Squeezed Light at Sideband Frequencies below 100 kHz

Roman Schnabel, H. Vahlbruch, S. Chelkowski,
A. Franzen, N. Große, H.-A. Bachor,
W. P. Bowen, P. K. Lam, K. Danzmann.

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut),
Institut für Atom- und Molekülphysik, Universität Hannover

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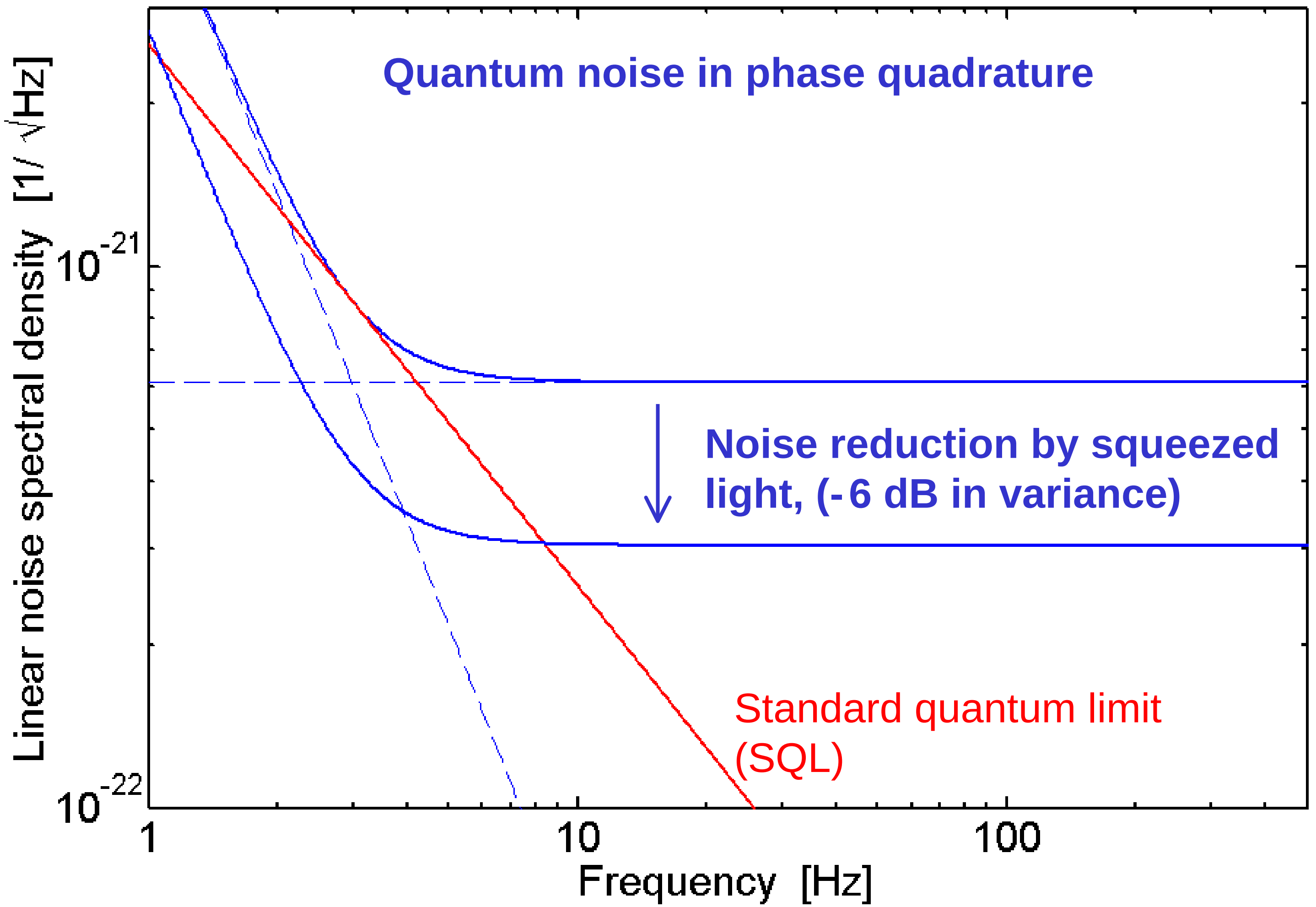
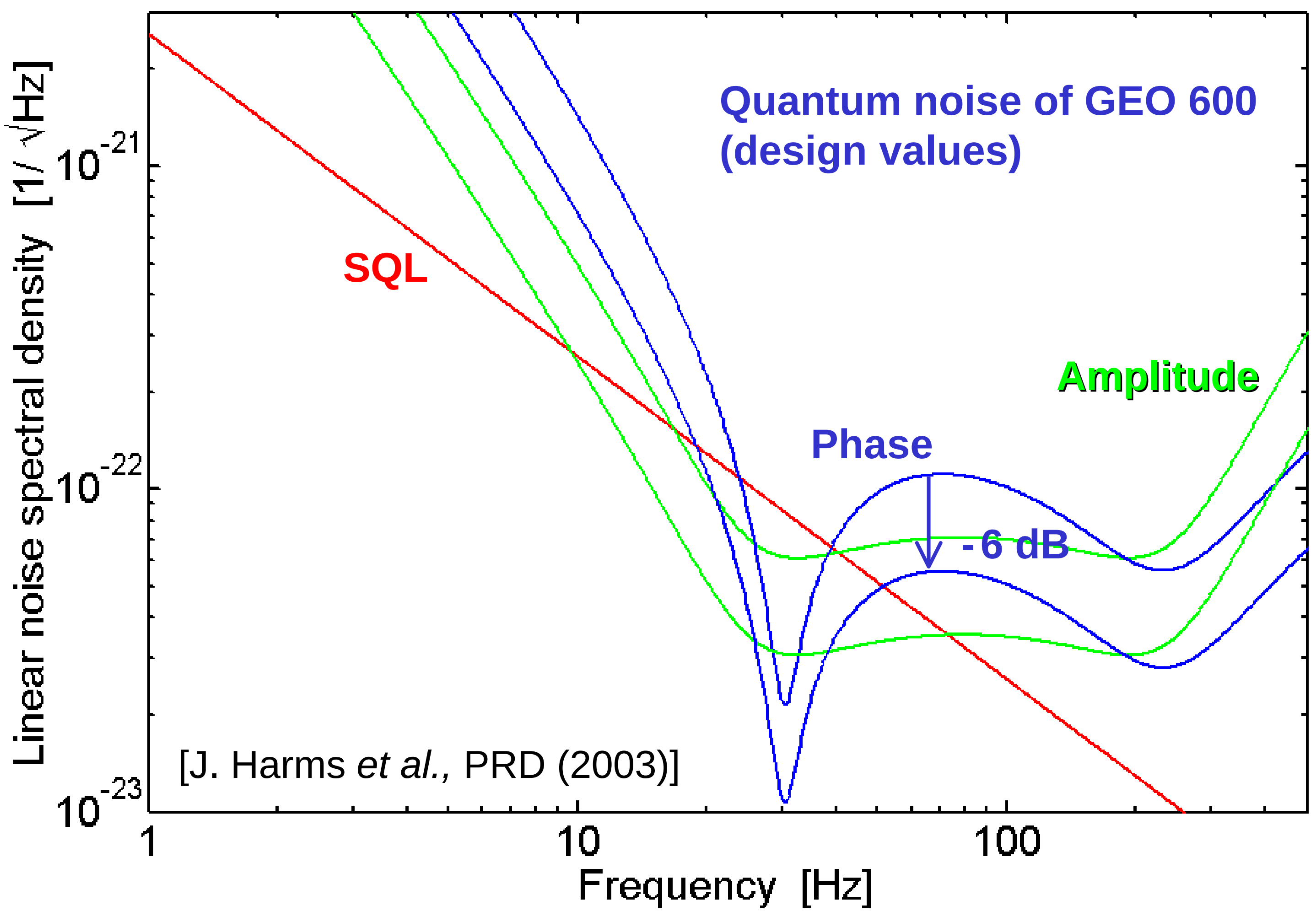
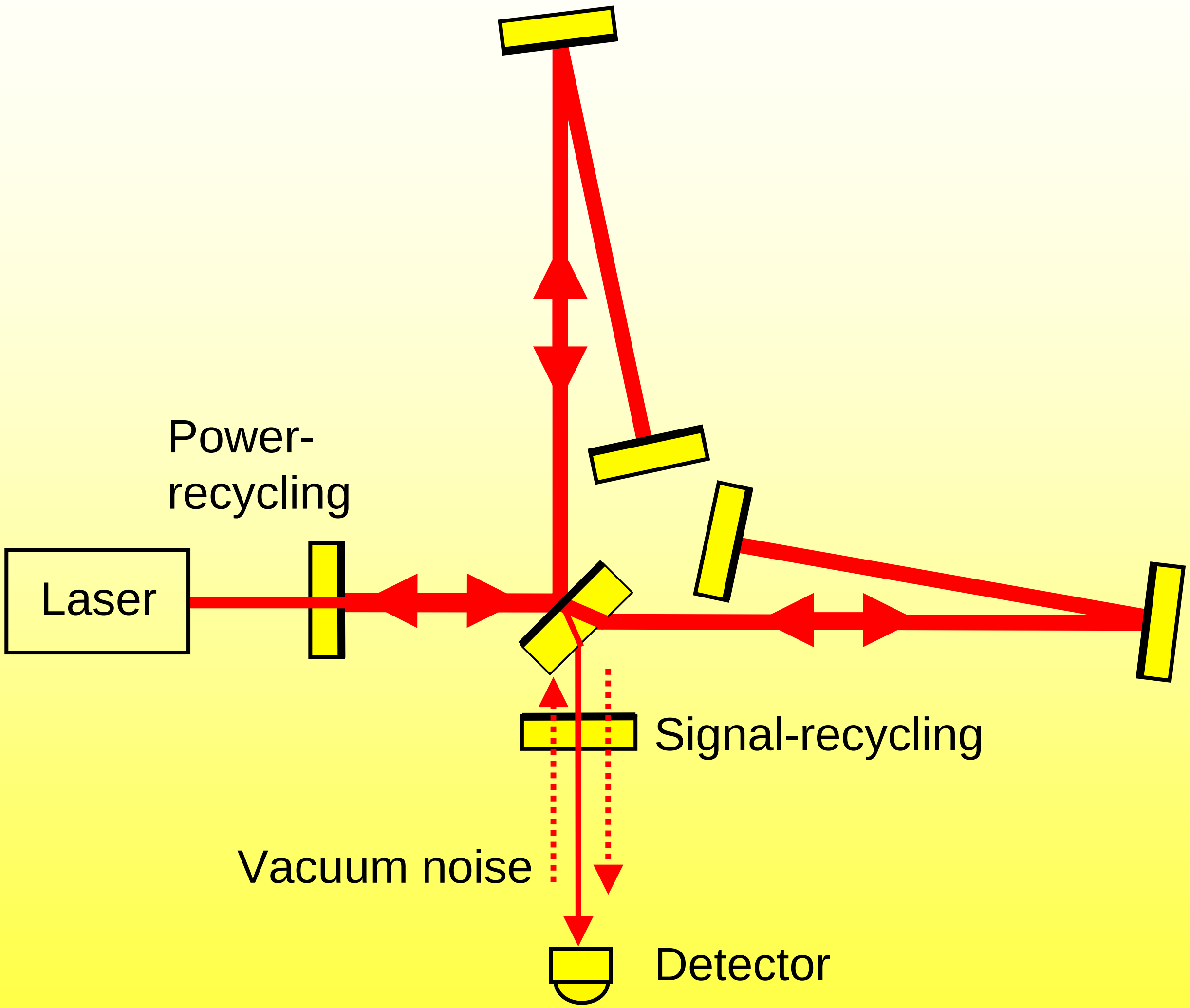
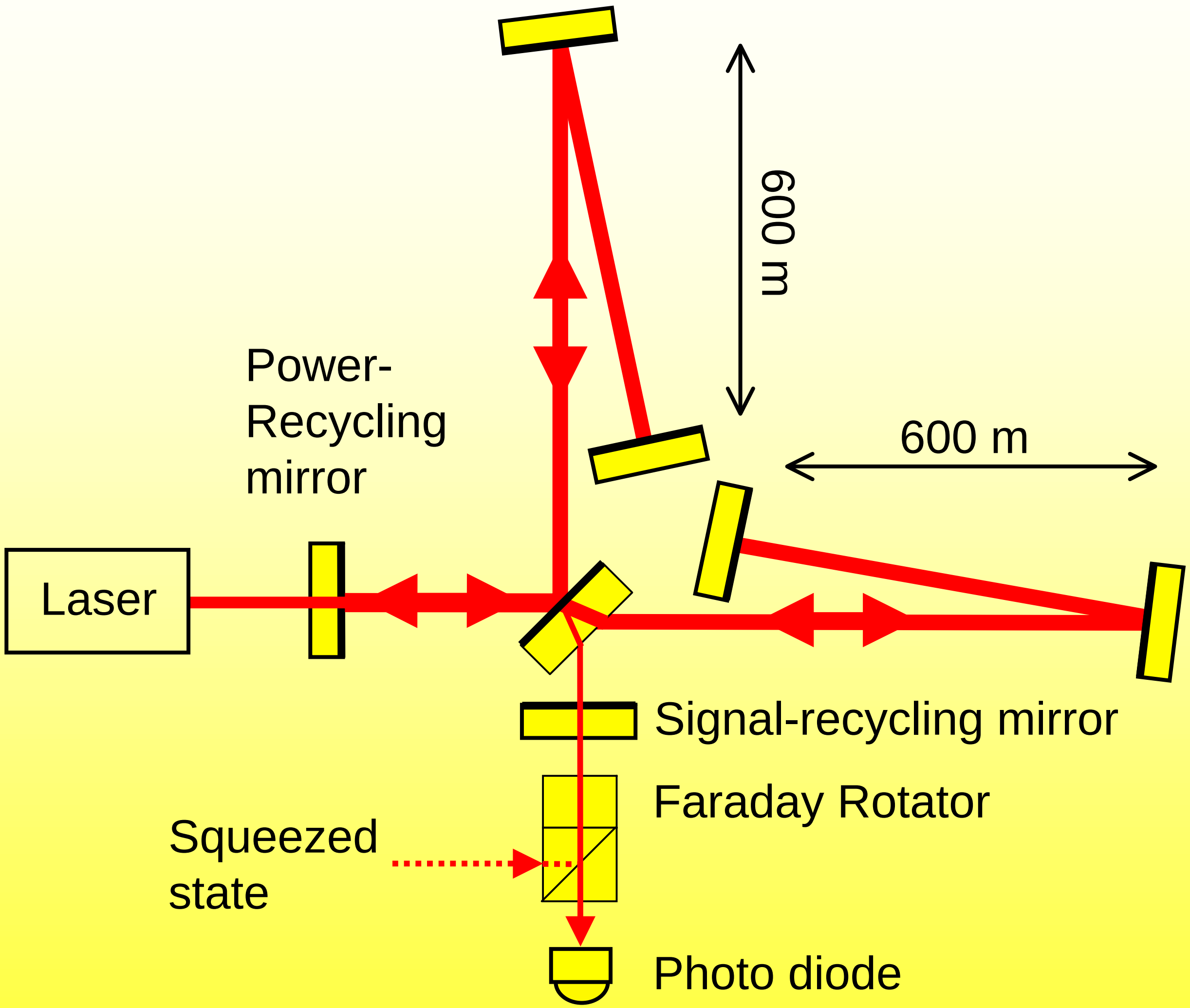
Quantum Noise of a Conventional MI



