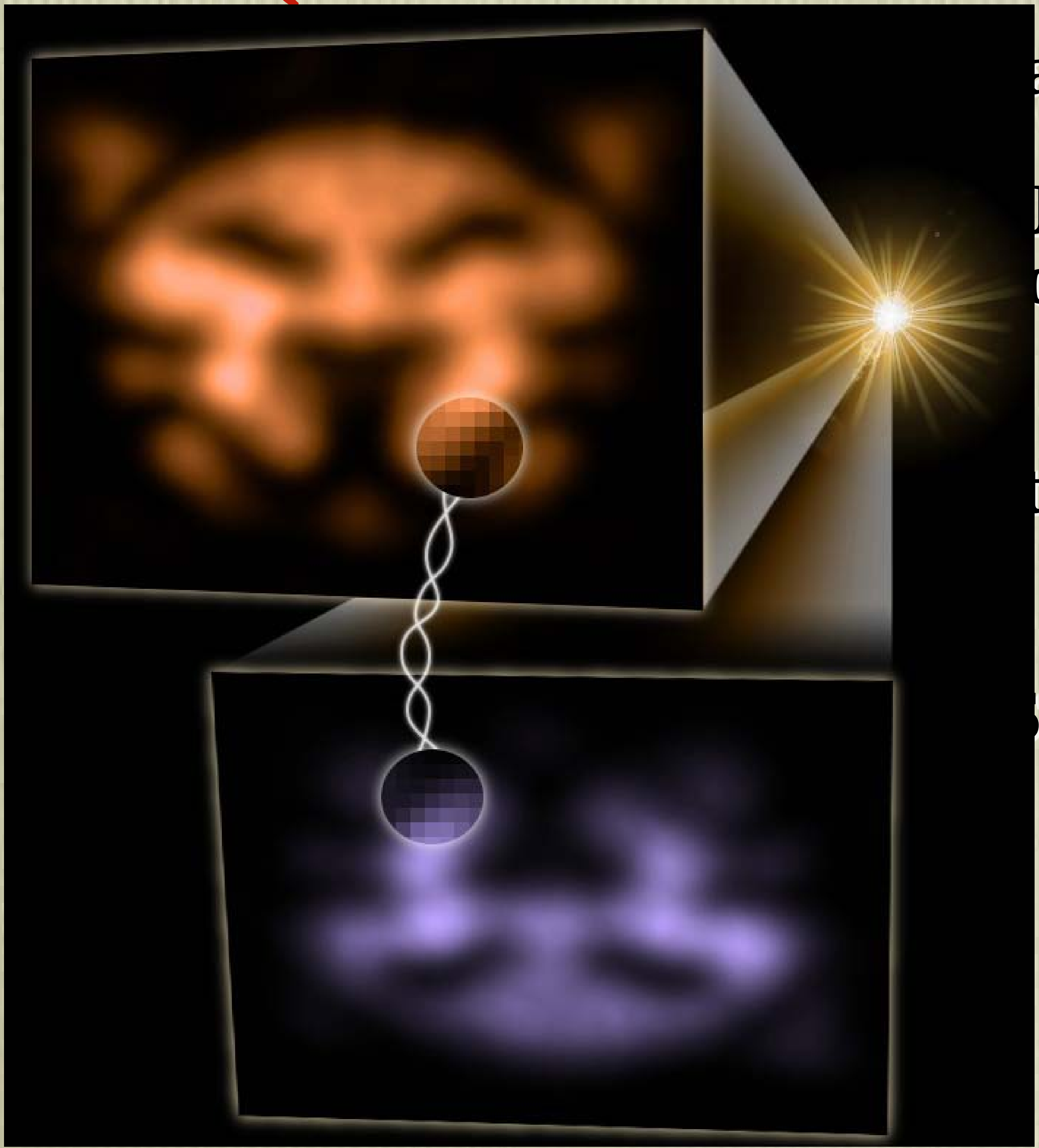
Quantum Imaging: Spooky images at a distance (and what to do with them)



aul D. Lett,
Jones*, Alberto Marino**,
Jeremy Clark, Ryan Glasser,
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and

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funding from AFOSR, DARPA

Ever wonder how to make a quantum image?
Probably not,...
but what you would do with a quantum image if you had one?

but first... just what **is** a "quantum image"?

Having faced these questions I can give you our answers...

motivation: quantum information processing
image processing
general marketing

Quantum Advantages?

using “squeezed light”

Note that there have not been an incredible number of applications that have rolled out over the years...

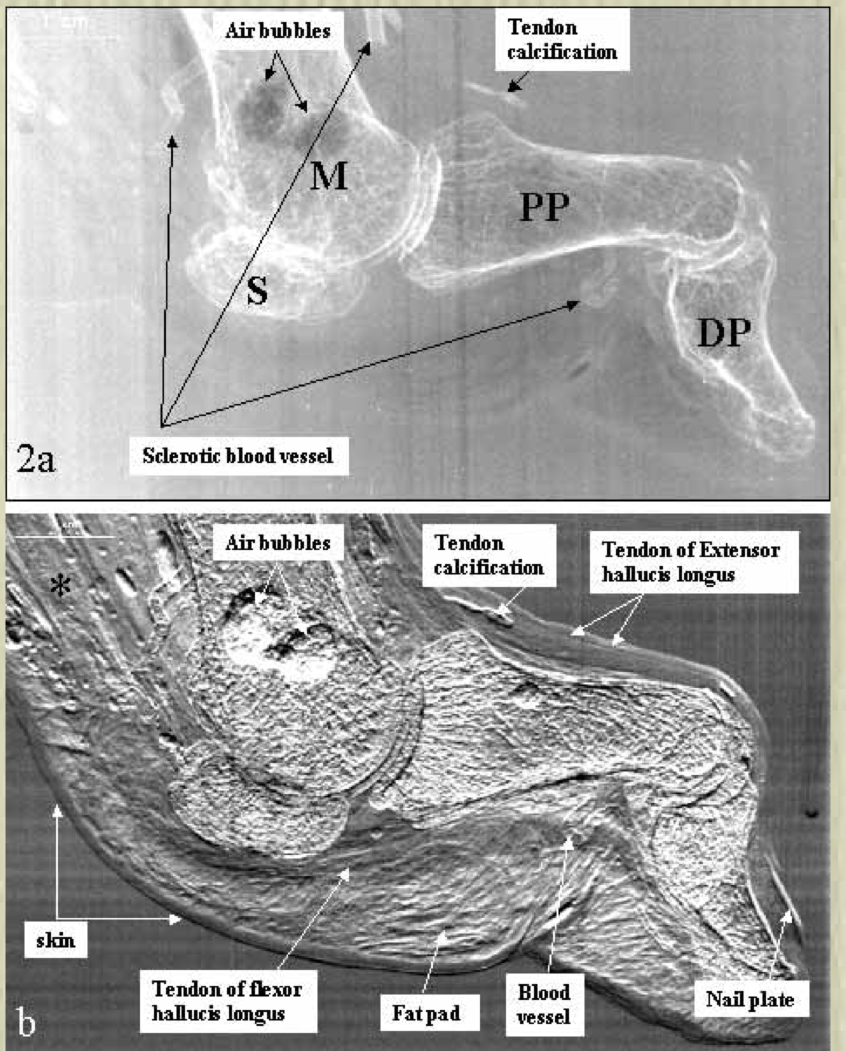
Generally it has to:

(1) be worth the substantial hassle, and

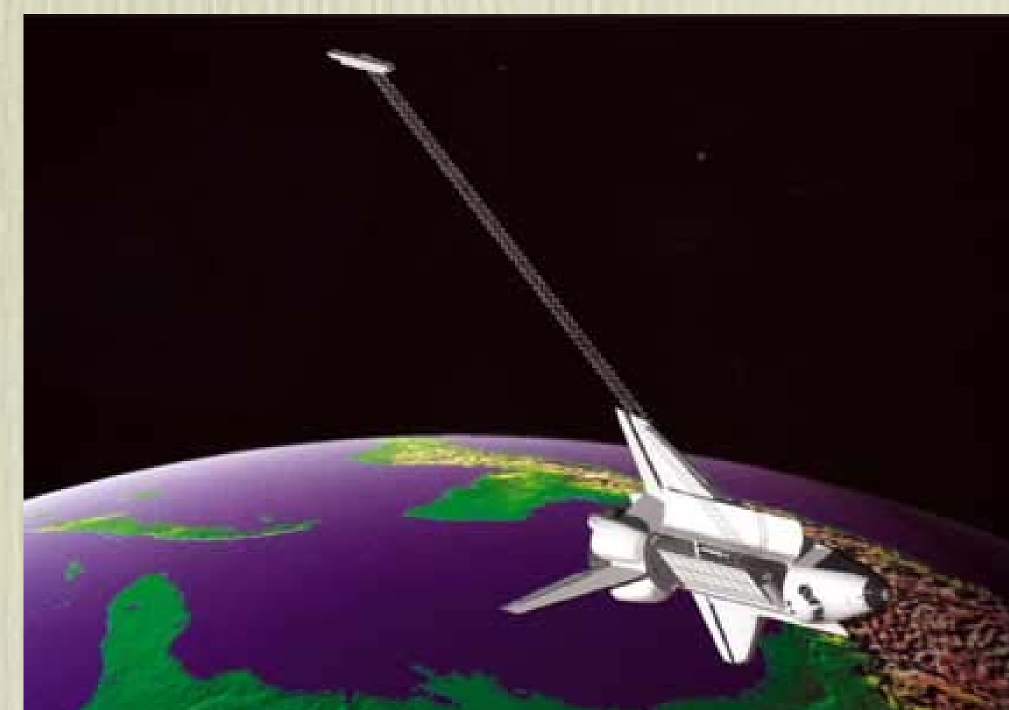
(2) not just be easier to turn up the power.

➔You are left with light-starved applications or places where you just can’t or don’t want to turn up the power for fear of burning things...

motivations...

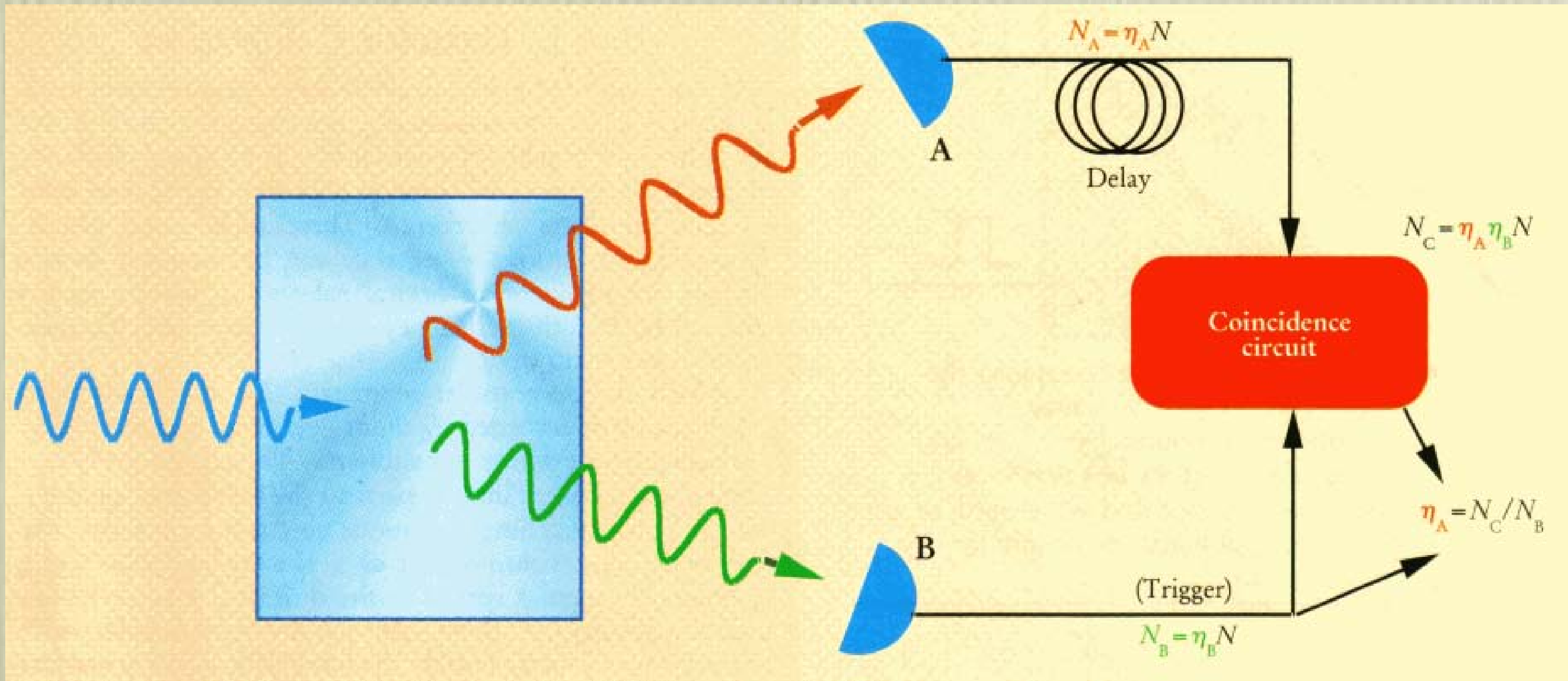


- lets face it... “quantum” generally means “fragile” as well - where is this potentially useful?
- soft tissue imaging or imaging live cells or other bits where you can’t turn up the laser
- satellite imaging?
- LIGO



metrology motivation

- interferometry
- length metrology
- sensitive detection
- quantum information processing
- photodiode calibrations/ calibrated light sources



we are NIST,
after all...

our program:

make quantum images
(and do something with them)

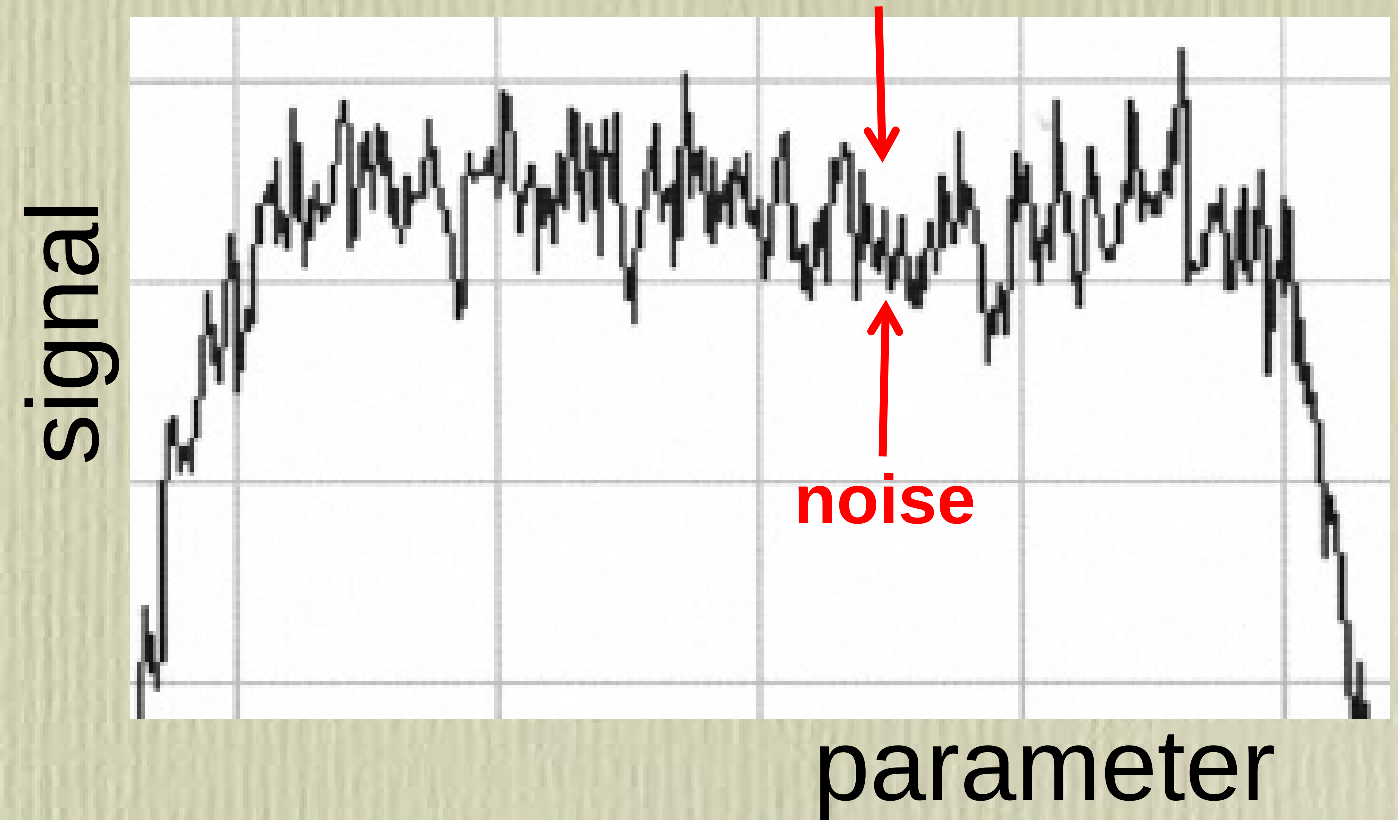
quantum images to make higher resolution or sensitivity

information processing (quantum or classical) with improved performance; optical memory

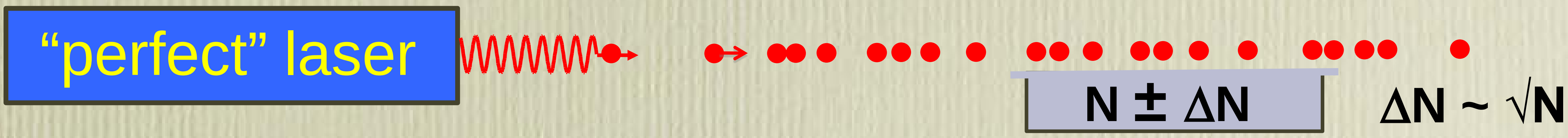
fundamental questions, such as, how fast can a quantum correlation go?

we are not alone... others have gone before us!

NIST: "Measurements Я Us"



Noise limits all measurements, and the ultimate limit of noise is quantum noise.



"Ordinary" laser light can never be measured better than this "shot noise" limit. Similar shot noise limitations apply to important measurements like atomic fountain and trapped ion clocks. These limitations are <u>fundamental</u>, based on Heisenberg's uncertainty principle.

Heisenberg:

$$\Delta x \Delta p \geq \hbar/2$$

$$\Delta N \Delta \phi \geq 1$$

For laser light: $\Delta\phi = 1/\sqrt{N}$ and $\Delta N = \sqrt{N}$ $\qquad \dfrac{\Delta N}{N} = \dfrac{1}{\sqrt{N}}$

But we can make ΔN *smaller* at the expense of making $\Delta\phi$ *larger*

(when we don't care about phase).

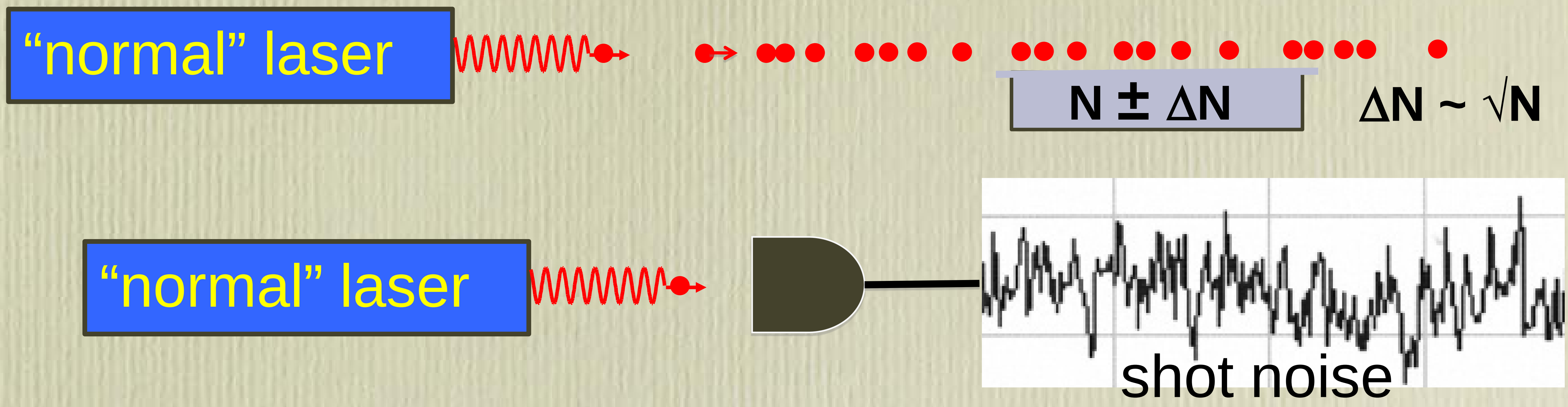
This is called "quantum squeezing."

Doing this is so hard that typically one just accepts the shot noise limit and makes N bigger. But sometimes the available or allowable N is small enough, and the application is critical enough that you turn to squeezing:

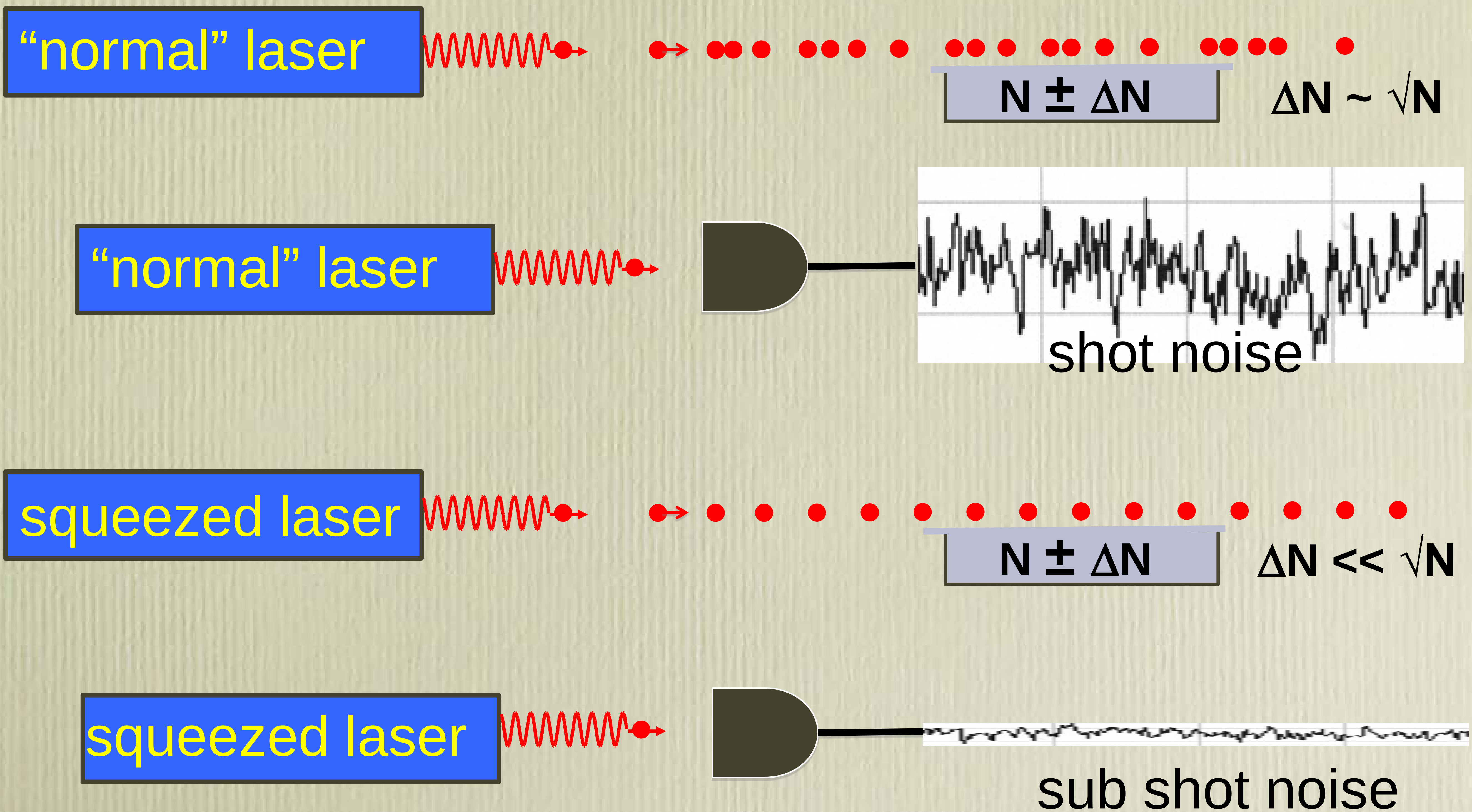
- Atomic Clocks;
- Laser Interferometer Gravity-wave Observatory (LIGO)

(neither of which *yet* use squeezing for "real" measurements.)

