# Manipulating the Quantum Noise : Squeezing, Entanglement and Teleportation

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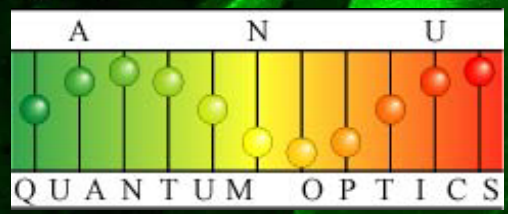


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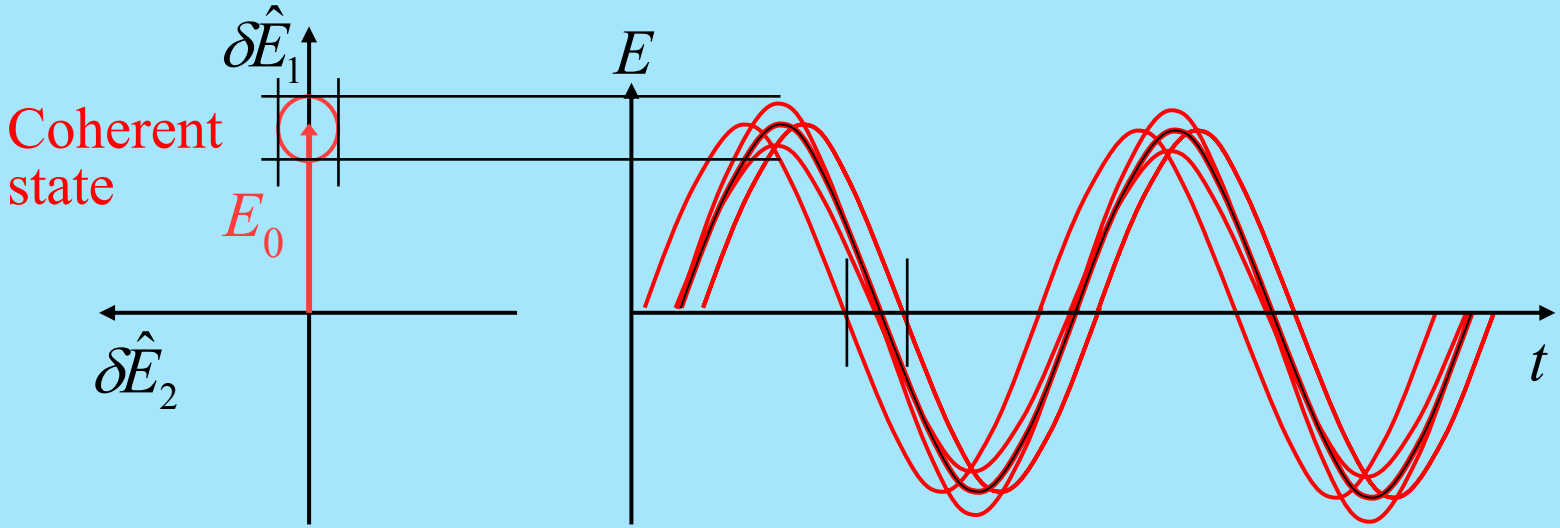
# Quadrature Amplitudes

