Squeezed states of light - generation and applications

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Fudan, December 24, 2013

People

From ray optics to semiclassical optics

Classical/Geometrical optics

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

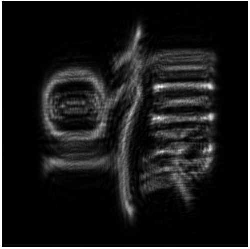
From ray optics to semiclassical optics

Classical/Geometrical optics

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

Semiclassical optics

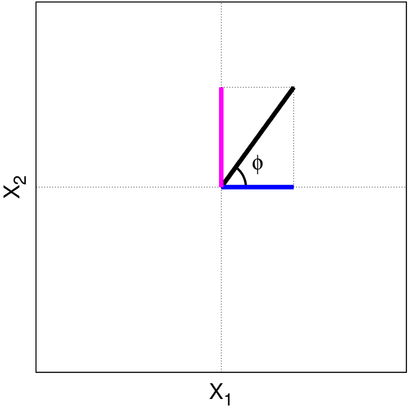
- light is a wave
- color (wavelength/frequency) is important
- amplitude (a) and phase are important, $E(t) = ae^{i(kz-\omega t)}$
- cannot explain residual measurements noise



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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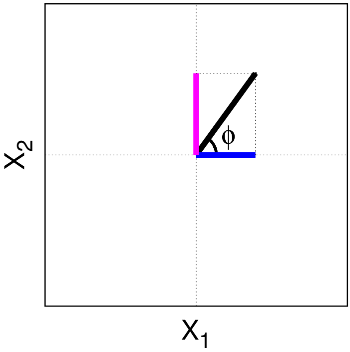

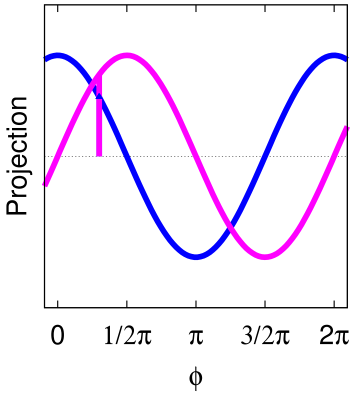

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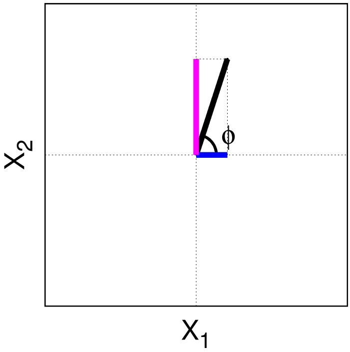

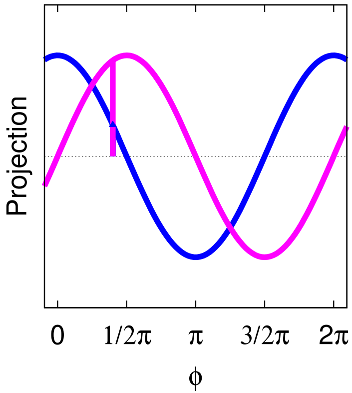

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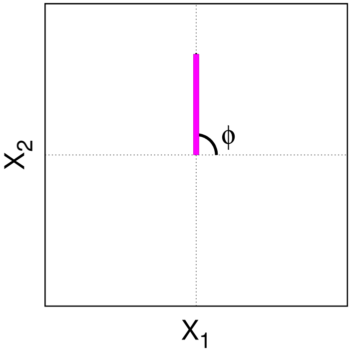

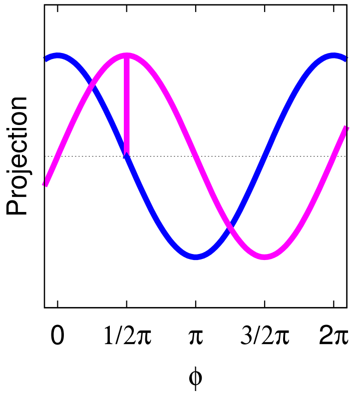

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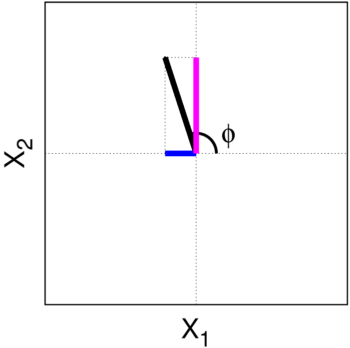

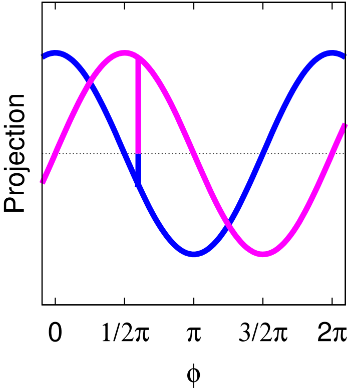

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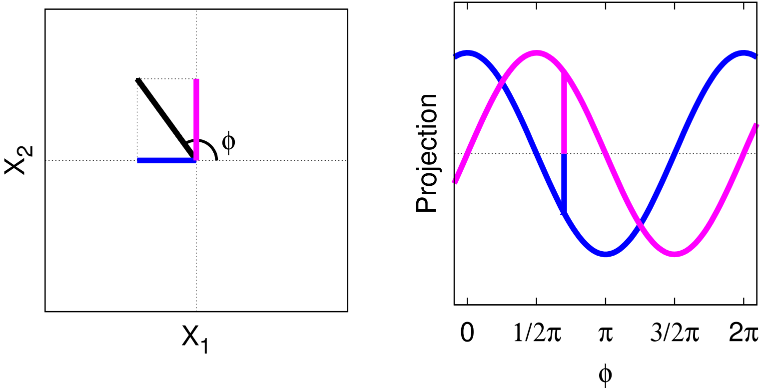

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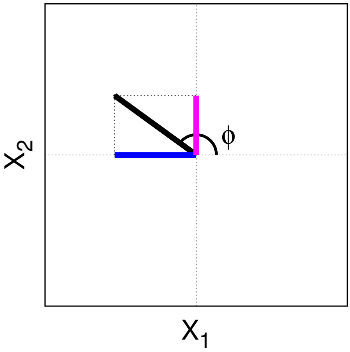

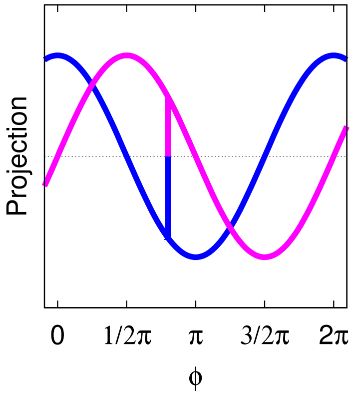

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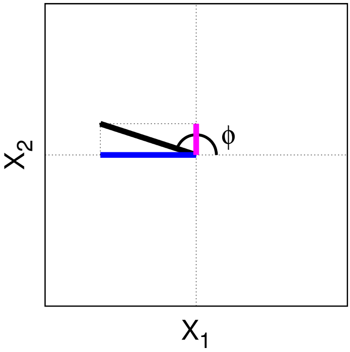

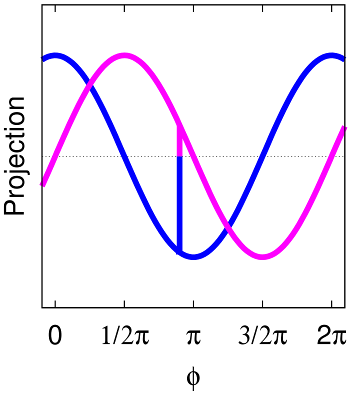

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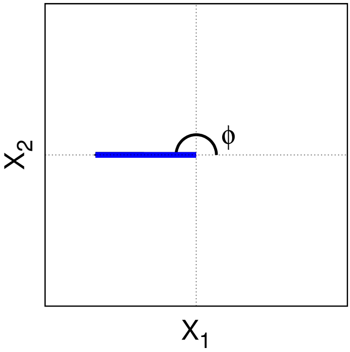

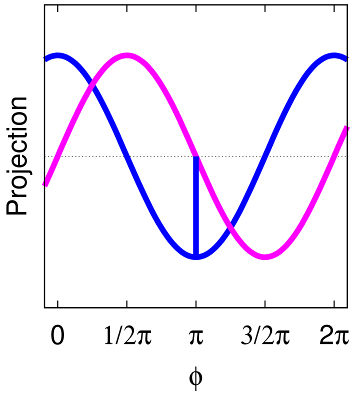

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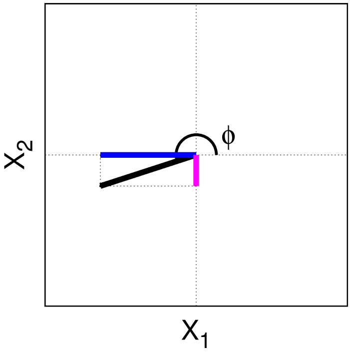

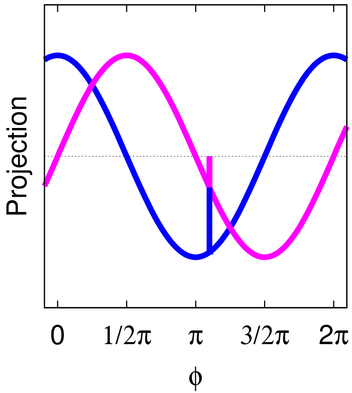

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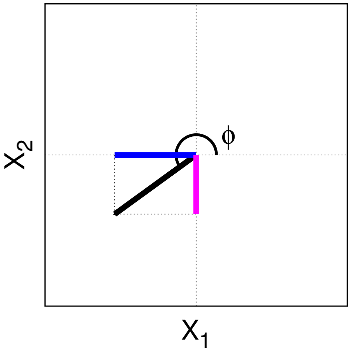

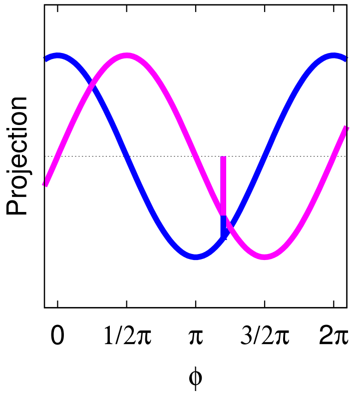

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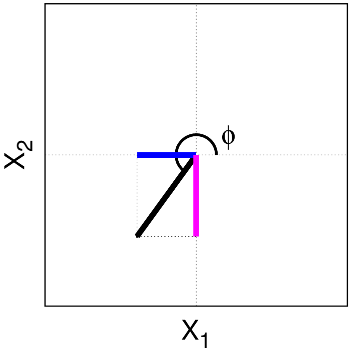

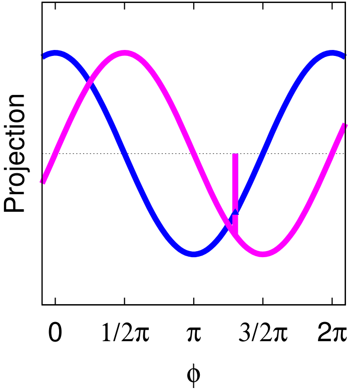

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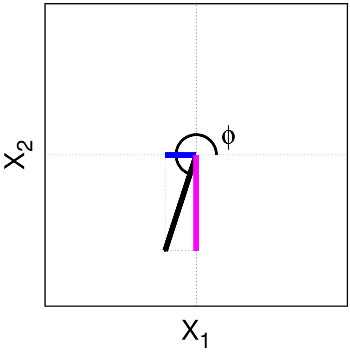

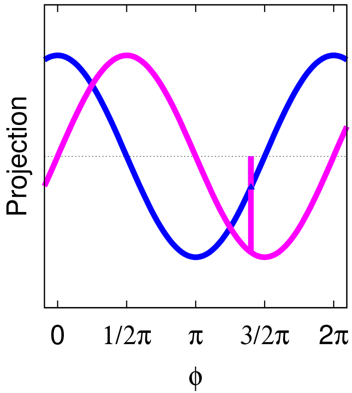

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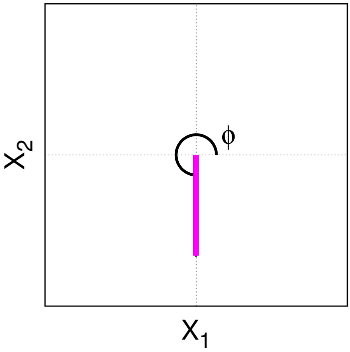

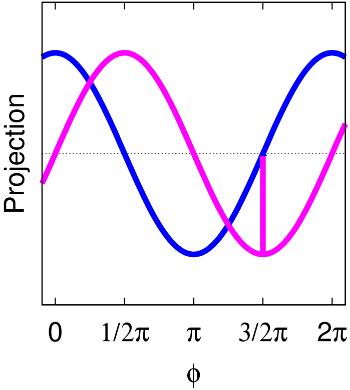

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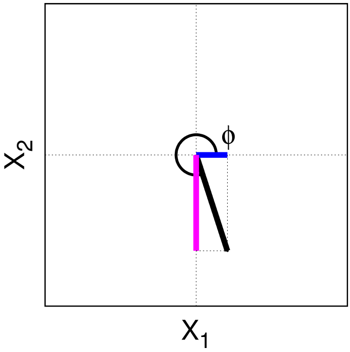

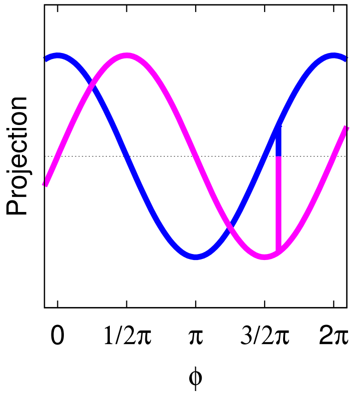

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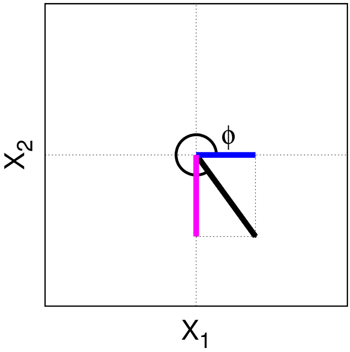

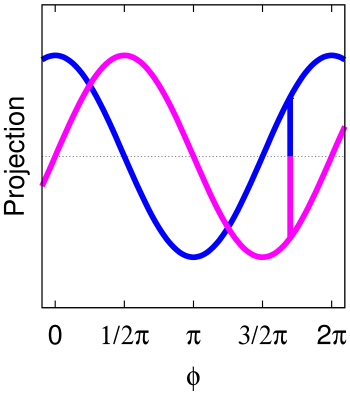

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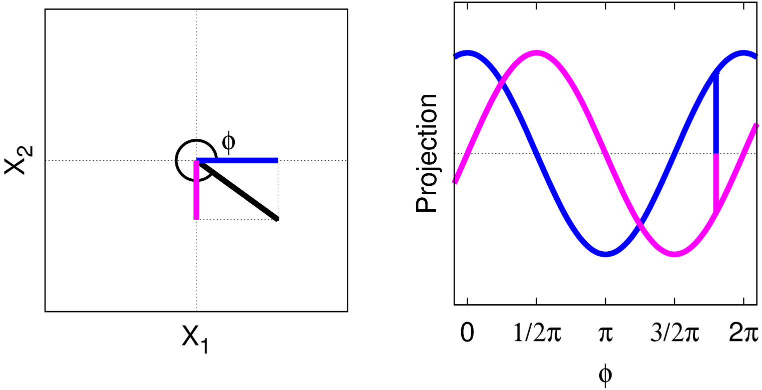

Classical quadratures vs time in a rotating frame

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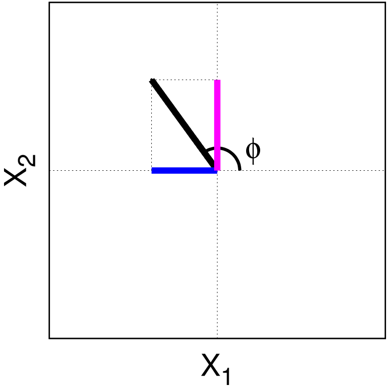

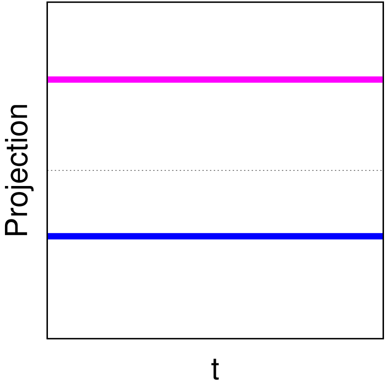

Reality check quadratures vs time

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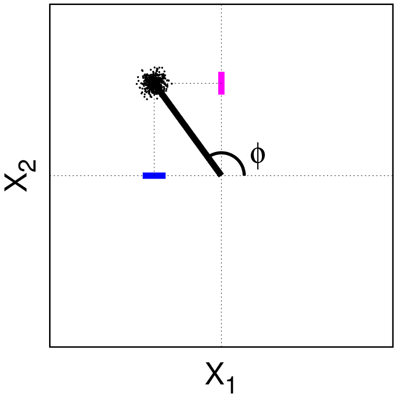
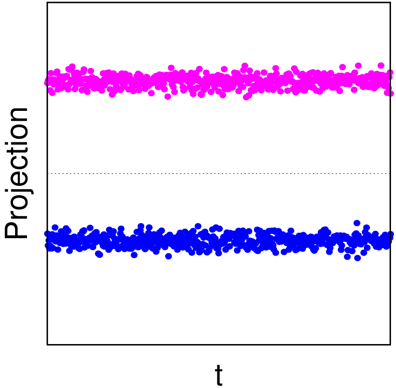
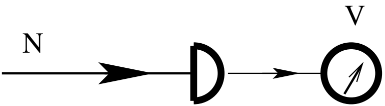




