Squeezed light for Quantum Sensors

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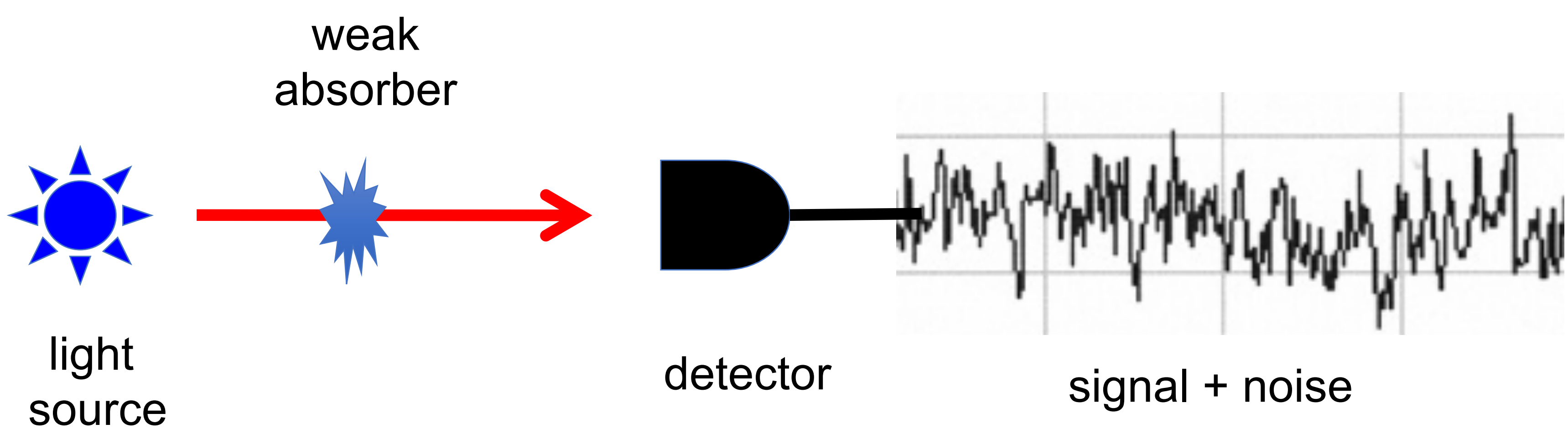
Squeezing and “brands” of squeezing

squeezing – beats shot-noise limit

- single mode
  intensity/phase versus quadrature squeezing
- two-mode or “twin-beam” squeezing
- polarization – variances of one or more Stokes parameters are smaller than coherent state values

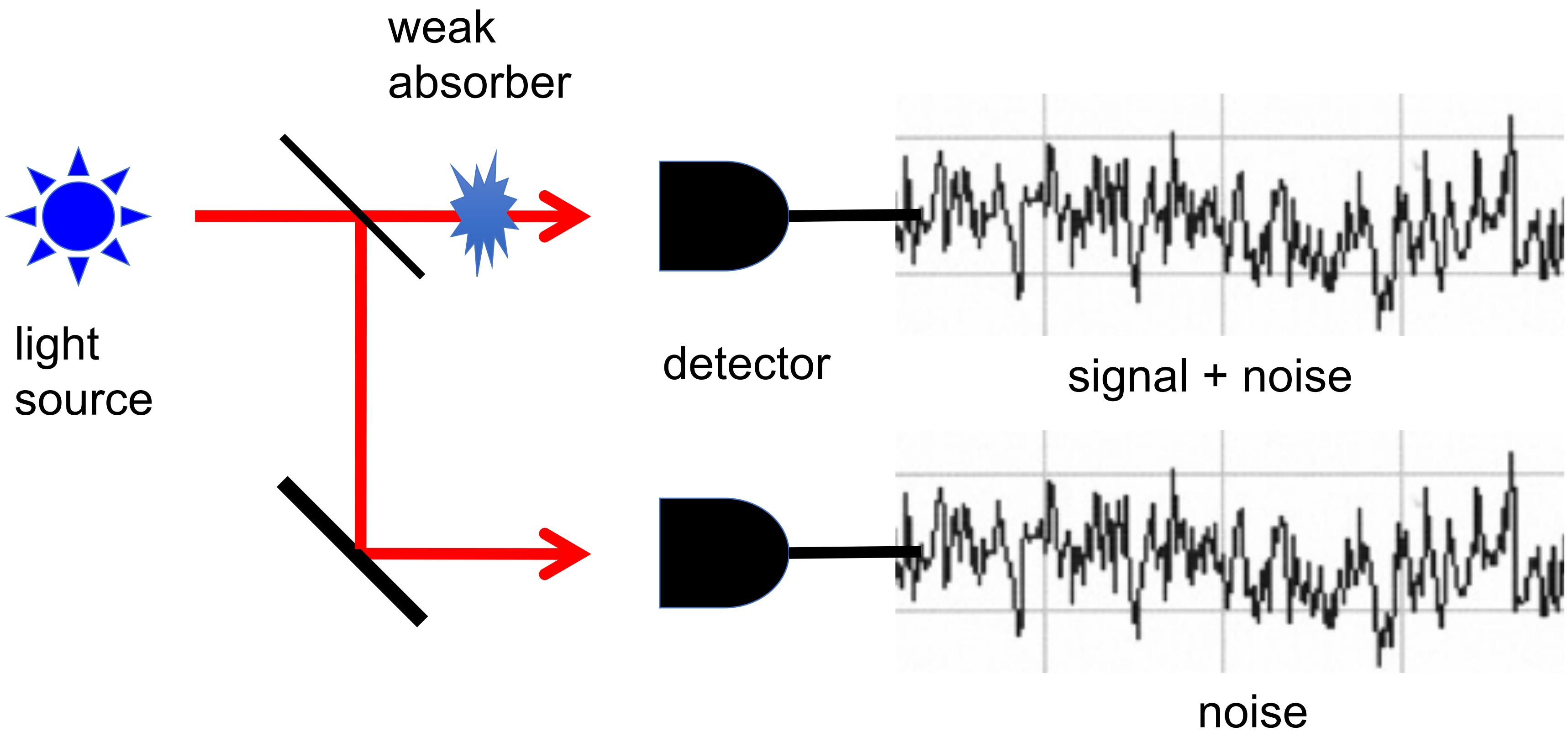
- losses quickly kill the effect!

