Quantum enhanced measurements

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People

From ray optics to semiclassical optics

Classical/Geometrical optics

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

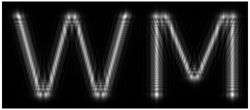
From ray optics to semiclassical optics

Classical/Geometrical optics

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

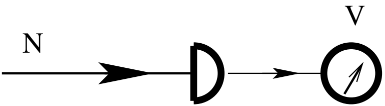
Semiclassical optics

- 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



Detector quantum noise

Simple photodetector



$V \sim N$

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

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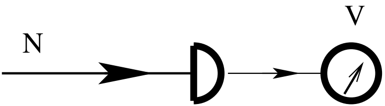
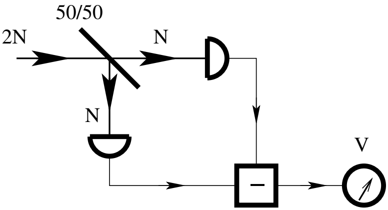


$$V \sim N$$

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

Balanced photodetector



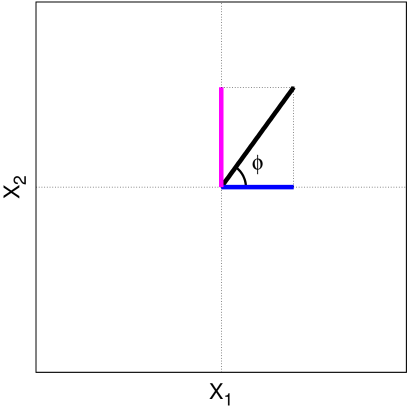
$$V = 0$$

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

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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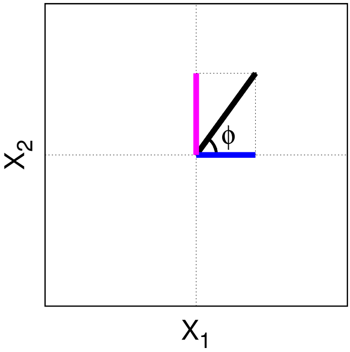

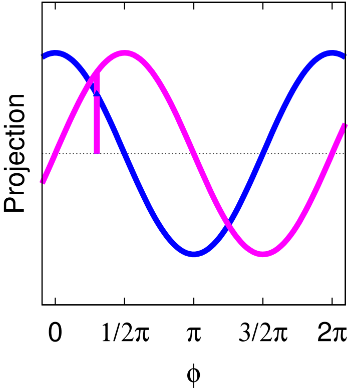

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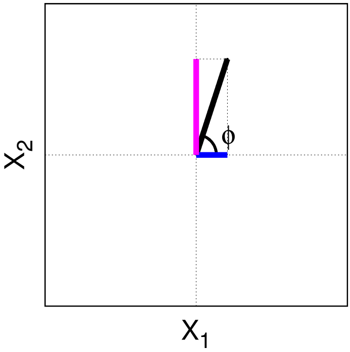

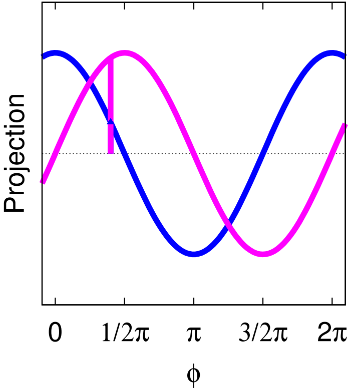

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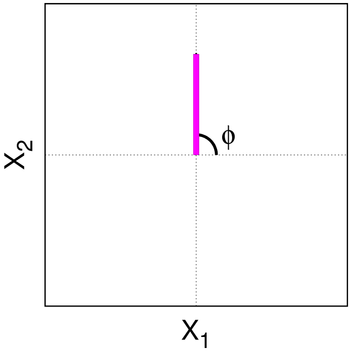

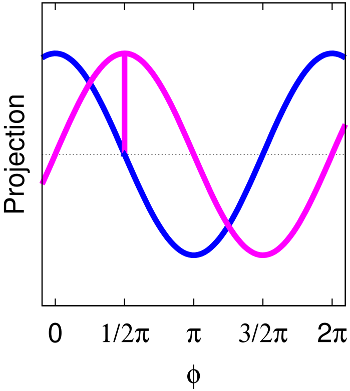

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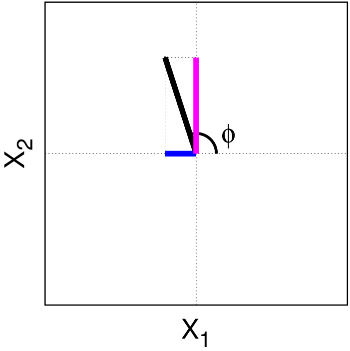

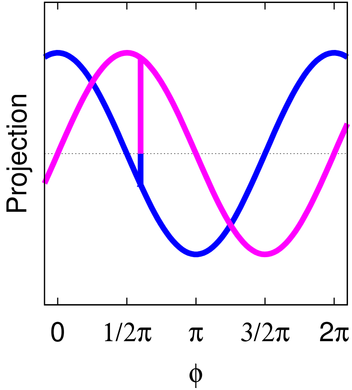

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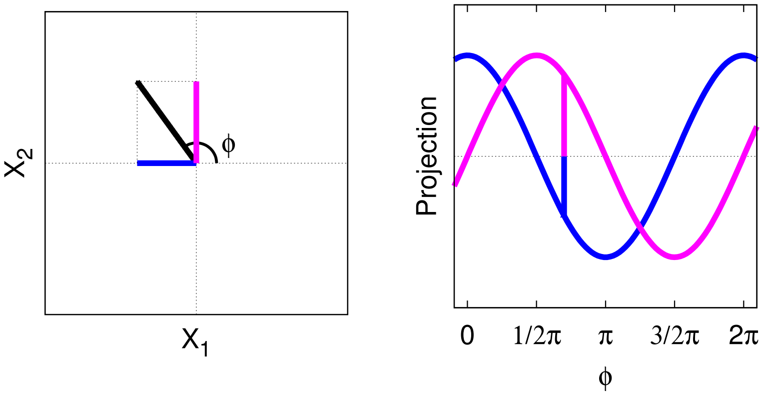

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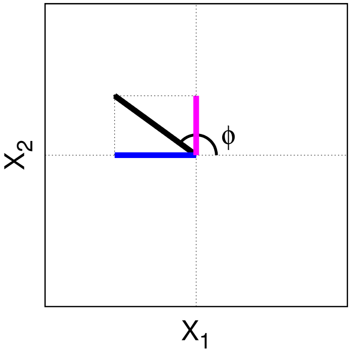

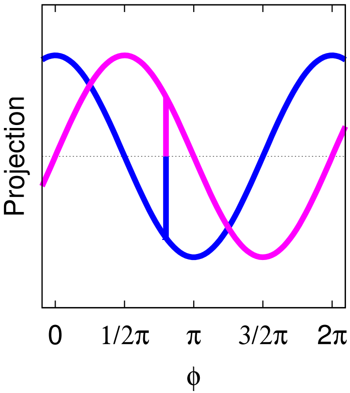

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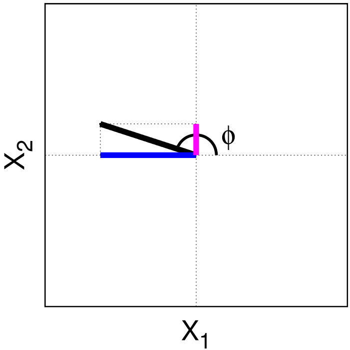

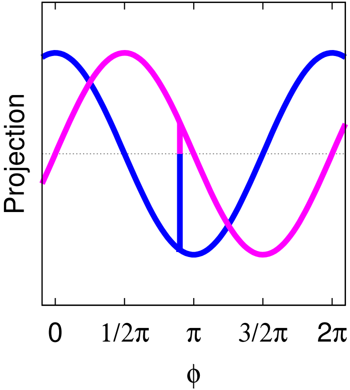

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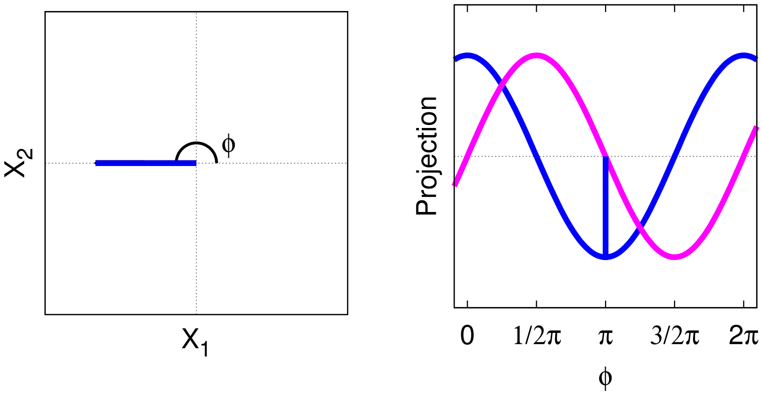

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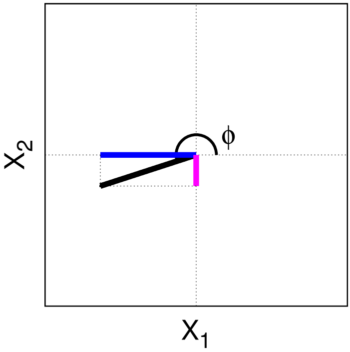

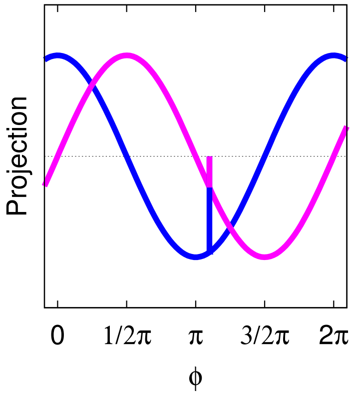

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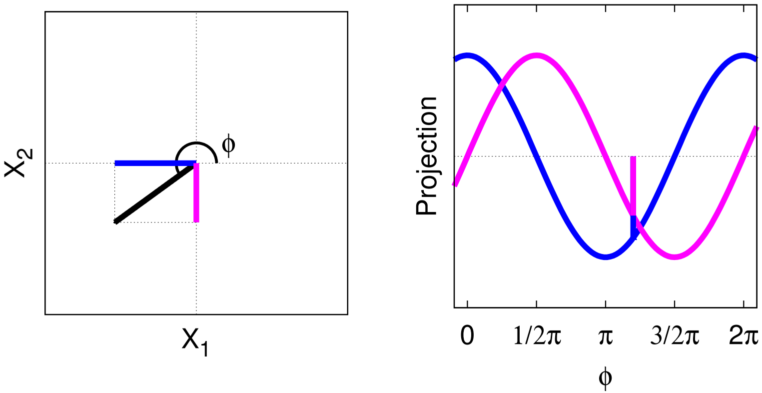

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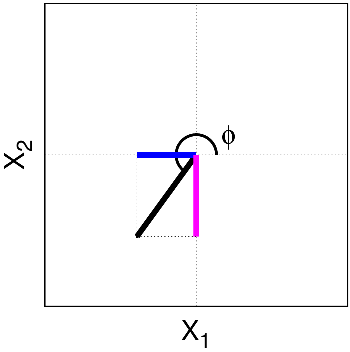

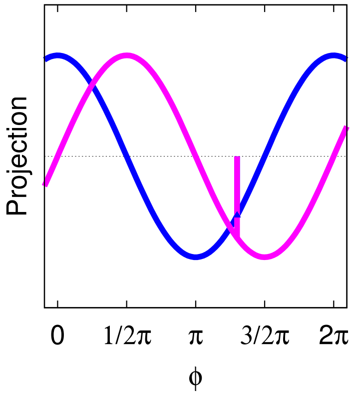

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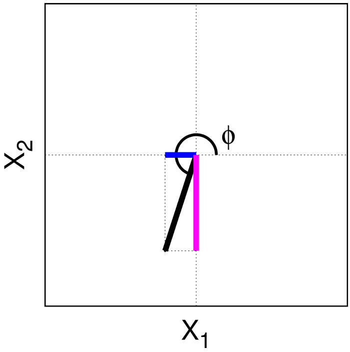

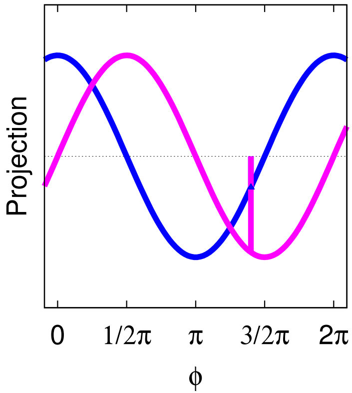

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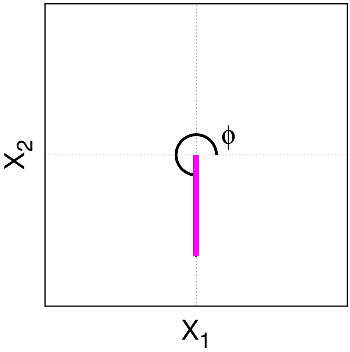

