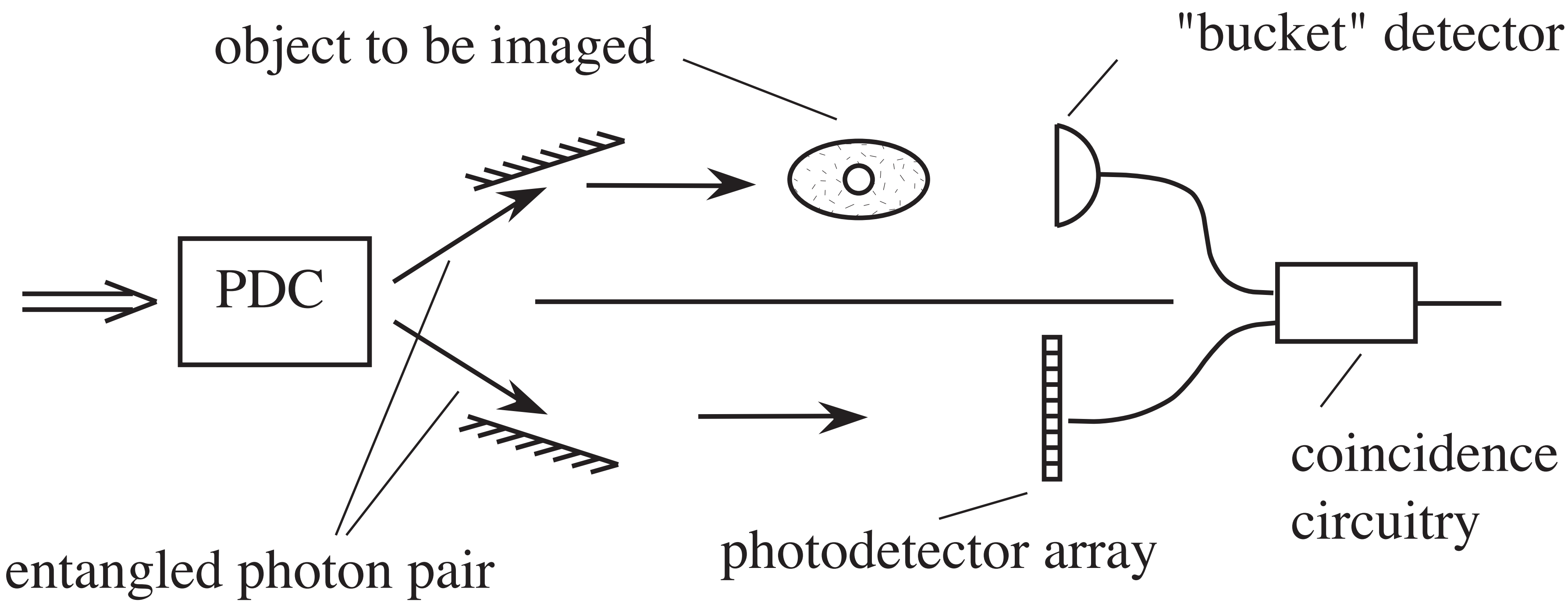
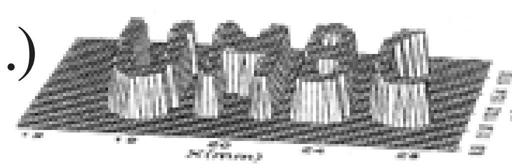
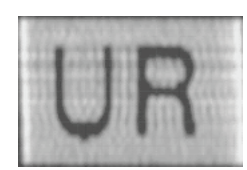
Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing!
  (imaging under adverse situations, bio, two-color, etc.)
- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)



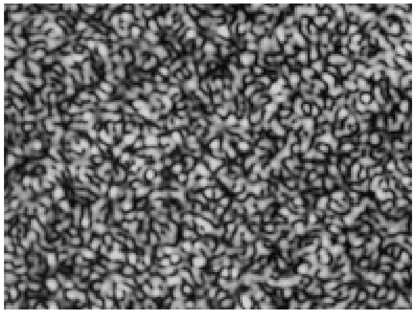


Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).
Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004)
Gatti, Brambilla, and Lugiato, 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.

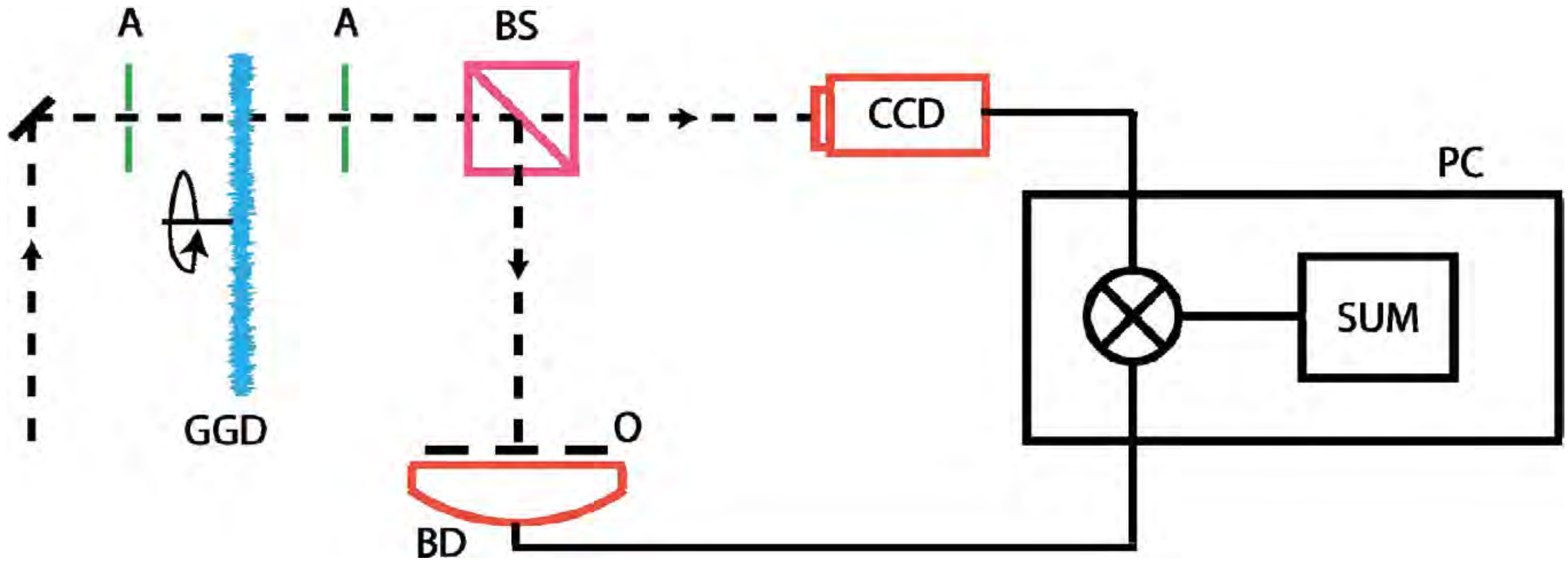
Recall that the intensity distribution of thermal light looks like a speckle pattern.