Optical Spring SR Interferometers




Power-
recycling
Laser
Signal-recycling
Vacuum noise
Detector



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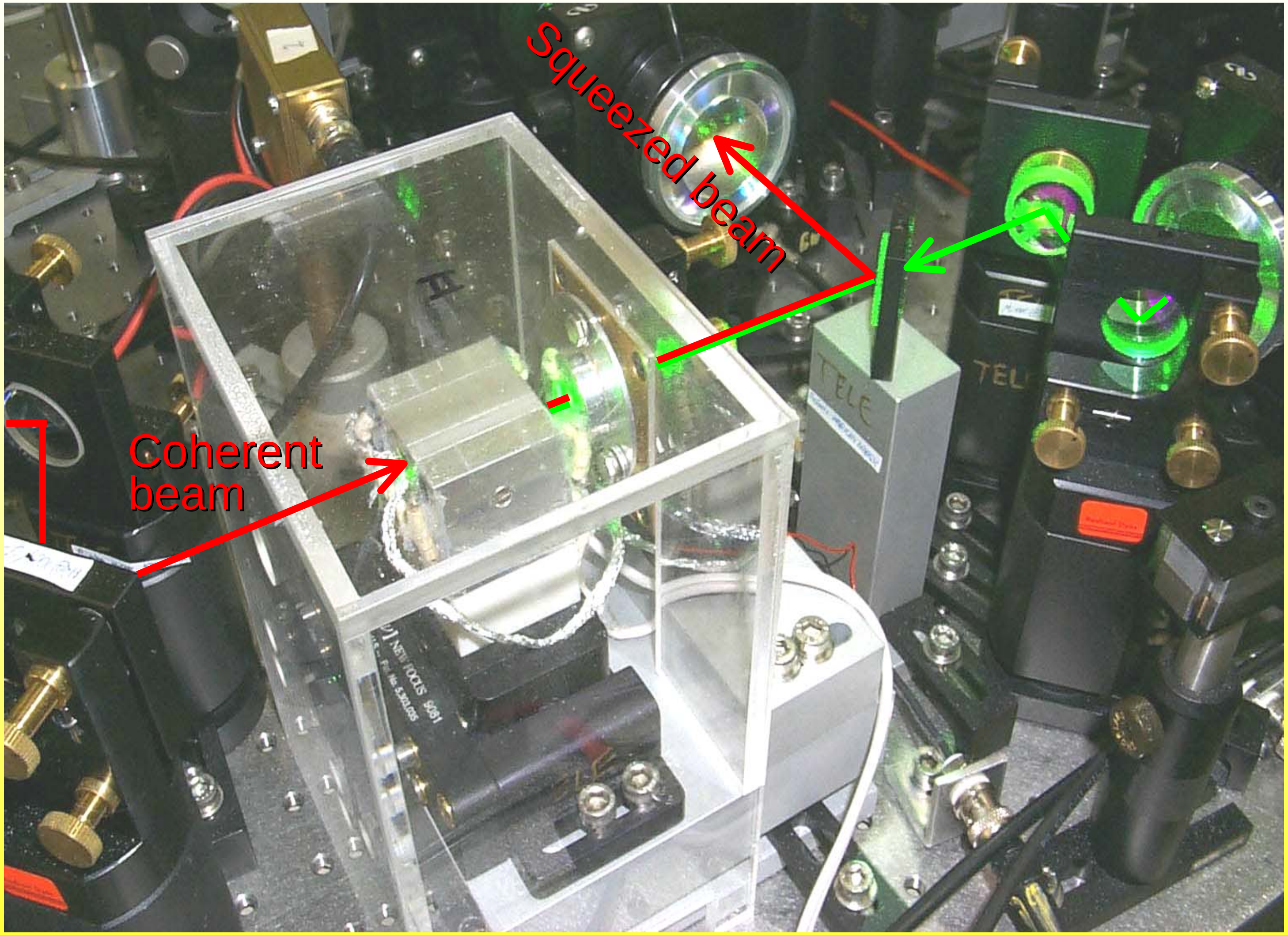
Squeezed Light from an OPA



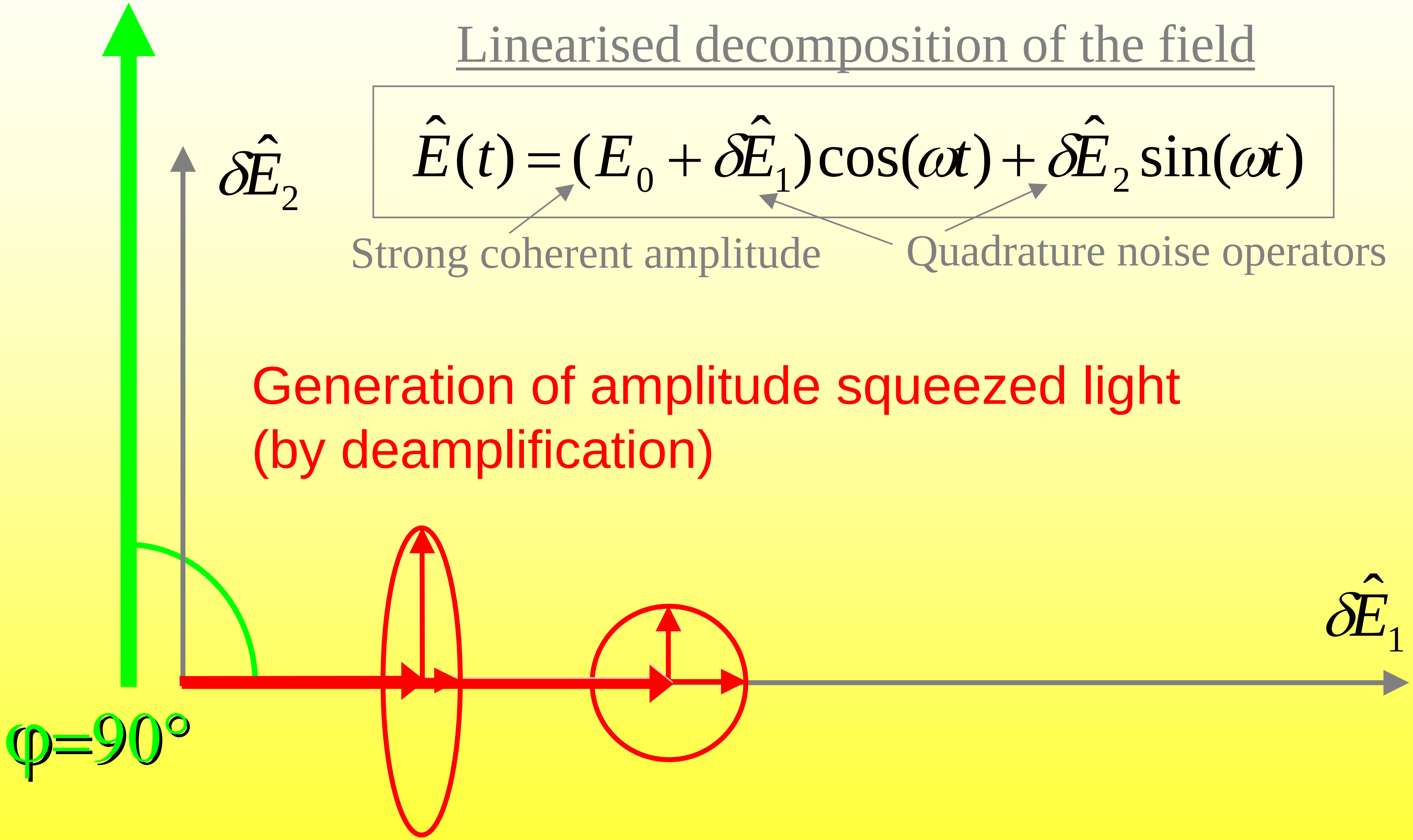
Optical Parametric Amplification (OPA)

