Intracavity amplifier for the high-frequency gravitational-wave detection

kHz detector workshop@Tsinghua University

Jul 2023

Tokyo Tech

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Self introduction

2004 PhD on control of detuned RSE

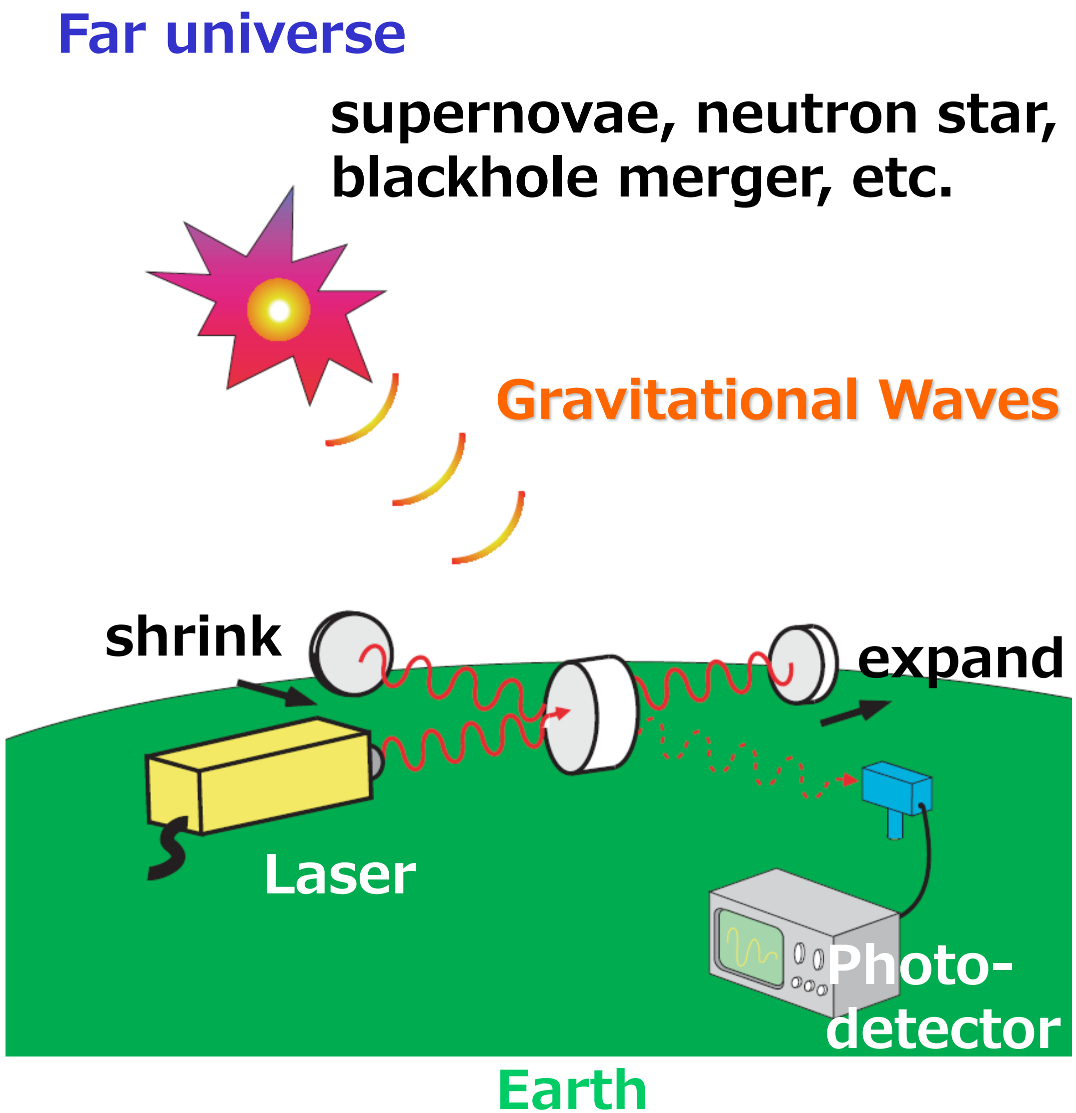
2005-07 AEI Potsdam
- Macroscopic Quantum Measurement
- aLIGO LSC development

2008-09 Caltech
- AEI 10m prototype design
- Finite-size coating thermal noise

2010- Japan (Waseda, Tokyo Tech)
- KAGRA design, SEO, IFI, OFI, OMC
- Parametric amplifier
- KAGRA+ and some other subjects

Home: Tokyo
Family: wife and son (6y)

Laser interferometric GW detector



Massive astronomical events

⇩

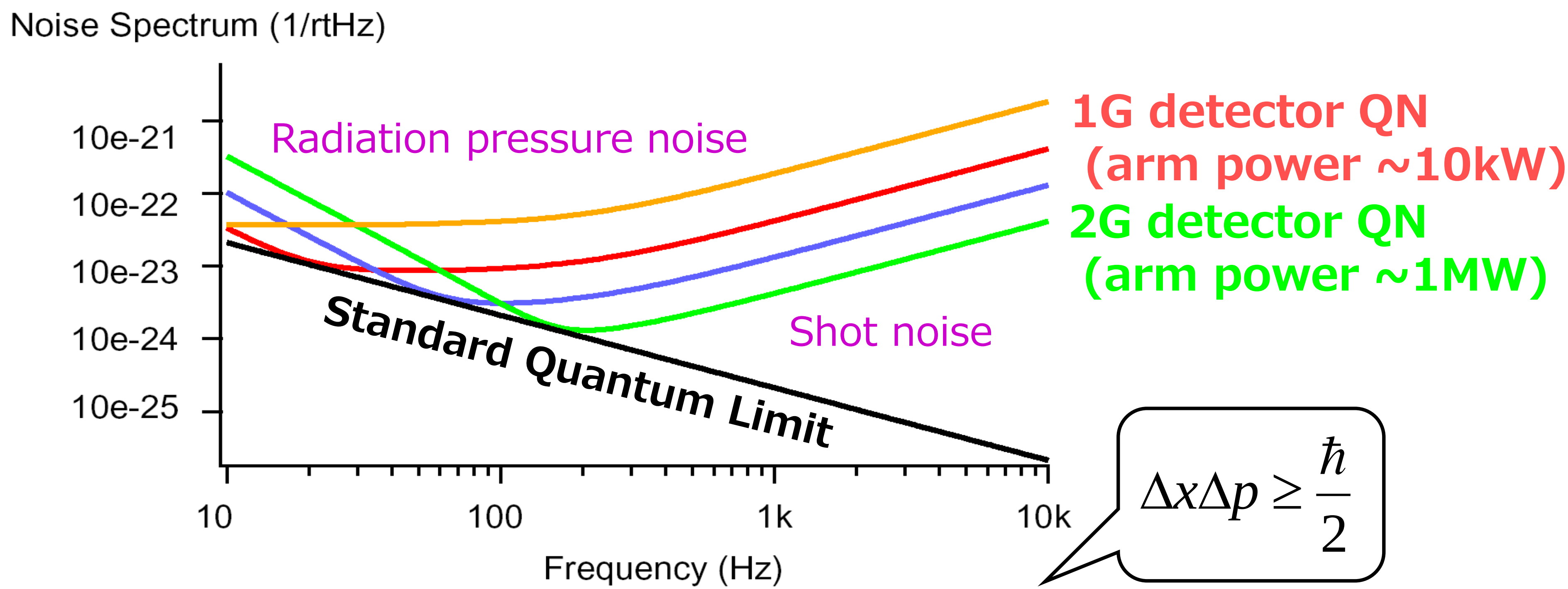
Optical path length changes

⇩

Can be observed by a large interferometer

- LIGO in US+India [4km]
- Virgo in Italy [3km]
- GEO in Germany [600m]
- KAGRA in Japan [3km]
- NEMO in Australia [4km]
- ET and CE [10~40km]

Quantum noise in GW detector



High precision —Uncertainty Principle→ **Back action**

||

Shot noise reduction w/high power laser

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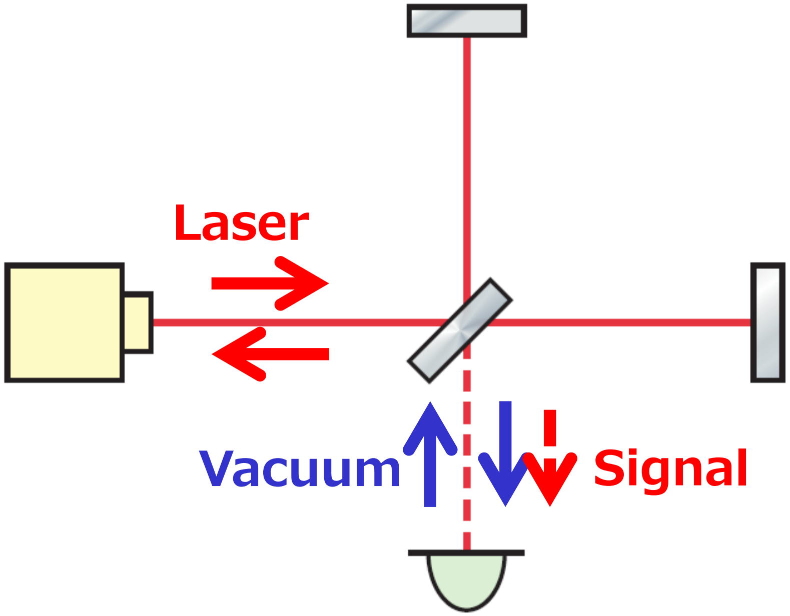
Radiation pressure

There is a limit that cannot be exceeded by simply increasing laser power.

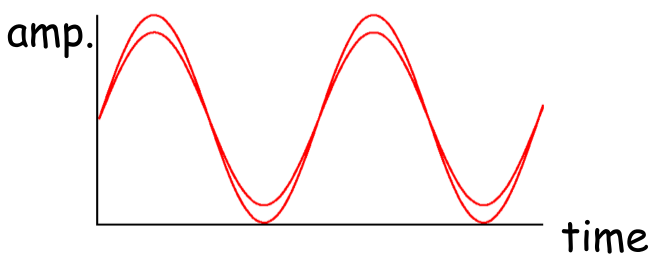
Source of quantum noise

(SQL=Standard Quantum Limit)

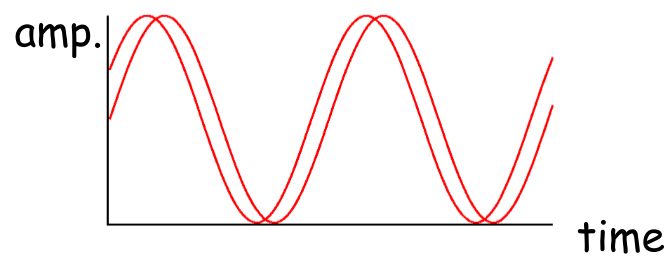


Vacuum field consists of amplitude and phase fluctuations.

SQL derives from a commutator of these two components.



photon number fluctuation
↓
radiation pressure noise

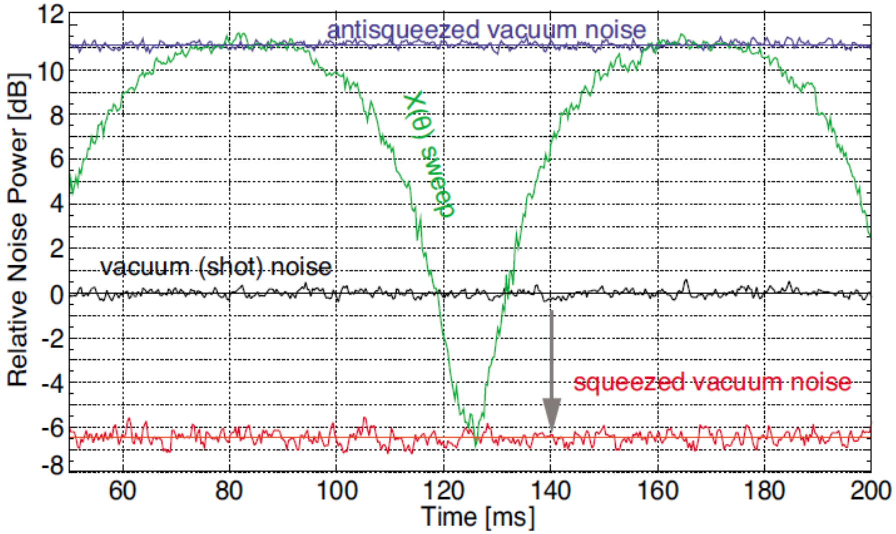


phase fluctuation
↓
shot noise

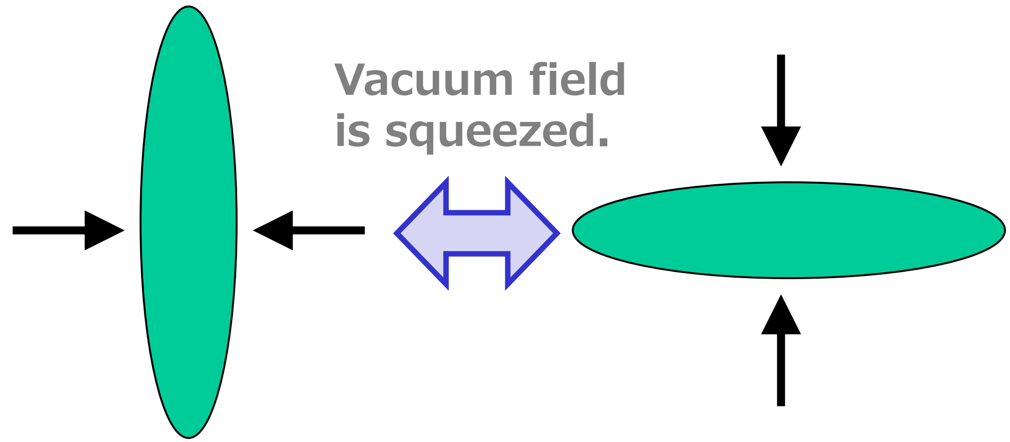
Optical squeezing

(RP=Radiation Pressure
LF=Low Frequency
HF=High Frequency)

[Mehmet, Opt.Lett. (2010)]



7dB squeezing



shot noise is low

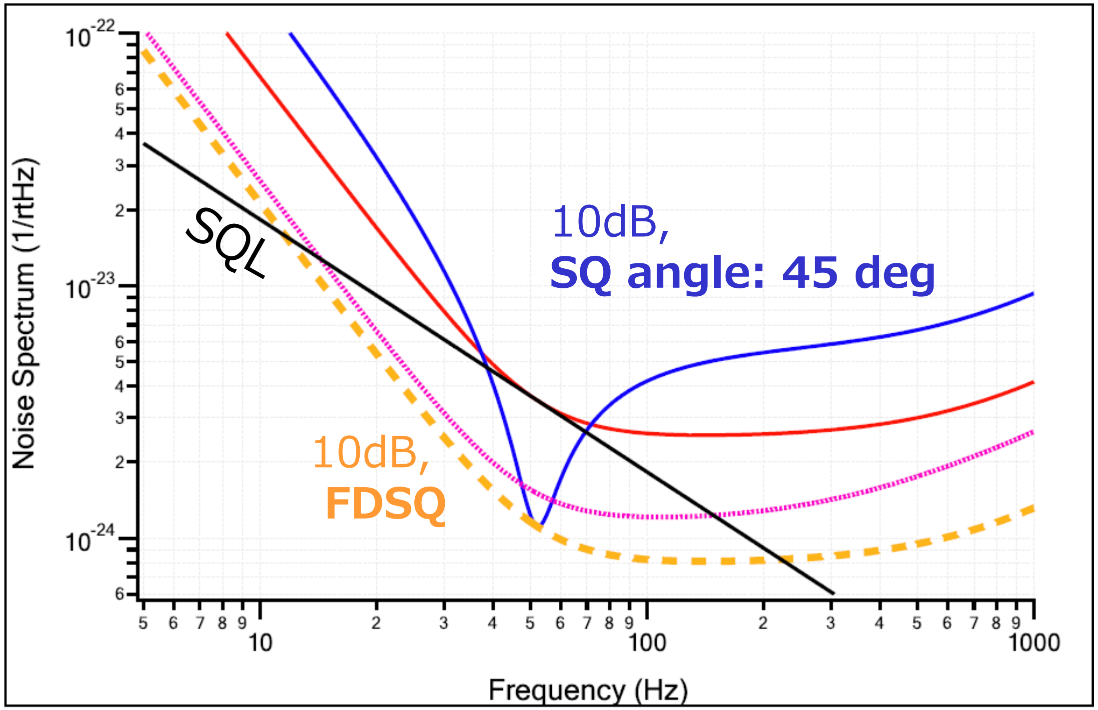
RP noise is low

Optical parametric amplification process creates a correlation in upper and lower sidebands.

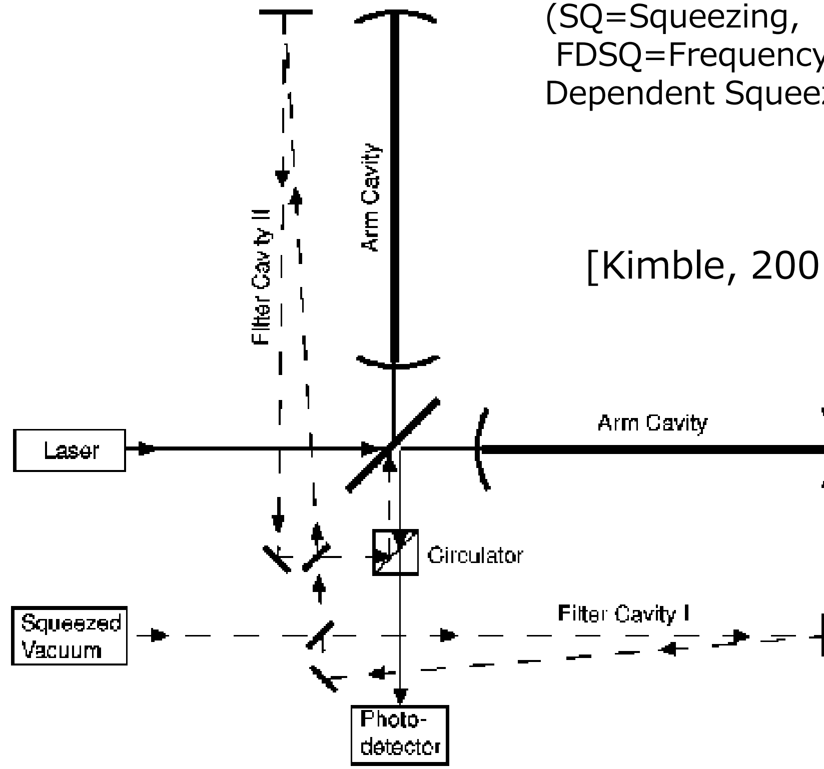
Sensitivity improves either at LF or HF according to the choise of the squeezing angle.

