Study of Spatial Structure of a Squeezed Vacuum Field

Ph. D Defense

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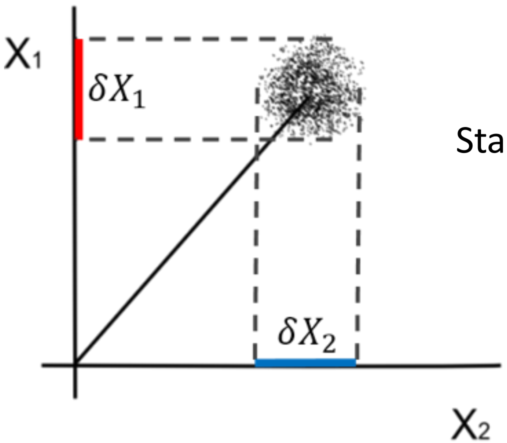
Squeezed field

Quantum Fluctuations in Light field:

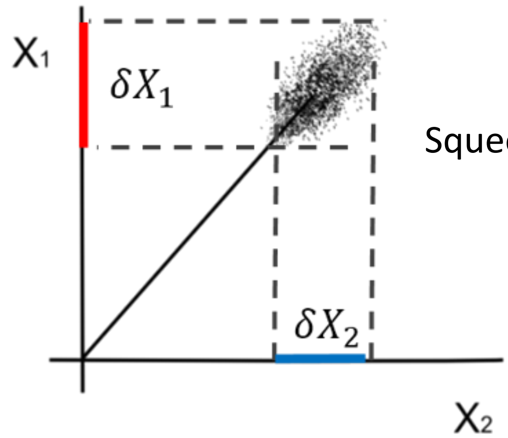
$$\hat{X} = \hat{X}_1 + \delta\hat{X}_1 + i\left(\hat{X}_2 + \delta\hat{X}_2\right)$$



Coherent State
Standard Quantum Limit

$$\delta X_1 = \delta X_2$$

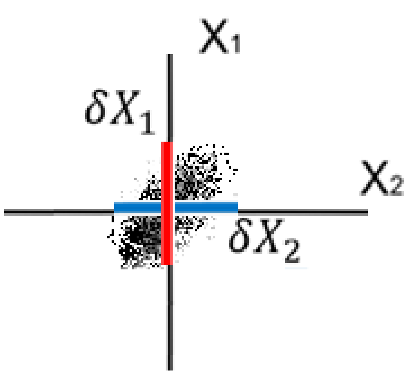
$$\delta X_1 \delta X_2 = \frac{1}{4}$$



Squeezed State
Squeezed Quantum Noise

$$\delta X_1 \neq \delta X_2$$

$$\delta X_1 \delta X_2 \geq \frac{1}{4}$$



Squeezed Vacuum State

$$\delta X_1 \neq \delta X_2$$

$$\delta X_1 \delta X_2 \geq \frac{1}{4}$$

Precision measurements

-Magnetometer

-LIGO

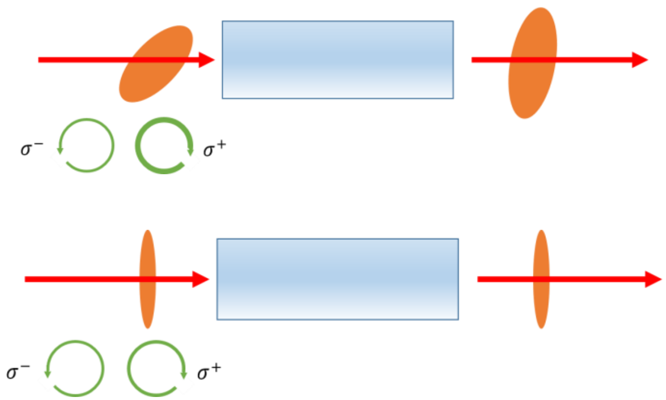
Quantum imaging

Quantum information

Polarization self rotation effect

Elliptically polarized light rotates by $\phi_{SR} = g\varepsilon L$.

For linearly polarized light, the orthogonal polarization gets squeezed.



Predictions of the PSR-generated squeezing in the Rb atomic vapor : - 8 dB

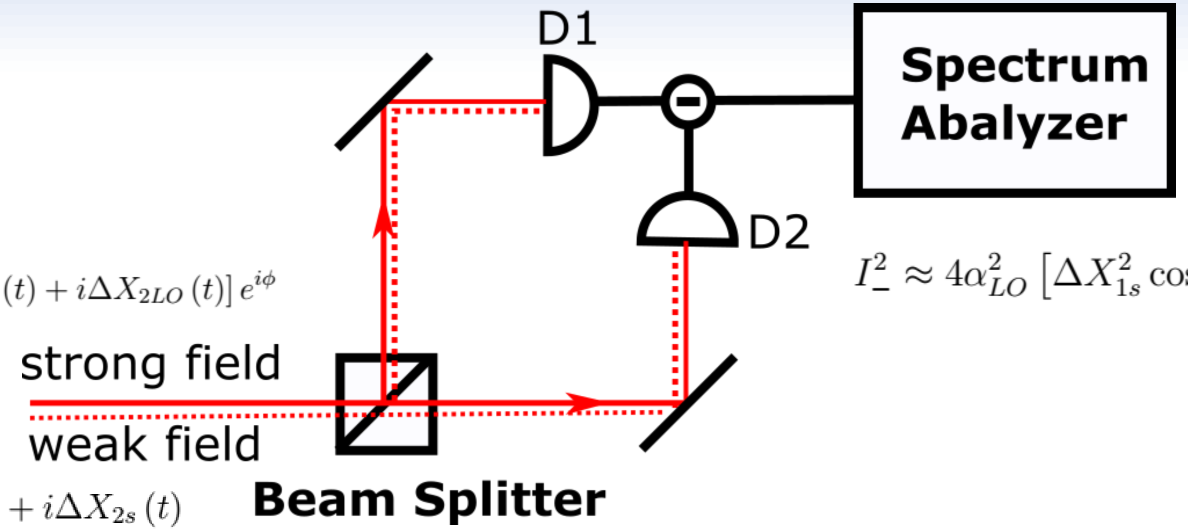
A. B. Matsko, I. Novikova, G. R. Welch, D. Budker, D. F. Kimball, and S. M. Rochester
Phys. Rev. A **66**, 043815 – Published 30 October 2002

Current best : - 3 dB

S. Barreiro, P. Valente, H. Failache, and A. Lezama
Phys. Rev. A 84, 033851 – Published 28 September 2011

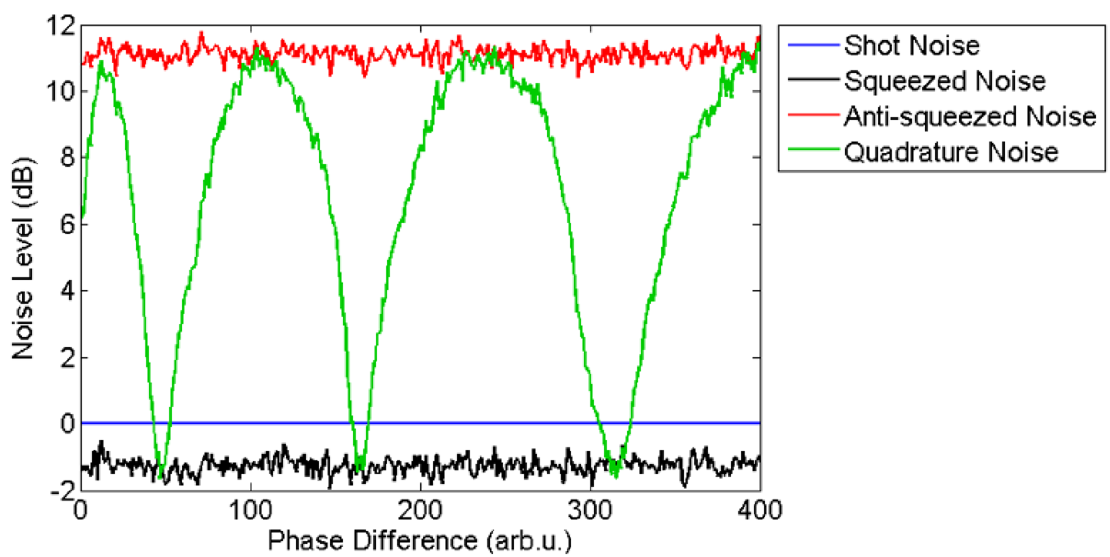
Homodyne Detection scheme

$\alpha_{LO}(t) = [\alpha_{LO} + \Delta X_{1LO}(t) + i\Delta X_{2LO}(t)]\, e^{i\phi}$

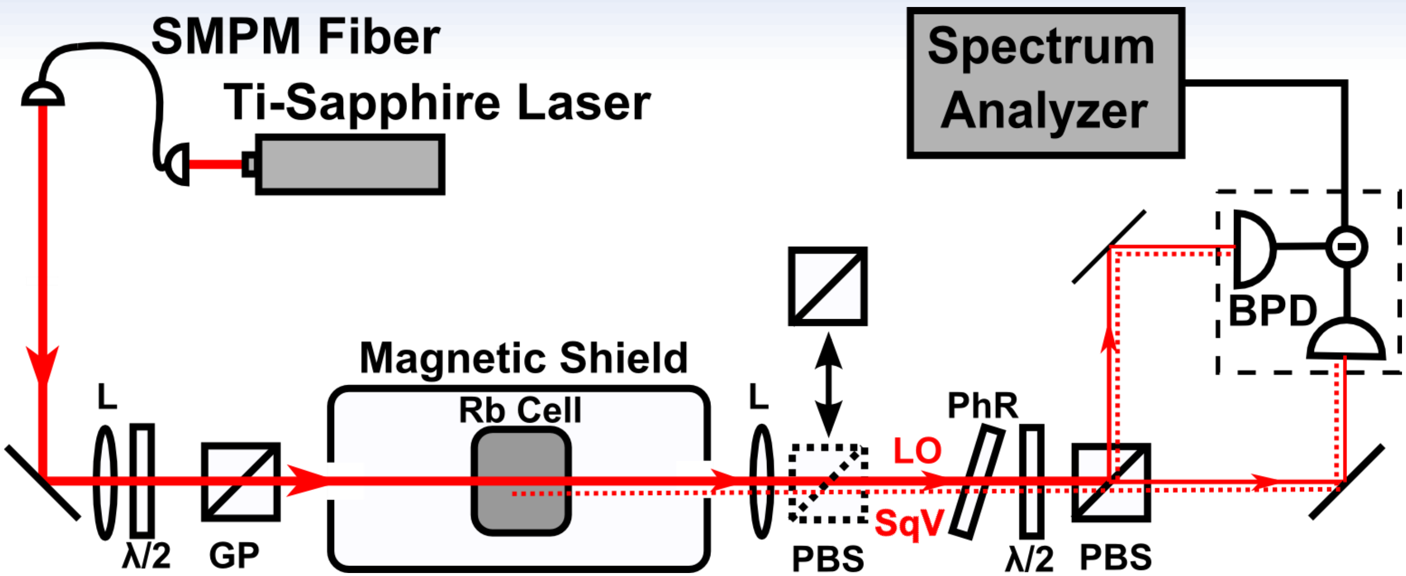


$I_-^2 \approx 4\alpha_{LO}^2 \left[\Delta X_{1s}^2 \cos^2\phi + \Delta X_{2s}^2 \sin^2\phi\right]$

$\alpha_s(t) = \alpha_s + \Delta X_{1s}(t) + i\Delta X_{2s}(t)$



Experimental setup



SMPM fiber – single-mode polarization-maintaining fiber
$^{\lambda}/_{2}$ – half-wave plate
GP – Glan-laser polarizer
PBS – polarizing beam splitter
PhR – phase-retarding wave plate
BPD – balanced photodetector

Parameters affect squeezing:

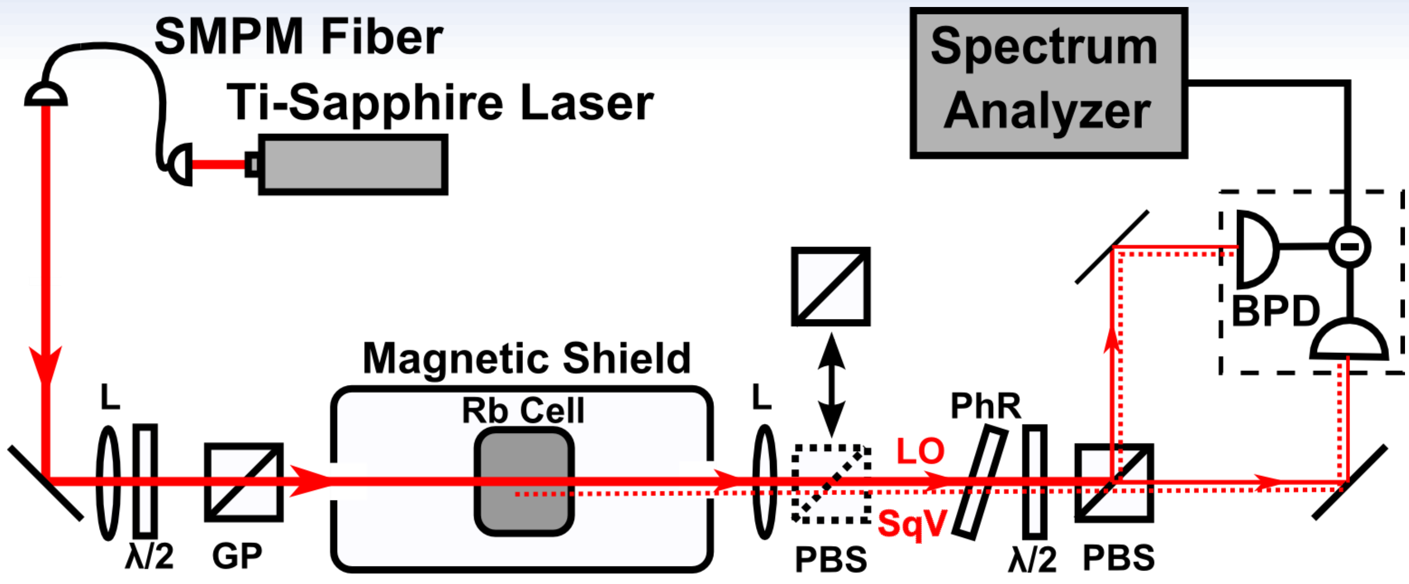
Pump beam intensity

Beam size

Atomic density of medium

Beam focus position in the cell

Experimental setup



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Beam size

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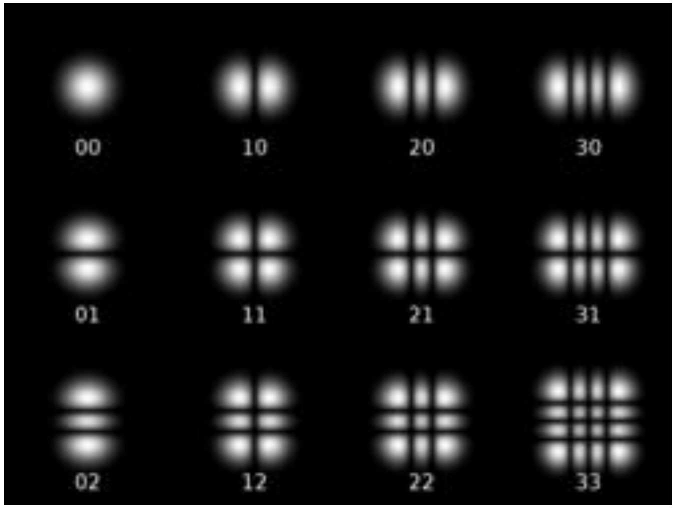
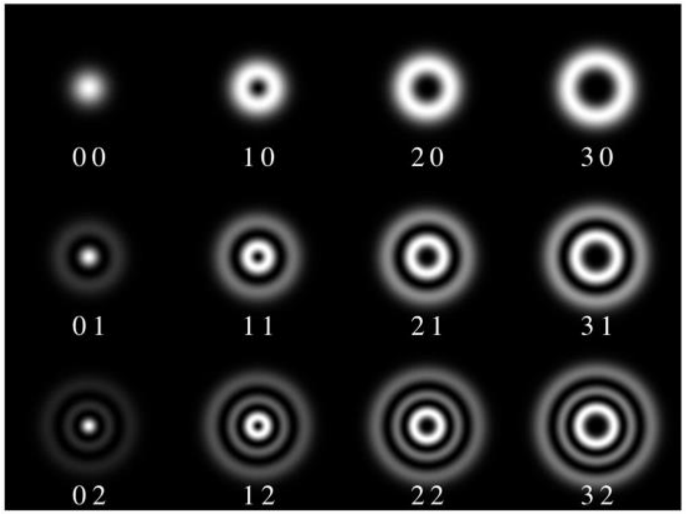
Beam focus position in the cell

Spatial modes of light



Hermite Gaussian modes



Laguerre Gaussian modes

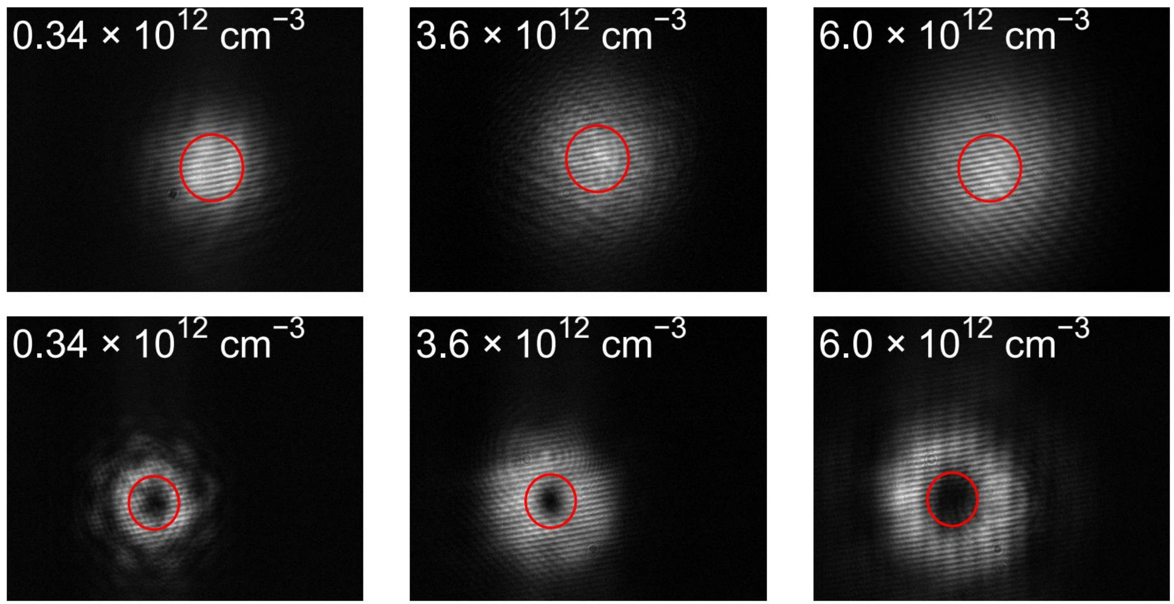
Figure source: Wikipedia page-Gaussian beam

Self-focusing of beam

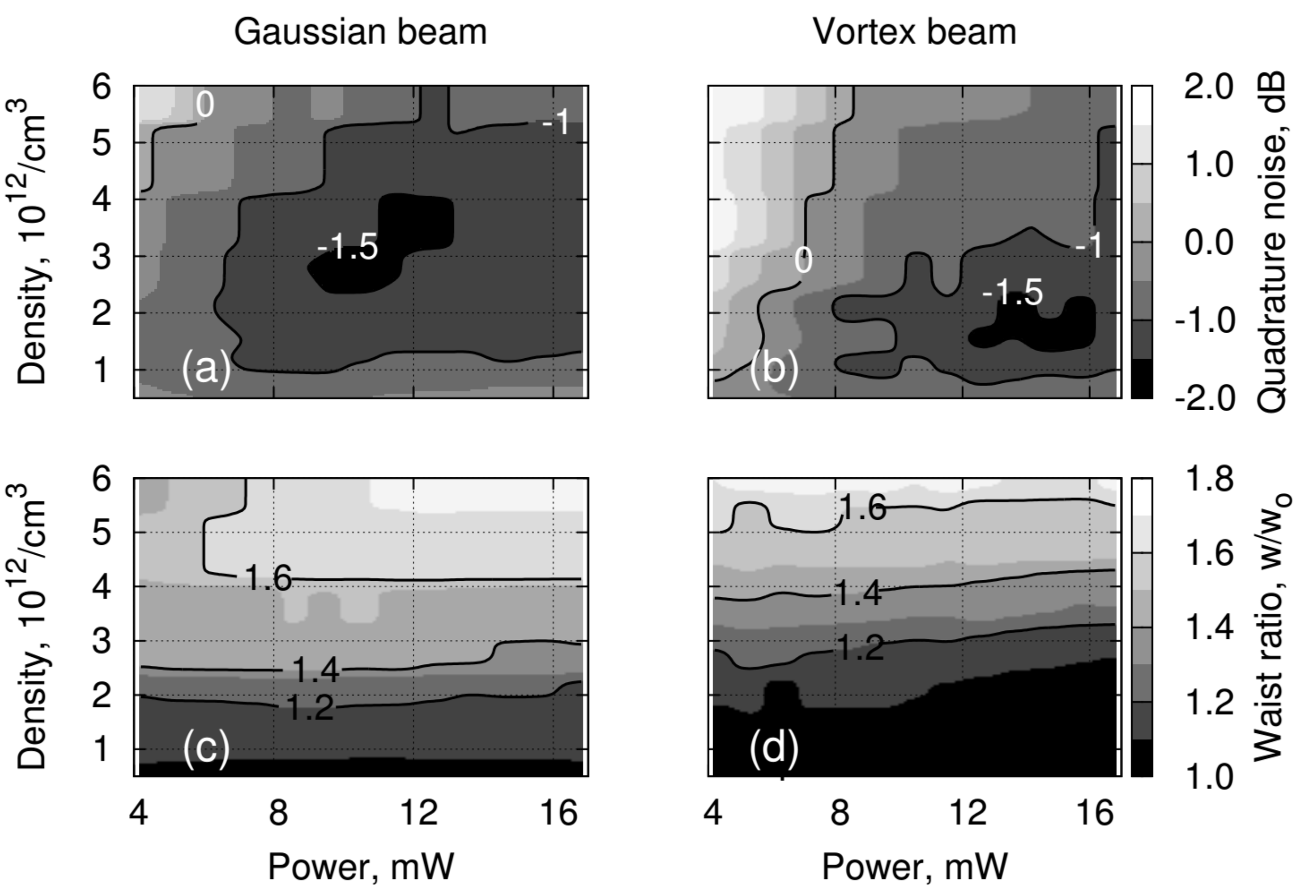
A nonlinear process in medium,
caused by the intensity distribution change in strong field

$$I(r) = I_0 e^{\frac{-2r^2}{w^2}}$$

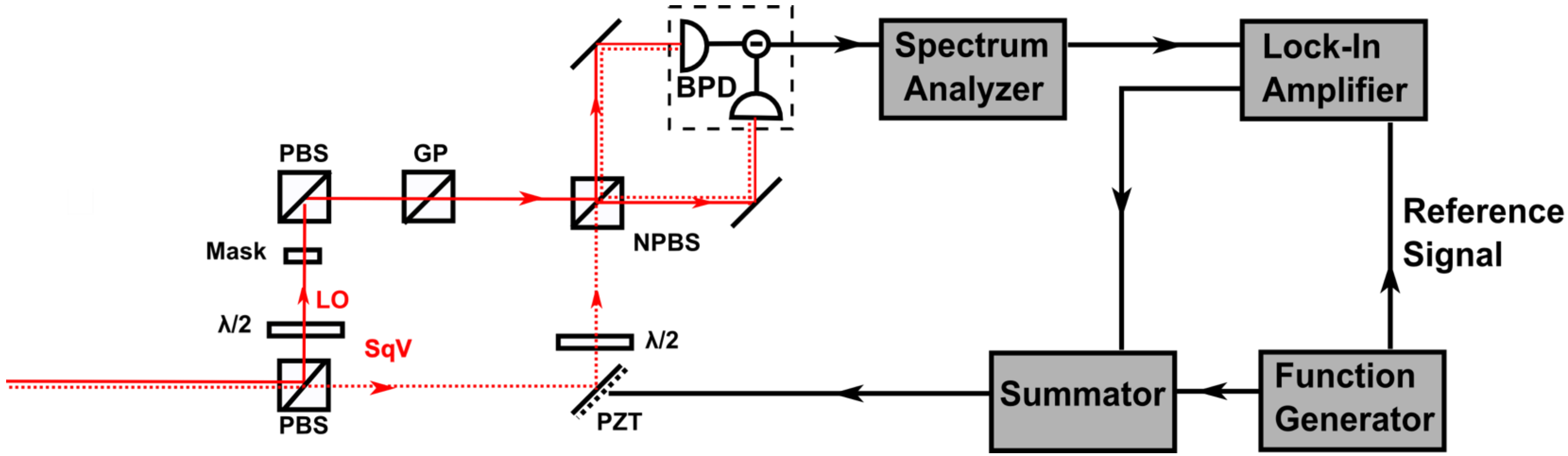
$$I(r) = I_0 \frac{r^2}{w^2} e^{-\frac{2r^2}{w^2}}$$



