Recent Results in Quantum Imaging

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with Kam Wai Chan, Ksenia Dolgaleva, Anand Jha, Colin O'Sullivan, Heedeuk Shin, Petros Zerom, Mehul Malik, John Howell, John’s students and many others.

Presented at the SPIE Optics and Photonics Conference August 10-14 2008, San Diego, CA.

Recent Results in Quantum Imaging

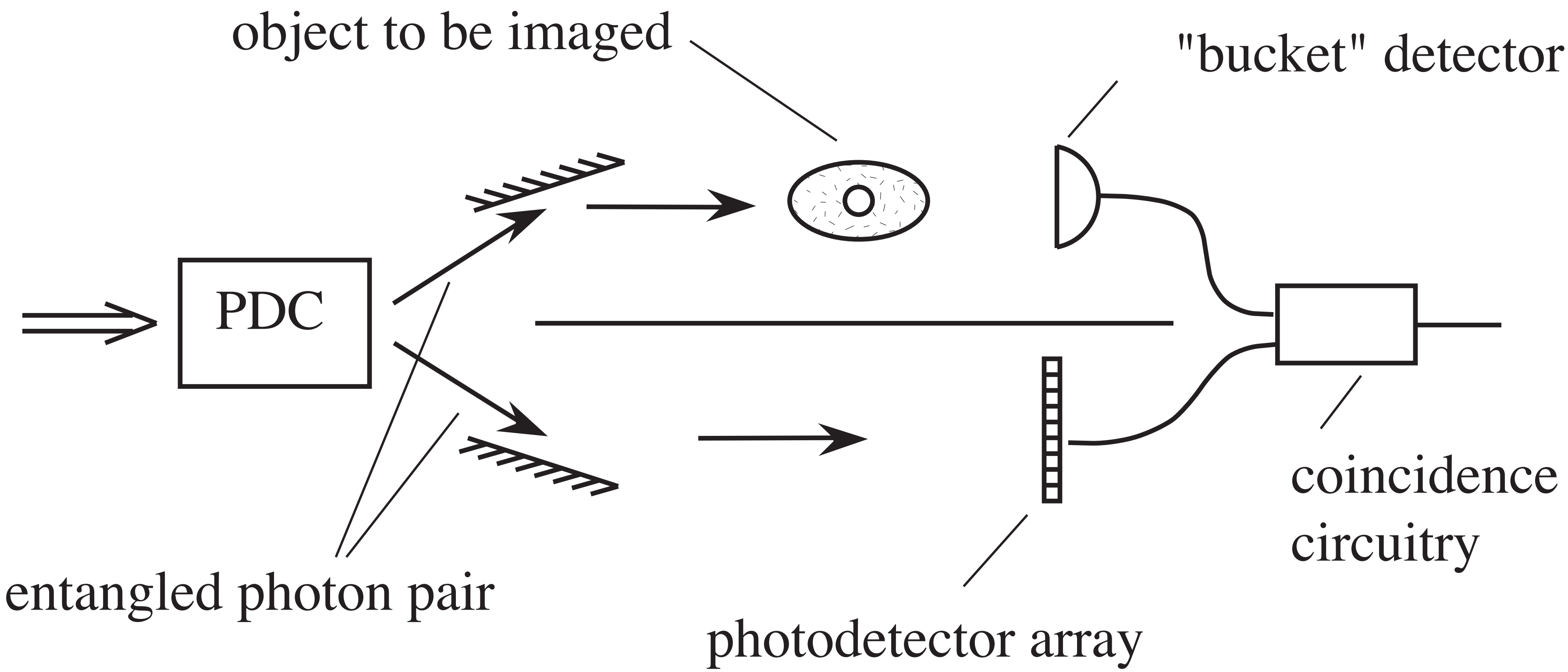
Nature of Quantum Imaging:

Image formation with higher resolution or better sensitivity through use of quantum states of light.

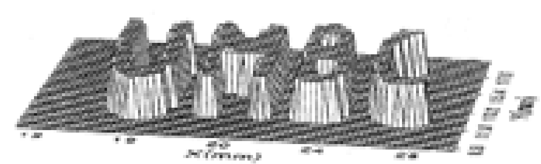
Outline of This Presentation:

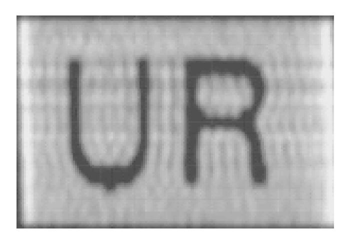
- New results on ghost imaging
- Use of OAM states for quantum communication
- Imaging with single photons

Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)



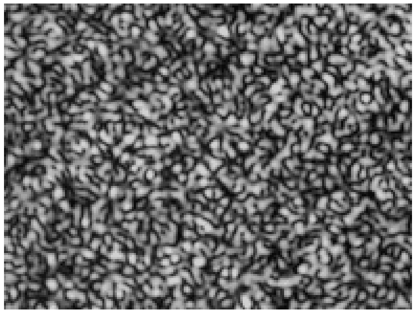


Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).

Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004)
Gatti, Brambilla, and Lugiato, PRL 90 133603 (2003)
Gatti, Brambilla, Bache, and Lugiato, PRL 93 093602 (2003)

Thermal Ghost Imaging

Instead of using quantum-entangled photons, one can perform ghost imaging using the correlations of a thermal light source, as predicted by Gatti et al. 2004.



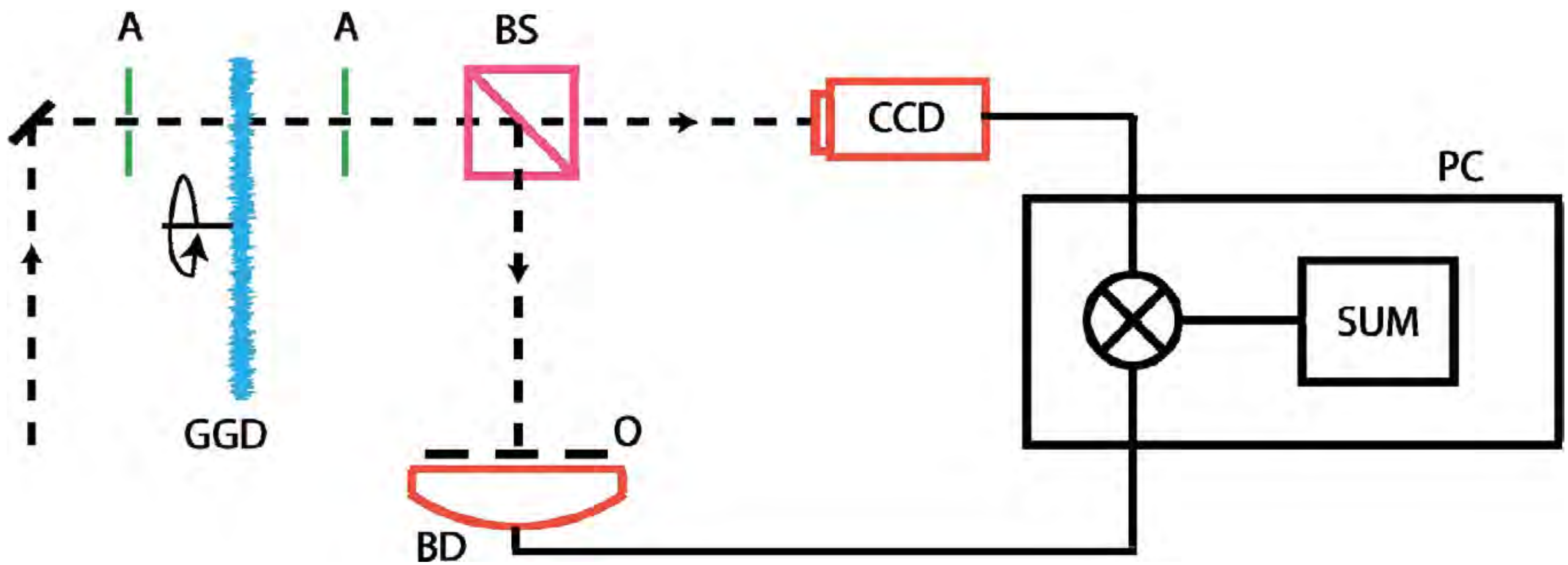
Recall that the intensity distribution of thermal light looks like a speckle pattern.

We use pseudothermal light inour studies: we create a speckle pattern with the same statistical properties as thermal light by scattering a laser beam off a ground glass plate.

Thermal ghost imaging has been observed previously by several groups; our interest is in performing careful studies of its properties.

Meyers, Deacon, Shih (2008)

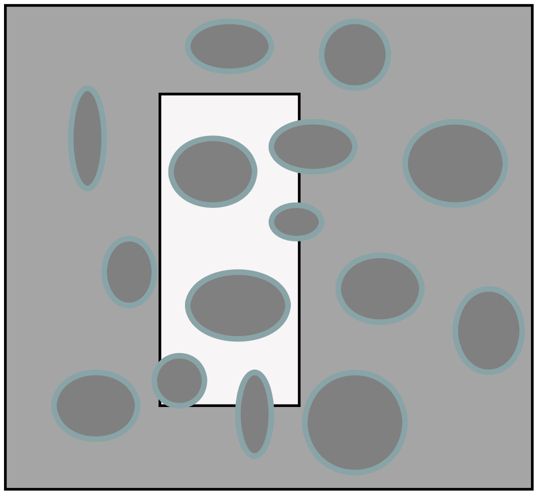
How does thermal ghost imaging work?

