Quantum correlations in twin beams of light

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"twin beam" correlations

Quantum correlations play an important role in the field of quantum optics (and in many other areas, like cold atom studies).

A very particular part of this field concerns "twin beams" of light – two beams that have correlations that are stronger than "classical" physics allows. Such beams require nonlinear processes to generate these correlations and there are a number of ways in which we can try to measure the correlations.

This is not a universally useful set of things to know…

On the other hand, understanding correlations in this context is useful in many other situations as well!

5 lectures on correlations in twin beams

We will discuss what twin beams are, how to generate twin beams, and how to characterize them.

Because I have worked with nonlinear optics, and in particular, 4-wave mixing in Rb vapors, that is what you will mostly get for examples.

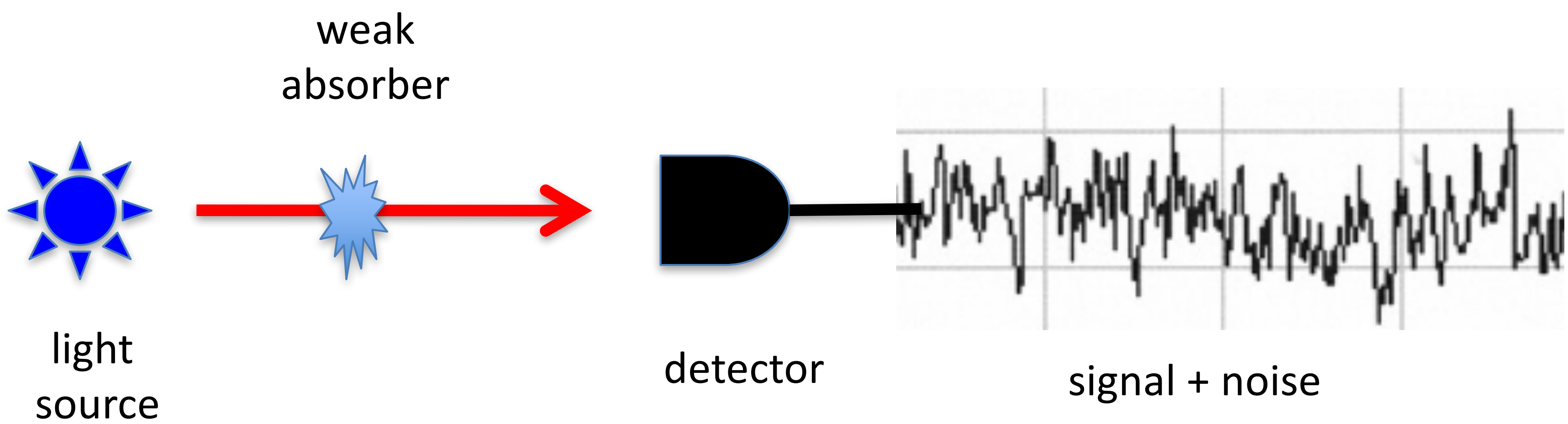
As we go you will see more complex (interesting?) examples of how twin beams are used, in interferometry, for example, and we can discuss how "twin beams" of atoms can be produced via 4-wave mixing in atoms.

You are invited to dream up even more interesting ideas!

Lecture 1 outline

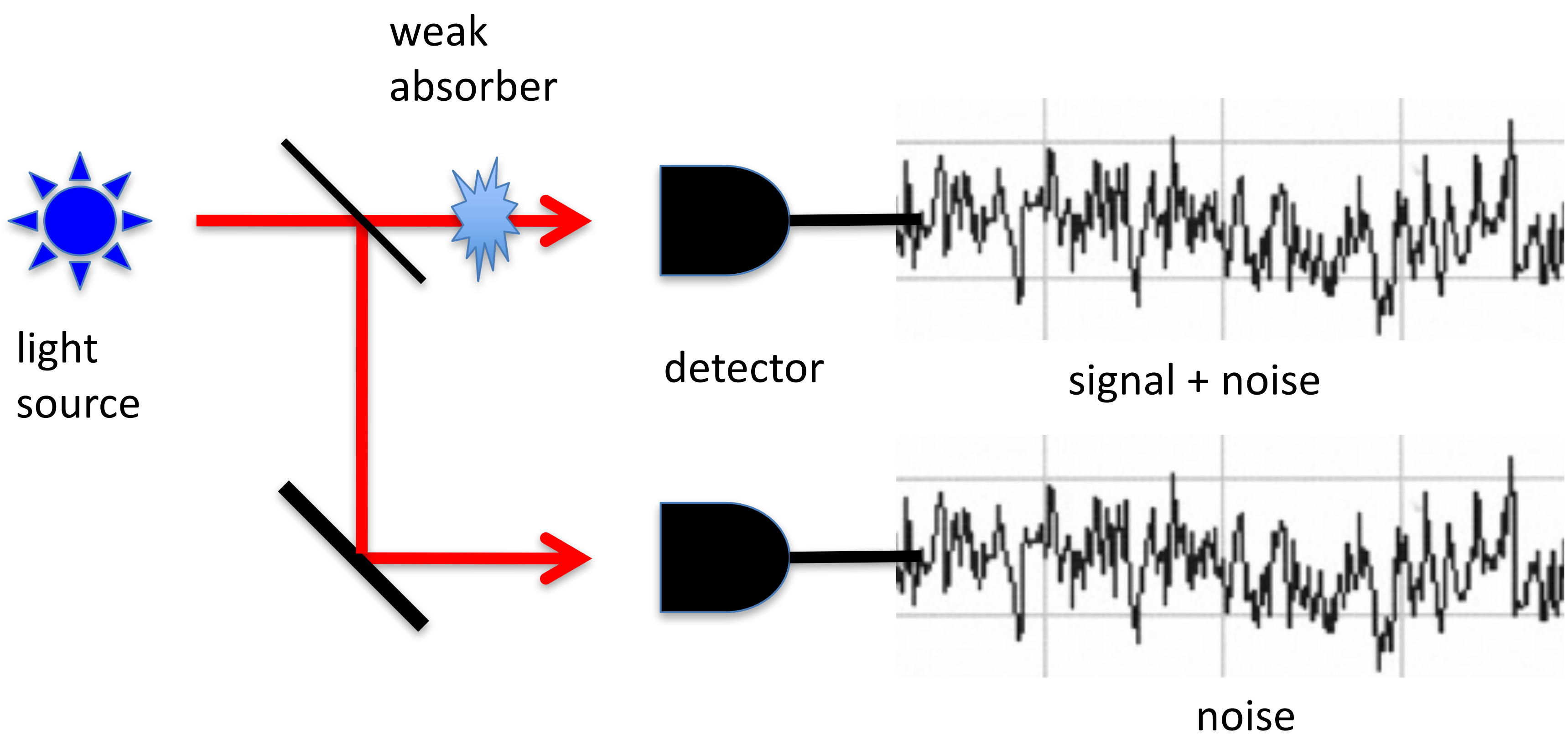
nonlinear optics
generating twin beams
    4WM as well as PDC
squeezed light (single mode)
2-mode squeezing versus multi-spatial-mode 2-mode squeezing
noise
measuring noise/squeezing
homodyne detection

making use of correlations



A weak signal, buried in noise, is hard to detect.

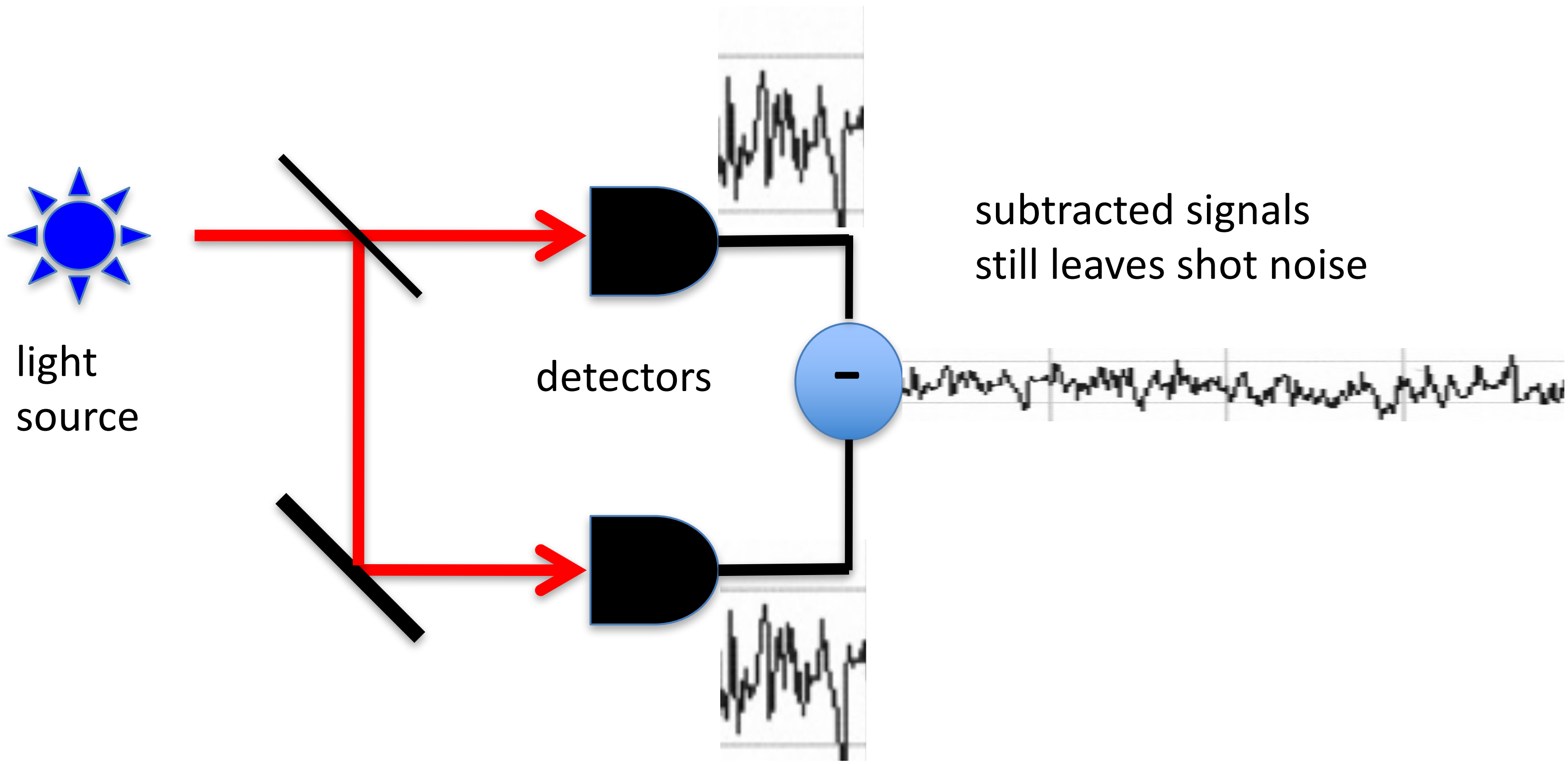
the advantage of classical correlations



If we *exactly duplicate* the fluctuating probe,
then subtract the noise,

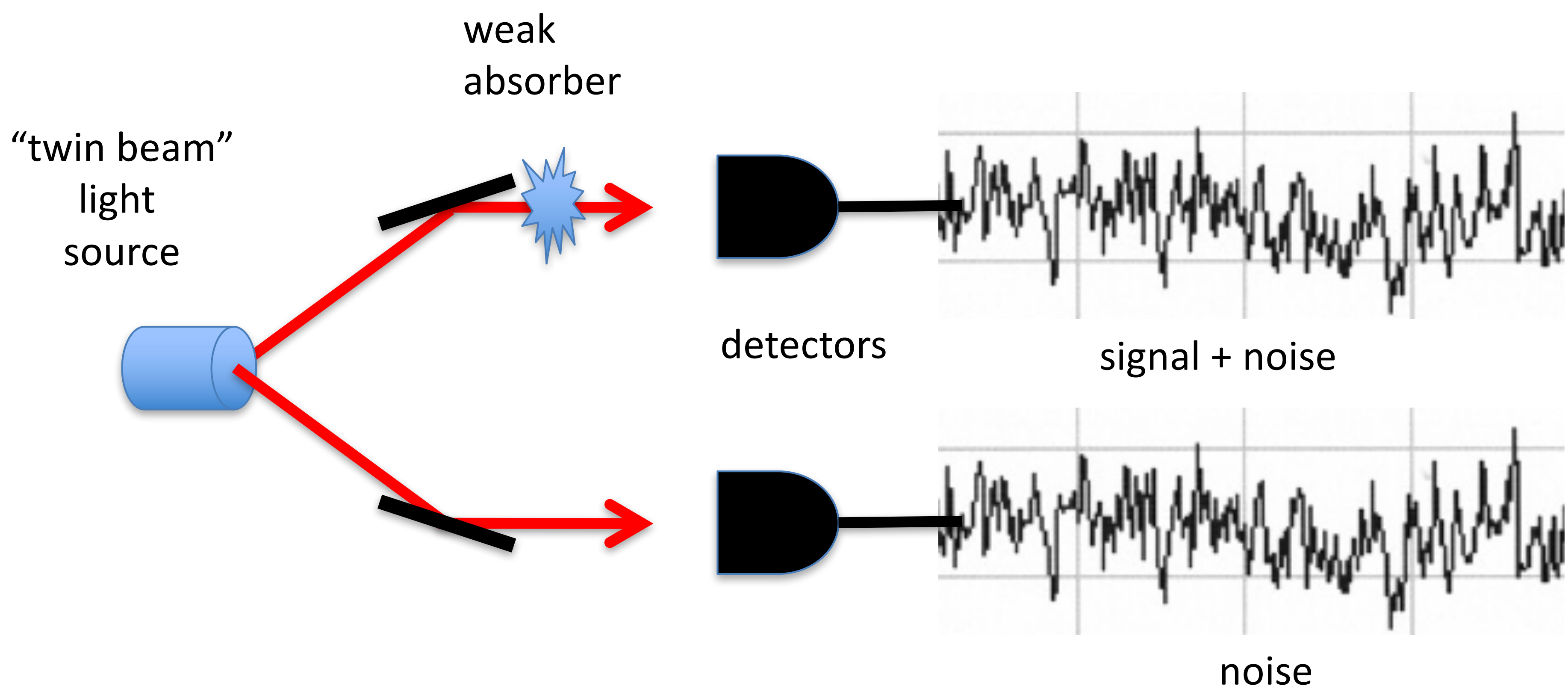
it is easier to detect the signal.