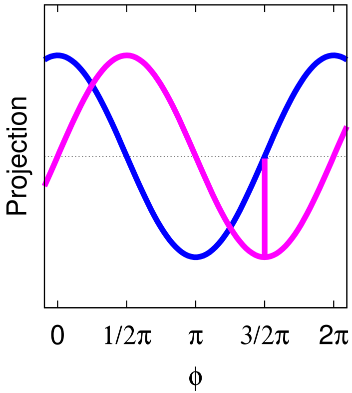

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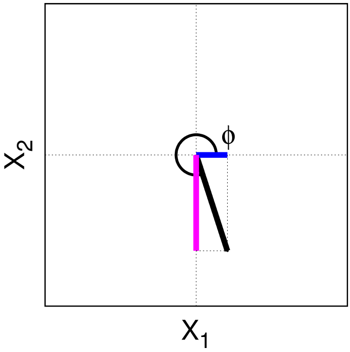

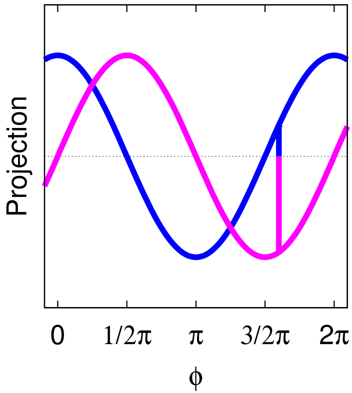

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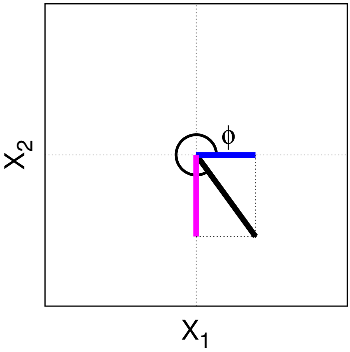

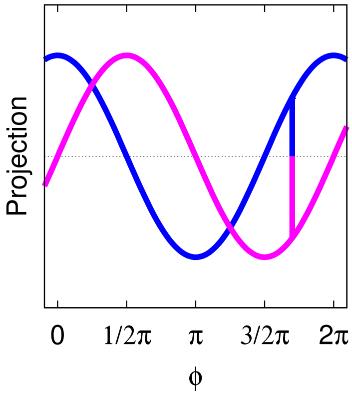

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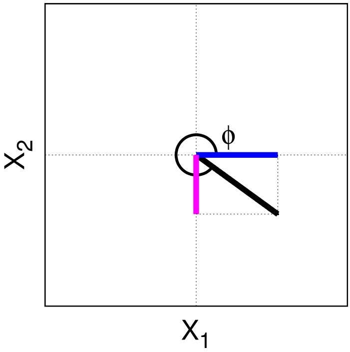
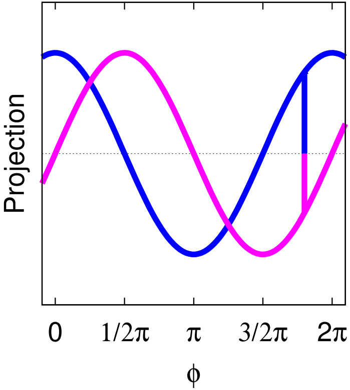
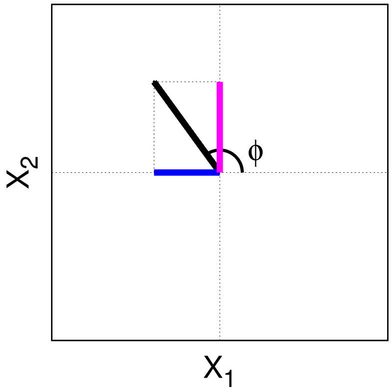
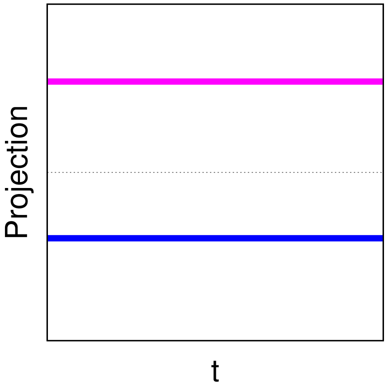




Classical quadratures vs time in a rotating frame

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





Reality check quadratures vs time

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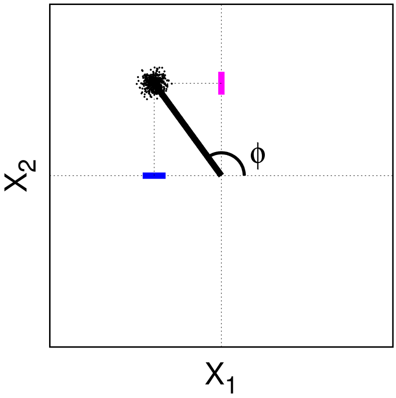
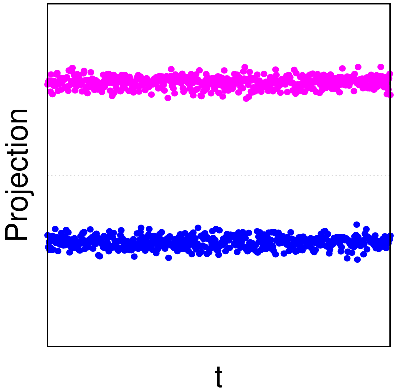


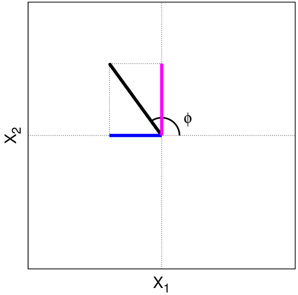


Transition from classical to quantum field

Classical analog

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

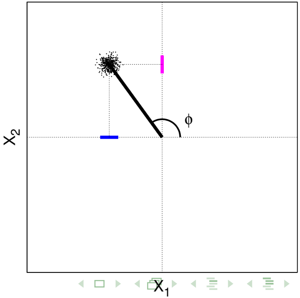
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



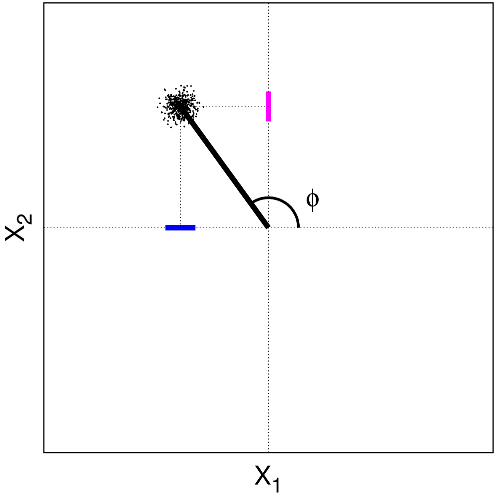
Quantum approach

- 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

Heisenberg uncertainty principle and its optics equivalent

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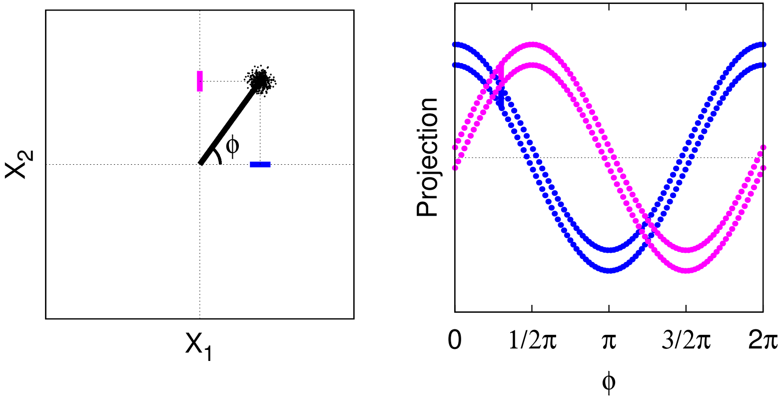
Optics equivalent strict definition

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

Coherent state is minimum uncertainty state

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



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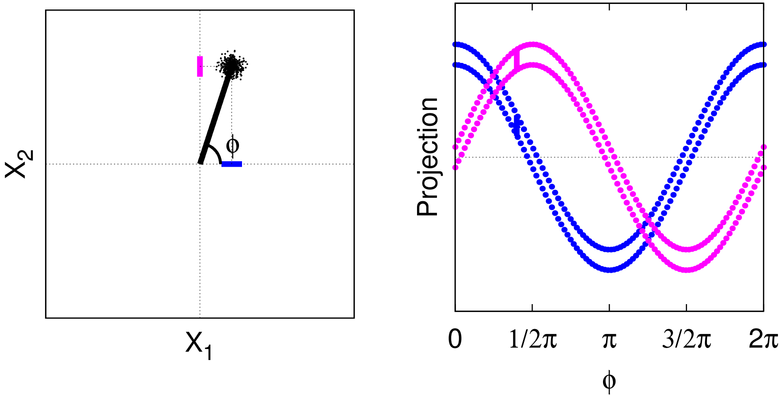

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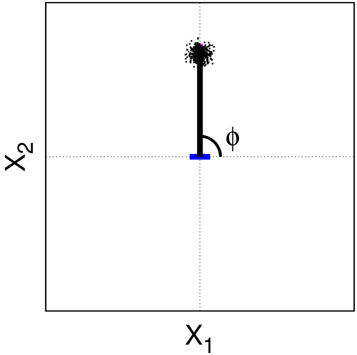

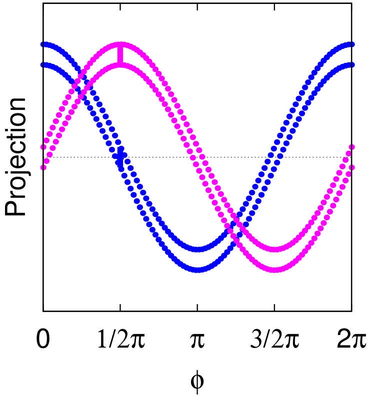

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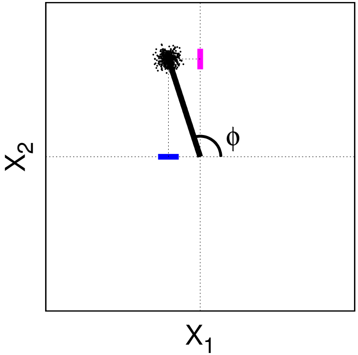

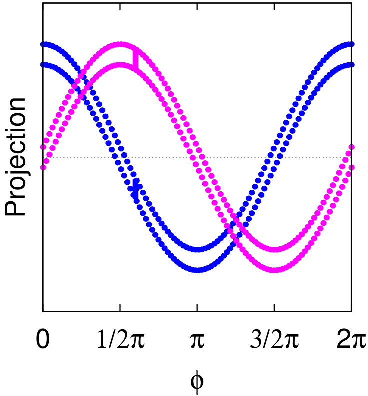

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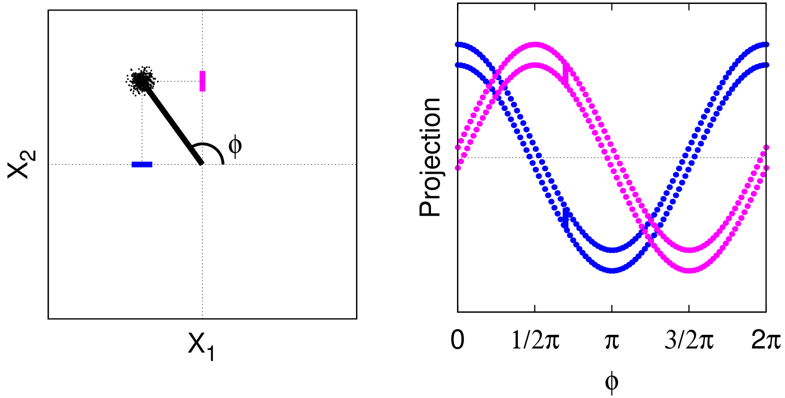