Frequency-dependent squeezing

orage: lossless, pink: with loss



(SQ=Squeezing, FDSQ=Frequency-Dependent Squeezing)



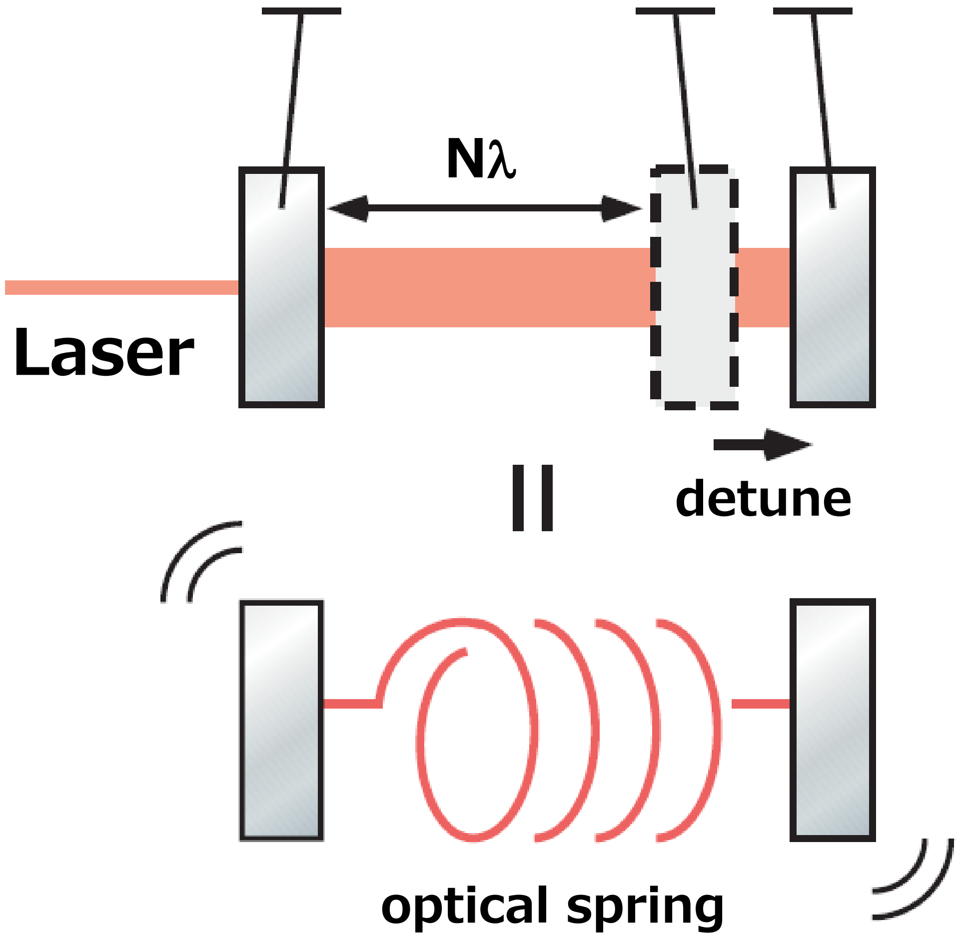
[Kimble, 2001]

- **SQ angle is rotated in filter cavities**
- **Rotation angle depends on the frequency**

This technique has been installed in LIGO & Virgo.

Optical spring

(RP=Radiation Pressure
GW=Gravitational Wave
OS=Optical Spring)



Far from reso → less RP

Approach to reso → more RP

⇩

Optomechanical restoring force

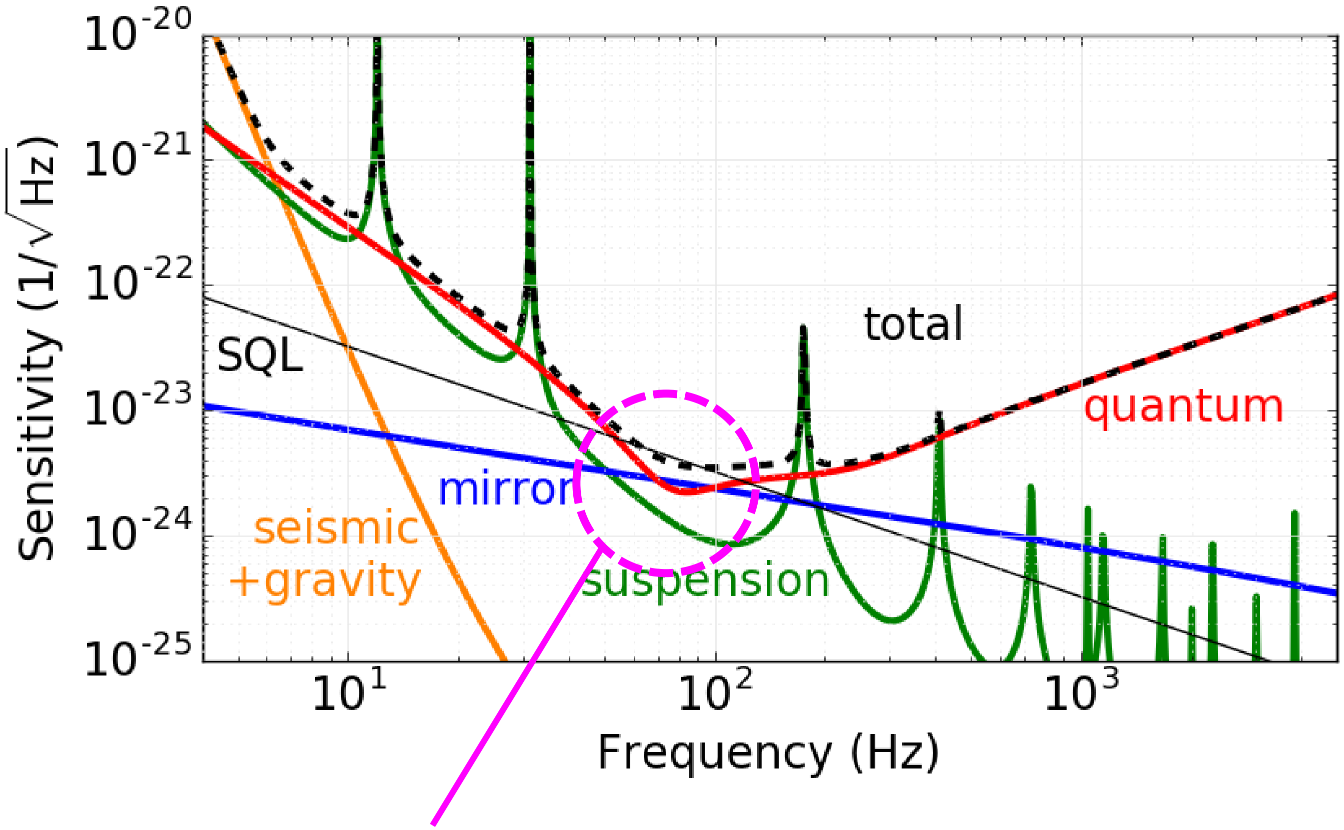
GW response increases at OS resonance and the sensitivity can exceed SQL.

KAGRA plans to implement this technique.

Optical spring

(QN=Quantum Noise
NS=Neutron Star
SQL=Standard Quantum Limit
HP=Home Page)

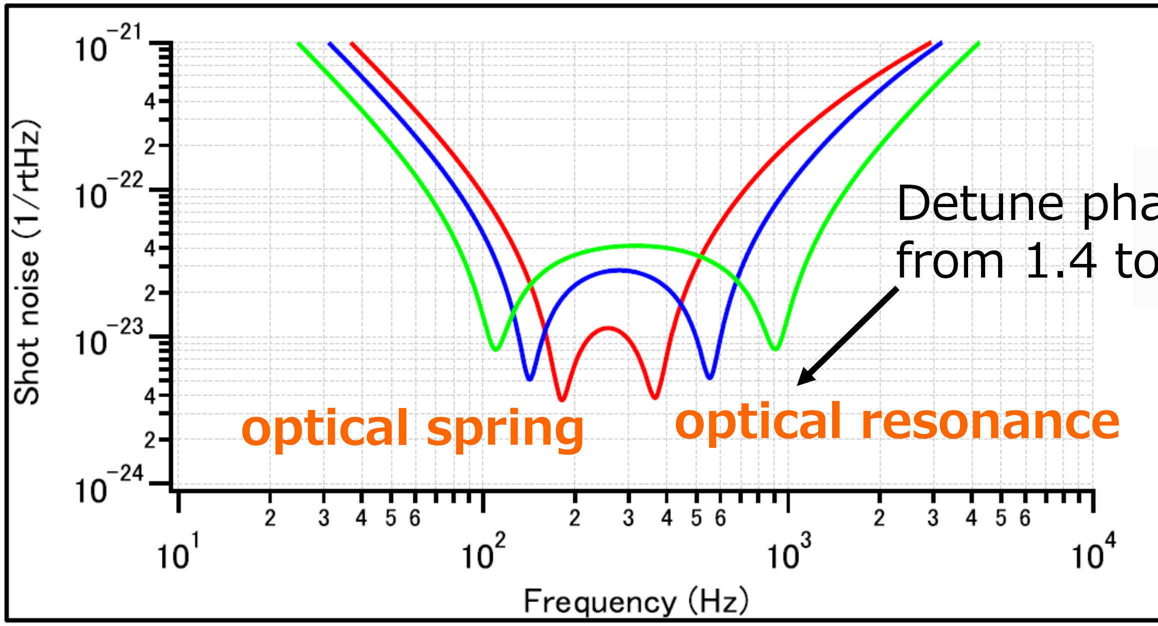
KAGRA design sensitivity



[KAGRA HP]

QN exceeds the SQL at the optical spring frequency.
⇒ 20% sensitivity improvement to observe binary NS.

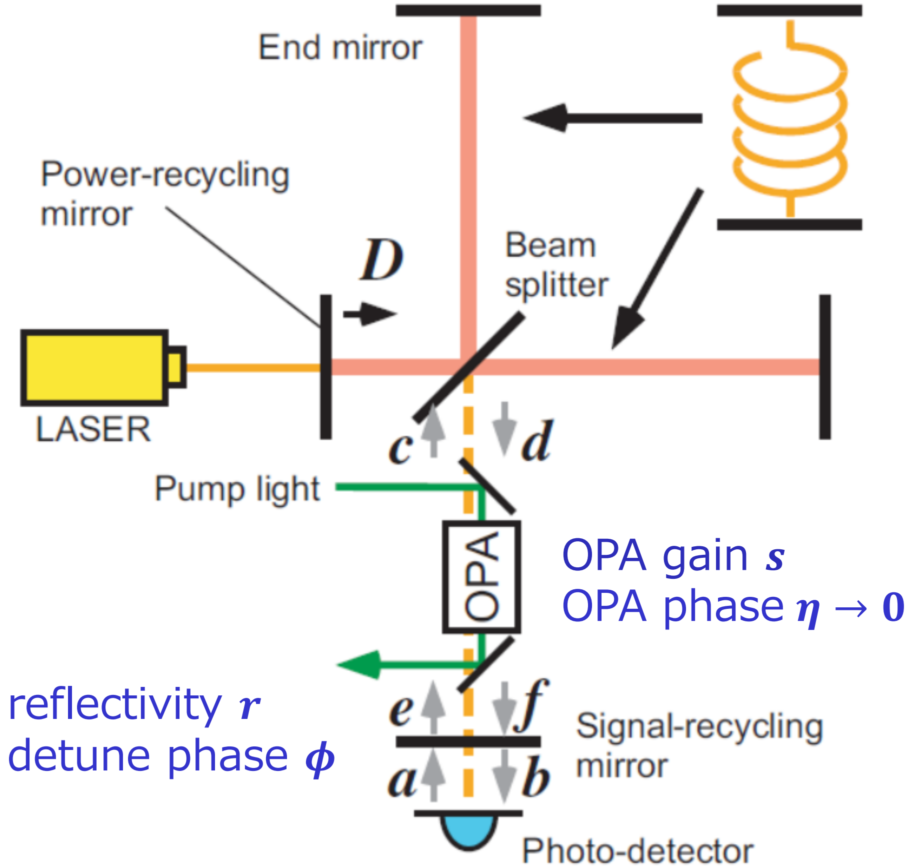
Can we have optical spring at kHz?



Optical spring $\Omega \propto \sqrt{\dfrac{\sin 2\phi}{\left(r + \frac{1}{r}\right) - 2\cos 2\phi}}$ decrease with the detune phase ϕ

Optical resonance $\Omega \propto \dfrac{\sin 2\phi}{\left(r + \frac{1}{r}\right) + 2\cos 2\phi}$ increase with the detune phase ϕ

Parametric signal amplification



Optical spring w/o OPA

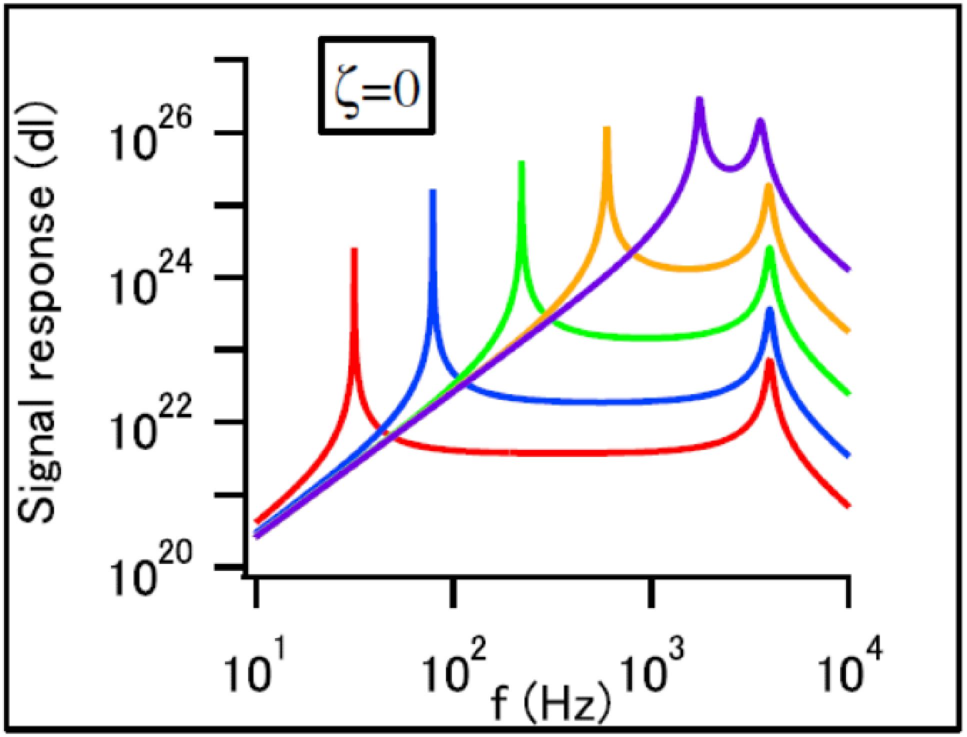
$$\Omega_{os} \propto \sqrt{\frac{\sin 2\phi}{\left(r + \frac{1}{r}\right) - 2\cos 2\phi}}$$

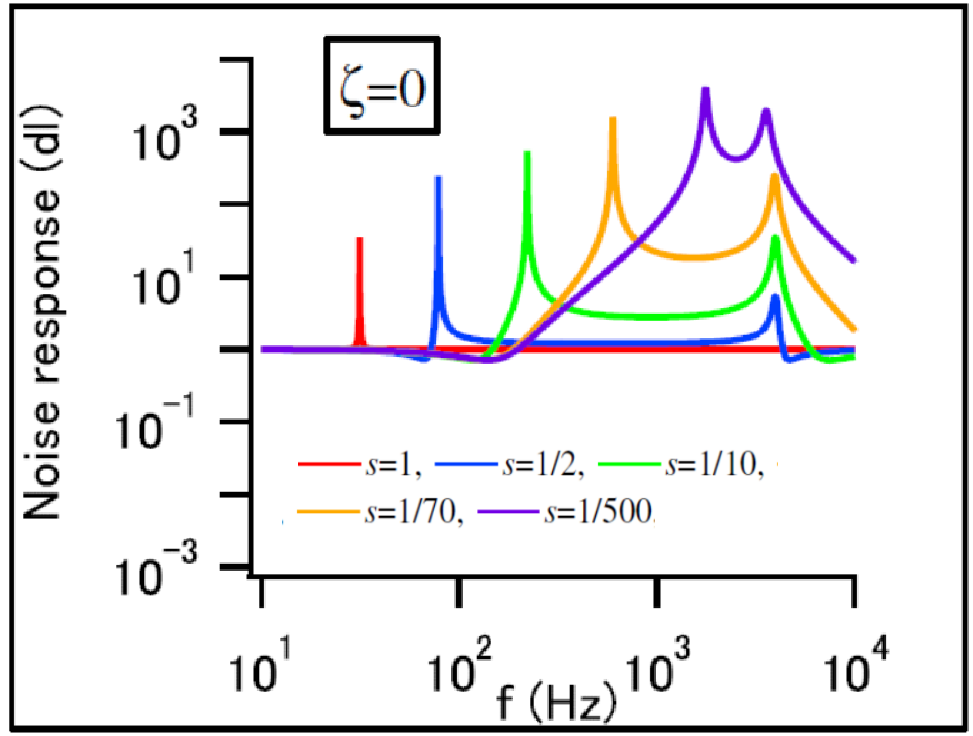
Optical spring with OPA

$$\Omega_{os} \propto \sqrt{\frac{\frac{1}{s}\sin 2\phi}{\left(r + \frac{1}{r}\right) - \left(s + \frac{1}{s}\right)\cos 2\phi}}$$