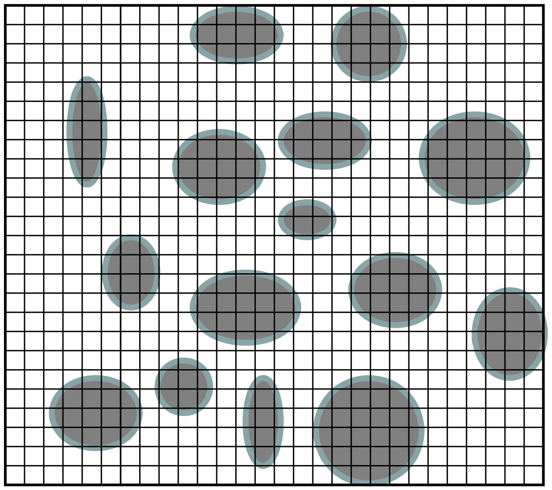


- Ground glass disk (GGD) and beam splitter (BS) create two identical speckle patterns
- Many speckles are blocked by the opaque part of object, but some are transmitted, and their intensities are summed by BD
- CCD camera measures intensity distribution of speckle pattern
- Each speckle pattern is multiplied by the output of the BD
- Results are averaged over a large number of frames.

Origin of Thermal Ghost Imaging

Create identical speckle patterns in each arm.





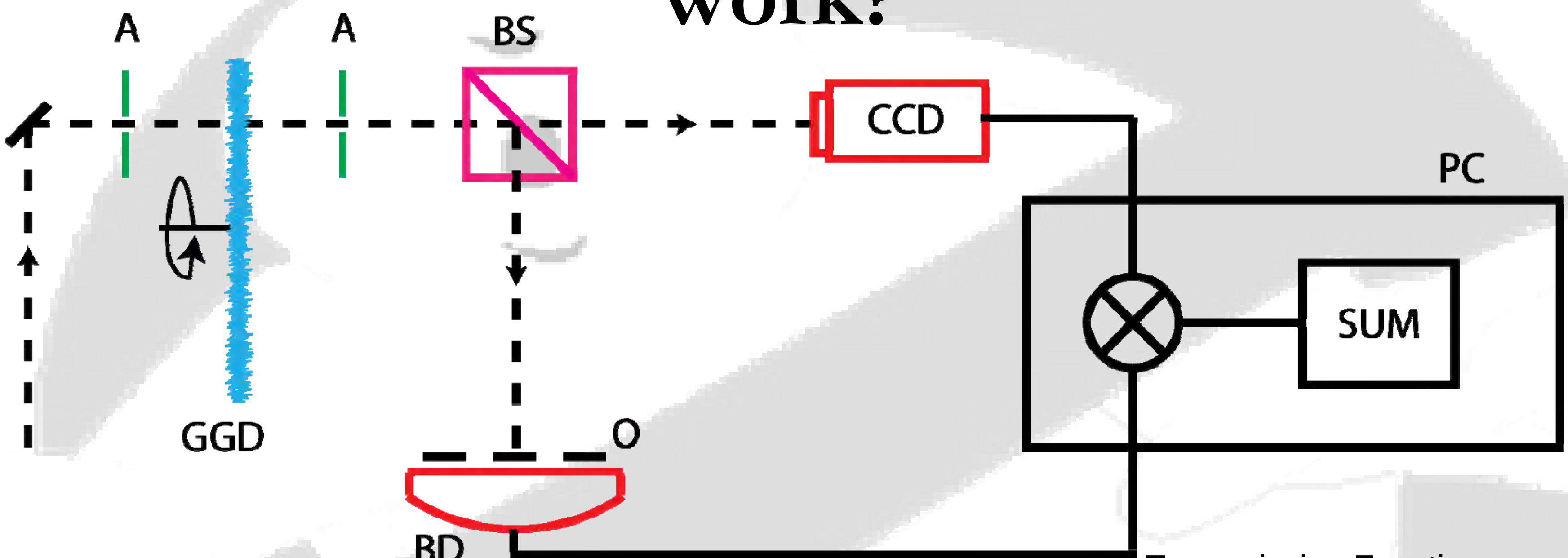
object arm
(bucket detector)

reference arm
(pixelated imaging detector)

$g_1(x,y)$ = (total transmitted power) x (intensity at each point x,y)

Average over many speckle patterns

How does thermal ghost imaging work?



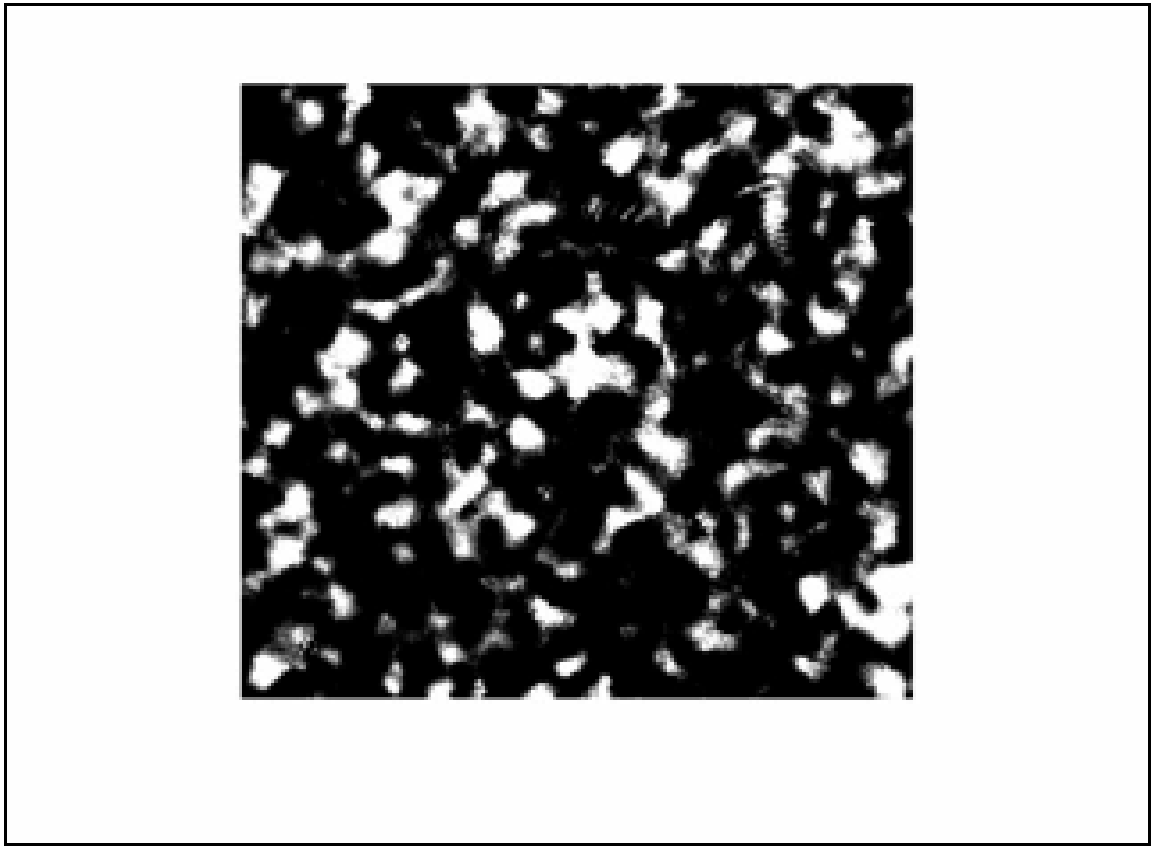
$$\text{Image} = \frac{\langle I_{ccd}(x_i) I_{bucket} \rangle}{\langle I_{ccd}(x_i) \rangle \langle I_{bucket} \rangle} = 1 + \left(\frac{\langle I_{speckle}{}^2 \rangle}{\langle I_{speckle} \rangle^2} - 1 \right) \frac{T(x_i)}{\mathrm{T}}$$

Transmission Function of Object

Background

Number of Speckles that fit in object times av transmission

Demonstration of Image Buildup in Thermal Ghost Imaging

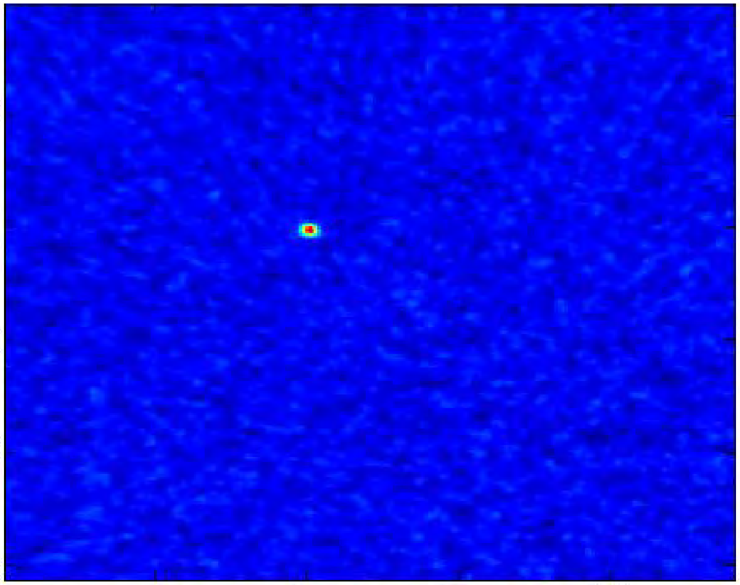


(click within window to play movie)

