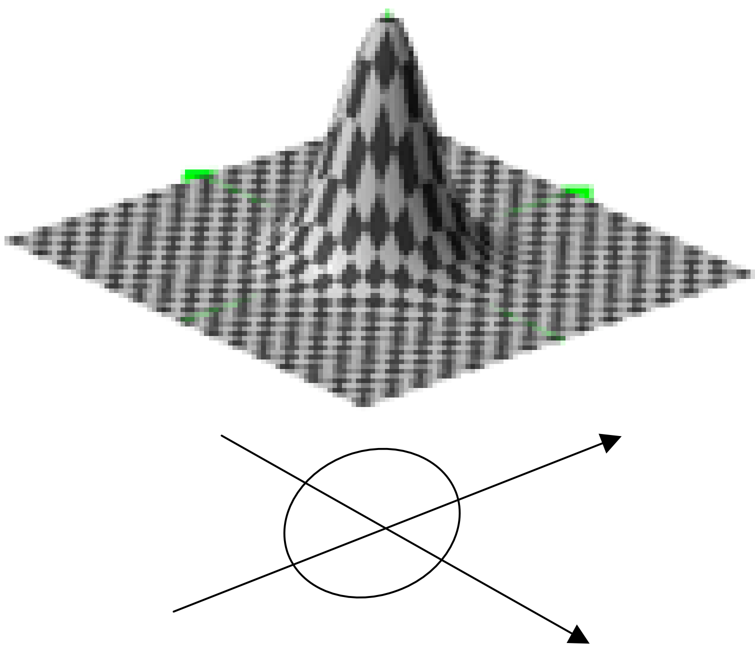
Lecture 4

- What is squeezed light ?
- Formalism
- Properties
- Examples of experiments

Other possible states

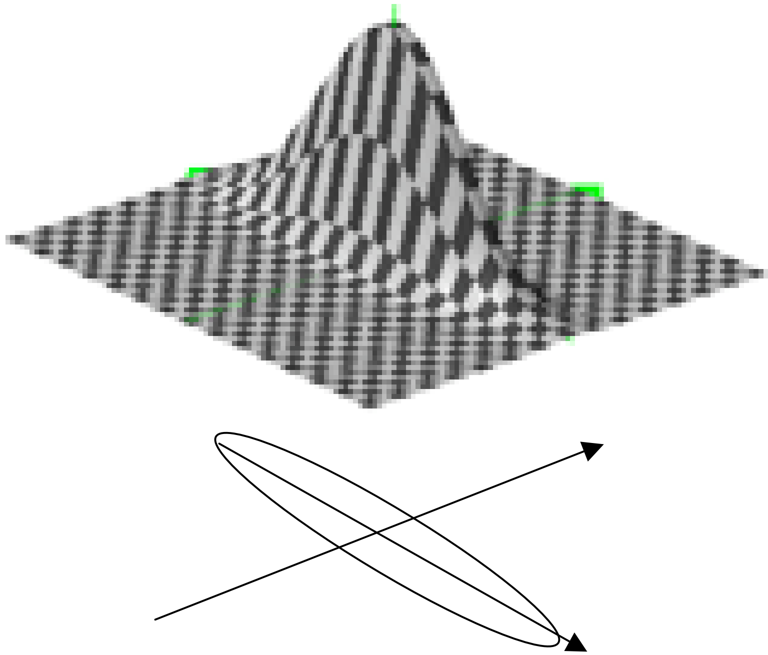
Coherent state
V1 = V2

V1 V2 = 1



Squeezed state
V1 ≠ V2

V1 V2 ≥ 1



Squeezed states

Theoretically they are a different class:

$$| \alpha, \xi > \; = \; S(\xi) \; D(\alpha) \; |0>$$

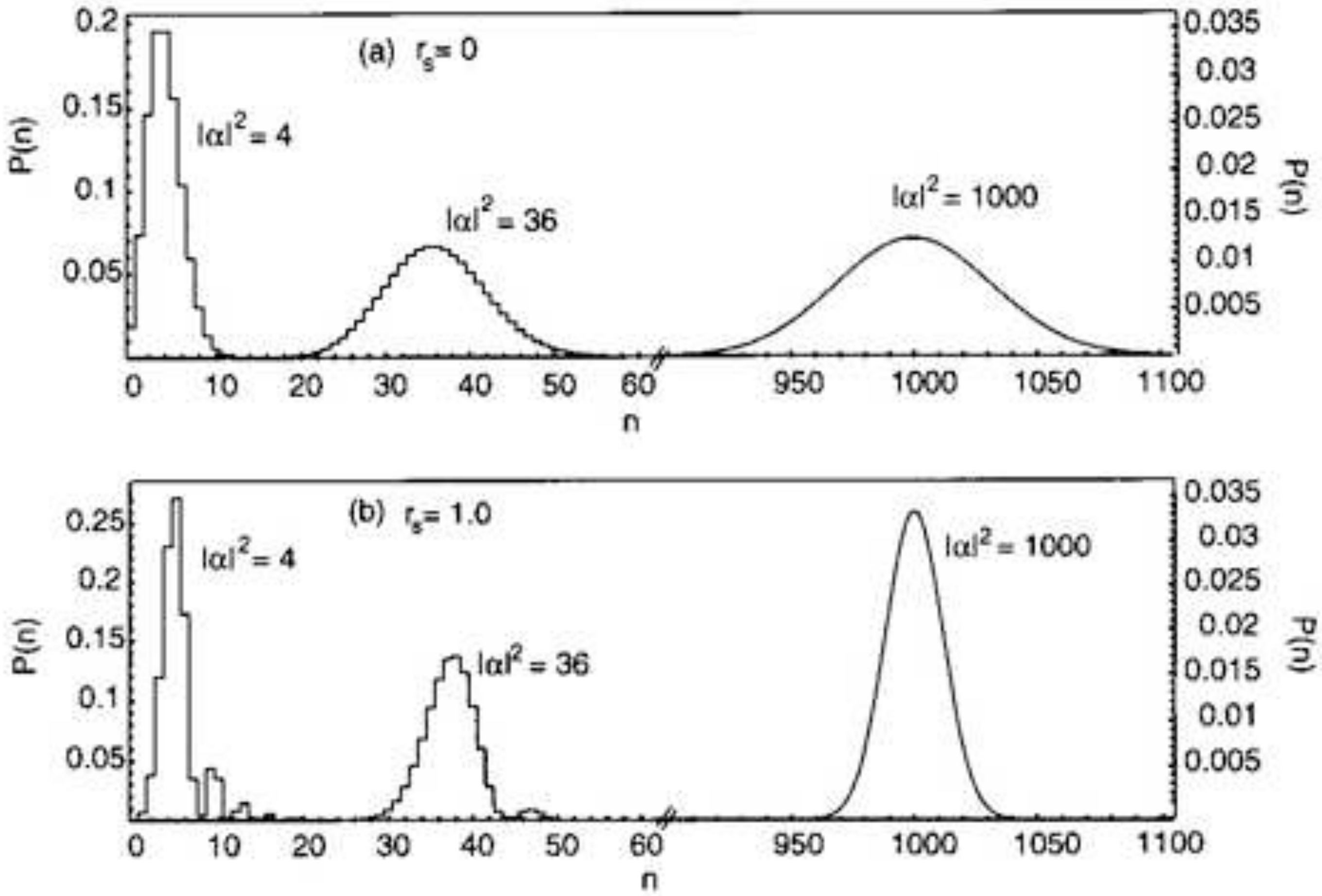
2 photon correlated state, displace first,
then apply squeezing operator **Yuen**

$$| \alpha, \xi > \; = \; D(\alpha) \; S(\xi) \, |0>$$

squeezed state , squeeze first,
then apply displacement operator **Walls**

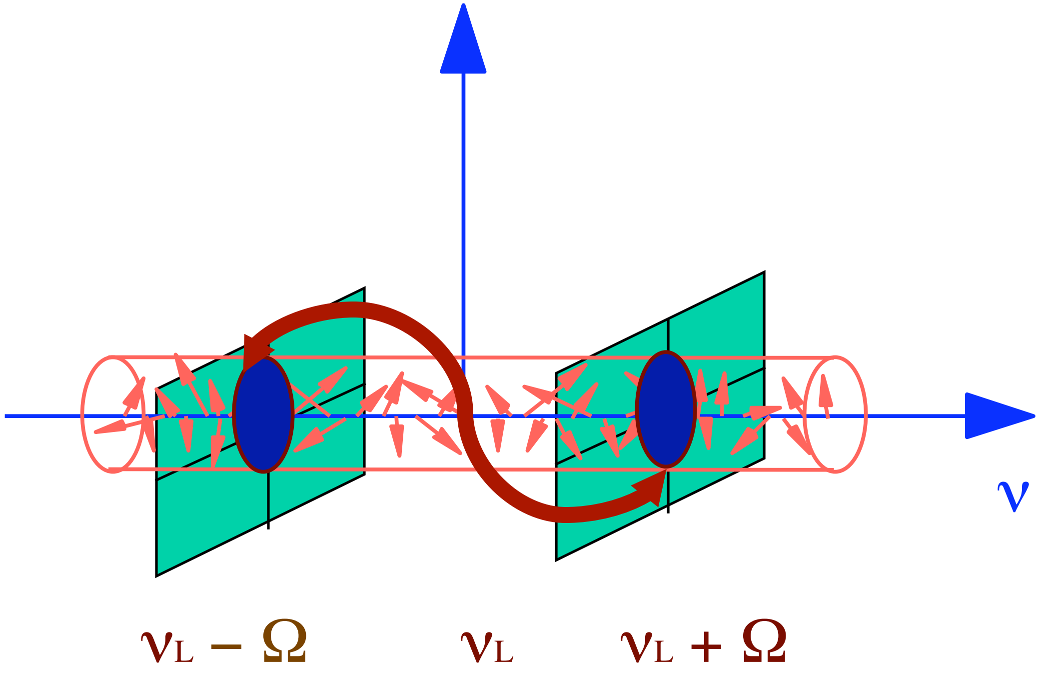
$\xi = r$ **degree of squeezing,** Θ_s **squeezing angle**

Photon disribution for squeezed light



Comparison of coherent state with squeezed state (r=1) , for three different mean photon numbers: $|\alpha|^2$ = 4, 36 and 1000. For low photon numbers there is structure , for high photon numbers we get a narrower Gaussian.

A model for squeezing



The two sidebands are no longer independent. The nonlinear process couples , correlates , the two side bands. These are both contributing to the beat frequency detected at Ω.

The two contribution can cancel each other => noise < QNL

There are now extra photons in the sideband.