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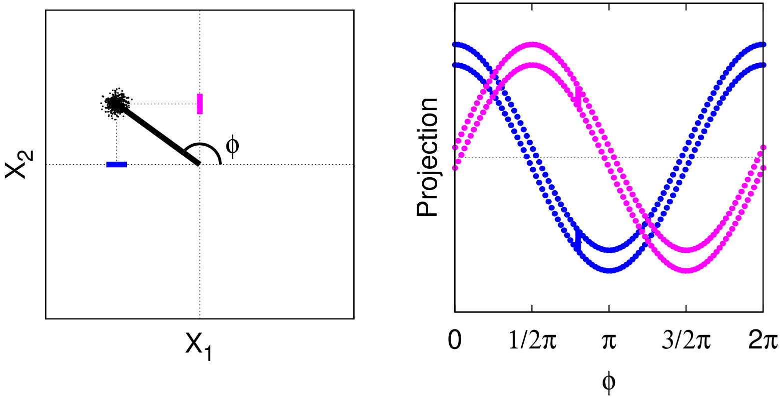

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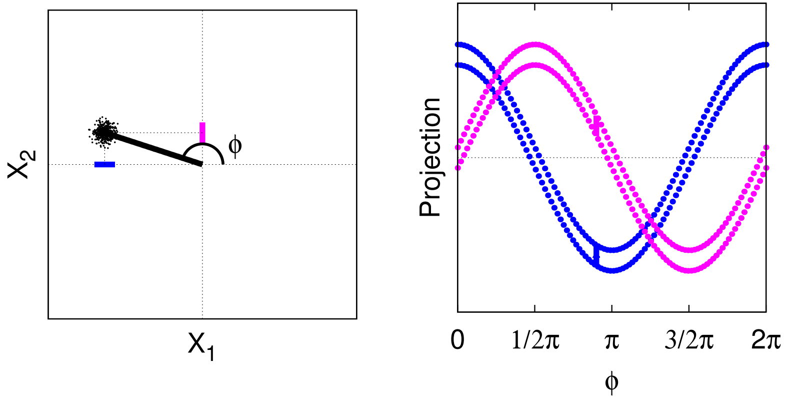

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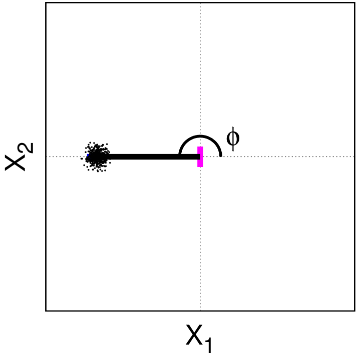

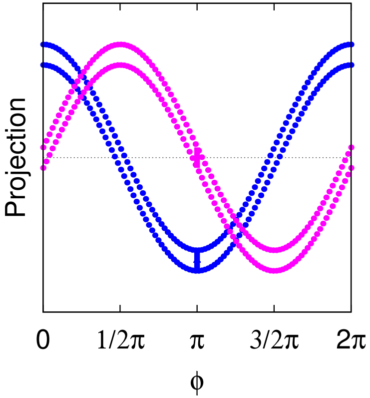

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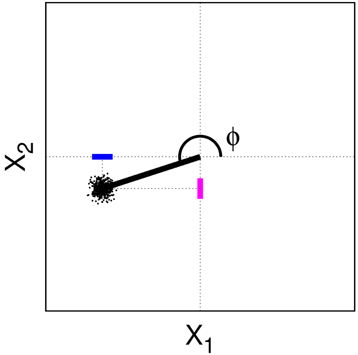

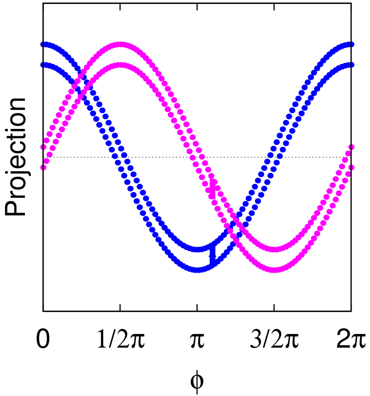

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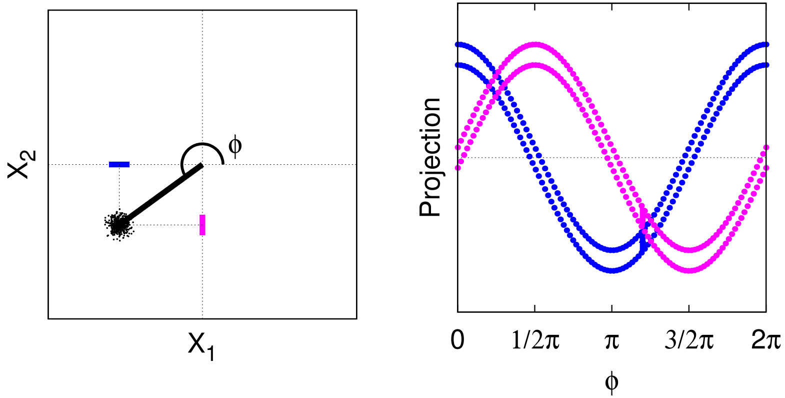

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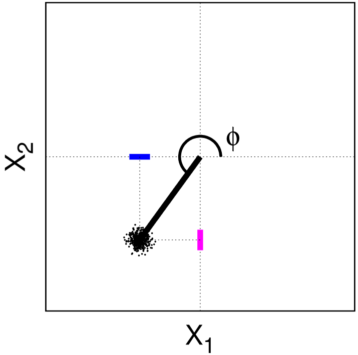
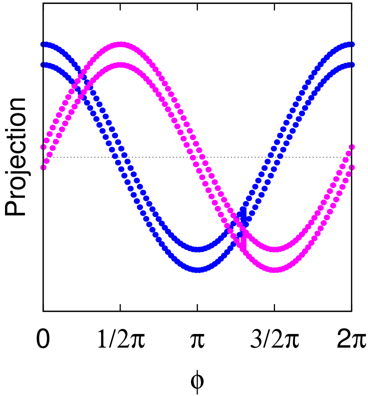
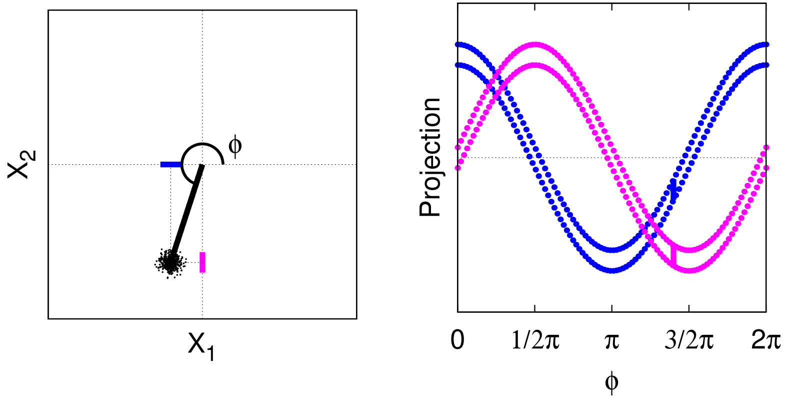




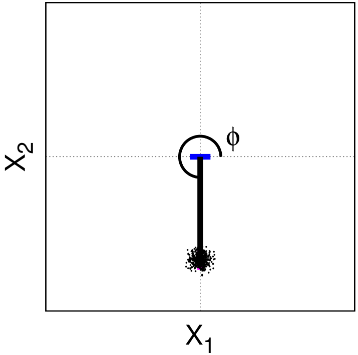
Coherent state is minimum uncertainty state

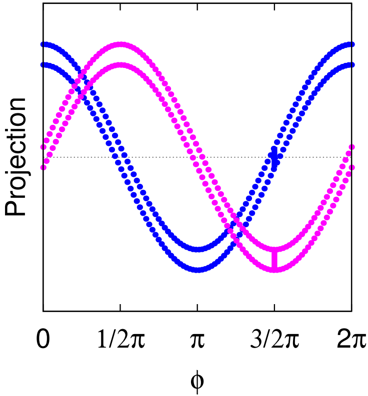
$\Delta X_1 \Delta X_2 = 1/4$



Coherent state is minimum uncertainty state

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





Coherent state is minimum uncertainty state

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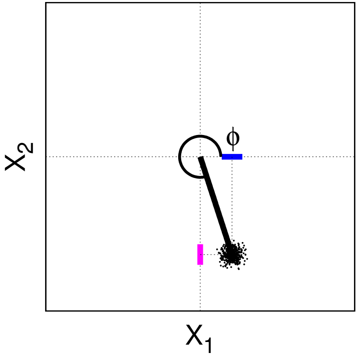
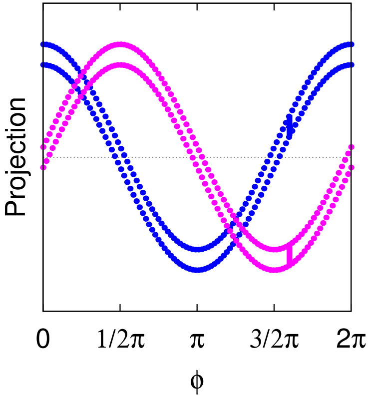
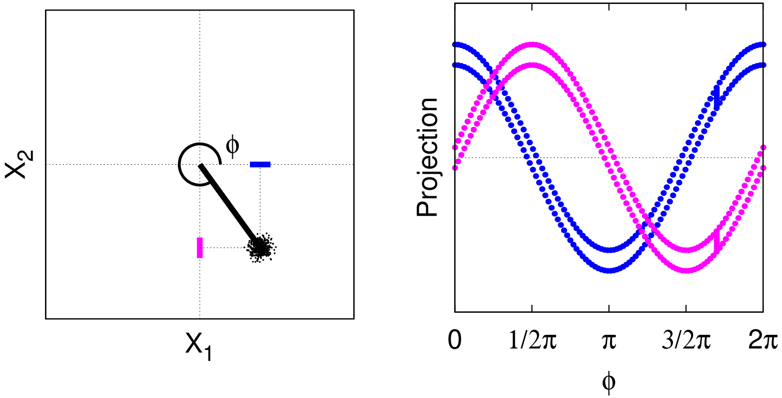




Coherent state is minimum uncertainty state

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



Coherent state is minimum uncertainty state

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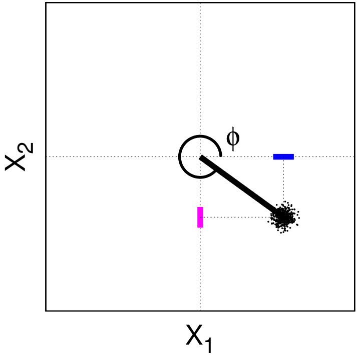
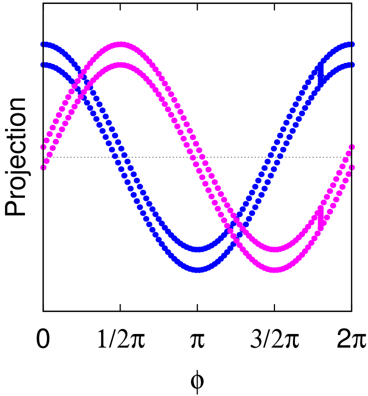
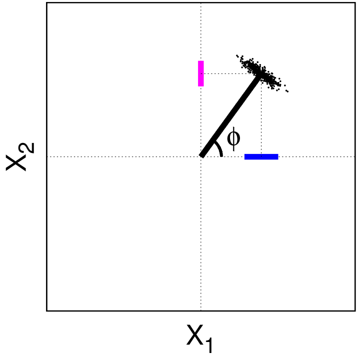
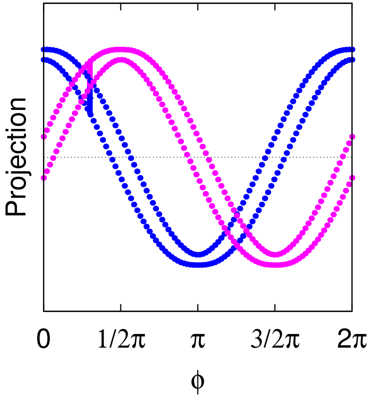




Amplitude squeezed states

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





Amplitude squeezed states

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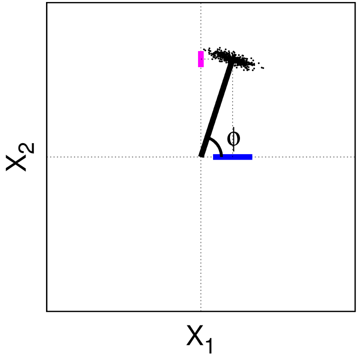