the PROBLEM of classical correlations



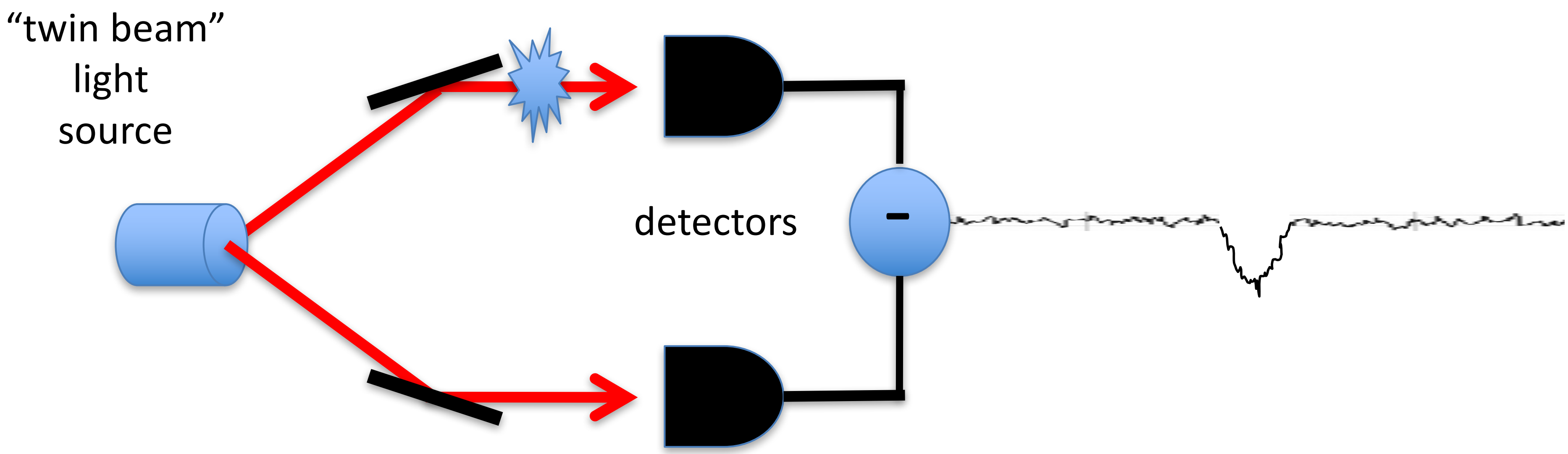
A beamsplitter or half-silvered mirror can "duplicate" only the classical noise on the beam; the "shot noise" due to photons "randomly deciding" which way to go is uncorrelated and adds.

the advantage of quantum correlations



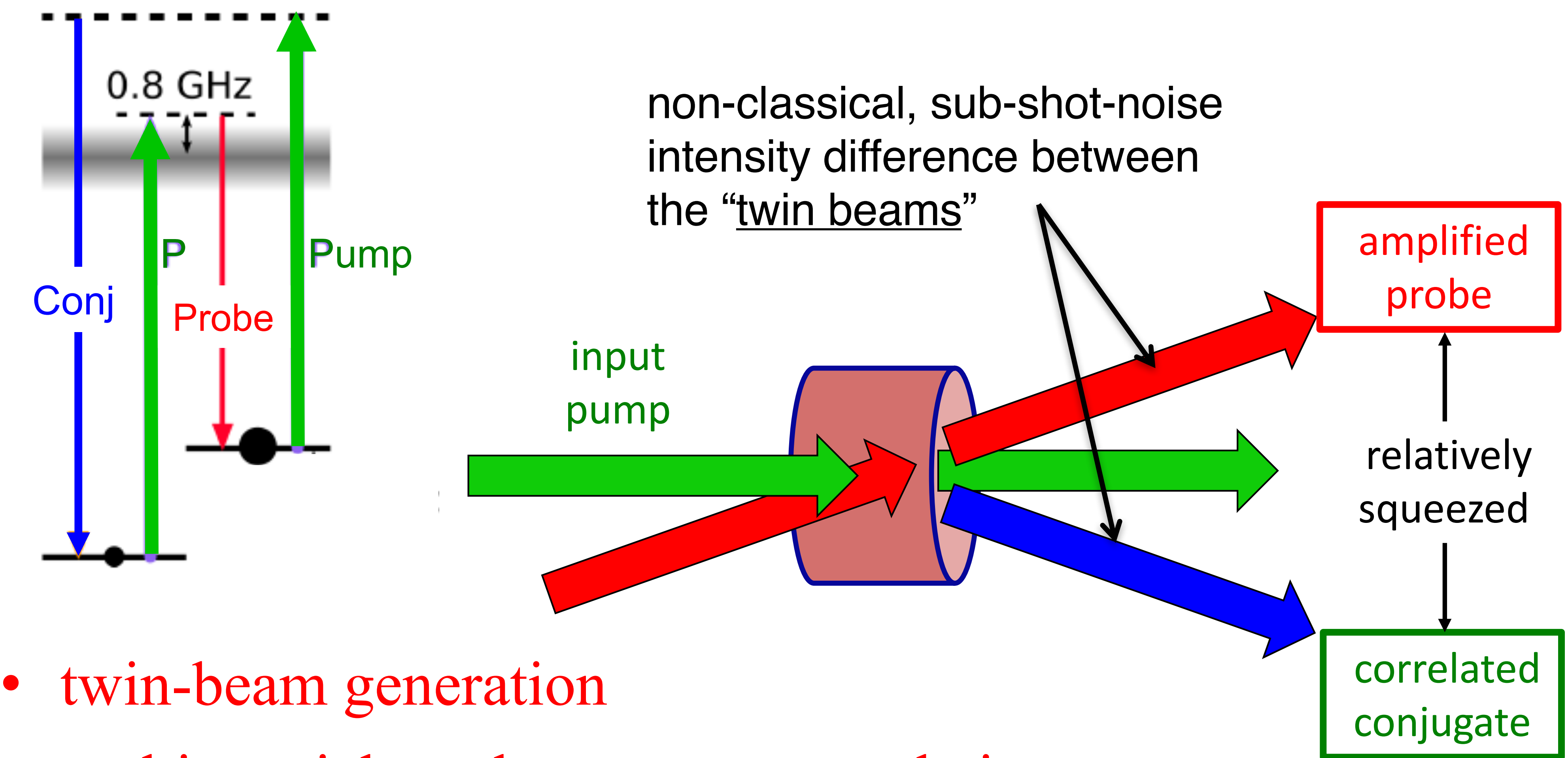
If we duplicate the fluctuating probe, *including* its quantum noise, then subtract, it is even easier to detect the signal.

the advantage of quantum correlations



A "twin beam" squeezed-light source will duplicate the fluctuating probe, including any quantum noise. Thus we can subtract even the quantum noise, and detect previously undetectable signals.

4-Wave-Mixing in the quantum limit

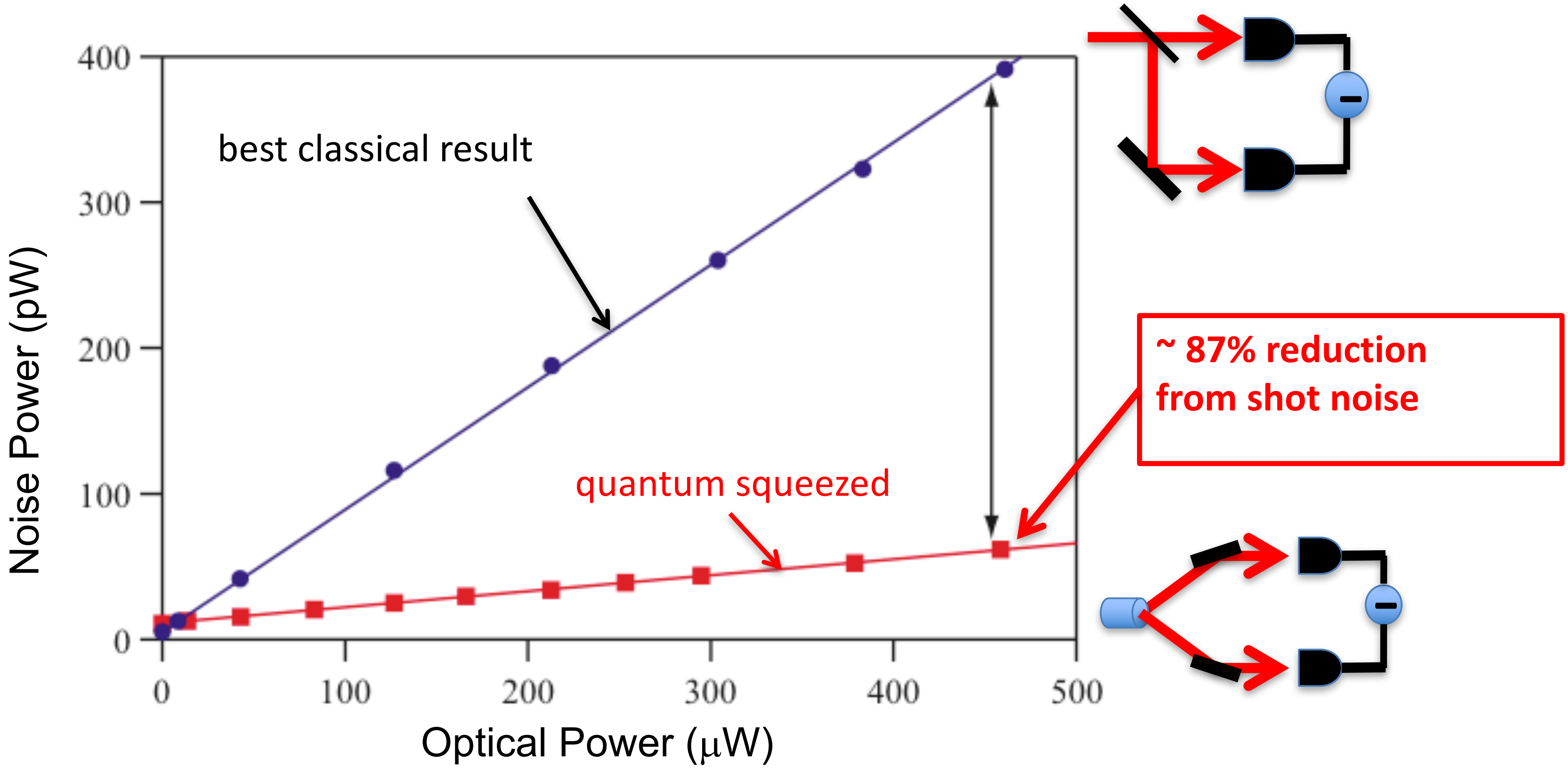


- twin-beam generation
- multi-spatial-mode quantum correlations (quantum imaging)
- acts as a phase insensitive amplifier (PIA)

The heart of the experiment

This inexpensive, low-tech device helps produce cutting-edge quantum squeezed light!

twin-beam squeezing



photodiode difference measurement shows intensity-difference squeezing

how do quantum correlations help?

It allows us to avoid some of the limitations of classical light on resolution and noise in optical systems.

It is useful in position sensing, interferometry, and image processing.

How do we get quantum correlations?

nonlinear optics

- frequency converter:

  couple 3 optical fields to make a 4th:

  $$E_4 = \chi^{(3)} E_1 E_2 E_3$$

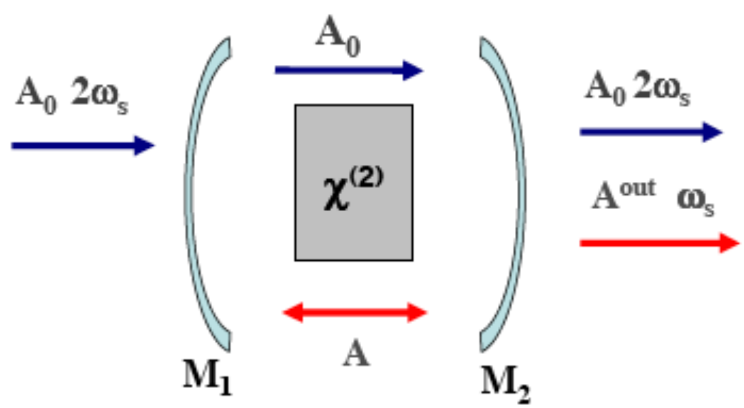
- requires that energy and momentum are conserved between input and output

  energy: $\omega_1 + \omega_2 = \omega_3 + \omega_4$

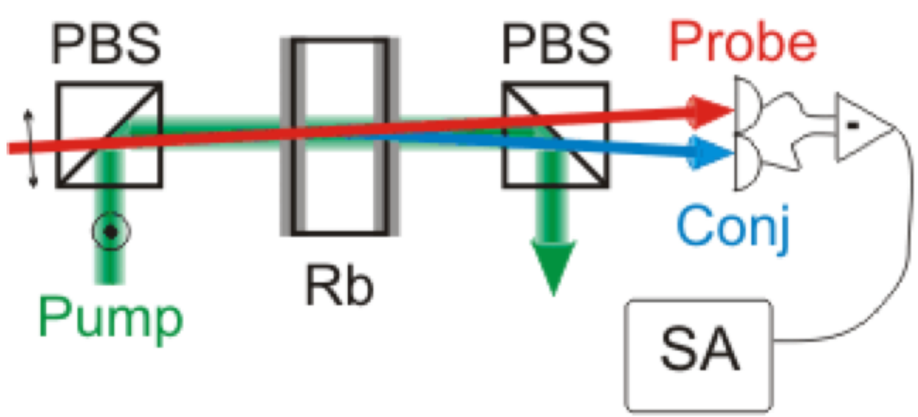
  momentum: $k_1 + k_2 = k_3 + k_4$

If we are careful about how we do it, inserting 3 fields gets us a 4th with some "magic" properties

4wm vs. OPOs ...or... $\chi^{(3)}$ vs $\chi^{(2)}$ media



OPO
(optical
parametric
oscillator)



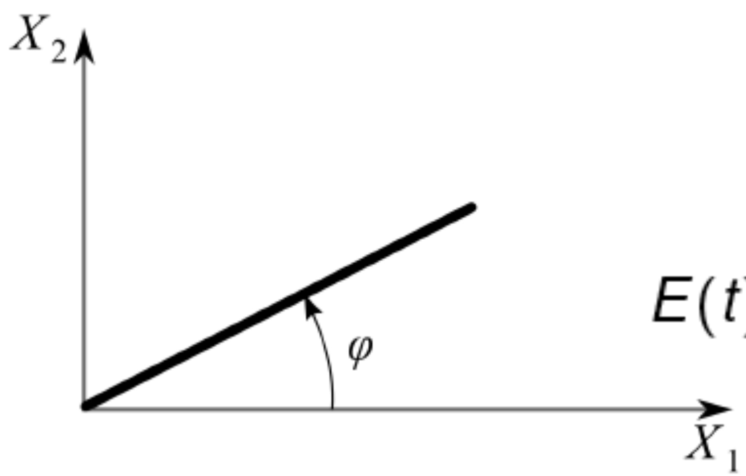
four-wave mixing (4WM)
(count 2 pump photons in
the 4 waves!)

photon correlations vs. squeezing

PDC is often generated with low efficiency and so "digital" single-photon correlations are studied. Properties such as the polarization are often the most important.