We use pseudothermal light in our 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.

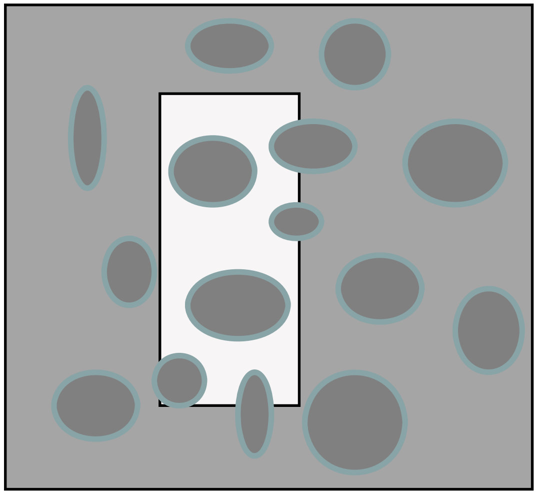
How does thermal ghost imaging work?

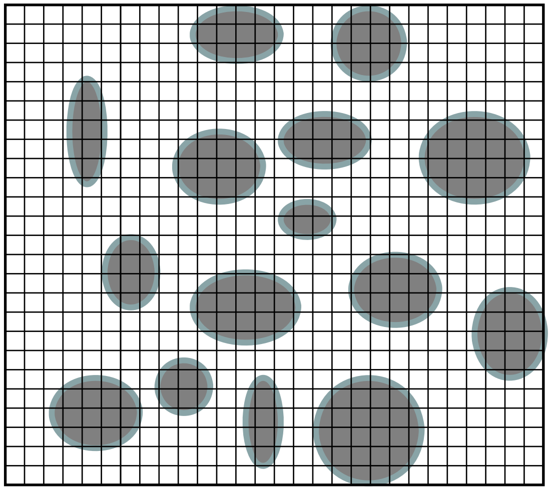


- Ground glass disk (GGD) and beam splitter (BS) create two identical speckle patterns
- Many speckles are blocked by the opaque part of object, but some are transmitted, and their intensities are summed by BD
- CCD camera measures intensity distribution of speckle pattern
- Each speckle pattern is multiplied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





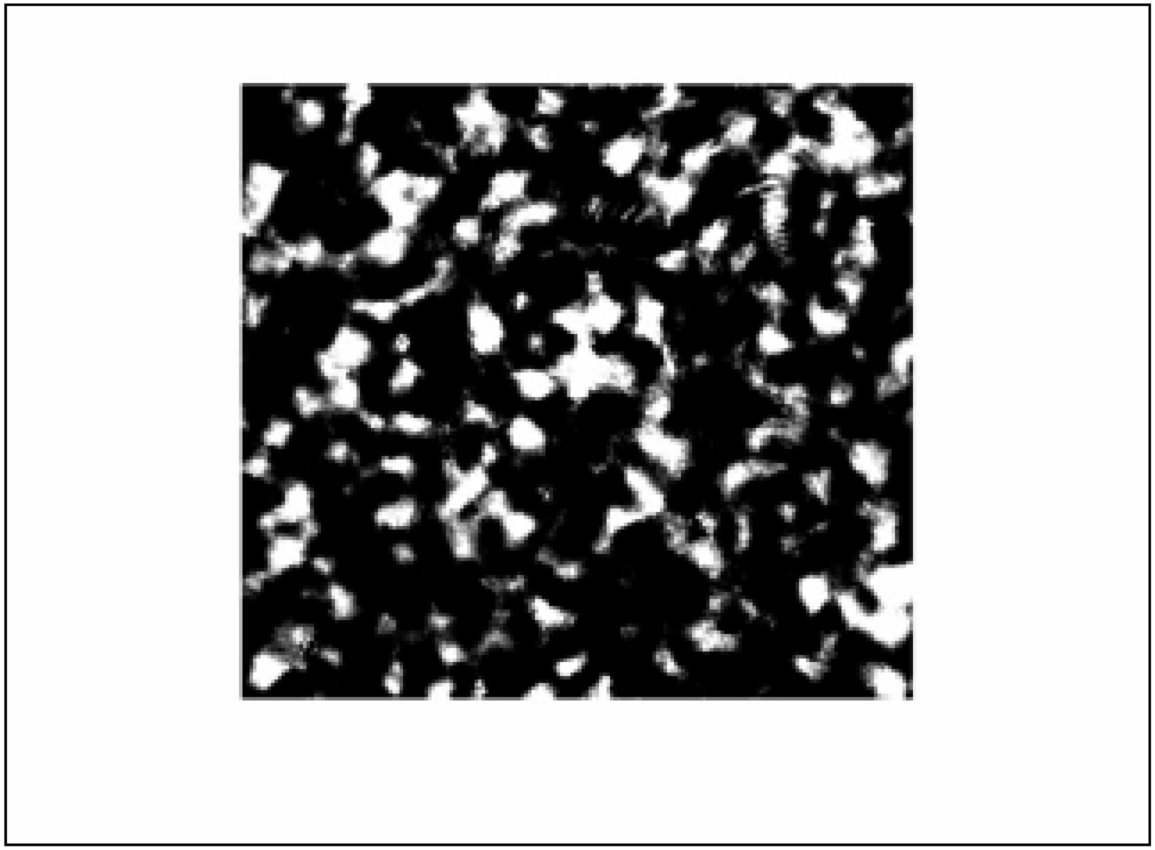
object arm
(bucket detector)

reference arm
(pixelated imaging detector)