making use of correlations



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

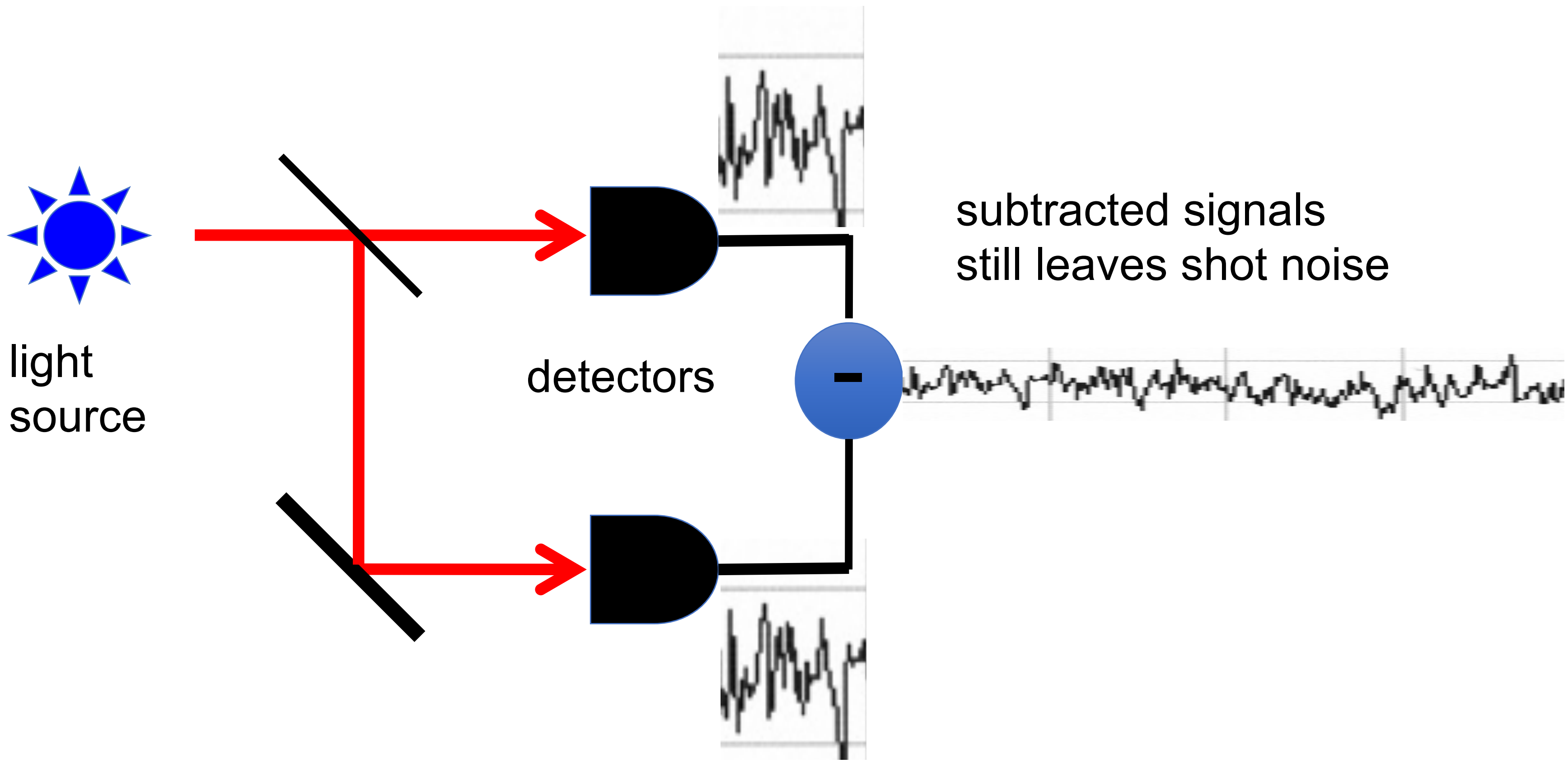
the advantage of classical correlations



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

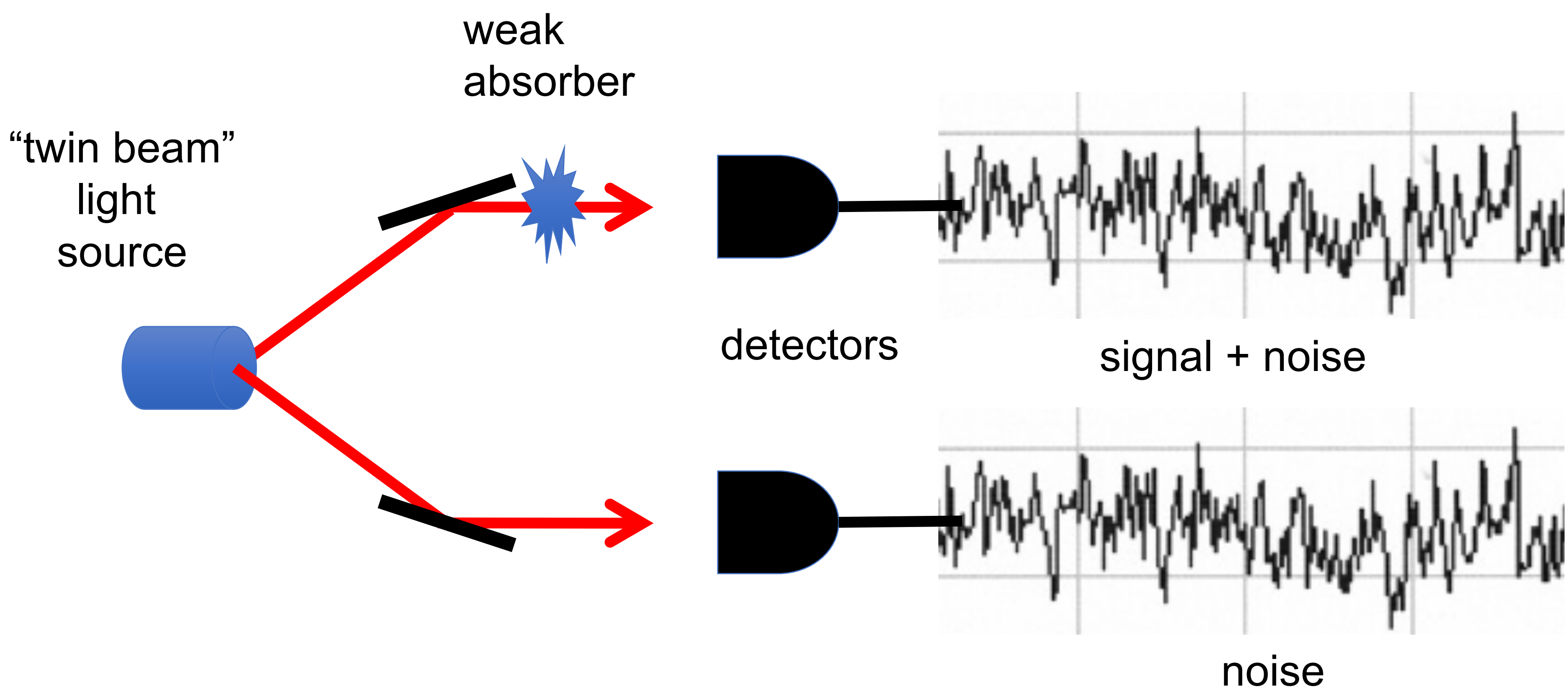
it is easier to detect the signal.

the PROBLEM of classical correlations



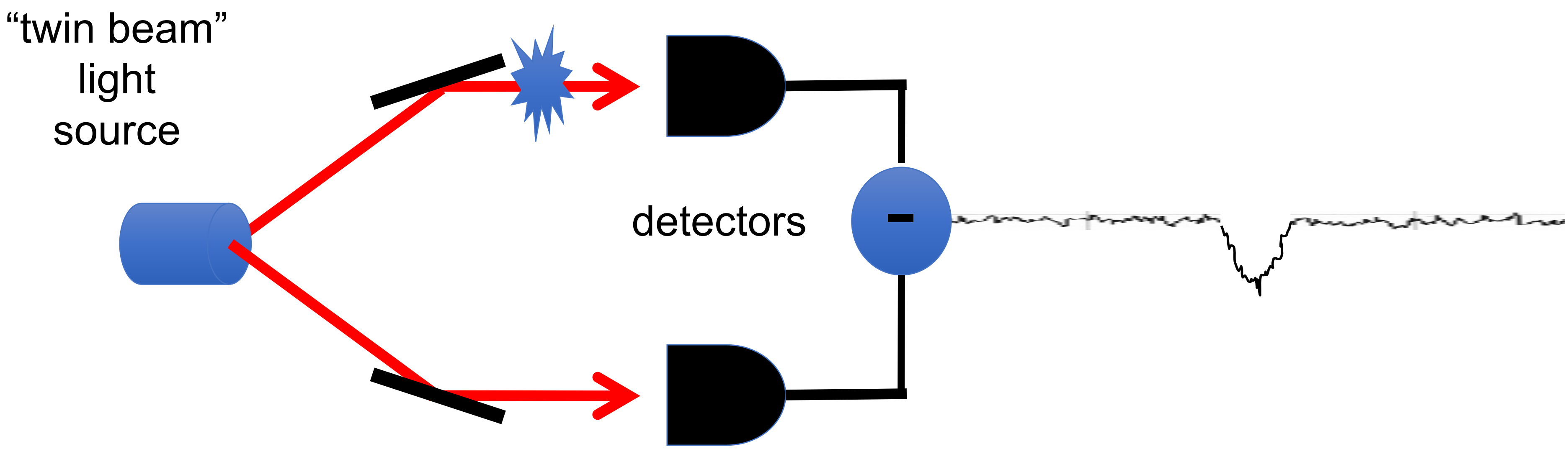
A beamsplitter or half-silvered mirror can “duplicate” only the classical noise on the beam;
the “shot noise” due to photons “randomly deciding” which way to go is uncorrelated and adds.

the advantage of quantum correlations



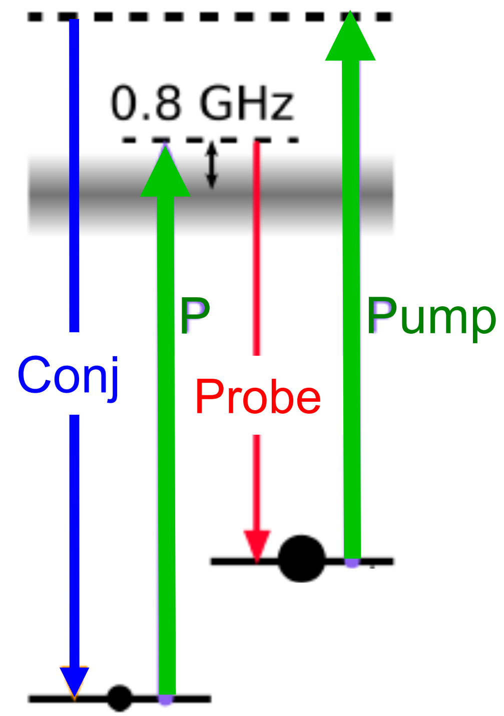
If we duplicate the fluctuating probe, *including* its quantum noise, then subtract, it is even easier to detect the signal.

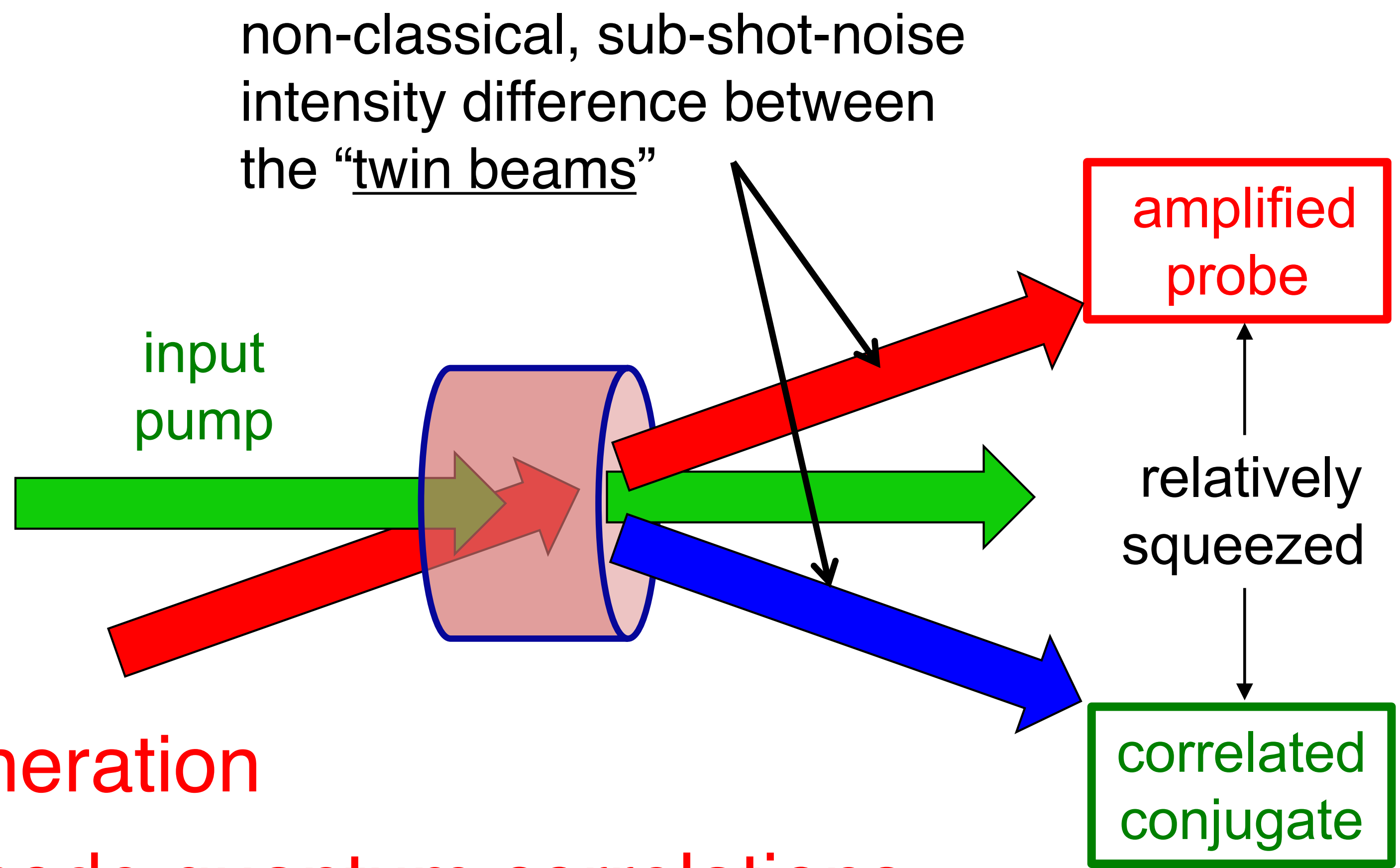
the advantage of quantum correlations



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.

