Use of phase sensitive amplifier for the back-action evasion scheme

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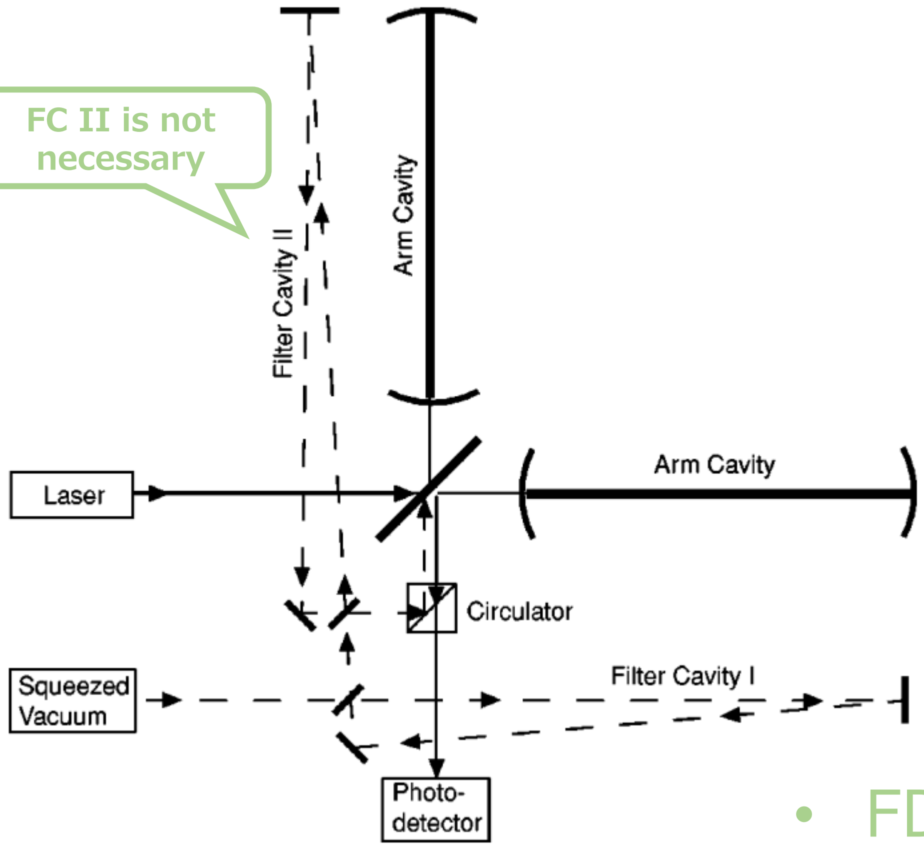
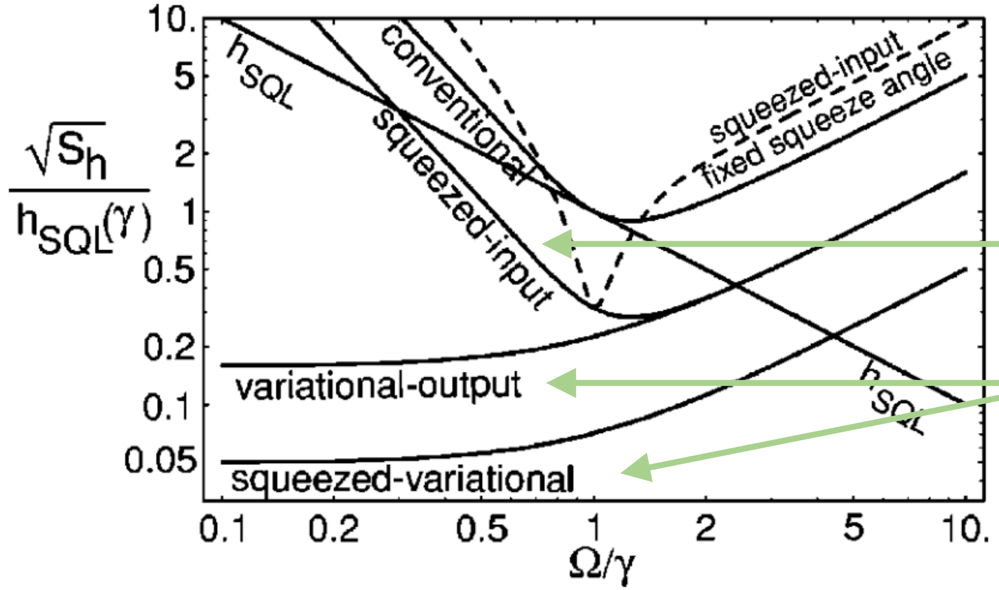
Frequency-dependent squeezing

FC II is not necessary



[Kimble 2001]



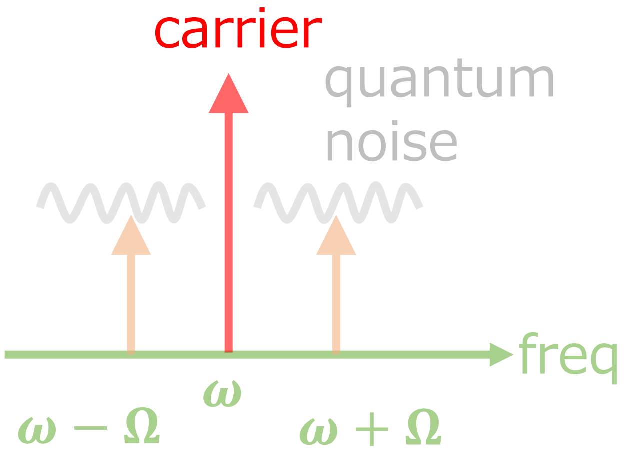
(lossless)

