Revealing invisible spatial structure of Quantum Squeezed Vacuum.

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Pratik J. Barge, Hwang Lee, Lior Cohen[2]

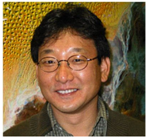
1
WILLIAM & MARY
CHARTERED 1693
2
LSU

People


Charris Gabaldon


Irina Novikova


Lior Cohen

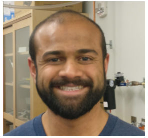

Hwang Lee


Savannah Cuozzo


Ziqi Niu

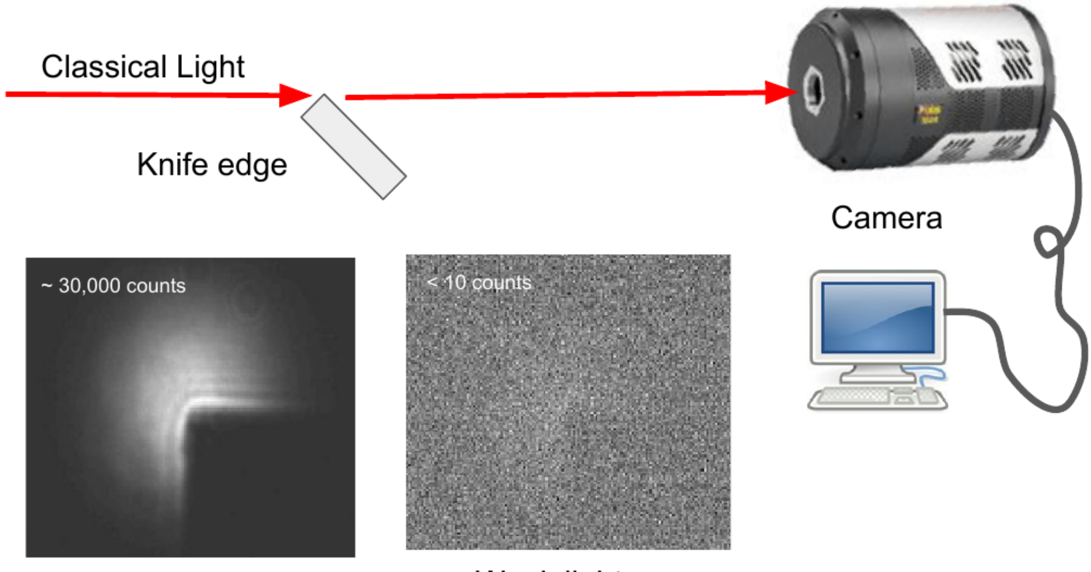

Pratik Barge


Narayan Bhusal

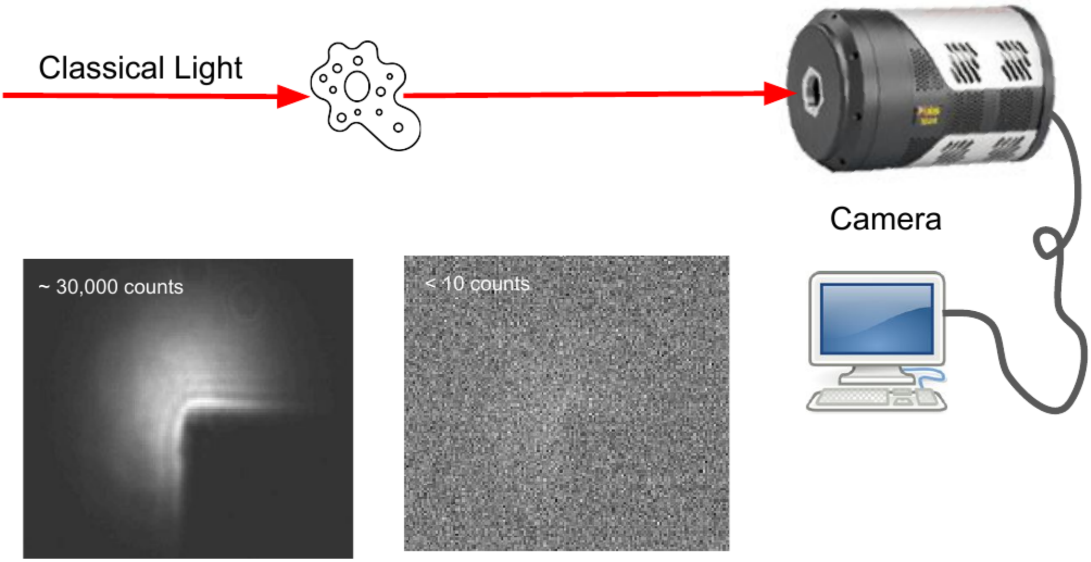

Nikunjkumar Prajapati


Jon Dowling (1955-2020)