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

Average over many speckle patterns

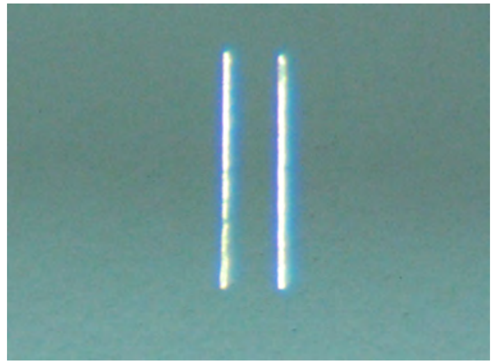
Demonstration of Image Buildup in Thermal Ghost Imaging



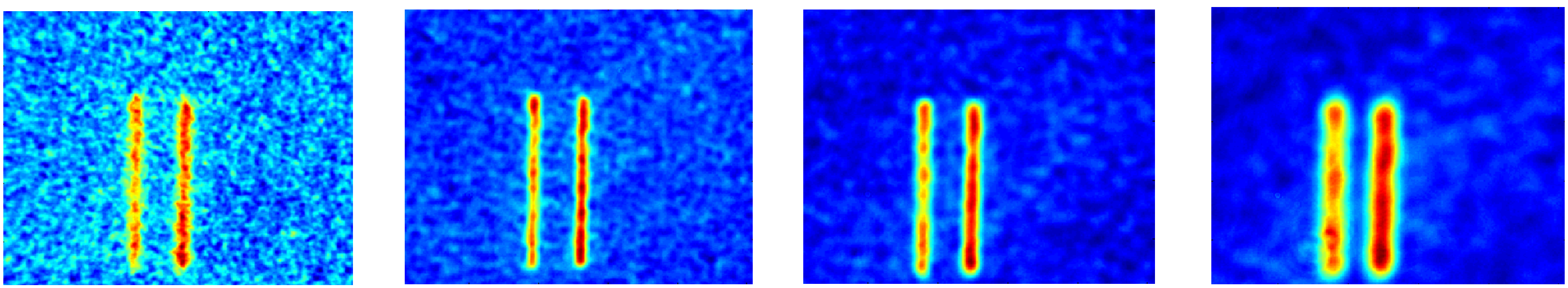
(click within window to play movie)

Influence of Speckle Size on Spatial Resolution

Test object
(stencil)



small speckle → large speckle

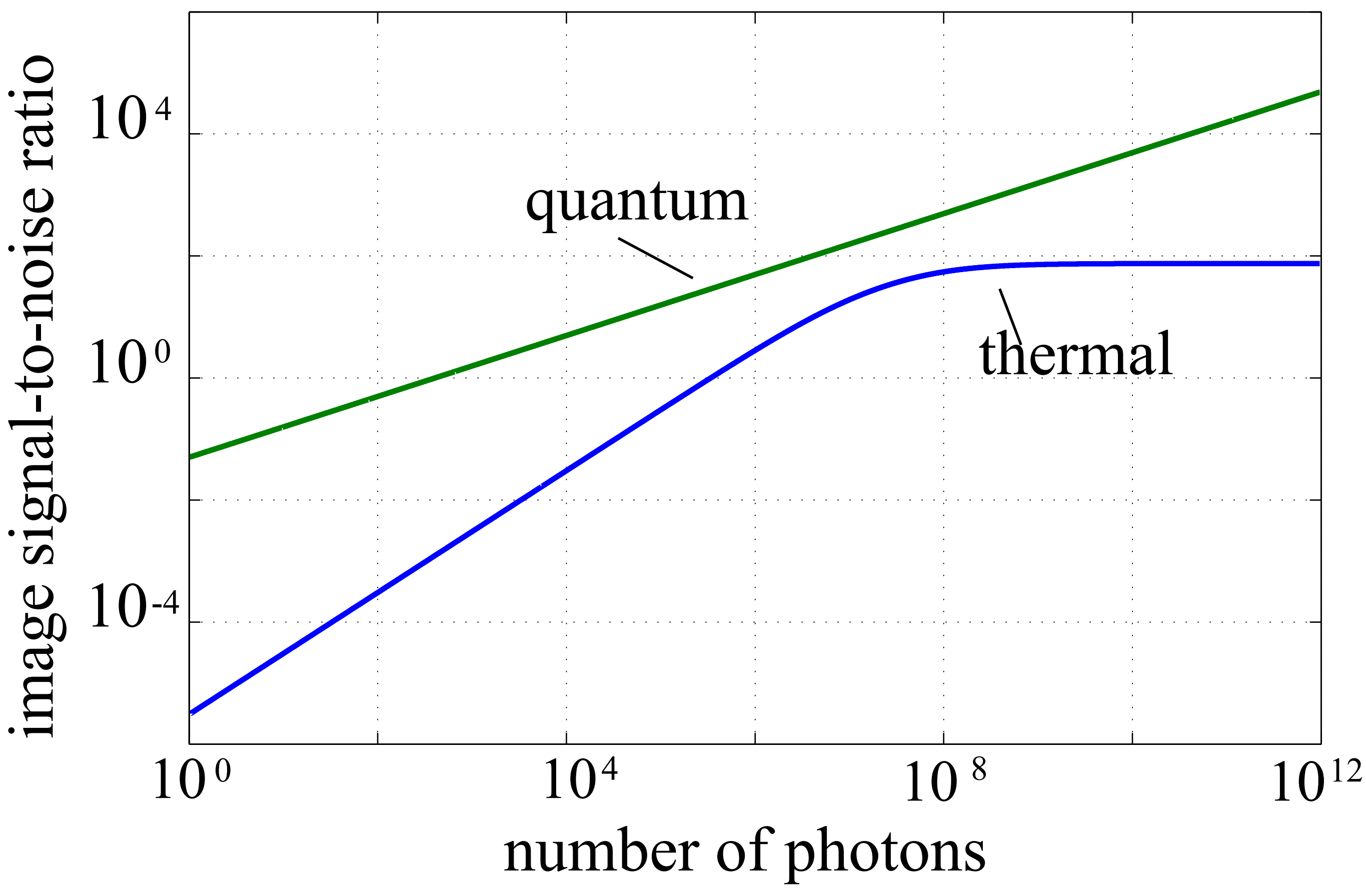


As the speckle size increases, the resolution decreases but the signal-to-noise ratio increases.

