Time-Modulated Bright Beam Squeezing and Non-Gaussian States of Light

Olivier Pfister

Russell Bloomer

Raphael Pooser

Darou Xie

Matthew Pysher

Hussain Zaidi

James Troupe

Outline

- Define squeezing
  - Frequency Domain Squeezing
  - Time Domain Squeezing
- Time-modulated squeezing
- Current Status
- Future Experiment
  - Quantum Tomography

Squeezing

Squeezed State is where the noise in one quadrature is reduced below the minimum uncertain of a coherent state

Quadrature of light is $A_\theta = e^{-i\theta} a + e^{i\theta} a^\dagger$

Noise of a quadrature is its variance

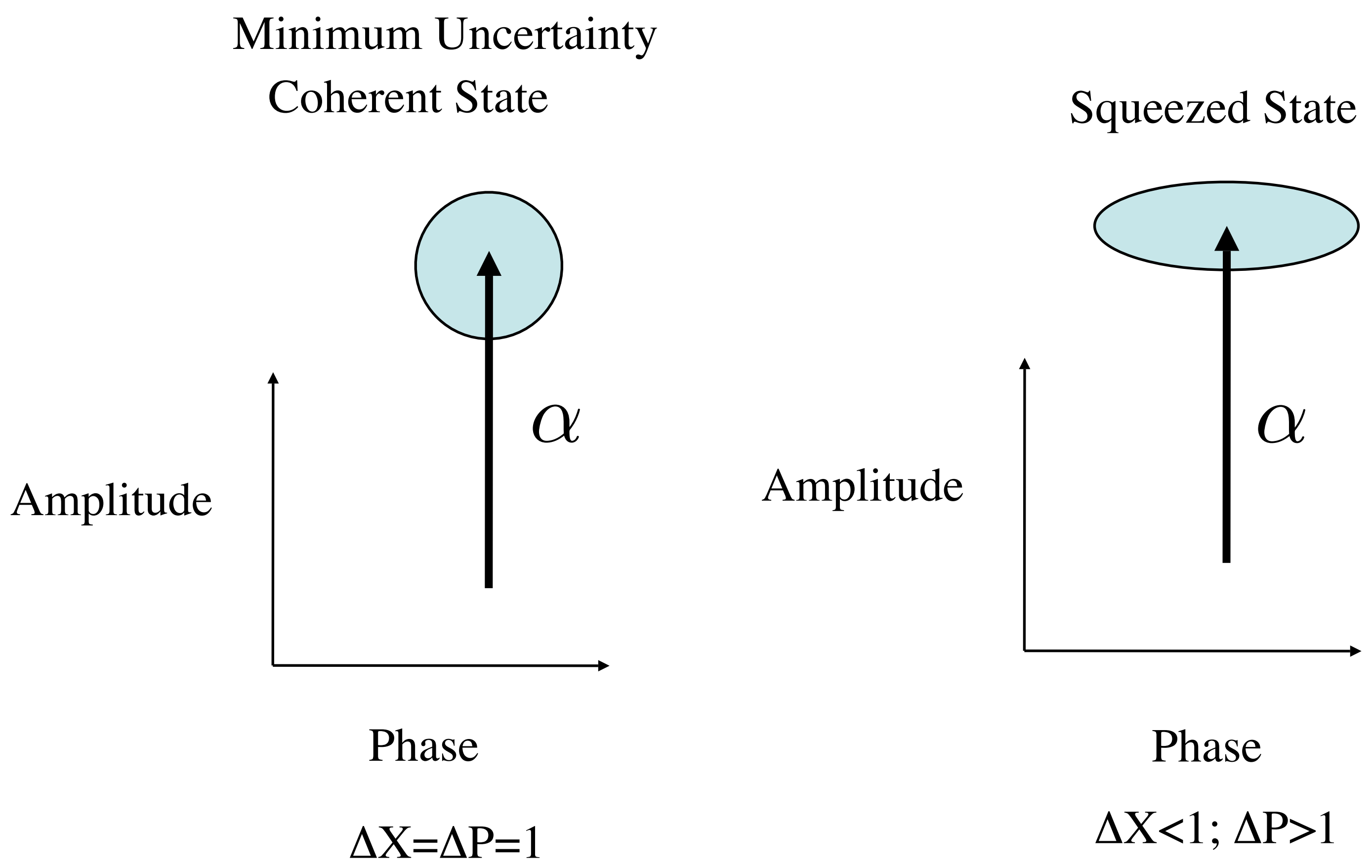
For a coherent state it is $(\Delta A_\theta)^2 = 1$

The Heisenberg Uncertainty Principle is $\Delta X \Delta P \geq 1$

$\Delta A_0 = \Delta X = 1$

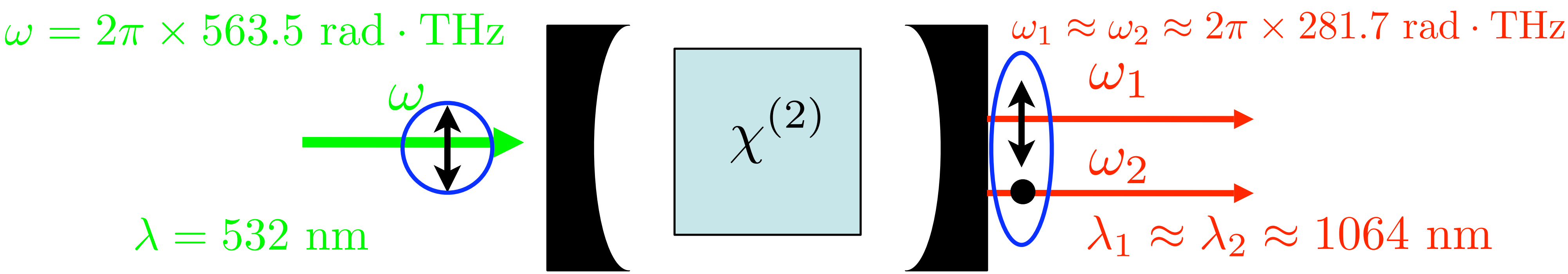
$\Delta A_{\frac{\pi}{2}} = \Delta P = 1$