From bright to low light imaging

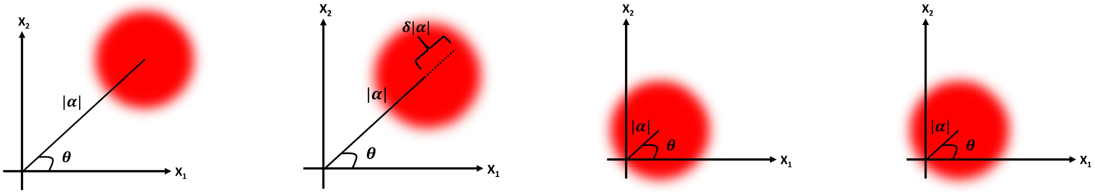


From bright to low light imaging

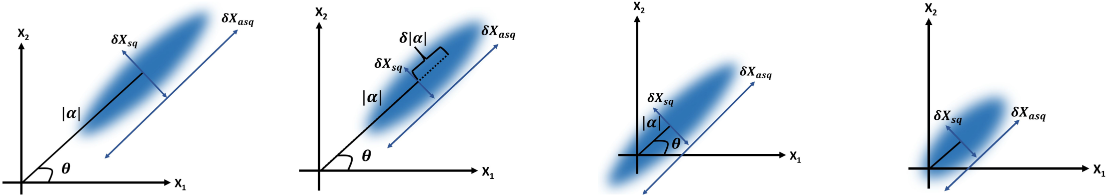


Let's look at quantum picture

Bright state in | Bright state out | Low-light state in | Low-light out

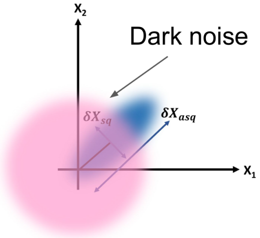


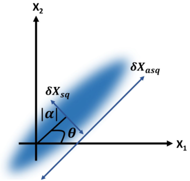
$$\alpha_{out}^2 = \alpha_{in}^2 T$$

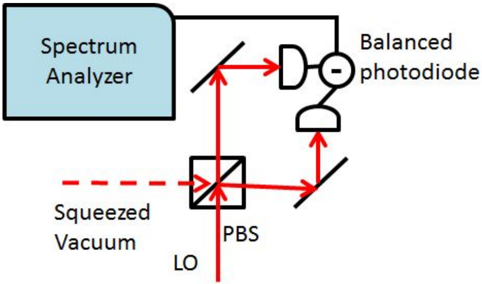


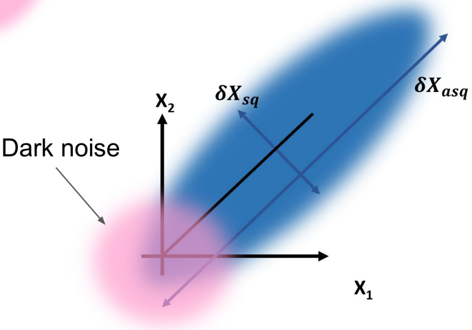
$$V = 1 + (\delta X_{sq/asq}^2 - 1)|\mathcal{O}|^2 T$$

