Quantum Imaging: Enhanced Image Formation Using Quantum States of Light

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With special thanks to Kam Wai Clifford Chan, Anand Jha, Mehul Malik, Colin O'Sullivan, Heedeuk Shin, and Petros Zerom

Presented at the SPIE Defense, Science, and Sensing Conference, Orlando, Florida, April 16, 2009.

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?

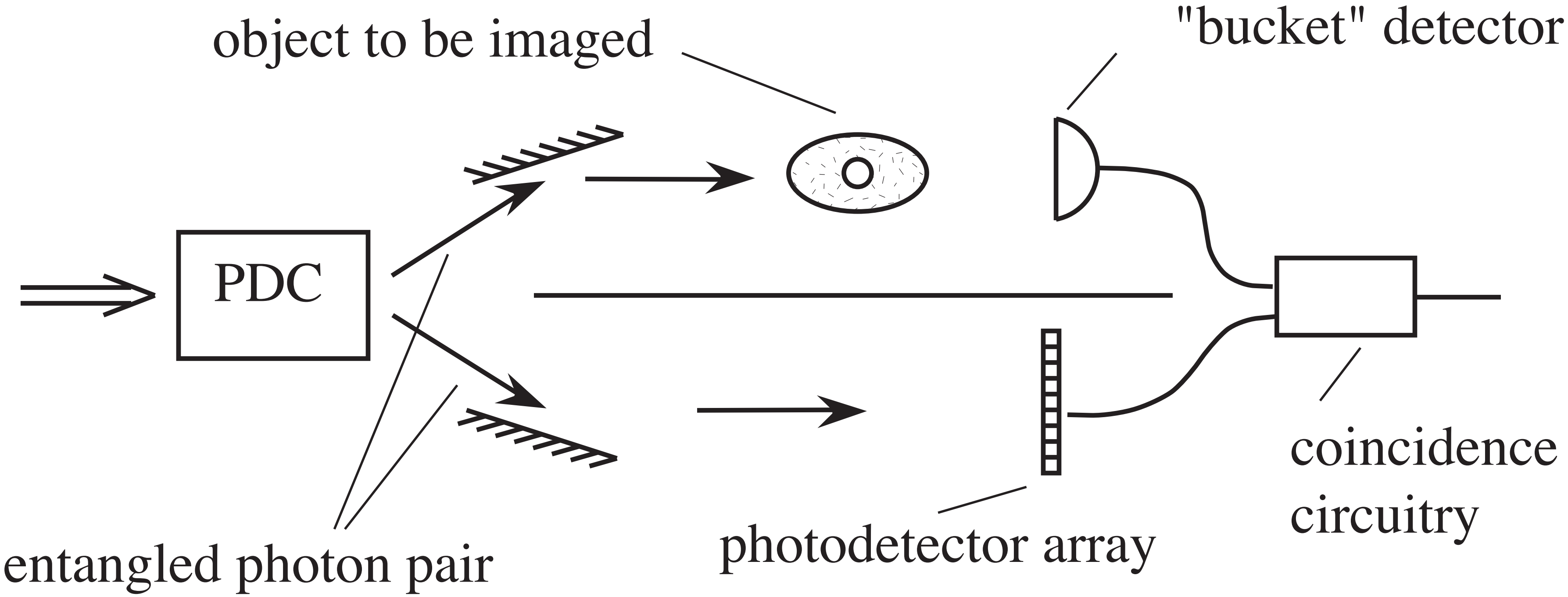
What are the implications of “interaction free” and “ghost” imaging

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

Quantum Imaging: Talk Overview

1. Very brief introduction
2. Some results on "ghost" imaging
3. Some results on "single photon" imaging
4. What about "single-photon ghost" imaging?
5. Can we transmit quantum states through the turbulent atmosphere?
6. Development of a single-photon light source
7. How to describe quantum light fields

Ghost (Coincidence) Imaging



object to be imaged

"bucket" detector

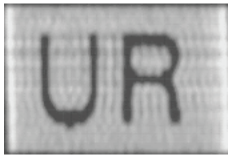
PDC

coincidence circuitry

entangled photon pair

photodetector array

- 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)

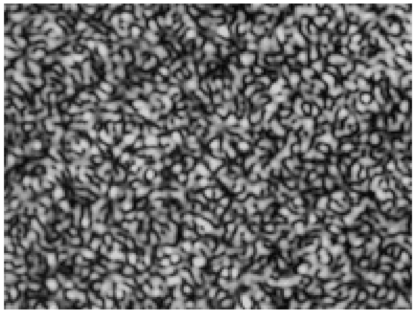


Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).