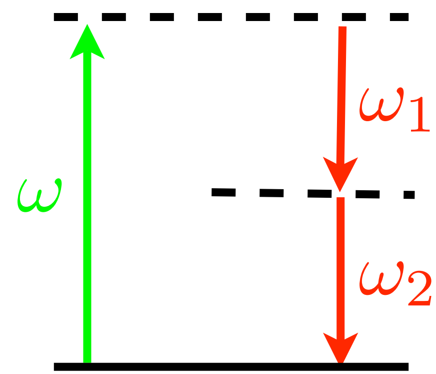
Visual of an Amplitude Squeezed State



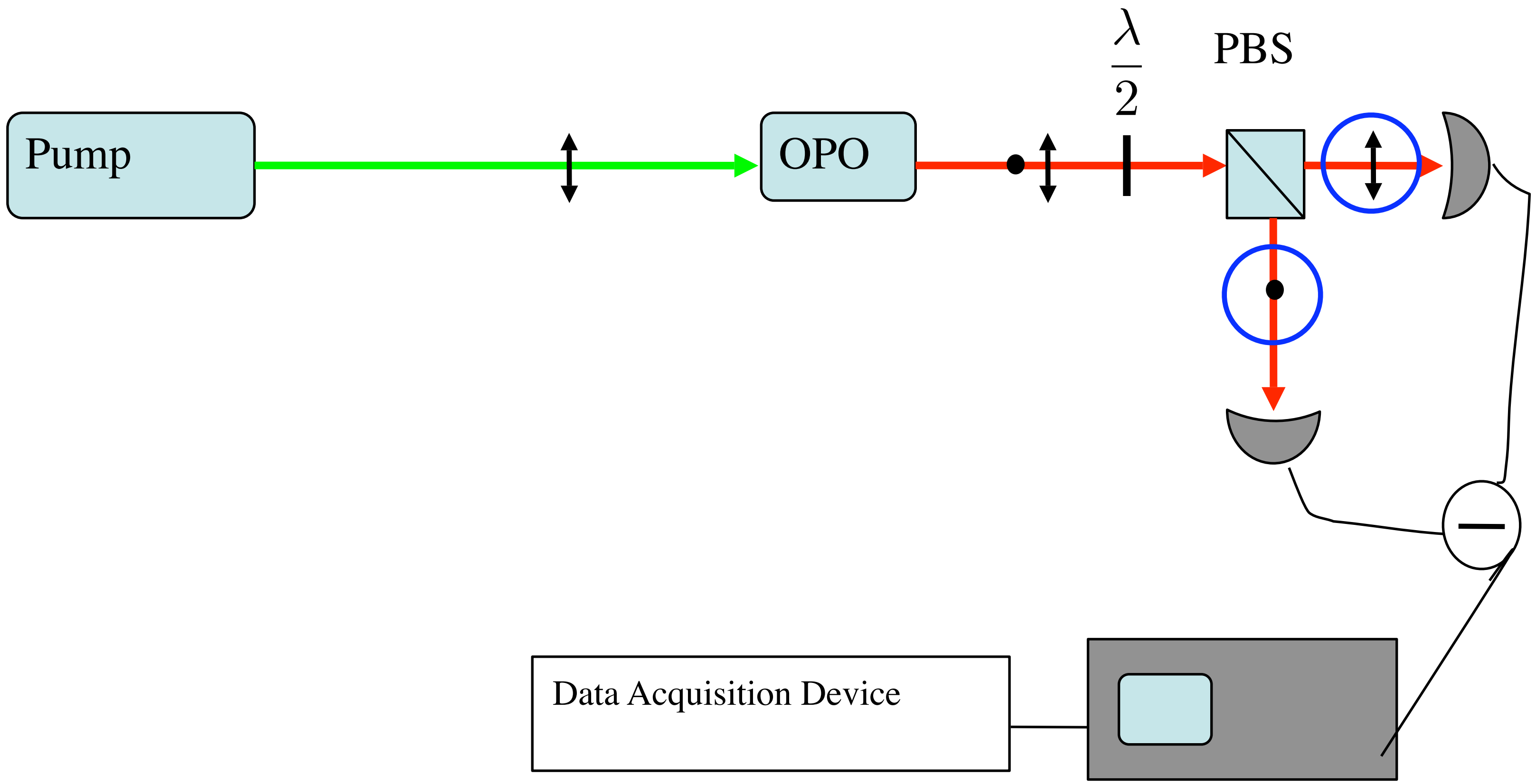
Optical Parametric Oscillator

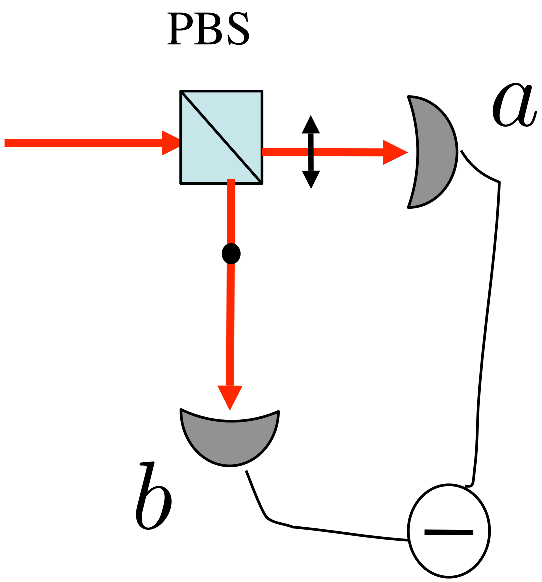
$$\omega = \omega_1 + \omega_2$$





Squeezing





$$N_a = a^\dagger a \approx \alpha^2 + \alpha\delta X_a(t)$$
$$N_b = b^\dagger b \approx \beta^2 + \beta\delta X_b(t)$$

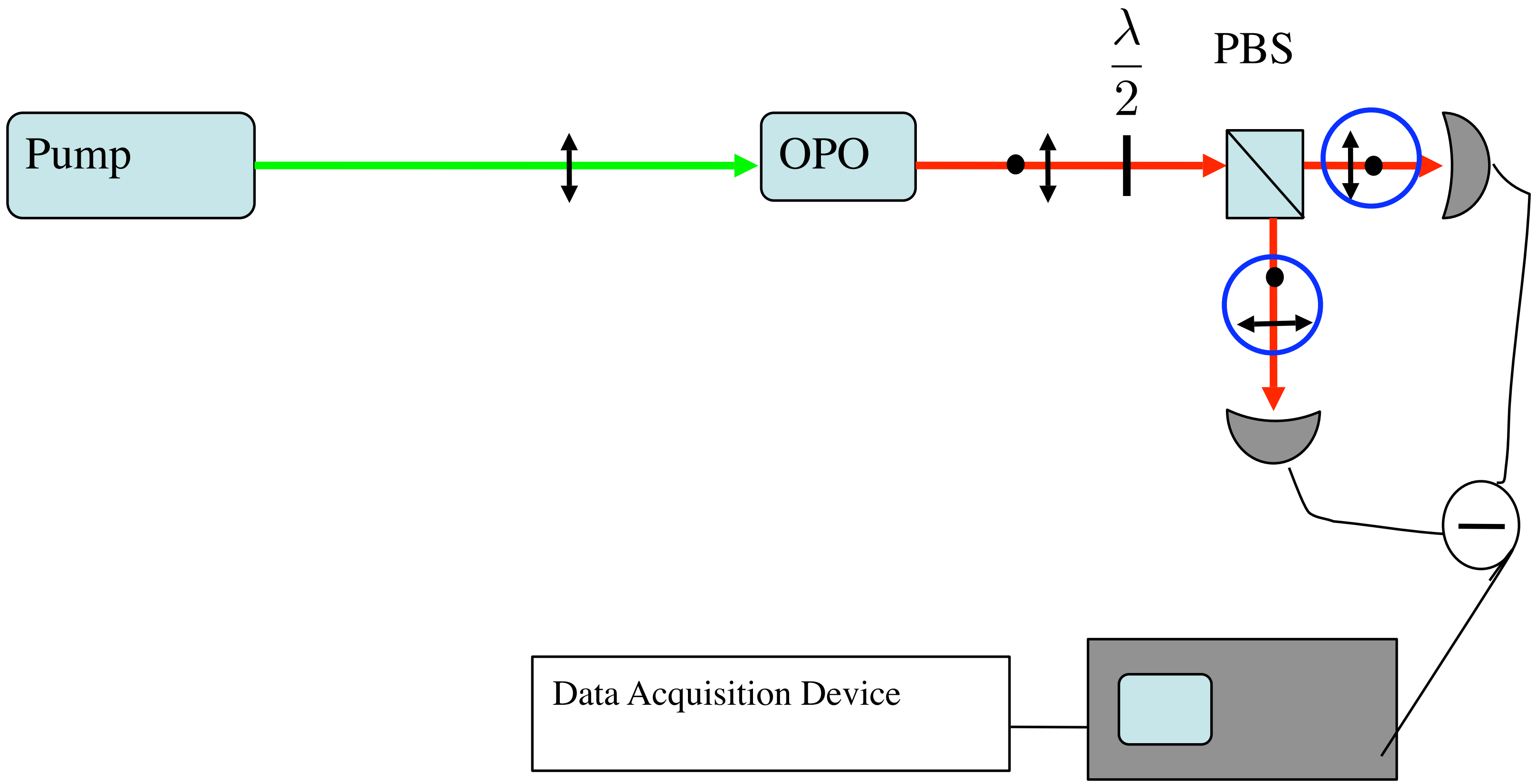
$$i_-(t) \propto N_a - N_b$$
$$\propto \alpha^2 - \beta^2 + \alpha\delta X_a(t) - \beta\delta X_b(t)$$

