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Exploring the multi-mode structure of atom-generated squeezed light

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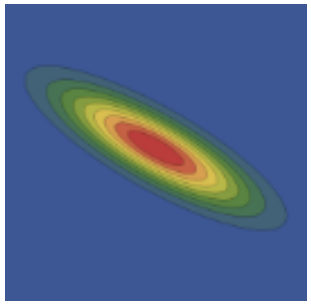
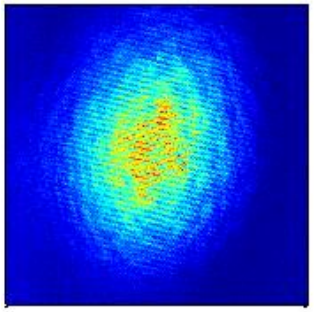
Outline





- Introduction to light quadratures
  - Squeezed light
  - Applications
  - Squeezing through atoms
- Experiment
  - Noise detection
  - Pump beam mode optimization
  - Local oscillator mode shaping
- Conclusions and outlook
  - Spatial photon statistics

Quantum fluctuations

$$\hat{E}(z,t) = E_0(z)\left(\hat{a}e^{-i\omega t} + \hat{a}^{\dagger}e^{i\omega t}\right)$$
$$= 2E_0(z)(\hat{X}_1 cos\omega t + \hat{X}_2 sin\omega t)$$

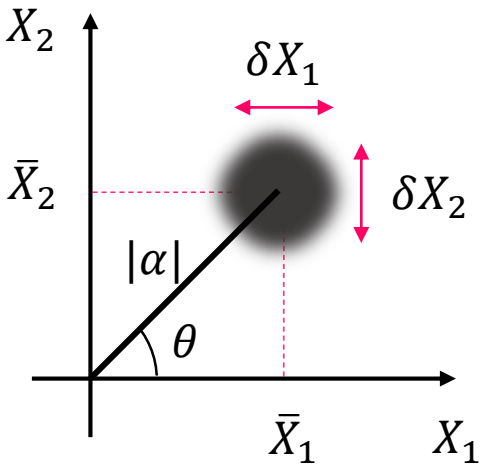
Quantization of the EM-field

Quadrature operators

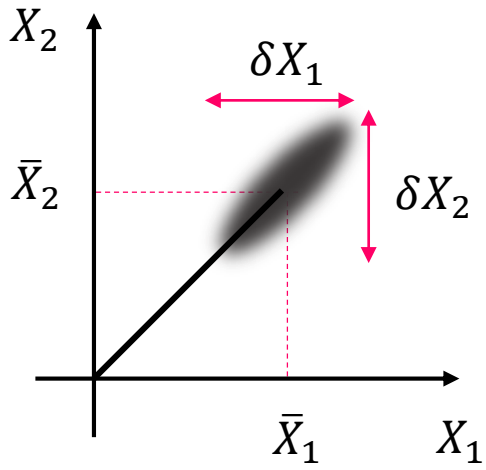
$$\hat{X}_1 = (\hat{a}^{\dagger} + \hat{a})/2$$
$$\hat{X}_2 = i(\hat{a}^{\dagger} - \hat{a})/2$$

Non-commutative: $\delta X_1 \delta X_2 \geq \frac{1}{4}$

Coherent state $(\delta X_1 = \delta X_2 = \frac{1}{2})$



Squeezed state $(\delta X_{sq} < \frac{1}{2})$

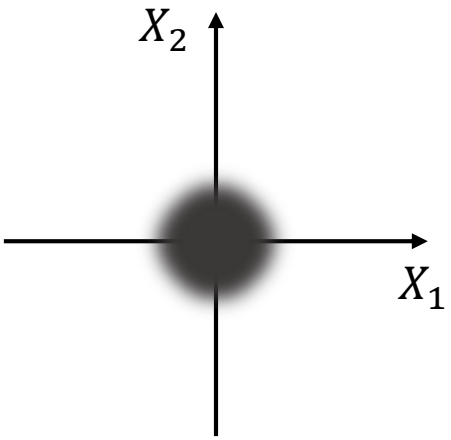


Squeezed vacuum

$$\langle 0|\, \hat{E}\, |0\rangle = 0$$

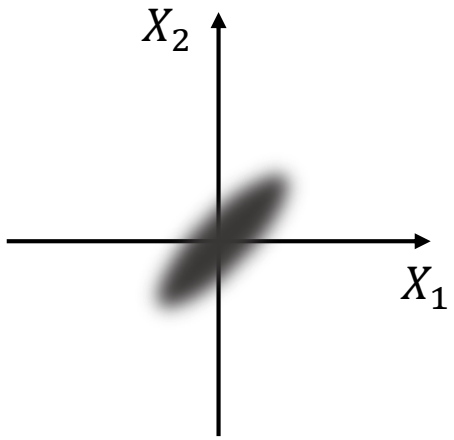
Coherent vacuum

$(\delta X_1 = \delta X_2)$



Squeezed vacuum

$(\delta X_{sq} < 1/2)$

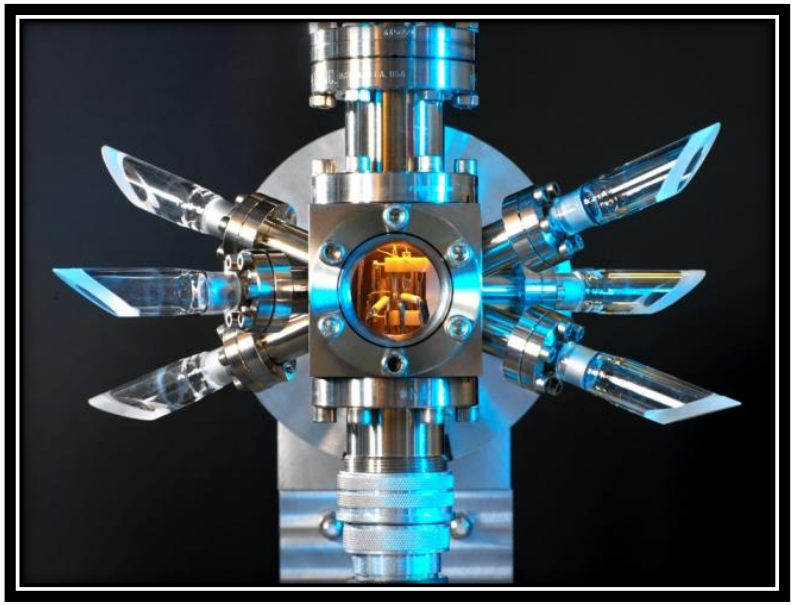


Applications:

- Quantum probe in EIT-based quantum memory
- Enhanced laser interferometry (GEO600, LIGO)
- Precision metrology

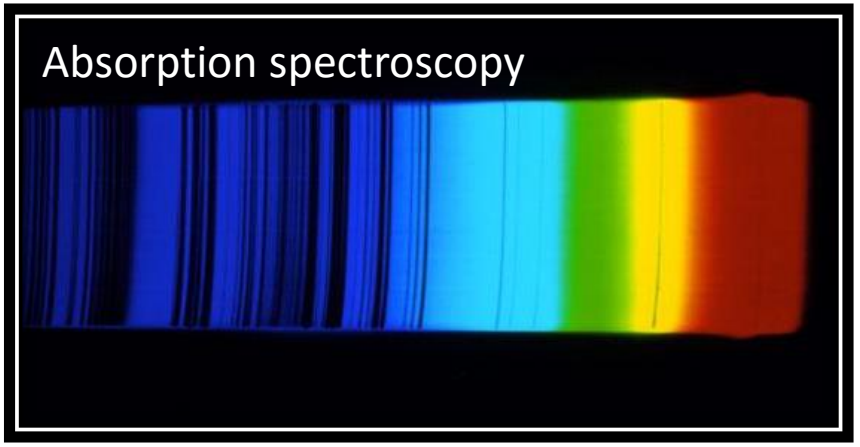
Applications

Atomic clocks



Interferometric gravitational wave detectors

2 dB squeezing: 26% sensitivity improvement[1]



[1]H. Grote et al. *Phys. Rev. Lett.* **110**, 181101 (2013).

