Advanced techniques to further improve the kHz sensitivity

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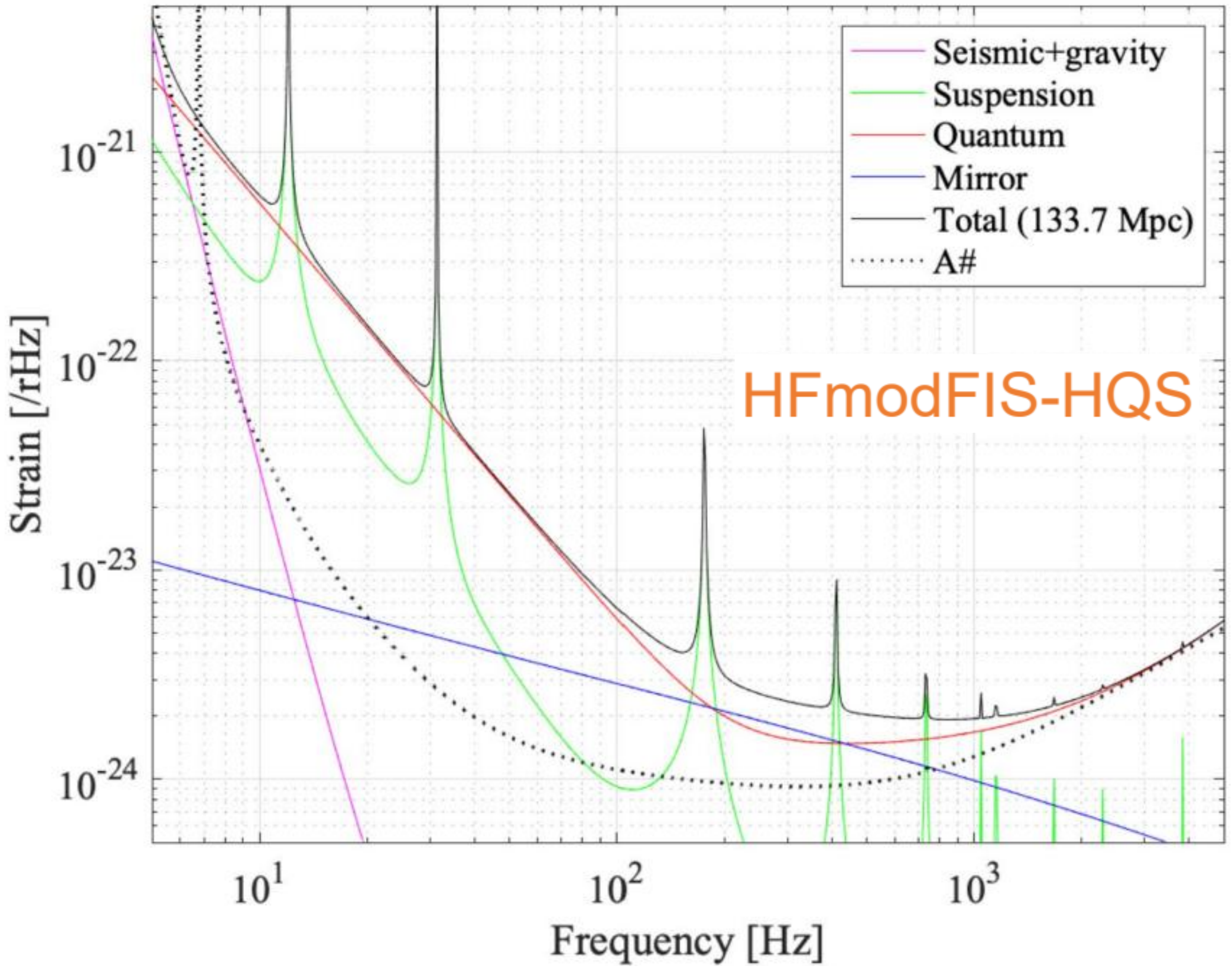
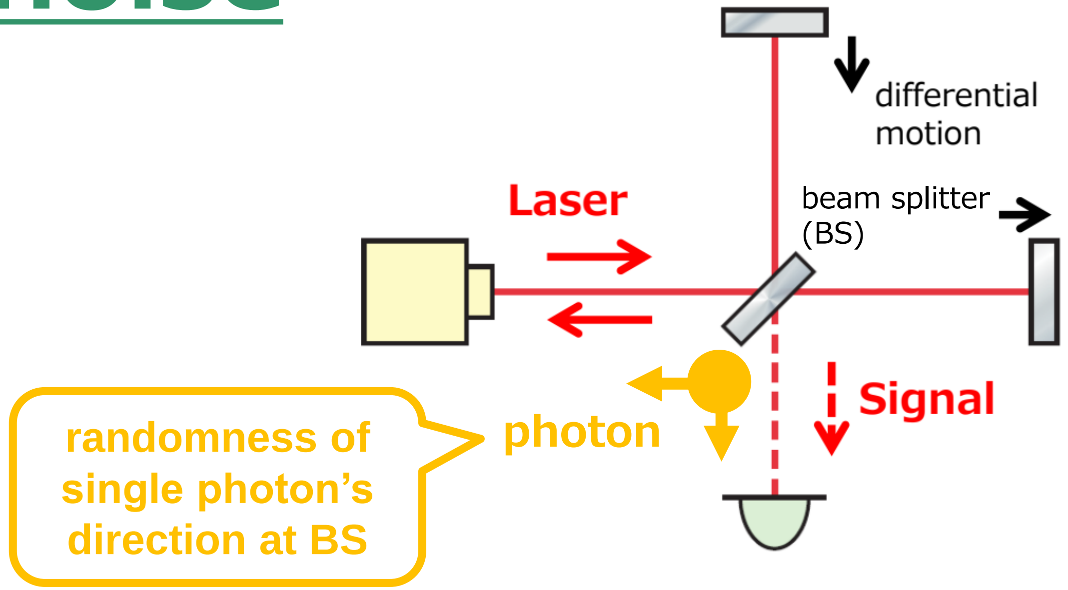
Contents of talk

- We might need a sensitivity better than 10^{-24} (1/rtHz) at 3-4kHz.
- Is there a hope to realize such a good sensitivity?
- If there is, how feasible is the technique?

Quantum noise



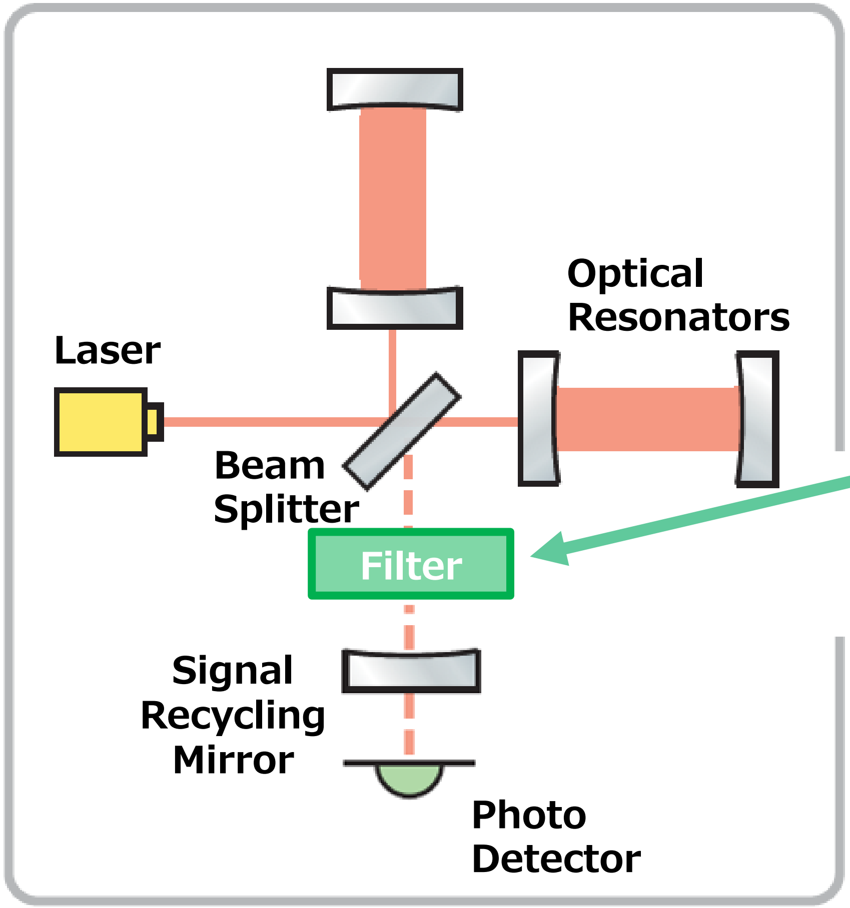


← Quantum noise

← Thermal noise

High-freq sensitivity is limited by quantum noise of light

Quantum filters



Quantum noise changes with a filter in the Signal-Recycling cavity

(current detectors)