Linearised decomposition of the field

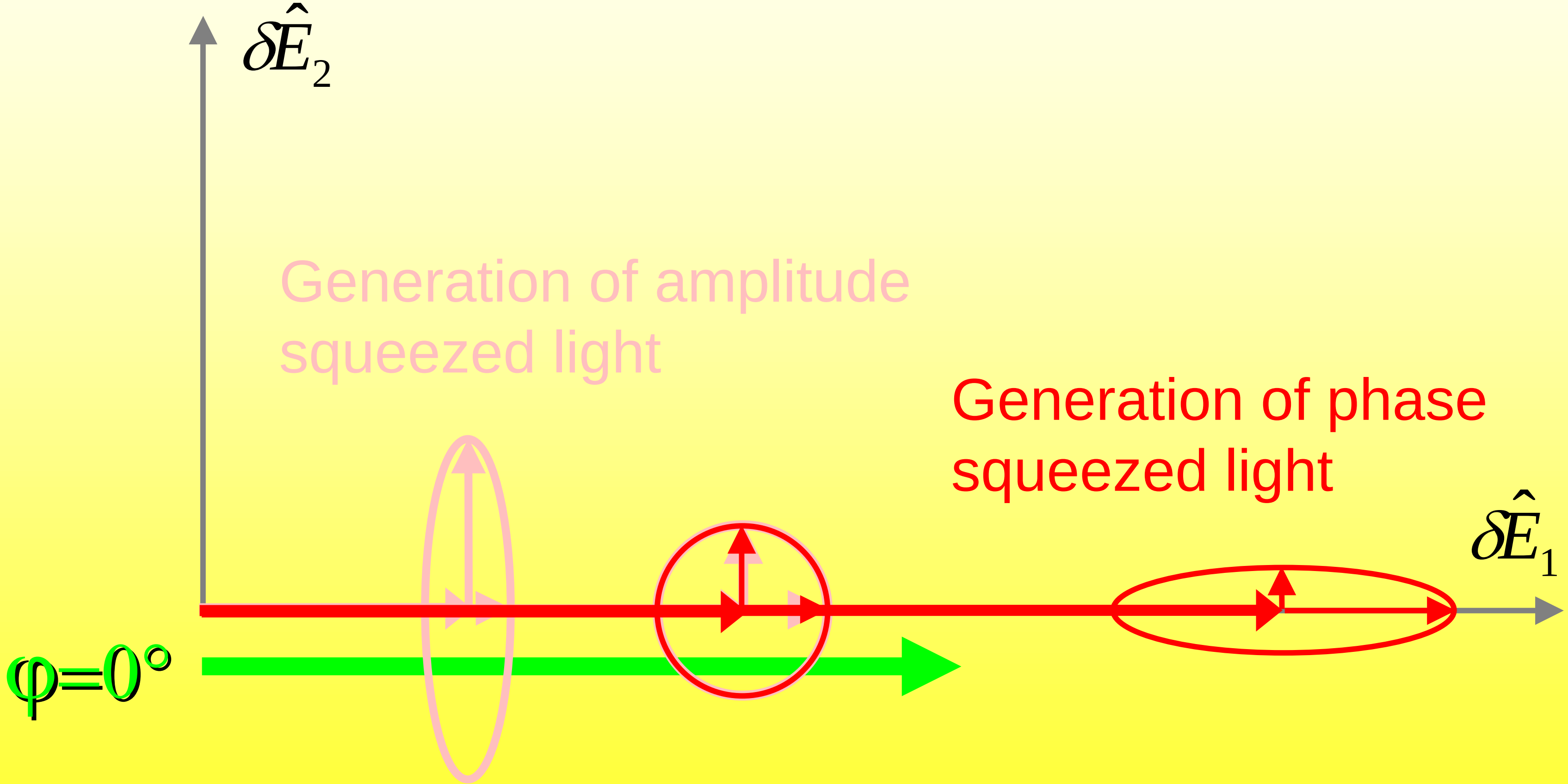
$$\hat{E}(t) = (E_0 + \delta\hat{E}_1)\cos(\omega t) + \delta\hat{E}_2 \sin(\omega t)$$

Strong coherent amplitude — Quadrature noise operators

Generation of amplitude squeezed light
(by deamplification)



Optical Parametric Amplification



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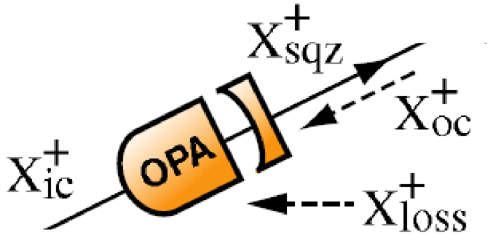
OPA Amplitude Noise Transfer Function

Amplitude quadratures in frequency space



$$\hat{X}^+_{\rm sqz} = \Big\{ \sqrt{4\kappa_{\rm ic}\kappa_{\rm oc}}\hat{X}^+_{\rm ic} + \sqrt{4\kappa_{\rm loss}\kappa_{\rm oc}}\hat{X}^+_{\rm loss} + (2\kappa_{\rm oc} - i\Omega - \kappa + g)\hat{X}^+_{\rm oc} \Big\} / (i\Omega + \kappa - g)$$

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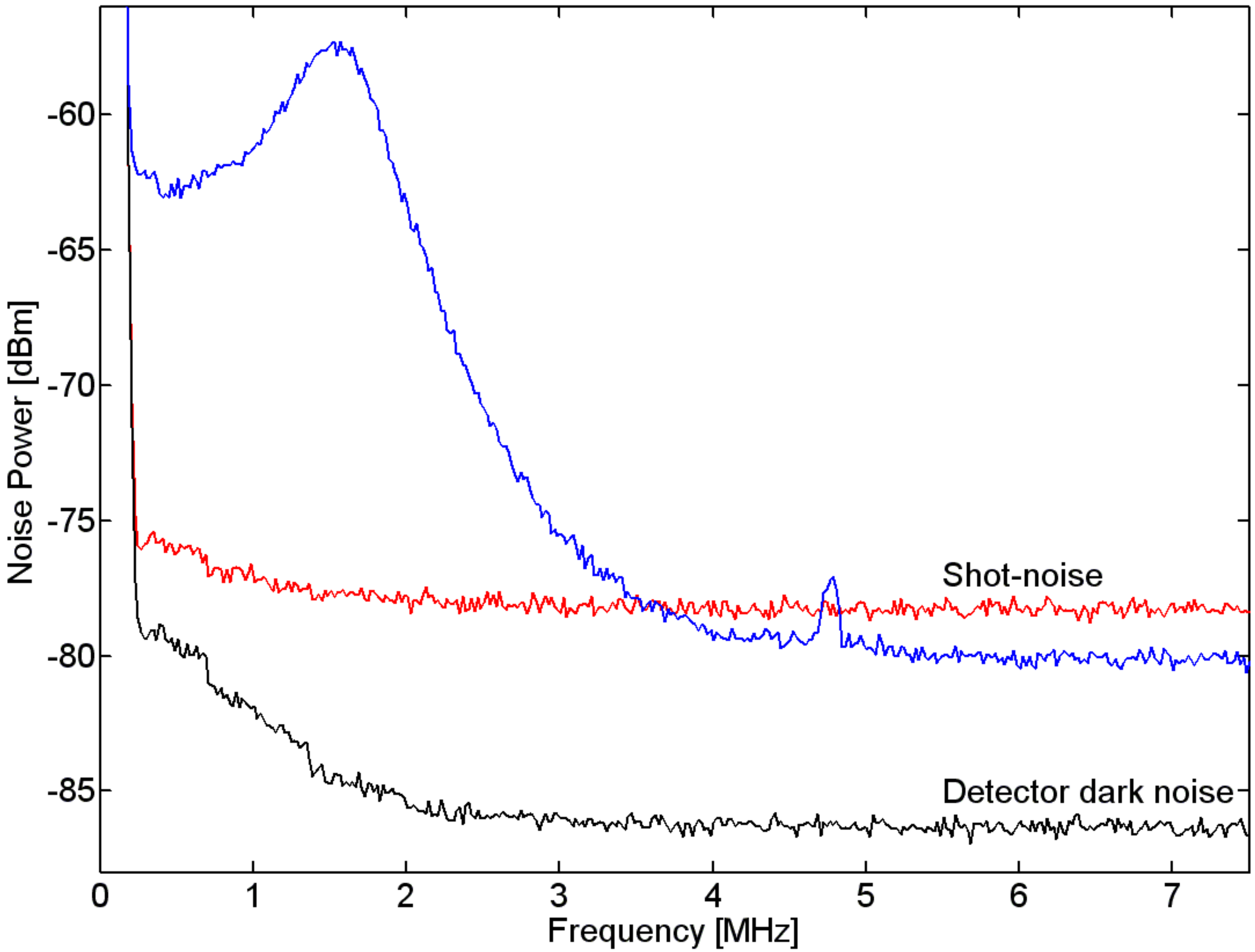
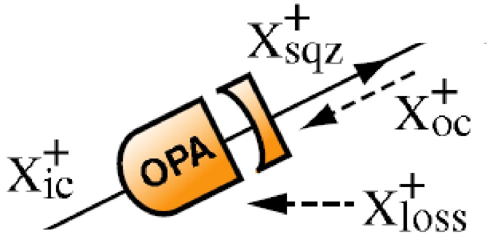
Locked Amplitude Squeezed Light