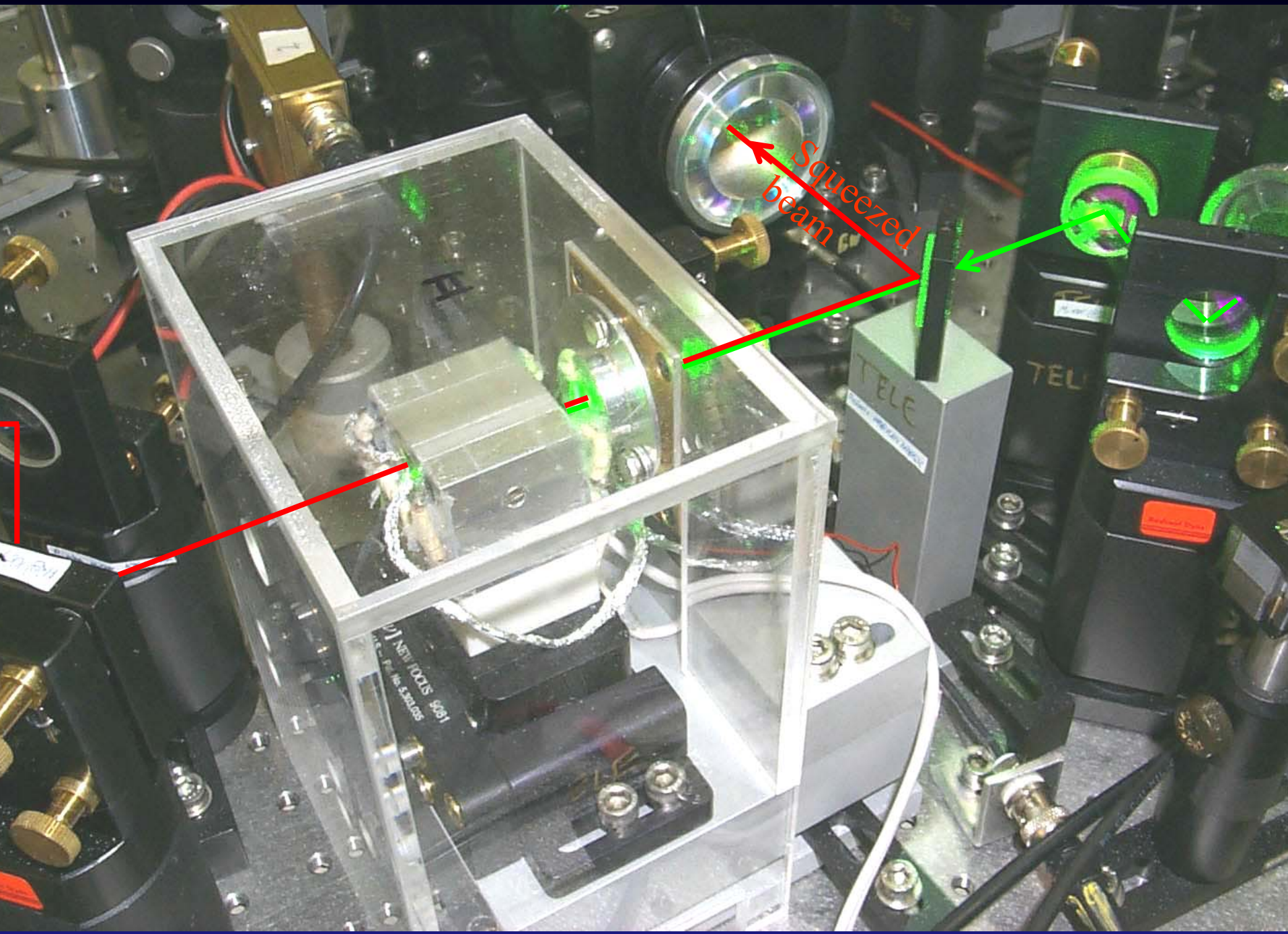



Variance

$$Var(\hat{E}_i) = Var(\delta\hat{E}_i) = \left\langle \delta\hat{E}_i^2 \right\rangle - \left\langle \delta\hat{E}_i \right\rangle^2 = \left\langle \delta\hat{E}_i^2 \right\rangle$$

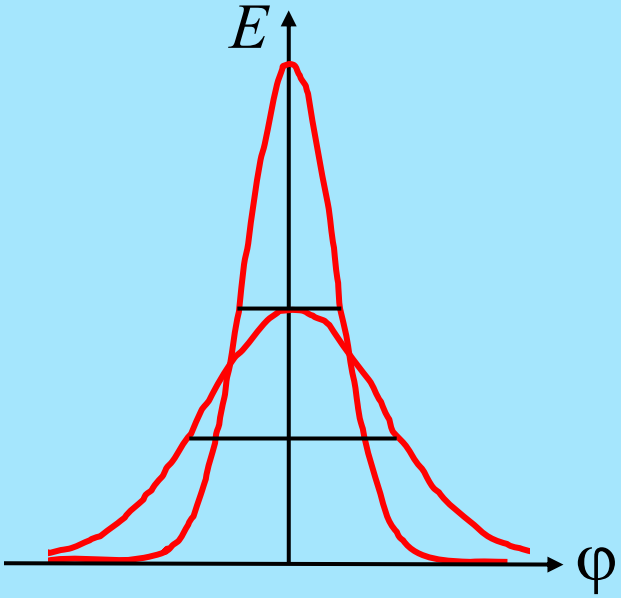
Heisenberg uncertainty relation

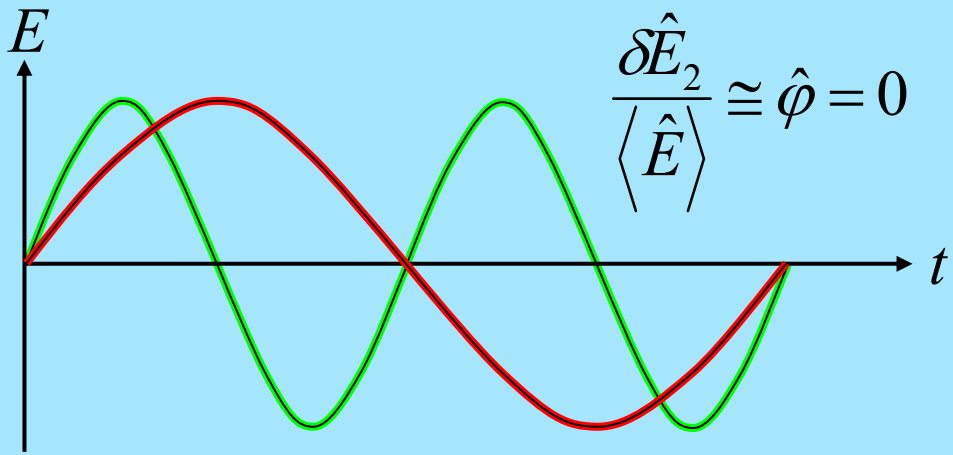
$$\left\langle \delta\hat{E}_1^2 \right\rangle \cdot \left\langle \delta\hat{E}_2^2 \right\rangle \geq \left(\frac{\hbar\omega}{4\pi V}\right)^2$$