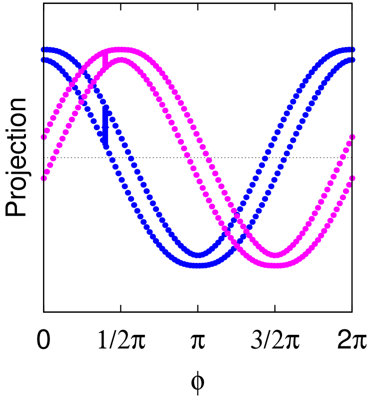

Amplitude squeezed states

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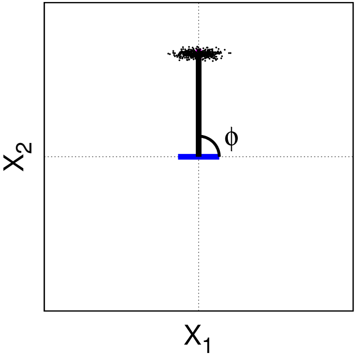

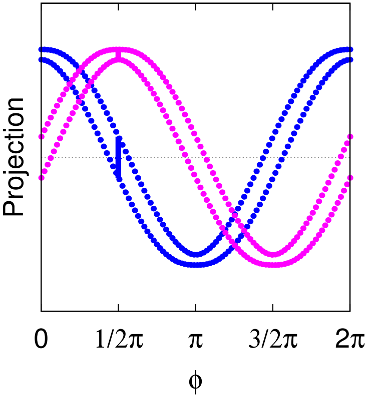

Amplitude squeezed states

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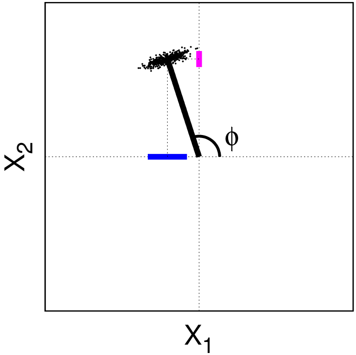

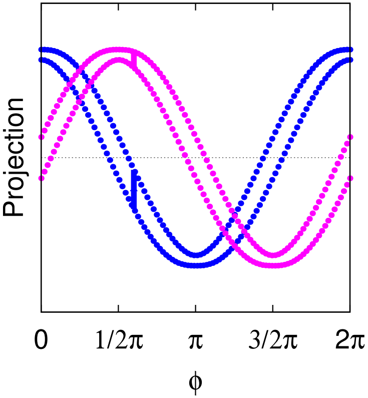

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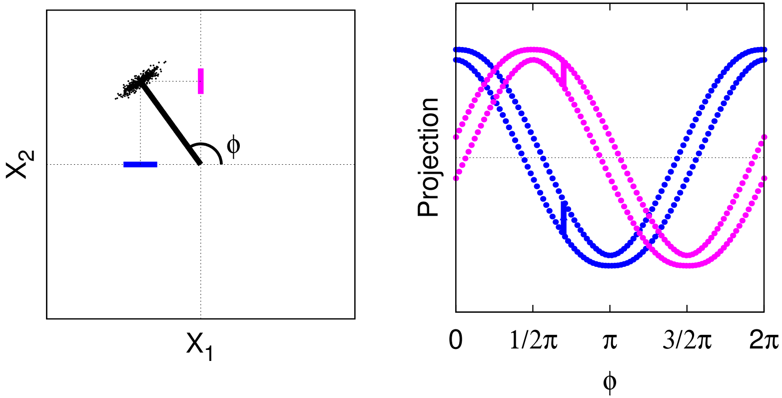

Amplitude squeezed states

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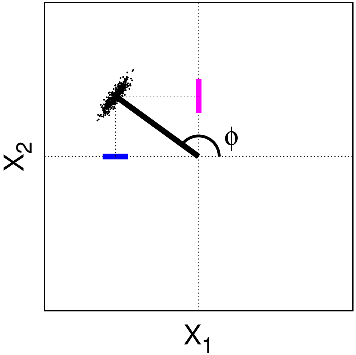

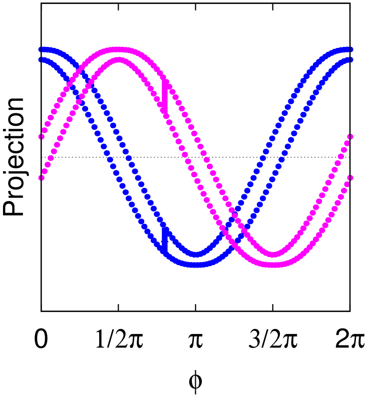

Amplitude squeezed states

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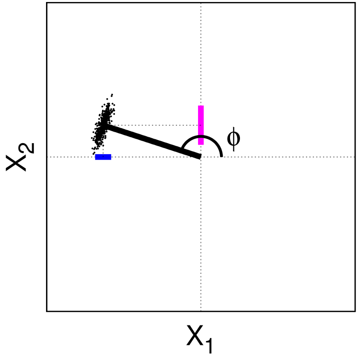

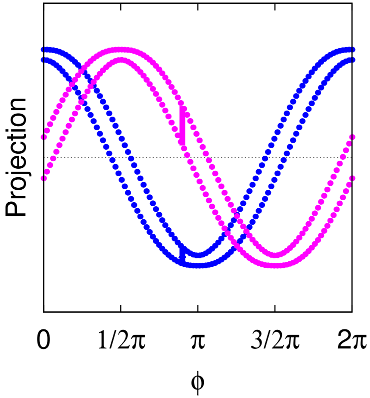

Amplitude squeezed states

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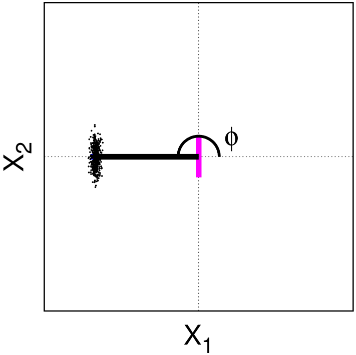

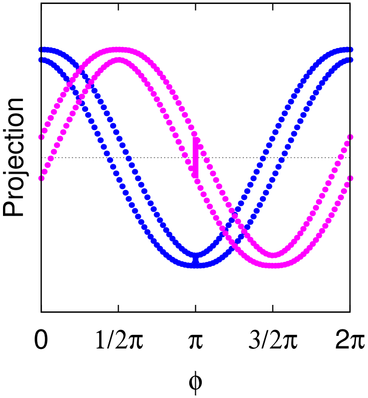

Amplitude squeezed states

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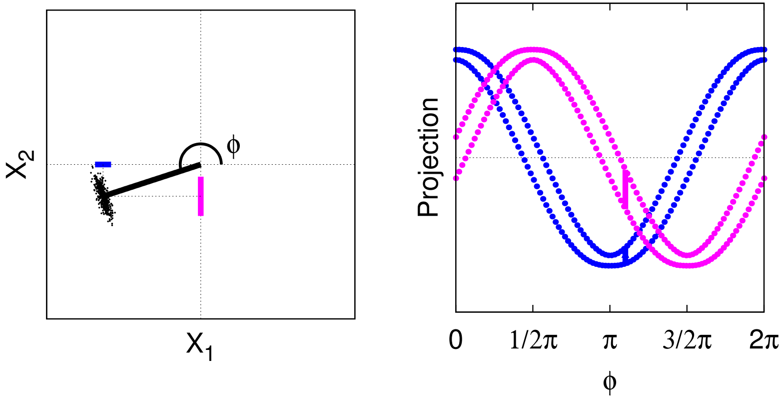

Amplitude squeezed states

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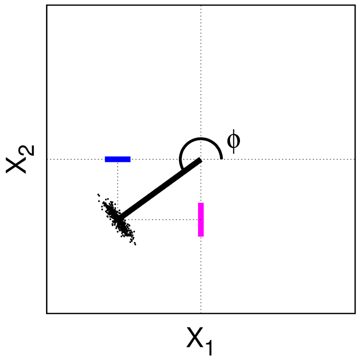

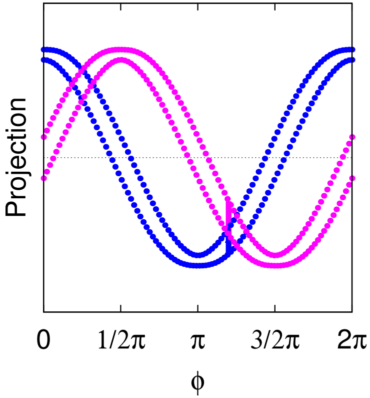

Amplitude squeezed states

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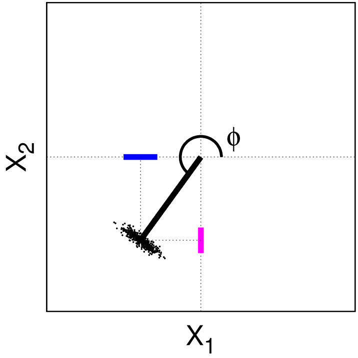

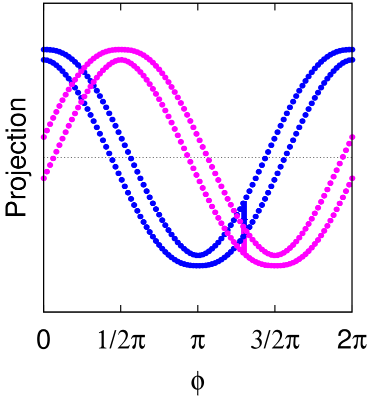

Amplitude squeezed states

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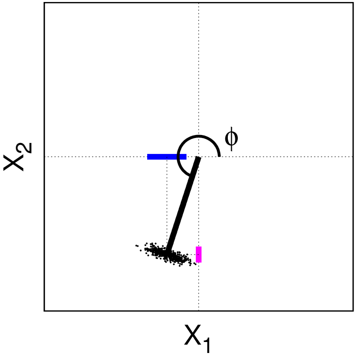

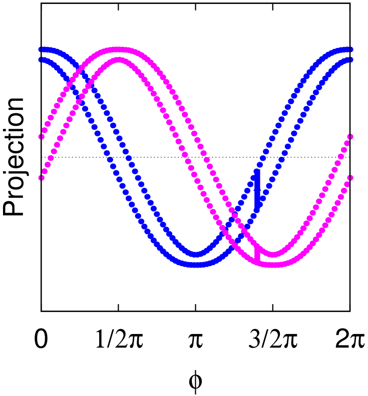

Amplitude squeezed states

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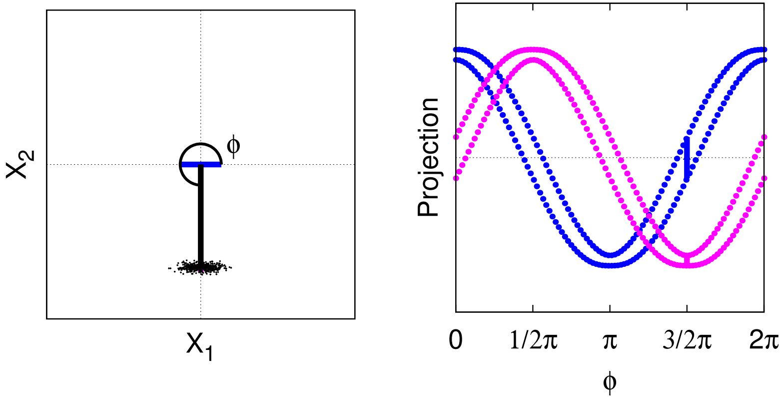

Amplitude squeezed states

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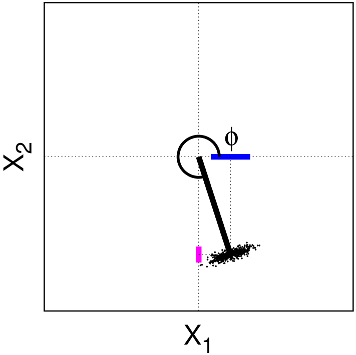

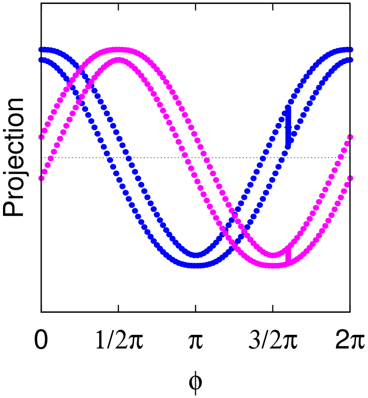

Amplitude squeezed states

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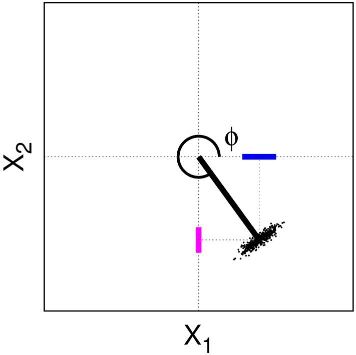