LIGO/Virgo: none

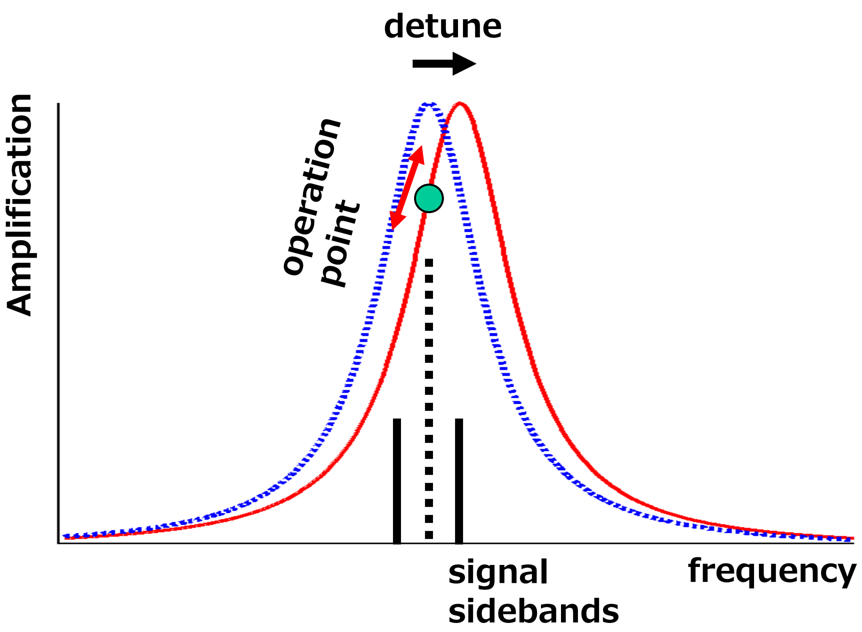
KAGRA: microscopic detune

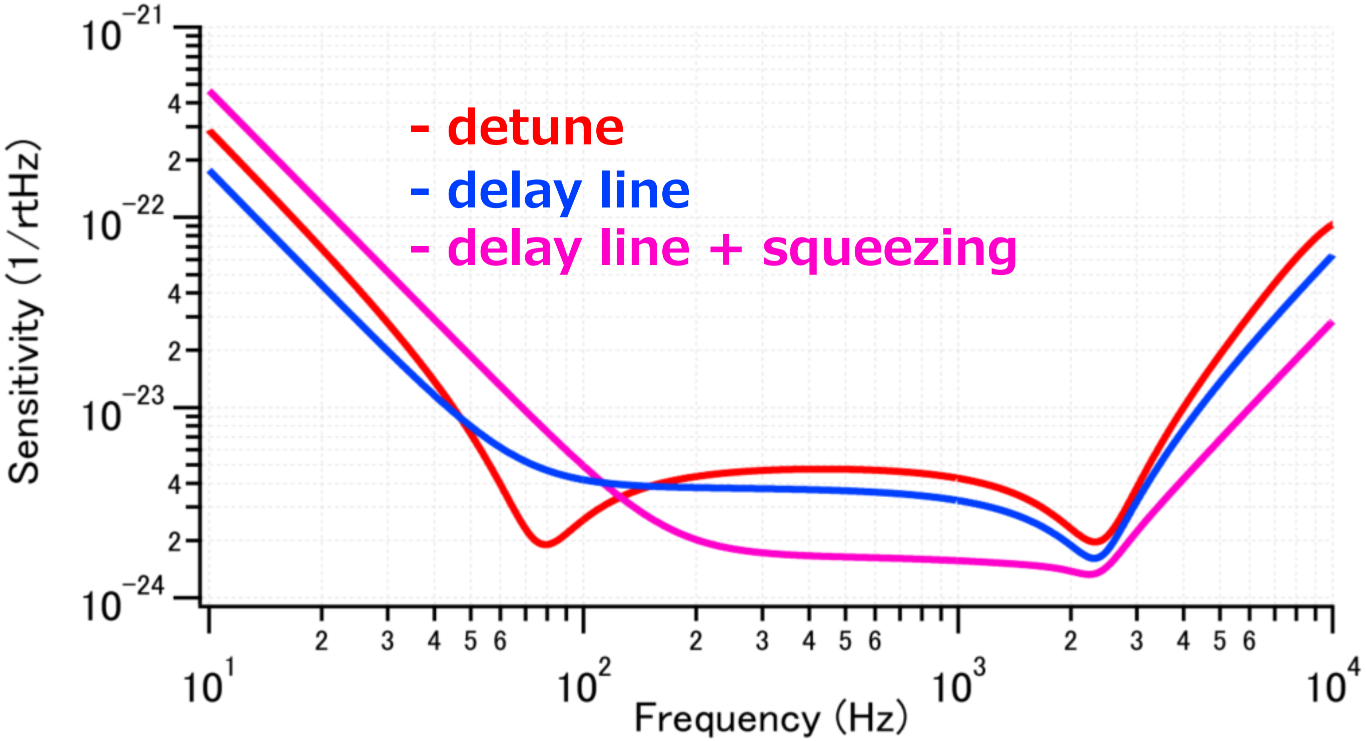
(HF detectors)

- **Delay Line** **(Long-SRC)**
- **Sloshing cavity** **(speed-meter)**
- **Non-linear crystal**
- **Microcavity**

Active filters

Microscopic detune and delay line





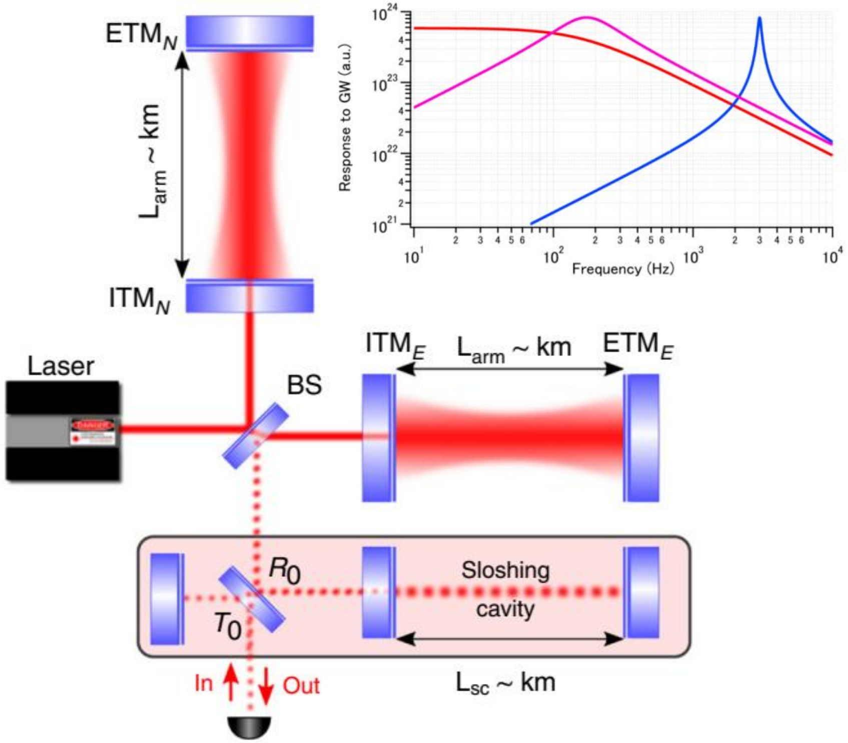
	detune	delay line
arm power	5MW	5MW
squeezing	0dB	0dB/10dB
SRC length	66.6m	66.6m
SRC detune	3.5 deg	0 deg
SRC loss	2000ppm	2000ppm
PD loss	10%	10%
arm loss	100ppm	100ppm

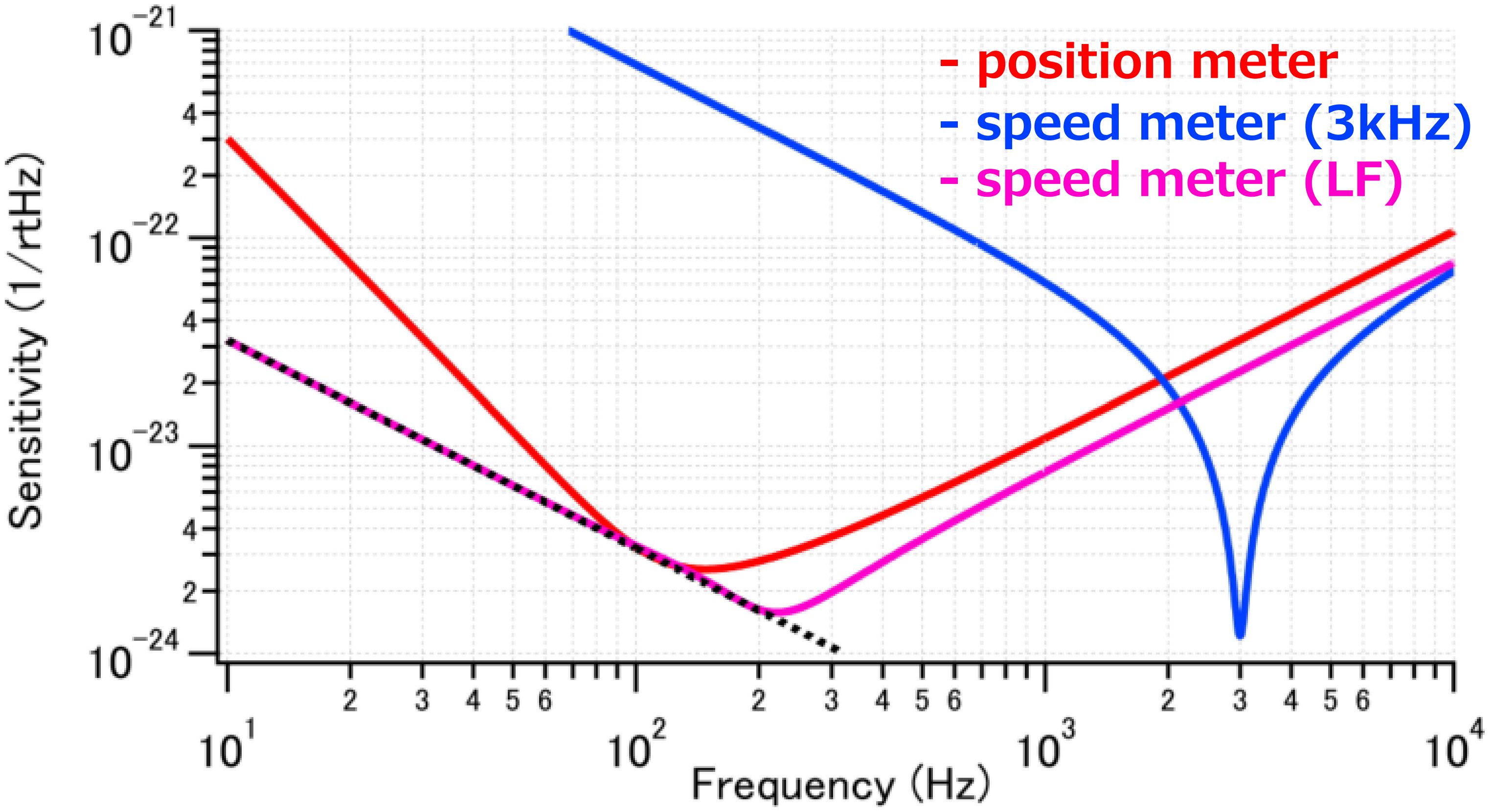
SRC=Signal Recycling Cavity, PD=Photo Detector

Delay line + squeezing is better, but the gain is limited by optical loss in the recycling cavity.