10dB Freq-dependent SQ

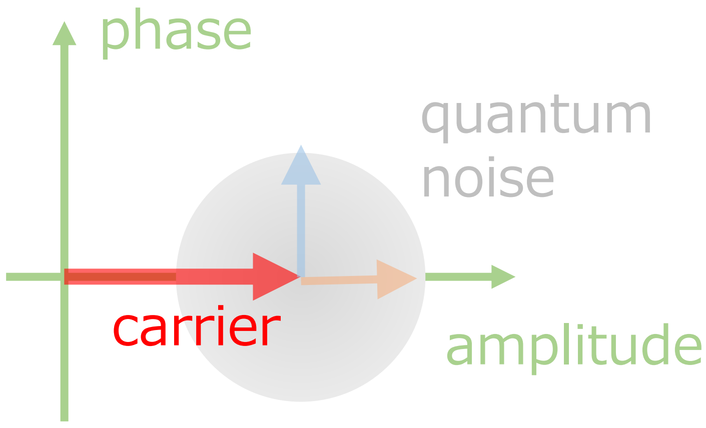
Variational readout (x10 power, 10dB SQ)

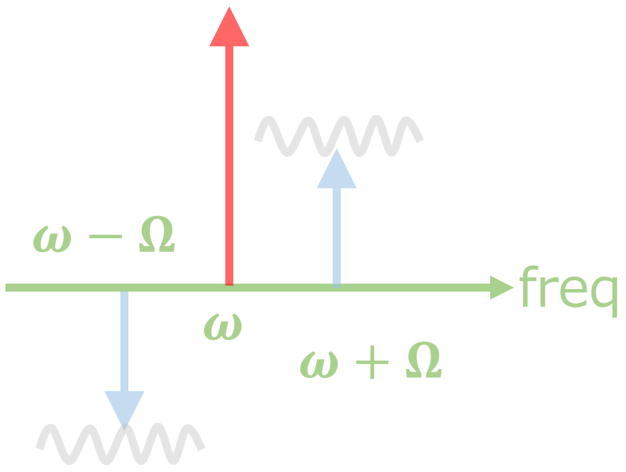
- FDSQ reduces quantum noise in broadband
- FDSQ has been implemented in LIGO & Virgo
- Variational Readout is another option but is weak against optical losses

Shot noise and radiation pressure

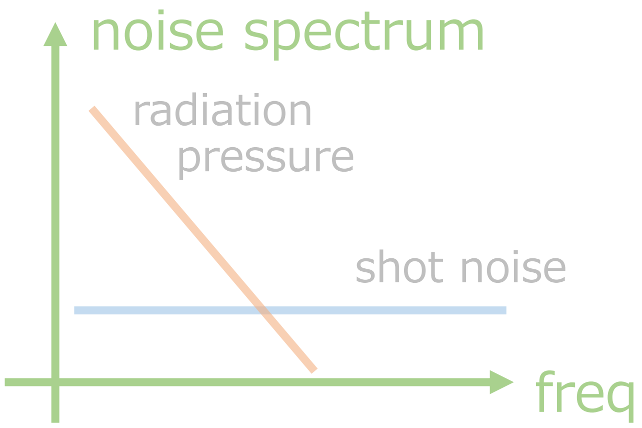


Quantum-noise sidebands are in-phase to carrier.
→ amplitude fluctuation
→ radiation pressure noise



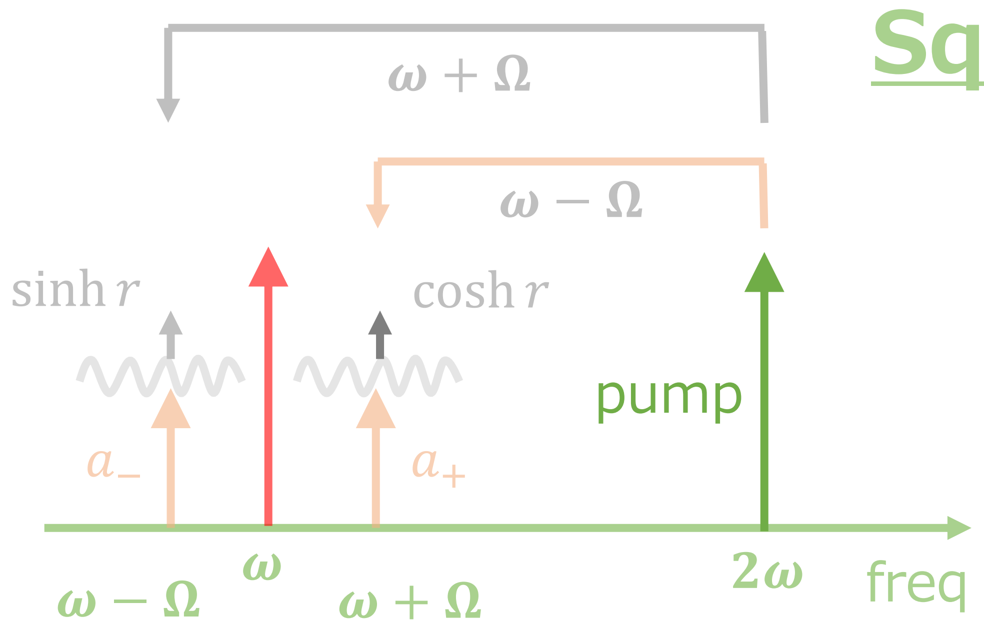


Quantum-noise sidebands are out-of-phase to carrier.
→ phase fluctuation
→ shot noise