Influence of Speckle Size on Point Spread Function

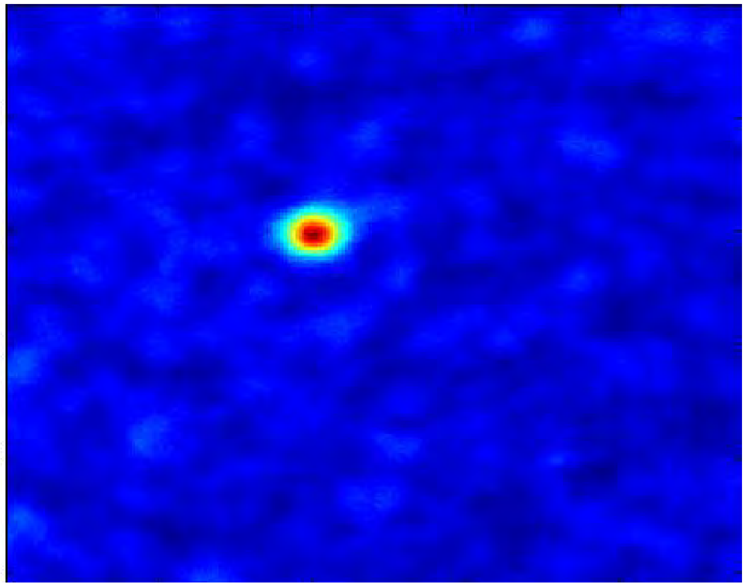
small speckle size

(150 μm)



large speckle size

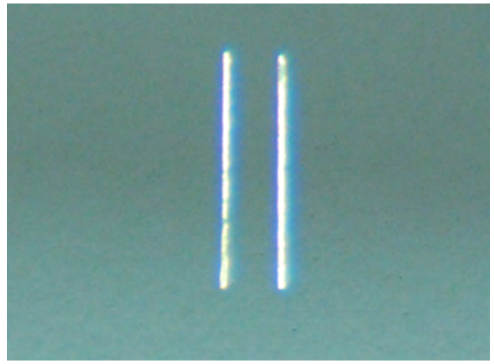
(560 μm)



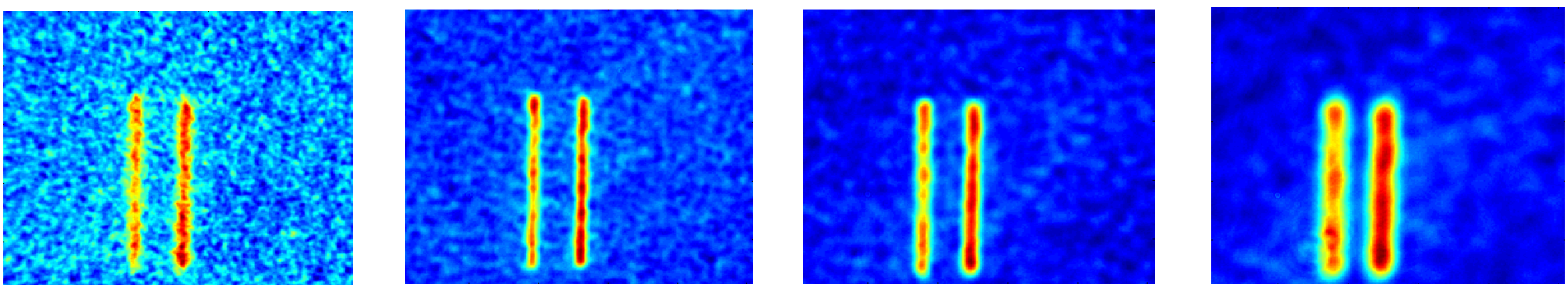
Note that spatial resolution is approximately equal to speckle size

Influence of Speckle Size on Spatial Resolution

Test object (stencil)



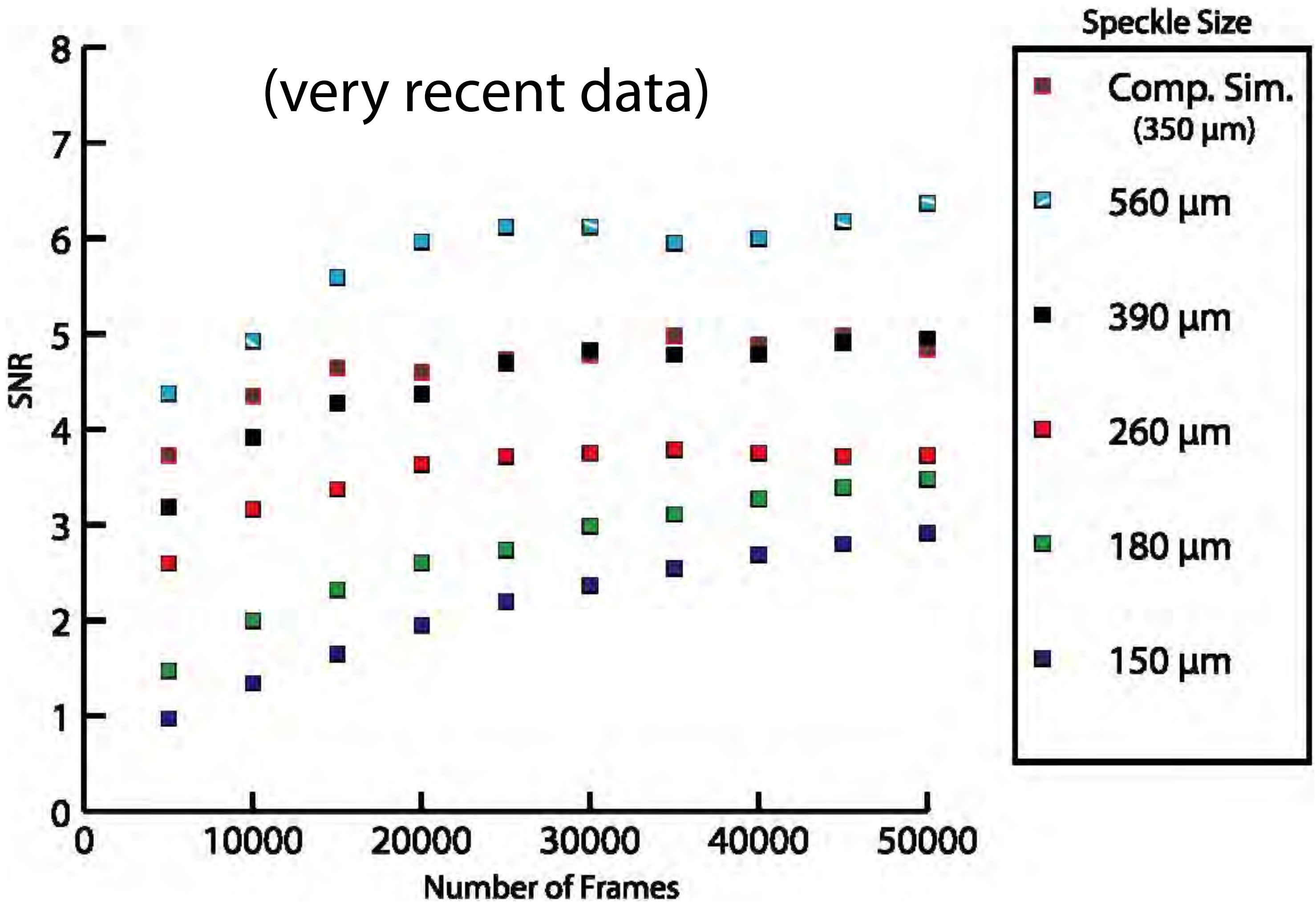
small speckle → large speckle



As the speckle size increases, the resolution decreases but the signal-to-noise ratio increases.

Influence of Speckle Size on Signal-to-Noise Ratio

The SNR decreases (not increases!) with decreasing pixel size because of the decreasing image contrast.