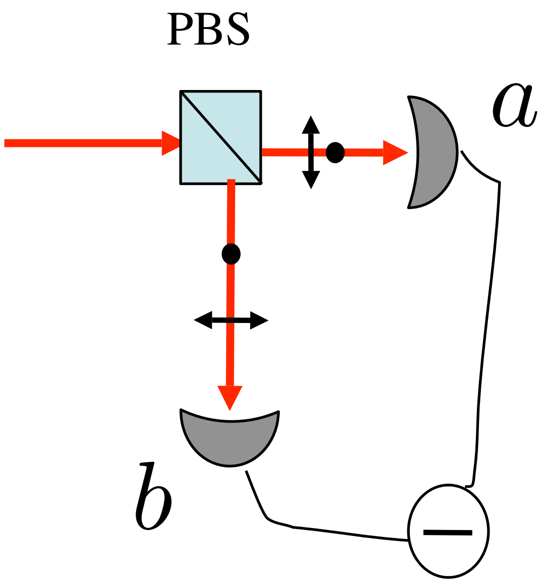
$$\widetilde{i}_-(\Omega) \propto \left(\alpha^2 - \beta^2\right)\delta(\Omega) + \alpha\delta\widetilde{X}_a(\Omega) - \beta\delta\widetilde{X}_b(\Omega)$$

$$\langle|\widetilde{i}_-(\Omega)|^2\rangle \propto \left(\alpha^2 - \beta^2\right)^2\delta(\Omega)$$
$$+ \alpha^2\langle|\delta\widetilde{X}_a(\Omega)|^2\rangle + \beta^2\langle|\delta\widetilde{X}_b(\Omega)|^2\rangle$$
$$- 2\alpha\beta\langle\delta\widetilde{X}_a(\Omega)\delta\widetilde{X}_b(\Omega)\rangle$$

$$\boxed{\langle\delta\widetilde{X}_a(\Omega)\delta\widetilde{X}_b(\Omega)\rangle \rightarrow 1}$$

Shot Noise





$$N_a = a^\dagger a \approx \alpha^2 + \alpha \delta X_a(t)$$
$$N_b = b^\dagger b \approx \beta^2 + \beta \delta X_b(t)$$

$$\begin{aligned} i_-(t) &\propto N_a - N_b \\ &\propto \alpha^2 - \beta^2 + \alpha\delta X_a(t) - \beta \delta X_b(t) \end{aligned}$$

$$\widetilde{i}_-(\Omega) \propto \left(\alpha^2 - \beta^2\right) \delta(\Omega) + \alpha \delta \widetilde{X}_a(\Omega) - \beta \delta \widetilde{X}_b(\Omega)$$

$$\begin{aligned} \langle |\widetilde{i}_-(\Omega)|^2 \rangle \propto & \left(\alpha^2 - \beta^2\right)^2 \delta(\Omega) \\ & + \alpha^2 \langle |\delta \widetilde{X}_a(\Omega)|^2 \rangle + \beta^2 \langle |\delta \widetilde{X}_b(\Omega)|^2 \rangle \\ & - 2\alpha\beta \langle \delta \widetilde{X}_a(\Omega) \delta \widetilde{X}_b(\Omega) \rangle \end{aligned}$$

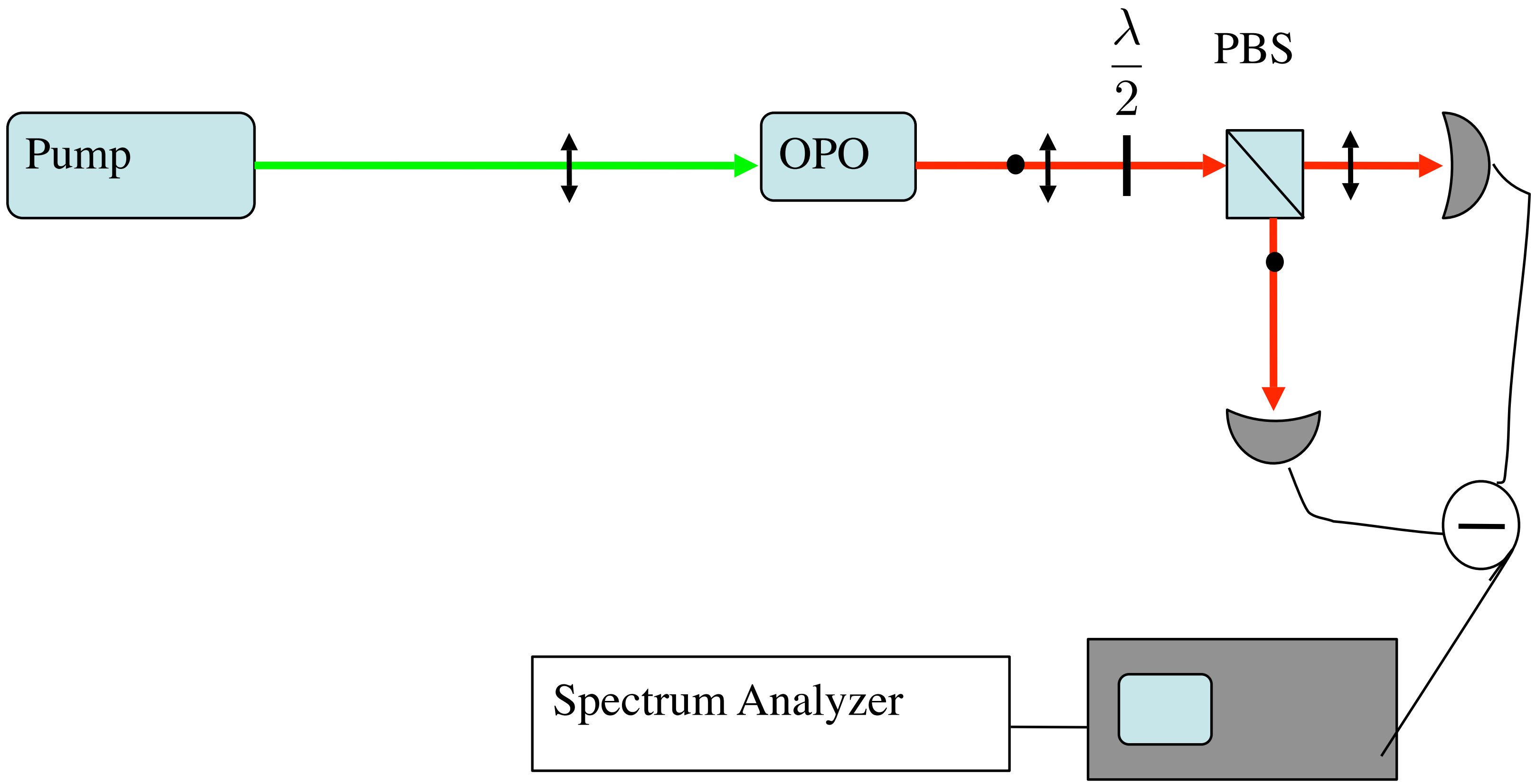
$$\boxed{\langle \delta \widetilde{X}_a(\Omega) \delta \widetilde{X}_b(\Omega) \rangle = 0}$$