Squeezing measurement

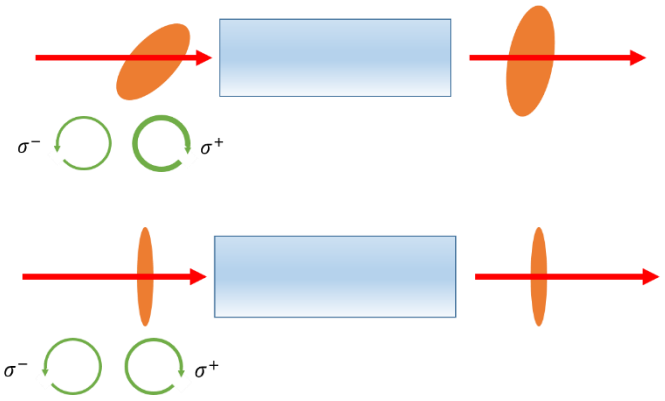
- Polarization self-rotation
  - Predicted squeezing: -8 dB

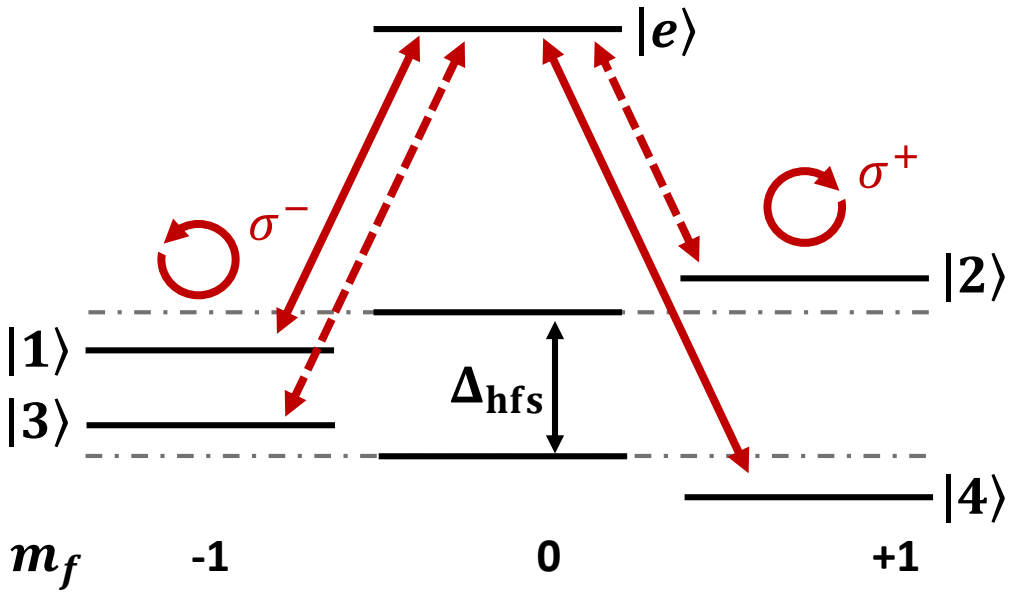
    A. B. Matsko, I. Novikova, G. R. Welch, D. Budker, D. F. Kimball, and S. M. Rochester. Phys. Rev. A **66**, 043815 (2002)

  - Best squeezing: -3 dB

    S. Barreiro, P. Valente, H. Failache, and A. Lezama Phys. Rev. A 84, 033851 (2011)

  - Our squeezing: -2.7 dB



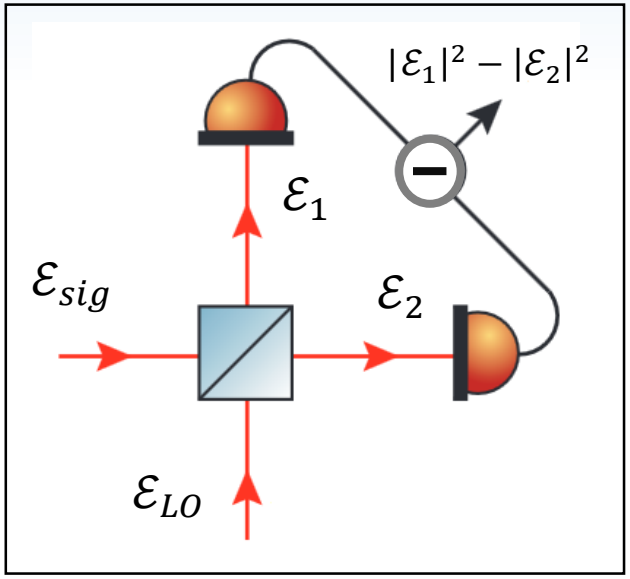


Homodyne detection

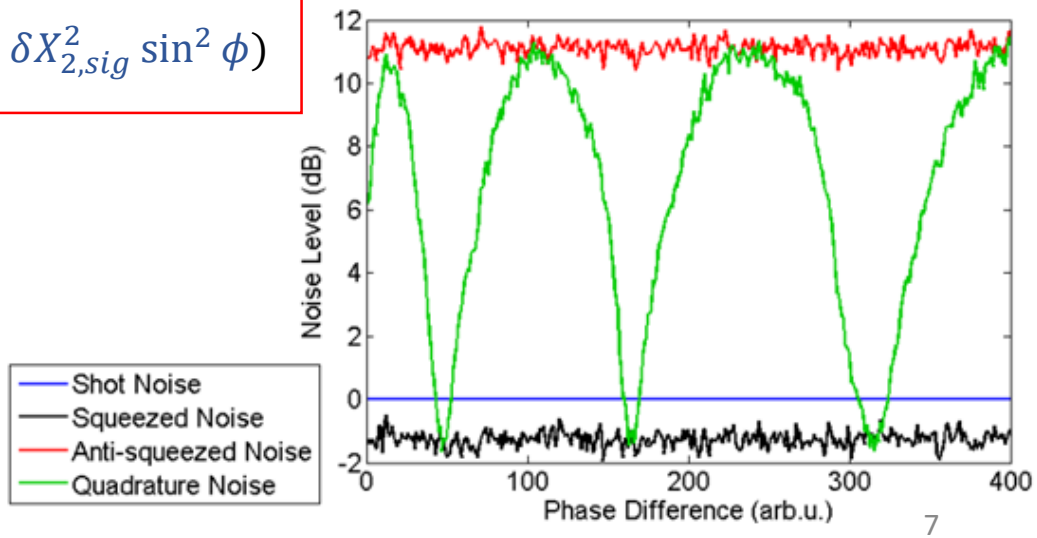
$$\mathcal{E}_{sig}(t) = \mathcal{E}_{sig} + \delta X_{1,sig}(t) + \delta X_{2,sig}(t)$$
$$\mathcal{E}_{LO}(t) = \left[\mathcal{E}_{LO} + \delta X_{1,LO}(t) + \delta X_{2,LO}(t)\right]e^{i\phi}$$

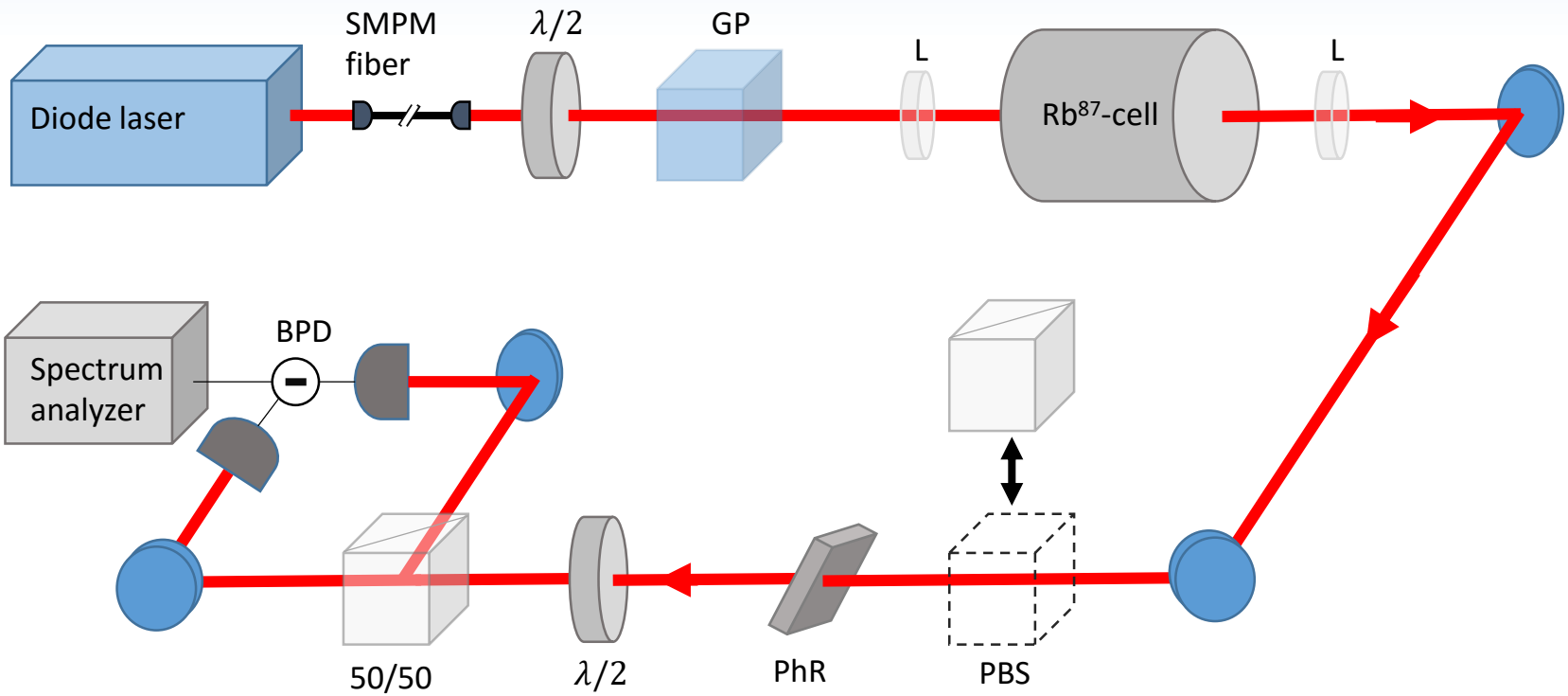
$$\mathcal{E}_1 = \sqrt{1/2}\mathcal{E}_{LO}(t) + \sqrt{1/2}\mathcal{E}_{sig}(t)$$
$$\mathcal{E}_2 = \sqrt{1/2}\mathcal{E}_{LO}(t) - \sqrt{1/2}\mathcal{E}_{sig}(t)$$

