Squeezed states of light - generation and applications

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From ray optics to semiclassical optics

Classical/Geometrical optics

- light is a ray
- which propagates straight
- cannot explain diffraction and interference

LSU

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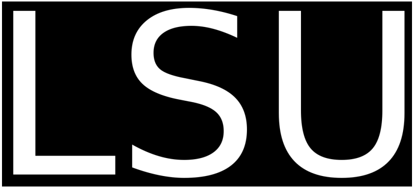
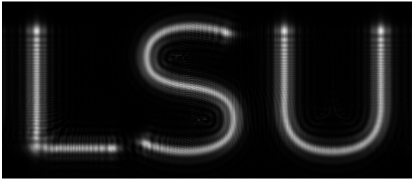


Semiclassical optics

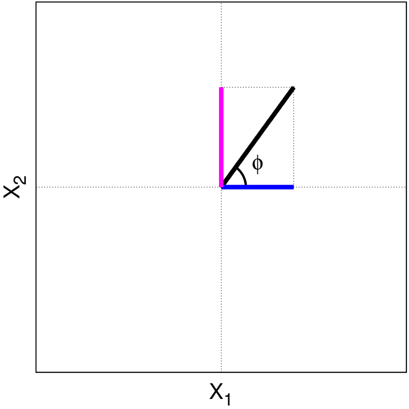
- light is a wave
- color (wavelength/frequency) is important
- amplitude (a) and phase are important, $E(t) = ae^{i(kz - \omega t)}$
- cannot explain residual measurements noise



Classical field

$$E(\phi) = |a|e^{-i\phi} = |a|\cos(\phi) + i|a|\sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz$$

Detectors sense the real part of the field (X_1) but there is a way to see X_2 as well



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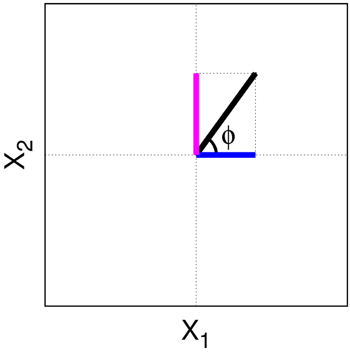

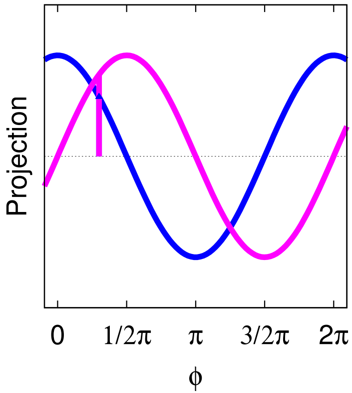

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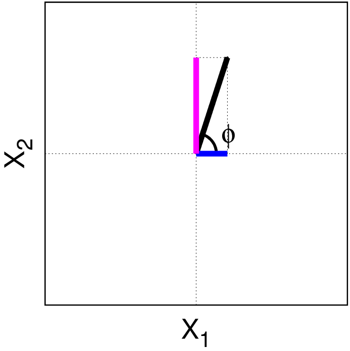

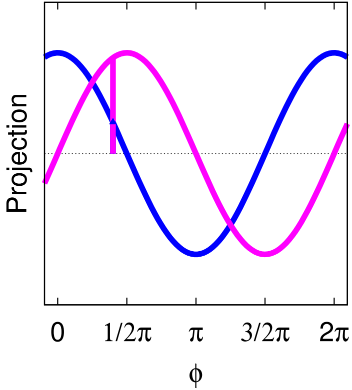

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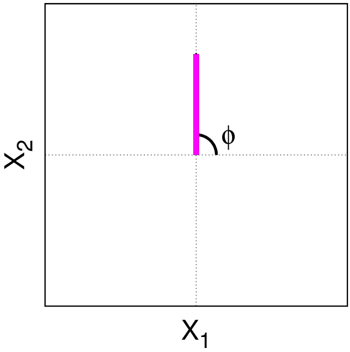

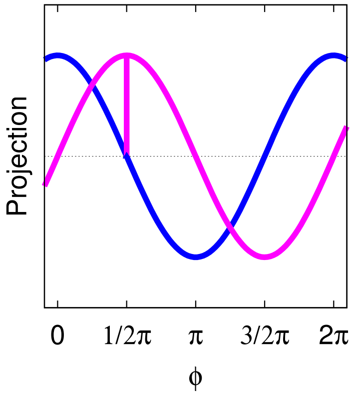

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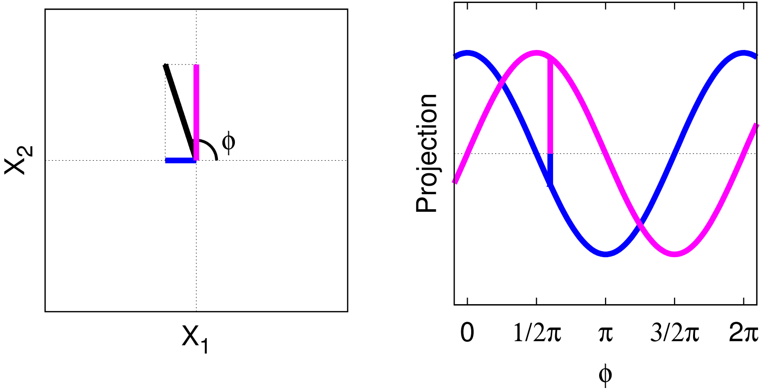

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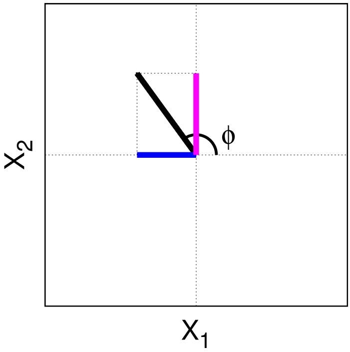

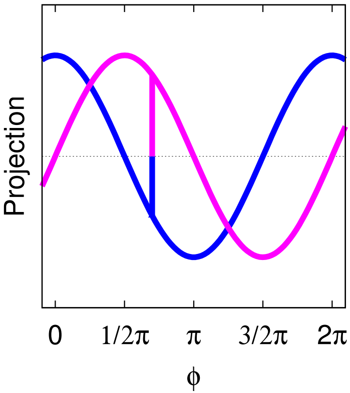

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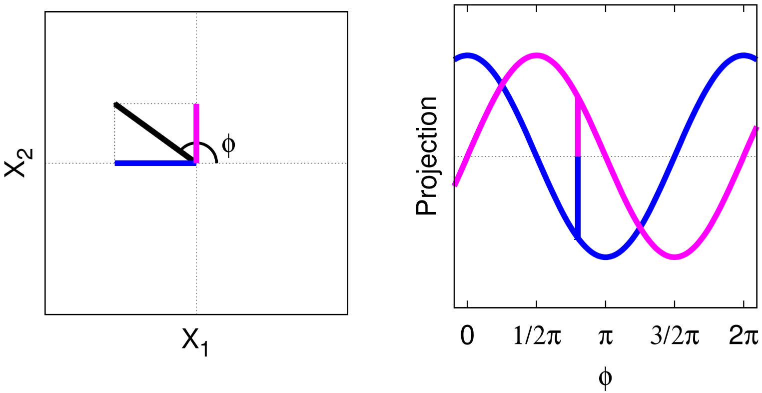

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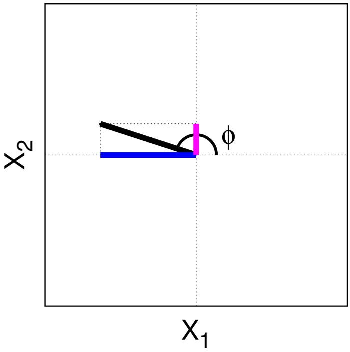

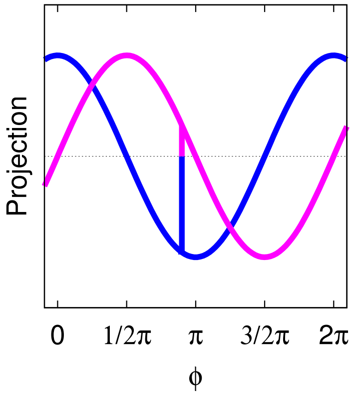

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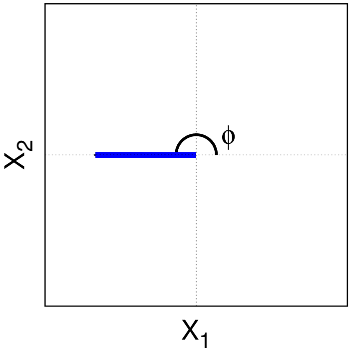

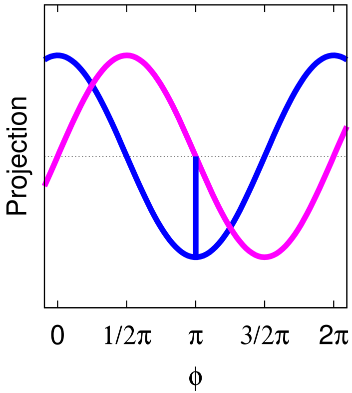

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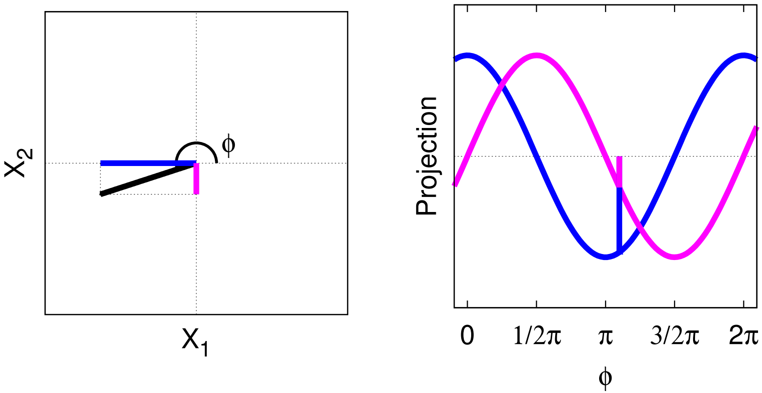

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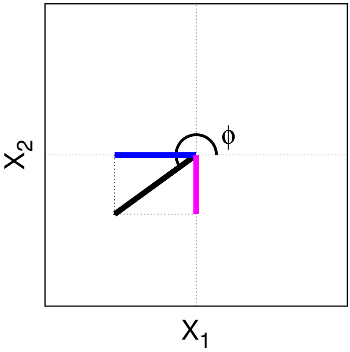

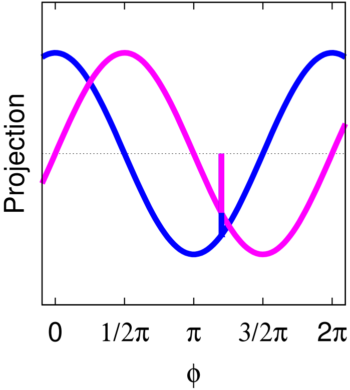

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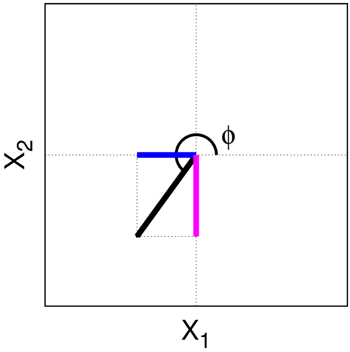

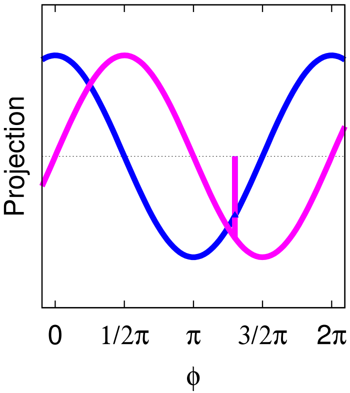

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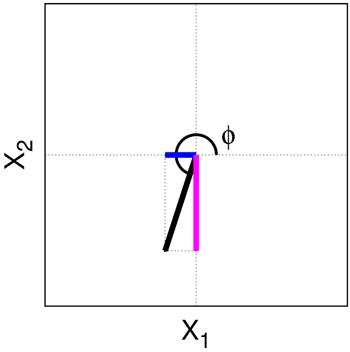

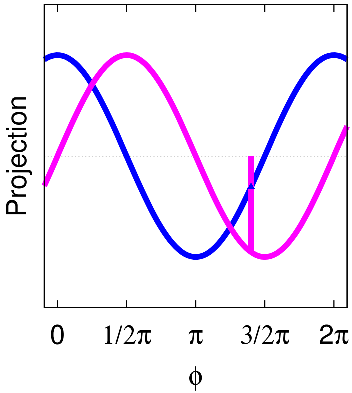

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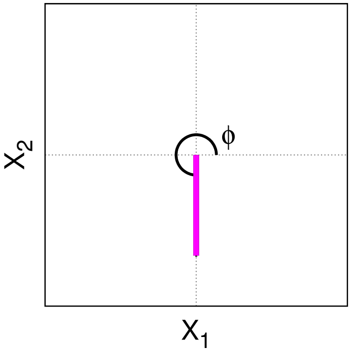

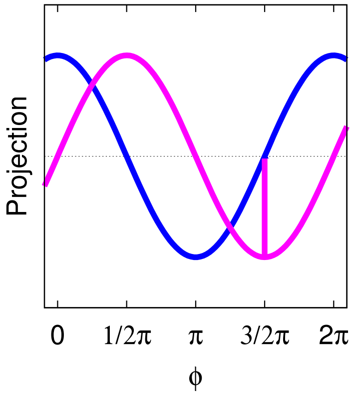

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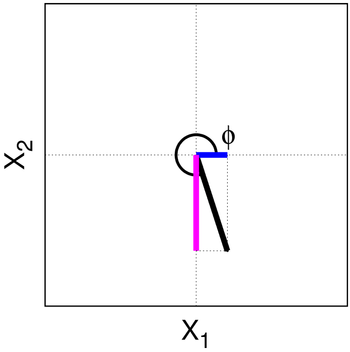

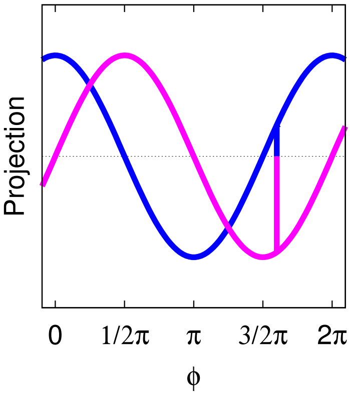

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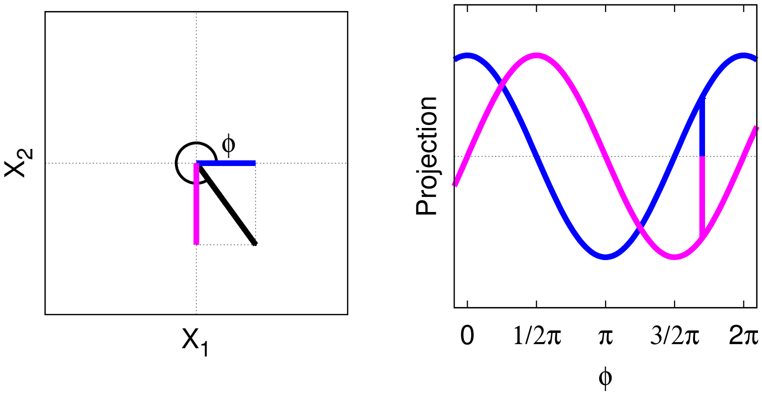