Detector dark noise

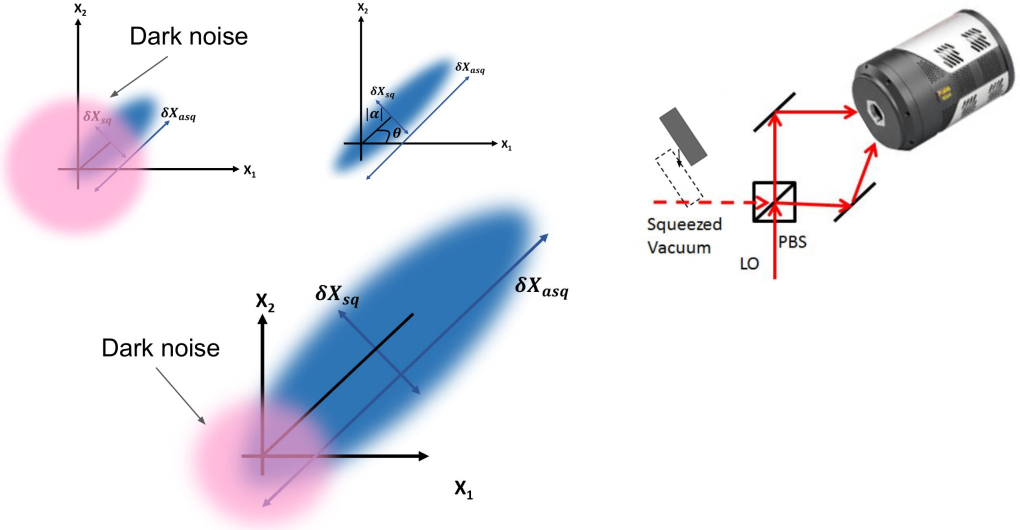




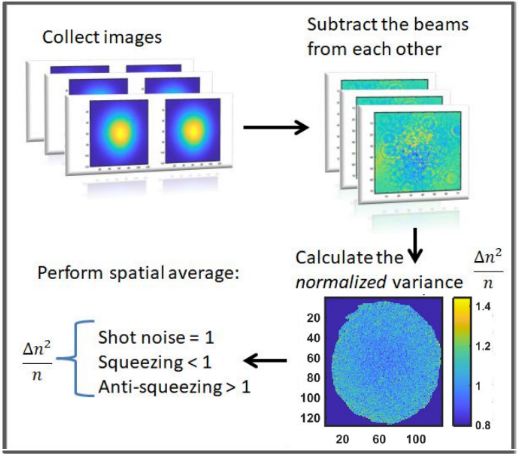


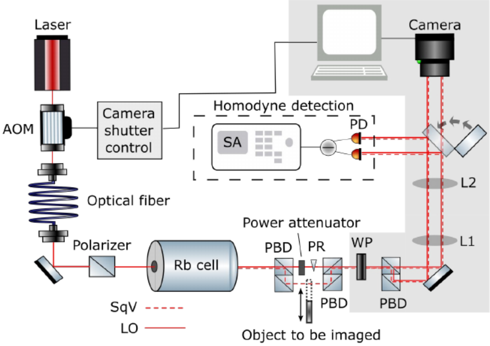


Detector dark noise

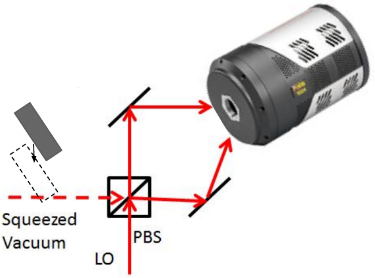


Imaging quantum noise

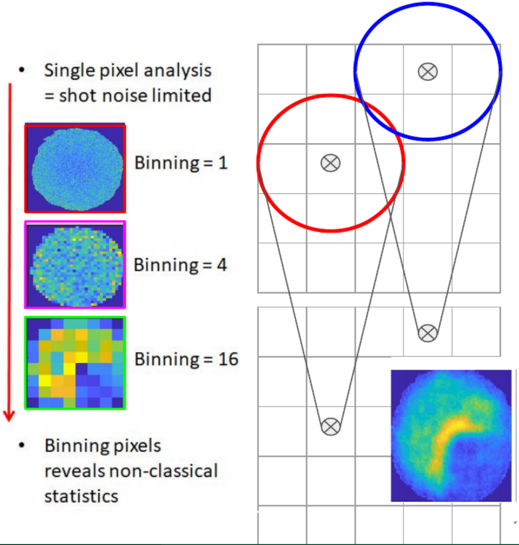




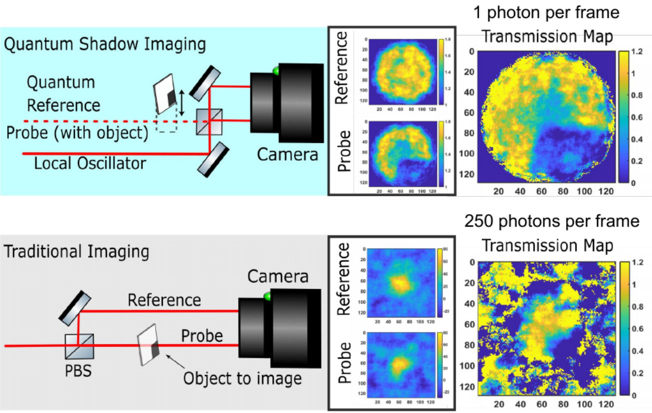
Imaging quantum noise with binning



$$V = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}|^2 T$$

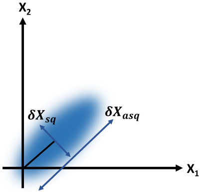


Shadow imaging

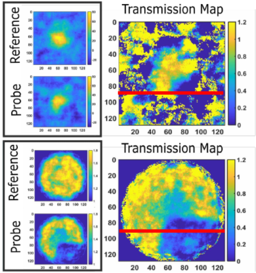


$$V_{pr} = 1 + (\delta X_{ref}^2 - 1)|\mathcal{O}|^2 T$$

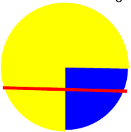
$$T = \frac{V_{pr} - 1}{V_{ref} - 1}$$



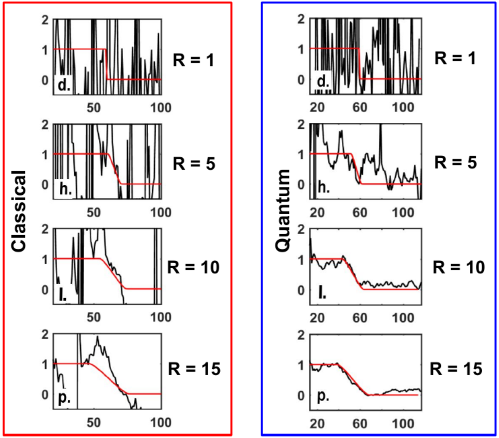
$$T = \frac{|\alpha_{pr}|^2}{|\alpha_{ref}|^2} = \frac{N_{pr}}{N_{ref}}$$