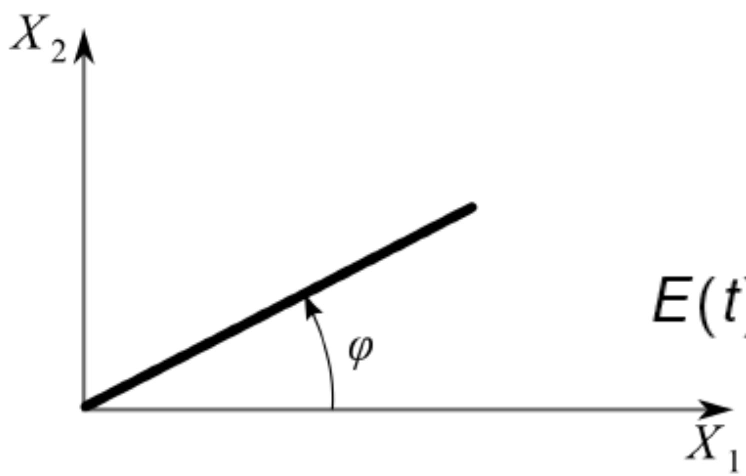
4-Wave-Mixing in the quantum limit





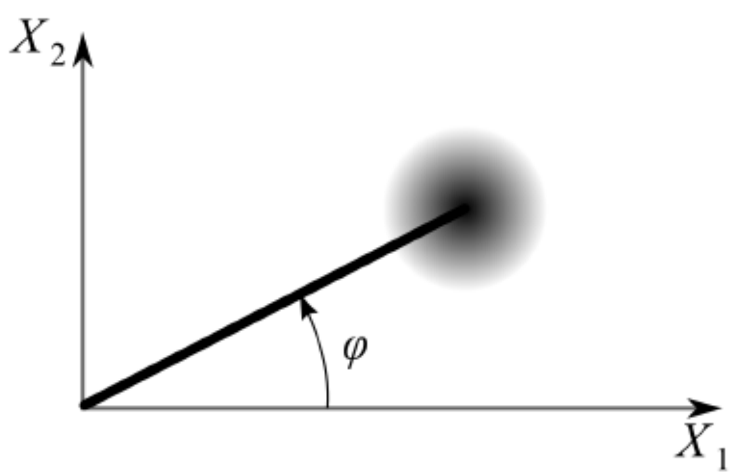
- twin-beam generation
- multi-spatial-mode quantum correlations (quantum imaging)
- acts as a phase insensitive amplifier (PIA)

light



amplitude and phase
or
quadratures

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



quantum version
with noise

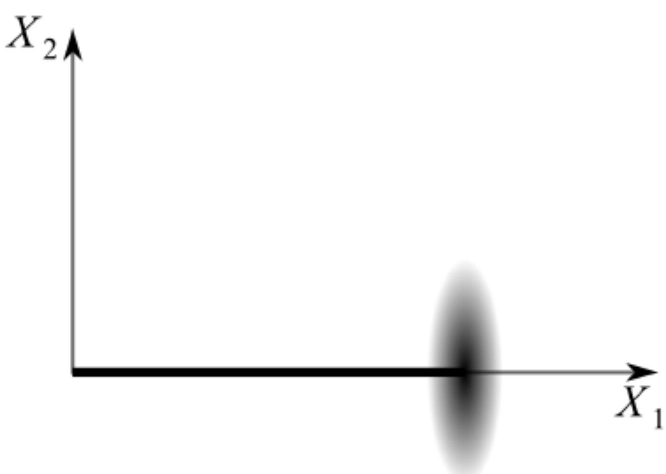
coherent states
have minimum-
sized, round fuzz-
ball

squeezed light

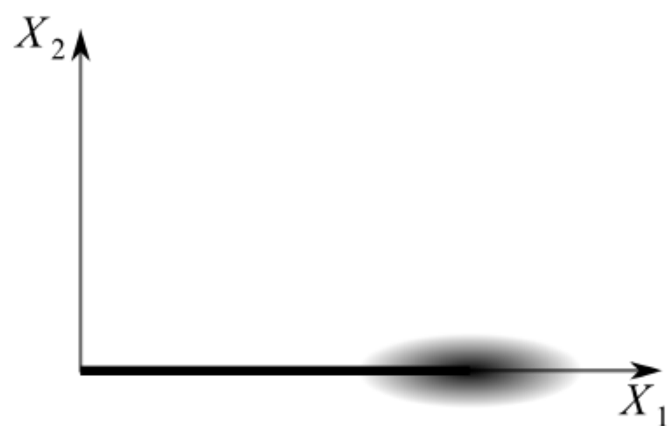
what does it mean for light to be "squeezed"?

classical fields have symmetric noise

amplitude



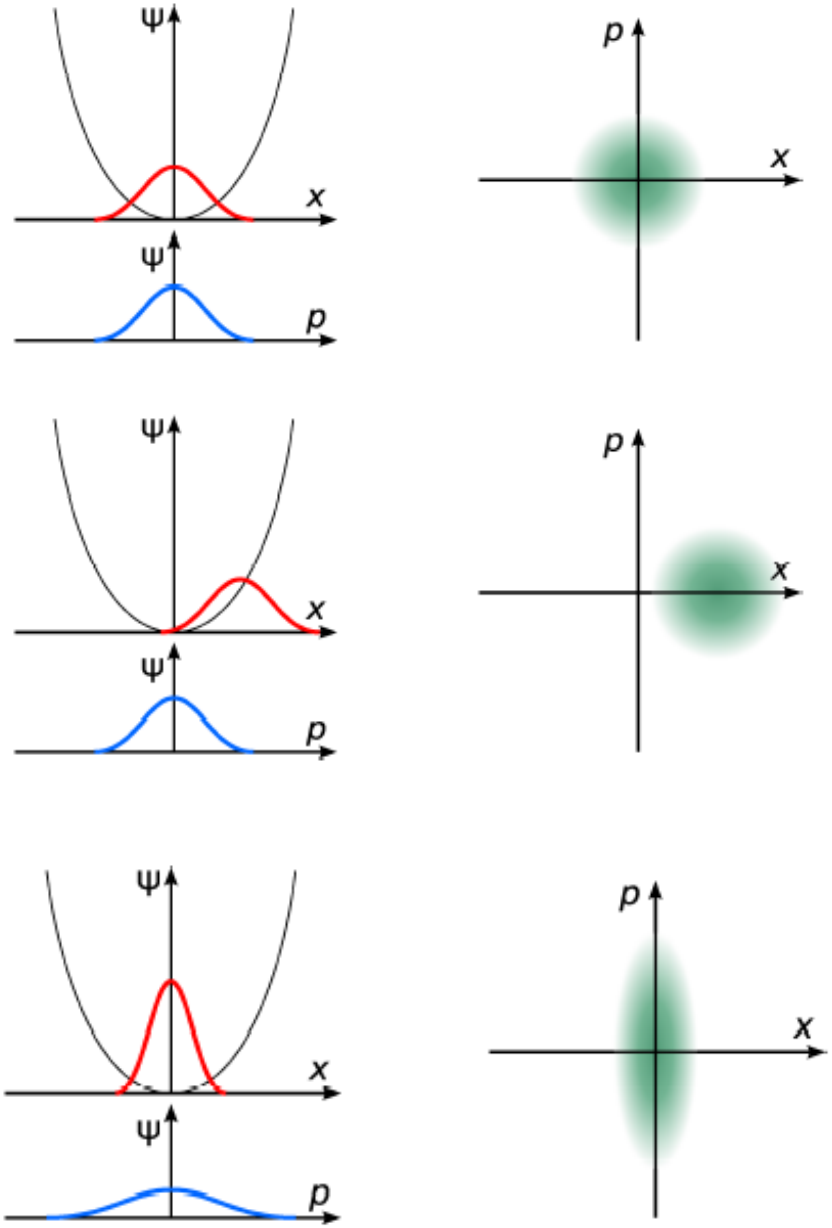
phase



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

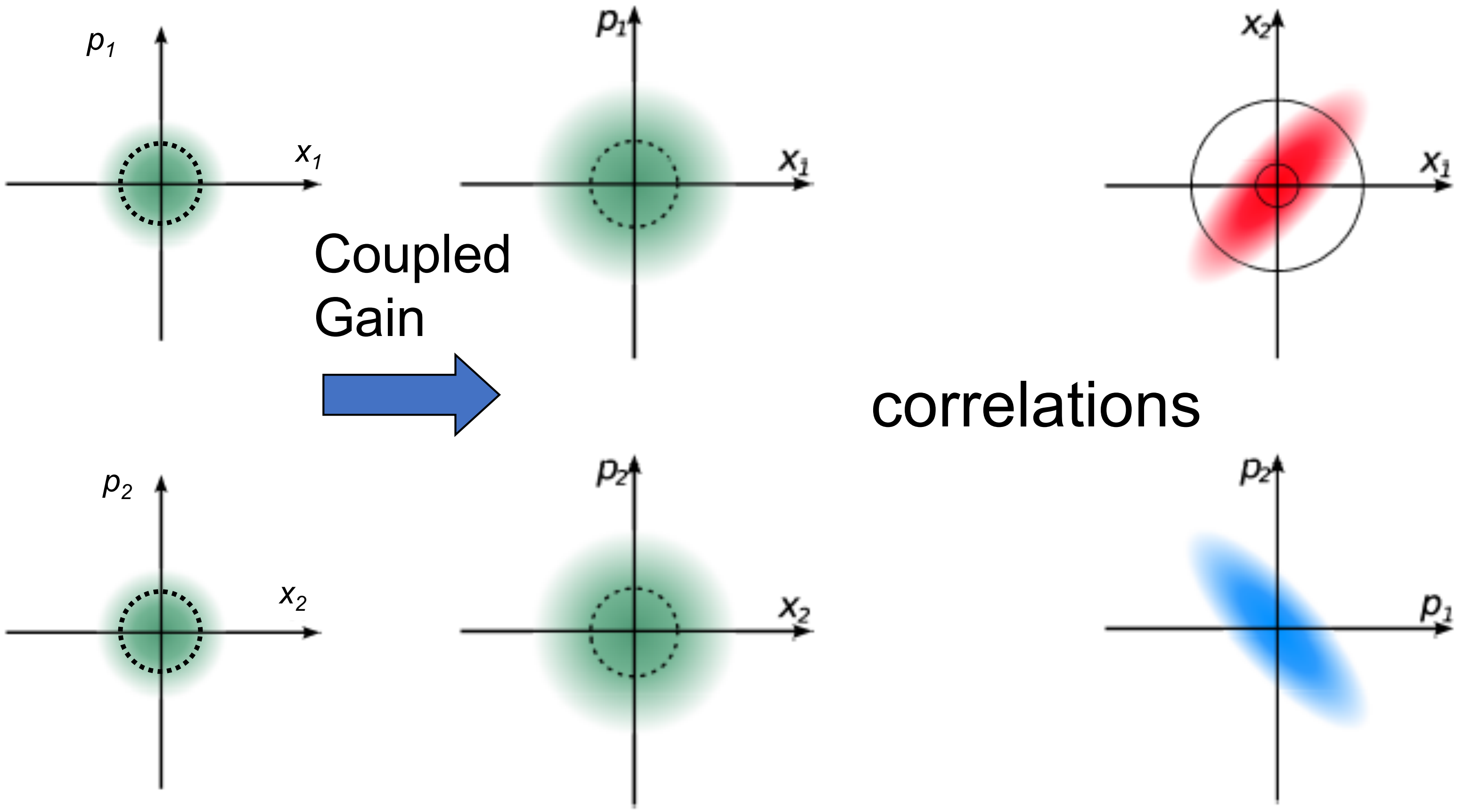
$$E(t) \propto X_1 \cos(\omega t) + X_2 sin(\omega t)$$