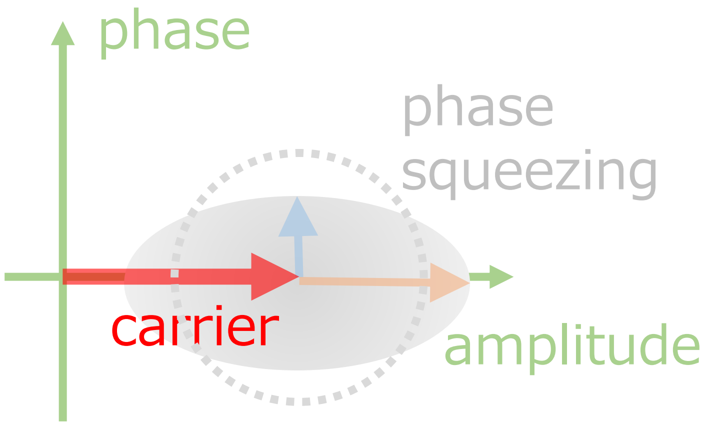


Squeezing

r: squeeze factor
$r = 0.69$ for 6dB SQ



Injecting the carrier and pump beams into a non-linear crystal, either amplitude or phase fluctuation increases and the other one decreases.



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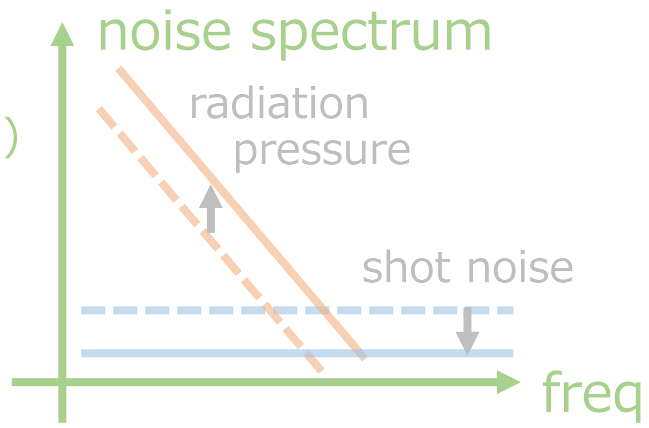
Squeezing
(Optical Parametric Amplification)
"Degenerated OPA"

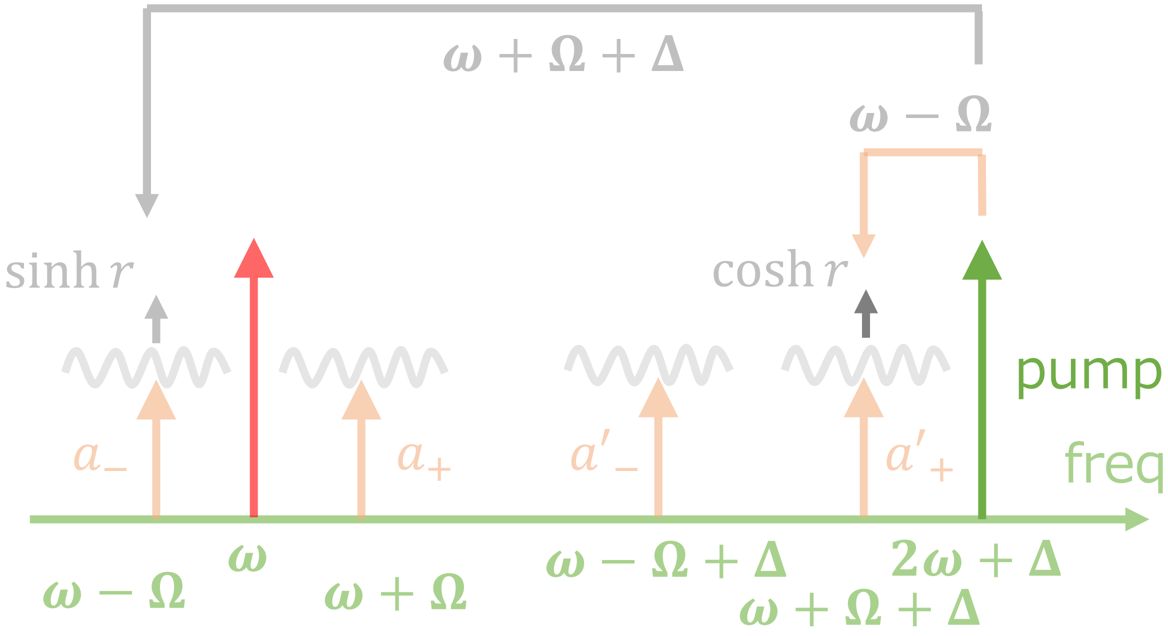
$$S\left[\begin{pmatrix} a_+ \\ a_-^\dagger \end{pmatrix}\right] = \begin{pmatrix} \cosh r & \sinh r \\ \sinh r & \cosh r \end{pmatrix} \begin{pmatrix} a_+ \\ a_-^\dagger \end{pmatrix}$$