Speed meter

[Purdue+Chen 2002] [Danilishin 2019]





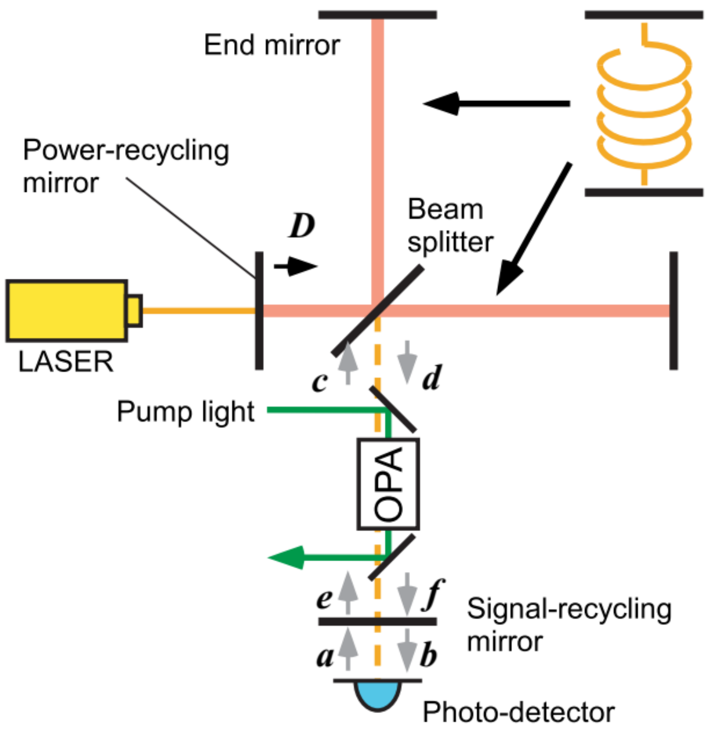
	SM (LF)	SM (3kHz)
arm power	0.5MW	0.5MW
squeezing	0dB	0dB
sloshing length	3km	3km
coupler transmission	14%	0.05%

Optical losses are not included in the calculation.

Looks promising, but maybe this is in principle the same as the long SRC.

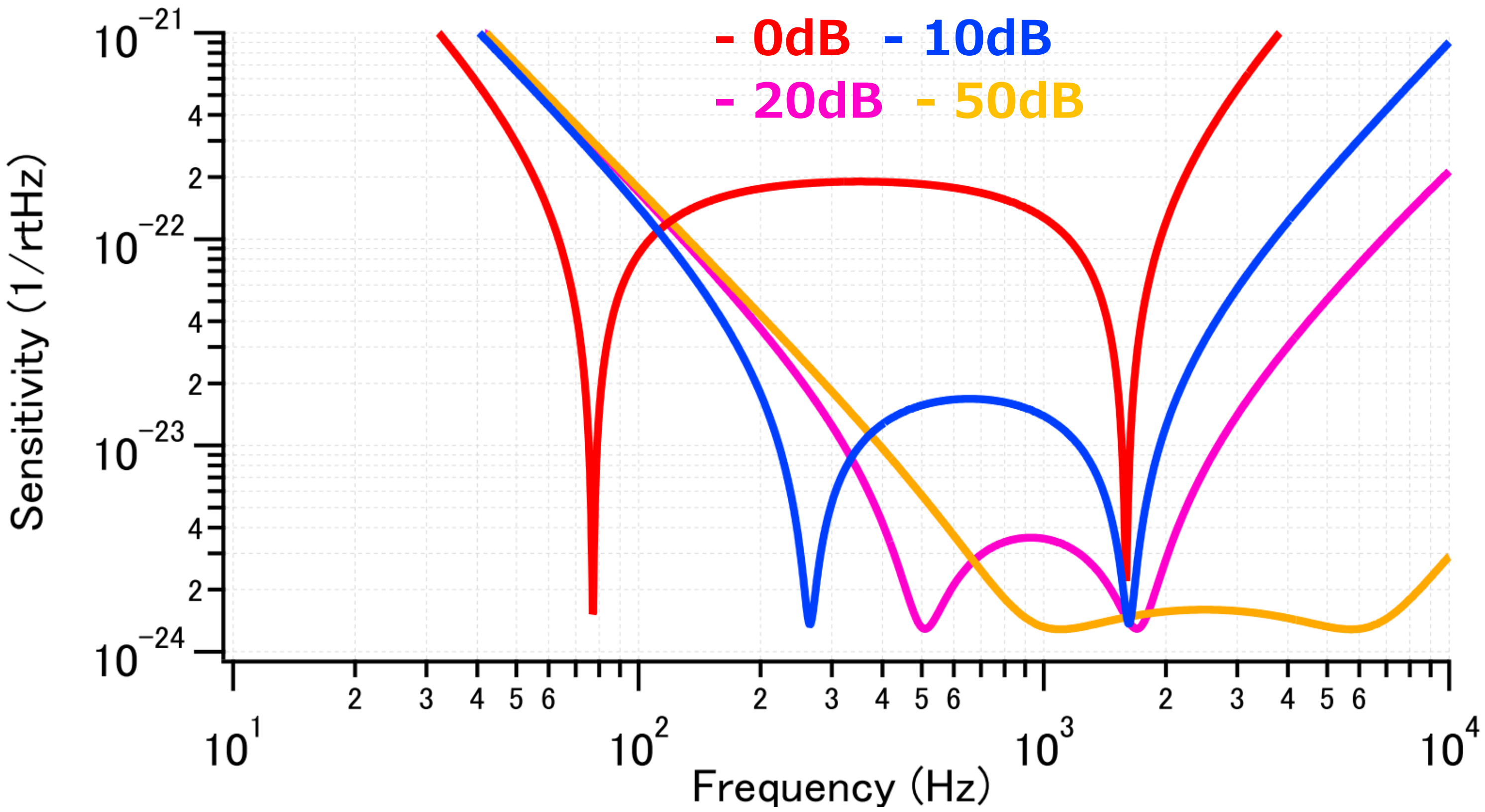
Parametric amplifier

[Somiya 2023]



arm power	0.3MW
mass	0.5kg
amplifier	0dB, 10dB, 20dB, 50dB
squeezing	0dB
SRC loss	1000ppm

