Laboratory Investigations of Quantum Imaging and Quantum Metrology

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Quantum Imaging: Talk Overview

1. Very brief introduction
2. Some results on “ghost imaging”
3. Some results on “single photon” imaging
4. Quantum protocols with OAM states of light
5. Quantum protocols with time-energy entanglement

Research in Quantum Imaging

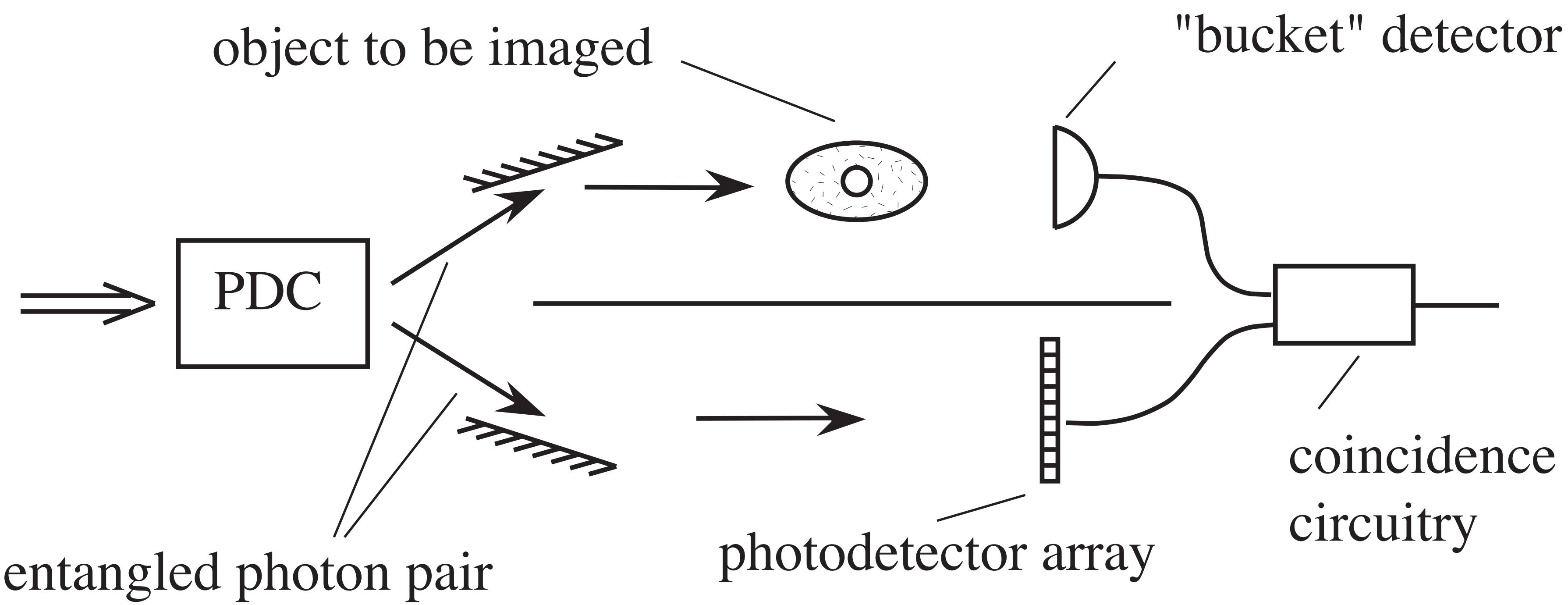
Can images be formed with higher resolution or better sensitivity through use of quantum states of light?

Can we "beat" the Rayleigh criterion?

What are the implications of “interaction free” and “ghost” imaging

Quantum states of light: For instance, squeezed light or entangled beams of light.

Ghost (Coincidence) Imaging



object to be imaged

"bucket" detector

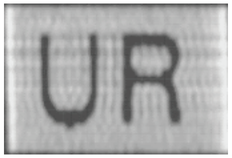
PDC

entangled photon pair

photodetector array

coincidence circuitry

- 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)



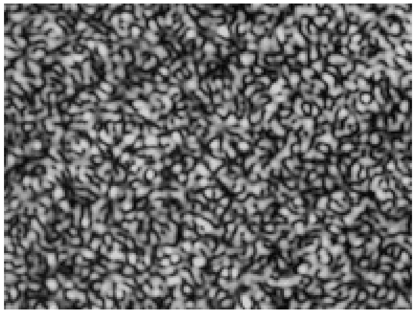
Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).

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.

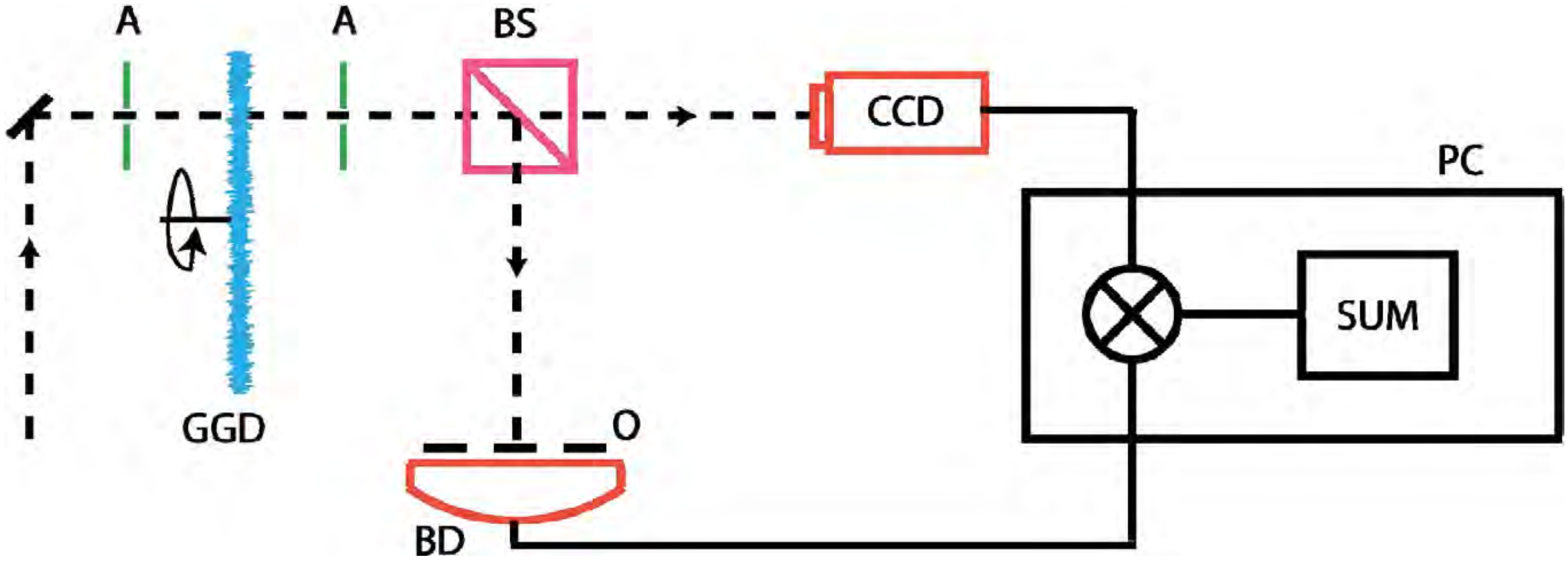
Recall that the intensity distribution of thermal light looks like a speckle pattern.



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.

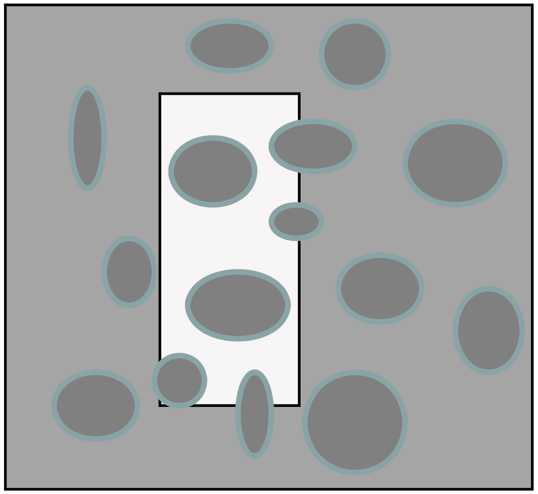
How does thermal ghost imaging work?



- 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.

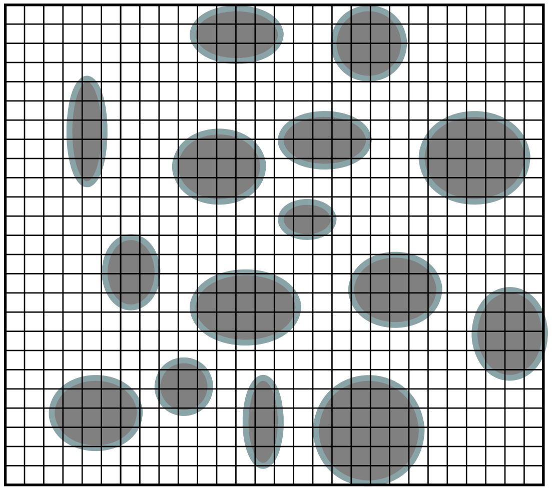
Origin of Thermal Ghost Imaging

Create identical speckle patterns in each arm.



object arm

(bucket detector)



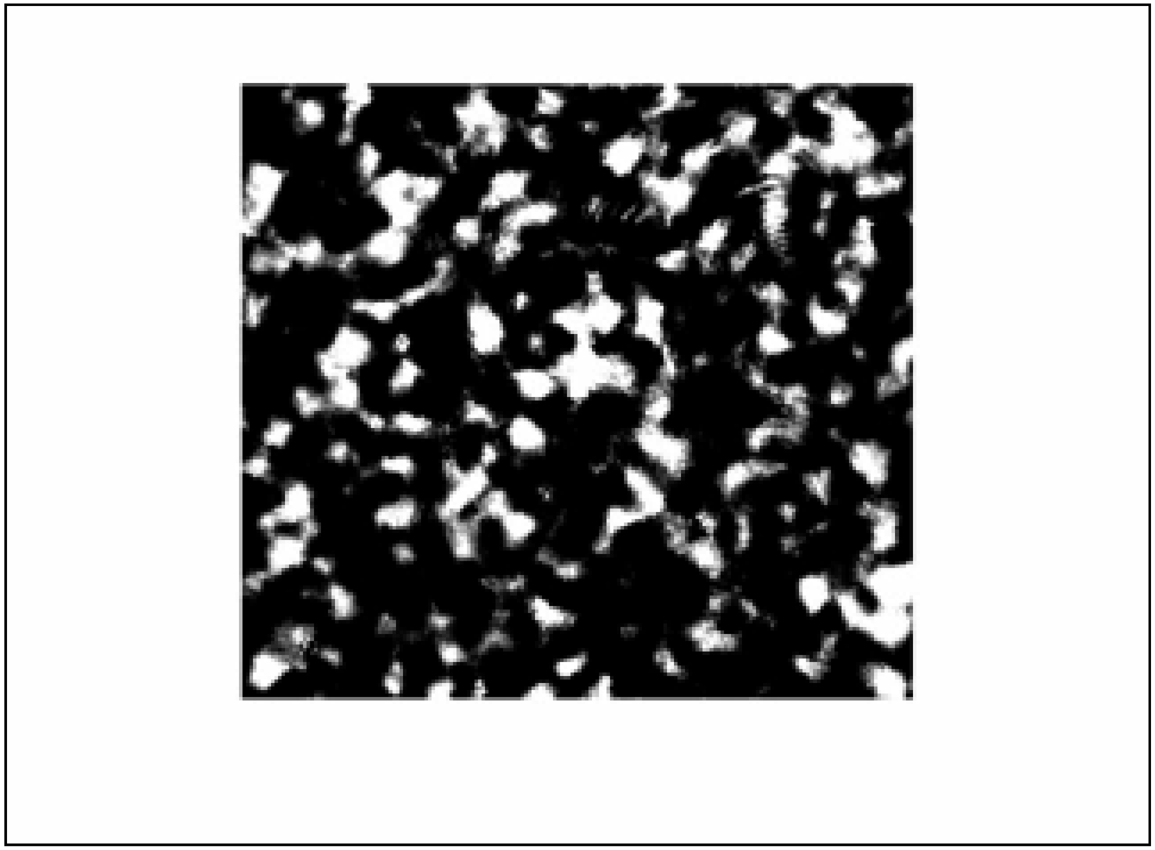
reference arm

(pixelated imaging detector)