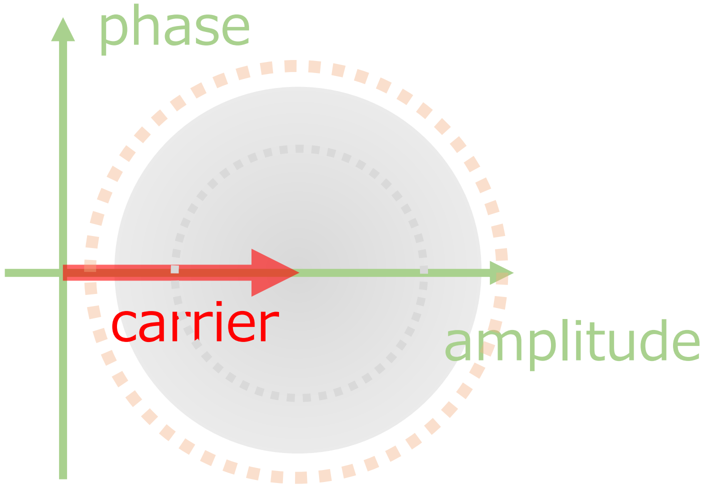
$$S\left[\begin{pmatrix} a_{\mathrm{amp}} \\ a_{\mathrm{phase}} \end{pmatrix}\right] = \frac{1}{2} S\left[\begin{pmatrix} a_+ + a_-^\dagger \\ a_+ - a_-^\dagger \end{pmatrix}\right] = \begin{pmatrix} e^r & 0 \\ 0 & e^{-r} \end{pmatrix} \begin{pmatrix} a_{\mathrm{amp}} \\ a_{\mathrm{phase}} \end{pmatrix}$$

Using an optical cavity as a frequency filter, frequency-dependent squeezing can be realized.



Non-degenerated OPA





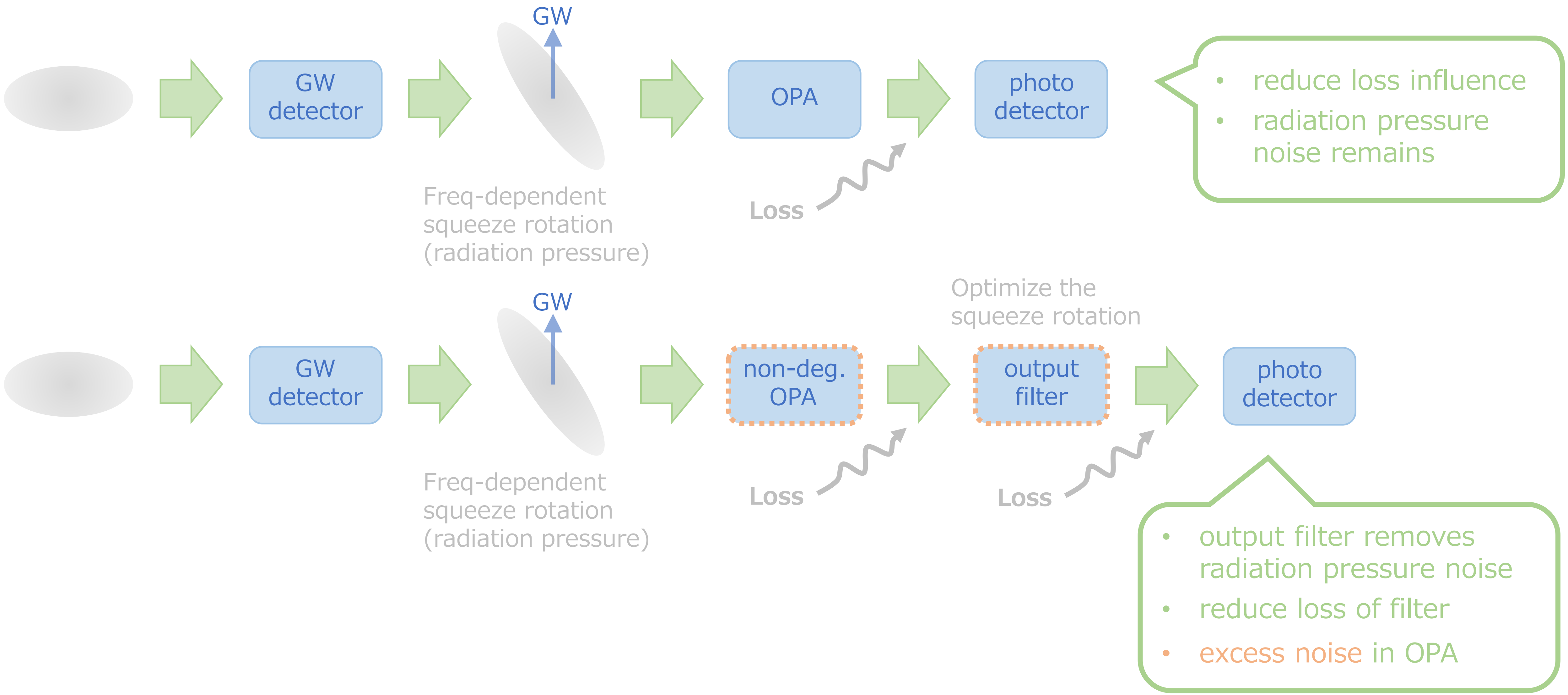
$$S\left[\begin{pmatrix} a_+ \\ a_-^\dagger \\ a'_+ \\ a'^\dagger_- \end{pmatrix}\right] = \begin{pmatrix} \cosh r & \cdots & \sinh r \\ \vdots & \ddots & \vdots \\ \sinh r & \cdots & \cosh r \end{pmatrix} \begin{pmatrix} a_+ \\ a_-^\dagger \\ a'_+ \\ a'^\dagger_- \end{pmatrix}$$

$$\Rightarrow \quad S\left[\begin{pmatrix} a_{\mathrm{amp}} \\ a_{\mathrm{phase}} \end{pmatrix}\right] = \begin{pmatrix} \cosh r \times a_{\mathrm{amp}} - \sinh r \times a'_{\mathrm{amp}} \\ \cosh r \times a_{\mathrm{phase}} + \sinh r \times a'_{\mathrm{phase}} \end{pmatrix}$$

A non-degenerated OPA works as a phase-insensitive amplifier.