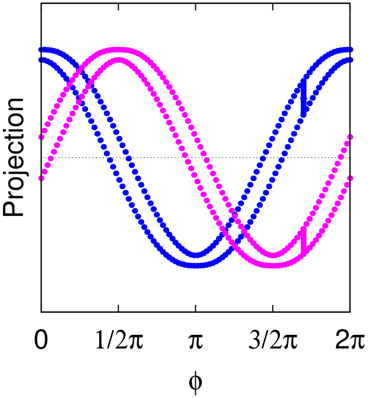

Amplitude squeezed states

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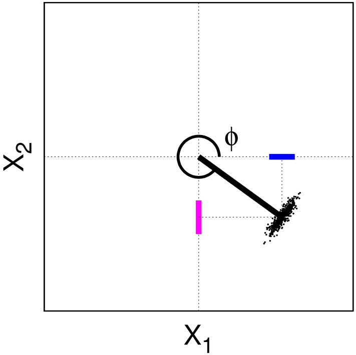
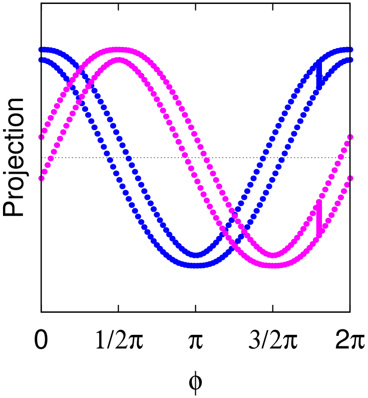
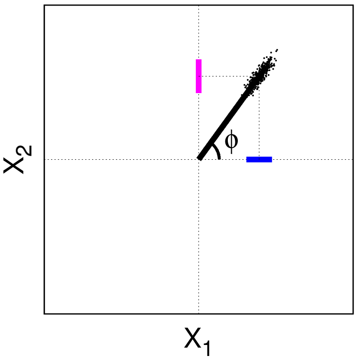
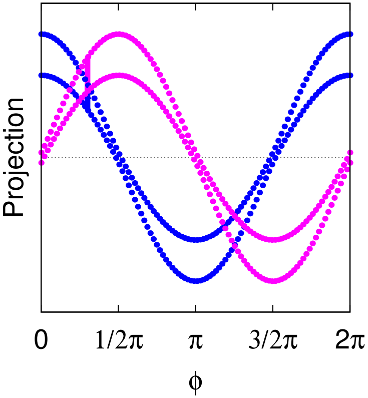




Phase squeezed states

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





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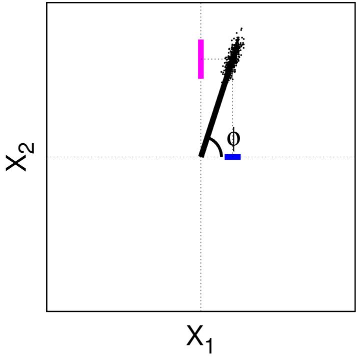

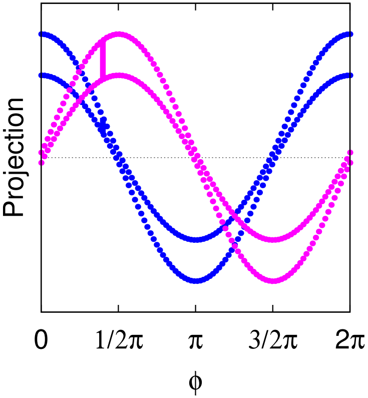

Phase squeezed states

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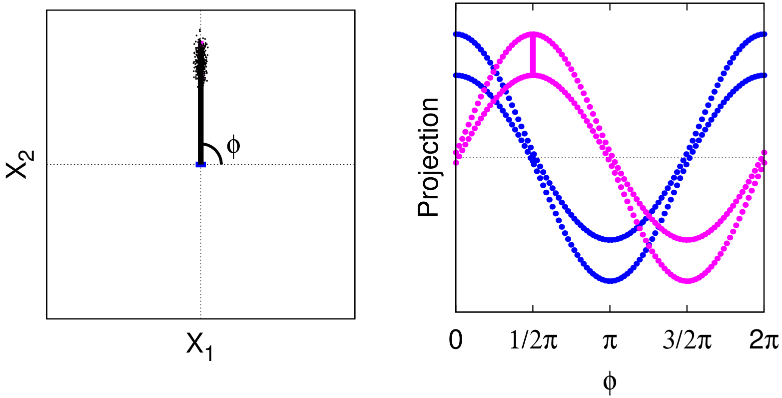

Phase squeezed states

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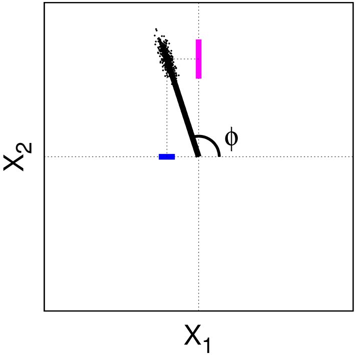

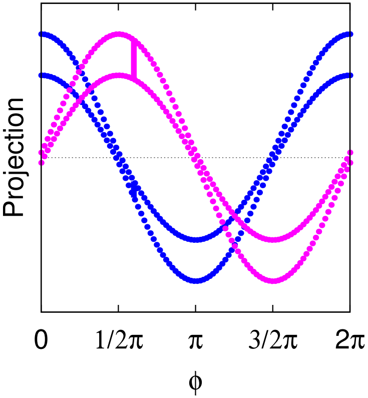

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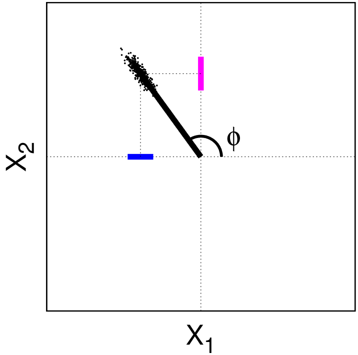

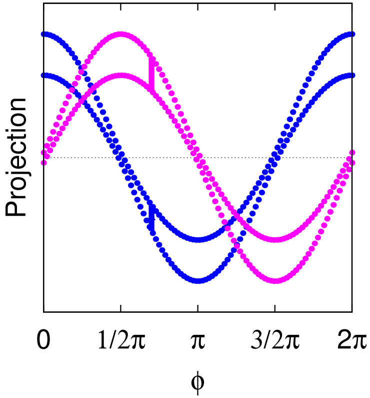

Phase squeezed states

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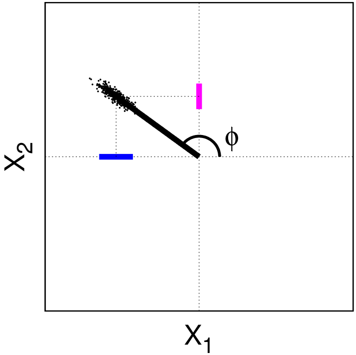

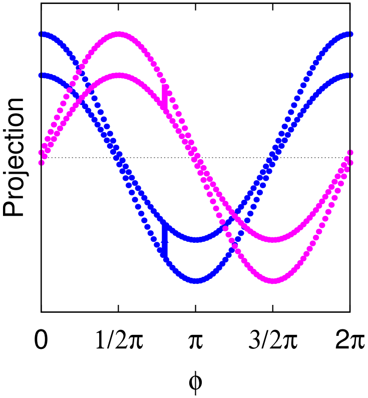

Phase squeezed states

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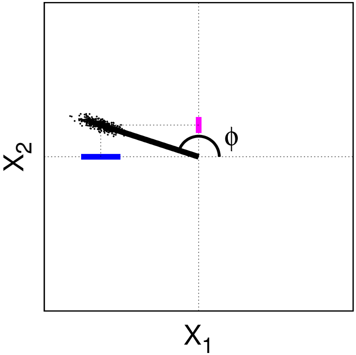

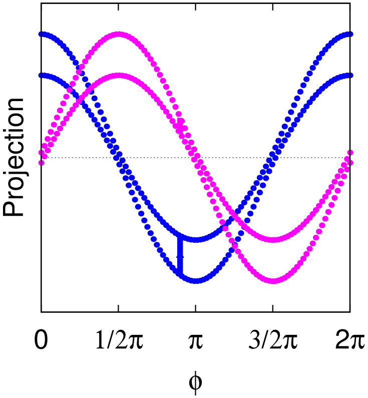

Phase squeezed states

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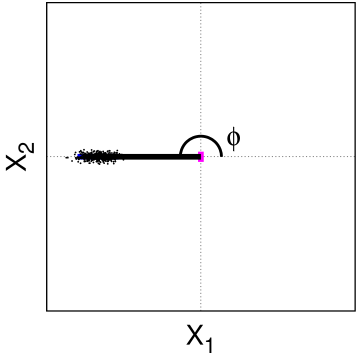

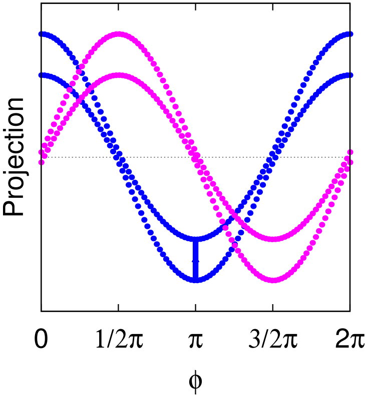

Phase squeezed states

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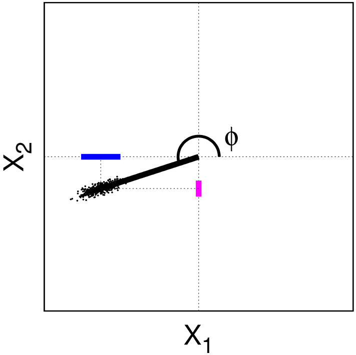

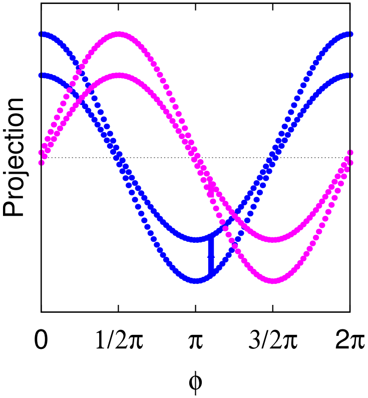

Phase squeezed states

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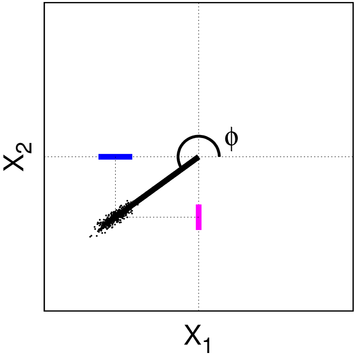

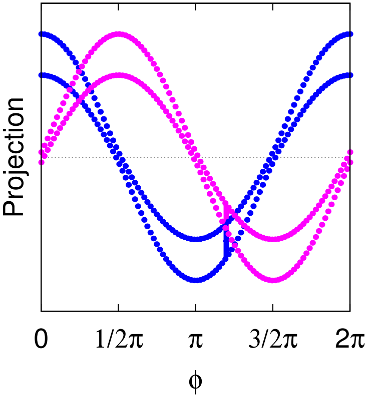

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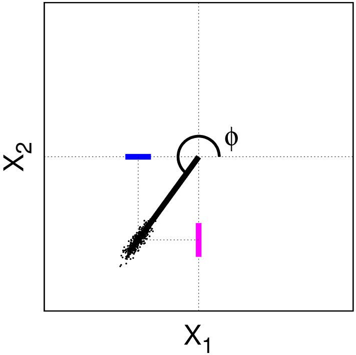

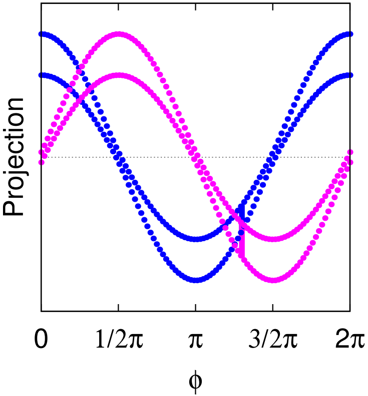

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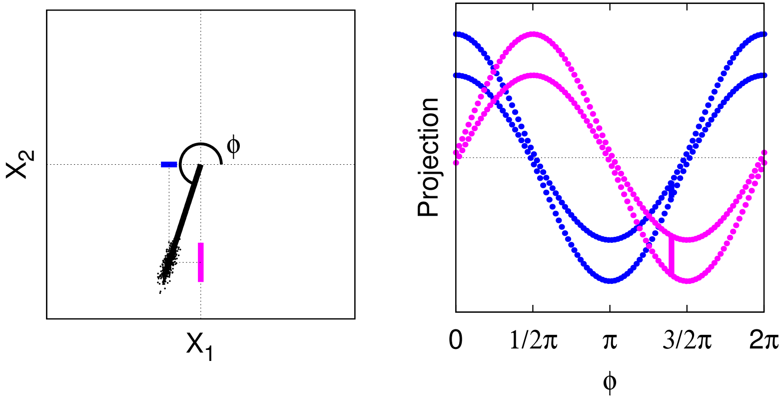