Squeezing properties

The noise depends on the detection angle Θ

Var $(X(\Theta) = \cosh^2(r) - \quad | \sinh(r) \; \exp(i\,2\,(\Theta + \Theta_s)\,|^2$

it is best to go into a rotated frame of reference

VY1 = Var $(X(\Theta_s) = \exp(-2r)$

VY2 = Var $(X(\Theta_s + \pi/2) = \exp(2r)$

and note that both $\Theta_s(\Omega)$ and $r(\Omega)$ depend on the detection frequency

Plotting Var $(X(\Theta_s))$

VY1 = Var $(X(\Theta_s))$ = exp (- 2**r**)

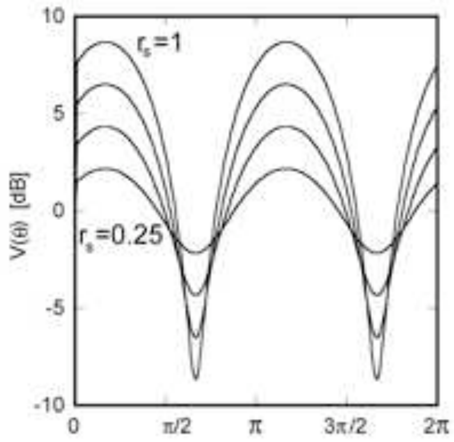
VY2 = Var $(X(\Theta_s + \pi/2))$ = exp (2**r**)

(a) linear scale, both
squeezing and anti-squeezing

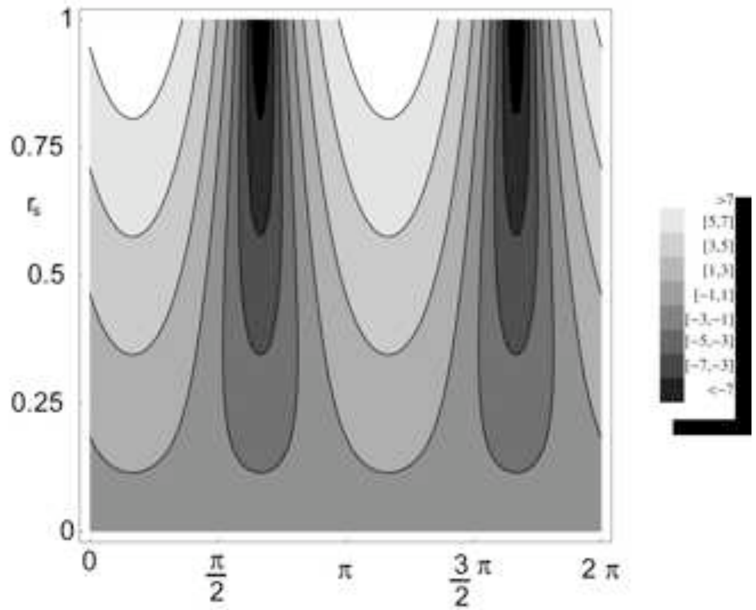
(b) logarithmic scale
squeezing occurs in a very
narrow range of projections

(c) polar plots of Var $(X(\Theta_s))$

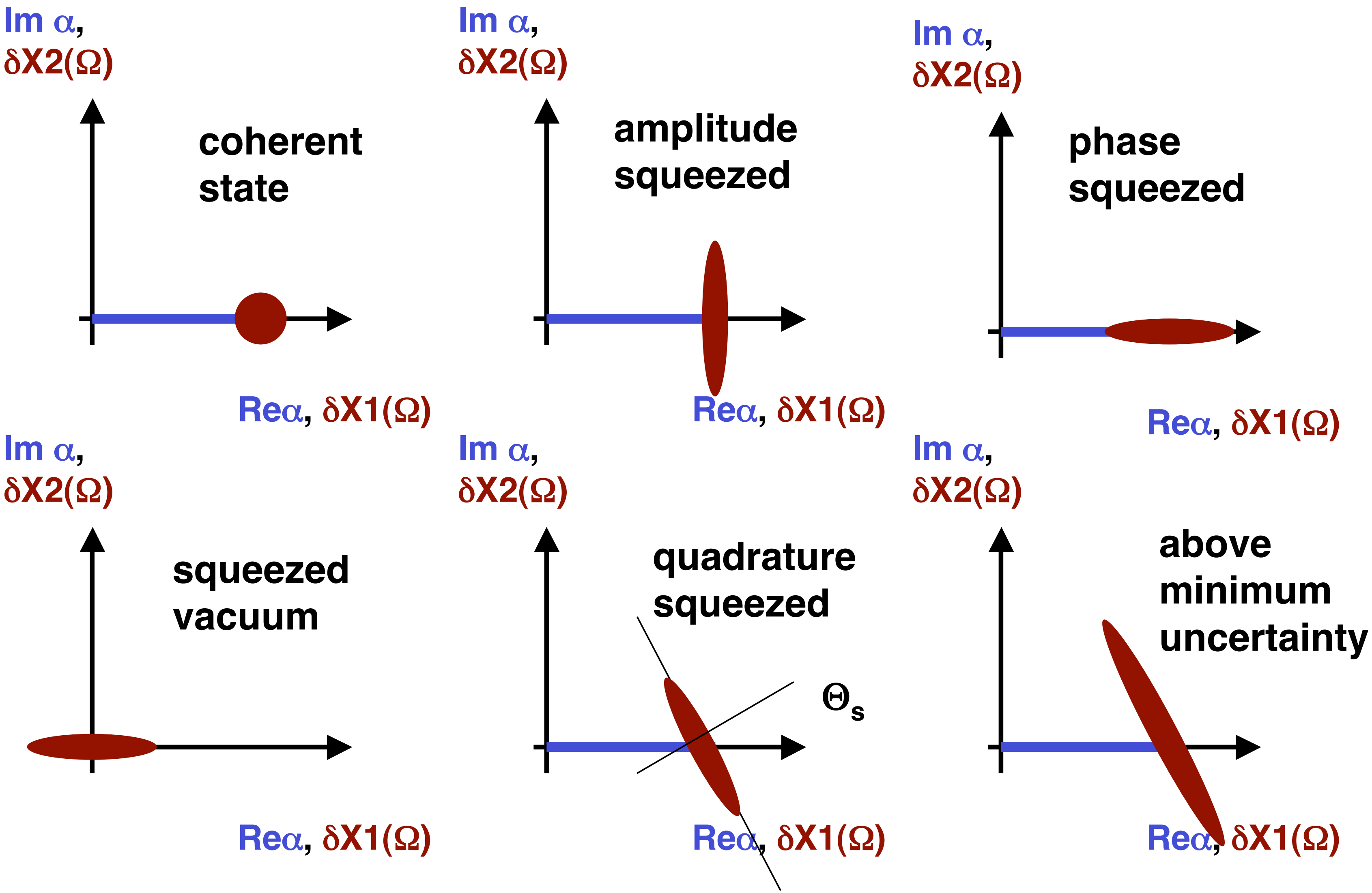
(a)



(b)