Correlation between self squeezing and squeezing



Interferometric scheme of detection

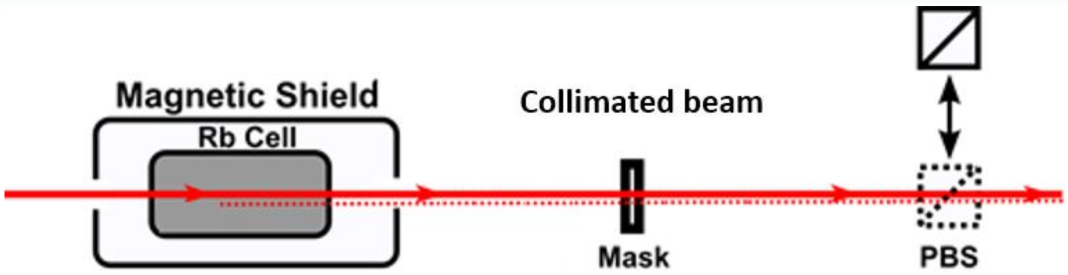


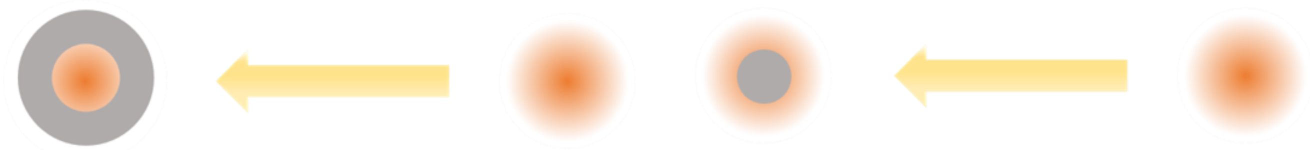
To calibrate a good mode match, we introduce a parameter visibility

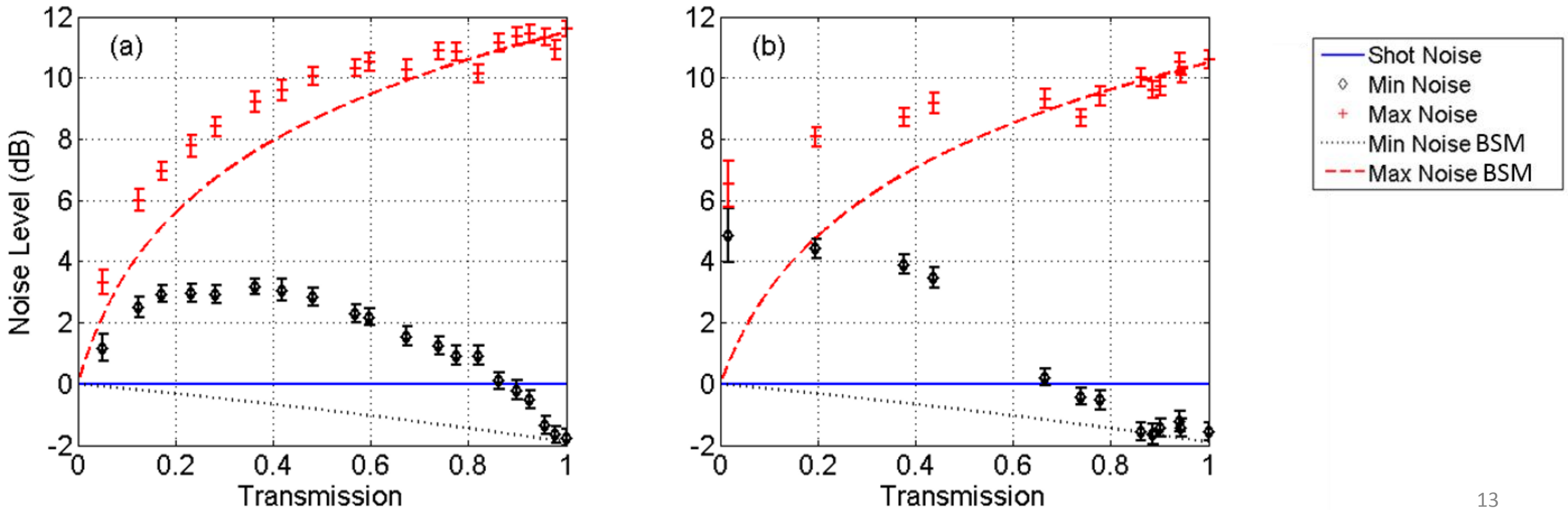
$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Usually in similar detecting scheme, a visibility of 90% is necessary to detect squeezing. We had V = 98%, but no squeezing was observed.