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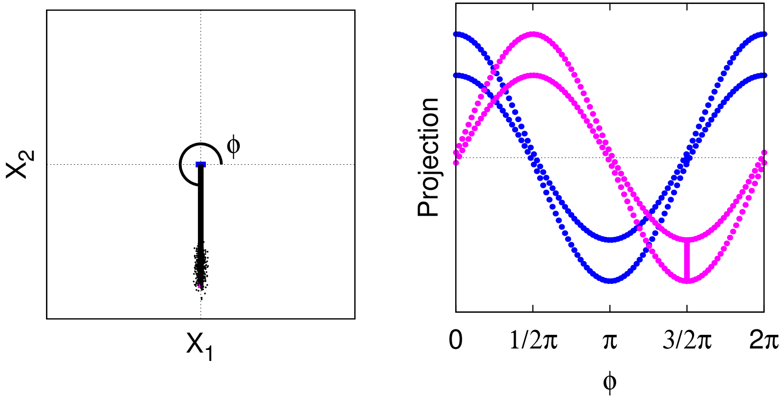

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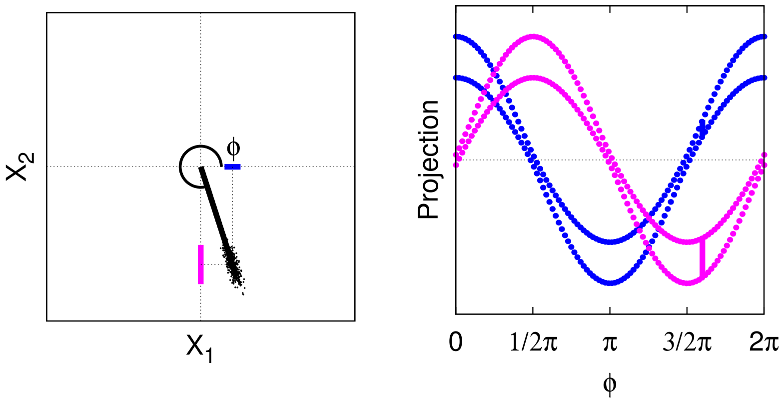

Phase squeezed states

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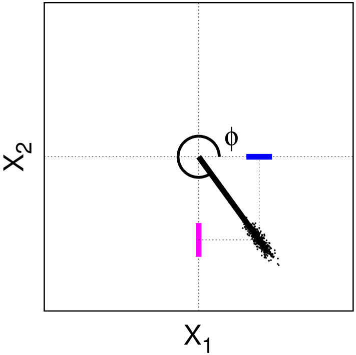

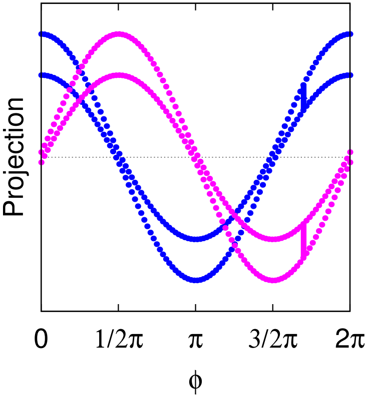

Phase squeezed states

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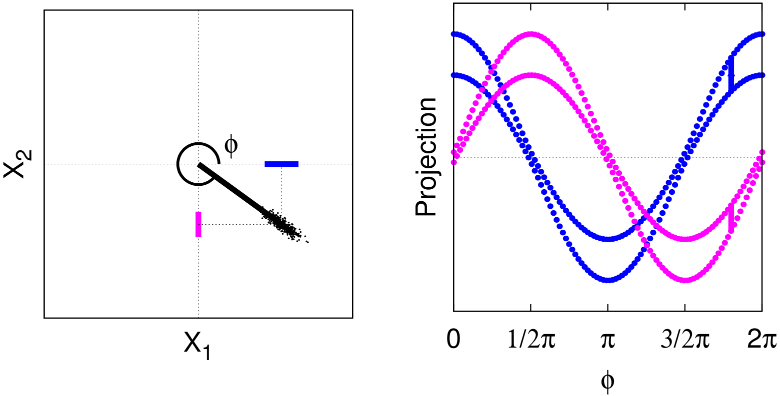
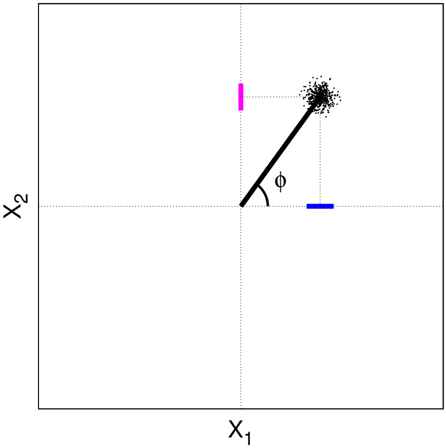
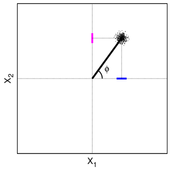


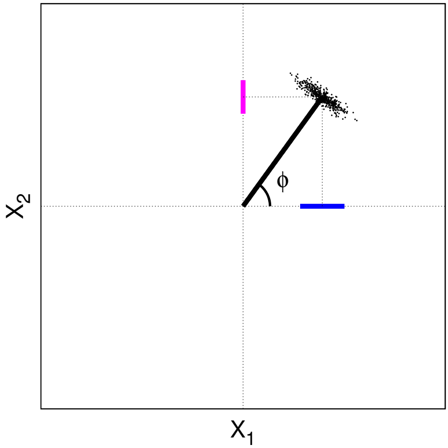
Squeezed quantum states zoo



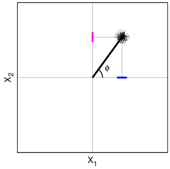
Unsqueezed coherent



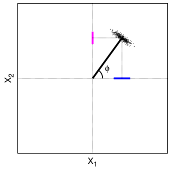
Squeezed quantum states zoo



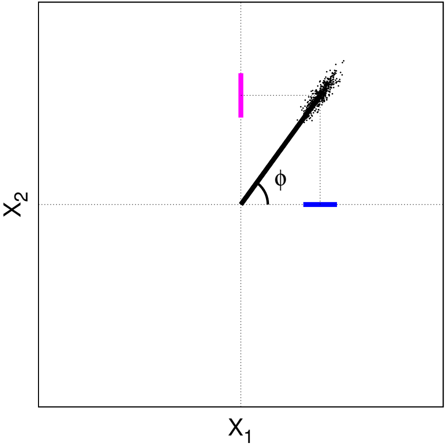
Unsqueezed coherent



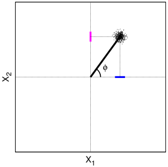
Amplitude squeezed



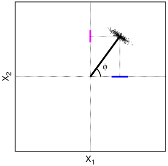
Squeezed quantum states zoo



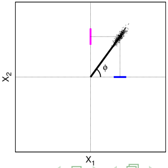
Unsqueezed coherent



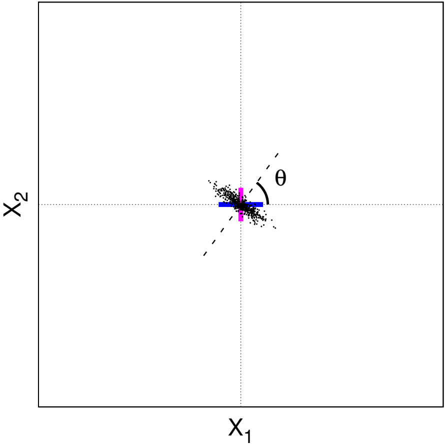
Amplitude squeezed



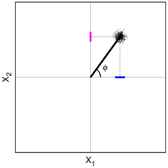
Phase squeezed



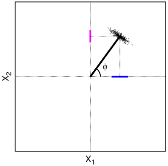
Squeezed quantum states zoo



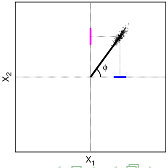
Unsqueezed coherent



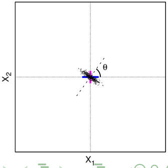
Amplitude squeezed



Phase squeezed

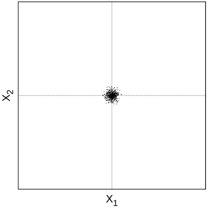


Vacuum squeezed



Squeezed field generation recipe

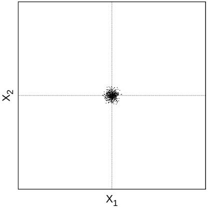
Take a vacuum state $|0>$



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

Squeezed field generation recipe

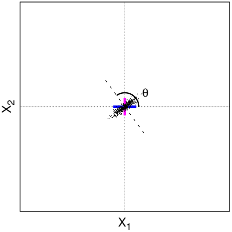
Take a vacuum state $|0>$



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

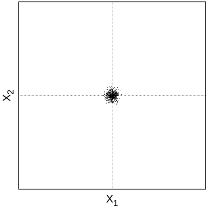
Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

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



Squeezed field generation recipe

Take a vacuum state $|0>$



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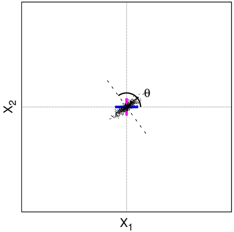
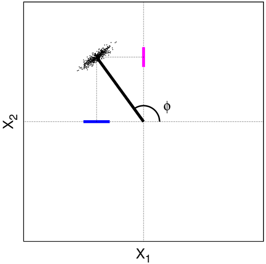
$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}$$



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

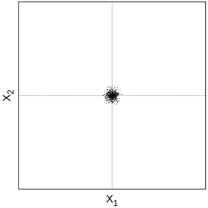
$$\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$$



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

Squeezed field generation recipe

Take a vacuum state $|0>$

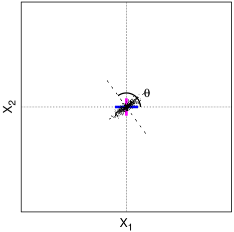


$$H = \frac{1}{2}$$

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

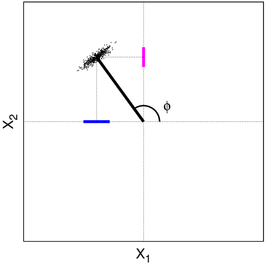
Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

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



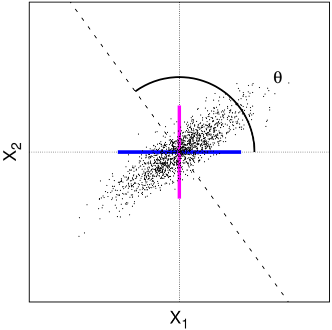
Apply displacement operator $|\alpha, \xi >= \hat{D}(\alpha)|s>$

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



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

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



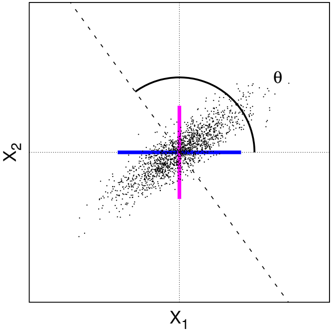
$$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^{\dagger 2}}, \xi = re^{i\theta}$$

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

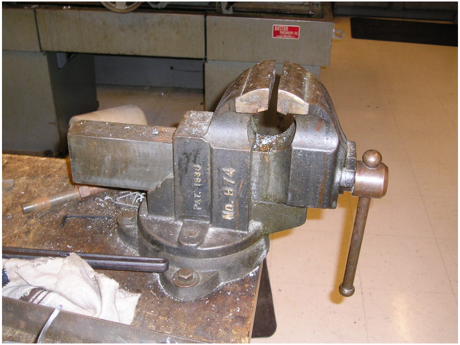
$$C_{2m+1} = 0$$

Average number of photons in general squeezed state

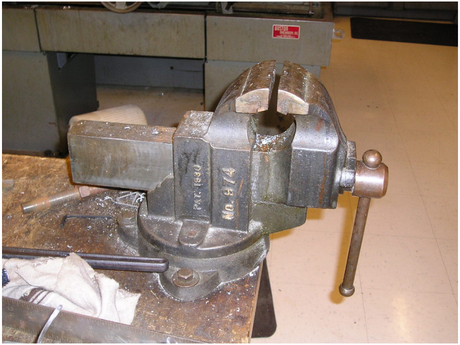
$$< \alpha, \xi|a^\dagger a|\alpha, \xi >= \alpha + \sinh^2 r$$