Squeezed
beam

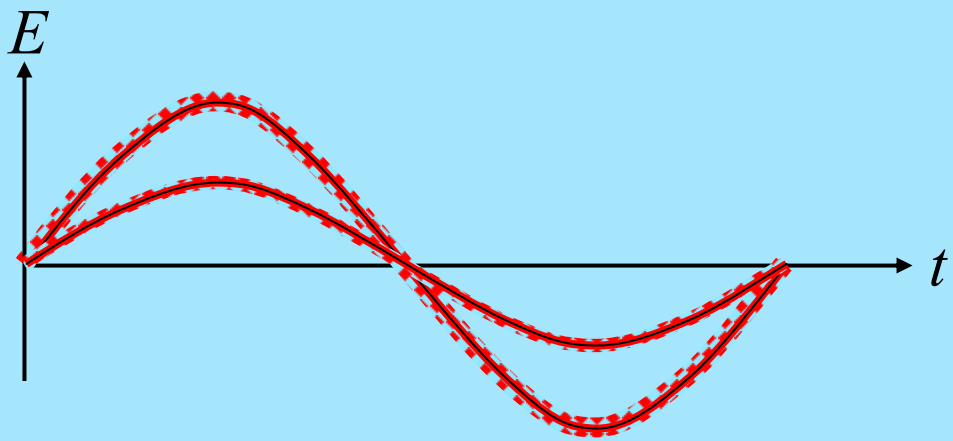
# OPA Quadrature Squeezing

OPA:
Optical
Parametric
Amplifier

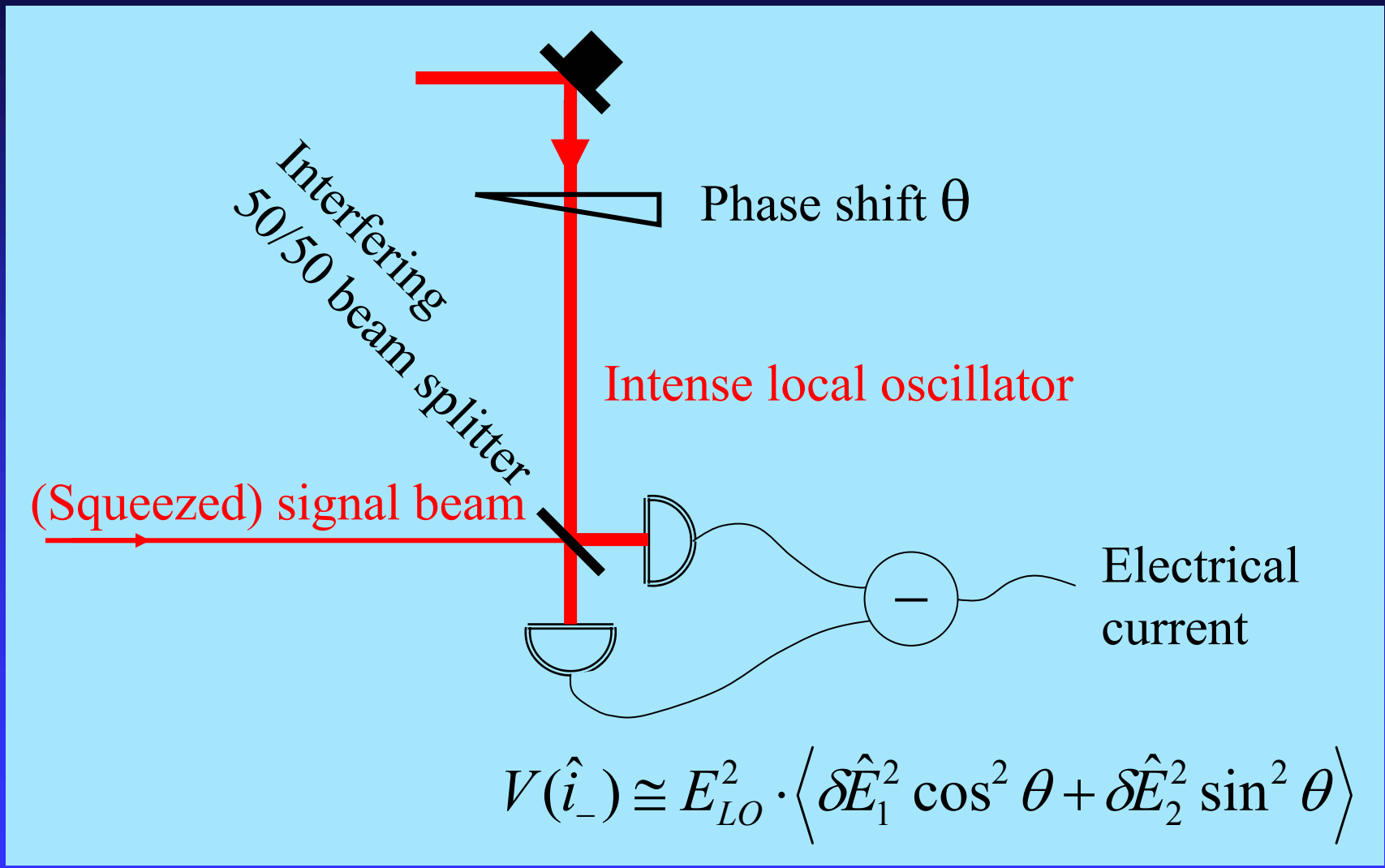



$$\frac{\delta\hat{E}_2}{\langle\hat{E}\rangle} \cong \hat{\varphi} = 0$$