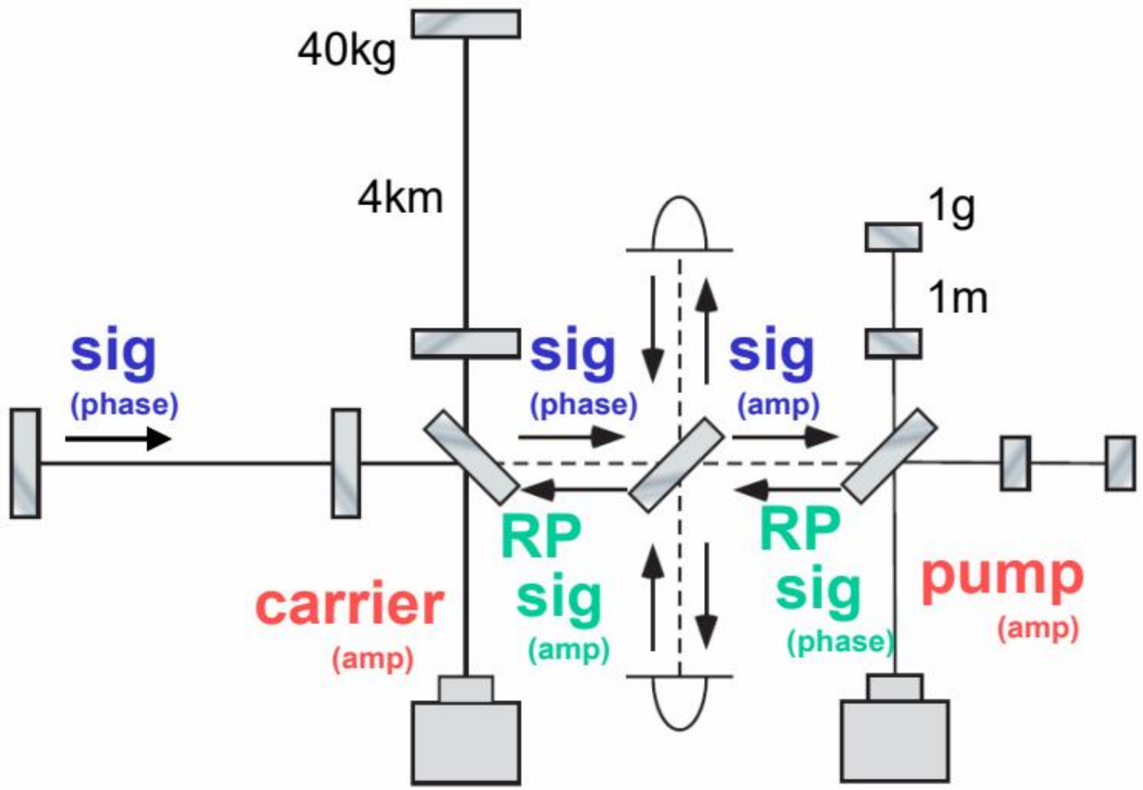
OPA=Optical Parametric Amplifier

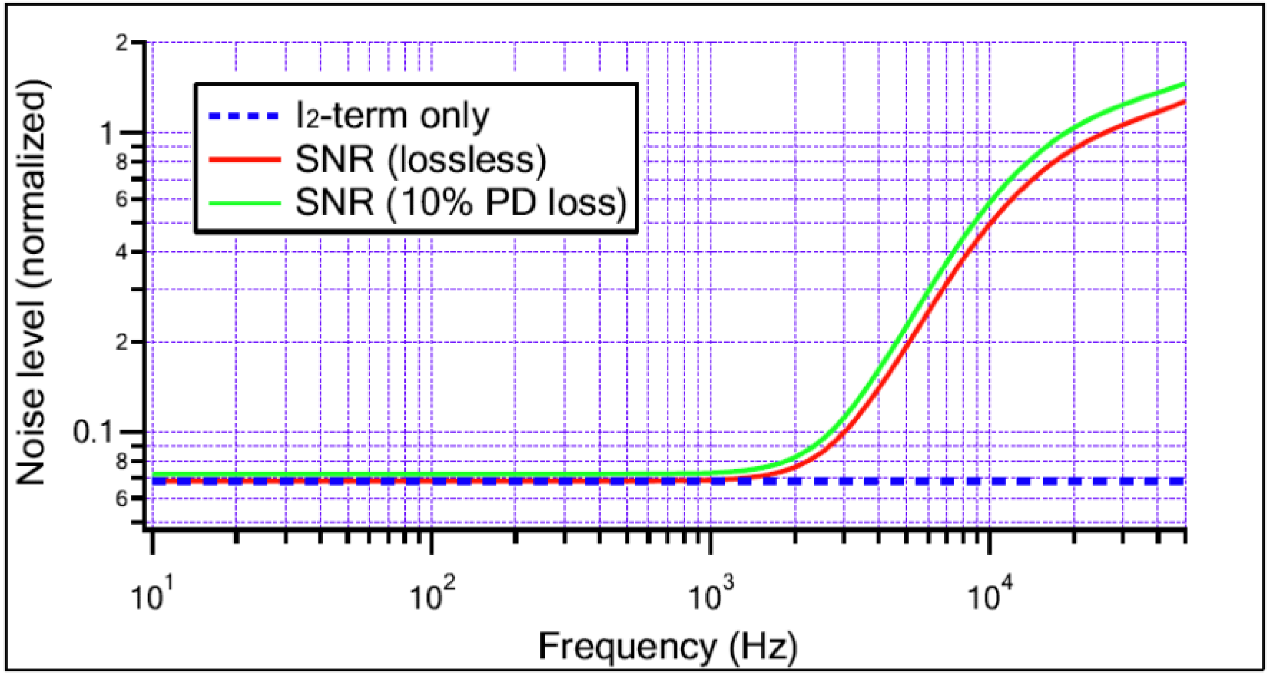


Using an external energy source, a good HF sensitivity can be achieved; it is limited by internal loss.

Ponderomotive amplifier

[Somiya+Chen 2010]





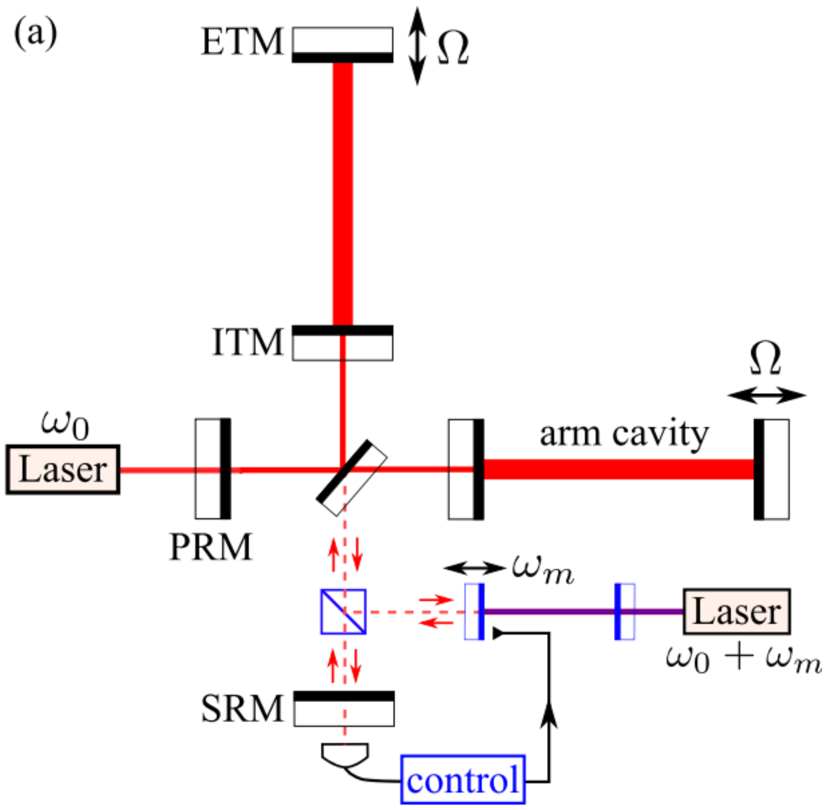
arm power	1kW/100W
mass	40kg/1g
coupler	80%
detune	1.5rad

RP=Radiation Pressure

Broadband amplification is possible below the optical spring frequency of the small interferometer.

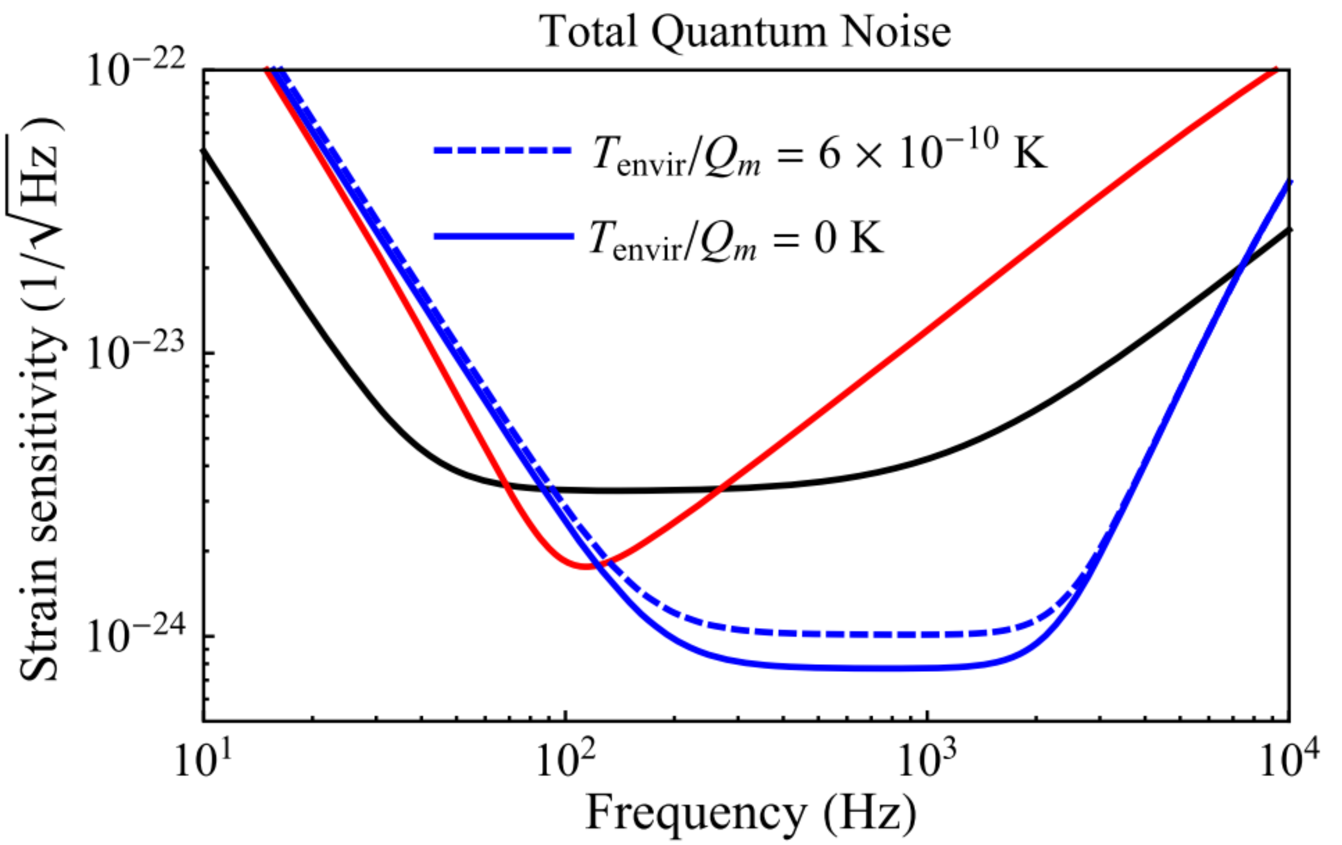
White light cavity

[Miao 2015]