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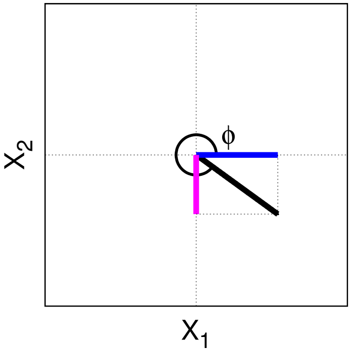
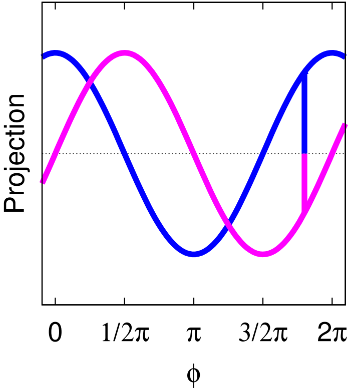
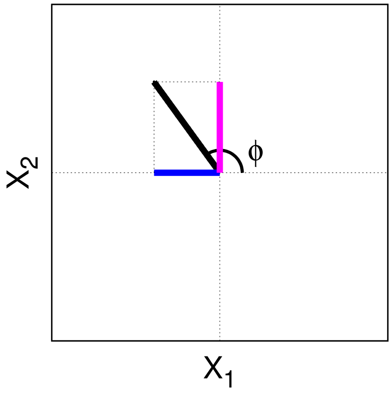
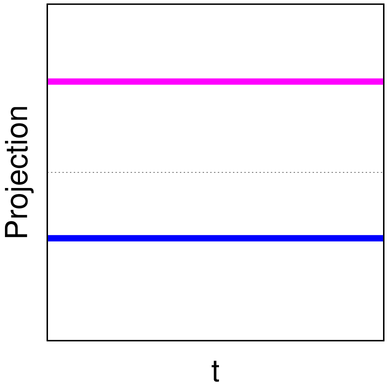




Classical quadratures vs time in a rotating frame

$$E(\phi) \quad = \quad |a|e^{-i\phi} = |a|\cos(\phi) + i|a|\sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz$$





Reality check quadratures vs time

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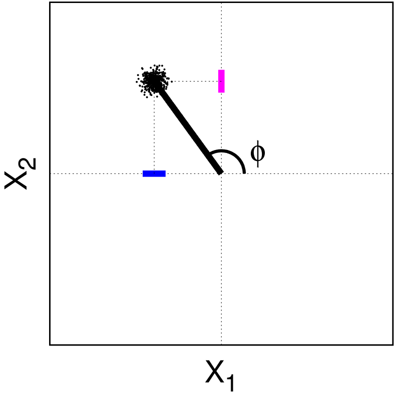
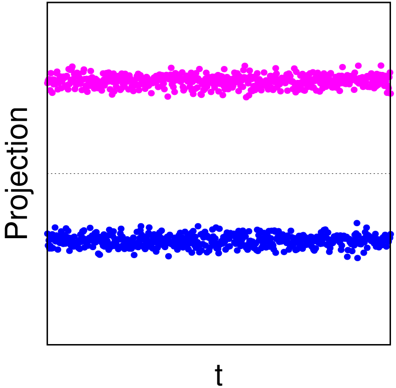
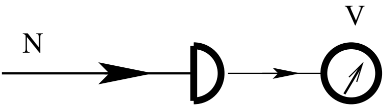




Detector quantum noise

Simple photodetector



$$V \sim N$$

$$\Delta V \sim \sqrt{N}$$

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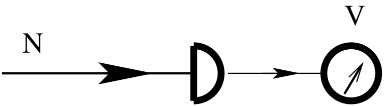

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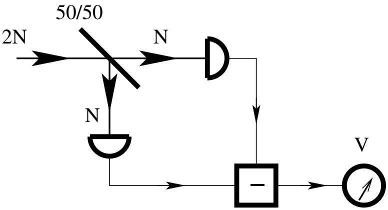
Balanced photodetector



$$V = 0$$

$$\Delta V \sim \sqrt{N}$$

Transition from classical to quantum field

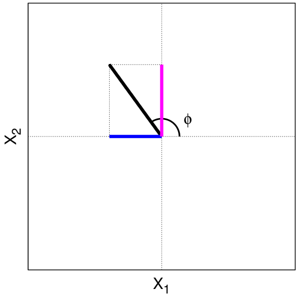
Classical analog

- Field amplitude a
- Field real part
  $X_1 = (a^* + a)/2$
- Field imaginary part
  $X_2 = i(a^* - a)/2$

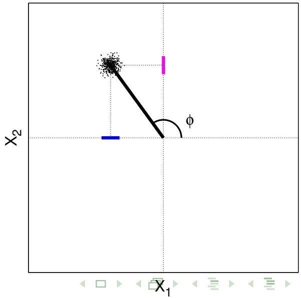
Quantum approach

- Field operator $\hat{a}$
- Amplitude quadrature
  $\hat{X}_1 = (\hat{a}^\dagger + \hat{a})/2$
- Phase quadrature
  $\hat{X}_2 = i(\hat{a}^\dagger - \hat{a})/2$

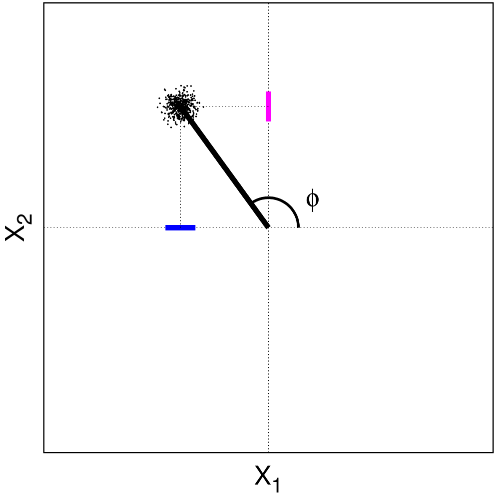
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



$$\hat{E}(\phi) = \hat{X}_1 + i\hat{X}_2$$



Quantum optics summary



Light consist of photons

- $\hat{N} = a^\dagger a$

Commutator relationship

- $[a, a^\dagger] = 1$
- $[X_1, X_2] = i/2$

Detectors measure

- number of photons $\hat{N}$
- Quadratures $\hat{X}_1$ and $\hat{X}_2$

Uncertainty relationship

- $\Delta X_1 \Delta X_2 \geq 1/4$

Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

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

The more precisely the POSITION is determined, the less precisely the MOMENTUM is known, and vice versa

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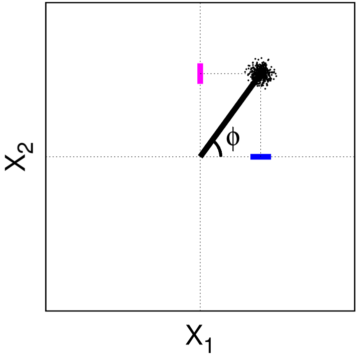
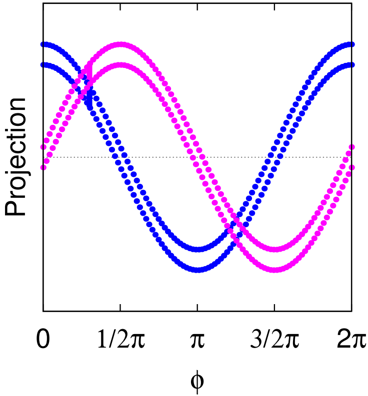
Optics equivalent strict definition

$\Delta X_1 \Delta X_2 \geq 1/4$

Coherent state is minimum uncertainty state

$\Delta X_1 \Delta X_2 = 1/4$





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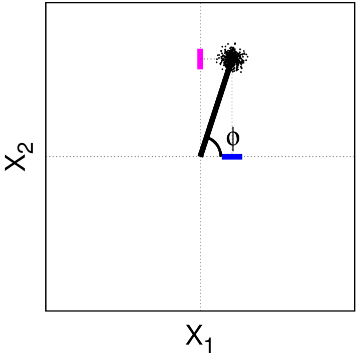

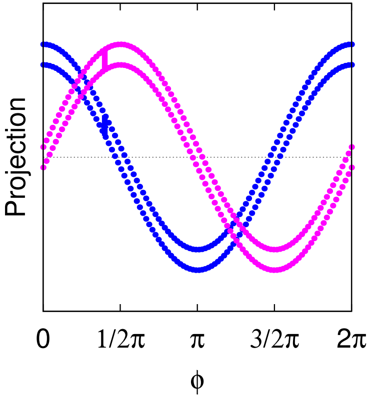

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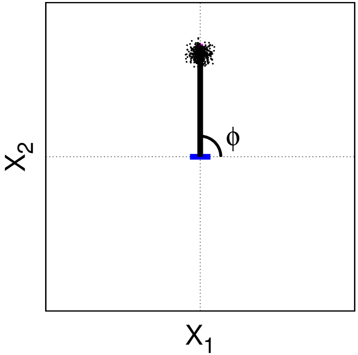

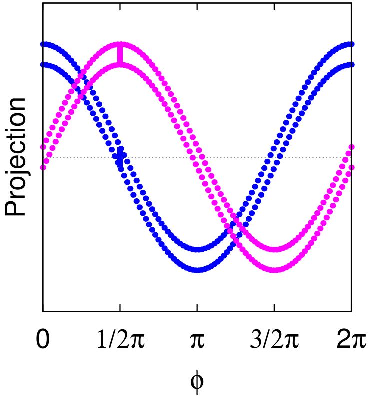

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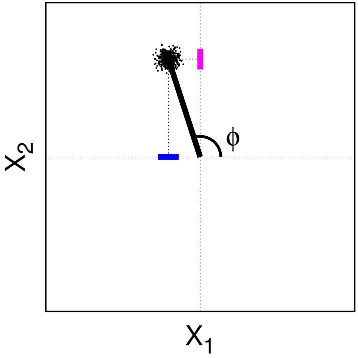

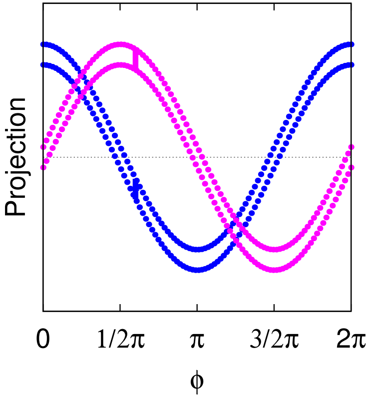

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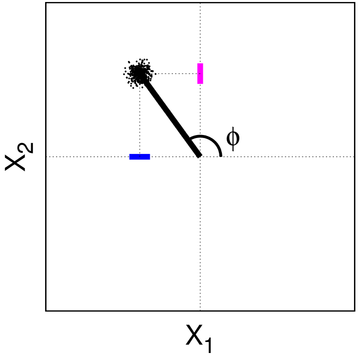

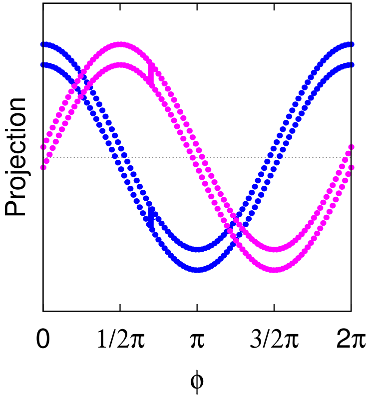

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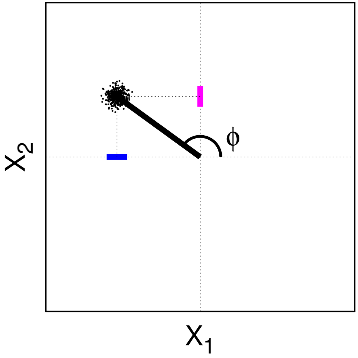

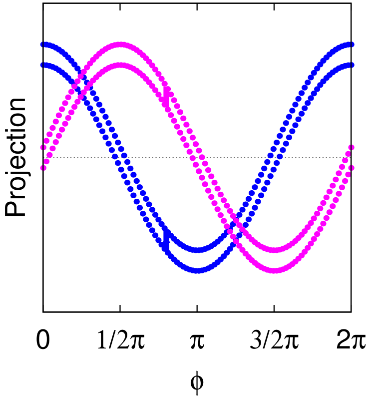

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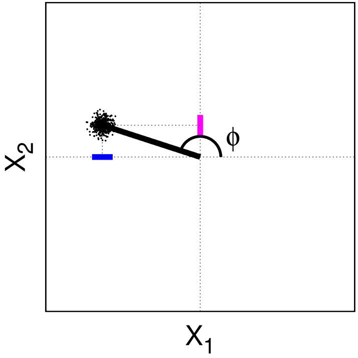

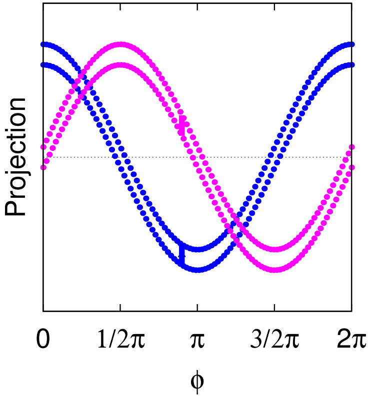

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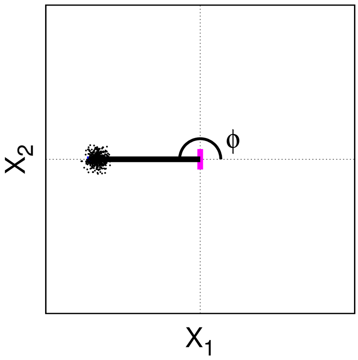
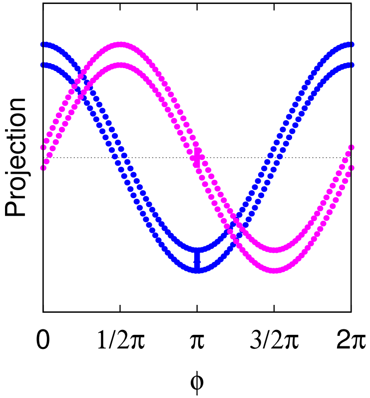
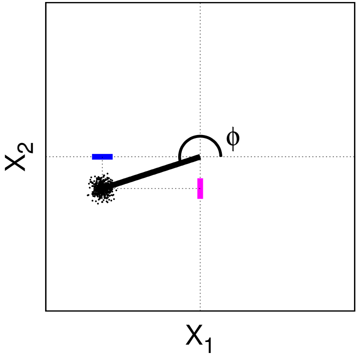
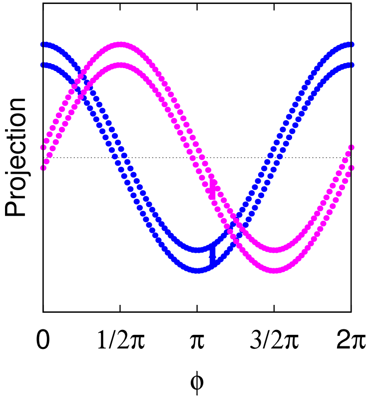