Ideal case: T_o

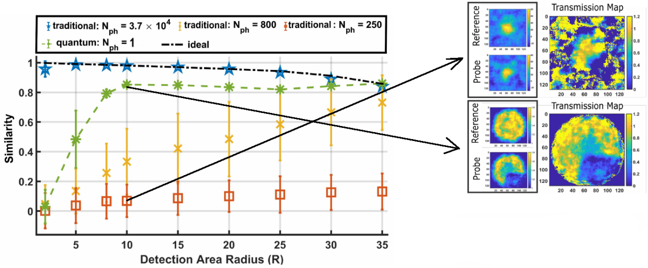


Transmission Map Cross-section



$$S = \frac{\sum T_{exp} T_o}{\sqrt{\sum T_{exp}^2 \sum T_o^2}}$$

Similarity Parameter

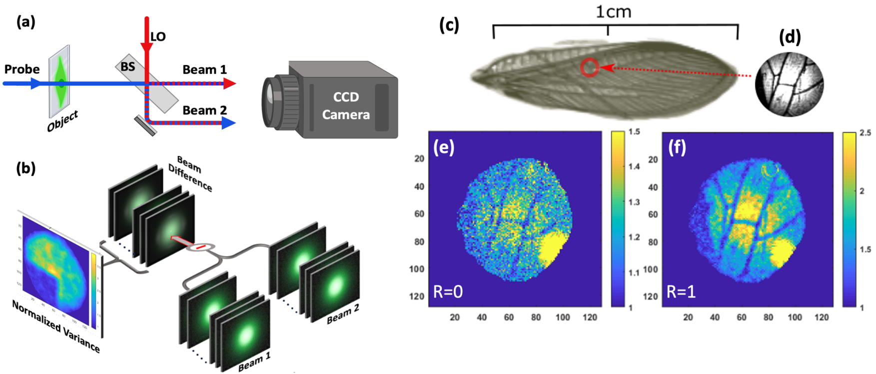


Savannah Couzzo

$$S = \frac{\sum T_{exp} T_o}{\sqrt{\sum T_{exp}^2 \sum T_o^2}}$$

"Low-Light Shadow Imaging Using Quadrature-Noise Detection with a Camera", Advanced Quantum Technologies, 2100147, (2022).

Imaging with thermal light



Ziqi Niu

"Weak Thermal State Quadrature-Noise Shadow Imaging", Optics Express, Issue 16, 30, 29401–29408, (2022).

Structural light imaging: single pixel camera

Single-pixel imaging 12 years on: a review

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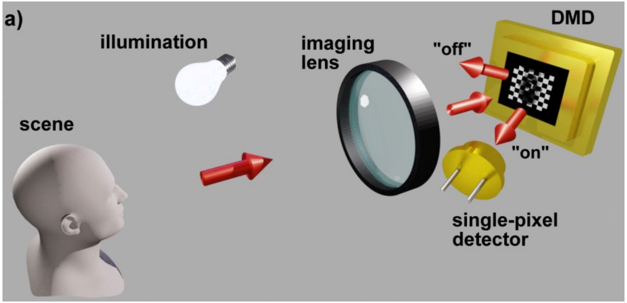
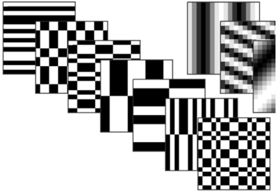
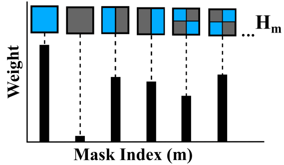
https://www.gla.ac.uk/schools/physics/ourresearch/groups/optics/