Frequency Domain Squeezing

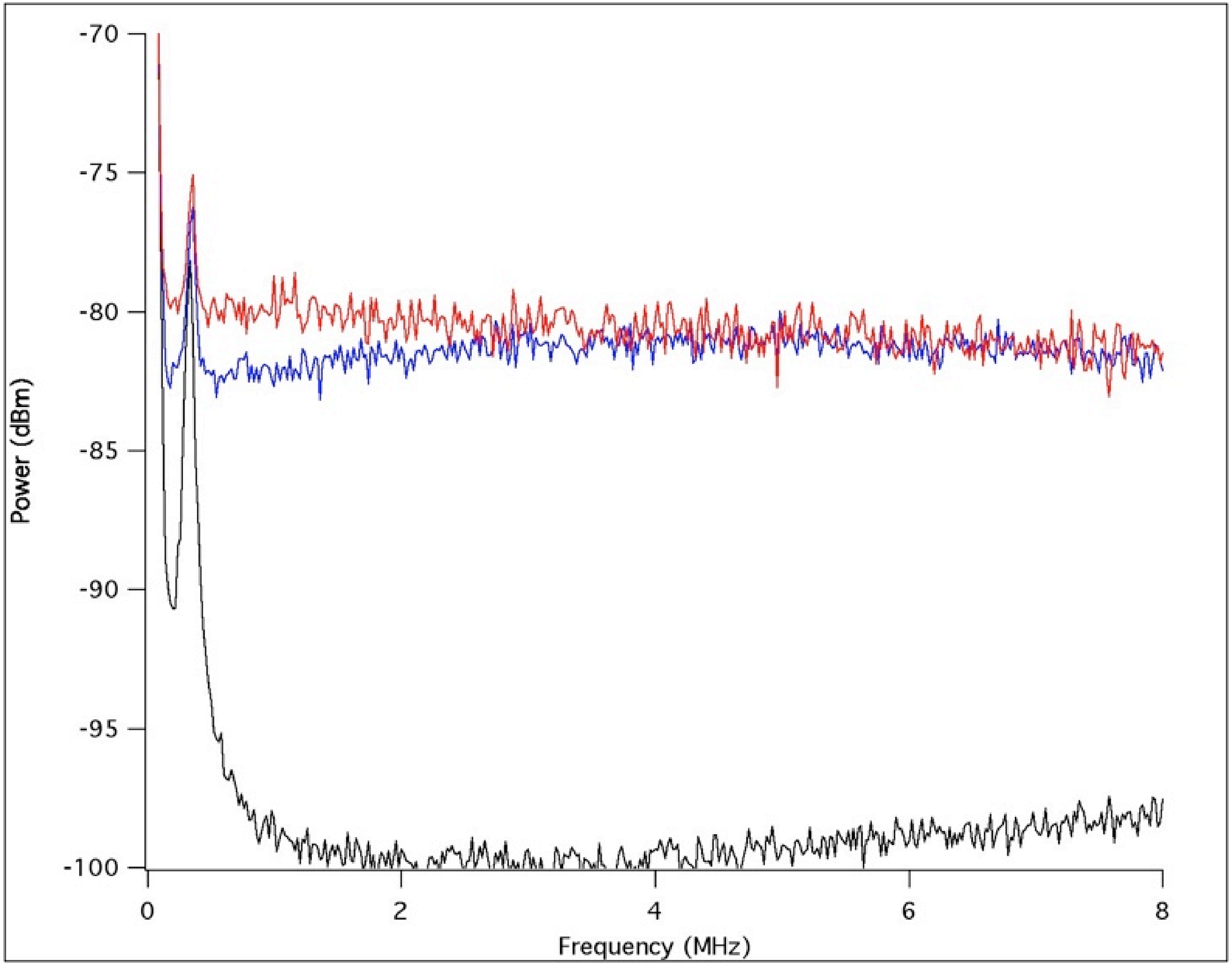
Noise reduction of the signal at each frequency

$$\langle |\widetilde{i}_{-}(\Omega)|^2 \rangle = S(\Omega) = 1 - \frac{4d}{(1+d)^2 + (2\pi\Omega)^2}$$

Setup



Frequency Domain Squeezing



Time-Domain Squeezing

Time-Domain Squeezing is the noise reduction in time.

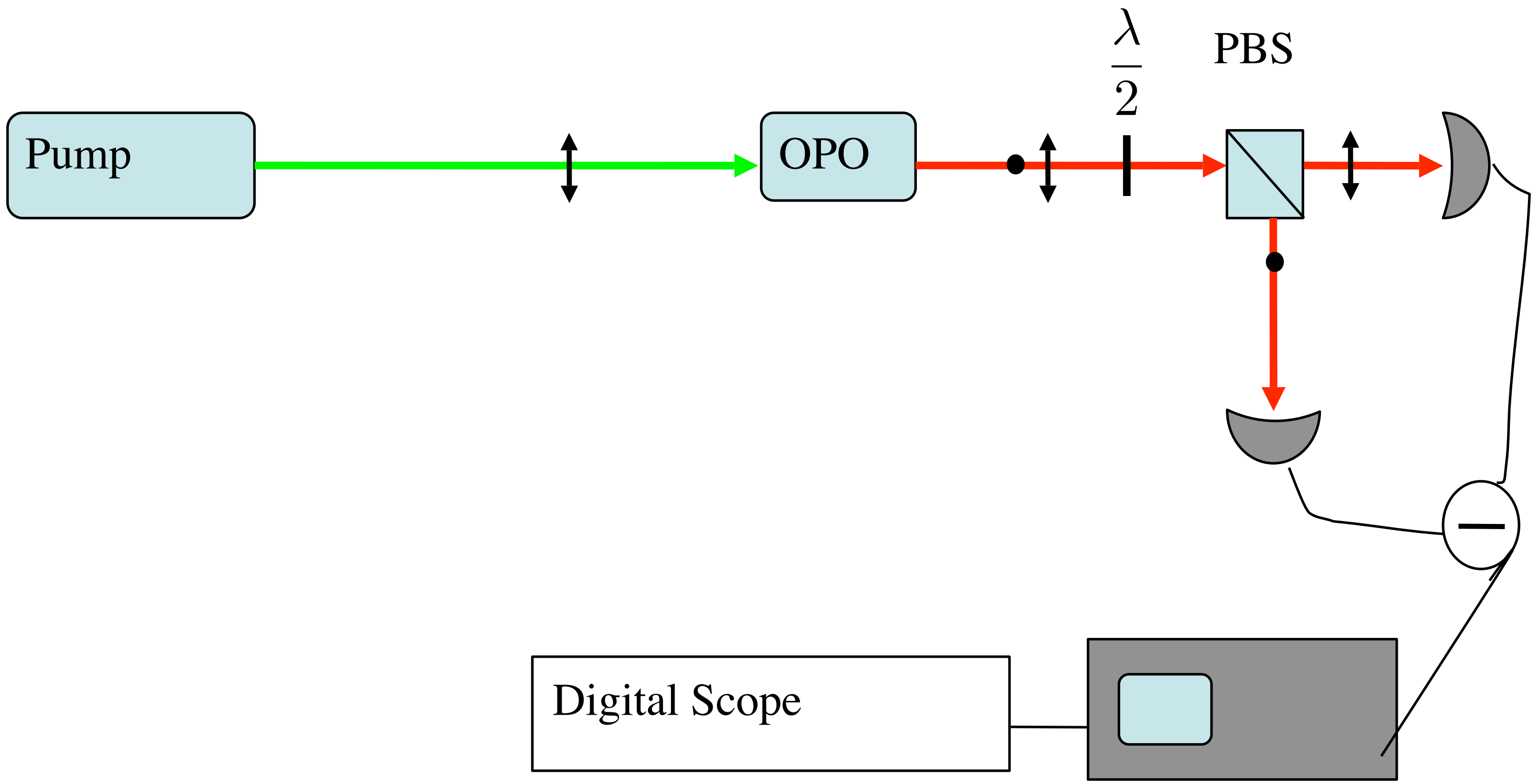
Instead of $\langle|\widetilde{i}(\Omega)|^2\rangle \rightarrow \langle|i(t)|^2\rangle$

This is a measure of total squeezing

Total Squeezing

- Total Squeezing is the noise reduction of light integrated over the bandwidth of the OPO
- The variance of the total squeezing has a limit of $V(X_i) = 1/2$

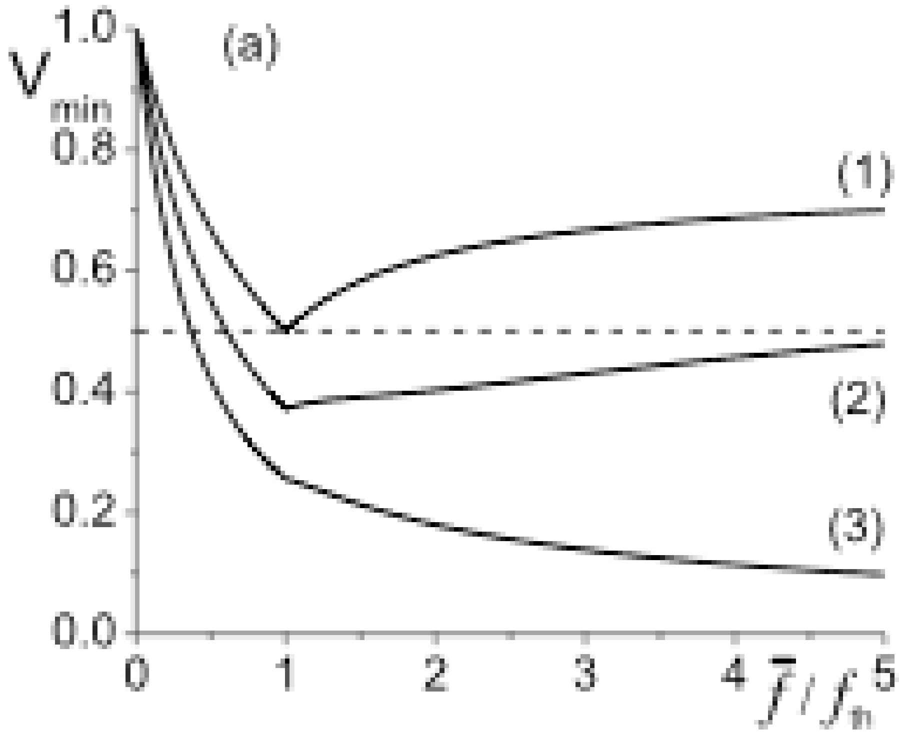
Setup



Time-Modulated Squeezing

- Time-modulated squeezing is squeezing from an OPO that has a modulated pump
- The modulation rate of the pump is equal to the bandwidth of the OPO
- This rate is in between continuous wave and pulsed limits

Why Modulate the Pump?