Opt spring freq can be enhanced by tuning OPA gain s

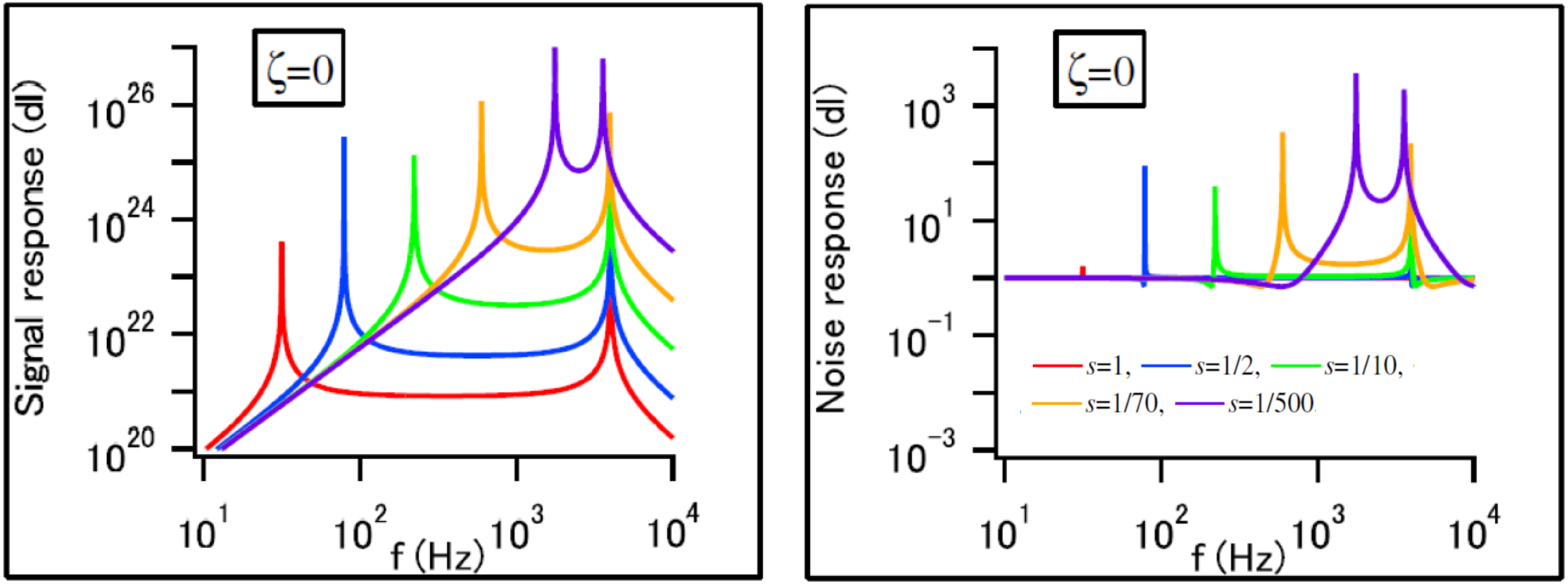
Sensitivity improvement at HF





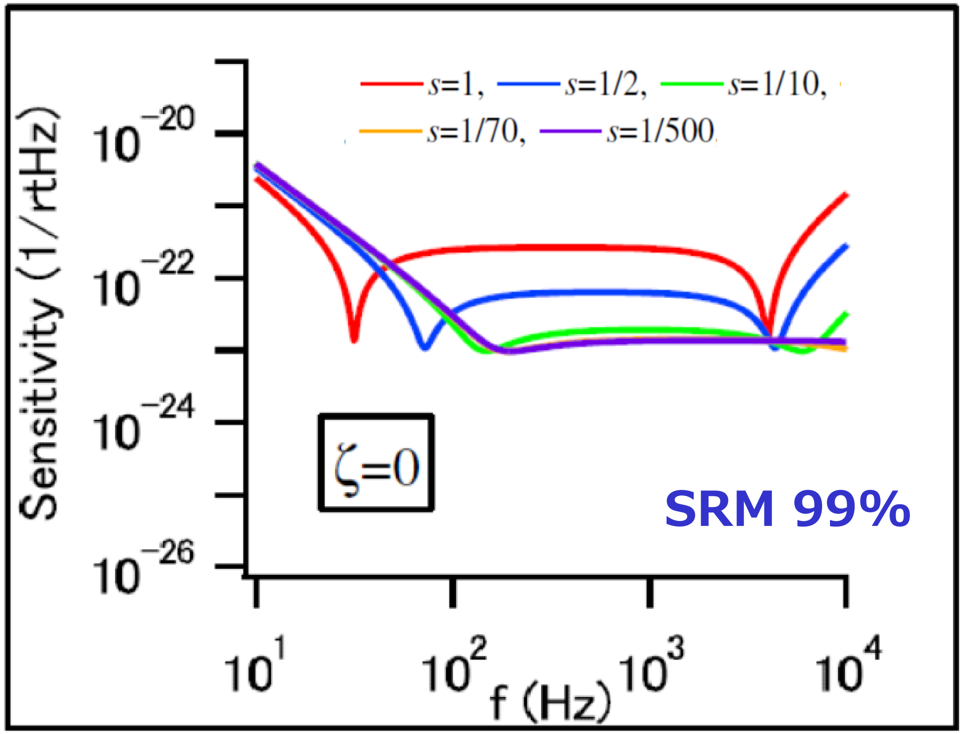
- **Detune phase ϕ is chosen to make the opt reso at 4kHz**
- **Optical losses are not inluced, readout phase is fixed to 0**
- **SRM reflectivity is 99%**
  -> Vacuum from dark port is amplifed as signal at HF $(s \geq 1/10)$
  -> Optical spring does not appear in the sensitivity curve

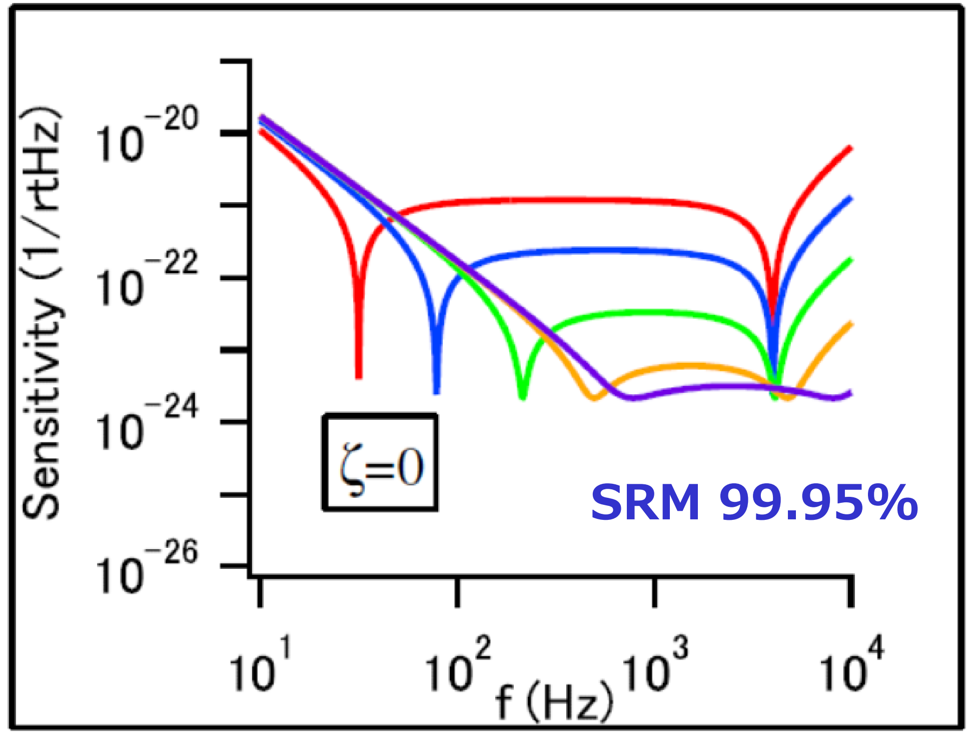
Sensitivity improvement at HF



- Detune phase ϕ is chosen to make the opt reso at 4kHz
- Optical losses are not inluced , readout phase is fixed to 0
- SRM reflectivity is 99.95%
  -> Vacuum from dark port is less amplifed at HF
  -> Optical spring appears in the sensitivity curve

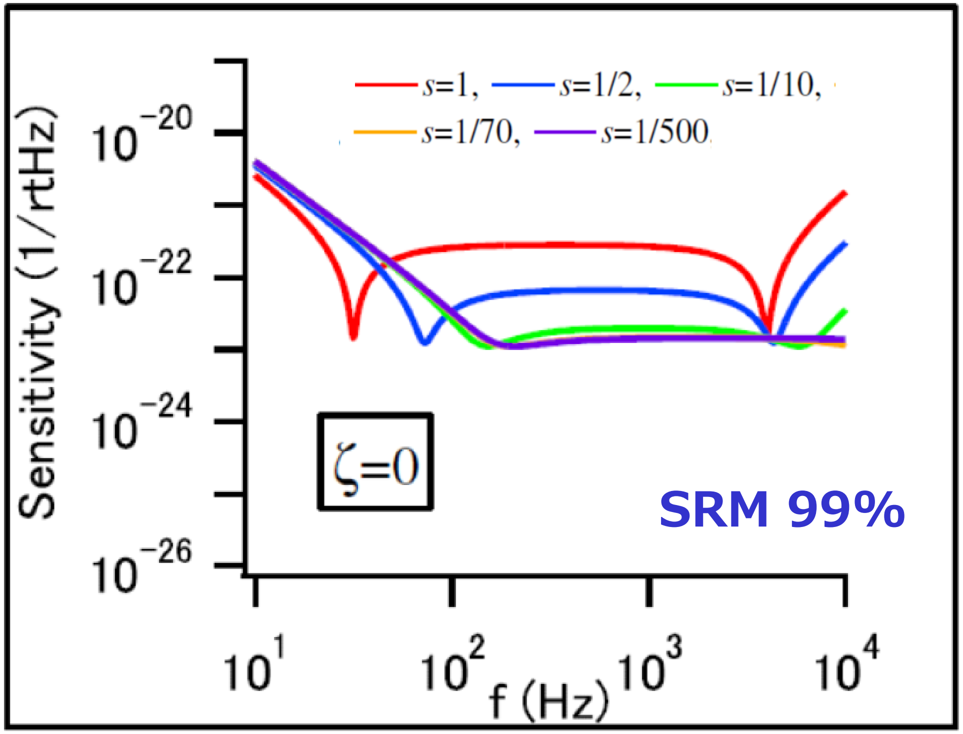
Sensitivity comparison

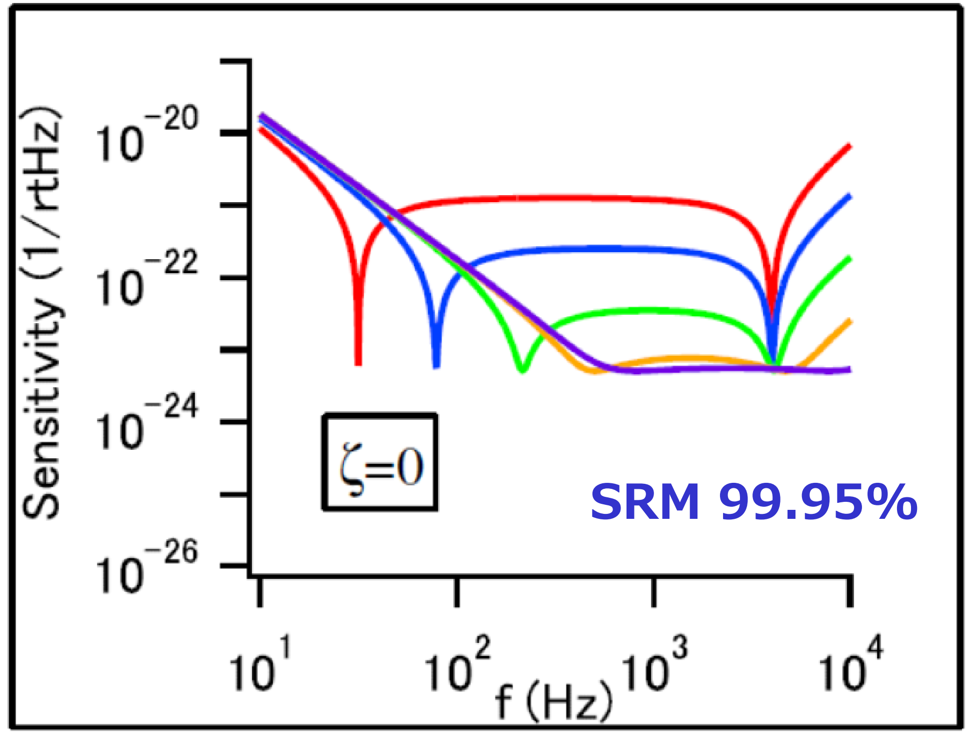




- **HF sensitivity is better with 99.95% SRM**
- **Other parameters: m=1kg, I_{BS}=100kW, readout phase=0**
- **Lossless**

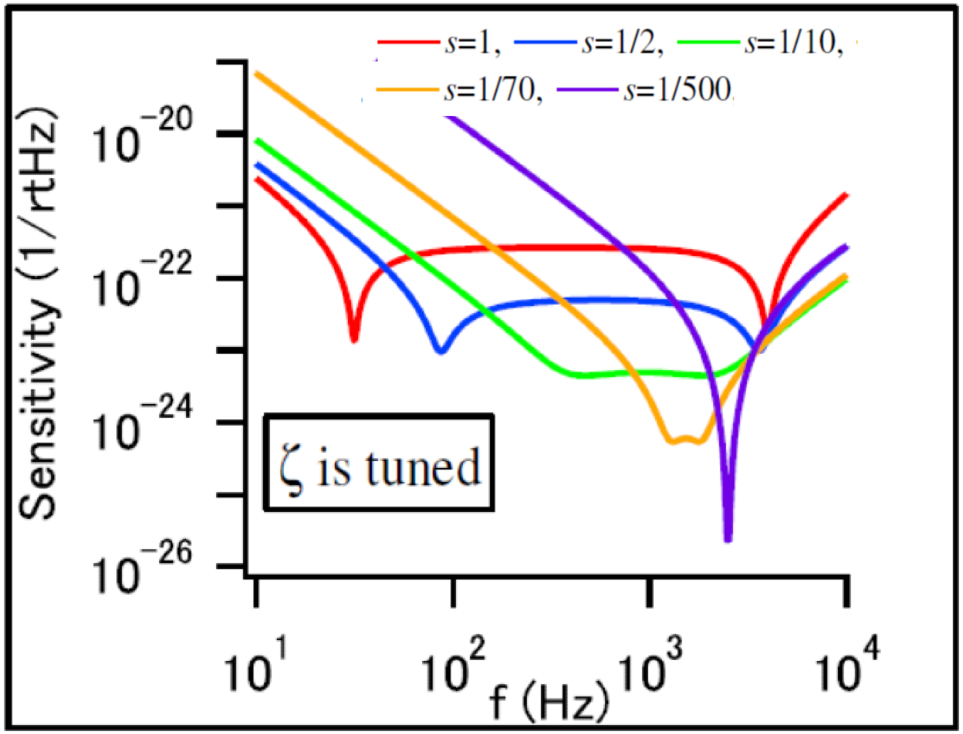
Sensitivity comparison (with loss)

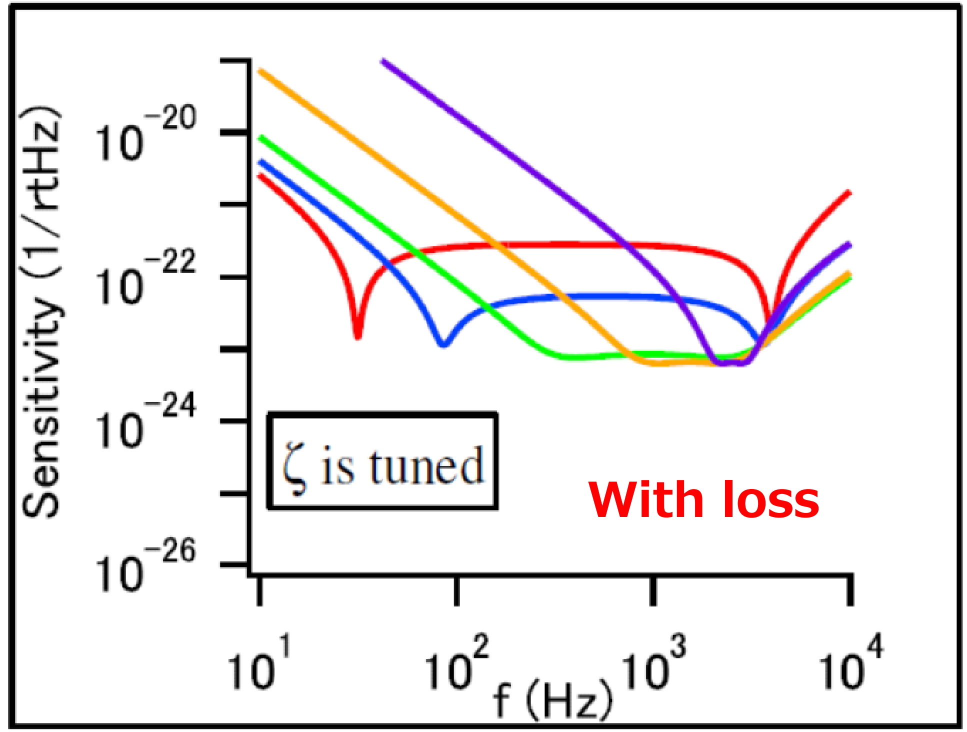




- HF sensitivity is better with 99.95% SRM
- Other parameters: m=1kg, I_{BS}=100kW, readout phase=0
- With loss (1000ppm at SRC and 10% at PD)