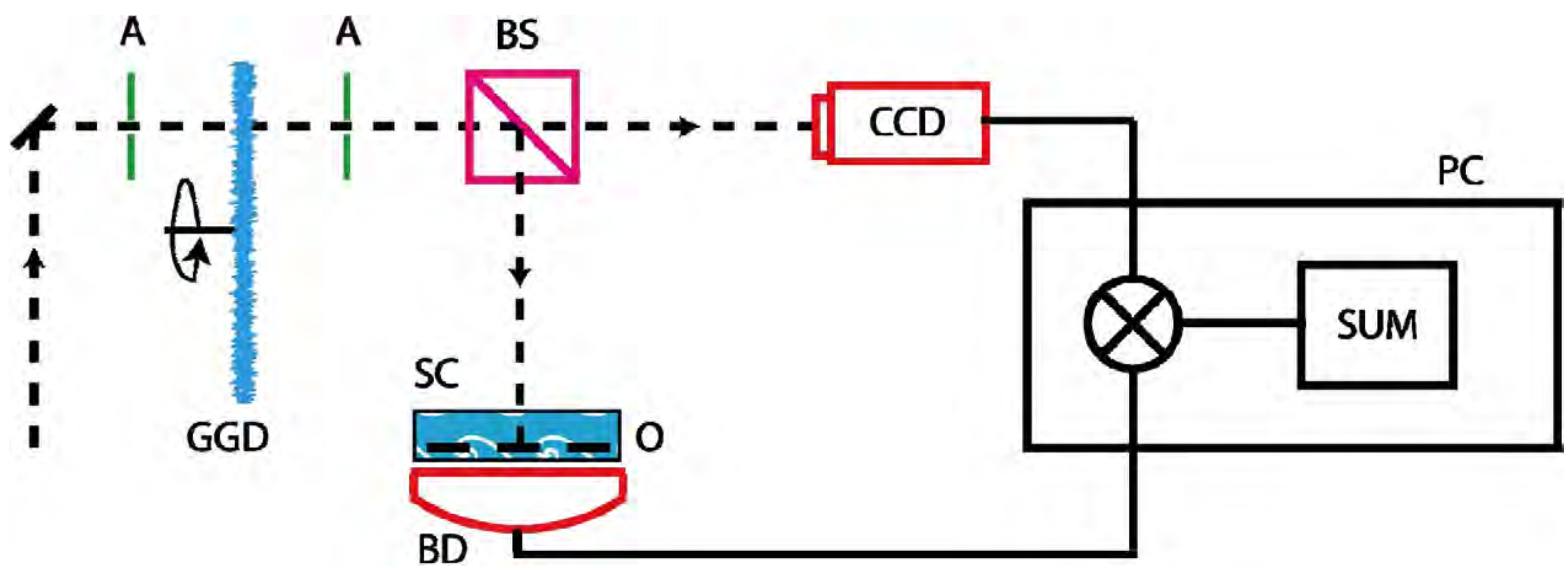


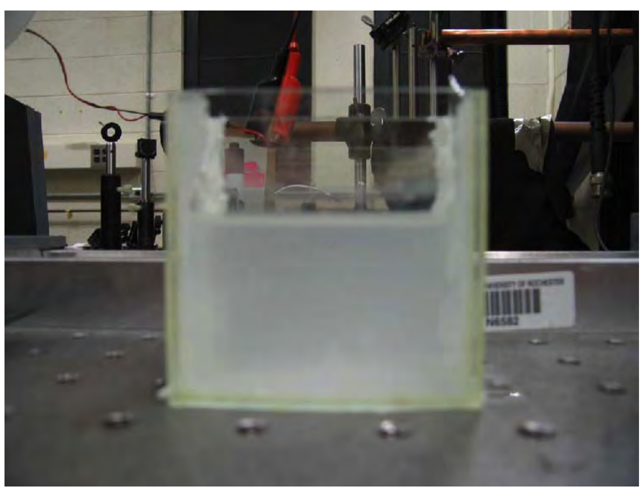
signal = (the mean signal at pixel with unit transmission) - (the mean signal at pixel with zero transmission

noise = sqrt[(variance of the signal at pixel with unit transmission) + (variance of the signal at pixel with zero transmission)]

How Badly is Ghost Imaging Influenced by Scattering?

Embed object within a strongly scattering medium

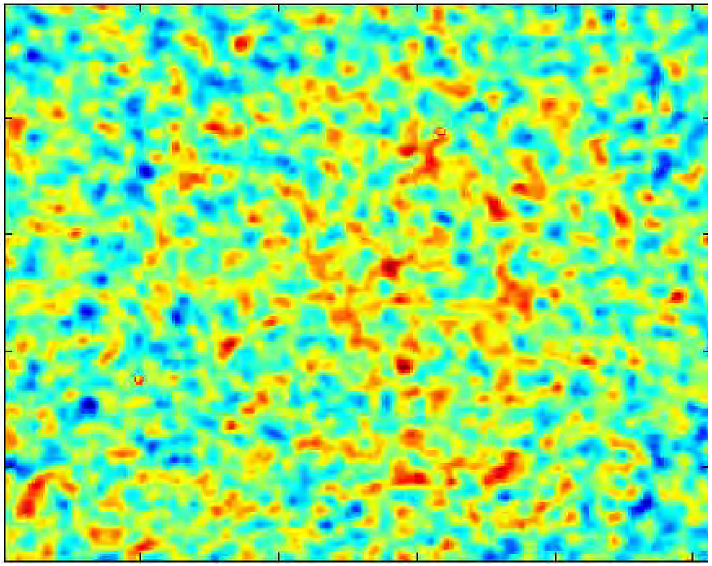




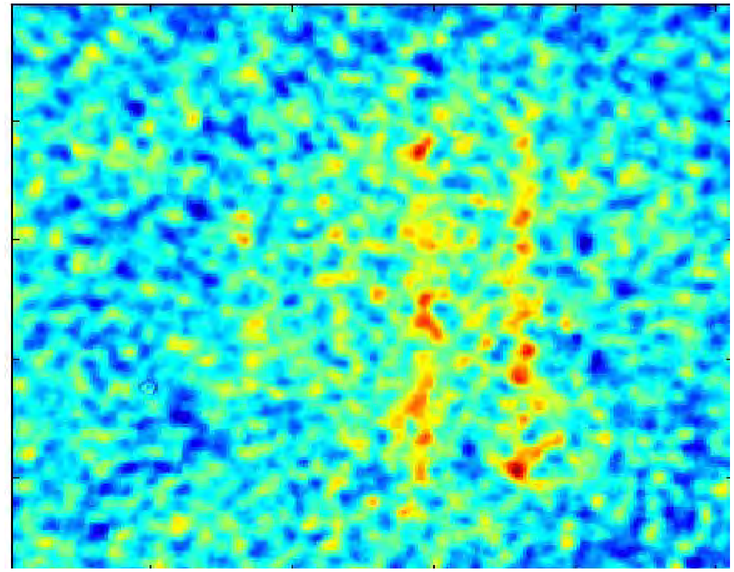
Scattering cell: latex spheres suspended in water.

Transmission controllable; typically 10%

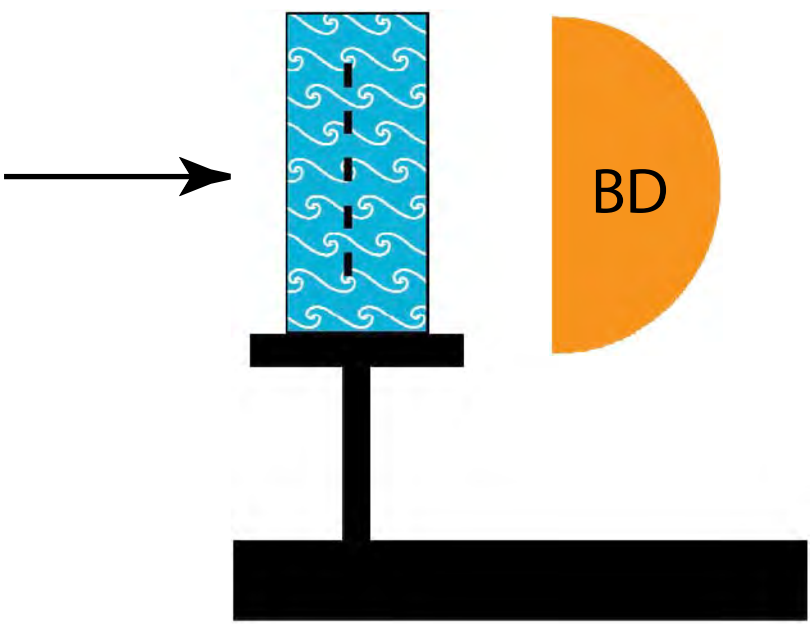
Results of Scattering Experiment

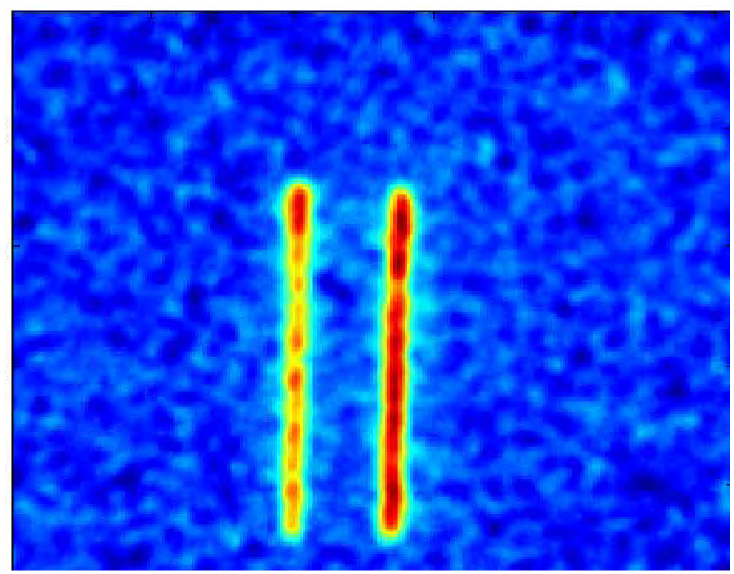


Object at back of cell



Object at center of cell





Object at front of cell

Thermal Ghost Imaging Conclusions

- Small speckles = low SNR, high resolution
- Large speckles = high SNR, low resolution
- Scattering behind object does not degrade resolution
- Scattering in front of object does degrade resolution
- Ghost imaging has promising future applications

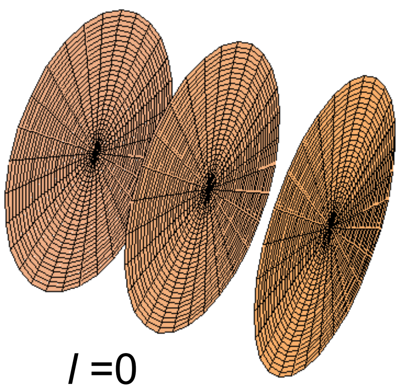
Use of the Orbital Angular Momentum of Light to Carry Quantum Information

Orbital angular momentum (OAM) spans an infinite-dimensional Hilbert space

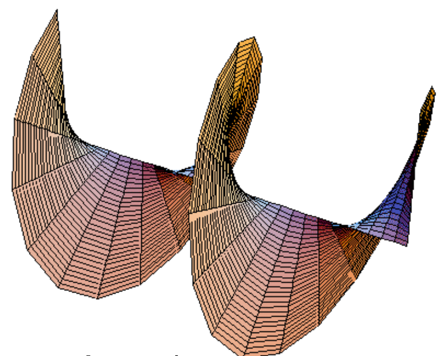
Offers new potentialities for quantum information science

- How robust are the OAM states?
- Can we use them for free-space communications?
- How are they influenced by atmospheric turbulence?