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

Average over many speckle patterns

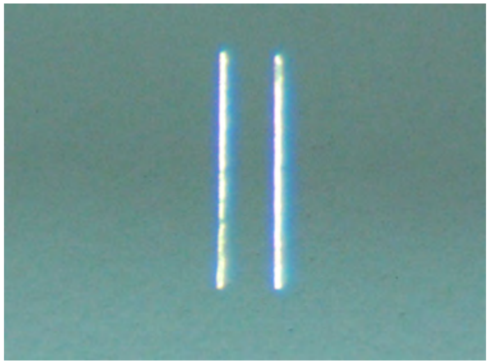
Demonstration of Image Buildup in Thermal Ghost Imaging



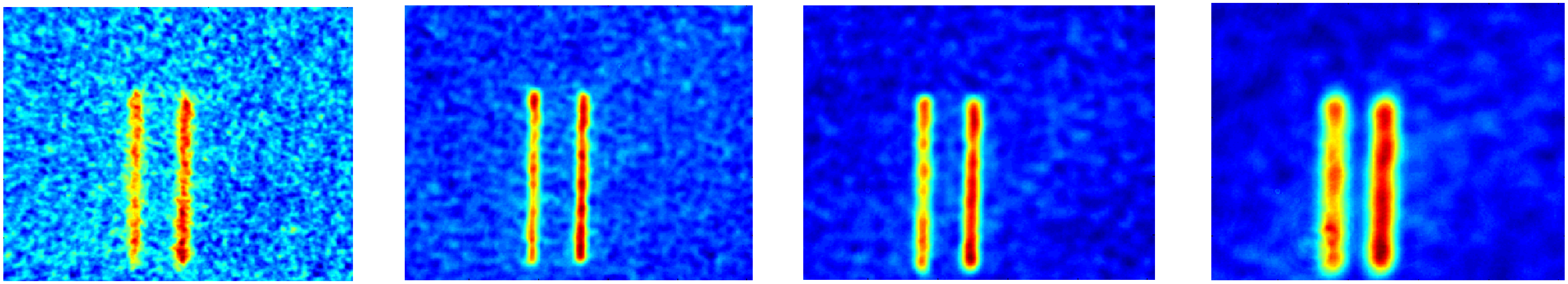
(click within window to play movie)

Influence of Speckle Size on Spatial Resolution

Test object
(stencil)



small speckle → large speckle

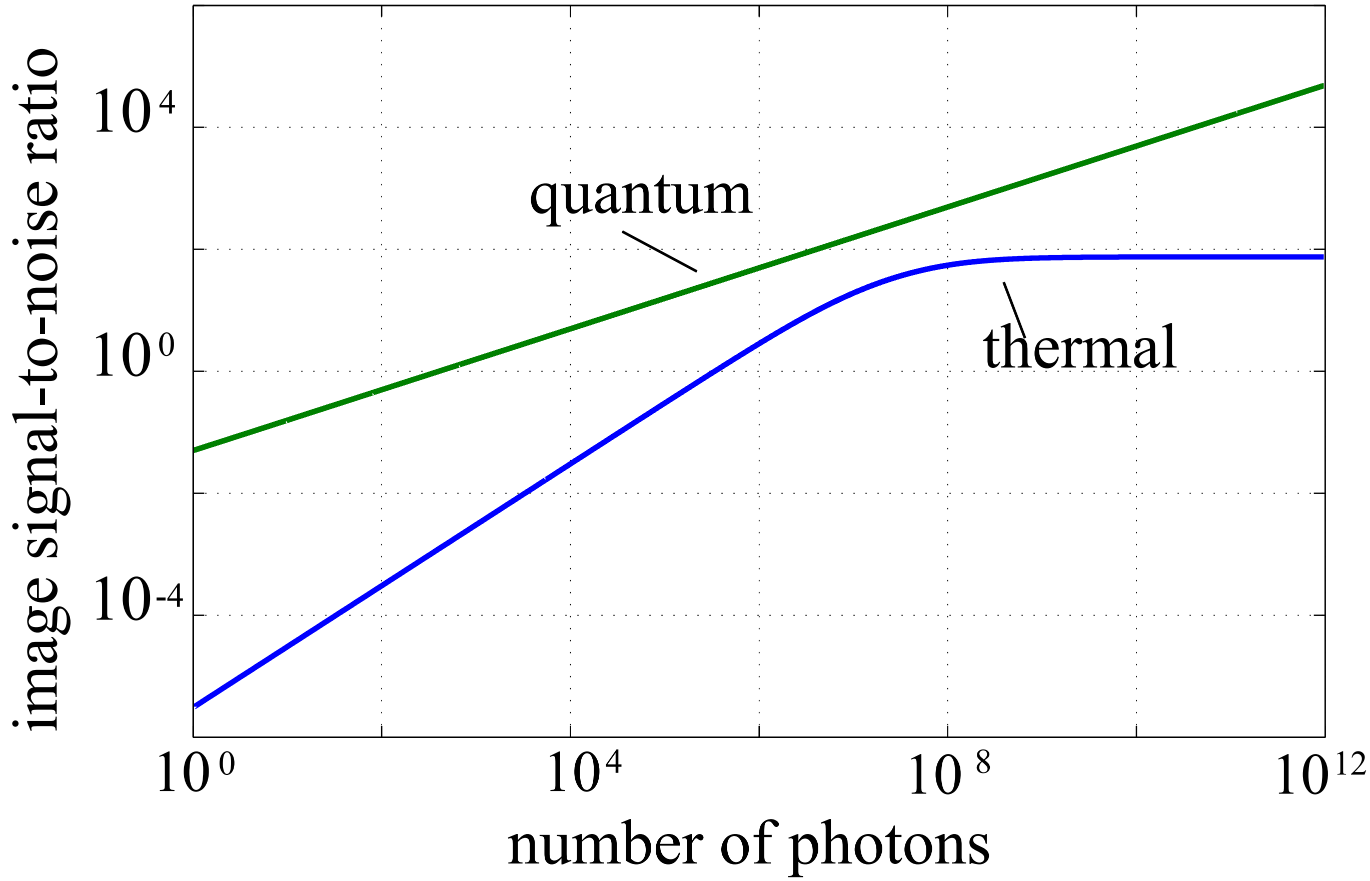


As the speckle size increases, the resolution decreases but the signal-to-noise ratio increases.

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?



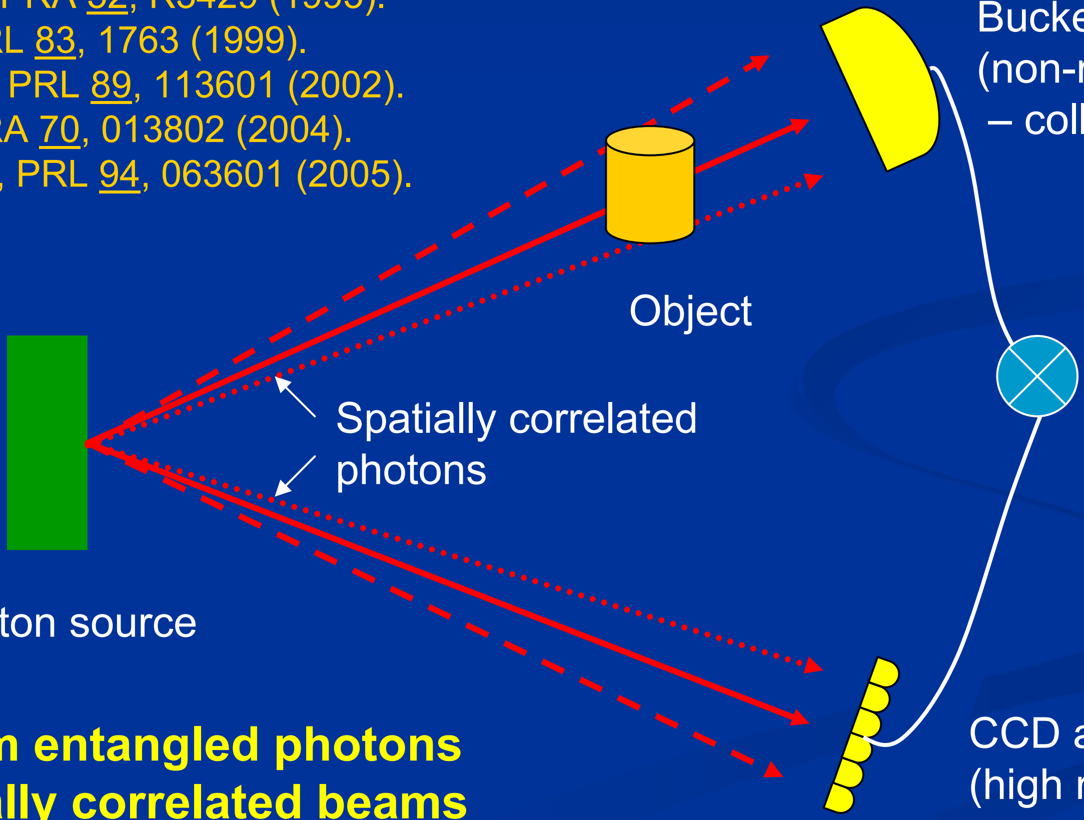
Preliminary result; work still in progress

(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).



Bucket detector
(non-resolving detector)
– collects all photons

Object

Spatially correlated
photons

Photon source

Signal processing

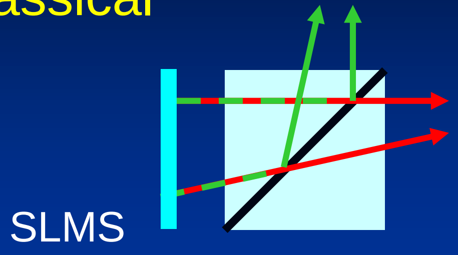
(coincidence
measurement)

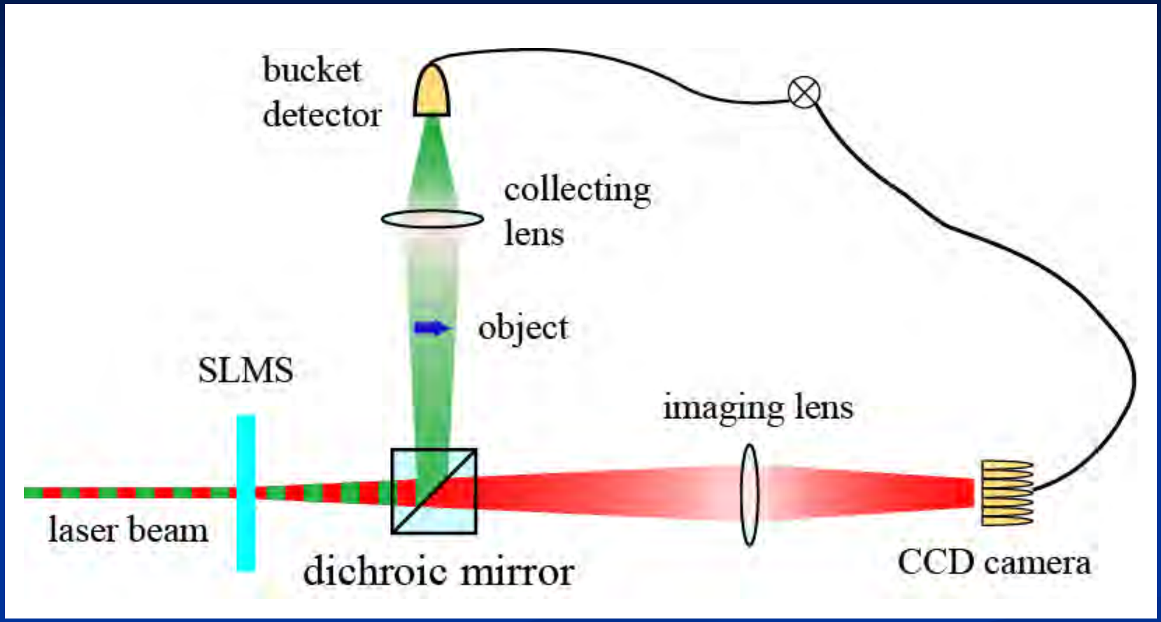
CCD array
(high resolution detector)