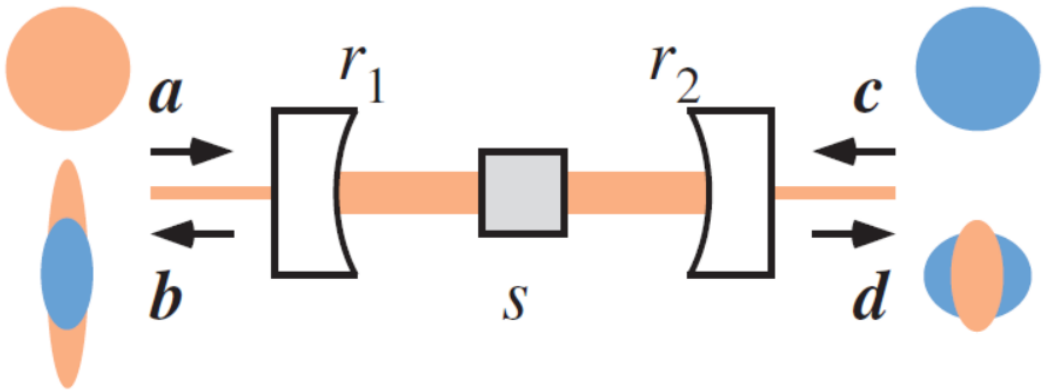
Tuning readout phase ζ



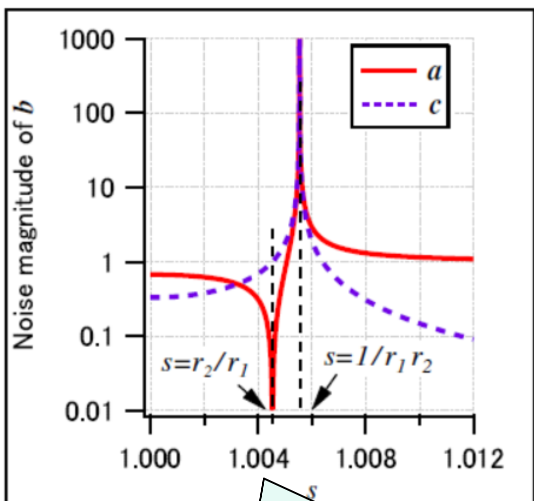


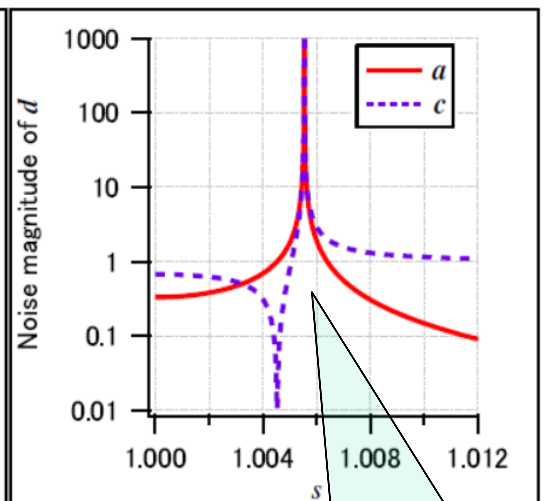
- **Here the SRM reflectivity is 99%**
- **Readout phase ζ is tuned for each OPA gain s (left panel)**
- **In right panel, losses are included; ζ is same as left**
- **Sensitivity improvement is not by signal amplification at opt spring but by ponderomotive squeezing**

Amplification of internal loss



- Let us consider a simple case with a cavity and an intracavity OPA. $r_1 < r_2$.
- Vacuum field a and loss field c enters the cavity and output is b and d.
- Coherent sum of a in b and a in d equals to original a.
- With OPA, each component (a in b or a in d) can exceed the size of a

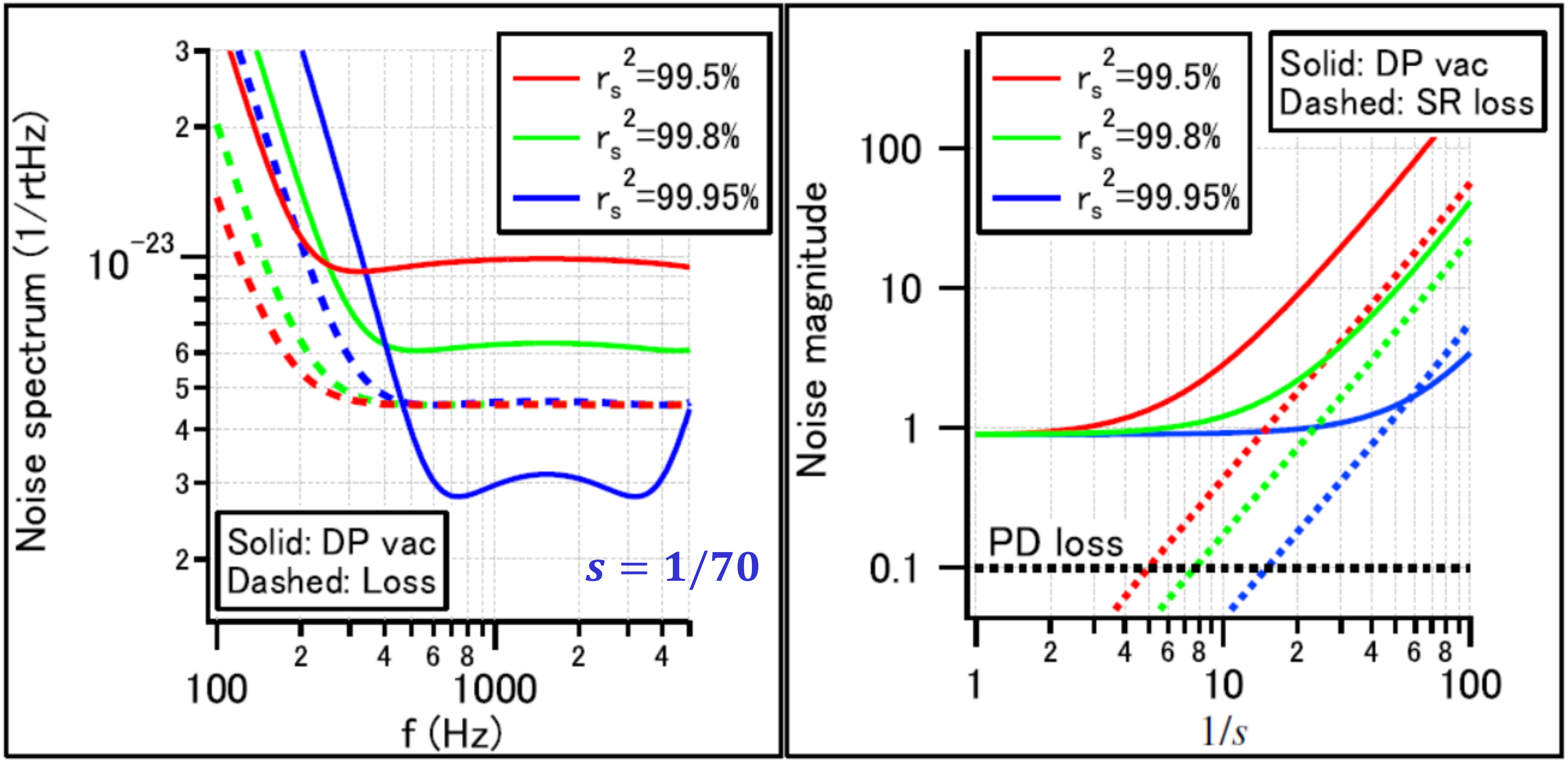




Sign flips at $s = r_2/r_1$.

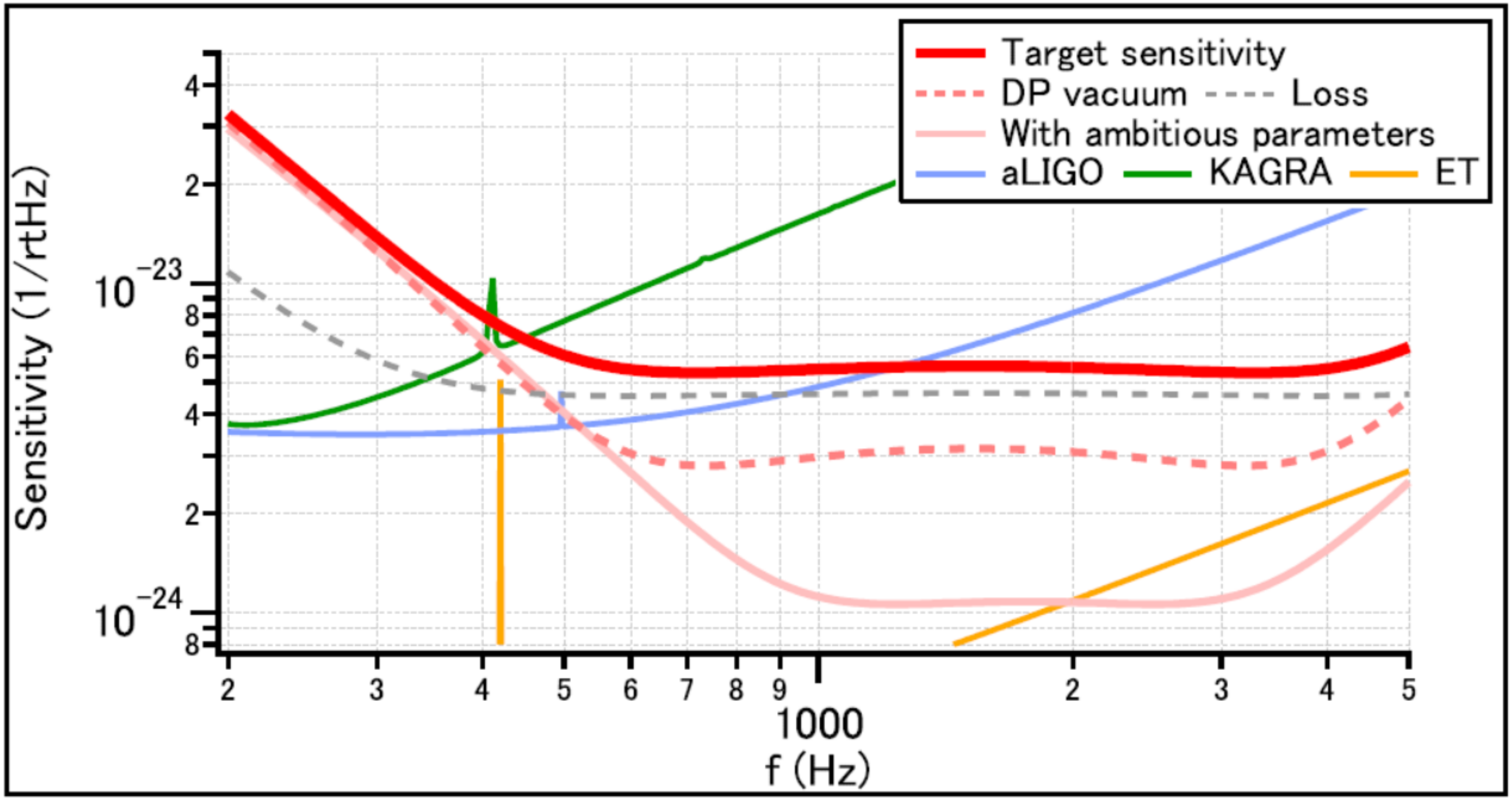
Unstable at $s = 1/r_1 r_2$.

Amplification of internal loss



- **Left: internal loss contribution does not change much with SRM reflectivity (optimal would be 99.95% or so)**
- **Right: noise magnitude (size of noise ellipse) starts increasing after s exceeds the threshold**

Target sensitivity



- **The red solid is the target sensitivity (QN only, with loss, L=1.2km). It is better than aLIGO above 2kHz.**
- **The pink is with ambitious parameters either with 100ppm loss in SRC or with L=3km. Circulating power is 300kW.**

Experimental demonstration

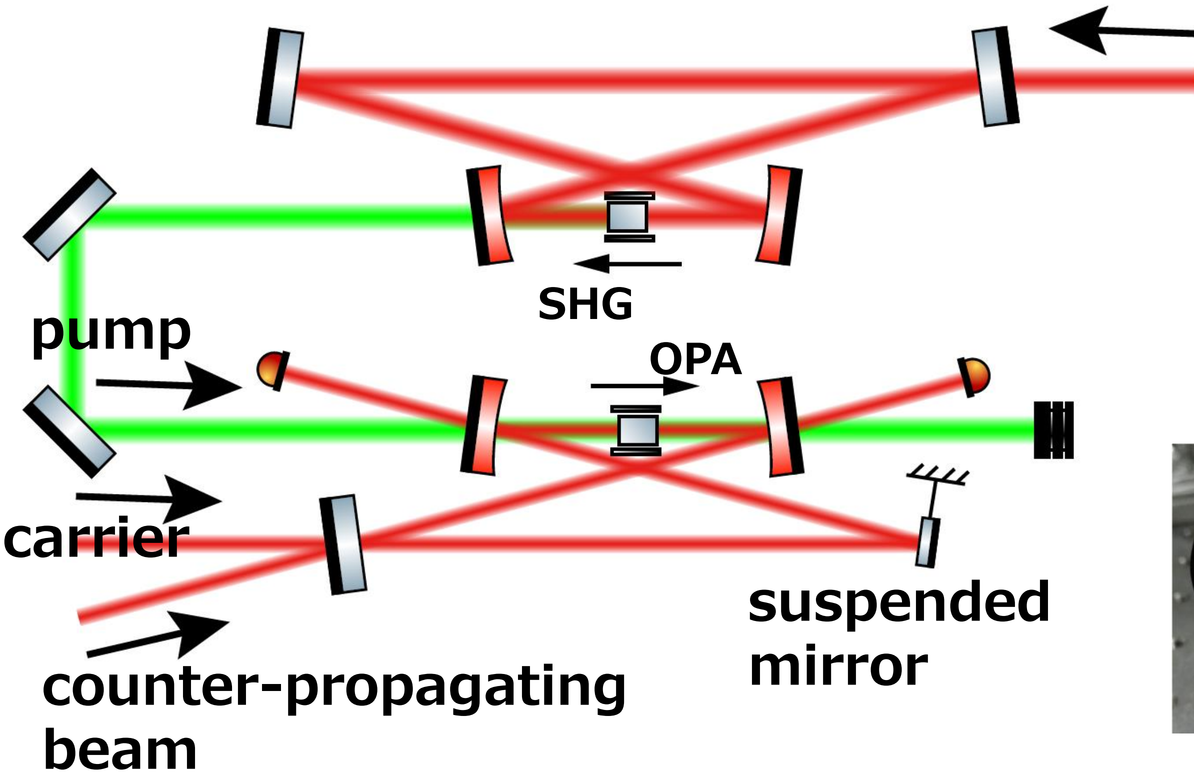
- In 2016, I proposed to implement this technique in GEO600. Prof Danzmann said, "the idea is attractive, we will consider it if two prototype experiments succeeded in a demonstration."

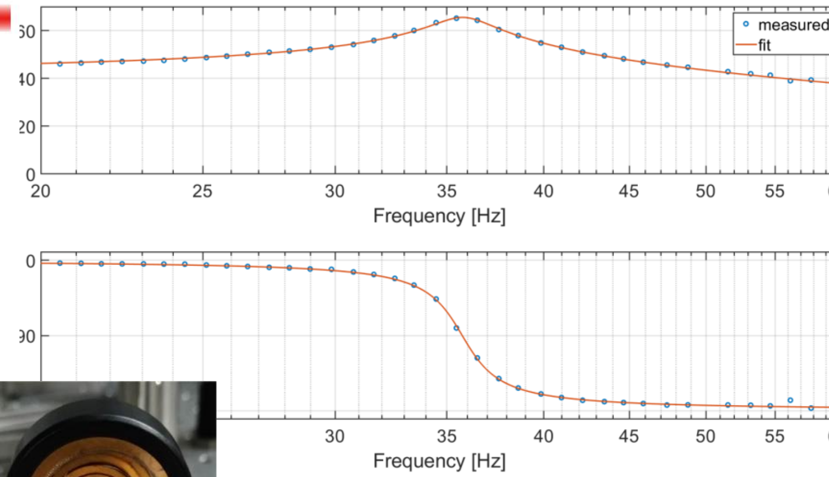
- We have been working on a proof-of-principle experiment with SRMI, aiming at an observation of a shift of optical spring with an intracavity OPA.

- We also performed an experiment of a single Fabry-Perot cavity with intracavity OPA. UWA people performed a similar experiment with a membrane.

(1) A single cavity with OPA

[Otabe, thesis 2023]

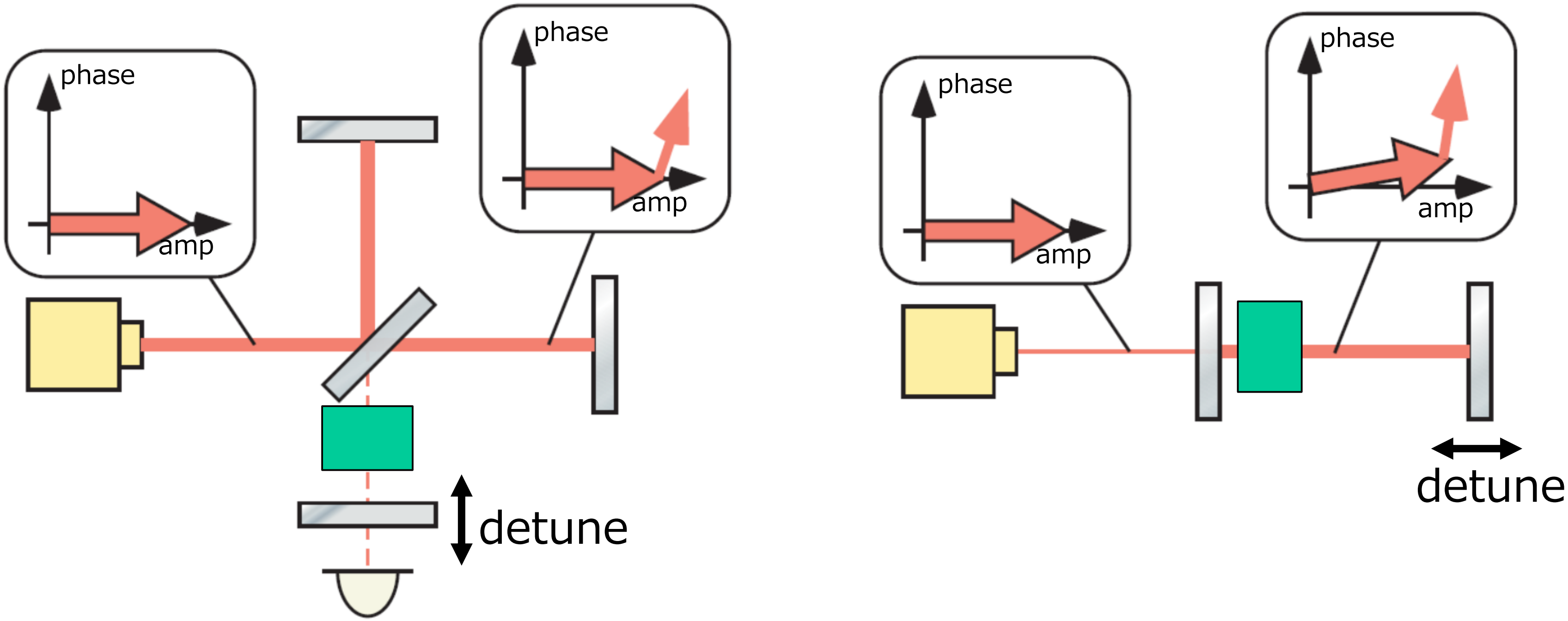




double-sided BeCu spiral spring (m=200mg)