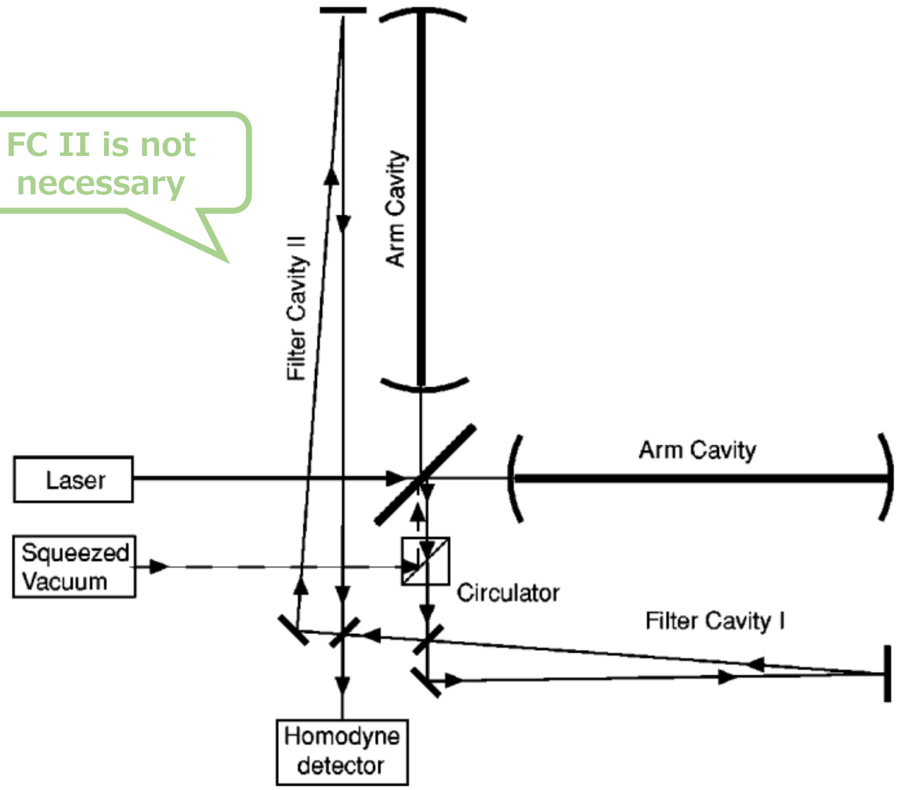
	device	amplification	excess noise
phase-sensitive amplifier	degenerated OPA	either phase or amplitude	no
phase-insensitive amplifier	non-degenerated OPA	both phase and amplitude	yes

Output filter and output amplifier

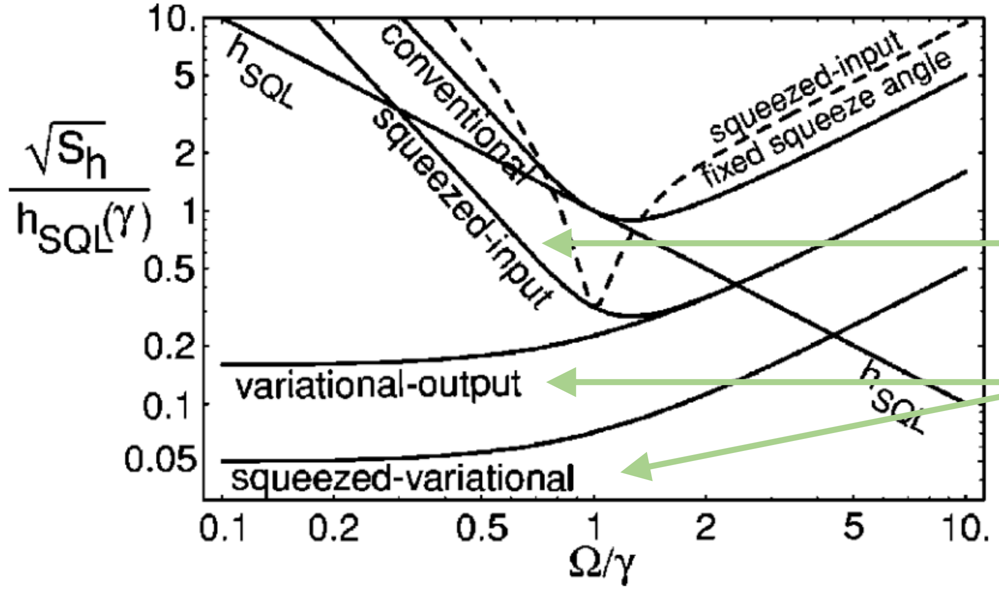


Variational readout scheme

FC II is not necessary



[Kimble 2001]