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

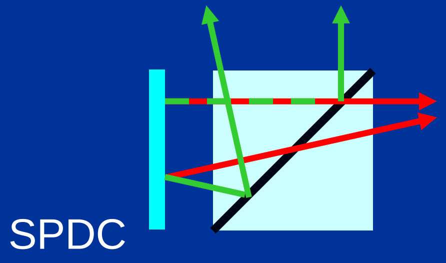
Two-Color Ghost Imaging: Theory

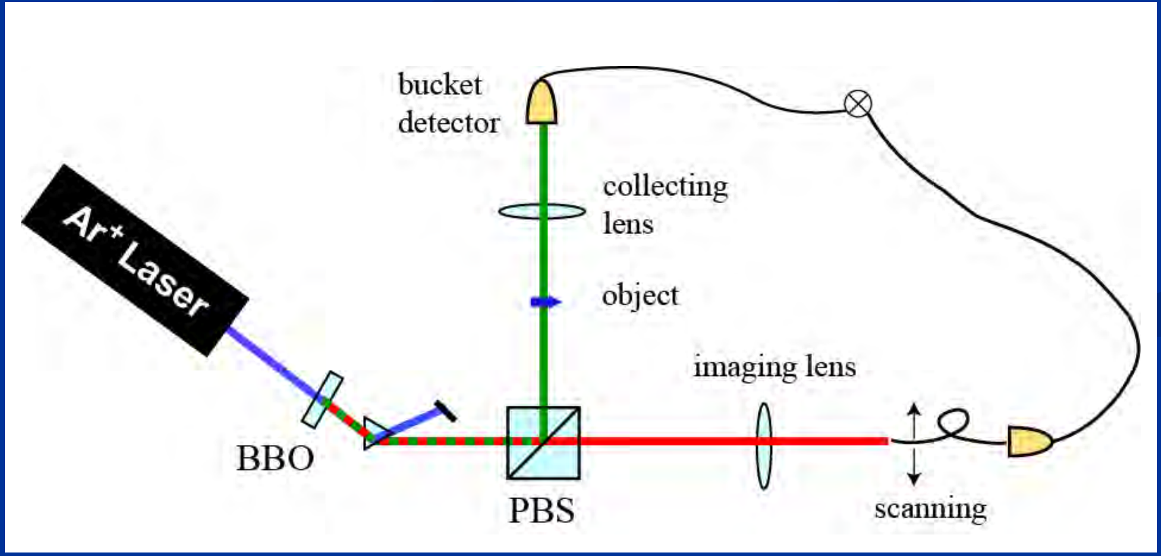
Classical





Quantum





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

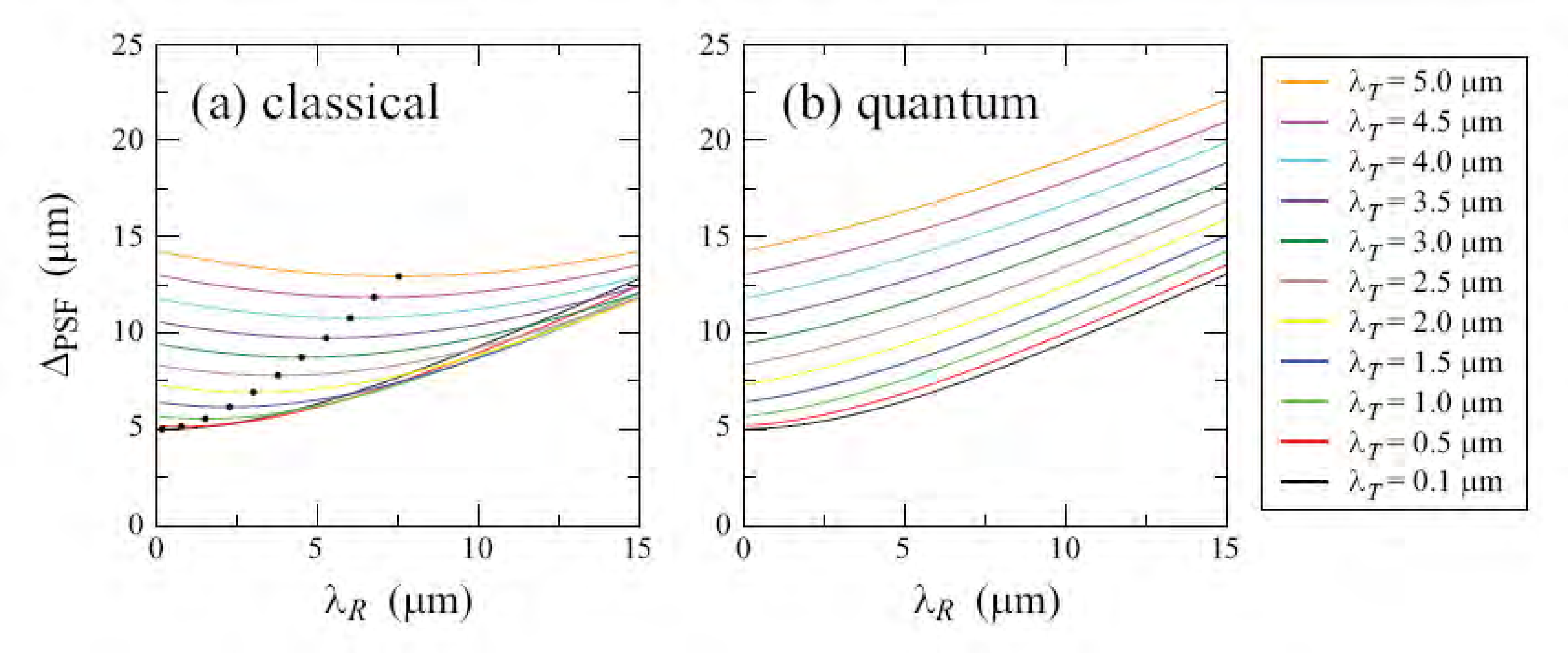
Correlation area
$\sigma_x = 5\mu m$

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)]

Single-Photon Imaging

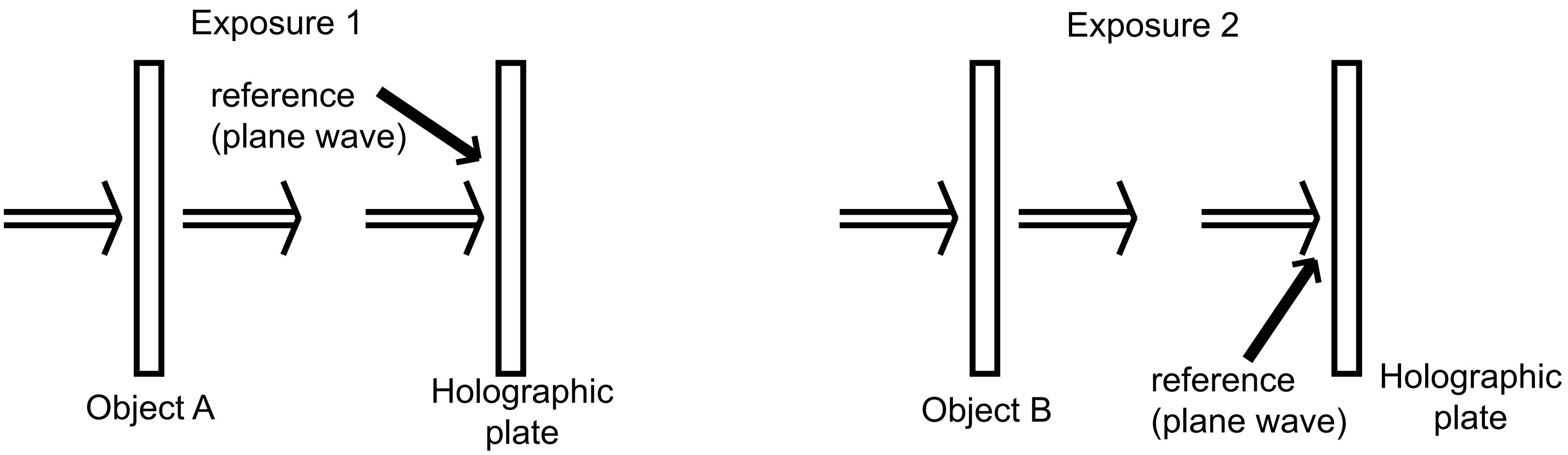
Joint Project: Boyd and Howell Groups

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

Holography, matched filtering, and single-photon Imaging

- Writing the matched filter (a multiple exposure hologram)


Exposure 1

reference
(plane wave)

Object A

Holographic
plate

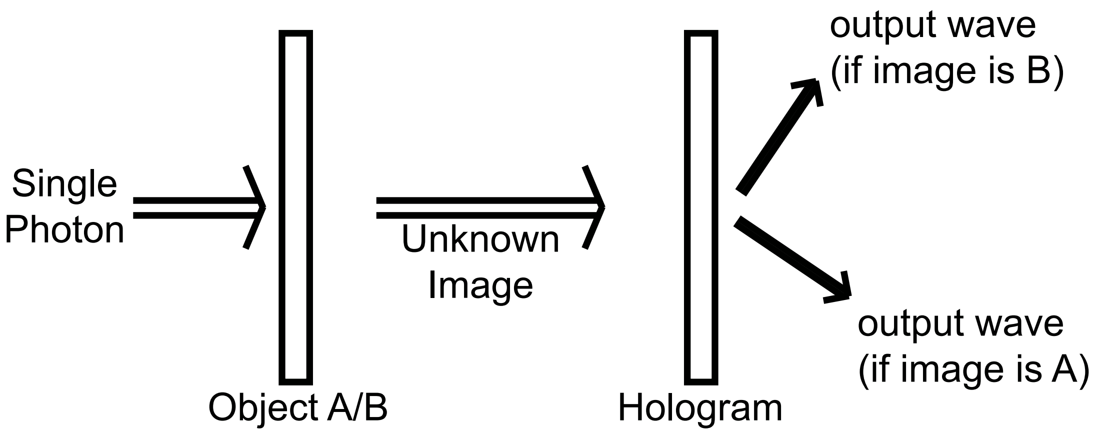
Exposure 2

Object B

reference
(plane wave)

Holographic
plate

- Reading the hologram (with a single-photon)