- **Comparing the spectra of carrier and counter-propagating beam, we can see the signal amplification rate by the OPA.**
- **This setup has an advantage to having more power on the suspended mirror, but careful treatment is necessary to properly interpret the result to that with SRMI.**

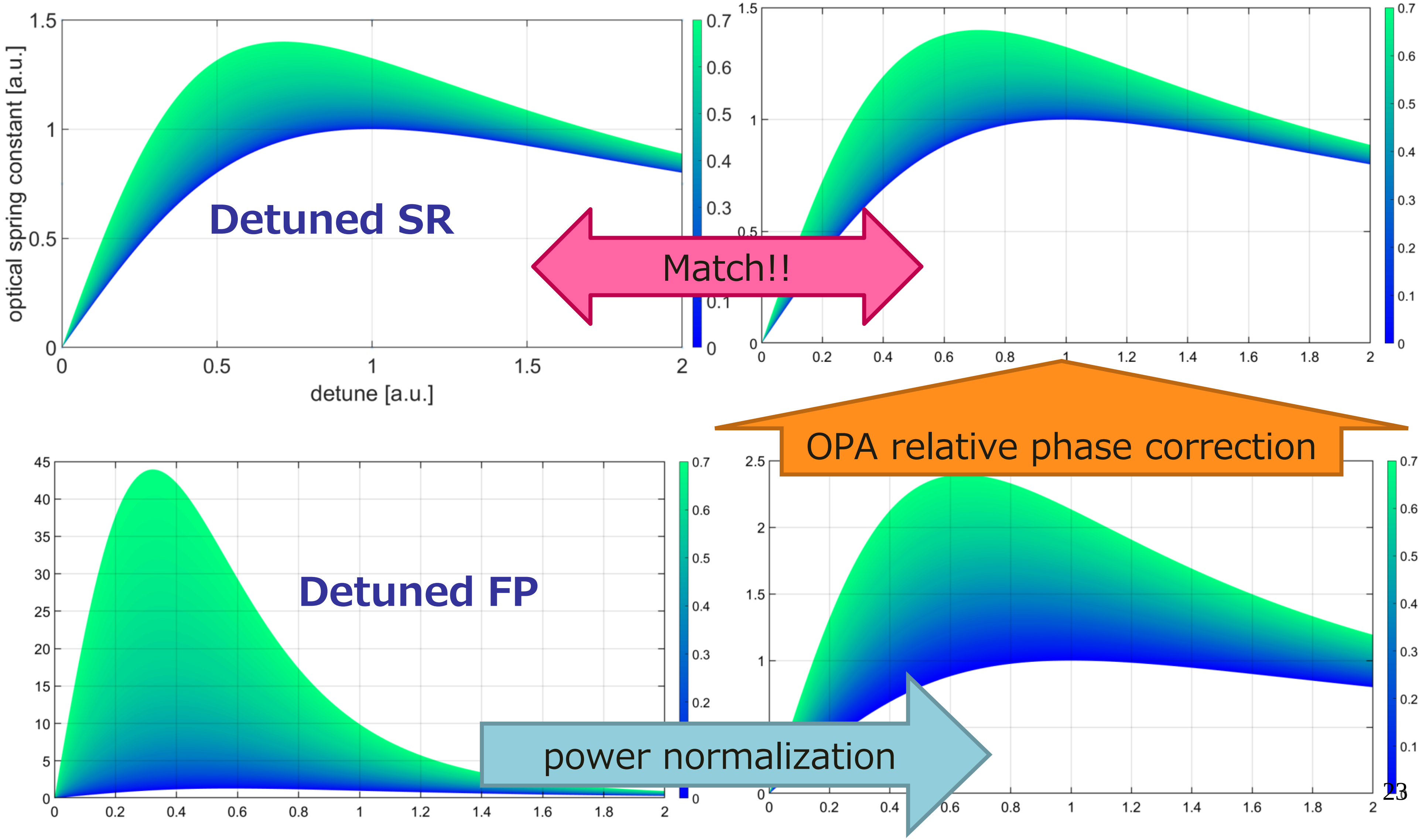
Interpretation to SRMI



- **Treatment 1: intracavity power changes with OPA and it should be normalized to see a net signal amplification rate**
- **Treatment 2: relative phase between carrier and signal changes with OPA and it should be modified for each detuning. [It is not right to maximize the carrier power at each detuning.]**

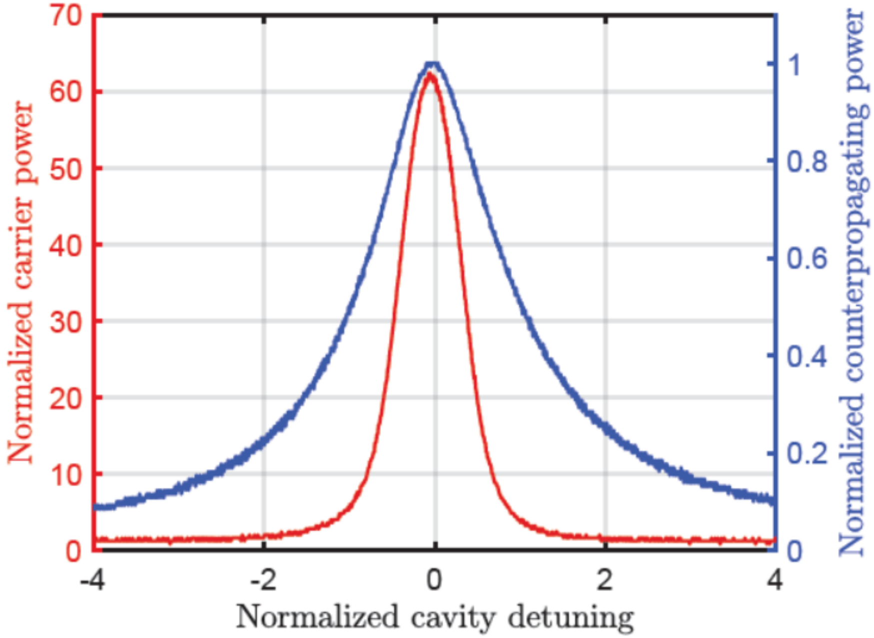
Interpretation to SRMI

[Otabe, 2019]

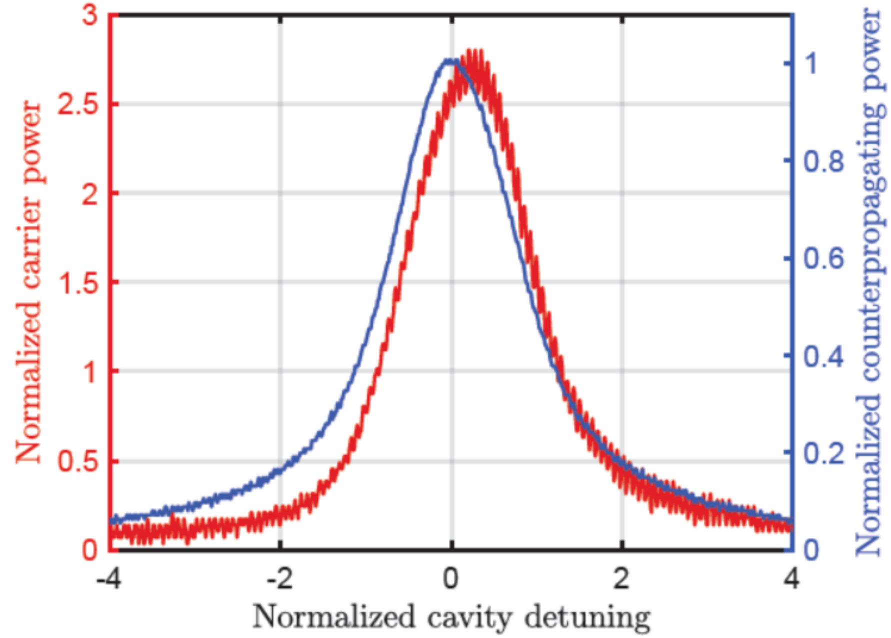


Measured spectrum

[Otabe thesis, 2023]



0.5mW input
power gain=62
signal gain=1.62

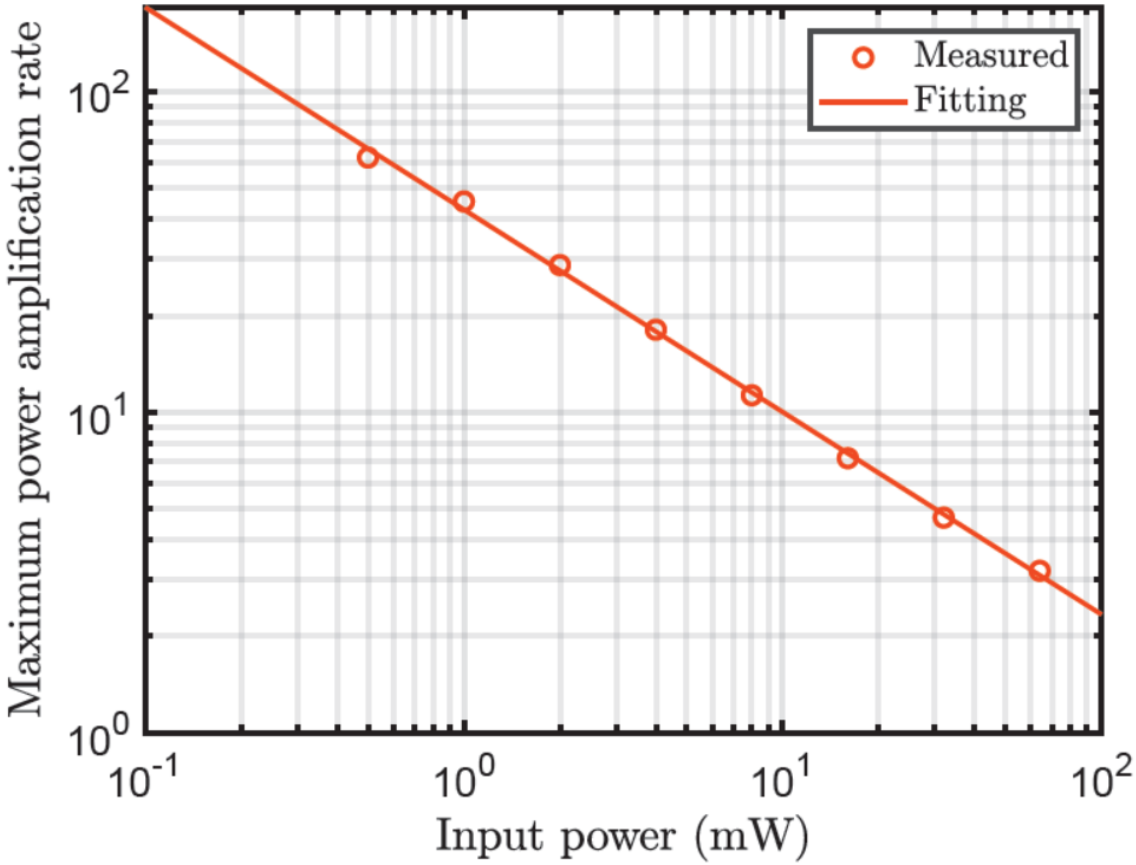


50mW input
power gain=2.7
signal gain=1.08

- **The gain decreases with high input power due to the SHG loss**
- **We observed optical spring with 150mW input and no OPA, so a few mW should be enough to see the amplification effect.**

SHG loss

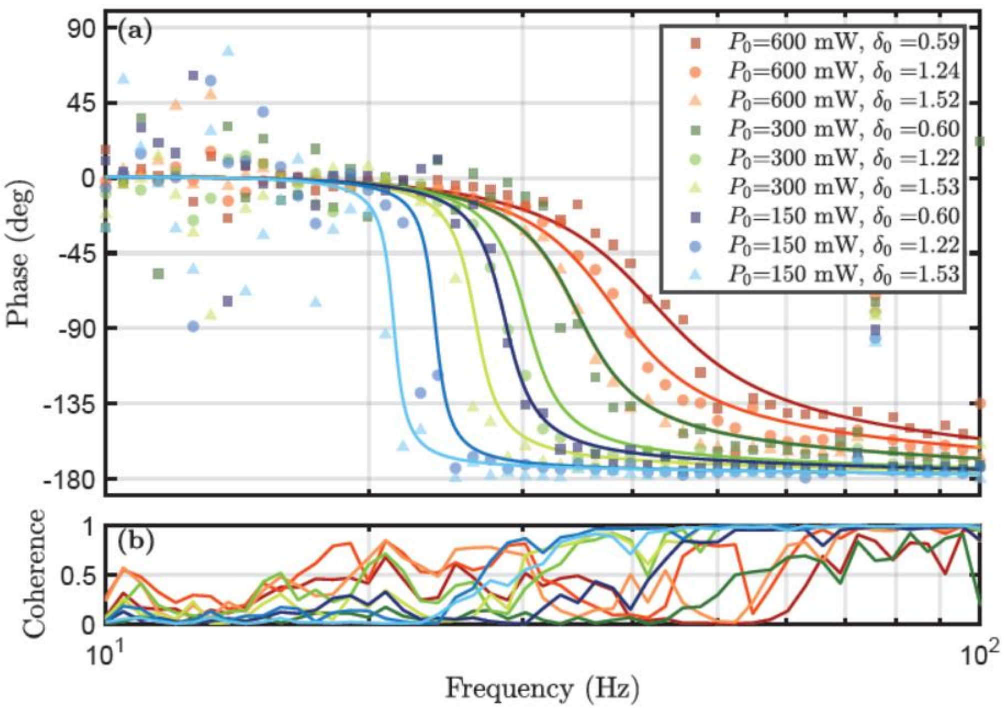
[Otabe thesis, 2023]

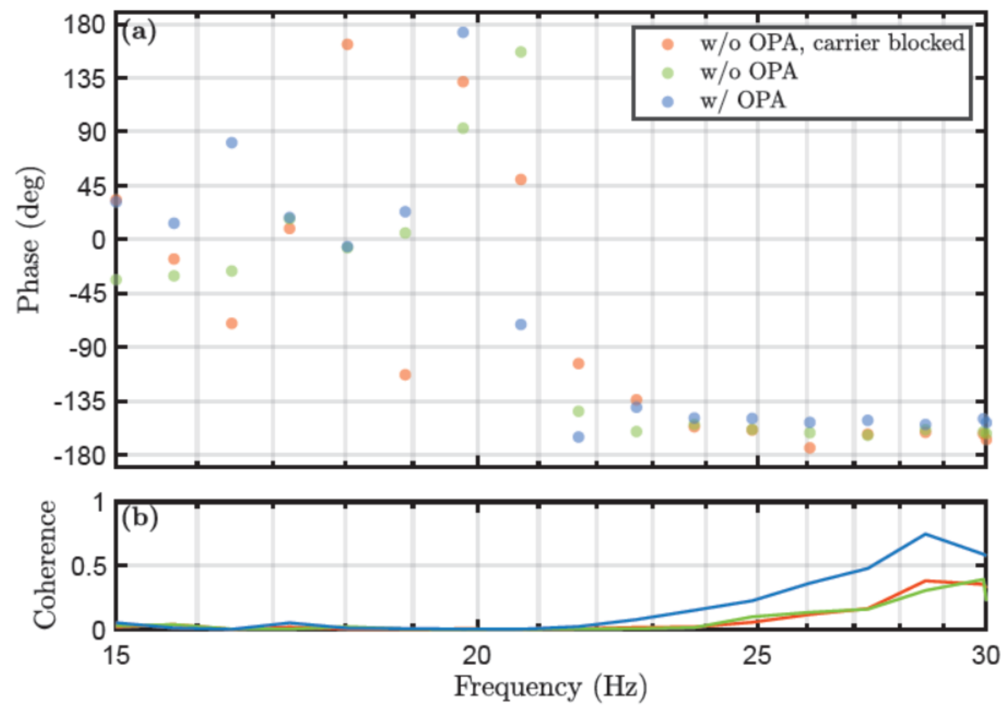


Interestingly, the amplification rate is proportional to $P_{in}^{-0.63}$. We could not model this from the theory.

Optical spring measurement

[Otabe thesis, 2023]



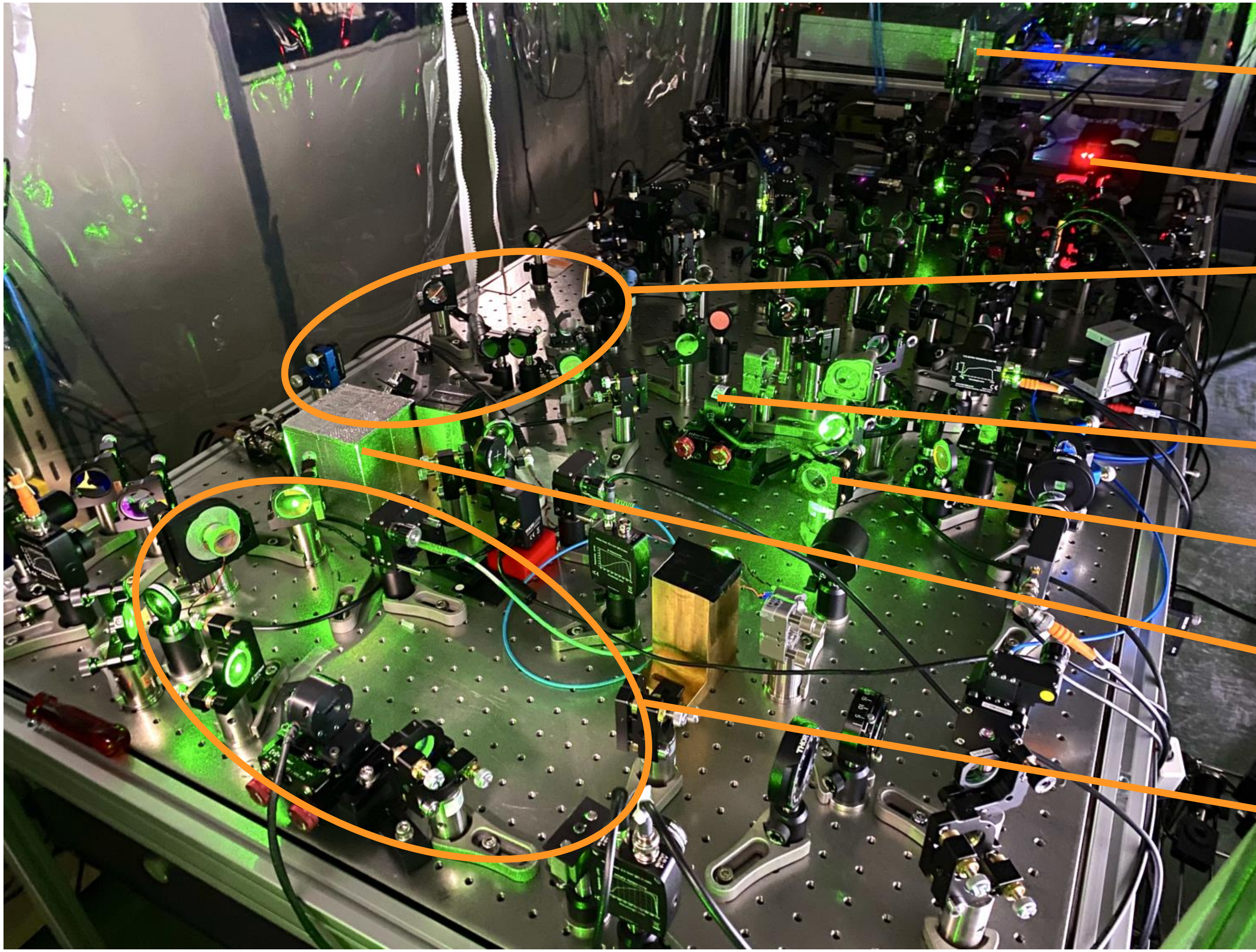


Left: Without OPA, the optical spring was observed in phase of the transfer function.