Single-mode squeezing



- Mode of frequency $\omega \equiv$ harmonic oscillator of frequency ω
- $$\hat{x} \rightarrow \hat{X}$$
  $$\hat{p} \rightarrow \hat{Y}$$
  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

Two-mode squeezing: phase-insensitive amplifier



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

nonlinear optics

- frequency converter:

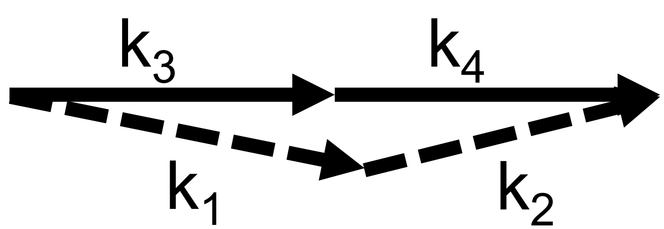
  couple 3 optical fields to make a 4th:

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

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

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

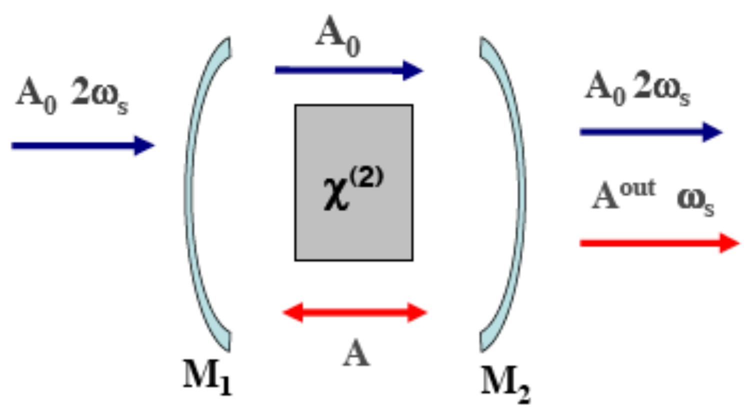
  momentum: $k_1 + k_2 = k_3 + k_4$



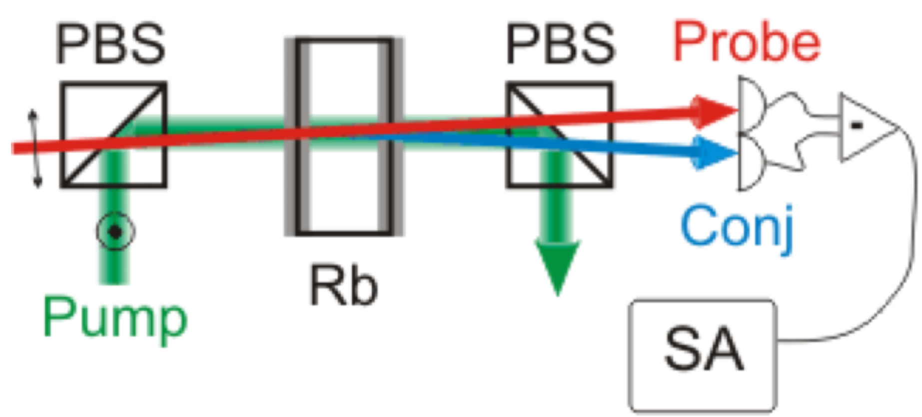
If we are careful about how we do it, inserting 3 fields gets us a 4th with some "magic" properties

the key is an interaction that looks like: $\hat{a}^{\dagger}{}_3 \hat{a}^{\dagger}{}_2 \hat{a}_1 \hat{a}_1$

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

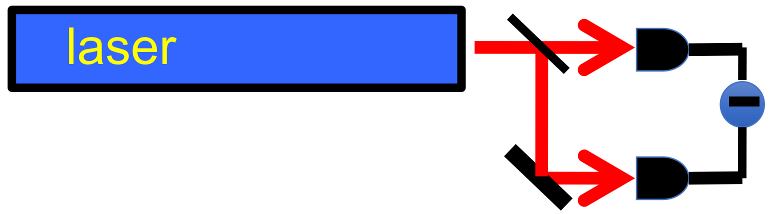


OPO
(optical
parametric
oscillator)

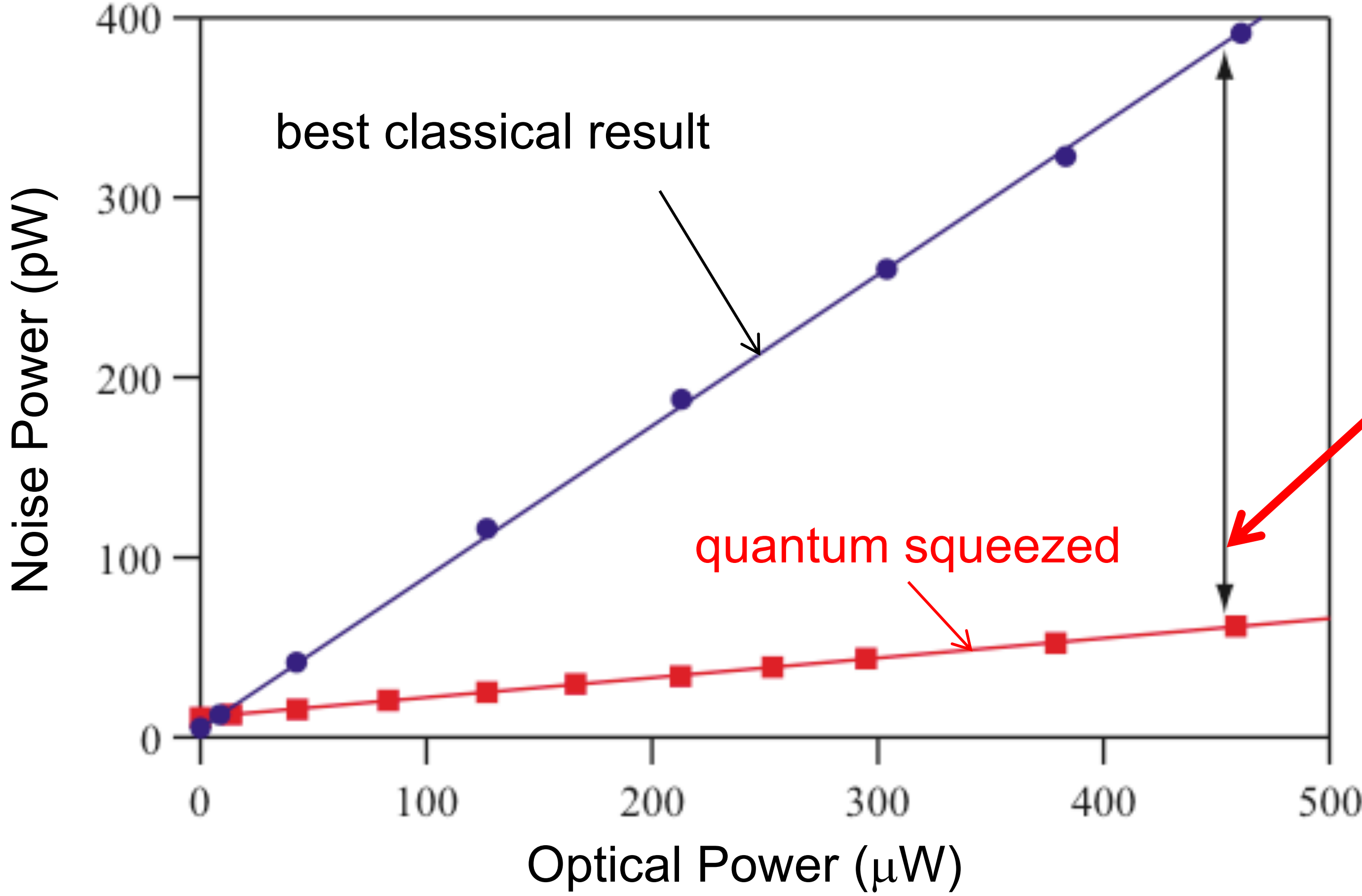


four-wave mixing (4WM)
(count 2 pump photons in
the 4 waves!)

intensity-difference squeezing

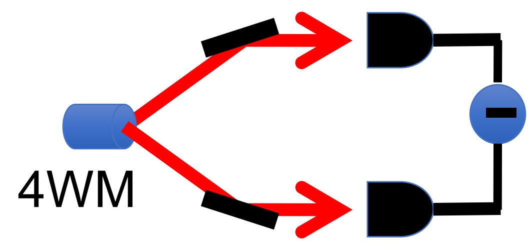


laser beam through
a 50/50 beamsplitter
difference



~87% reduction from shot noise

“twin-beam” intensity difference



problems with squeezed light

before you think that all is just sweetness and light here:

- optical losses always limit the gains
(to win as 1/N you need 1-1/N efficiency)
- the optical nonlinearities are often resonant and narrowband

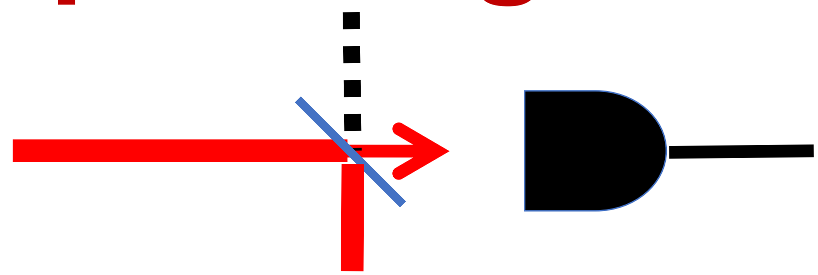
→ this means that both the color of light that you get to use is limited, and that the detection bandwidth that you get to use is limited

problems with squeezed light

It is often much easier to increase the laser power and win as $1/\sqrt{N}$ rather than fight for a 1/N gain, unless you are limited in what you can do by some other problem.