Intensity Squeezing

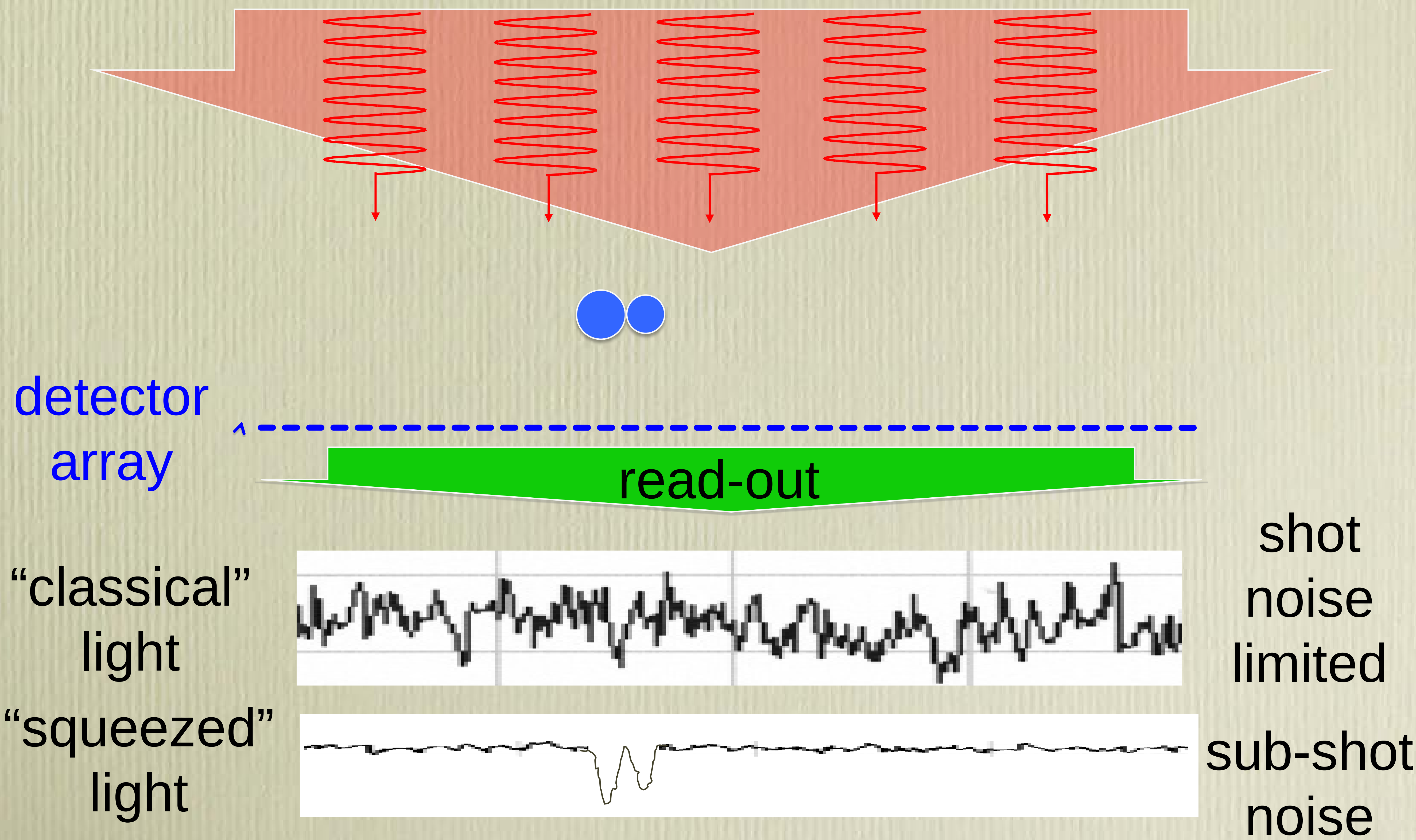


Intensity Squeezing

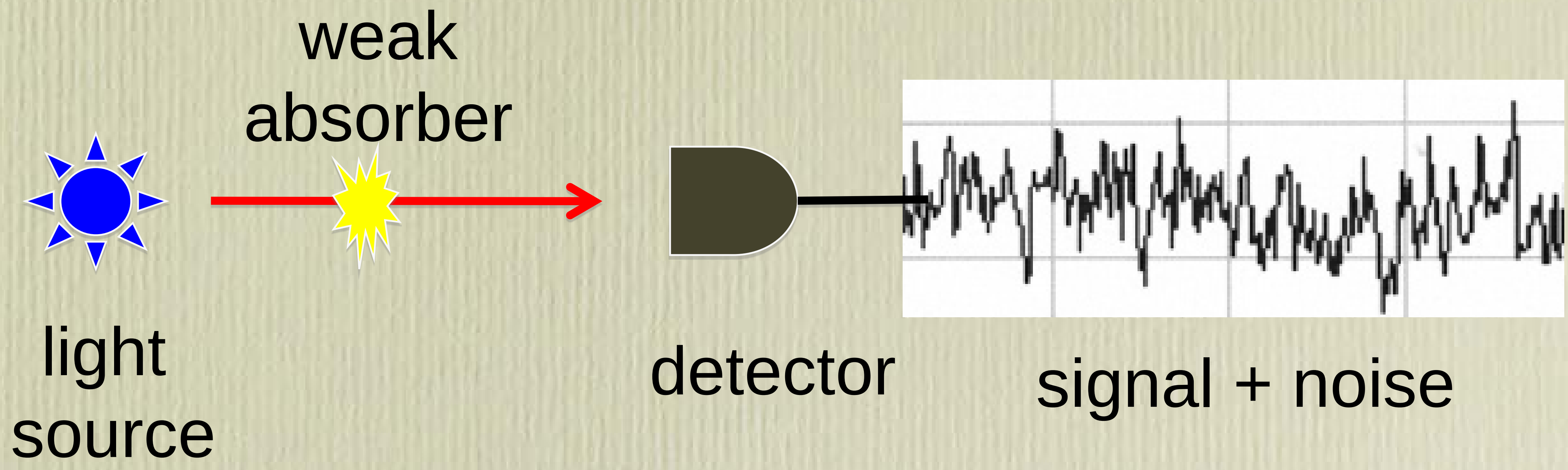


Another Application for Quantum Light: Imaging

N.B.: over-simplified example

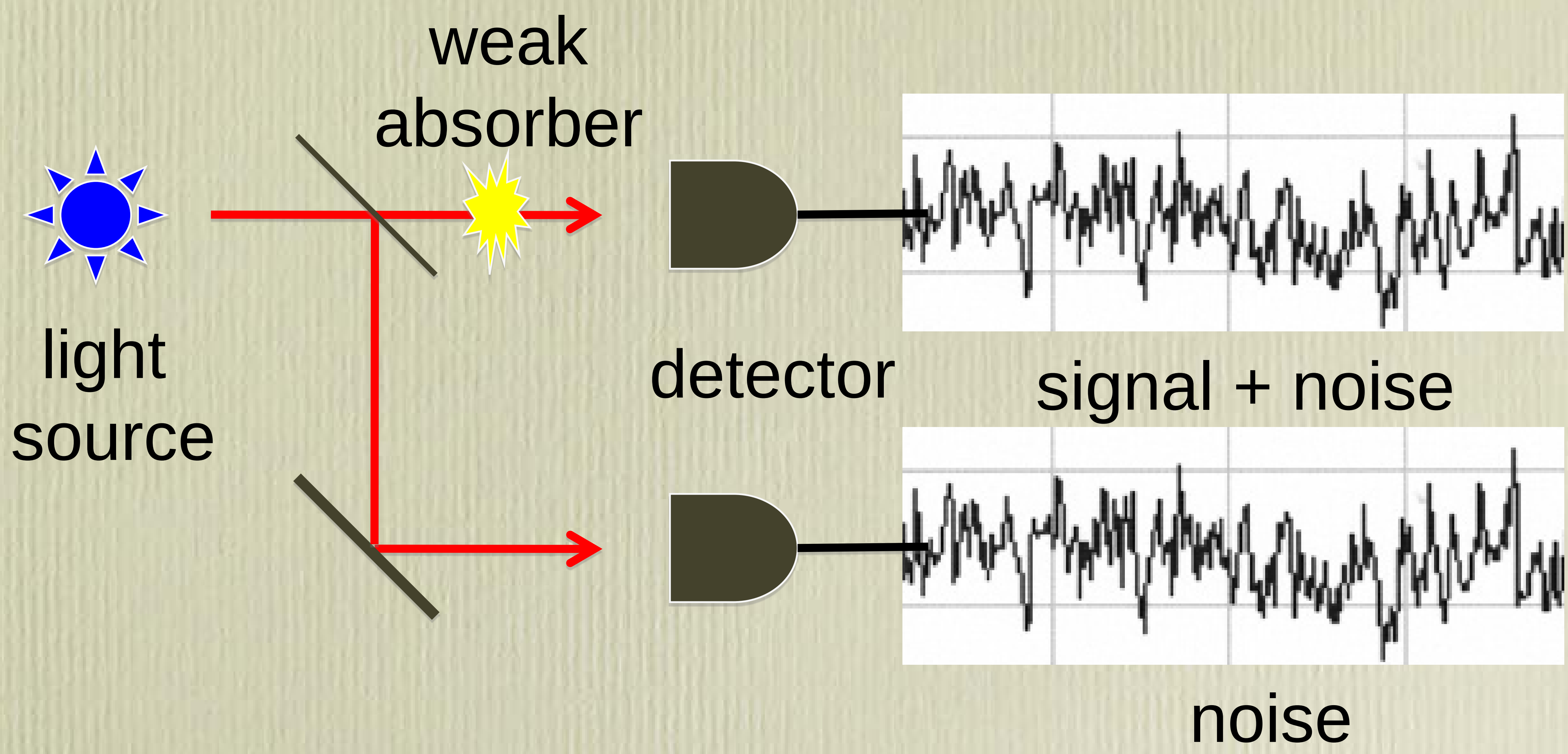


making use of correlations



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

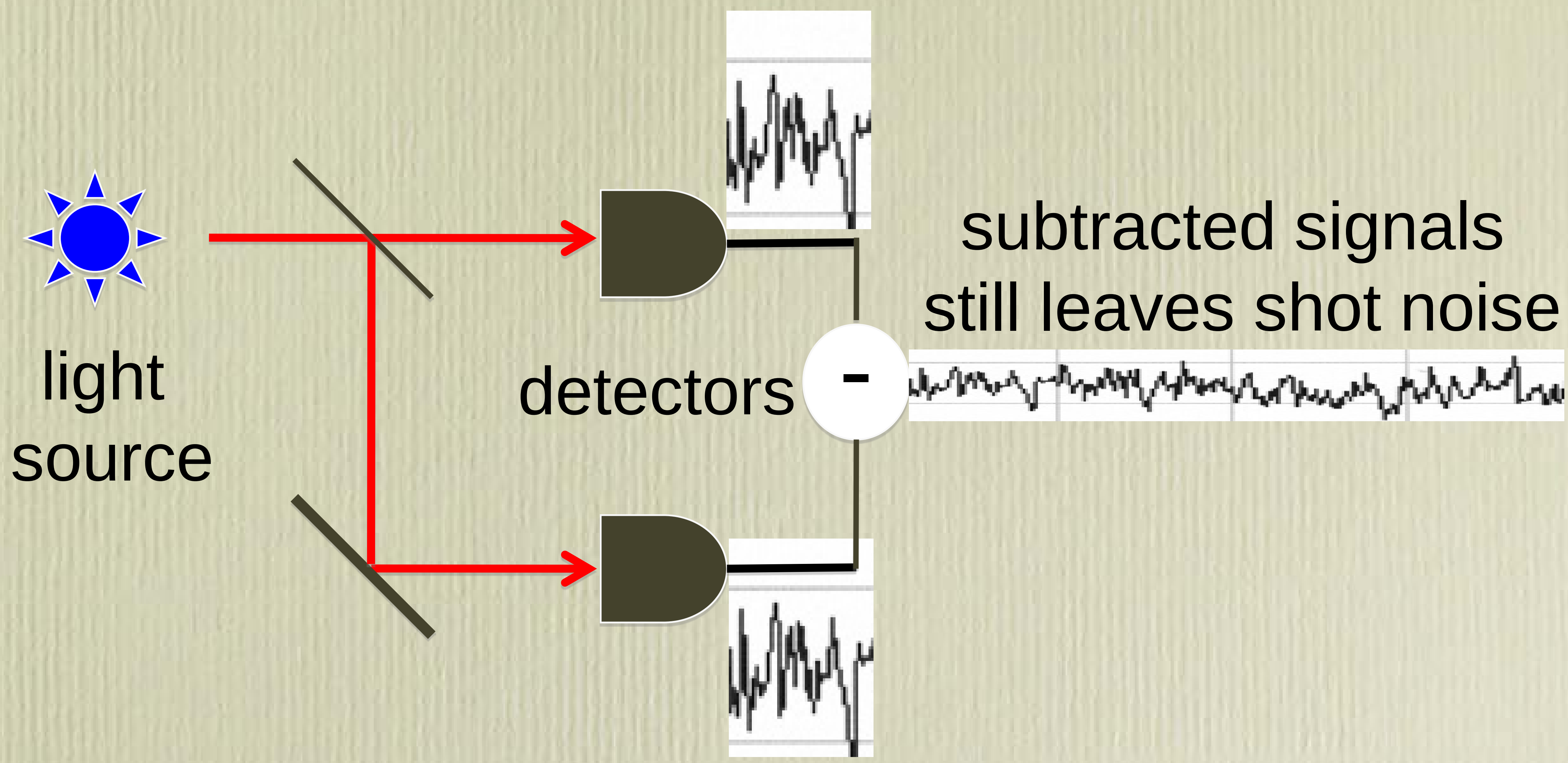
the advantage of classical correlations



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

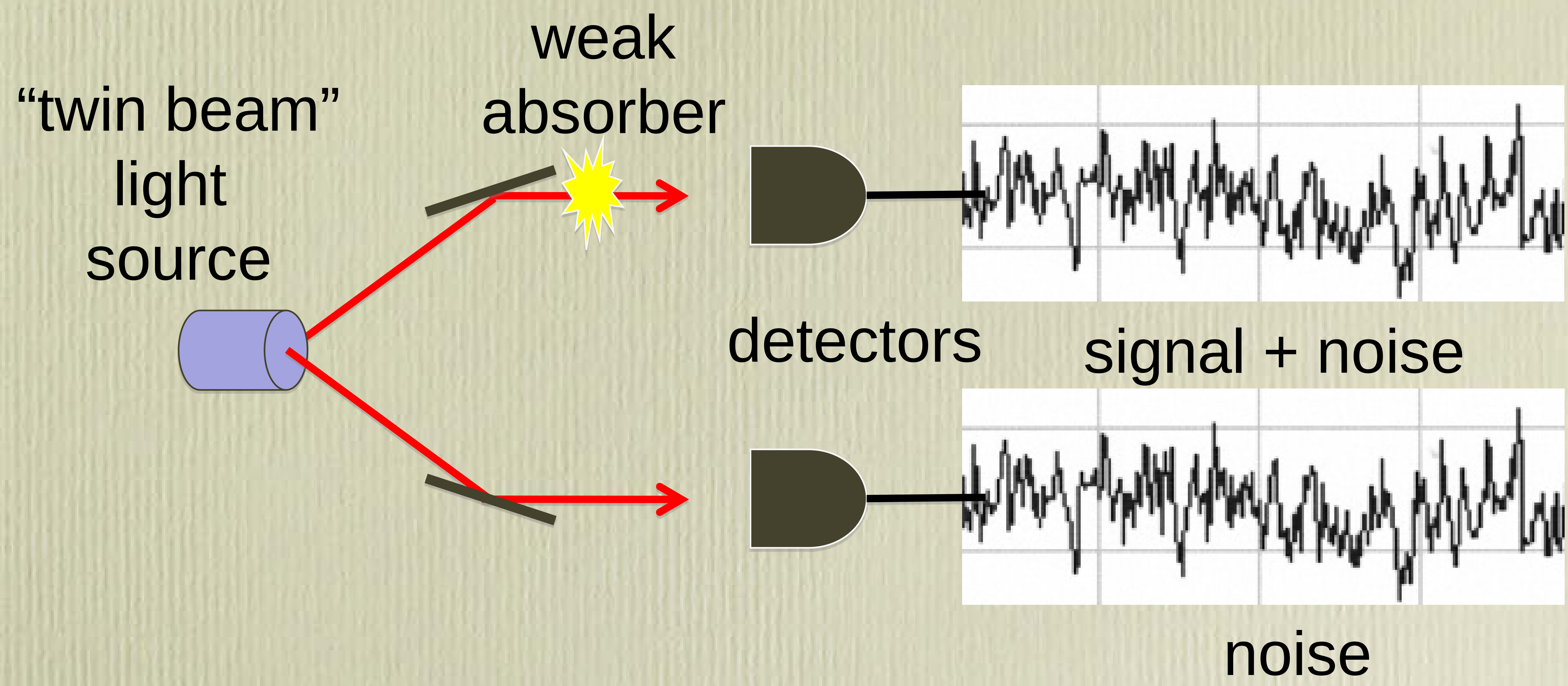
it is easier to detect the signal.

the PROBLEM of classical correlations



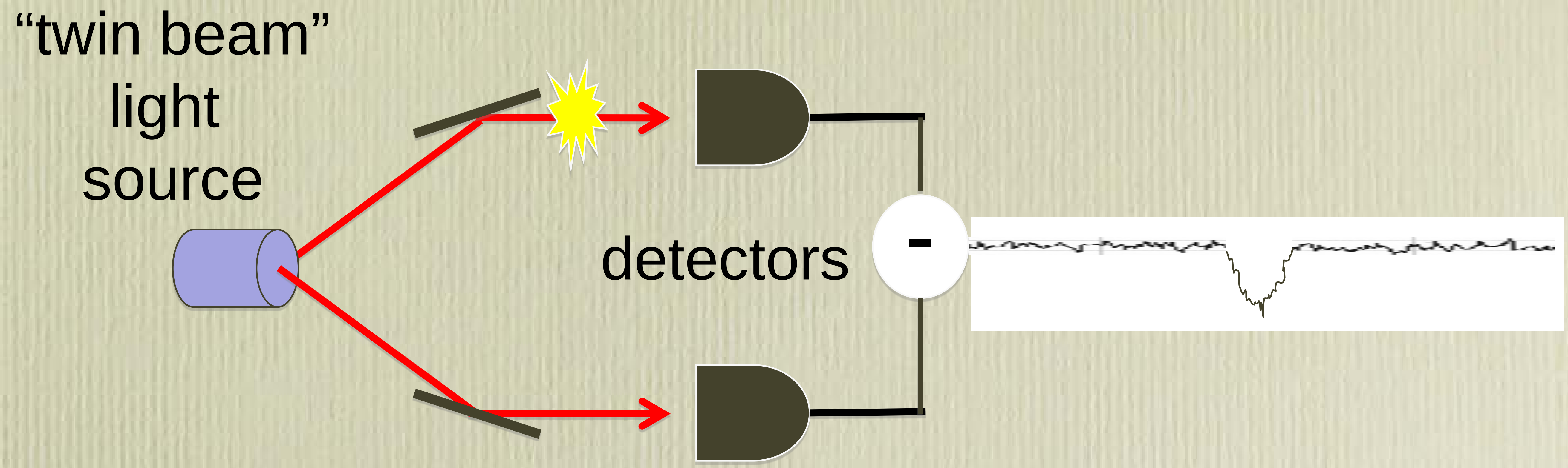
A beamsplitter or half-silvered mirror can "duplicate" only the classical noise on the beam; the "shot noise" due to photons "randomly deciding" which way to go is uncorrelated and adds.

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

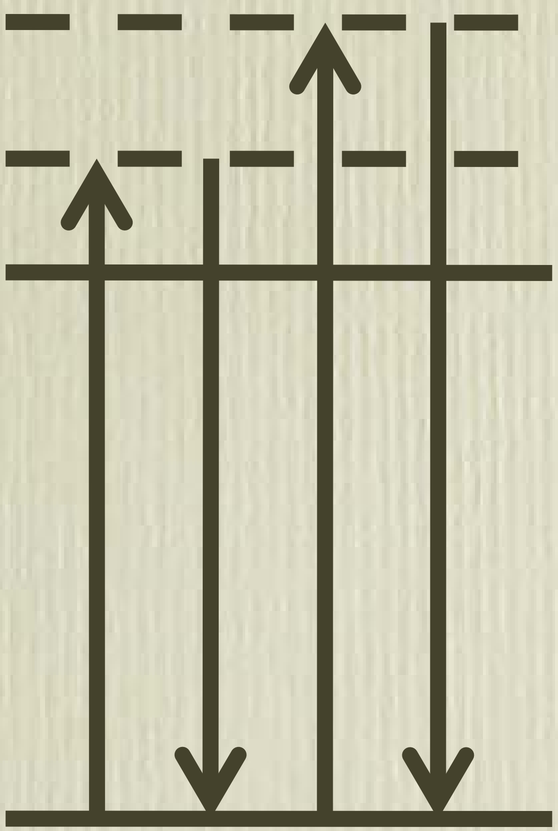


A “twin beam” squeezed-light source will duplicate the fluctuating probe, including any quantum noise. Thus we can subtract even the quantum noise, and detect previously undetectable signals.

4-Wave Mixing

$$P_4(t) = \chi^{(3)} E_1(t)E_2(t)E_3(t)$$

a "parametric" process; it leaves the (atomic) medium in the state that it started in...



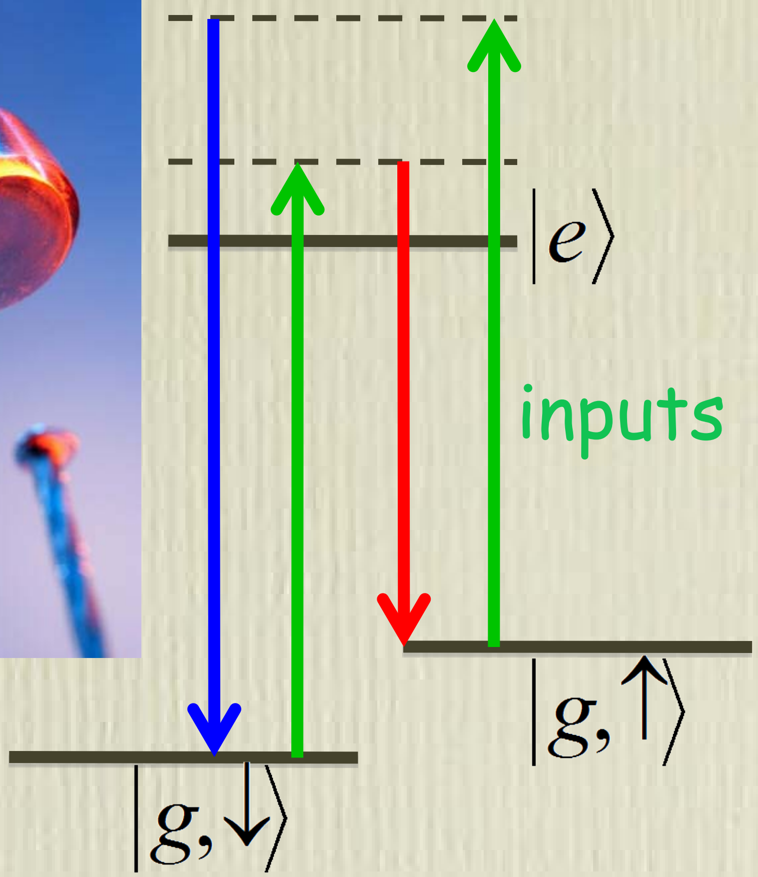
it does not have to involve a "real" transition and can be off-resonant

four-wave mixing
(the optical scientist's universal tool)

when you have a hammer
everything looks like a nail

we use it to make:

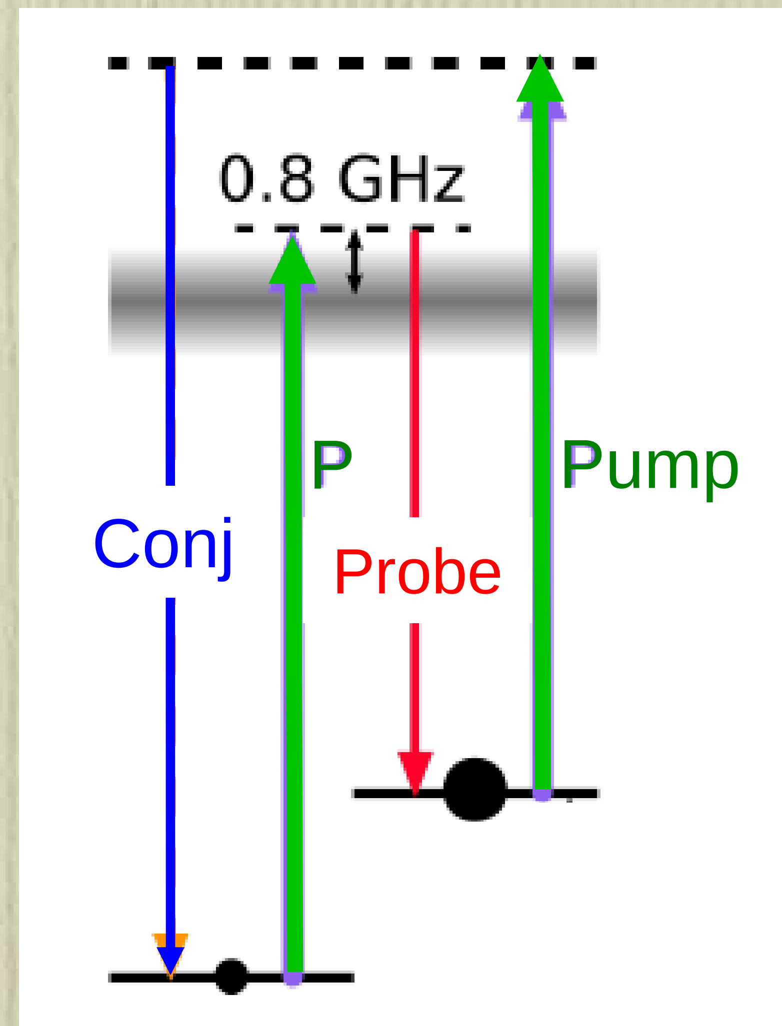
- squeezed light
- amplifiers
- slow light
- fast light



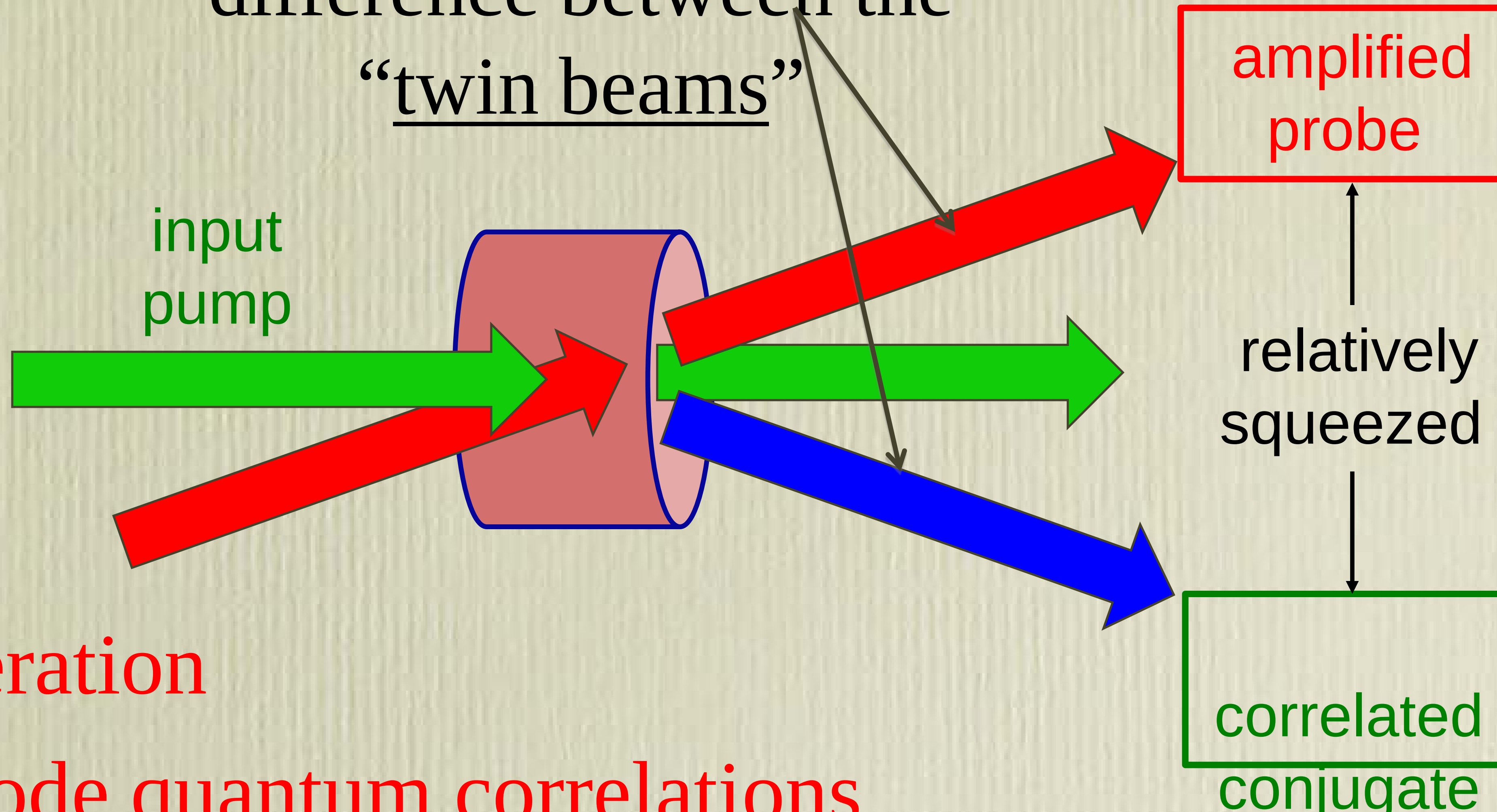
Squeezed
outputs

when it works... you go with it

What do we expect from 4-Wave-Mixing (4WM) in the quantum limit?