Right: With OPA, the 4mW carrier was amplified by a factor of 16.7 but no optical spring was observed.

(2) SRMI with OPA

[Harada 2022]
[Suzuki 2023]



Fiber amplifier (Pmax~12W)

Main laser

Michelson interferometer

OPA

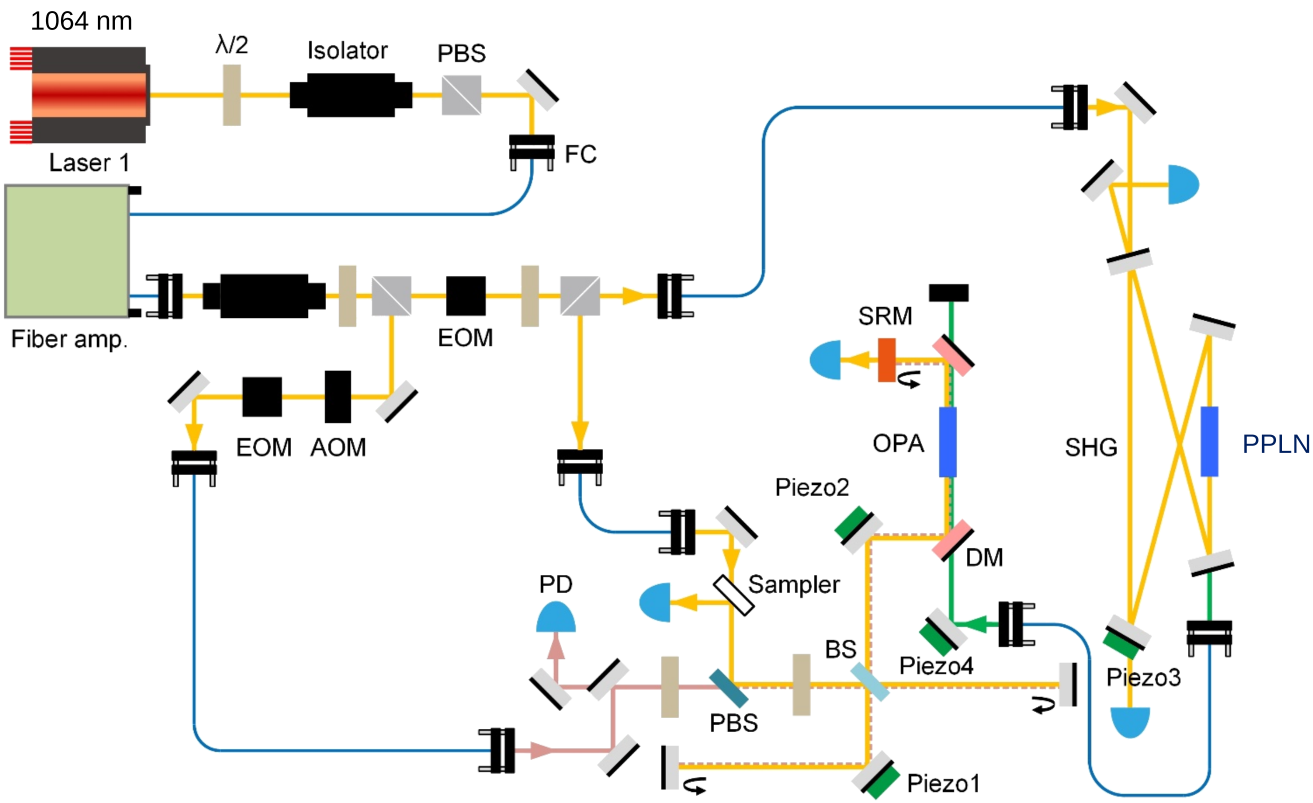
Signal-Recycling Mirror (SRM)

Suspended mirror (0.2g)

SHG

Locking the interferometer

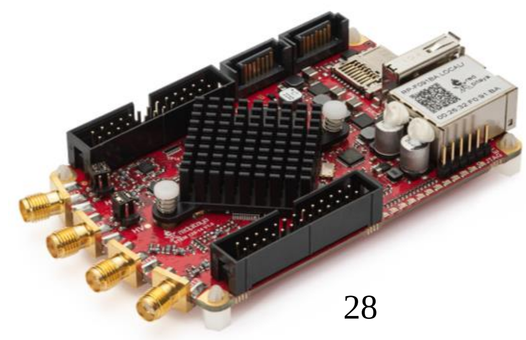
[Harada 2022]
[Suzuki 2023]



5DoF control

- Michelson dark fringe
- SRC w/70MHz p-pol
- SHG
- PLL (20MHz s-pol)
- OPA phase: coherent-control with 20MHz

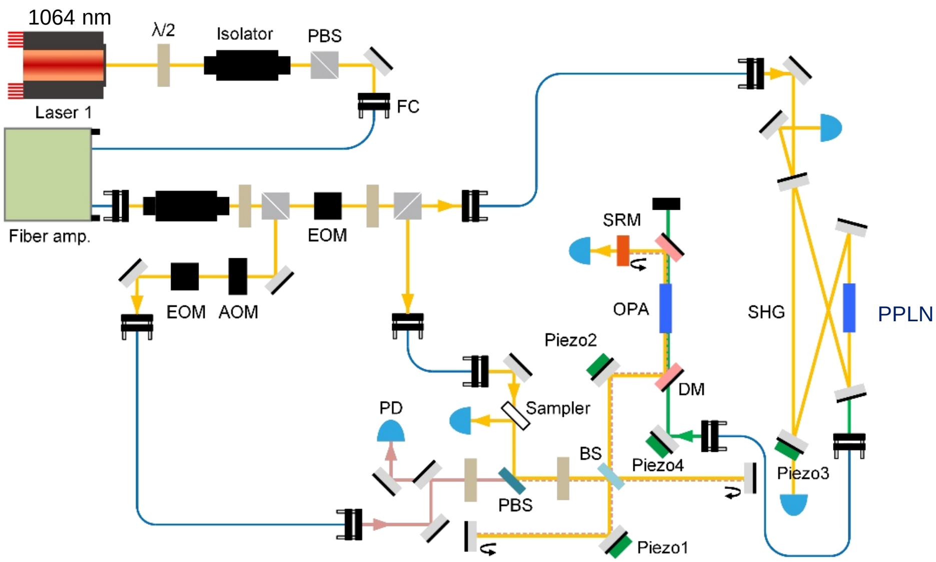
Digitally controlled by single-board computers (RedPitaya)

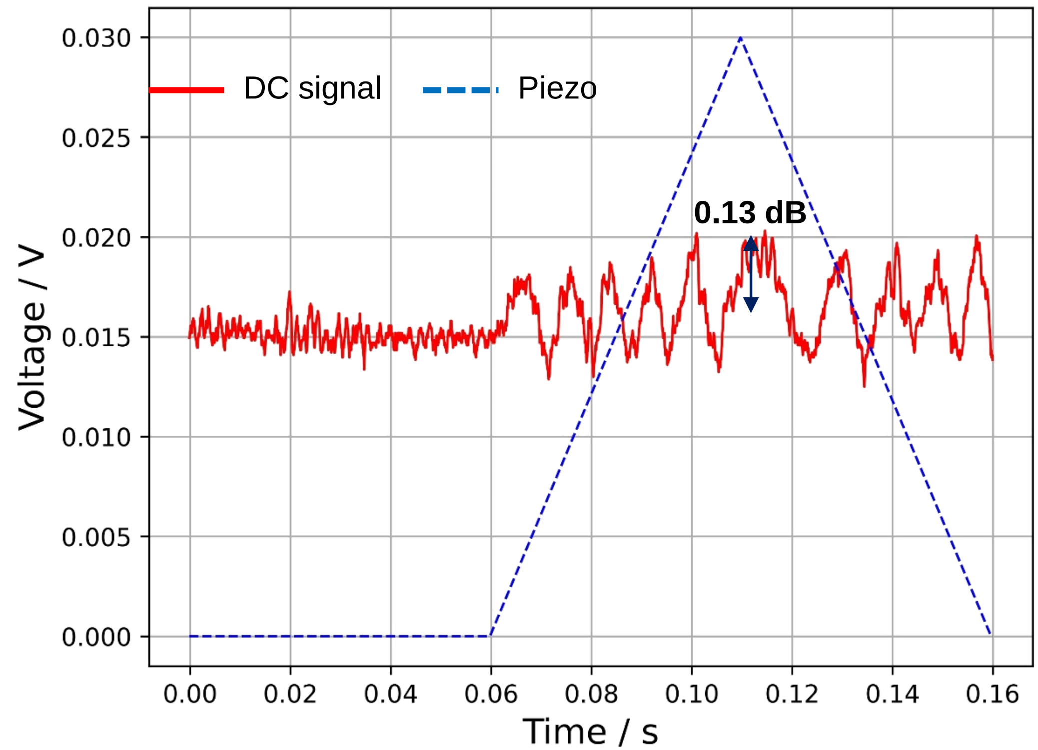


We succeeded the simultaneous control of all the 5 DoFs, then tested if the 1kHz Michelson signal increases with OPA.

Signal amplification with OPA

[Harada 2022]
[Suzuki 2023]

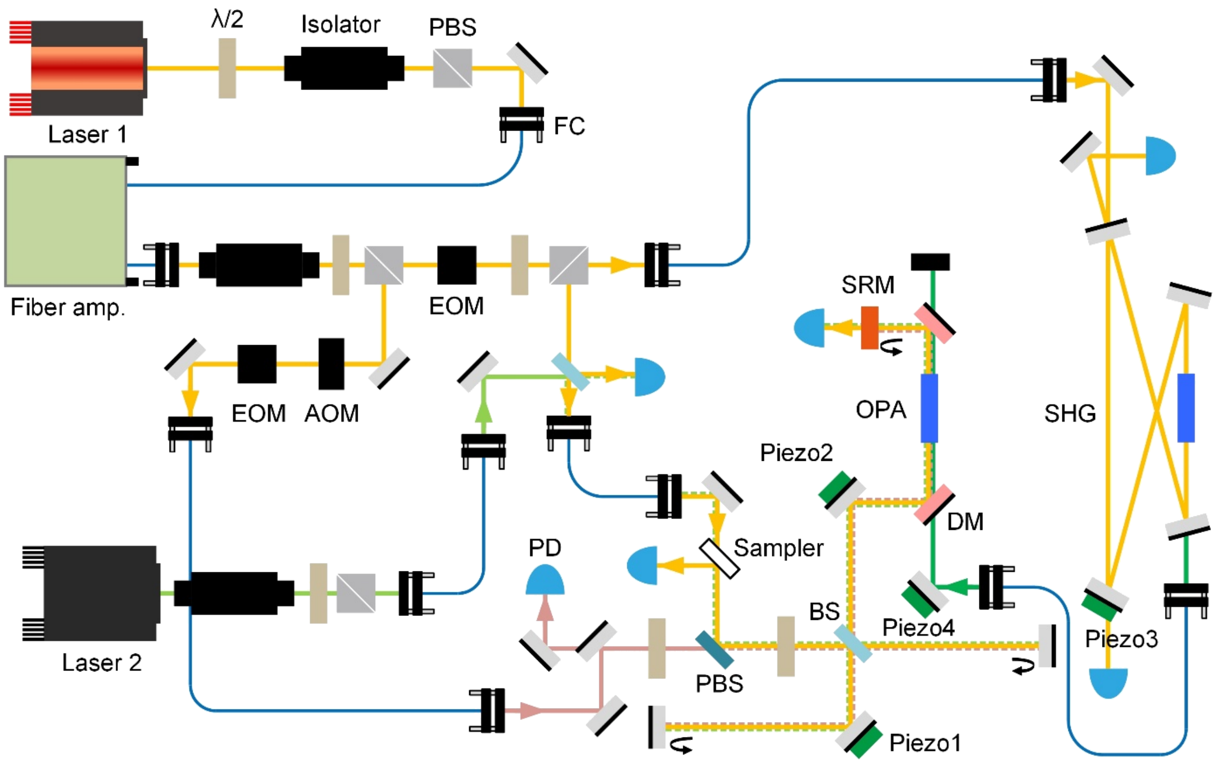


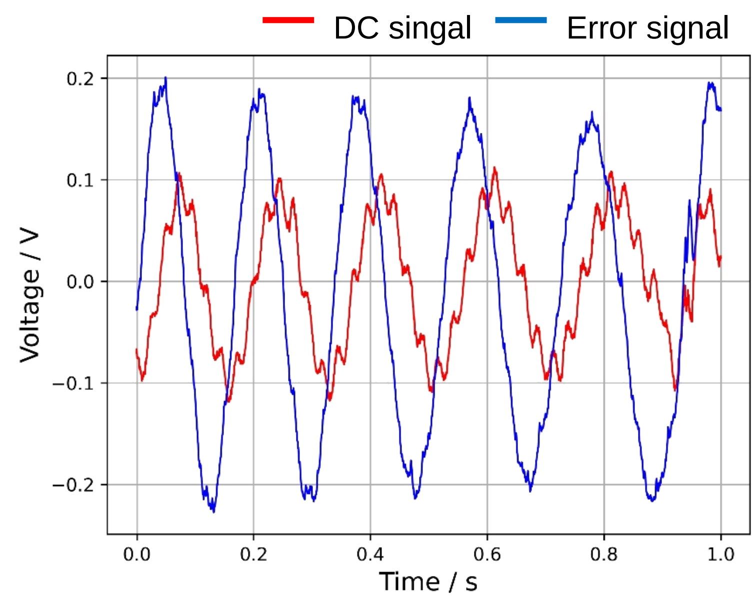


Dithering the arm at 1kHz and sweeping the pump phase, we found a 0.13dB oscillation of output of a lock-in amplifier at dark port.

Locking the OPA phase

[Harada 2022]
[Suzuki 2023]

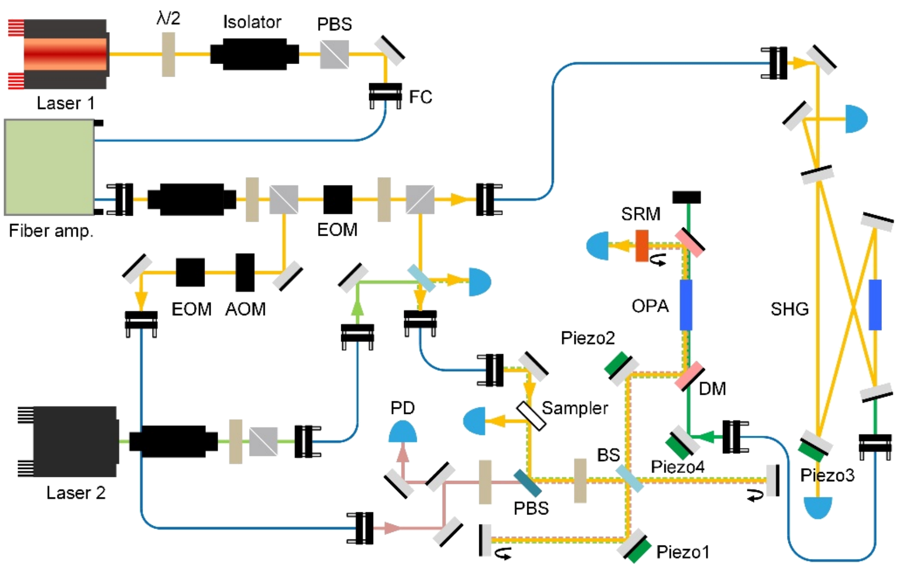


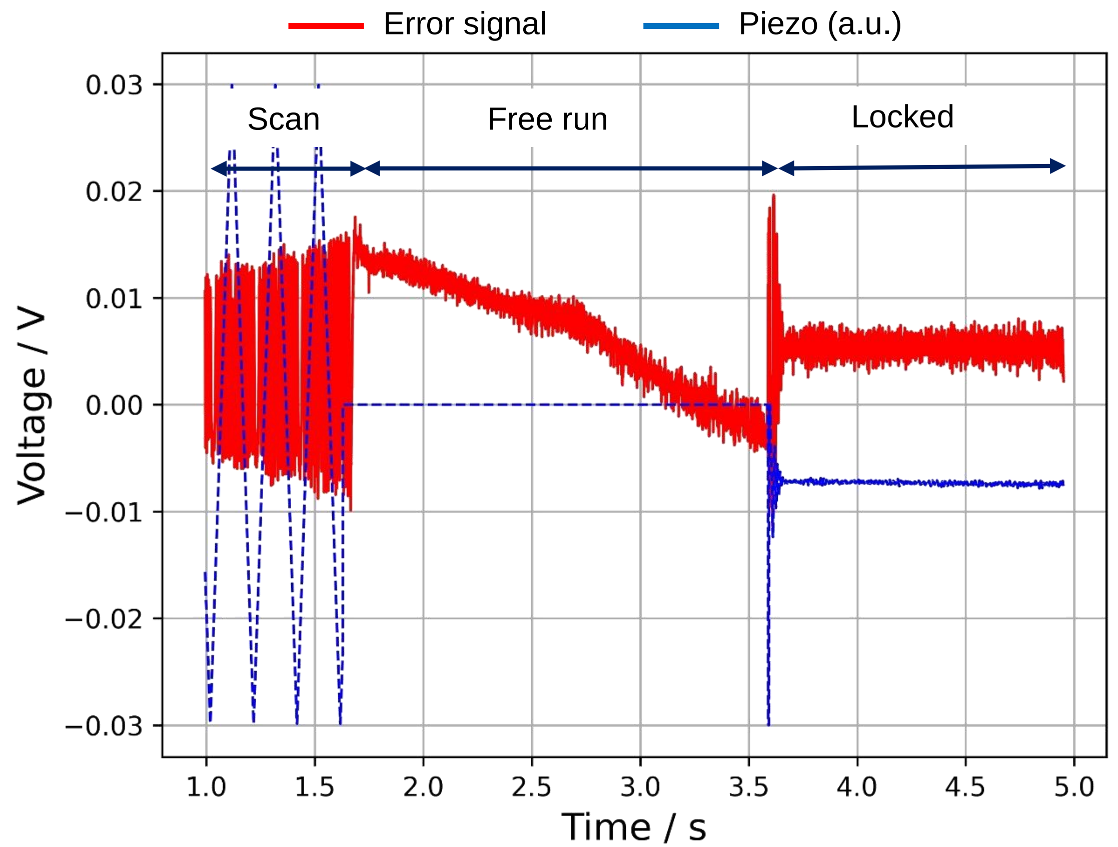


We use a secondary laser (20MHz different from main laser) and perform coherent-control method to obtain the error signal (demod at 40MHz).