$$|\mathcal{E}_1|^2 - |\mathcal{E}_2|^2 \approx 2\mathcal{E}_{LO}\left(\delta X_{1,sig}\cos\phi + \delta X_{2,sig}\sin\phi\right)$$



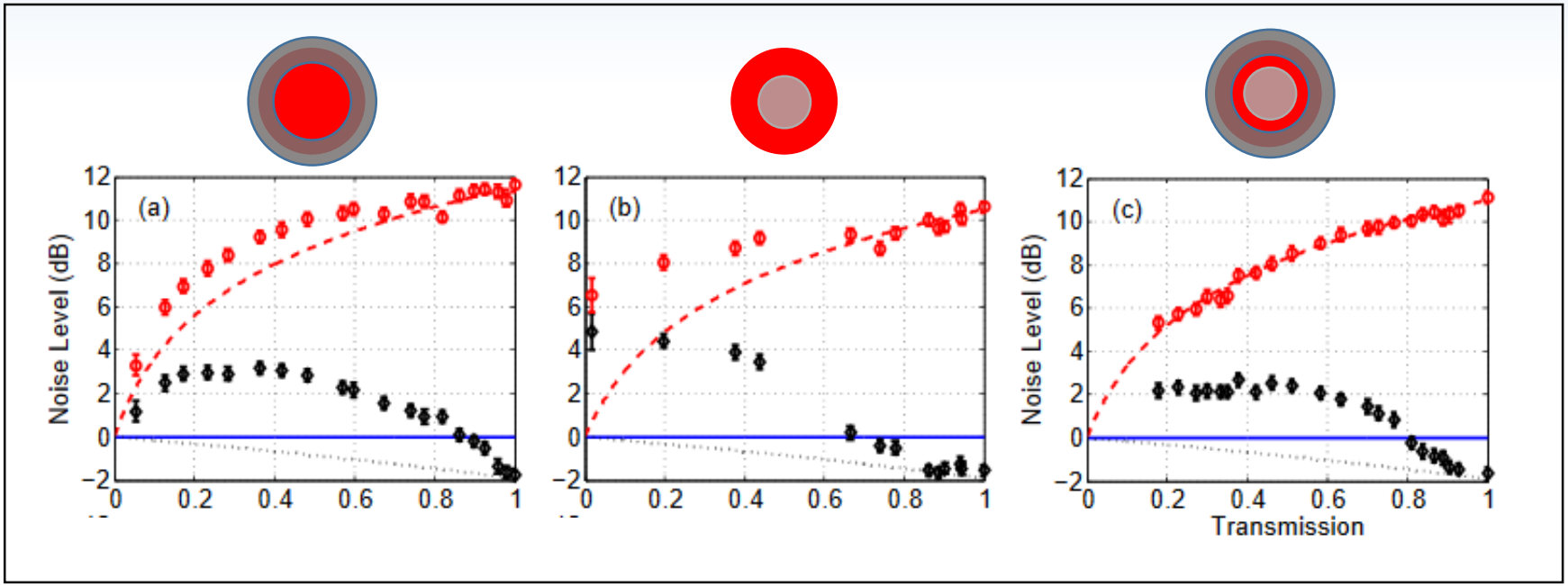
$$V[|\mathcal{E}_1|^2 - |\mathcal{E}_2|^2] \propto 4\mathcal{E}_{LO}^2(\delta X_{1,sig}^2\cos^2\phi + \delta X_{2,sig}^2\sin^2\phi)$$



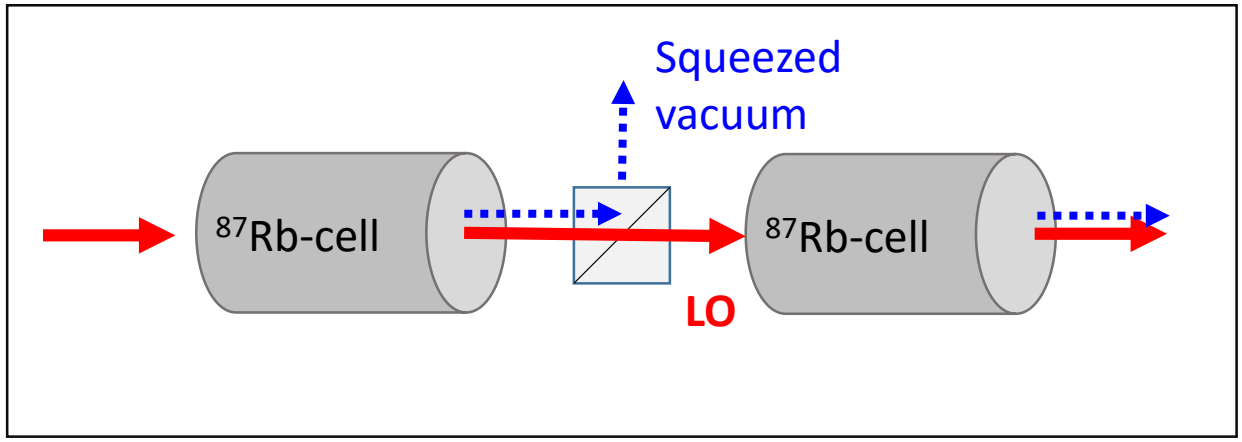


SMPM	Single-mode polarization-maintaining
M	Mirror
SLM	Spatial light modulator
GP	Glenn Polarizer
PhR	Phase-retarding plate
BPD	Balanced photodiodes