Single
Photon

Object A/B

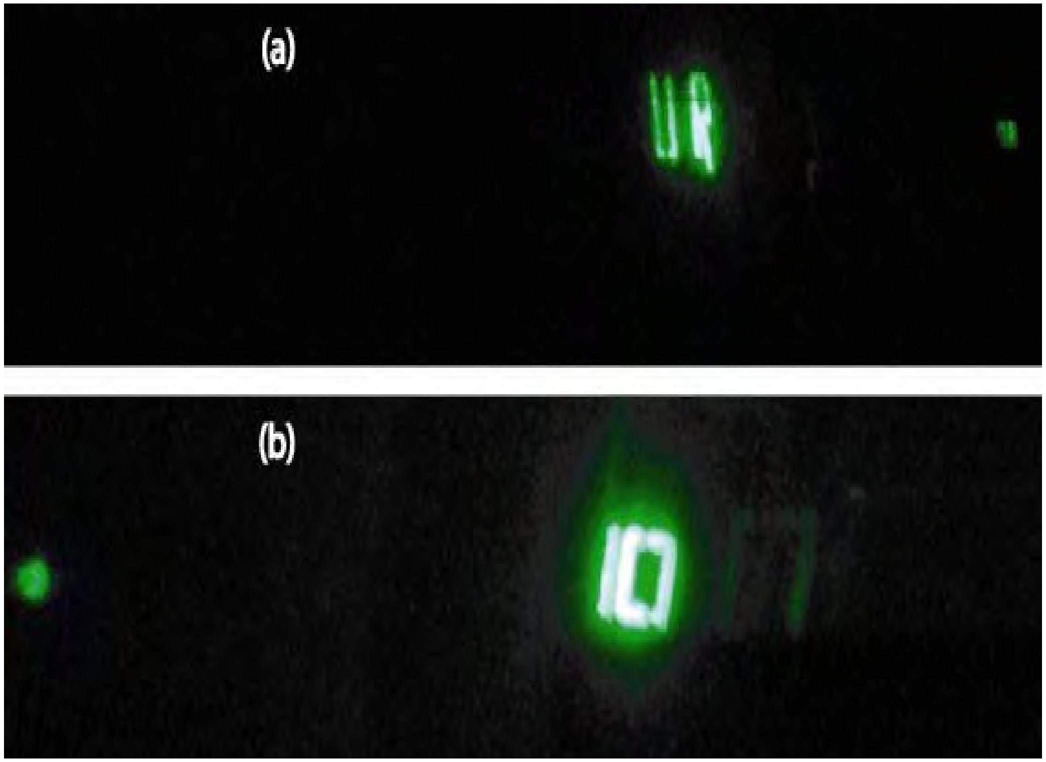
Unknown
Image

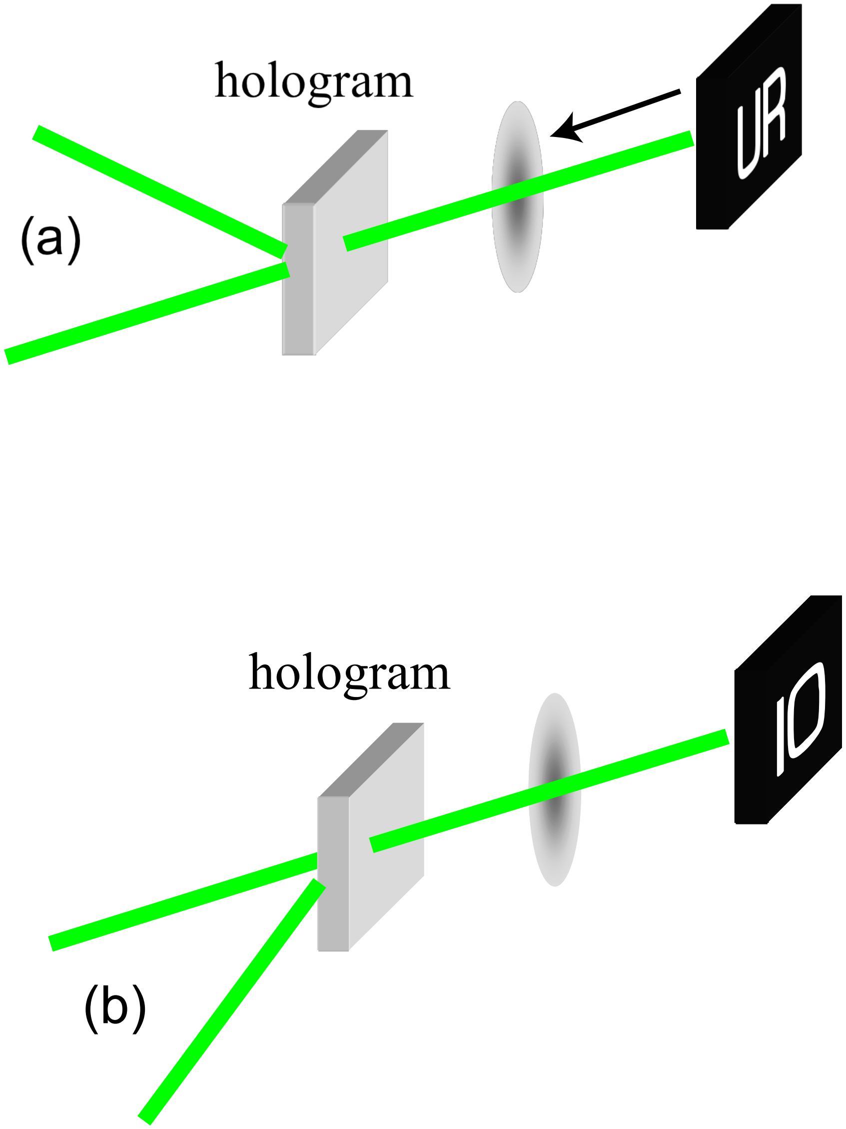
Hologram

output wave
(if image is B)

output wave
(if image is A)

Reconstruction - with structured reference beam





- Very little cross-talk (less than 1%)

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

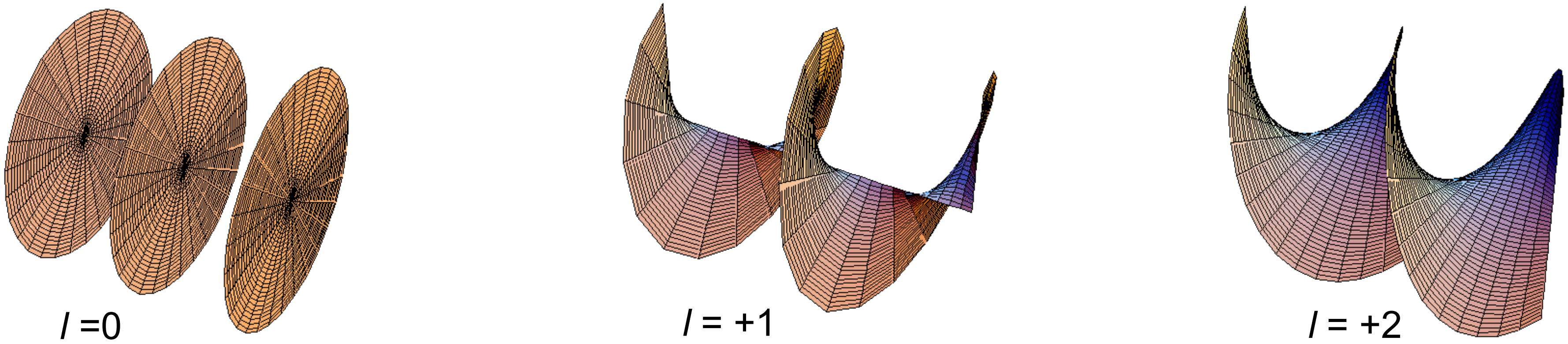
Use of the Orbital Angular Momentum of Light to Carry Quantum Information

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?

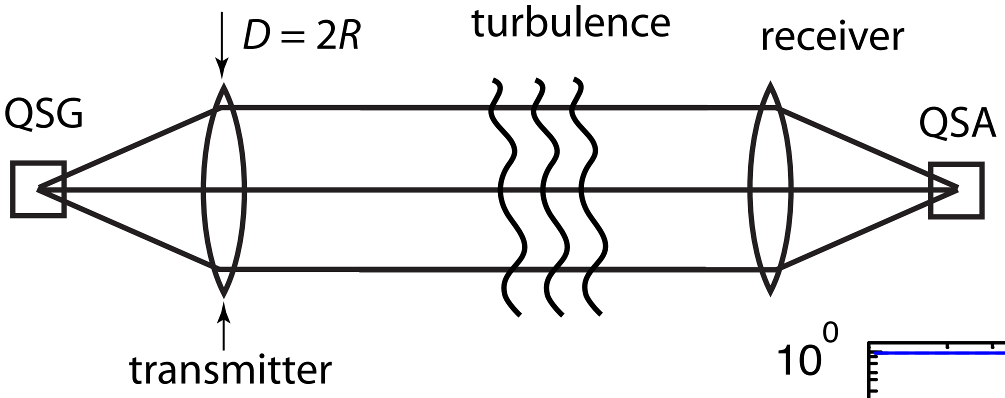
Phase-front structure of some OAM states



$l = 0$ $l = +1$ $l = +2$

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).
G. Molina-Terriza, J. P. Torres, and L. Torner, Phys. Rev. Lett. 88, 013601 (2002).
M. T. Gruneisen, W. A. Miller, R. C. Dymale and A. M. Sweiti, Appl. Opt. 47, A33 (2008).
N. Gisin and R. Thew, Nature Photonics, 1, 165 (2007).
C. Paterson, Phys. Rev. Lett. 94, 153901 (2005).
C. Gopaul and R. Andrews, New J. of Physics, 9, 94 (2007).
G. Gbur and R. K. Tyson, J. Opt. Soc. Am. A, 25, 255 (2008).

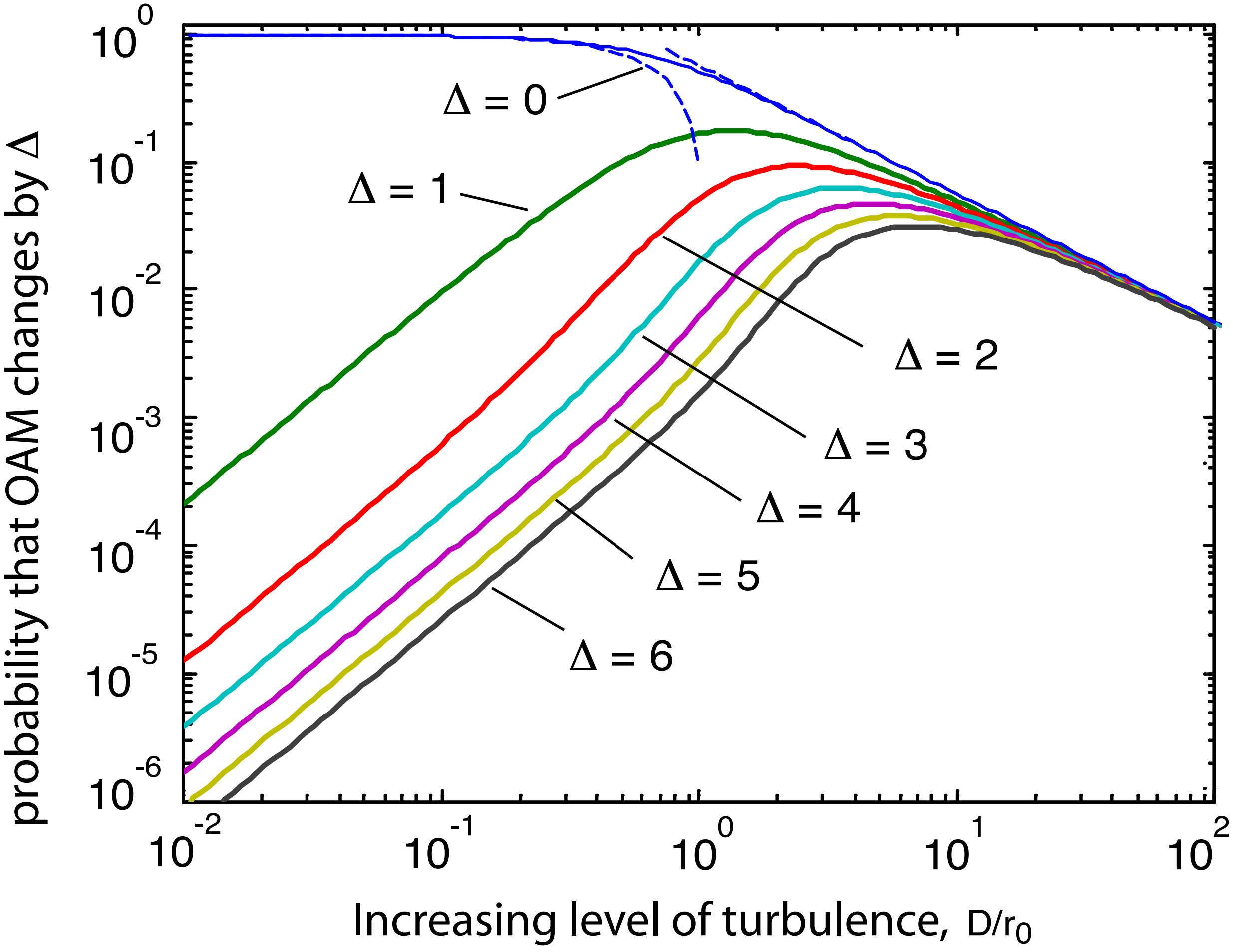
Influence of Atmospheric Turbulence on the Propagation of Quantum States of Light Carrying Orbital Angular Momentum