Coherent state is minimum uncertainty state

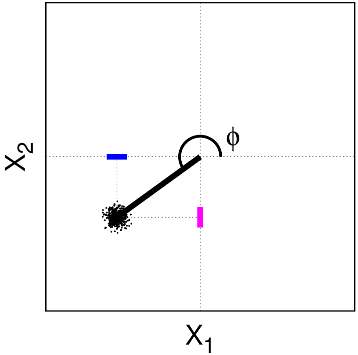
$\Delta X_1 \Delta X_2 = 1/4$

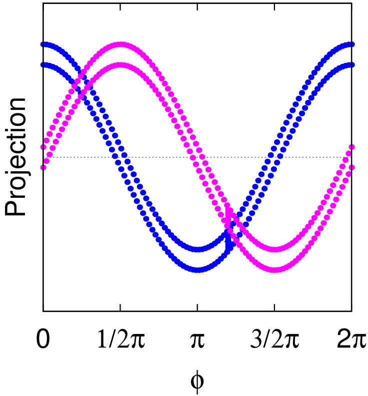




Coherent state is minimum uncertainty state

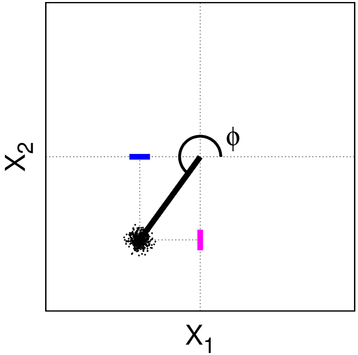
$\Delta X_1 \Delta X_2 = 1/4$

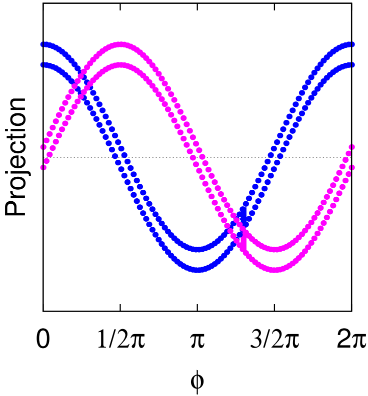




Coherent state is minimum uncertainty state

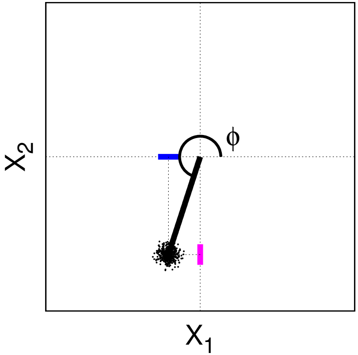
$\Delta X_1 \Delta X_2 = 1/4$

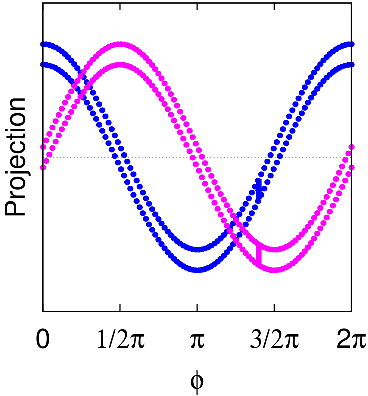




Coherent state is minimum uncertainty state

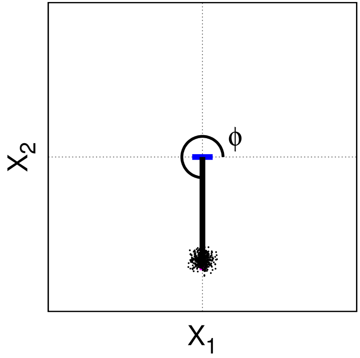
$\Delta X_1 \Delta X_2 = 1/4$

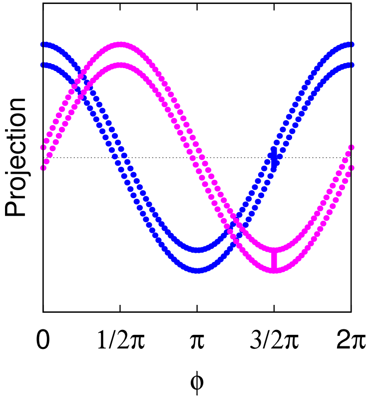




Coherent state is minimum uncertainty state

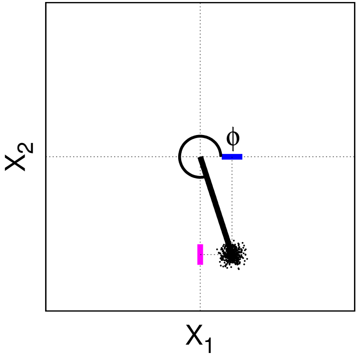
$\Delta X_1 \Delta X_2 = 1/4$

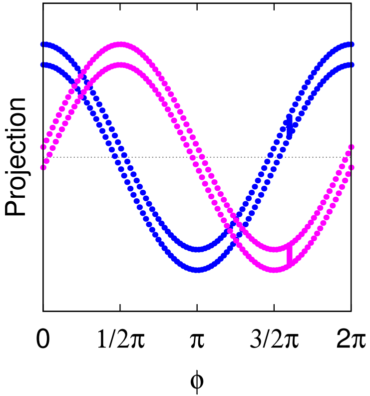




Coherent state is minimum uncertainty state

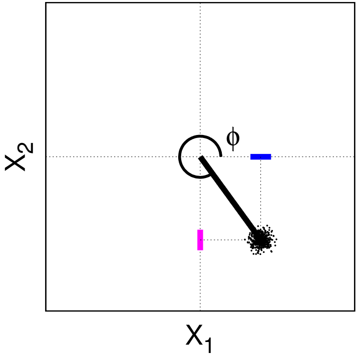
$\Delta X_1 \Delta X_2 = 1/4$

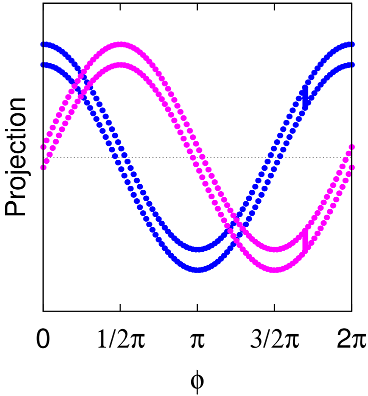




Coherent state is minimum uncertainty state

$\Delta X_1 \Delta X_2 = 1/4$





Coherent state is minimum uncertainty state

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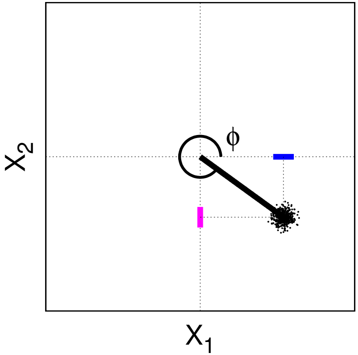
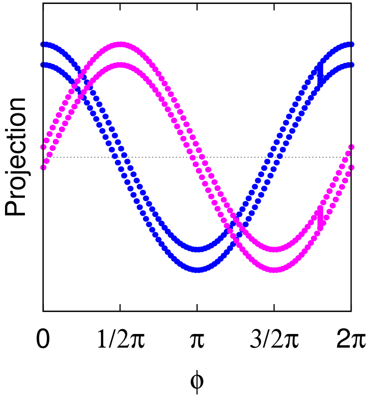
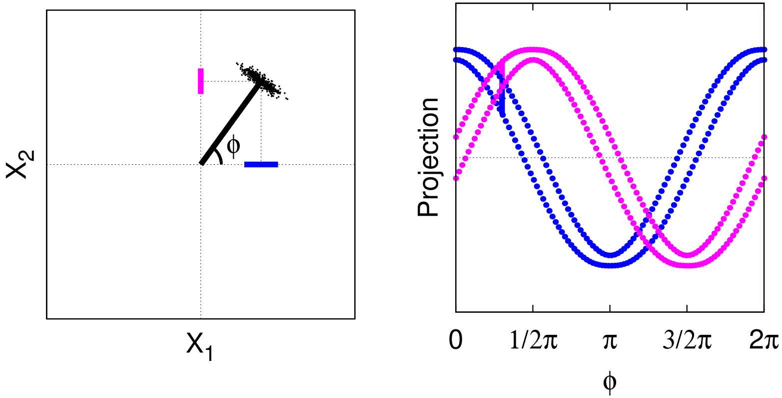




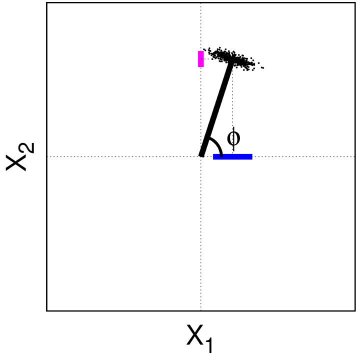
Amplitude squeezed states

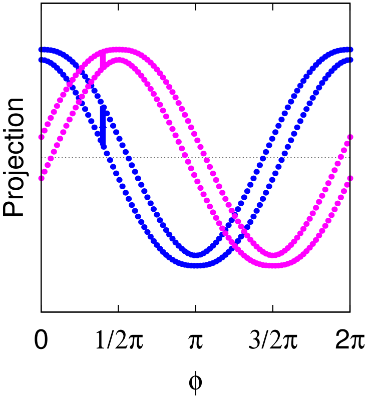
$\Delta X_1 \Delta X_2 = 1/4$



Amplitude squeezed states

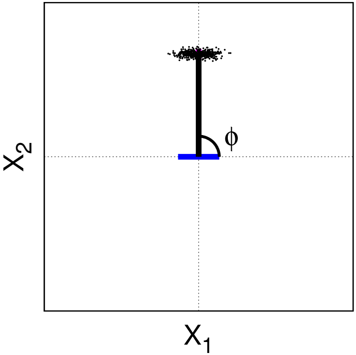
$\Delta X_1 \Delta X_2 = 1/4$

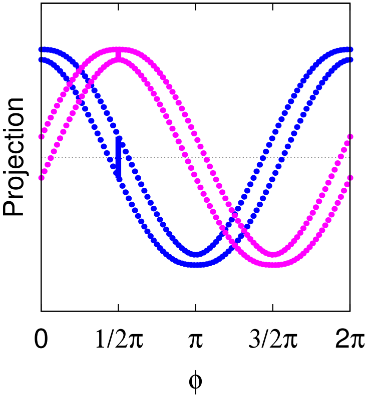




Amplitude squeezed states

$\Delta X_1 \Delta X_2 = 1/4$





Amplitude squeezed states

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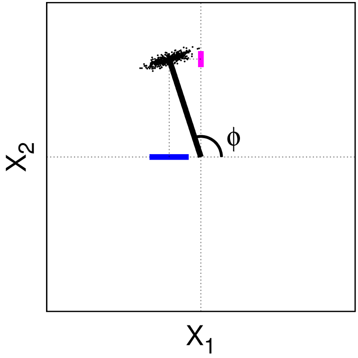

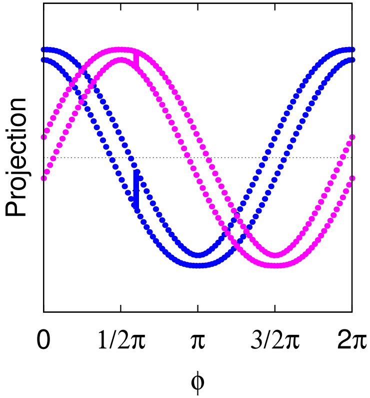

Amplitude squeezed states

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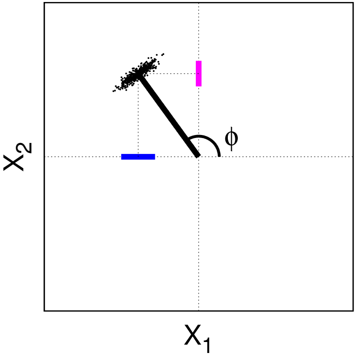
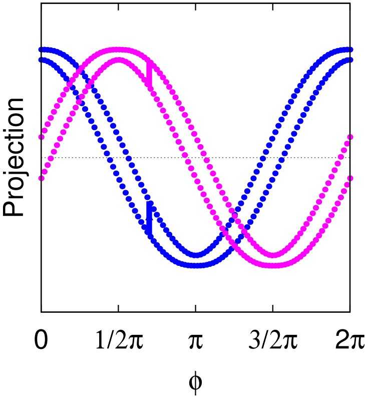
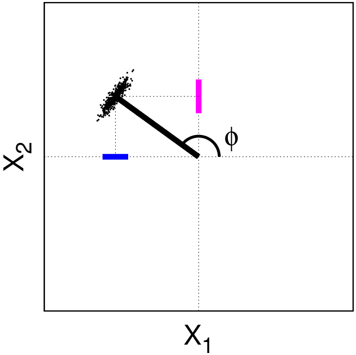
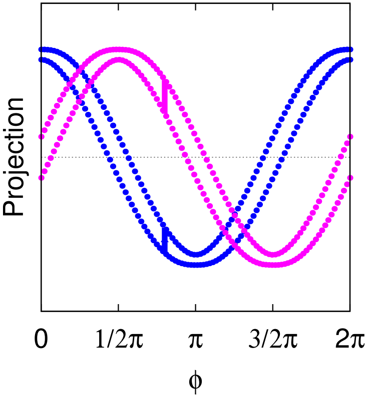




Amplitude squeezed states

$\Delta X_1 \Delta X_2 = 1/4$





Amplitude squeezed states

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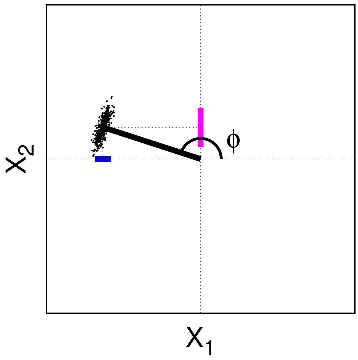

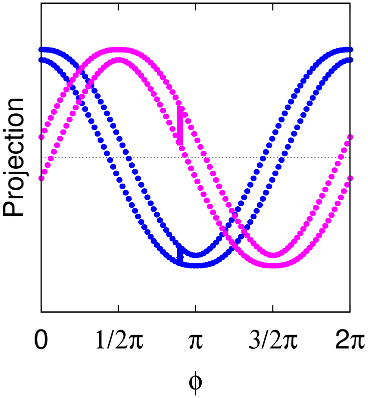

Amplitude squeezed states

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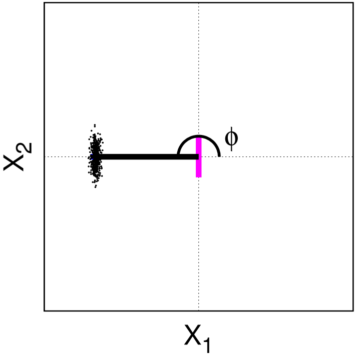

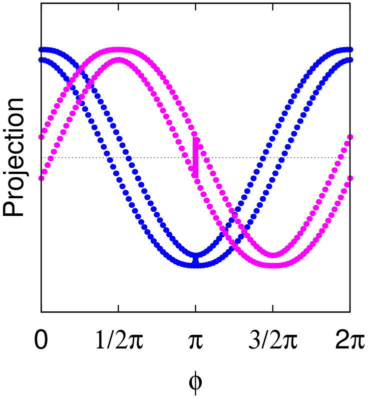

Amplitude squeezed states

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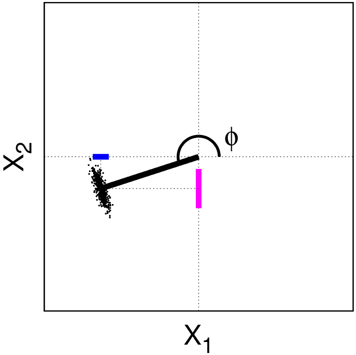

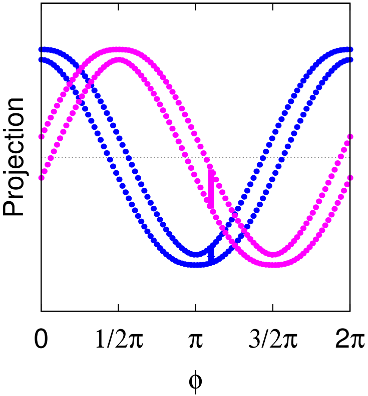

Amplitude squeezed states

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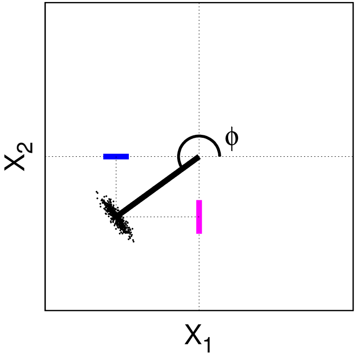