Detector quantum noise

Simple photodetector



$$V \sim N$$

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

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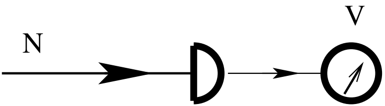

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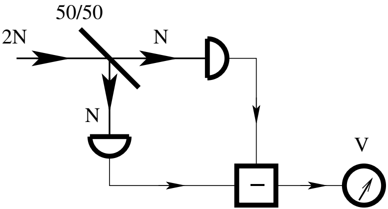
Balanced photodetector



$V = 0$

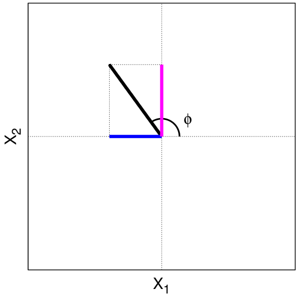
$\Delta V \sim \sqrt{N}$

Transition from classical to quantum field

Classical analog

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

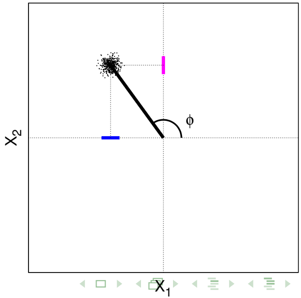
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



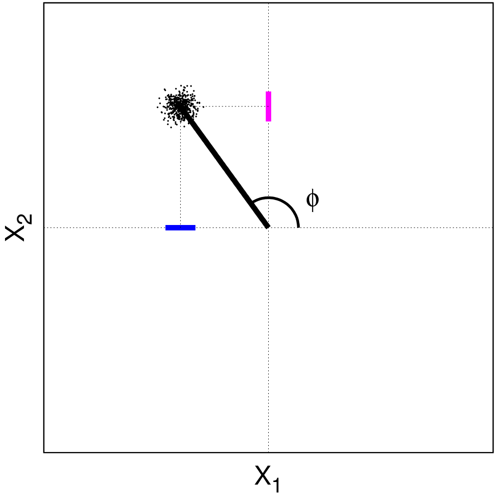
Quantum approach

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

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



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

Heisenberg uncertainty principle and its optics equivalent

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Optics equivalent

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

The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

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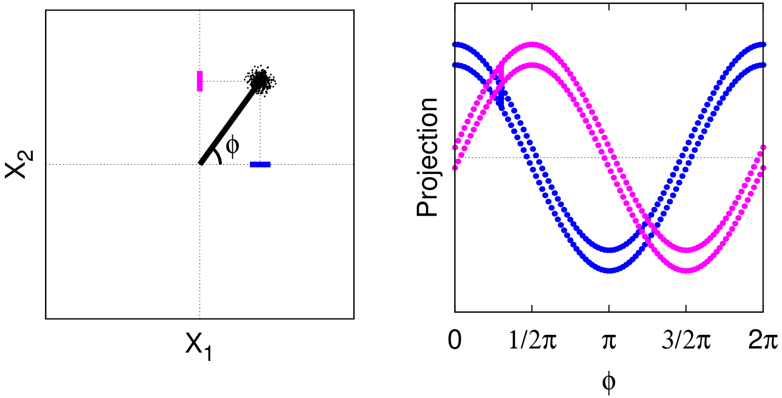
Optics equivalent strict definition

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

Coherent state is minimum uncertainty state

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



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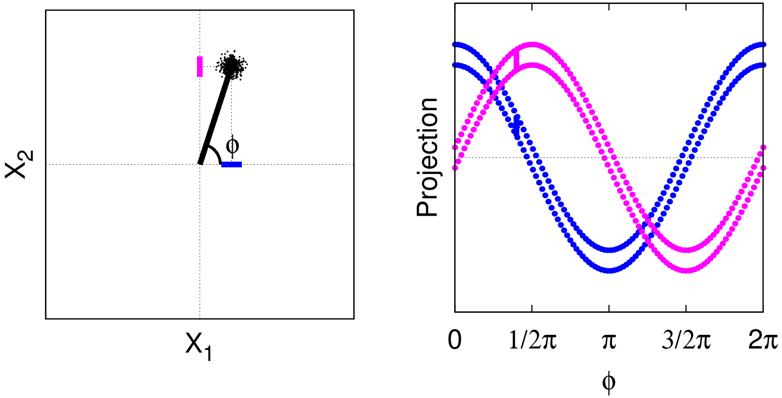

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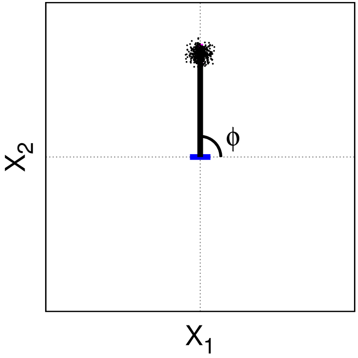

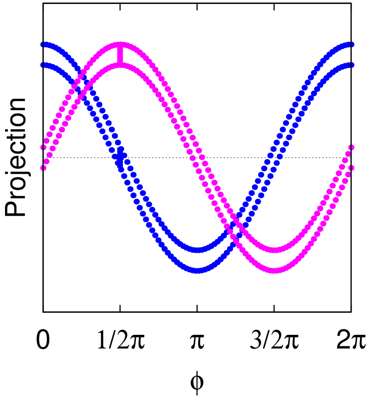

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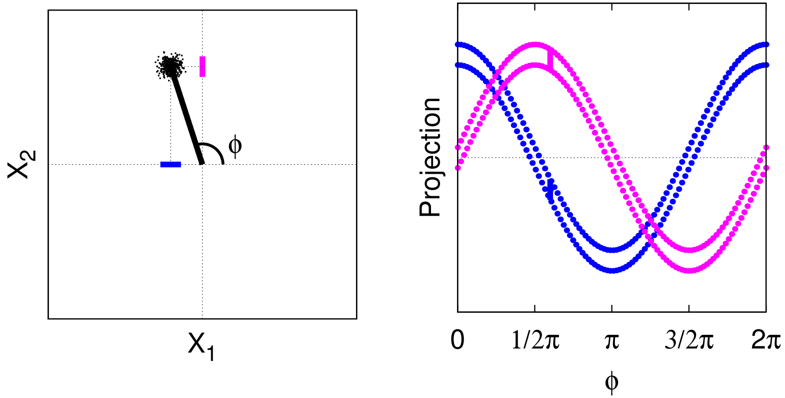

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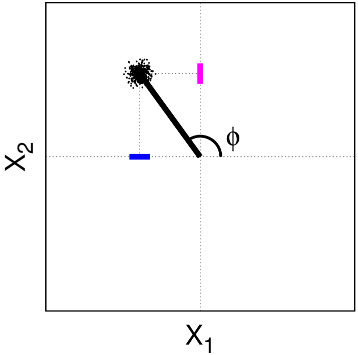

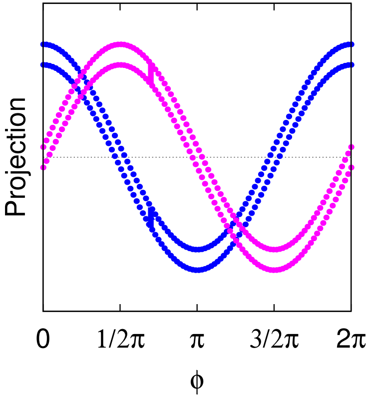

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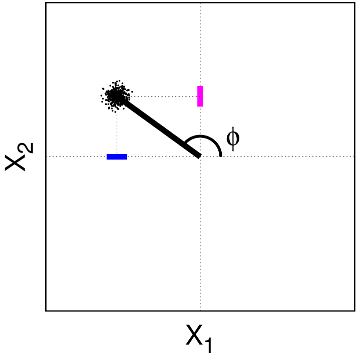

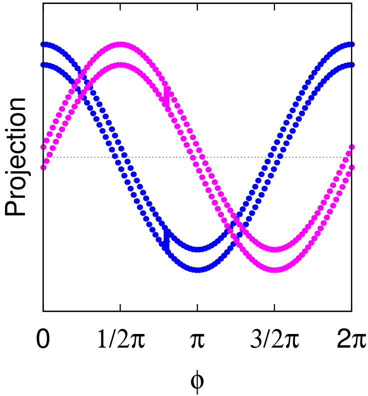

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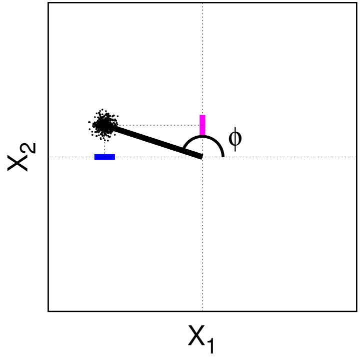

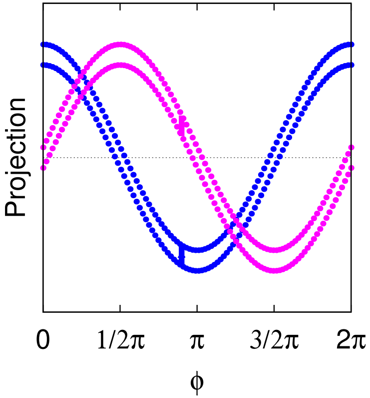

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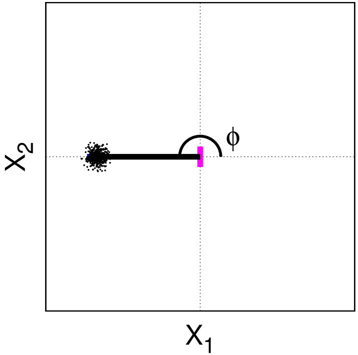

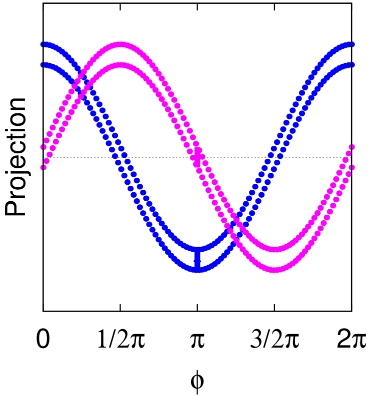

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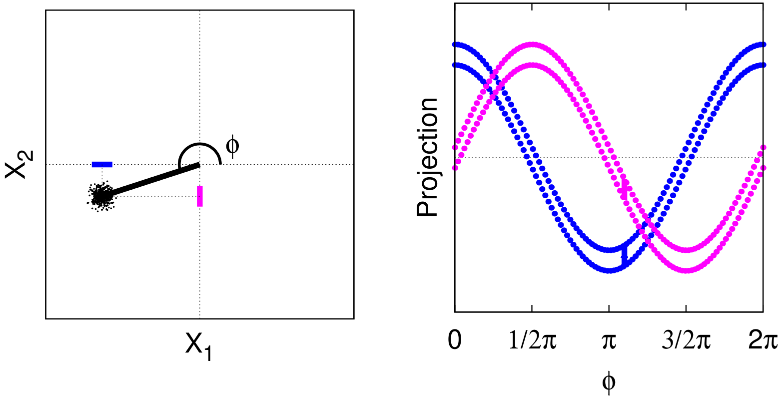

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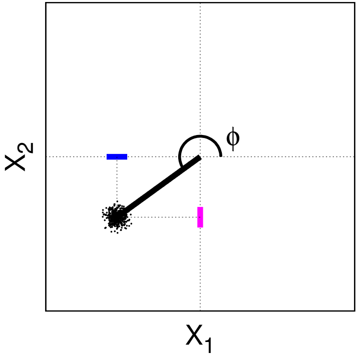
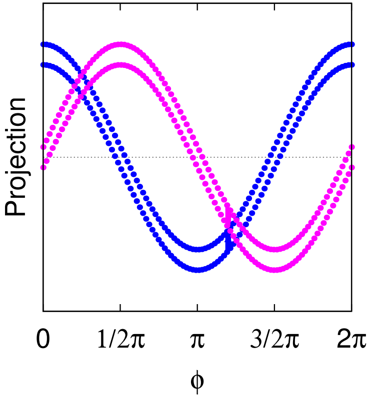
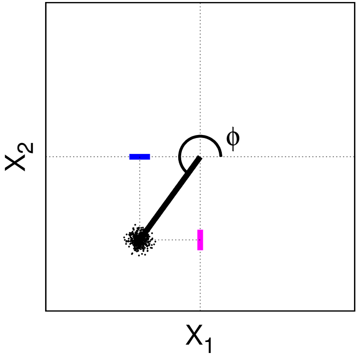
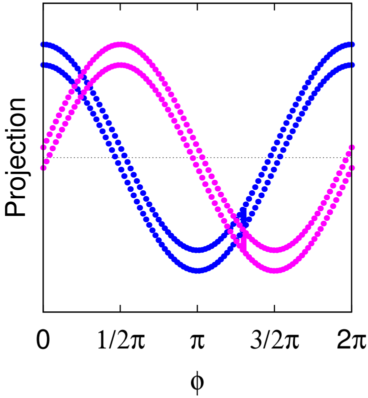