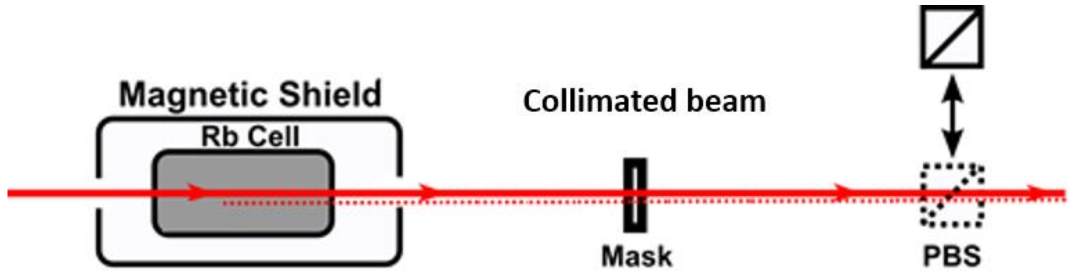
Circular beam mask

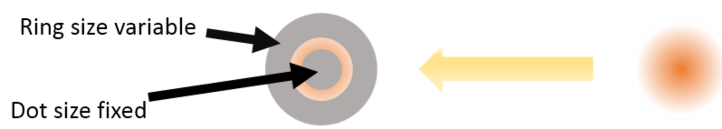


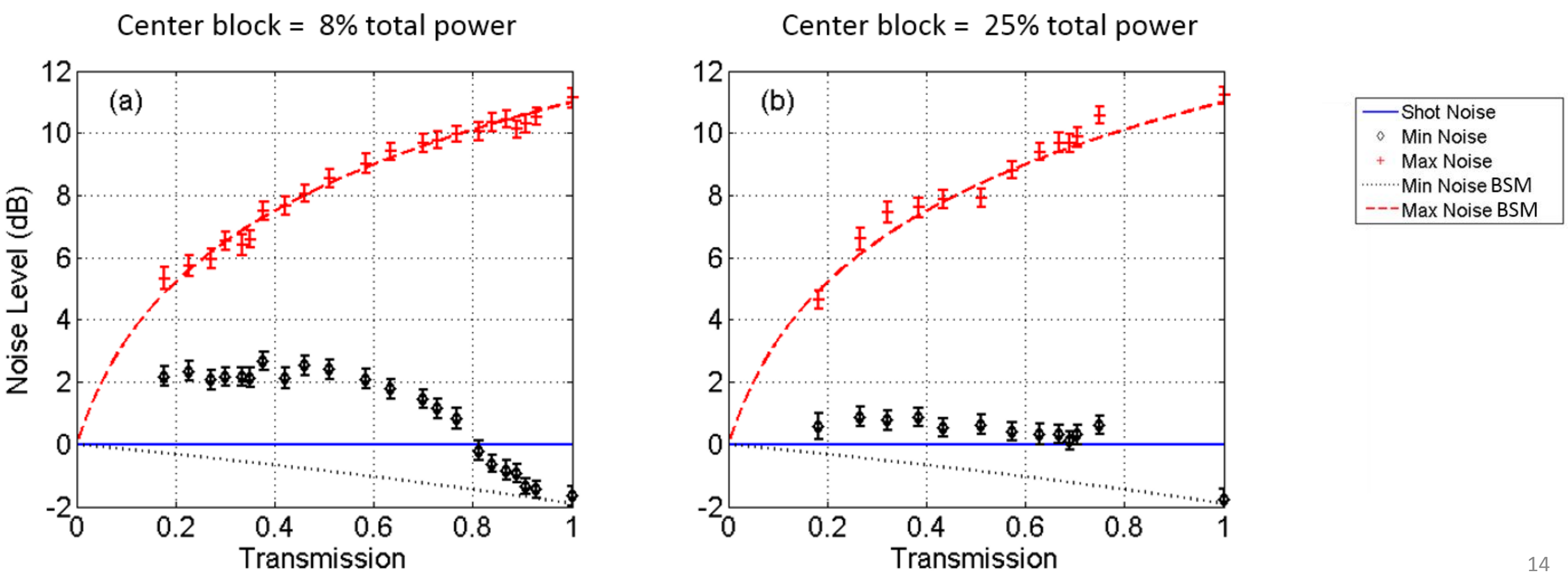




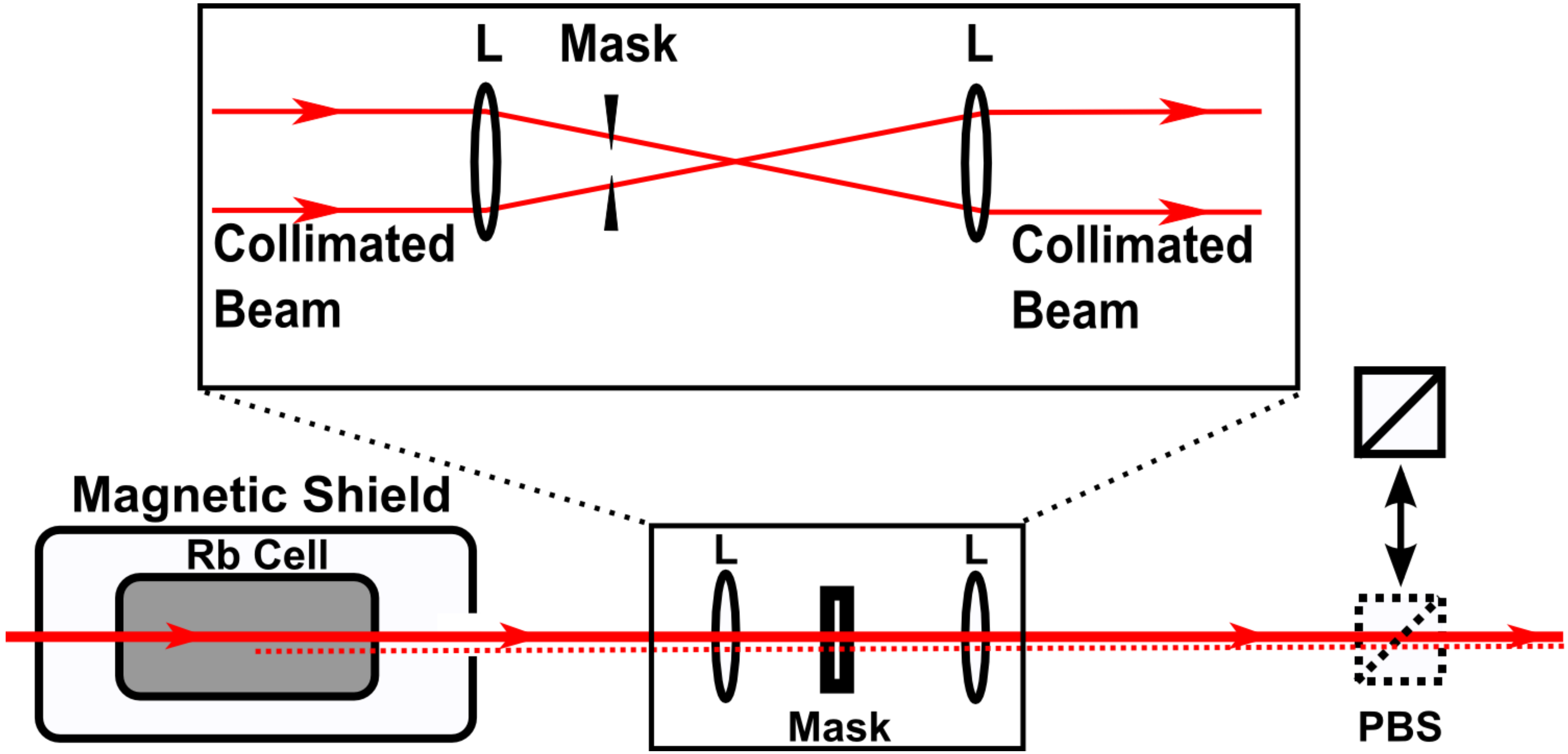
Circular beam mask



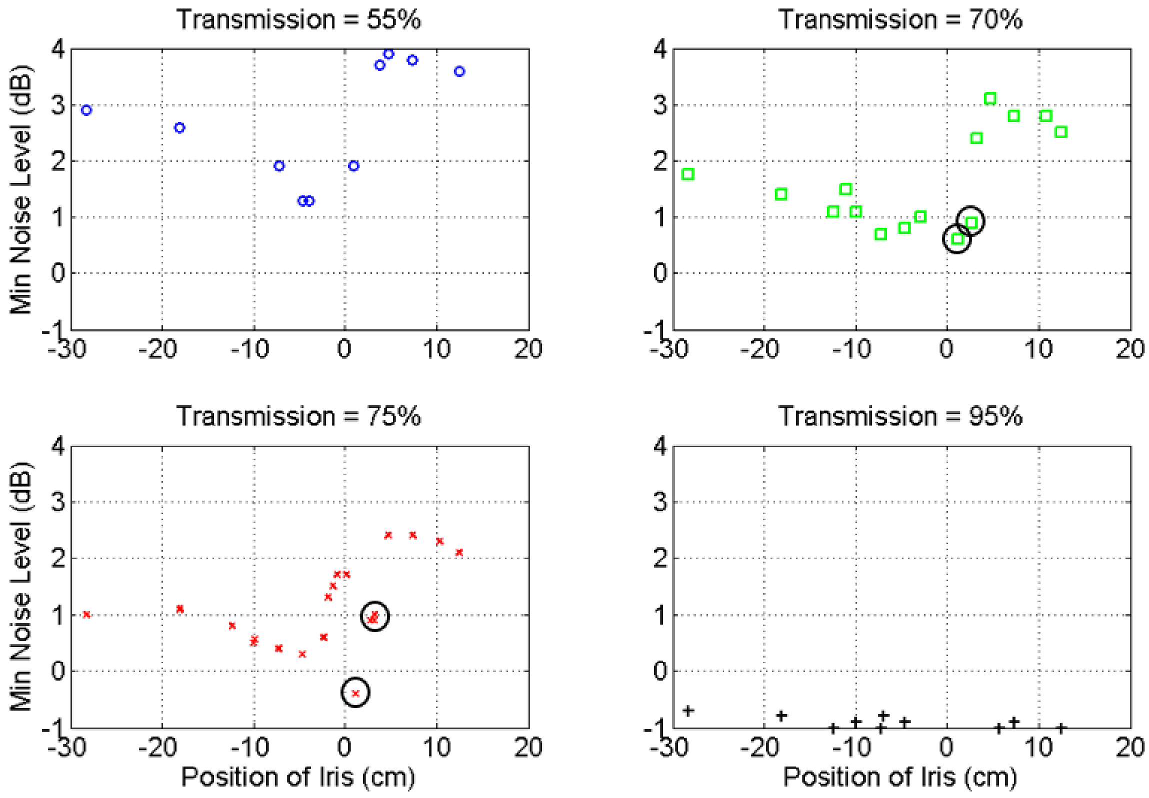




"Telescope"

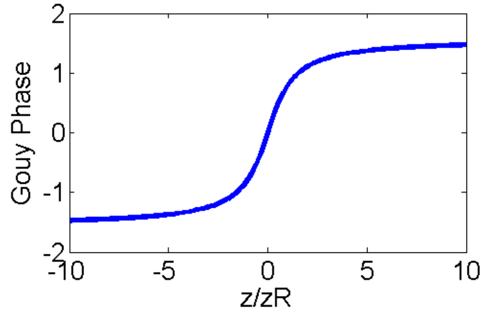

L
Mask
L
Collimated
Beam
Collimated
Beam
Magnetic Shield
Rb Cell
L
L
Mask
PBS

Iris transmission fixed

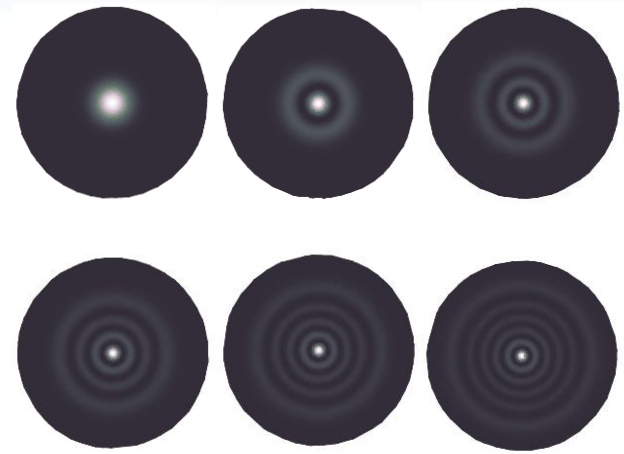


Guoy Phase $\varsigma(z) = arctan\left(\frac{z}{z_R}\right)$,

has a π shift across the focus



Theoretical explanation



Q: How Many Modes Should We Keep?!?

A: 5.

An analysis reveals we must keep up to p=5 in our superposition.