Engineering Comparison of Quantum and Thermal Ghost Imaging

Q: Which is better, quantum or thermal ghost imaging?
A: It depends on what you want to accomplish

One criterion: What is the minimum number of photons illuminating the target required to produce a specified signal-to-noise ratio?



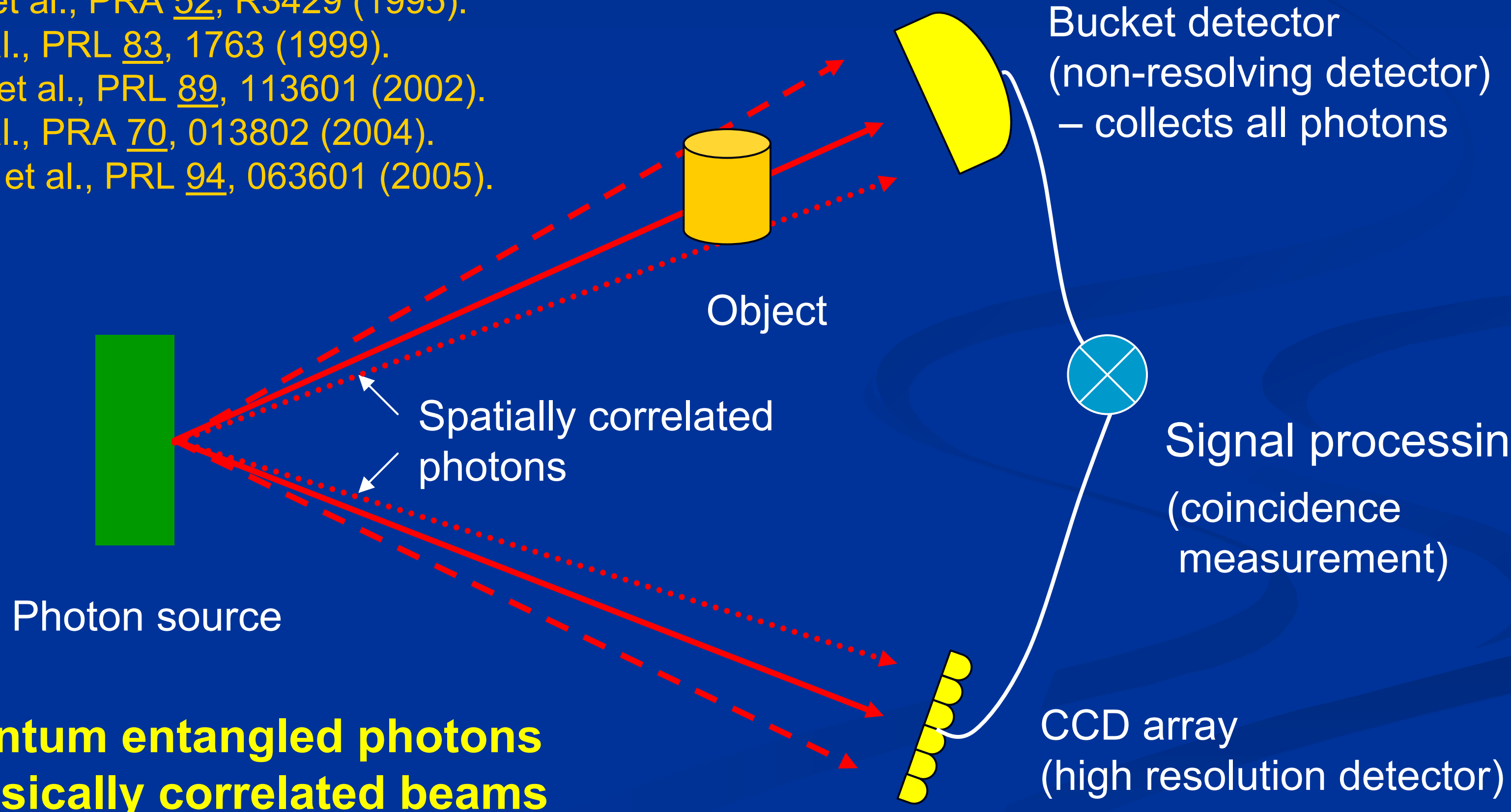
Preliminary result; work still in progress

(numerical result assumes 10^6 frames for thermal case)

Two-Color Ghost Imaging: Motivation

- **Also called correlated / coincidence imaging**
- **Nonlocal imaging method**

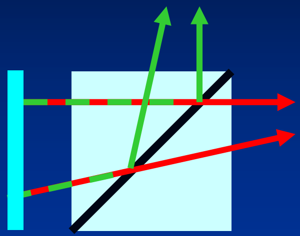
Strekalov et al., PRL 74, 3600 (1995).
Pittman et al., PRA 52, R3429 (1995).
Gatti et al., PRL 83, 1763 (1999).
Bennink et al., PRL 89, 113601 (2002).
Gatti et al., PRA 70, 013802 (2004).
Valencia et al., PRL 94, 063601 (2005).