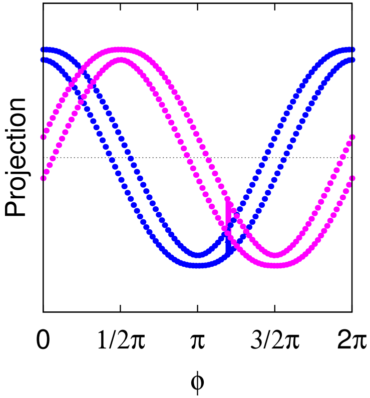

Amplitude squeezed states

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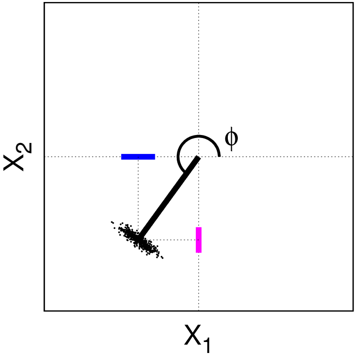
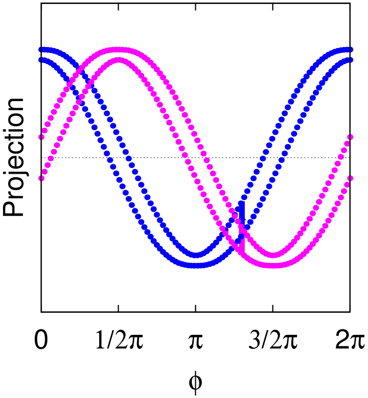
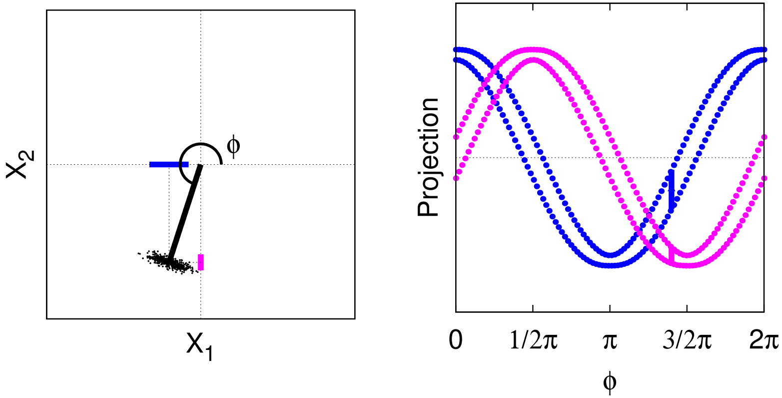




Amplitude squeezed states

$\Delta X_1 \Delta X_2 = 1/4$



Amplitude squeezed states

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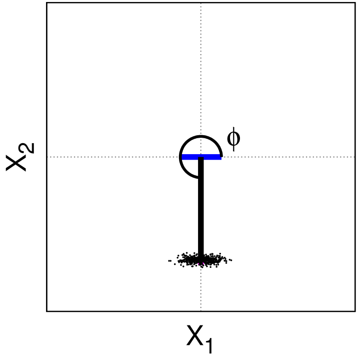

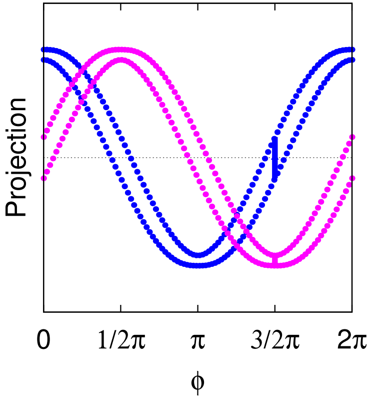

Amplitude squeezed states

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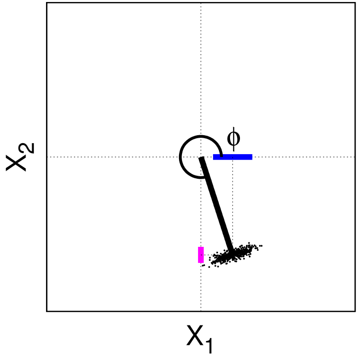

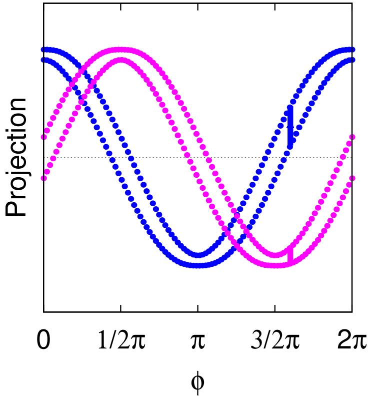

Amplitude squeezed states

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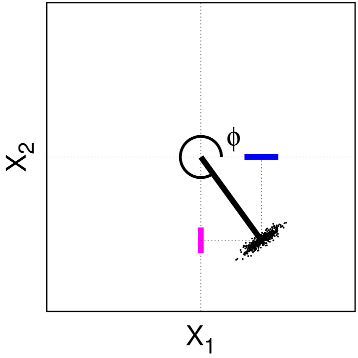

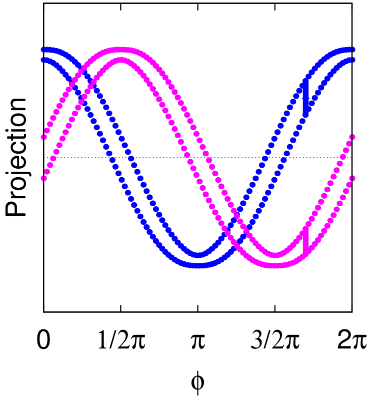

Amplitude squeezed states

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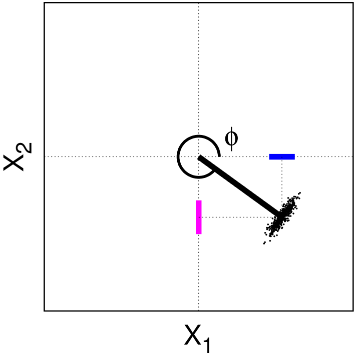
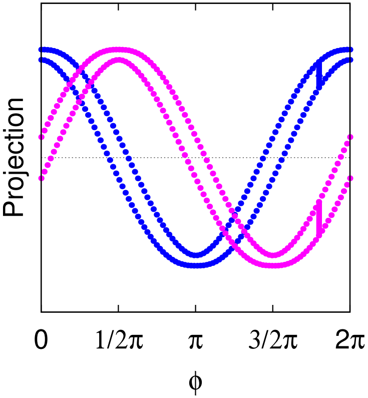
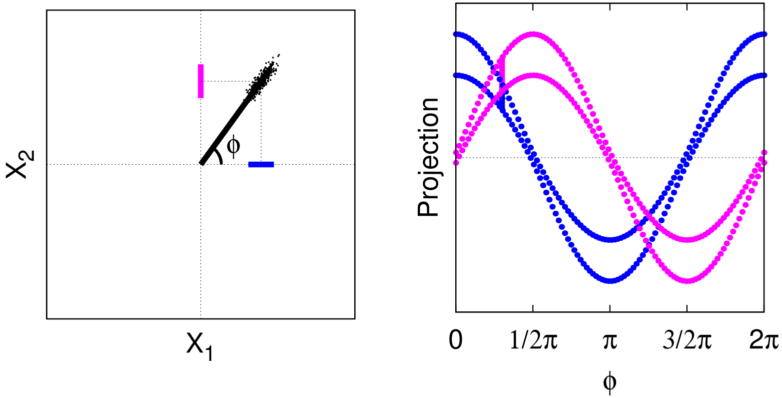




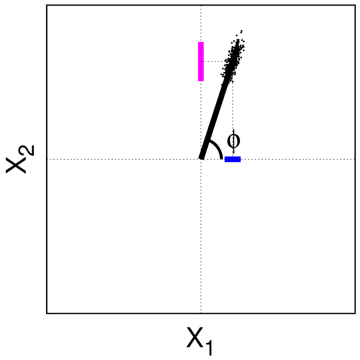
Phase squeezed states

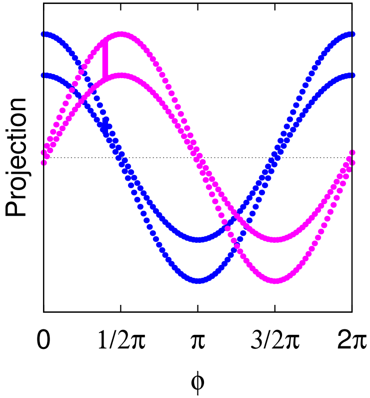
$\Delta X_1 \Delta X_2 = 1/4$



Phase squeezed states

$\Delta X_1 \Delta X_2 = 1/4$





Phase squeezed states

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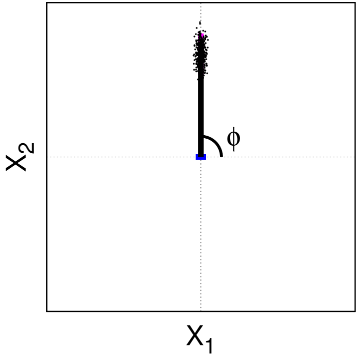

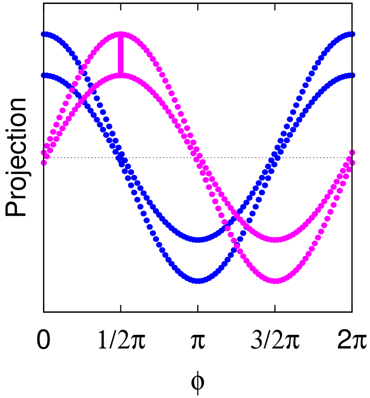

Phase squeezed states

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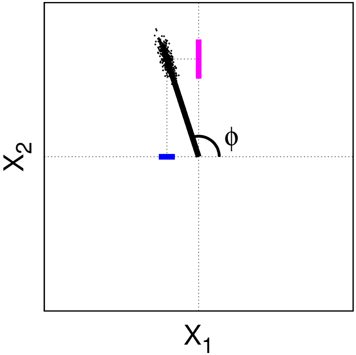

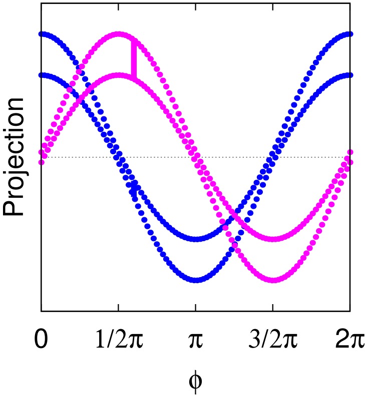

Phase squeezed states

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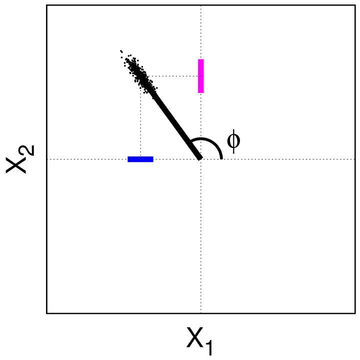

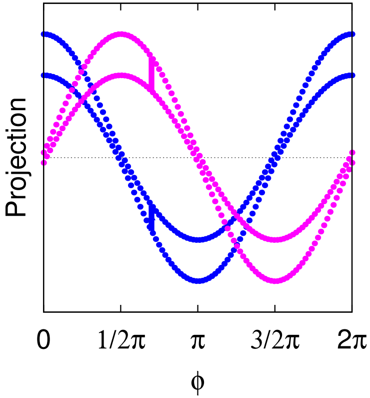

Phase squeezed states

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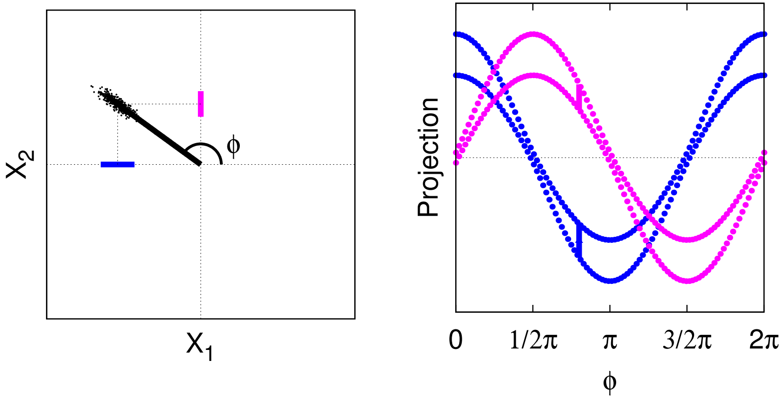

Phase squeezed states

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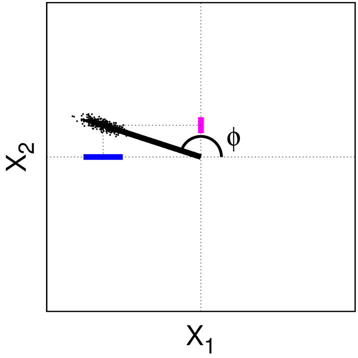

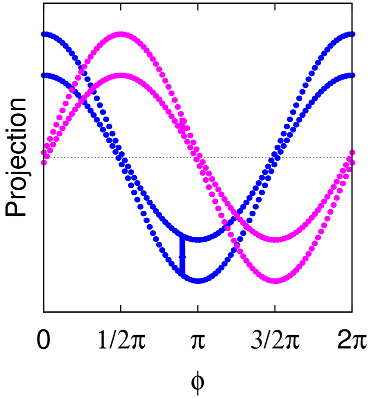

Phase squeezed states

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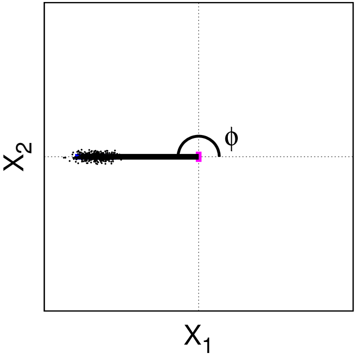

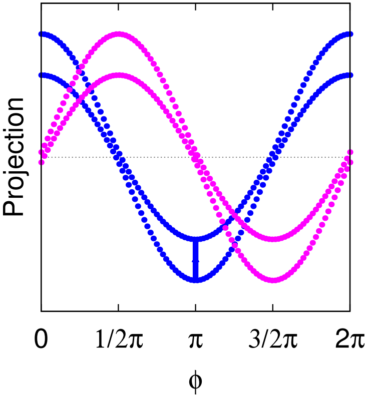

Phase squeezed states

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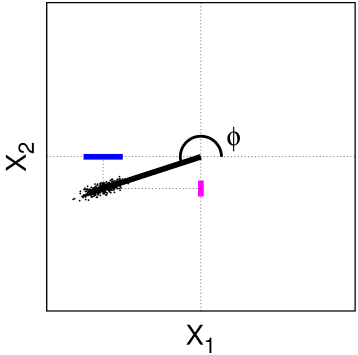

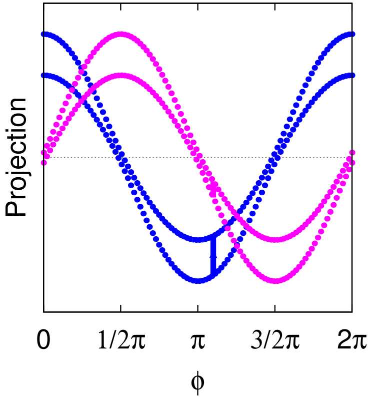

Phase squeezed states

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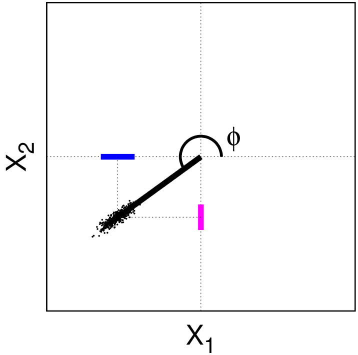