Probability that initial state is retained:

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

r_0 = Fried parameter

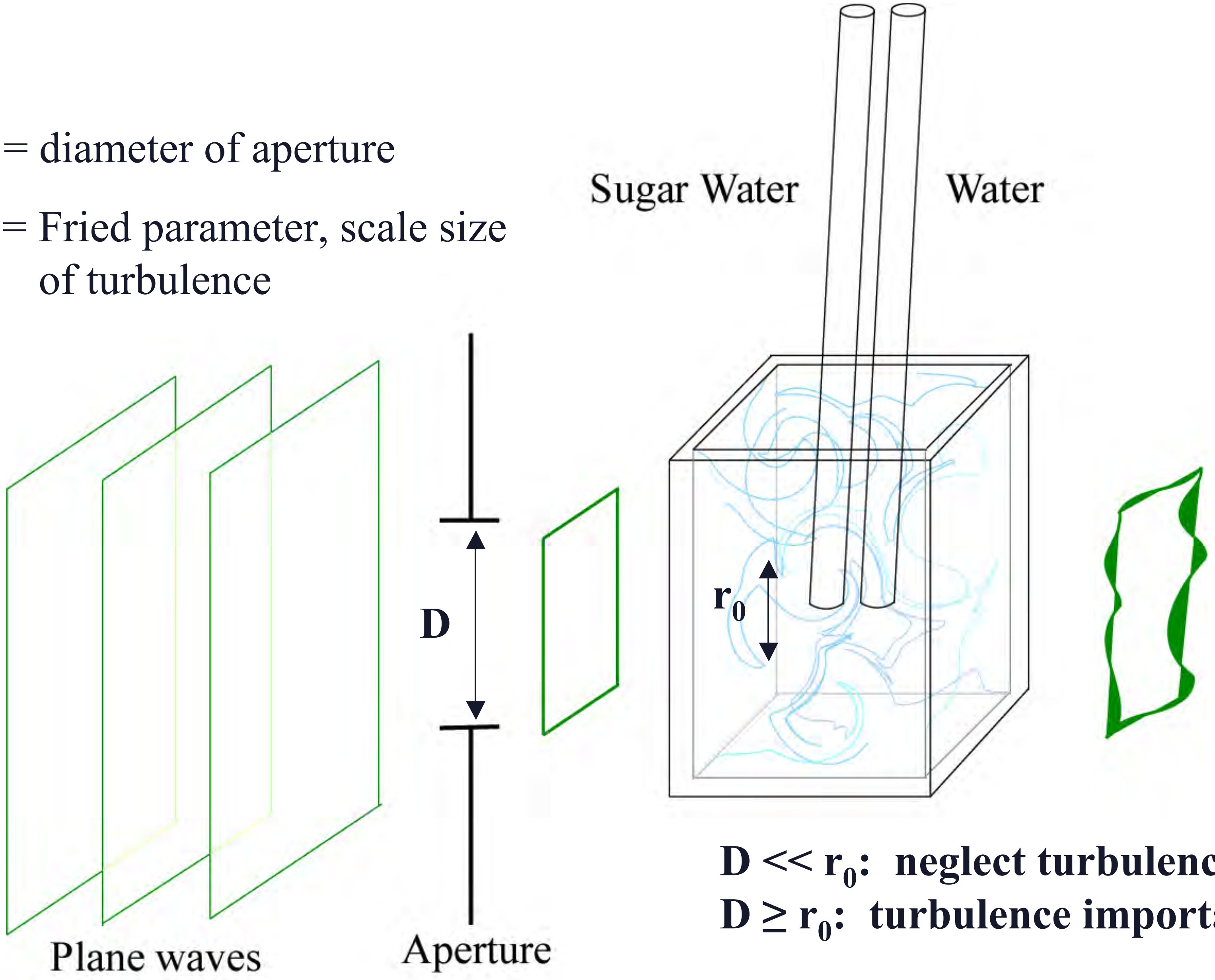


Our results are qualitatively similar to those of Paterson (2005), but differ in detail because Paterson considered LG modes whereas we consider pure vortex beams. See also Smith and Raymer (2006).

G. A. Tyler and R. W. Boyd, Opt Lett (2009).

Influence of Atmospheric Turbulence on the Quantum States of Light

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



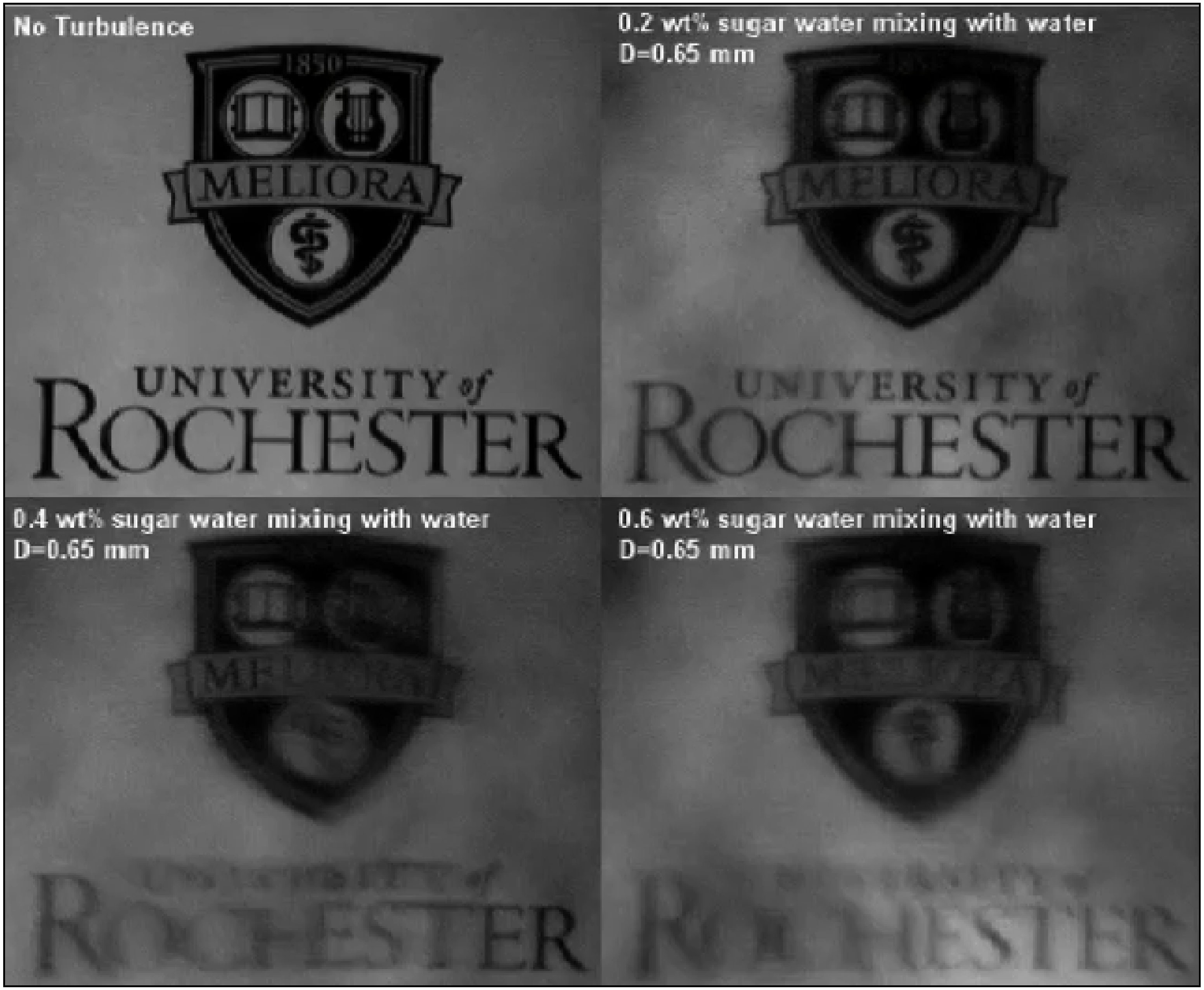
D = diameter of aperture

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

$D \ll r_0$: neglect turbulence

$D \geq r_0$: turbulence important

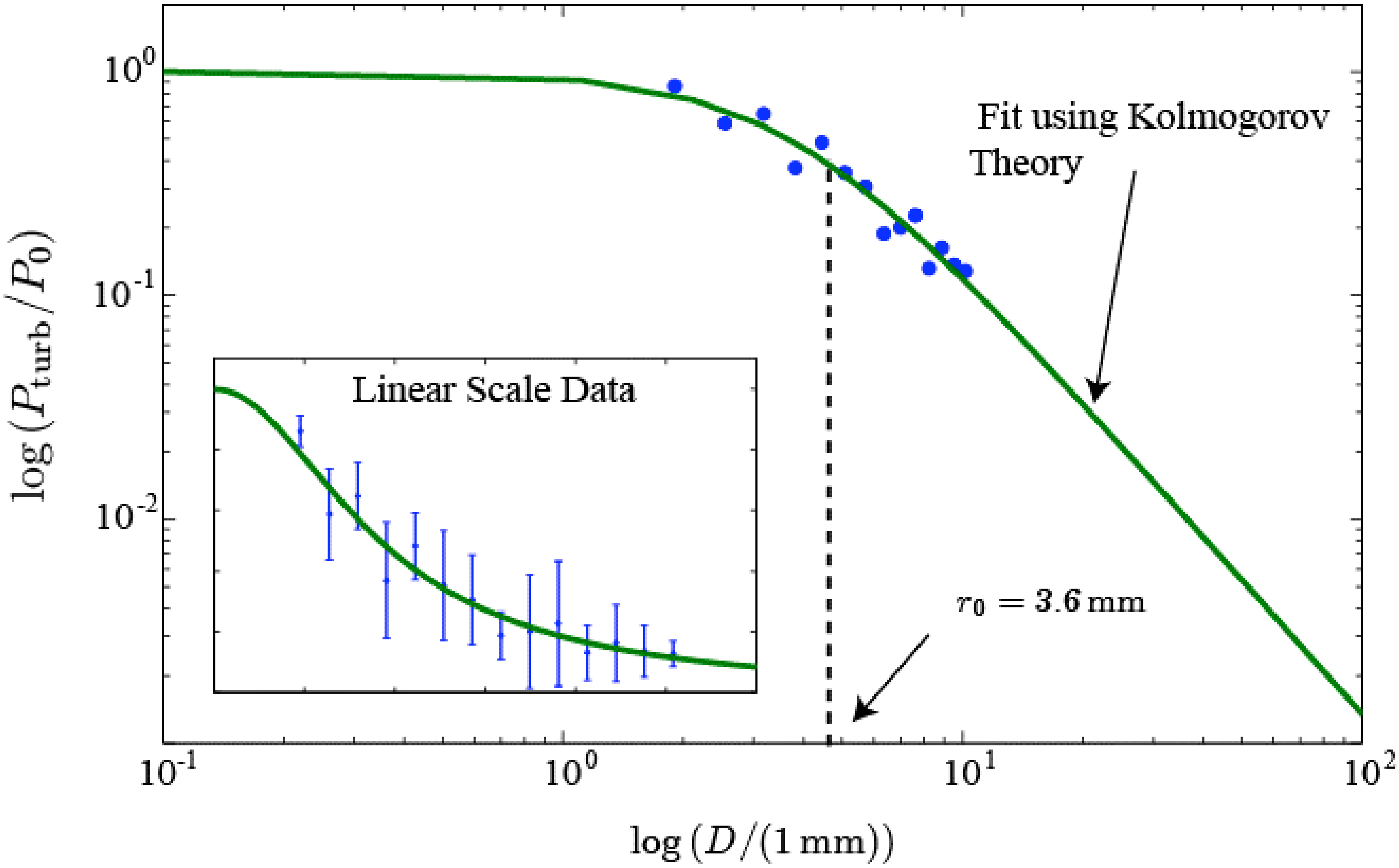
Demonstration of the Operation of the Turbulence Cell



(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



Coherence and Indistinguishability in Two-Photon Interference

Anand Kumar Jha, Malcolm N. O'Sullivan-Hale,
Kam Wai Chan, and Robert W. Boyd

Institute of Optics, University of Rochester

What are the relevant degrees of freedom of a biphoton?