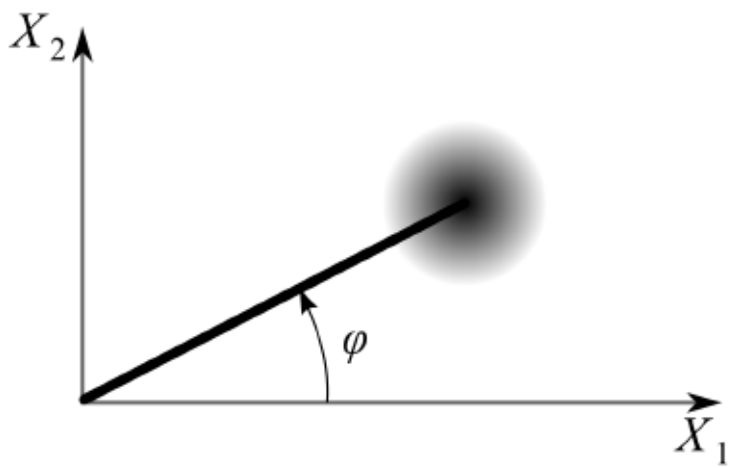
4WM usually has a much stronger nonlinearity and the light produced is often at a high enough intensity that a continuous variable description ("squeezed light") is more appropriate. Often continuous parameters such as the phase of the beam are important.

light



amplitude and phase
or
quadratures

$$E(t) \propto X_1 \cos(\omega t) + X_2 sin(\omega t)$$



quantum version
with noise

coherent states have
minimum-sized,
round fuzz-ball

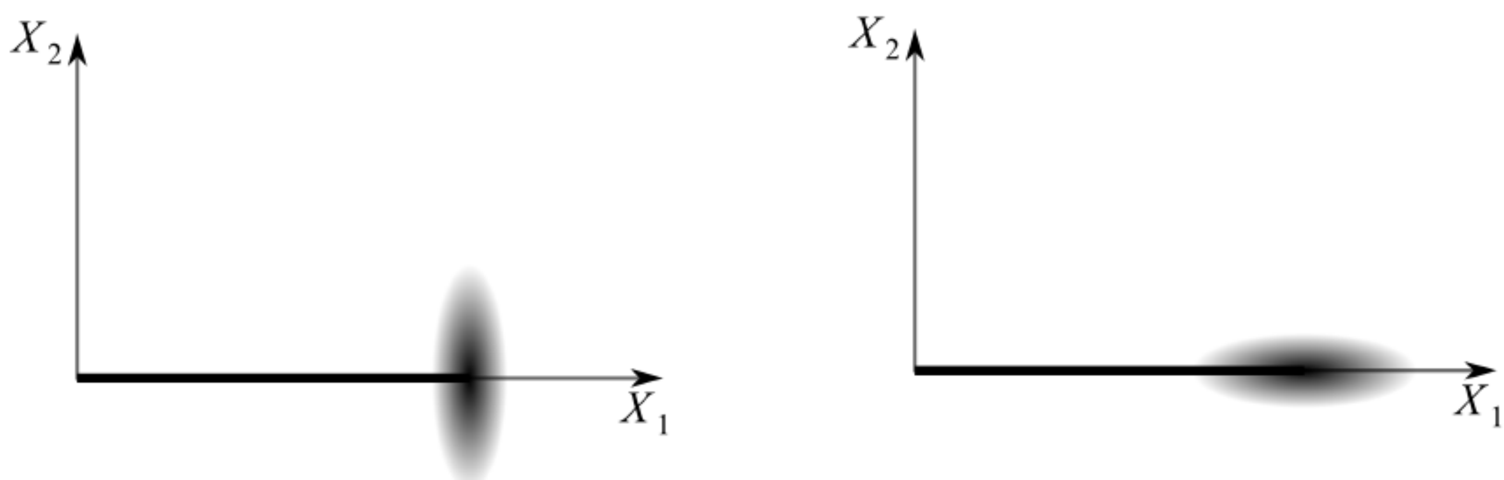
squeezed light

what does it mean for light to be "squeezed"?

classical fields have symmetric noise

amplitude

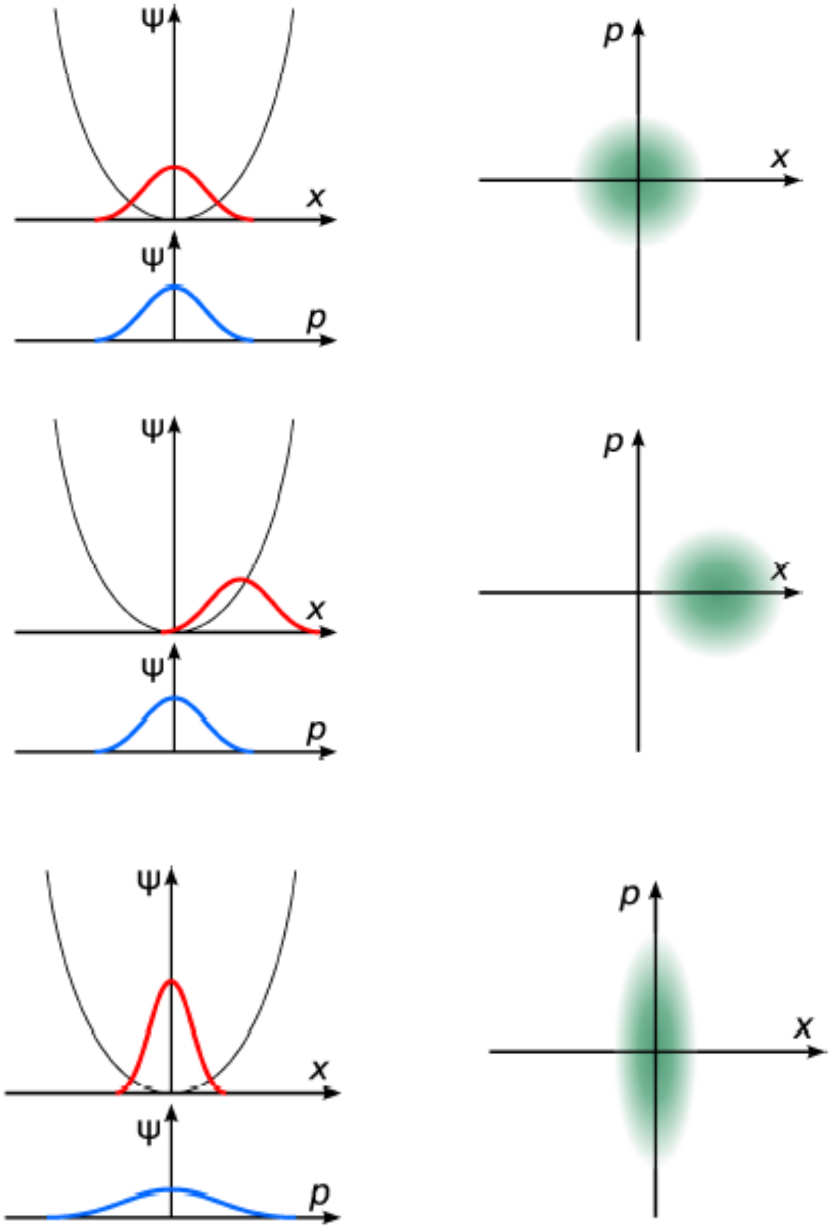
phase



- different kinds of squeezing:
- amplitude/phase or quadrature

$$E(t) \propto X_1 \cos(\omega t) + X_2 sin(\omega t)$$

Single-mode squeezing

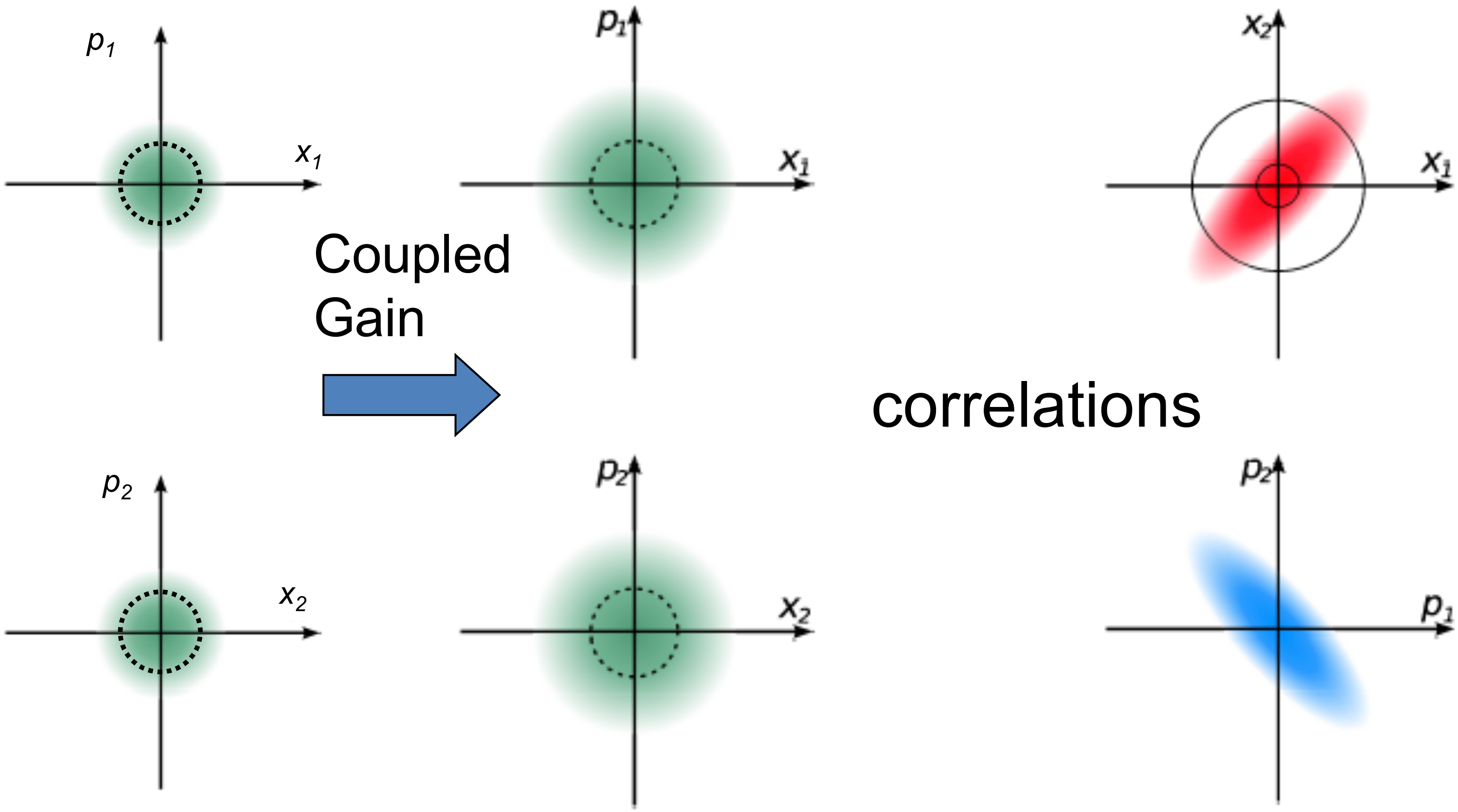


- Mode of frequency $\omega \equiv$ harmonic oscillator of frequency ω
- $$\hat{x} \to \hat{X}$$ $$\hat{p} \to \hat{Y}$$ with the rotation taken out
- Coherent state: $$\langle \Delta \hat{X}^2 \rangle = 1$$ $$\langle \Delta \hat{Y}^2 \rangle = 1$$
- Squeezing: $$\langle \Delta \hat{X}^2 \rangle < 1$$ $$\langle \Delta \hat{Y}^2 \rangle > 1$$
- Pairs of photons
- Generalize to bright beam

we will mostly talk about “twin-beam squeezing” and not (single mode) “quadrature squeezing”

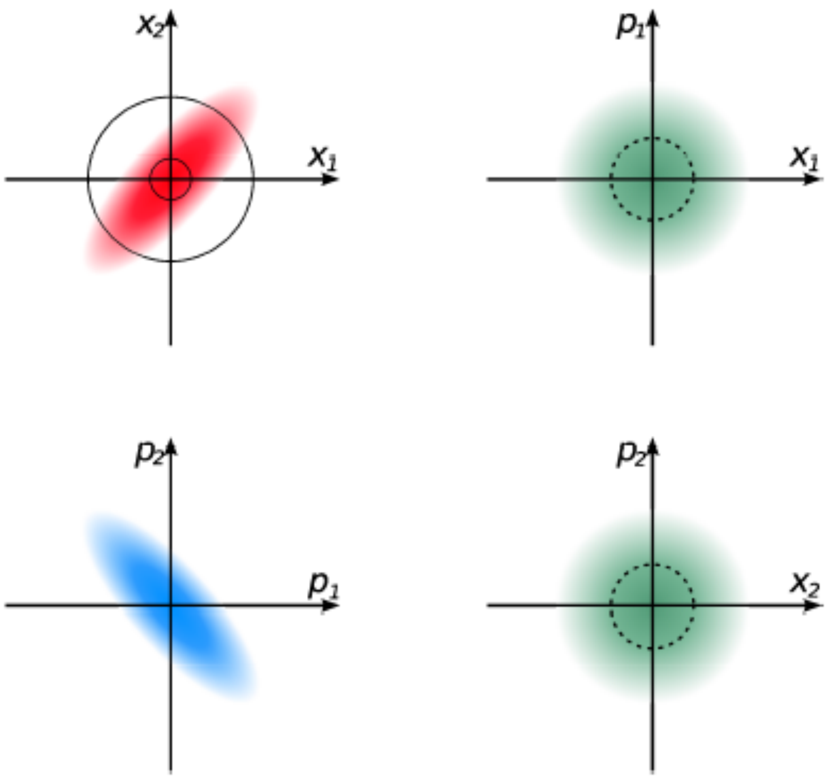
Instead of amplitude and phase of a single beam, the interesting variables here are the intensity difference and the phase sum of these “twin” beams.