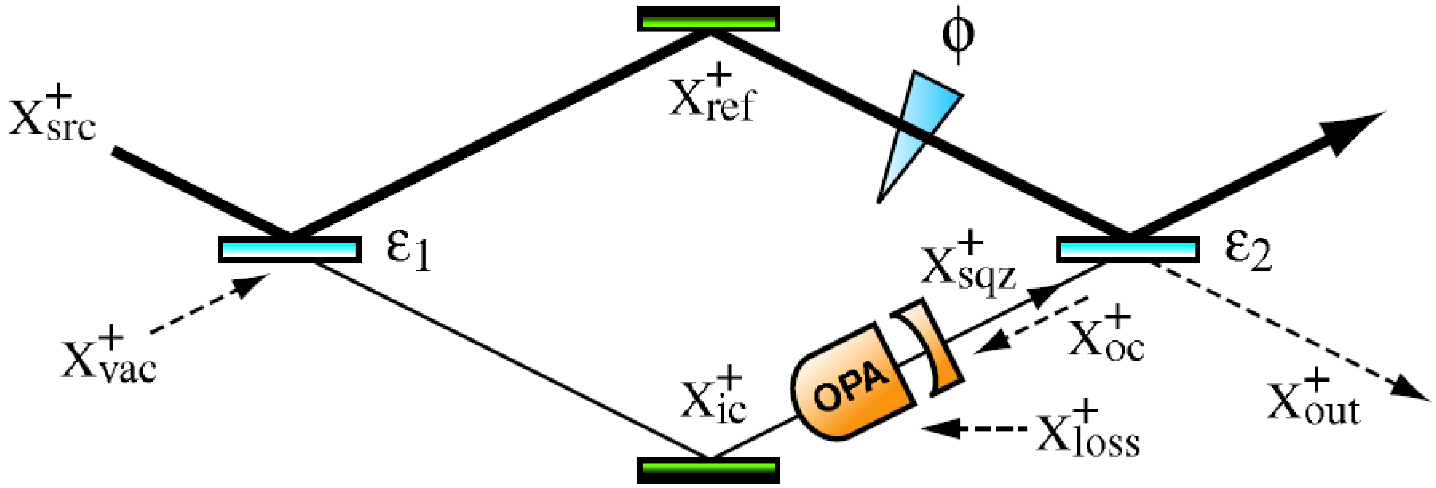
OPA Amplitude Noise Transfer Function



$$\hat{X}^{+}_{\mathrm{sqz}} = \Big\{ \sqrt{4\kappa_{\mathrm{ic}}\kappa_{\mathrm{oc}}}\hat{X}^{+}_{\mathrm{ic}} + \sqrt{4\kappa_{\mathrm{loss}}\kappa_{\mathrm{oc}}}\hat{X}^{+}_{\mathrm{loss}}$$

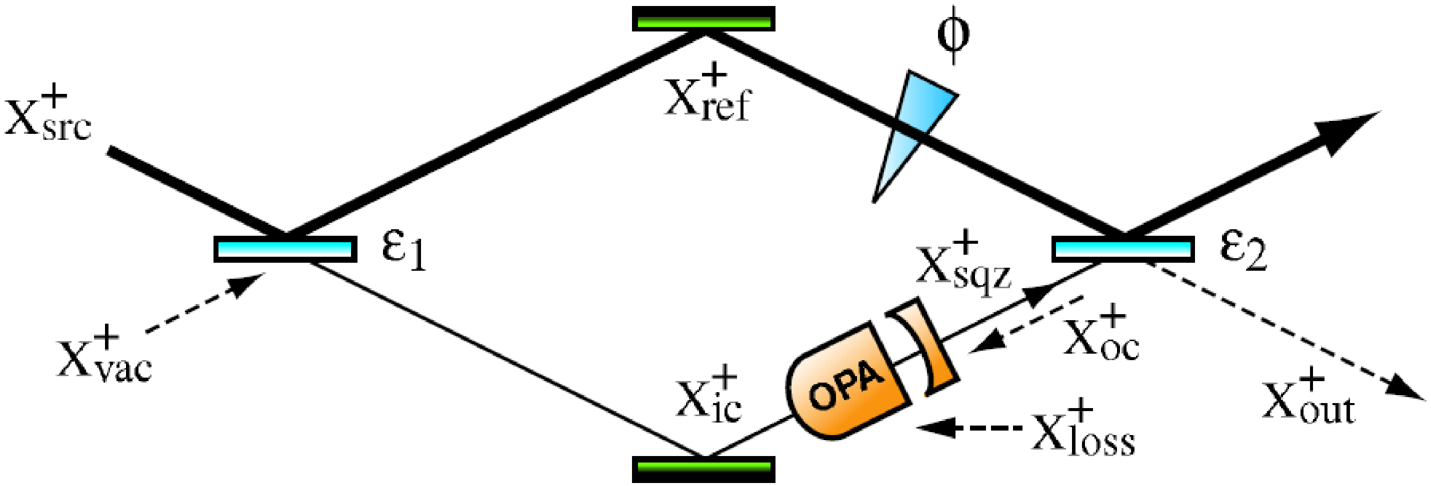
$$+(2\kappa_{\mathrm{oc}} - i\Omega - \kappa + g)\hat{X}^{+}_{\mathrm{oc}} \Big\} / (i\Omega + \kappa - g)$$

Common Mode Noise Cancellation



$$\hat{X}^+_{\rm sqz} = \Big\{\sqrt{4\kappa_{\rm ic}\kappa_{\rm oc}}\hat{X}^+_{\rm ic} + \sqrt{4\kappa_{\rm loss}\kappa_{\rm oc}}\hat{X}^+_{\rm loss} + (2\kappa_{\rm oc} - i\Omega - \kappa + g)\hat{X}^+_{\rm oc}\Big\}/(i\Omega + \kappa - g)$$

Common Mode Noise Cancellation

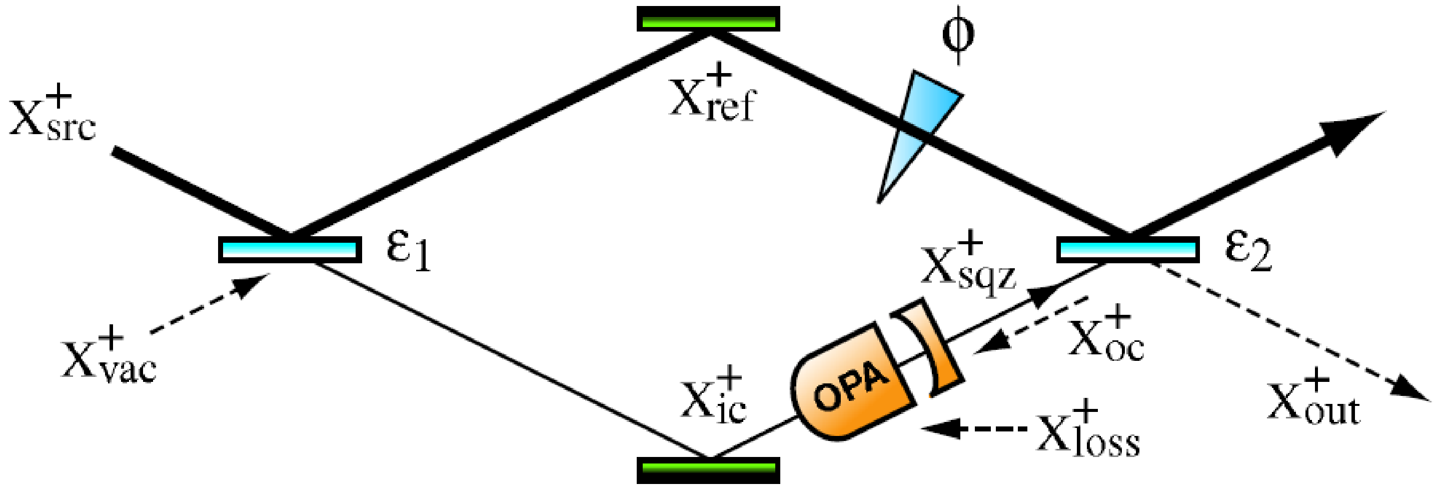


$$\hat{X}^+_{ic} = \sqrt{\varepsilon_1}\hat{X}^+_{vac} + \sqrt{1-\varepsilon_1}\hat{X}^+_{src}$$

$$\hat{X}^+_{ref} = \sqrt{1-\varepsilon_1}\hat{X}^+_{vac} - \sqrt{\varepsilon_1}\hat{X}^+_{src}$$

$$\hat{X}^+_{out} = \sqrt{\varepsilon_2}\hat{X}^+_{sqz} + e^{-i\phi}\sqrt{1-\varepsilon_2}\hat{X}^+_{ref}$$