Coherent state is minimum uncertainty state

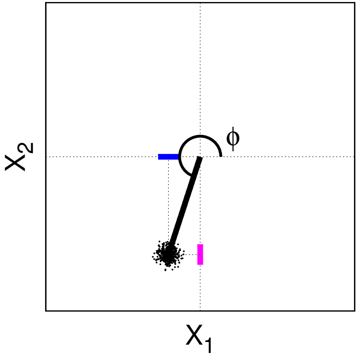
$\Delta X_1 \Delta X_2 = 1/4$

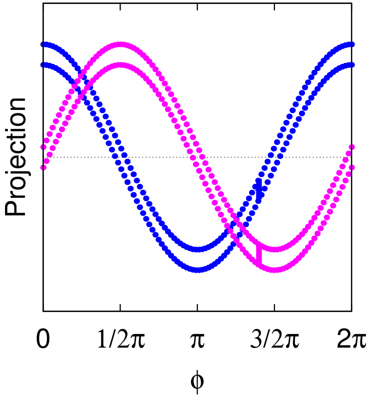




Coherent state is minimum uncertainty state

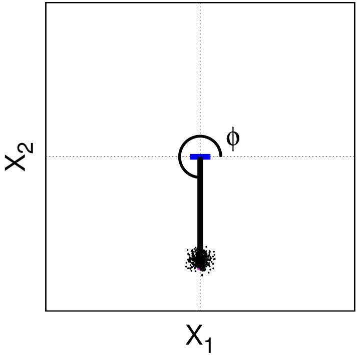
$\Delta X_1 \Delta X_2 = 1/4$

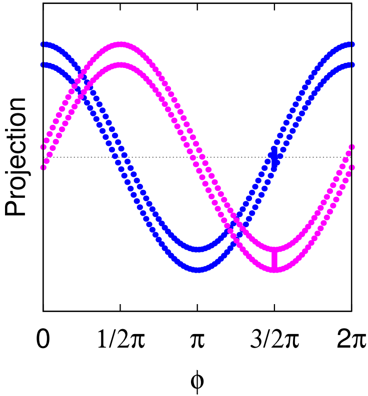




Coherent state is minimum uncertainty state

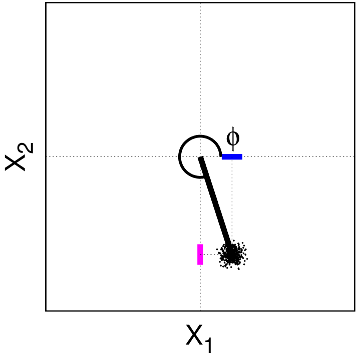
$\Delta X_1 \Delta X_2 = 1/4$

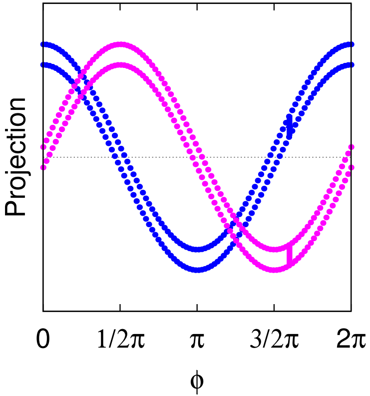




Coherent state is minimum uncertainty state

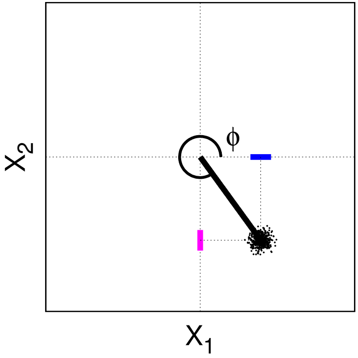
$\Delta X_1 \Delta X_2 = 1/4$

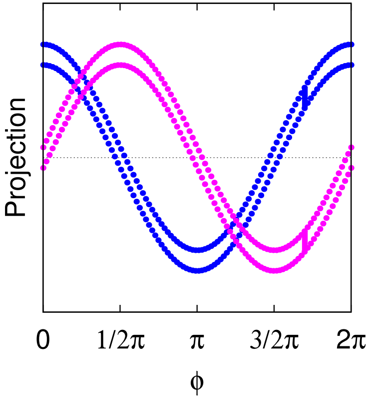




Coherent state is minimum uncertainty state

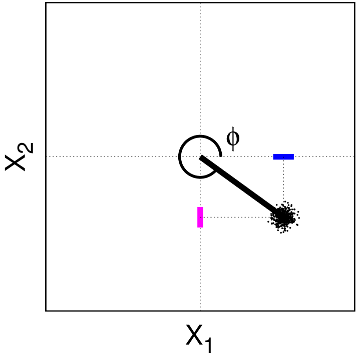
$\Delta X_1 \Delta X_2 = 1/4$

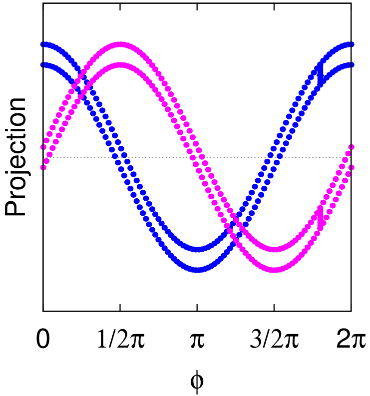




Coherent state is minimum uncertainty state

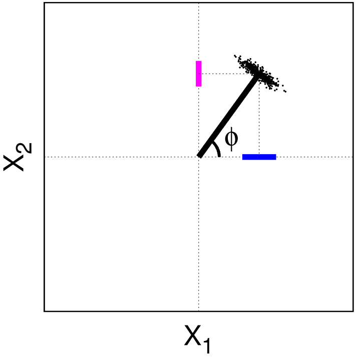
$\Delta X_1 \Delta X_2 = 1/4$

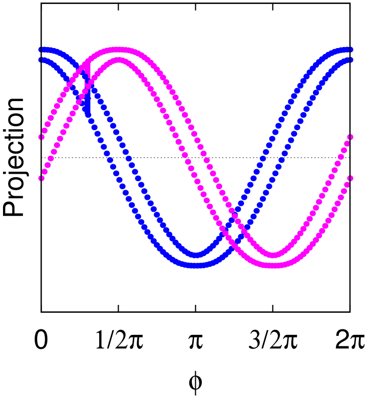




Amplitude squeezed states

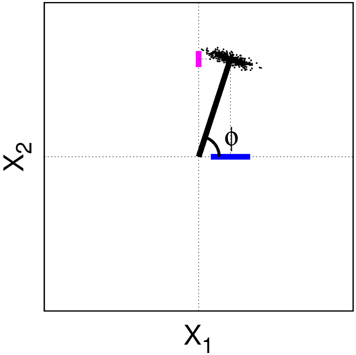
$\Delta X_1 \Delta X_2 = 1/4$

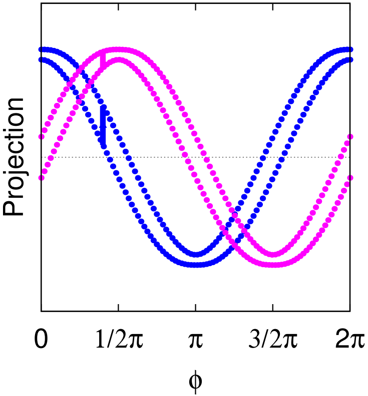




Amplitude squeezed states

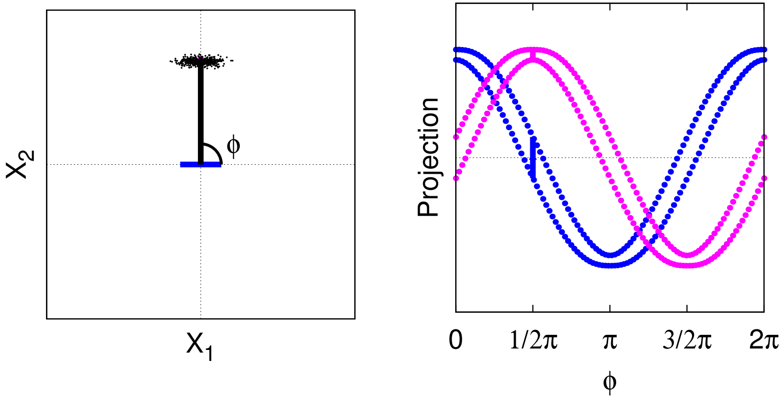
$\Delta X_1 \Delta X_2 = 1/4$





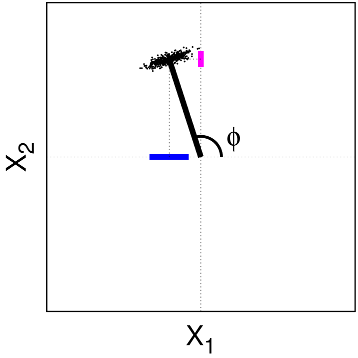
Amplitude squeezed states

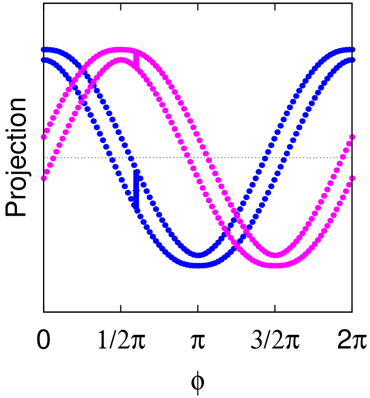
$\Delta X_1 \Delta X_2 = 1/4$



Amplitude squeezed states

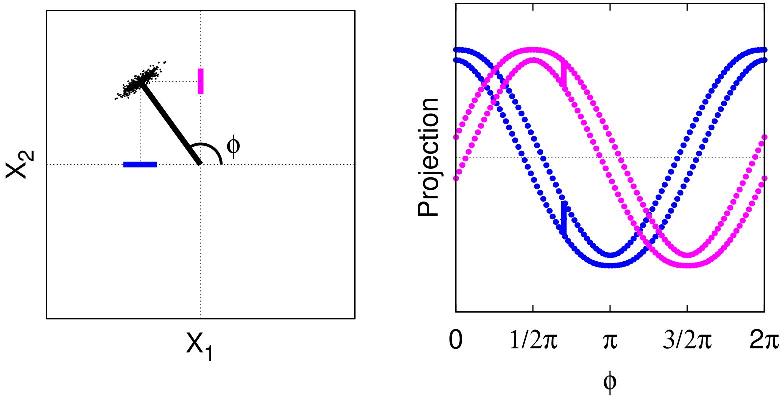
$\Delta X_1 \Delta X_2 = 1/4$





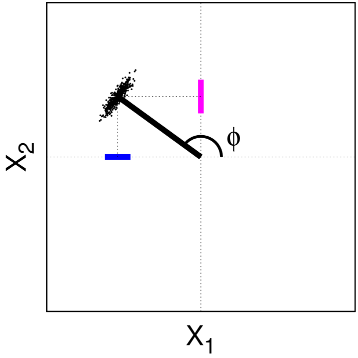
Amplitude squeezed states

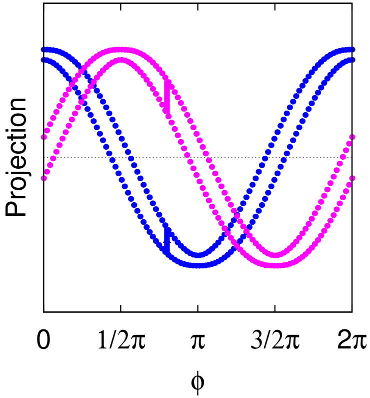
$\Delta X_1 \Delta X_2 = 1/4$



Amplitude squeezed states

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





Amplitude squeezed states

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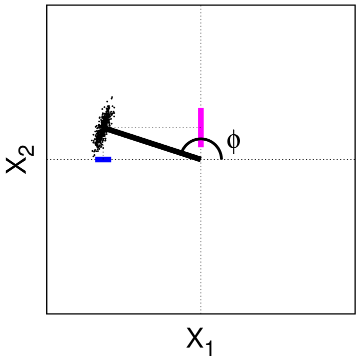
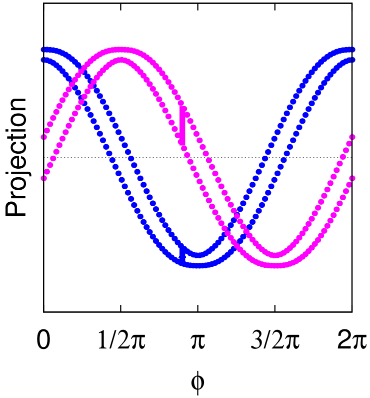
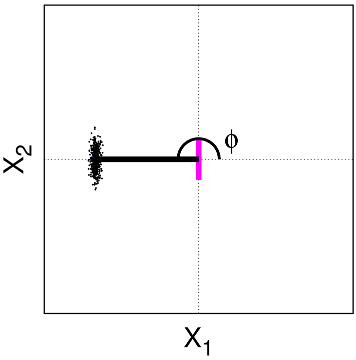
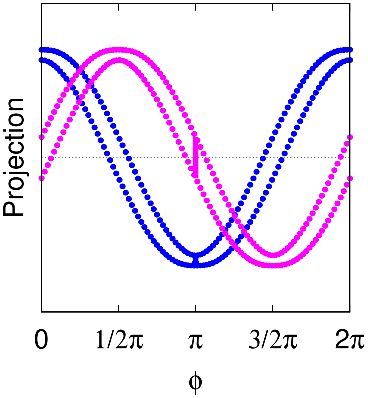




Amplitude squeezed states

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





Amplitude squeezed states

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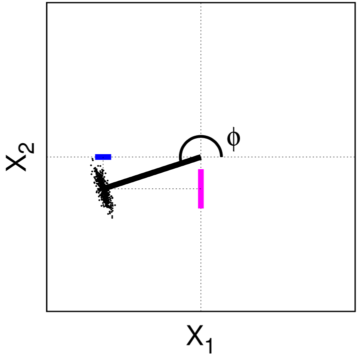

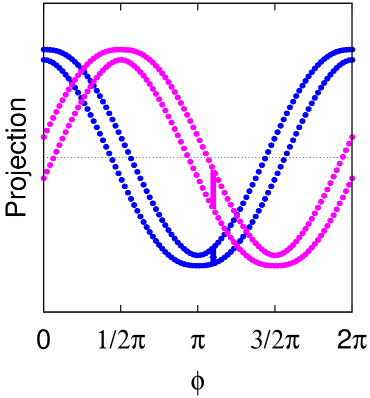

Amplitude squeezed states

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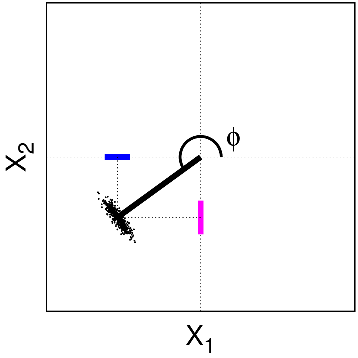
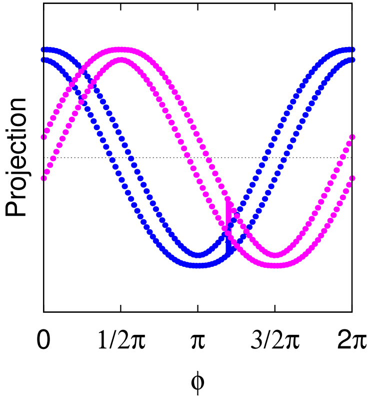
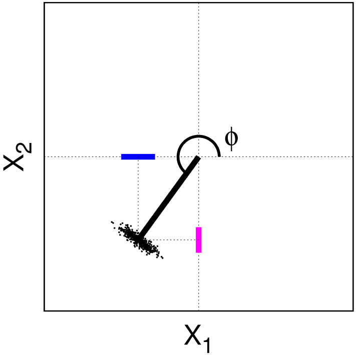
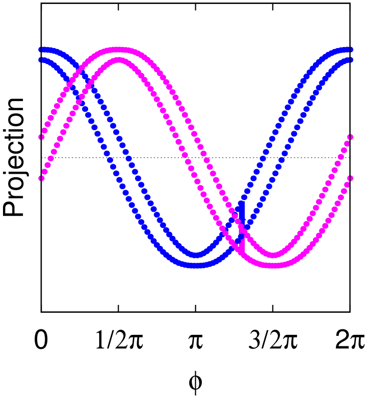




Amplitude squeezed states

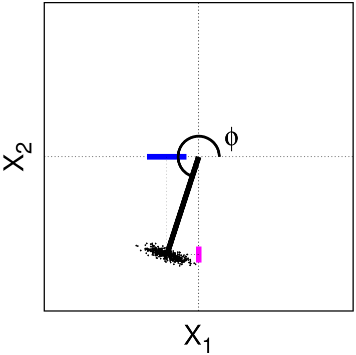
$\Delta X_1 \Delta X_2 = 1/4$

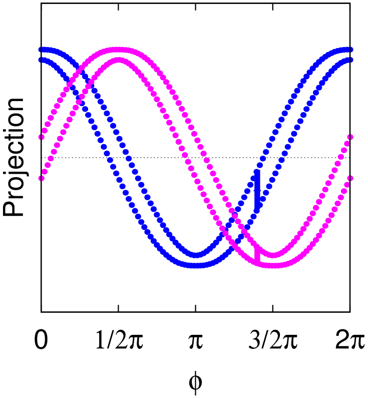




Amplitude squeezed states

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





Amplitude squeezed states

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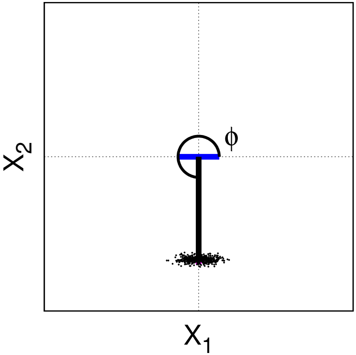

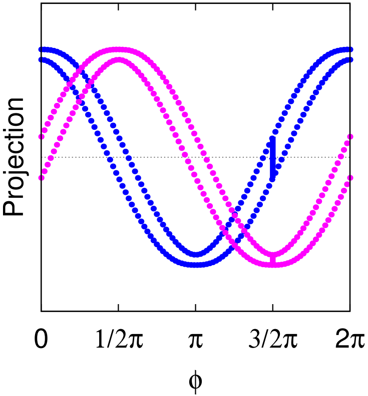

Amplitude squeezed states

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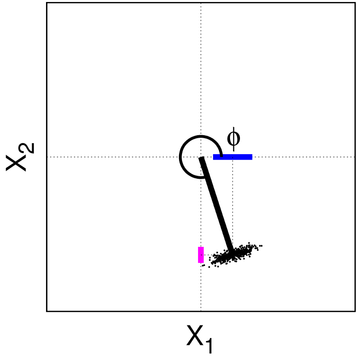
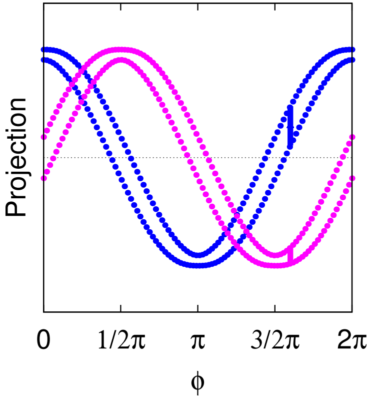
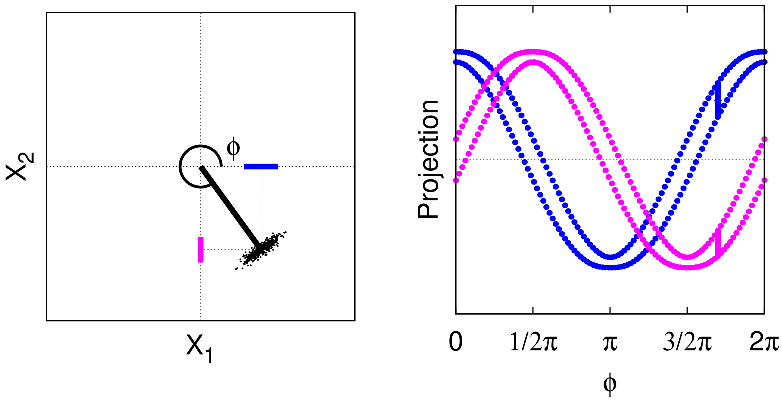