Two-mode squeezing: phase-insensitive amplifier



two vacuum modes → two noisy, but entangled, vacuum modes

Squeezing quadratures



- Generalized quadratures:

$$\hat{X}_- = \frac{1}{\sqrt{2}}(\hat{X}_1 - \hat{X}_2)$$
$$\hat{Y}_+ = \frac{1}{\sqrt{2}}(\hat{Y}_1 + \hat{Y}_2)$$

- Squeezing:

$$\langle \Delta \hat{X}_-^2 \rangle < 1$$
$$\langle \Delta \hat{Y}_+^2 \rangle < 1$$

- Individual modes are noisy:

$$\langle \Delta \hat{X}_1^2 \rangle > 1$$
$$\langle \Delta \hat{Y}_1^2 \rangle > 1$$

squeezing light

compare to "shot noise"

if we detect N particles, on average, during a time t,
and the statistics are "random" (Poissonian)
then the standard deviation of the detected number will be $\sqrt{N}$

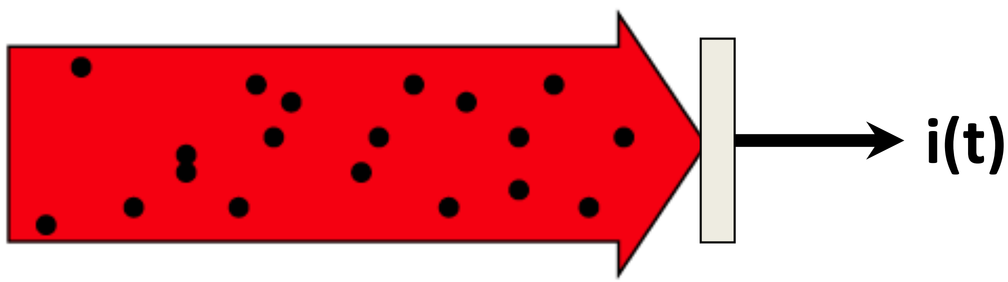
$$\mathrm{Var} = \langle (n - \langle n \rangle)^2 \rangle = \langle (n - N)^2 \rangle = N$$

If the variance is more than that it is "super-Poissonian"
(this is not unusual – "technical noise")

If the variance is less than that it is "sub-Poissonian"
(this is unusual - and is a sign of non-classical effects in light)

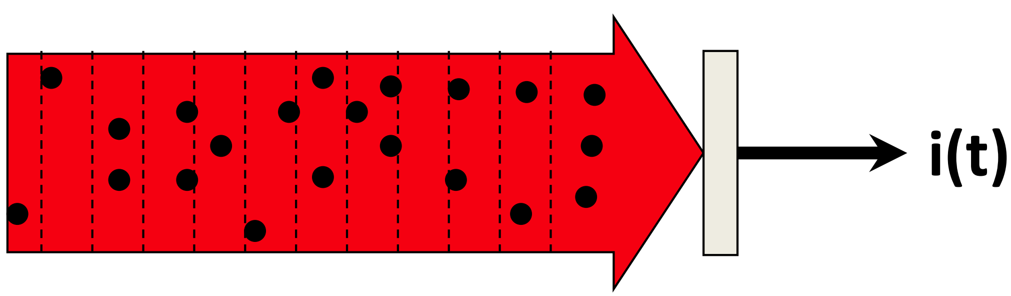
“Normal” squeezing (in time)

classical or coherent light
random arrivals in time and space



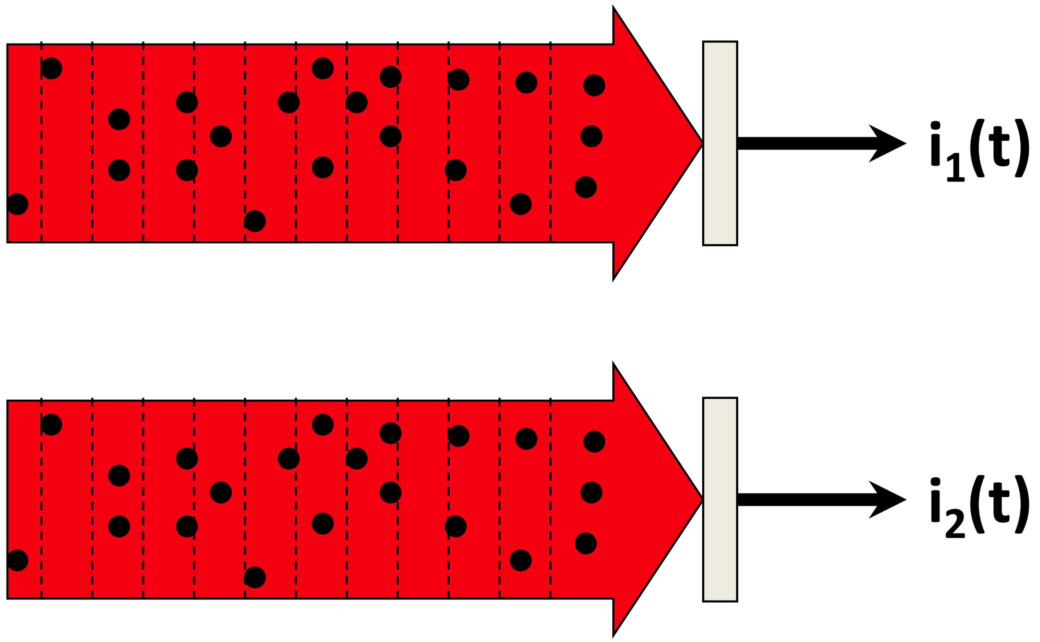
“shot noise”
random in time;
no correlations

squeezing; ordered in time; reduced fluctuations



can be used to reduce noise in measurements

"Twin beam" or relative-intensity squeezing

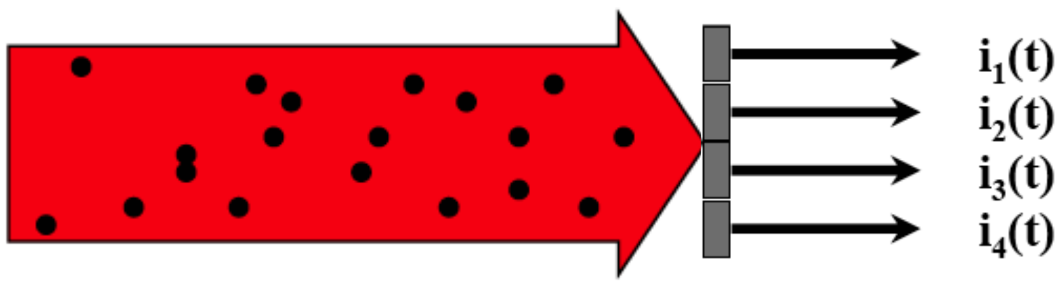


$i_1(t) = i_2(t)$
to better than
"shot noise"
allows

I can't clone a photon, but I can create 2 (nearly) identical photons or beams of them

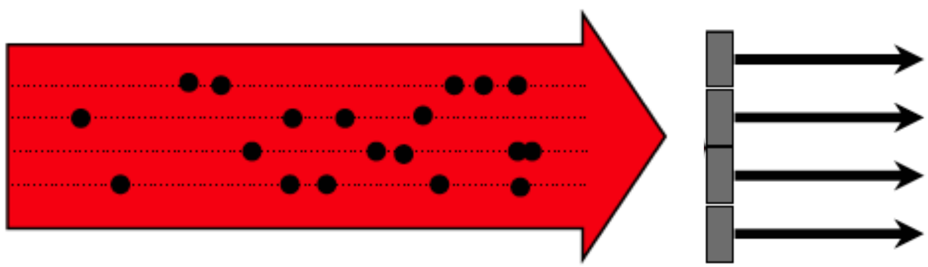
spatial squeezing: “quantum imaging”

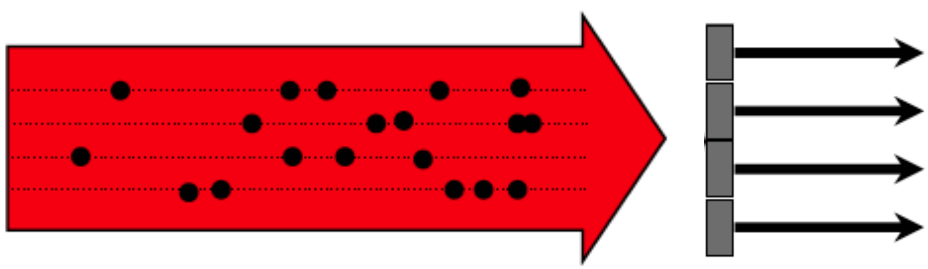
classical or coherent light
random arrivals in time and space



“shot noise” on each pixel
no correlations between pixels

spatial squeezing; ordered in space, correlations between pixels



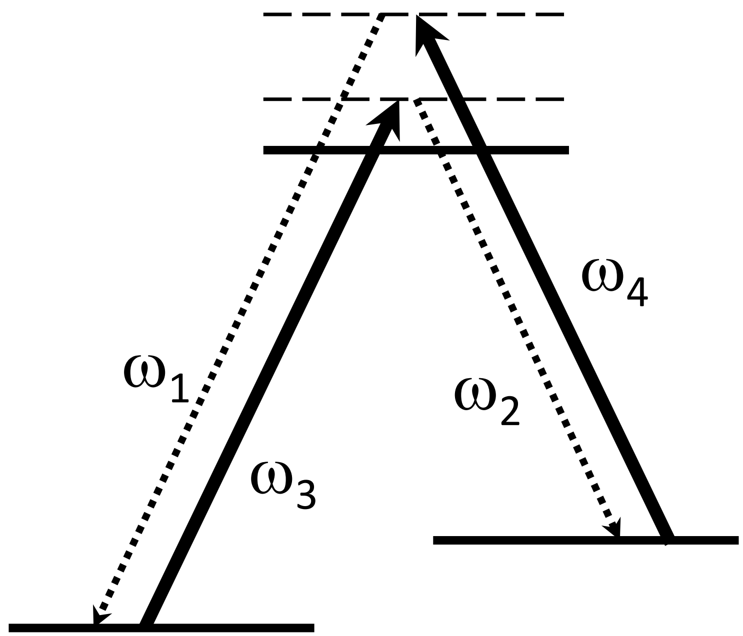


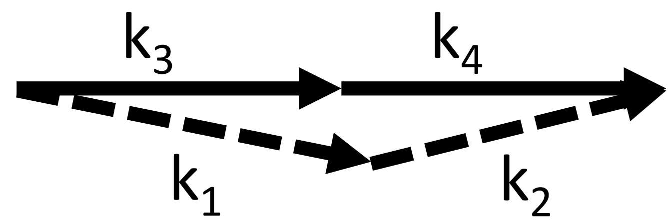
we have both time and spatial squeezing!

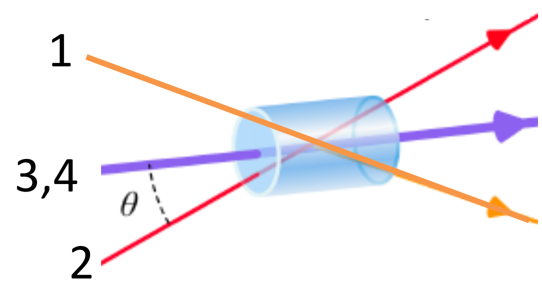
can be used to reduce noise in spatial information

Phase matching

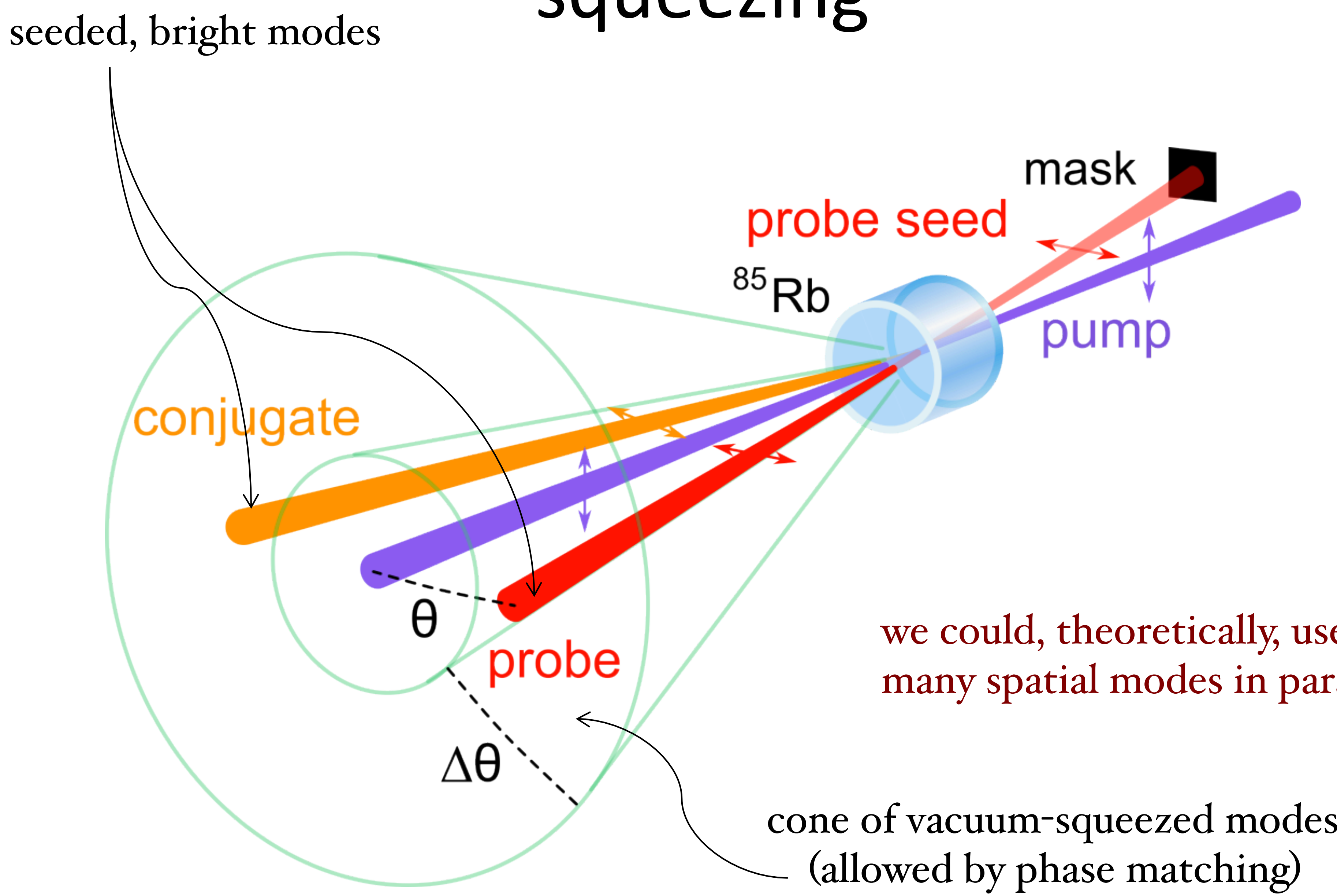
conserve energy: $\omega_1 + \omega_2 = \omega_3 + \omega_4$
conserve momentum: $k_1 + k_2 = k_3 + k_4$