$\bar{f}/f_{th} =$ The pump strength
Normalized to the threshold

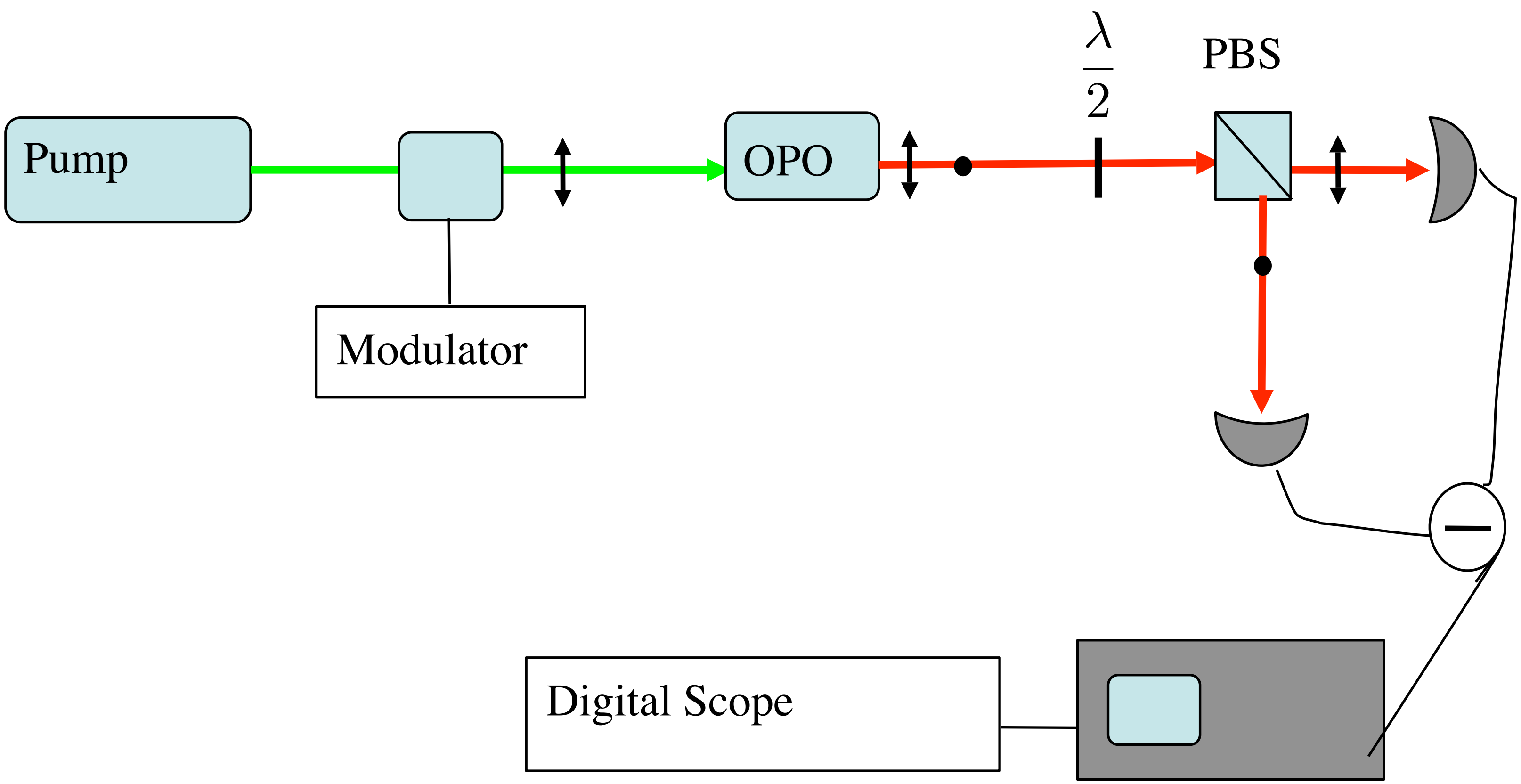
(1) Modulation power $= 0$

(2) Modulation power $= 0.75 \times$ pump

(3) Modulation power $= 3.0 \times$ pump

H.H. Adamyan and G. Yu. Kryuchkyan, Phys. Rev. A **74** 028130 (2006)

Setup



Current Status

- Measured Frequency Domain Squeezing of 3 dB
- Replaced the 1% Transmission Output Mirror with a 2% Transmission Mirror
    - Squeezing is proportional to the Transmittivity
    - Threshold is proportional to the square of the Transmittivity
- Ordered new Nonlinear crystal

Quantum Tomography

- Classical Tomography is finding the shape of an object from its shadow
- From balanced homodyne detection we can measure quasi-probability distribution in quantum phase space
- Each measurement is a slice of the quantum state

Gaussian States of Light

- A Gaussian state of light is a state which the quasi-probability distribution can be described by a Gaussian
- For a Coherent state, the probability in ΔX and ΔP are equal, so it is a symmetric Gaussian
- For a Squeezed state, ΔX and ΔP are not equal

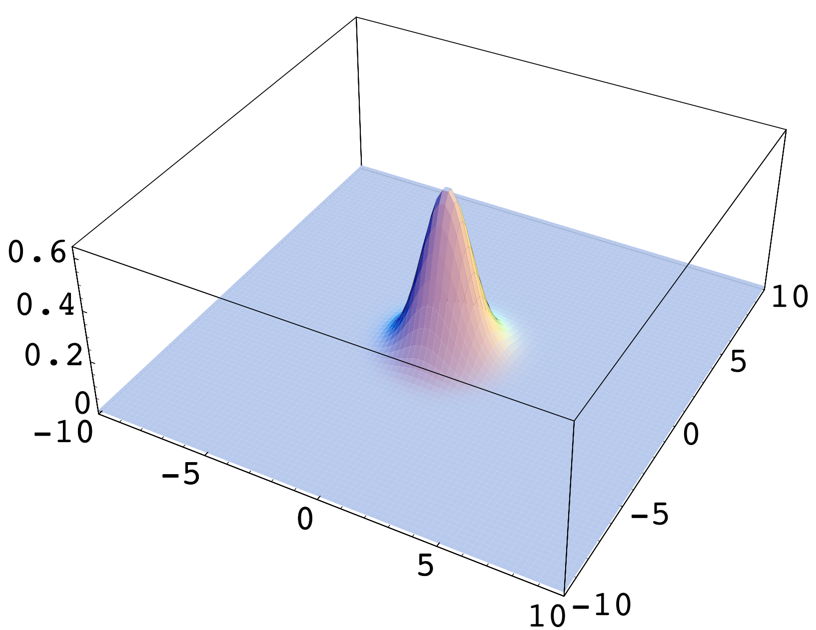
Wigner Function

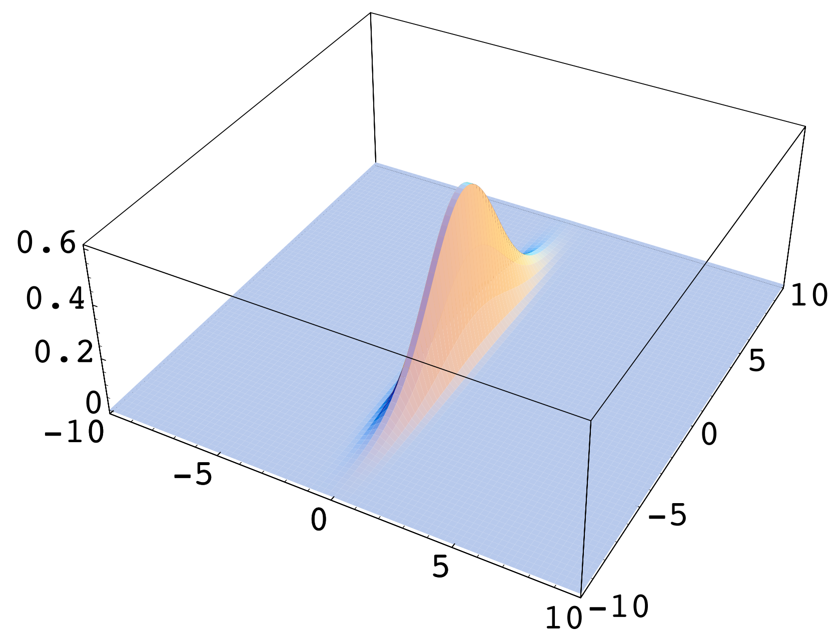
- Quasi-probability distribution
- For a Gaussian, it is never negative
- For a squeezed state the Wigner function is never negative, also