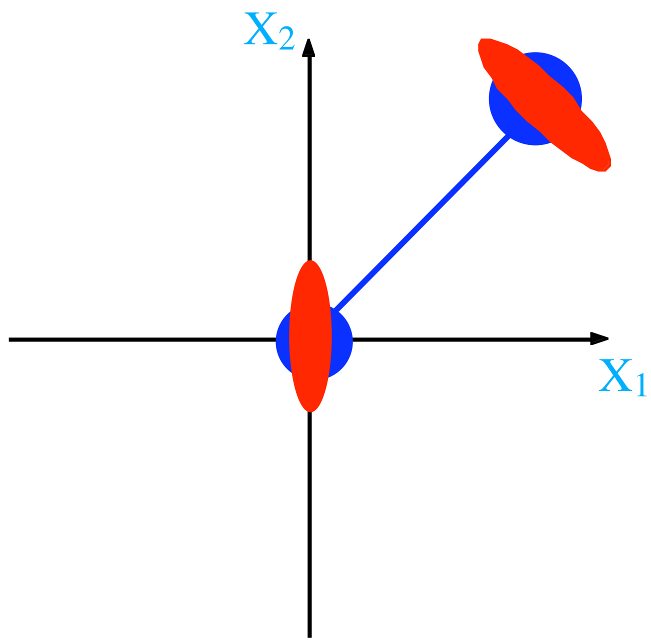


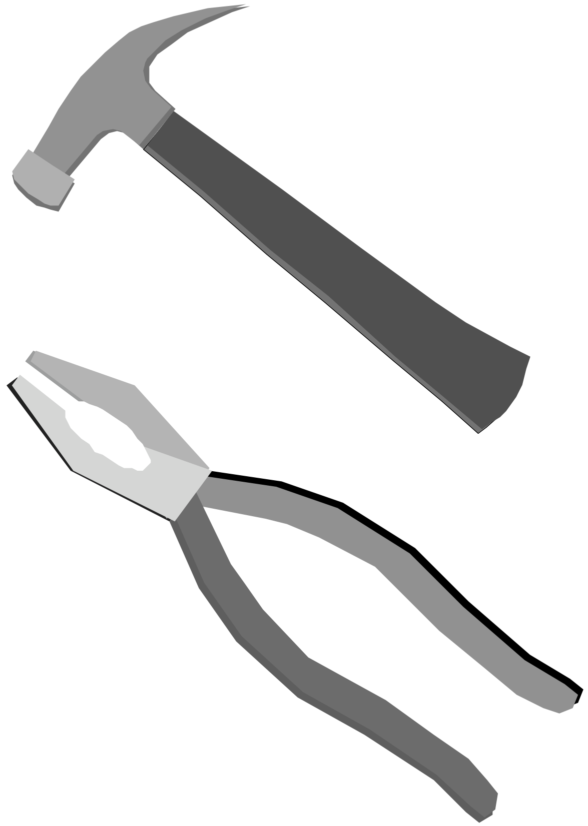
Different types of squeezed states



The tools for squeezing

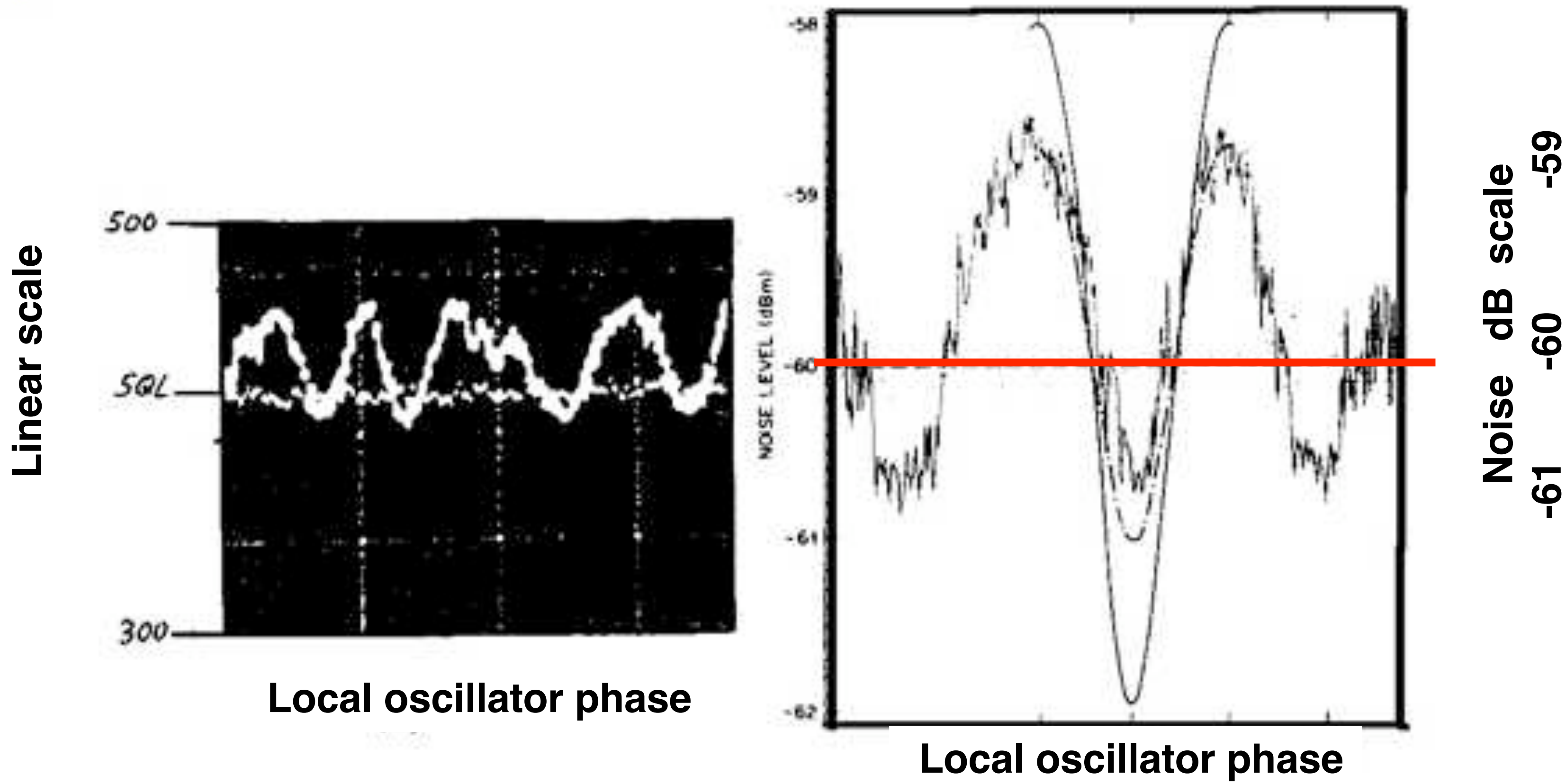
- **Is it possible to change the shape of the minimum uncertainty circle using some optical tools?**





- **Can we make a light state that is quieter than the vacuum state of light?** **--- A Squeezed Vacuum**

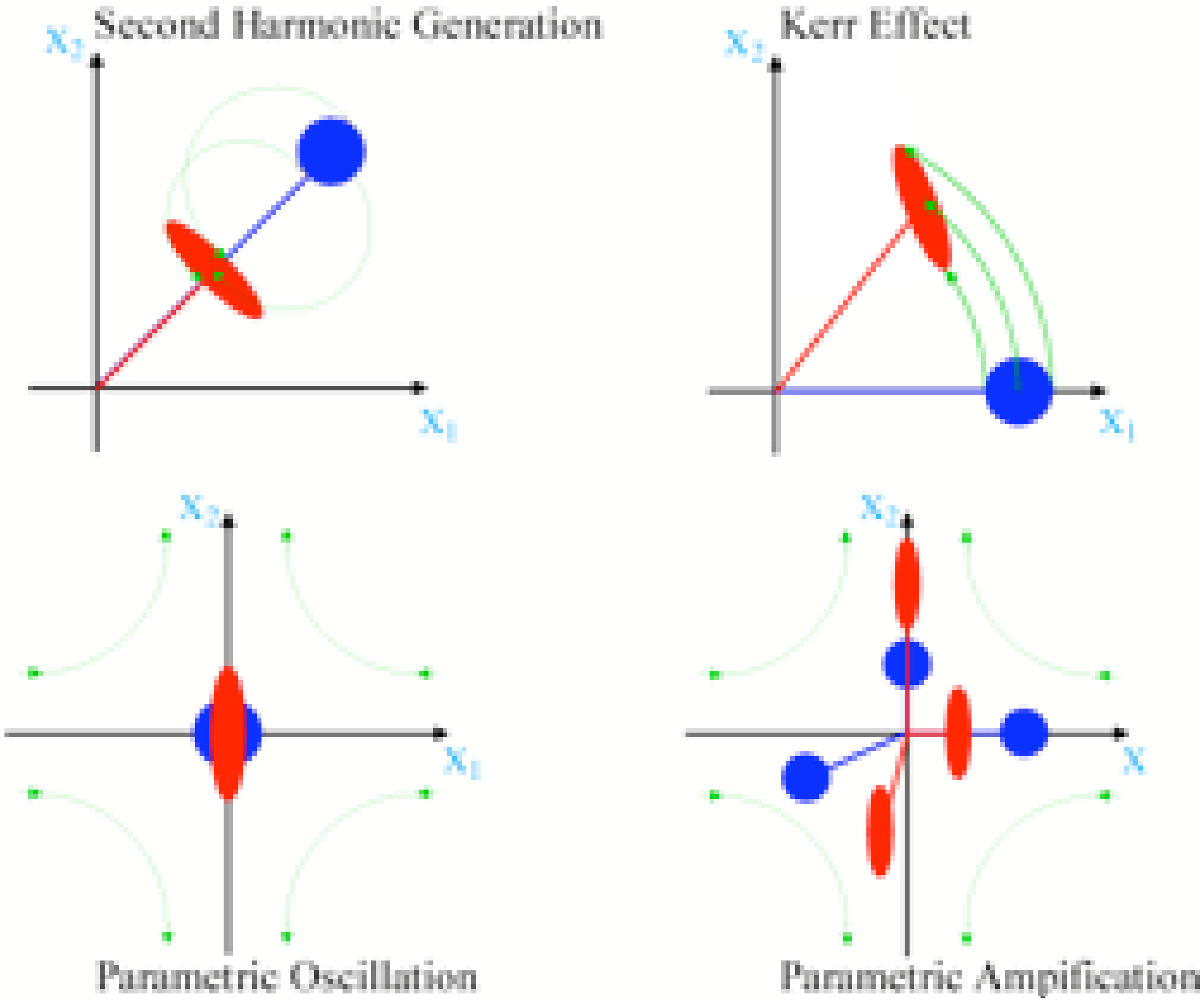
First squeezing results (4WM in Na)



The first squeezing results, obtained at Bell labs by 4WM in a sodium vapour and later results after optimisation. Solid line: theory prediction.

R.E.Slusher, L.W.Hollberg, B.Yurke, J.C.Mertz, J.F.Valley, PRL 55, 2409 (1985)
R.E.Slusher, B.Yurke, P.Grangier, A.LaPorta, D.F.Walls, M.Reid, J.O.S,A. B4, 1453 (1987)

Squeezing with nonlinear processes



The Kerr effect

$n(\alpha) = n_0 + n_2\,\alpha^2$

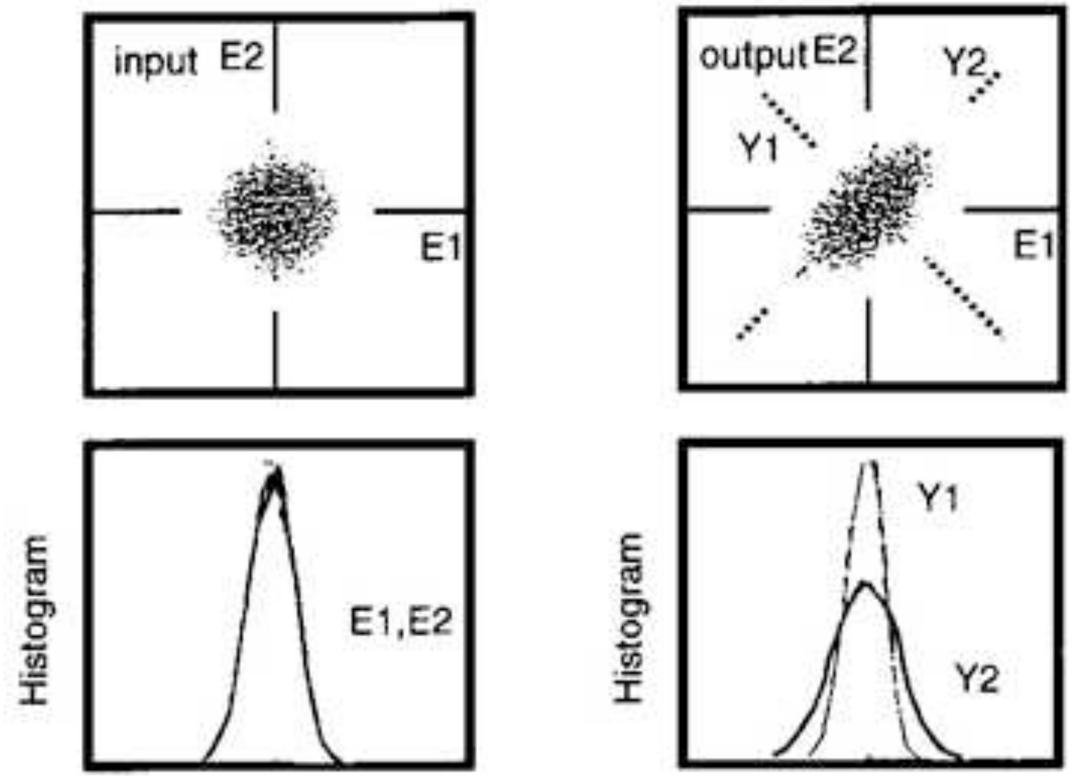
$\Phi_{out} = 2\,\pi\,L/\,\lambda\,(n_0 + n_2\,(\alpha+\delta X1)^2)$

$\delta X2_{out} = \delta X2_{in} + 2\,r_{kerr}\,\delta X1_{in} \quad r_{kerr} = 2\,\pi\,n_0 n_2 L\,\alpha^2\,/\,\lambda$