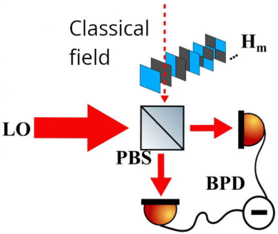


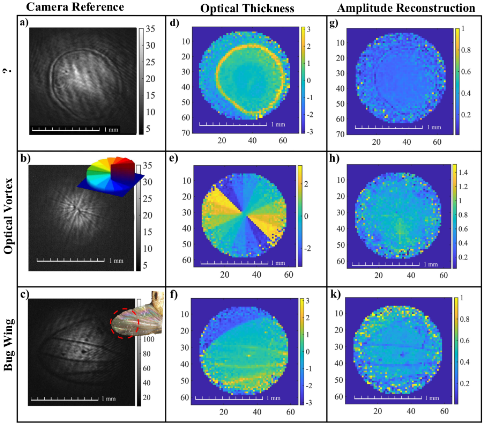
Reconstructed object

$$Ob(x,y) = \frac{1}{M} S_m P_m(x,y)$$

Structural light classical homodyning

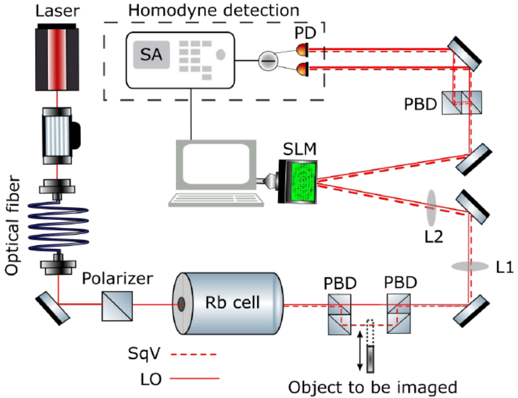
Charris Gabaldon

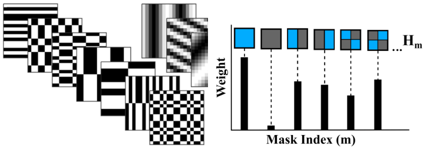


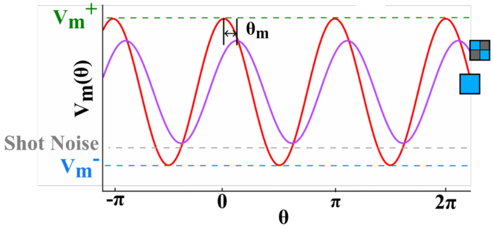


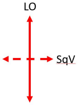
"Wave-Front Reconstruction via Single-Pixel Homodyne Imaging", Optics Express, Issue 21, 30, 37938–37945, (2022).

Structural light imaging with quantum noise







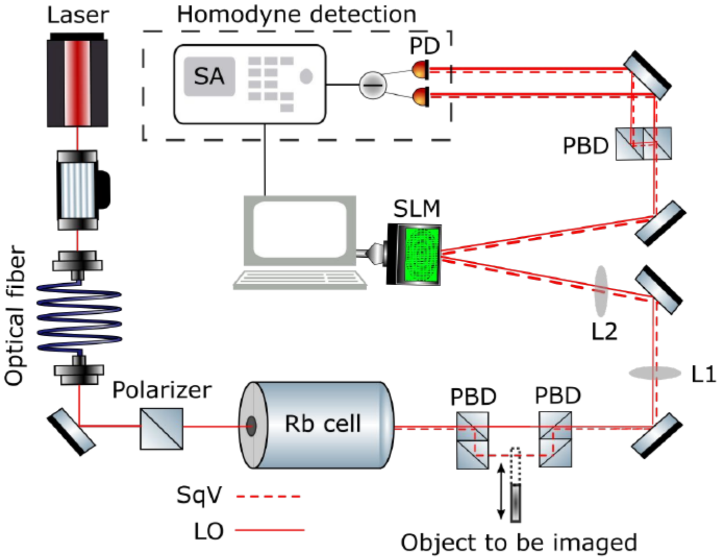


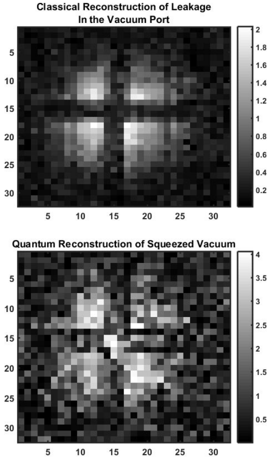
$$V_m = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}_m|^2$$

$$\mathcal{O}_m = \int_A P_m u_{lo} u_q^* T dA$$

$$u_{lo} u_q^* T = \frac{1}{M} \sum \mathcal{O}_m P_m(x, y)$$

Structural light imaging with quantum noise

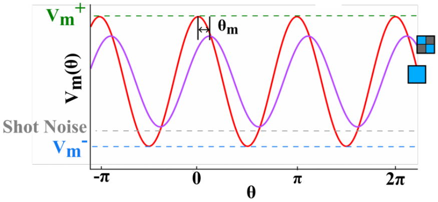




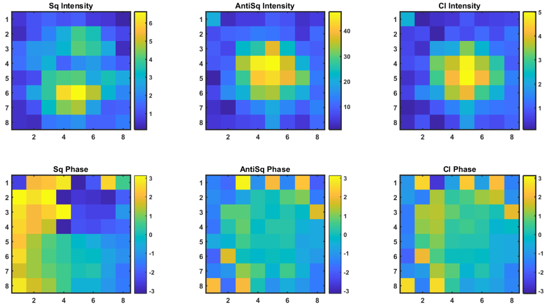
Structural light using different quadratures