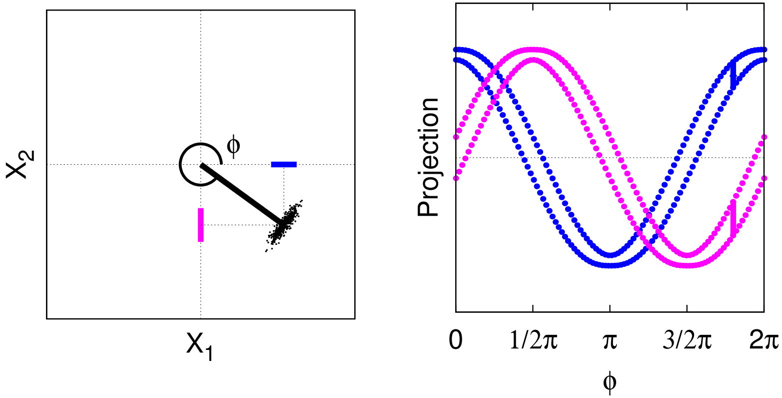
Amplitude squeezed states

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



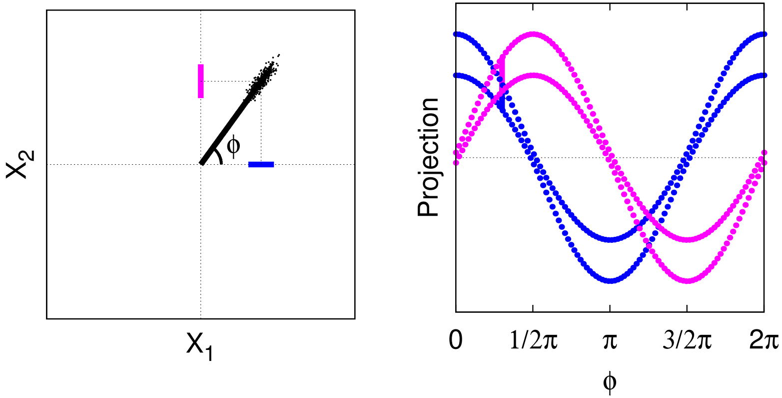
Amplitude squeezed states

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



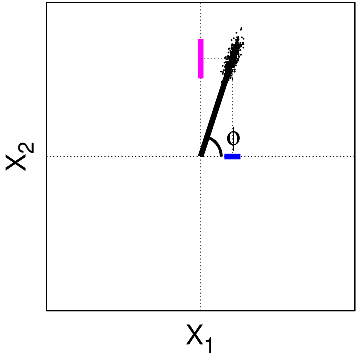
Phase squeezed states

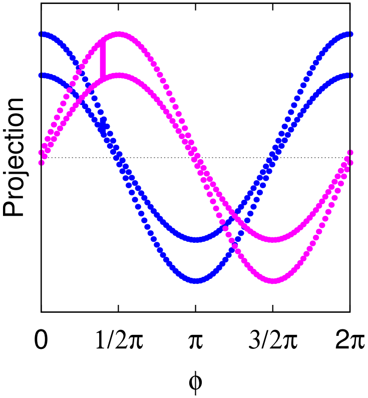
$\Delta X_1 \Delta X_2 = 1/4$



Phase squeezed states

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





Phase squeezed states

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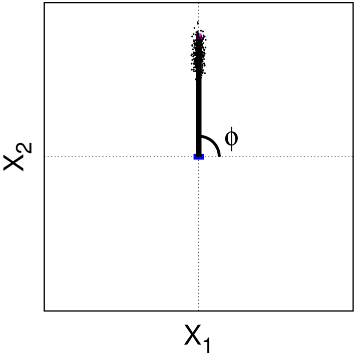

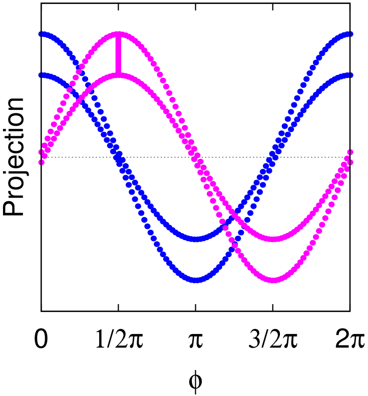

Phase squeezed states

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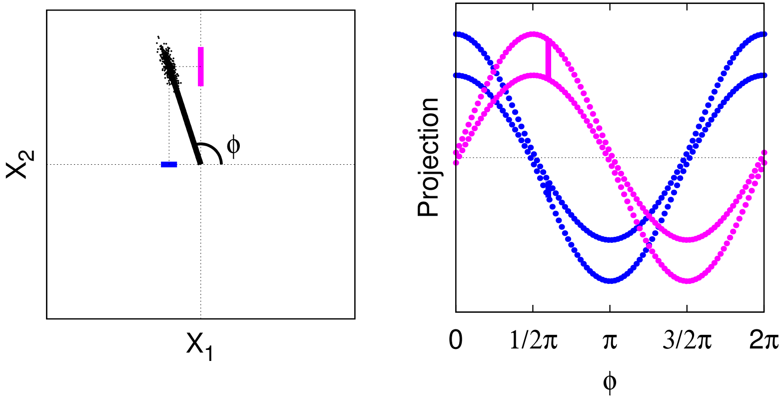

Phase squeezed states

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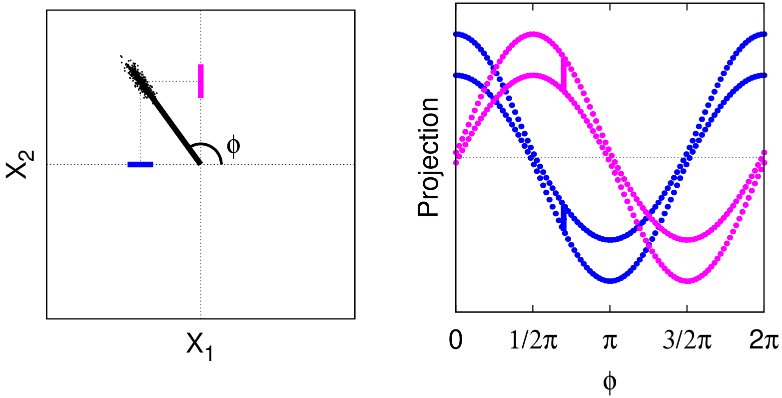

Phase squeezed states

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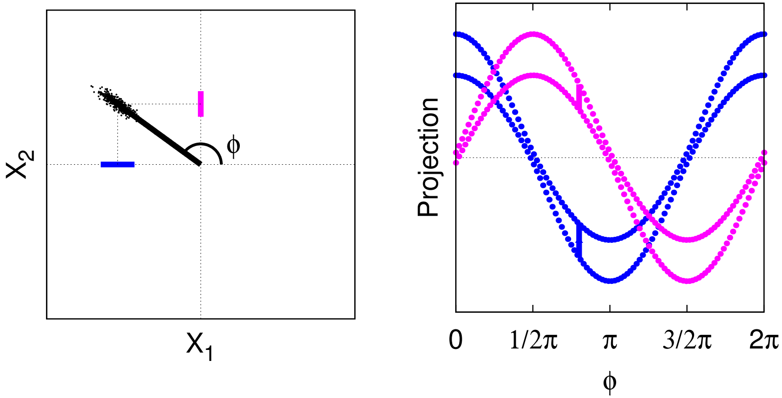

Phase squeezed states

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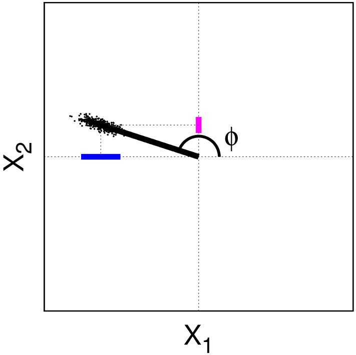

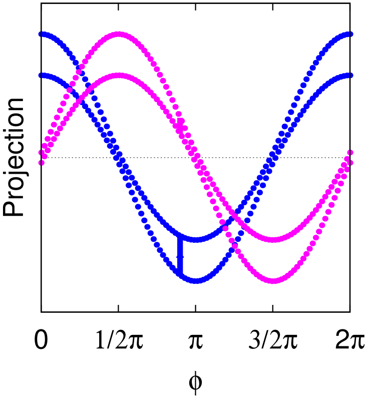

Phase squeezed states

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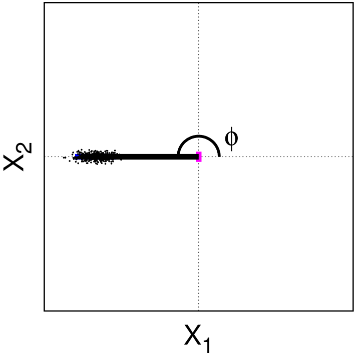
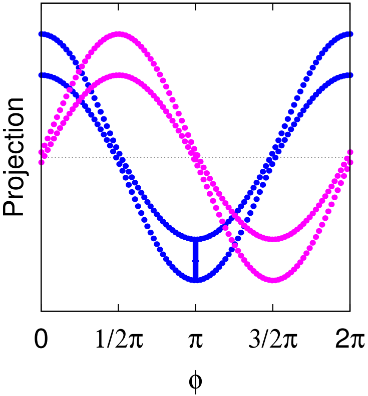
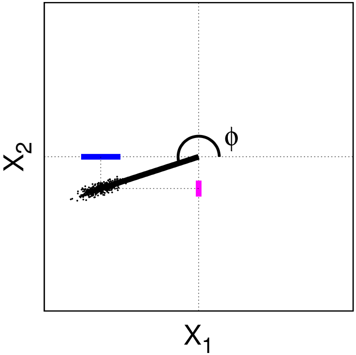
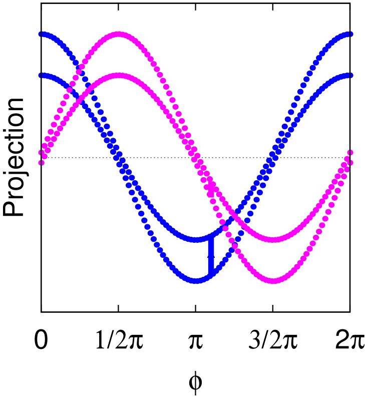




Phase squeezed states

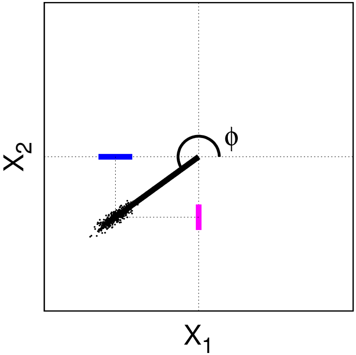
$\Delta X_1 \Delta X_2 = 1/4$

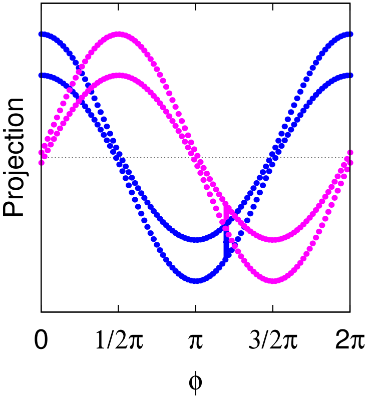




Phase squeezed states

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





Phase squeezed states

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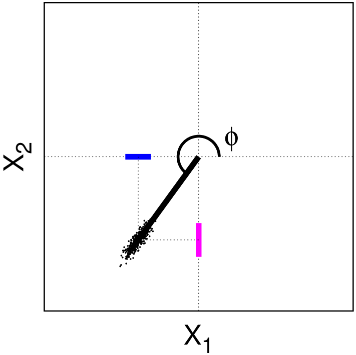
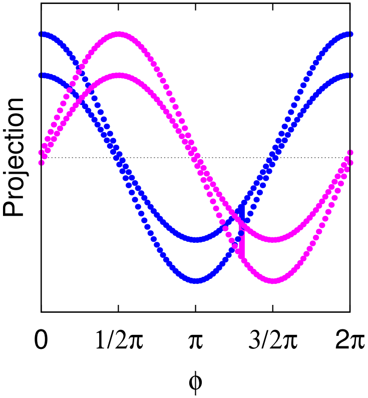
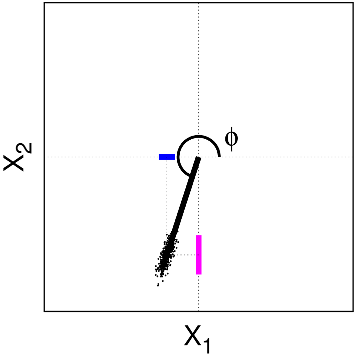
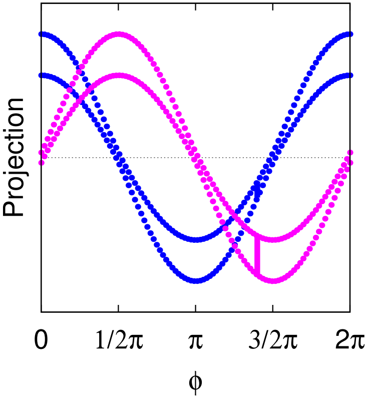




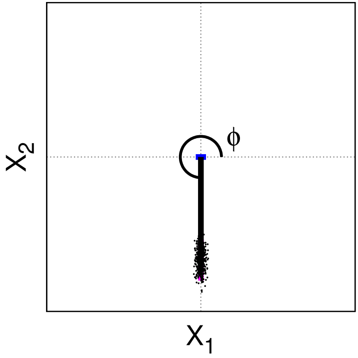
$\Delta X_1 \Delta X_2 = 1/4$

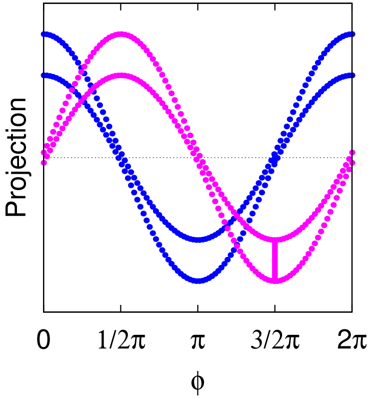




Phase squeezed states

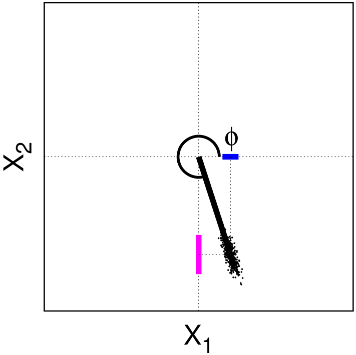
$\Delta X_1 \Delta X_2 = 1/4$

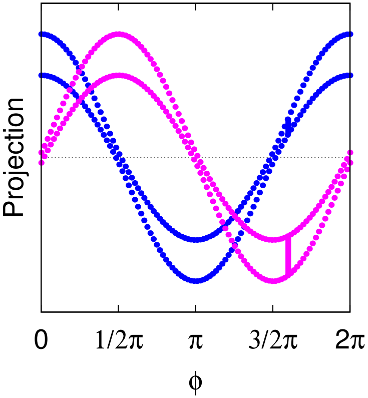




Phase squeezed states

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





Phase squeezed states

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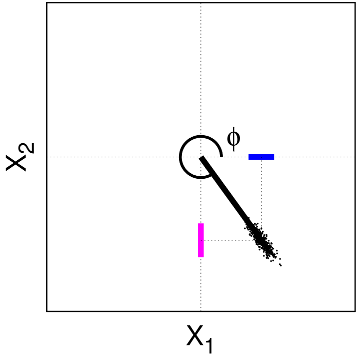
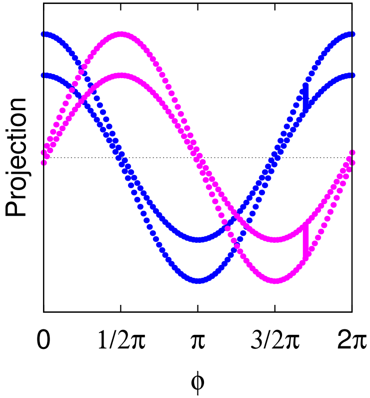
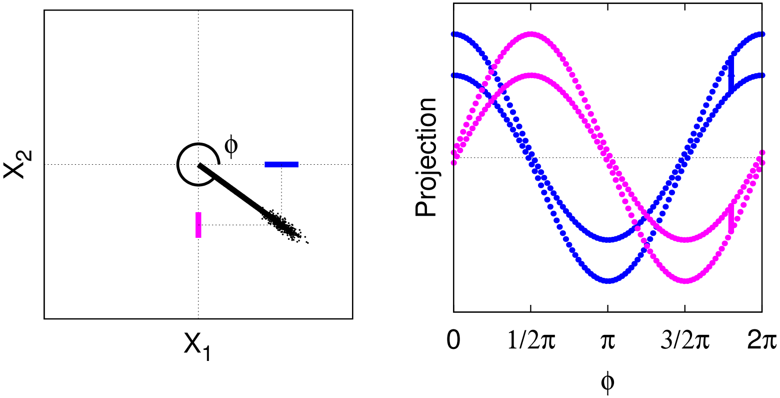