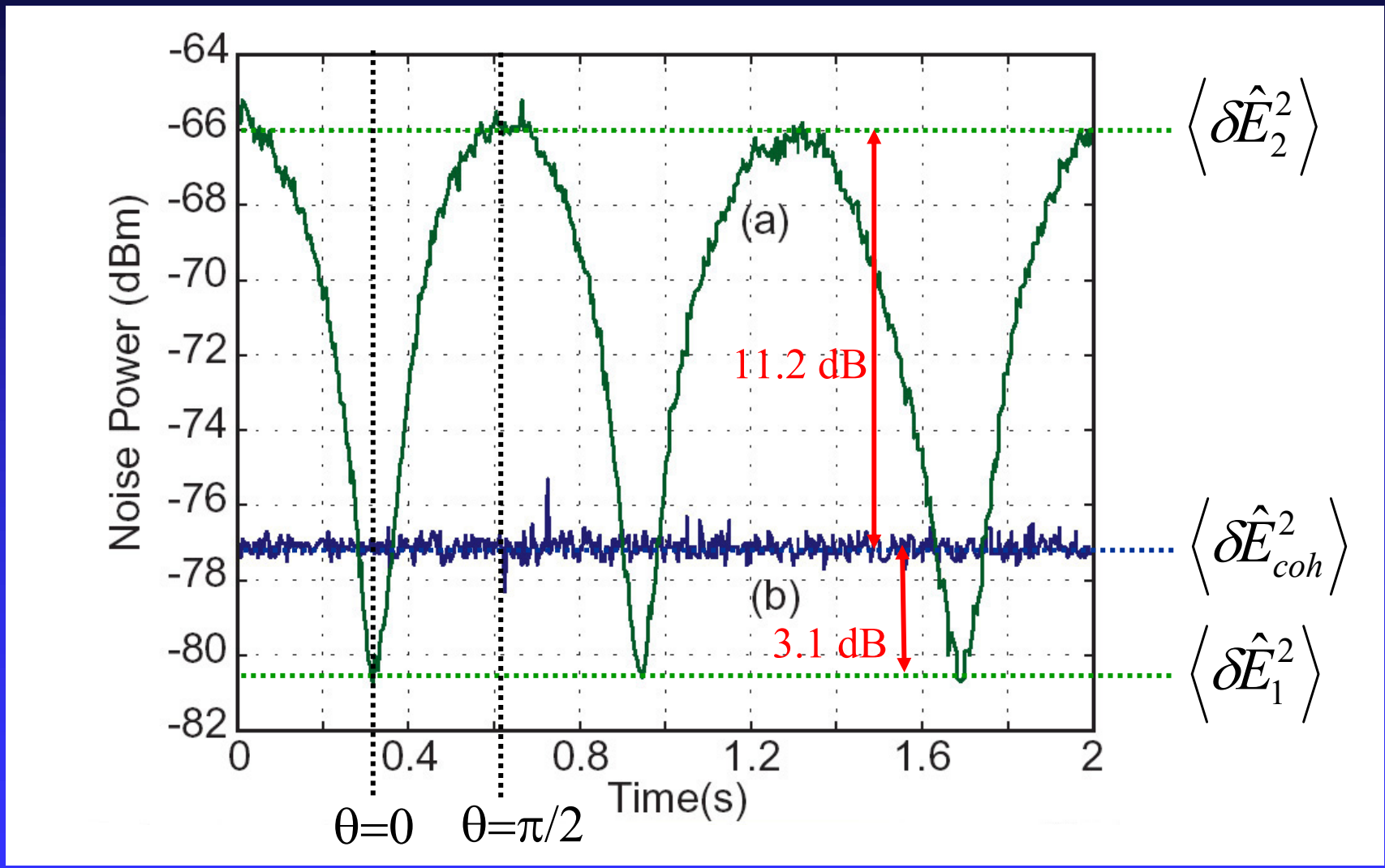


# The Homodyne Detector




$$V(\hat{i}_-) \cong E_{LO}^2 \cdot \left\langle \delta\hat{E}_1^2 \cos^2\theta + \delta\hat{E}_2^2 \sin^2\theta \right\rangle$$