Locking the OPA phase

[Harada 2022]

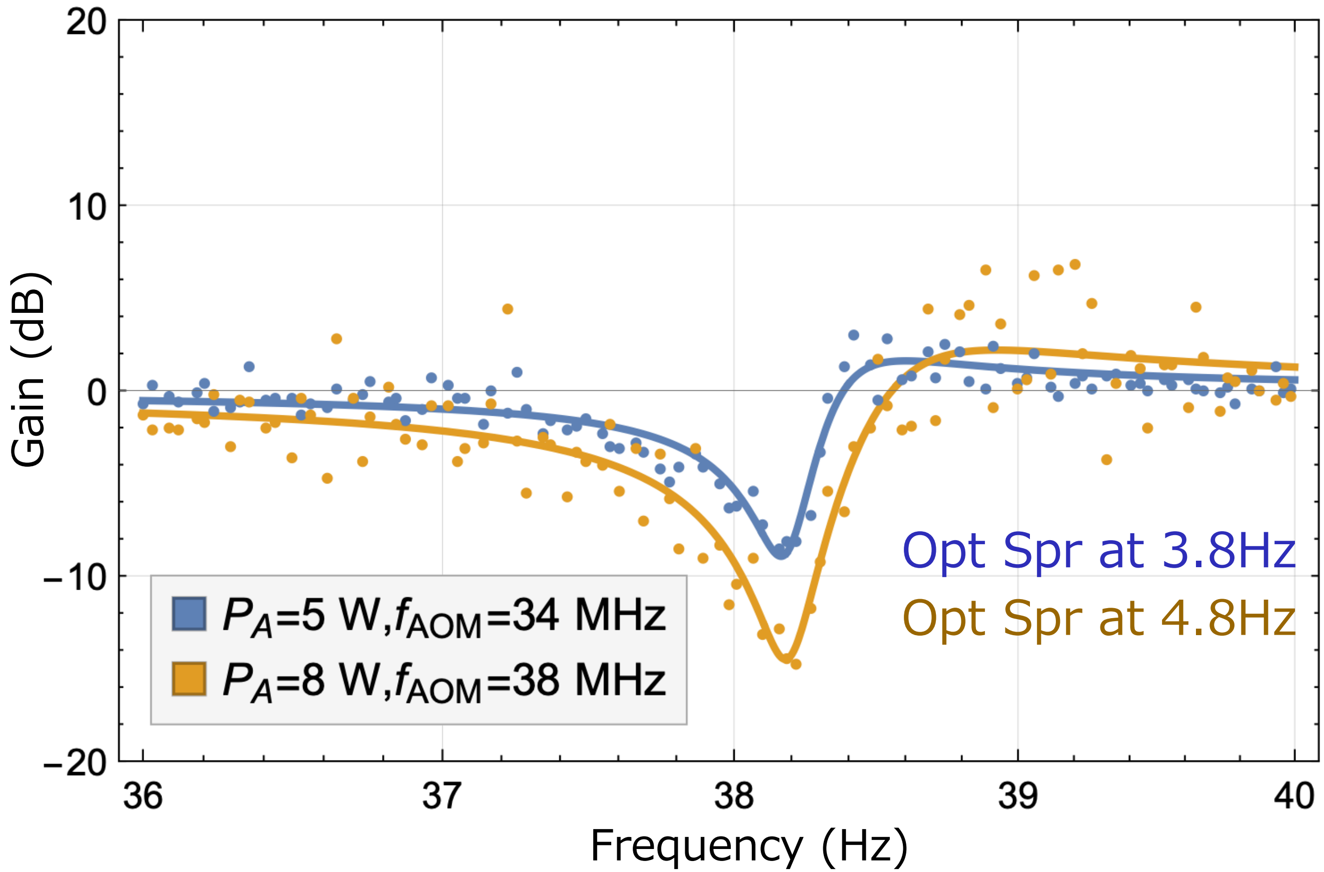




With the coherent control, the OPA phase is locked to the amplitude squeezing condition. Now we are ready to measure the transfer function of SRMI with OPA.

Observation of optical spring

[Suzuki 2023]



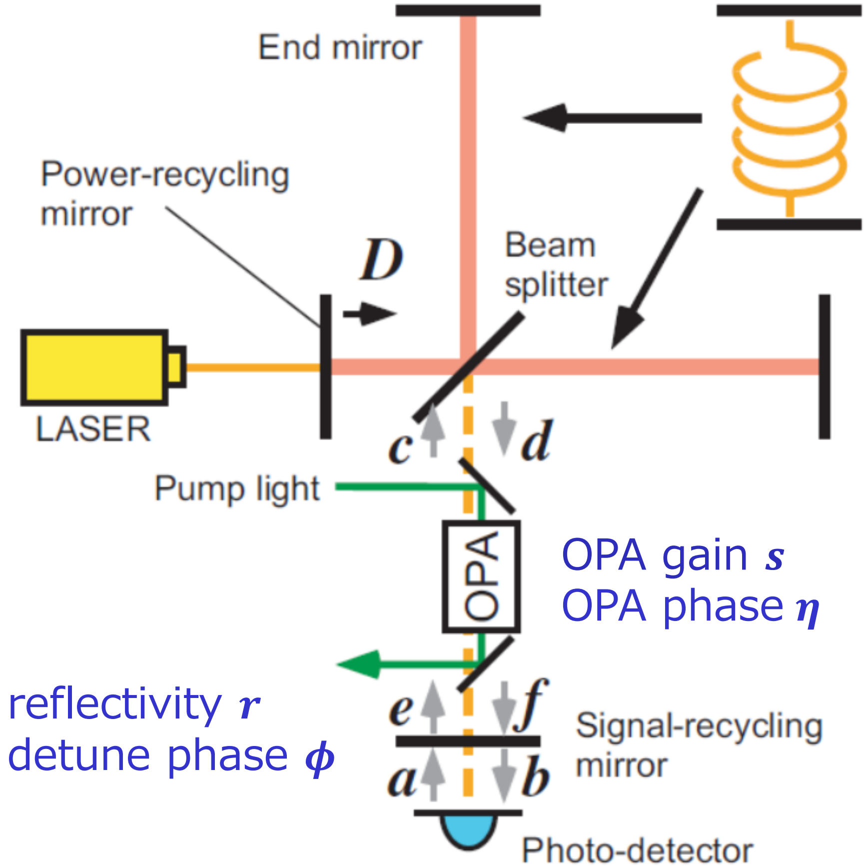
We observed an optical spring without OPA, and are currently working to see it shift with OPA.

Summary

- **Intracavity amplification technique improves the sensitivity at high frequencies, though internal optical losses turned out to be a limiting factor.**
- **A single cavity experiment was performed to reveal a challenge to observe the optical spring shift due to the second-harmonic generation loss.**
- **A SRMI experiment is being conducted; optical spring has been observed, its shift with OPA is to be observed soon.**

Supplementary slides

Parametric signal amplification



Optical spring w/o OPO

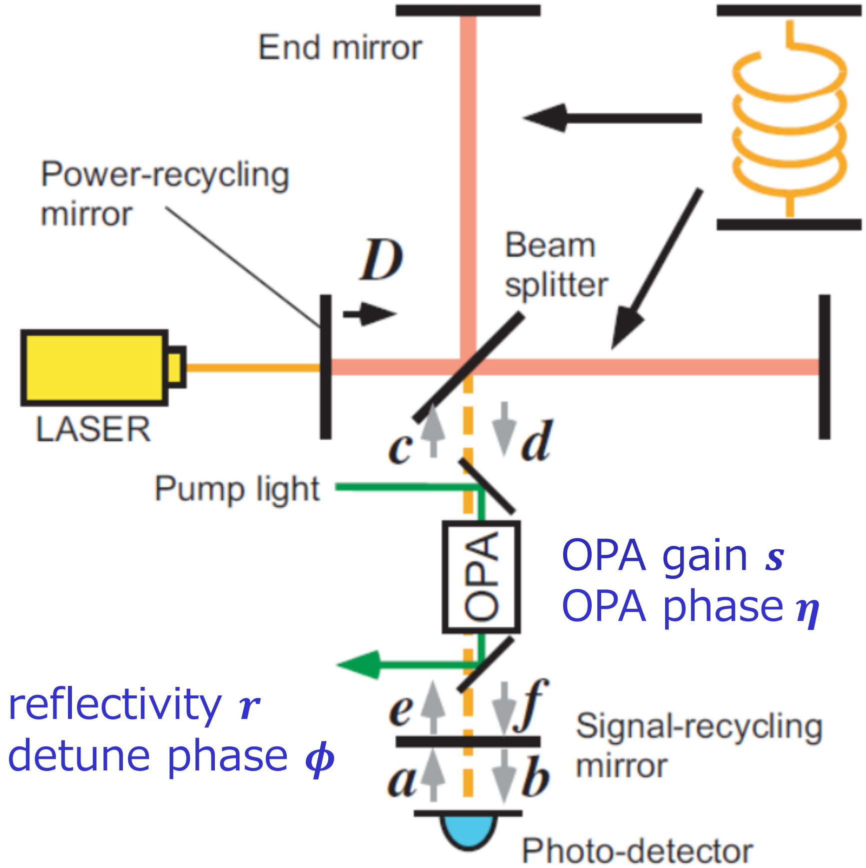
$$\Omega_{os} \propto \sqrt{\frac{2\sin 2\phi}{\left(r+\frac{1}{r}\right)-2\cos 2\phi}}$$

Optical spring with OPO

$$\Omega_{os} \propto \sqrt{\frac{\left(s+\frac{1}{s}\right)\sin 2\phi-\left(s-\frac{1}{s}\right)\sin(2\phi+2\eta)}{\left(r+\frac{1}{r}\right)-\left(s+\frac{1}{s}\right)\cos 2\phi}}$$

- **Opt spring freq can be enhanced by tuning OPA gain s**
- **SRMI response can be changed by η (instead of ϕ)**

Optical resonance also moves with OPA



Optical resonance w/o OPO

$$\Omega_{\mathrm{res}} \simeq \frac{\phi c}{L}$$

Optical resonance with OPO

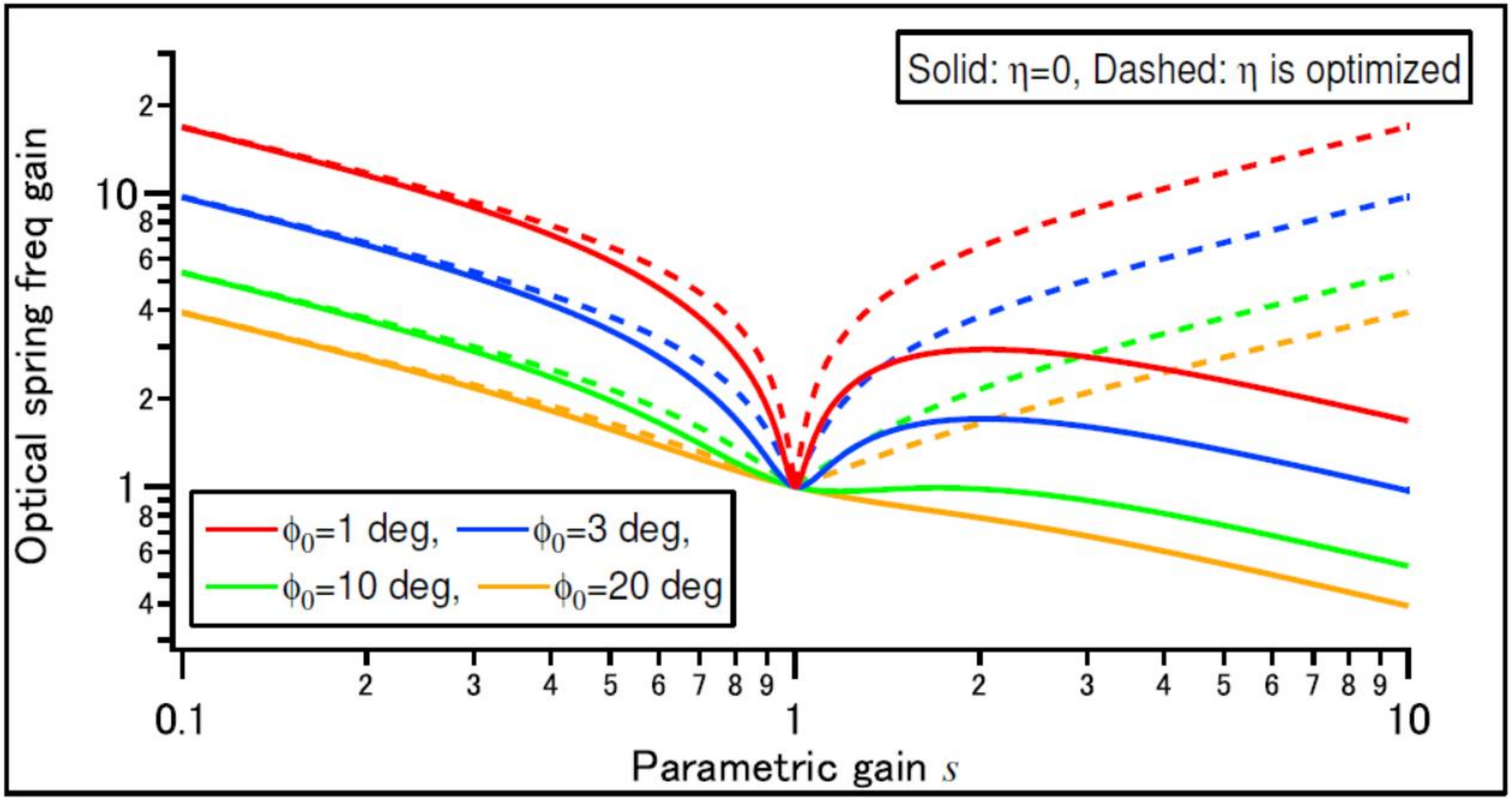
$$\Omega_{\mathrm{res}} \simeq \frac{\phi_s c}{L}$$

where

$$\cos 2\phi_s = \frac{1}{2}\left(s + \frac{1}{s}\right)\cos 2\phi$$

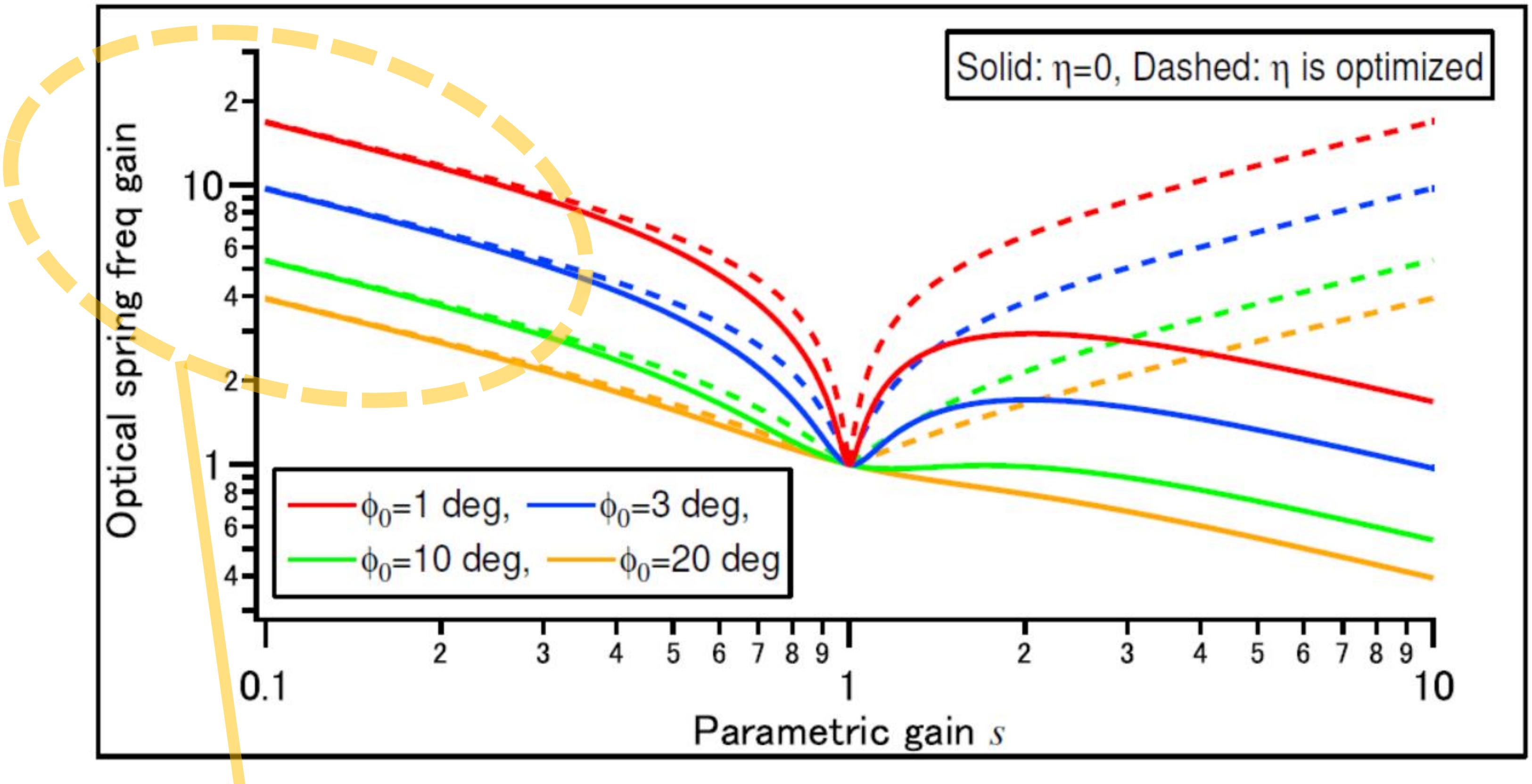
We shall define the detuned phase with OPA as above.
The optical resonance frequency is then fixed.