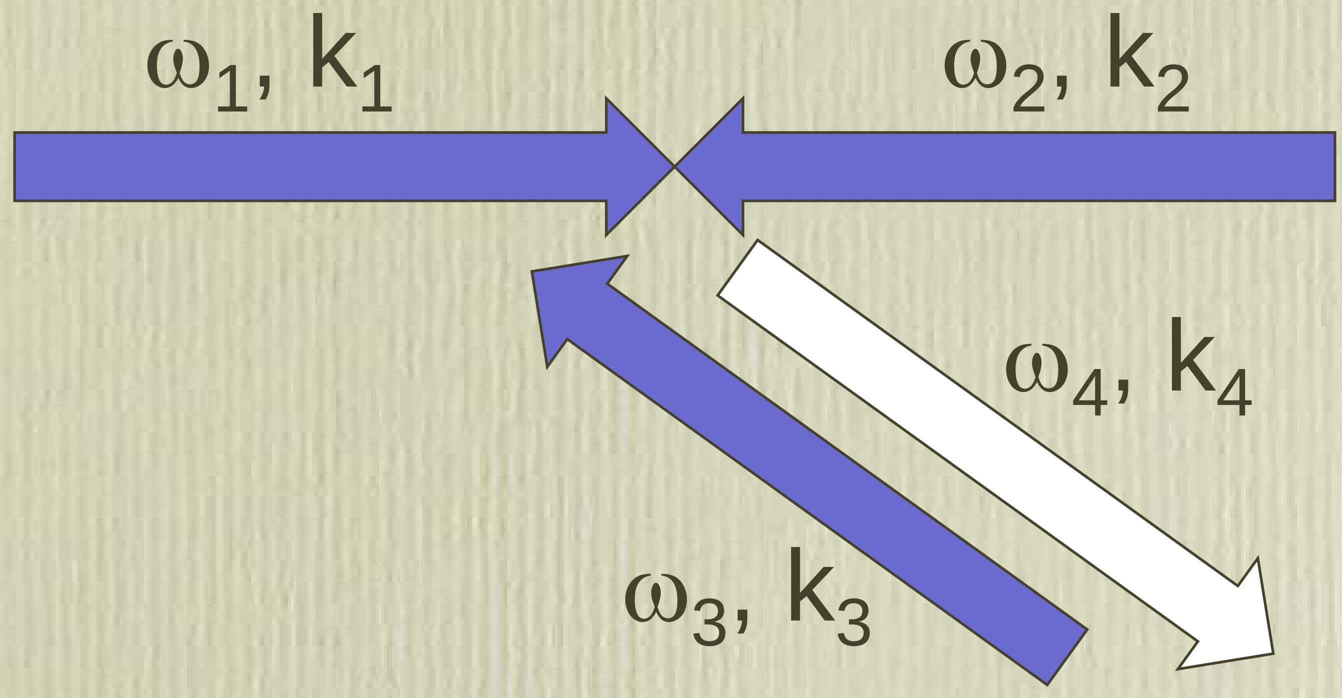
non-classical, sub-shot-noise intensity difference between the "<u>twin beams</u>"



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

phase matching conditions

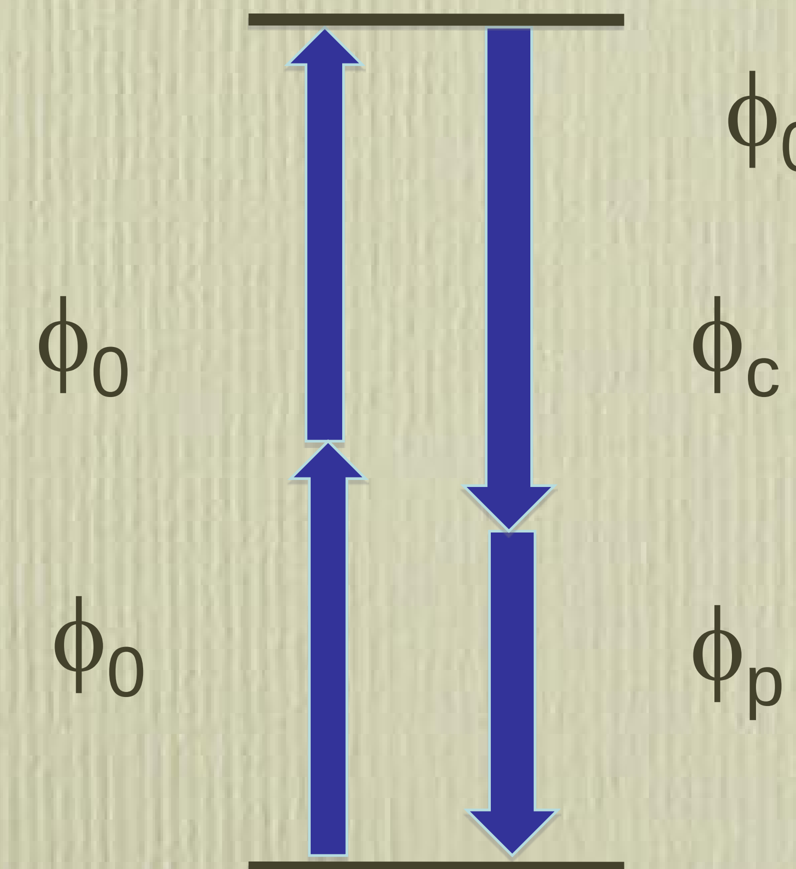
energy conservation: $\omega_1 + \omega_2 = \omega_3 + \omega_4$



momentum conservation: $\vec{k}_1 + \vec{k}_2 = \vec{k}_3 + \vec{k}_4$

phase sum and intensity difference relations

phase-sum squeezing



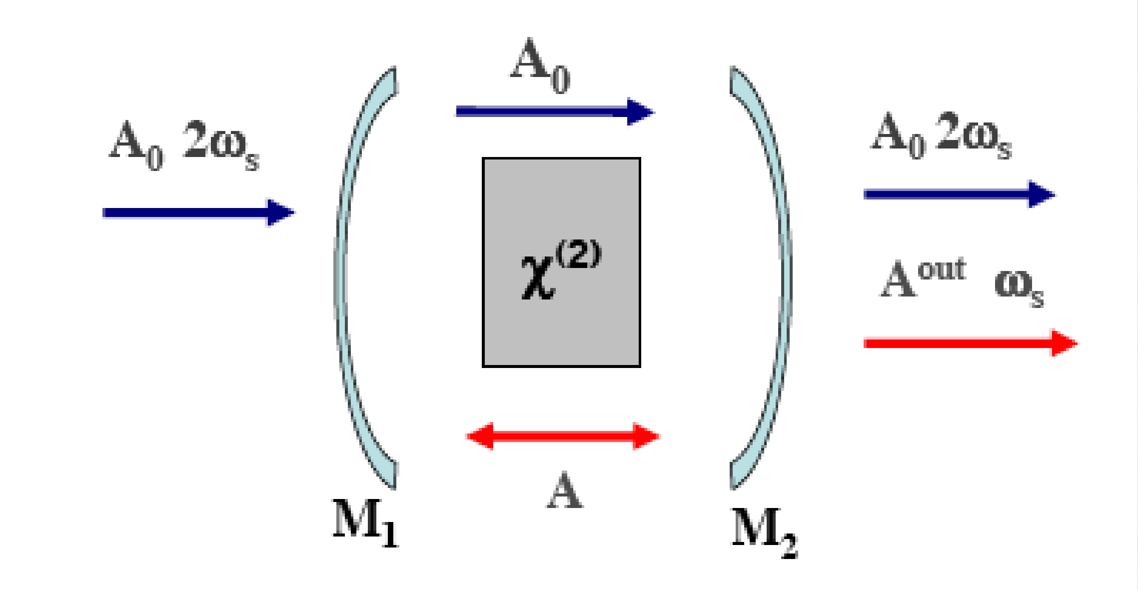
$\phi_0 + \phi_0 = \phi_p + \phi_c$

“intensity-difference squeezing”

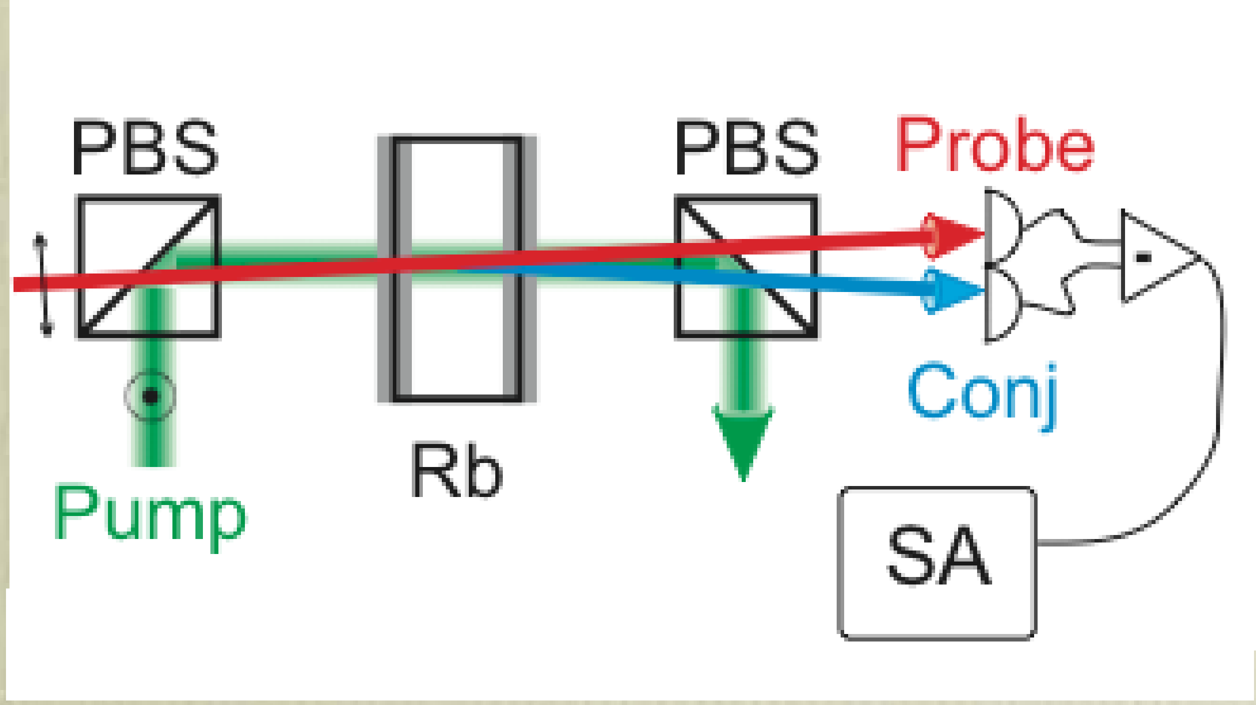
is really “photon-number-difference squeezing”

(same number of photons in each beam)

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



OPO
(optical
parametric
oscillator)



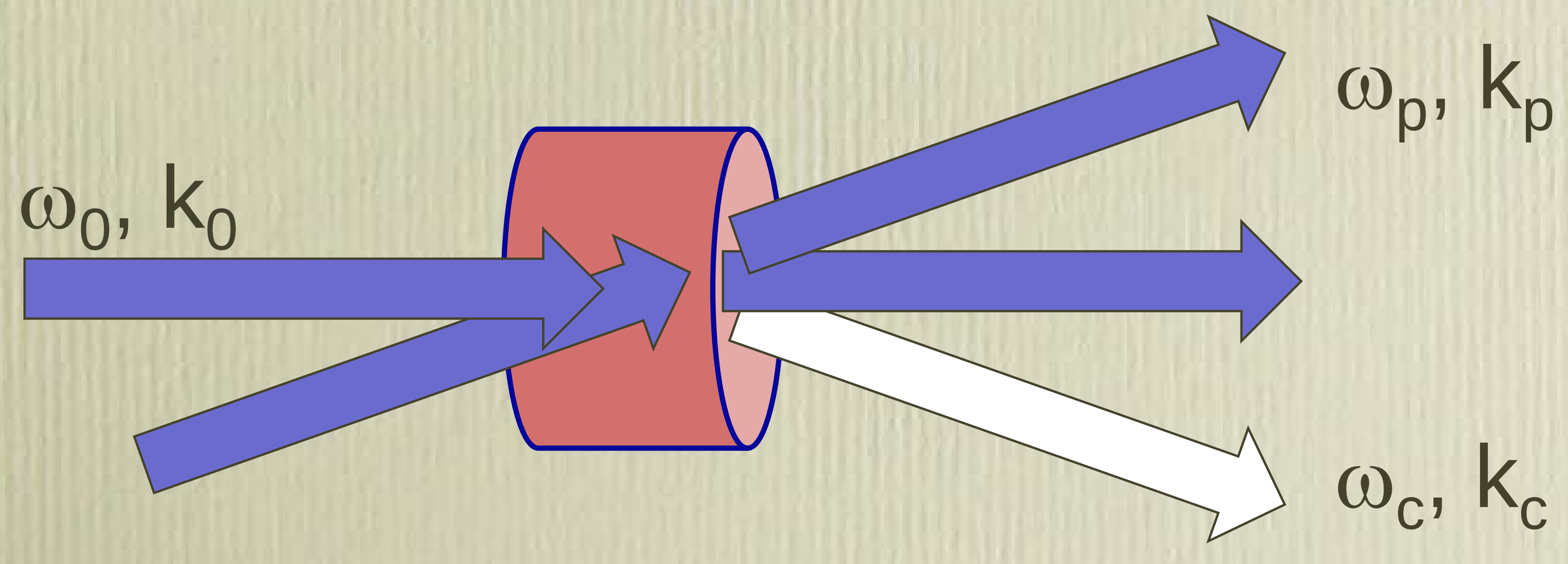
4WM
(four-wave
mixing)

entangled twin beams

- intensity difference squeezing tells you about correlations
- entanglement requires two variables simultaneously squeezed:

intensity-difference and phase-sum correlations

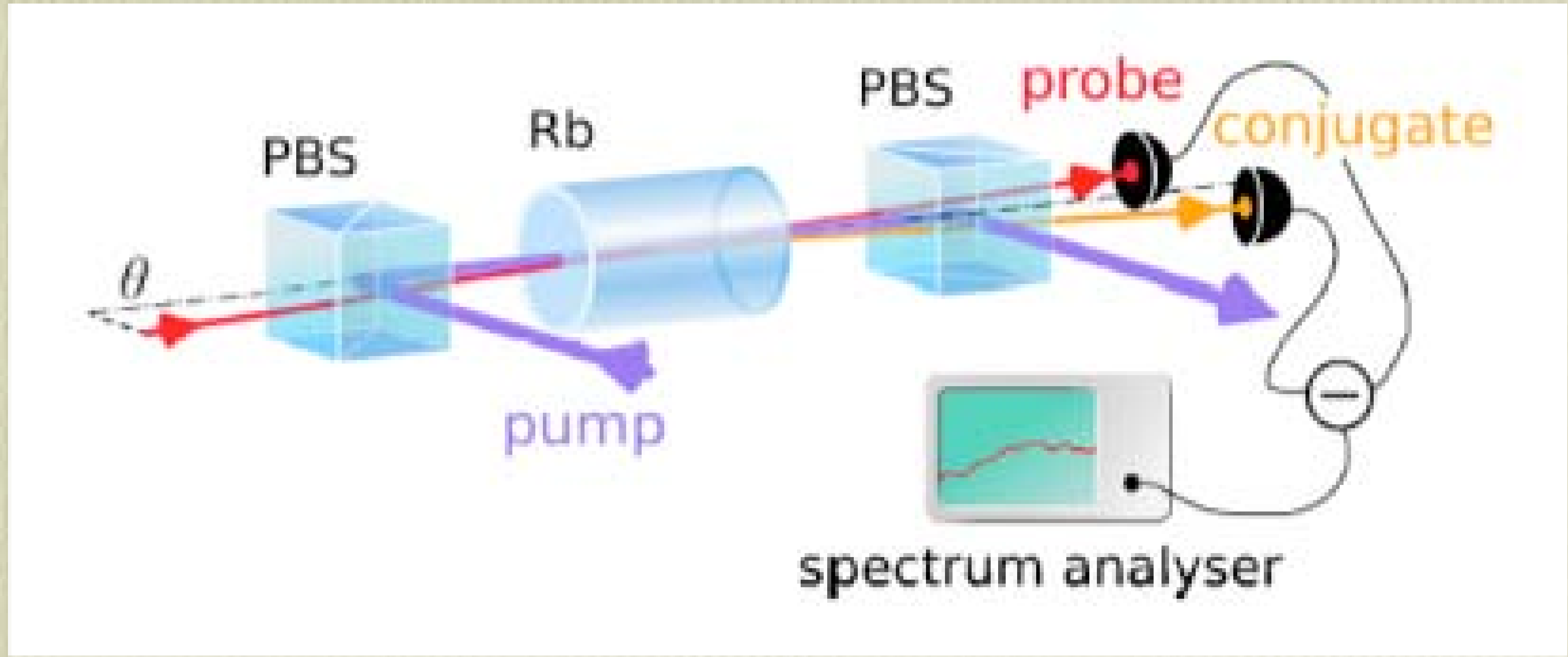
- inseparability of the wavefunction
- continuous-variable EPR violations (guarantee for mixed state) require a level of squeezing beyond 50% (3 dB) in each variable



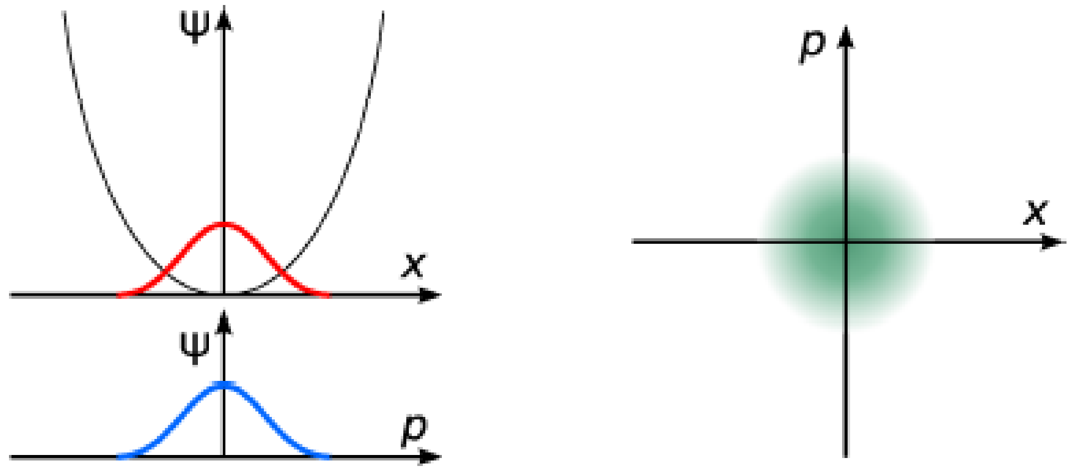
high-tech equipment:

ok, we have some nice lasers too...

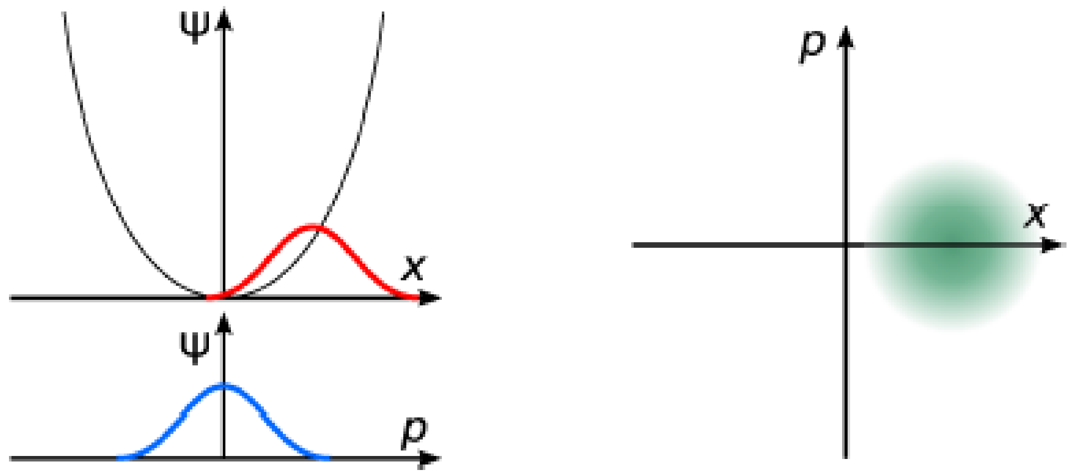
sophisticated experimental arrangements



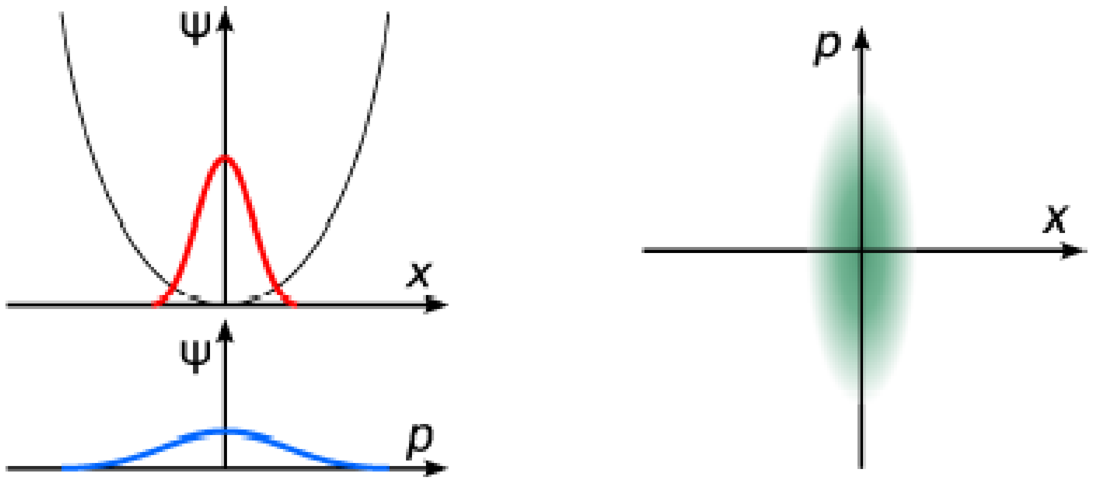
Single-mode squeezing



- 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

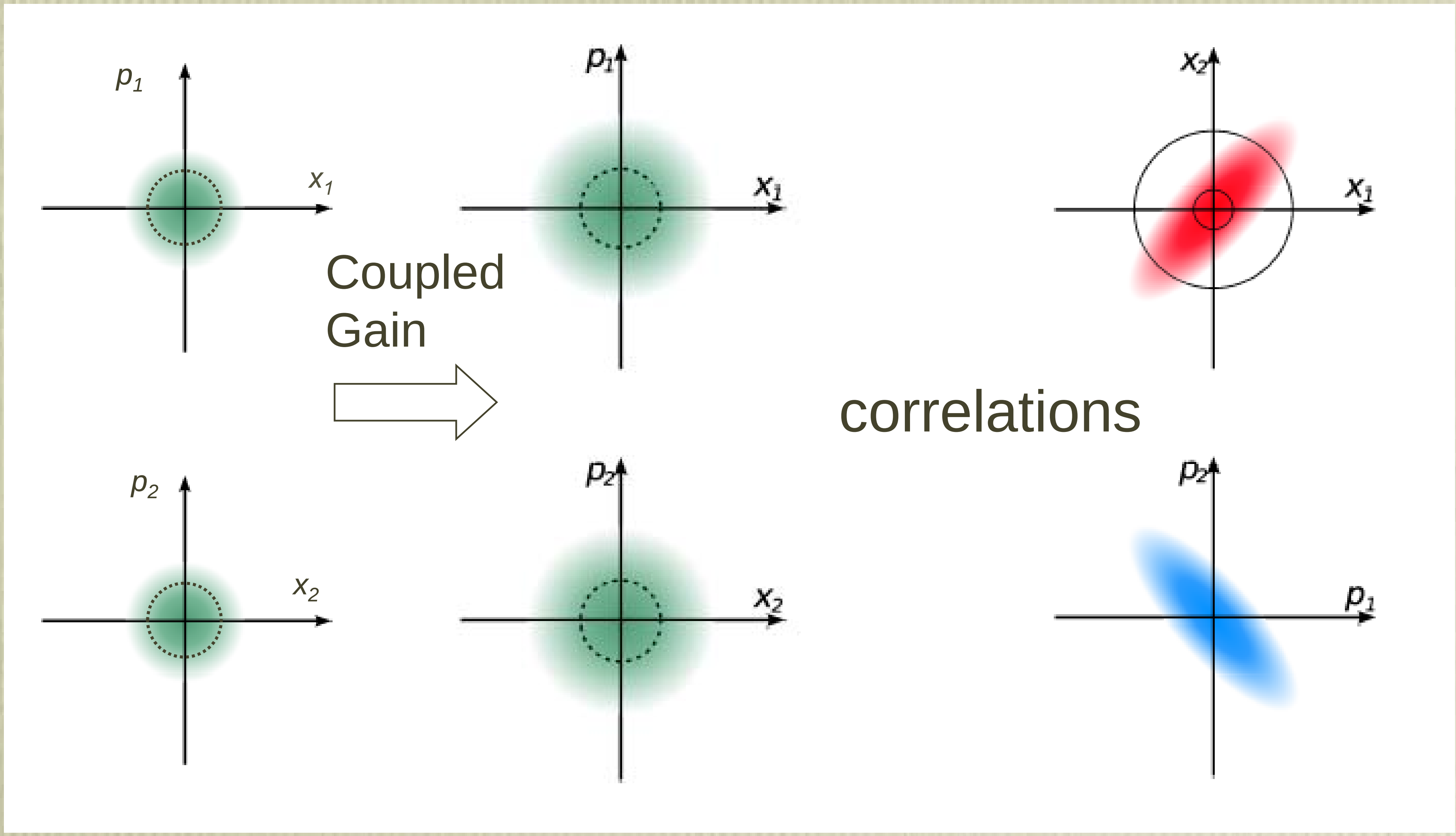


- Coherent state: $$\langle \Delta \hat{X}^2 \rangle = 1$$ $$\langle \Delta \hat{Y}^2 \rangle = 1$$