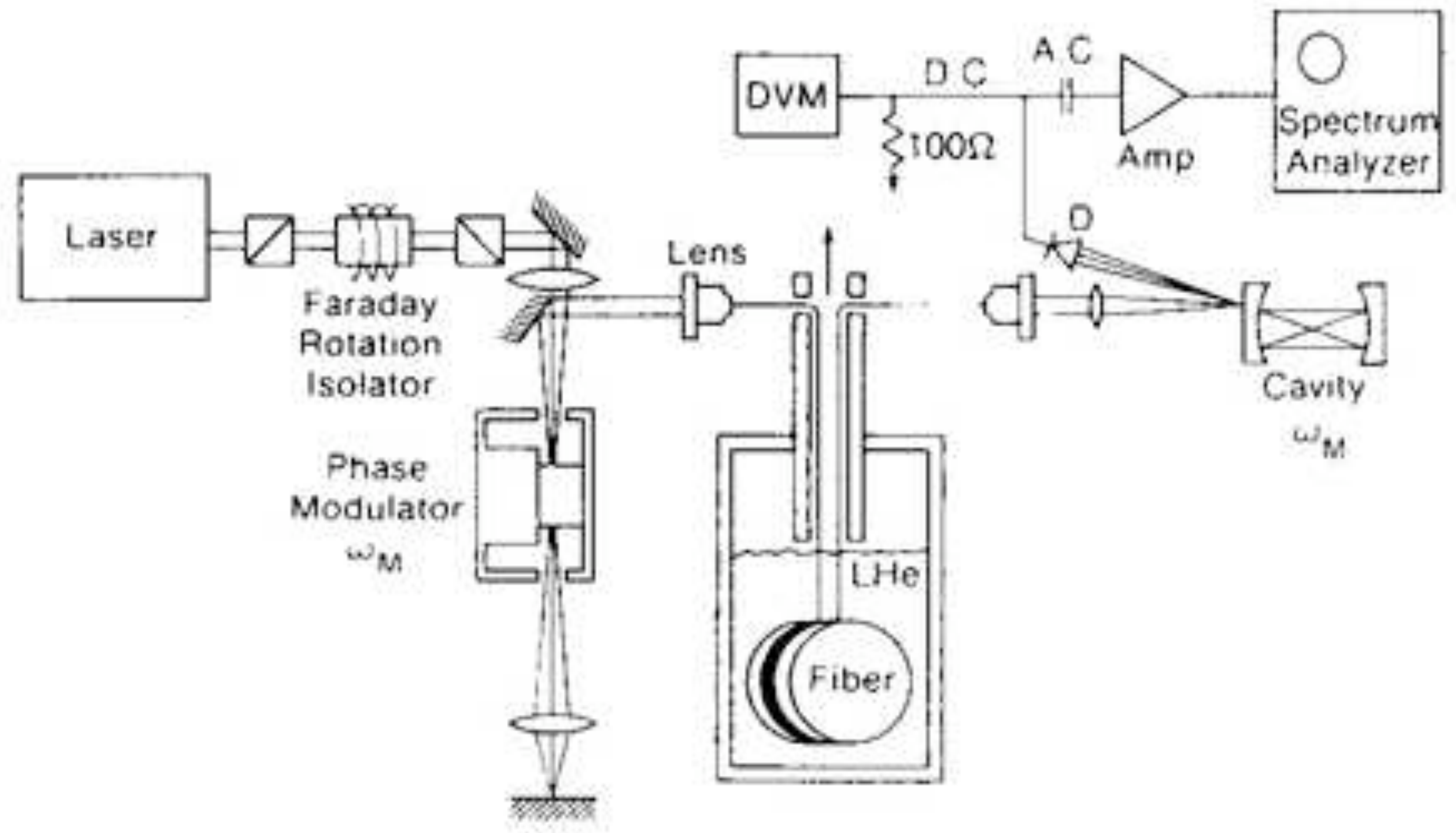
The Kerr effect links the fluctuations in the intensity to changes in the refractive index.

The Kerr effect does not preserve minimum uncertainty states. It adds noise.

But: in one direction the noise is below the quantum limit.

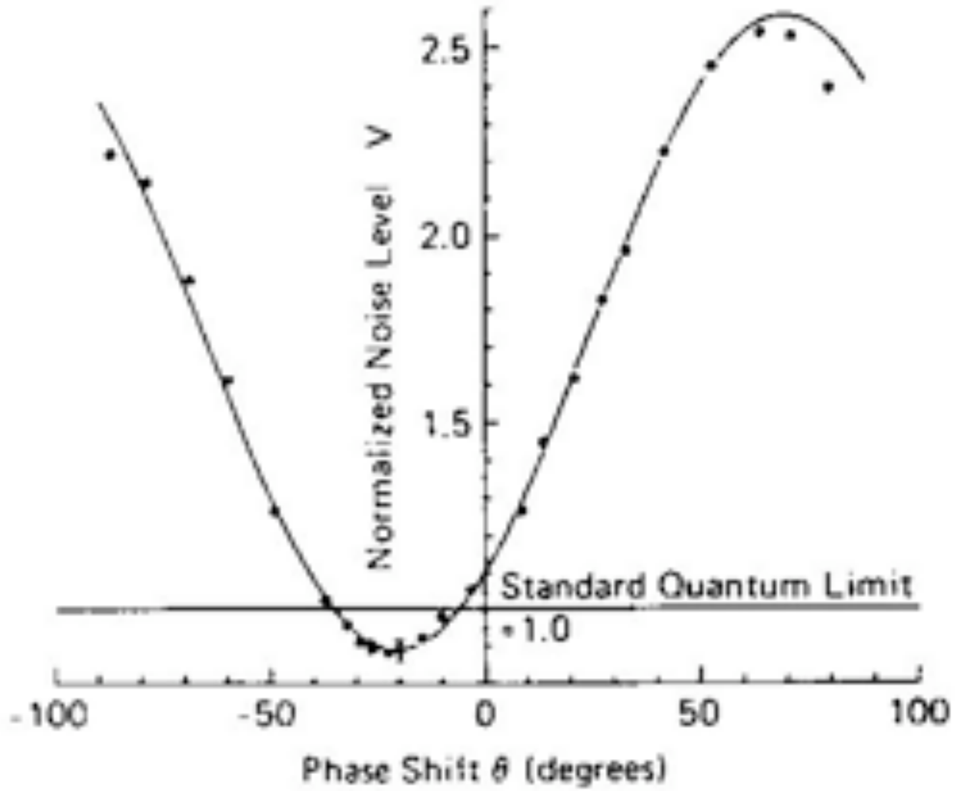


Kerr effect in a fibre



First experimental results with Kerr effect: long fibre , cooled to suppress noise, many modes to avoid Brillouin scattering, detected by rotating the quadratures with a cavity. ***M.Levenson , R.M.Shelby, S.H.Perlmutter , Opt.Lett. 514 (1985)***

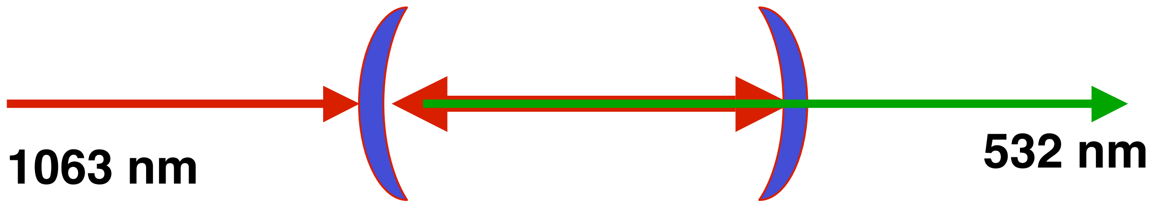
First Kerr squeezing results



The minimum of the noise is at an angle rotated to X1 and X2. This can be measured by using a detuned cavity to rotate the quadratures. The noise suppression is small, but reproducible and fits the theoretical prediction.

G.J.Milburn, M.D.Levenson, R.M.Shelby, S.H.Perlmutter, R.G.deVoe, D.F.Walls
J.O.S.A. B 4 , 1476 (1987)

SHG squeezing idea



Nonlinear crystal can convert from $\nu 1$ to $2\,\nu 1$

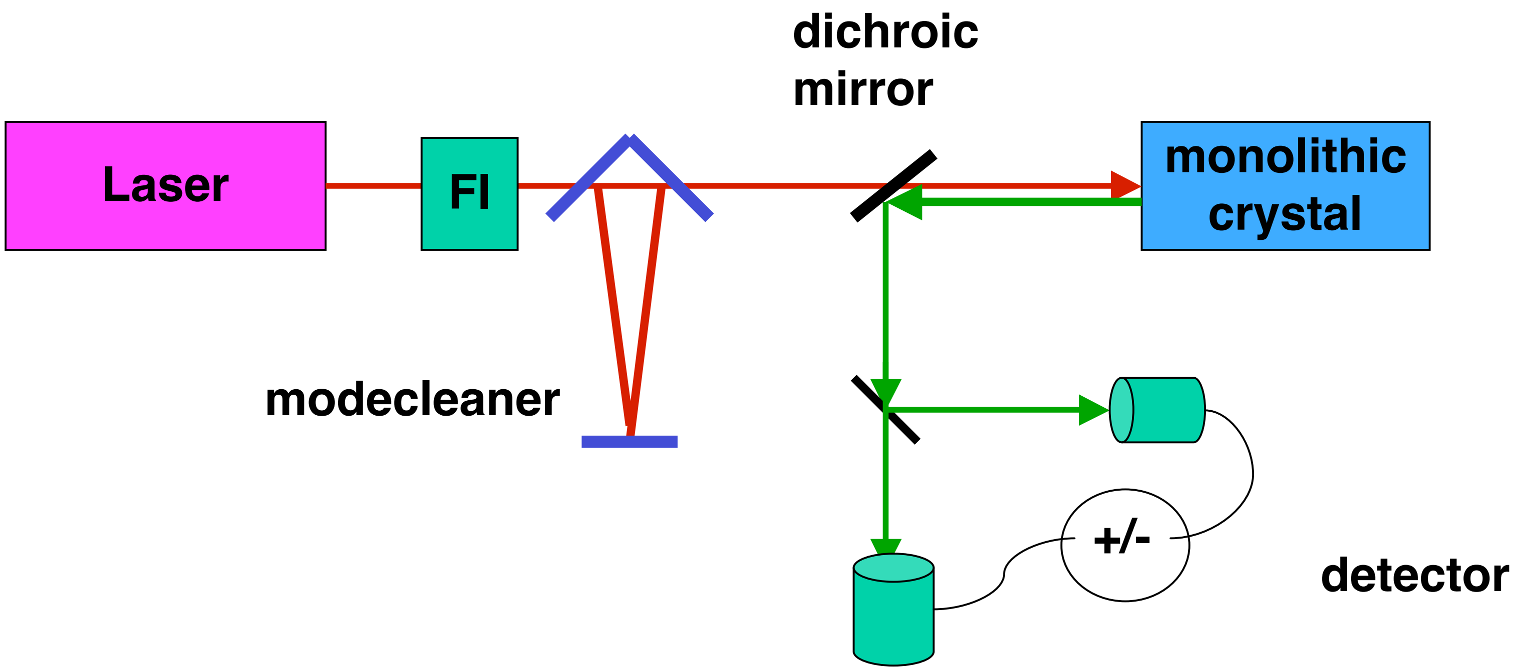
cavity which is resonant for fundamental (1063 nm)
has one reflector for the second harmonic (532 nm)

$$d\,a_s/dt = -(\kappa_{f1} + i\Delta f)\,a_s + 1/2\,\xi\,a^\dagger_f\,a_f + \sqrt{2}\,\kappa_1\,A_{s1} + \sqrt{2}\kappa_2\,A_{s2} + \sqrt{2}\,k_{loss}\,A_{loss}$$