Spring enhancement with optimal η



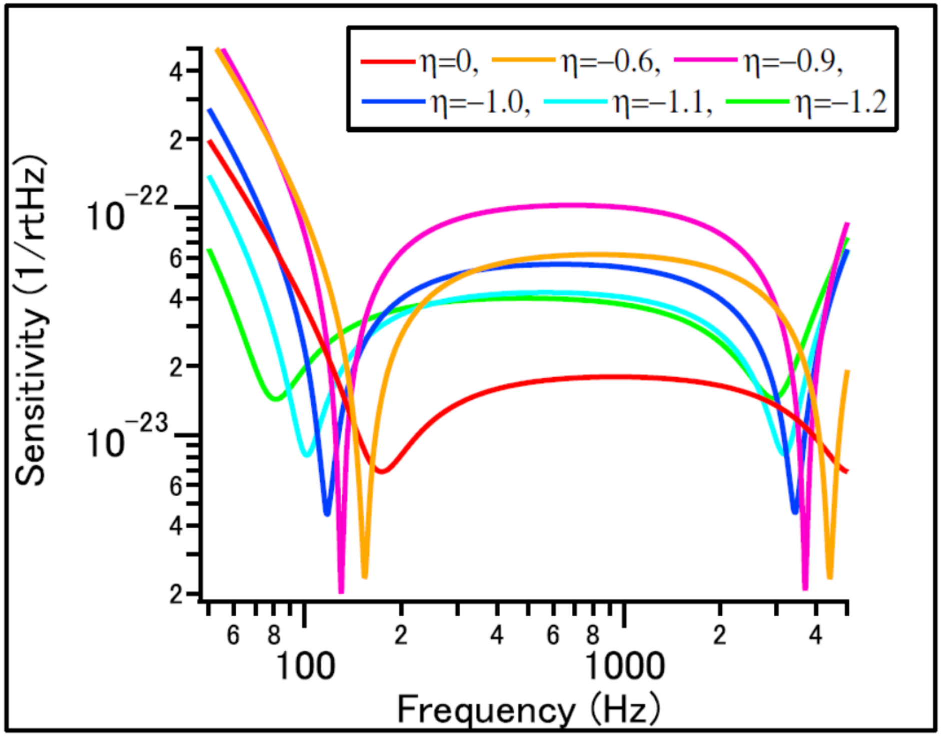
- Detune phase ϕ is chosen for each s to make ϕ_s fixed to ϕ_0
- OPA phase η is optimized -> enhancement is symmetric with s
- Rapid enhancement near $s = 1$; denominator approaches zero (No rapid enhancement with high detune)

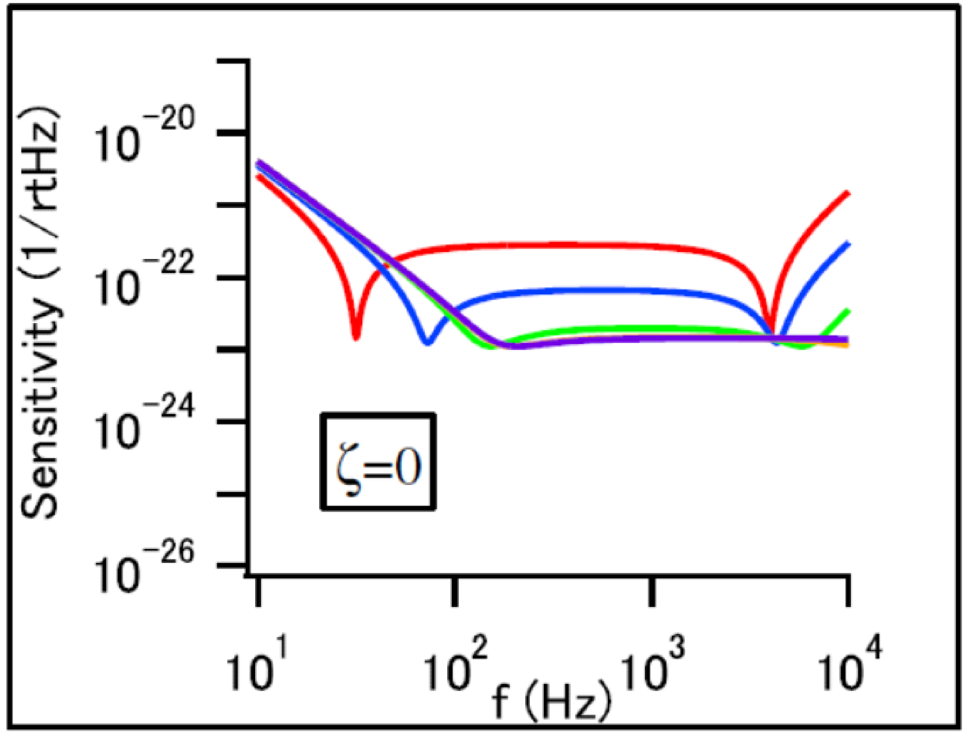
Spring enhancement with optimal η



In our work hereafter, we focus on this region of parameters, so it would be ok to assume $\eta = 0$.

Frequency-dependent intra-OPA?





- If we could realize a freq-dependet intra-OPA **phase**, the sensitivity would look like the envelope of these curves (left)
- If we could realize a freq-dependet intra-OPA **gain**, the sensitivity would look like the envelope of these curves (right)
- Or we can dynamically change s or η with the inspiral. (as was proposed in Zhang et al.)

Ponderomotive amplifier to reduce shot noise

GWADW @ Kyoto

May. 2010

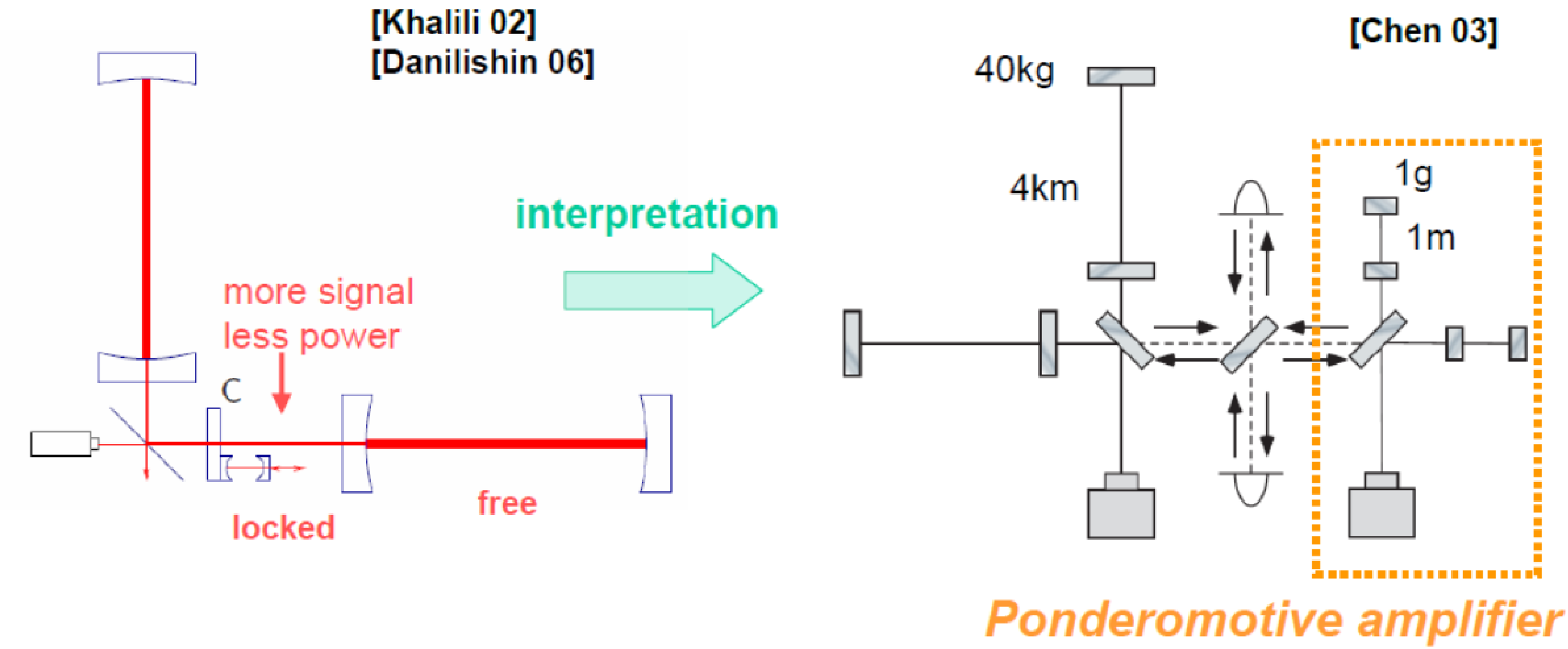
Kentaro Somiya[1] and Yanbei Chen[2]

Waseda Inst. for Adv. Study[1] and Caltech[2]

K.Somiya

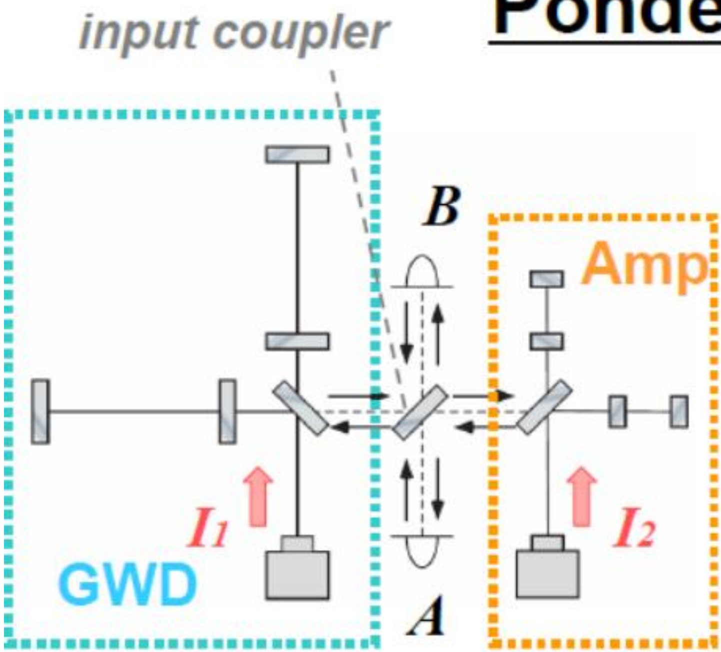
LIGO-G1000568-v1

Optical lever



- Reasonable power on the small mirrors
- Chen-type optical lever is rather an amplifier
- GW signal converts to radiation pressure in PA

Ponderomotive amplifier



θ: detune phase
T: transmittance of input coupler

$$\begin{cases} A = \cdots \\ B = \cdots \end{cases}$$

⇓ *maximize SNR*

$$I_1 \times [\ \cdots\ ] + I_2 \times [\ \cdots\ ] + [\ \cdots\ ]$$

$\|$

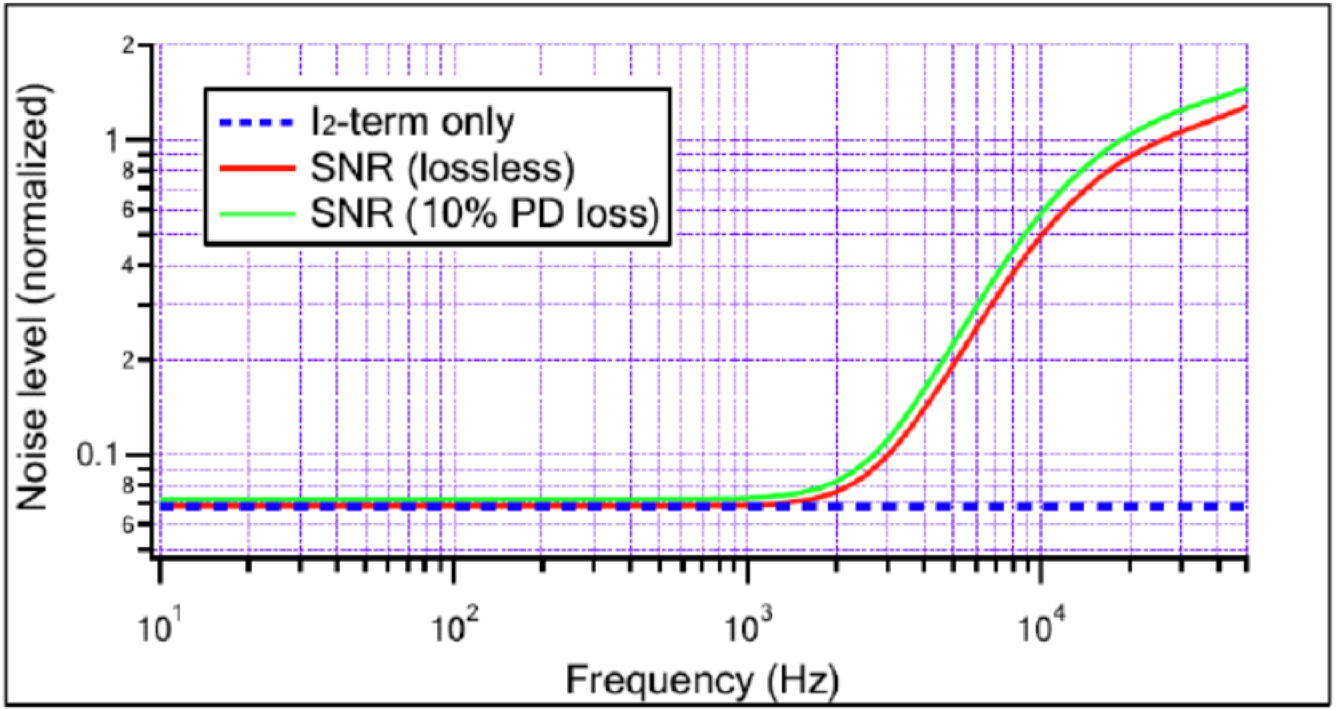
I_2 × [vacuum + signal + disp-noise]

If I_2-term is dominant…

$$\frac{\text{Shot noise}}{\text{Signal}} \propto \sqrt{\frac{4T\cos\theta}{I_1(1-T)}}$$

Signal is amplified and SNR increases

Sensitivity gain



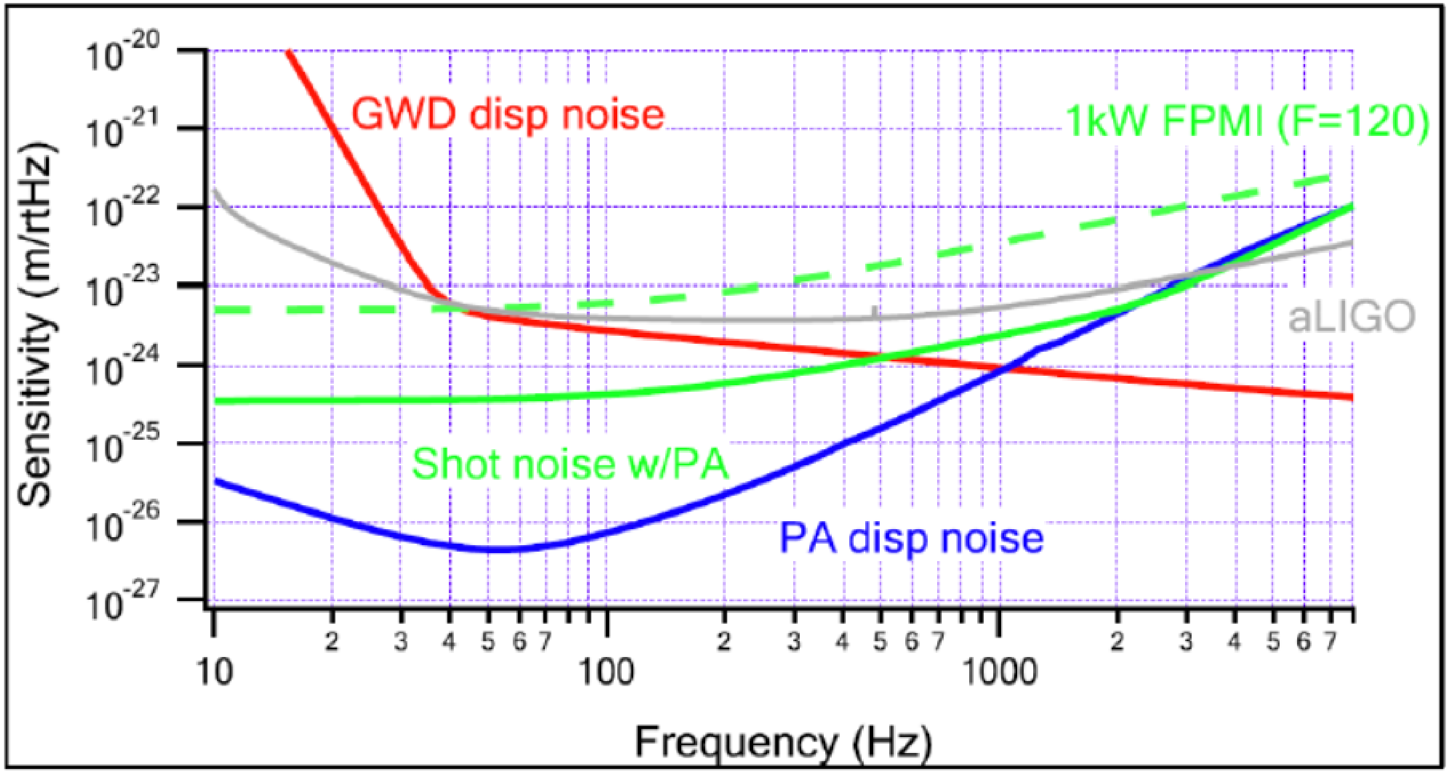
GWD
L=4km, m=40kg,
I0=1kW, F=120

PA
L=10cm, m=1g,
I0=100W, F=6000

IC
R=81%, ϕ=1.5rad

- Big reduction of shot noise up to kHz
- Strong against PD losses
- Power on PA might be a bit high…

Sensitivity curve



- **Not yet fully optimized**
- **Good sensitivity with low power**
- **PA noise limits the sensitivity at high freq**