- Squeezing: $$\langle \Delta \hat{X}^2 \rangle < 1$$ $$\langle \Delta \hat{Y}^2 \rangle > 1$$
- Pairs of photons
- Generalize to bright beam

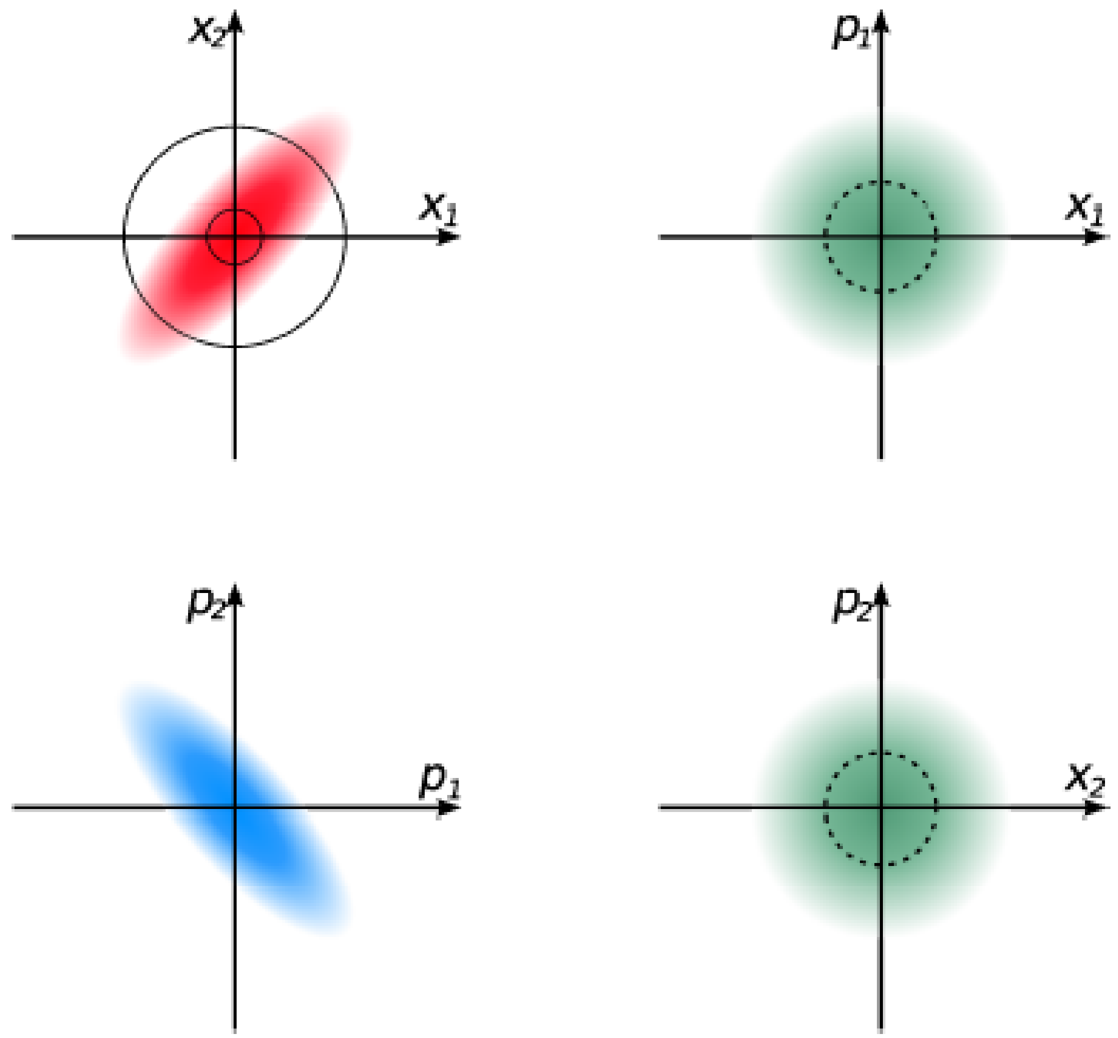
Two-mode squeezing: phase-insensitive amplifier



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:

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

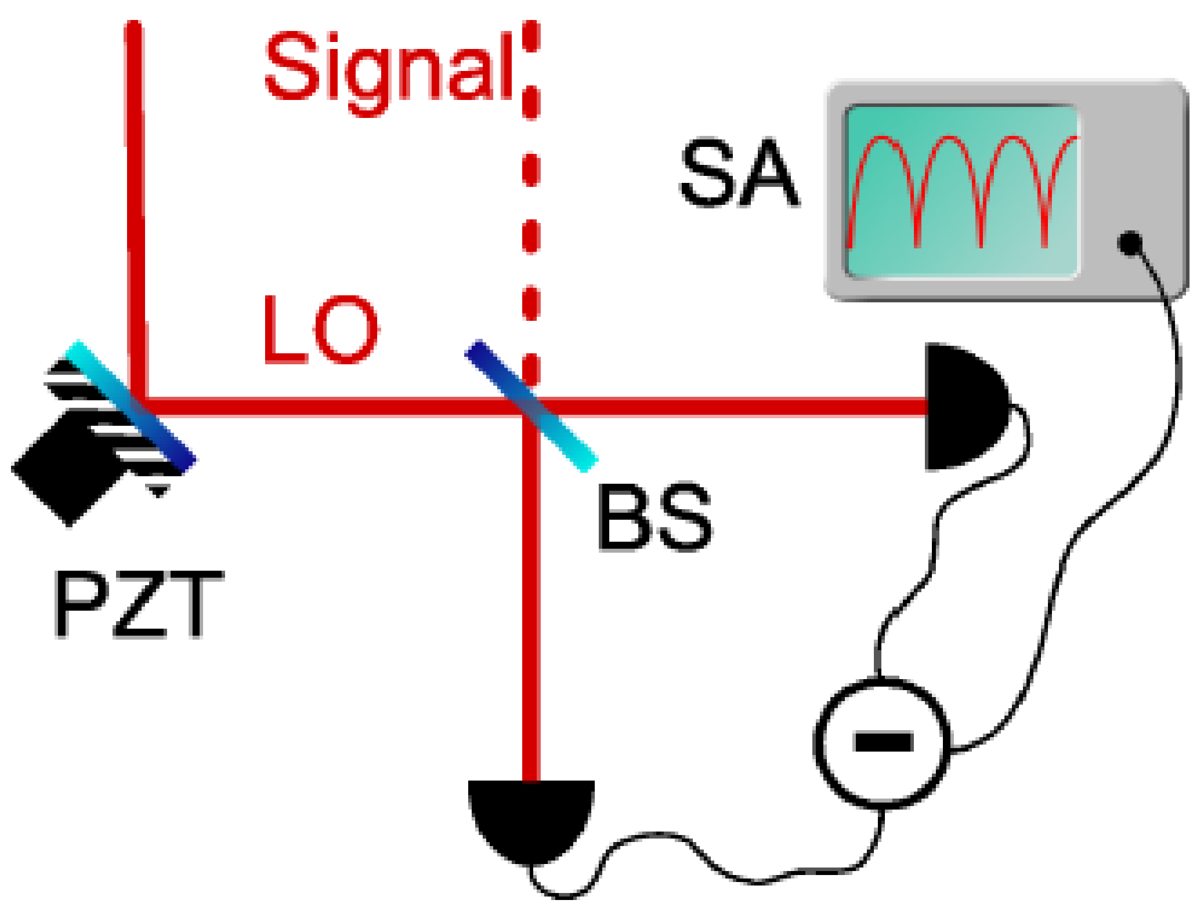
$$\langle \Delta \hat{Y}_+^2 \rangle < 1$$

- Individual modes are noisy:

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

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

homodyne detection



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

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

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

$$E >> \varepsilon$$

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

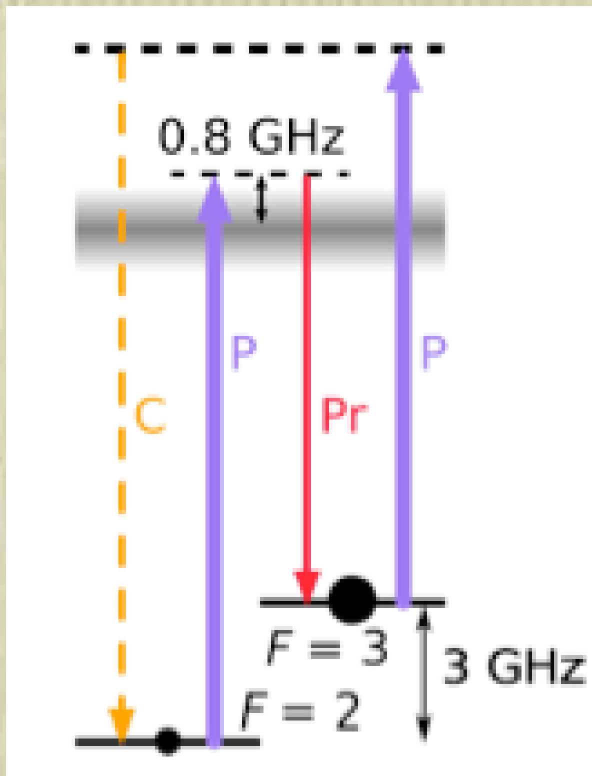
world records:

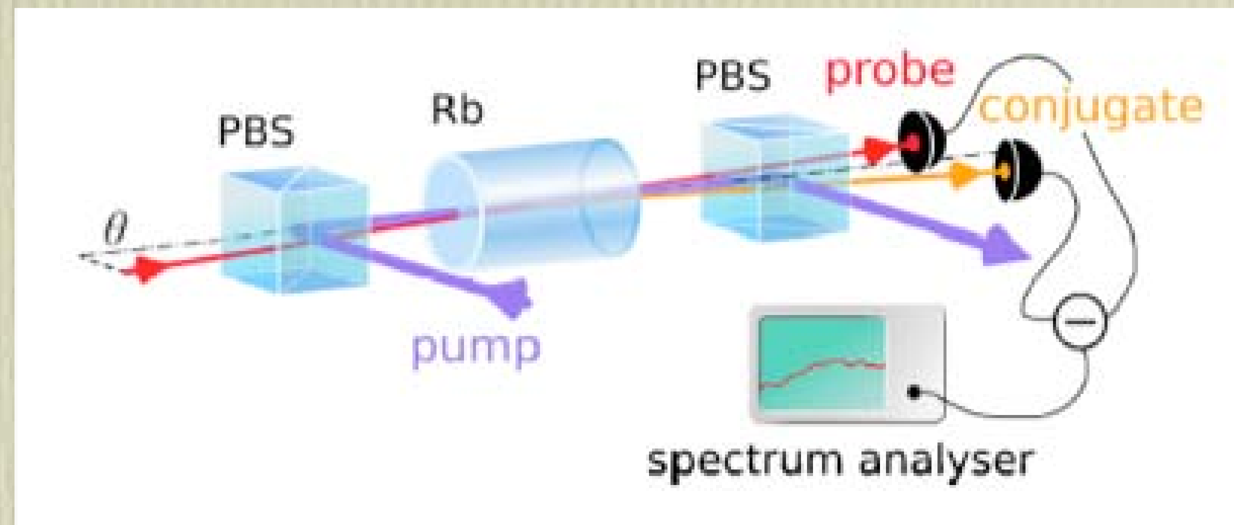
(using an OPO): -9.7 dB (11%) for twin beams

last week: -10.6 dB (9%) from 4WM!

-12.5 dB for single-mode quadrature squeezing

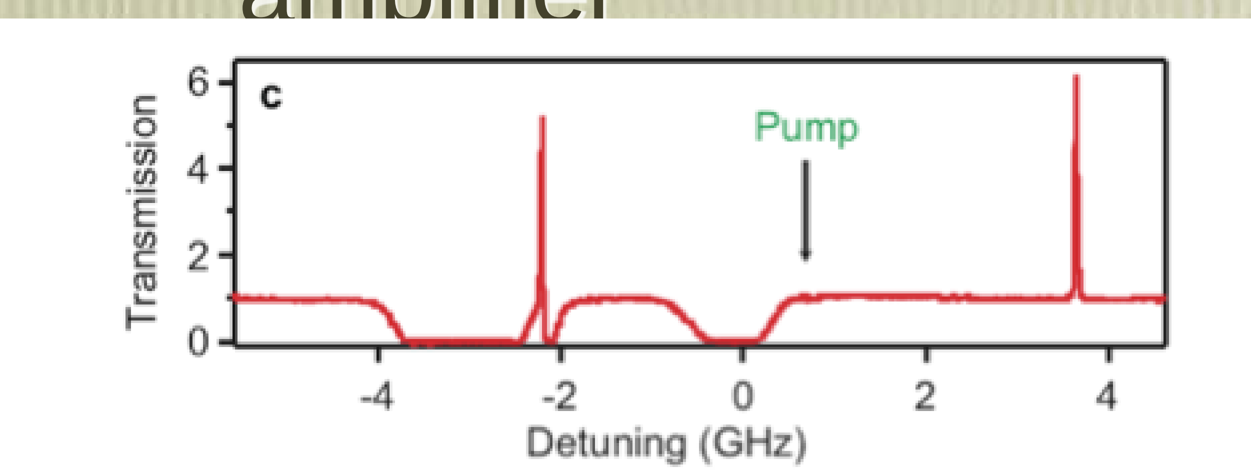
4WM to generate quantum correlations





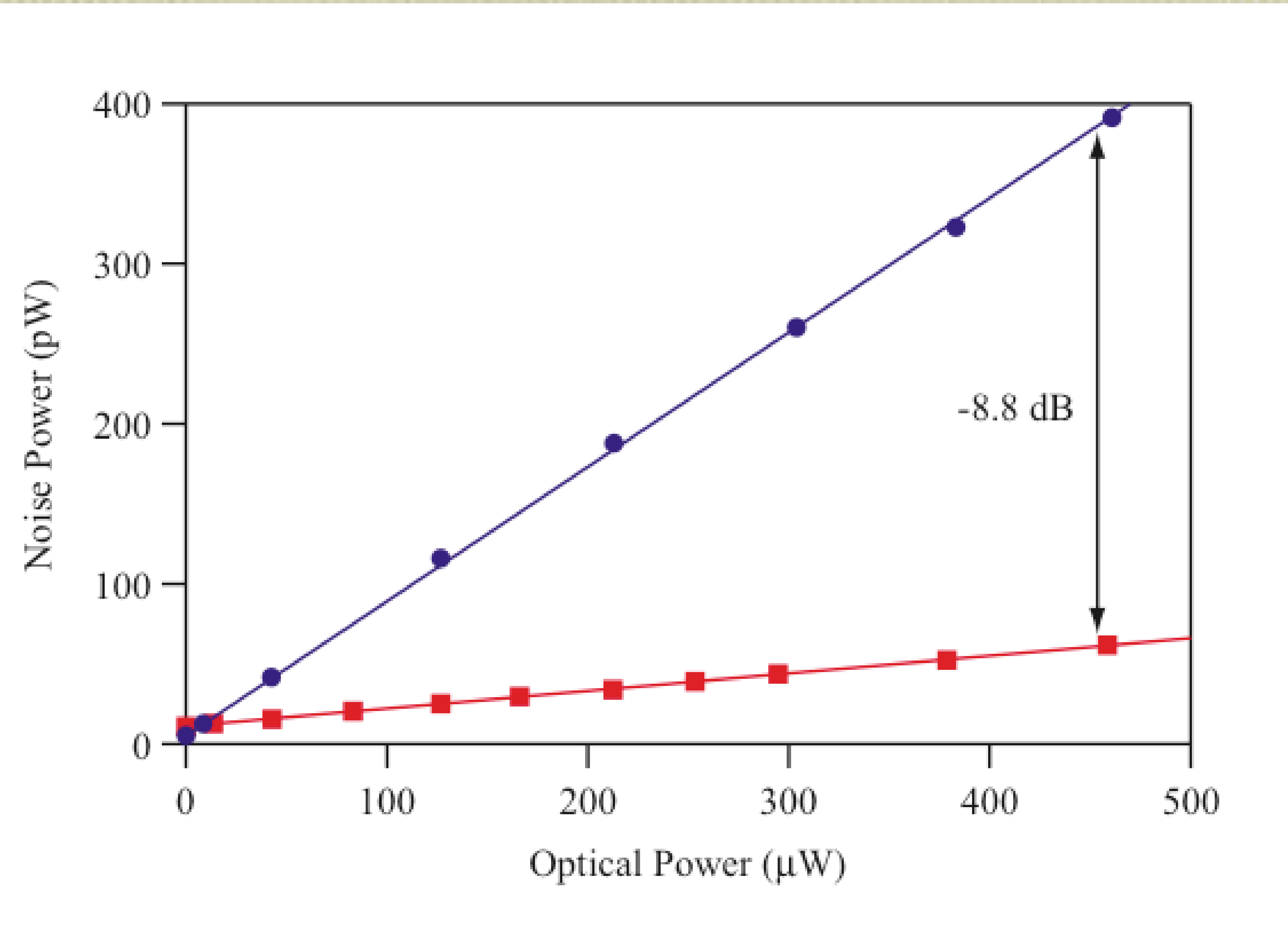
- twin-beam generation
- multi-spatial-mode squeezing
- acts as a phase insensitive amplifier

^{85}Rb in a 12 mm cell
Temp. ~ 120 C
~1 GHz detuned
~400 mW pump
~100 ⌠W probe
narrowband
no cavity



double-⊄ scheme; ground state coherences with modest gain but very little loss

strong twin-beam squeezing



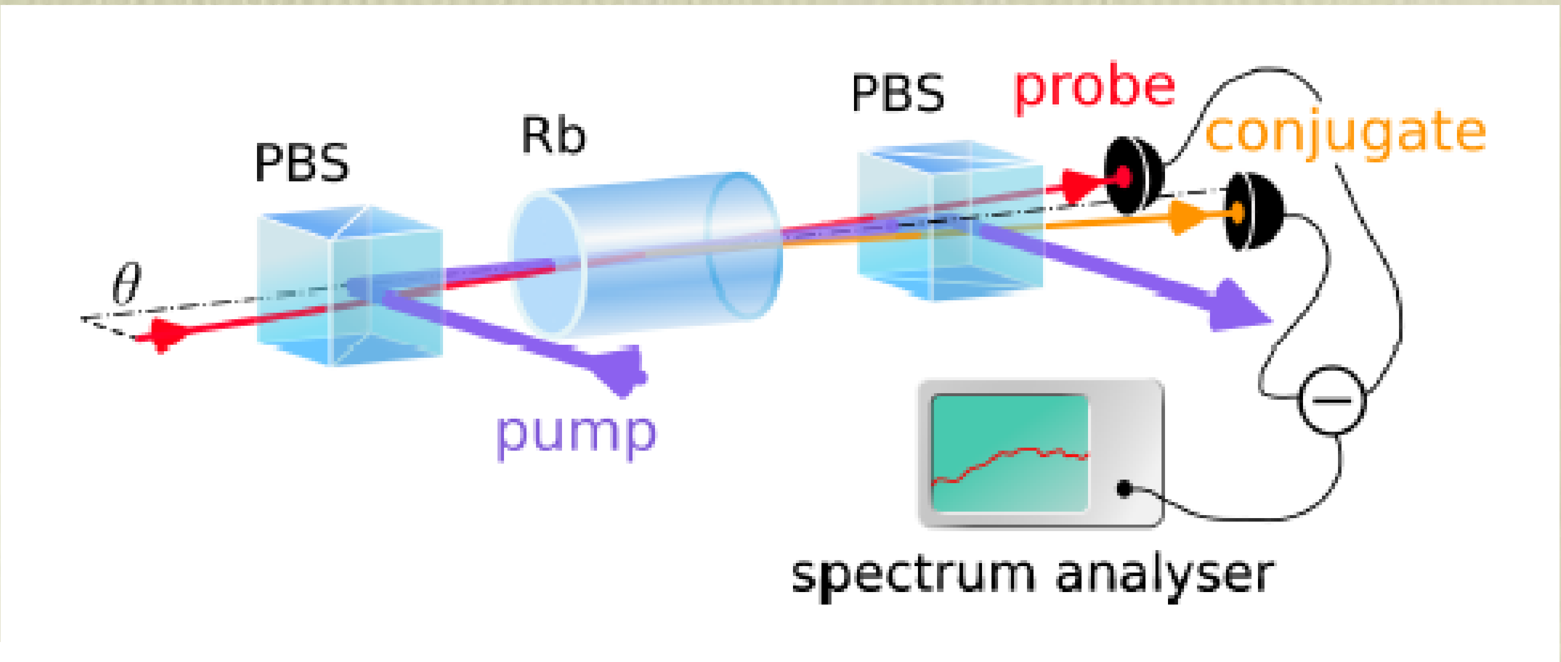
1 MHz detection frequency
RBW 30 kHz
VBW 300 Hz
pump detuning 800 MHz
Raman detuning 4 MHz
~95% detector efficiency

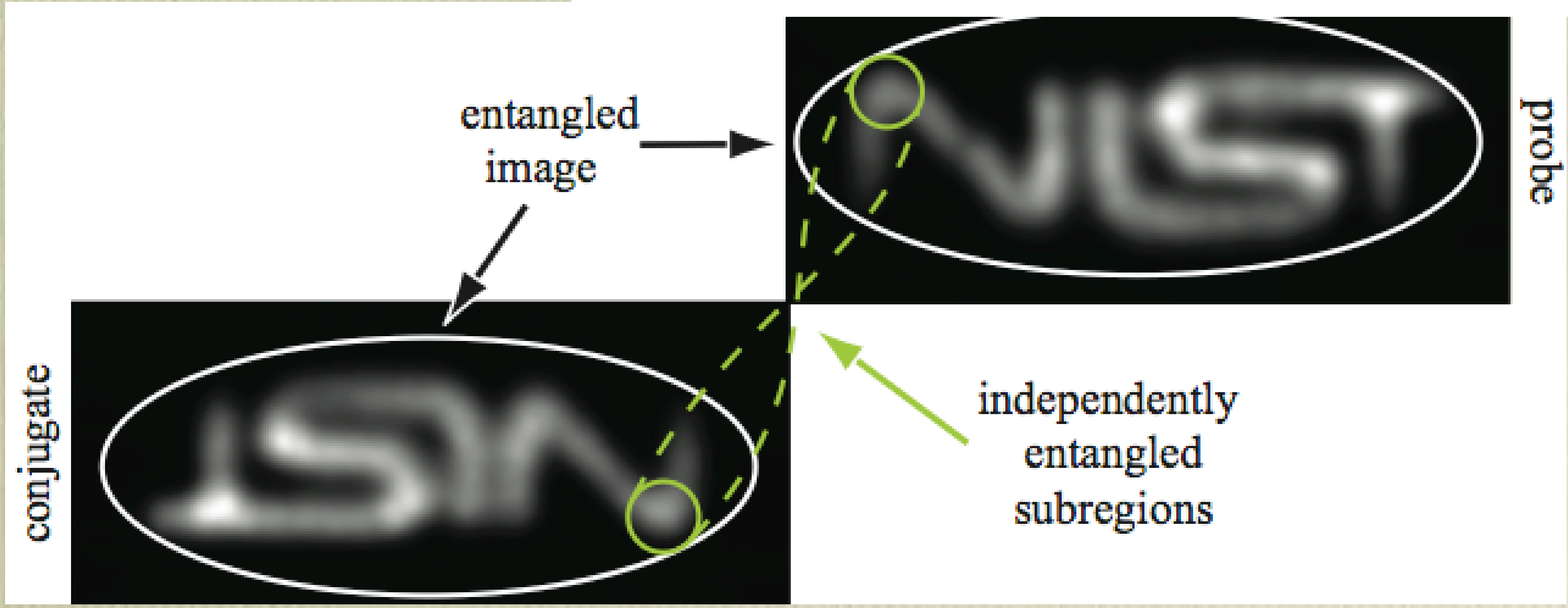
intensity-difference squeezing indicates correlations but homodyne detection required to demonstrate entanglement

C. McCormick, et al., Phys Rev A **78**, 043816 (2008).

Images

no cavity, so freedom for complex and multiple spatial modes!