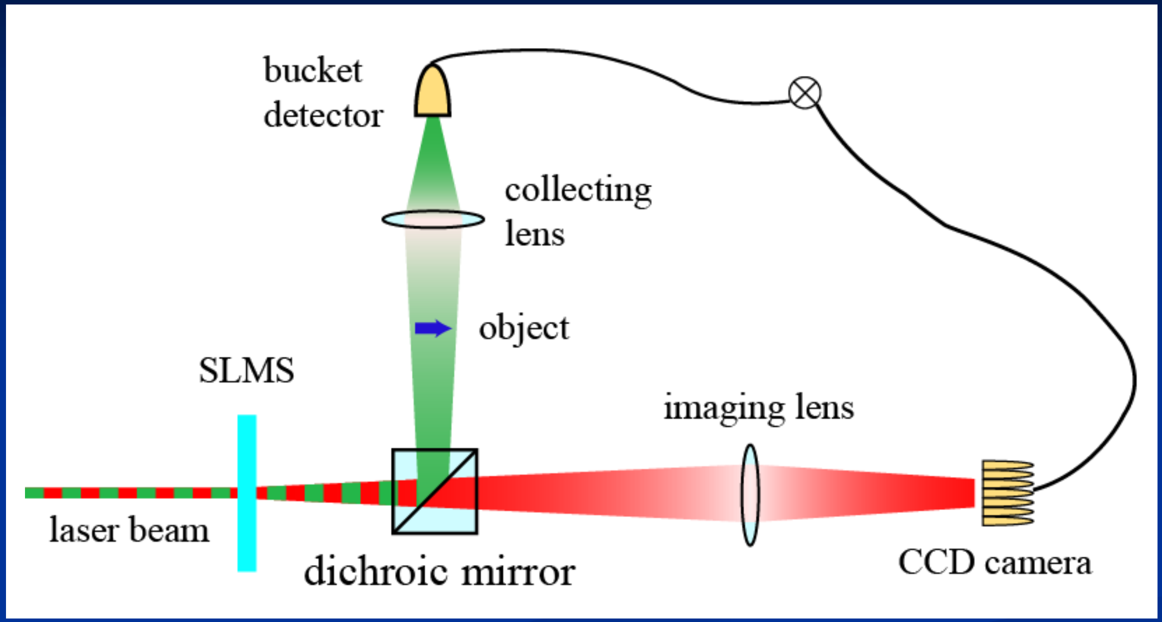
- **Quantum entangled photons**
- **Classically correlated beams**

Two-Color Ghost Imaging: Theory

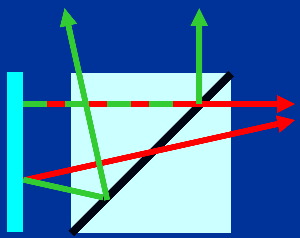
Classical



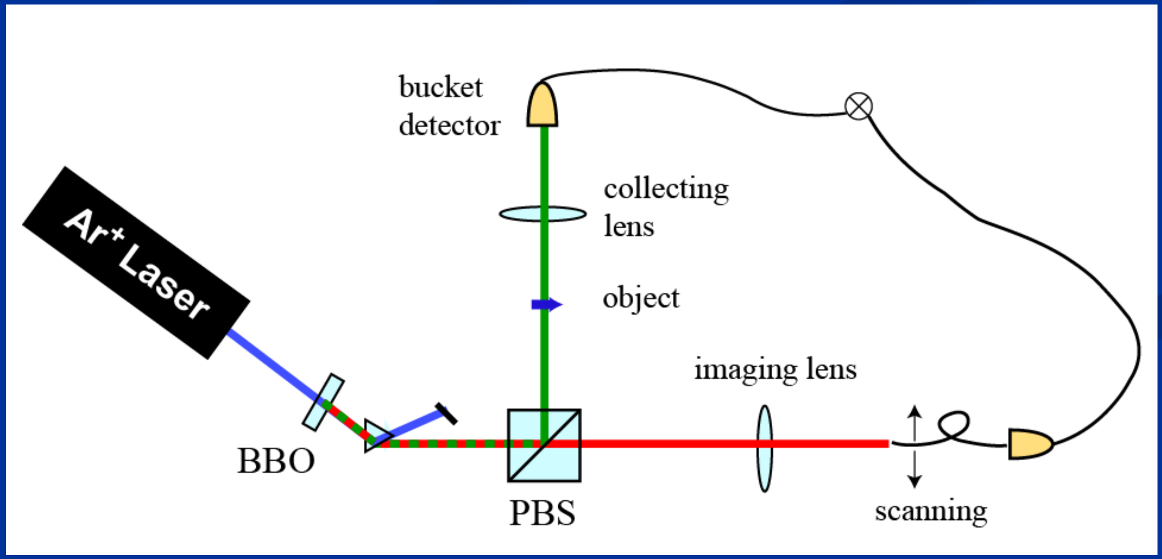
SLMS



Quantum



SPDC



Two-Color Ghost Imaging: Model

Classical

Gaussian-Schell model

$$W(x,x') = \exp\left[-\frac{x^2 + x'^2}{4D_A^2}\right] \exp\left[-\frac{(x-x')^2}{2\sigma_x^2}\right]$$

$$D_A \gg \sigma_x$$

Lens aperture:

$$\exp\left[-\frac{x^2}{2A_R^2}\right]$$

Quantum

Gaussian approximation

$$\Psi(x,x') = \exp\left[-\frac{x^2 + x'^2}{4D_A^2}\right] \exp\left[-\frac{(x-x')^2}{2\sigma_x^2}\right]$$

