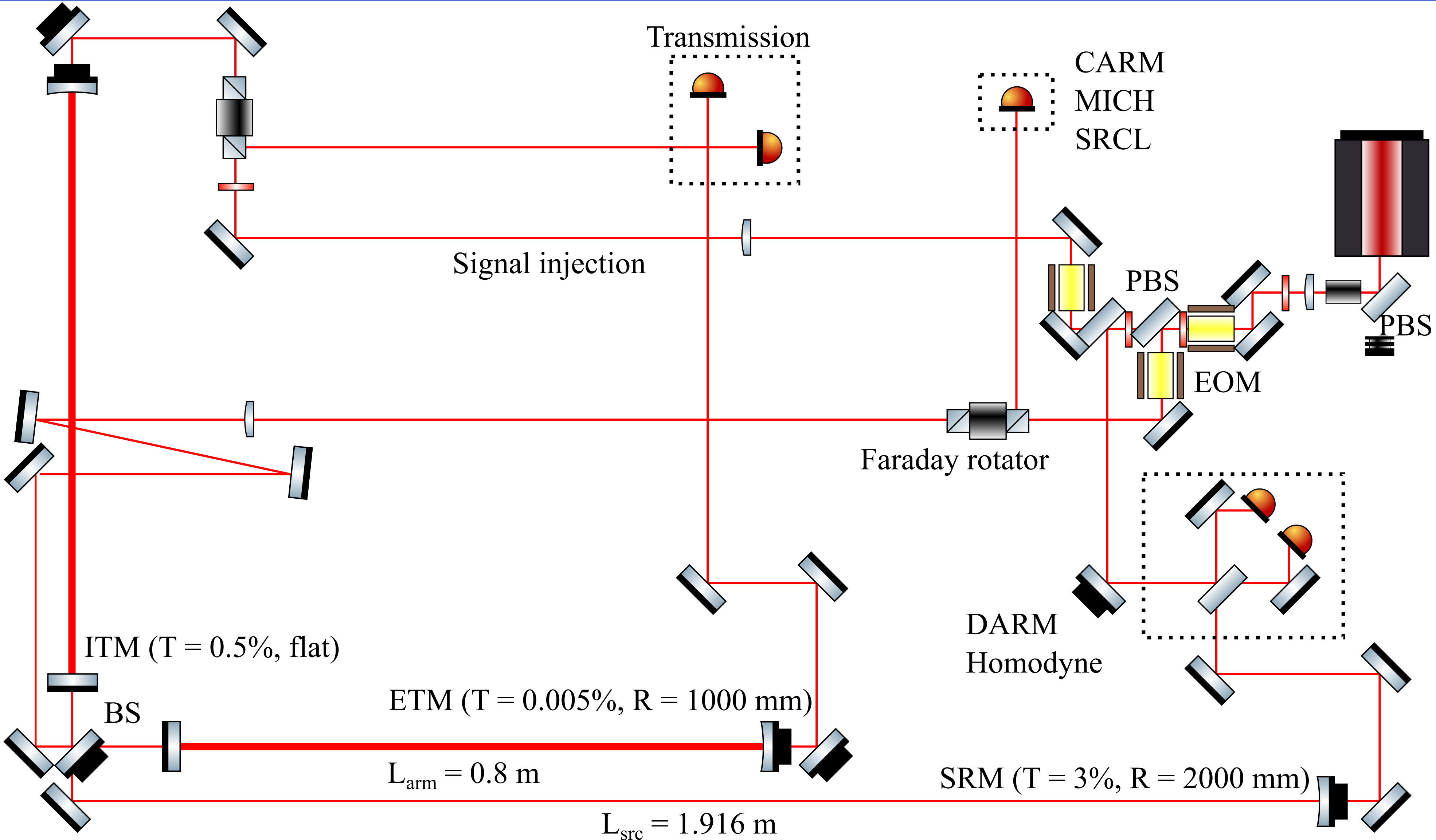
Experimental plan

- Demonstration of LSRC at the table-top scale with SRFPMI



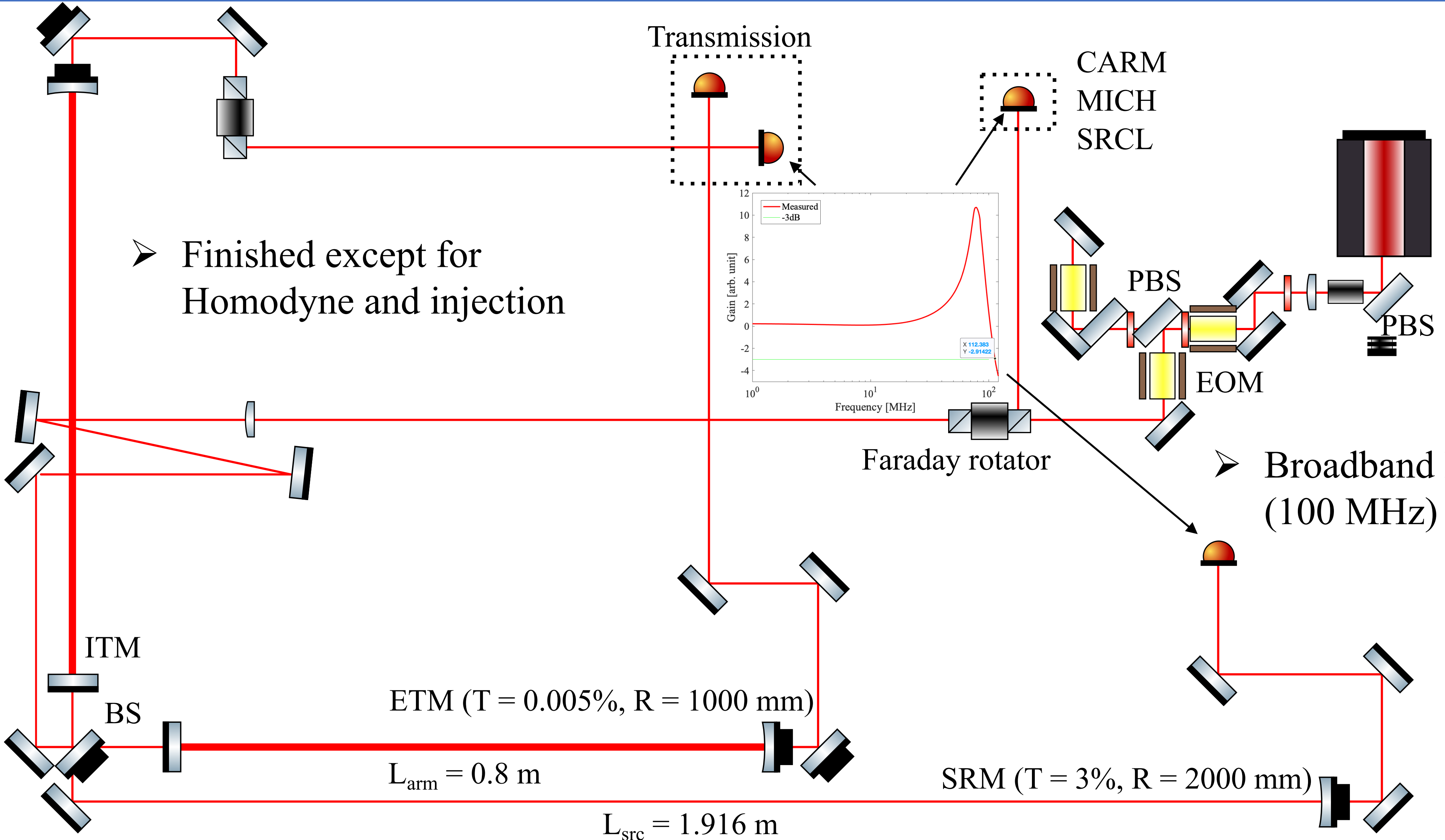


Optical layout



Current status

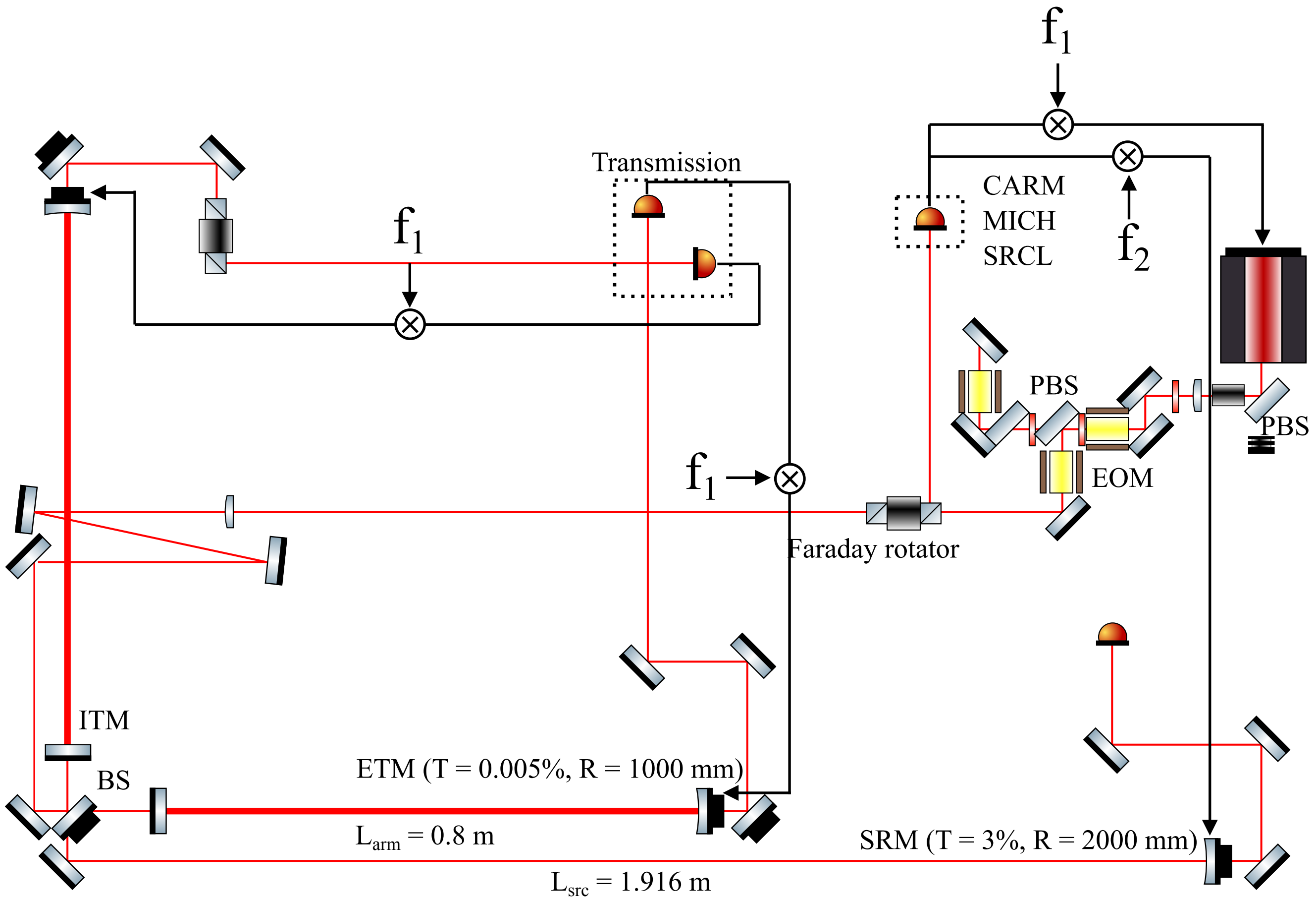
- Finished except for Homodyne and injection



- Broadband RFPD (100 MHz)

Length sensing and control (old)

- FPMI
  - Each arm: transmission PDH
  - Another method: CARM (DARM) control by frequency (one ETM) feedback
  - MICH: Q-phase, though very stable even without control
- SRMI
  - Second sideband ~80 MHz (2-m SRC FSR)



Current issue

- ➢Not succeeded in RSE yet, two issues