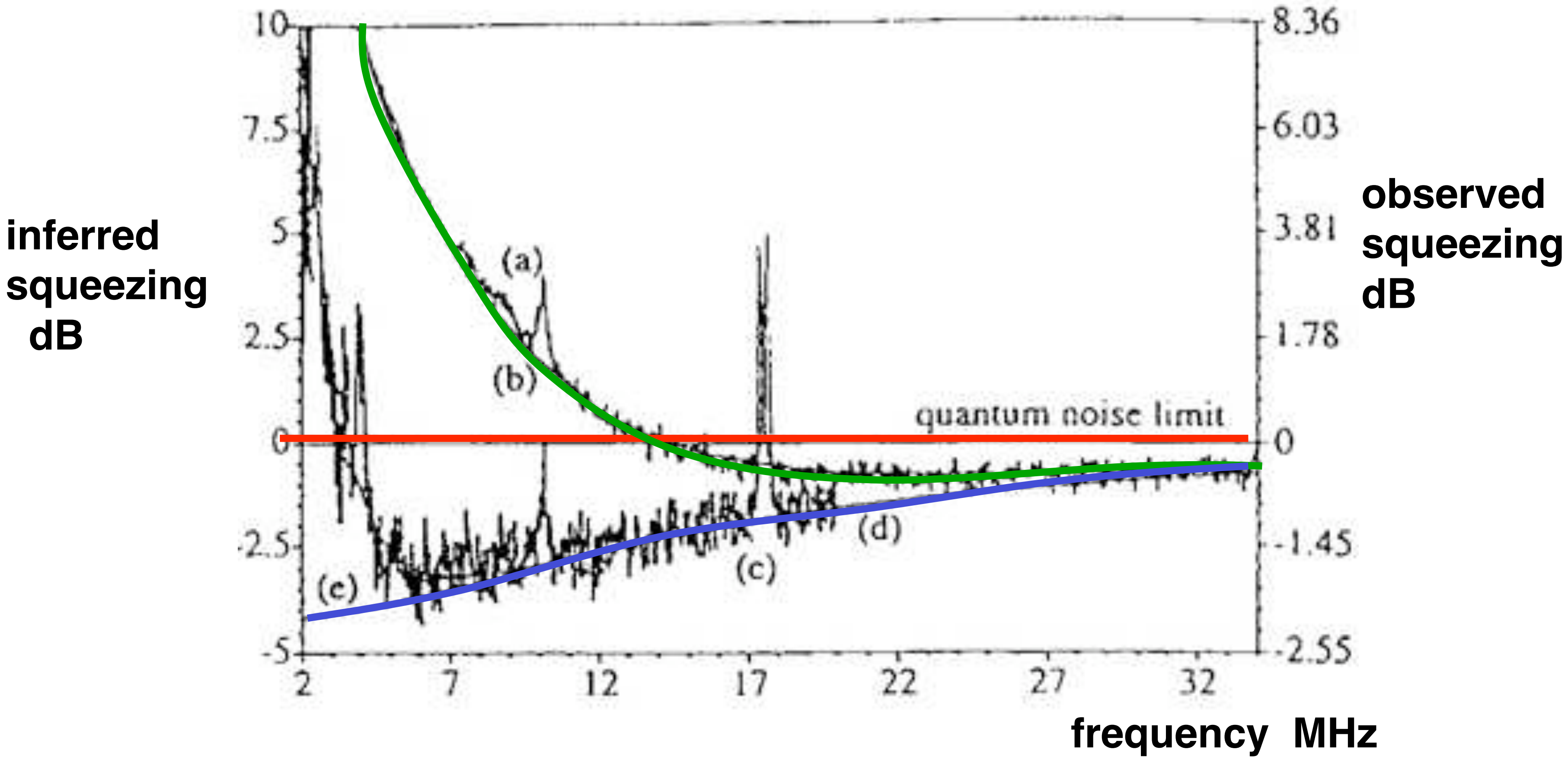
$$V1s(\Omega) = 1 - 8\,\kappa_{nl}^2 - 8\,\kappa_{nl}\kappa_{nf}\,(V1_{las} - 1)\,/\,[\,(3\,\kappa_{nl} + \kappa_{nf})^2 + (2\,\pi\Omega)^2]$$

$$\kappa_{nl} = \xi\,/\,2\,\kappa_s\,|\alpha|^2$$

SHG squeezing apparatus

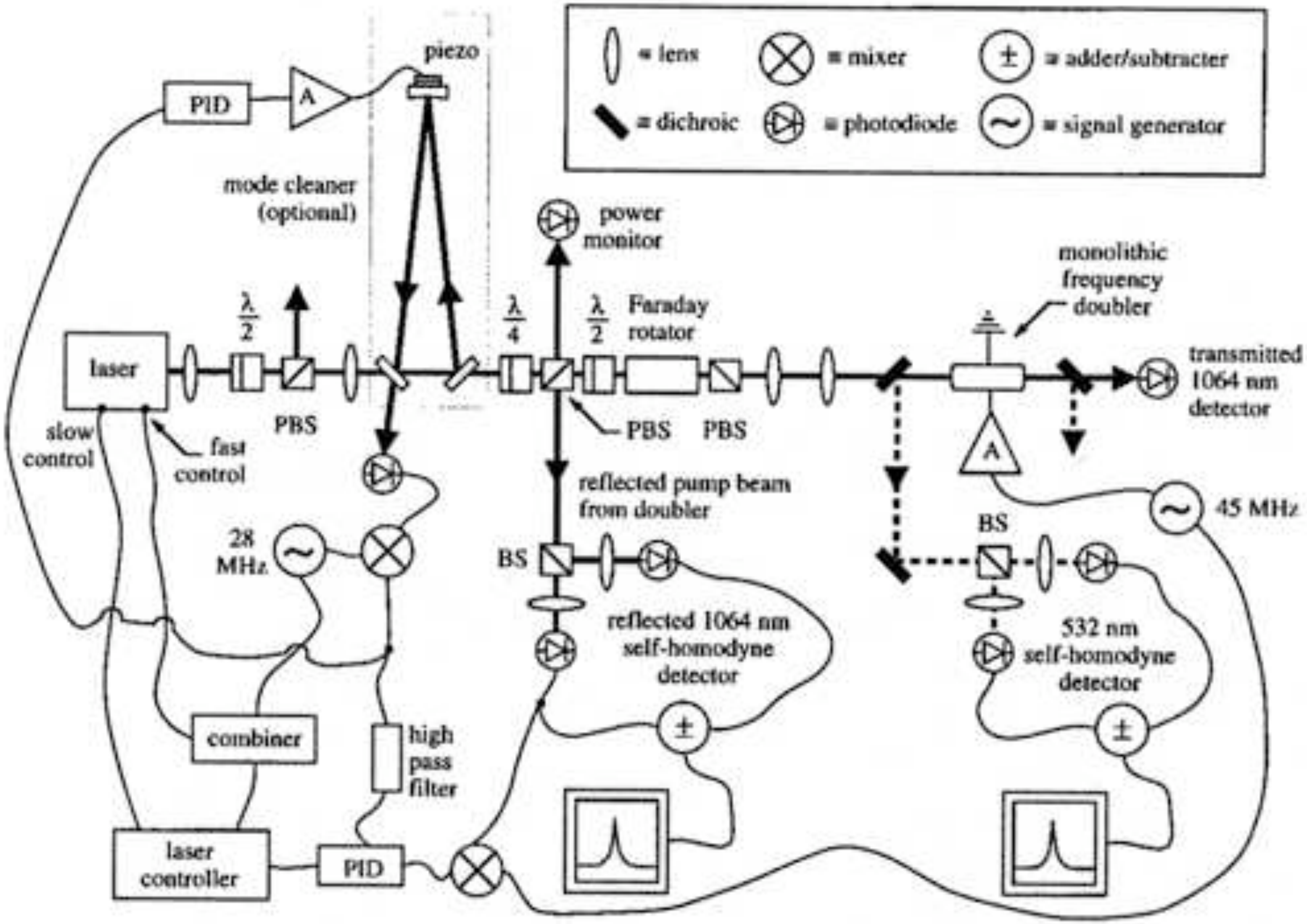


SHG results

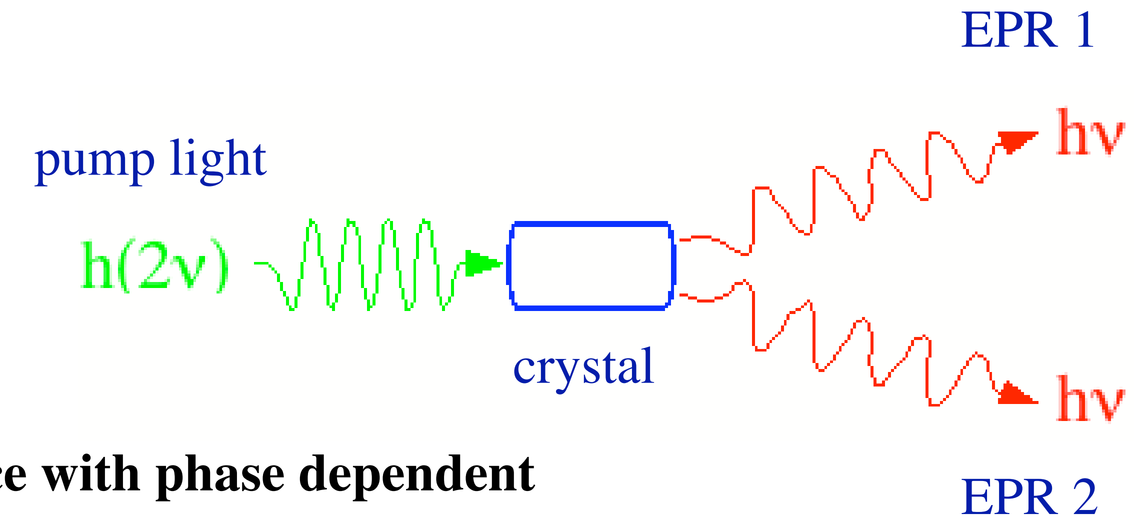


(a) theory (b) experiment **no mode cleaner**
(c) theory (d) experiment **with mode cleaner**