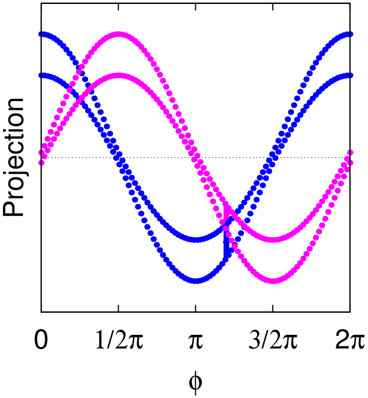

Phase squeezed states

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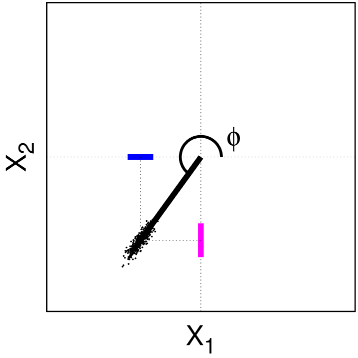

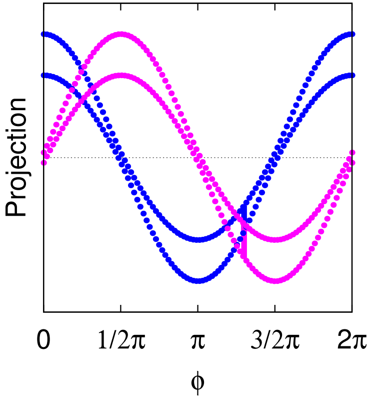

Phase squeezed states

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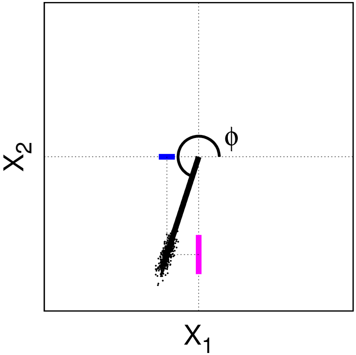
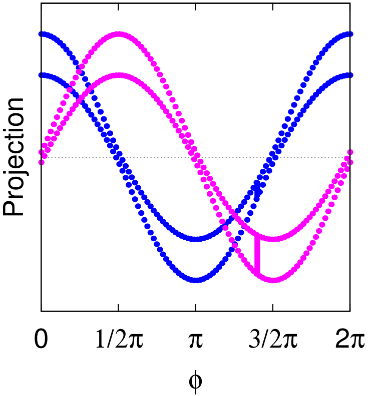
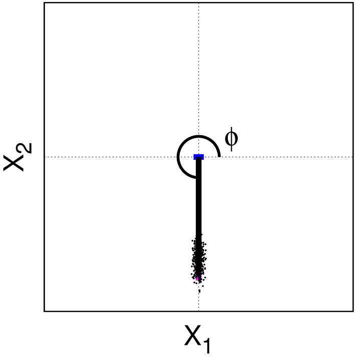
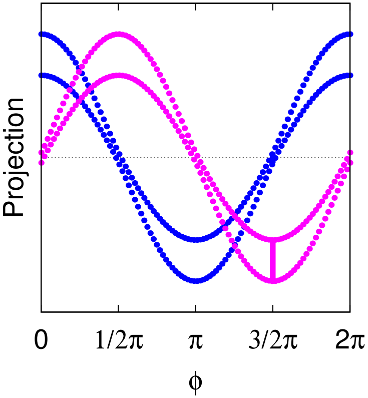




Phase squeezed states

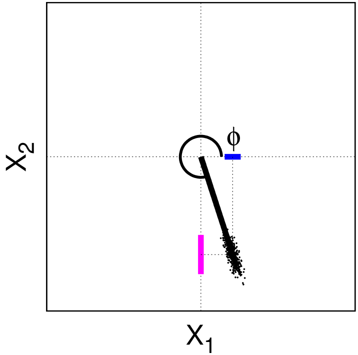
$\Delta X_1 \Delta X_2 = 1/4$

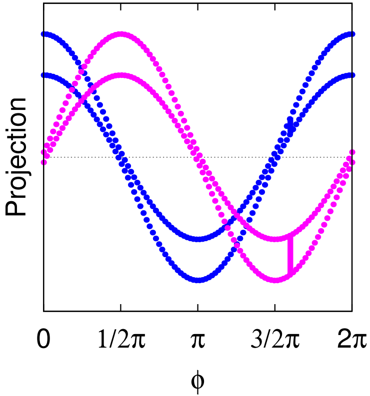




Phase squeezed states

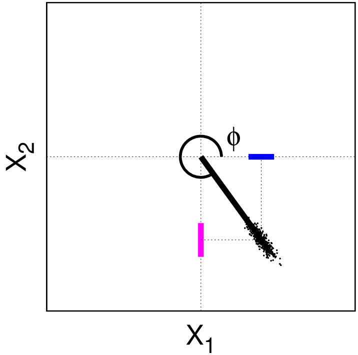
$\Delta X_1 \Delta X_2 = 1/4$

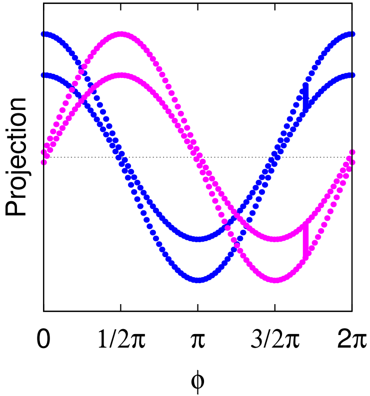




Phase squeezed states

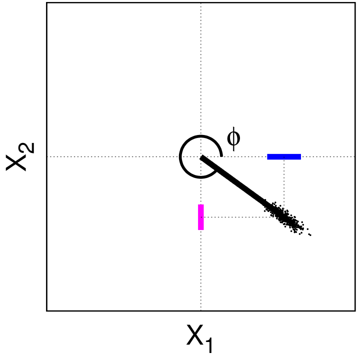
$\Delta X_1 \Delta X_2 = 1/4$

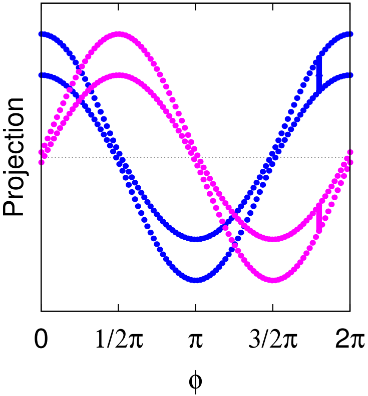




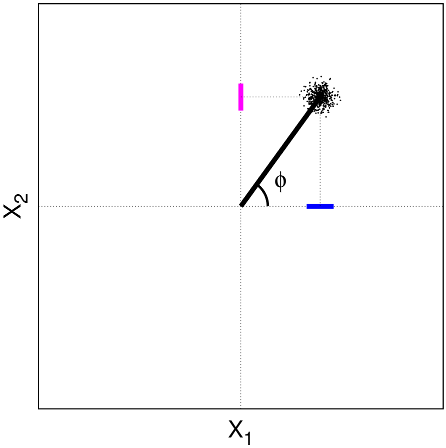
Phase squeezed states

$\Delta X_1 \Delta X_2 = 1/4$

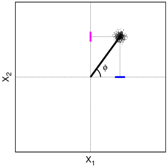




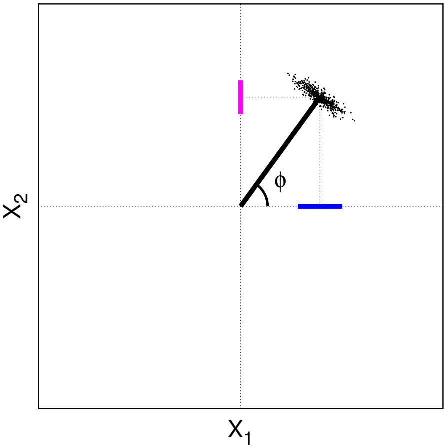
Squeezed quantum states zoo



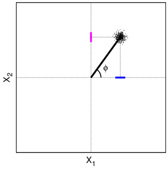
Unsqueezed coherent



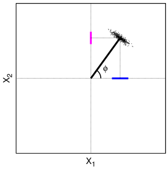
Squeezed quantum states zoo



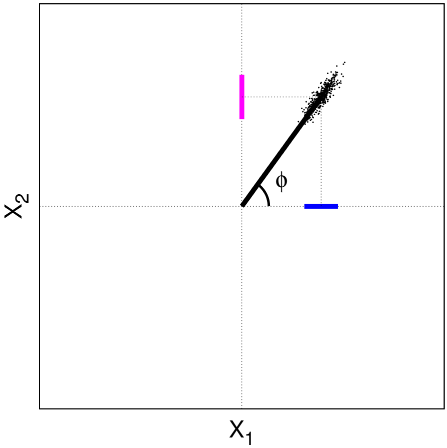
Unsqueezed coherent



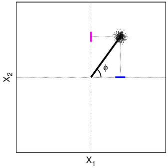
Amplitude squeezed



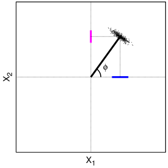
Squeezed quantum states zoo



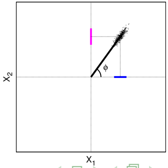
Unsqueezed coherent



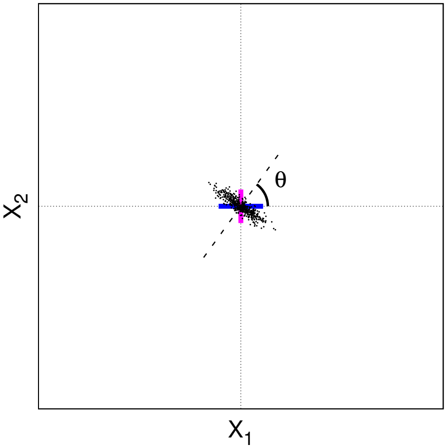
Amplitude squeezed



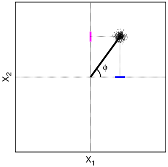
Phase squeezed



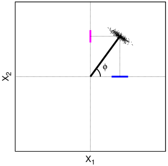
Squeezed quantum states zoo



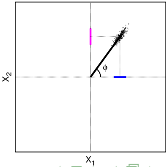
Unsqueezed coherent



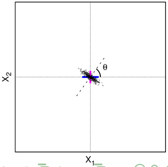
Amplitude squeezed



Phase squeezed

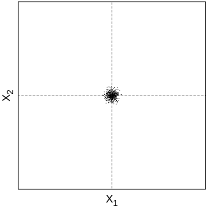


Vacuum squeezed



Squeezed field generation recipe

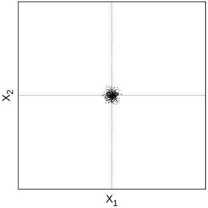
Take a vacuum state $|0>$



$$H = \frac{1}{2}$$

Squeezed field generation recipe

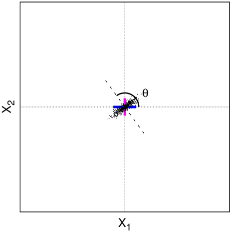
Take a vacuum state $|0>$



$$H = \frac{1}{2}$$

Apply squeezing operator $|\xi>= \hat{S}(\xi)|0>$

$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}$$



Squeezed field generation recipe

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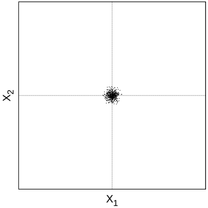

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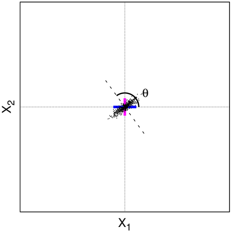
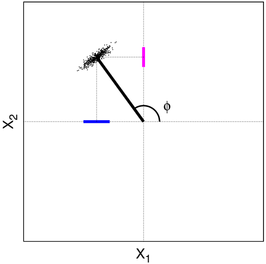
$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}$$



Apply displacement operator $|\alpha, \xi>= \hat{D}(\alpha)|s>$

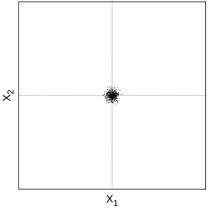
$$\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$$



$$< \alpha, \xi | X_1 | \alpha, \xi > = Re(\alpha),$$
$$< \alpha, \xi | X_2 | \alpha, \xi > = Im(\alpha)$$

Squeezed field generation recipe

Take a vacuum state $|0>$

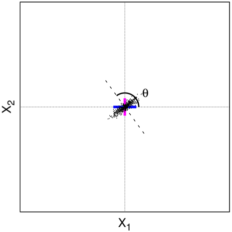


$$H = \frac{1}{2}$$

Notice $\Delta X_1 \Delta X_2 = \frac{1}{4}$

Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}$$



Apply displacement operator $|\alpha, \xi >= \hat{D}(\alpha)|s>$

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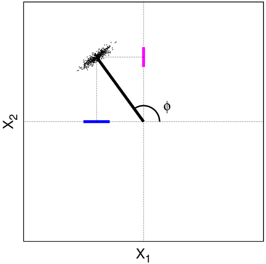
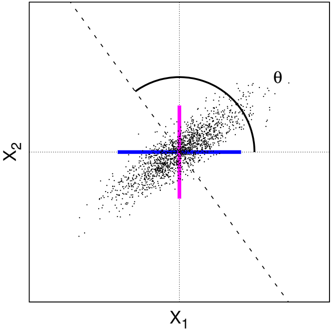


$$\begin{aligned} <\alpha, \xi|X_1|\alpha, \xi > &= Re(\alpha), \\ <\alpha, \xi|X_2|\alpha, \xi > &= Im(\alpha) \end{aligned}$$

Squeezed state $|\xi>=\hat{S}(\xi)|0>$ properties



$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}, \xi = re^{i\theta}$$

If $\theta = 0$

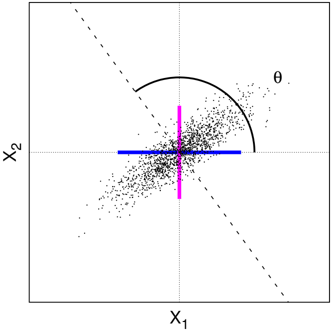
$$< \xi|(\Delta X_1)^2|\xi > = \frac{1}{4}e^{-2r}$$

$$< \xi|(\Delta X_2)^2|\xi > = \frac{1}{4}e^{2r}$$

$$< \xi|(\Delta X_1)^2|\xi > = \frac{1}{4}(\cosh^2 r + \sinh^2 r - 2\sinh r \cosh r \cos\theta)$$

$$< \xi|(\Delta X_2)^2|\xi > = \frac{1}{4}(\cosh^2 r + \sinh^2 r + 2\sinh r \cosh r \cos\theta)$$

Photon number of squeezed state $|\xi>$



Probability to detect given number of photons $C =< n|\xi >$ for squeezed vacuum

- even

$$C_{2m} = (-1)\frac{\sqrt{(2m)!}}{2^m m!}\frac{(e^{i\theta}\tanh r)^m}{\sqrt{\cosh r}}$$

- odd

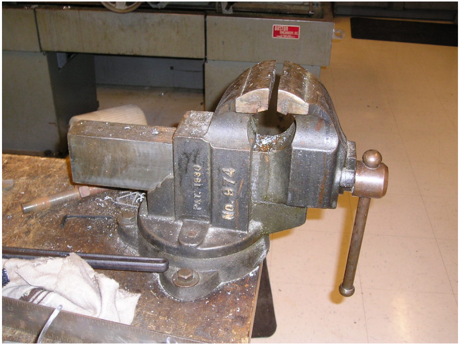
$$C_{2m+1} = 0$$

Average number of photons in general squeezed state

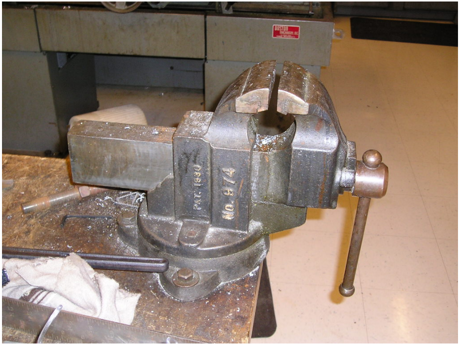
$$< \alpha, \xi|a^\dagger a|\alpha, \xi >= \alpha + \sinh^2 r$$