arm power	~1MW
mass	40kg
arm length	4km
small mass	0.1mg
filter power	100W

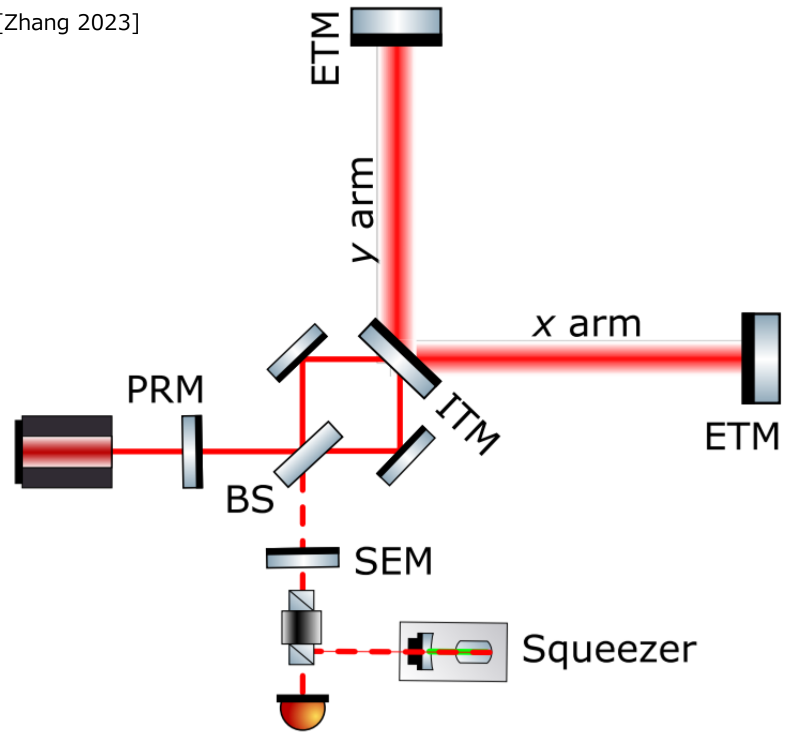
PRM=Power Recycling Mirror
SRM=Signal Recycling Mirror



1e-24 (1/rtHz) can be realized in broad band but the requirement on microcavity is tough.

L-shape detector

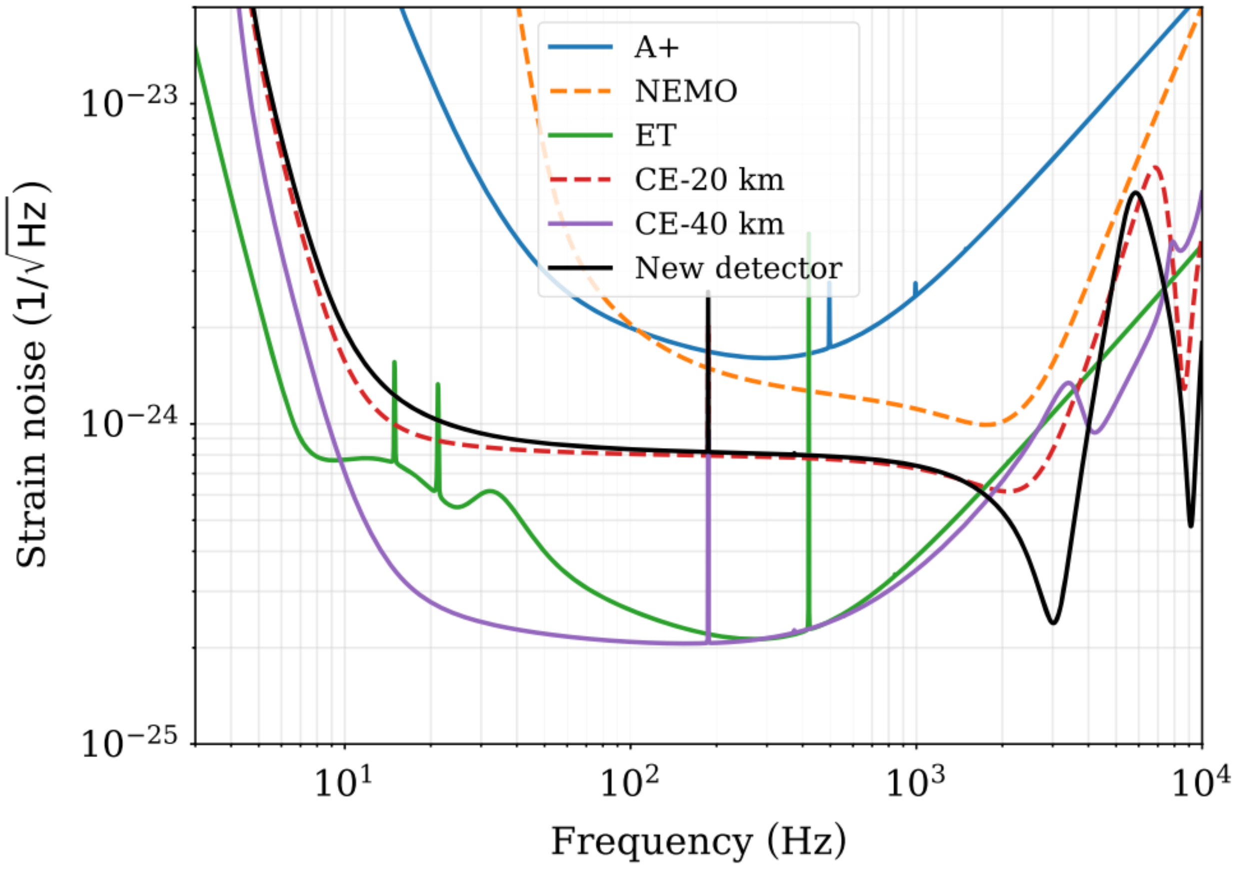
[Zhang 2023]



arm power	1.5MW
arm length	25km
ITM trans	1.4%
SEM trans	6%

SEM=Signal Extraction Mirror (~SRM)

Check out Akutsu's poster about a related work.



The dip frequency is determined by the arm length (25km→3kHz). Loss is reduced at the frequency.

Universal Interferometer

[Krenn 2025]

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Digital Discovery of Interferometric Gravitational Wave Detectors

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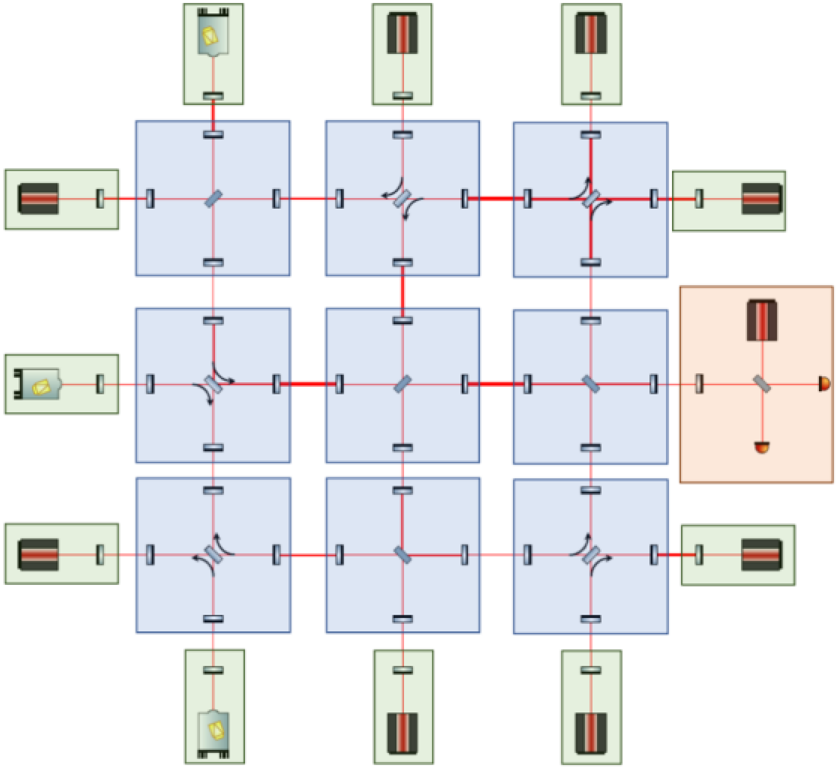
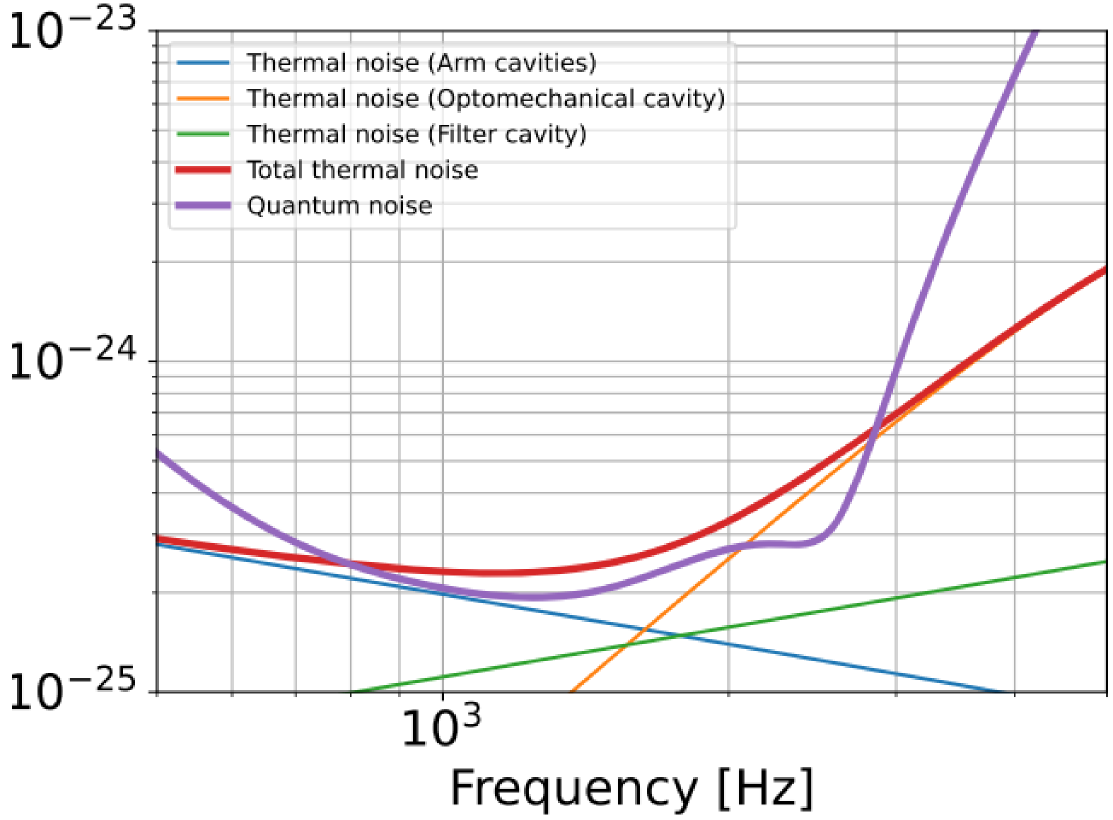
(b) Quasi-Universal Interferometer (UIFO)