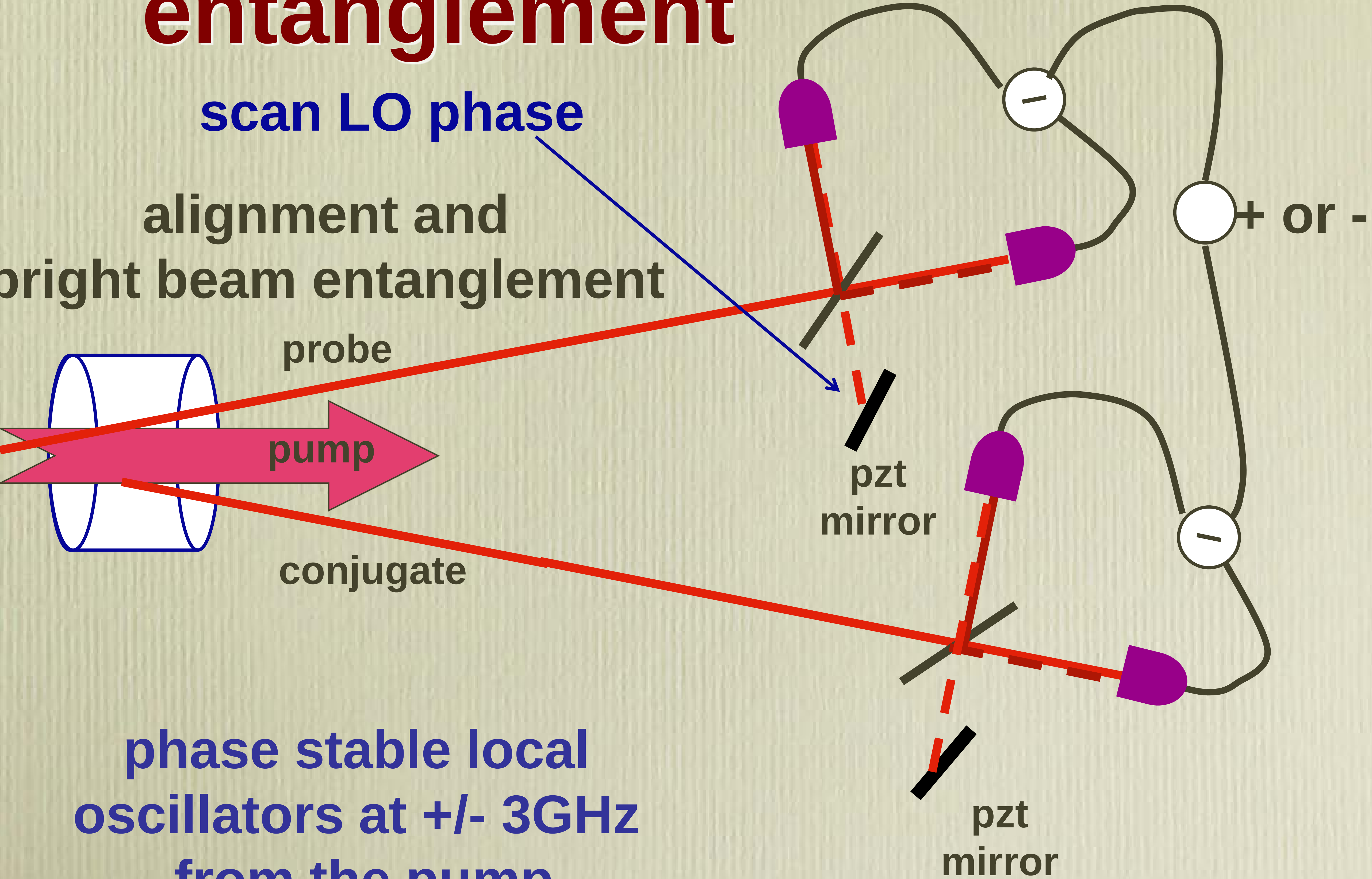




demonstrating entanglement

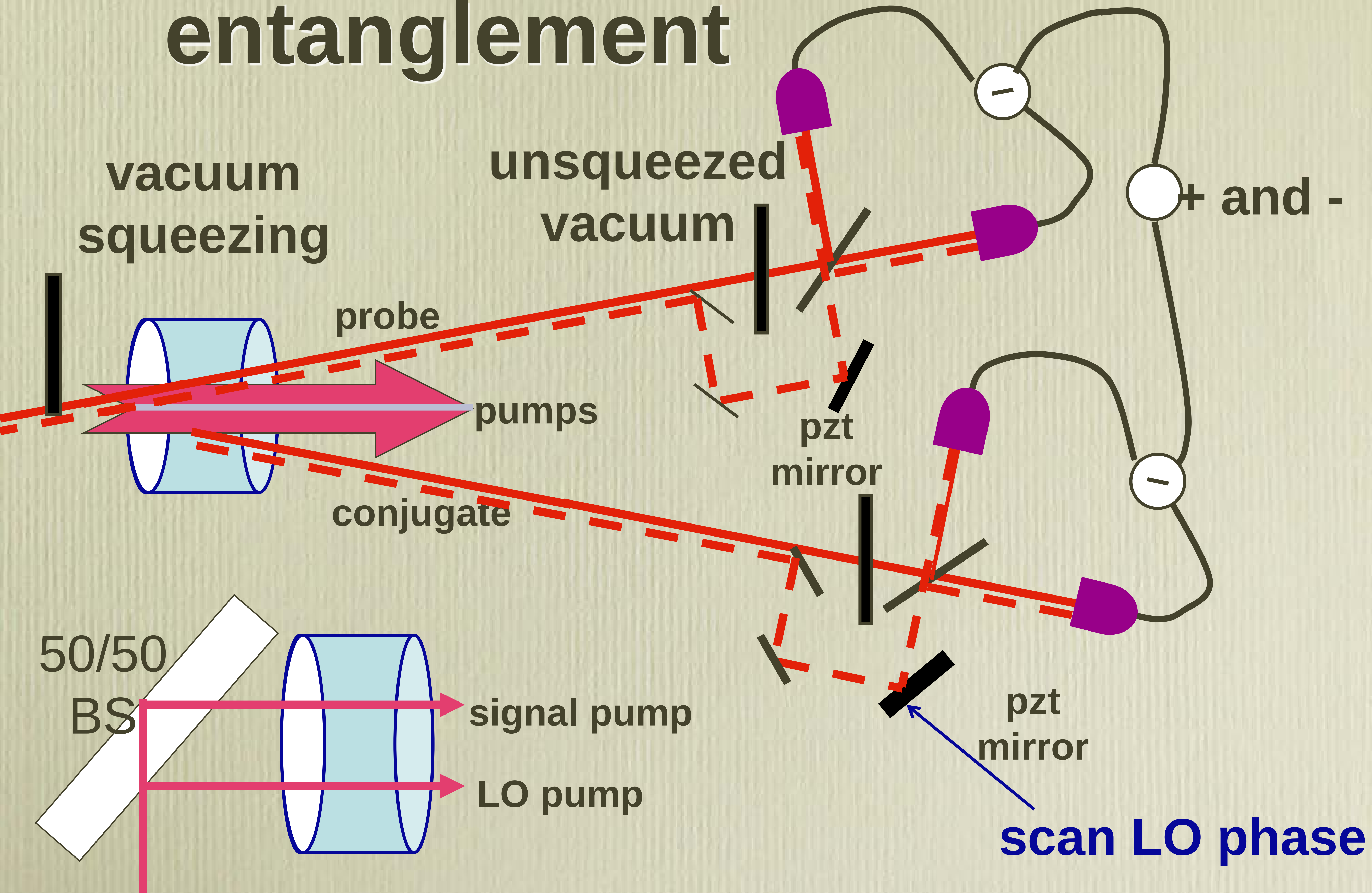
scan LO phase

alignment and bright beam entanglement

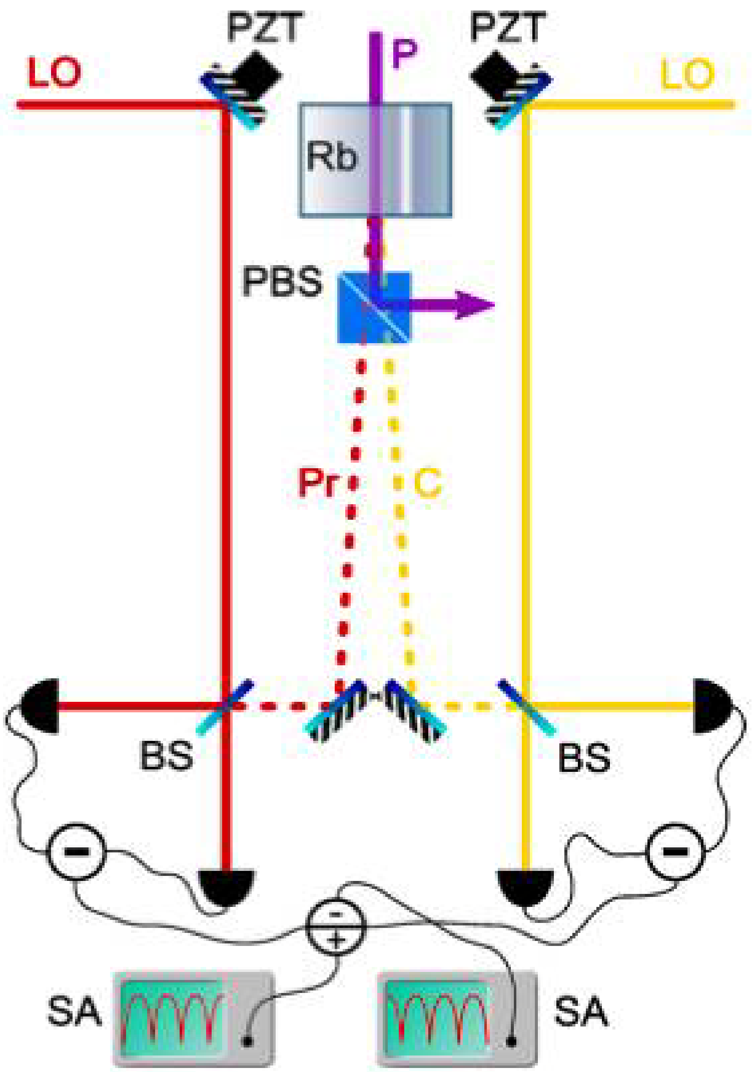


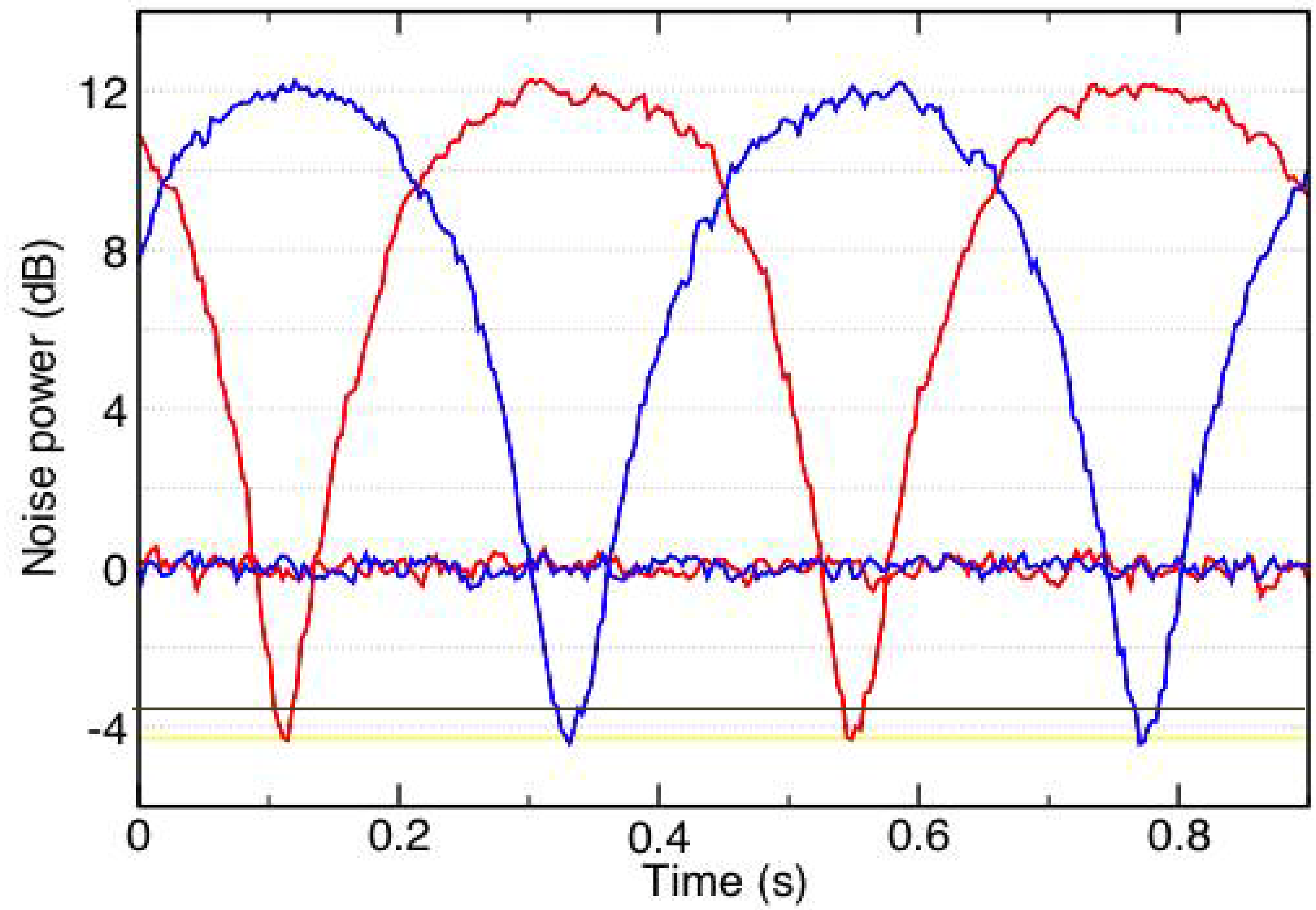
phase stable local oscillators at +/- 3GHz from the pump

demonstrating entanglement



“twin beam” vacuum quadrature entanglement

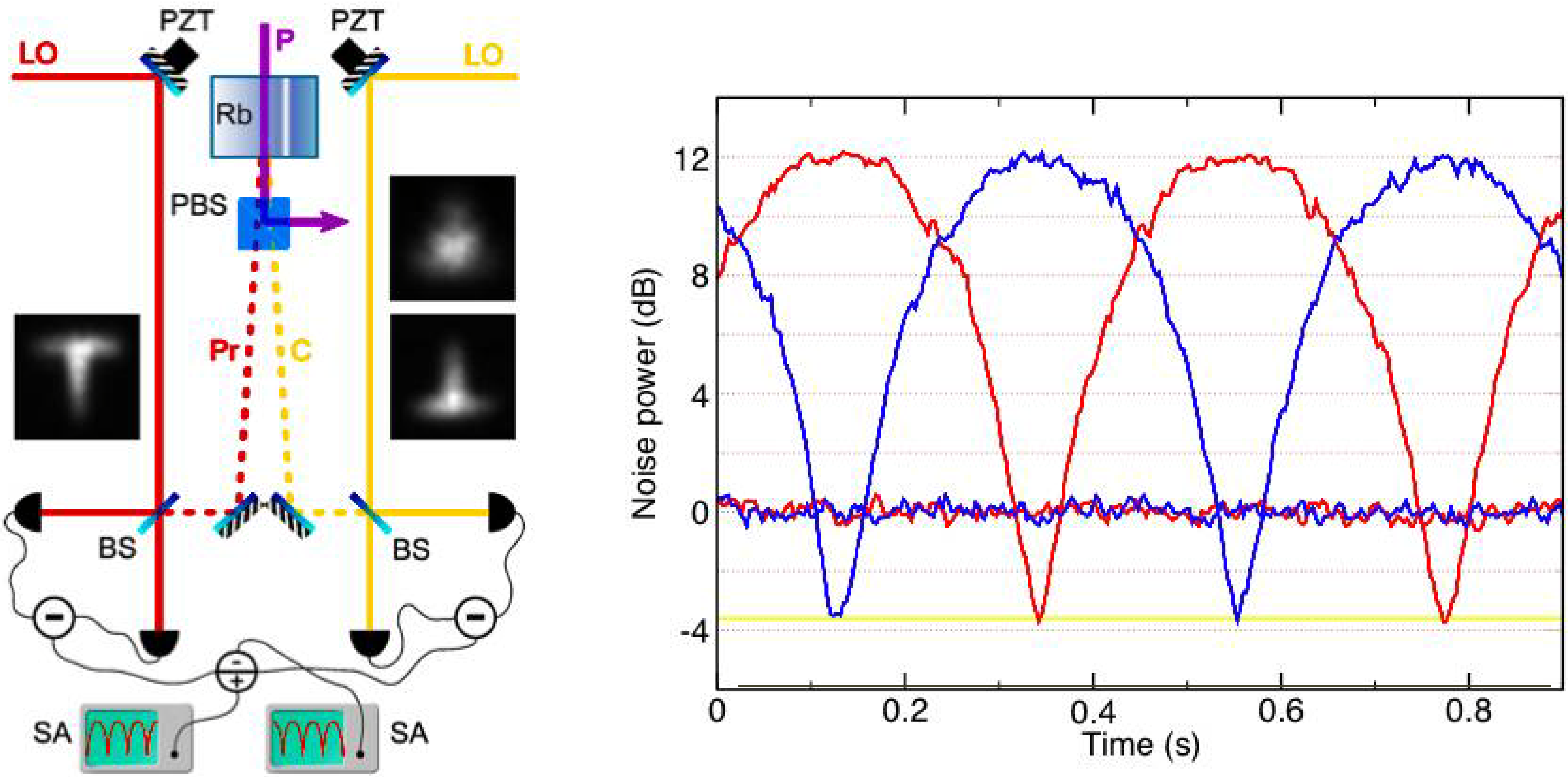




measurements at 0.5 MHz

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

entangled images



- Almost arbitrary mode shape
- High penalty for mode mismatch

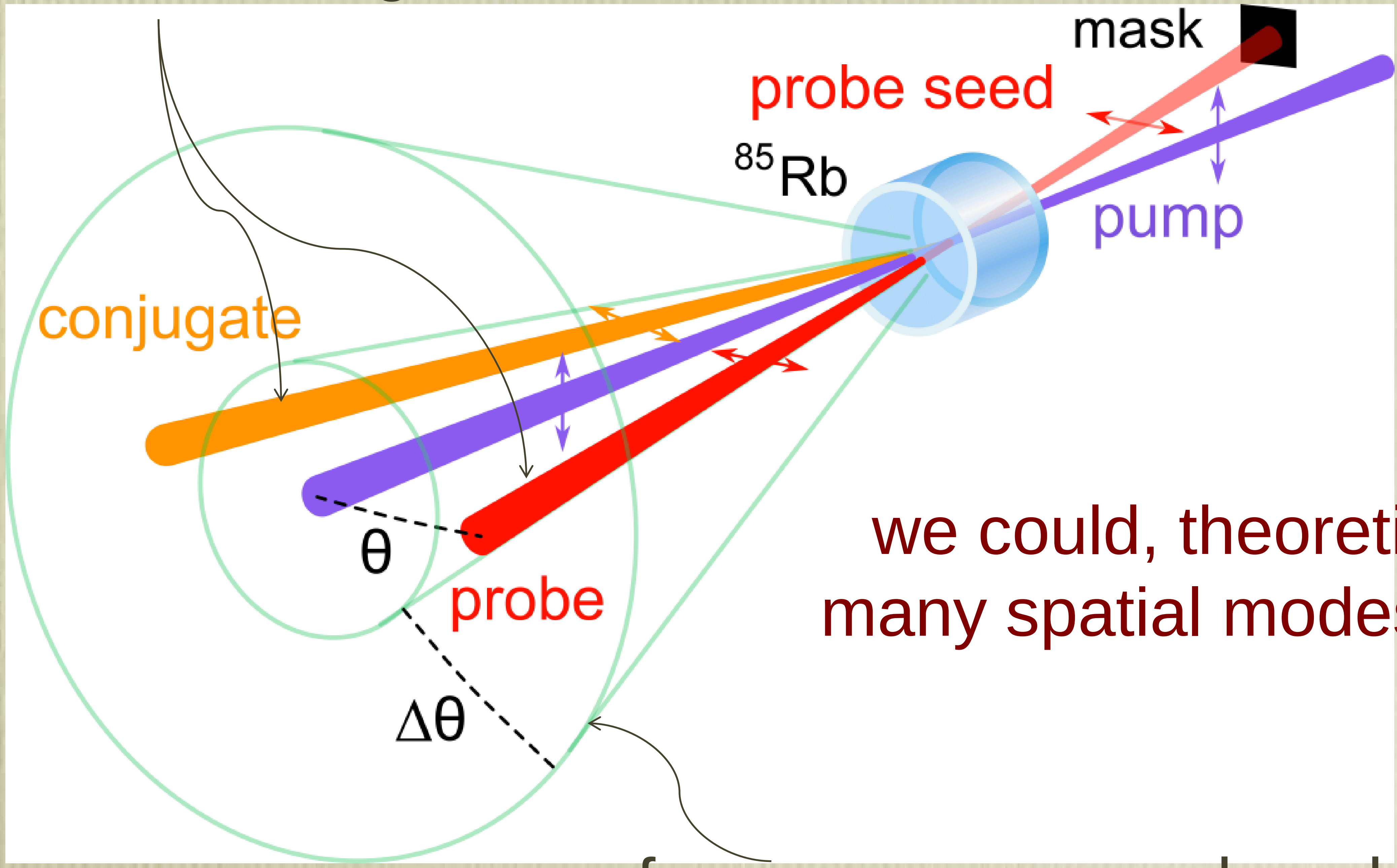
measurements at 0.5 MHz

NIST

• V. Boyer, A.M. Marino, R.C. Pooser, and P.D. Lett, Science **321**, 544 (2008).

many modes possible in photon 4WM

seeded, bright modes



we could, theoretically, use many spatial modes in parallel

cone of vacuum-squeezed modes
(allowed by phase matching)

entangled "images"

arbitrarily-shaped local oscillators can be used

(we used a "T"-shaped beam)

squeezing in both quadratures;

(equivalent results in all quadratures)

Gaussian bright-beam (-3.5 dB) or

vacuum (-4.3 dB); T-shaped vacuum (-3.7 dB)

implies EPR-levels of CV-entanglement could be measured in each case

$E_{12} = \mathrm{var}(X_1|X_2)\mathrm{var}(Y_1|Y_2)$ $I = \mathrm{var}(X_-) + \mathrm{var}(Y_+)$

no feedback loops or mode cleanup cavities!