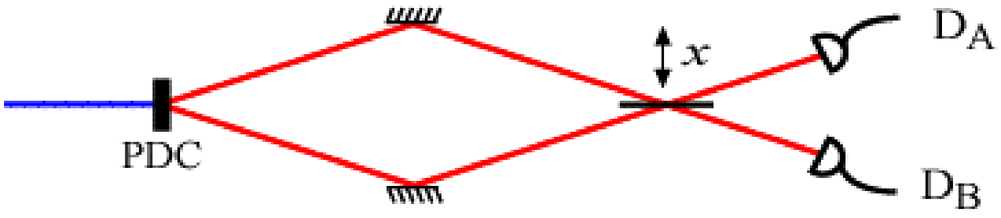
What are the generic features of two-photon interference?

Phys. Rev. A, 77 021801 (R) (2008)

Two-Photon Interference -- How to Understand?

- **Hong-Ou-Mandel effect (1987)**

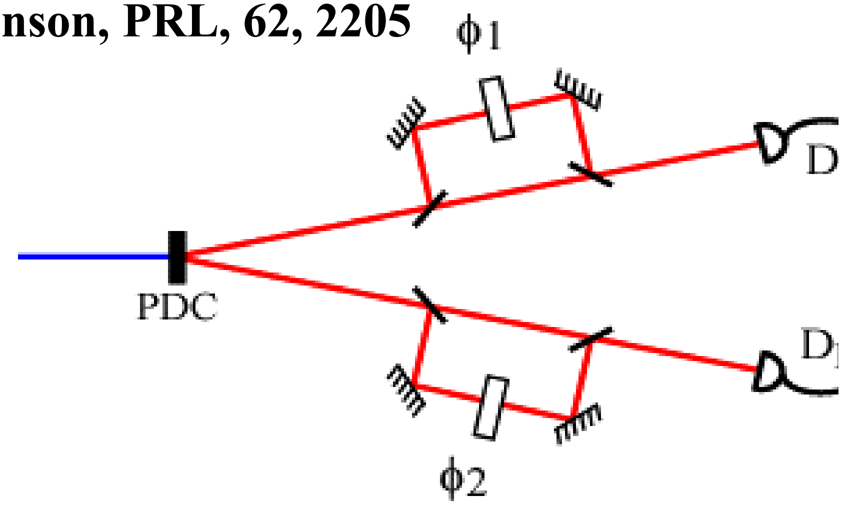
PRL, 59, 2044



Anti-bunching of indistinguishable photons

- **Bell Inequality for position and time (1989)**

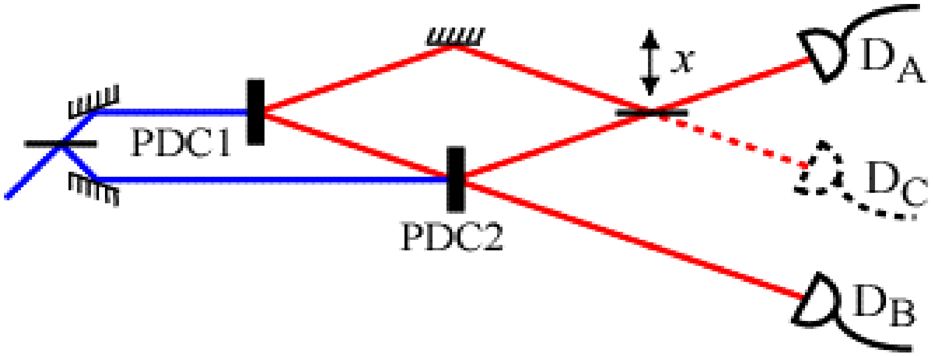
Franson, PRL, 62, 2205



Time-energy entanglement

- **Induced Coherence (1991)**

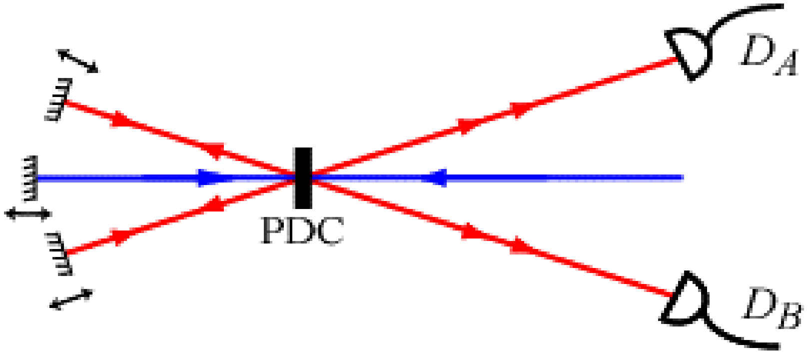
Zou et al. PRL, 67, 318



"mind-boggling"

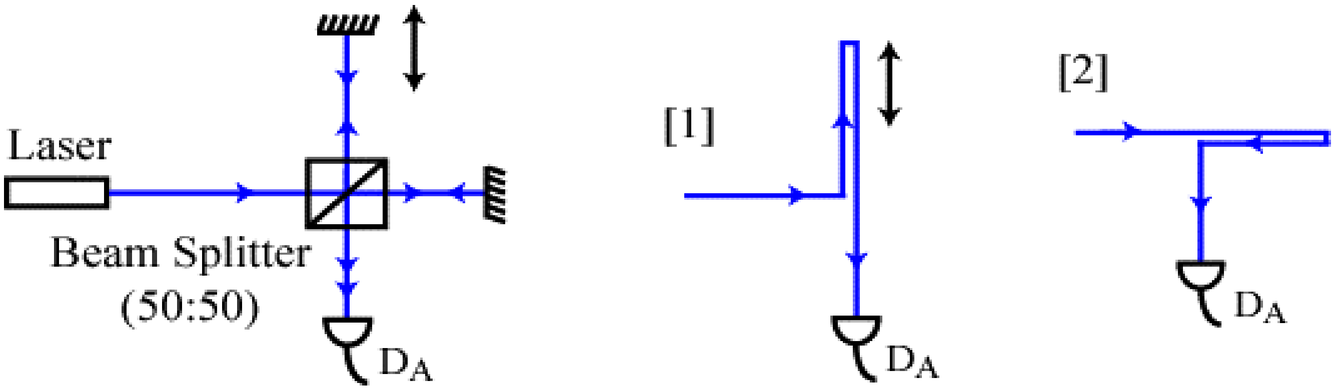
- **Frustrated two-photon creation (1994)**

Herzog et al. PRL, 72, 629

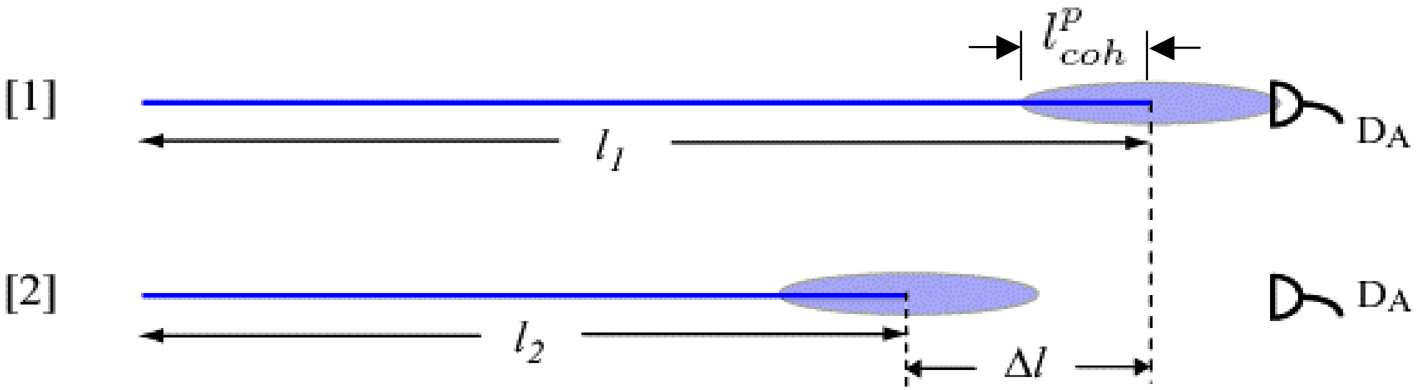


Quantum eraser

Single-Photon Interference: “A photon interferes only with itself ” - Dirac



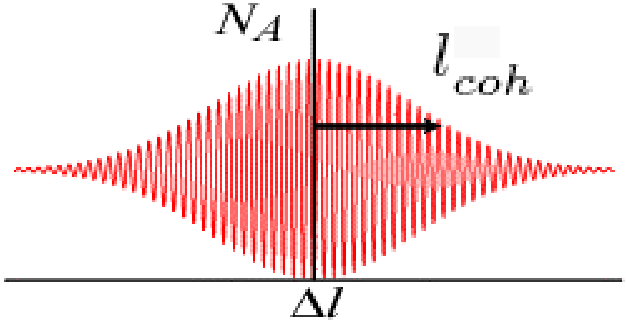
Add probability amplitudes for alternative pathways [1] and [2]



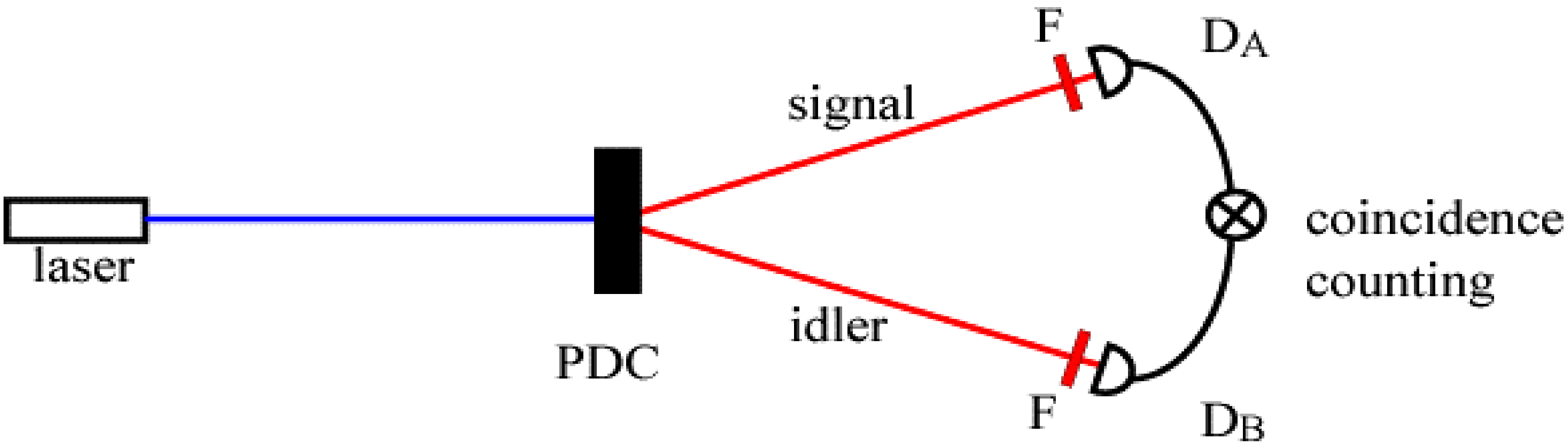
(unfolded paths)