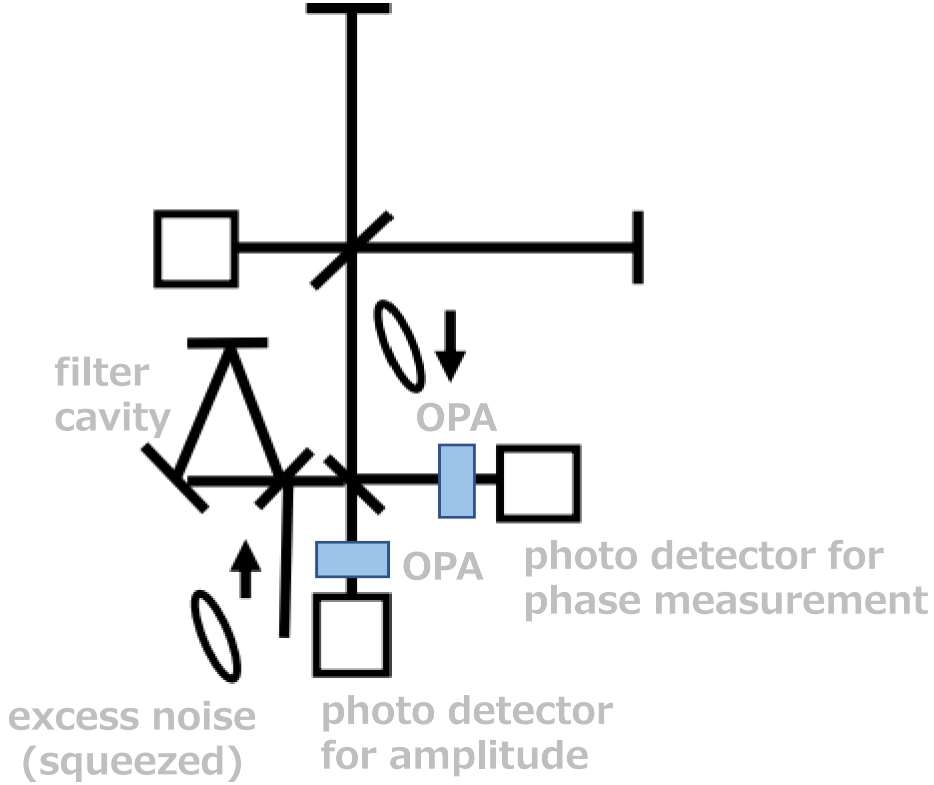
(lossless)

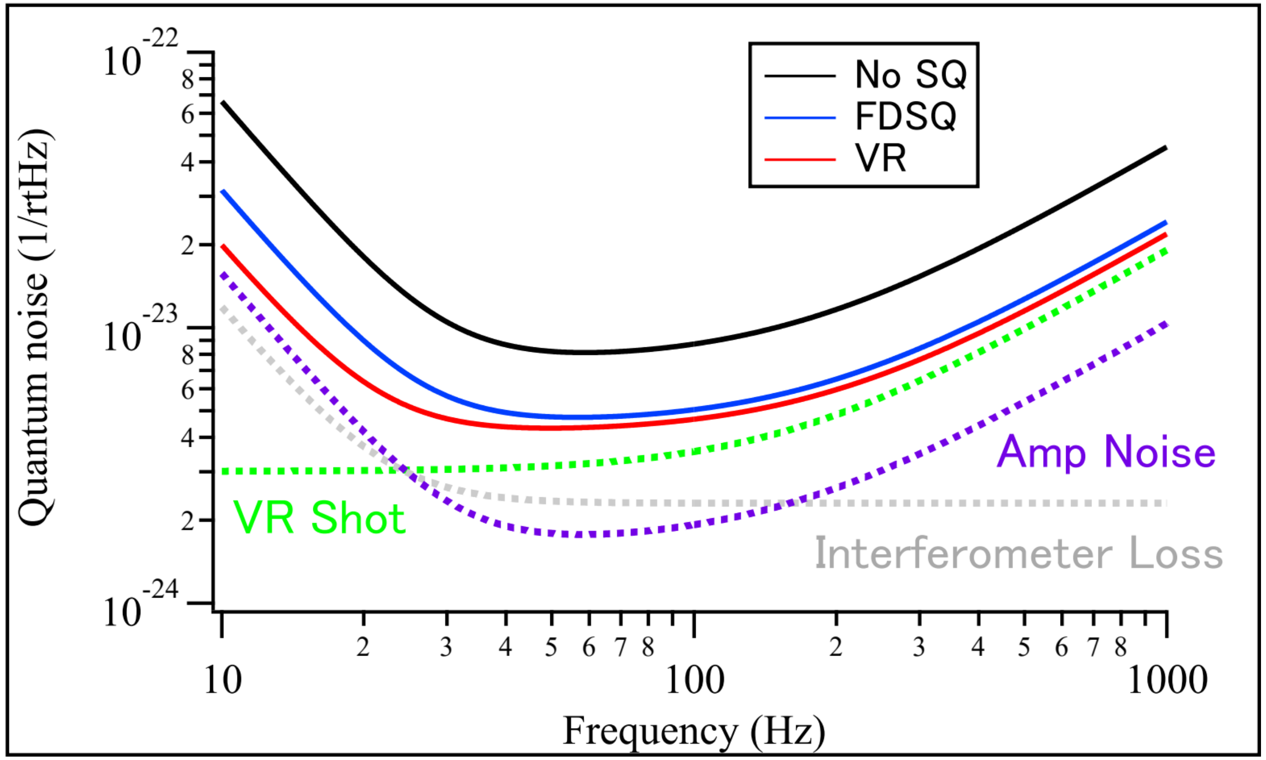
10dB Freq-dependent SQ

Variational readout (x10 power, 10dB SQ)

- Variational Readout is weak against optical losses
- It would be nice if we can use an amplifier to reduce the loss and realize variational readout
  → We have found two different ways.