► If you cannot increase the laser power any more for materials reasons (LIGO) or that you will just toast the object (biological imaging) this is often a tough path to a relatively small gain - note that LIGO is talking about gaining a factor of ~4 in sensitivity by this route!

inferring squeezing



- $R_{meas} = 1 - \eta + \eta R_0$

where η is the detection/collection efficiency

and R is the (linear) fraction of shot noise

from -7.1 dB measured intensity-difference squeezing

we infer -10.2 dB at the source

from $\eta = 0.95 \times 0.93 = 0.89$

detector quantum efficiency and beam-path losses

PSAs and PIAs

Quantum-noise-limited amplifiers can be constructed.

The most general is a phase-insensitive amplifier:

- the limit is a 3 dB loss in signal-to-noise

Input-output operator commutation relations constrain the noise properties.

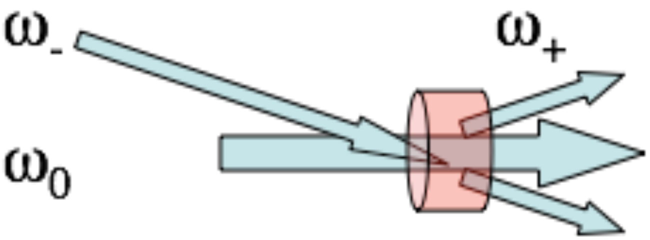
A noiseless, but phase-sensitive amplifier can also be constructed.

PSAs versus PIAs

- “perfect detectors” for optical signals
- unfortunately, only for a small range of colors(?)
- fiber PSAs

phase sensitive 4WM

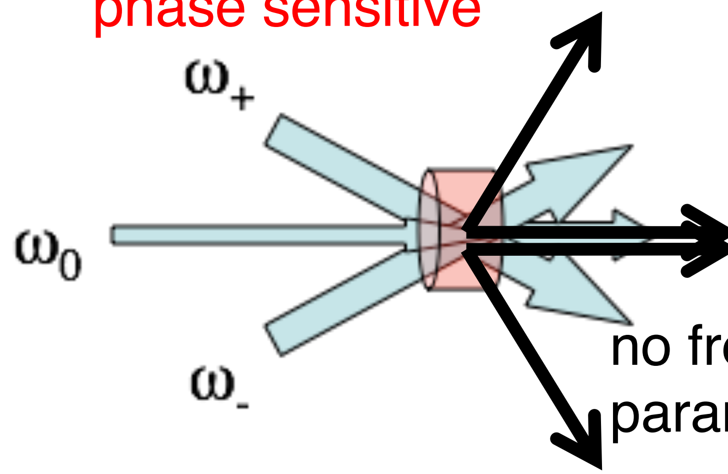
phase insensitive



given the phase of 3 "input" beams the 4th phase is free to adjust for gain

$$\phi_+ = 2\phi_0 - \phi_-$$

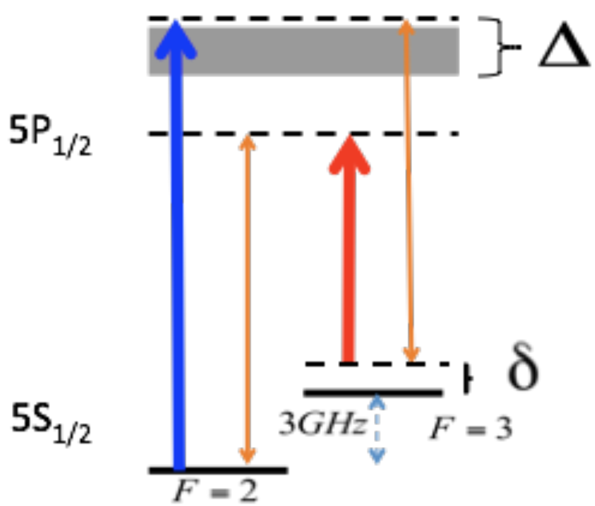
phase sensitive



no free parameters

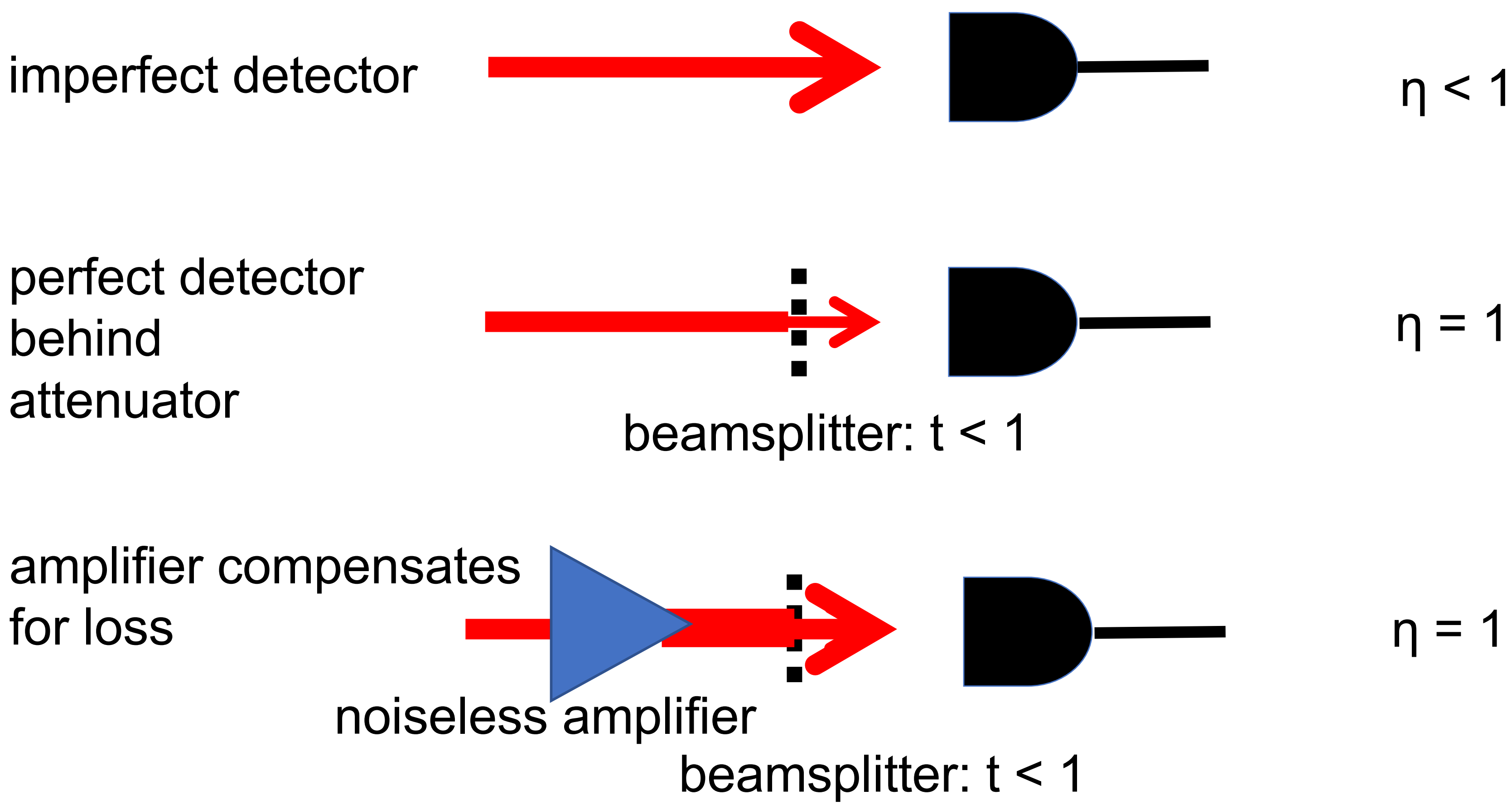
gain condition:

$$0 = 2\phi_0 - \phi_- - \phi_+$$



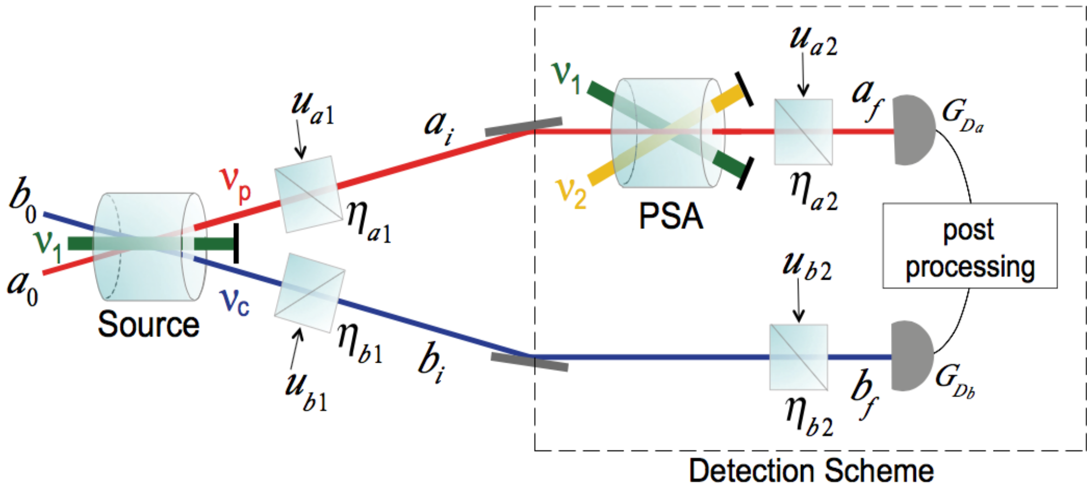
different detuning conditions required to suppress other processes as much as possible

“perfect detectors”



Amplification is stochastic, as is attenuation, so the ”perfect detector” is only “perfect” in the large gain limit.