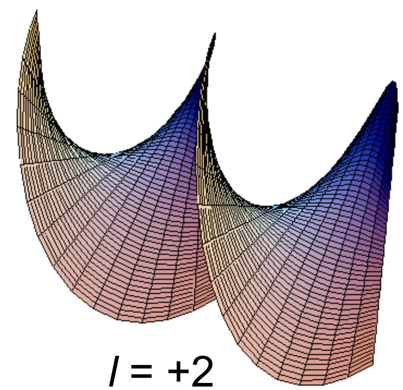
Phase-front structure of some OAM states



l =0



l = +1



l = +2

J. Leach, J. Courtial, K. Skeldon, S. M. Barnett, S. Franke-Arnold and M. J. Padgett, Phys. Rev. Lett. 92, 013601 (2004).
A. Mair, A. Vaziri, G. Weihs and A. Zeilinger, Nature, 412, 313 (2001).
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N. Gisin and R. Thew, Nature Photonics, 1, 165 (2007).
C. Paterson, Phys. Rev. Lett. 94, 153901 (2005).
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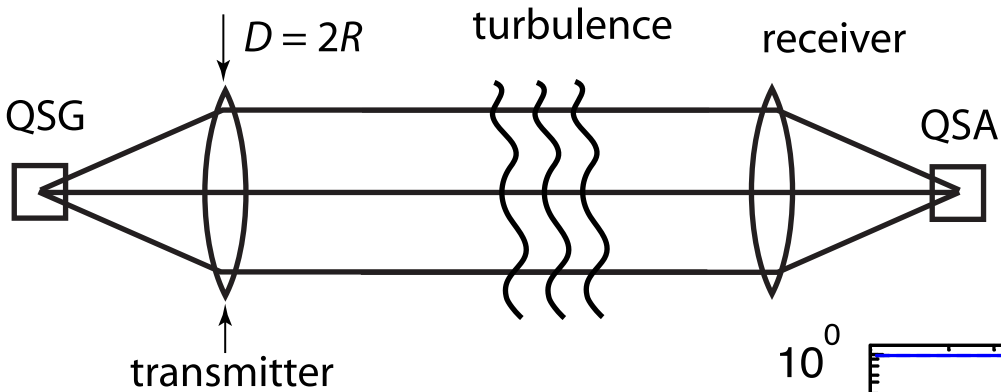
G. Gbur and R. K. Tyson, J. Opt. Soc. Am. A, 25, 255 (2008).

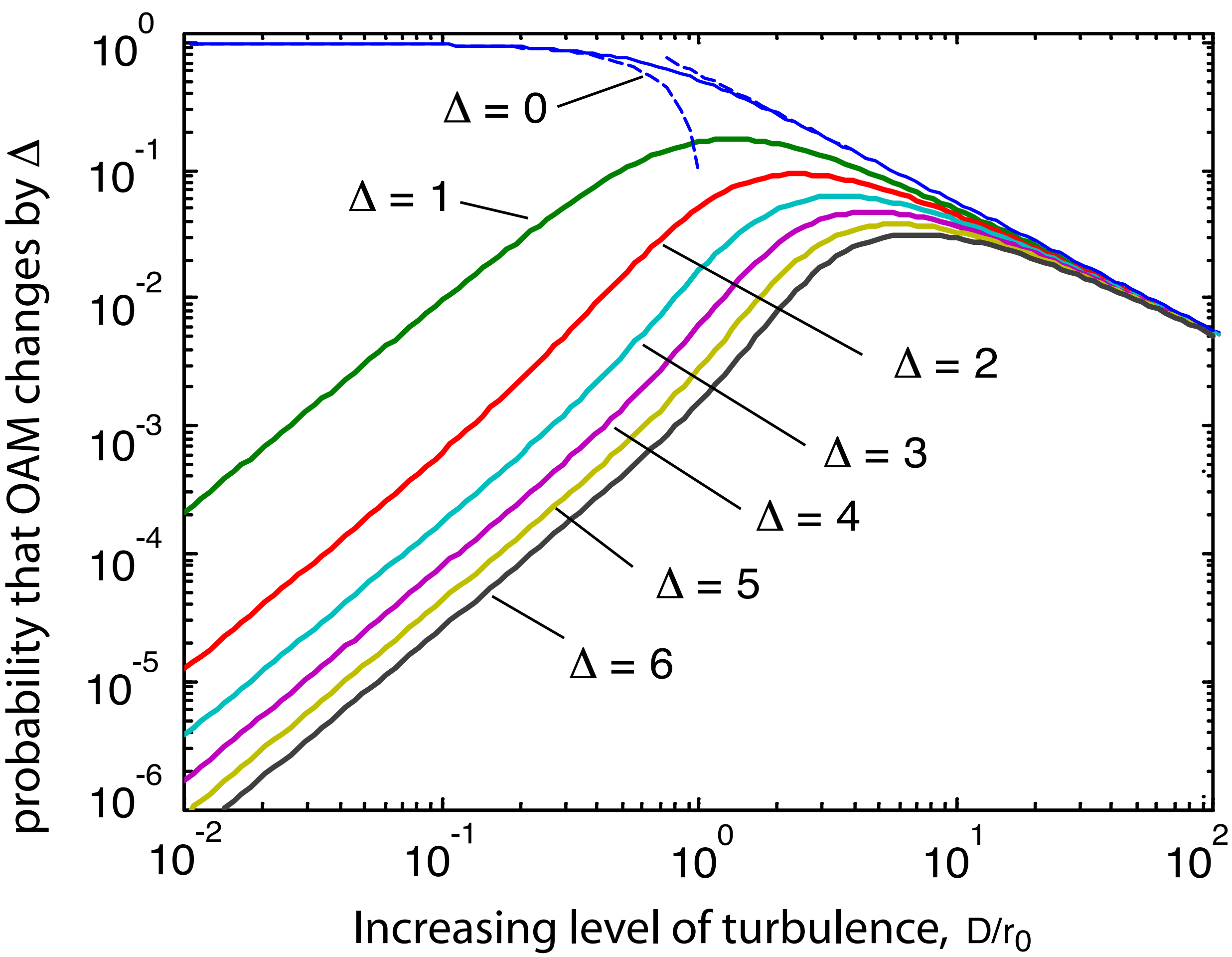
Influence of Atmospheric Turbulence on the Propagation of Quantum States of Light Carrying Orbital Angular Momentum



Probability that initial state is retained:

$$\langle s_0 \rangle = [1 + (1.845\, D/r_0)^2]^{-1/2}$$

r_0 = Fried parameter



Our results are qualitatively similar to those of Paterson (2005), but differ in detail because Paterson considered LG modes whereas we consider pure vortex beams.

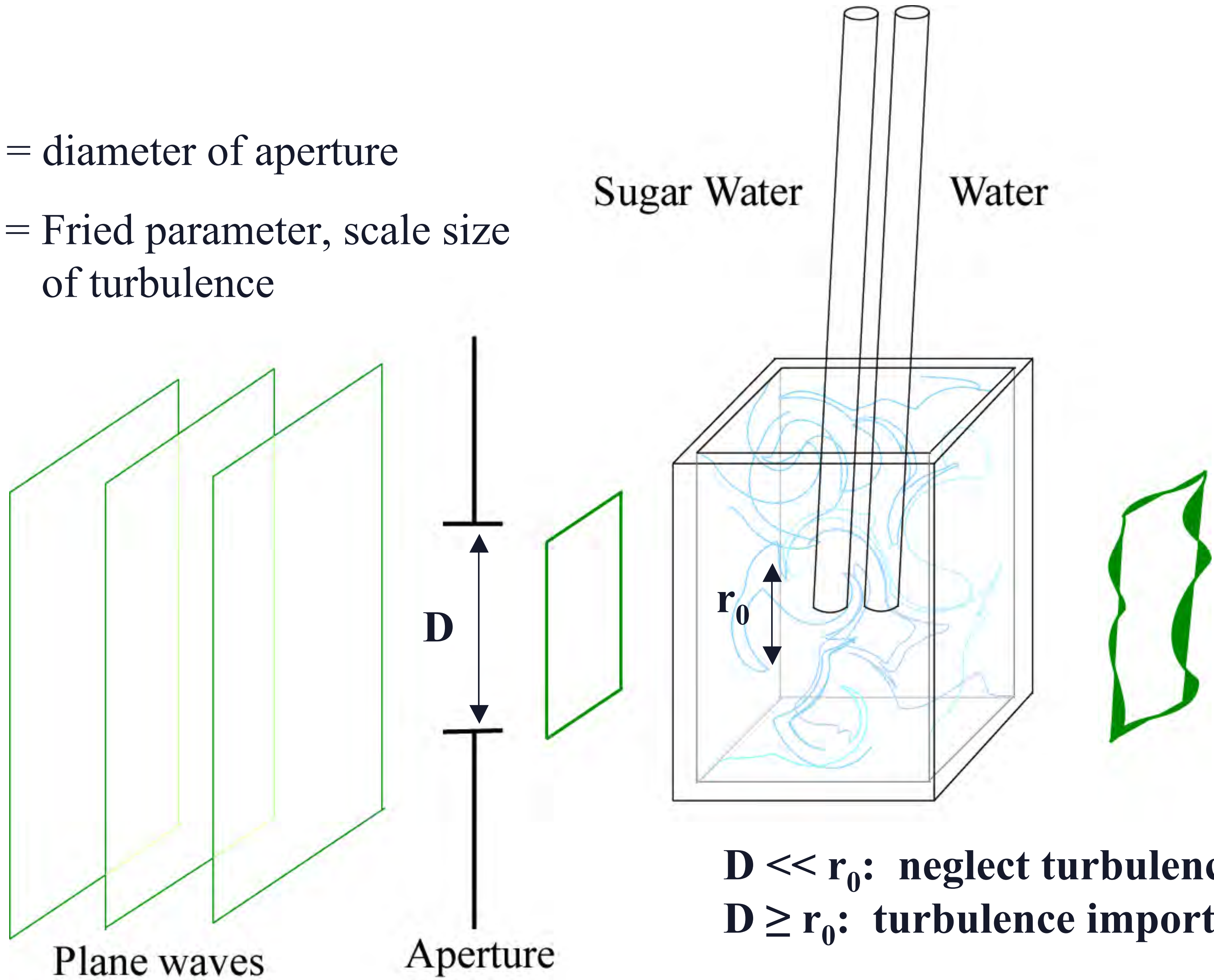
G. A. Tyler and R. W. Boyd, in review.