Probe LO

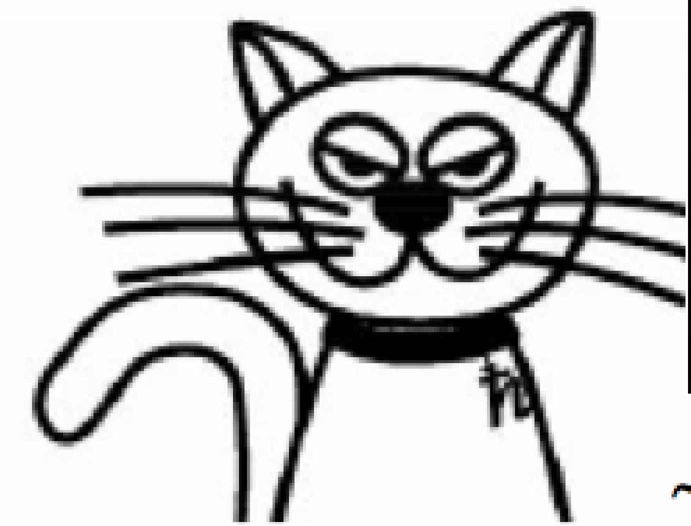
Conjugate LO

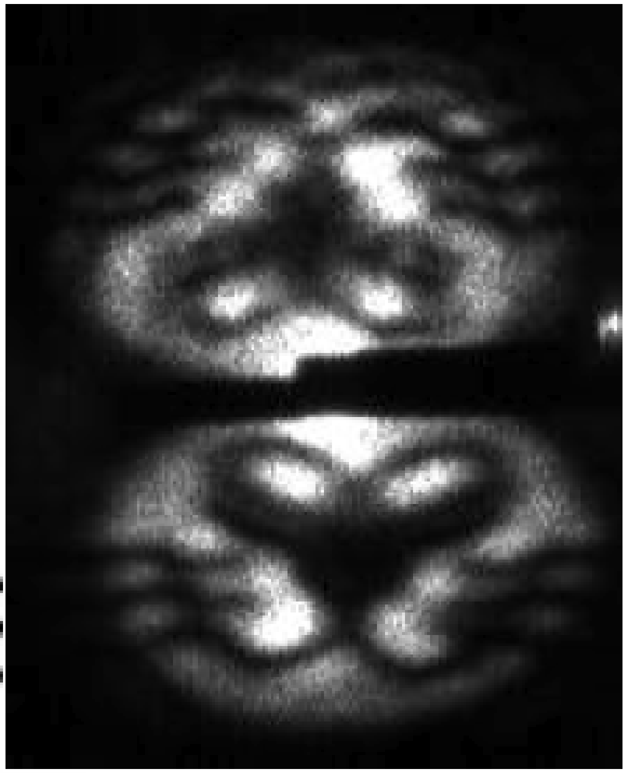
local oscillators for measurements of 1 dB quadrature squeezed vacuum

squeezed and entangled cats

bright beams showing intensity-difference squeezing

squeezed cats



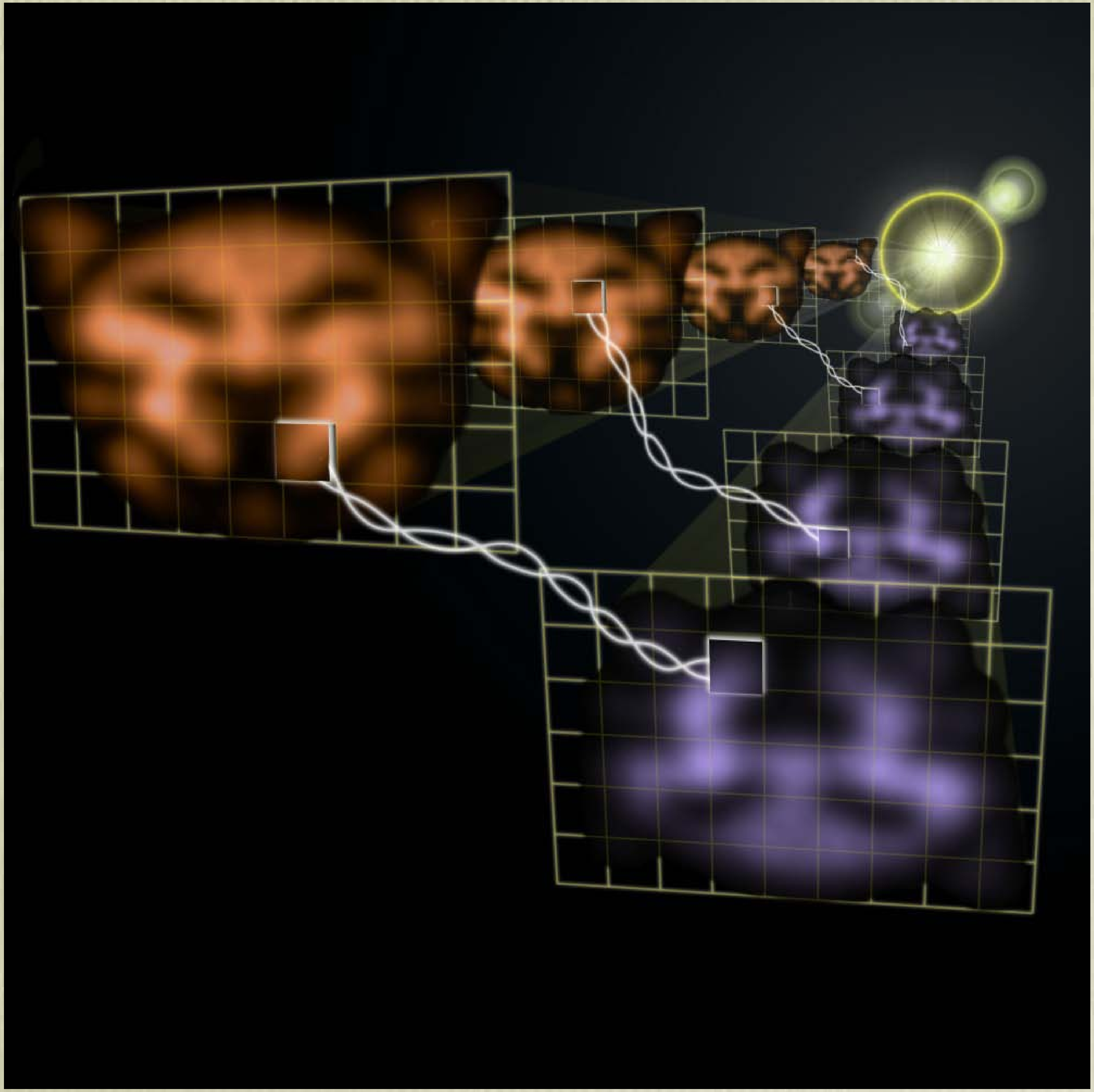


probe

conjugate

~1 dB "whole image" intensity-difference squeezing

enhanced graphics!



Another (indirect) result of the uncertainty principle:

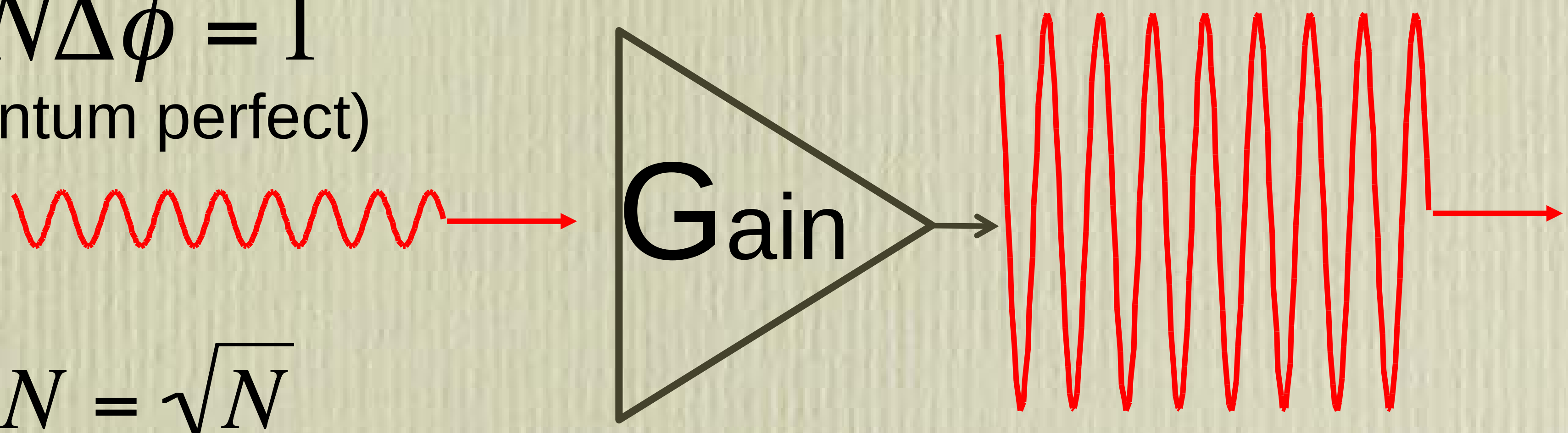
No perfect amplifiers!

$$\Delta N \Delta \phi = 1$$

(quantum perfect)

$$\Delta N = \sqrt{N}$$

(perfect "coherent" state, Poisson statistics)



$$\Delta N \Delta \phi > 1$$

(worse than the quantum limit)

$$\Delta N > \sqrt{N}$$

(noisier than Poisson statistics)

But a **phase-sensitive** quantum amplifier **CAN** be "perfect" (for a certain phase of the input); the price is that it de-amplifies, and increases the noise, for signals out-of-phase.

Noiseless image amplification

sounds too good to be true; like something that must be forbidden...

There is a "no-cloning theorem" which might say that ...

...but if you don't want "all the information" ... maybe something can be done.

Images typically contain amplitude, but not phase information. If you are happy to amplify the intensity and throw extra noise into the phase, you can do it.

Phase-sensitive amplifiers have been built and can perform noiseless image amplification!

Choi, S.-K., M. Vasilyev, and P. Kumar, Phys. Rev. Lett. 83, 1938 (1999);
Marable, M., S.-K. Choi, and P. Kumar, Opt. Expr., 2, 84, (1998).

PSAs and PIAs

- quatum information processing
- most activity related to fiber amplifiers and fiber communications; better noise figure
- EU PHASORS program

  Phase Sensitive Amplifier Systems and Optical Regenerators and their applications

  (fiber communications)
- DARPA Quantum Sensors Program (P. Kumar, Northwestern)
- multi-mode parametric downcoversion (Italy, France, US...)

  (images)   - our work falls into this area as well;

low gain, low resolution, but proof-of-concept amps

set to stun?

PHASORS

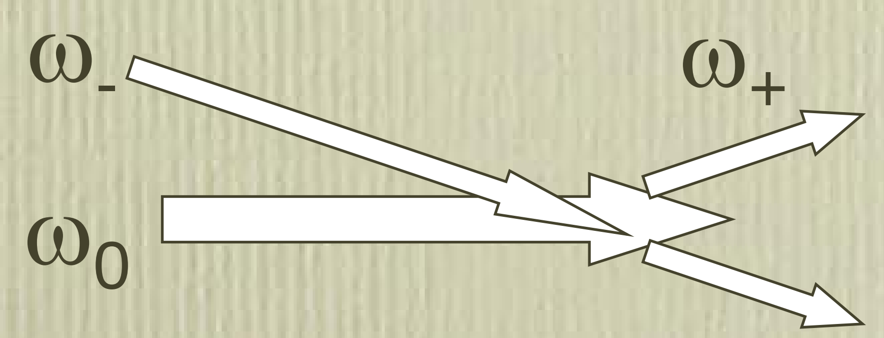
SET TO STUN

phase-(in)sensitive amplifiers

the phase of the injected beam, with respect to those of the pumps, will determine whether the beam will be amplified or de-amplified

One can design an amplifier for given field quadratures - useful for signal processing!

phase-<u>in</u>sensitive

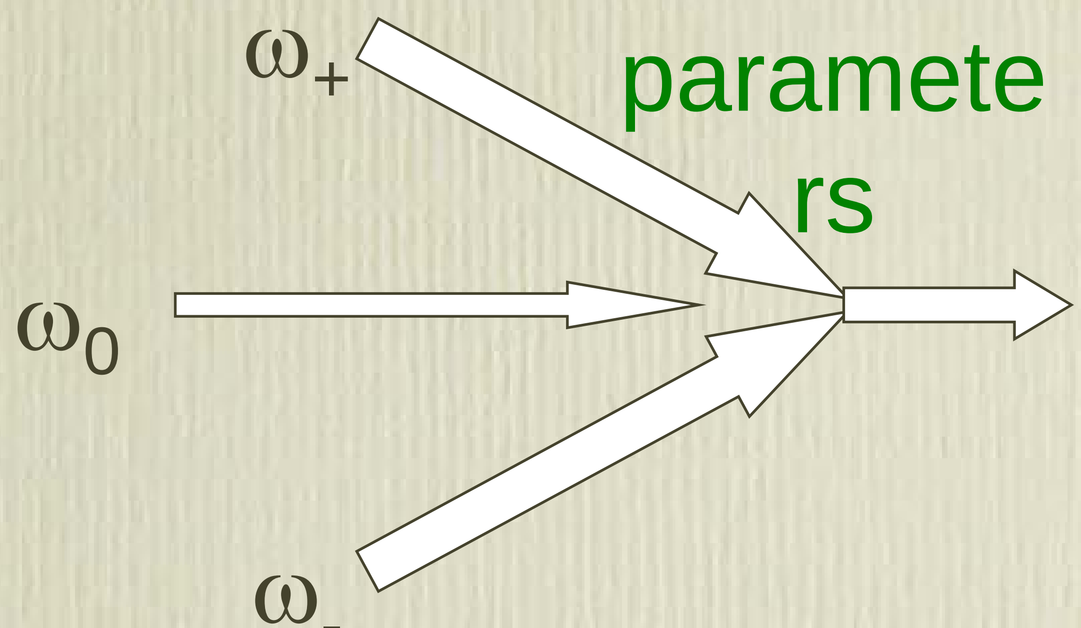


given the
phase of 3
“input”
beams the
4th phase is
free to
adjust for

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

phase-sensitive

no free
paramete
rs



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

noise limits

phase insensitive amplifier

PIA: $NF = SNR_{in}/SNR_{out} = \frac{2G-1}{G} \Rightarrow 2$

large G limit

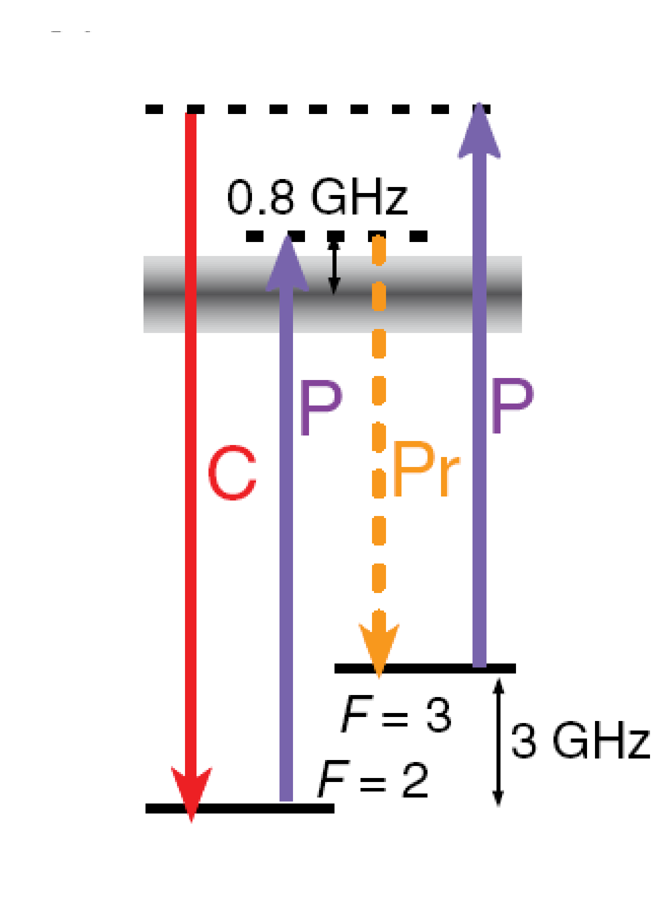
phase sensitive amplifier

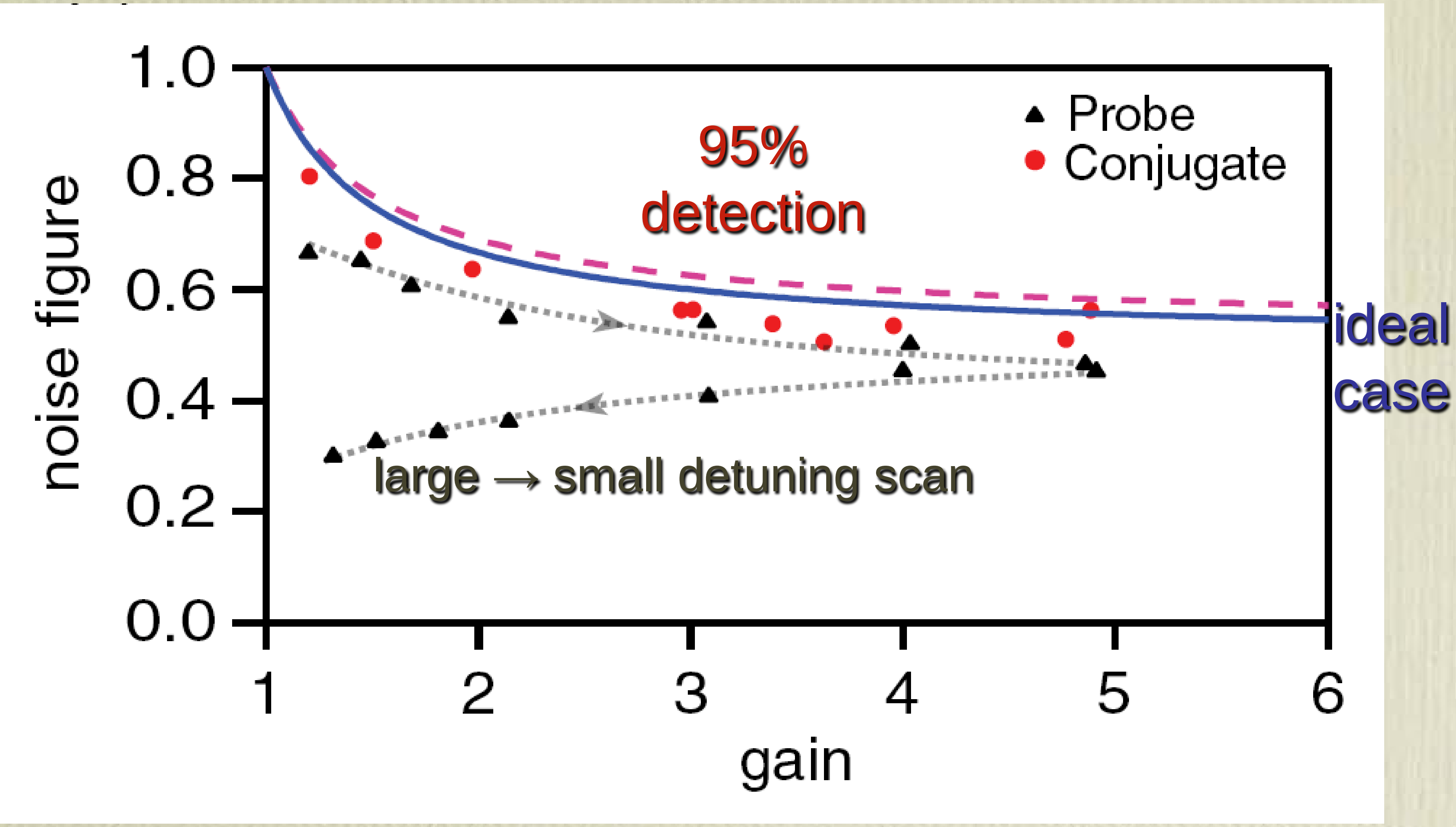
PSA: $NF = 1$

(in the ideal case, for the correct choice of signal phase)

Phase-insensitive amplifier

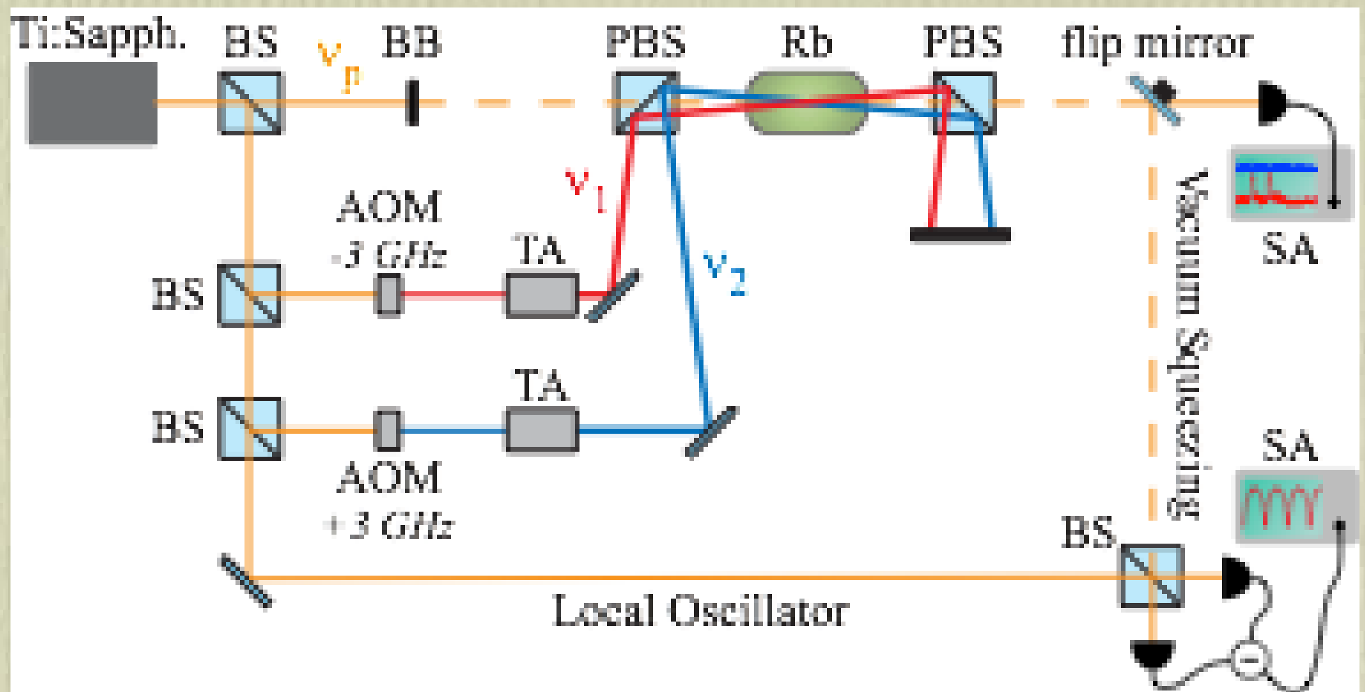
- 1 MHz **classical** signal amplified with moderate gain
- noise figure (SNR_{out}/SNR_{in})<1 is close to theoretical limit

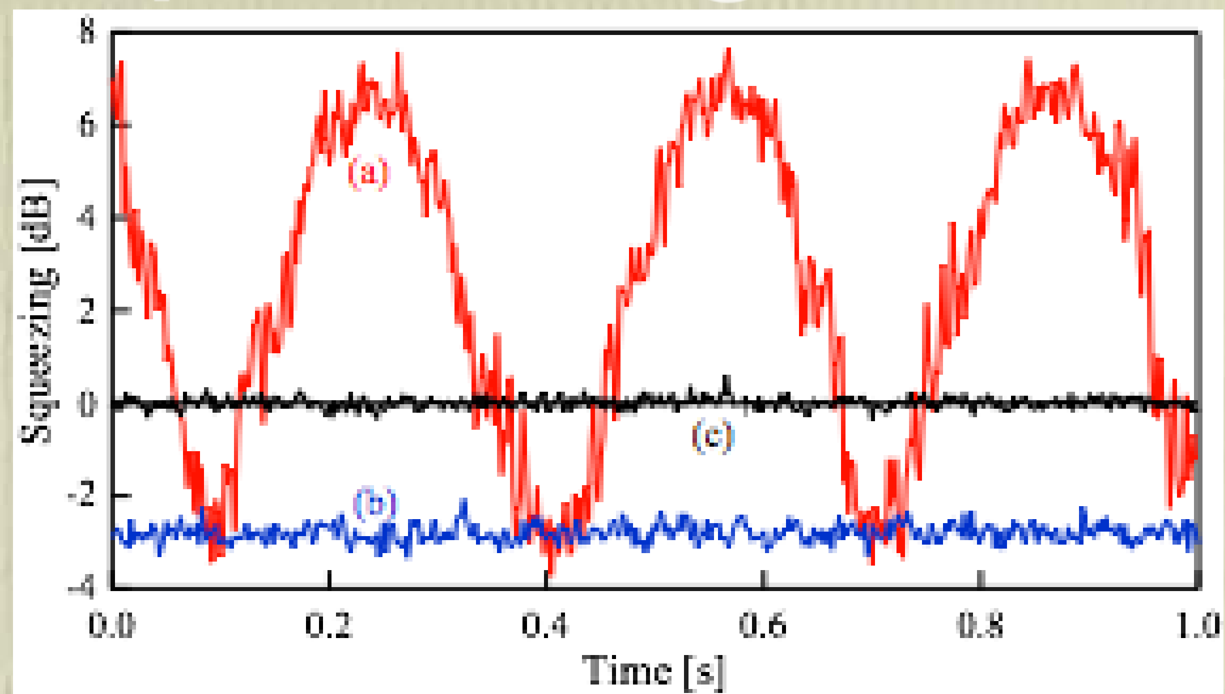




Pooser, R. C., Marino, A. M., Boyer, V., Jones, K. M. & Lett, P. D. "Low-noise amplification of a continuous variable quantum state," Phys. Rev. Lett. 103, 010501 (2009).