Common Mode Noise Cancellation



Amplitude noise variance:

$$V^+_{\rm out} = \langle(\hat{X}^+_{\rm out})^2\rangle - \langle\hat{X}^+_{\rm out}\rangle^2$$

inside OPA cavity bandwidth:

$$|\Omega| << |\kappa|$$

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$$
\begin{aligned}
V_{\rm out}^{+} = \Big\{ & V_{\rm src}^{+}\Big[\sqrt{(1-\varepsilon_1)\varepsilon_2}\sqrt{4\kappa_{\rm ic}\kappa_{\rm oc}/\kappa^2} \\
& -\sqrt{\varepsilon_1(1-\varepsilon_2)}(1-g/\kappa)\Big]^2 \\
& +V_{\rm vac}^{+}\Big[\sqrt{\varepsilon_1\varepsilon_2}\sqrt{4\kappa_{\rm ic}\kappa_{\rm oc}/\kappa^2} \\
& +\sqrt{(1-\varepsilon_1)(1-\varepsilon_2)}(1-g/\kappa)\Big]^2 \\
& +V_{\rm oc}^{+}\Big[\sqrt{\varepsilon_2}\,(2\kappa_{\rm oc}/\kappa-1+g/\kappa)\Big]^2 \\
& +V_{\rm loss}^{+}\Big[\sqrt{\varepsilon_2}\sqrt{4\kappa_{\rm loss}\kappa_{\rm oc}/\kappa^2}\Big]^2\Big\}/(1-g/\kappa)^2
\end{aligned}
$$

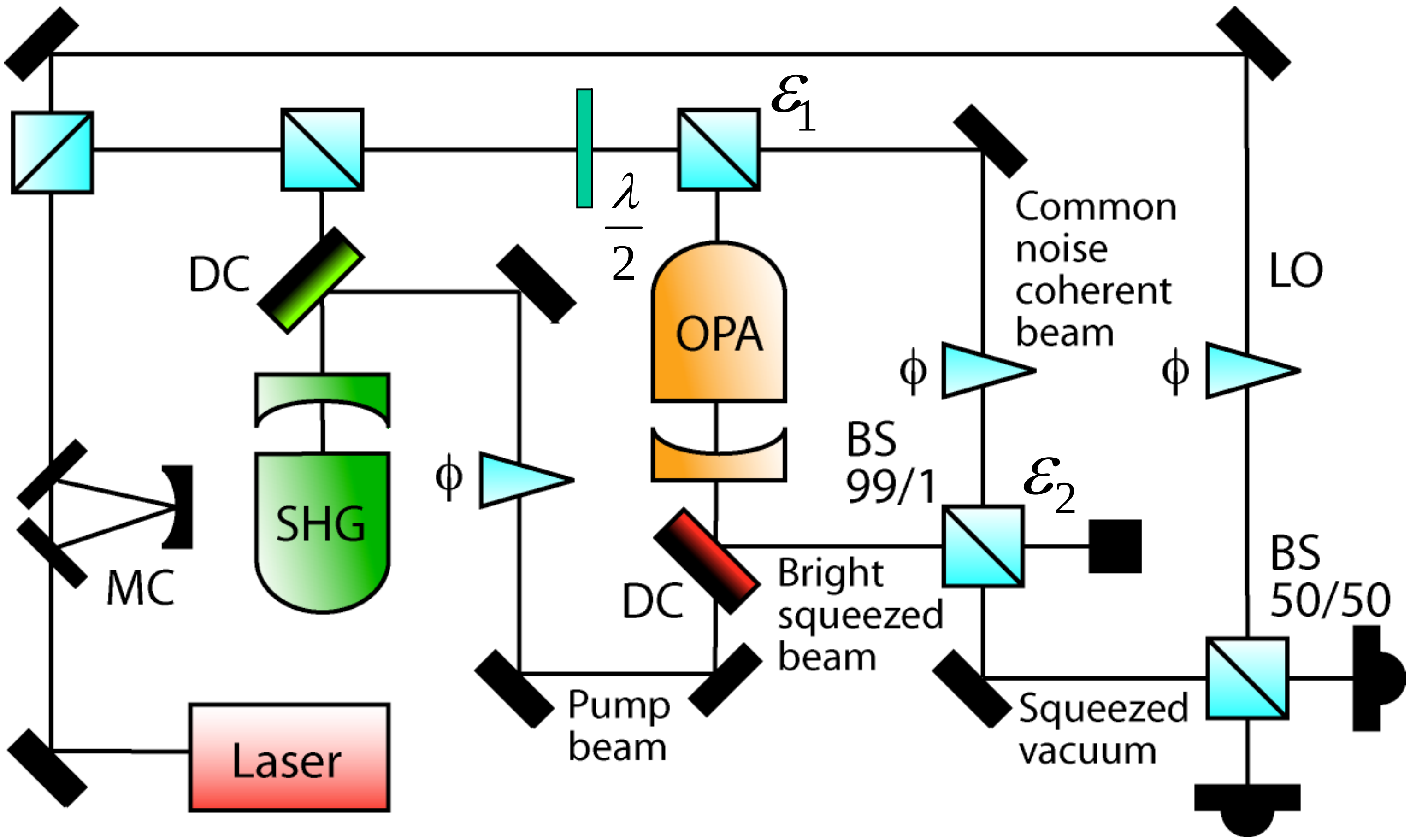
=0 !

Common Mode Noise Cancellation

$$\rightarrow \quad \varepsilon_1^+ = 1 - \left[1 + \frac{\varepsilon_2}{(1-\varepsilon_2)} \frac{4\kappa_{\mathrm{ic}}\kappa_{\mathrm{oc}}/\kappa^2}{(1-g/\kappa)^2}\right]^{-1}$$

$$V_{\mathrm{out}}^+(\varepsilon_1 = \varepsilon_1^+) = V_{\mathrm{sqzvac}}^+ = 1 + \varepsilon_2 \frac{4\kappa_{\mathrm{oc}} g}{(\kappa - g)^2}$$