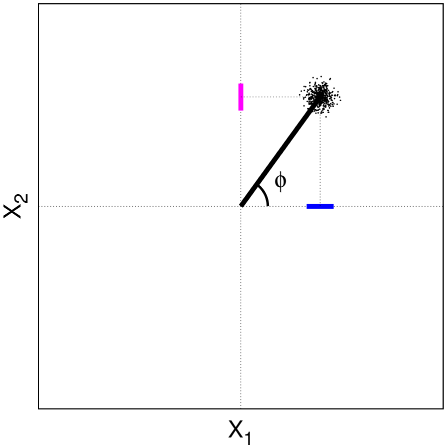


Phase squeezed states

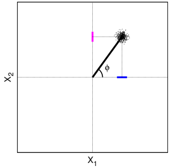
$\Delta X_1 \Delta X_2 = 1/4$



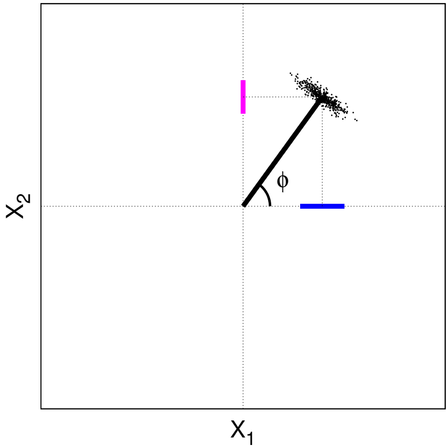
Squeezed quantum states zoo



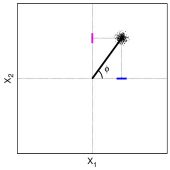
Unsqueezed coherent



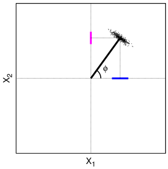
Squeezed quantum states zoo



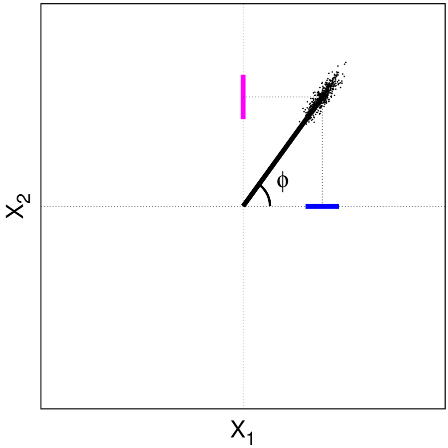
Unsqueezed coherent



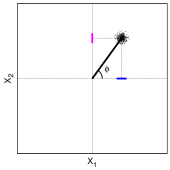
Amplitude squeezed



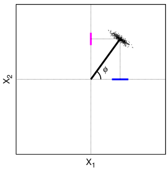
Squeezed quantum states zoo



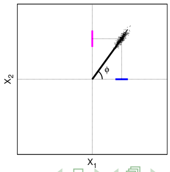
Unsqueezed coherent



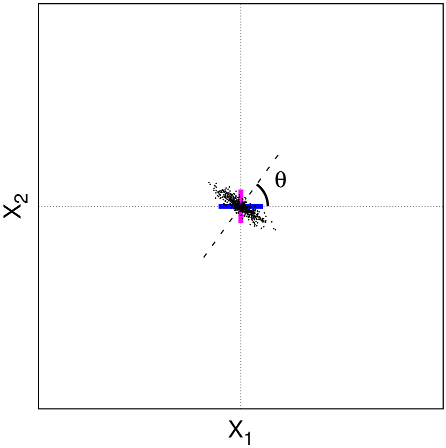
Amplitude squeezed



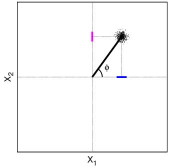
Phase squeezed



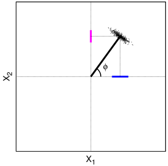
Squeezed quantum states zoo



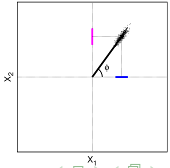
Unsqueezed coherent



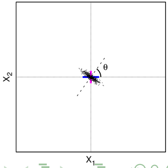
Amplitude squeezed



Phase squeezed

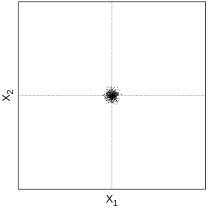


Vacuum squeezed



Squeezed field generation recipe

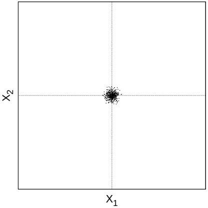
Take a vacuum state $|0>$



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

Squeezed field generation recipe

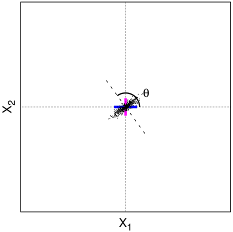
Take a vacuum state $|0>$



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

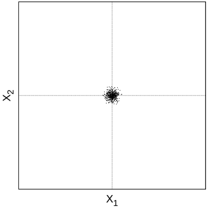
Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

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



Squeezed field generation recipe

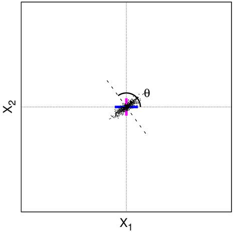
Take a vacuum state $|0>$



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

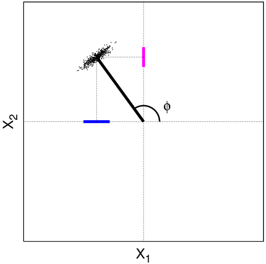
Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

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



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

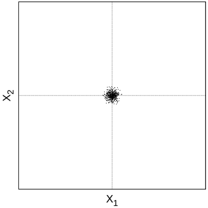
$$\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$$



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

Squeezed field generation recipe

Take a vacuum state $|0>$

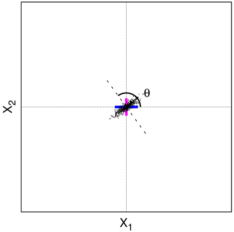


$$H = \frac{1}{2}$$

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

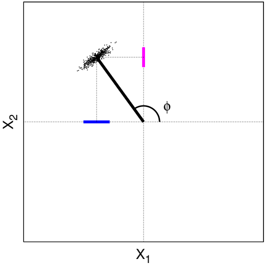
Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

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



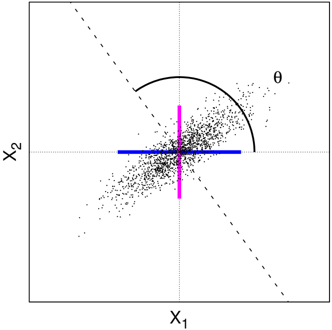
Apply displacement operator $|\alpha, \xi >= \hat{D}(\alpha)|s>$

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



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

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



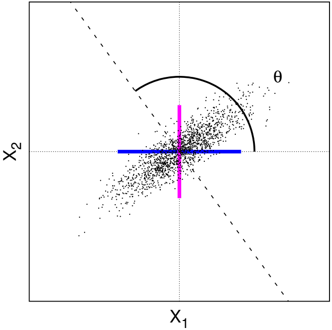
$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}, \xi = re^{i\theta}$$

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

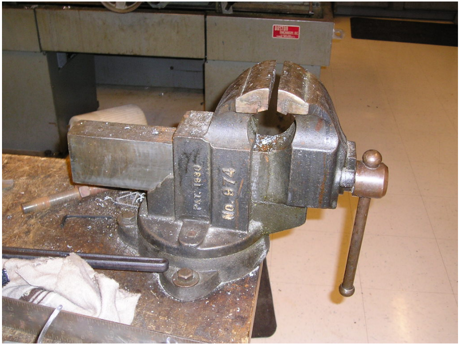
$$C_{2m+1} = 0$$

Average number of photons in general squeezed state

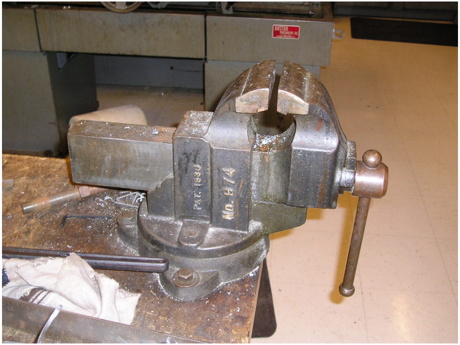
$$< \alpha, \xi|a^\dagger a|\alpha, \xi >= \alpha + \sinh^2 r$$

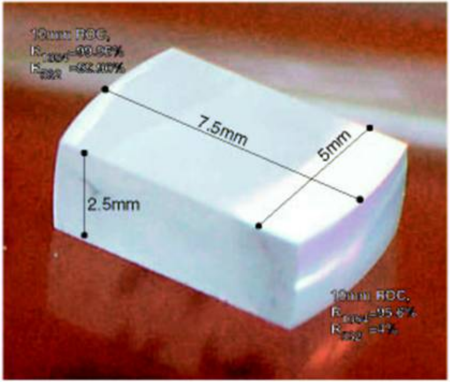
Tools for squeezing

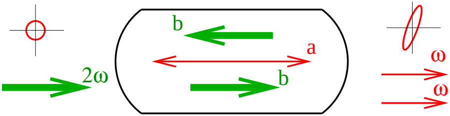
Tools for squeezing



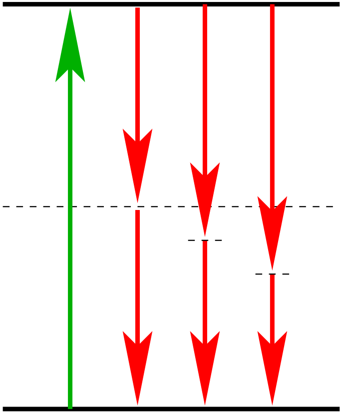
Tools for squeezing







Two photon squeezing picture

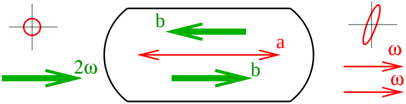


Squeezing operator

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

Parametric down-conversion in crystal

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

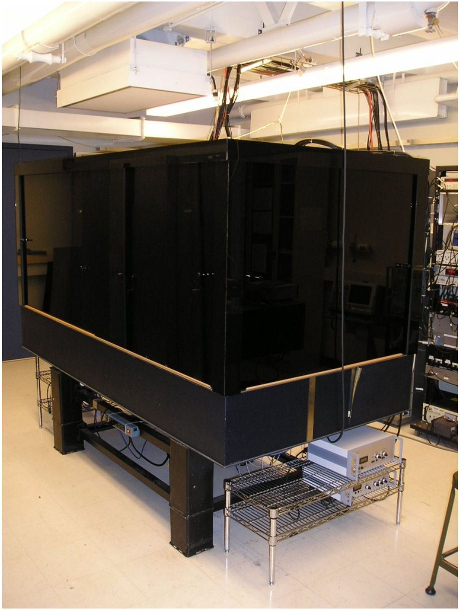


Squeezing

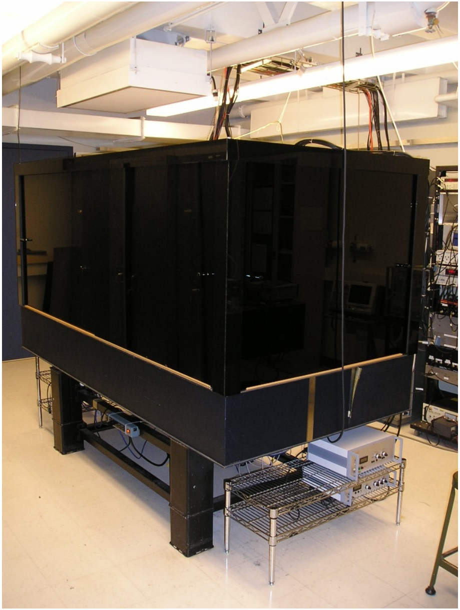
result of correlation of upper and lower sidebands

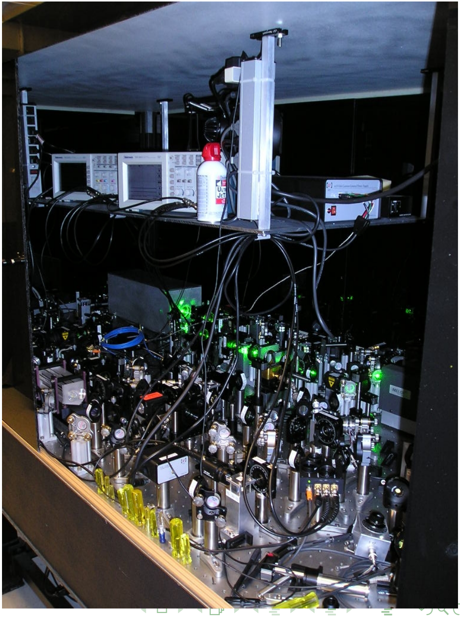
Squeezer appearance

Squeezer appearance



Squeezer appearance





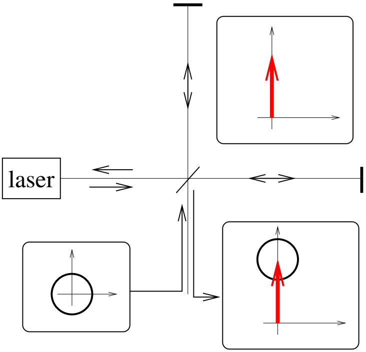
Possible squeezing applications

- 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

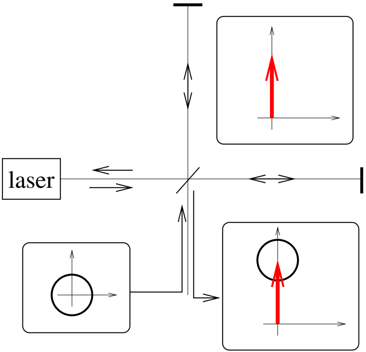
Squeezing and interferometer

Vacuum input

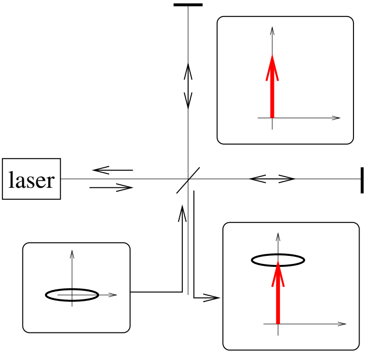


Squeezing and interferometer

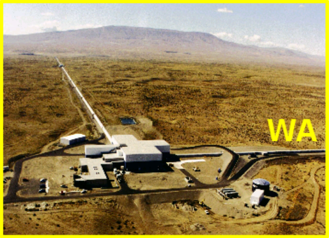
Vacuum input



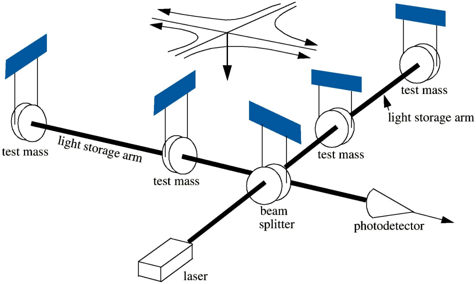
Squeezed input



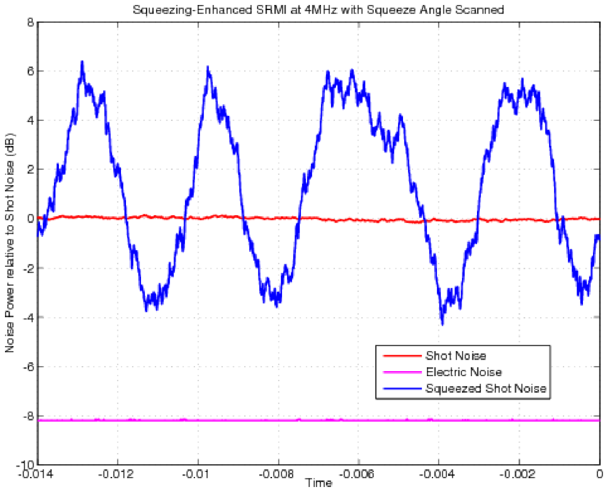
Laser Interferometer Gravitational-wave Observatory



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

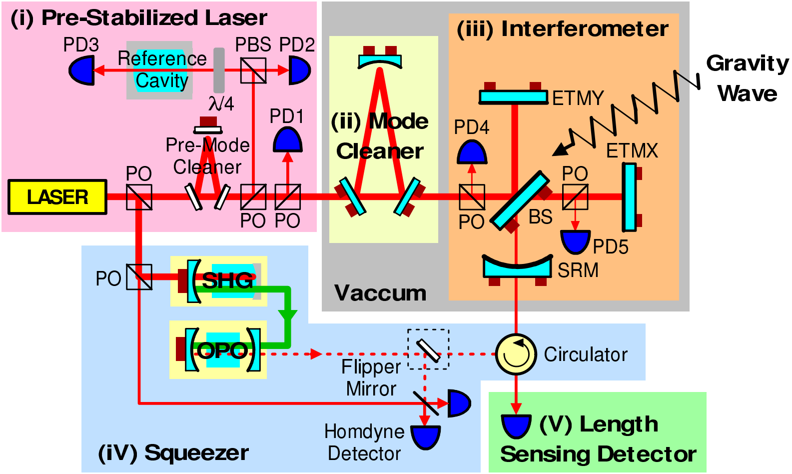


Squeezing level vs time (unlocked)

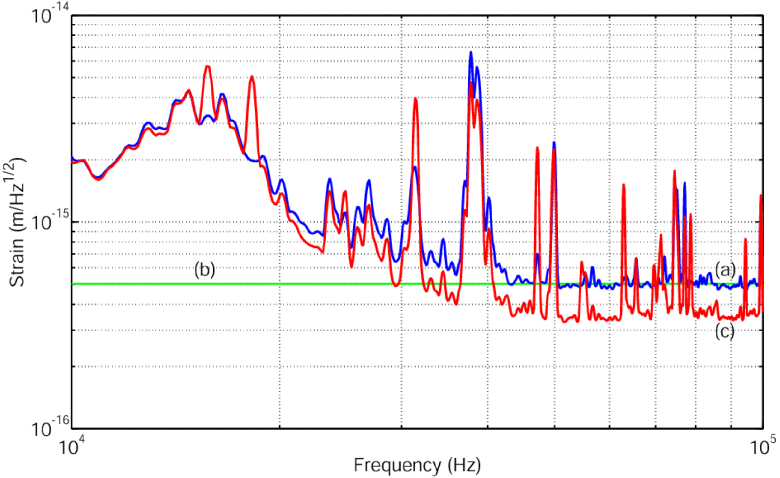


“A quantum-enhanced prototype gravitational-wave detector”, Nature Physics, **4**, 472-476, (2008).