- ➢Lock acquisition
  - Rarely succeeding in the FPMI lock with SRM aligned due to career reflection

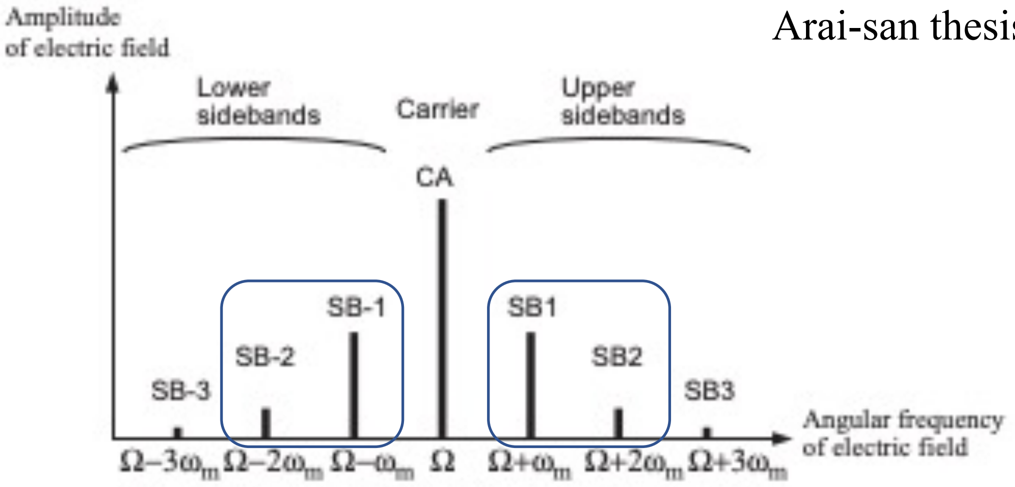
- ➢Noise
  - RMS of relative transmission fluctuation ~0.1, corresponding to the detuning fluctuation ~0.3 cavity line width
  - Enhanced by the SRM reflection, more noisy

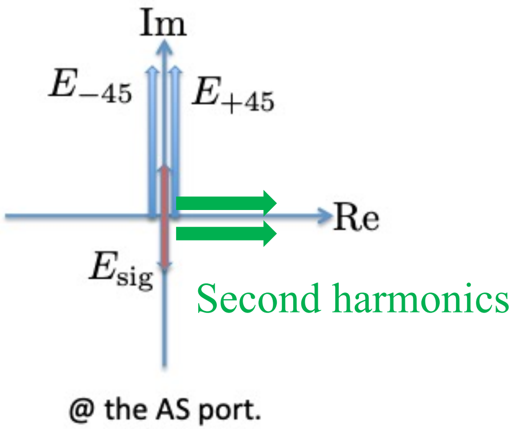
How to solve

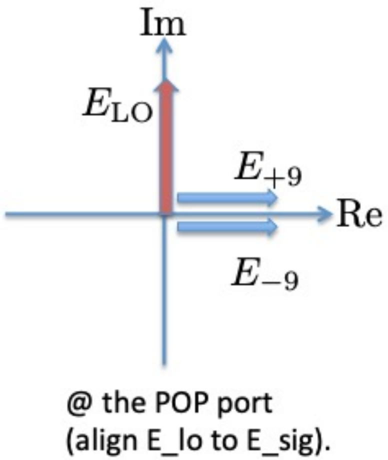
- Lock acquisition
  - SRC control by the third harmonic demodulation
  - Beating of 40 MHz and 80 MHz resonating in the SRC
  - Career free control to keep the SRMI lock during the FPMI lock