Common Mode Noise Cancellation



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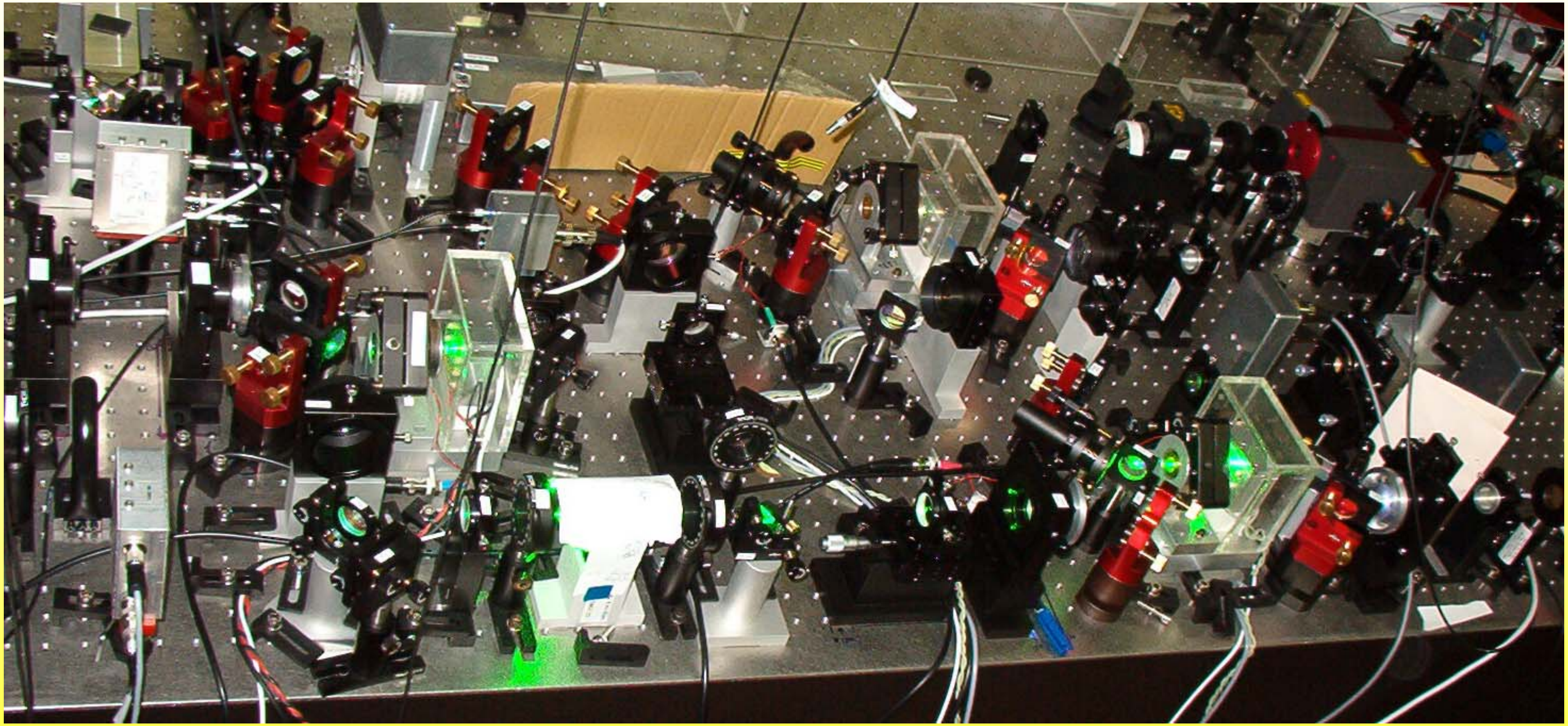
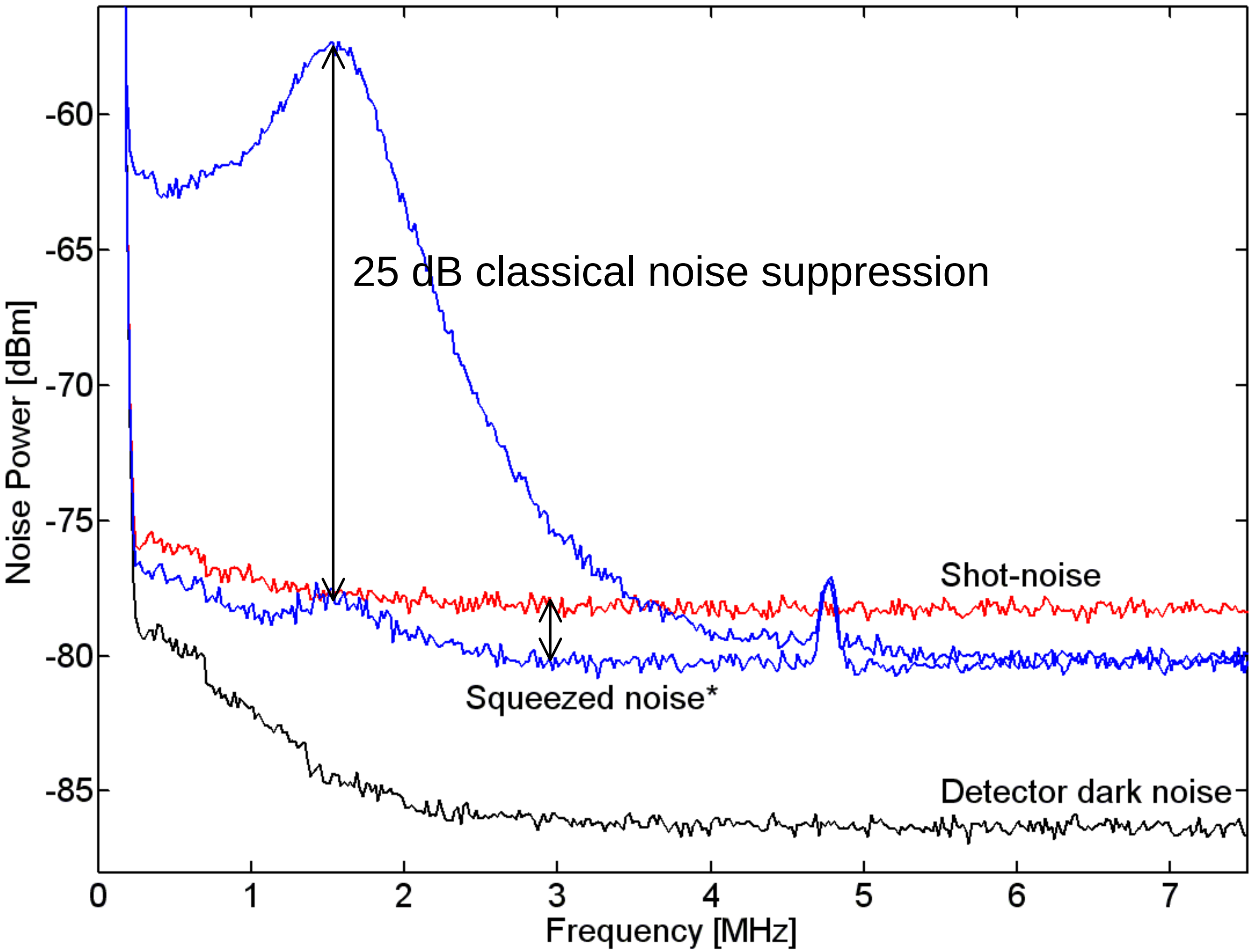
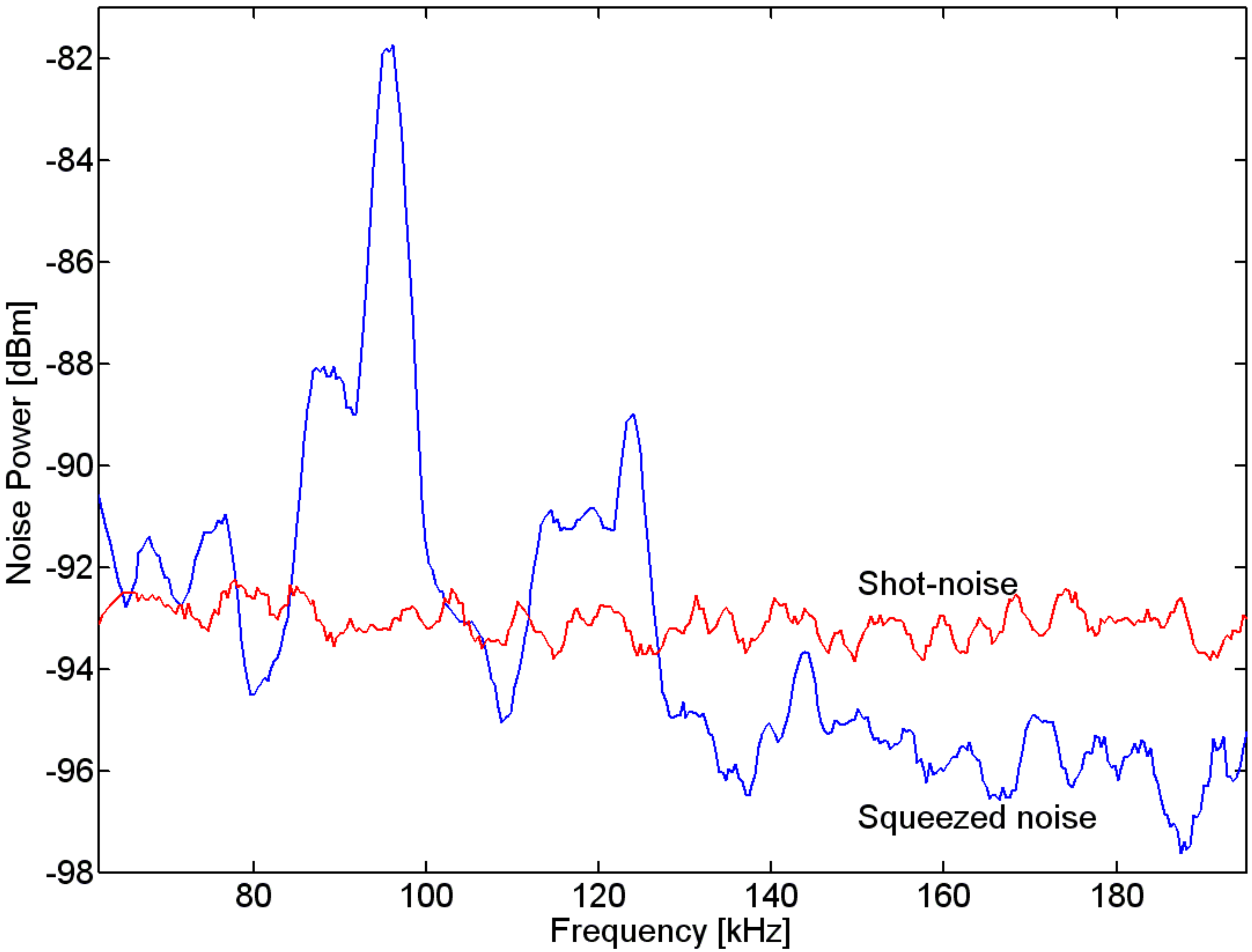
The Hannover Squeezing Experiment