multi-spatial mode two-mode squeezing



we could, theoretically, use many spatial modes in parallel

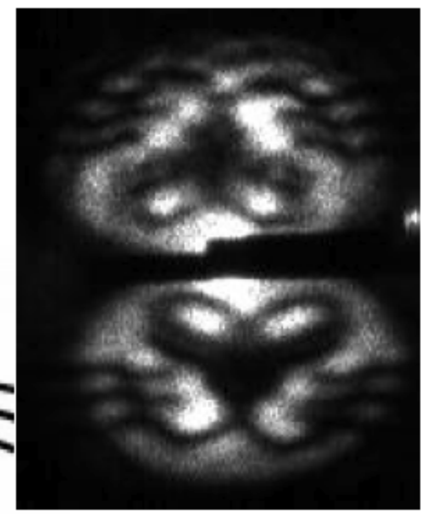
squeezed and entangled cats

Probe LO

Conjugate LO

local oscillators for measurements of 1 dB quadrature squeezed vacuum

squeezed cats



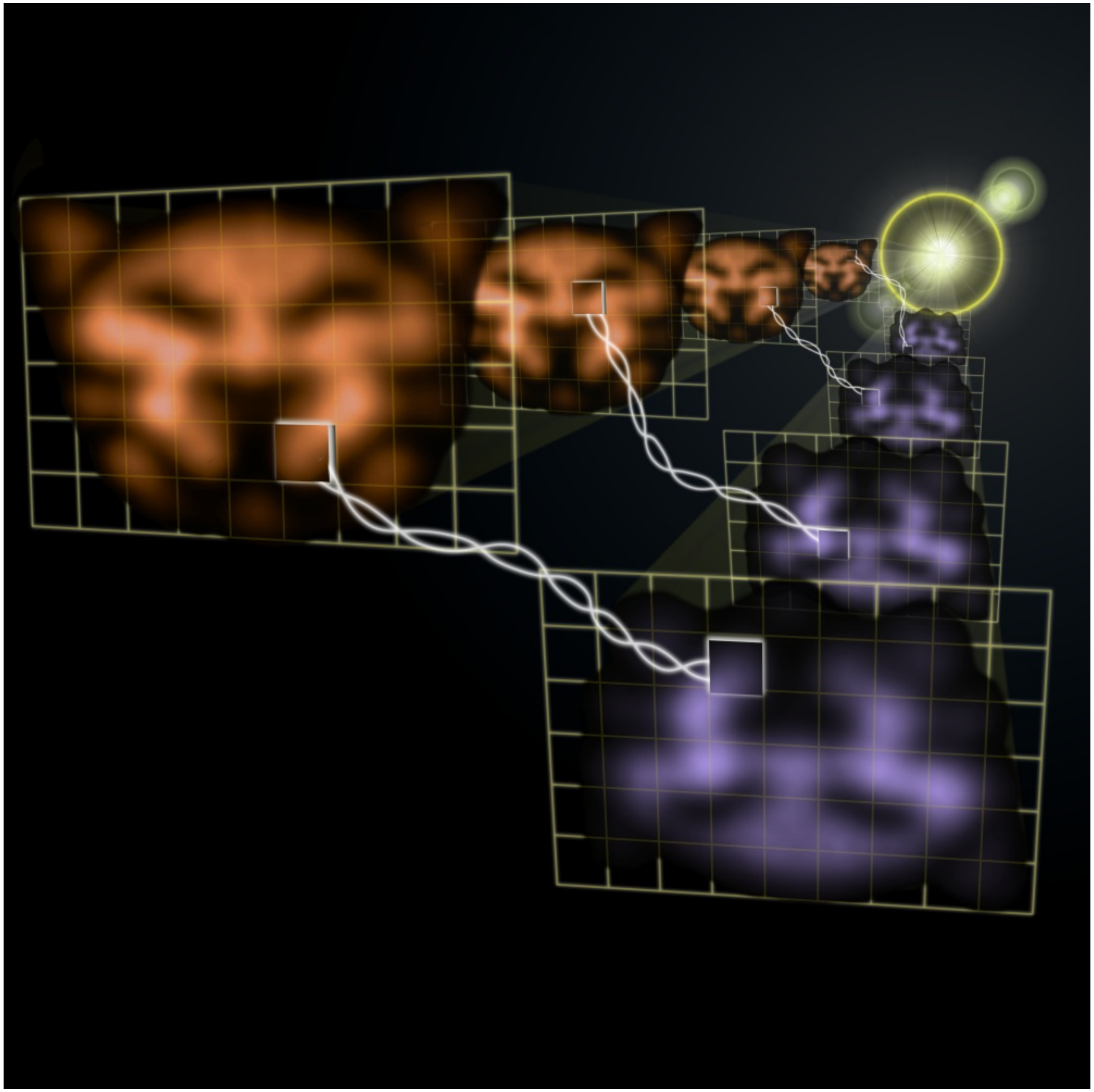
probe

conjugate

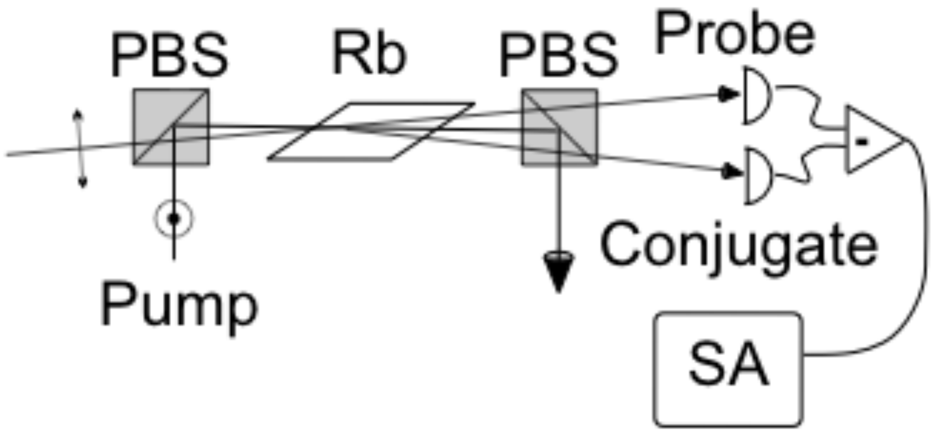
~1 dB “whole image” intensity-difference squeezing

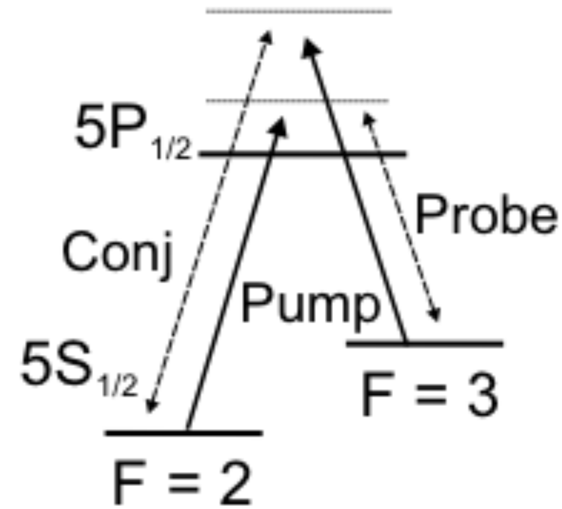
bright beams showing intensity-difference squeezing

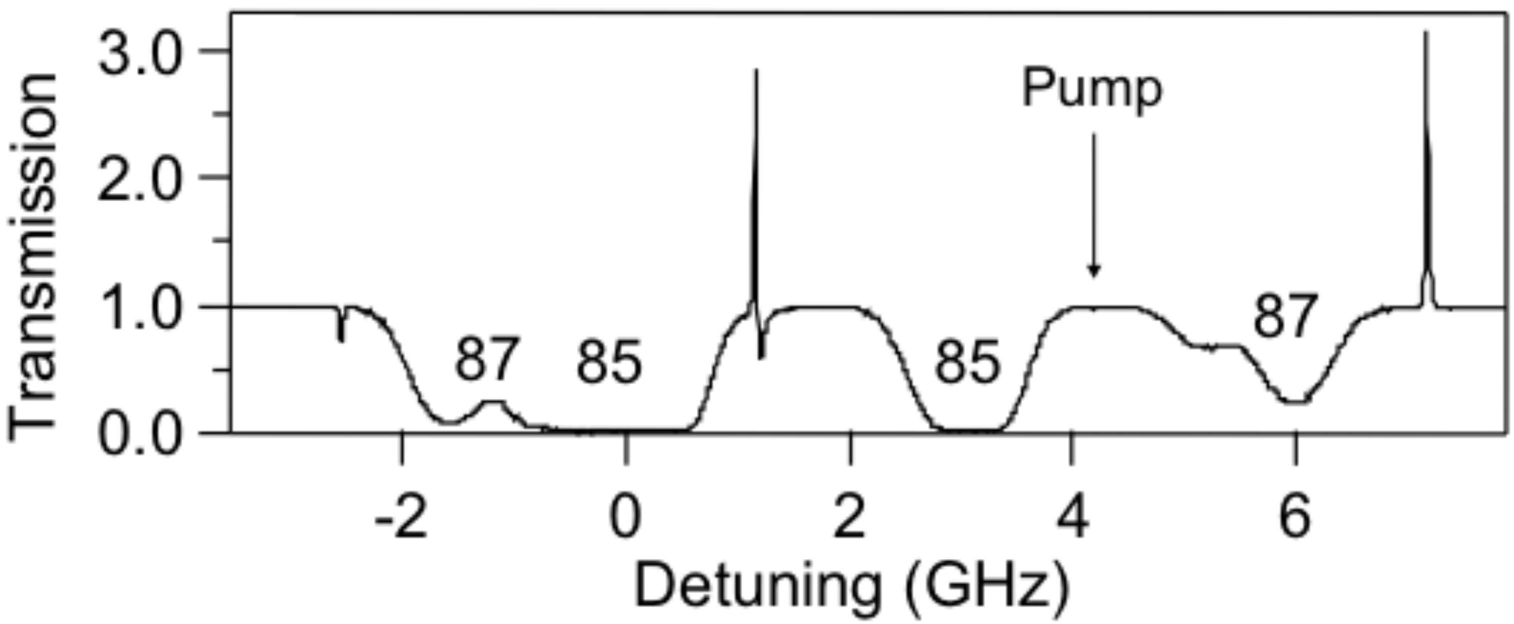
enhanced graphics!



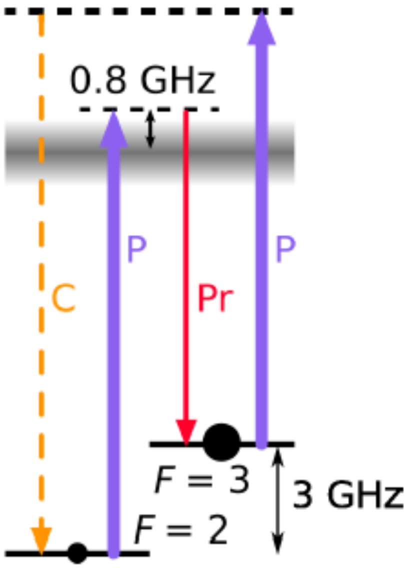
Experimental scheme

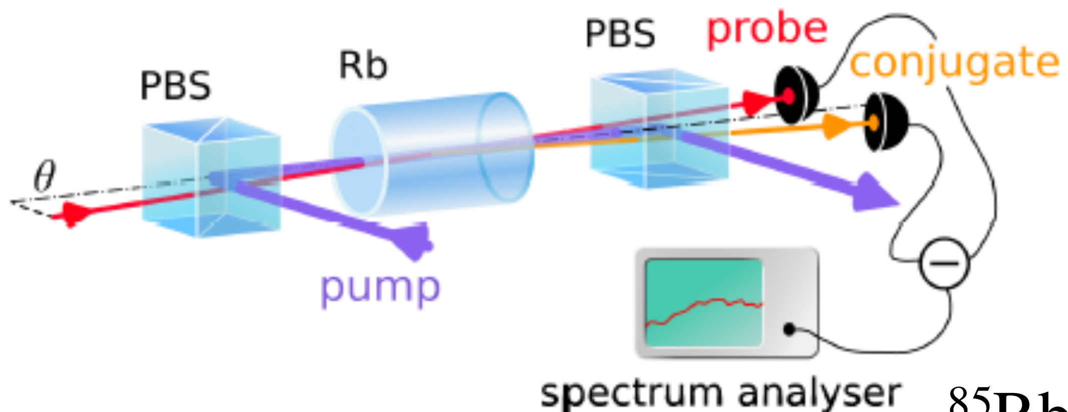


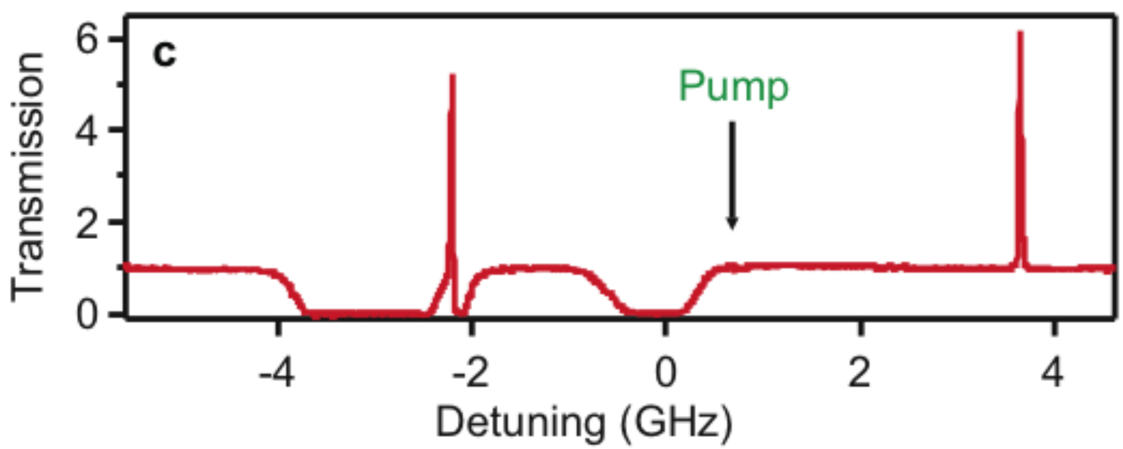




squeezing from 4WM in hot Rb vapor







^{85}Rb in a double-Λ scheme

~1 GHz detuned

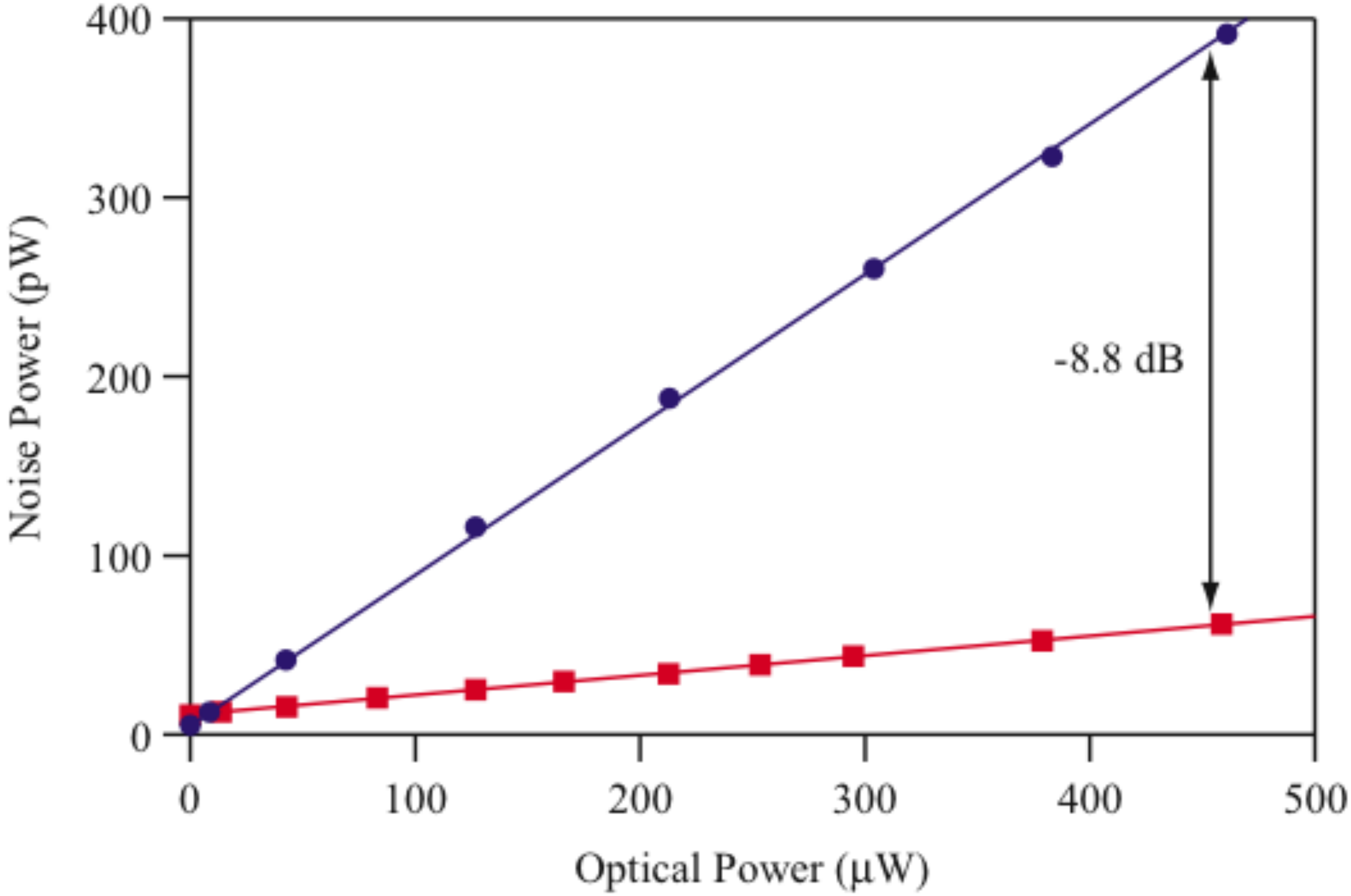
~400 mW pump

~100 μW probe

narrowband

no cavity

strong intensity-difference squeezing measured



1 MHz detection frequency
RBW 30 kHz
VBW 300 Hz
pump detuning 800 MHz
Raman detuning 4 MHz
~95% detector efficiency

noise

- “squeezed light” implies, in some form, reduced fluctuations
- this is usually compared to “shot noise”
- N particles/second => noise ~ $N^{1/2}$

- state of the art; (linear and log)
- 3 dB = factor of 2; 10% noise = -10 dB
- We have achieved -9.7 dB (~11% of “shot noise”)
- world record (using an OPO): -15 dB (~3%)
- previous best with 4WM in atoms: -2.2 dB
- LIGO will use -6 dB of squeezing in phase II

measuring squeezing

Squeezing is given as a noise power; 10 $\log_{10}(R)$ where R is the (linear) noise reduction from shot noise

This comes from an electrical engineering approach to measuring noise power

R = 0.1 => -10 dB of squeezing

Inferred squeezing (in the lab)

If you correct for losses in transmission and detection of photons, and assume the beams are balanced, you can project what might have been measured in a more perfect world...