- Good for Homodyne measurement
  - The original plan is to use demodulation of f_2-f_1
  - Just $2f_2$ demodulation is suitable because it is an amplitude fluctuation

Arai-san thesis



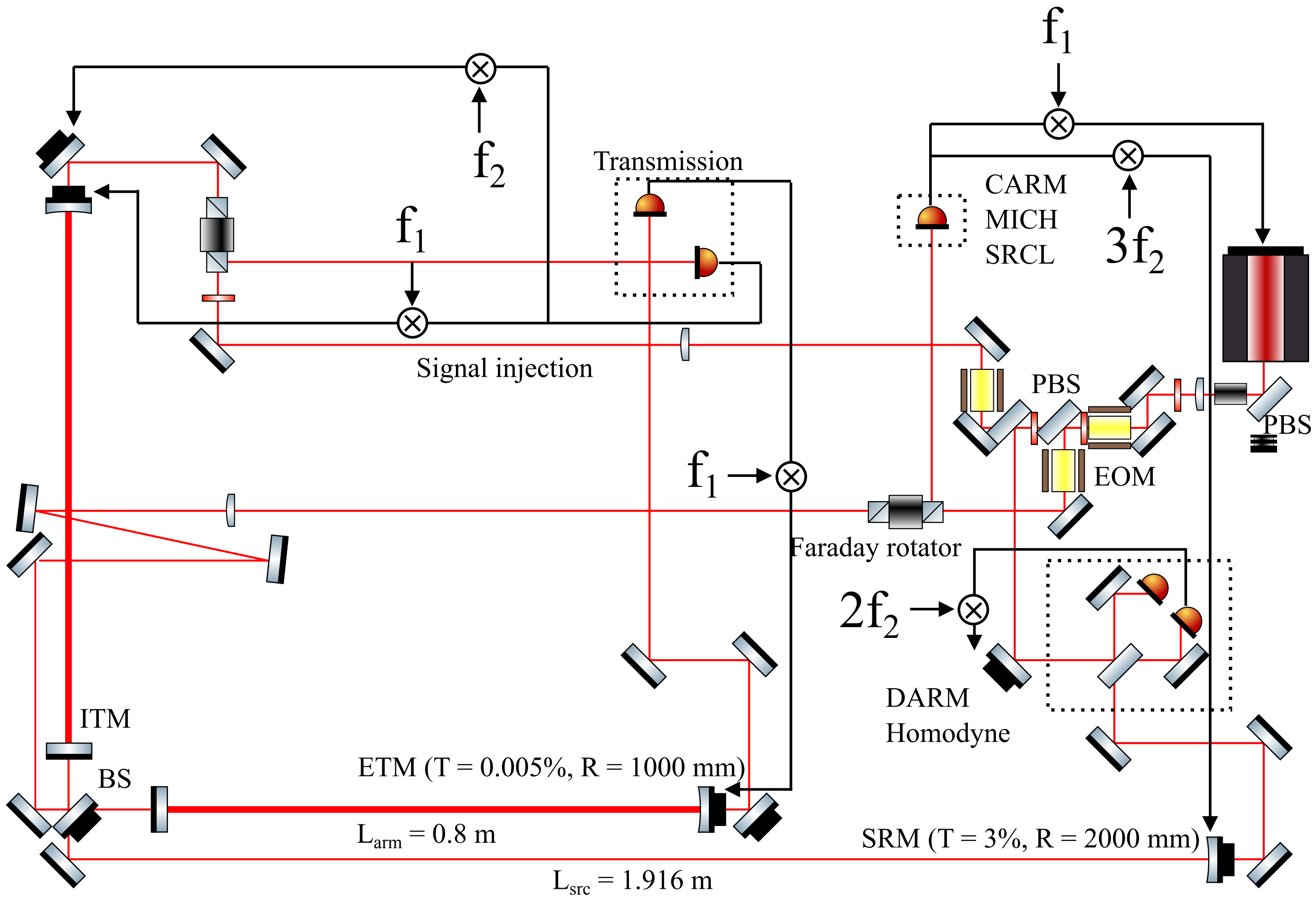




LIGO-dcc G1702485

Length sensing and control (new)

- FPMI
  - Each arm: f_1 (0.7 MHz) transmission PDH
  - MICH: f_2 (40 MHz) Q-phase
- SRC
  - $3f_2$ (120 MHz)
- Homodyne
  - $2f_2$ (80 MHz)
- Injection
  - f_2 (40 MHz)

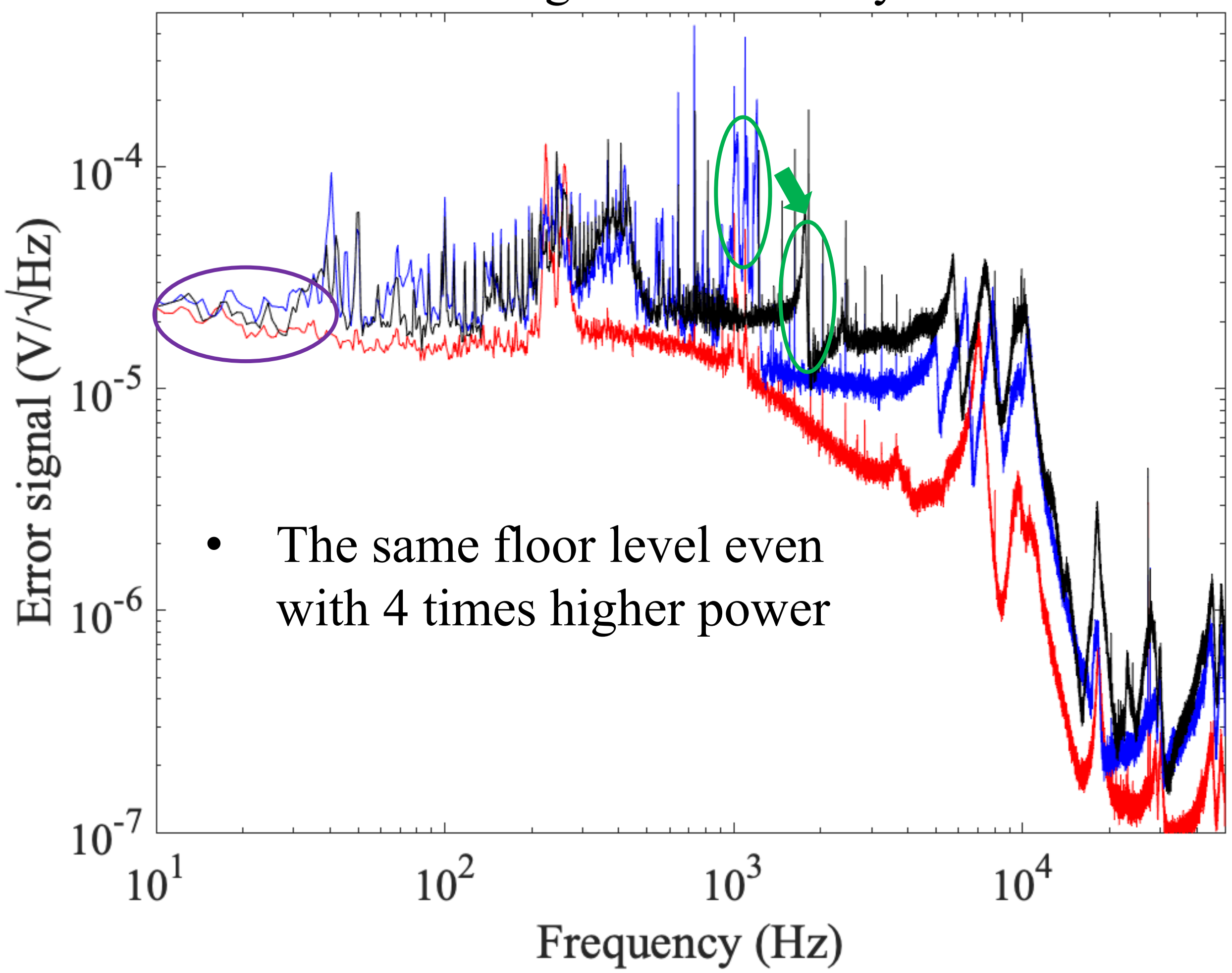


Solving the noise issue

- Mainly two methods
  - Increasing the power to reduce the Moku:Go ADC noise (red to blue)
  - Lowering the height of the pedestal to make the parasitic resonant frequency higher (blue to black)