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.

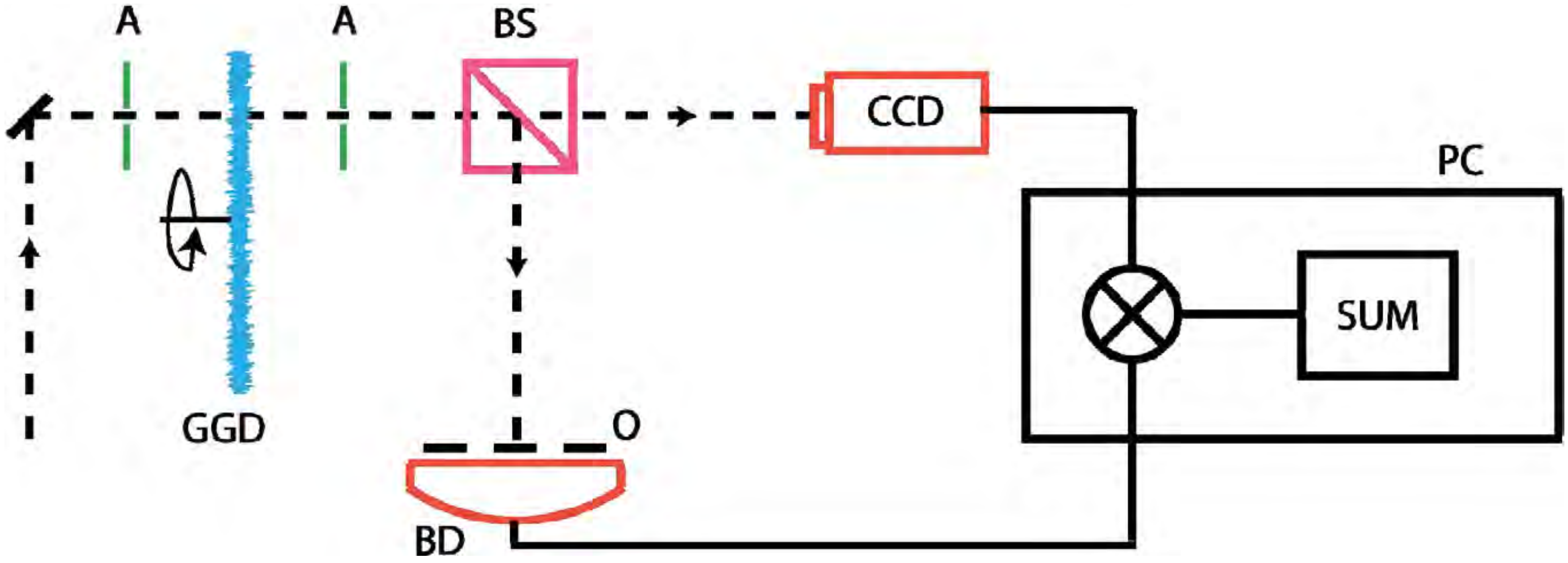


Recall that the intensity distribution of thermal light looks like a speckle pattern.

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.

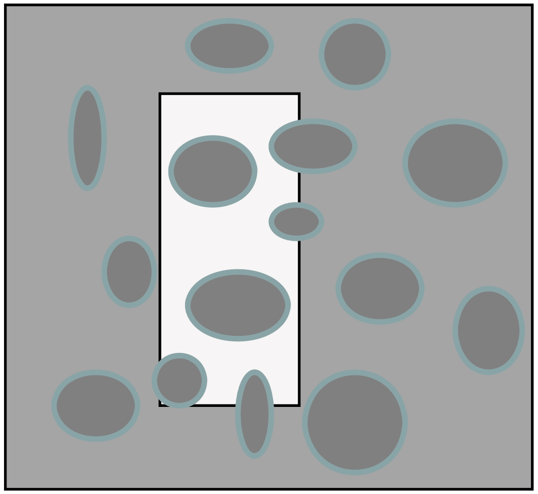
How does thermal ghost imaging work?