GW 40m detector and squeezer

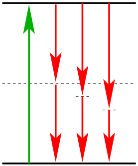


GW 40m detector with 4dB of squeezed vacuum

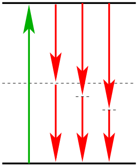


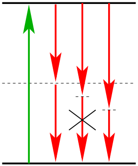
Signal to noise improvement by factor of 1.43

Cavity parameters with squeezing

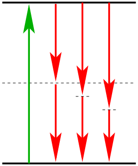


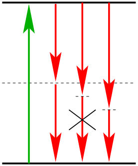
Cavity parameters with squeezing

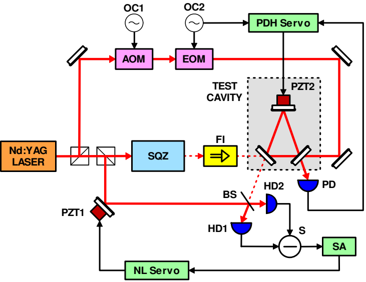




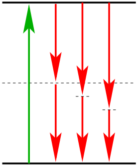
Cavity parameters with squeezing

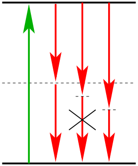


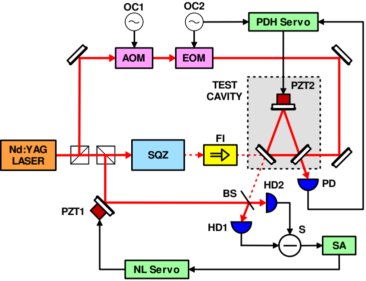


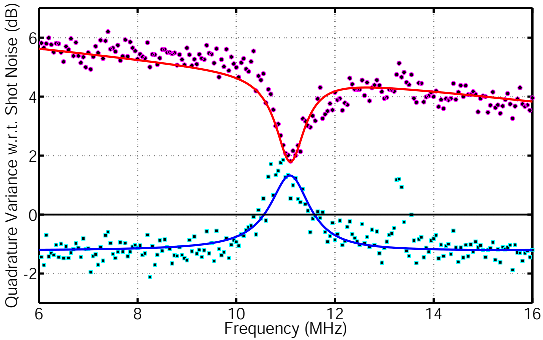


Cavity parameters with squeezing









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

Summary for crystal squeezing

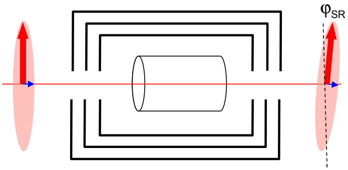
Pros

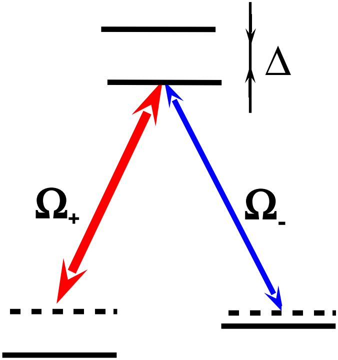
- mainstream: many different nonlinear crystals available
- so far the best squeezers
  - maximum squeezing value detected 11.5 dB at 1064 nm
  - Moritz Mehmet, Henning Vahlbruch, Nico Lastzka, Karsten Danzmann, and Roman Schnabel, "Observation of squeezed states with strong photon-number oscillations", 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

Self-rotation of elliptical polarization in atomic medium

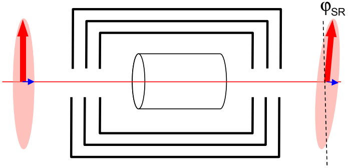


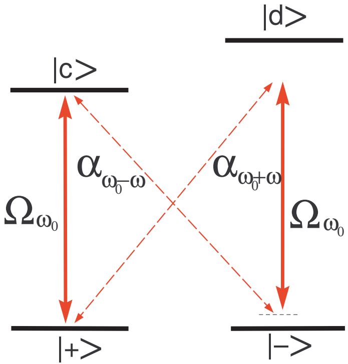


A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

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

Self-rotation of elliptical polarization in atomic medium

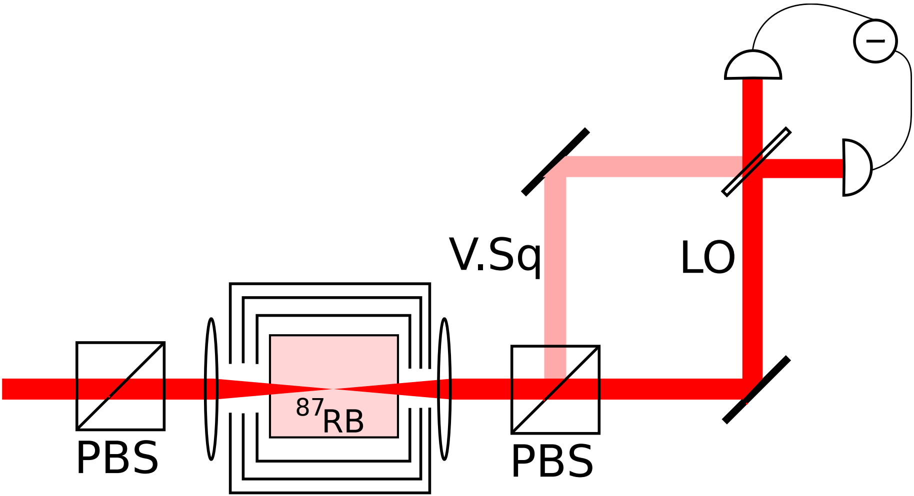




A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

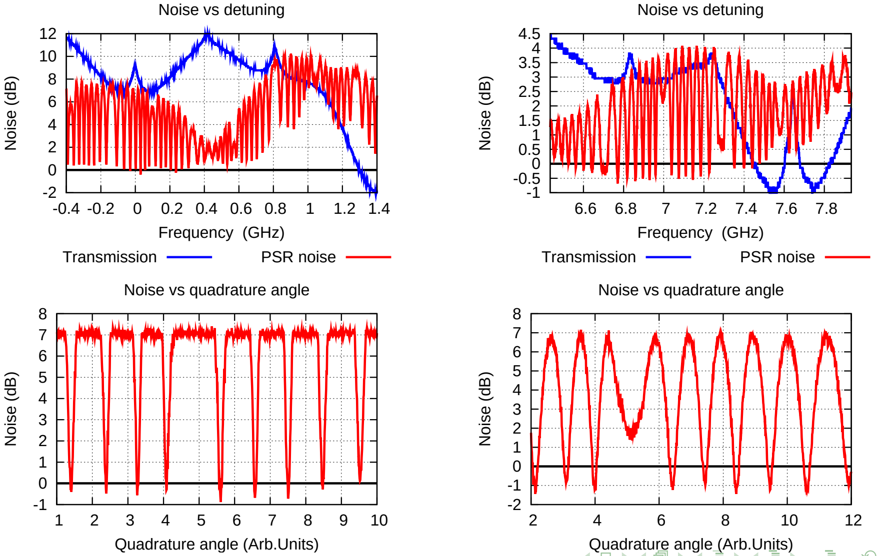
$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in})$$

Setup

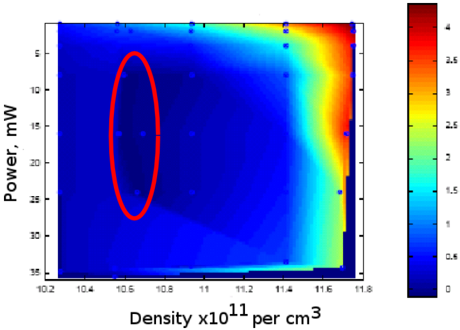


Noise contrast vs detuning in hot ^{87}Rb vacuum cell

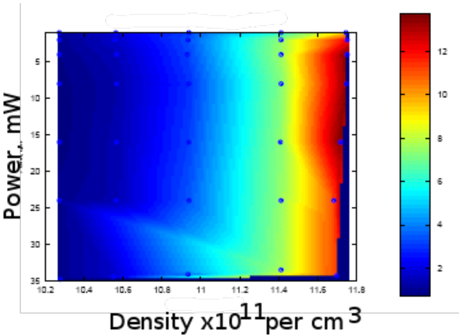
$F_g = 2 \rightarrow F_e = 1, 2$ | $F_g = 1 \rightarrow F_e = 1, 2$



Squeezing



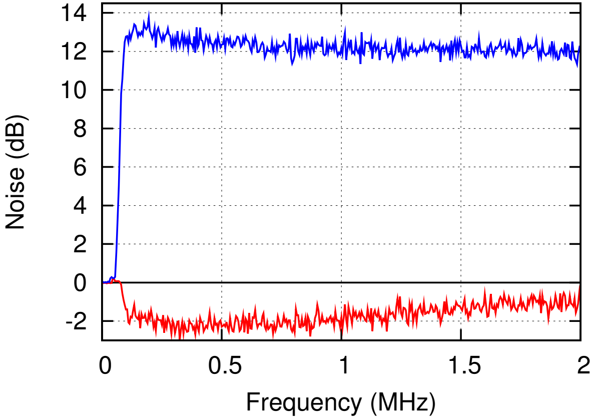
Anti-squeezing



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

Maximally squeezed spectrum with ^{87}Rb

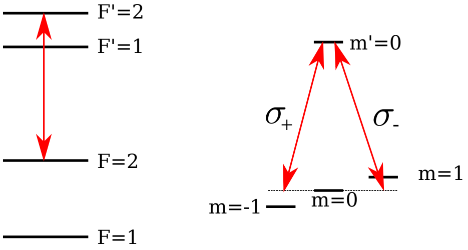
W&M team. ^{87}Rb $F_g = 2 \rightarrow F_e = 2$, laser power 7 mW, T=65° C



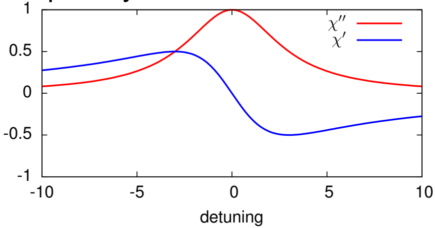
Lezama et.al report 3 dB squeezing in similar setup
Phys. Rev. A 84, 033851 (2011)

Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



Susceptibility vs B



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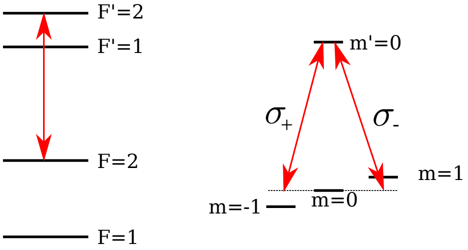
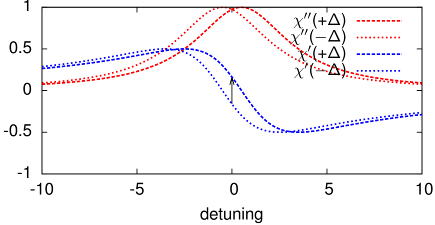


Susceptibility vs B



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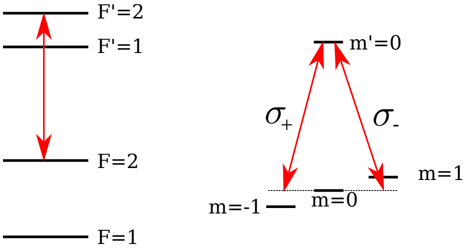

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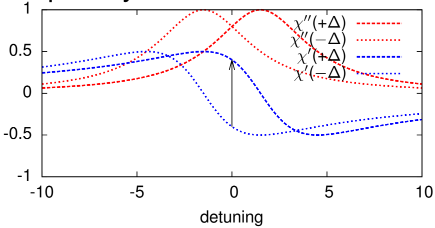
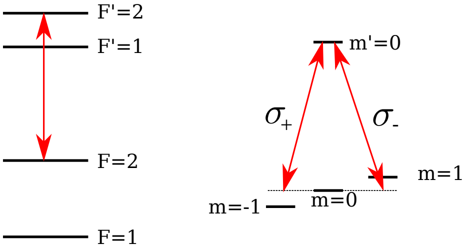
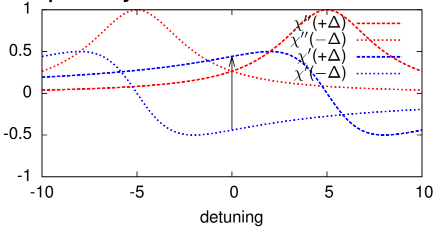


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

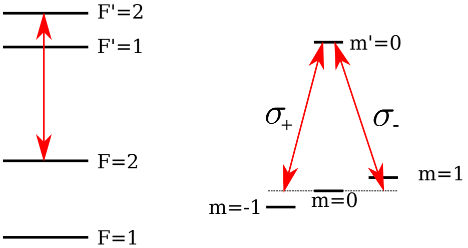


Susceptibility vs B

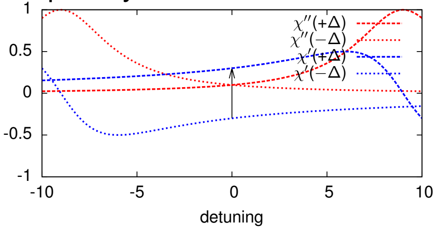


Optical magnetometer based on Faraday effect

^{87}Rb D$_1$ line

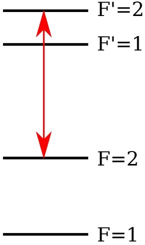


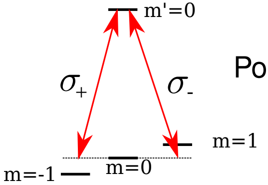
Susceptibility vs B



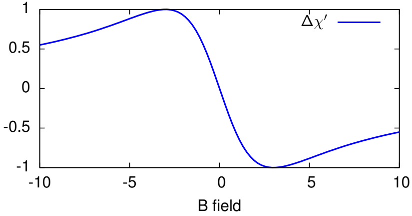
Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

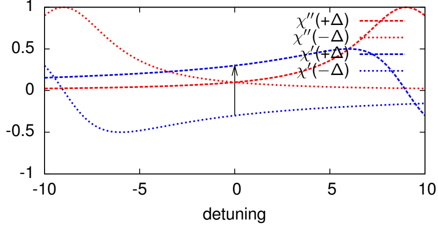




Polarization rotation vs B



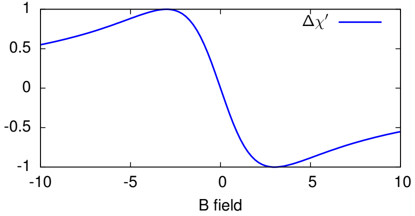
Susceptibility vs B

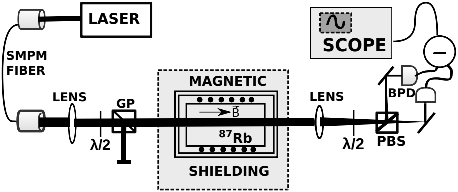


Optical magnetometer and non linear Faraday effect

Naive model of rotation

Experiment





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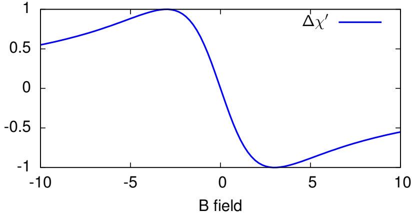
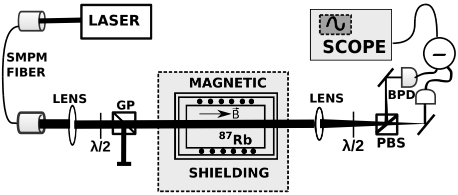
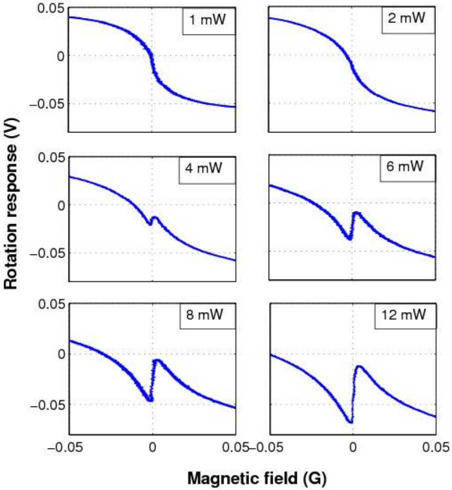
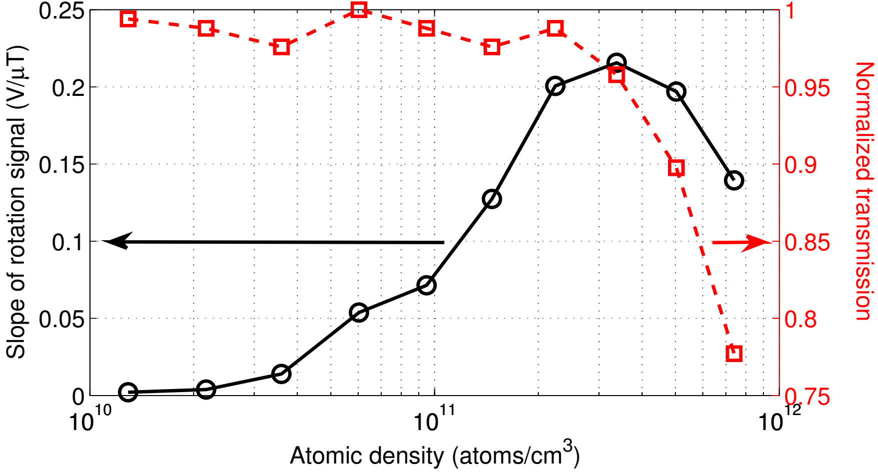