Mode structure

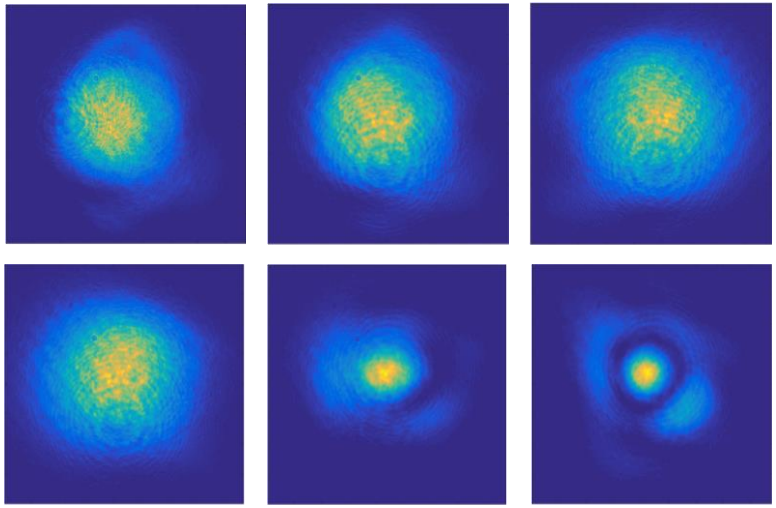


M. Zhang, et al. *Phys. Rev. A*, 93:013853, 2016.



Multi-mode generation

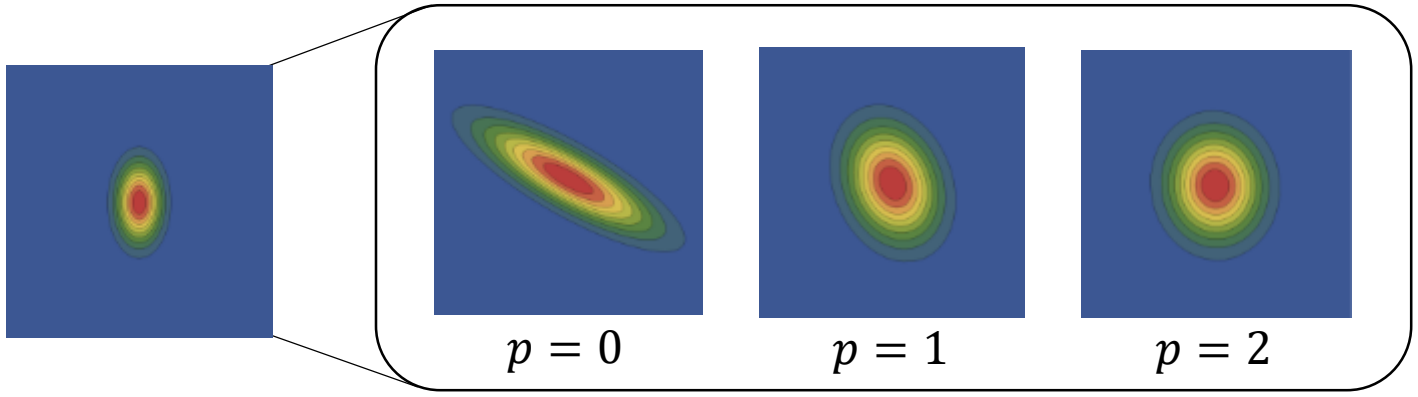
Local oscillator imaging

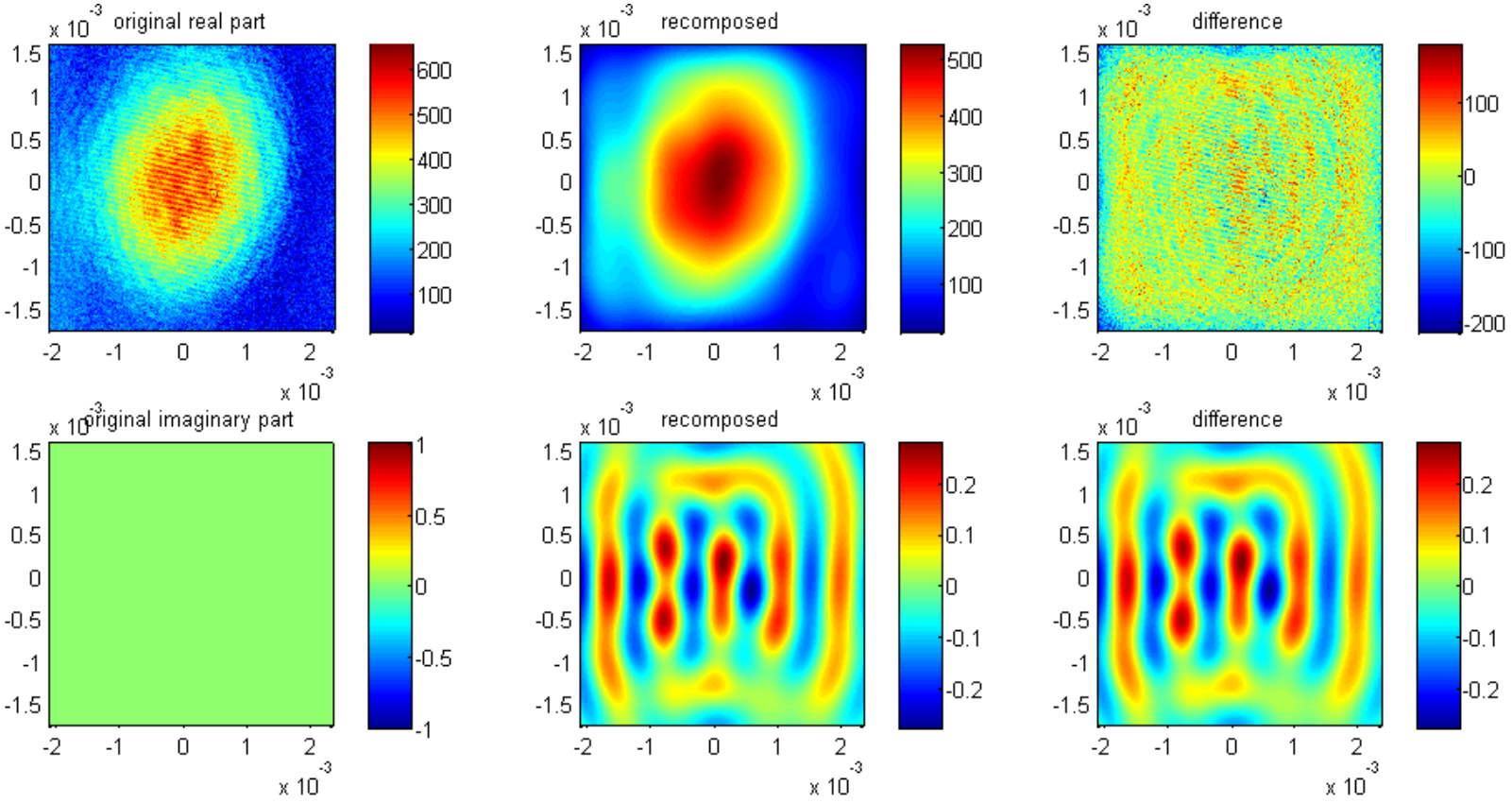


Increasing atomic density ⟶

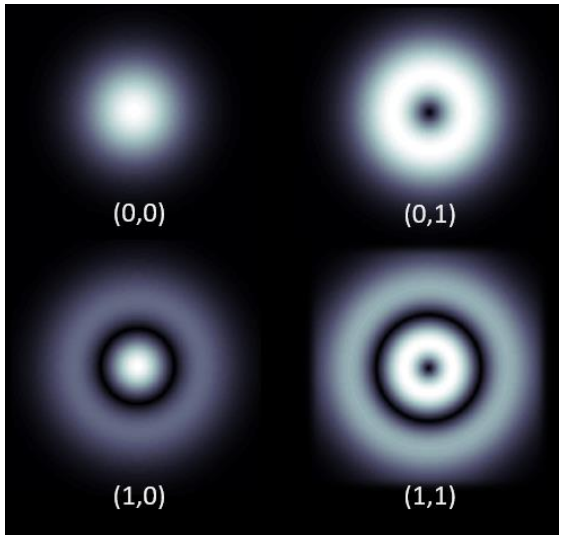
Mi Zhang, R. Nicholas Lanning, Zhihao Xiao, Jonathan P. Dowling, Irina Novikova, and Eugeniy E. Mikhailov, Phys. Rev. A **93**, 01385 (2016)

- Complex spatial structure of the squeezed field
  - Local oscillator and vacuum field both experience spatial dependence on atomic density
  - Spatial distribution of pump beam influences squeezing