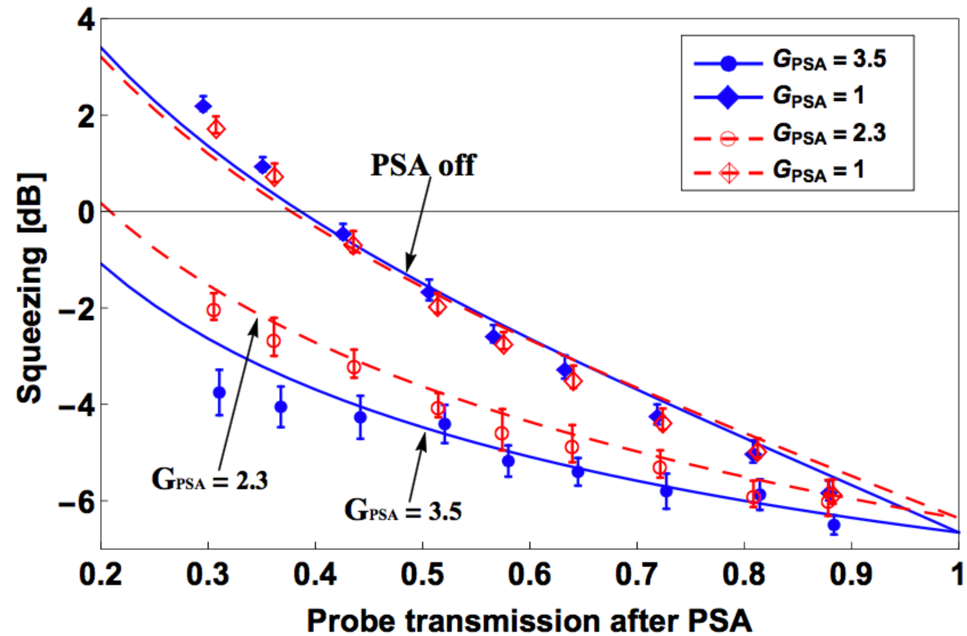
“perfect” quantum efficiency detector (for one quadrature)



Noiseless (but stochastic) amplification of the intensity quadrature in one arm.

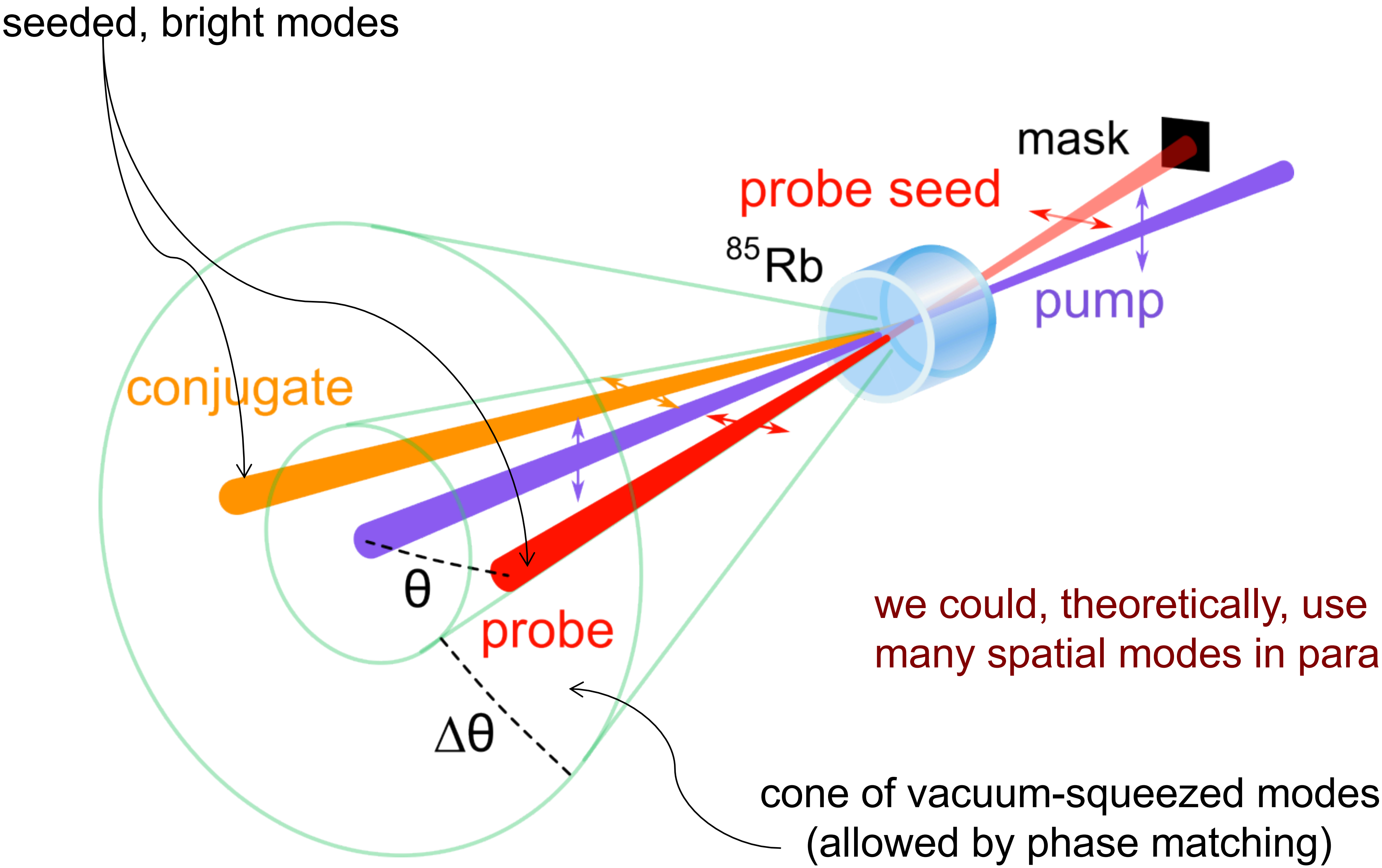
Quantum noise properties preserved in the face of increasing detector losses.

Our PSA has gain limitations to about G ~ 4.



Li, T., et al. Opt. Expr. **25**, 21301 (2017)

multi-spatial-mode two-mode squeezing



we could, theoretically, use many spatial modes in parallel

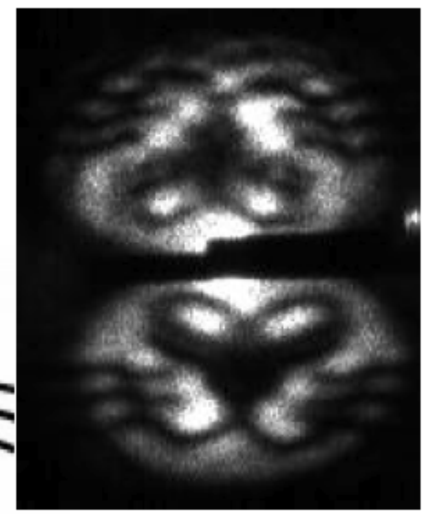
squeezed and entangled cats

Probe LO

Conjugate LO

local oscillators for measurements of 1 dB quadrature squeezed vacuum

squeezed cats

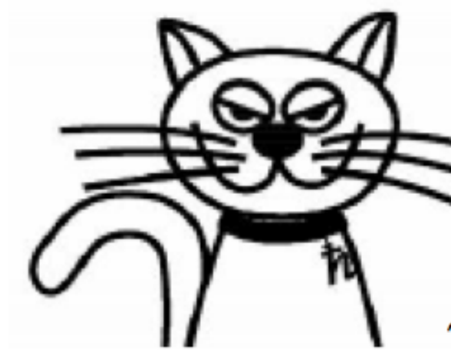


probe

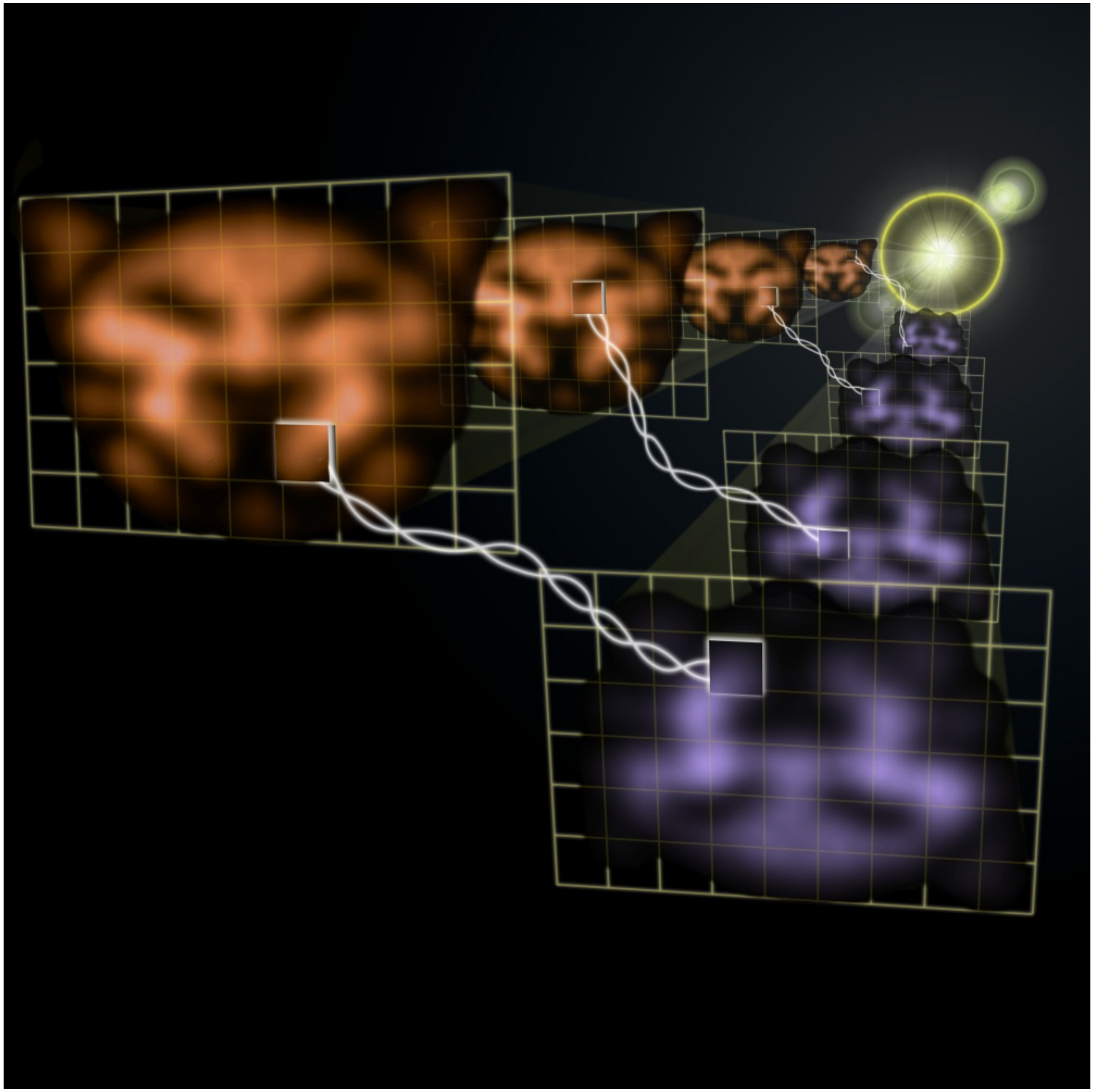
conjugate

~1 dB “whole image” intensity-difference squeezing

bright beams showing intensity-difference squeezing



enhanced graphics!