$$D_A \gg \sigma_x$$

Two-Color Ghost Imaging: Results

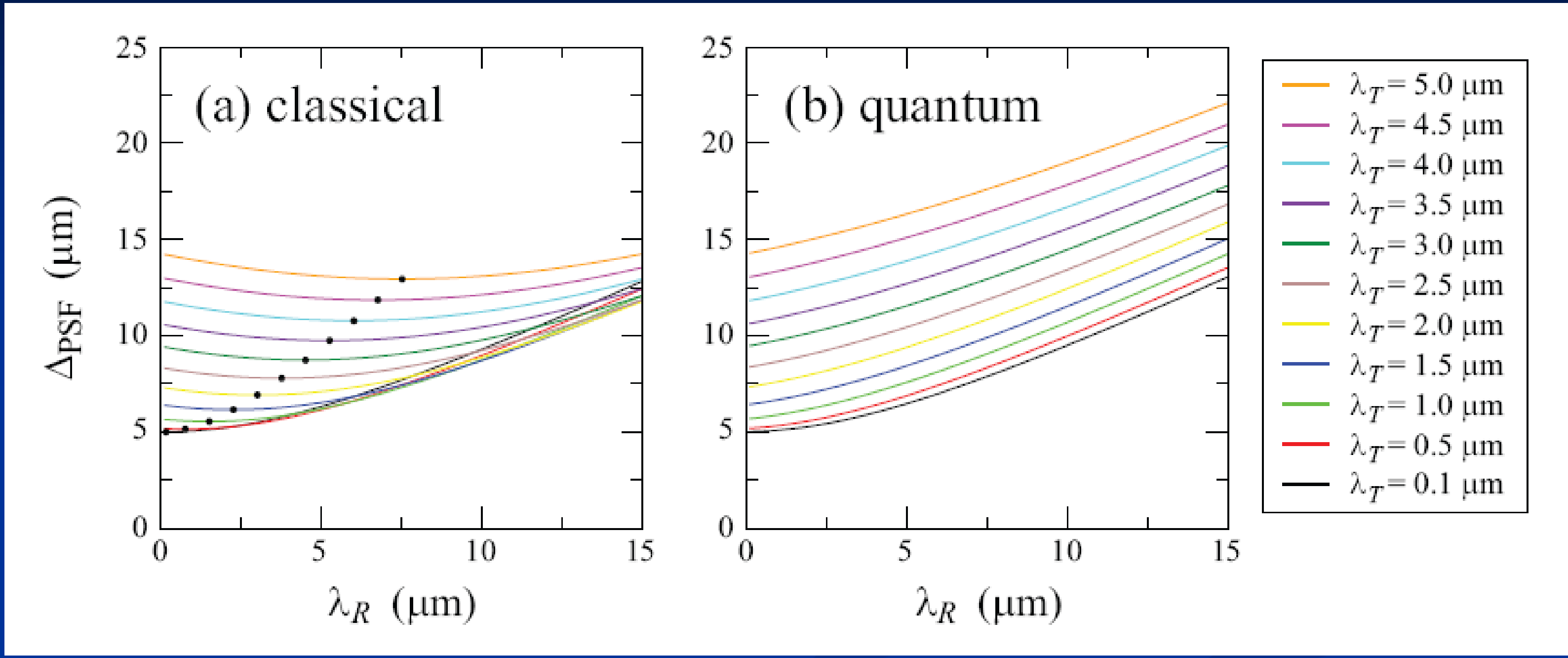
Correlation area
σ_x = 5μm

Beam radius
D_A = 10mm

Lens radius
A_R = 20mm

Object distance
l_T = 100mm

Lens distance
l_{R1} = 150mm



Classical

$$\Delta_{\mathrm{PSF}}^{(\mathrm{classical})} = \sqrt{\sigma_x^2 + \left(\frac{\lambda_T l_T}{2\pi D_A}\right)^2 + \frac{(\lambda_R l_{R1} - \lambda_T l_T)^2}{(\lambda_R l_{R1}/D_A)^2 + (2\pi A_R)^2}}$$

Quantum

$$\Delta_{\mathrm{PSF}}^{(\mathrm{quantum})} = \sqrt{\sigma_x^2 + \left(\frac{\lambda_T l_T}{2\pi D_A}\right)^2 + \frac{(\lambda_R l_{R1} + \lambda_T l_T)^2}{(\lambda_R l_{R1}/D_A)^2 + (2\pi A_R)^2}}$$

[Chan, O'Sullivan & Boyd (in preparation)]

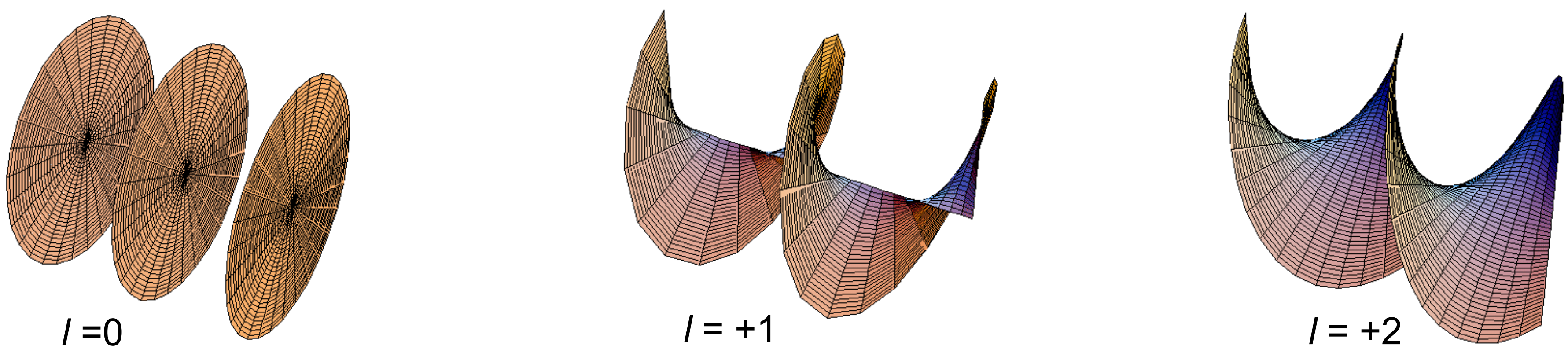
Use of the Orbital Angular Momentum of Light to Carry Quantum Information

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



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C. Paterson, Phys. Rev. Lett. 94, 153901 (2005).
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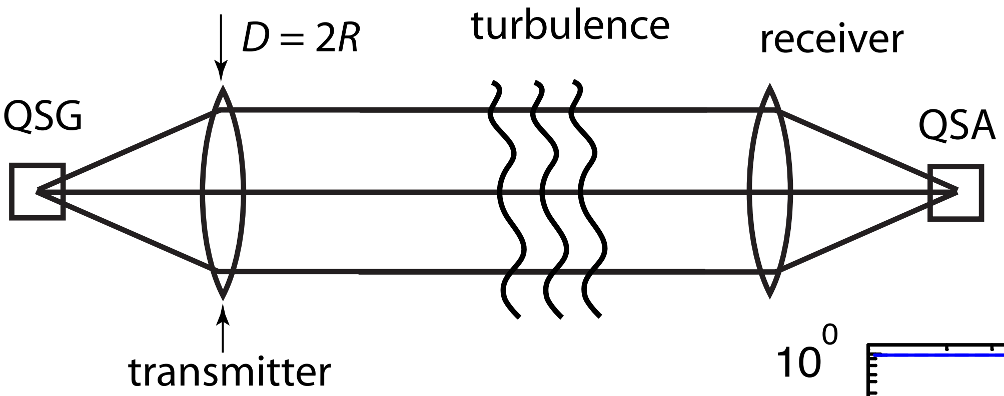
Influence of Atmospheric Turbulence on the Propagation of Quantum States of Light Carrying Orbital Angular Momentum