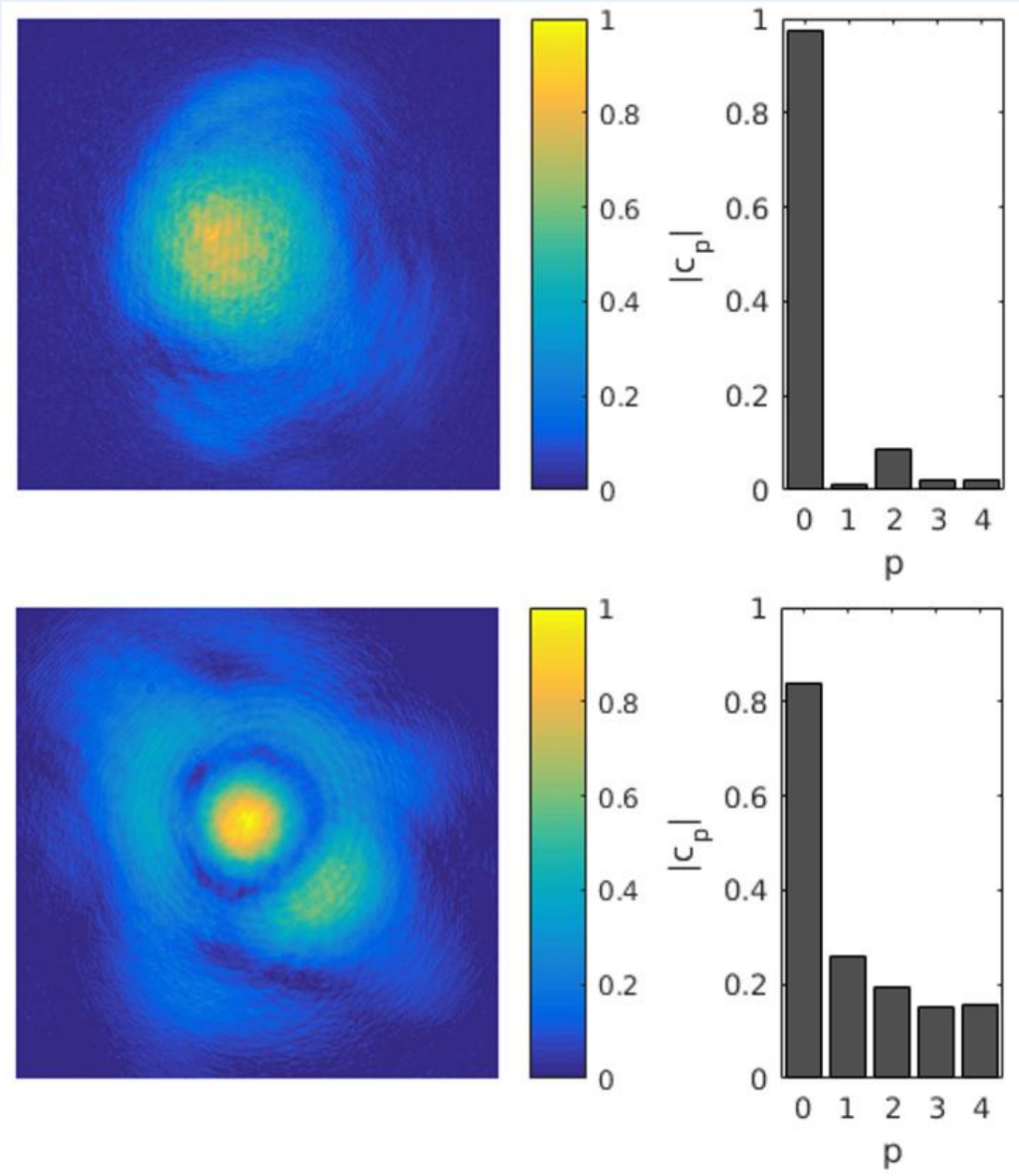



original real part
recomposed
difference
original imaginary part
recomposed
difference
x 10^-3

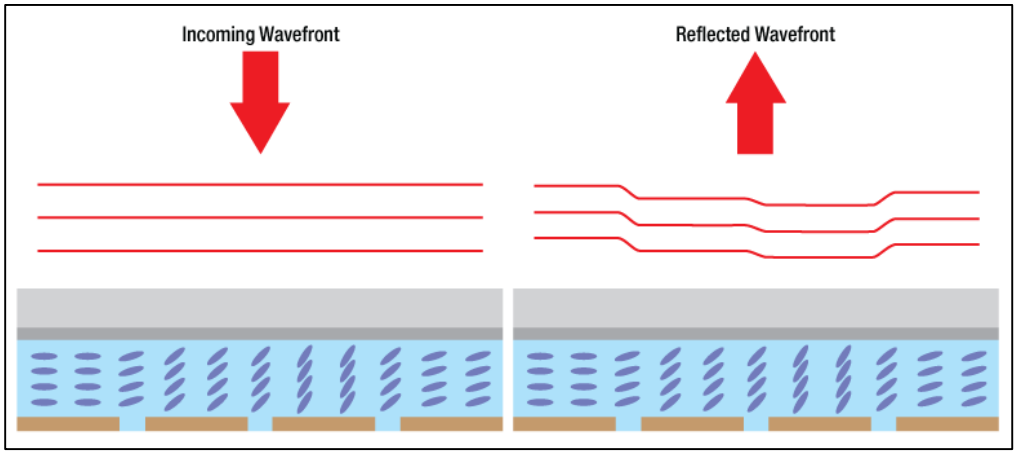
Laguerre-Gaussian (LG) modes

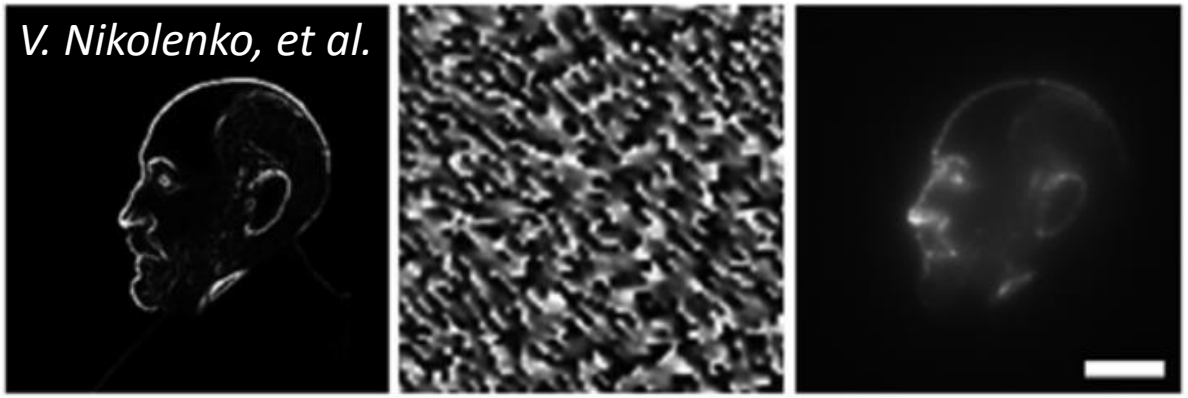


- Higher order mode generation
  - Power moved from Gaussian mode to higher order LG modes