# Noise Power of Coherent and Squeezed Light

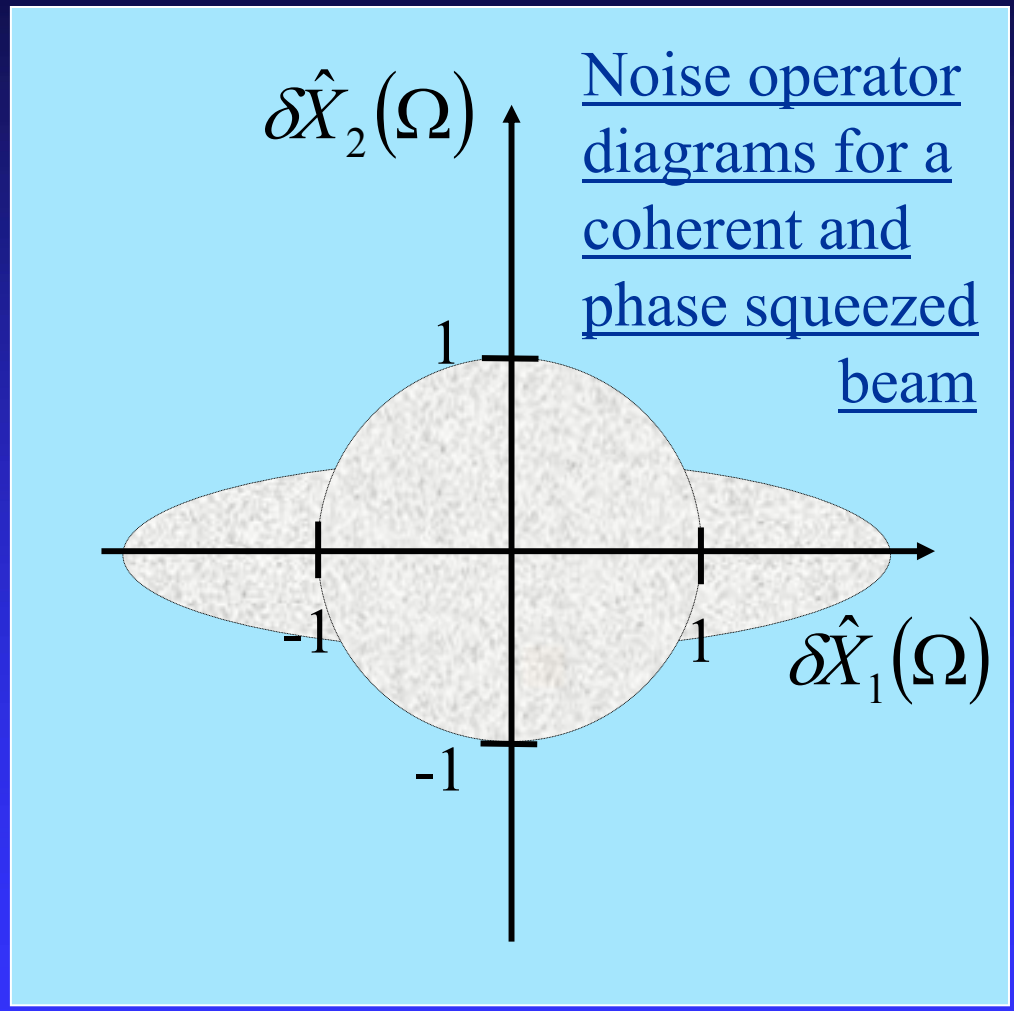


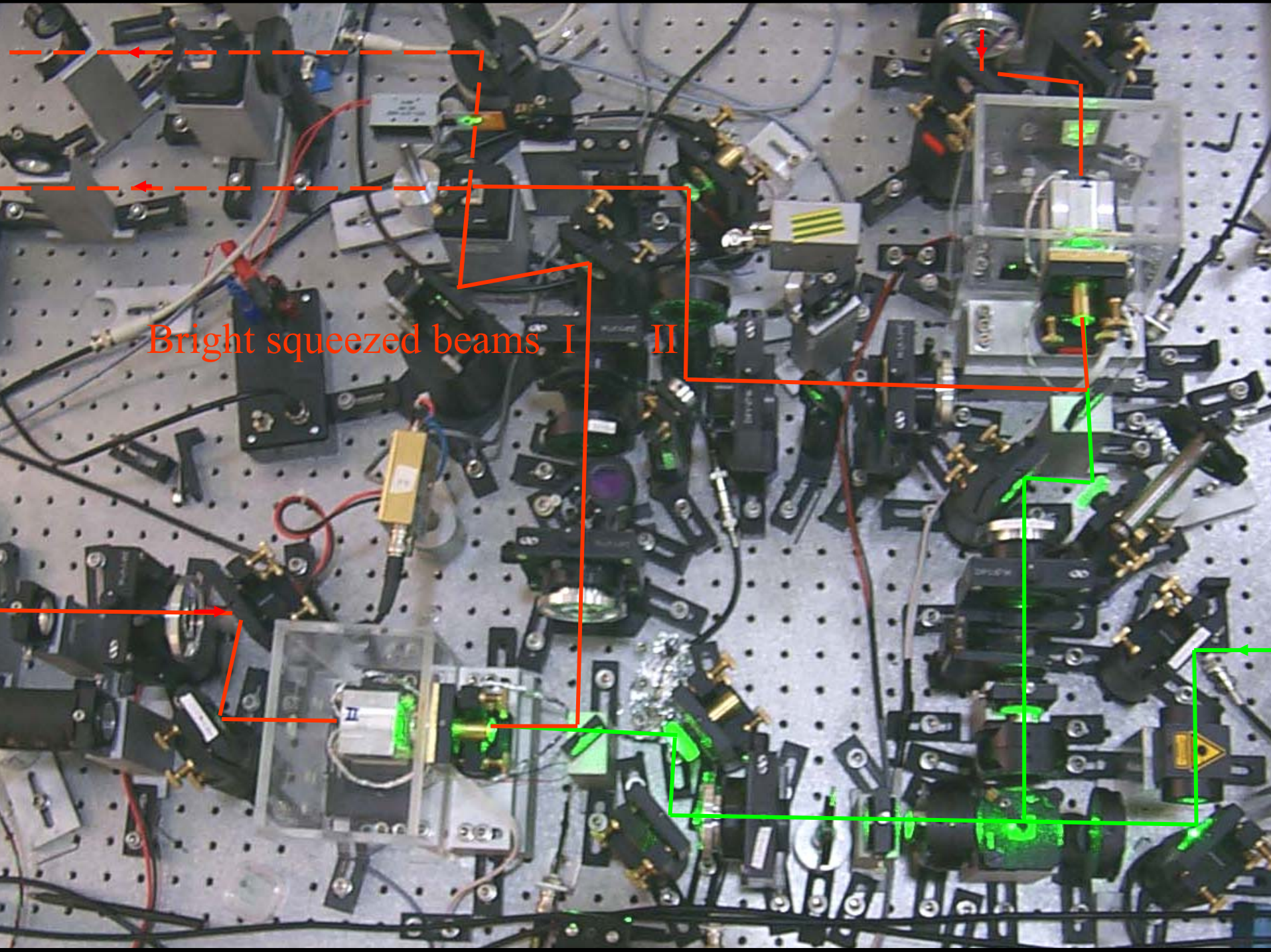
# Quadrature Noise Operators

$$\delta\hat{X}_1(\Omega) = \delta\hat{a}^\dagger(\Omega) + \delta\hat{a}(\Omega)$$