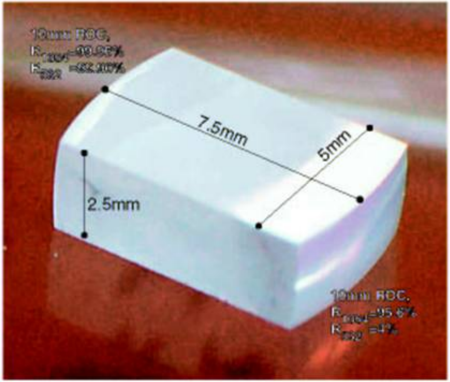
Tools for squeezing

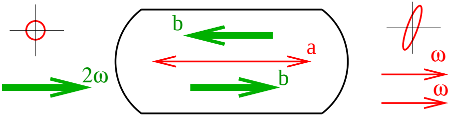
Tools for squeezing



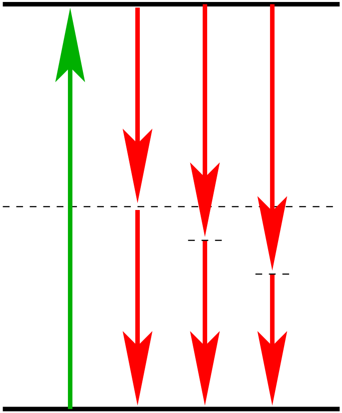
Tools for squeezing







Two photon squeezing picture

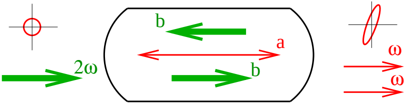


Squeezing operator

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

Parametric down-conversion in crystal

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

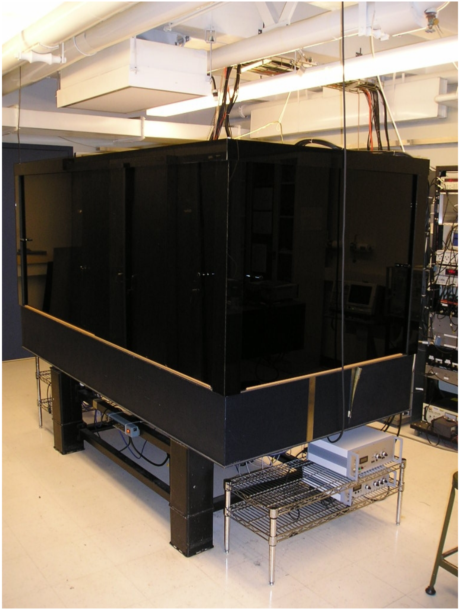


Squeezing

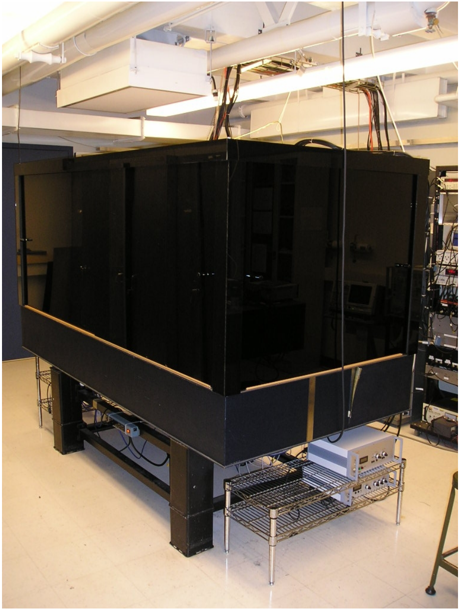
result of correlation of upper and lower sidebands

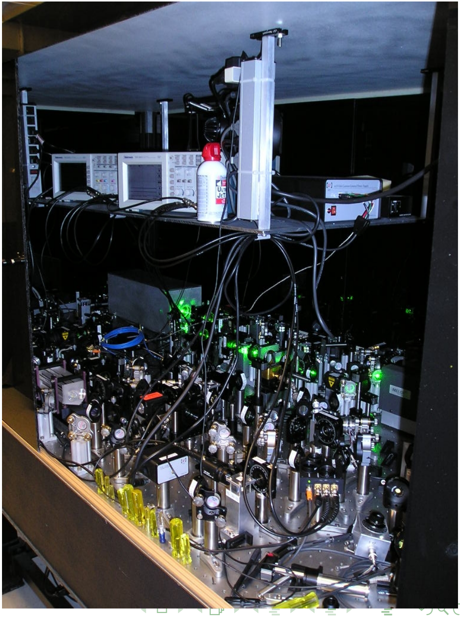
Squeezer appearance

Squeezer appearance



Squeezer appearance



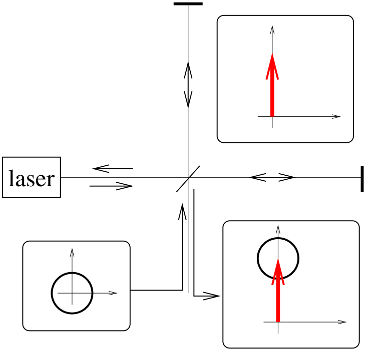


Possible squeezing applications

- 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

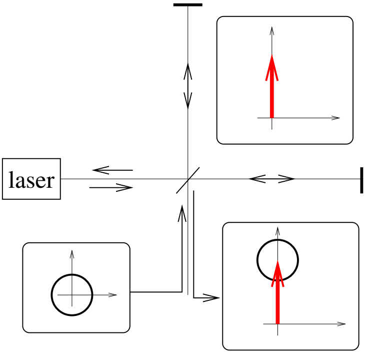
Squeezing and interferometer

Vacuum input

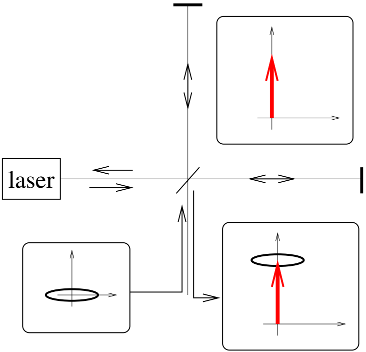


Squeezing and interferometer

Vacuum input

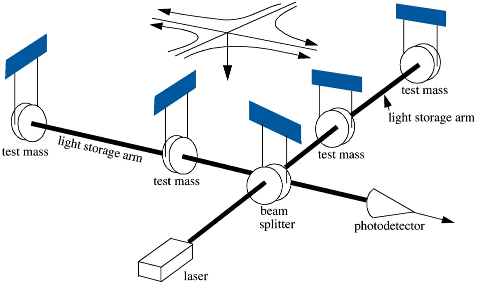


Squeezed input

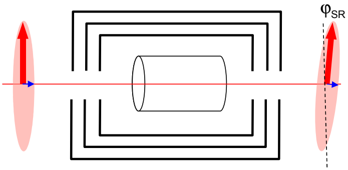


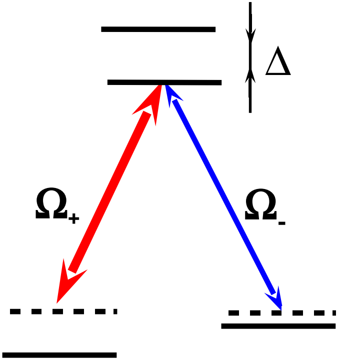
Laser Interferometer Gravitational-wave Observatory

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



Self-rotation of elliptical polarization in atomic medium

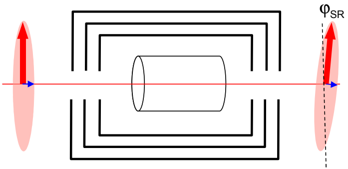


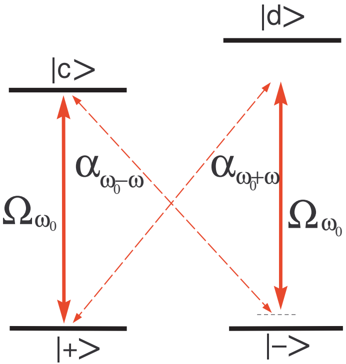


A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

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

Self-rotation of elliptical polarization in atomic medium





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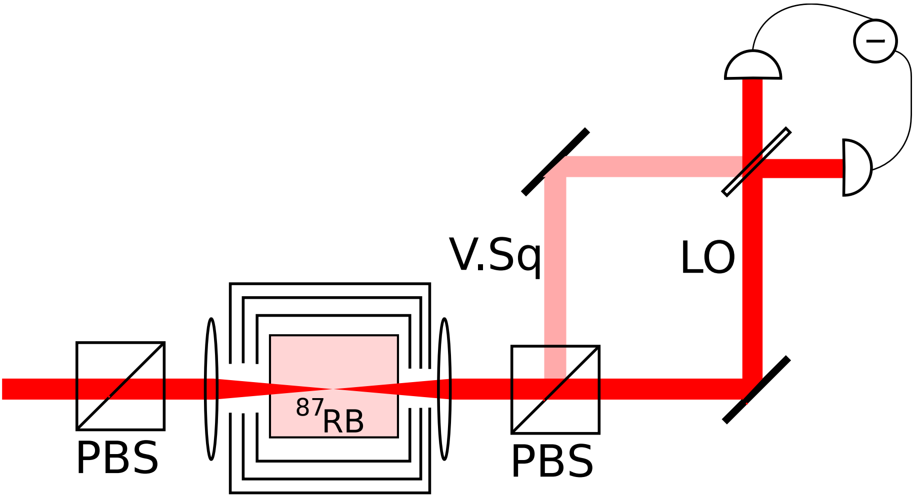
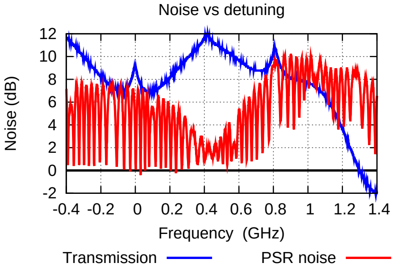
$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in})$$

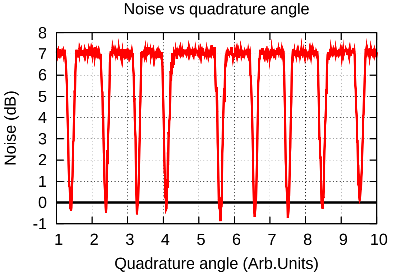
Setup



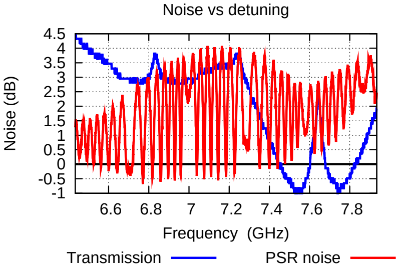
Noise contrast vs detuning in hot ^{87}Rb vacuum cell

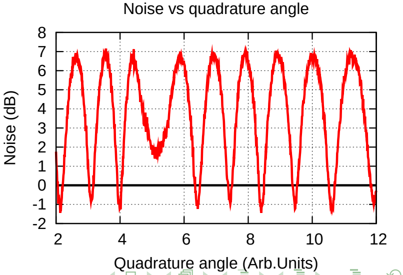
$F_g = 2 \rightarrow F_e = 1, 2$





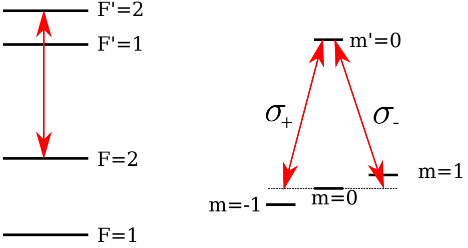
$F_g = 1 \rightarrow F_e = 1, 2$



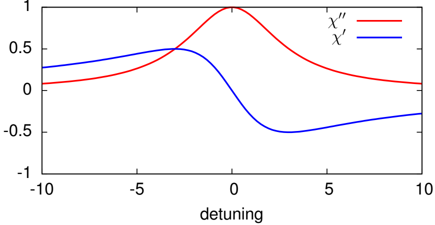


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



Susceptibility vs B



Optical magnetometer based on Faraday effect

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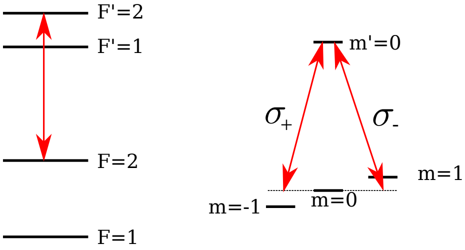

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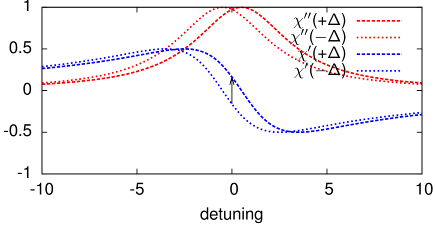