Influence of Atmospheric Turbulence on the Quantum States of Light

To test these predictions in a laboratory setting, we have build a turbulence cell

D = diameter of aperture

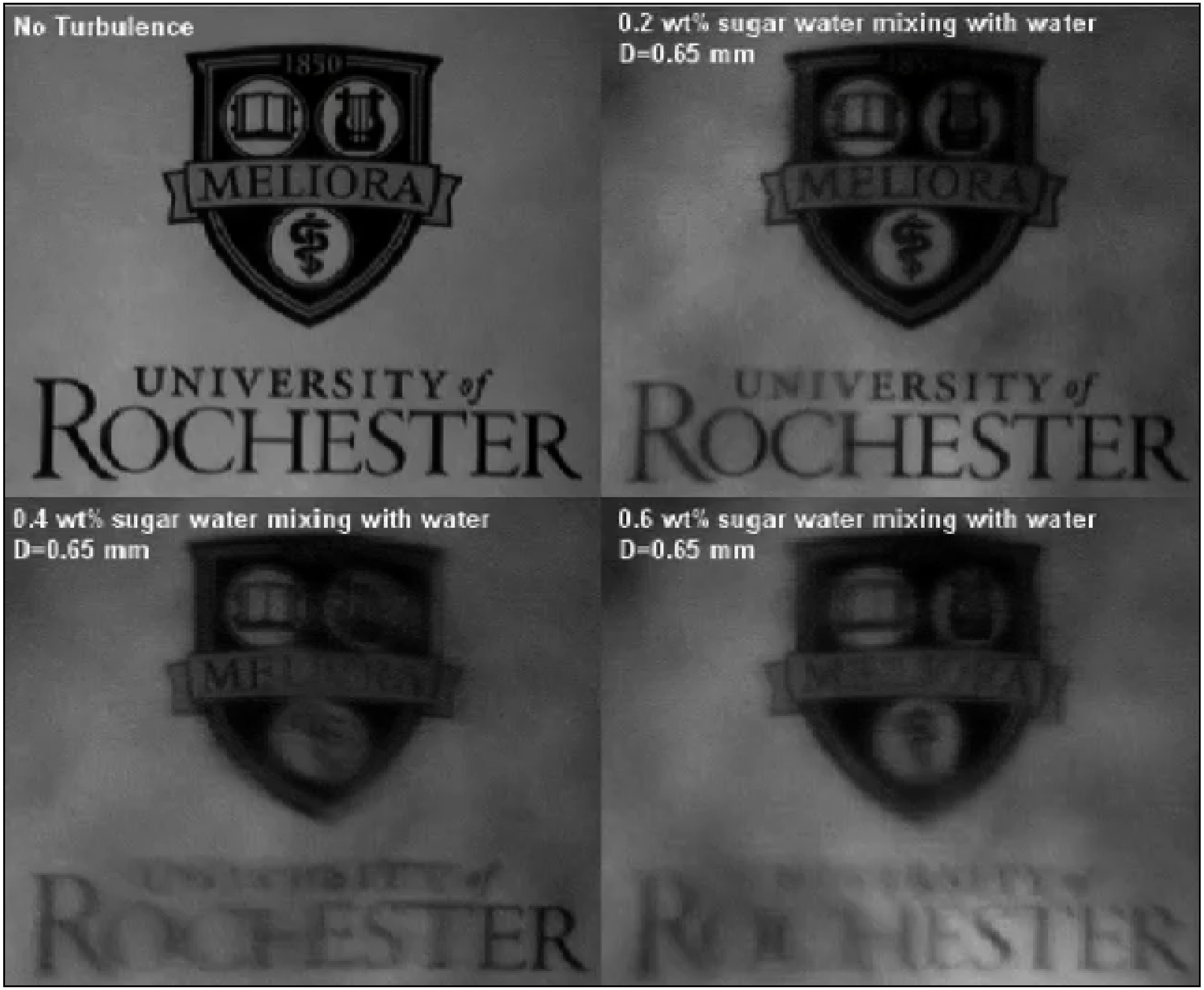
$\mathbf{r_0}$ = Fried parameter, scale size of turbulence



D << r_0: neglect turbulence

D ≥ r_0: turbulence important

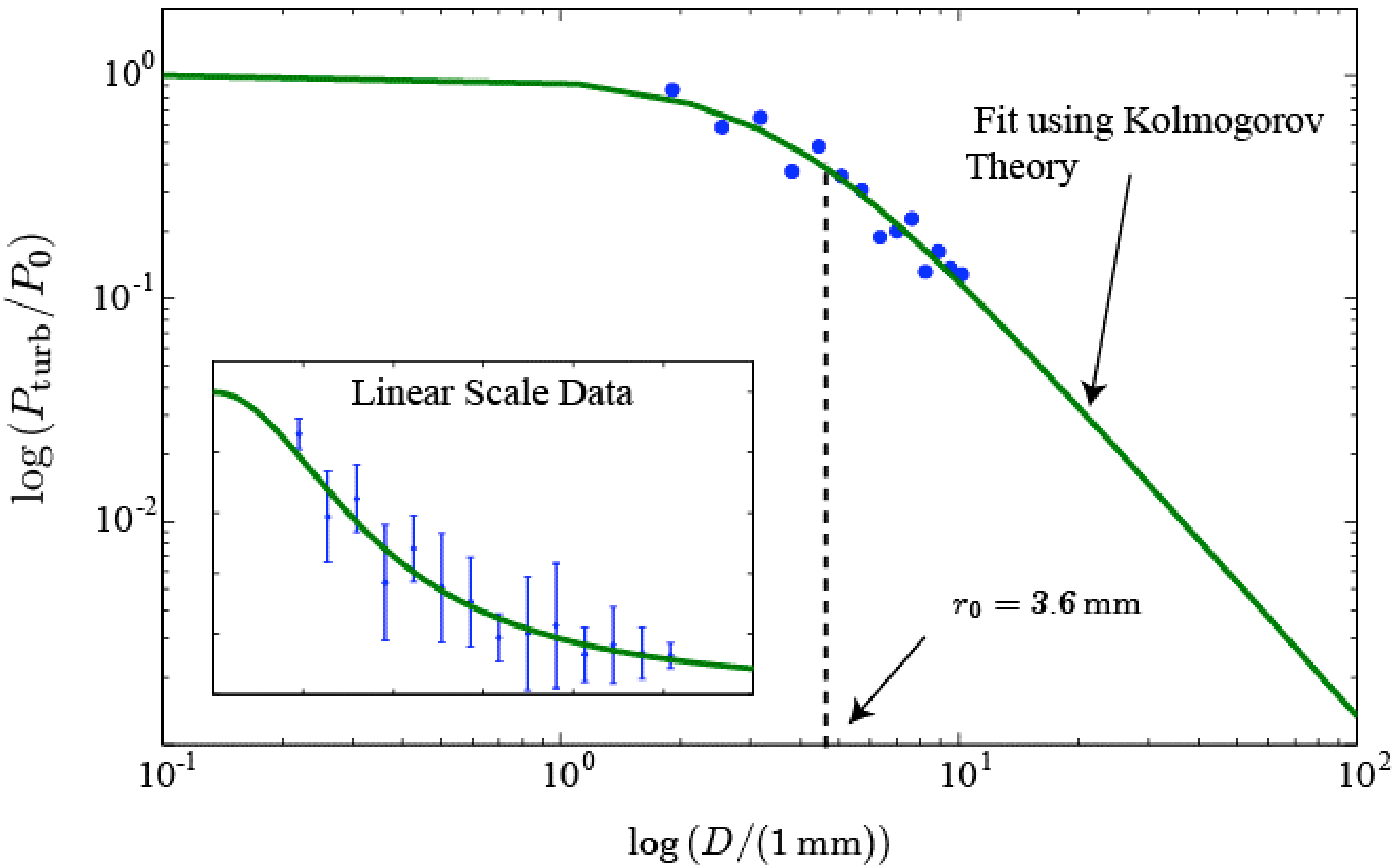
Demonstration of the Operation of the Turbulence Cell



(click within window to play movie)

Influence of Atmospheric Turbulence on the Quantum States of Light

- Progress report: we are presently characterizing our turbulence cell
- As a first step, we measure the Strehl ratio as a function of beam diameter
- Strehl ratio is ratio of maximum beam intensity with and without turbulence
- Our data well modeled by Kolmogorov theory with r_0 = 3.6 mm