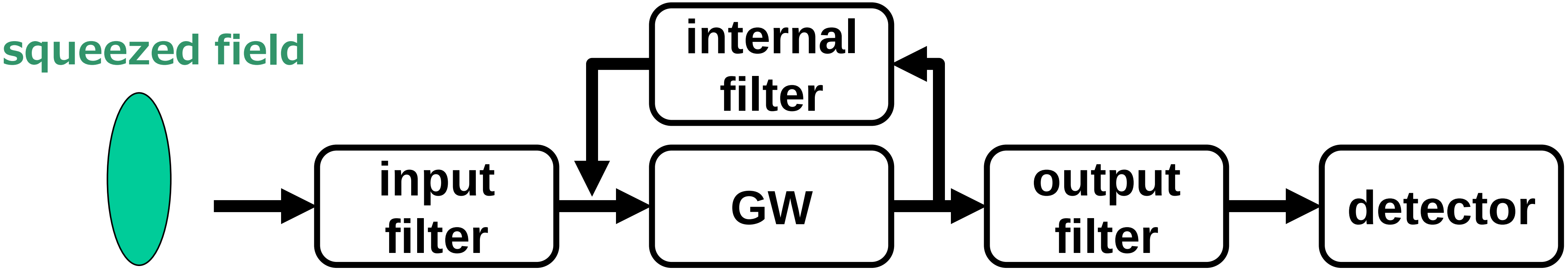


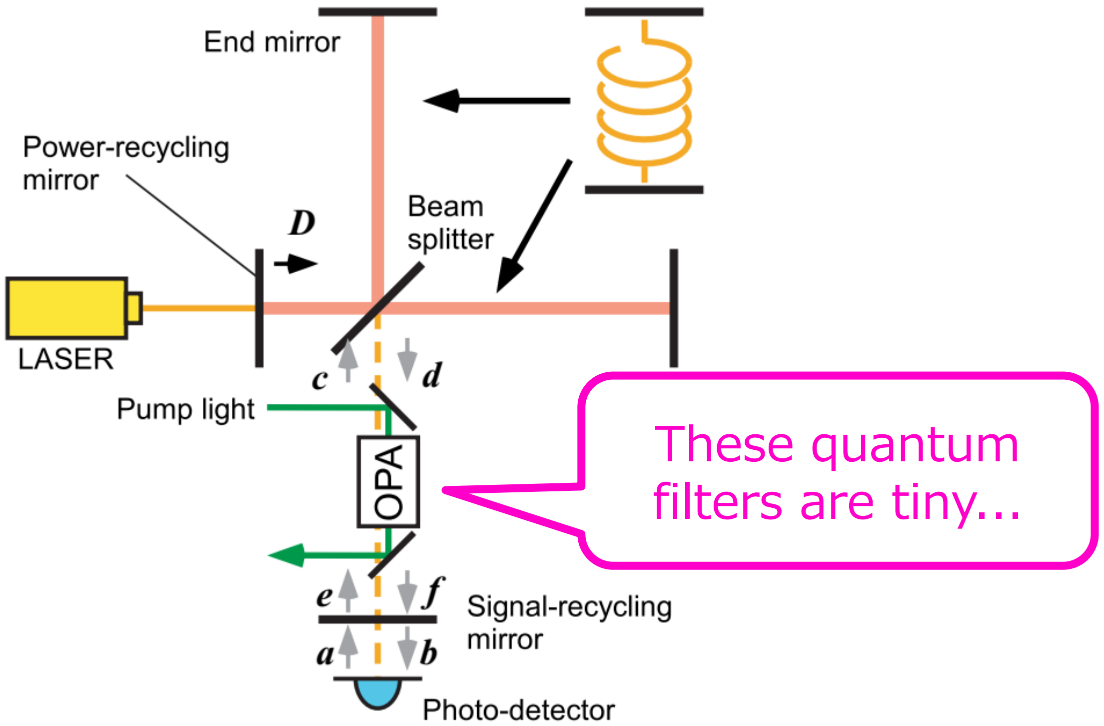
(c) Postmerger



AI picked the configuration.

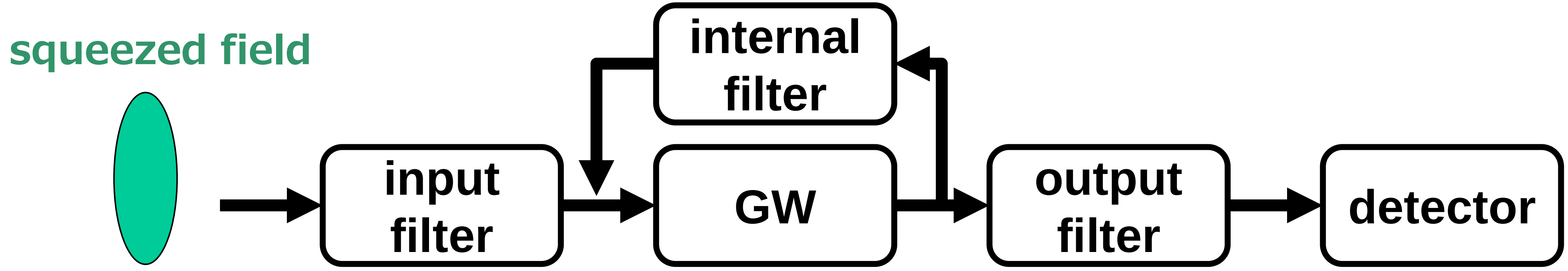
Feasibility

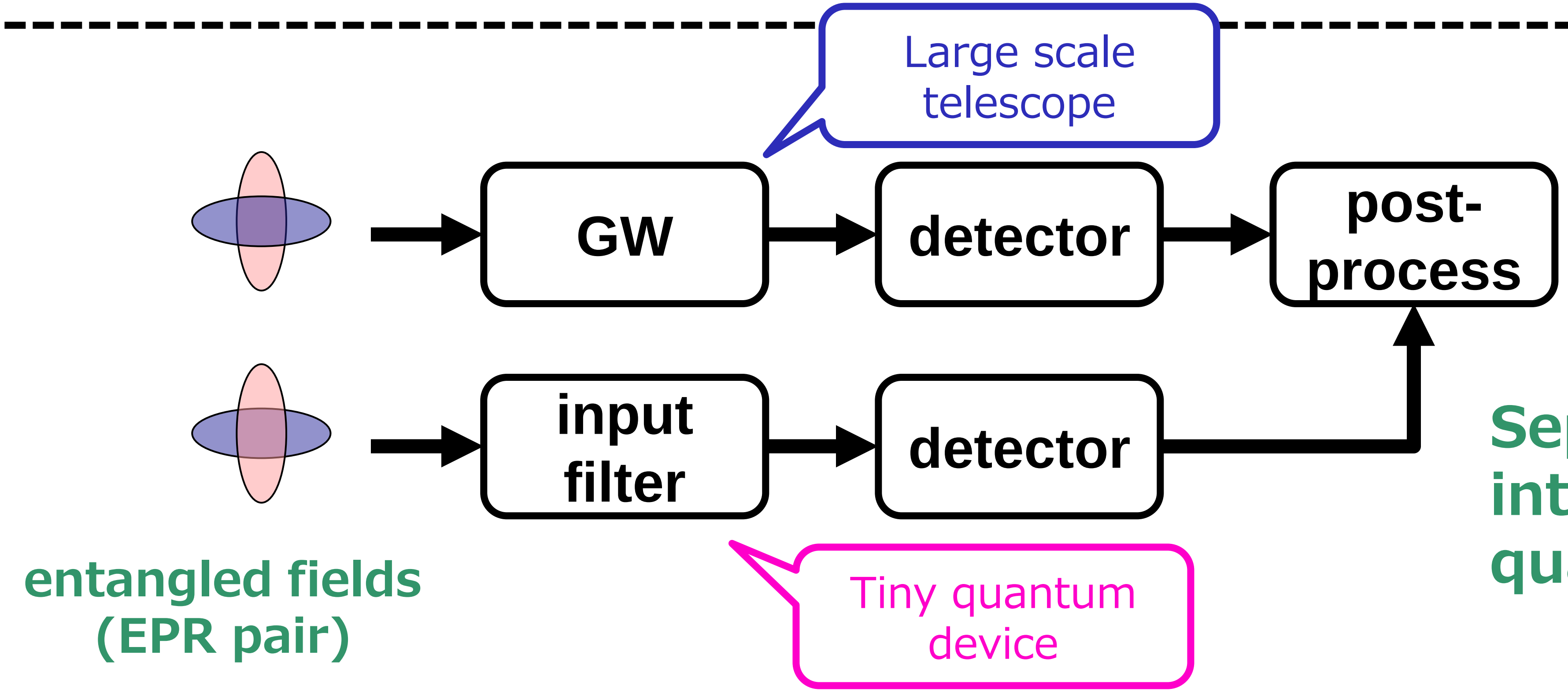




- Beam size on mirrors is ~3cm, while that in a filter is ~100um.
- Junk light in the recycling cavity may cause scatter light.