$$V_m = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}_m|^2$$

$$\mathcal{O}_m = \int_A P_m u_{lo} u_q^* T dA$$



$$u_{lo} u_q^* T = \frac{1}{M} \sum \mathcal{O}_m P_m(x, y)$$

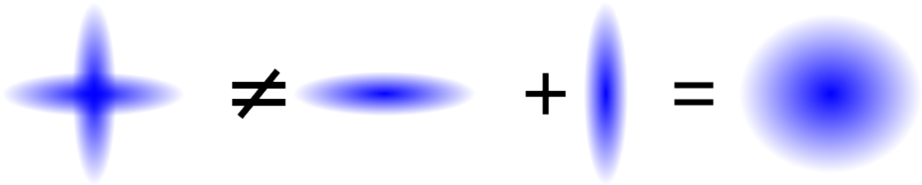


"Quantum fluctuations spatial mode profiler", AVS Quantum Science, 5, 025005, (2023).

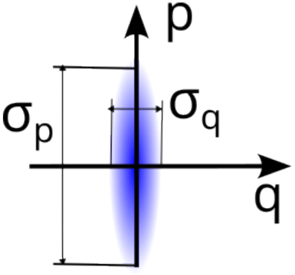
What is the mode?

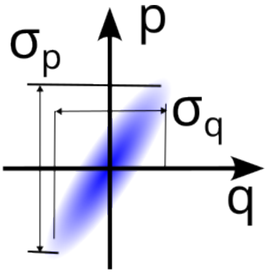
Classical modes (Electric field distribution)

Quadratures probability



Gaussian state, joint probability density and covariance matrix





$$W(q,p) = \frac{1}{2\pi}\frac{1}{\sigma_q\sigma_p} e^{-\frac{1}{2}\left(\frac{q^2}{\sigma_q^2}+\frac{p^2}{\sigma_p^2}\right)}$$

$$W(q,p) = \frac{1}{2\pi}\frac{1}{\sqrt{\Sigma}} e^{-\frac{1}{2}((q,p)\Sigma^{-1}(q,p)^T)}$$

$$\Sigma = \begin{pmatrix} \sigma_q^2 & C \\ C & \sigma_p^2 \end{pmatrix}, C = \langle qp \rangle$$

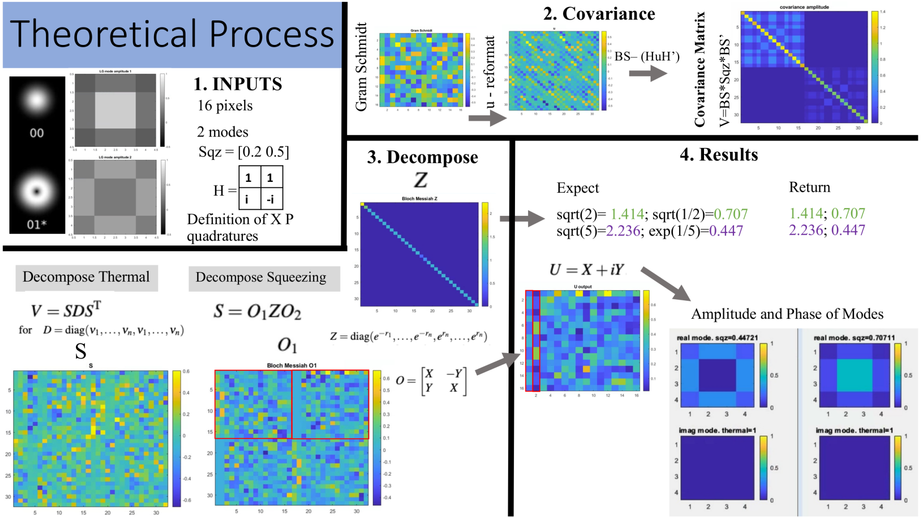
Gaussian states mixture

$$W(q_1, p_1, q_2, p_2, \cdots q_n, p_n) = \frac{1}{(2\pi)^n} \frac{1}{\sqrt{\Sigma}} e^{-\frac{1}{2}((q_1,p_1,q_2,p_2,\cdots q_n,p_n)\Sigma^{-1}(q_1,p_1,q_2,p_2,\cdots q_n,p_n)^T)}$$

$$\Sigma = \begin{pmatrix} \Sigma_1 & & & & & \\ & \Sigma_2 & & & & \\ & & \cdot & & & \\ & & & \cdot & & \\ & & & & \cdot & \\ & & & & & \Sigma_n \end{pmatrix}$$