$$\langle q|\hat{U}(\theta)\hat{\rho}\hat{U}^\dagger(\theta)|q\rangle = \int_{-\infty}^{\infty} W(q\cos\theta - p\sin\theta, q\sin\theta + p\cos\theta)dp$$

Wigner Function of Coherent and Squeezed Light

$$W_s(q,p) = \frac{1}{\pi} \exp\left(-e^{2r} q^2 - e^{-2r} p^2\right)$$

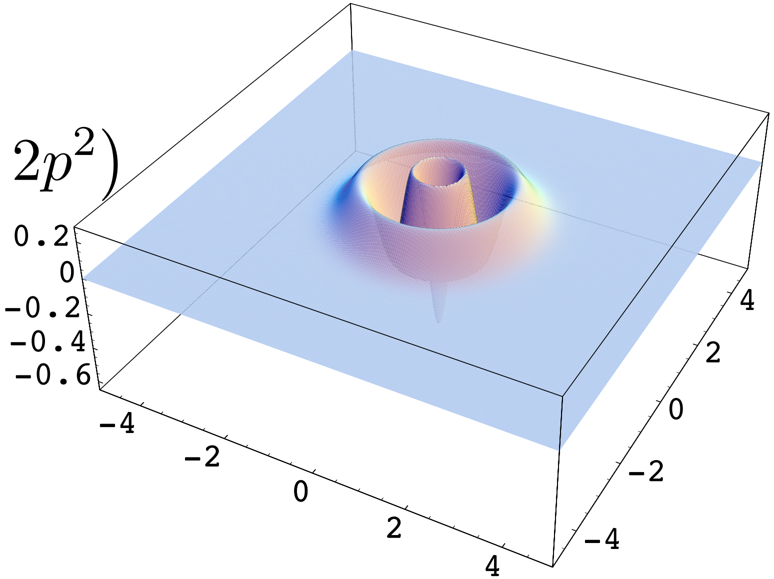




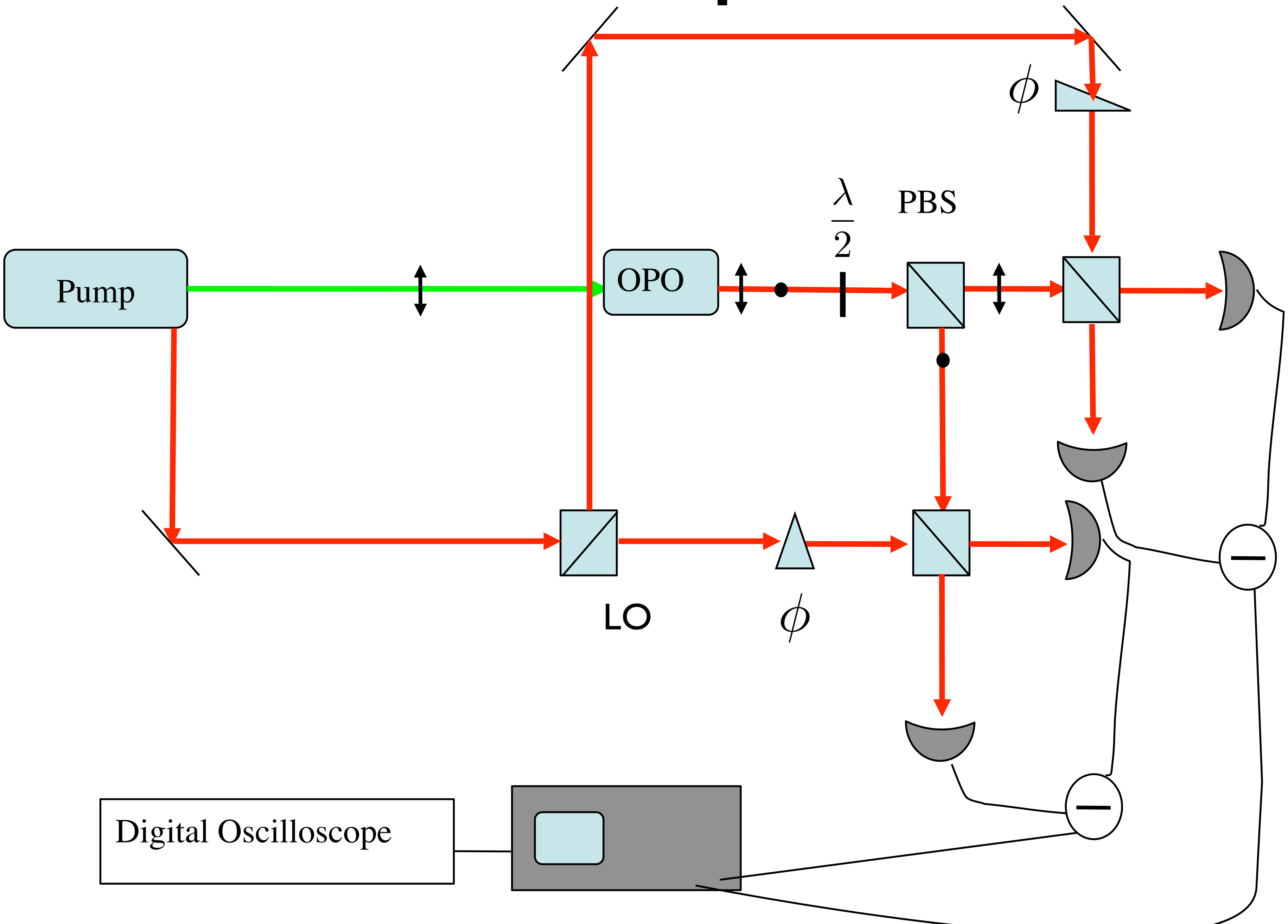
Negative Wigner Function

- A negative Wigner function is one that has a negative value at some position in phase space.
- An example is the Fock states

$$W_n(q,p) = \frac{(-1)^n}{\pi} \exp\left(-q^2 - p^2\right) L_n\left(2q^2 + 2p^2\right)$$