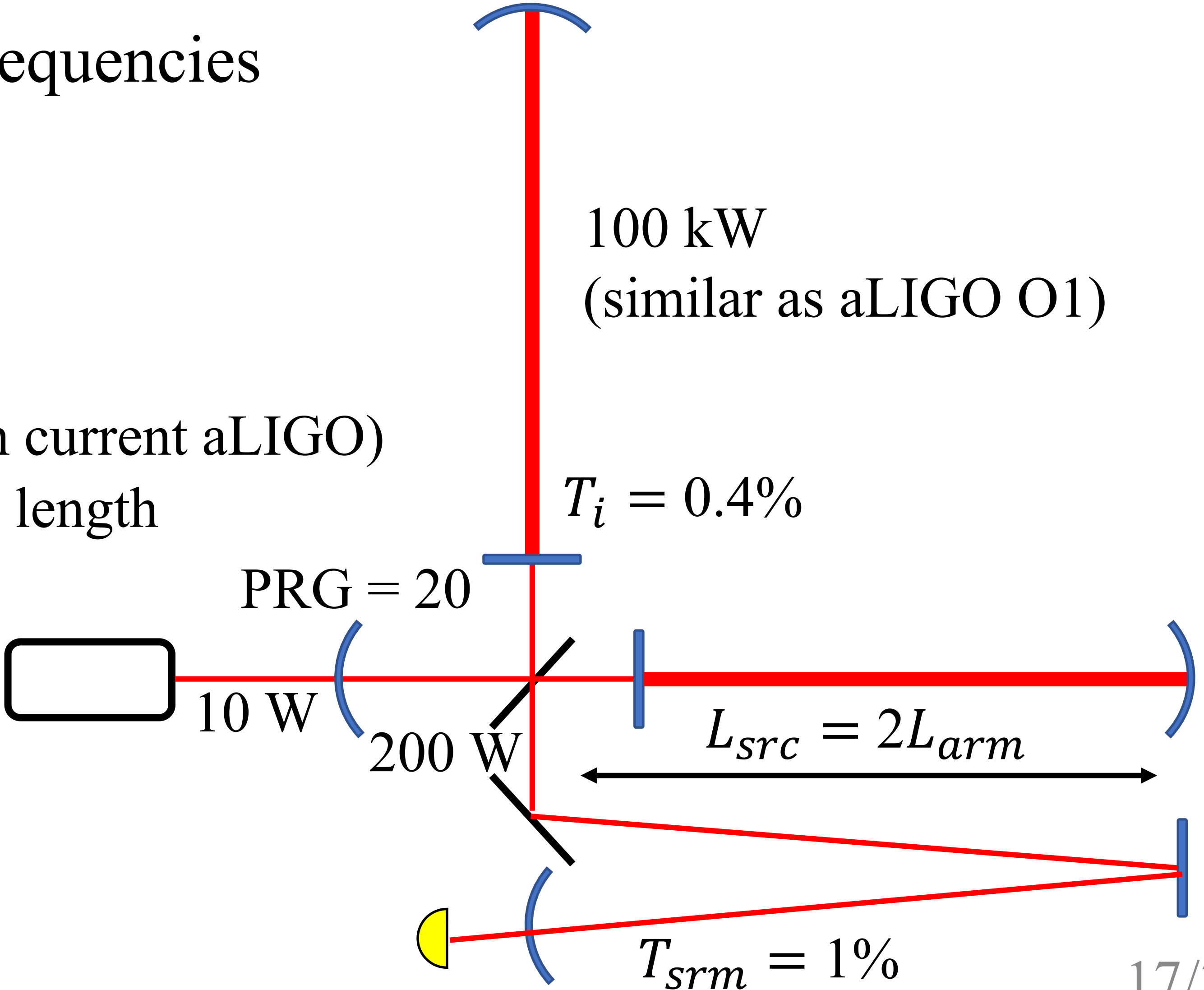
- Next step
  - Increasing the trans-impedance gain of the PD to further reduce the ADC noise
  - Checking the noise with the SRM aligned

Raw error signal without any calibration



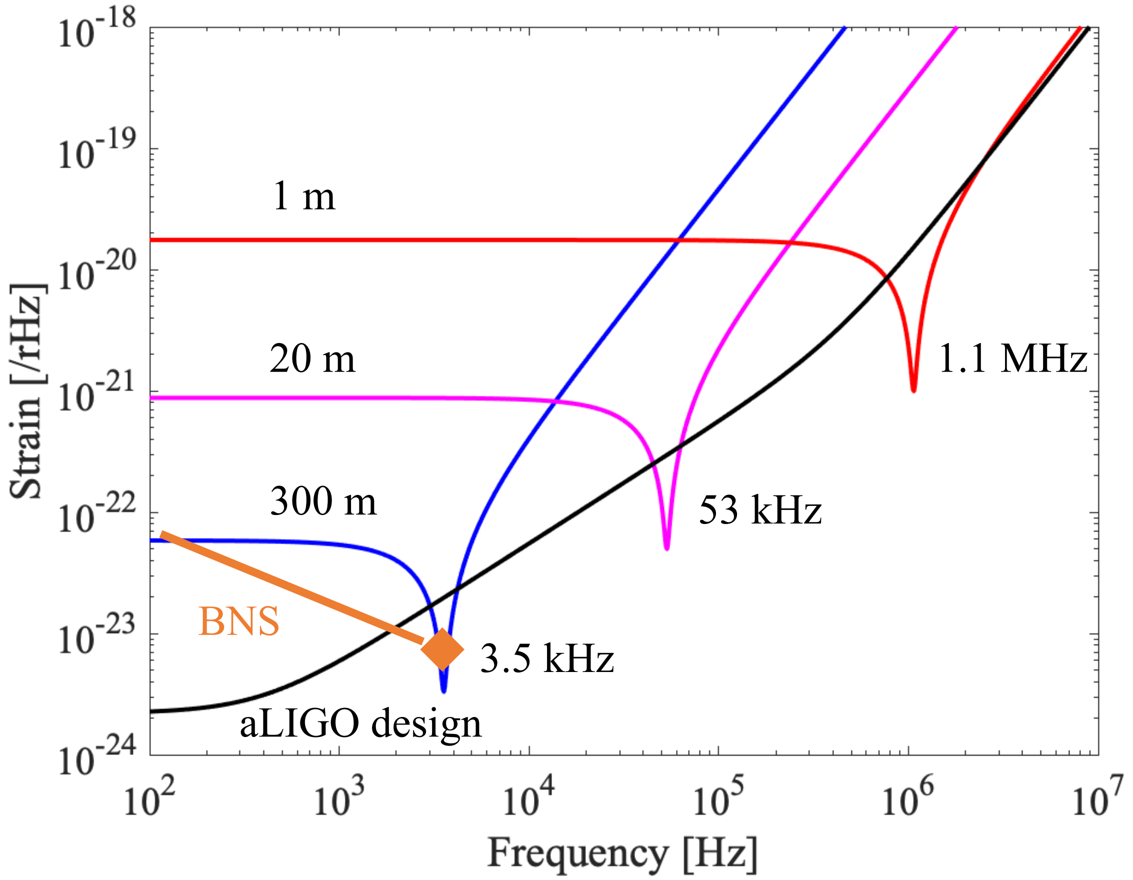
Future

- GW observation at various frequencies
- Interferometer parameters
  - ITM transmissivity 0.4%
    (the same as KAGRA)
  - Power at BS 200 W
    (order of magnitude lower than current aLIGO)
  - SRC length is twice as the arm length
  - SRM transmission 1%
  - Roundtrip loss 100 ppm
  - SRM loss 1%
  - Detection loss 10%
  - 6 dB squeezing