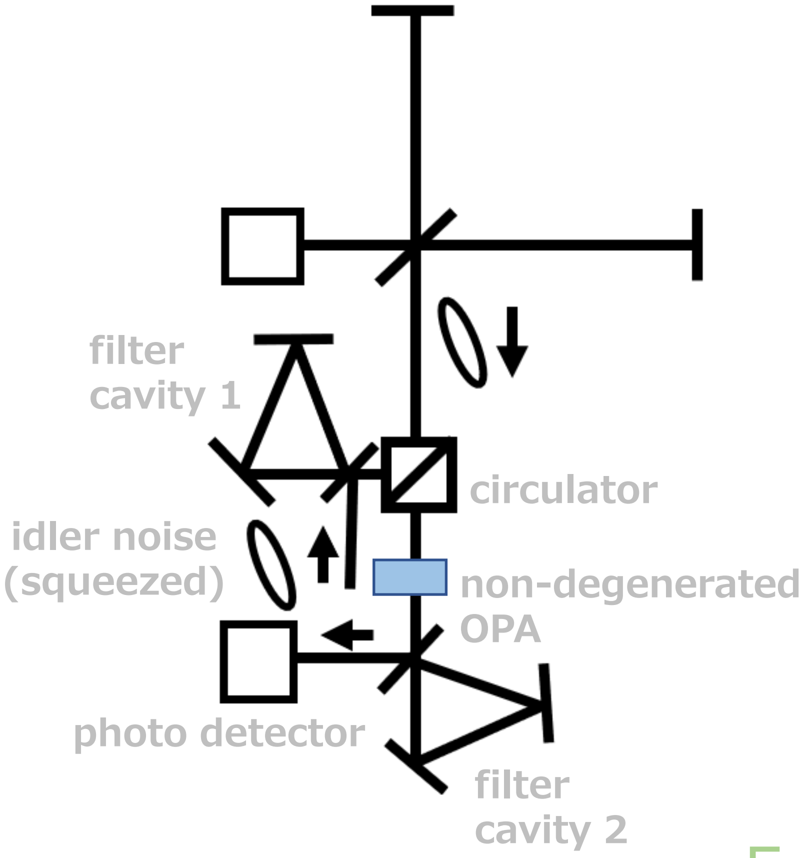
Use of amplifier with variational readout (1)

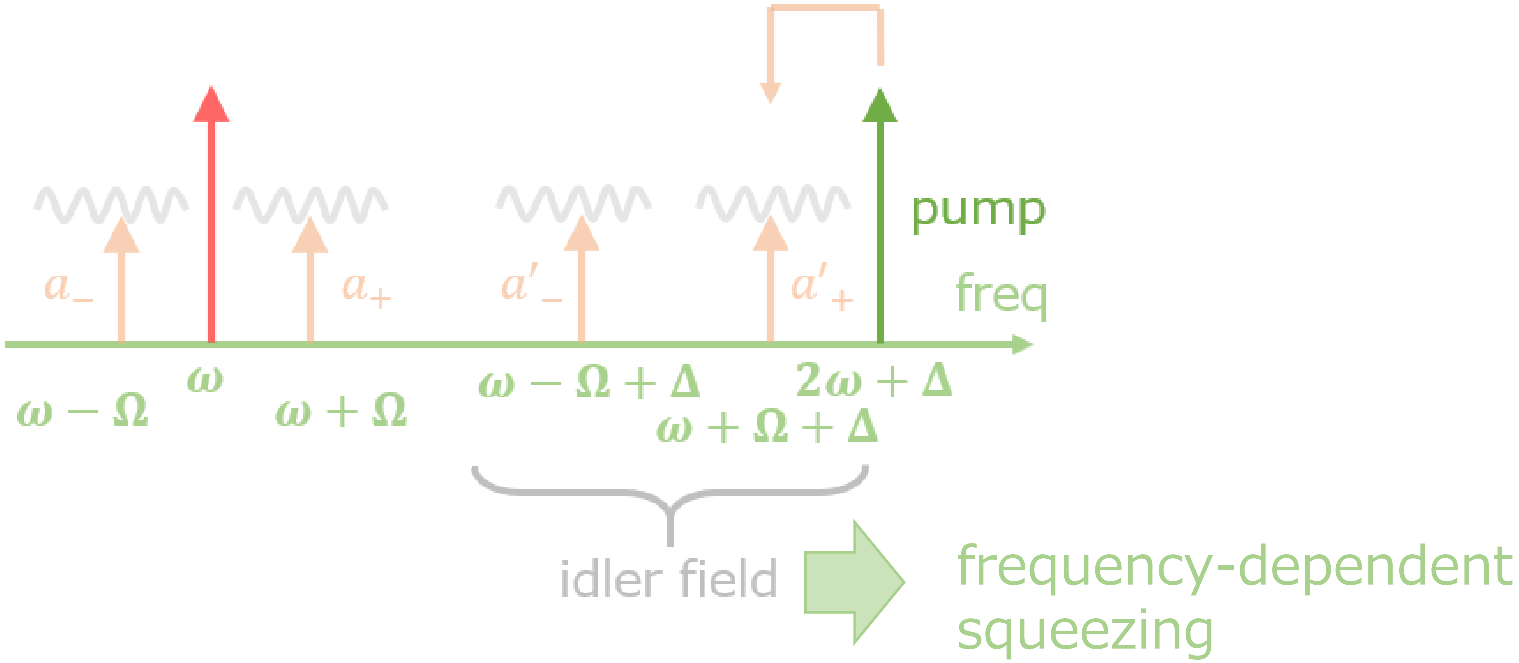




- Post-processing of phase/amplitude measurements realizes the variational readout
- In this way, the amplifier for each measurement can be a phase-insensitive amplifier