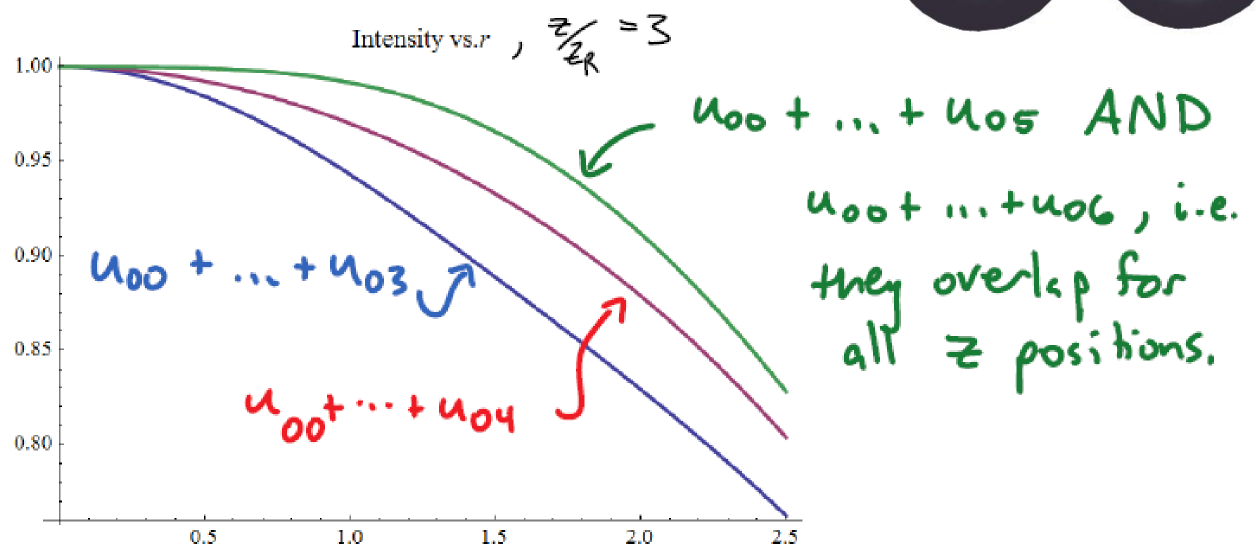


Figure credit: R. N. Lanning

Theoretical explanation

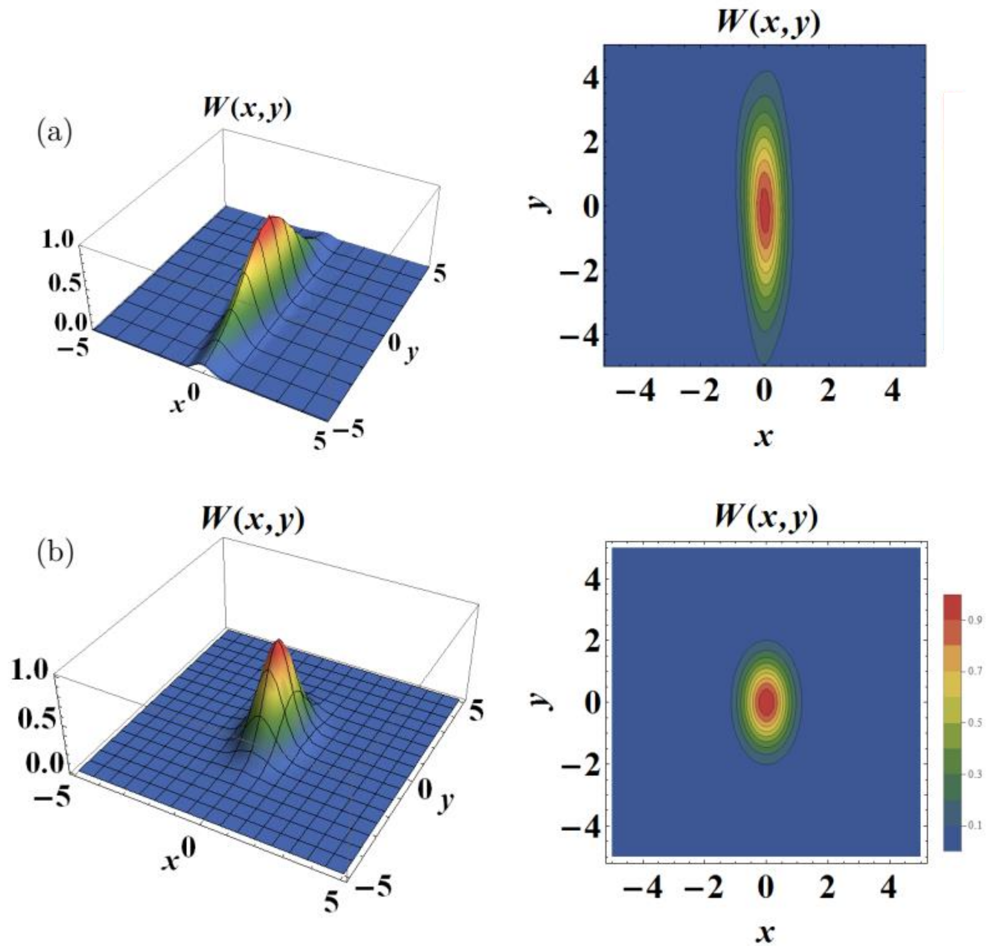


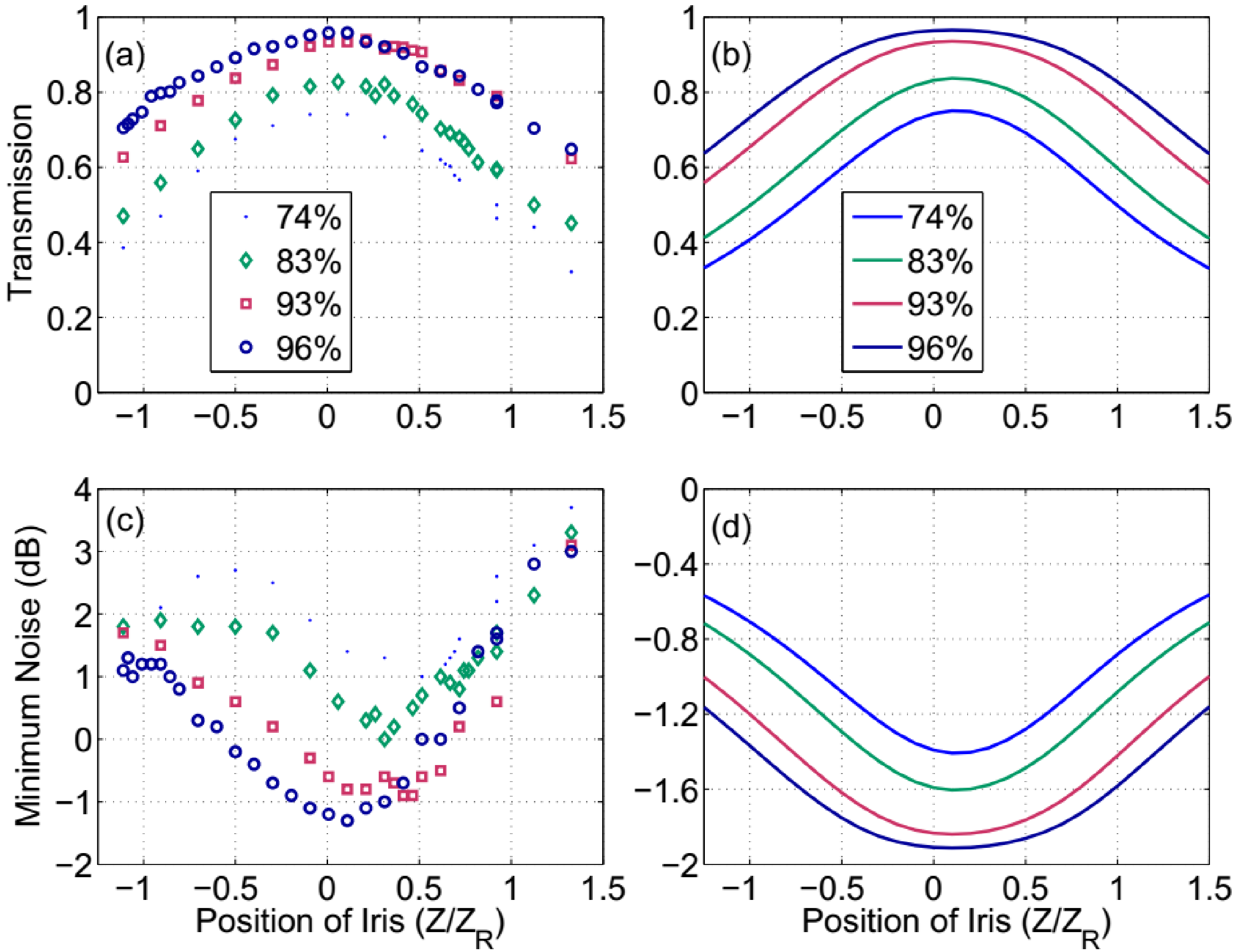
TABLE 5.1: Squeezing Parameters for Various Modes

p	r'_p	$\theta_p/2$	$\lvert O_p \rvert$	$\mathrm{Arg}(O_p)$
0	1.297	160°	0.995	71°
1	0.315	113°	0.091	101°
2	0.149	97°	0.031	123°
3	0.029	25°	0.006	76°
4	0.011	171°	0.004	38°
5	0.010	18°	0.002	160°

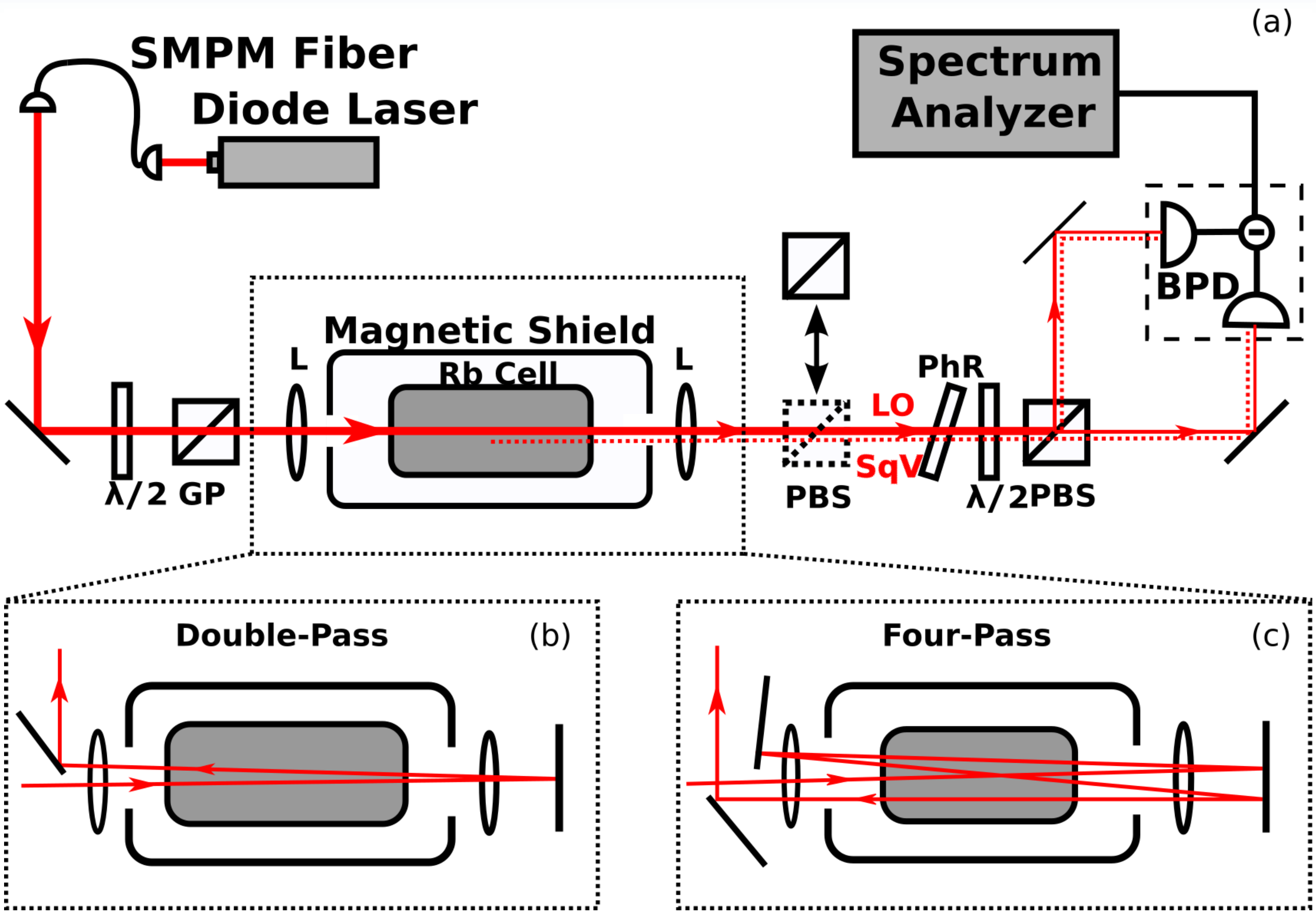
Multi-mode field generated in the vapor cell, resulting in a bad mode match and less effective detection of squeezing.

M Zhang, RN Lanning, Z Xiao, JP Dowling, I Novikova, EE Mikhailov
Physical Review A 93 (1), 013853