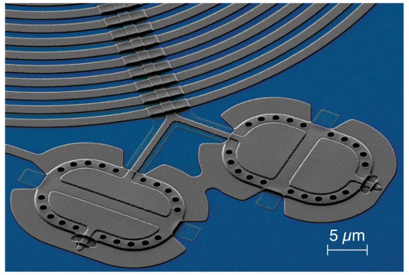
Future

- LSRC can surpass the aLIGO design sensitivity at the dip frequency (ignoring FSR effect)
- The dip frequency with 300-m arms is similar as the BNS merger frequency
- Revival of TAMA-300 as a GW observatory



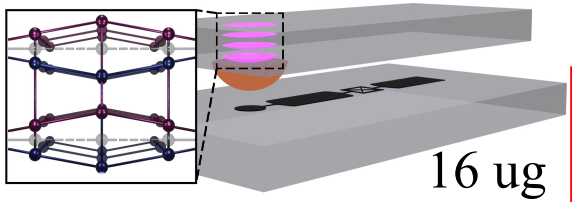
Background

➢The massive quantum (16 ug) and the lightest gravity (90 mg)



70 pg

Science 372, 622 (2021)



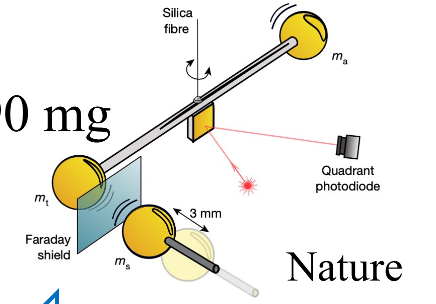
16 ug

Arxiv:2211.00449
✓ Bulk acoustic wave
✓ Electro-mrchanics

Quantum

Planck mass
22 ug

90 mg



Nature 591, 225 (2021)

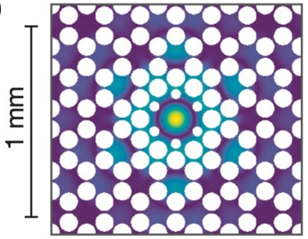
Gravity

Mass

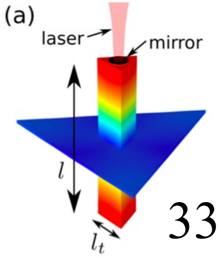
pg | ng | ug | mg | g

Nat. Phys. 15, 745 (2019)

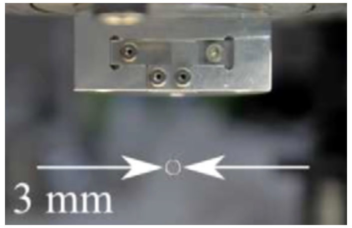
10 ng



50 ng



33 ug



7 mg

Beyond standard quantum limit

Will be entangled soon

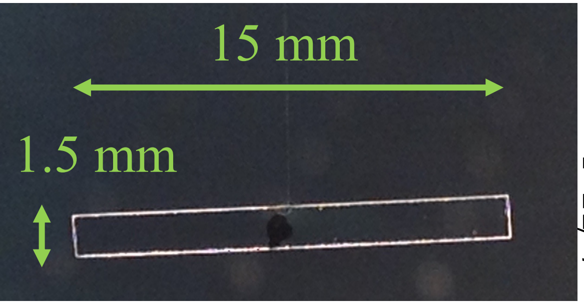
Near quantum

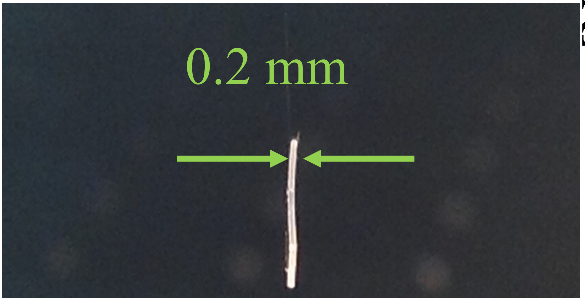
arxiv:2104.11648

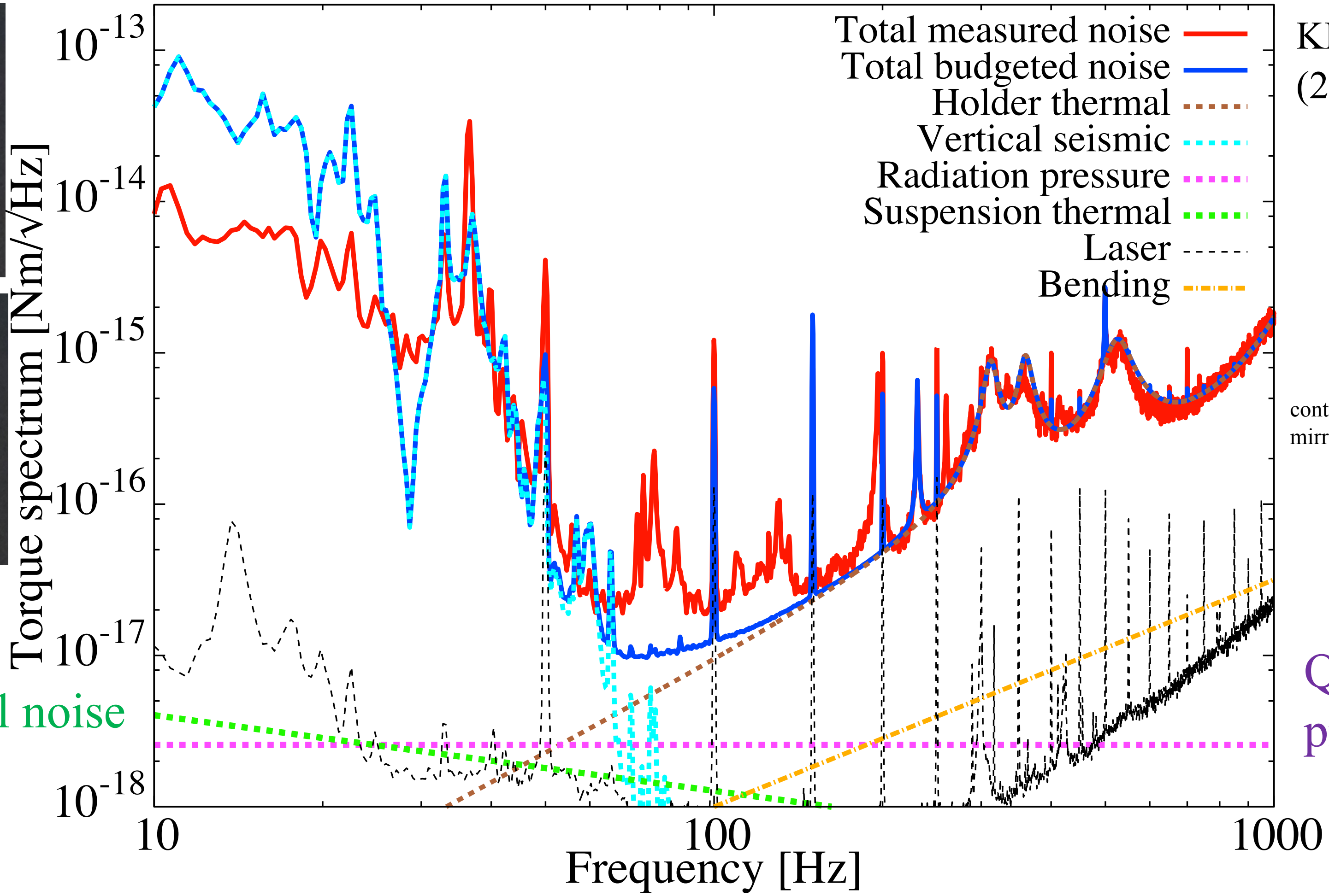
PRL 122, 071101 (2019)