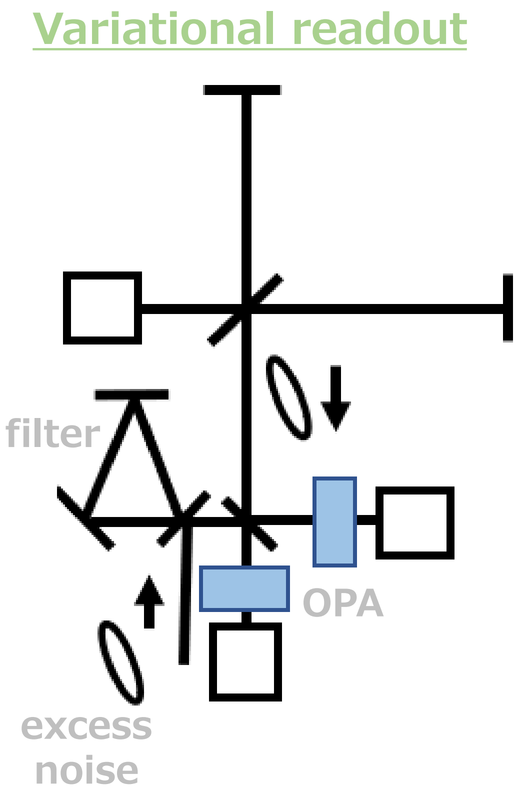
Use of amplifier with variational readout (2)

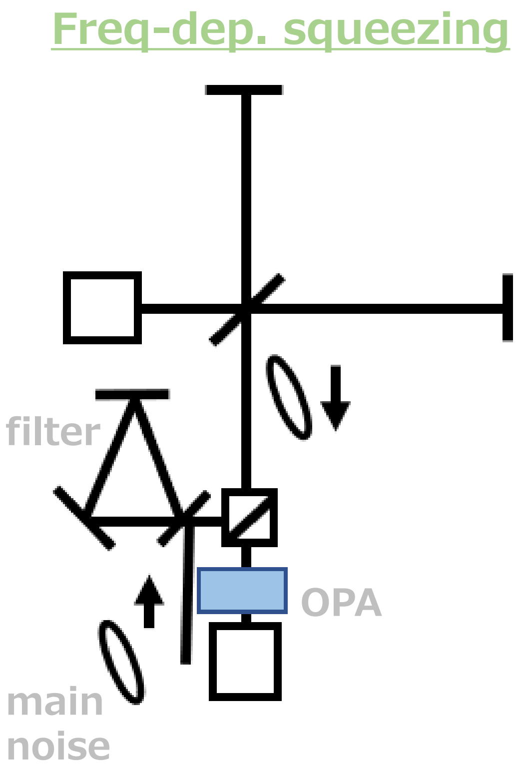


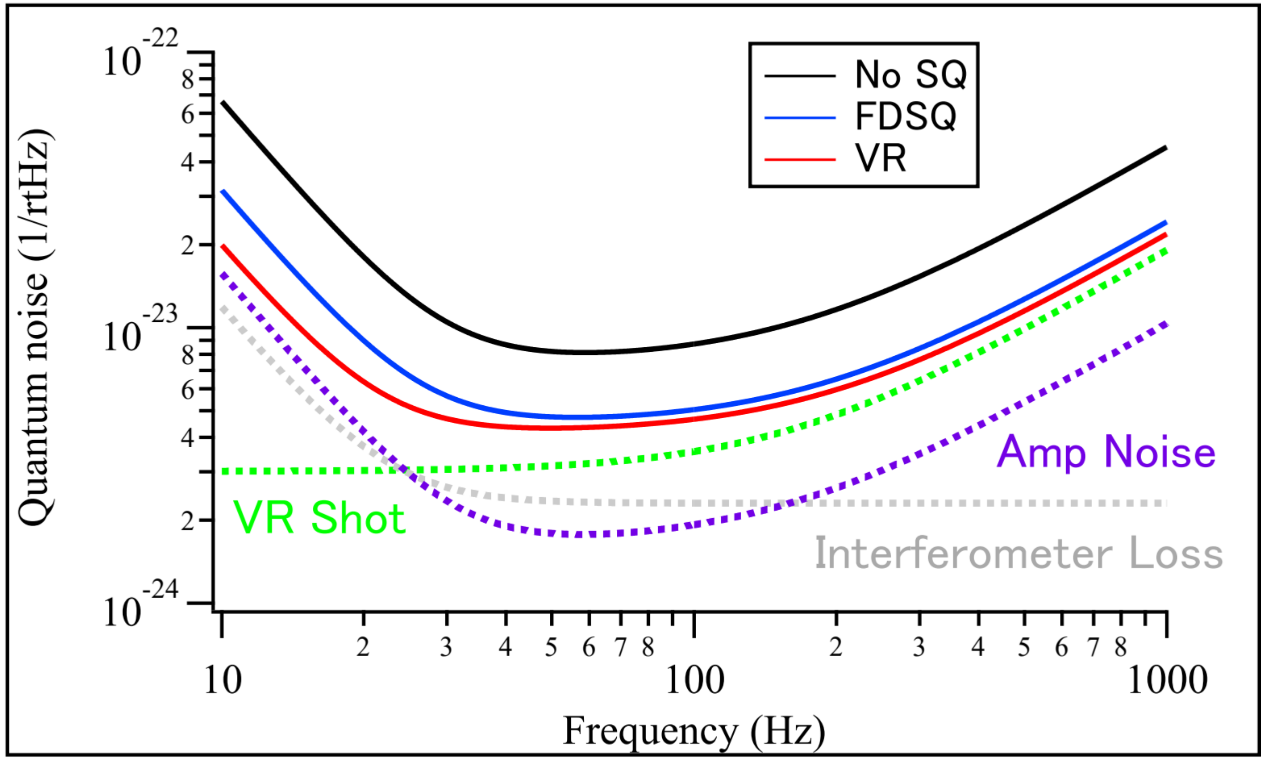


- Frequency-dependent squeezing on the idler field reduces influence of excess noise at each frequency
- Quantum noise spectrum is the same as the previous one.

Summary







- We introduced 2 ways to use optical amplifiers with variational readout.
- Quantum noise can be slightly improved compared with frequency-dependent squeezing that is used in current GW telescopes.