New scheme with entanglement

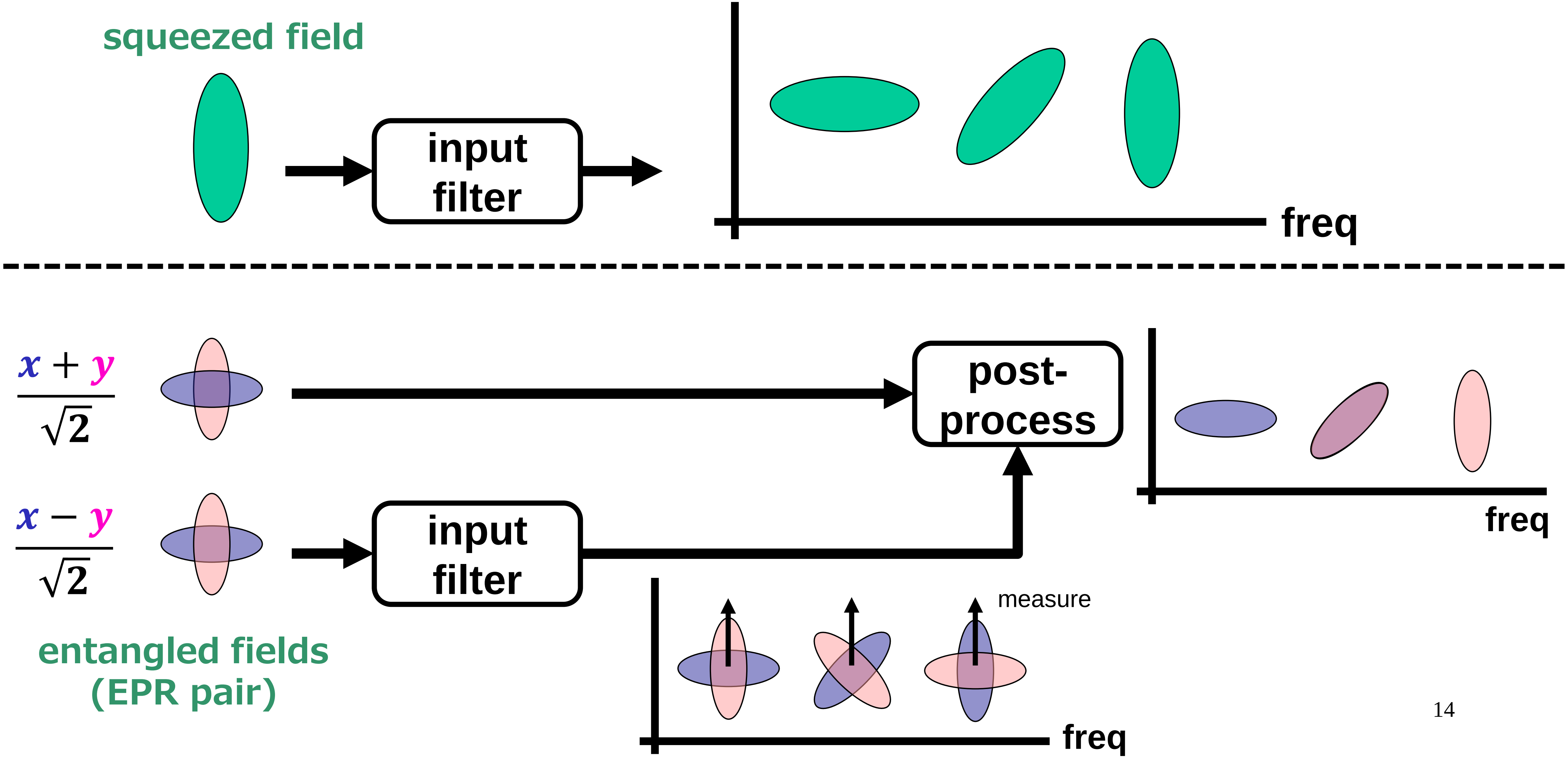




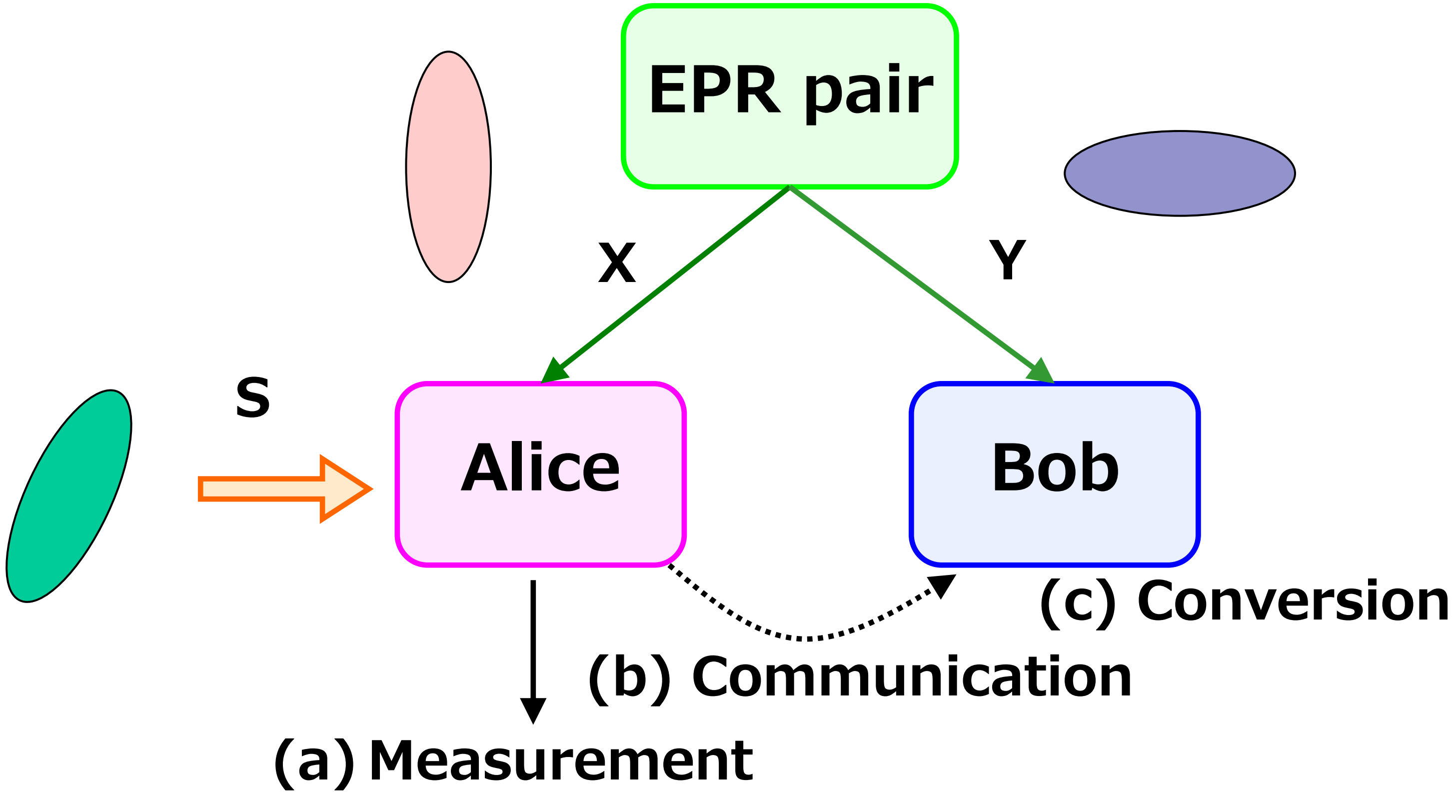
Separation of main interferometer and quantum filters.