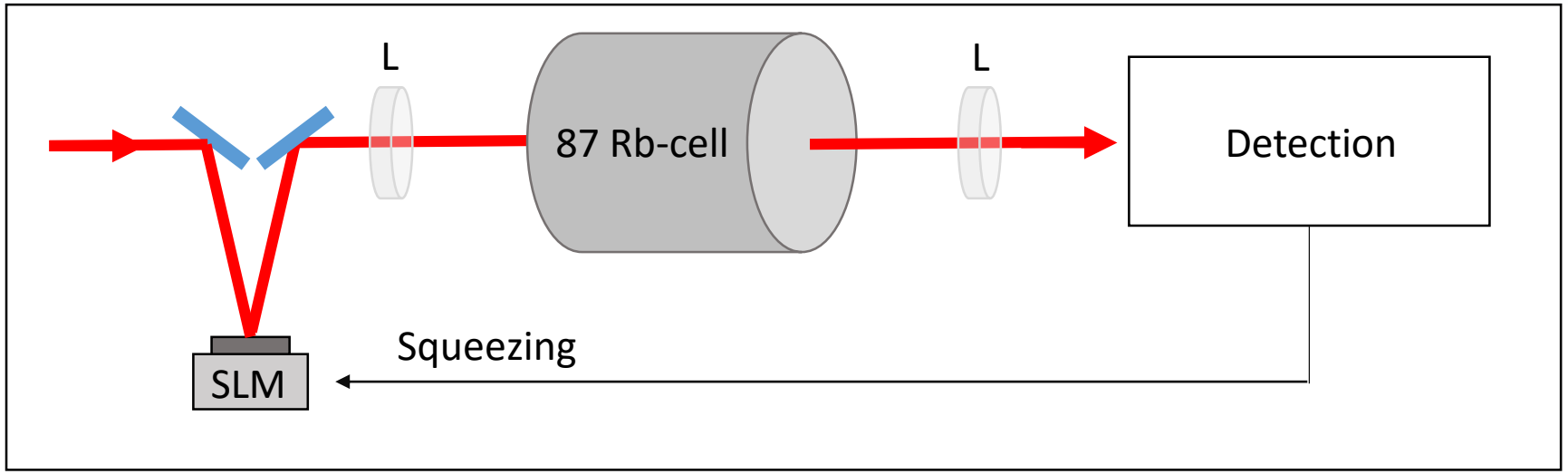


Spatial light modulator





Desired image Phase mask Fluorescence

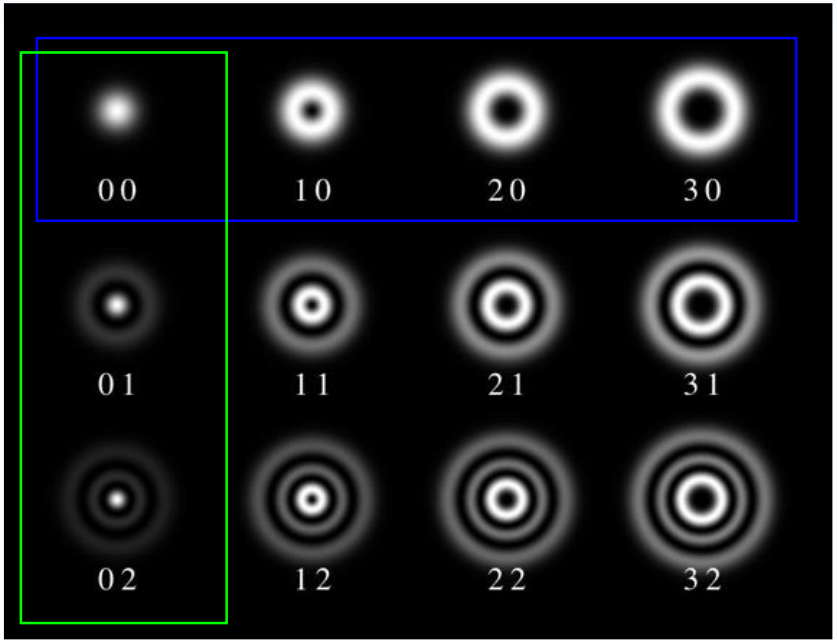


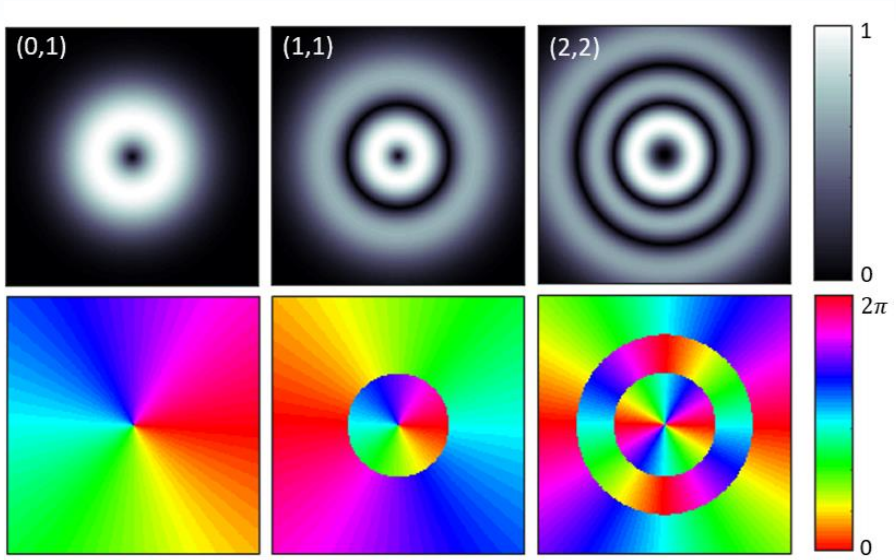
Pump beam mode structure optimization:

1. Set an initial phase mask
2. Measure squeezing
3. Alter the phase mask
4. Measure squeezing
5. Reject or accept move

$$p = \exp\left(-\frac{E_{new} - E}{k_B T}\right)$$

Spatial optimization



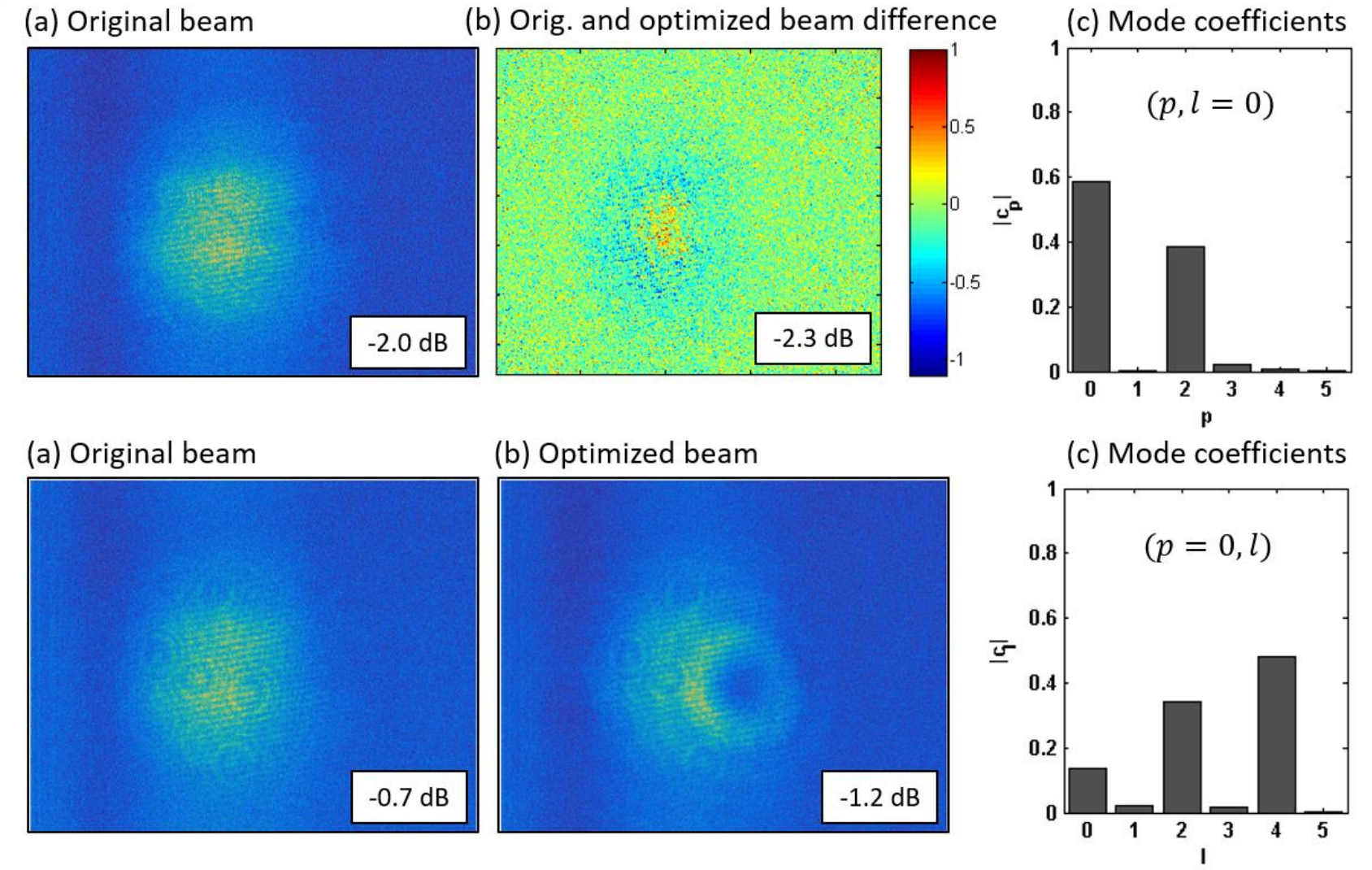


Phase mask applied to the SLM is composed of N higher modes, setting $l = 0$ or $p = 0$:

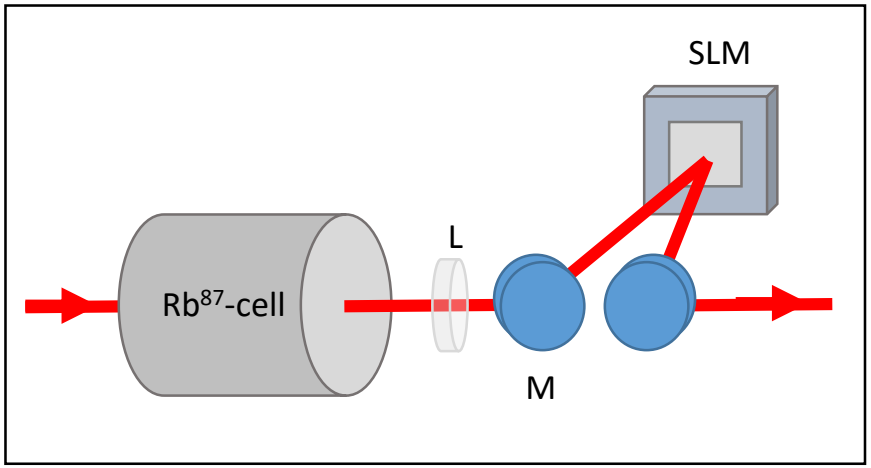
$$\Phi(x,y) = \sum_{i=1}^{N} (C_{iR} + iC_{iI})\, \Phi_i(x,y,w)$$

C_{iR} and C_{iI} are the real and imaginary components of the coefficient. $\Phi_i(x,y,w)$ is the phase of the i^{th} mode with waist w.