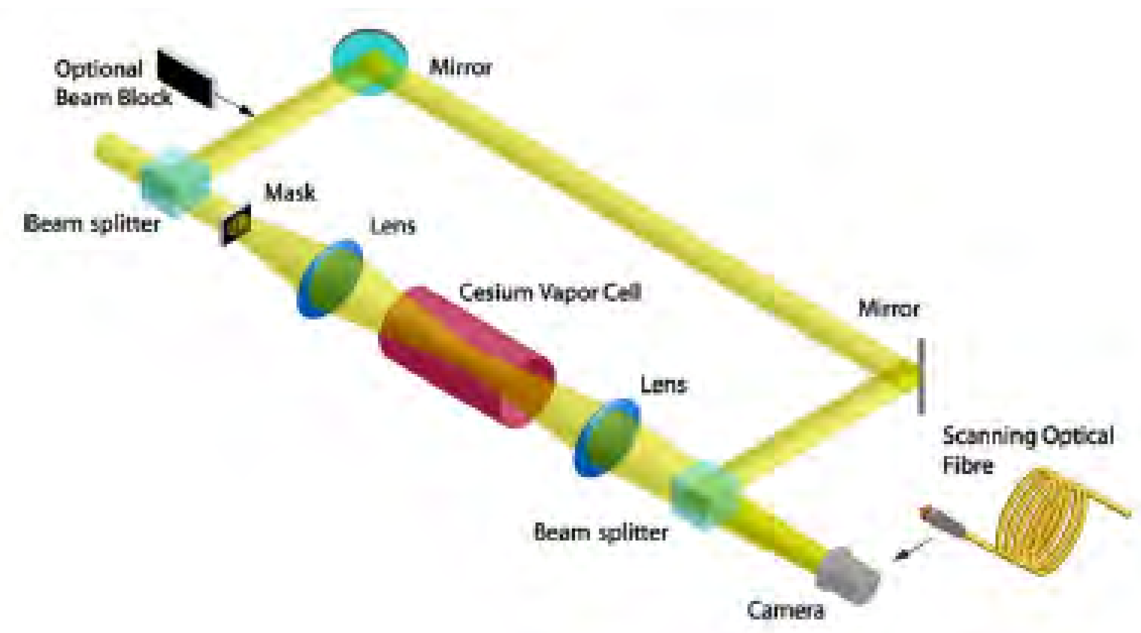
Single-Photon Imaging

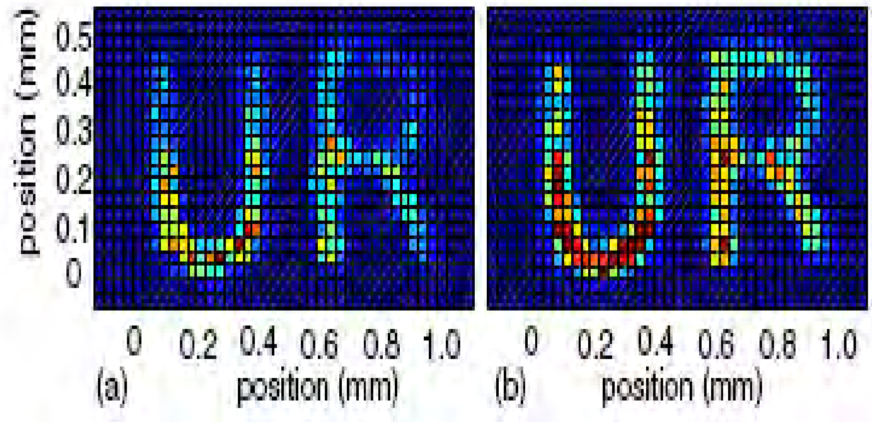
Joint Project: Boyd and Howell Groups

Petros Zerom, Heedeuk Shin, others

- We want to impress an entire image unto a single photon and later recover the image
- Our procedure is to "sort" the photons into classes determined by the image impressed on the photon
- We use holographic matched filtering to do the sorting
- We use heralded single photons created by PDC

Background





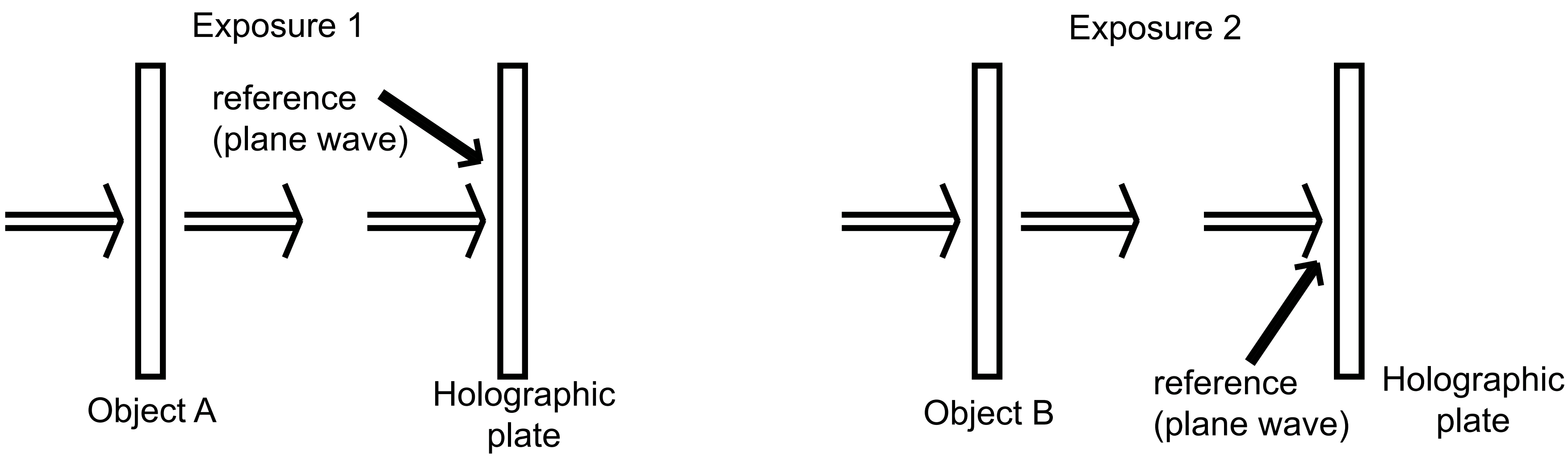
Delayed (9 ns) **Non-delayed**

- Delayed an image (with phase and amplitude characteristics preserved) by many pulse widths
- Delayed image using very weak light pulses (4 ns FWHM, <1 photon/pulse)
- Image reproduced with high fidelity and low noise
- But can read out image only one pixel at a time

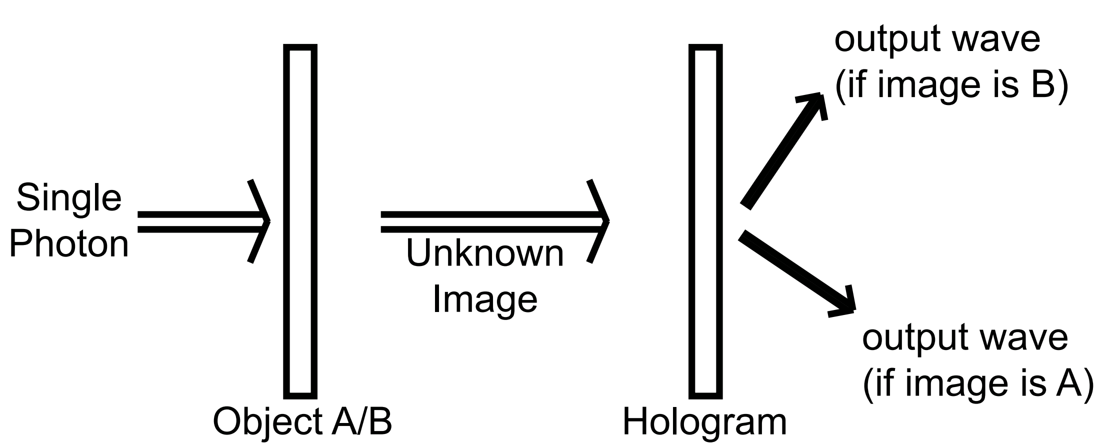
R. M. Camacho, *et al, PRL* ***98****, 043902 (2007)*

Holography, matched filtering, and single-photon Imaging

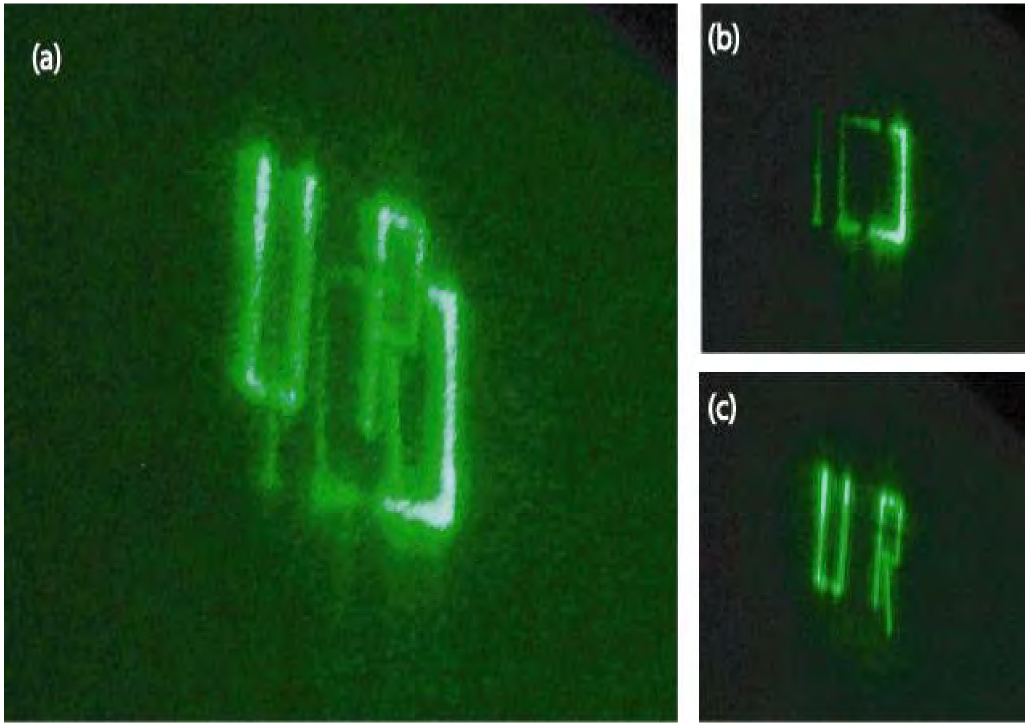
- Writing the matched filter (a multiple exposure hologram)