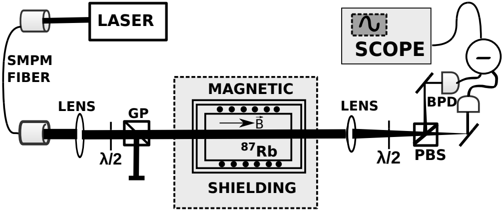
Experiment

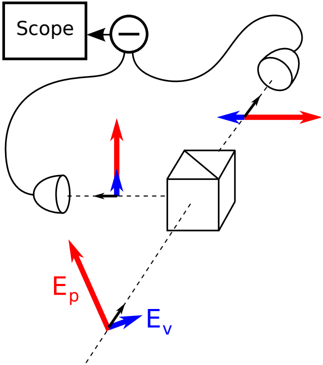


Magnetometer response vs atomic density



Shot noise limit of the magnetometer



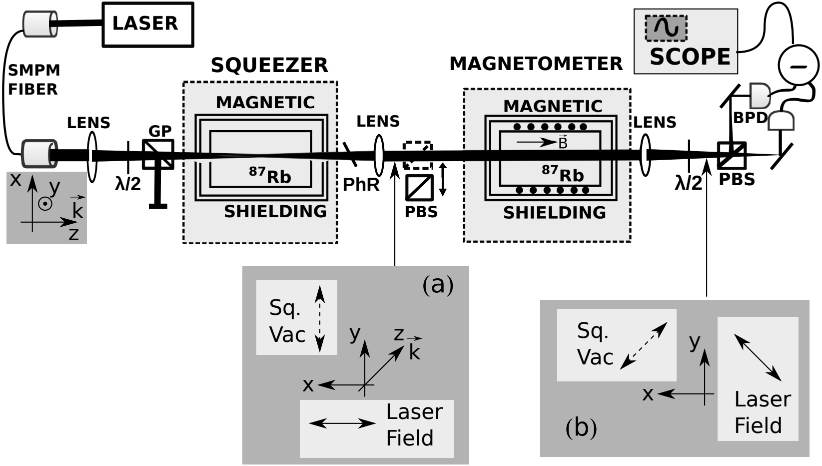


$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$

$$S = 4E_pE_v$$

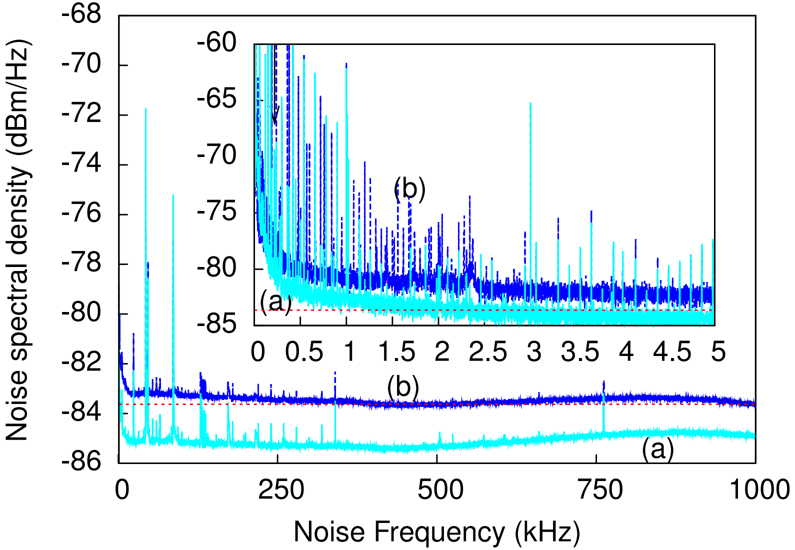
$$< \Delta S > \sim E_p < \Delta E_v >$$

Squeezed enhanced magnetometer setup

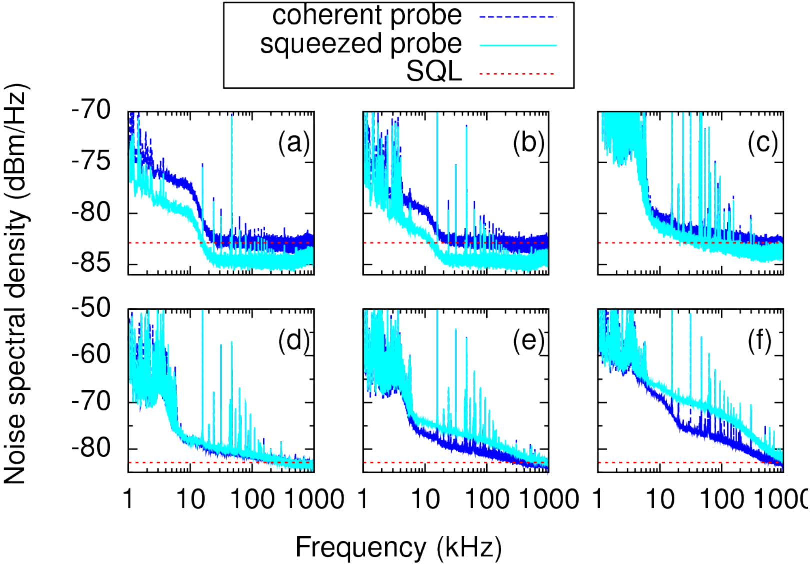


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements

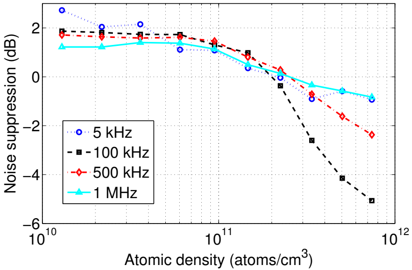


Magnetometer noise spectra

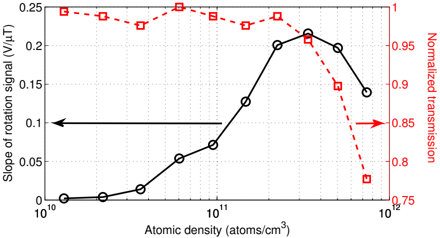


Noise suppression and response vs atomic density

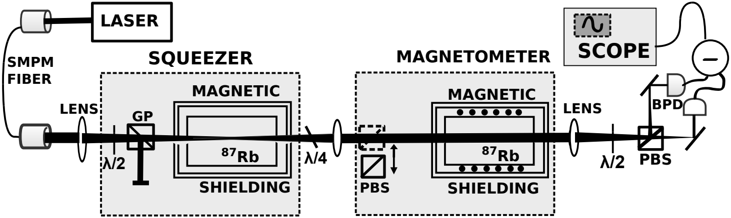
Noise suppression

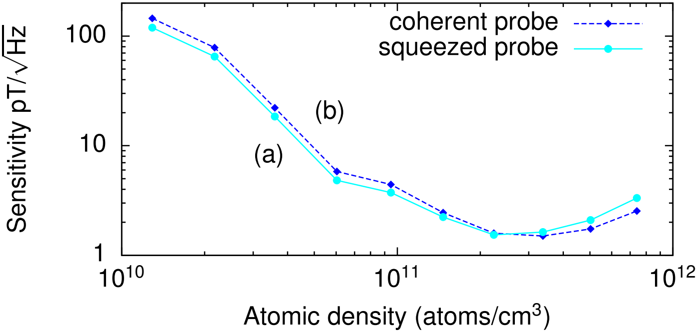


Response



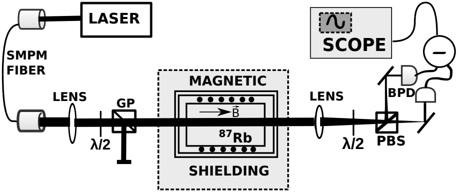
Magnetometer with squeezing enhancement

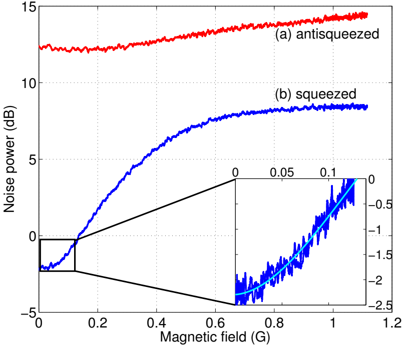




Squeezing vs magnetic field

Spectrum analyzer settings: Central frequency = 1 MHz, VBW = 3 MHz, RBW = 100 kHz





Travis Horrom et al. "All-atomic source of squeezed vacuum with full pulse-shape control", Journal of Physics B: Atomic, Molecular and Optical Physics, Issue 12, 45, 124015, (2012).

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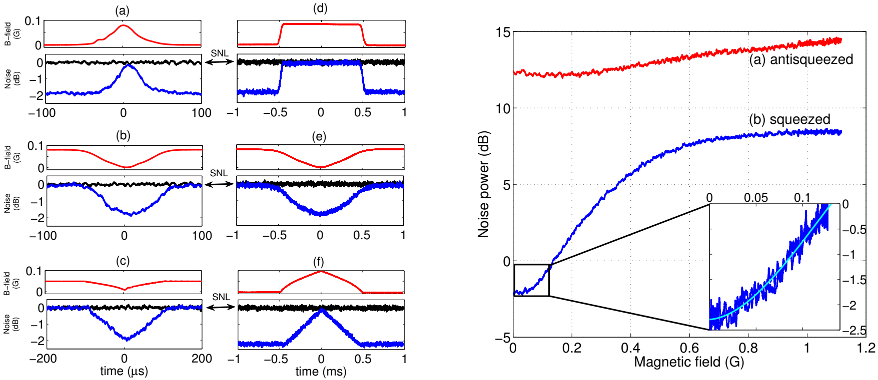
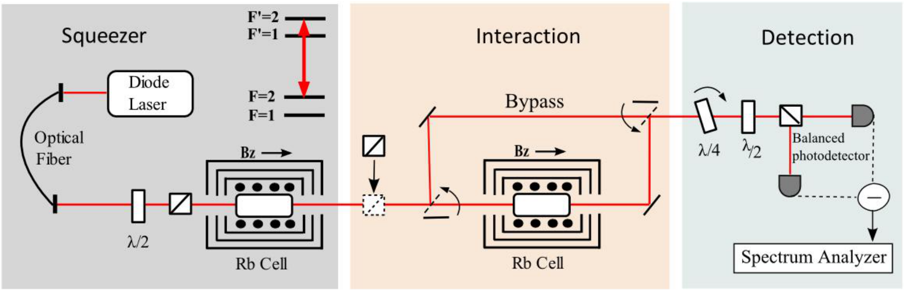
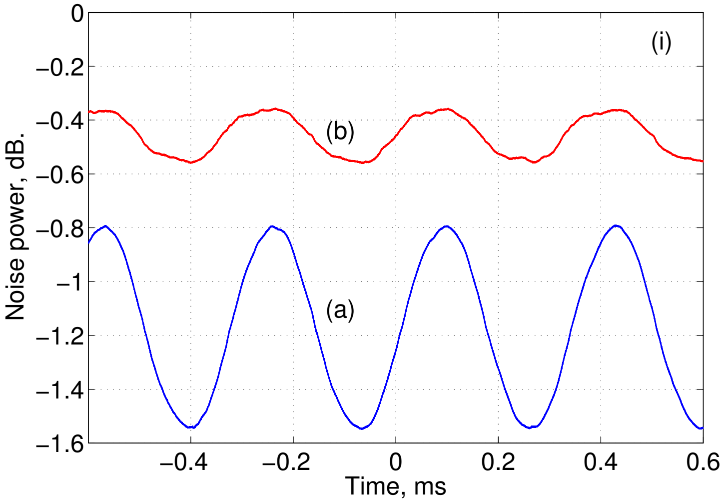


Travis Horrom et al. "All-atomic source of squeezed vacuum with full pulse-shape control", Journal of Physics B: Atomic, Molecular and Optical Physics, Issue 12, 45, 124015, (2012).

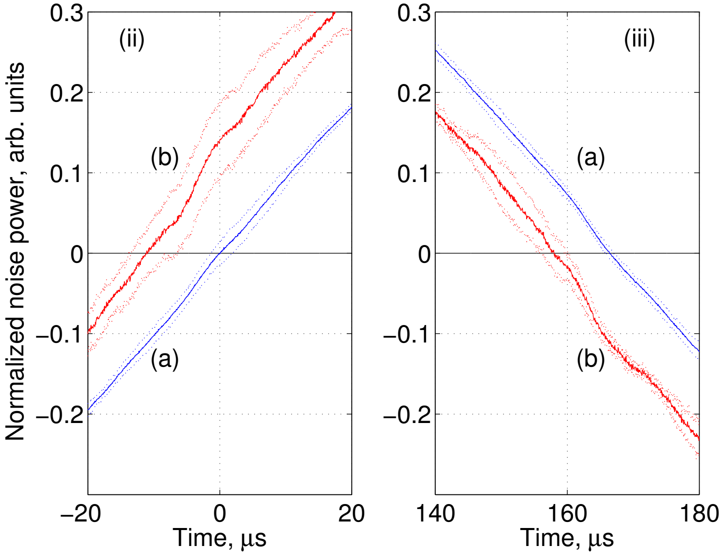
Time advancement setup



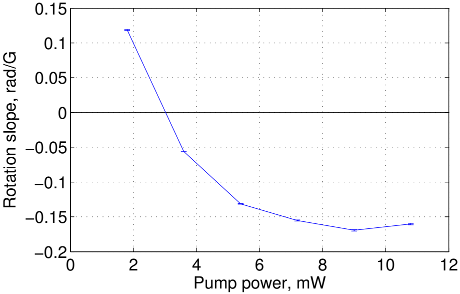
Squeezing modulation and time advancement



Squeezing modulation and time advancement



Advancement vs power



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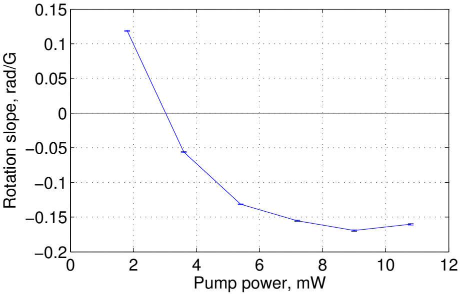
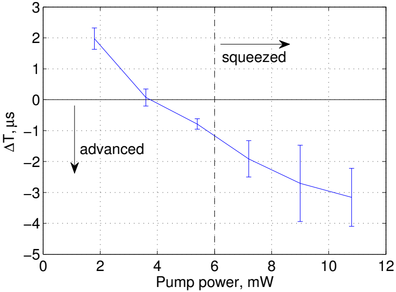
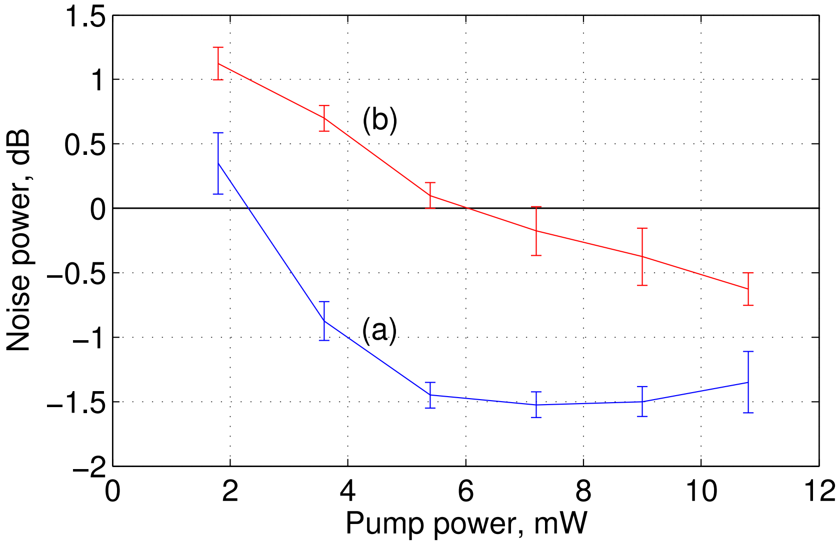
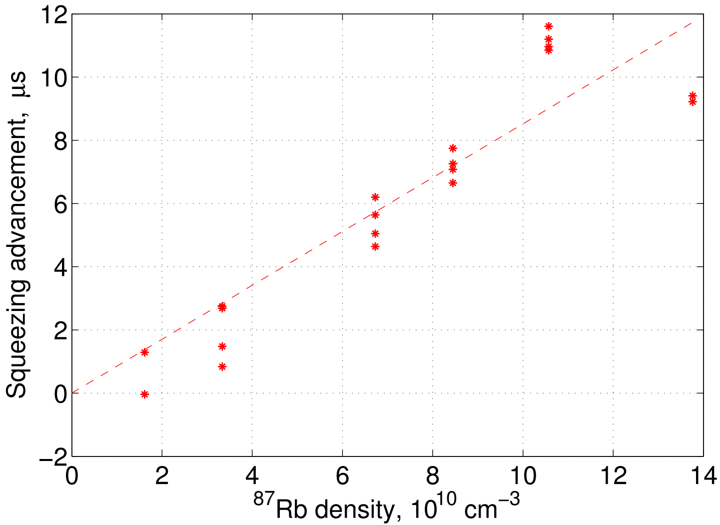




Squeezing level before and after advancement cell



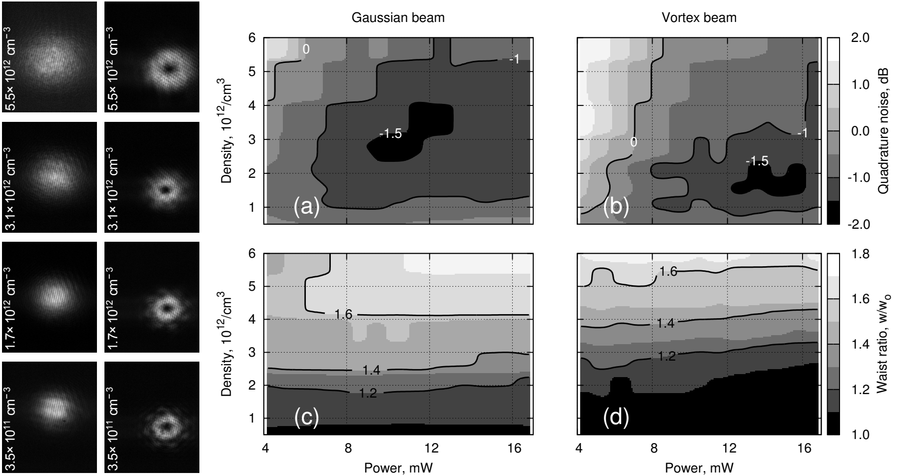
Squeezing advancement vs atomic density



Why superluminal squeezing?