Phase Sensitive Amplifier: Quadrature squeezing

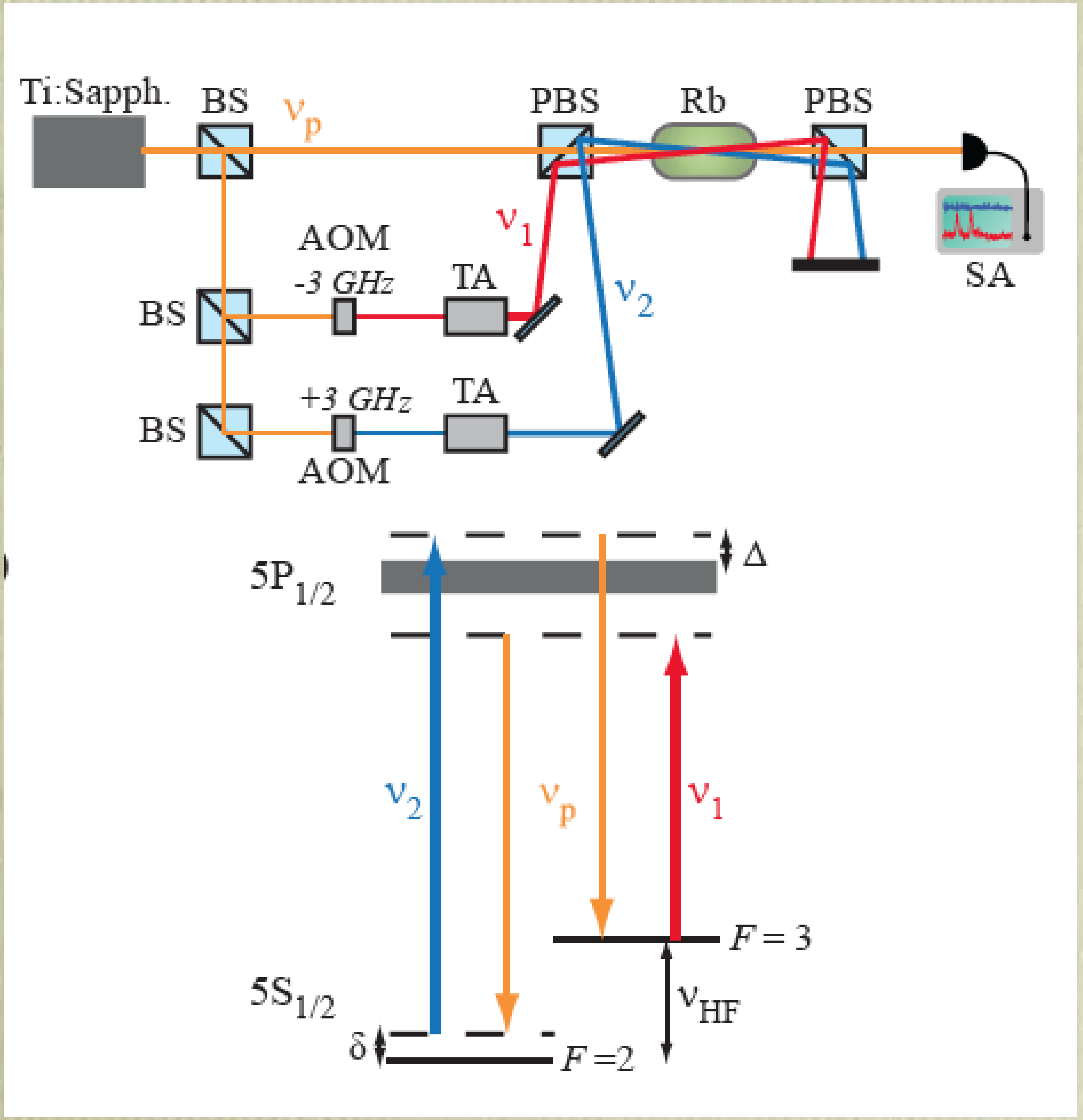




- de-amplification phase produces intensity squeezing
- 3 dB single-mode vacuum quadrature squeezing
- multiple spatial modes

Corzo, N., Marino, A. M., Jones, K. M. & Lett, P. D., "Multi-Spatial-Mode Single-Beam Quadrature Squeezed States of Light from Four-Wave Mixing in Hot Rubidium Vapor," Opt. Expr. 19, 21358 (2011).

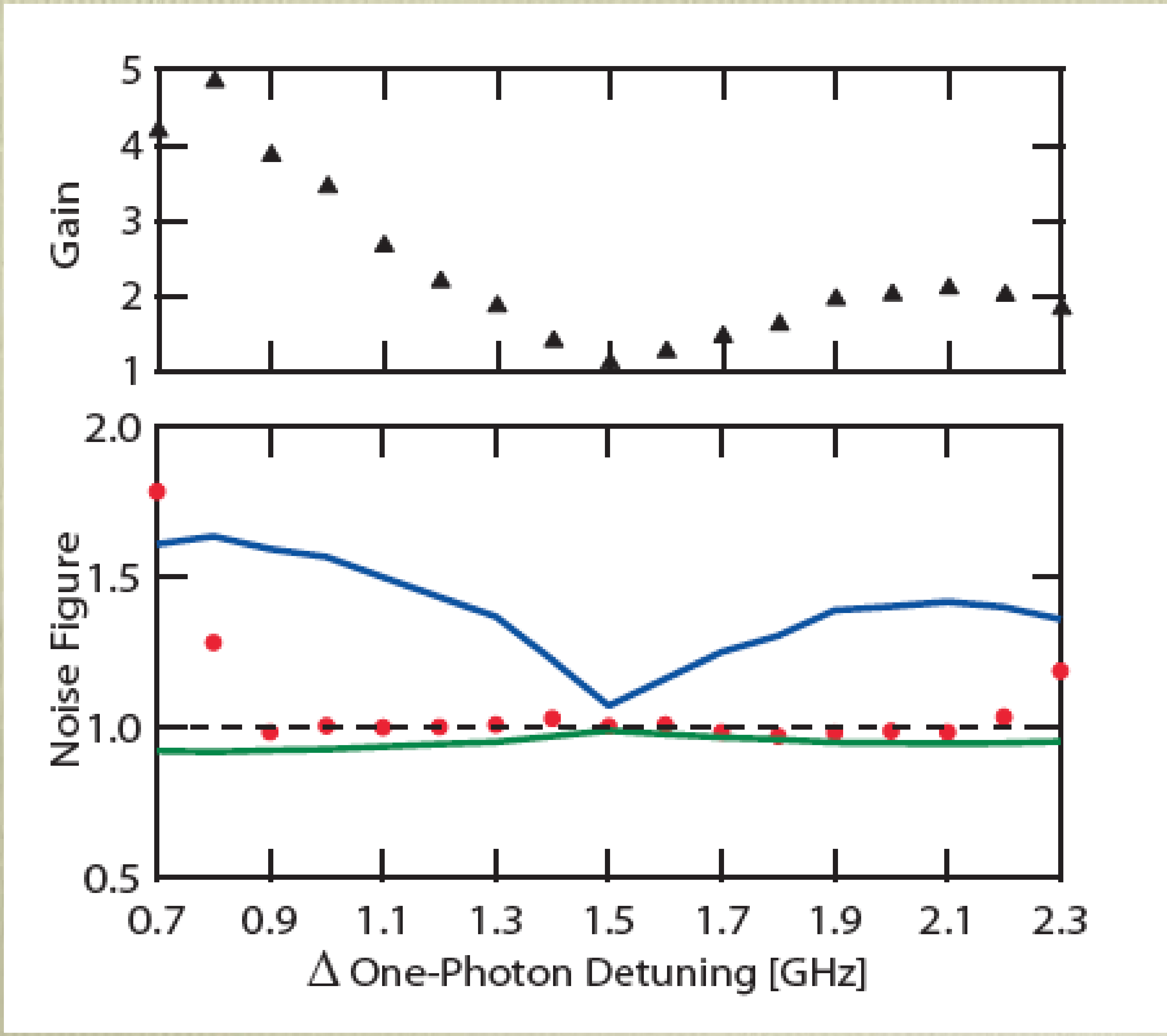
PSA noise figure measurement



- phase-sensitive amplifier can provide "noiseless" amplification
  NF = SNR_{in}/SNR_{0ut}
  (inverse of what we used before)
- modest gains, but multi-spatial-mode and nearly "noiseless"

EU PHASORS program has demonstrated higher gain <u>single-mode</u>, fiber-based PSA

PSA noise figure (cont.)



gain

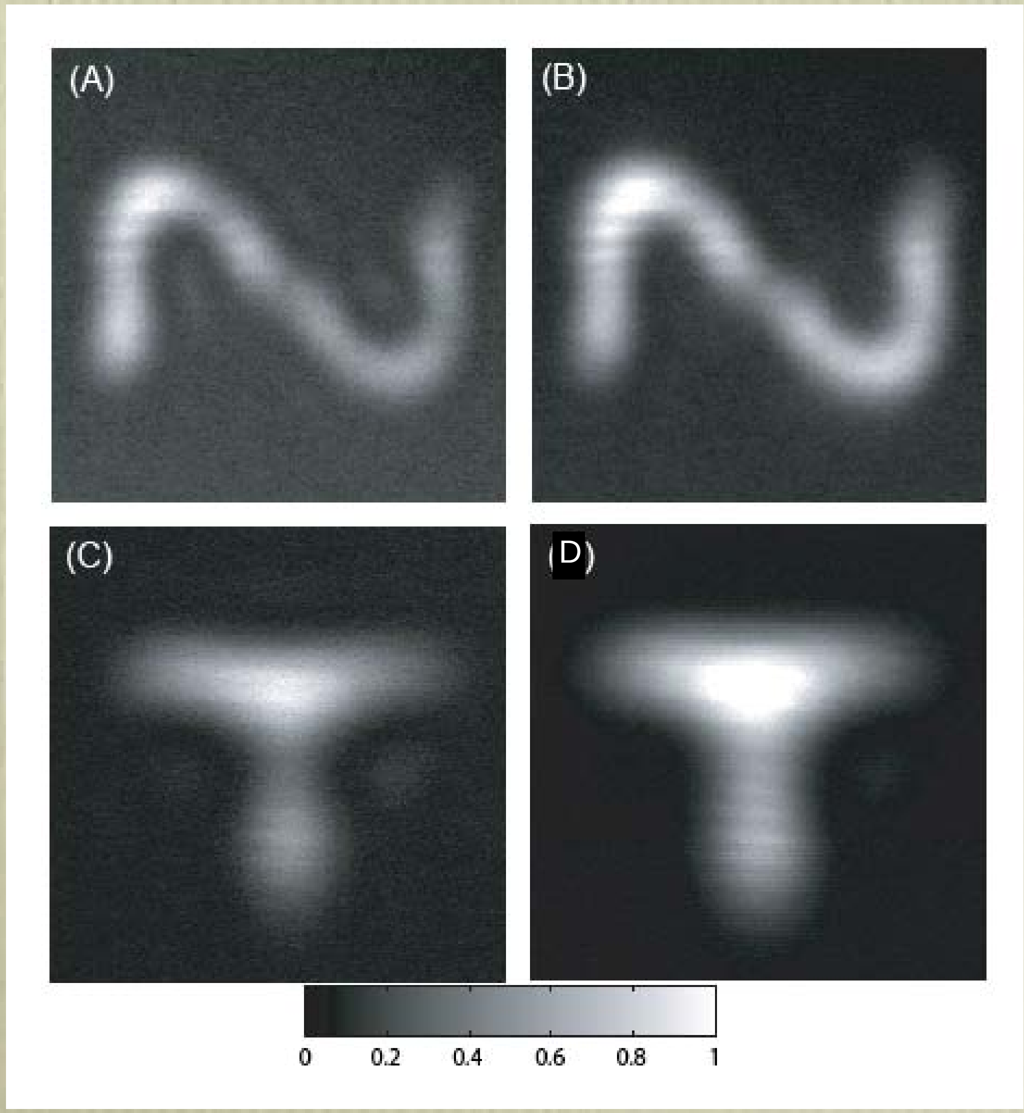
PIA limit

PSA

PSA w/ loss

“noiseless” image amplification

- “images” amplified, but thus far only good noise figure data from looking at a time-modulation signal
- We will need to look at spatial information and quantify with spatial Fourier transforms; noise spectral density and Detective Quantum Efficiency



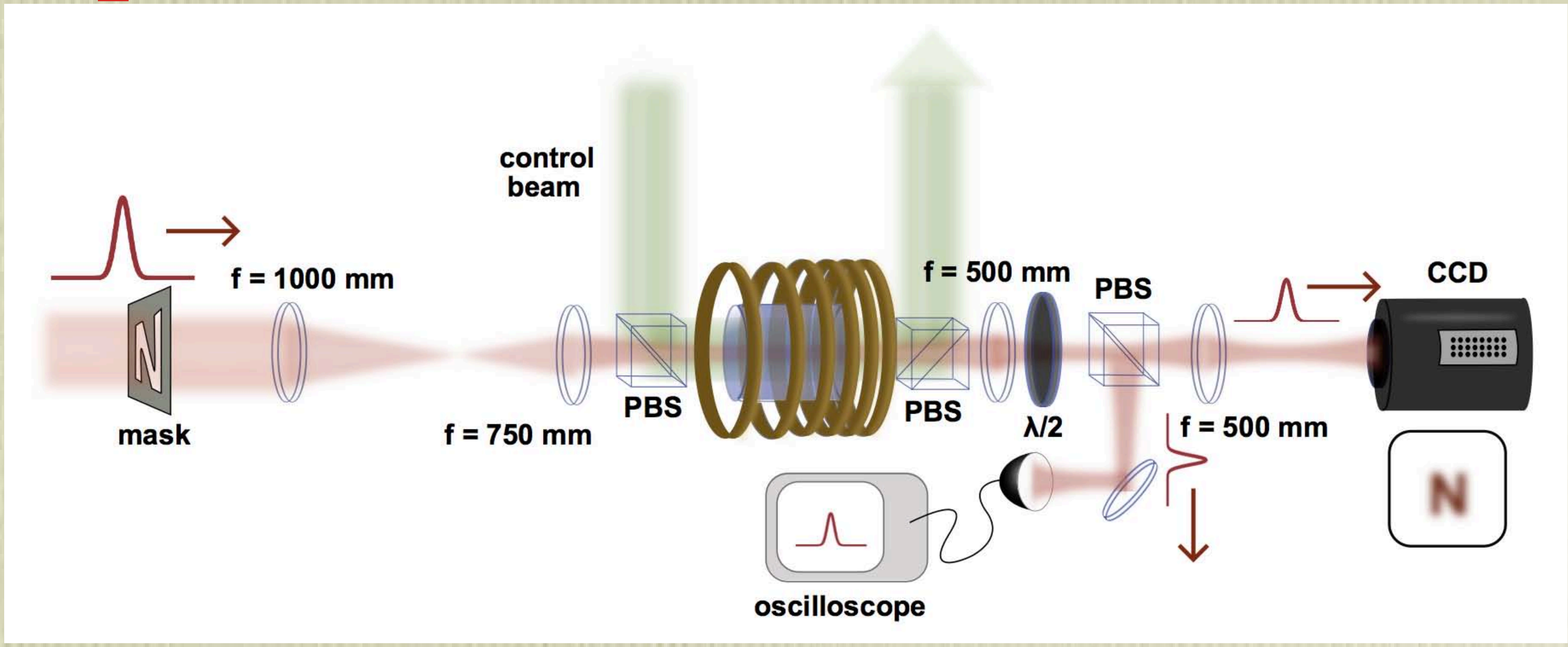
previous work:
J. Levenson et al., J. Opt. Soc. Am. B 10, 2233 (1993); J. Levenson et al., Phys. Rev. Lett. 70, 267 (1993).
S.-K. Choi, M. Vasilyev, and P. Kumar, Phys. Rev. Lett. 83, 1938 (1999); M. Marable, S.-K. Choi, and P. Kumar, Opt. Expr. 2, 84 (1998).A. Mosset, F. Devaux, and E. Lantz, Phys. Rev. Lett. 94, 223603 (2005); F. Devaux, J.-L. Blanchet, and E. Lantz, Opt. Lett. 32, 175 (2007).
Quantum Sensors Program (DARPA)
P. Kumar (NU), M. Vasilyev (UTA) (SPIE proceedings, to be published)

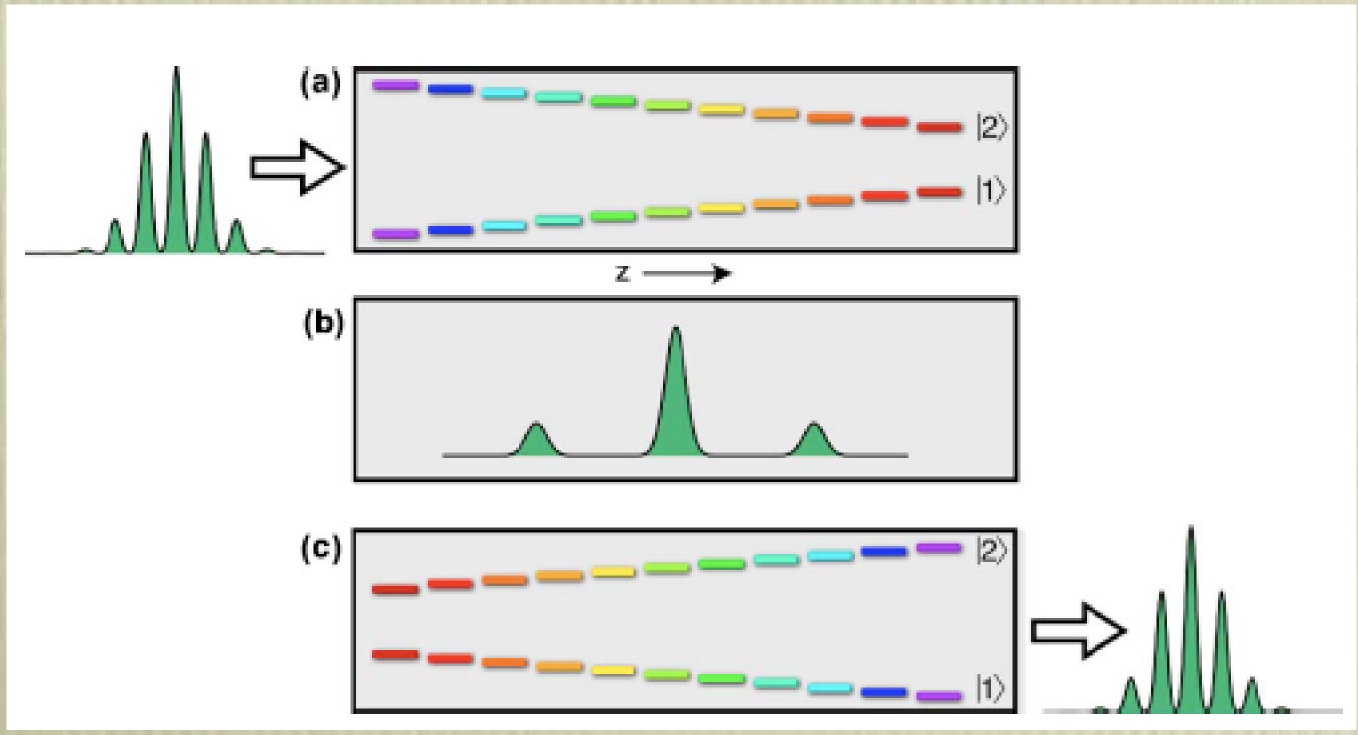
quantum memory

- we have chosen the gradient echo memory (GEM) technique developed at ANU (suited to Rb wavelength)
- ANU group has achieved 87% recovery efficiency using a Rb vapor system and demonstrated the ability to store and manipulate multiple pulses in a single spatial mode
- using a slightly different implementation (transitions, polarizations, detunings) we have achieved 62% recovery efficiency
- we have stored multi-spatial-mode images and even a (very short!) movie (classical!)

Hosseini, M., Campbell, G., Sparkes, B., Lam, P. K. & Buchler, B. "Unconditional room-temperature quantum memory," Nat. Phys. **7**, 794 (2011).

implementation of GEM memory



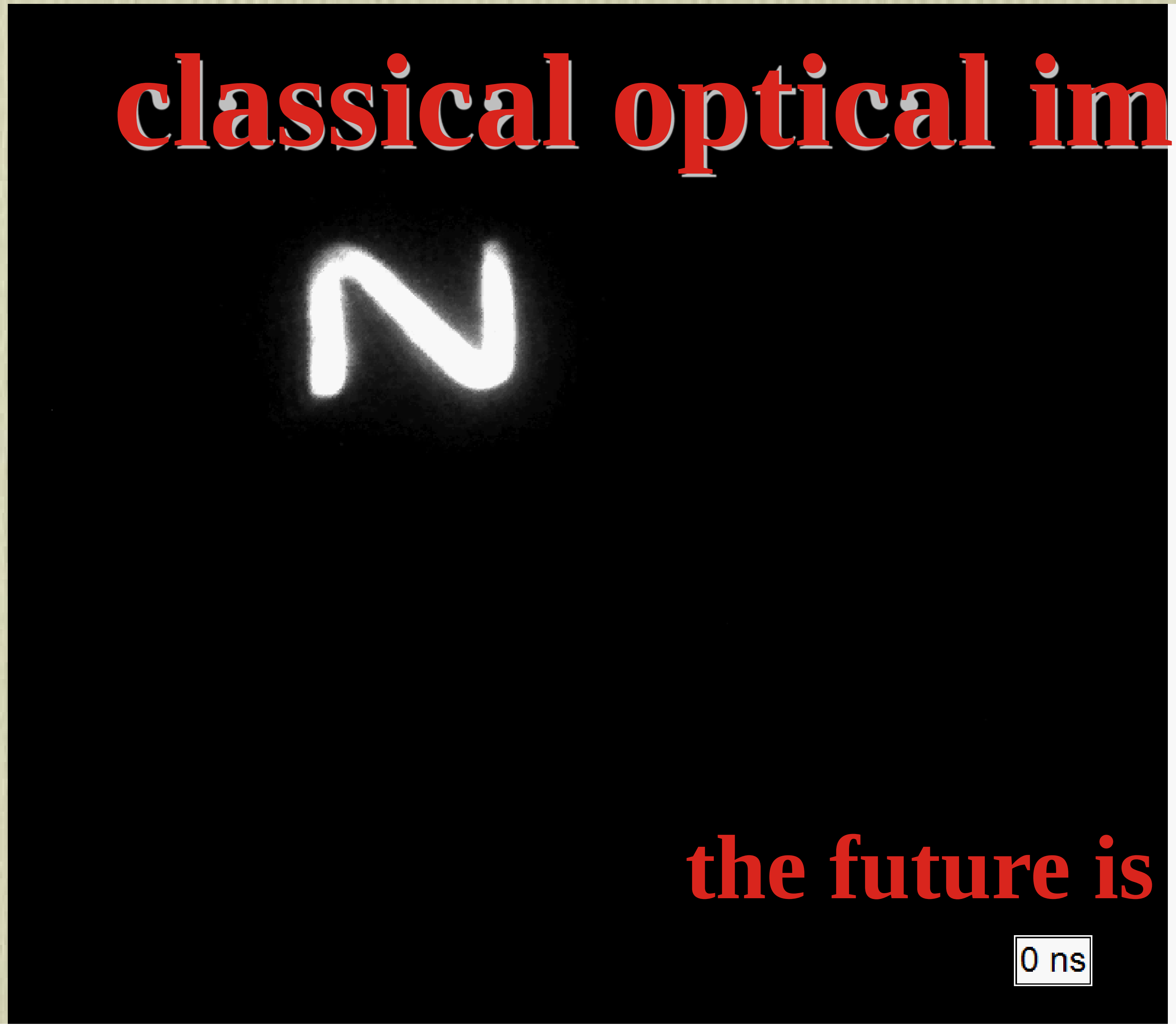


- apply magnetic field gradient
- store frequency components distributed in space
- (turn off control field for storage time)
- flip field gradient
- allow rephased dipoles to radiate echo

current status of GEM studies in our lab

- storage of images (classical)
- simultaneous multiple image storage
- studies of diffusion/storage time on resolution
- studies of crosstalk between stored images
- “random access” of local spatial regions
- stored “movie” (short)
- generation and detection of 4 dB of pulsed squeezing/entangled beams

classical optical image memory



0-800ns insert N
800-1700
insert T

1900-4000
recover T
4000-
recover N

the future is quantum (memory)

read-in read-out

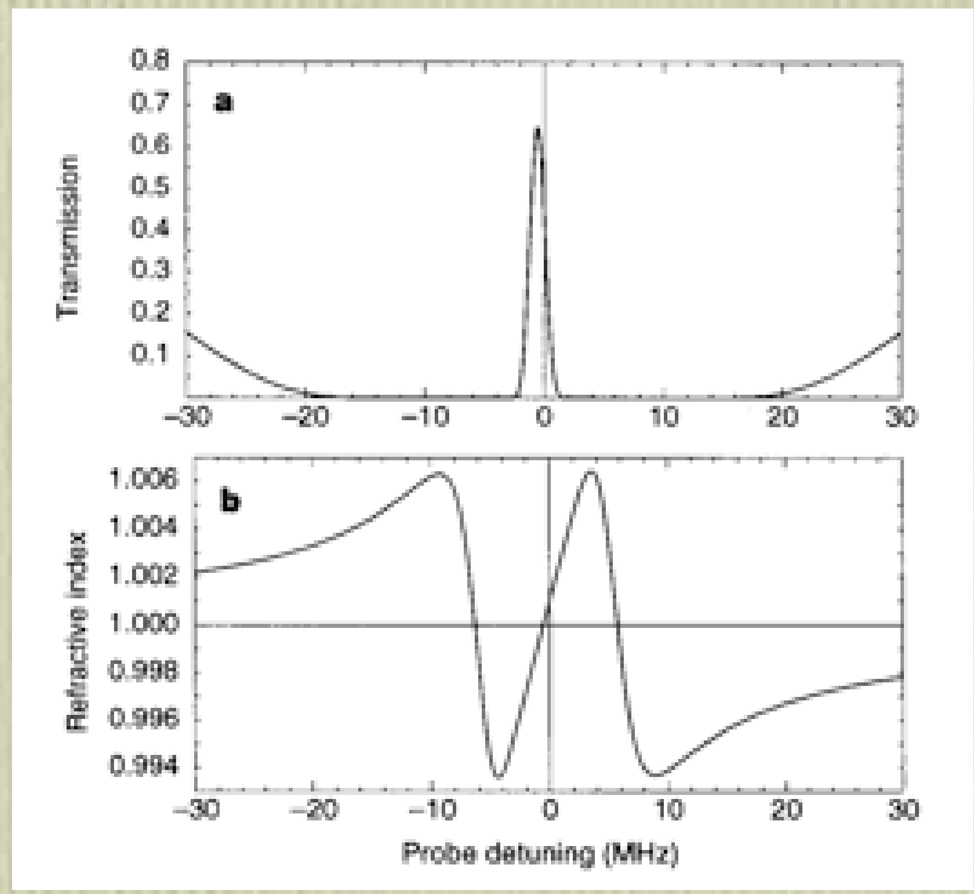
~2 microseconds of read-in, 2 microseconds of storage (flip magnetic field), and 2 microseconds of read-out

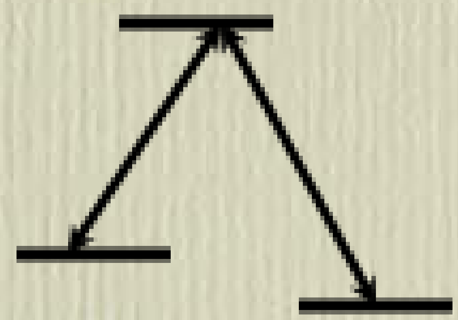
“Cloud Storage”

“random access” (low resolution)