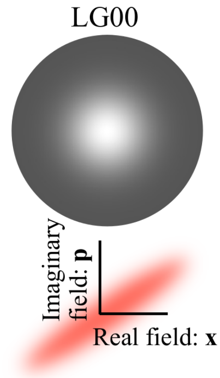
$$\Sigma_i = \begin{pmatrix} \sigma_{q_i}^2 & C_i \\ C_i & \sigma_{p_i}^2 \end{pmatrix}, C_i = \langle q_i p_i \rangle$$

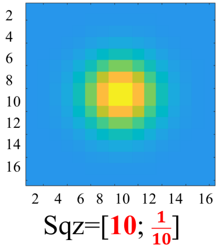
De-composition of covariance matrix to a basic states



Single mode in pixel space

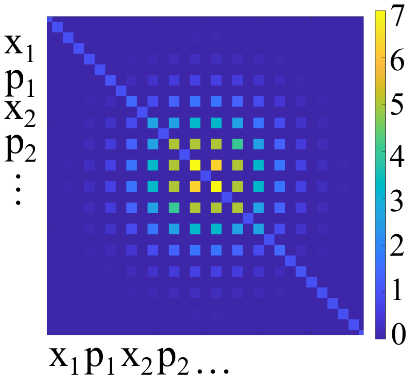
Shape $U(x, y)$





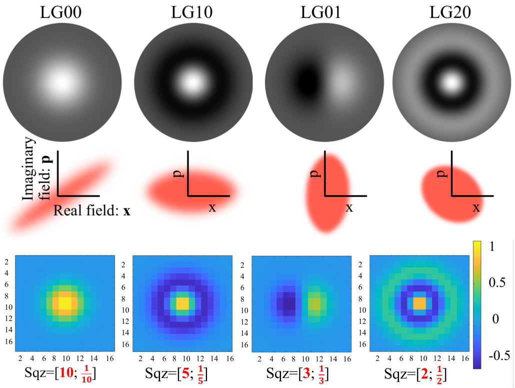
Probability $W(x, p)$

Covariance matrix Σ

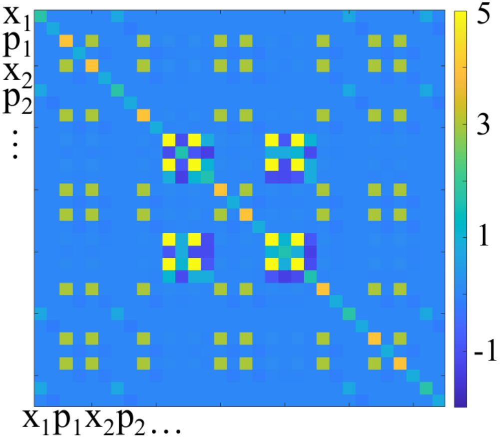


Gaussian states mixture

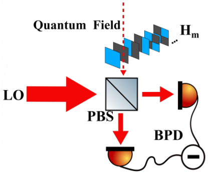
Input states

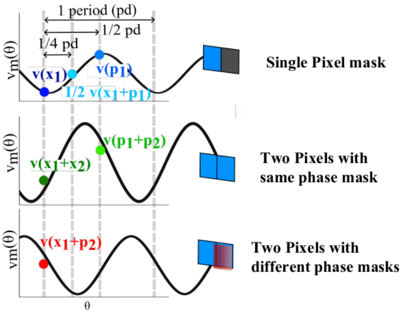


Truncated covariance matrix Σ



How to measure covariance matrix

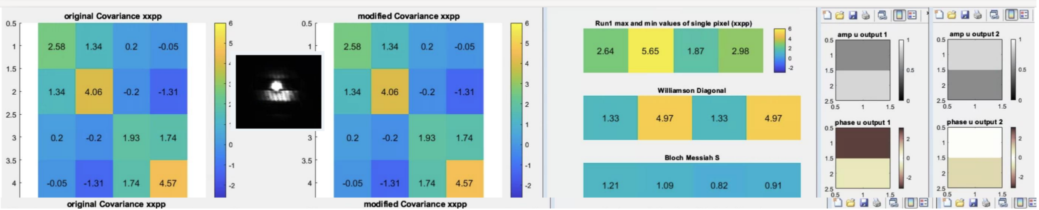


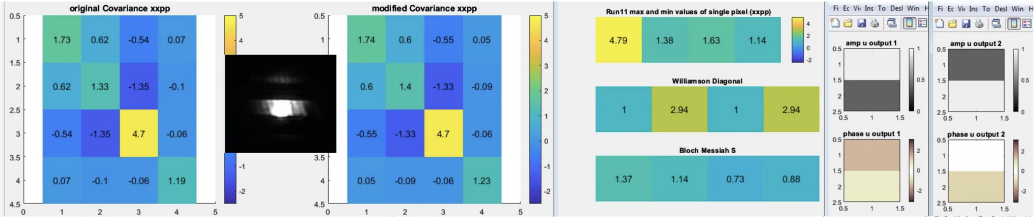


	x1	p1	x2	p2
x1	v(x1)	2Cov(x1,p1) = v(x1+p1) - v(x1) - v(p1)	2Cov(x1,x2) = v(x1+x2) - v(x1) - v(x2)	2Cov(x1,p2) = v(x1+p2) - v(x1) - v(p2)
p1	2Cov(p1,x1) = v(p1+x1) - v(p1) - v(x1)	v(p1)	2Cov(p1,x2) = v(p1+x2) - v(p1) - v(x2)	2Cov(p1,p2) = v(p1+p2) - v(p1) - v(p2)
x2	2Cov(x2,x1) = v(x2+x1) - v(x2) - v(x1)	2Cov(x2,p1) = v(x2+p1) - v(x2) - v(p1)	v(x2)	2Cov(x2,p2) = v(x2+p2) - v(x2) - v(p2)
p2	2Cov(p2,x1) = v(p2+x1) - v(p2) - v(x1)	2Cov(p2,p1) = v(p2+p1) - v(p2) - v(p1)	2Cov(p2,x2) = v(p2+x2) - v(p2) - v(x2)	v(p2)

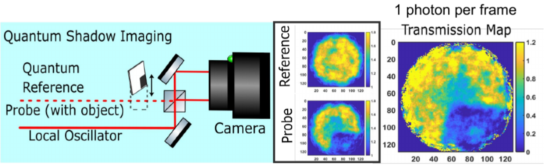
Required measurements: $(2N_p)^2/2$

Real data

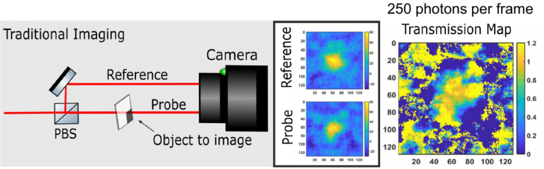