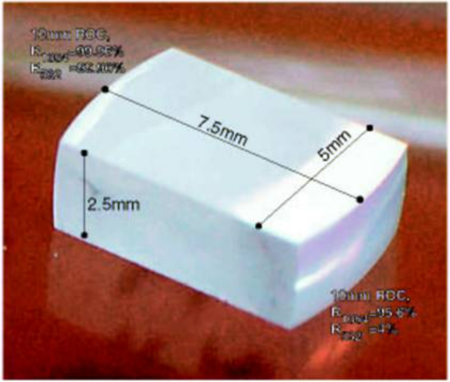
Tools for squeezing

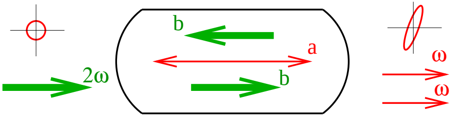
Tools for squeezing



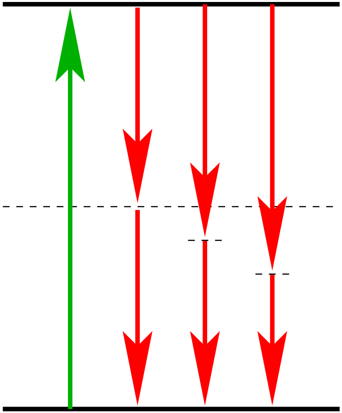
Tools for squeezing







Two photon squeezing picture

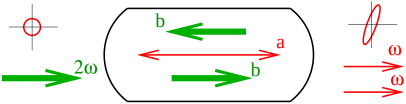


Squeezing operator

$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}$$

Parametric down-conversion in crystal

$$\hat{H} = i\hbar\chi^{(2)}(a^2 b^\dagger - a^{\dagger 2} b)$$

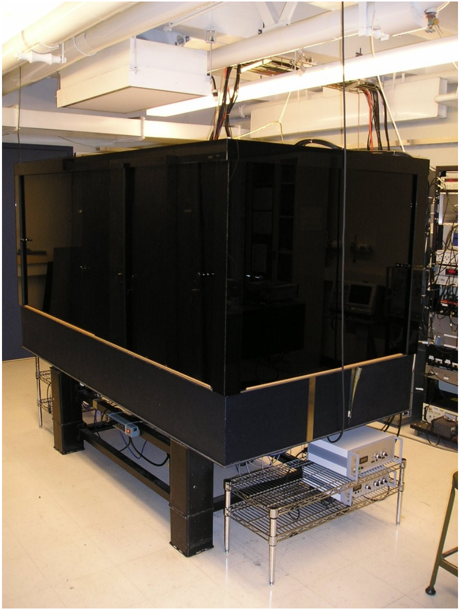


Squeezing

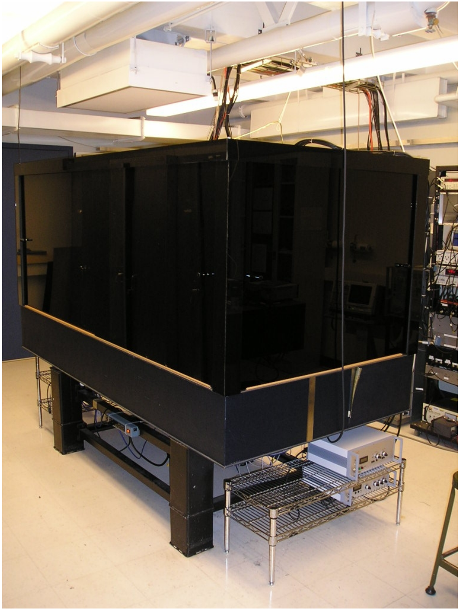
result of correlation of upper and lower sidebands

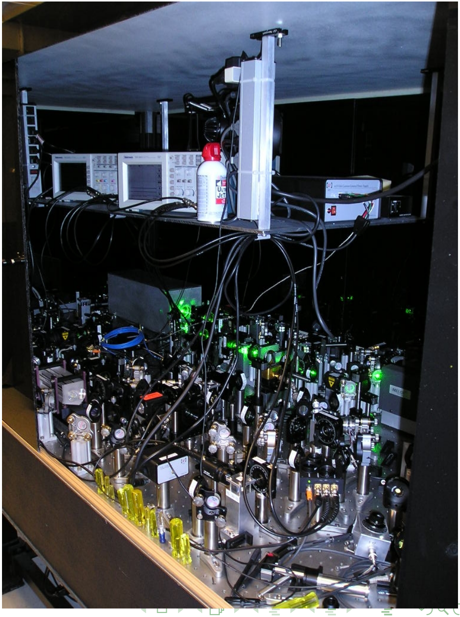
Squeezer appearance

Squeezer appearance

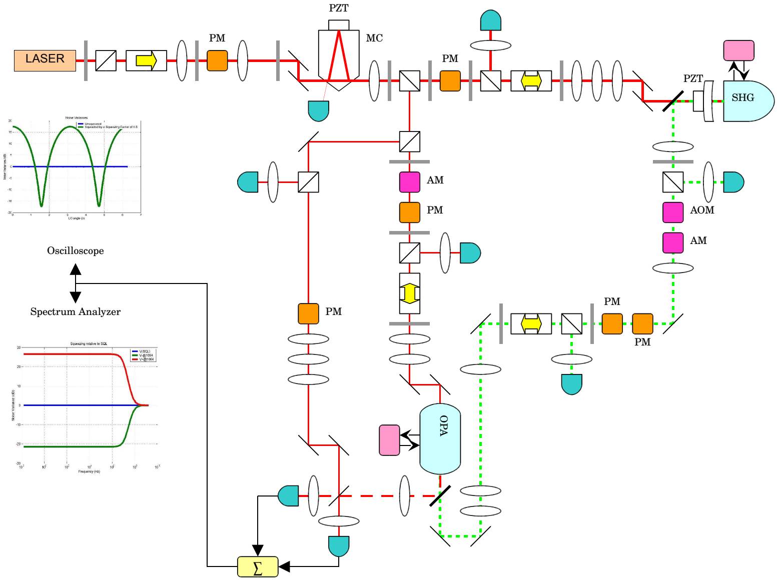


Squeezer appearance





Crystal squeezing setup scheme



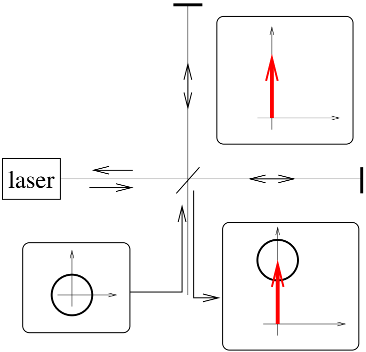
Possible squeezing applications

- improvements any shot noise limited optical sensors
- noiseless signal amplification
- photon pair generation, entanglement, true single photon sources
- interferometers sensitivity boost (for example gravitational wave antennas)
- light free measurements
- quantum memory probe and information carrier

Squeezing and interferometer

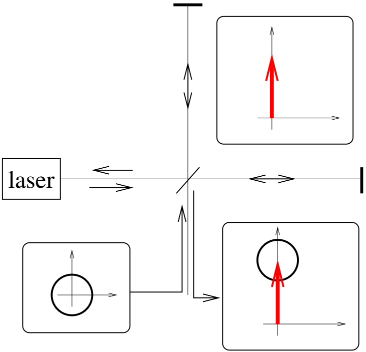
Squeezing and interferometer

Vacuum input

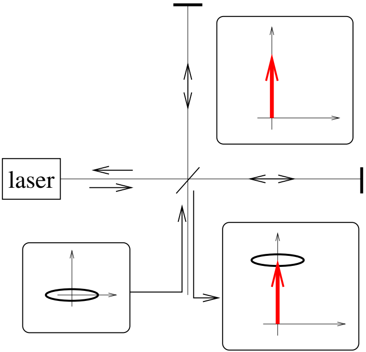


Squeezing and interferometer

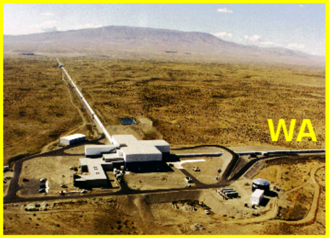
Vacuum input



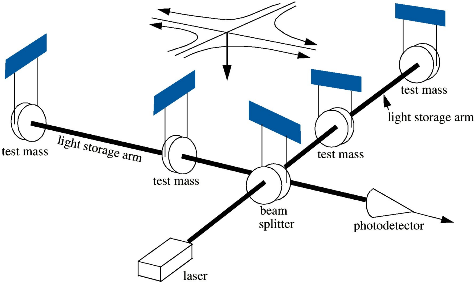
Squeezed input



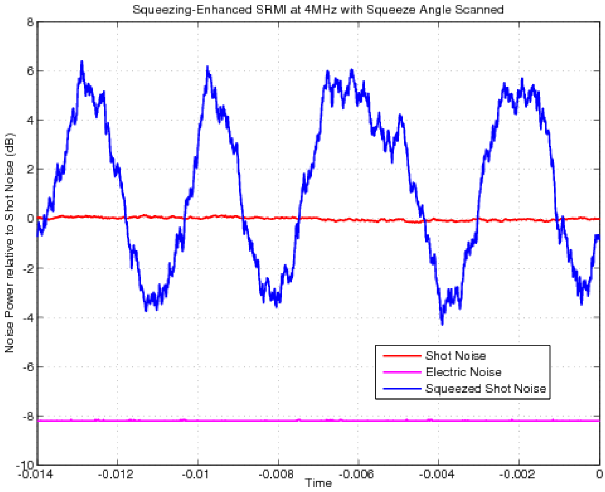
Laser Interferometer Gravitational-wave Observatory



- $L = 4$ km
- $h \sim 2 \times 10^{-23}$
- $\Delta L \sim 10^{-20}$ m

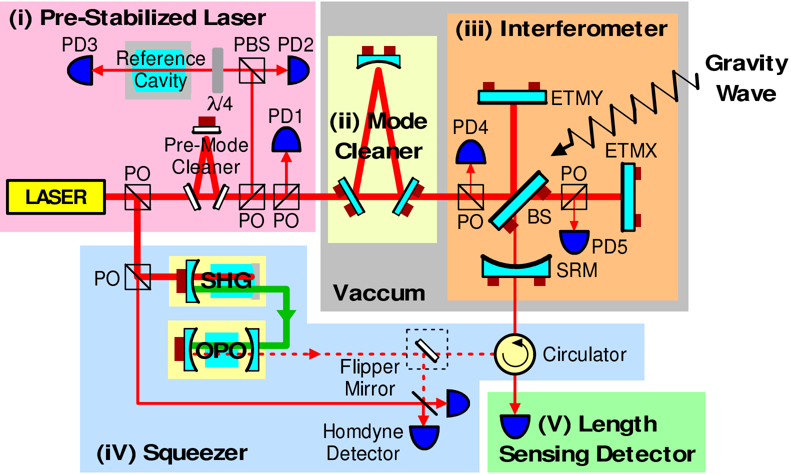


Squeezing level vs time (unlocked)

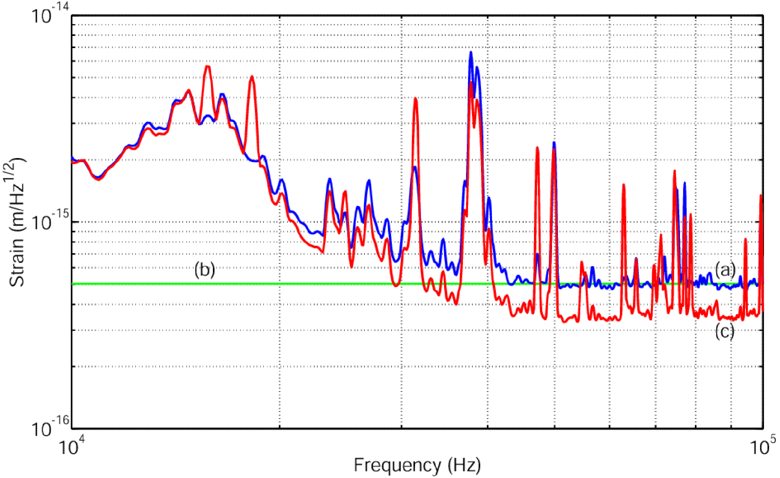


“A quantum-enhanced prototype gravitational-wave detector”, Nature Physics, **4**, 472-476, (2008).

GW 40m detector and squeezer

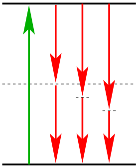


GW 40m detector with 4dB of squeezed vacuum



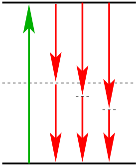
Signal to noise improvement by factor of 1.43

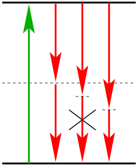
Cavity parameters with squeezing

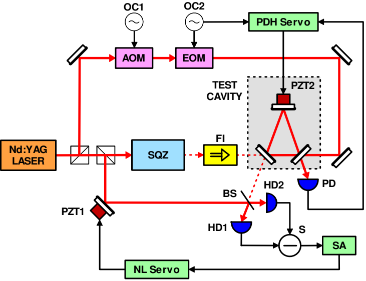


Cavity parameters with squeezing

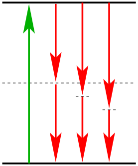
Cavity parameters with squeezing

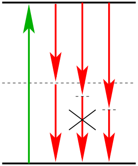


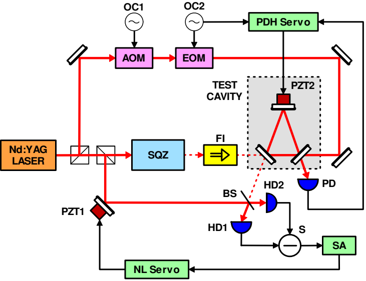


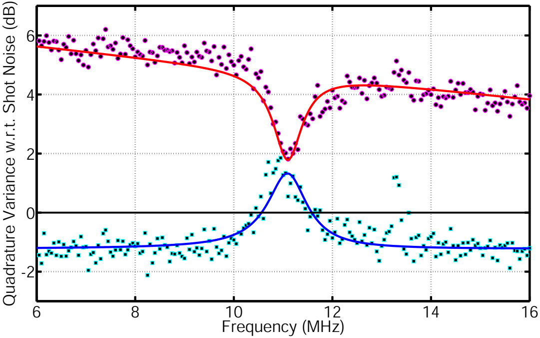


Cavity parameters with squeezing









"Noninvasive measurements of cavity parameters by use of squeezed vacuum", Physical Review A, **74**, 033817, (2006).