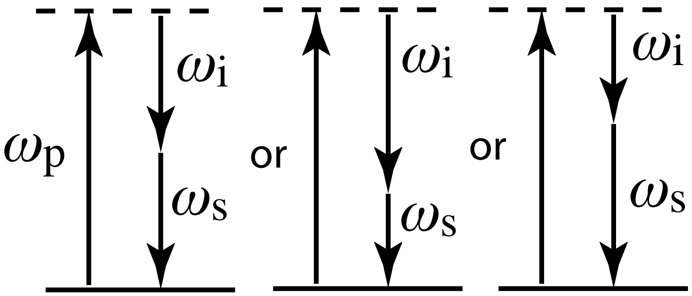
Necessary condition for one-photon interference

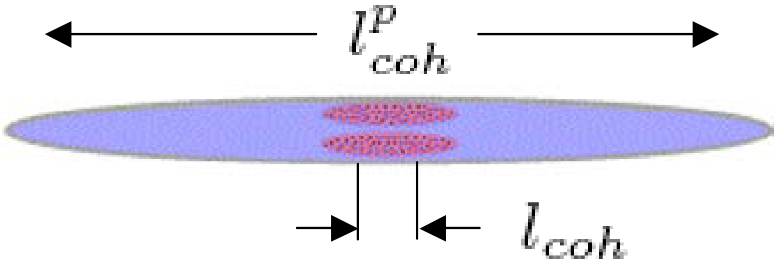
$$\boxed{\Delta l \; < \; l^{p}_{coh}}$$



Biphotons Are Created by Parametric Downconversion (PDC)







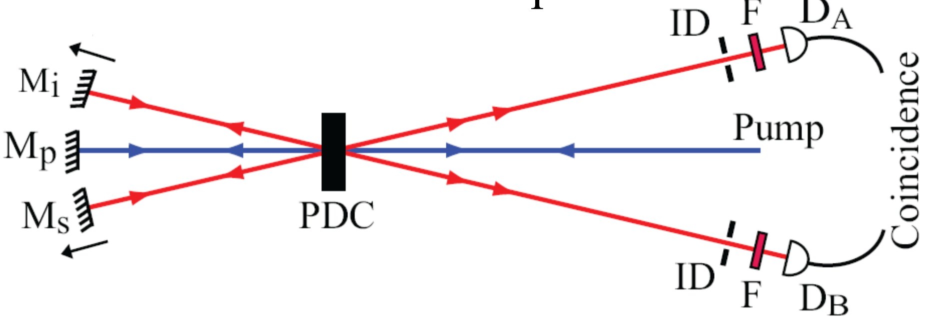
Length of two-photon wavepacket ~ coherence length of pump laser ~ 10 cm

Coherence length of signal/idler photons ~ c/Δω ~ 100 μm.

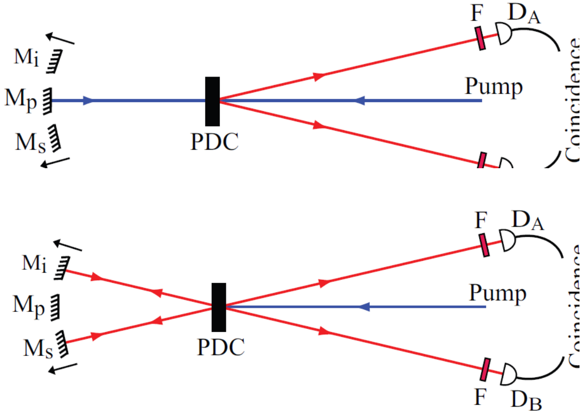
These photons are time-energy entangled!

Two-Photon Interference

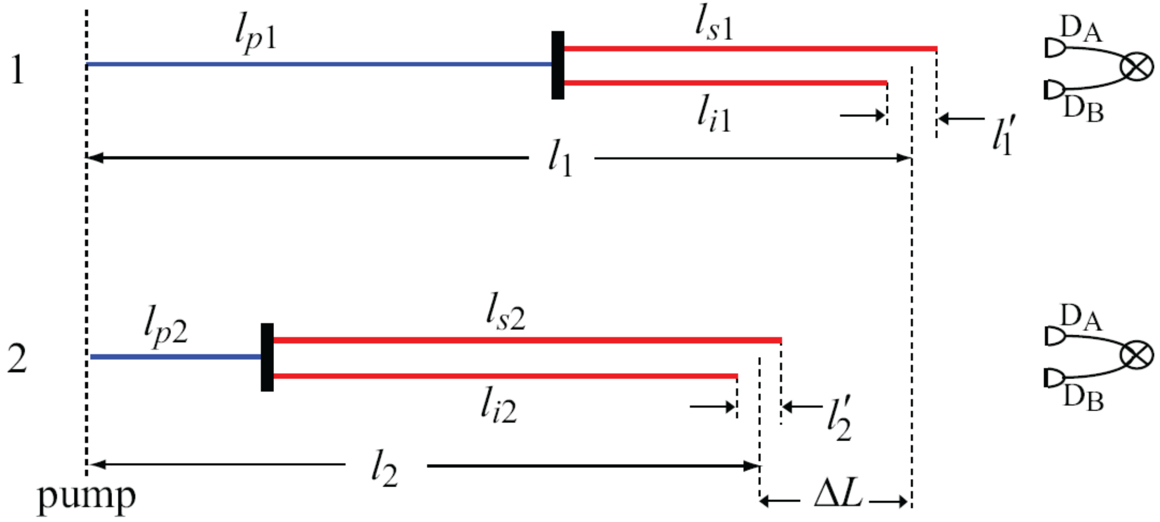
Generic Interference Setup



Two Interfering Alternatives



The alternative two-photon pathways



$$\Delta L \equiv l_1 - l_2$$

Biphoton path-length

$$\Delta L' \equiv l_1' - l_2'$$

Biphoton path-asymmetry length

$$R_{\mathrm{AB}} = C\left[1 + \gamma'\left(\Delta L'\right)\gamma\left(\Delta L\right)\cos\left(k_0 \Delta L\right)\right]$$

Jha et al., PRA 77, 021801(R) (2008)

Necessary conditions for two-photon interference:

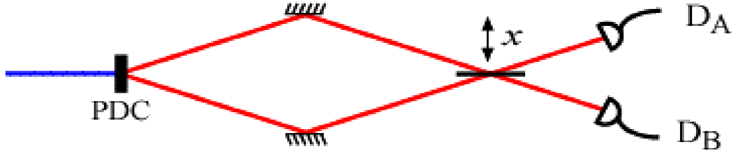
$$\Delta L < l_{\mathrm{coh}}^{p}$$

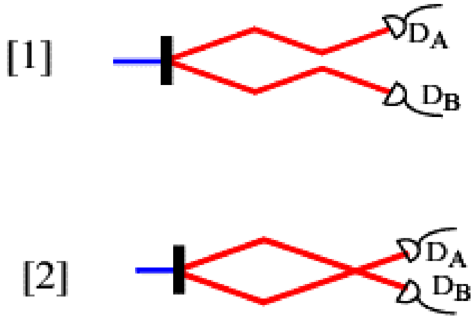
$$\Delta L' < l_{\mathrm{coh}}$$

$l_{\mathrm{coh}}^{p} \sim 10$ cm

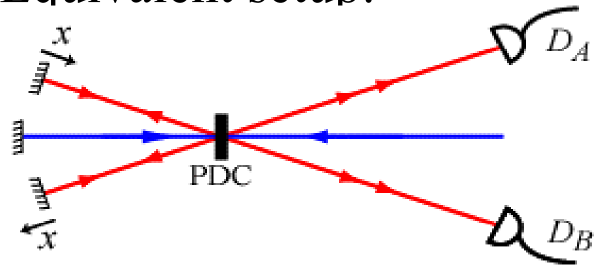
$l_{\mathrm{coh}} = \dfrac{c}{\Delta\omega} \sim 100\ \mu\mathrm{m}$

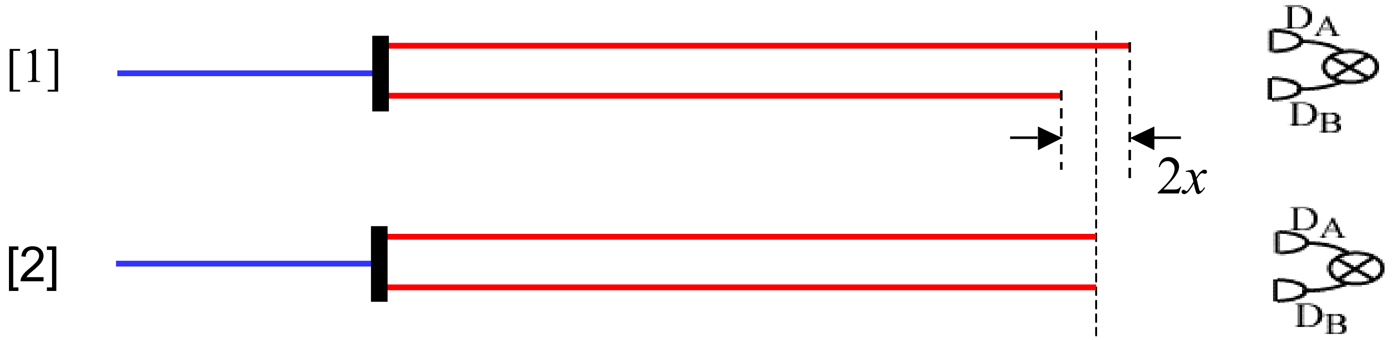
Hong-Ou-Mandel Experiment





Equivalent setup:

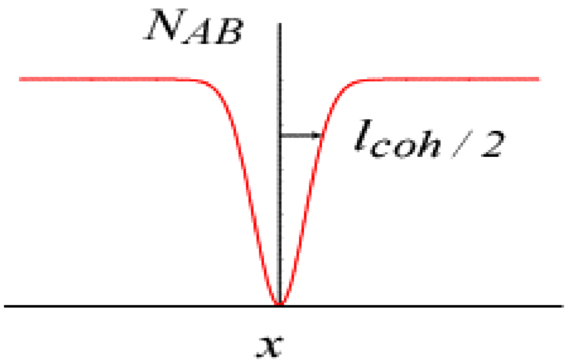




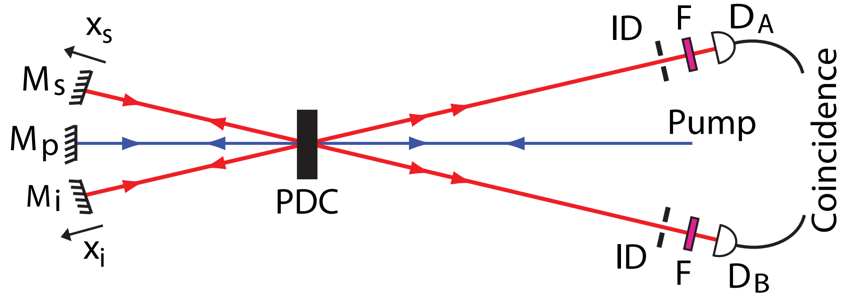
$\Delta L = 0 \qquad \Delta L' = 2x$

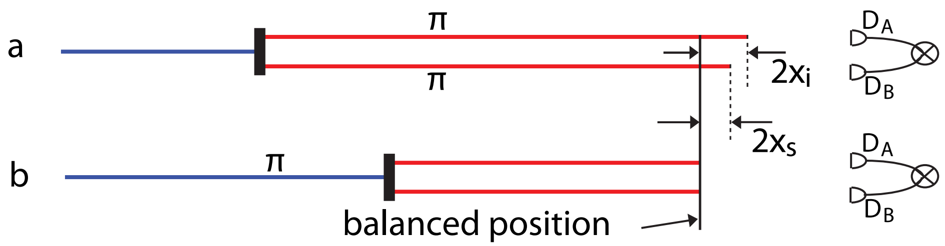
$$N_{AB} \propto 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