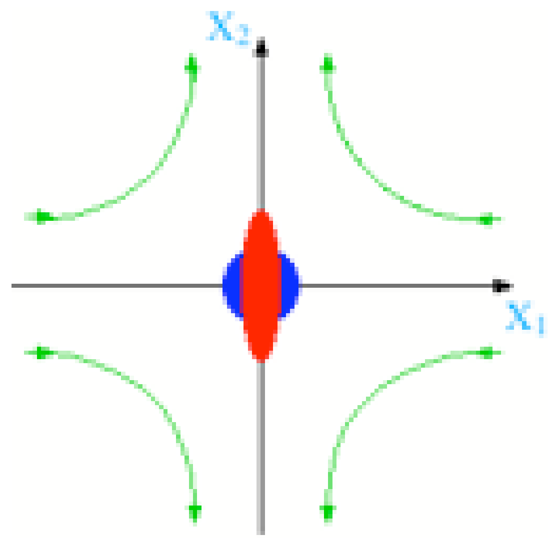
Details of the SHG experiment



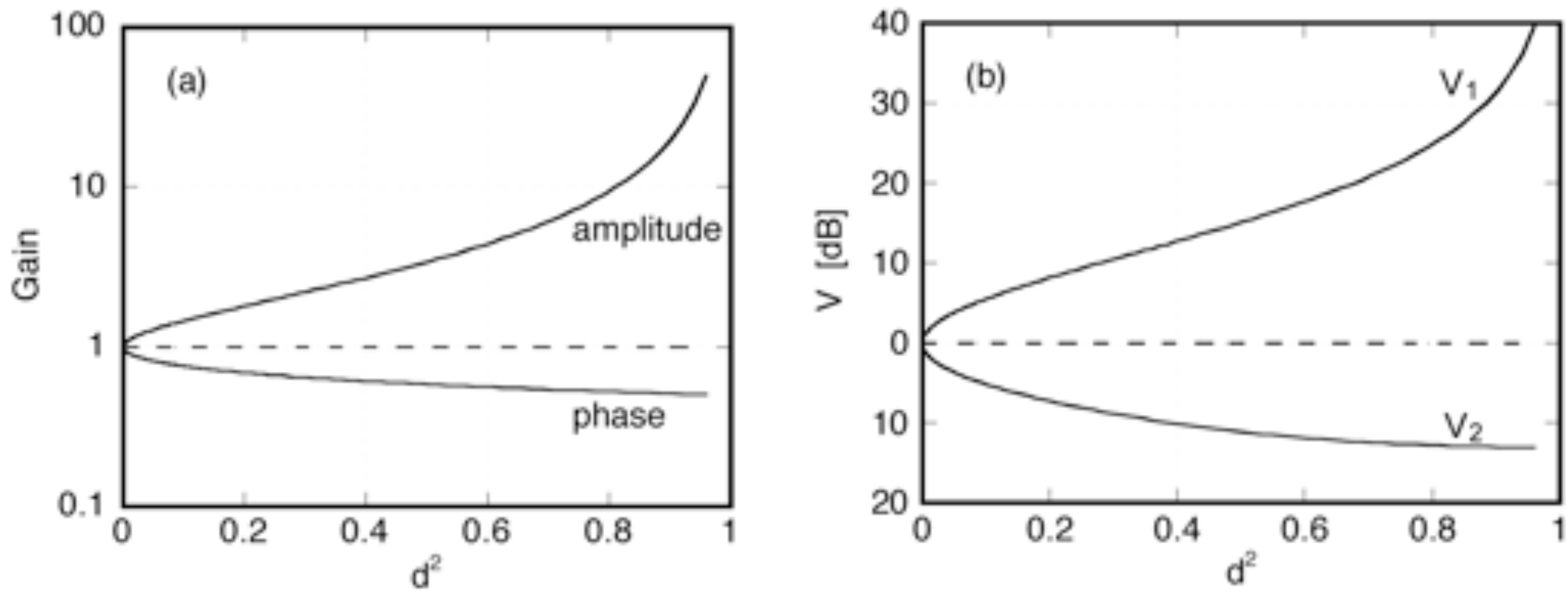
The principle of the OPO



- **A device with phase dependent gain.**
- **When vacuum fluctuation is in phase with the pump, it is amplified.**
- **When vacuum fluctuation is out-of-phase with the pump, it is de-amplified.**
- **It works even with a vacuum seed.**

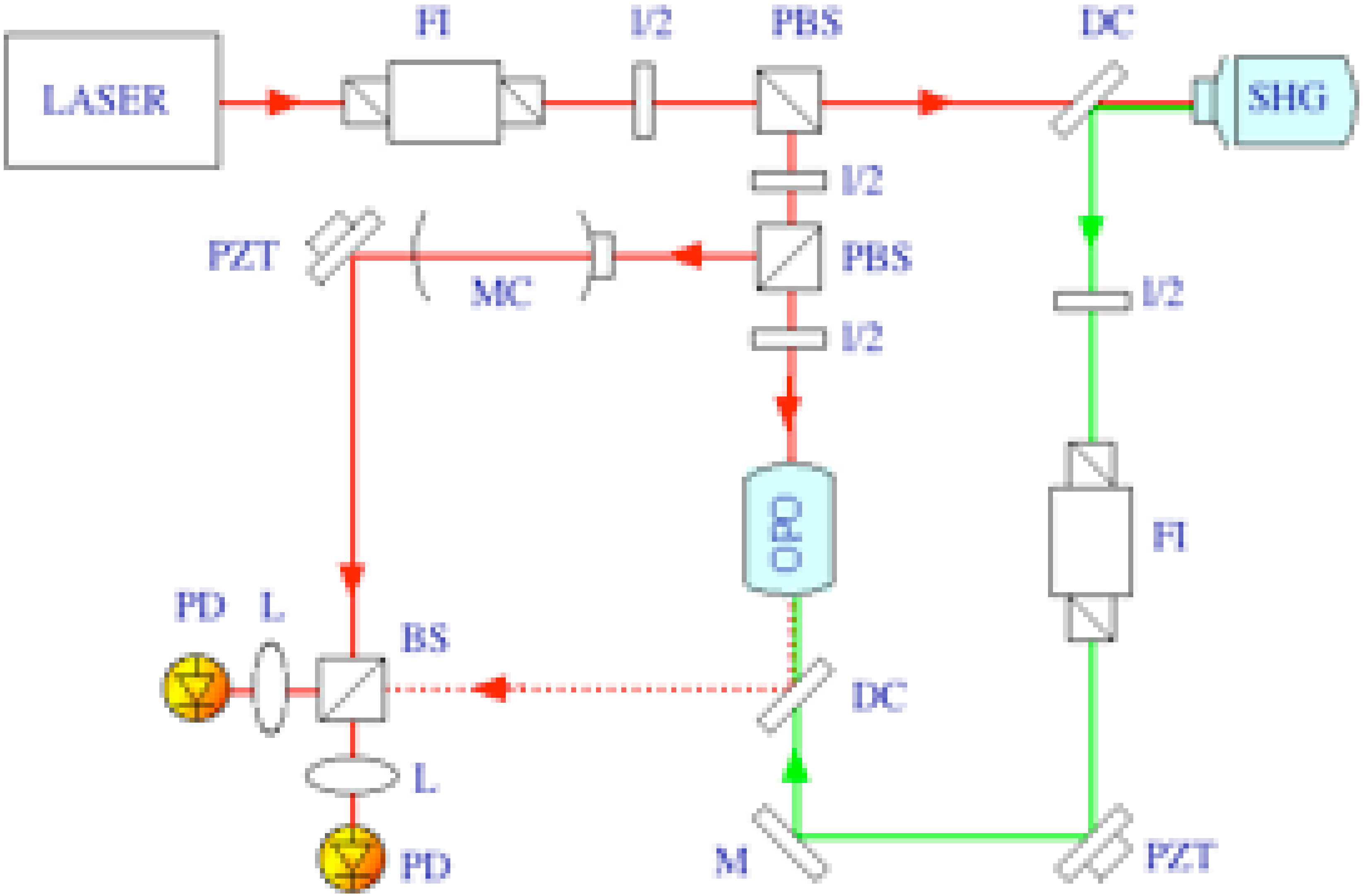


OPO squeezing



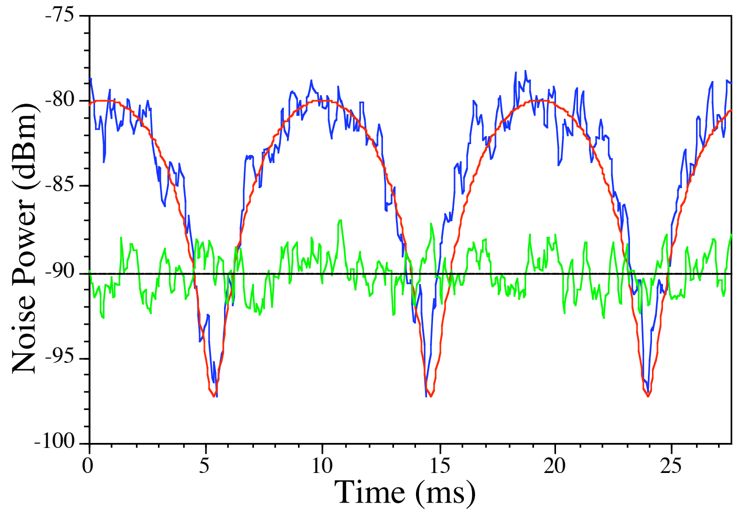
$$V2(\Omega) = 1- \ \eta\, 4\, d \,/\, [\, (1+d)^2 + (2\, \pi\, \Omega\,)^2]$$