My previous works

➢Best sensitivity of 20 aNm/√Hz in mg-scale torque sensors

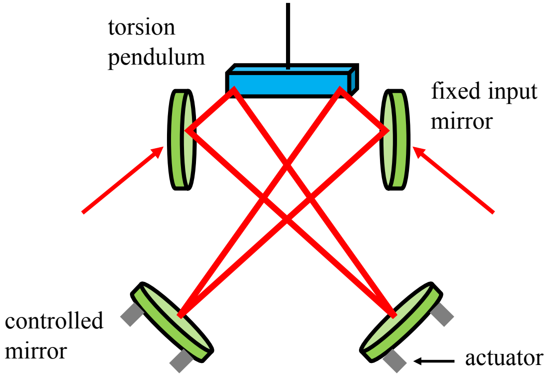






Suspension thermal noise

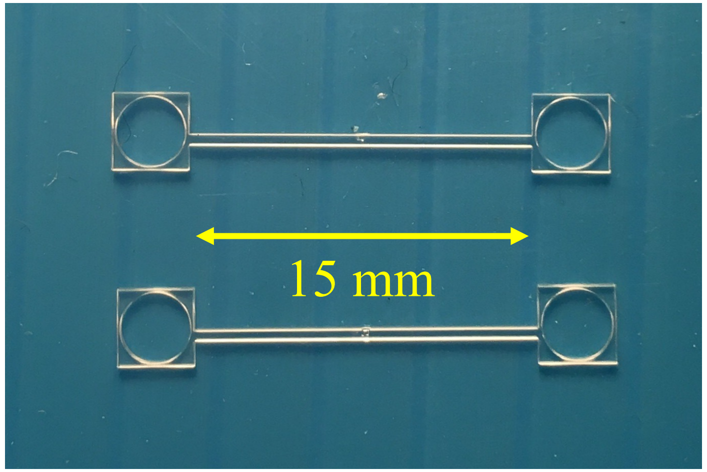
KK+, PRA 101, 011802 (R) (2020)



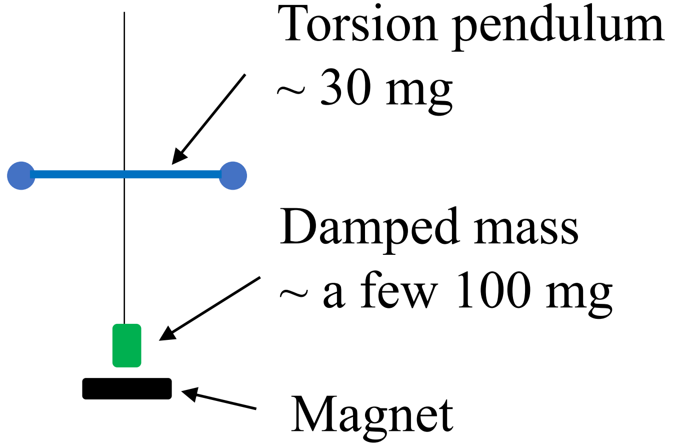
Quantum radiation pressure noise

Current status

- New silica spacer
  - Two holes for the curved mirror at each edge, made by Opto-science and NSC
- Intensity stabilization on-going

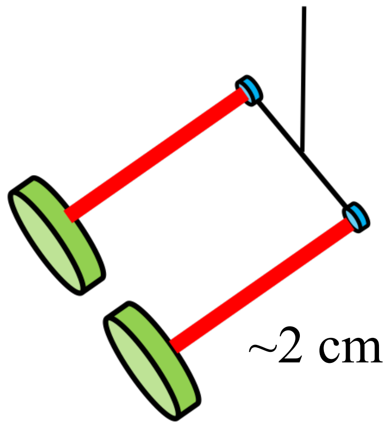


- Will test the new test mass suspension with both ends clamp
  - Damped mass at the bottom is heavier than the torsion pendulum
  - The pendulum mode frequency is increased by a factor of sqrt(mass ratio)
  - Better stability, easier fabrication



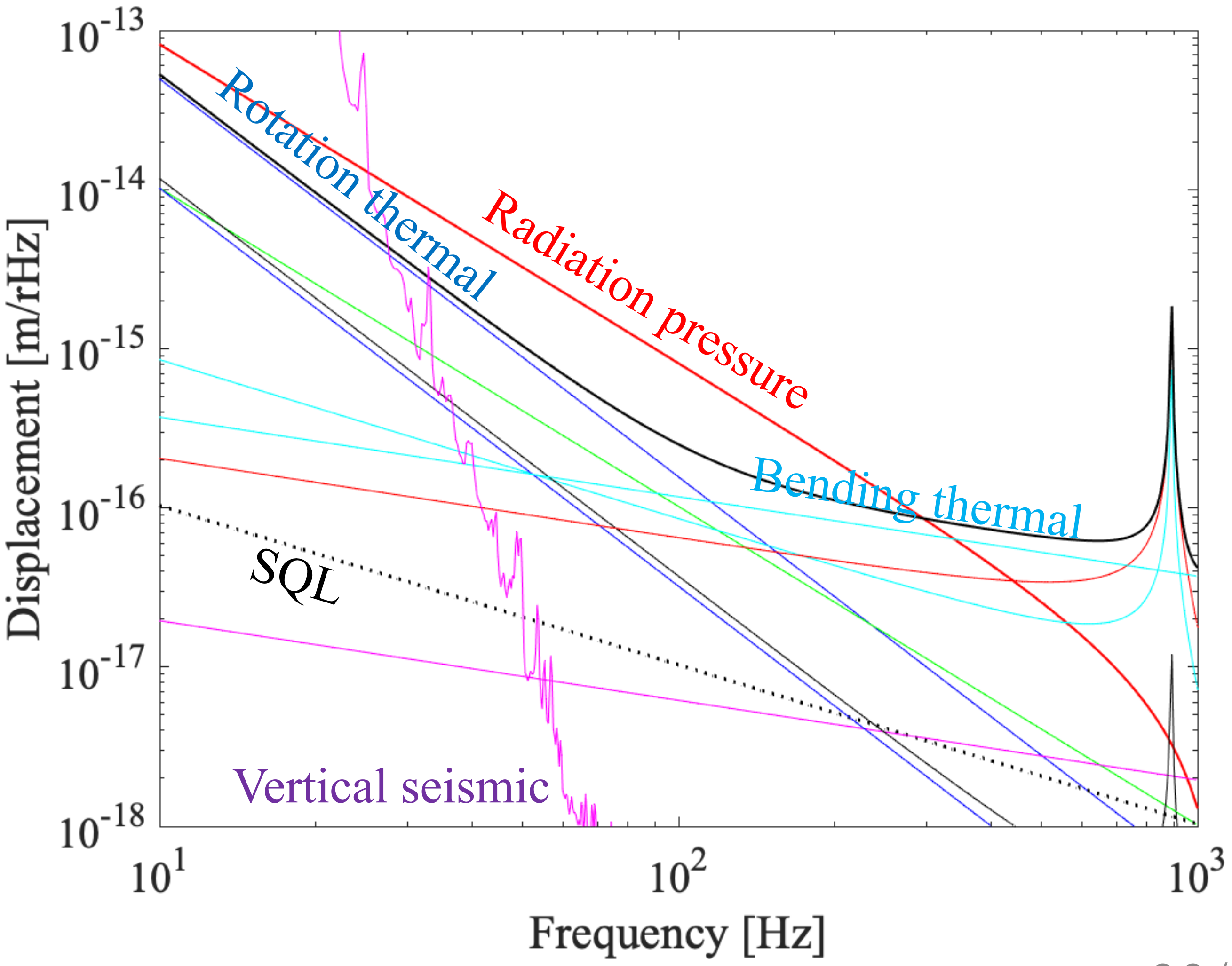
Short cavity

- The negative g-factor is not necessary, which is required for the simple linear cavity
- In the case of the torsion pendulum, the optical springs at the edges overwhelm the anti torque spring
- That we can shorten the cavity is another advantage of the torsion pendulum in terms of the frequency noise