$$\delta\hat{X}_2(\Omega) = i\left(\delta\hat{a}^\dagger(\Omega) - \delta\hat{a}(\Omega)\right)$$

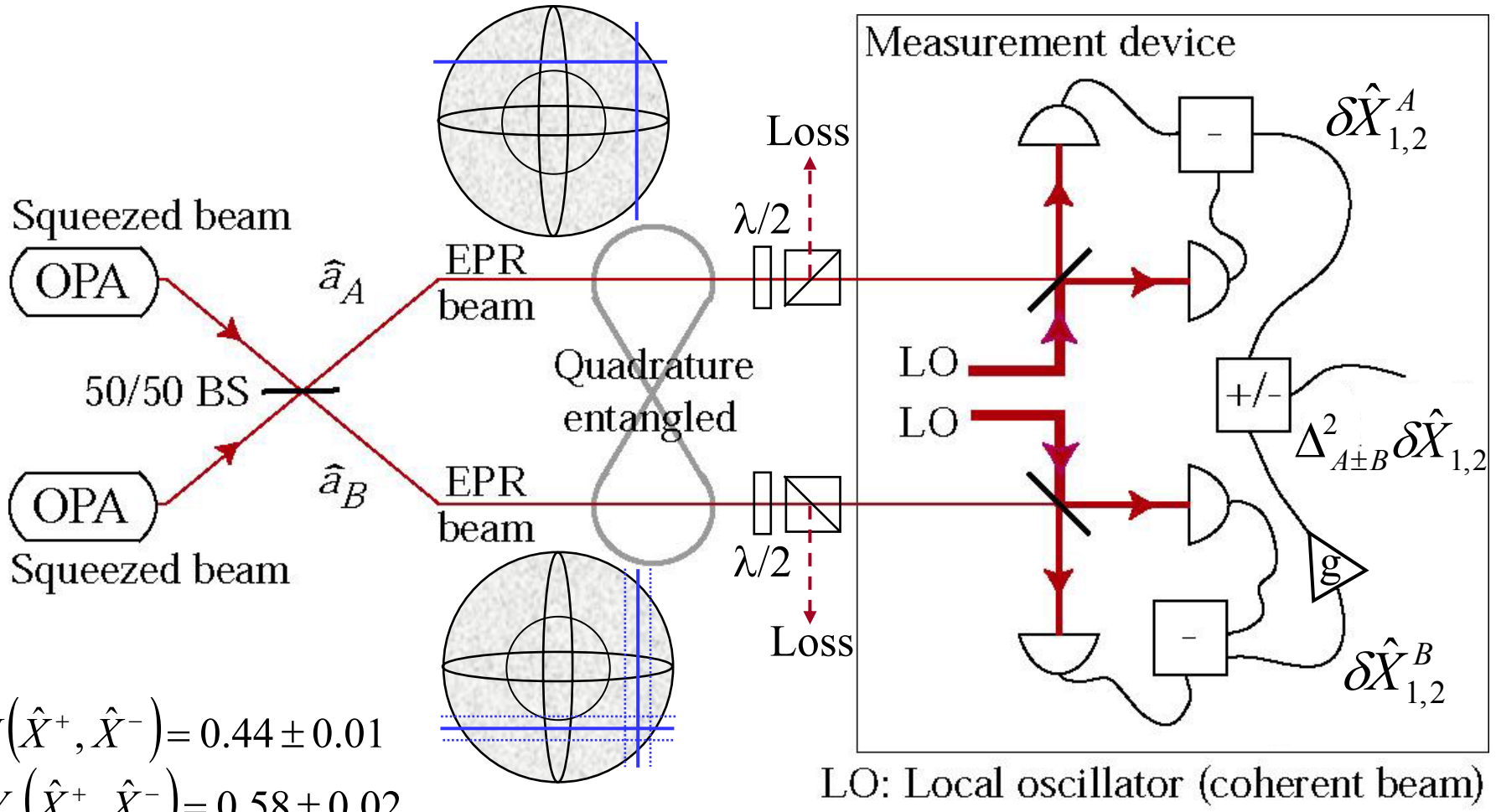
Linearized annihilation and creation operators