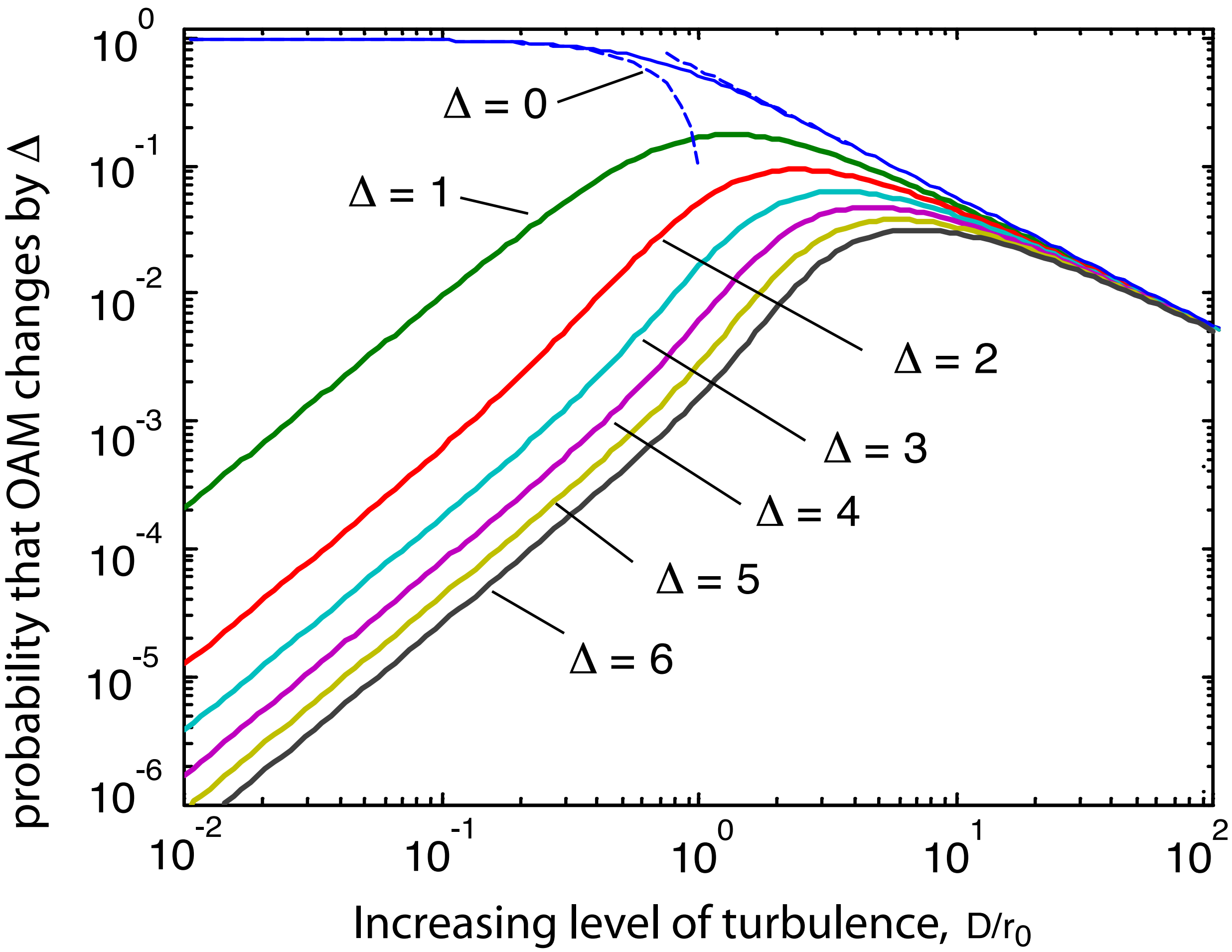


Probability that initial state is retained:

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

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.