Design sensitivity

- ➢Radiation pressure dominant from 30 Hz to 300 Hz
- ➢Vertical seismic noise at low frequencies
- ➢Bending (Bar) thermal noise at high frequencies

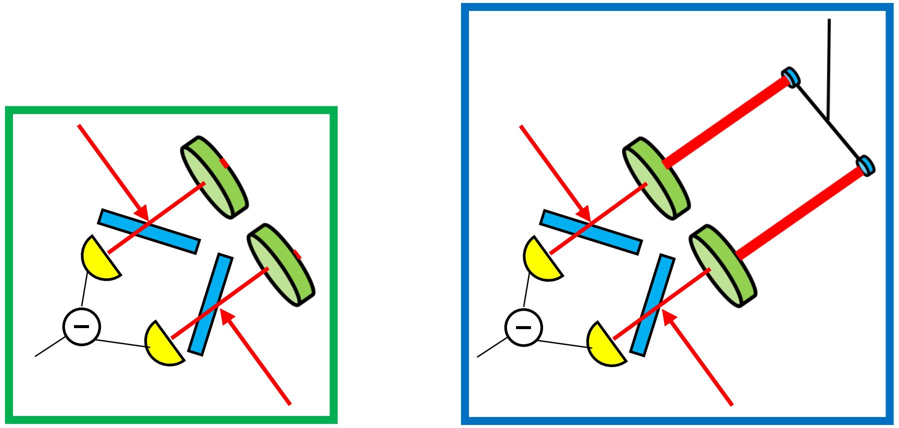


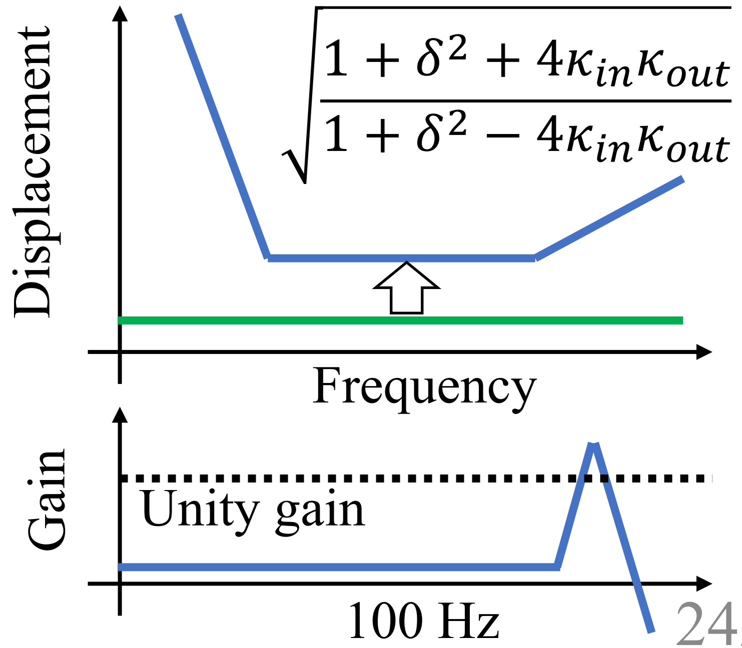
Measured spectrum

- ➢Targeting frequency is around 100 Hz, which is much smaller than the optical spring frequency ~ 1 kHz

- ➢Feedback only around the optical spring with small openloop gain at 100 Hz (error signal measurement)

- ➢Slight increasing of the floor compared to the shot noise without the cavity
  - A factor of ~ 1.3 with $\kappa_{in} = 0.9, \delta = 1/\sqrt{3}$





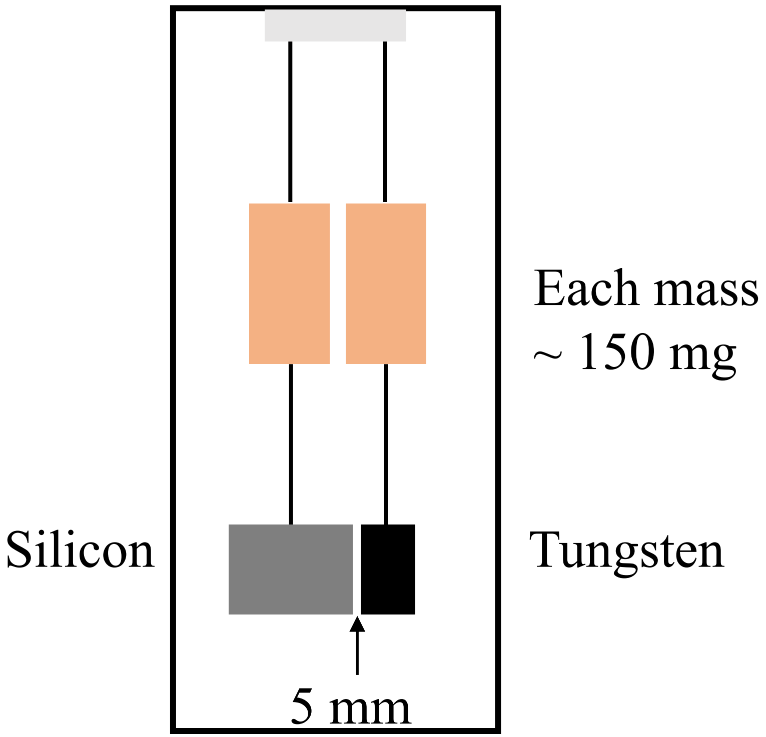
B-L dark matter

- $U(1)_{B\text{-}L}$ symmetry
- Different atoms feel different force
- Displacement of an optical cavity consisting of test masses made of different materials
- No experiments specifically targeting at the test