Simple example: squeeze rotation

[Ma 2017]



Quantum teleportation



(1) X is 12:00, Y is 3:00, and S is 1:00 but no one knows

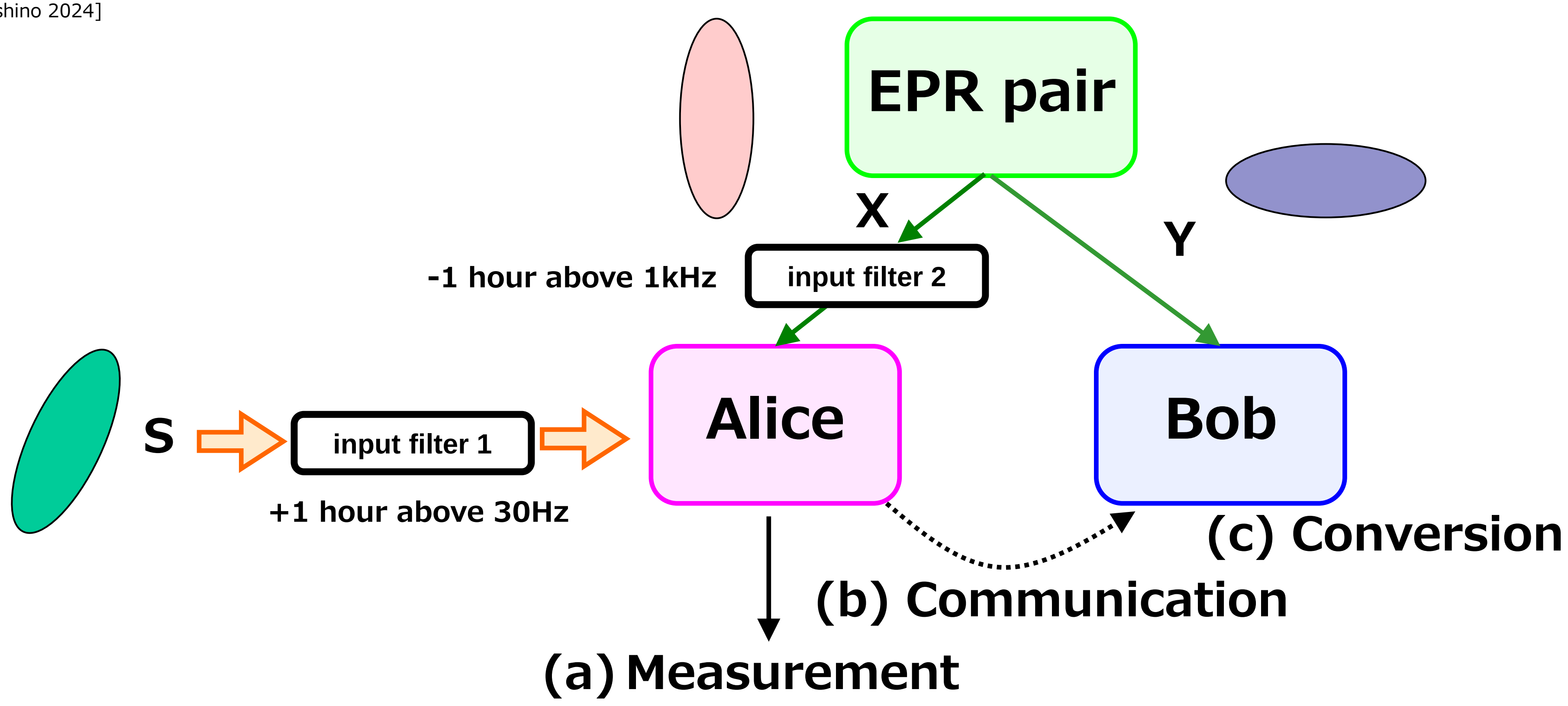
(2) We know “Y is 3 hours earlier than X”

(3) Alice’s measurement tells “S is 1 hour earlier than X”

(4) Bob delays Y by 3-1=2 hours, then Y becomes S

Double squeeze rotation with teleportation

[Nishino 2024]



Alice's measurement tells S is

(1) 1 hour earlier than X (f<30Hz)

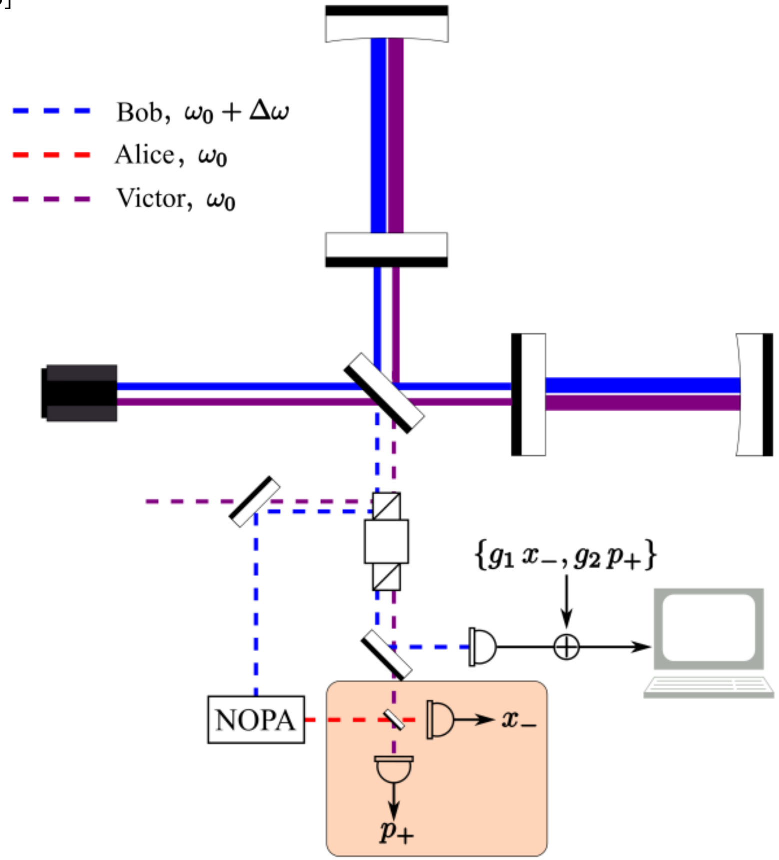
(2) 2 hours earlier than X (30Hz<f<1kHz)

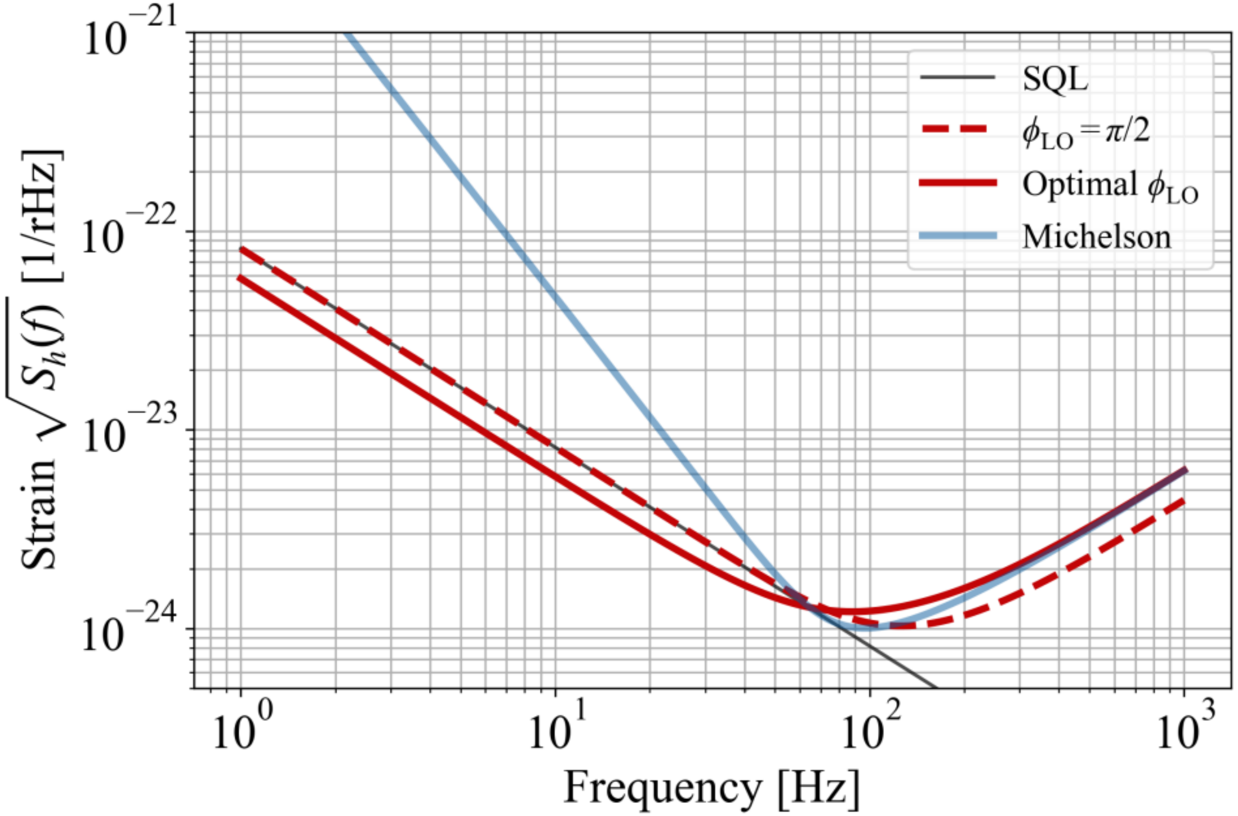
(3) 3 hours earlier than X (1kHz<f)

Y becomes frequency-dependent squeezing

Quantum-teleportation speed meter

[Nishino 2025]





This is one example that a configuration with a quantum filter can be realized with the teleportation scheme.

Summary

- There are variety of configurations that are about to reach 1e-24 at 3kHz.
- For some configurations, optical losses of the signal recycling cavity limit the sensitivity; there is an idea to circumvent this problem but with the 25km baseline.
- Implementation of quantum filters into a large scale interferometer can be an issue. Teleportation scheme and entanglement scheme may be useful.