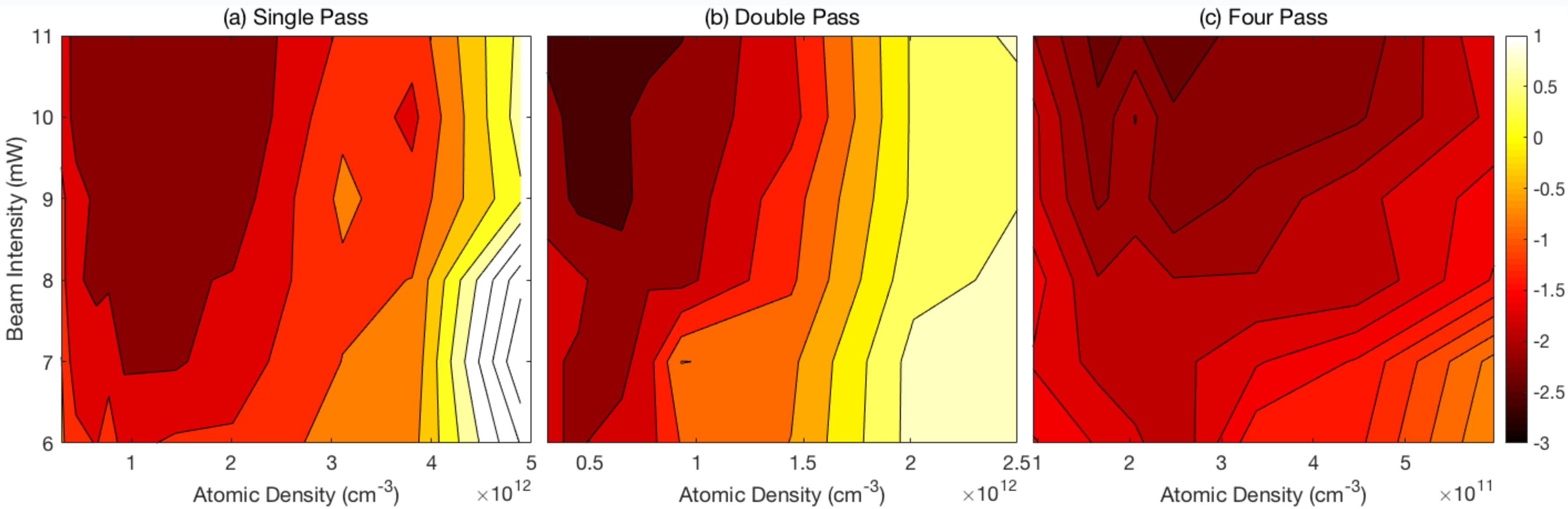
Iris size fixed



Optical depth study – multipass



Squeezing dependence on optical depth

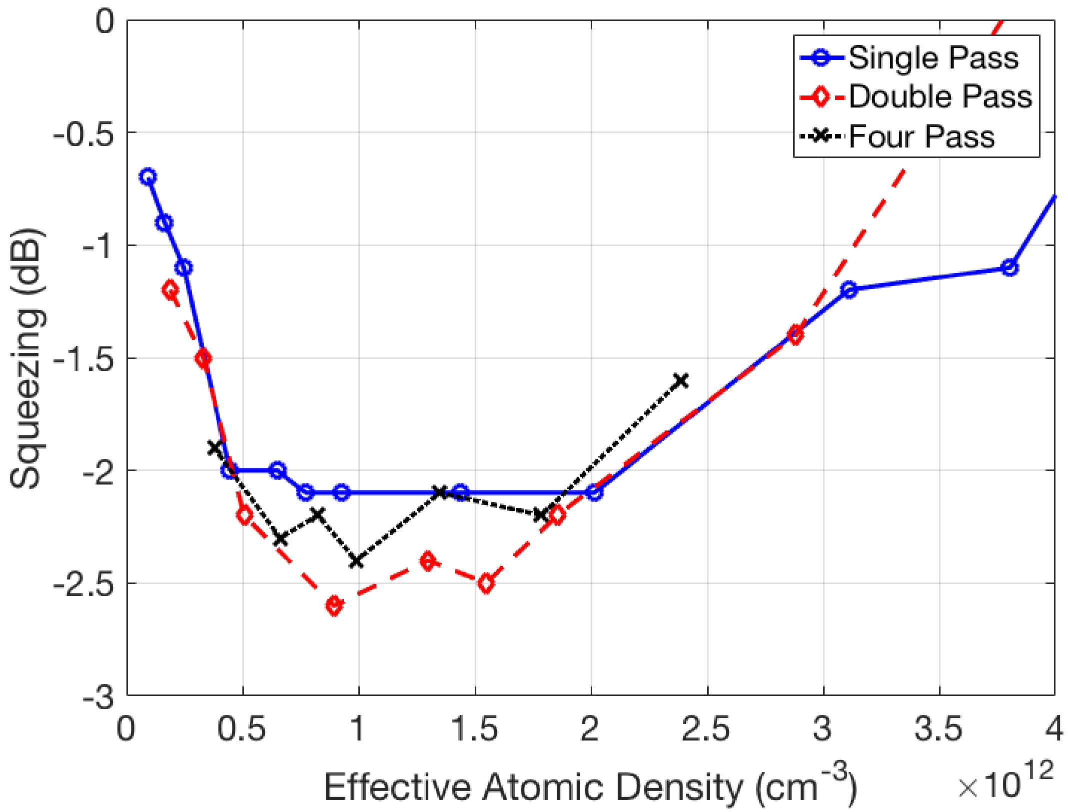


$N = 9.3 \times 10^{11}/cm^3$
$P = 11$ mW
Squeezing = -2.1 dB

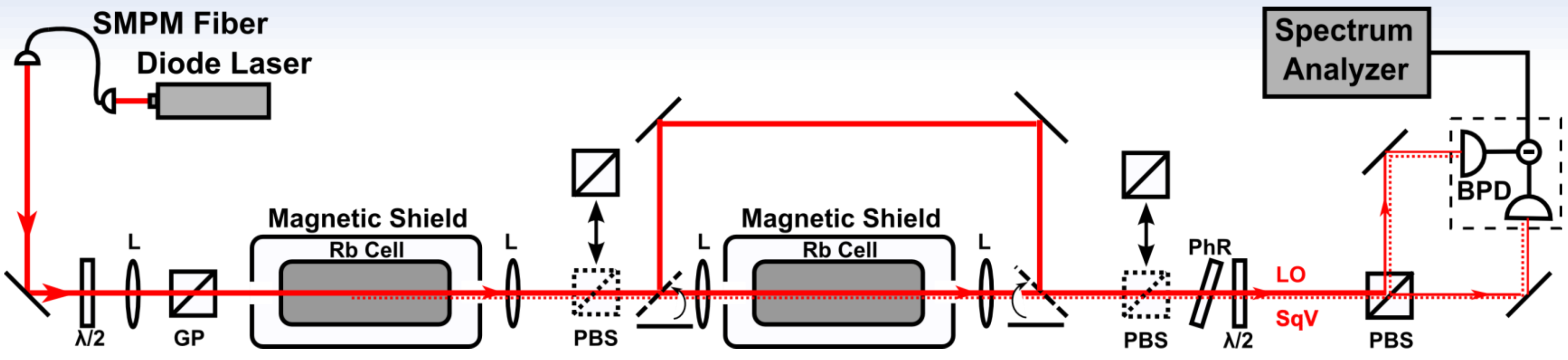
$N = 4.3 \times 10^{11}/cm^3$
$P = 11$ mW
Squeezing = -2.6 dB

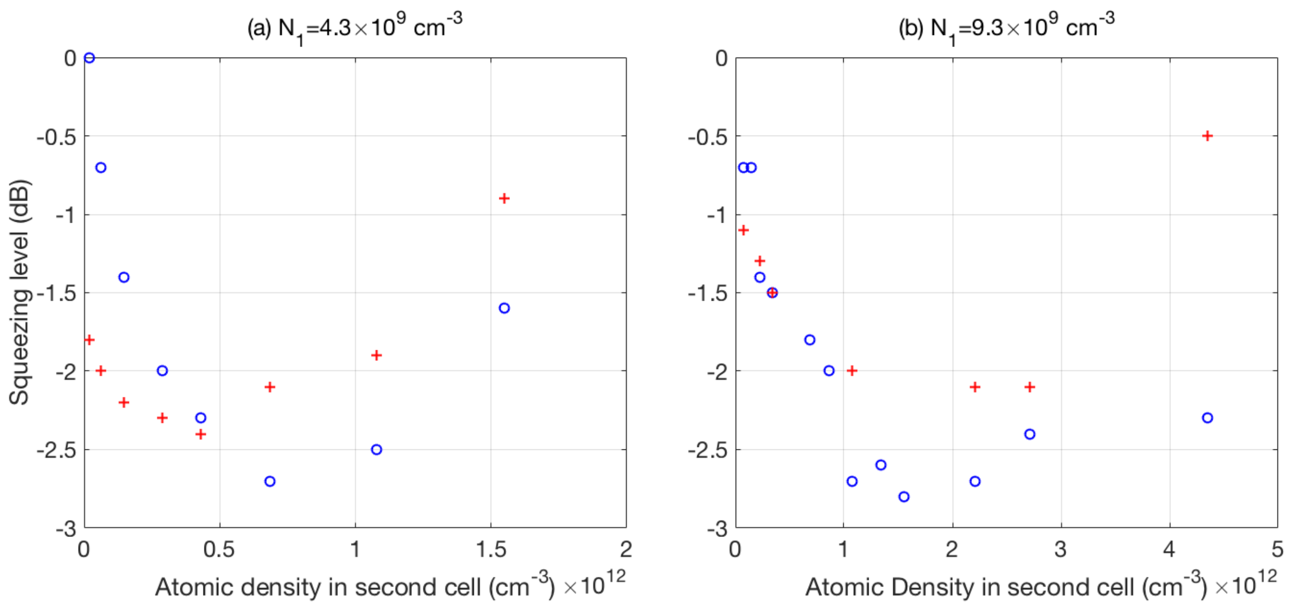
$N = 2.4 \times 10^{11}/cm^3$
$P = 11$ mW
Squeezing = -2.4 dB

Squeezing dependence on optical depth

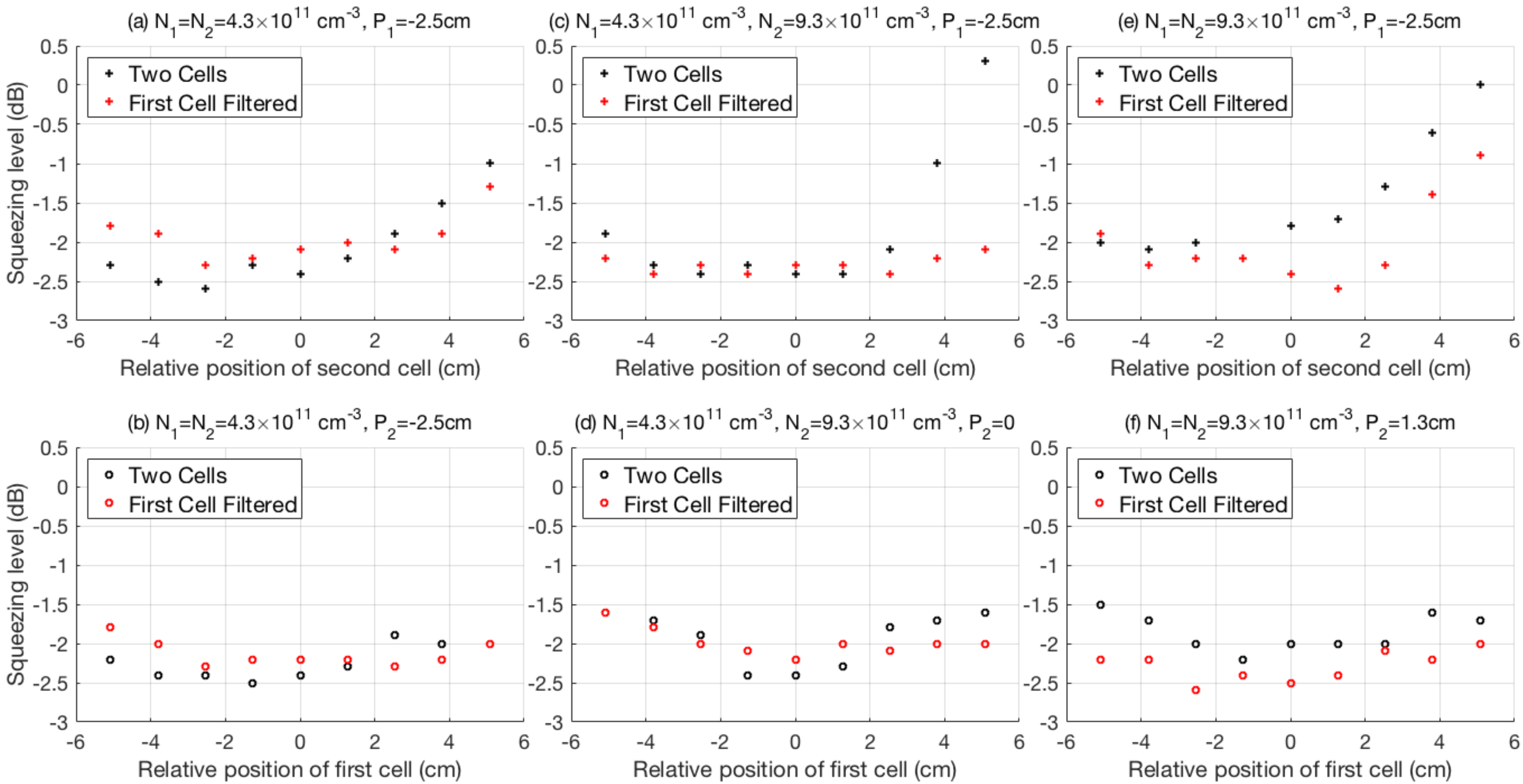


Two cells


SMPM Fiber
Diode Laser
Spectrum Analyzer
BPD
Magnetic Shield
Rb Cell
Magnetic Shield
Rb Cell
L
L
L
L
PhR
LO
SqV
λ/2
GP
PBS
PBS
λ/2
PBS

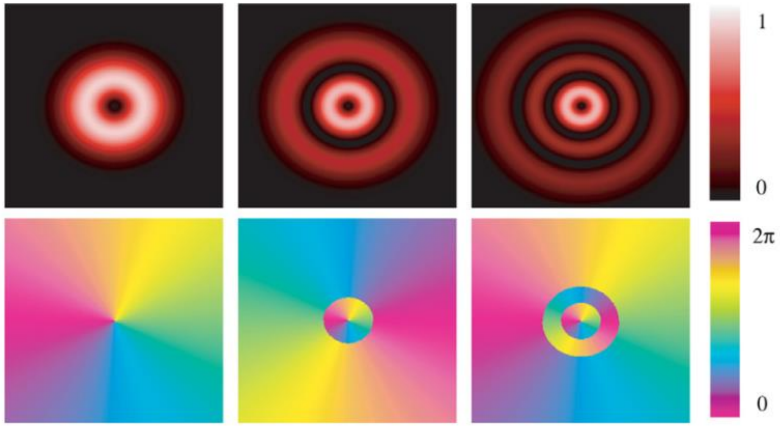

(a) N_1=4.3×10^9 cm^{-3}
(b) N_1=9.3×10^9 cm^{-3}
Squeezing level (dB)
Atomic density in second cell (cm^{-3}) ×10^{12}
Atomic Density in second cell (cm^{-3}) ×10^{12}

Entangled position



Spatial light modulator

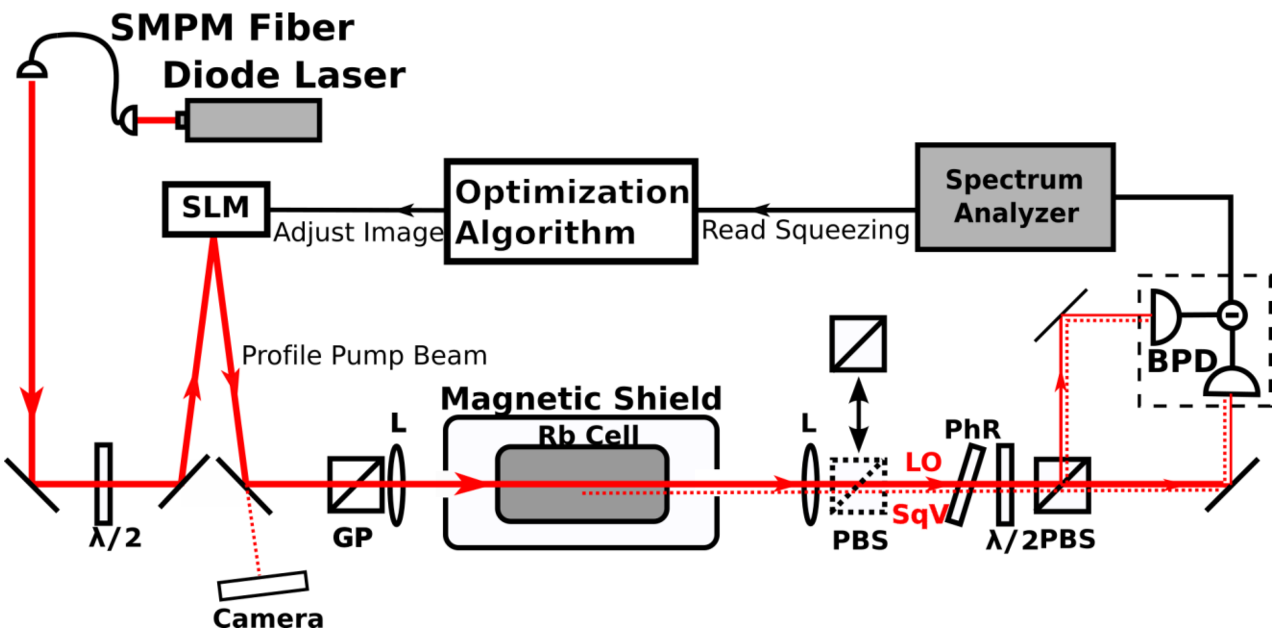
A reflective device that changes the phase retardation of light incident on screen.