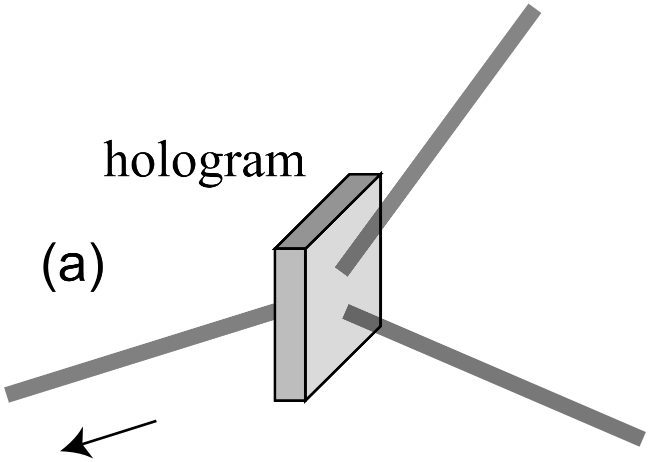


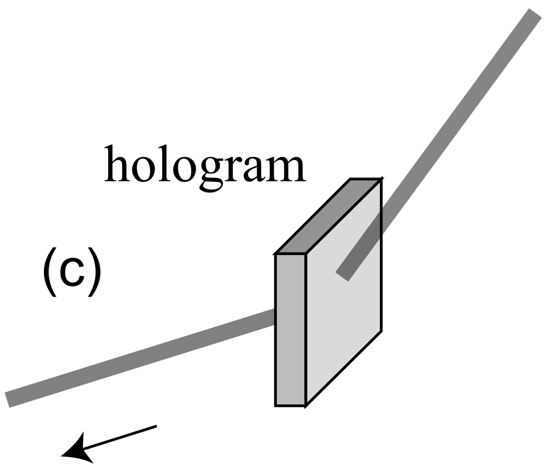
- Reading the hologram (with a single-photon)

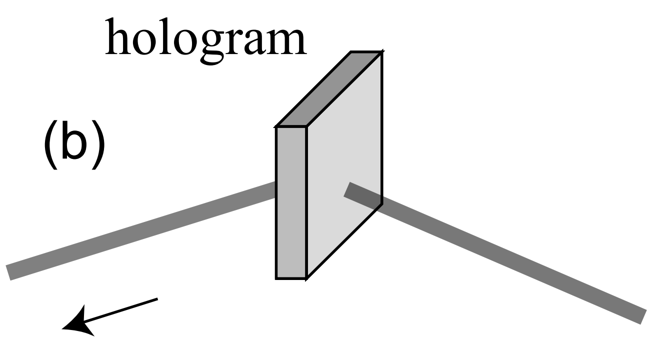


Reconstruction - with plane-wave reference beam

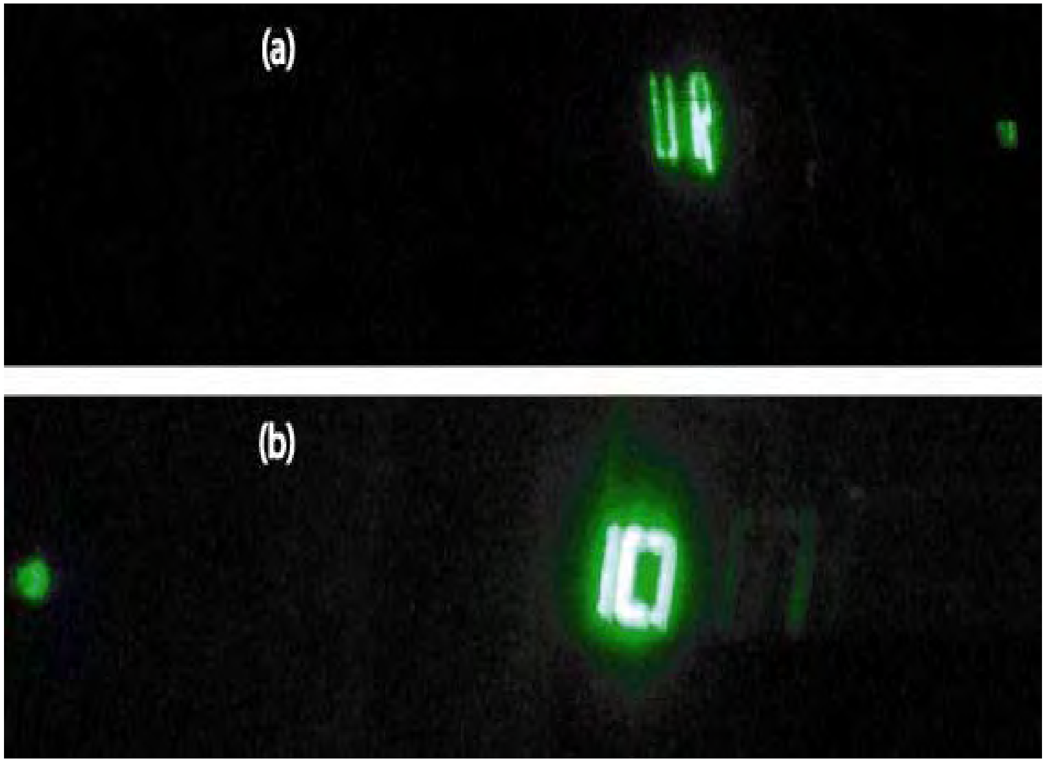


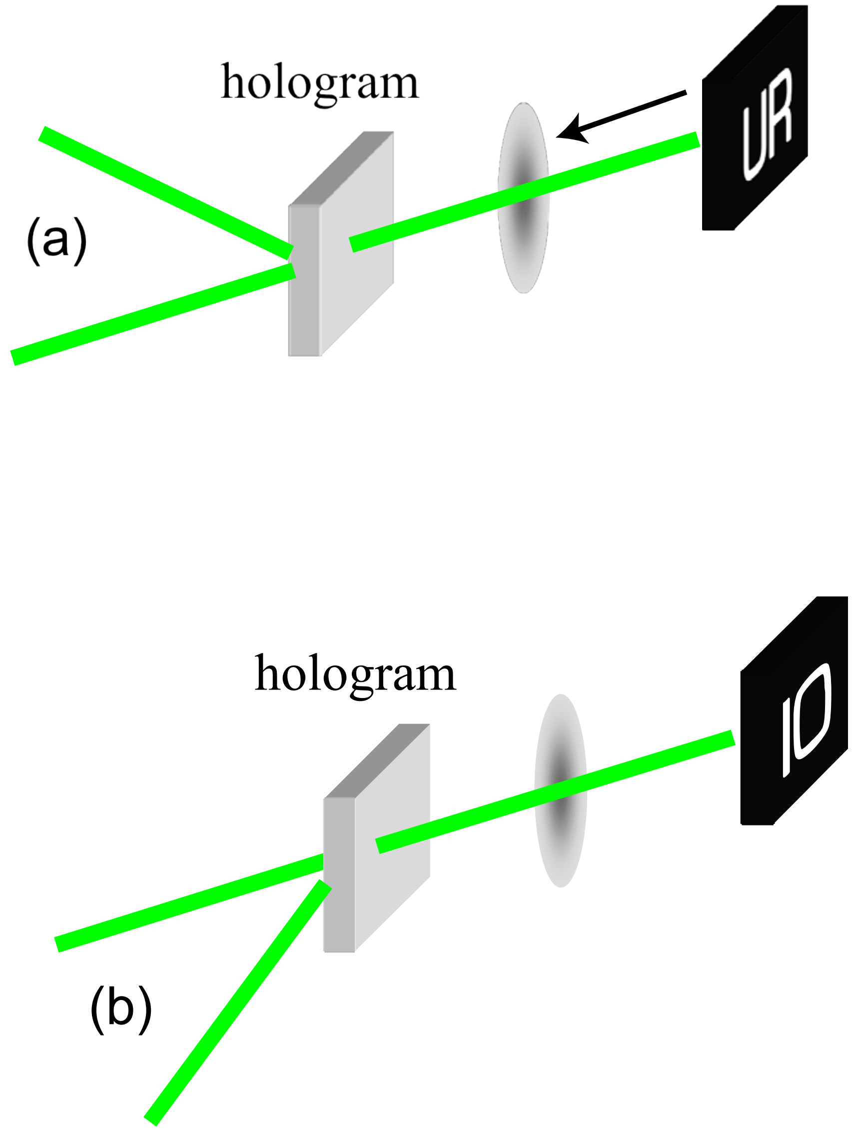






Reconstruction - with structured reference beam





- Very little cross-talk

Single-Photon Imaging - Latest Result

- We have just demonstrated that we can distinguish the “IO” photon from the “UR” photon at the level of an individual single photon
- We use very weak laser light (less than one photon per temporal mode) and place an APD at the location of the diffraction spot

High light level

Low light level

Count rate (1/s) **146** **24506**

High light level

Low light level

Count rate (1/s) **41387** **444**

Thank you for your attention!