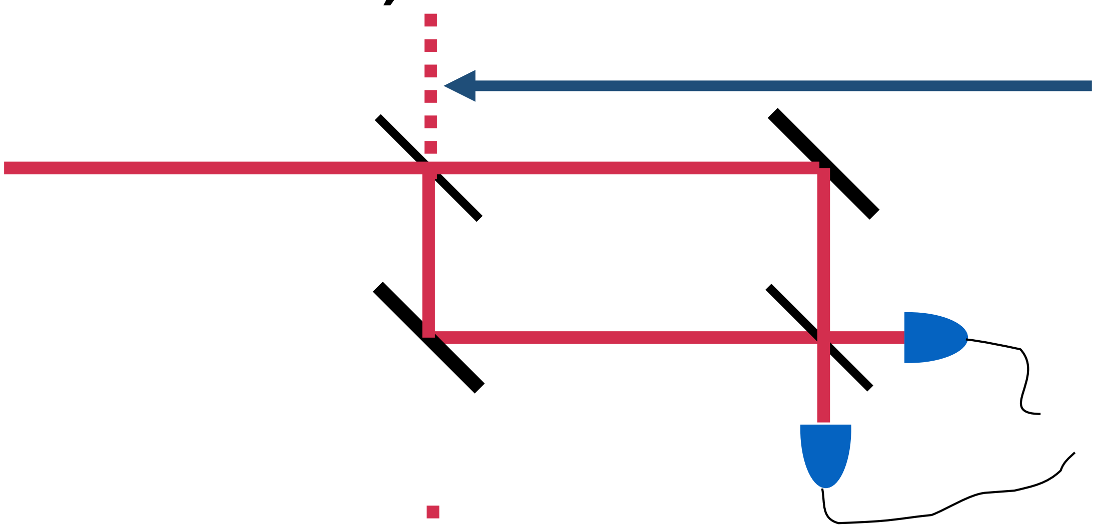
interferometers

interferometers

- **single-mode, LIGO-like; usual Mach-Zehnder or Michaelson with injected squeezing**
- **two-mode; nonlinear medium in the interferometer**

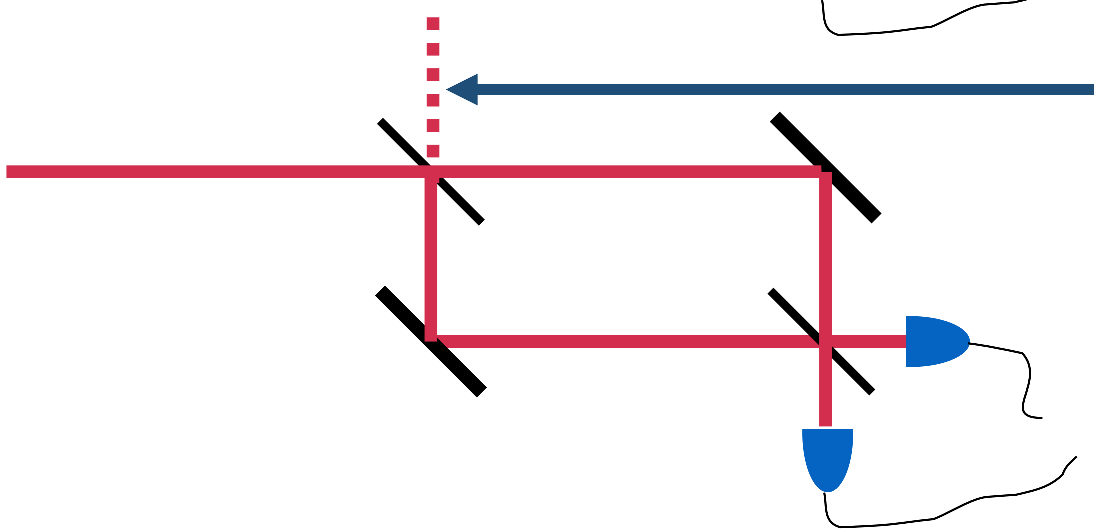
Mach-Zehnder

Passive interferometers (ex: Fabry-Perot, Mach-Zehnder, or Michaelson)



vacuum input; limits the SNR out

sensitivity scales as $N^{-1/2}$

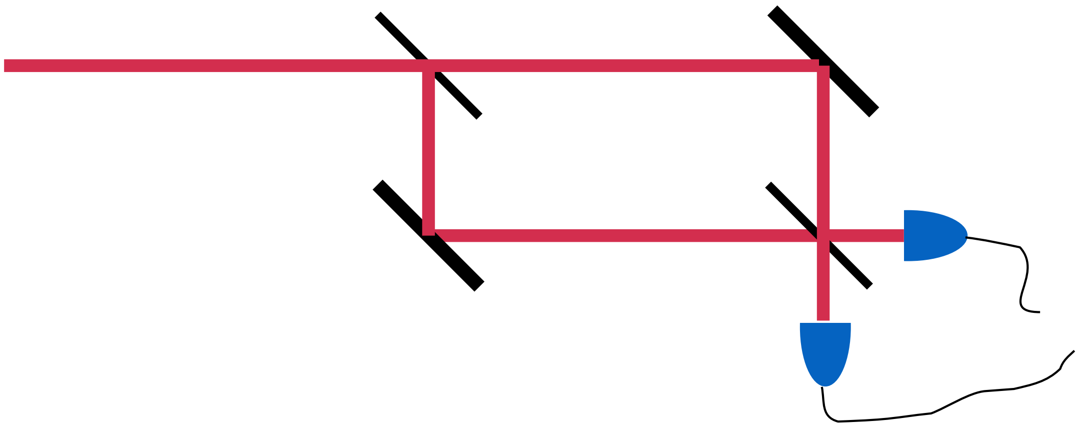


you could replace this with single-mode squeezed vacuum ~ LIGO

sensitivity scales as N^{-1}

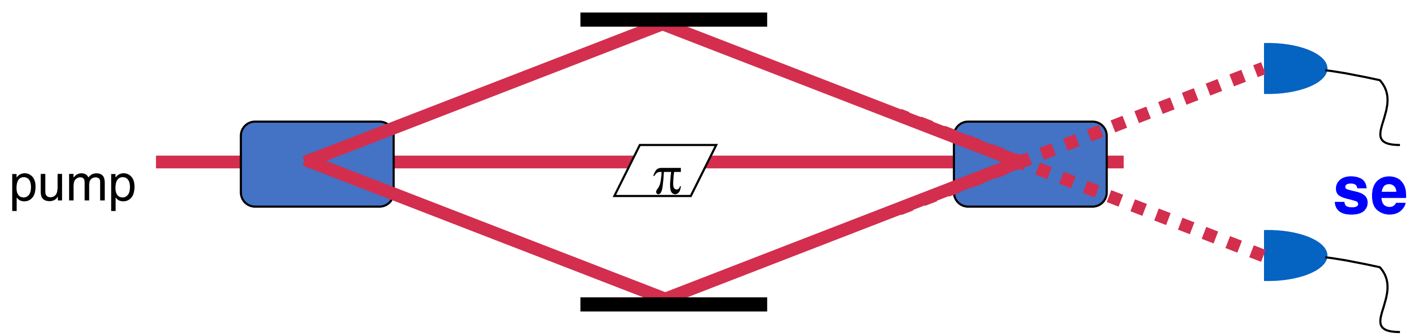
Active vs. Passive interferometers

Passive interferometers (ex: Fabry-Perot and Mach-Zehnder)



sensitivity scales as $N^{-1/2}$

Active interferometers - SU(1,1)