Design

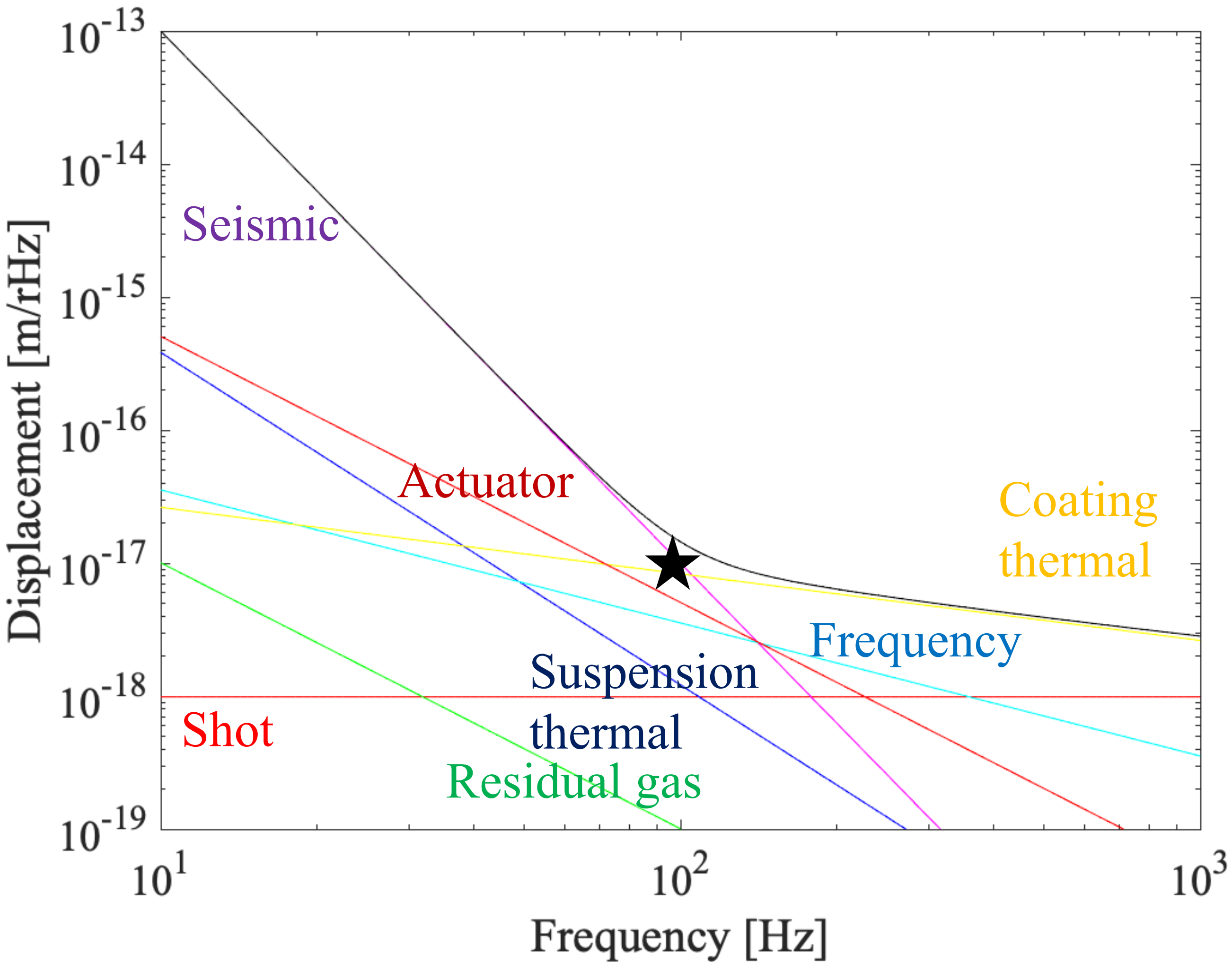
- Suspension
  - The double pendulum chain is separated in Ono-kun's suspension

- Optical parameters
  - Input power: 5 mW
  - Cavity finesse: 3000
  - Cavity length: 5 mm
  - Side lock at the normalized detuning of $1/\sqrt{2}$
  - Intensity stabilization to the shot noise
  - Frequency stabilization by 3 orders of magnitude



Design sensitivity

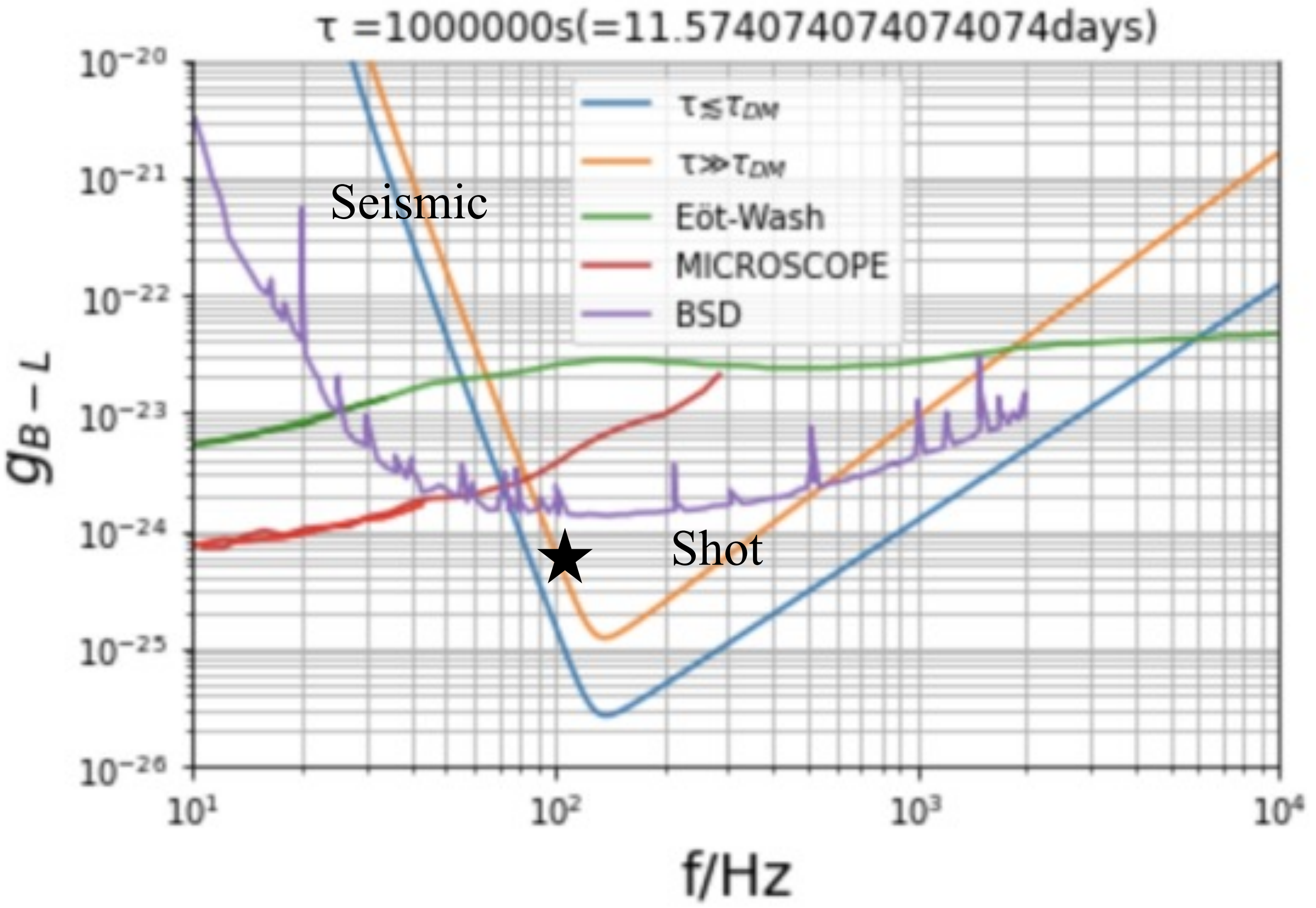
- Target: 1e-17 m/√Hz at 100 Hz
  - The seismic, coating thermal, and actuator noises are critical
  - The frequency noise is not dominant thanks to the short cavity length
  - AlGaAs coating can reduce the coating thermal noise drastically



Upper limit

- $g_{B-L} < 5e\text{-}25$ at 100 Hz
  - Beyond the previous works
  - Only 10 days

- Further improvement
  - More seismic isolation
  - AlGaAs coating
  - Longer operation



Tsuboi-kun's report

Time schedule in 2023

	Q1	Q2	Q3	Q4
Long SRC	Experiment →		Paper writing →	Preparation of MHz detector →
Optomecha	Intensity stabilization →	Both clamp test →	Construction →	Cavity lock →
B-L	Design →	Construction →	Comissioning →	Operation →

Summary

- LSRC
  - Improving the interferometer
  - Aiming at completing the experiment by September
  - MHz detector in the table top scale, kHz detector in TAMA-300

- Optomechanical torsion pendulum
  - Recovering the setup with the improved configuration

- B-L
  - Nice science with the realistic parameters