We infer approximately 12 dB of squeezing at the source in our work.

(from uncertainties and limited by seed light noise)

inferring squeezing (cont.)

$R_{meas} = 1 - \eta + \eta R_0$ R ~ linear fractional noise

and η is the detection/collection efficiency

from -7.1 dB measured

  we infer -10.2 dB at the source

  from η = 0.95(detectors) x 0.93(optics) = 0.89

from **-9.7 dB and** $\eta = 0.90$ we infer -12.8 dB

our intensity-difference squeezing is "degraded"
by the imbalance from an injected signal

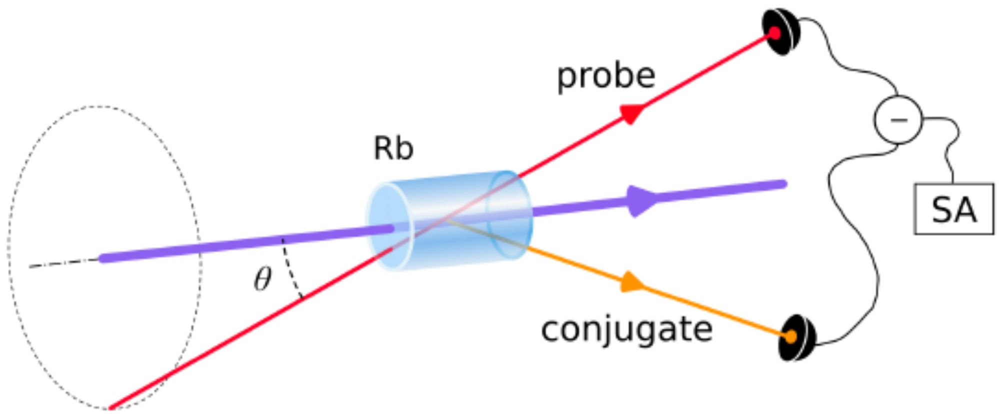
Correlations vs. Entanglement

Although entanglement is predicted in this system, we have only explored the relative-intensity correlations thus far. Correlations can be on a single variable; entanglement requires a non-commuting pair of variables.

We expect to see phase-sum, as well as intensity-difference squeezing in this system, and a continuous-variable EPR relationship can be established for this system. To show this we need two local oscillators.

Then we can do quantum information processing....

generating twin beams



correlated: If a particle in beam 1 has spin up, then the corresponding particle in beam 2 has spin down

entangled: I get to choose the spin axis randomly

homodyne measurements

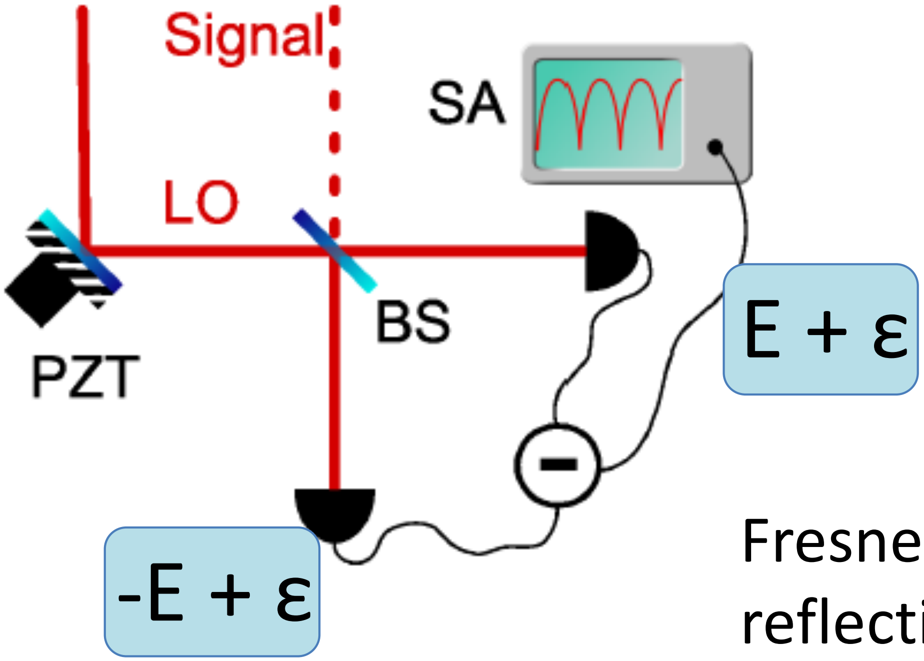
If we want to make phase-sensitive measurements of a field we need to have a phase reference in our measurement device.

The way we do this is to interfere it with a field with a known phase (a local oscillator - LO).

Homodyning also allows us to amplify and filter as well

Homodyne implies the LO is the same frequency as the signal, while heterodyne detection has the LO and signal at different frequencies.

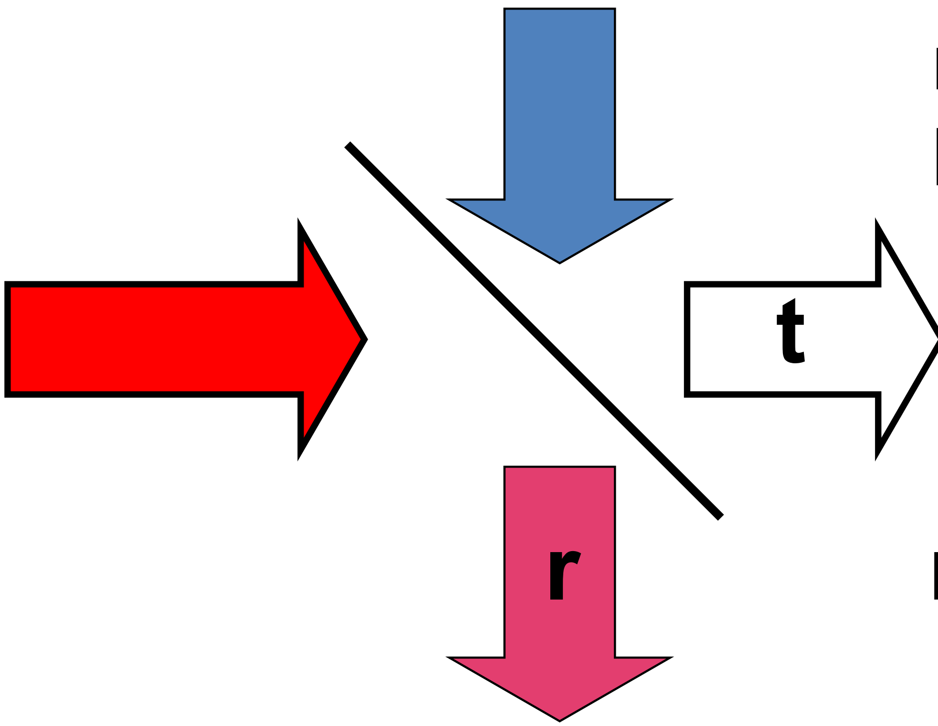
homodyning light



Fresnel equations for beamsplitter reflectivities tells you that one of the reflections must get a minus sign…

$$E(t) \propto X_1 \cos(\omega t) + X_2 sin(\omega t)$$

beamsplitter magic

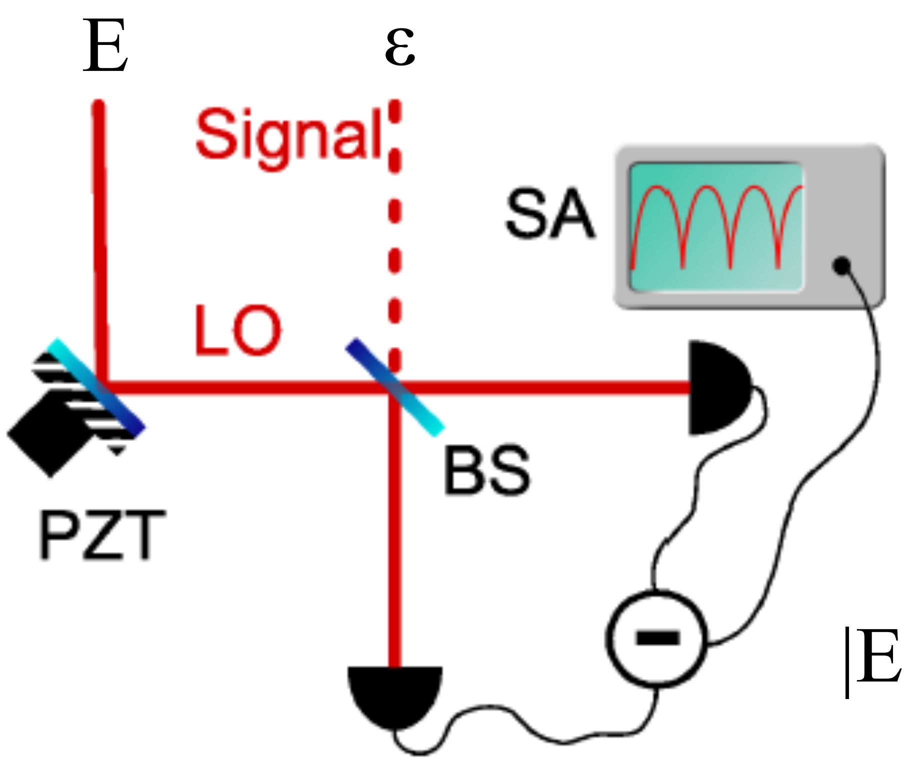


field amplitude relations at a beamsplitter

$$r^*t + t^*r = 0$$

$$|r|^2 + |t|^2 = 1$$

homodyne detection



- mix signal with bright beam of same frequency
- get amplification of a small signal
- local oscillator fluctuations cancel out
- phase sensitive

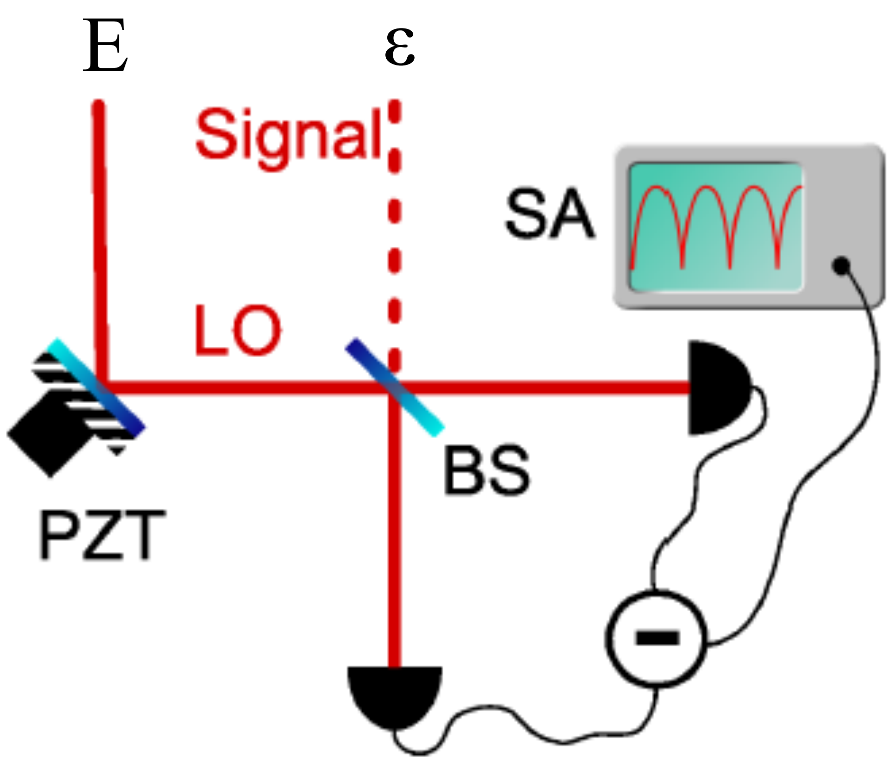
$$|E + \varepsilon|^2 = |E|^2 + |\varepsilon|^2 + E^*\varepsilon + E\varepsilon^*$$

$$|-E + \varepsilon|^2 = |E|^2 + |\varepsilon|^2 - E^*\varepsilon - E\varepsilon^*$$

$E >> \varepsilon$

subtract: signal = $2\mathrm{Re}(E^*\varepsilon)$

homodyne (cont.)