Normalized intensity (top) and phase (bottom) plots of Laguerre–Gaussian modes: LG_{01}, LG_{11}, and LG_{21} (left to right) showing the $p + 1$ concentric rings and the effect on the phase pattern.

Yao, A.M., and Padgett, M.J. (2011) Orbital angular momentum: origins, behavior and applications. Advances in Optics and Photonics, 3 (2). p. 161. ISSN 1943-8206

Change of pump



The SLM changes the pump beam shape to generate different amount of noise suppression.
Squeezing is detected by the spectrum analyzer and sent to the optimization algorithm to decide how to modify the phase mask.

Feedback loop and Optimization algorithm

Optimization algorithm – Metropolis

- If squeezing is improved, accept change
- If not, accept change with a probability

Phase mask applied to the SLM is composed of N higher modes with l = 0 or p = 0

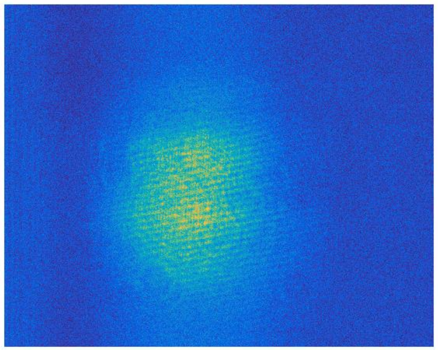
$$\Phi(x,y) = \sum_{i=1}^{N} (C_{iR} + iC_{iI})\, \Phi_i(x,y,w)$$

C_{iR} is the real coefficient of the ith mode and C_{iI} is the imaginary part.

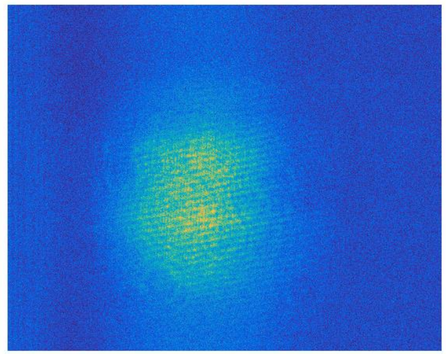
$\Phi(x,y)$ is the phase applied to a certain position (x, y), $\Phi_i(x,y,w)$ is the phase of the ith mode with waist w.

Optimized squeezing

(a)



(b)

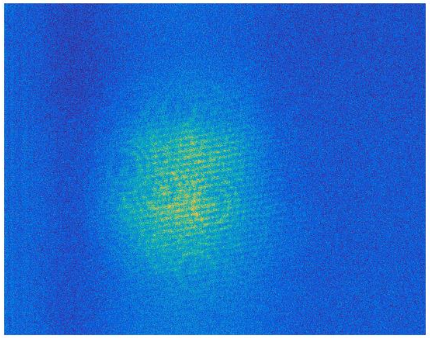


Optimal Mode Composition with 5 Higher p Modes

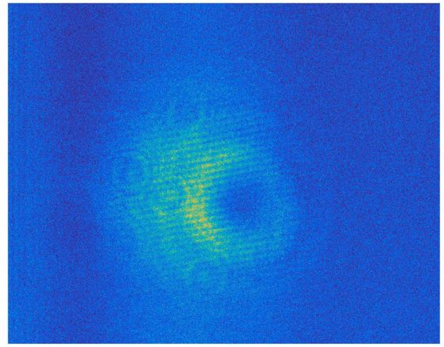
w	0.00357		
c_1	-0.00144	c_1^*	0.00131
c_2	0.789	c_2^*	-0.174
c_3	-0.00101	c_3^*	0.182
c_4	0.00810	c_4^*	0.127
c_5	0.0197	c_5^*	0.0234

Original squeezing = -2.0 dB   Improved squeezing = -2.3 dB

(a)



(b)

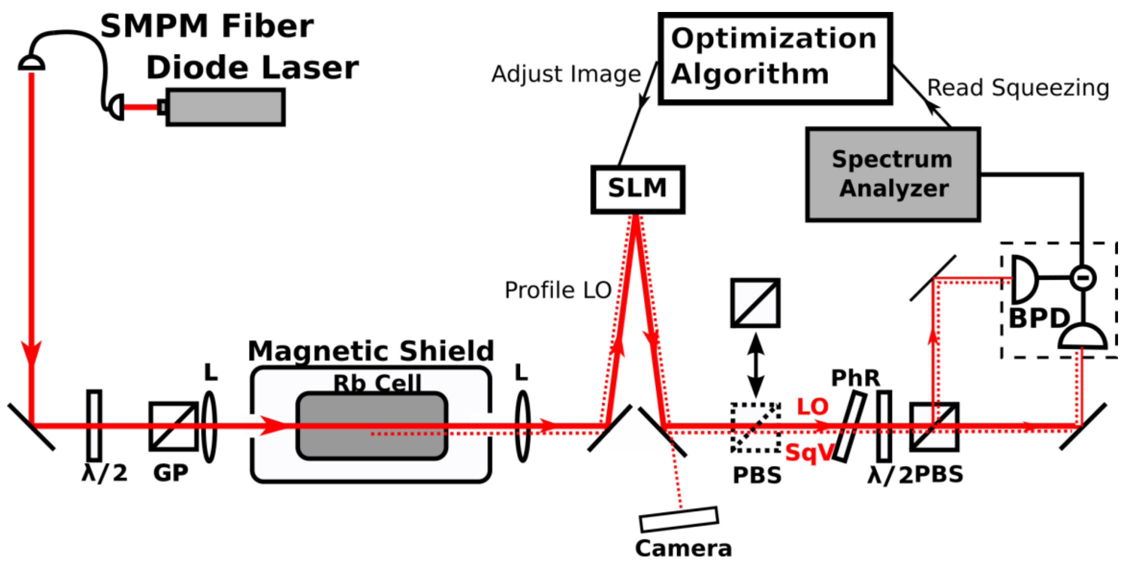


Optimal Mode Composition with 5 Higher l Modes

w	0.00101		
c_1	0.405	c_1^*	-0.000189
c_2	1.59	c_2^*	-0.0212
c_3	-0.334	c_3^*	-0.0395
c_4	1.88	c_4^*	0.00406
c_5	0.0196	c_5^*	-0.0120

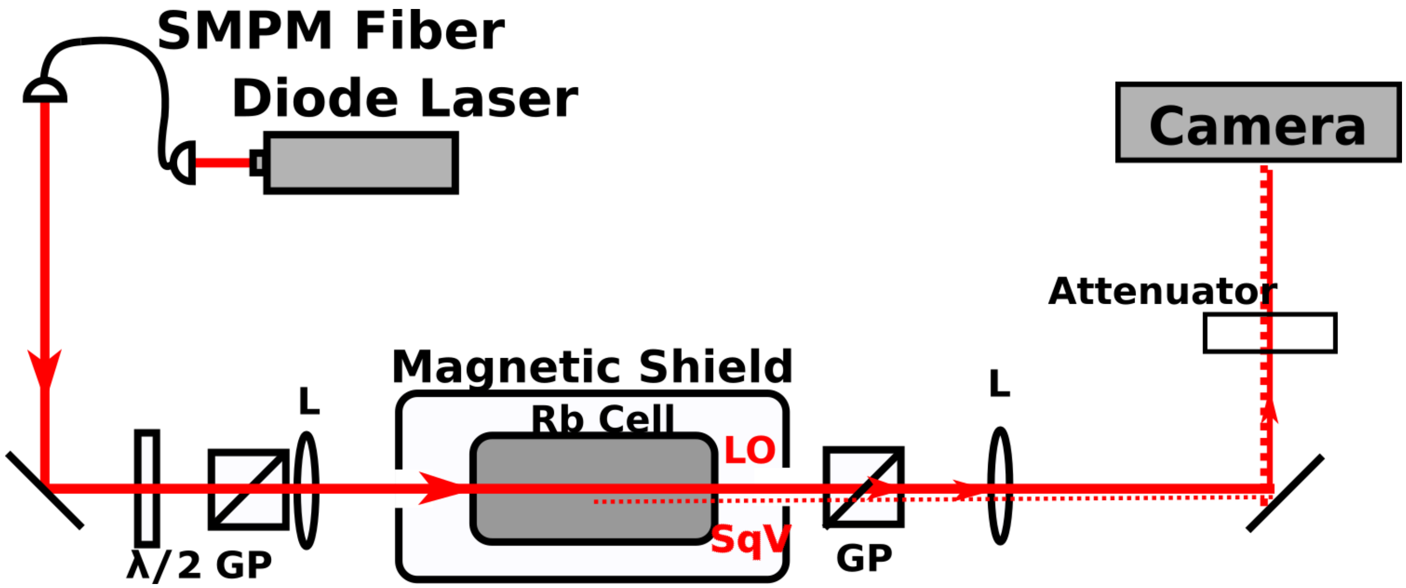
Original squeezing = -0.7 dB   Improved squeezing = -1.2 dB

Change of Local Oscillator



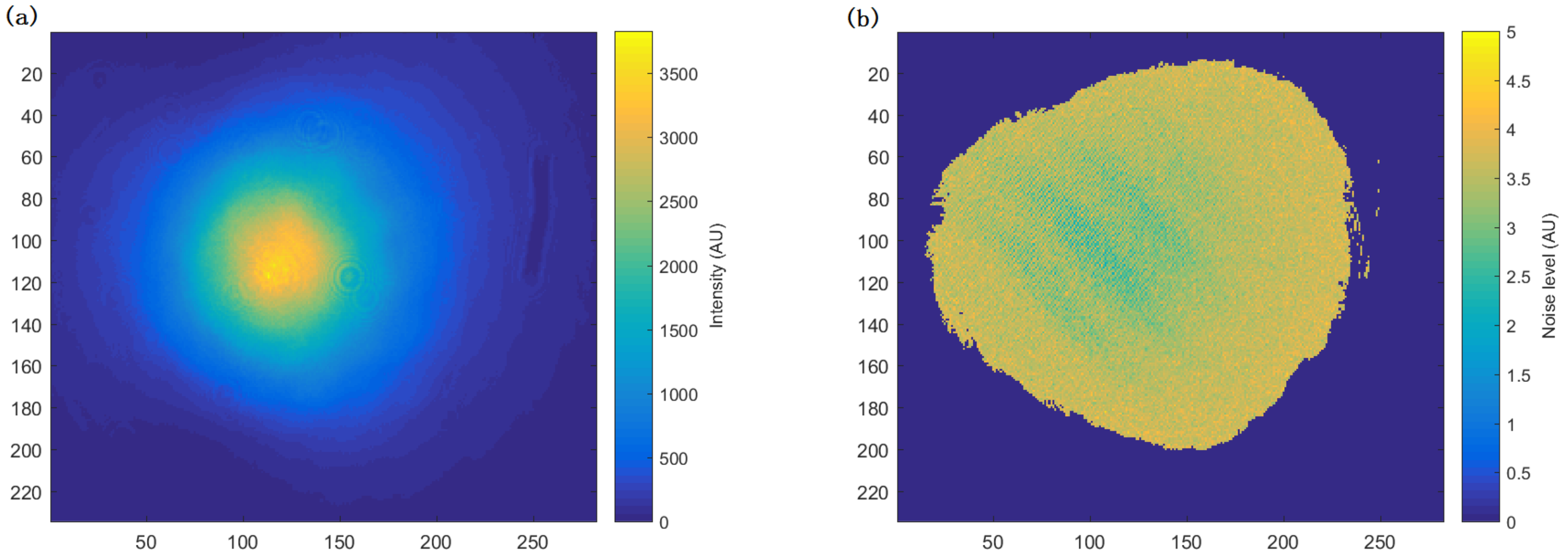
Original squeezing = -1.8 dB
Squeezing with SLM on = -1.0 dB