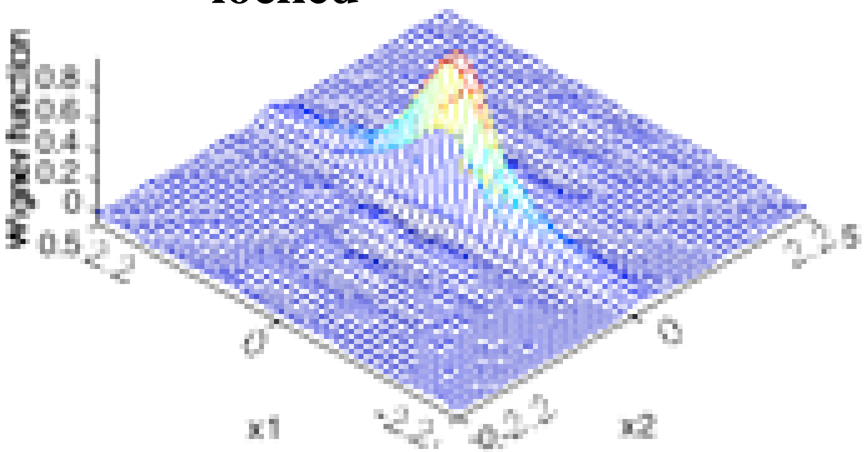
The experimental layout



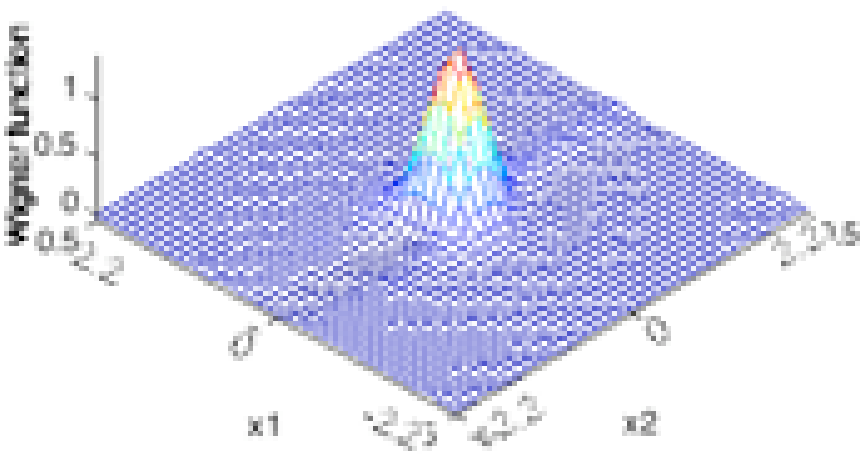
Results from OPO squeezing

- **Quieter than vacuum!!**
- **80% (7 dB) noise reduction for a few ms.**
- **72% (5.5 dB) noise reduction when locked**