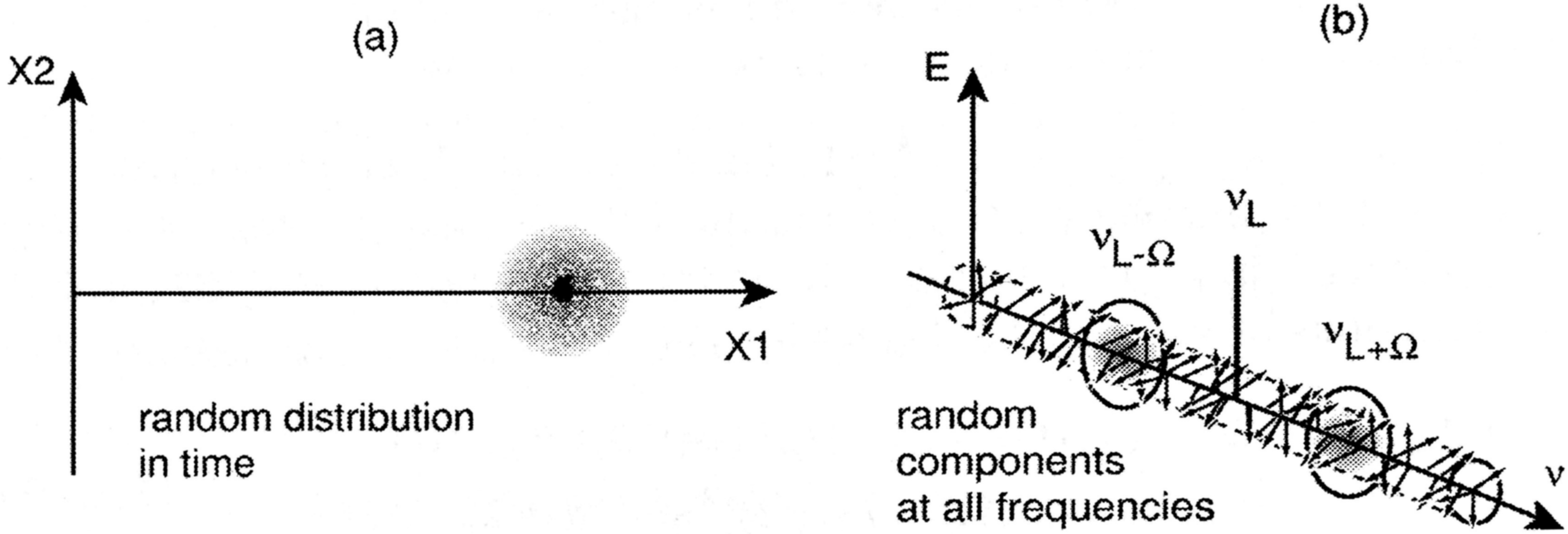
$E >> \varepsilon$

$$\text{signal} = 2\text{Re}(E^*\varepsilon)$$
$$= 2\,|E\,\varepsilon|\,\sin(\varphi_{LO} + \varphi_s)$$

Thus, one obtains a signal that is:

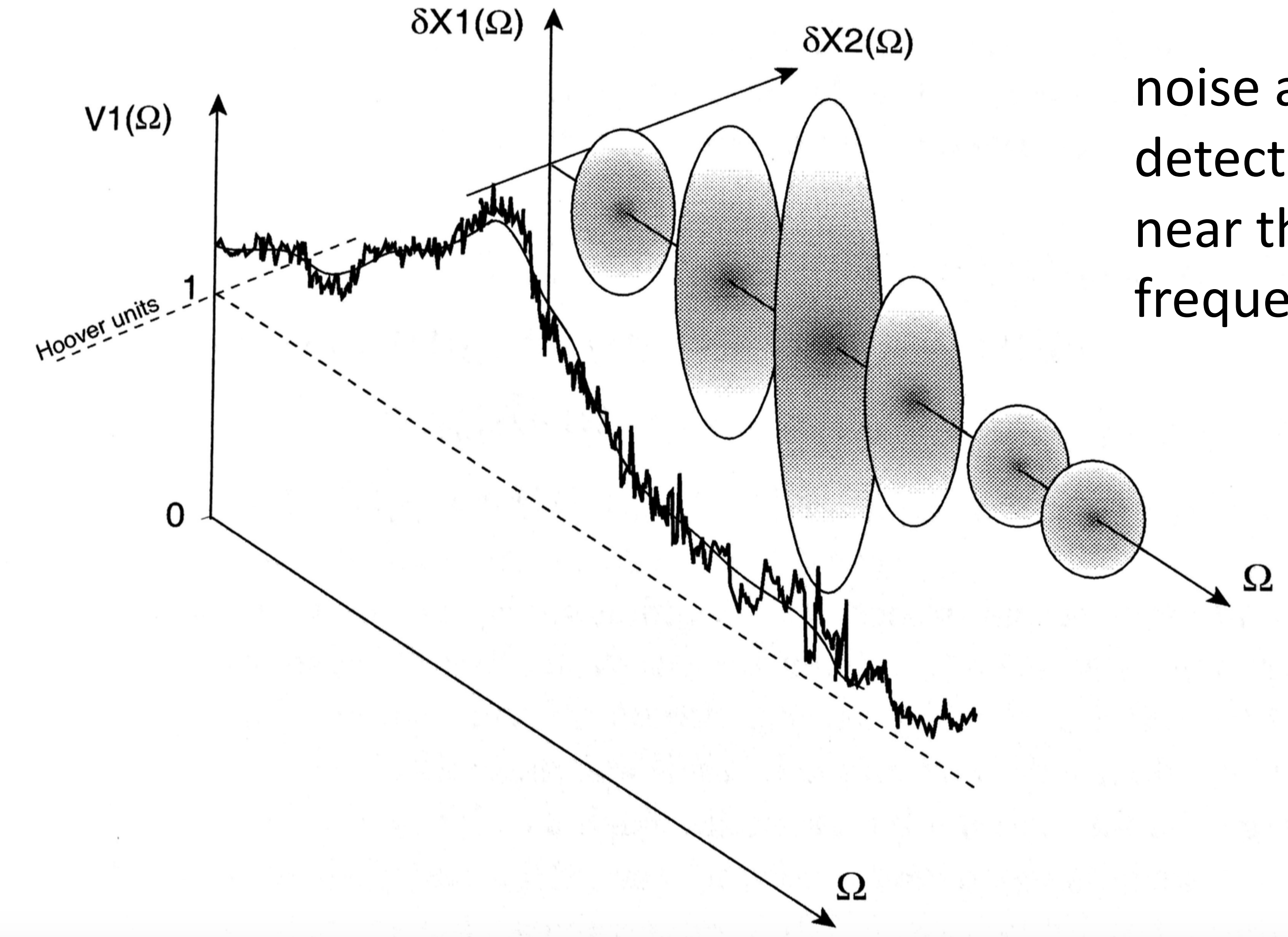
- proportional to the weak signal field (with phase)
- amplified by the strong local oscillator
- strongly filtered to the local oscillator frequency bandwidth

sideband picture for light



figures from “A guide to Experiments in Quantum Optics” by H. Bachor and T. Ralph

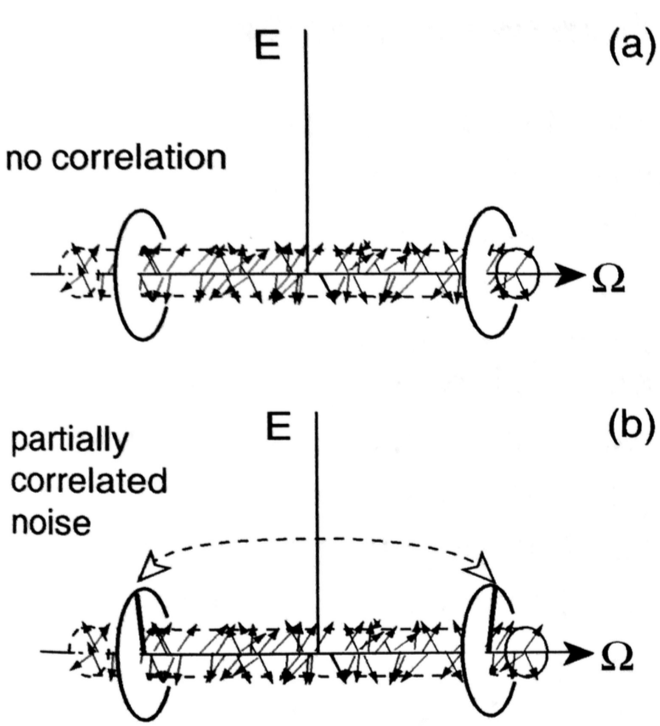
finite bandwidth signal

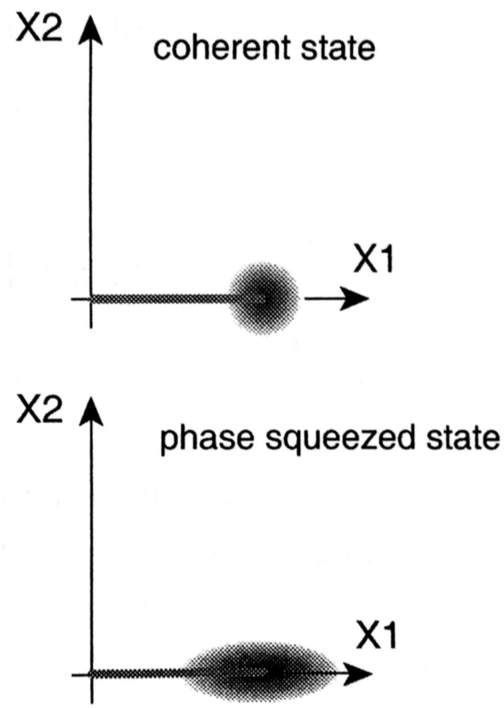


noise as a function of detection frequency near the center frequency of a signal

figures from “A guide to Experiments in Quantum Optics” by H. Bachor and T. Ralph

squeezing in this picture



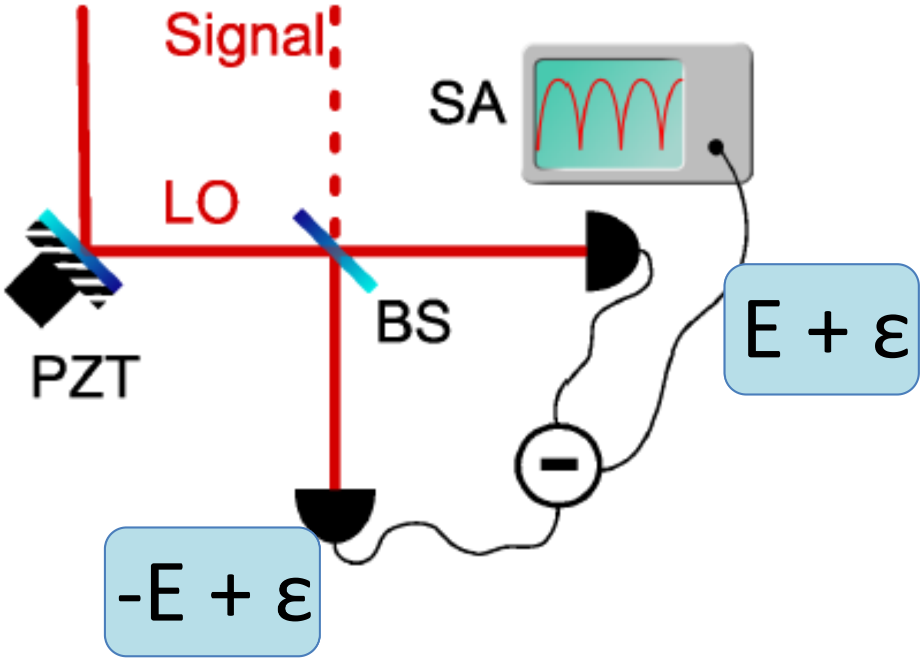


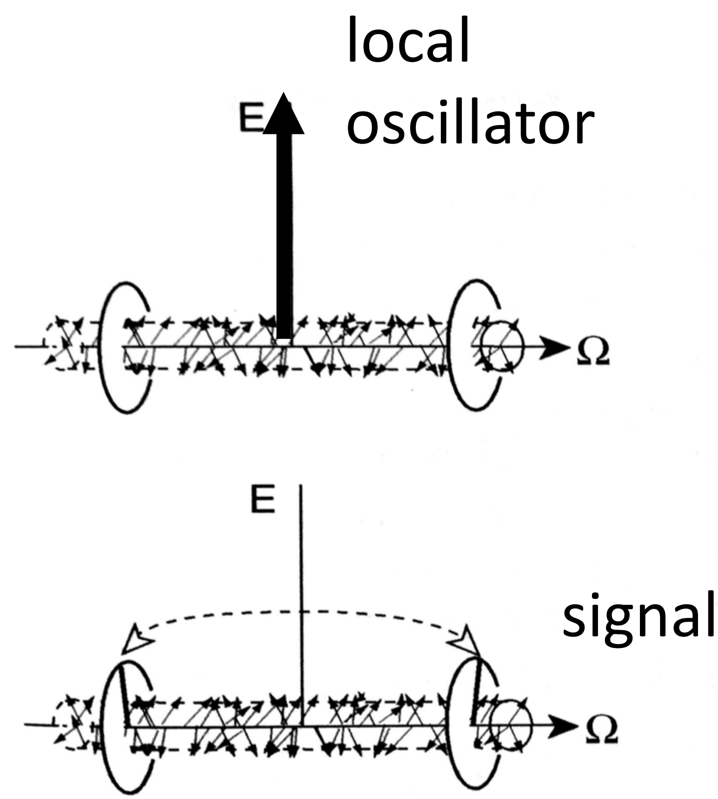
these pictures are for a given center frequency and sideband frequency

correlations in the sidebands are what result in "squeezing"; the relative phases of the sidebands determine if it is phase or intensity squeezing, etc.

figures from "A guide to Experiments in Quantum Optics" by H. Bachor and T. Ralph

homodyning light



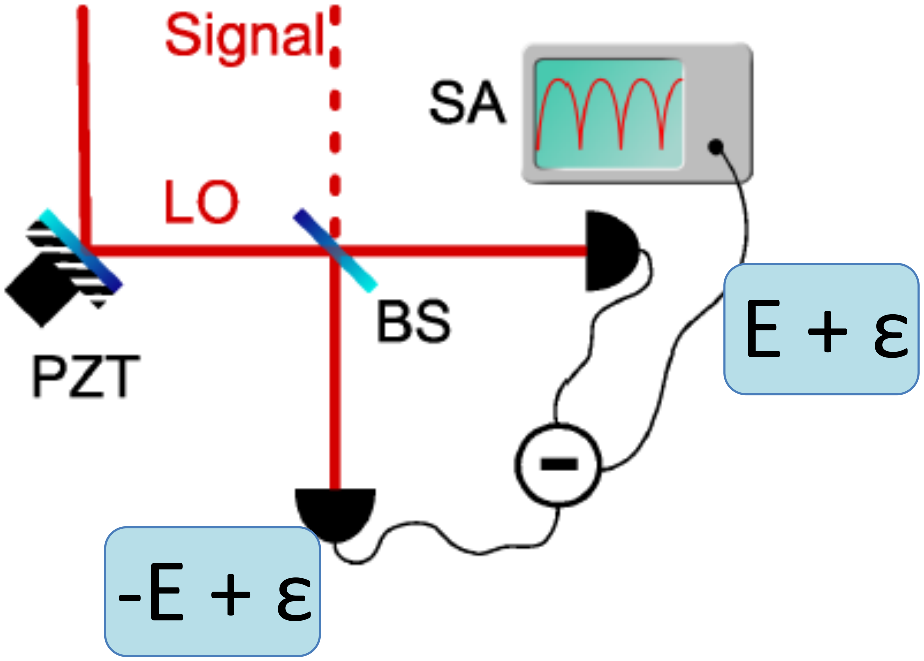


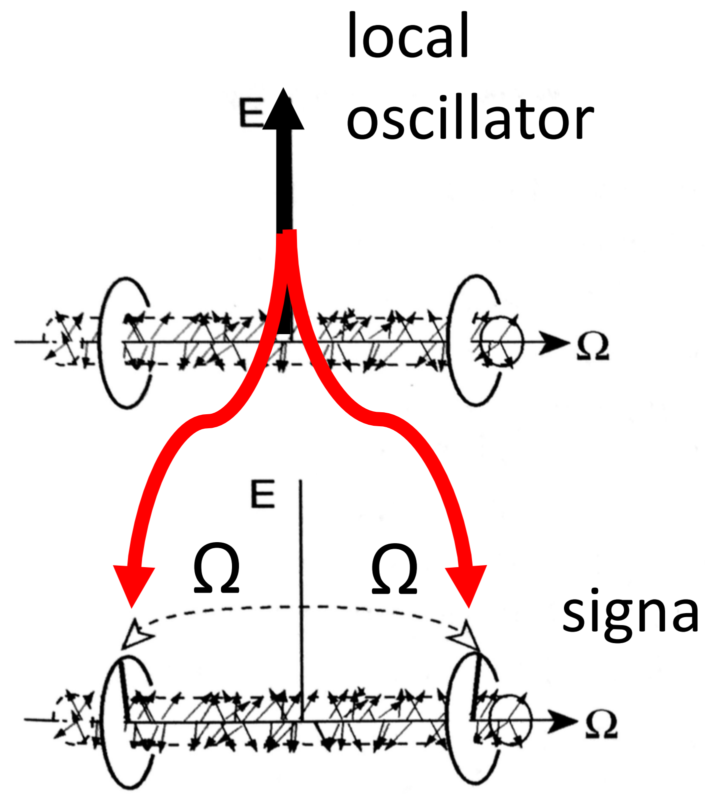
The main signal that we see coming out of the radio frequency spectrum analyzer (SA) at a given frequency is the carrier from the LO beating against the (correlated) signal sidebands.