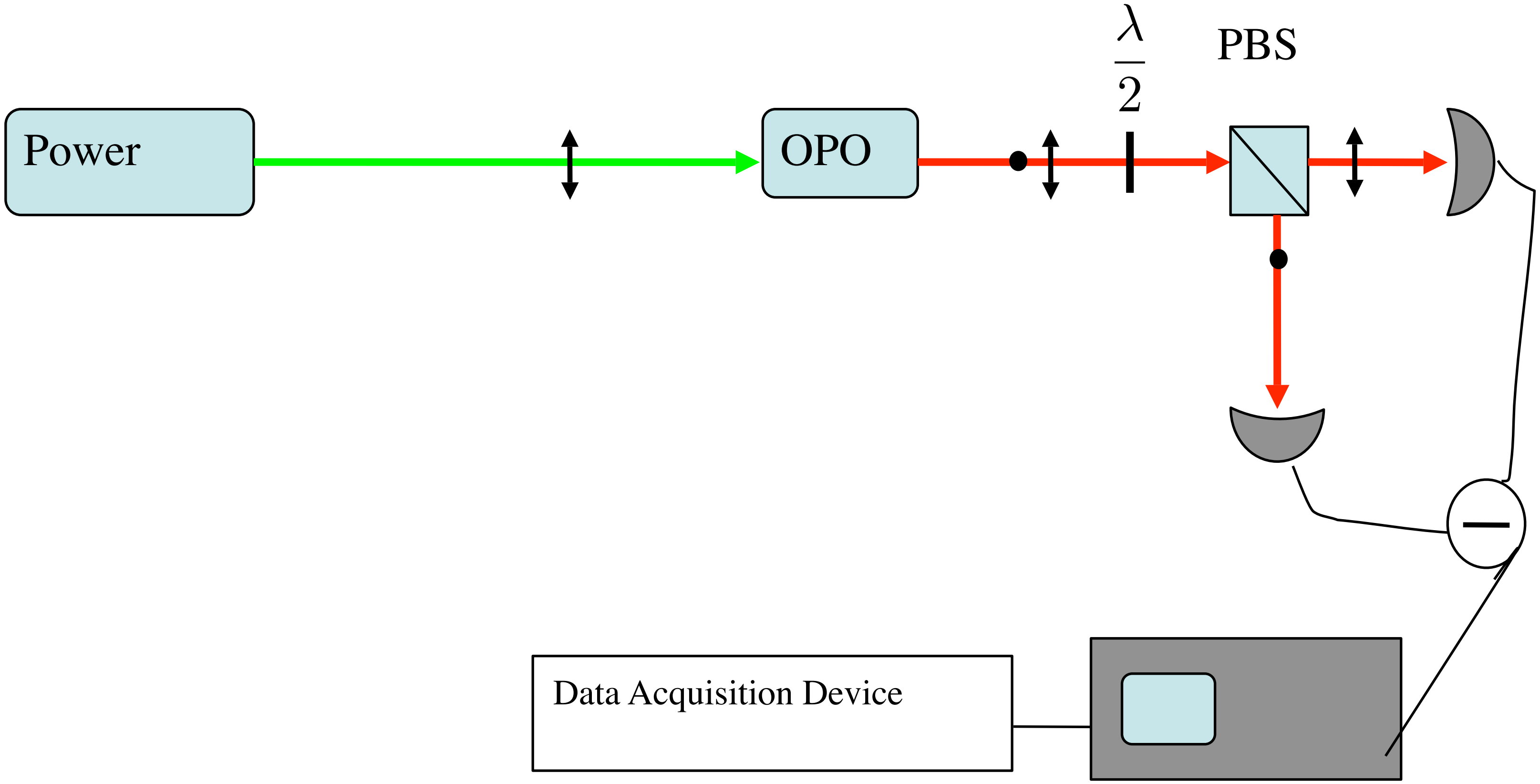
Setup



Conclusion

- Explained the current limitation of an OPO
- Method to increase squeezing by modulating the pump
- Current Status
- Explained Future Experiment
- Any Questions

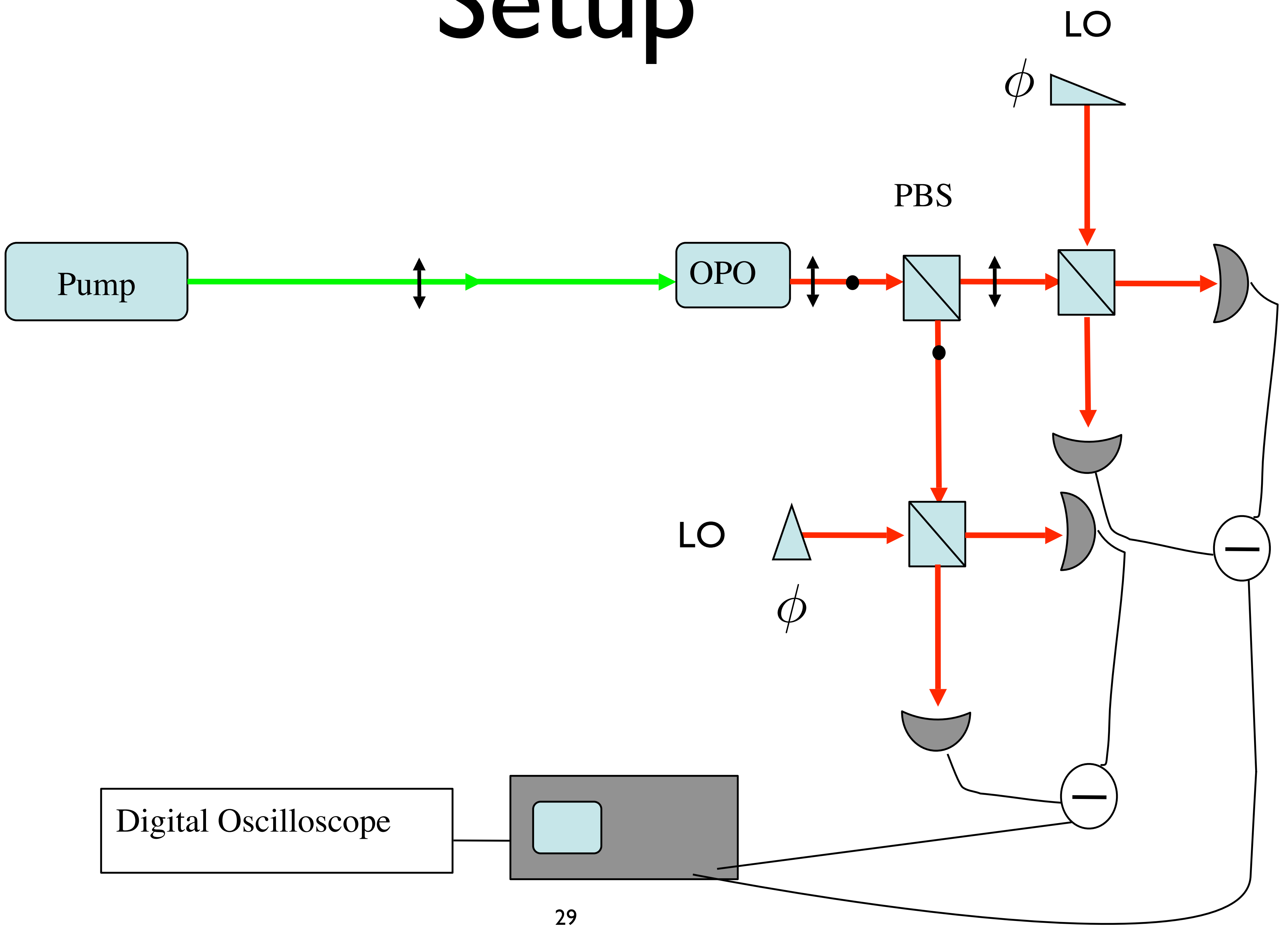
Setup



Possible Future Experiments

- Quantum Tomography of a non-gaussian state
- Quantum Teleportation of a Bright Squeezed state