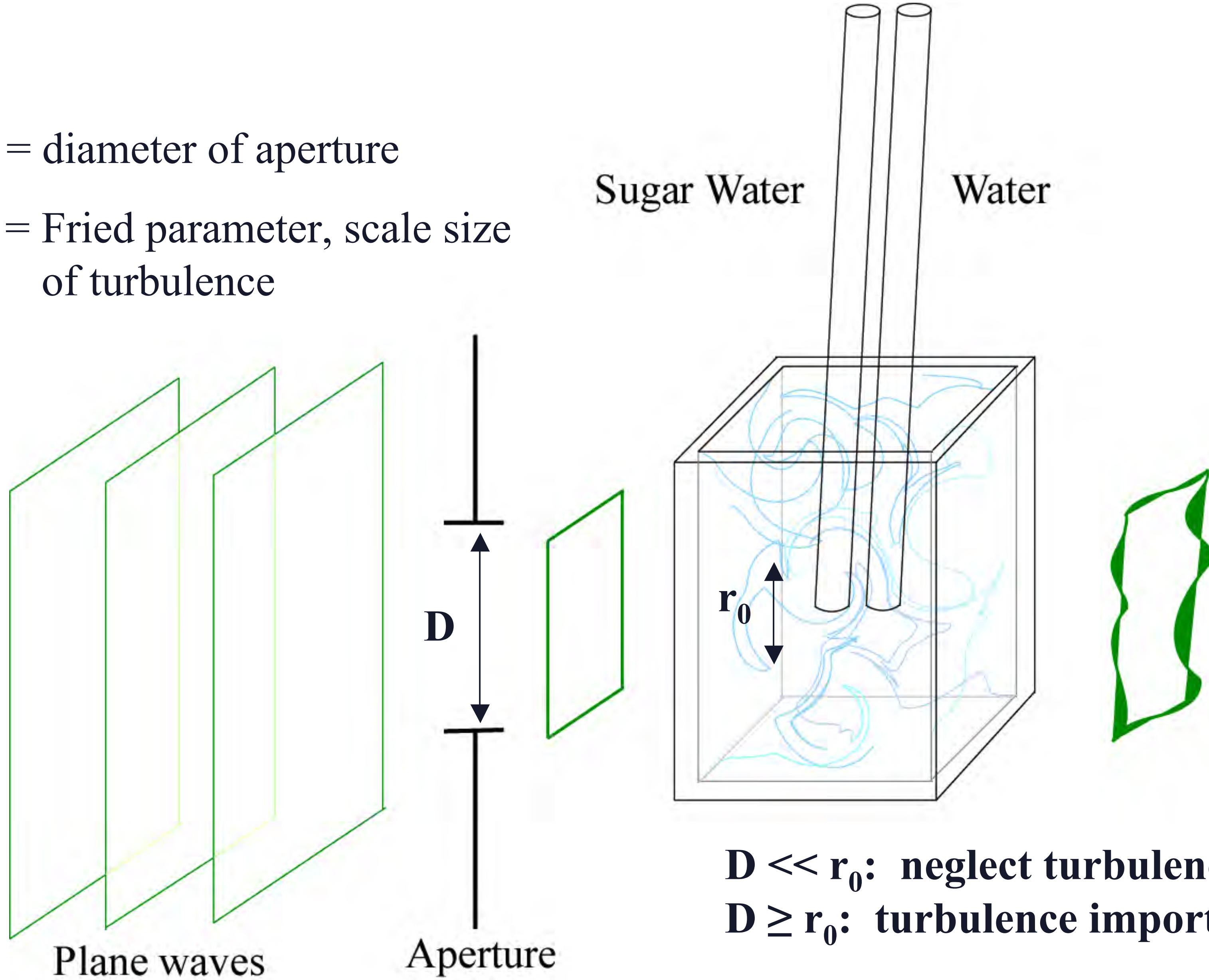
G. A. Tyler and R. W. Boyd, in review.

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

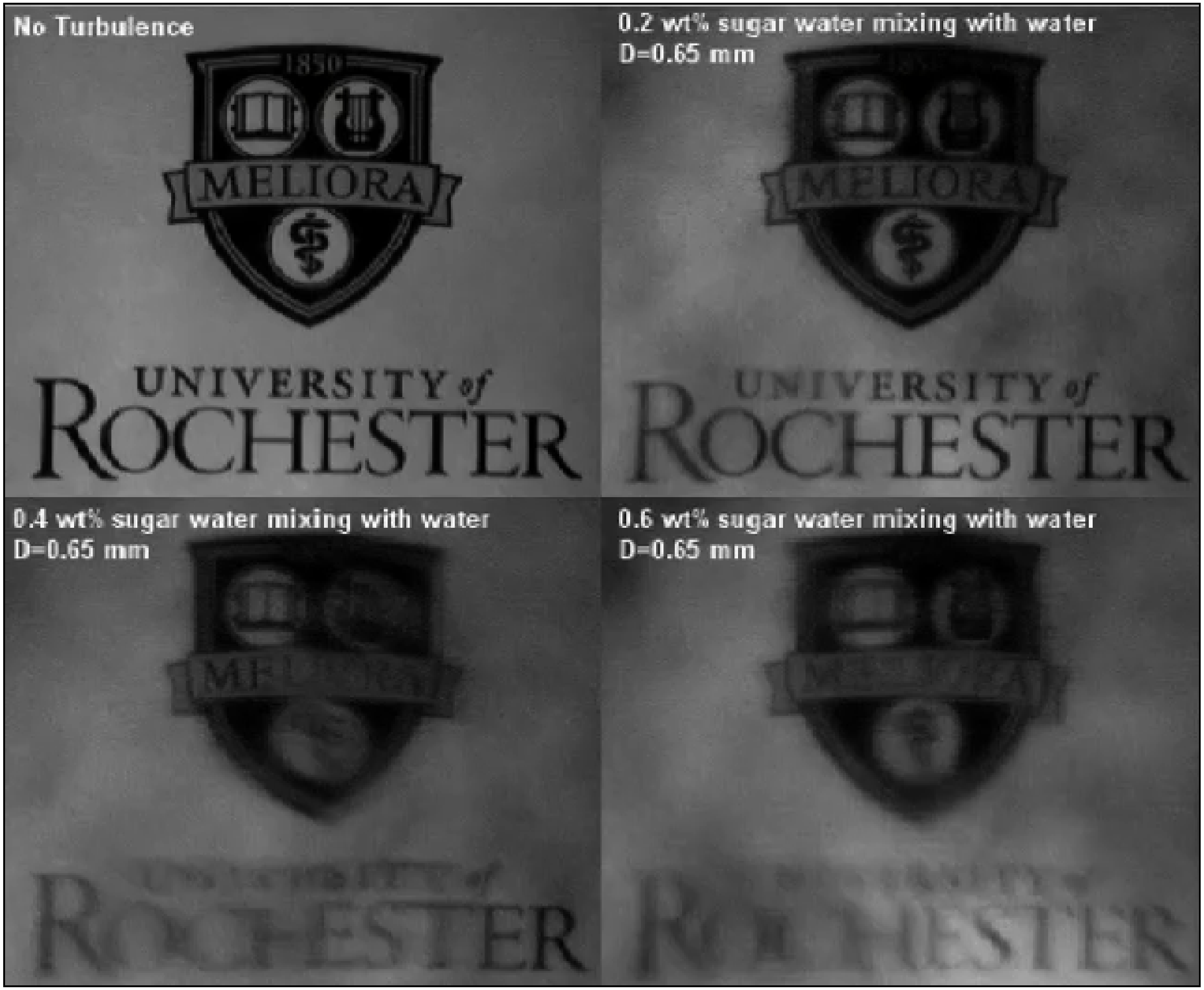
$\mathbf{r_0}$ = Fried parameter, scale size of turbulence



$D \ll r_0$: neglect turbulence

$D \geq r_0$: 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