Optical magnetometer based on Faraday effect

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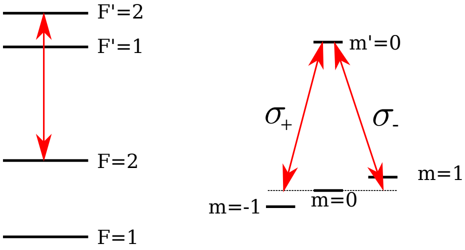

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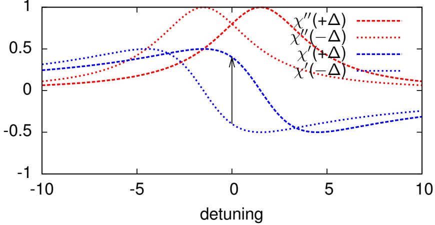

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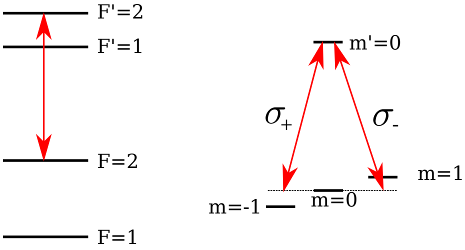
^{87}Rb D_1 line



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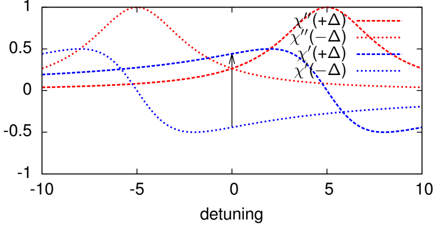
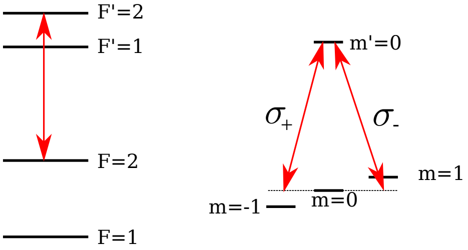
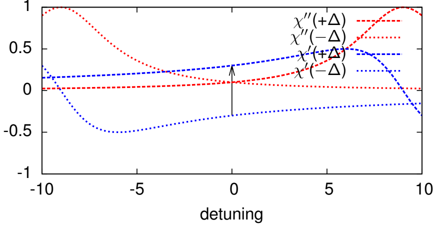


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

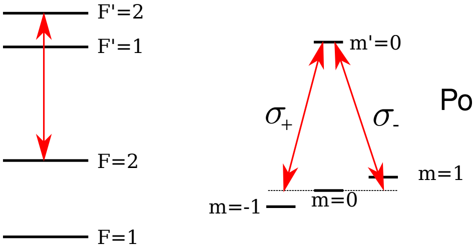


Susceptibility vs B

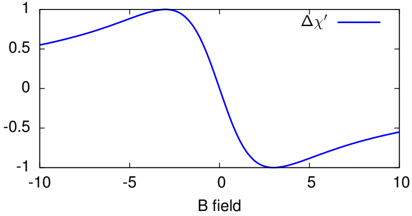


Optical magnetometer based on Faraday effect

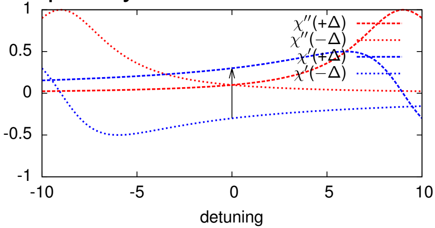
^{87}Rb D_1 line



Polarization rotation vs B

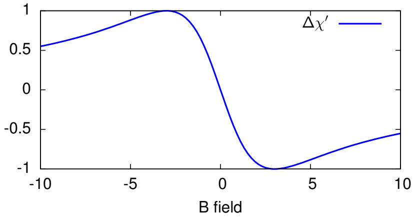


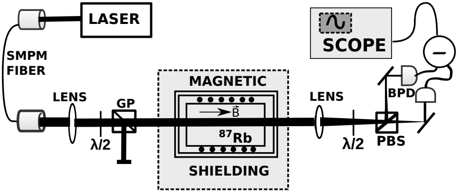
Susceptibility vs B



Optical magnetometer and non linear Faraday effect

Naive model of rotation

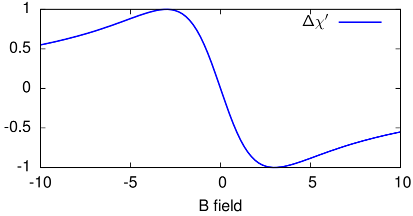


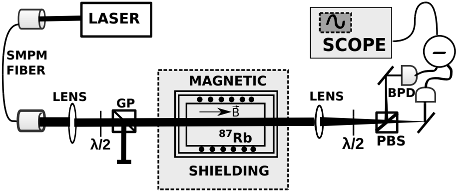


Experiment

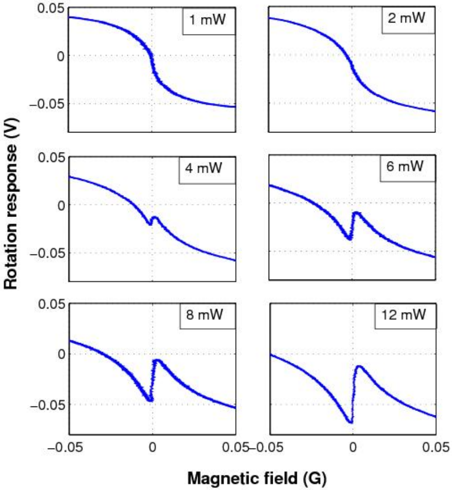
Optical magnetometer and non linear Faraday effect

Naive model of rotation

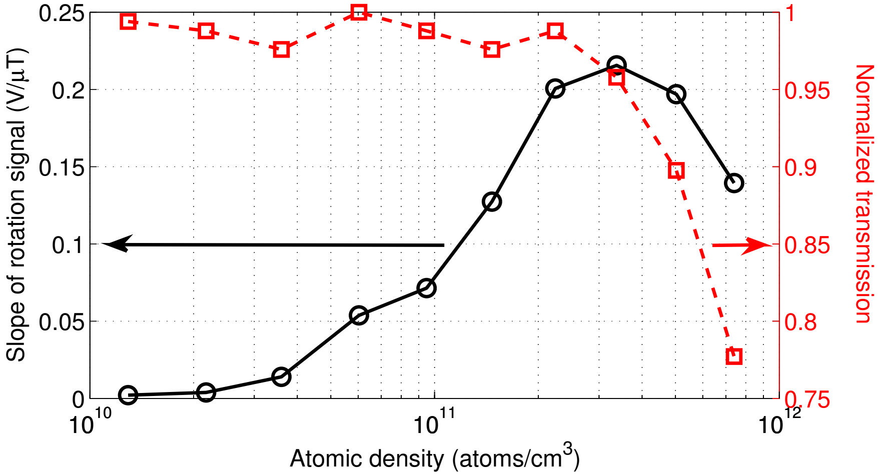




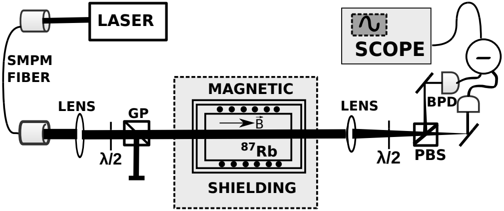
Experiment

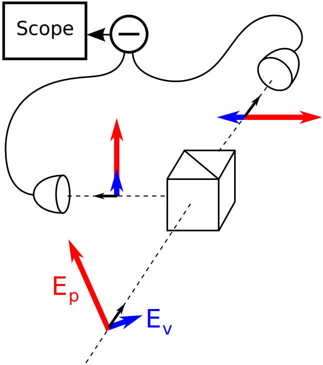


Magnetometer response vs atomic density



Shot noise limit of the magnetometer



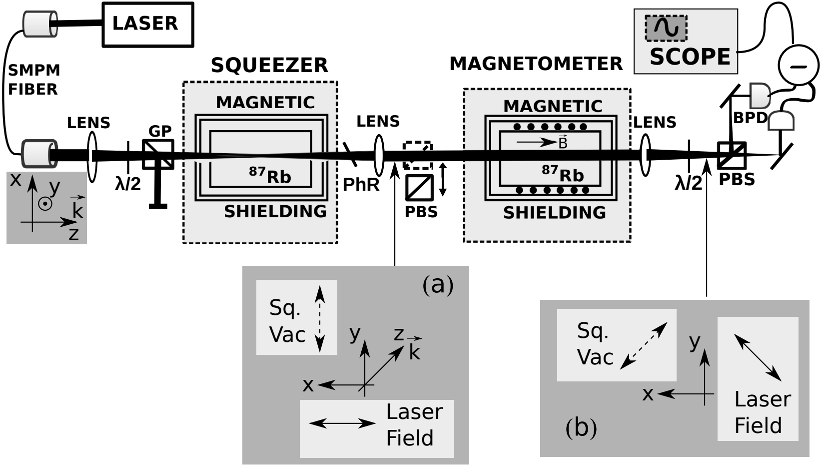


$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$

$$S = 4E_pE_v$$

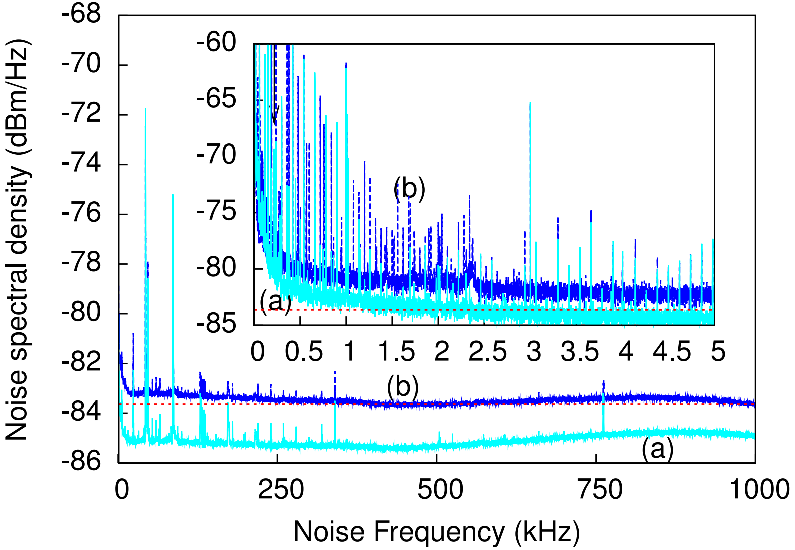
$$< \Delta S > \sim E_p < \Delta E_v >$$

Squeezed enhanced magnetometer setup



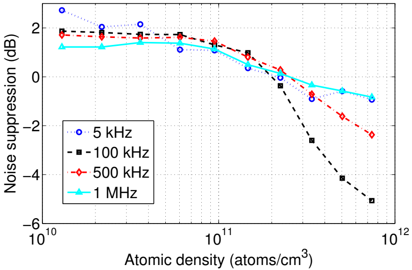
Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements

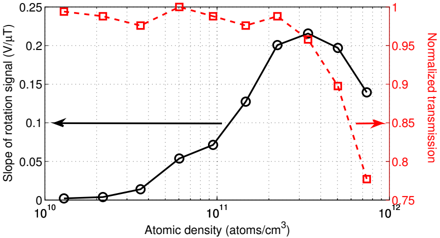


Noise suppression and response vs atomic density

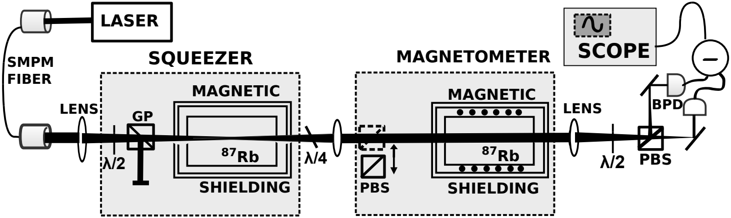
Noise suppression

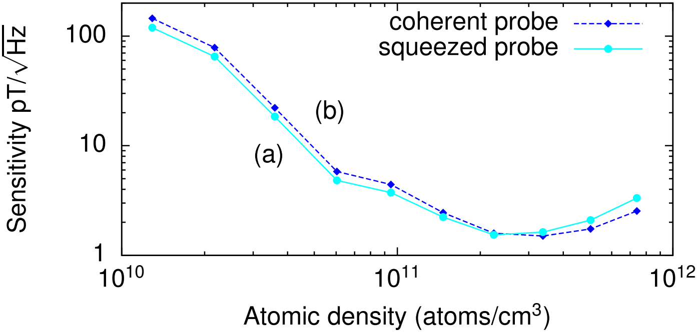


Response



Magnetometer with squeezing enhancement





Summary

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