original Covariance xxpp
2.58 1.34 0.2 -0.05
1.34 4.06 -0.2 -1.31
0.2 -0.2 1.93 1.74
-0.05 -1.31 1.74 4.57
modified Covariance xxpp
2.58 1.34 0.2 -0.05
1.34 4.06 -0.2 -1.31
0.2 -0.2 1.93 1.74
-0.05 -1.31 1.74 4.57
Run1 max and min values of single pixel (xxpp)
2.64 5.65 1.87 2.98
Williamson Diagonal
1.33 4.97 1.33 4.97
Bloch Messiah S
1.21 1.09 0.82 0.91
amp u output 1
amp u output 2
phase u output 1
phase u output 2


original Covariance xxpp
1.73 0.62 -0.54 0.07
0.62 1.33 -1.35 -0.1
-0.54 -1.35 4.7 -0.06
0.07 -0.1 -0.06 1.19
modified Covariance xxpp
1.74 0.6 -0.55 0.05
0.6 1.4 -1.33 -0.09
-0.55 -1.33 4.7 -0.06
0.05 -0.09 -0.06 1.23
Run11 max and min values of single pixel (xxpp)
4.79 1.38 1.63 1.14
Williamson Diagonal
1 2.94 1 2.94
Bloch Messiah S
1.37 1.14 0.73 0.88
amp u output 1
amp u output 2
phase u output 1
phase u output 2

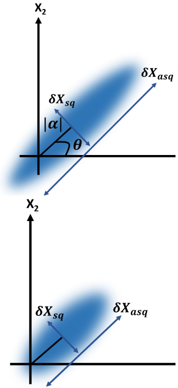
Summary



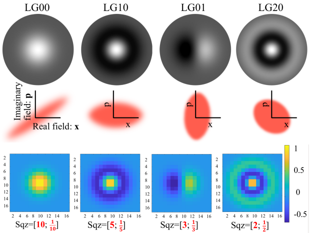
1 photon per frame
Transmission Map
Quantum Shadow Imaging
Quantum Reference
Probe (with object)
Local Oscillator
Camera
Reference
Probe



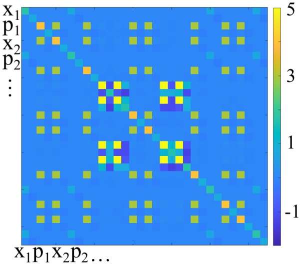
250 photons per frame
Transmission Map
Traditional Imaging
Camera
Reference
Probe
PBS
Object to image



X_2
δX_{sq}
δX_{asq}
$|\alpha|$
θ



LG00
LG10
LG01
LG20
Imaginary field: p
Real field: x
Sqz=[10; 1/10]
Sqz=[5; 1/5]
Sqz=[3; 1/3]
Sqz=[2; 1/2]



x_1
p_1
x_2
p_2
$x_1 p_1 x_2 p_2 \ldots$