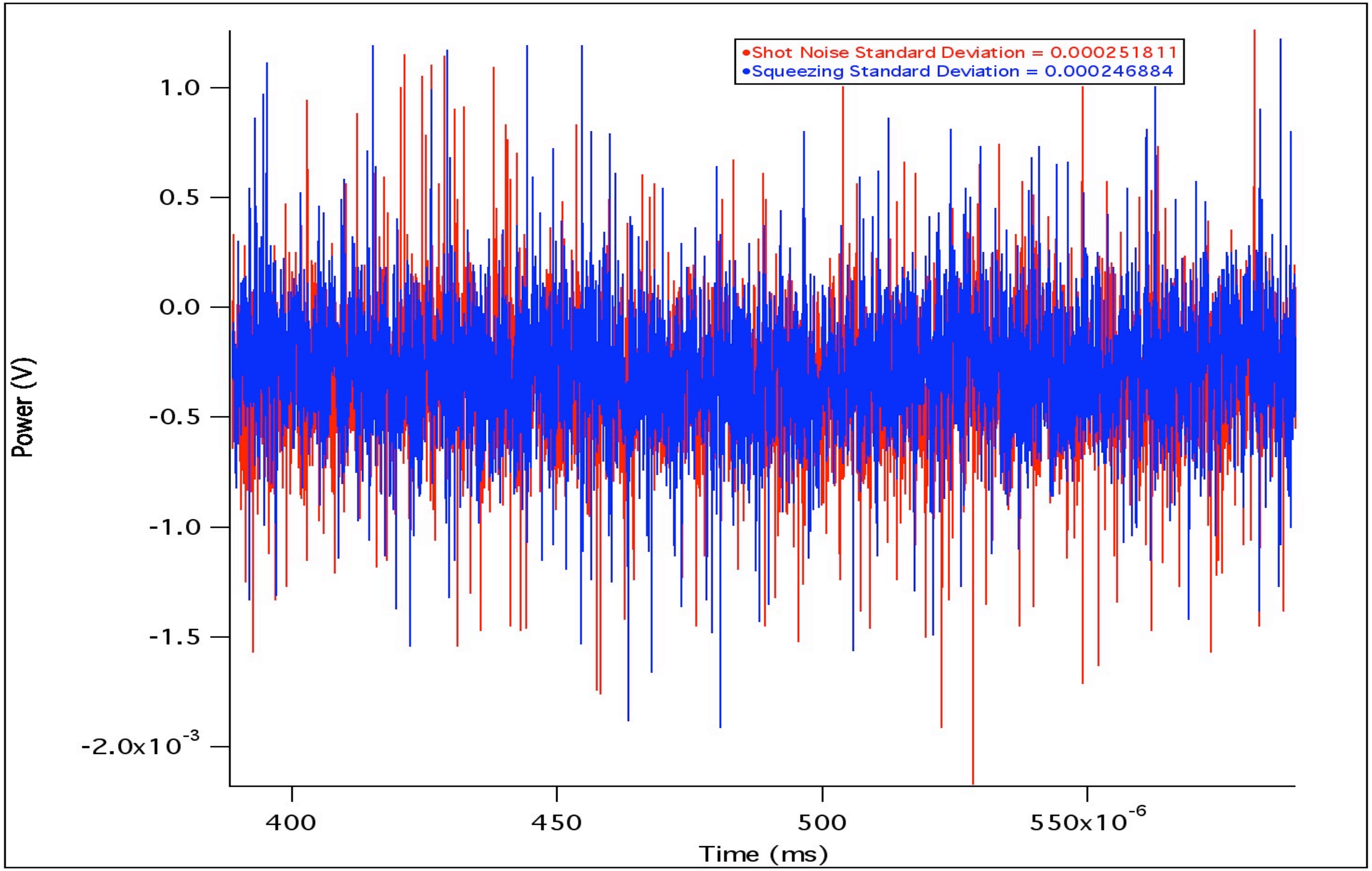
Setup



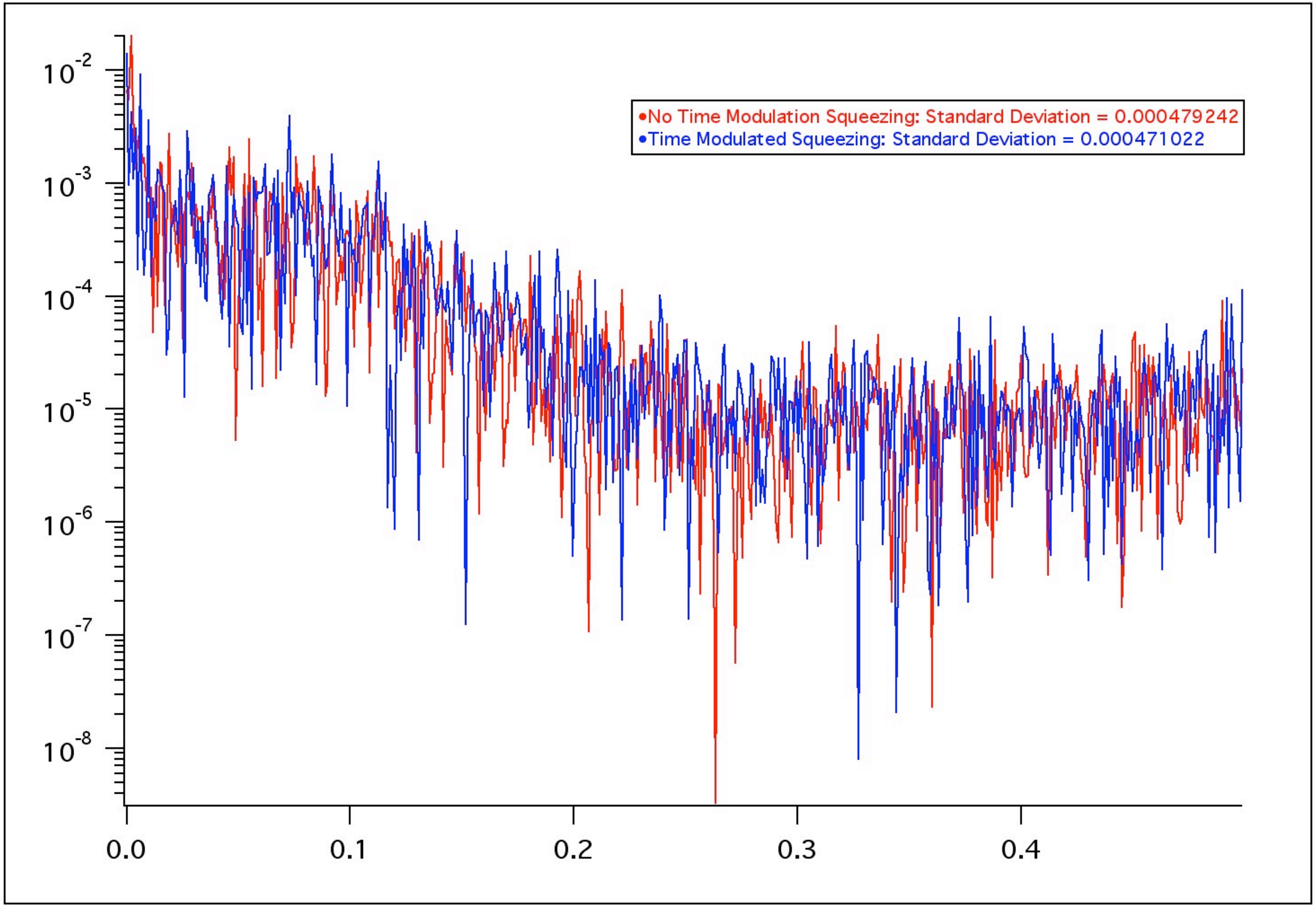
Some Basic Experiments

- Frequency Domain Squeezing
- Time Domain Squeezing

Time Domain Squeezing



Time-Modulated Squeezing



Quantum Teleportation

In Quantum Teleportation, an unknown quantum state can be transferred from Alice to Bob with high fidelity.

Setup

$\omega = 2\pi \times 563.5 \text{ rad/s}$ $\delta\alpha$

$\lambda = 532 \text{ nm}$

$\omega_1 \approx \omega_2 \approx 2\pi \times 281.7 \text{ rad/s}$

$$\int_{-\infty}^{\infty} W(q,p)\,dp = \langle q|\hat{\rho}|q\rangle$$

$\omega_1 = \omega_2 = 2\pi \times 281.7 \text{ rad} \cdot$

$\lambda_1 = \lambda_2 = 1064 \text{ nm}$

ΔX

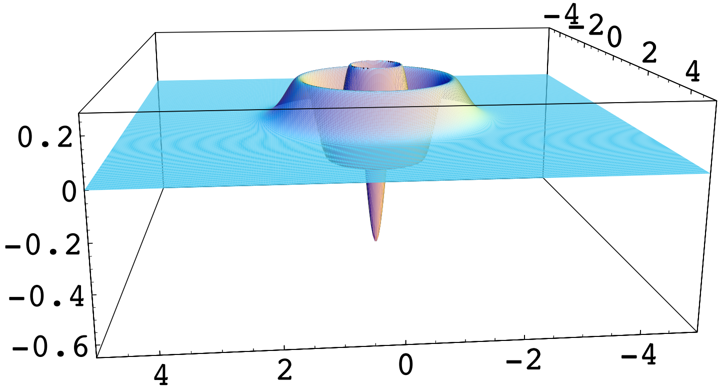
ΔP

$\omega_1 = \omega_2 = 2\pi \times 281.7 \text{ rad/s}$

ΔX ΔP

Compare with previous Results

Non-Gaussian States of Light



- Define Non-gaussain