Pump beam optimization



Local oscillator optimization

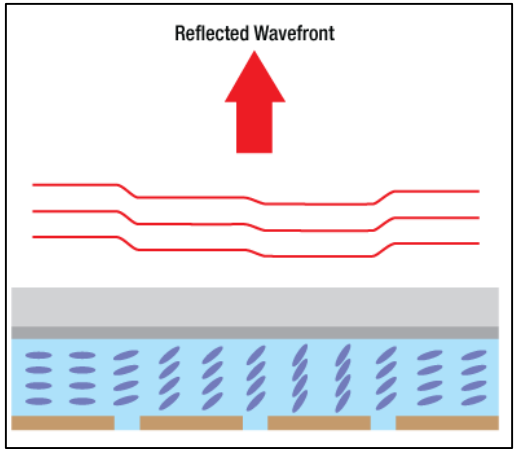


Original squeezing: -1.8 dB
Squeezing with SLM turned on: -1.0 dB

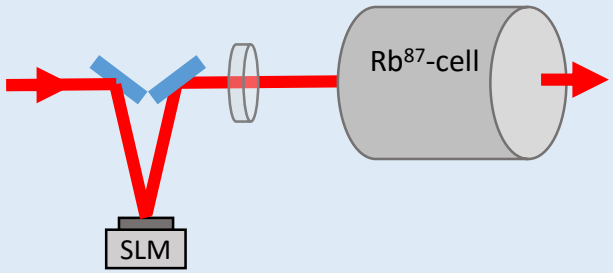
No improvement was observed.

Possible explanation:

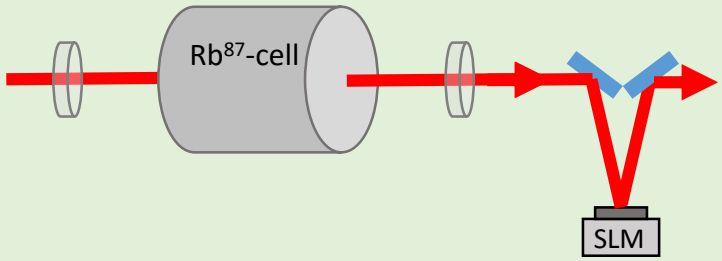
- Voltage applied to liquid crystals induces oscillations
- Oscillating crystals → Phase oscillations
- Induces cycling through quadratures, averaging greater noise



Optimization summary



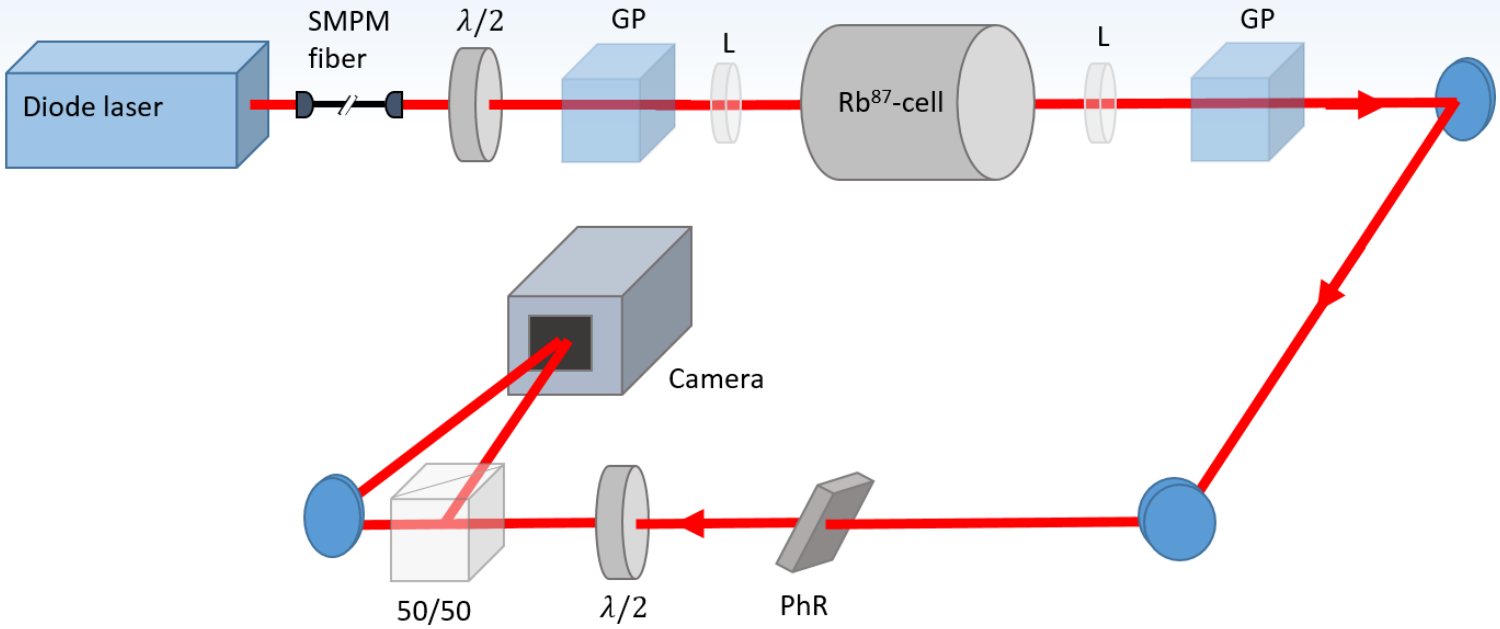
*Reshaping the **pump beam** using the SLM can improve squeezing under some conditions.*