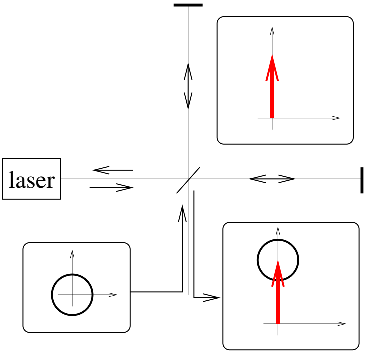
- Quantum memories
- M. S. Shahriar, et al. “Ultrahigh enhancement in absolute and relative rotation sensing using fast and slow light”, Phys. Rev. A 75(5), 053807, 2007.
- Yakir Aharonov, et al. “Quantum Limitations on Superluminal Propagation”, Phys. Rev. Lett. 81, 2190 (1998)

Squeezing and self-focusing

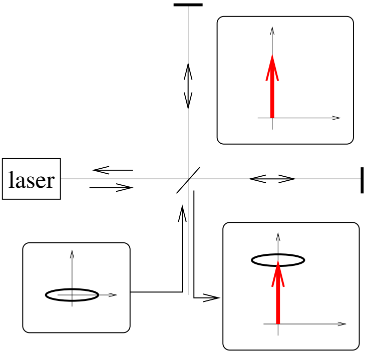


Quantum limited interferometers revisited

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

$$h \sim \sqrt{\frac{1}{P}} \quad (1)$$

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Photons impart momentum to mirrors

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

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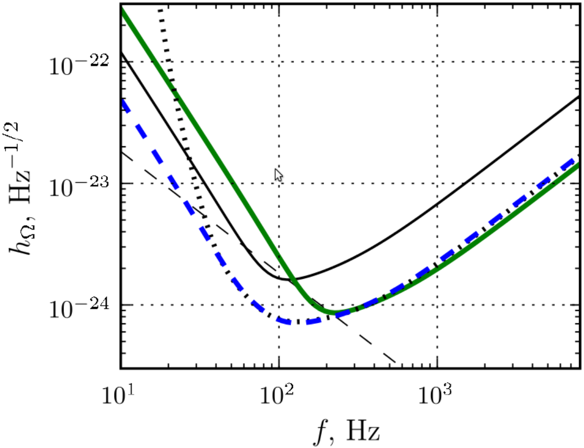
$$h \sim \sqrt{\frac{P}{M^2 f^4}} \quad (2)$$

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



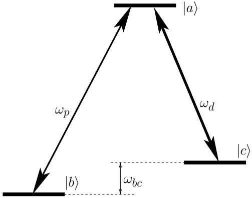
F. Ya. Khalili Phys. Rev. D 81, 122002 (2010)

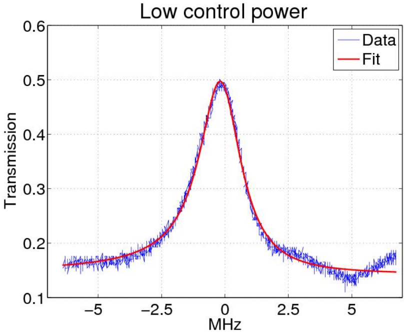
Squeezing and EIT filter

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

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

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





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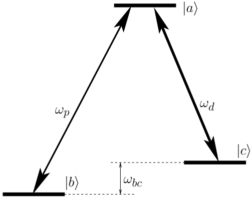

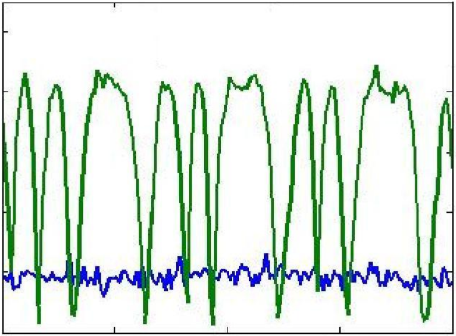

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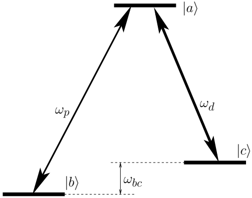

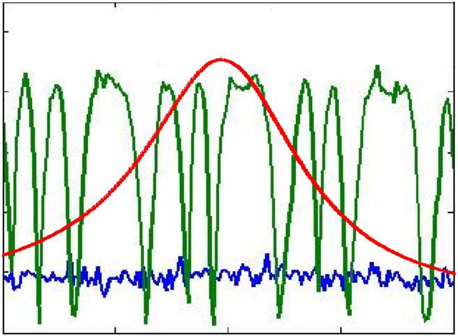

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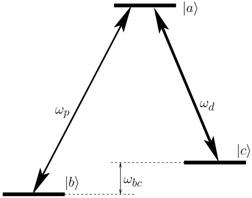
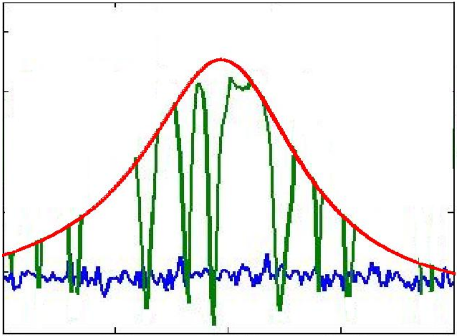
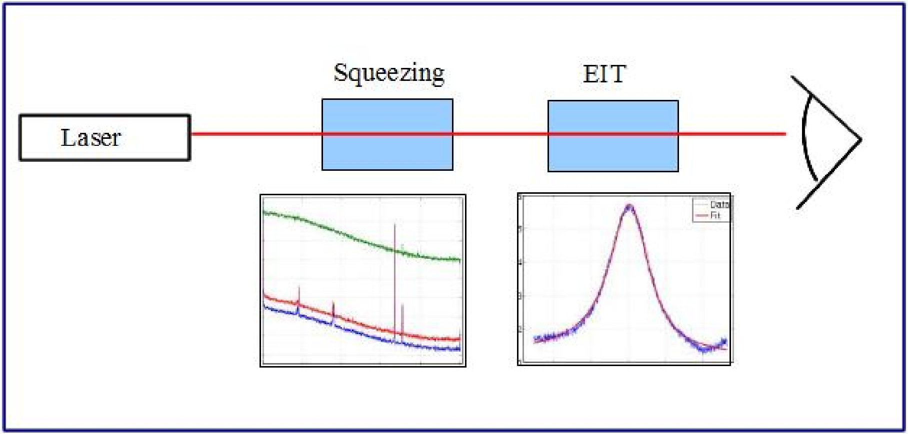
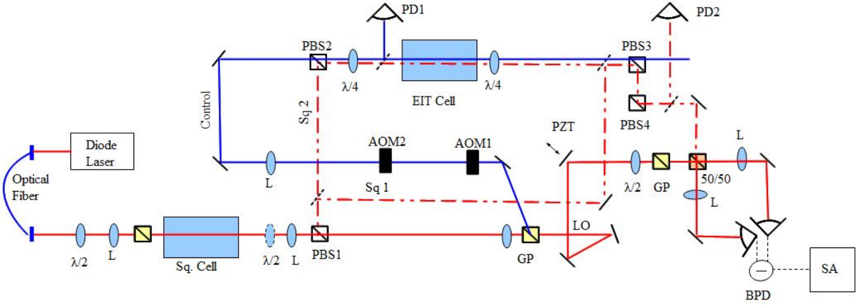




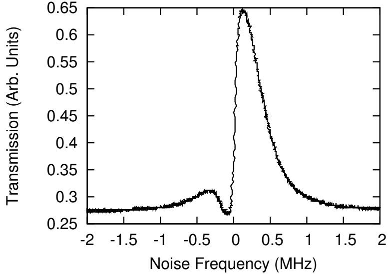
Squeezing and EIT filter setup



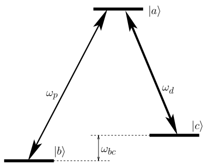
Squeezing and EIT filter setup



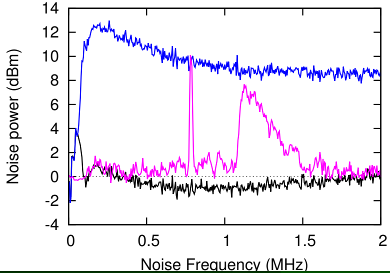
EIT filter and measurements without light

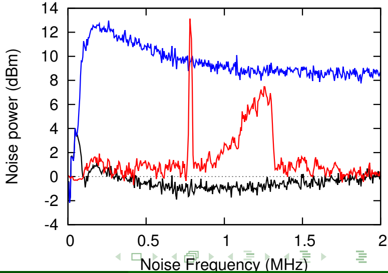


Coherent signal

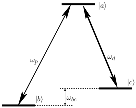


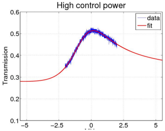
Signal in the noise quadratures



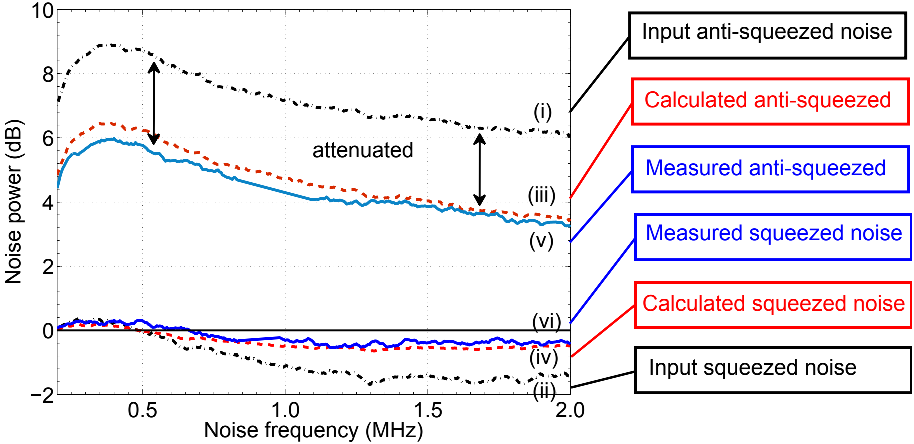


Wide EIT filter and squeezing

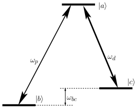


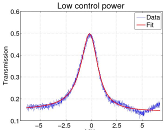


- Peak transmission = 52%
- FWHM= 4MHz

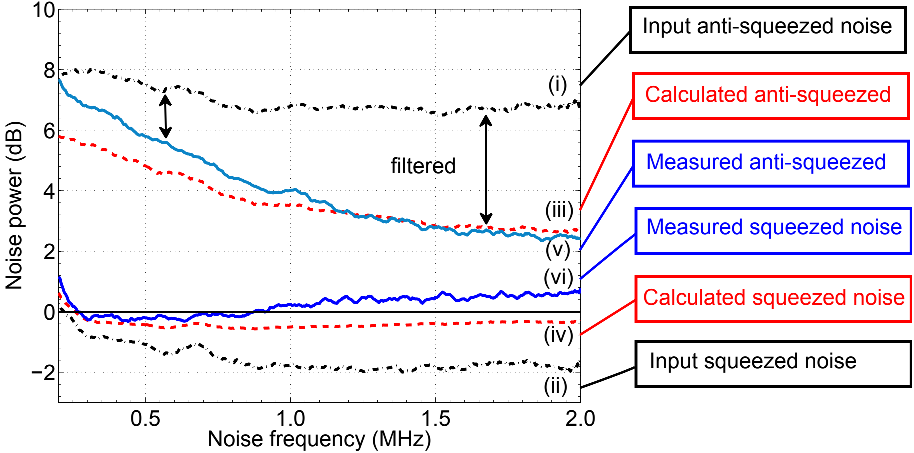


Narrow EIT filter and squeezing

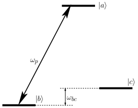


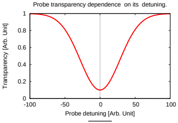


- Peak transmission = 50%
- FWHM= 2MHz

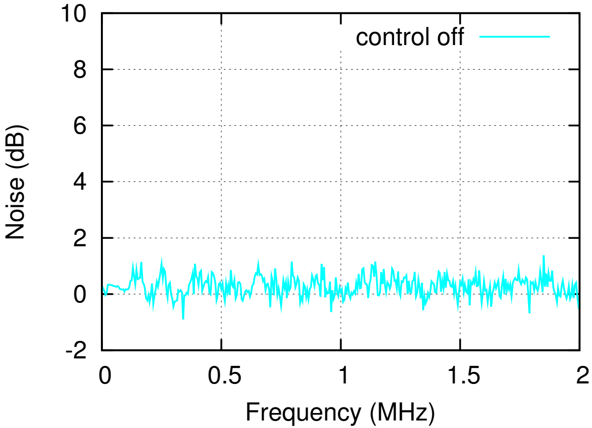


Control off no EIT and no squeezing at the output

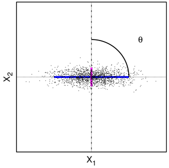


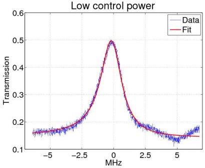


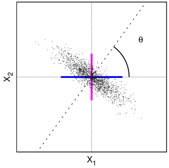
- Peak transmission = 0%



Squeezing angle rotation

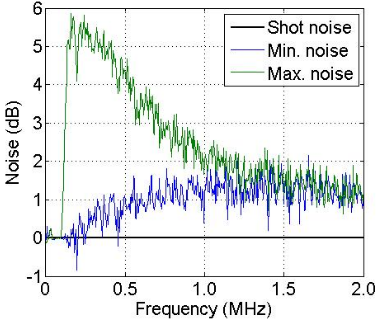




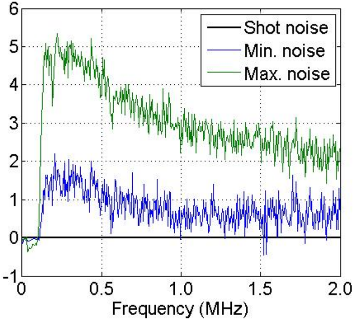


$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} \cos^2\varphi_+ & \sin^2\varphi_+ \\ \sin^2\varphi_+ & \cos^2\varphi_+ \end{pmatrix} \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right]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

Locked at 300kHz

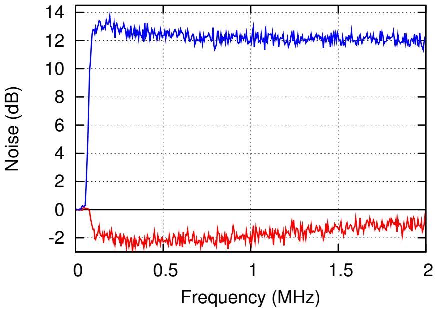


Locked at 1200kHz

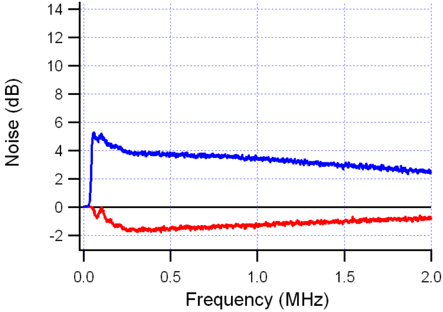


Potential squeezing improvement with coated cells

Vacuum cell

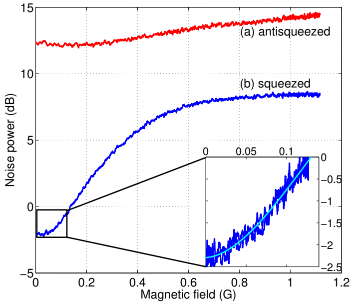


Coated cell

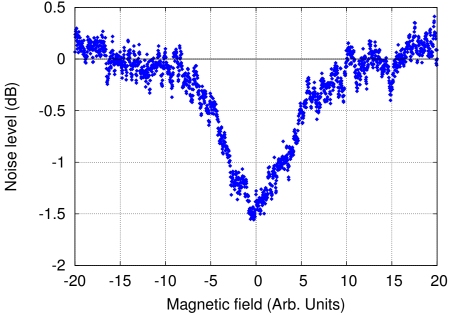


Potential squeezing improvement with coated cells

Vacuum cell



Coated cell



Summary

- We demonstrate fully atomic squeezed enhanced magnetometer with sensitivity as low as 1 pT/$\sqrt{\text{Hz}}$
- First demonstration of superluminal squeezing propagation with $v_g \approx -7'000$ m/s $\approx -c/43'000$ or time advancement of 11 μS
- Control over spacial mode and spectral profile of squeezing

But more importantly

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

Support from