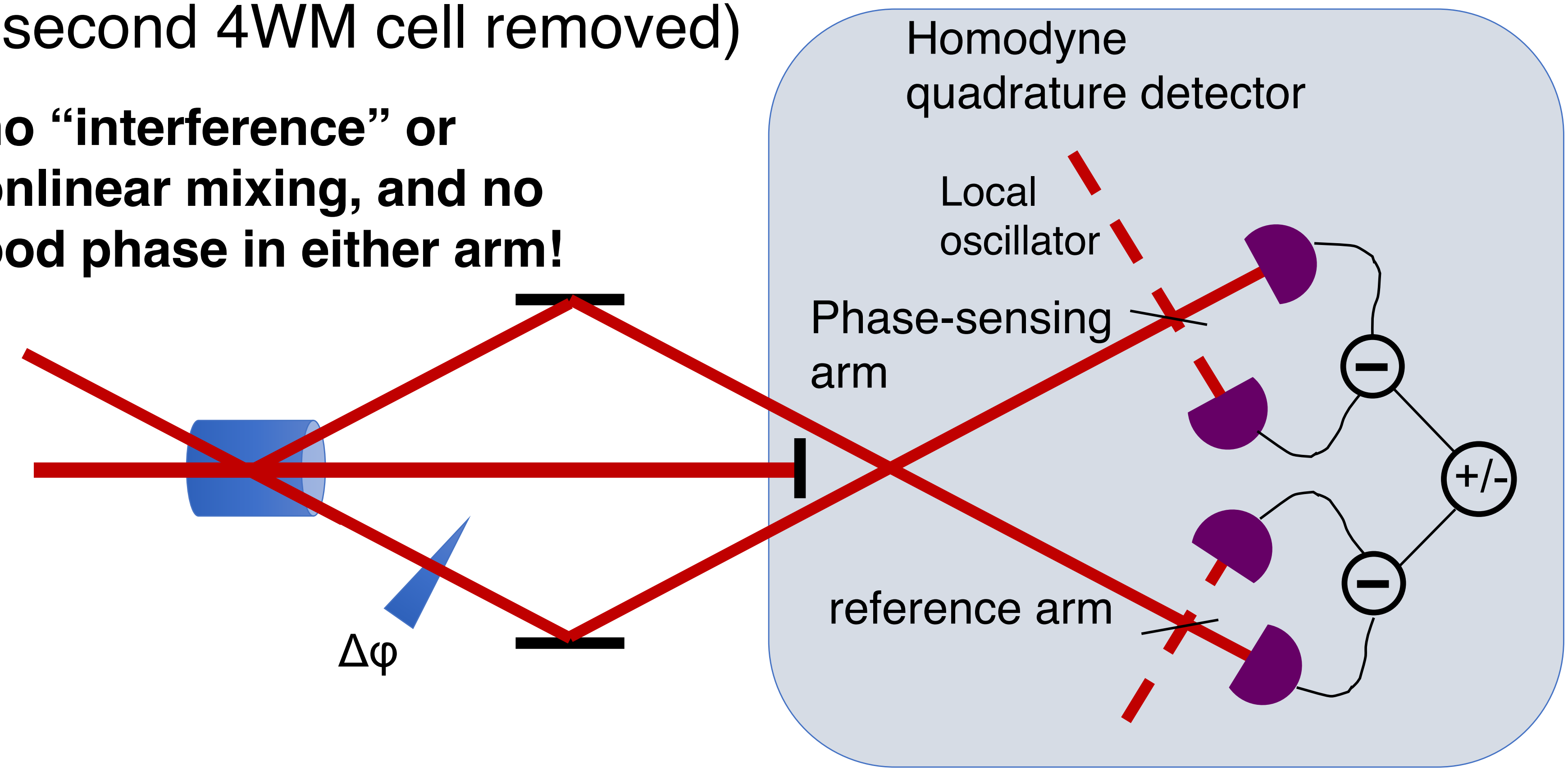
sensitivity scales as N^{-1}

Yurke, McCall, Klauder, “SU(2) and SU(1,1) interferometers,” PRA 33, 4033 (1986)

“truncated SU(1,1)”

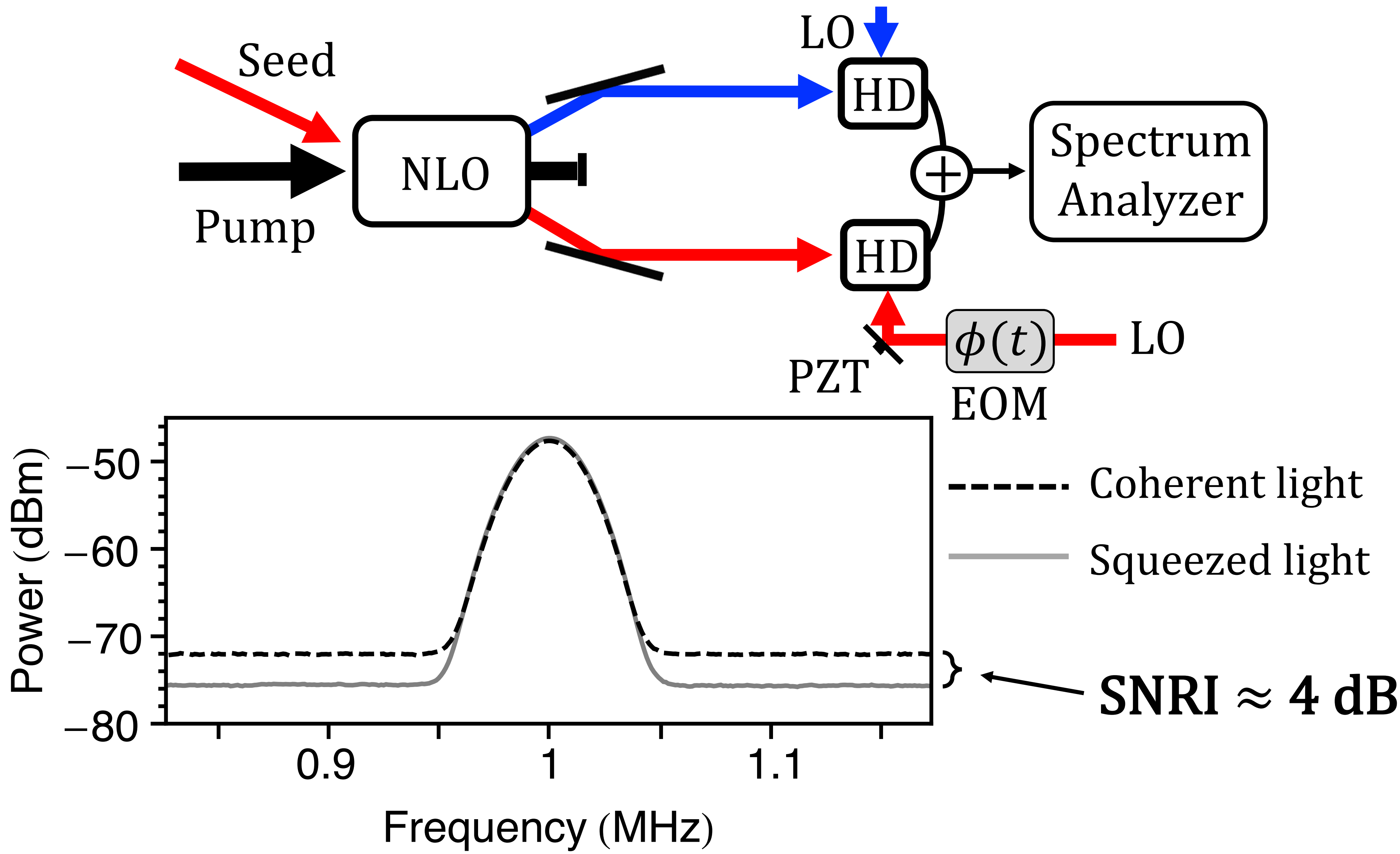
(second 4WM cell removed)

- no “interference” or nonlinear mixing, and no good phase in either arm!

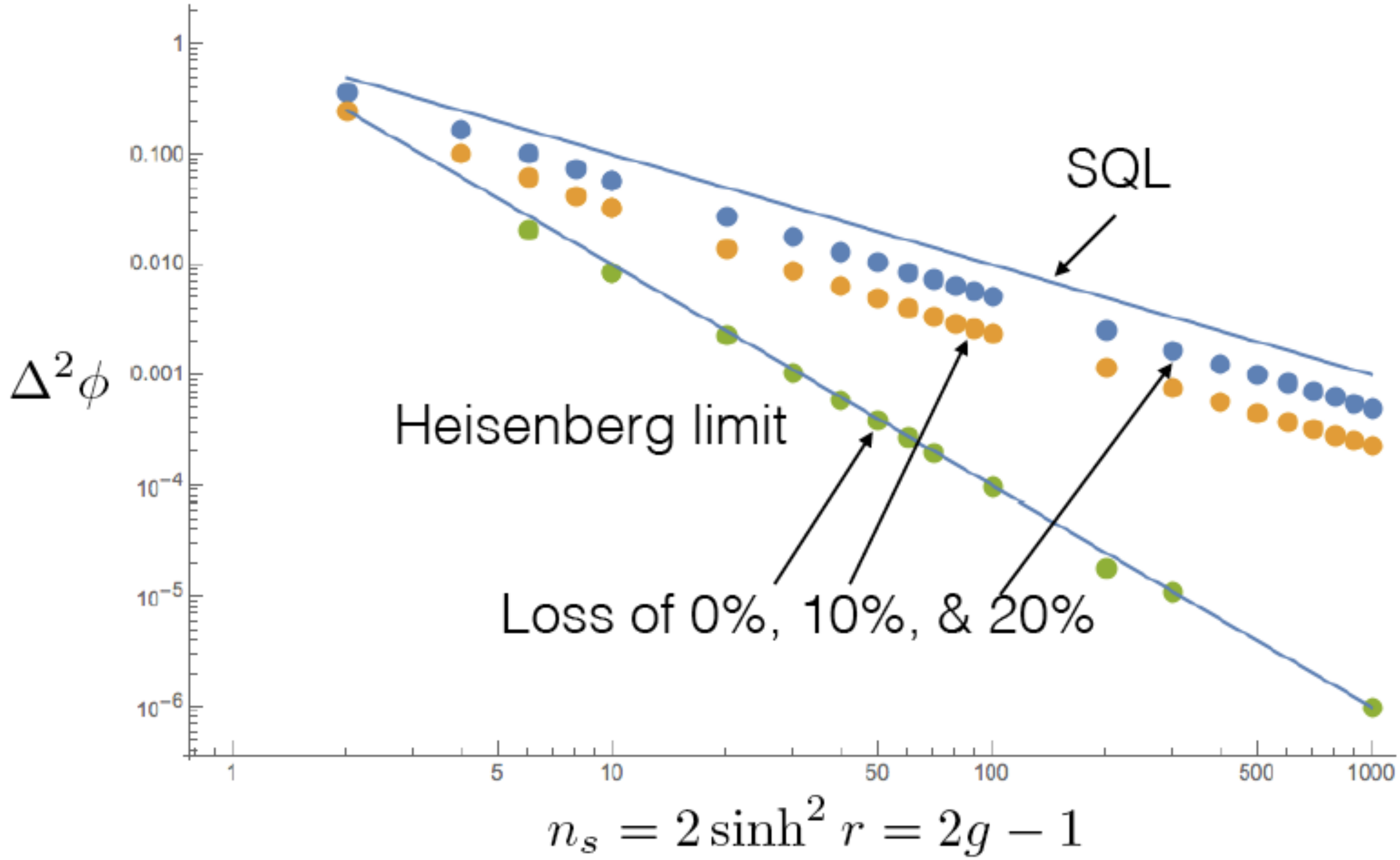


The “signal beam” here is a thermal state with a random phase; the “signal” is the quadrature-difference (or sum) noise when combined with the reference arm quadratures.... the noise on this signal is the noise on the quadrature-difference noise.

Experiment: the truncated SU(1,1) interferometer



Scaling for SU(1,1)



- sensitivity is improved, but only until losses limit the squeezing level

- scaling is 1/N, also only until losses limit the squeezing

conclusions

Squeezed light and entanglement in the optical fields can be used to improve measurements and make quantum sensors.

Limitations on squeezing (losses, bandwidth, wavelengths, difficulty of generation) can make this something of a "last resort" option – it is often just easier to turn up the laser power to get greater sensitivity, for instance. (You will notice that there are currently no commercial applications!)

Opportunities are still there both with conventional nonlinear optics, but also fiber-optic amplifiers, superconducting junction amplifiers for squeezed microwave fields, etc., and innovative quantum measurements.