$$\hat{a}(\Omega) = \alpha + \delta\hat{a}(\Omega)$$
$$\left[\delta\hat{a}(\Omega'), \delta\hat{a}^\dagger(\Omega)\right] = \delta(\Omega - \Omega')$$




Bright squeezed beams I
II

# Quadrature Entanglement




$$I\left(\hat{X}^+,\hat{X}^-\right)=0.44\pm0.01$$

$$V_c\left(\hat{X}^+,\hat{X}^-\right)=0.58\pm0.02$$

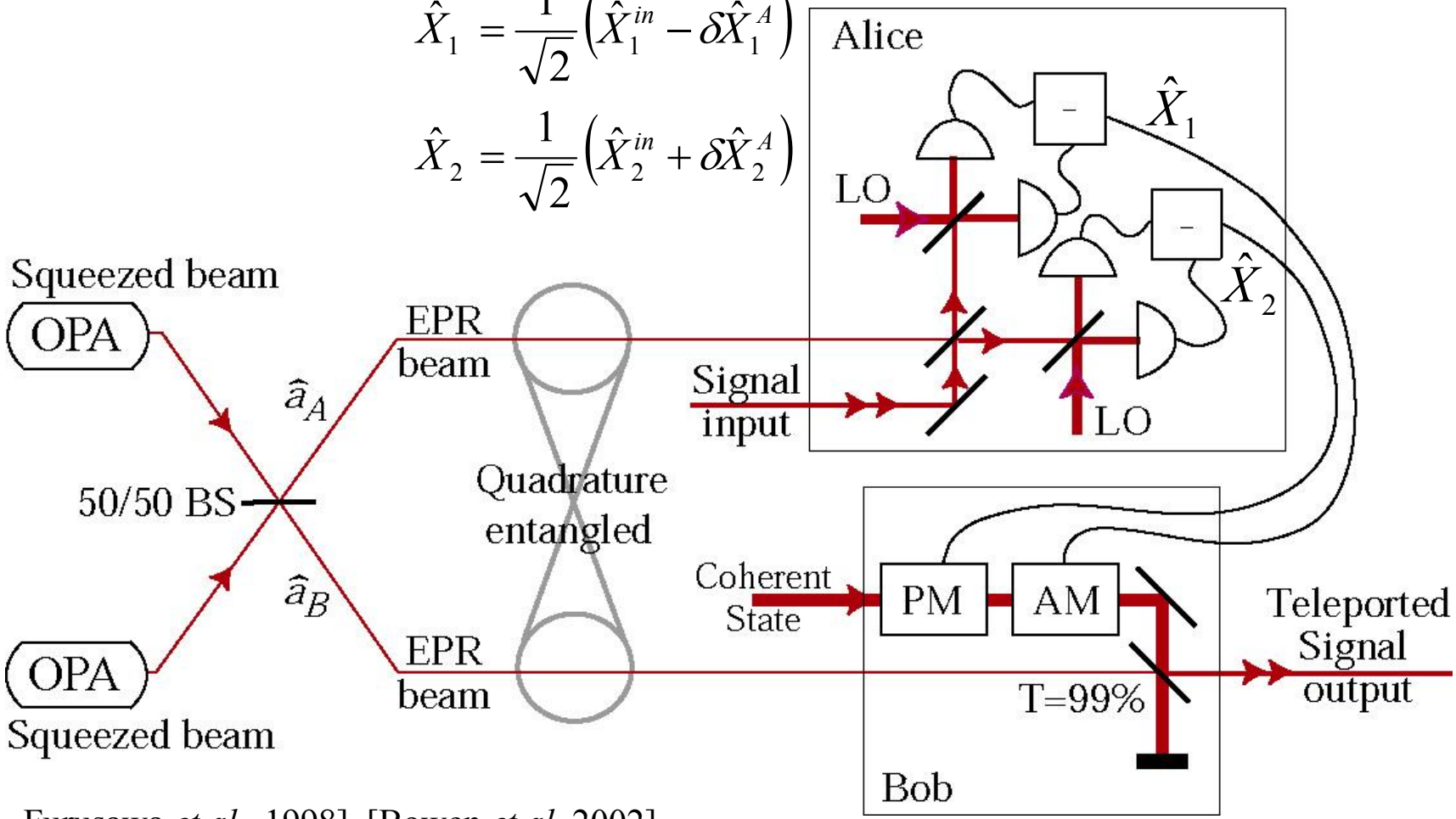
# Teleportation of Quantum Information

- Can all information of a quantum system be gathered?
  No!
- Can information be copied exactly?
  No!
- Can all the information be classically transmitted with arbitrarily high accuracy?
  Yes, under certain conditions!
  [Bennett et al. 1993]