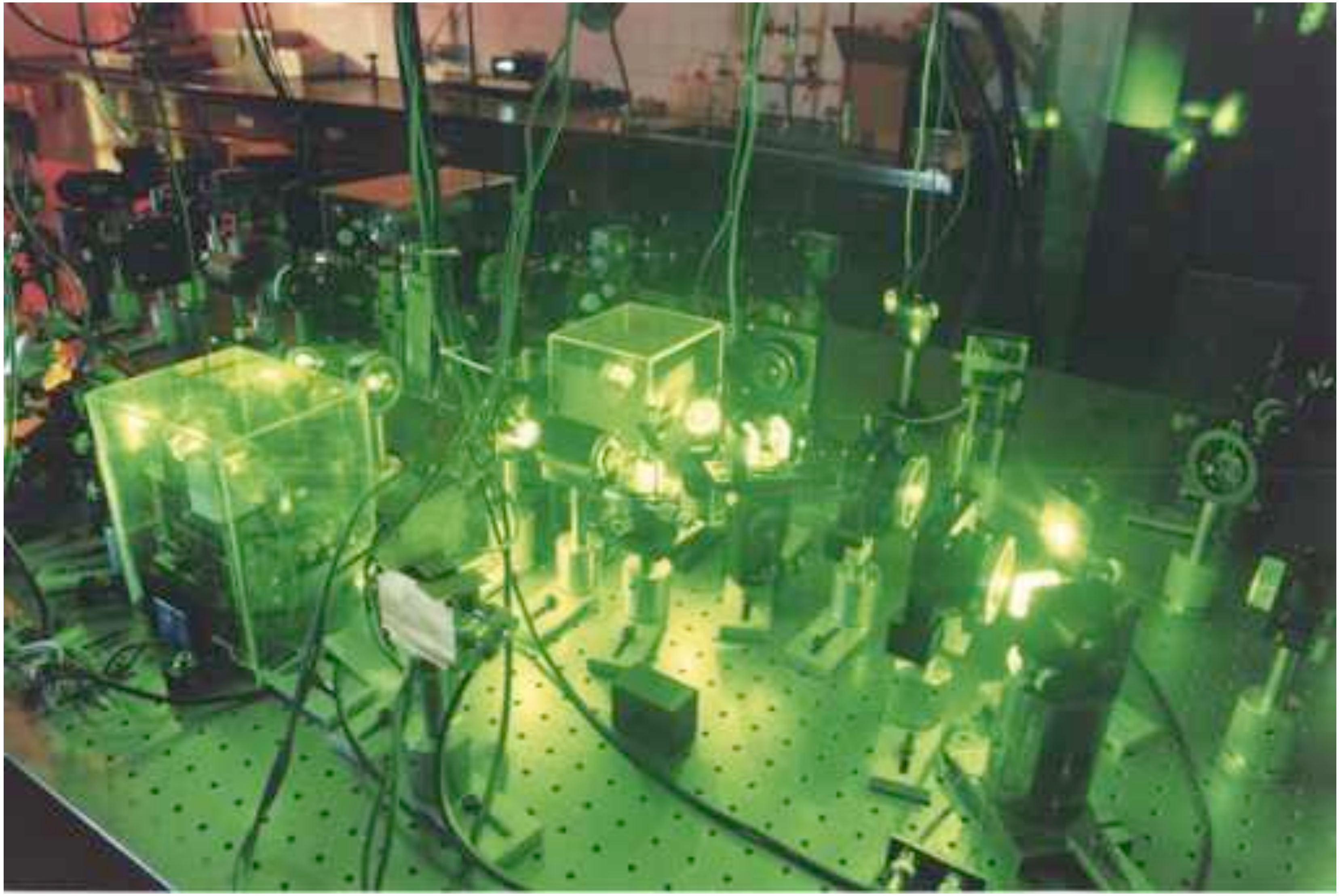


squeezed vacuum



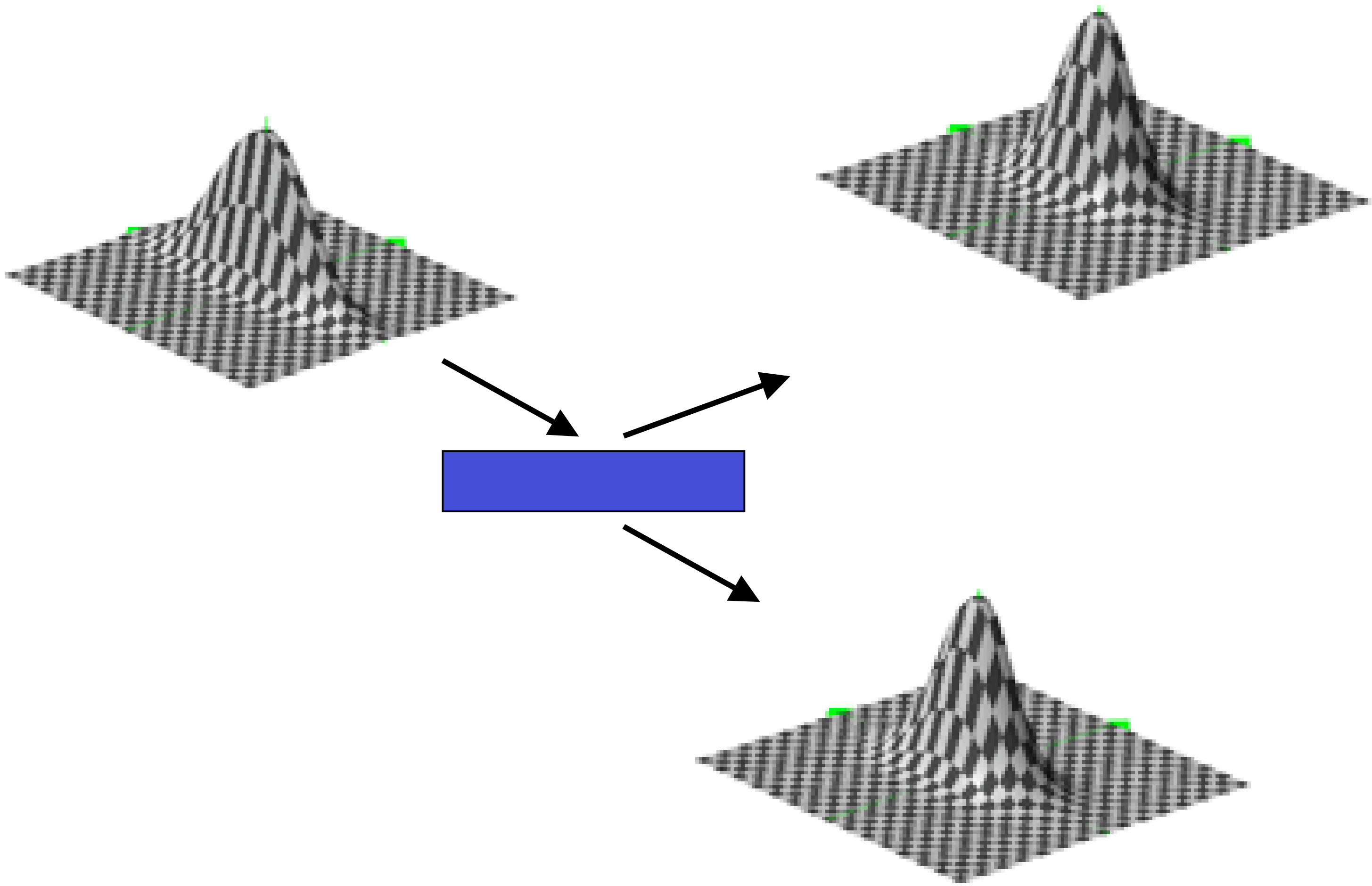
vacuum

A complete experiment

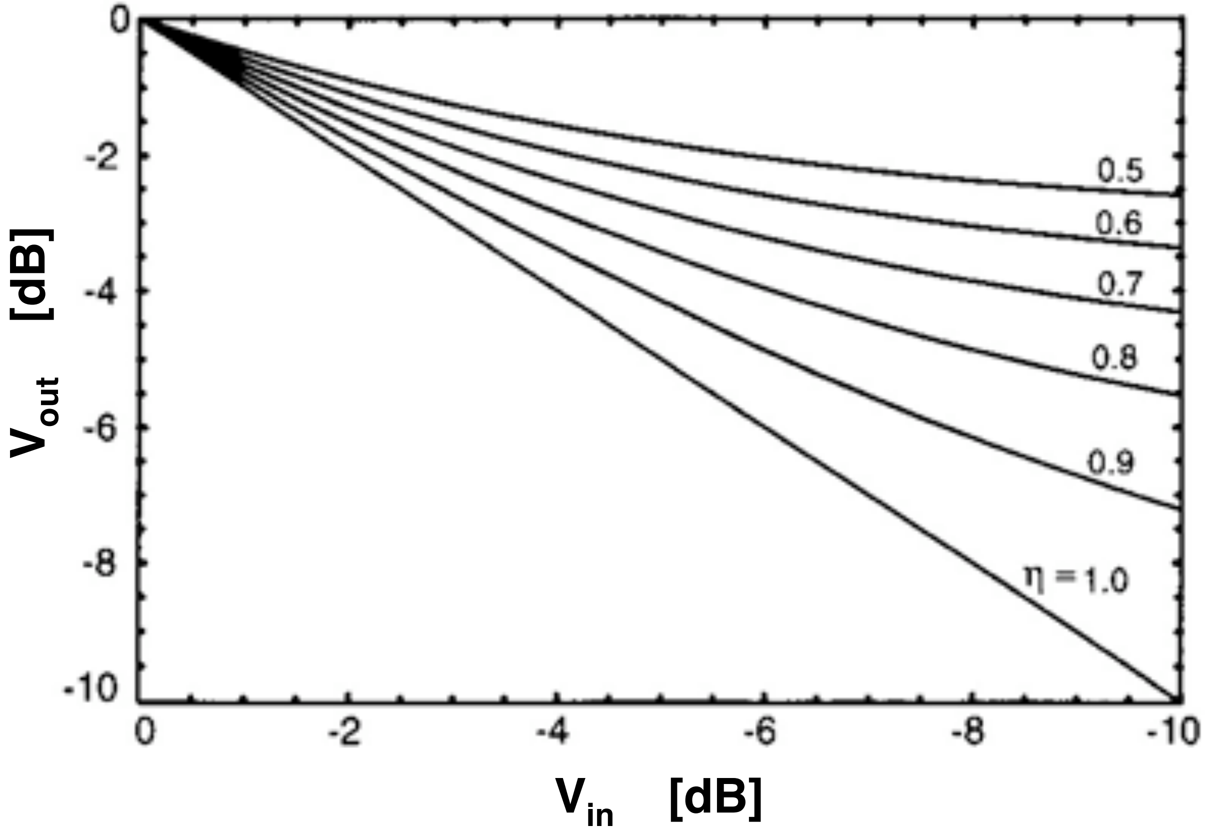


Example : Squeezing experiment at ANU P.K.Lam et al.

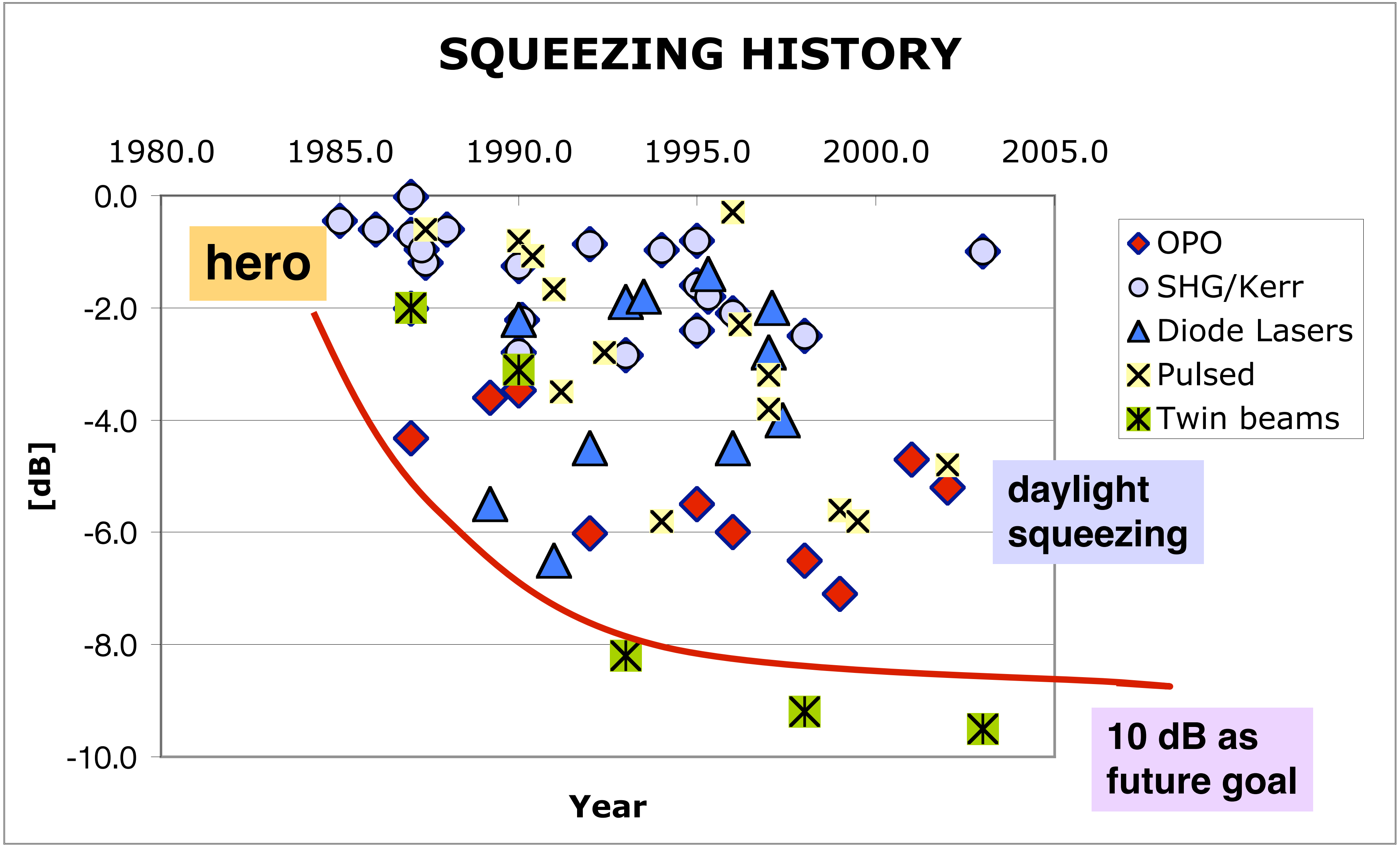
Effect of a beam splitter on squeezed light



Quantitative effect of loss

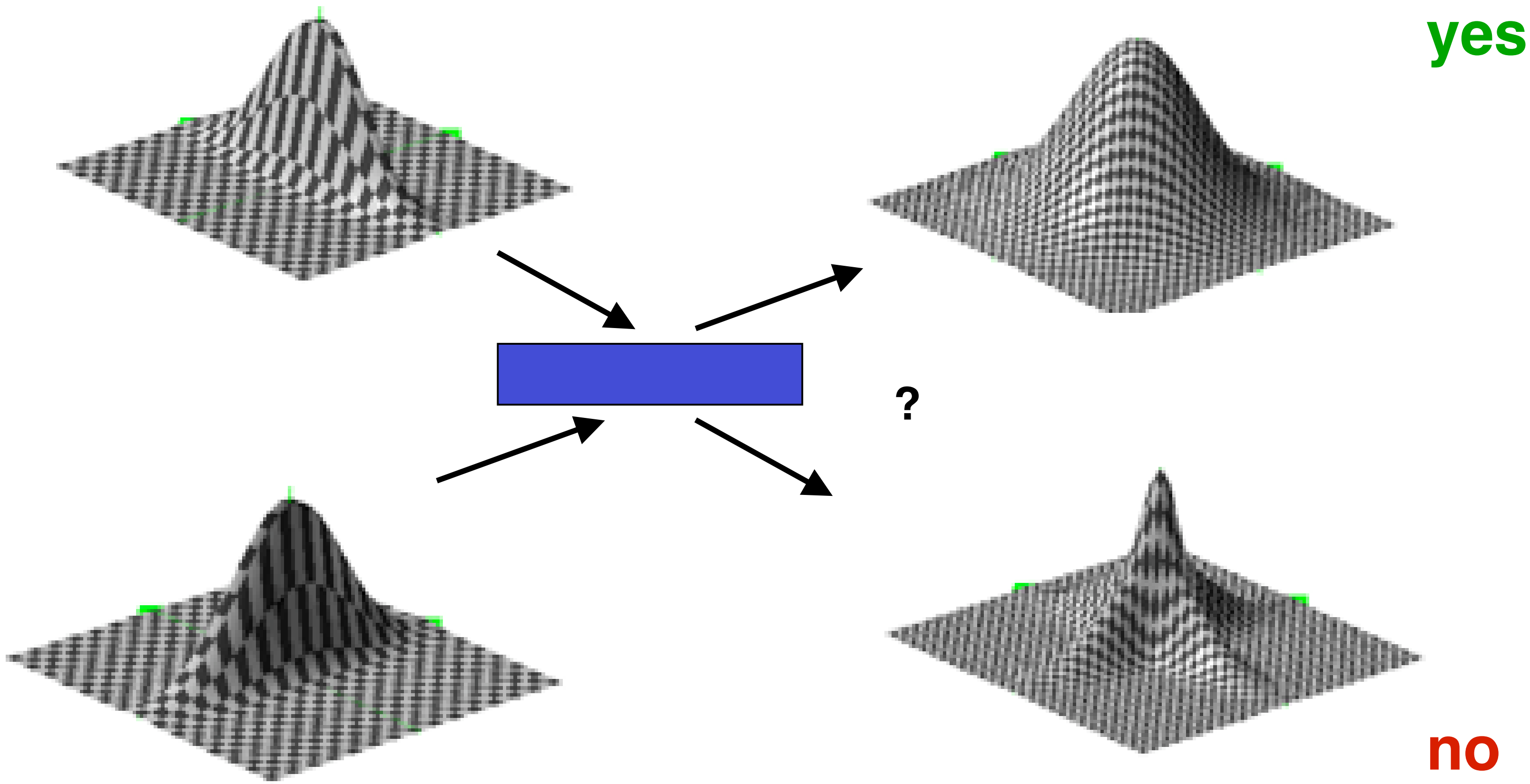


The quantitative effect of efficiencies h on the minimum variance. The squeezing values V_{in} and V_{out} are given in [dB], which is defined as 10 log (V). Deep squeezing is very sensitive to any losses.



SQUEEZING HISTORY
1980.0
1985.0
1990.0
1995.0
2000.0
2005.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
[dB]
Year
hero
daylight squeezing
10 dB as future goal
OPO
SHG/Kerr
Diode Lasers
Pulsed
Twin beams

Effect of a beam splitter on squeezed light?



Quantum Optics 1. level

Photon statistics	Quantum Noise limit QNL
Arrival times	Quantum noise in photo current
Poissonian Bunching Anti-bunching	Limit to signal to noise ratio SNR reduces with power
<u>Application :</u> Q. - cryptography	Limits to opt. Instruments (shot noise limit)