The LO phase determines which signal quadrature we see.

figures on right from "A guide to Experiments in Quantum Optics" by H. Bachor and T. Ralph

homodyning light



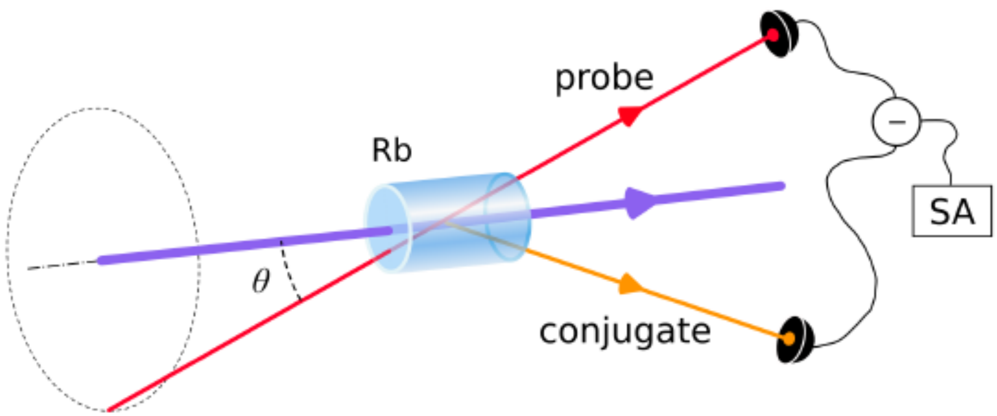


The main signal that we see coming out of the radio frequency spectrum analyzer (SA) at a given frequency is the carrier from the LO beating against the (correlated) signal sidebands.

The LO phase determines which signal quadrature we see.

figures on right from "A guide to Experiments in Quantum Optics" by H. Bachor and T. Ralph

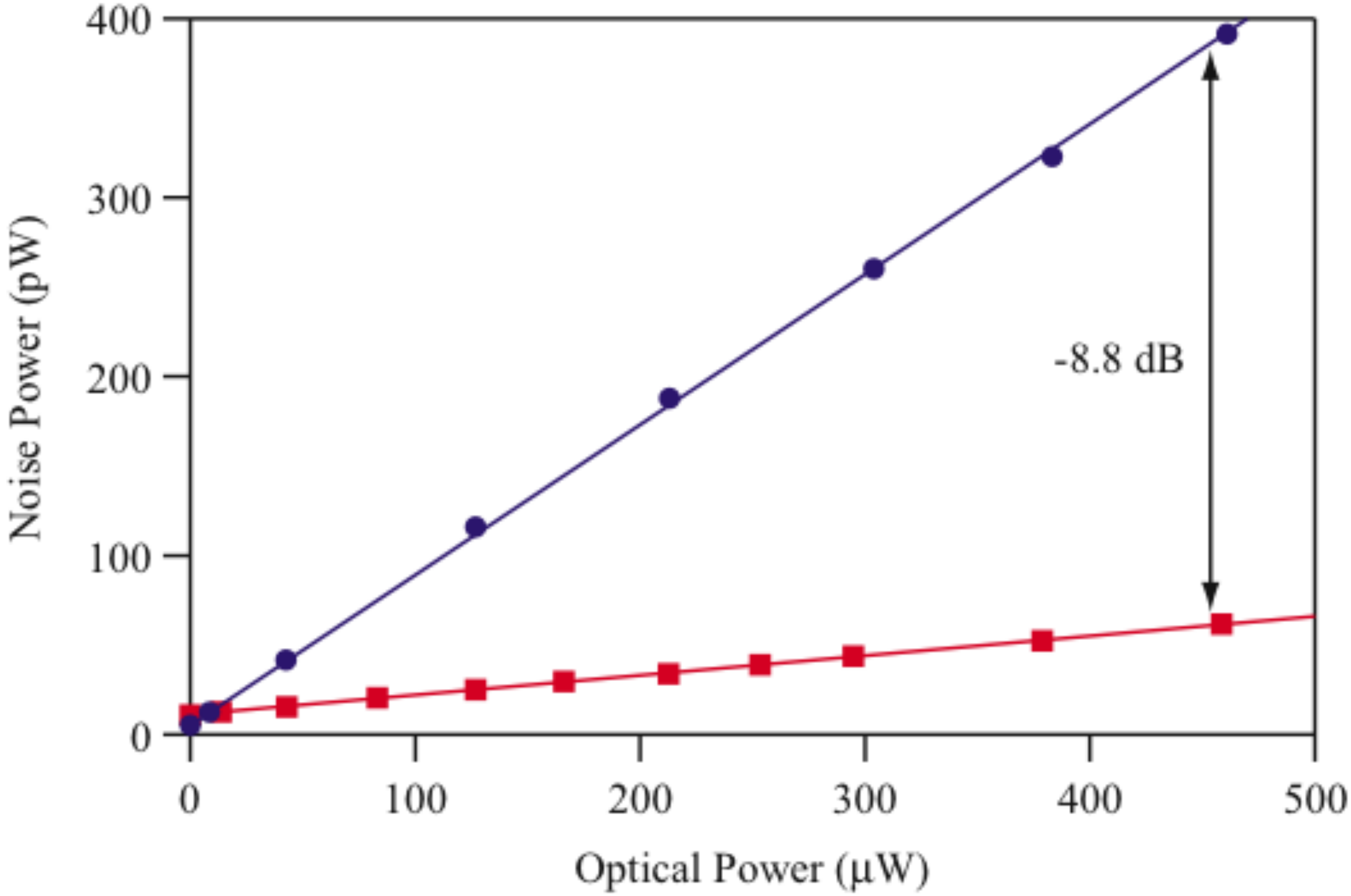
intensity-difference squeezing



noise power measured with rf spectrum analyzer

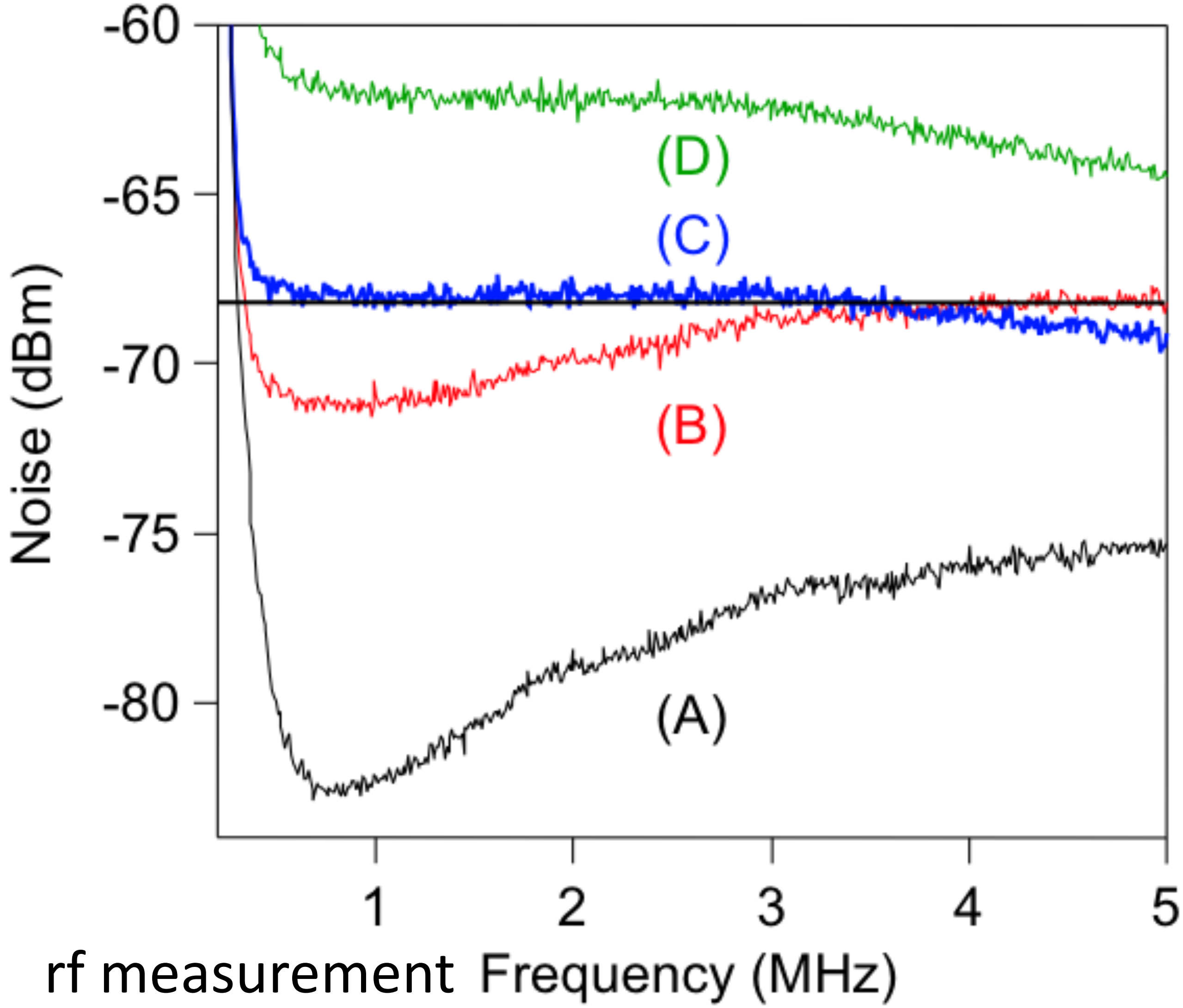
Taking the intensity signals and directly subtracting them (without homodyne detection) is essentially equivalent to looking at only the amplitude (or intensity) quadrature .

intensity-difference squeezing at a single frequency



1 MHz detection frequency
RBW 30 kHz
VBW 300 Hz
pump detuning 800 MHz
Raman detuning 4 MHz
~95% detector efficiency

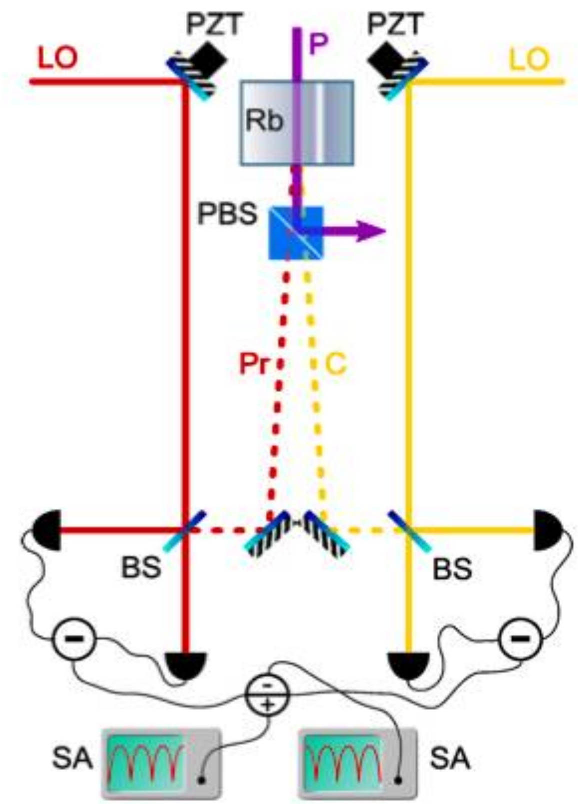
spectrum of (intensity-difference) squeezing

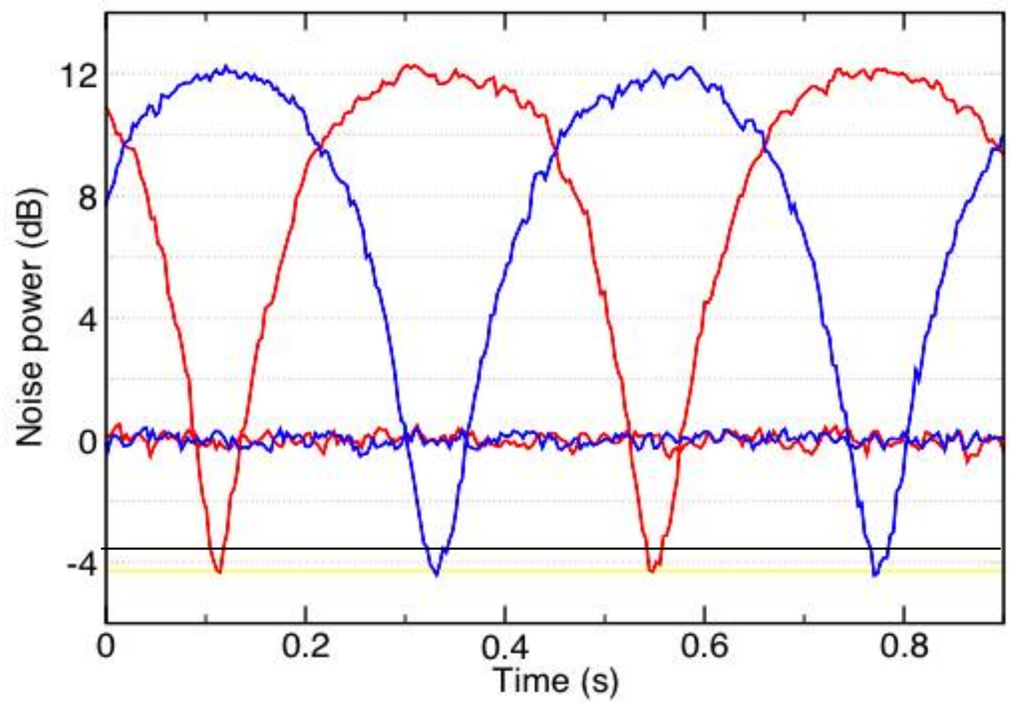


squeezing spectrum taken with amplified detectors with roll-off becoming apparent at ~ 3 MHz

A) electronic noise floor
B) relative intensity squeezed light
C) SQL for same intensity
D) noise from a single beam (on 1 detector) at same intensity

“twin beam” vacuum quadrature entanglement





measurements at 0.5 MHz

- Piezos are scanned simultaneously
- Local oscillators are created by 4WM

enough for one day…