# Teleportation of a Quadrature State

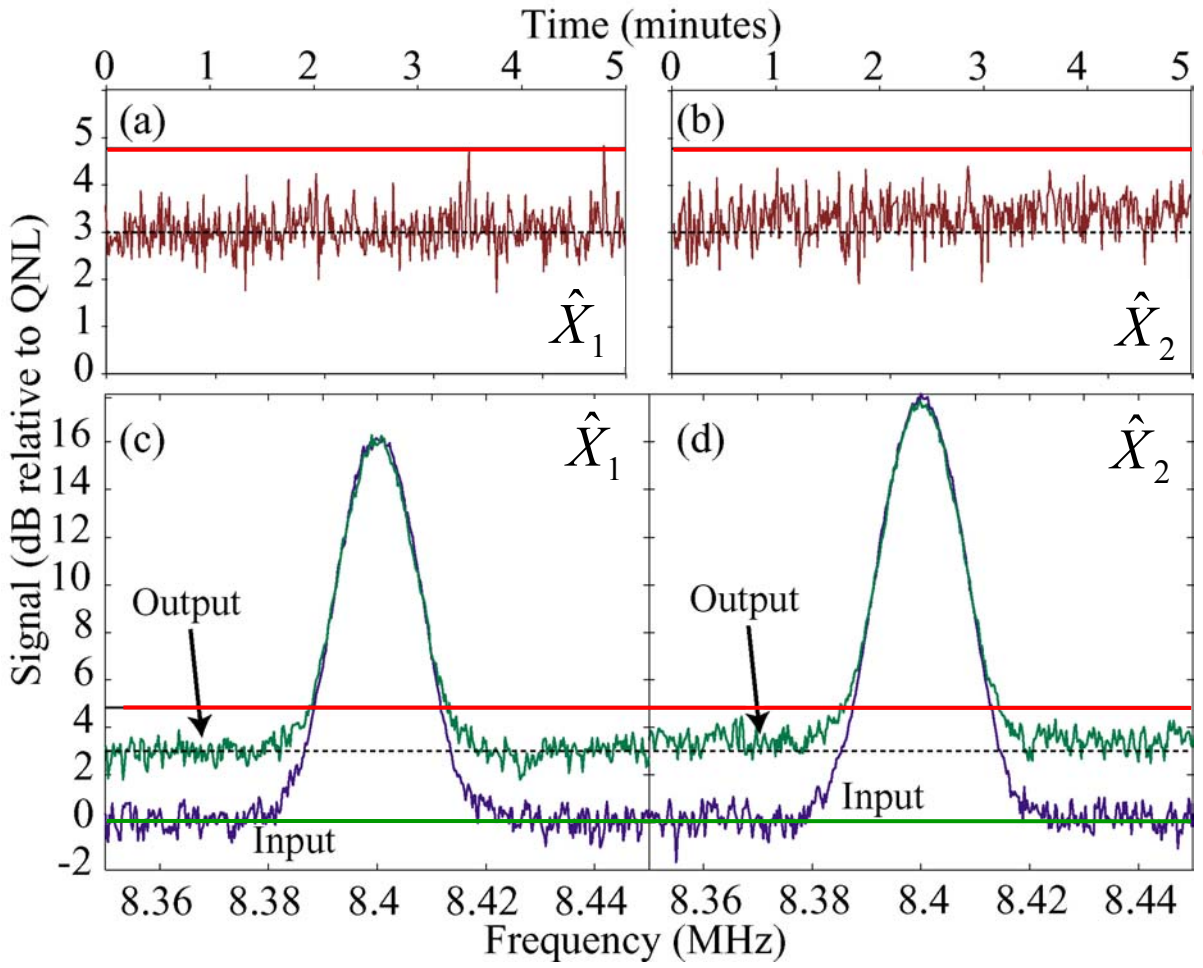
$$\hat{X}_1 = \frac{1}{\sqrt{2}}\left(\hat{X}_1^{in} - \delta\hat{X}_1^{A}\right)$$

$$\hat{X}_2 = \frac{1}{\sqrt{2}}\left(\hat{X}_2^{in} + \delta\hat{X}_2^{A}\right)$$




[A. Furusawa *et al.*, 1998], [Bowen *et al*. 2002]

# Teleporter Input and Output States




Classical limit

No-cloning limit

Classical limit

No-cloning limit

Perfect teleportation

W.P. Bowen *et al.,* Phys. Rev. A, accepted (2003)

# Summary

- Experiments were introduced where the quantum noise of a cw laser beam was manipulated and characterized.
- Squeezing and entanglement of quadrature operators were demonstrated.
- Entanglement was used to teleport a side-band modulation signal of a cw laser beam.