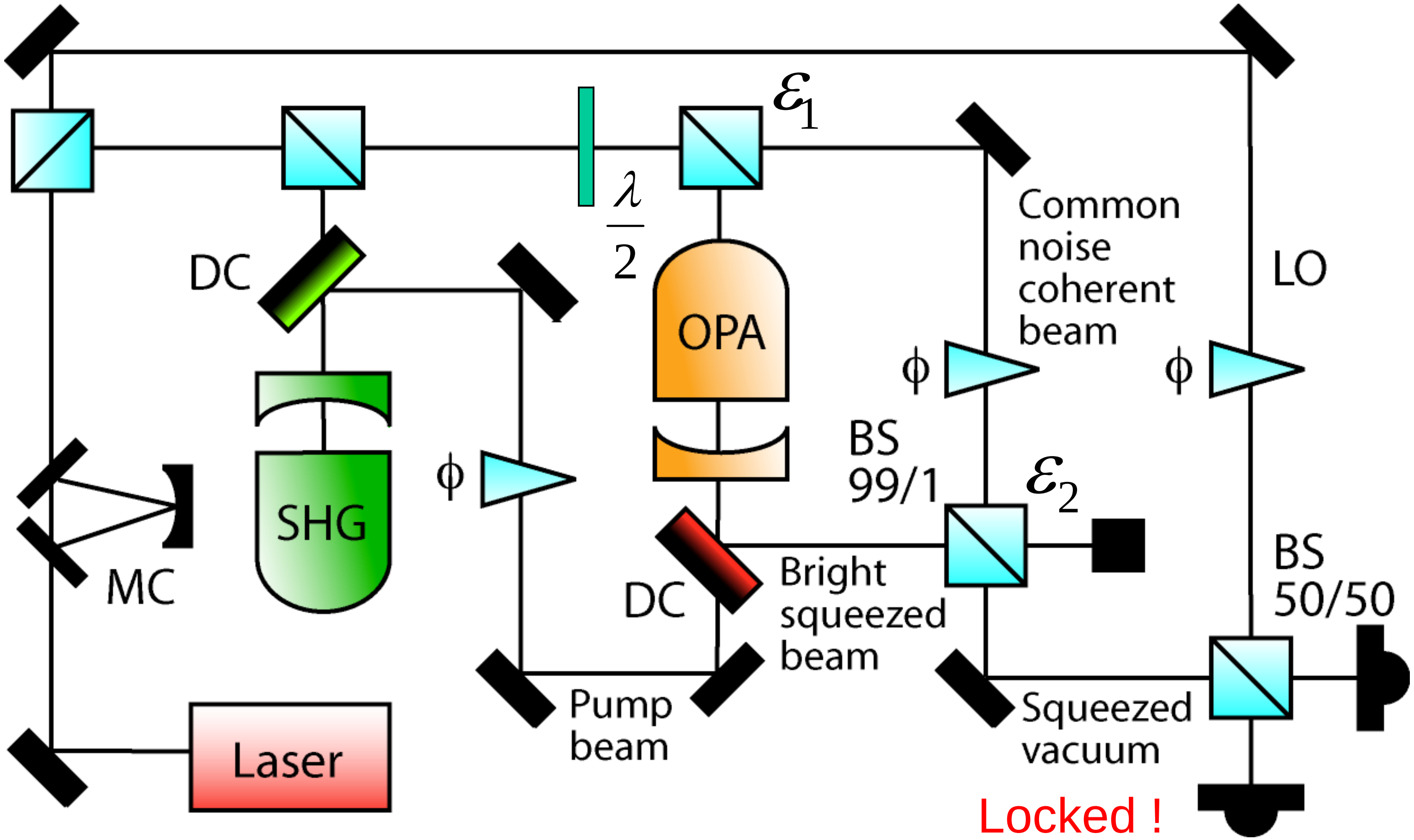
Squeezing Spectra



Squeezing Spectrum at Low Frequencies



Common Mode Noise Cancellation



Confer 2 OPA scheme by Bowen *et al.* (2002)

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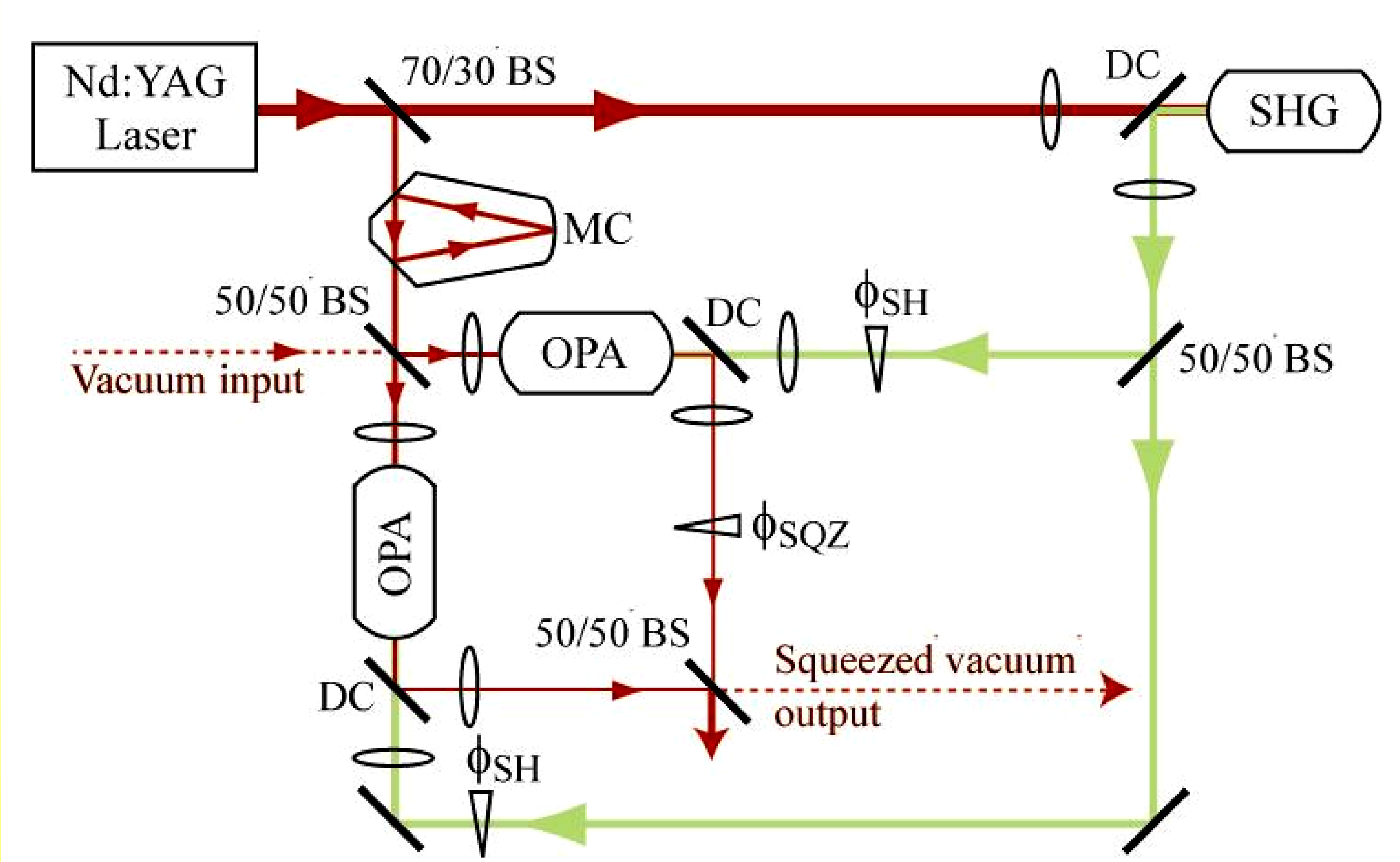
Bowen *et al.* (2002)



Summary

- Squeezed states below 100 kHz were demonstrated (carrier light at 1064 nm).
- We used a single OPA scheme employing 600 mW laser power in total.
- Further experiments will aim for acoustic frequencies.