Summary for crystal squeezing

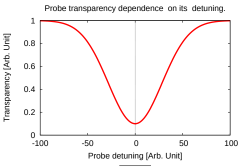
Pros

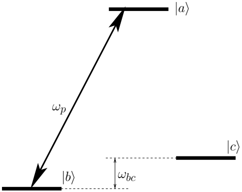
- mainstream: many different nonlinear crystals available
- so far the best squeezers
  - maximum squeezing value detected 11.5 dB at 1064 nm
  - Moritz Mehmet, Henning Vahlbruch, Nico Lastzka, Karsten Danzmann, and Roman Schnabel, “Observation of squeezed states with strong photon-number oscillations”, Phys. Rev. A **81**, 013814 (2010)
- well understood

Cons

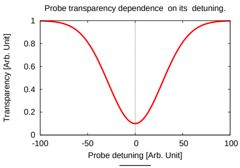
- crystals have limited transparency window
- thus squeezing is hard to generate at visible wavelength
  - at 795 nm only 4-6 dB squeezing is reported
- this limits applications of such squeezers for spectroscopy

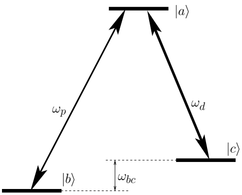
Quantum memory with atomic ensembles

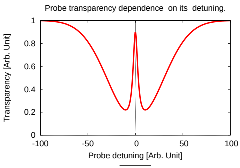




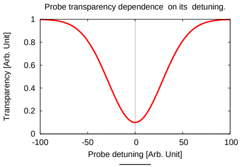
Quantum memory with atomic ensembles

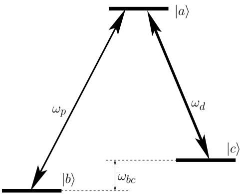


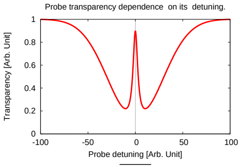




Quantum memory with atomic ensembles

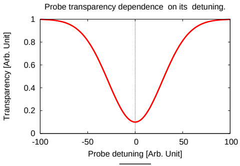


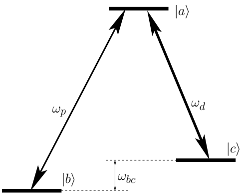


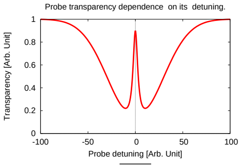


Storage and retrieval

Quantum memory with atomic ensembles



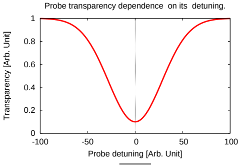


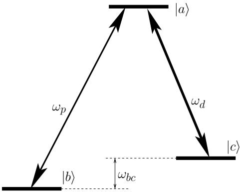


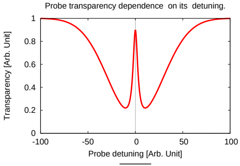
Storage and retrieval

- single photon

Quantum memory with atomic ensembles



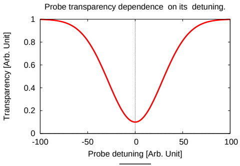


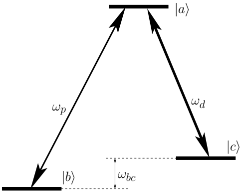


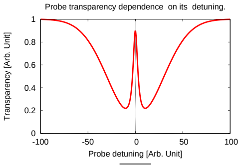
Storage and retrieval

- single photon
- squeezed state (Furusawa and Lvovsky PRL **100** 2008)

Quantum memory with atomic ensembles







Storage and retrieval

- single photon
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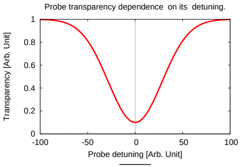
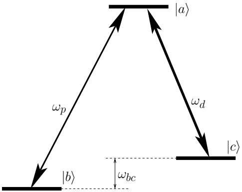
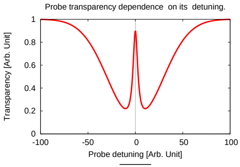
Squeezed state requirements for a quantum memory probe

Quantum memory with atomic ensembles







Storage and retrieval

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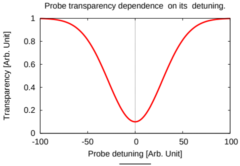
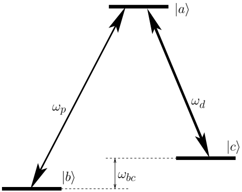
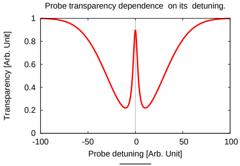
- squeezing carrier at atomic wavelength (780nm, 795nm)
- squeezing within narrow resonance window at frequencies($<$100kHz)

Quantum memory with atomic ensembles







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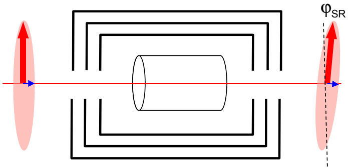
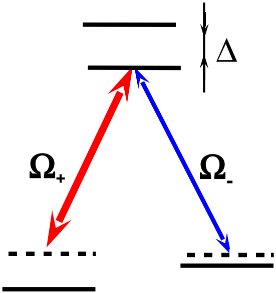
Traditional nonlinear crystal based squeezers are capable of it, but they are extremely technically challenging especially at short wave length.

Self-rotation of elliptical polarization in atomic medium

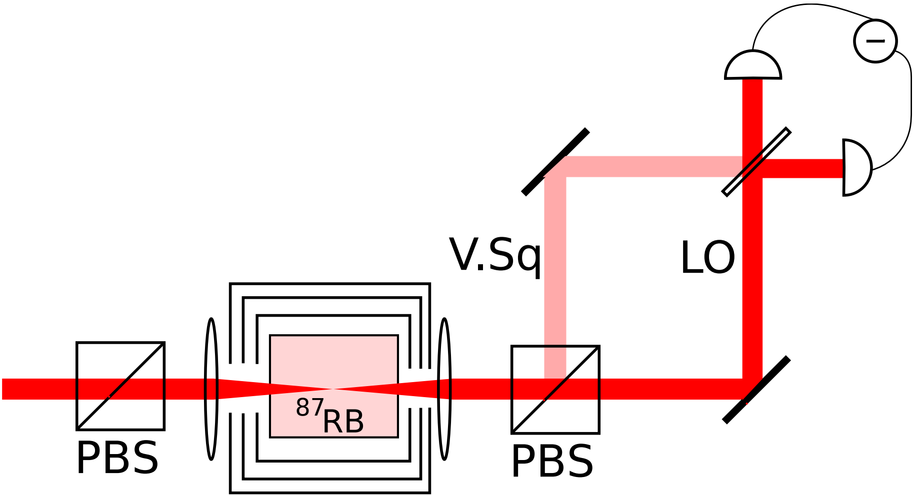




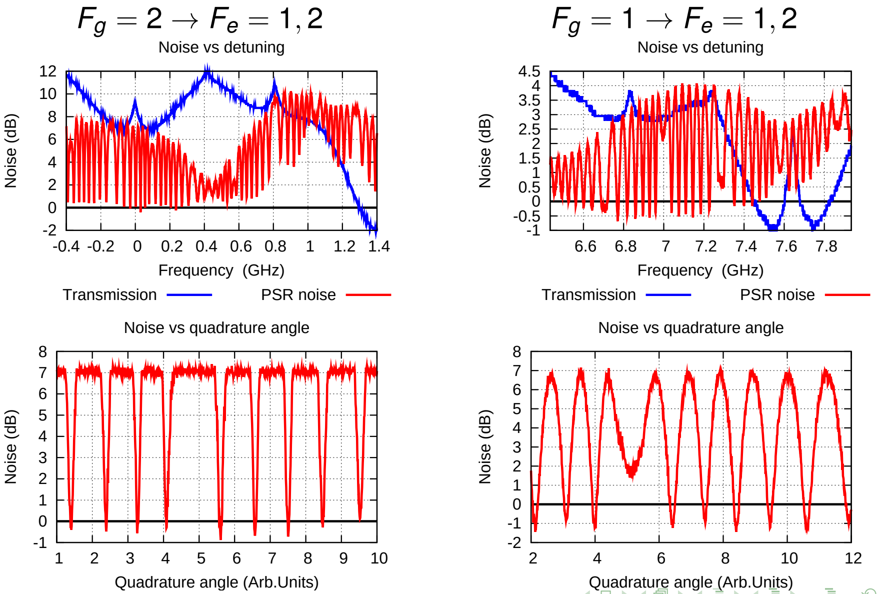
A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in}) \quad (2)$$

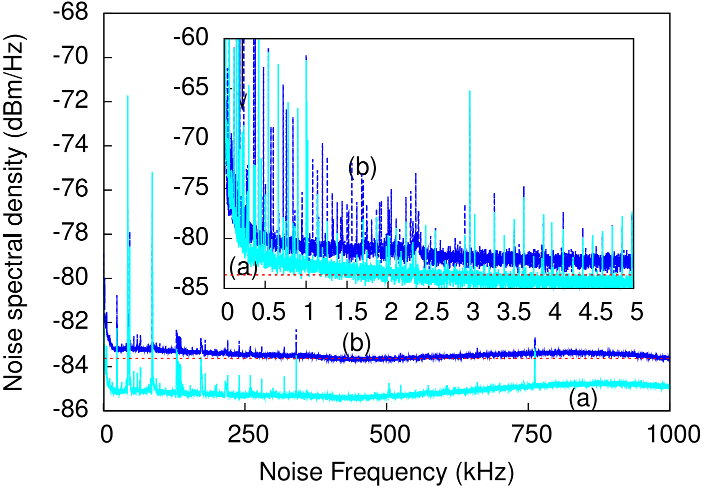
Setup



Noise contrast vs detuning in hot ^{87}Rb vacuum cell

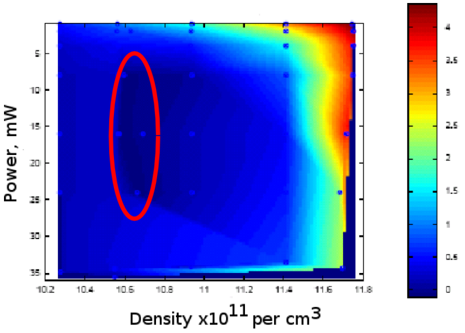


Atomic low frequency squeezing source

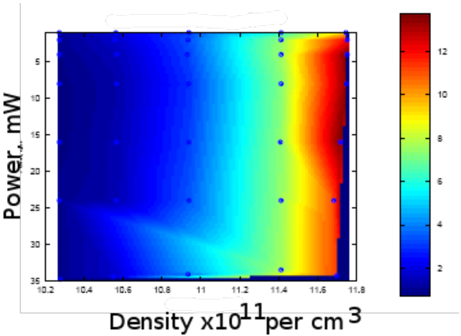


Squeezing region

Squeezing

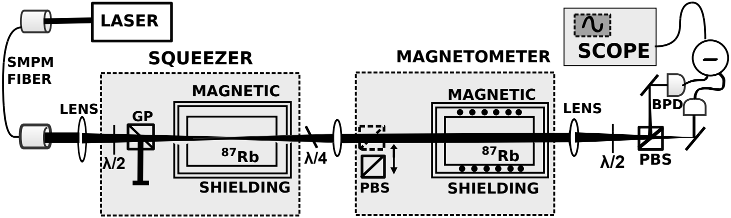


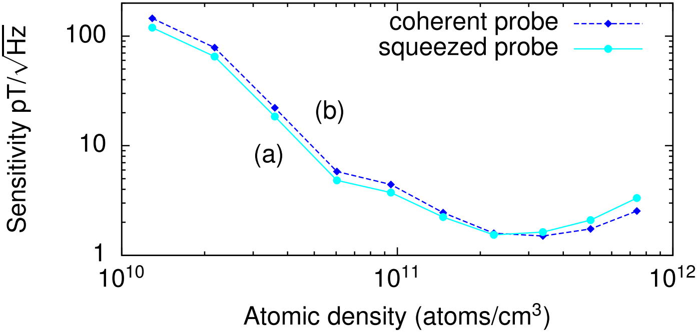
Anti-squeezing



Observation of reduction of quantum noise below the shot noise limit is corrupted by the excess noise due to atomic interaction with atoms.

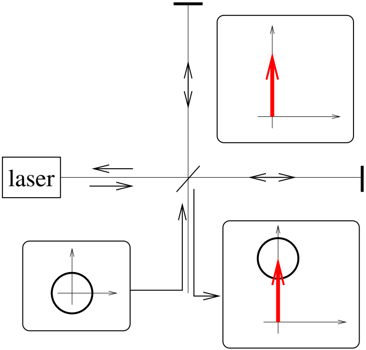
Magnetometer with squeezing enhancement



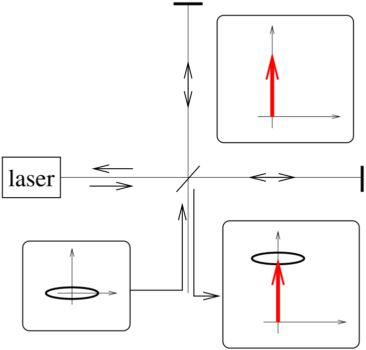


Quantum limited interferometers revisited

Vacuum input



Squeezed input



Limiting noise - Quantum Optical noise

Next generation of LIGO will be
quantum optical noise limited at almost all detection frequencies.

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shot noise

Uncertainty in number of photons

$$h \sim \sqrt{\frac{1}{P}} \tag{3}$$

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Photons impart momentum to mirrors

$$h \sim \sqrt{\frac{P}{M^2 f^4}} \qquad (4)$$

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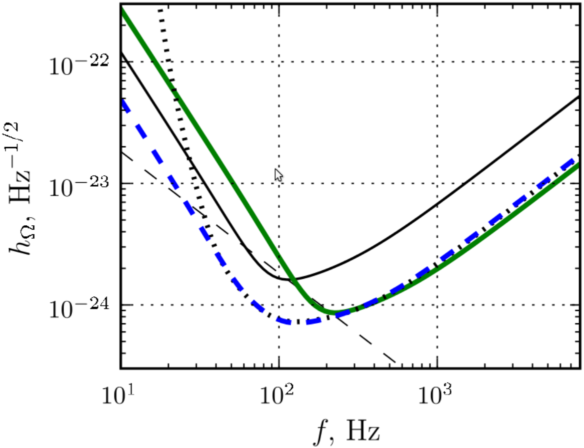
There is no optimal light power to suit all detection frequency.
Optimal power depends on desired detection frequency.