Direct observation of beam



Camera: Princeton Instruments PIXIS
Attenuator : neutral density filters

Noise calibration in a coherent beam



Averaged photon number
$\overline{N}$

Normalized photon number noise
$\overline{N}/\Delta N^2$

For coherent beam, there should be $\Delta N^2 = \overline{N}$

Figure credit: K. T. Kutzke

Noise statistics

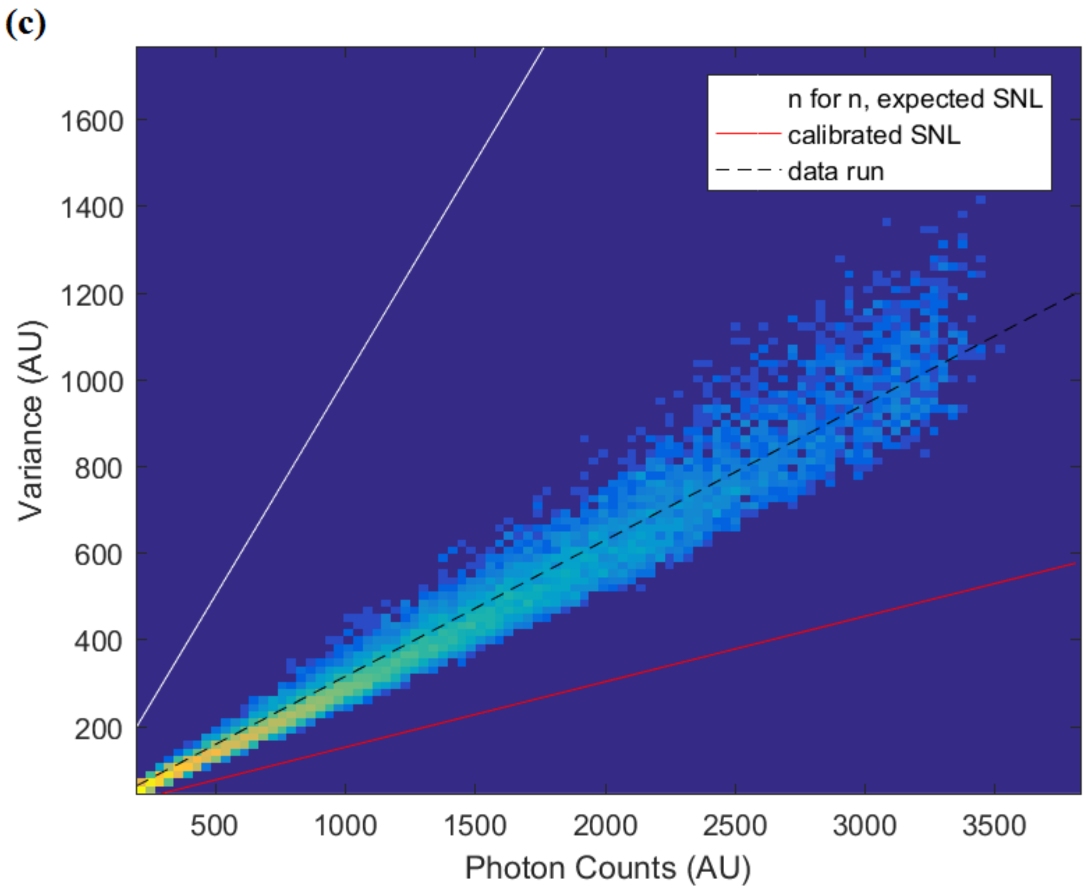
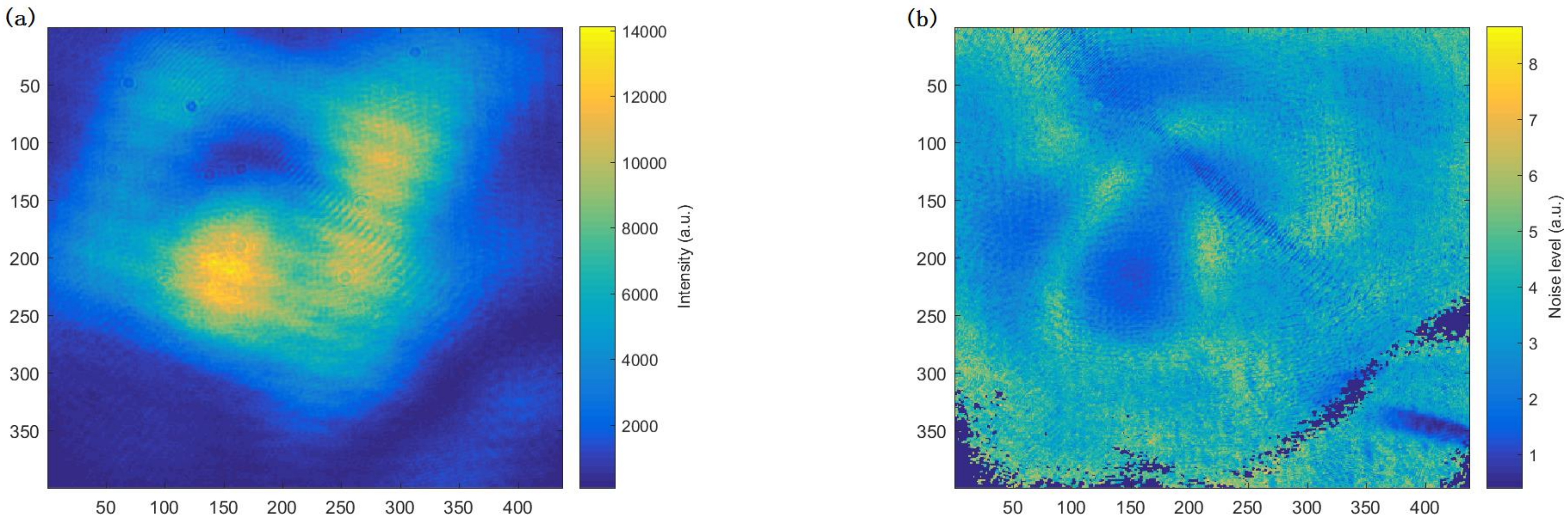


Figure credit: K. T. Kutzke

Squeezed field



Averaged photon number
$\bar{N}$

Normalized photon number noise
$\bar{N}/\Delta N^2$

The normalized noise map has a clear spatial structure.

Figure credit: K. T. Kutzke

Noise structure in a squeezed vacuum field

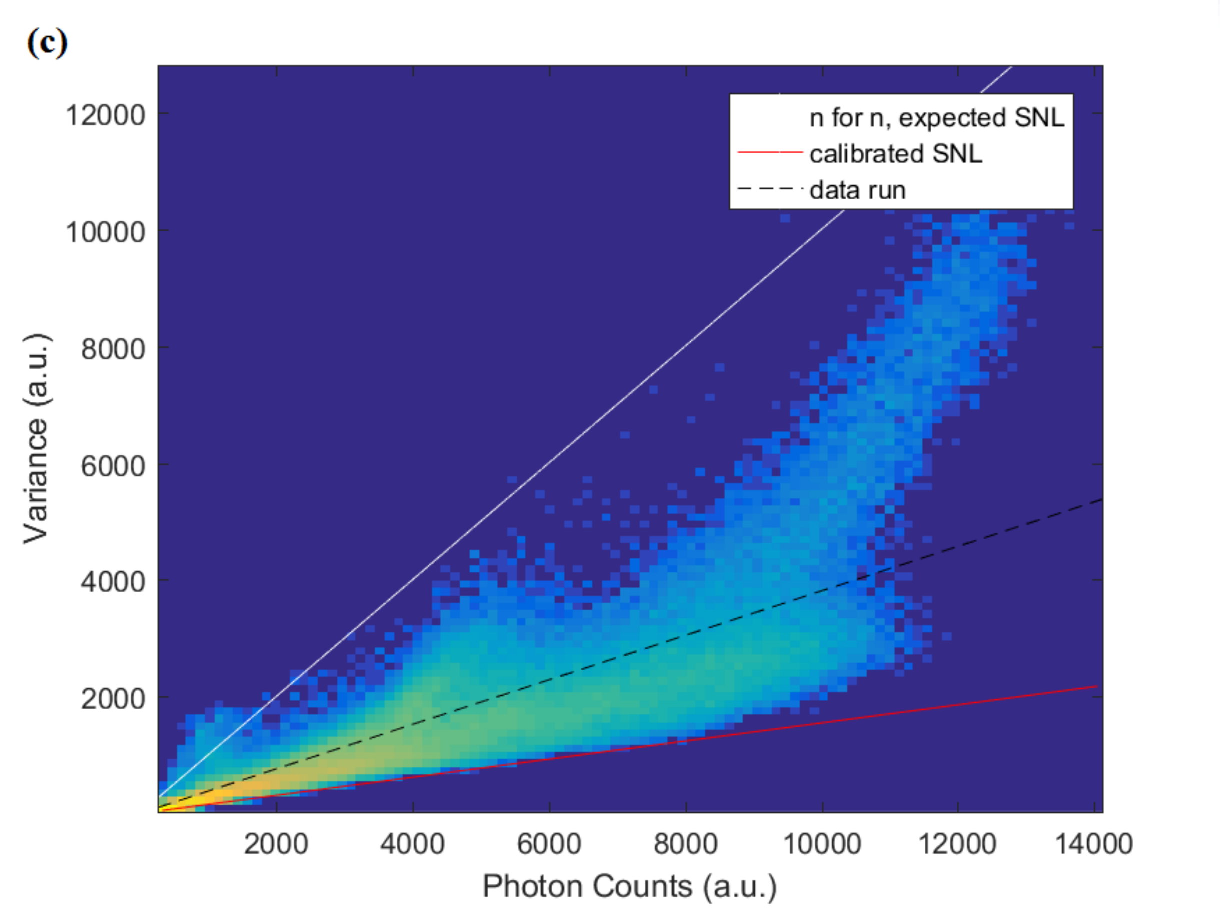


Figure credit: K. T. Kutzke

Conclusions

- We are able to produce -2.7 dB of squeezing below shot noise
- The squeezed vacuum field generated in hot Rb vapor is in a multi-mode structure
- The optical depth of medium is not the only factor that determines squeezing
- Pump beam shape influences the squeezing generated in the medium, and is possible to improve it.
- With a quantum noise limited camera, we can see a spatial dependence of noise in the squeezed vacuum field.

Acknowledgment

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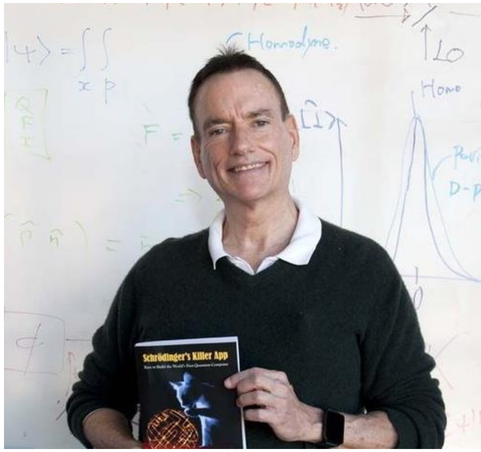
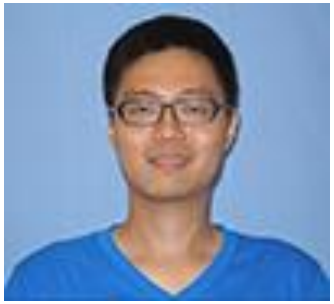
Quantum Optics Group @ College of William and Mary

Louisiana State University



Jonathan P. Dowling

R. Nicholas Lanning



Zhihao Xiao