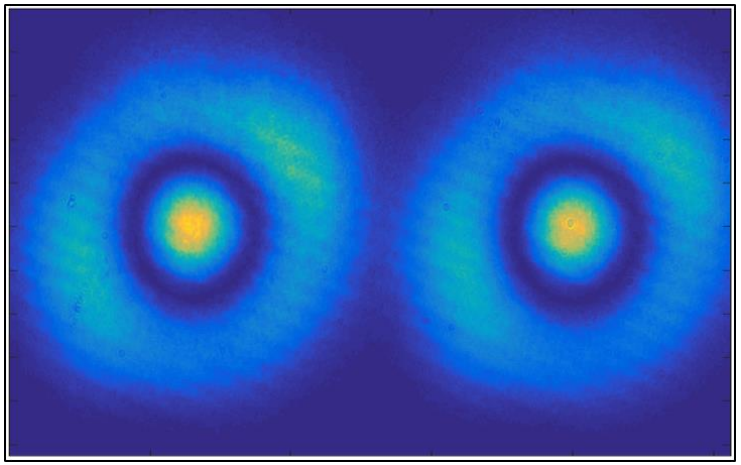


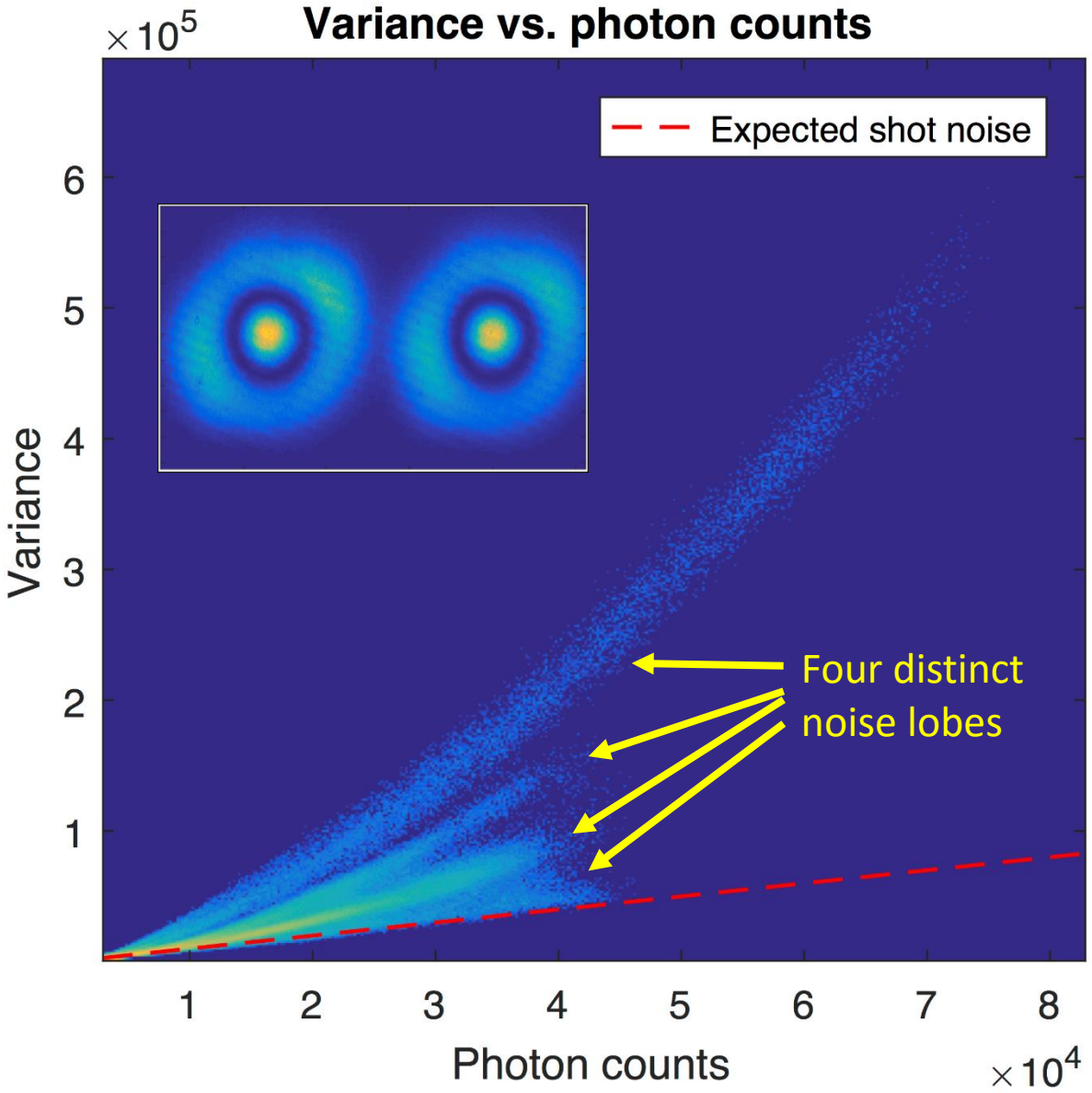
Reflection off of the SLM deteriorates squeezing in the on state.

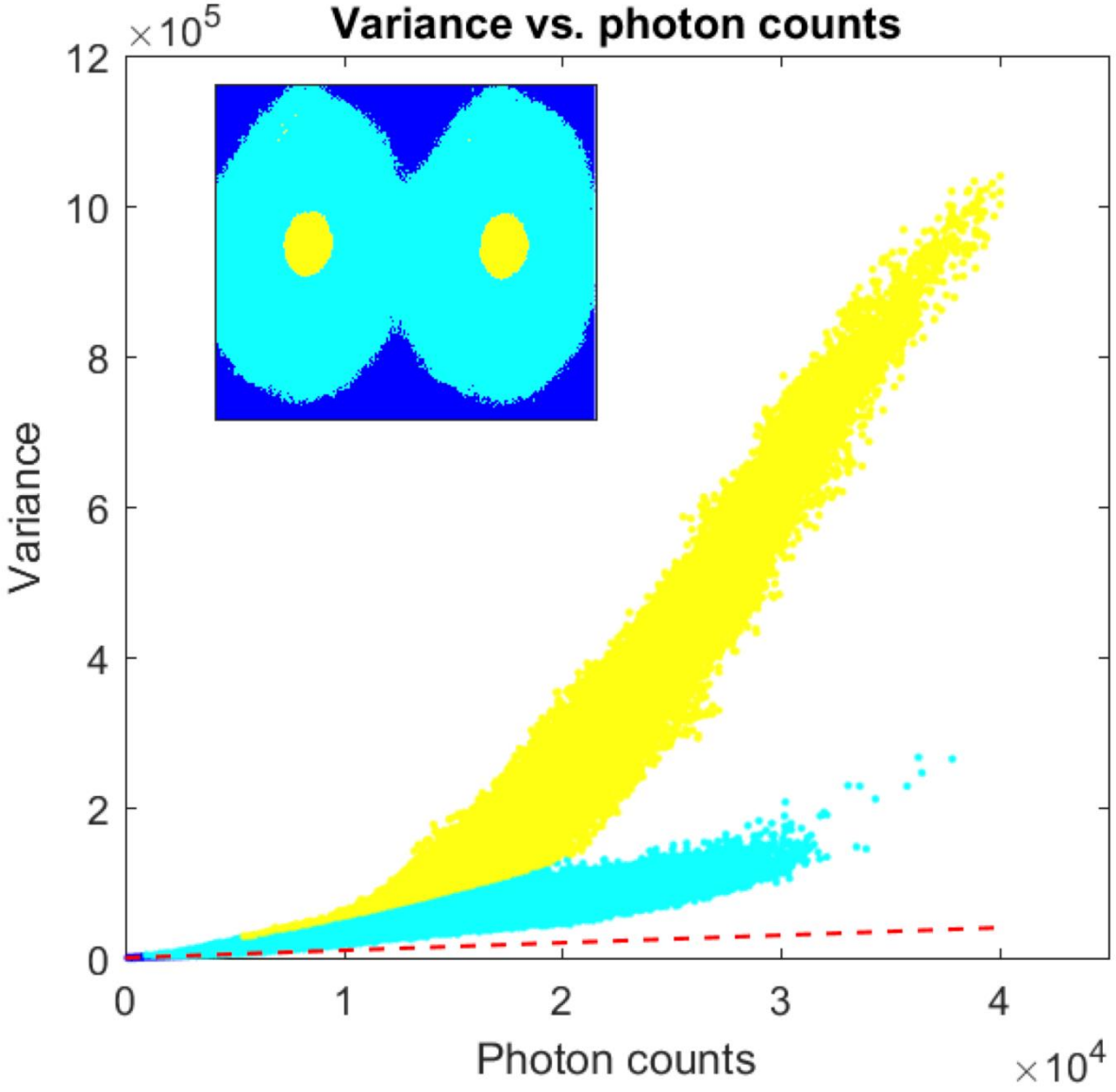
Looking at spatial squeezing directly?

- Quantum noise-limited camera
- Measure photon statistics


Diode laser
SMPM fiber
$\lambda/2$
GP
L
Rb^{87}-cell
L
GP
Camera
50/50
$\lambda/2$
PhR




Variance vs. photon counts
×10^5
Expected shot noise
Variance
6
5
4
3
2
1
Four distinct
noise lobes
1
2
3
4
5
6
7
8
Photon counts
×10^4


Variance vs. photon counts
×10^5
12
10
8
6
4
2
0
Variance
0
1
2
3
4
Photon counts
×10^4

Outlook

- AOM shutter
- Camera kinetic mode subtraction with knife blade
- Low frequency removal
- Camera artifact removal
- **Spatial correlations in noise**

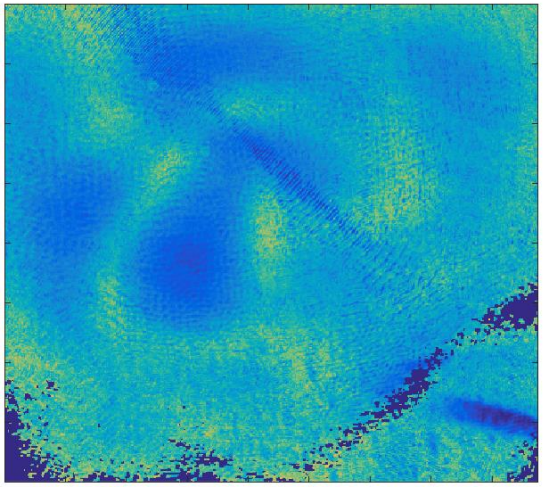
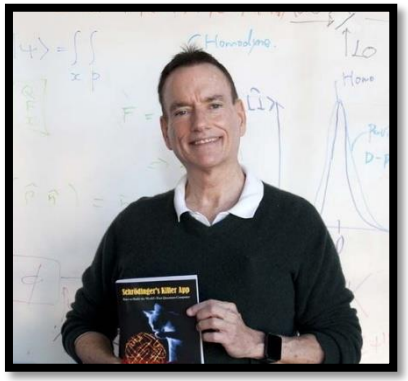


Figure source: africa-wildlife-detective.com

Acknowledgements

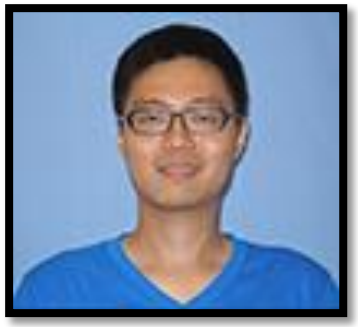
William & Mary
Quantum Optics Group

Louisiana State University



Jonathan P. Dowling

R. Nicholas Lanning



Zhihao Xiao

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