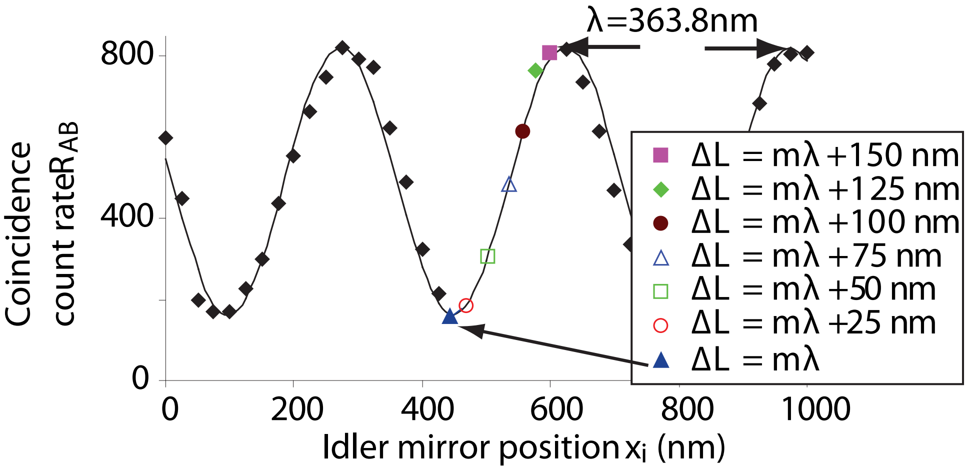
$$N_{AB} \propto 1 - \gamma'(2x)$$

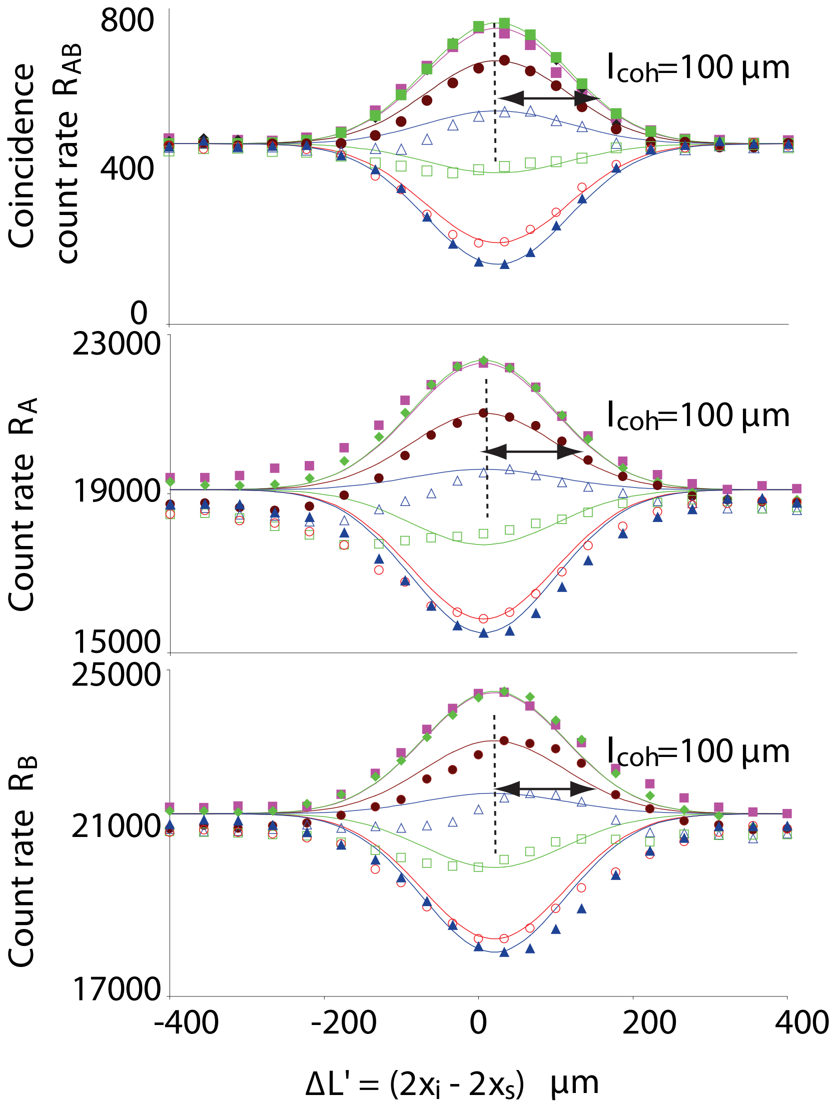


Our Experiment: Generalization of the Hong-Ou-Mandel Effect







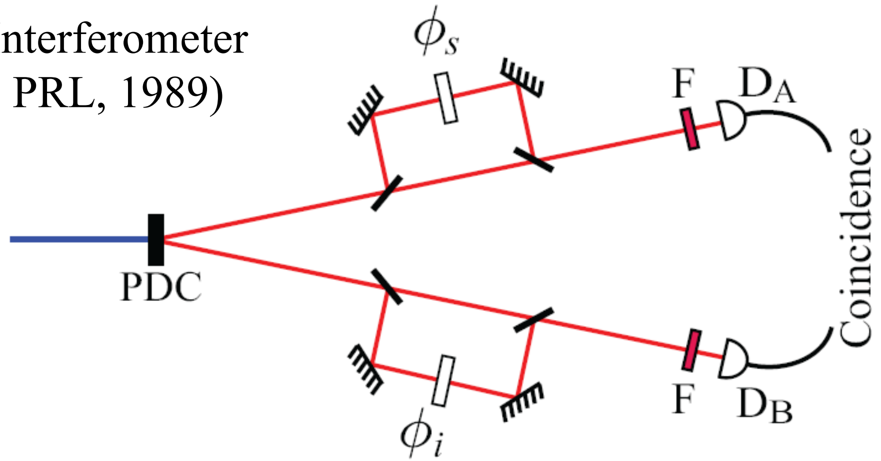


Jha et al., PRA 77, 021801(R) (2008).

We see either a dip or a hump (depending on the value of *ΔL*) in both the single and coincidence count rates as we scan *ΔL´*.

Bell Inequality for Energy-Time Entanglement Controlled by Geometric (Berry's) Phase

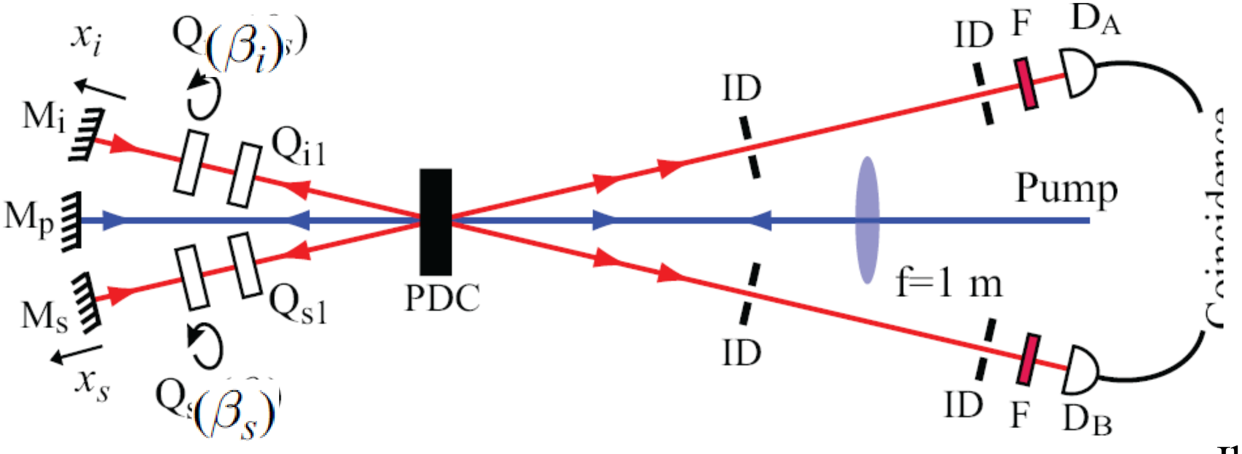
Franson Interferometer
(Franson, PRL, 1989)

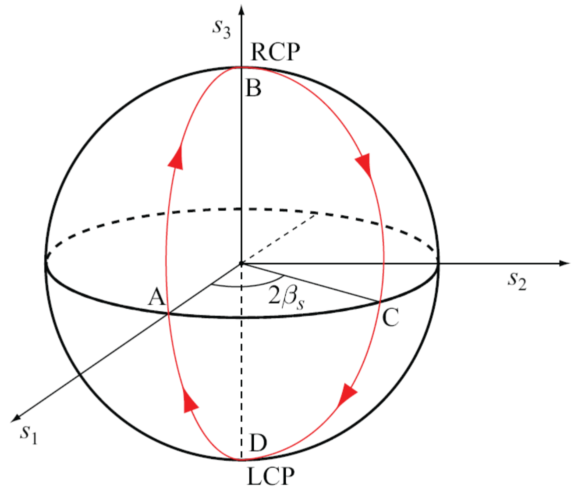


$$R_{AB} = C[1 + \cos(\phi_s + \phi_i)]$$

Violation of CHSH Bell Inequality using dynamic phase

Geometric Phase Implementation





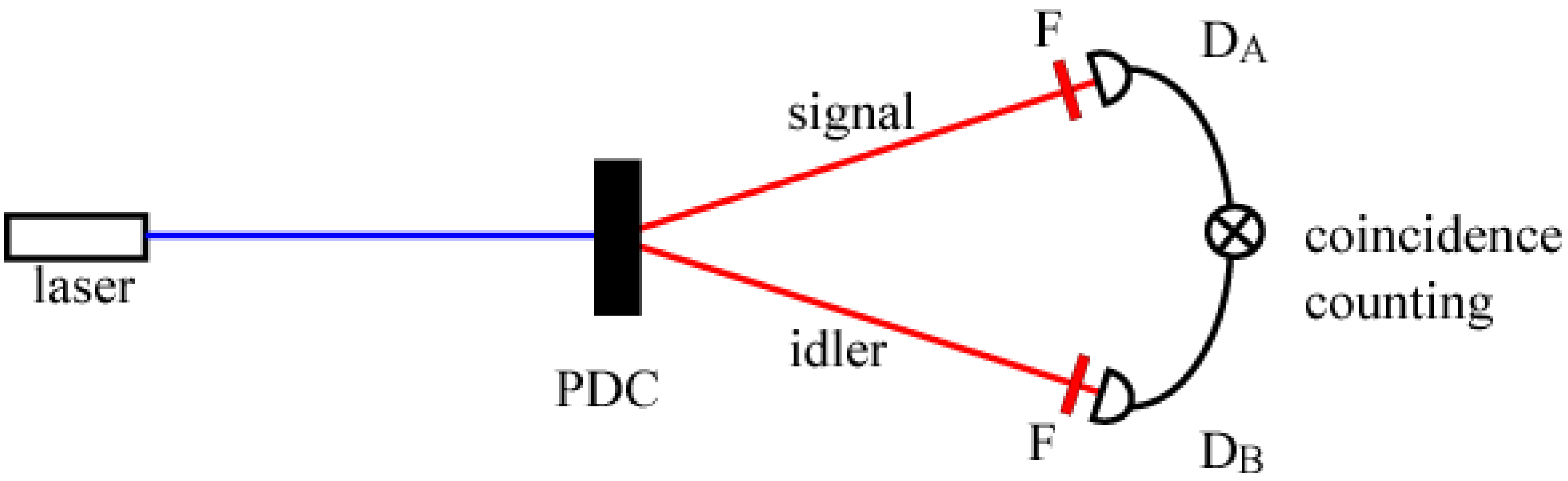
Jha, Malik, Boyd, PRL 101, 180405 (2008).

Violation of CHSH Bell Inequality using geometric (Pancharatnam, Berry) phase

$$R_{AB} = C\ \{\ 1 - \cos[k_0(x_s + x_i) + 2\beta_s + 2\beta_i]\}$$

Summary: Geometric phase is a suitable means for modifying quantum information

Parametric Downconversion: A Source of Entangled Photons



Conserved quantities

$\omega_p = \omega_s + \omega_i$ **Entanglement in emission-time and energy**

$\boldsymbol{k}_p = \boldsymbol{k}_s + \boldsymbol{k}_i$ **Entanglement in position and momentum**

$l_p = l_s + l_i$ **Entanglement in angular position and angular momentum**

Special Thanks to My Students and Research Associates