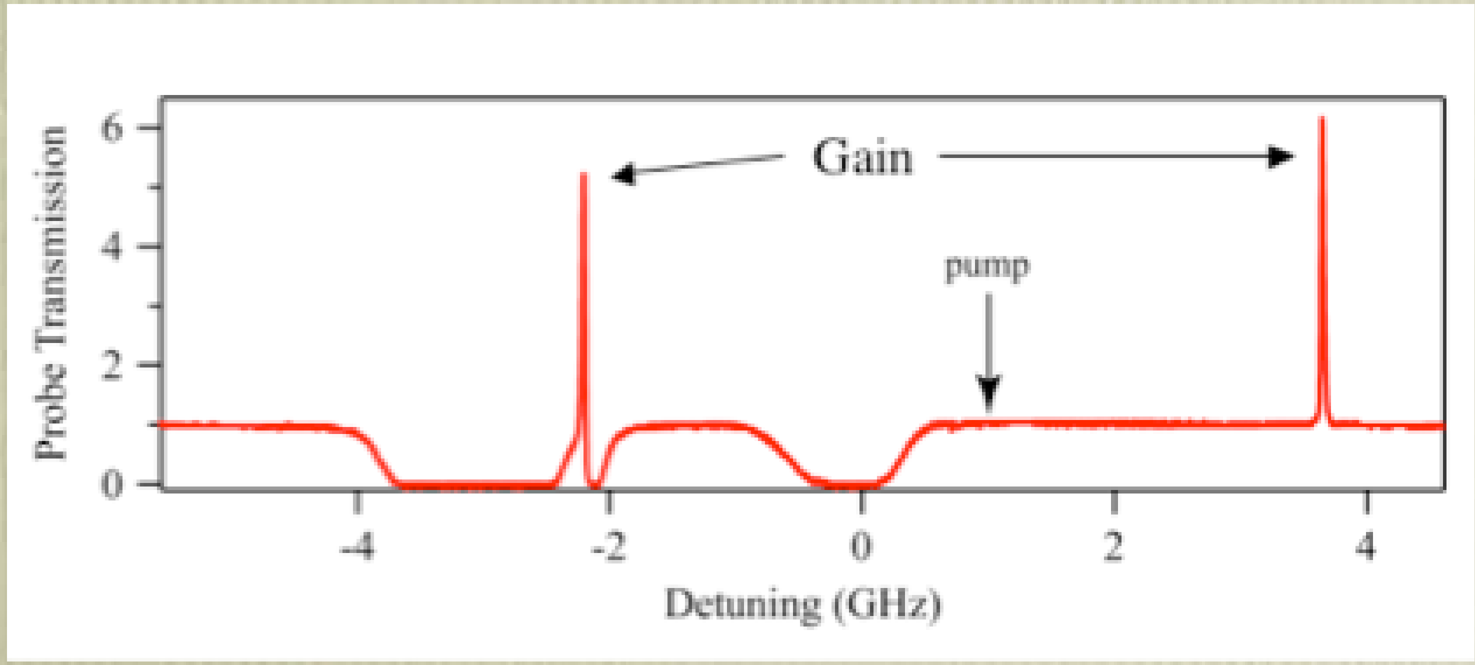
QuickTime™ and a
decompressor
are needed to see this picture.

manipulation of dispersion with 4WM



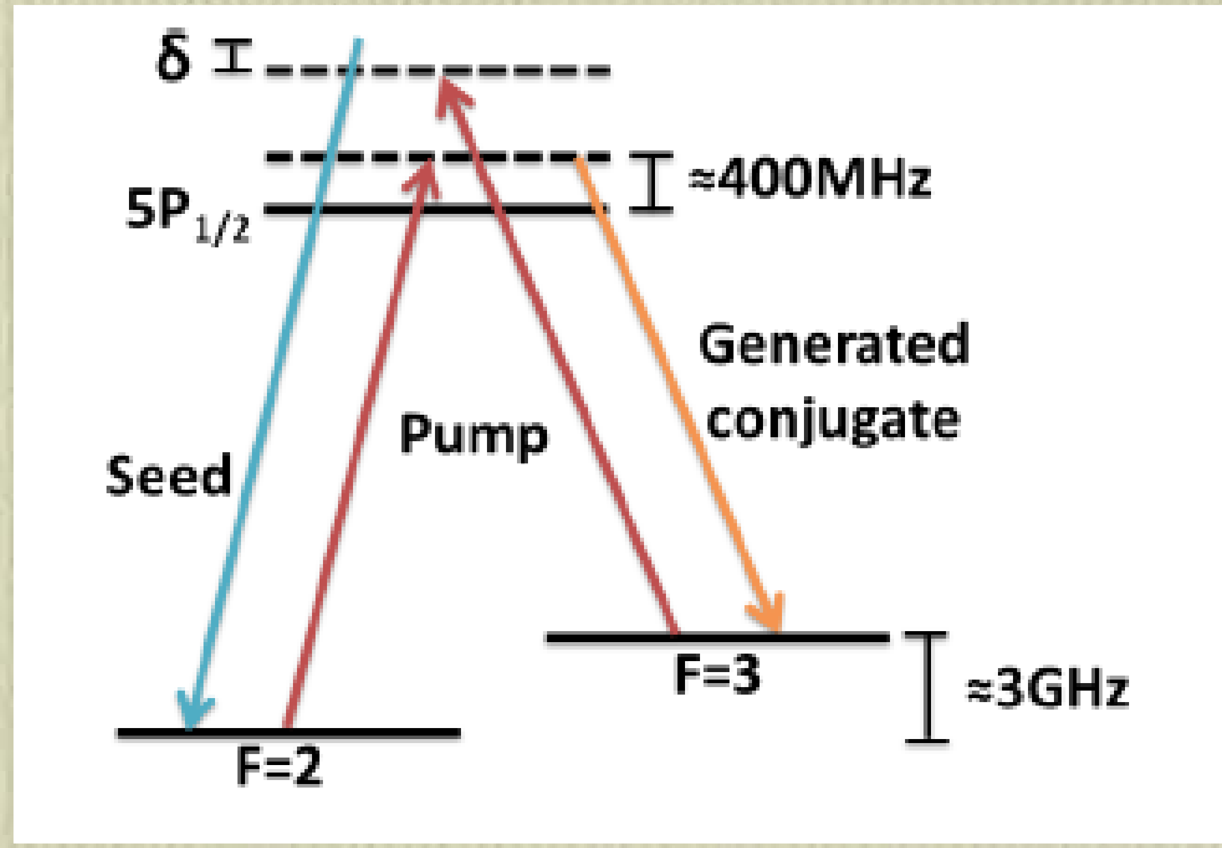


EIT (less loss) spectrum with associated dispersion

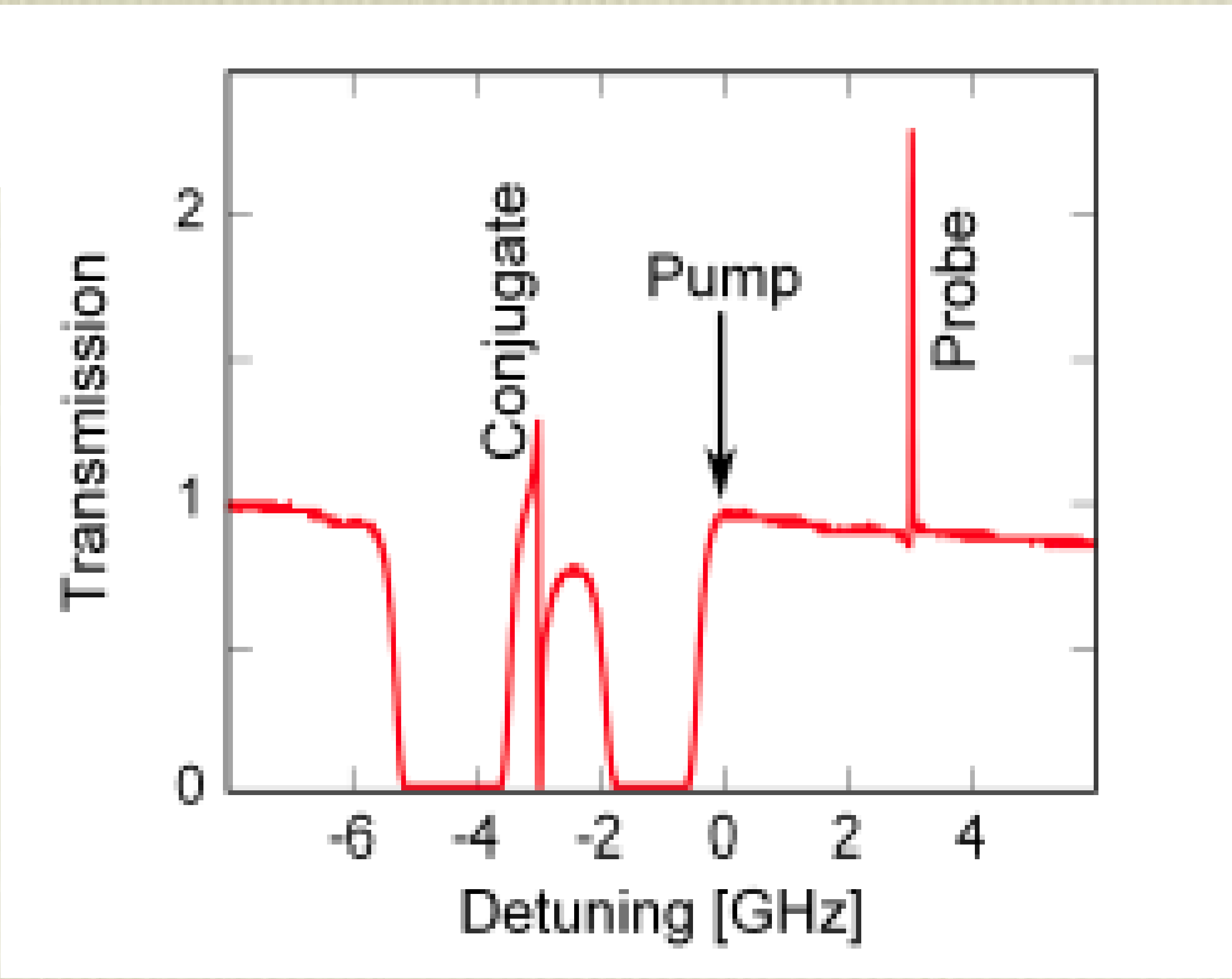


4WM gain features imply dispersion and slow light as well

4WM for "Fast Light"



a somewhat different 4WM configuration leads to a different dispersion character and "fast light"



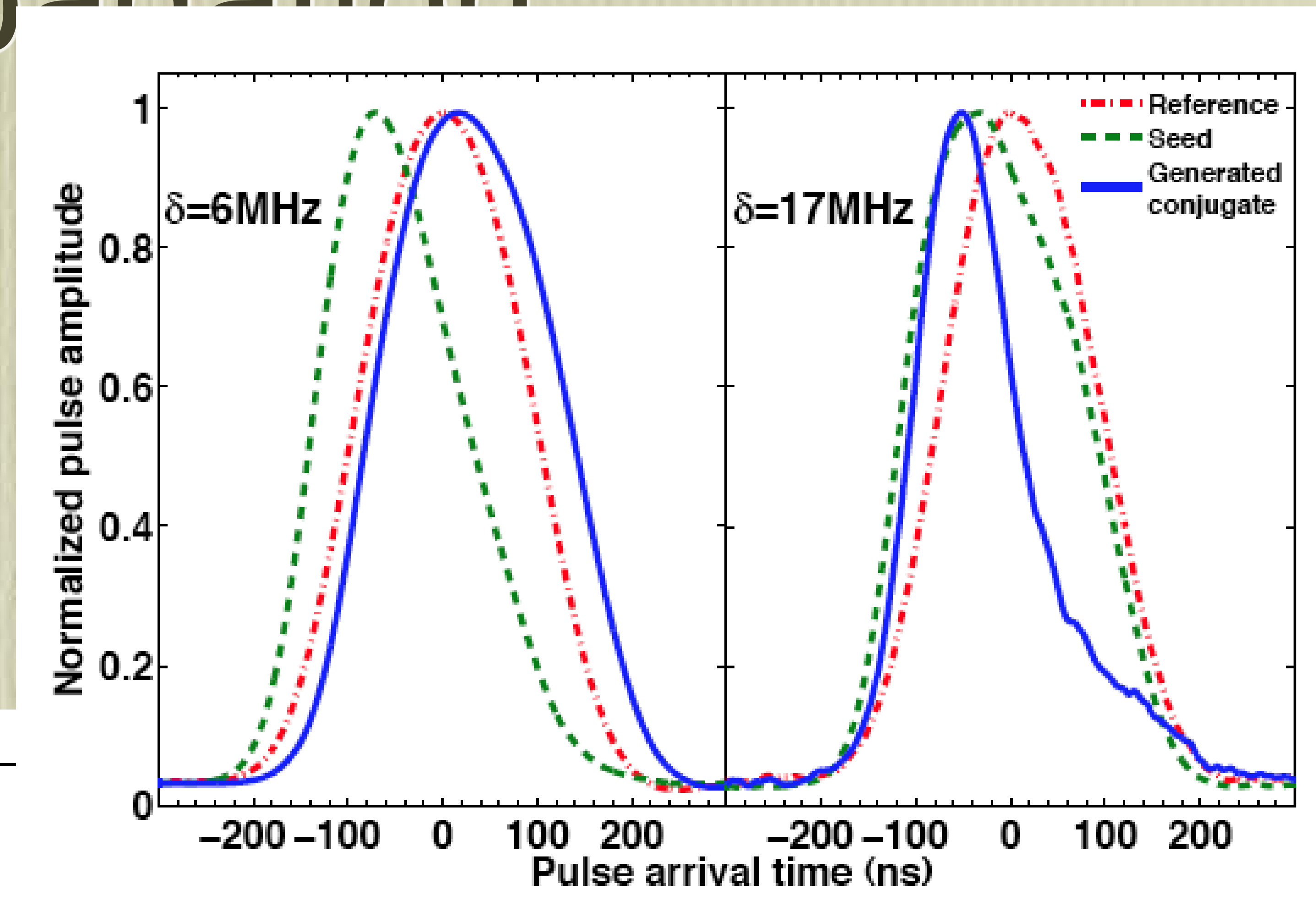
- effective fast light generation with 4WM system
- want to investigate "fast light" propagation of quantum information
- fast light with images

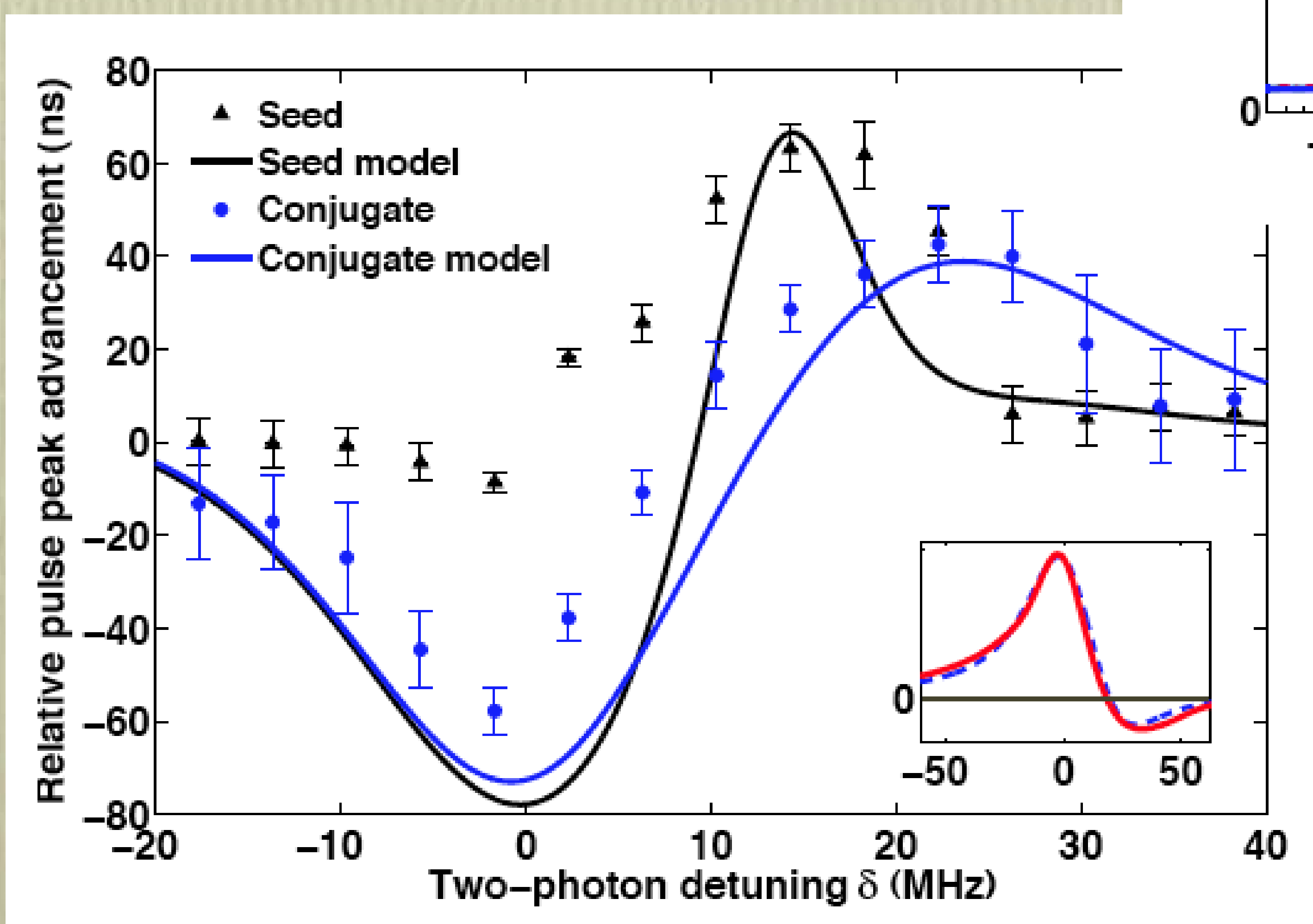
Superluminal pulse propagation

limits to fast light advance ~τ_p with reasonable gain (~100)

(ref: B. Macke, B. Segard and F. Wielonsky, “Optimal superluminal systems,” Phys. Rev. E 72, 035601 (2005))

here we achieve ~0.5 |$_p$ with gain ~ 1

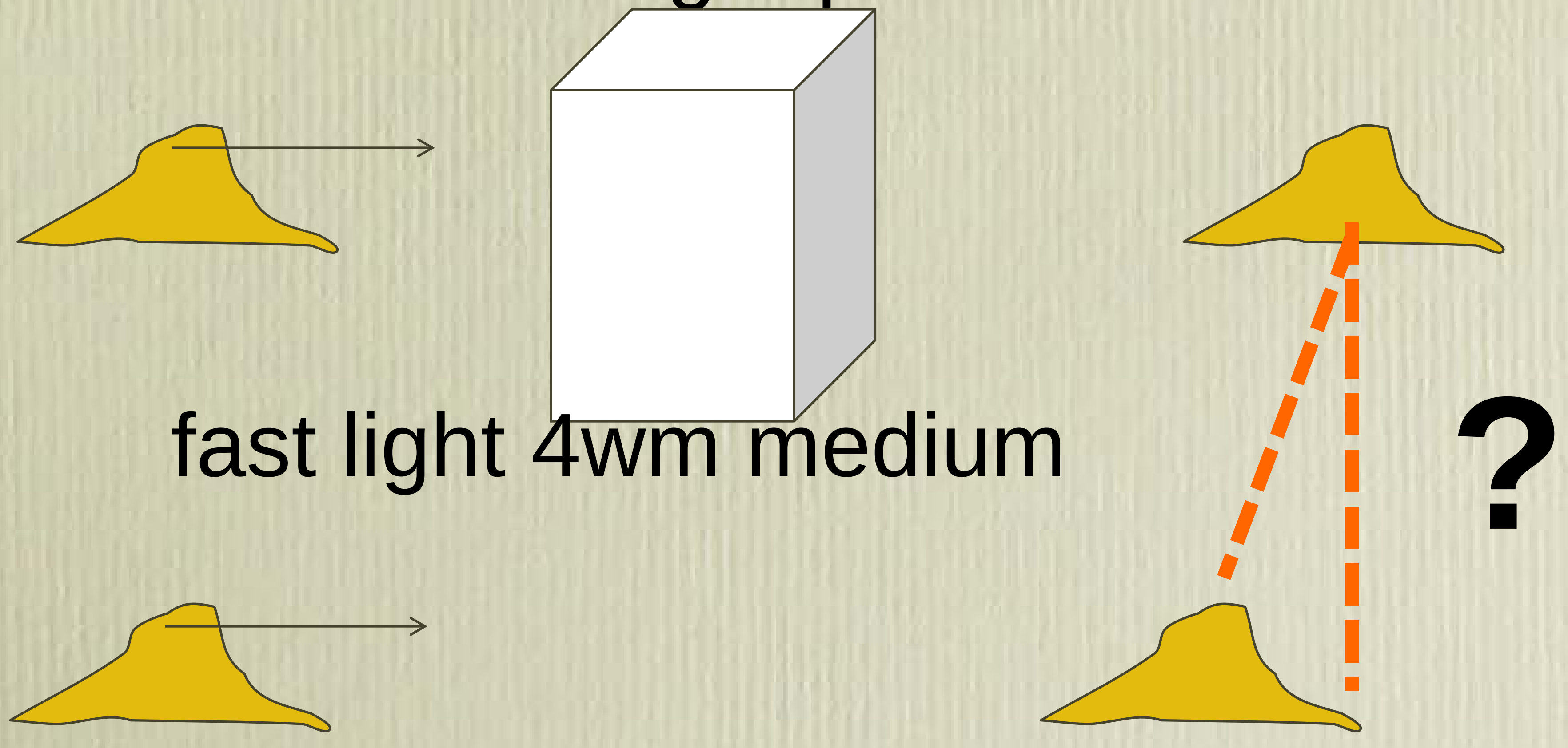




superluminal probe propagation plus generation of superluminal(?) conjugate beam

Fast Light studies

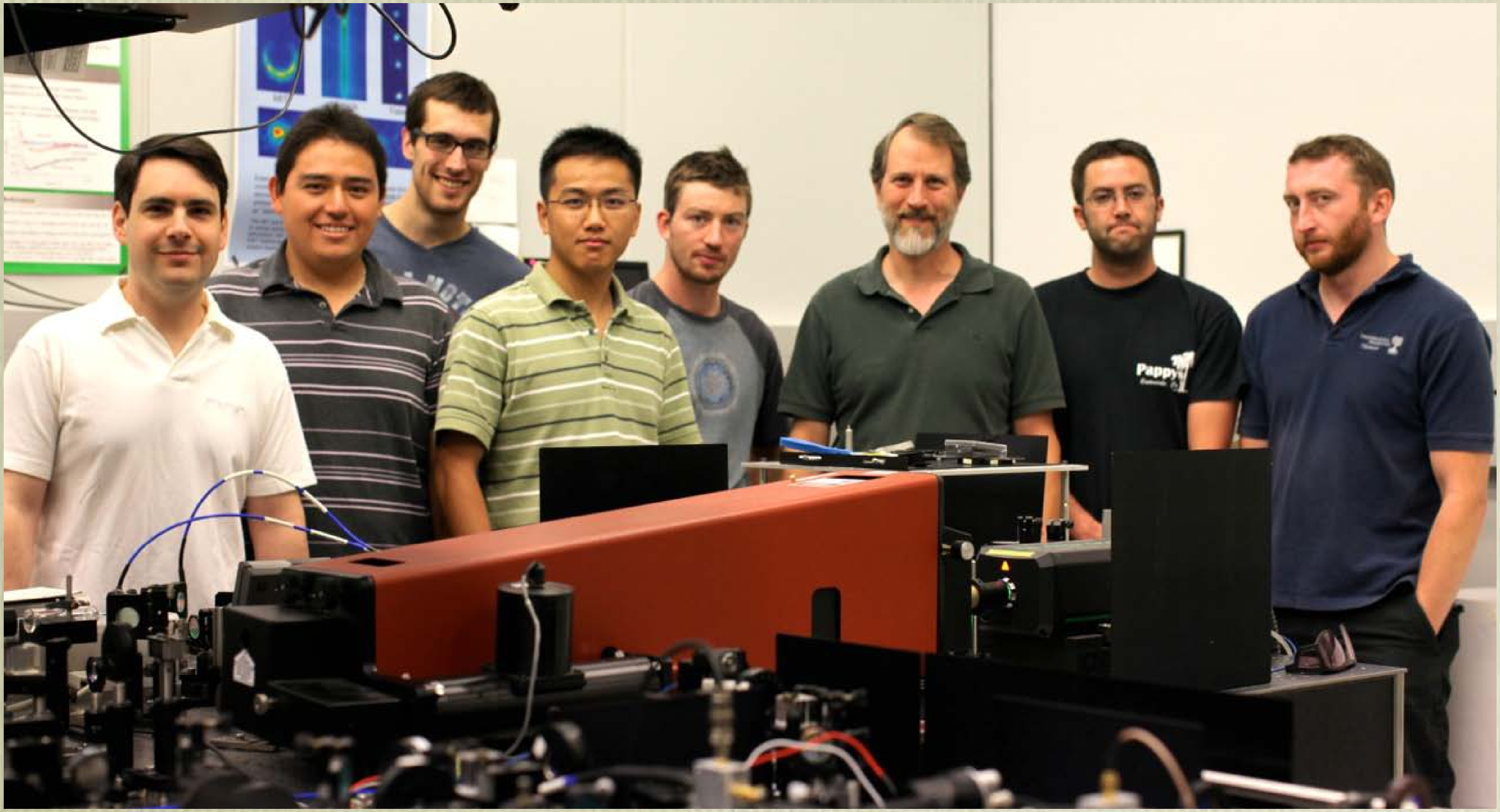
- some of the best pulse advances ever (65%)
- fast images
- fast classical (spatial) information
- fast quantum information ???
- correlate fast light pulses:



summary of future desires

credit to the team...

Jeremy Clark
Neil Corzo
Quentin Glorieux
Ulrich Vogl
Alberto Marino
Zhifan Zhou
Ryan Glasser



Kevin Jones and Yan Hua Zhai (not pictured)