Interferometer sensitivity improvement with squeezing

Projected advanced LIGO sensitivity

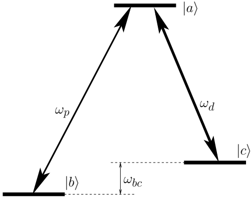


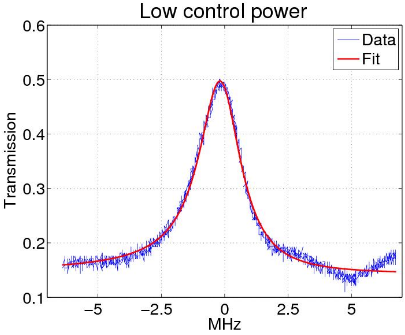
F. Ya. Khalili Phys. Rev. D 81, 122002 (2010)

$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$\varphi_\pm = \frac{1}{2}(\Theta_+ \pm \Theta_-)$$

$$A_\pm = \frac{1}{2}(T_+ \pm T_-)$$





Squeezing and EIT filter

$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

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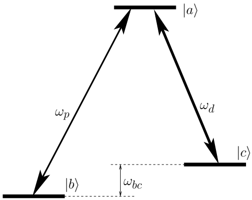

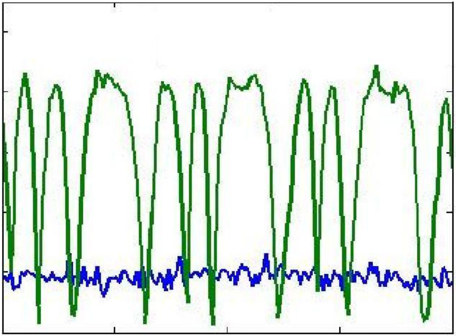

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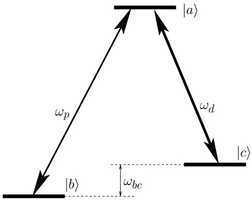

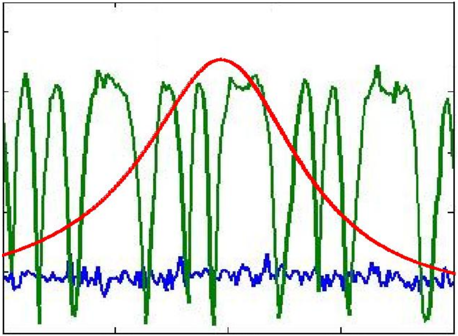

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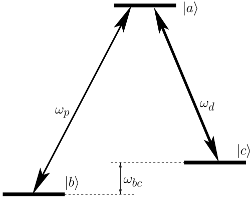
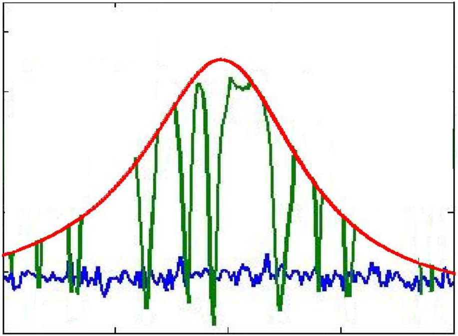
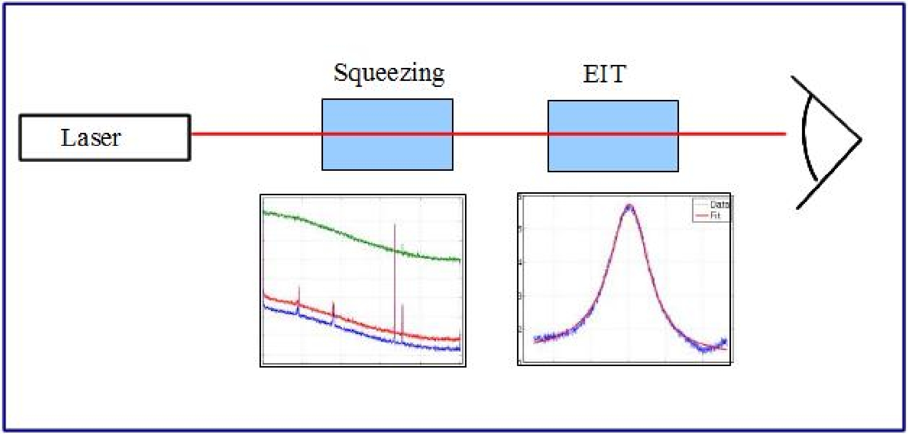
$$\begin{aligned} \varphi_\pm &= \frac{1}{2}(\Theta_+ \pm \Theta_-) \\ A_\pm &= \frac{1}{2}(T_+ \pm T_-) \end{aligned}$$





Squeezing and EIT filter setup



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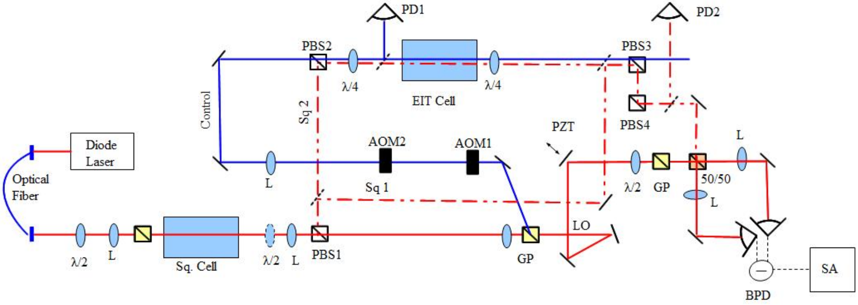
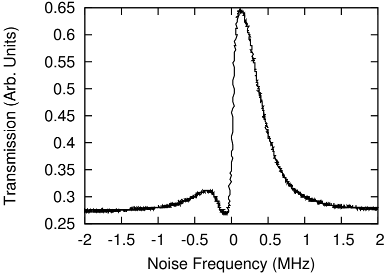
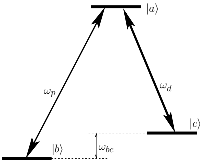


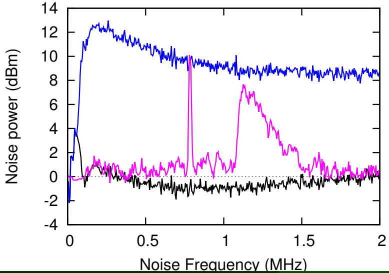
EIT filter and measurements without light

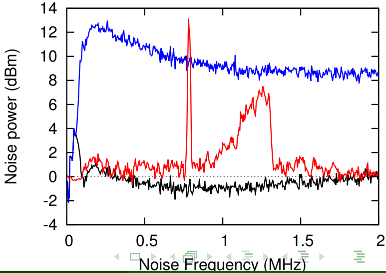


Coherent signal

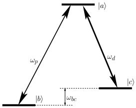


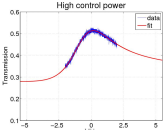
Signal in the noise quadratures



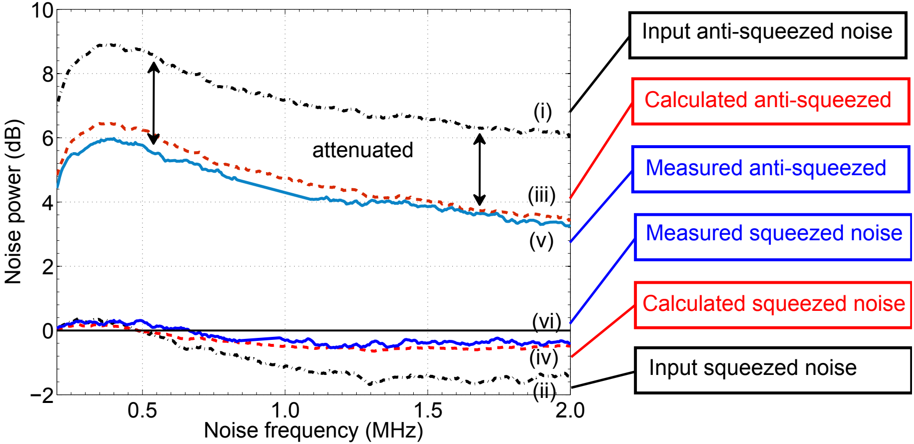


Wide EIT filter and squeezing

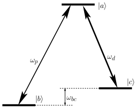


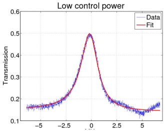


- Peak transmission = 52%
- FWHM= 4MHz

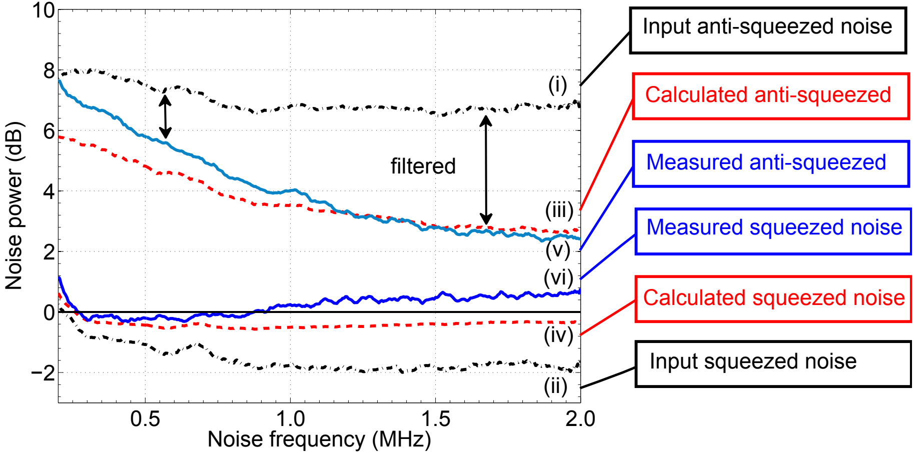


Narrow EIT filter and squeezing

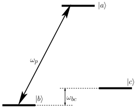


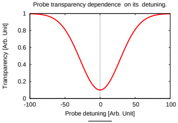


- Peak transmission = 50%
- FWHM= 2MHz

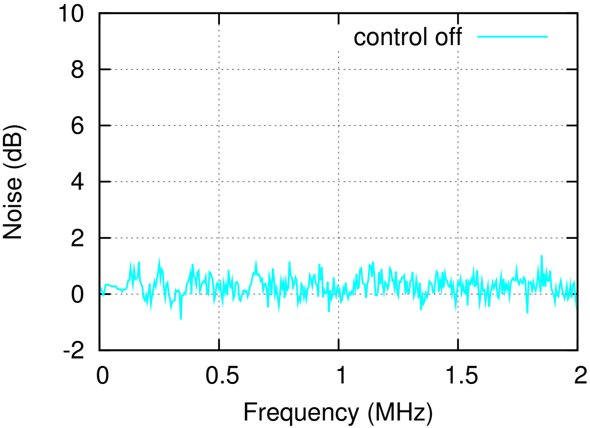


Control off no EIT and no squeezing at the output

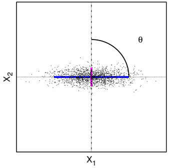


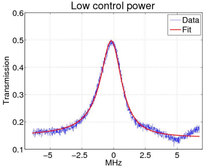


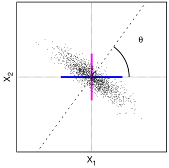
- Peak transmission = 0%



Squeezing angle rotation

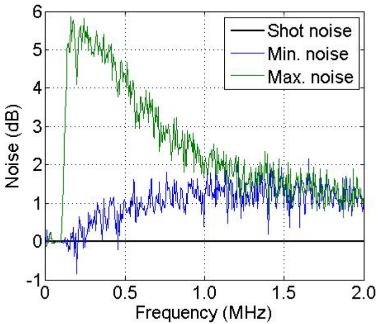




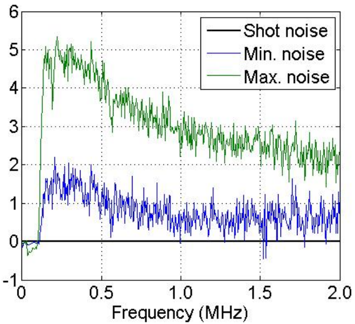


$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} \cos^2\varphi_+ & \sin^2\varphi_+ \\ \sin^2\varphi_+ & \cos^2\varphi_+ \end{pmatrix} \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

Locked at 300kHz

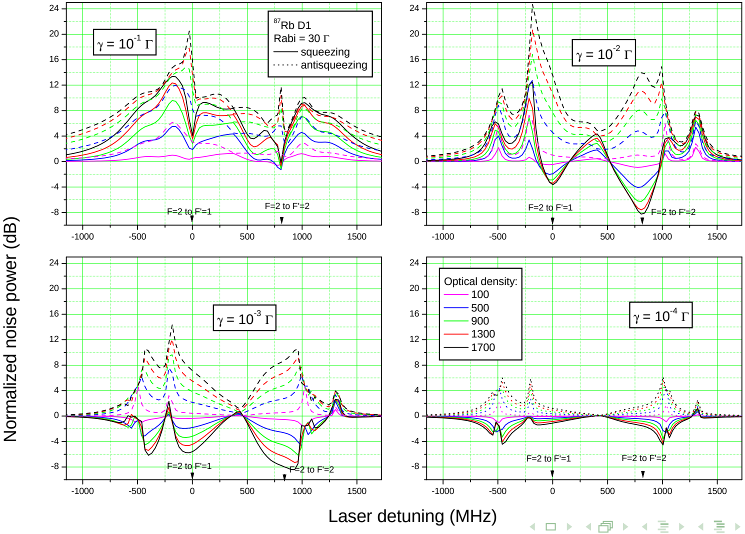


Locked at 1200kHz



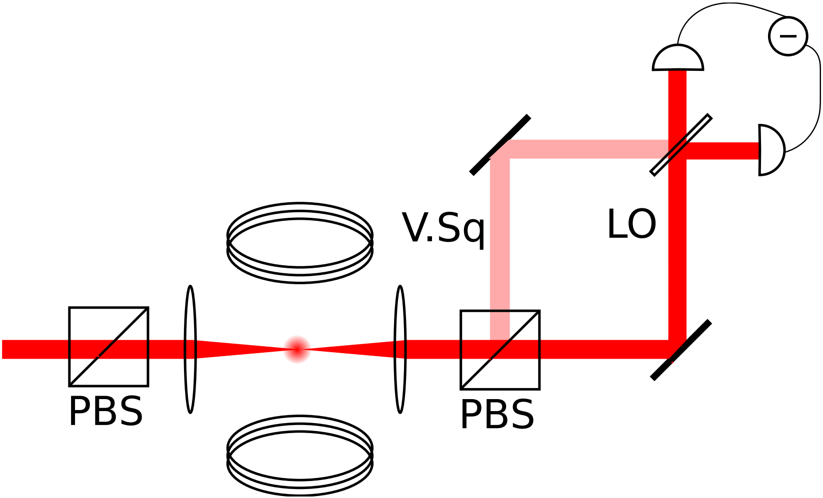
Theoretical prediction for MOT squeezing with ^{87}Rb

$F_g = 2 \rightarrow F_e = 1, 2$ high optical density is very important

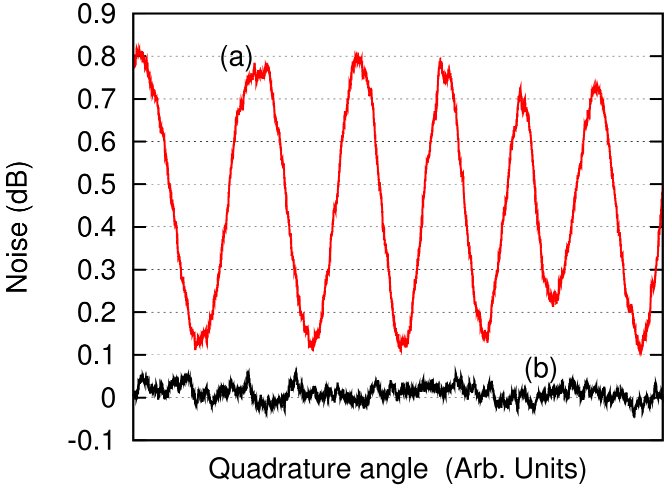


MOT squeezer

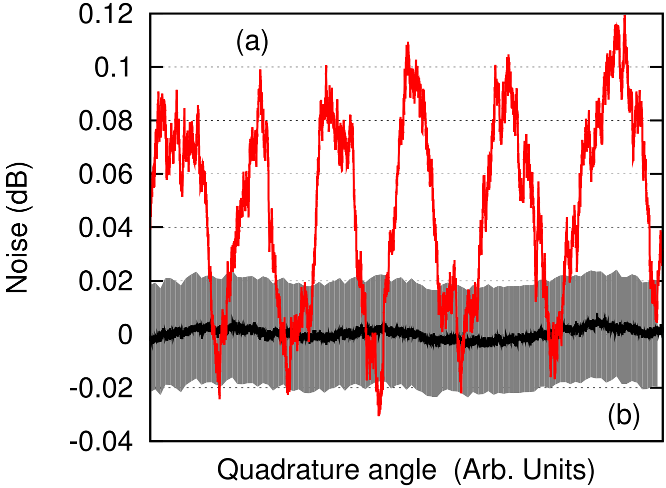
Cloud size =1 mm, T = 200 μK, N = 7 $\times$ 10^9 1/cm^3,
OD = 2, beam size = 0.1 mm, 10^5 interacting atoms



Noise contrast in MOT with ^{87}Rb $F_g = 2 \rightarrow F_e = 1$

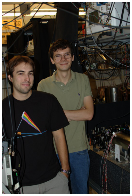


Squeezing in MOT with ^{87}Rb $F_g = 2 \to F_e = 1$



People

Travis Horrom and Gleb Romanov



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Summary

- Squeezing is exciting
- many applications benefit from squeezing
- there is still a lot of interesting physics to do

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