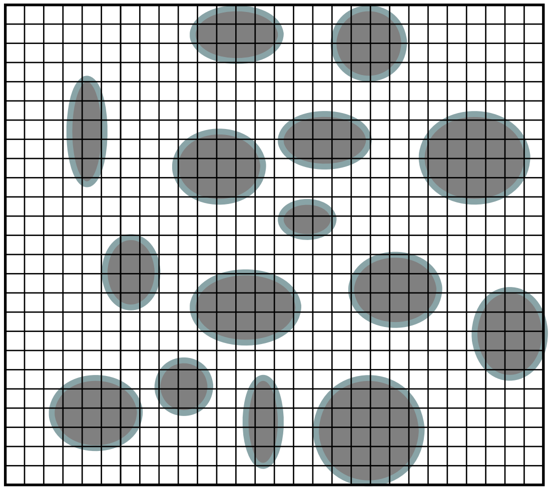
- Ground glass disk (GGD) and beam splitter (BS) create two identical speckle patterns
- Many speckles are blocked by the opaque part of object, but some are transmitted, and their intensities are summed by BD
- CCD camera measures intensity distribution of speckle pattern
- Each speckle pattern is multiplied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

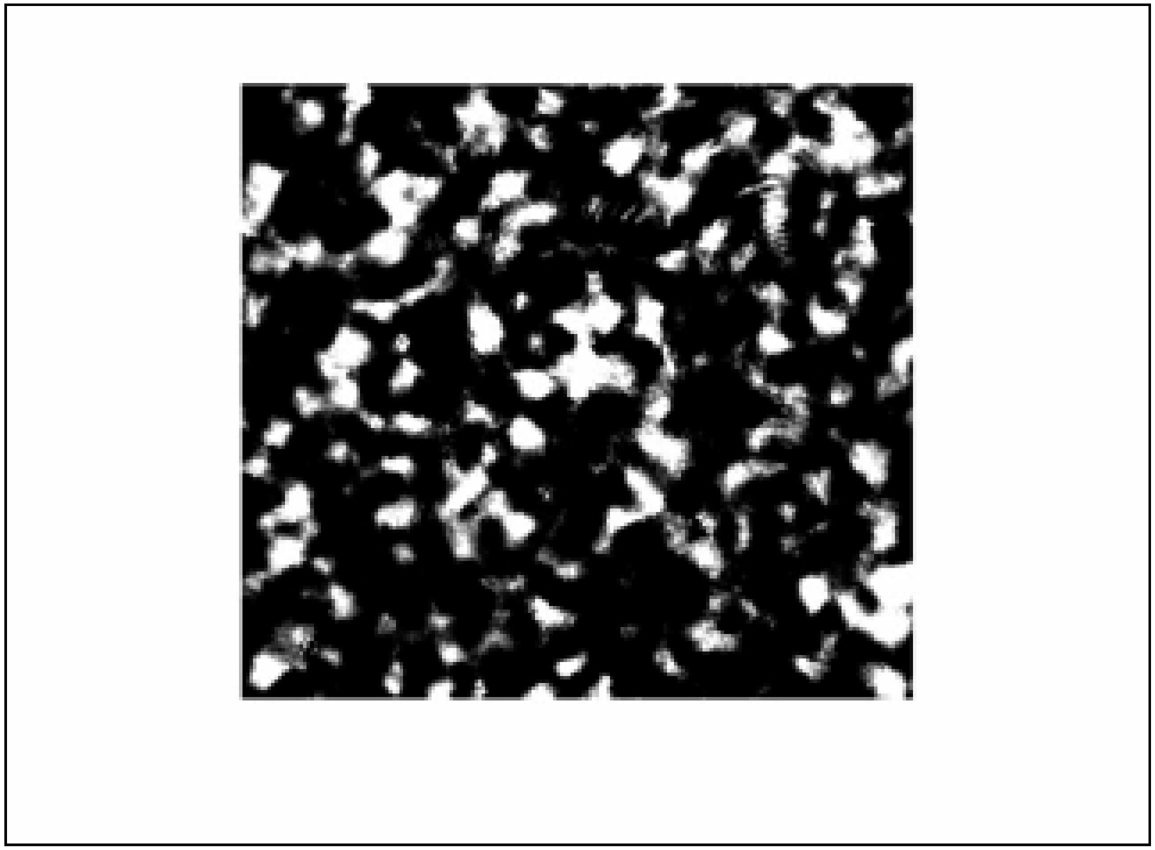


reference arm
(pixelated imaging detector)

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

Average over many speckle patterns

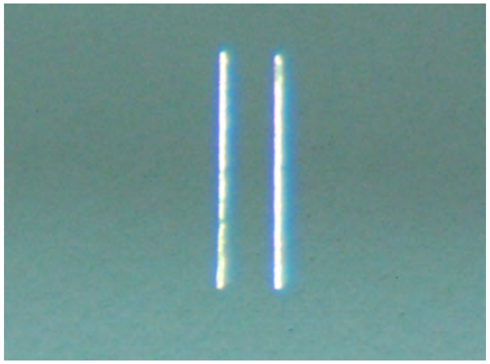
Demonstration of Image Buildup in Thermal Ghost Imaging



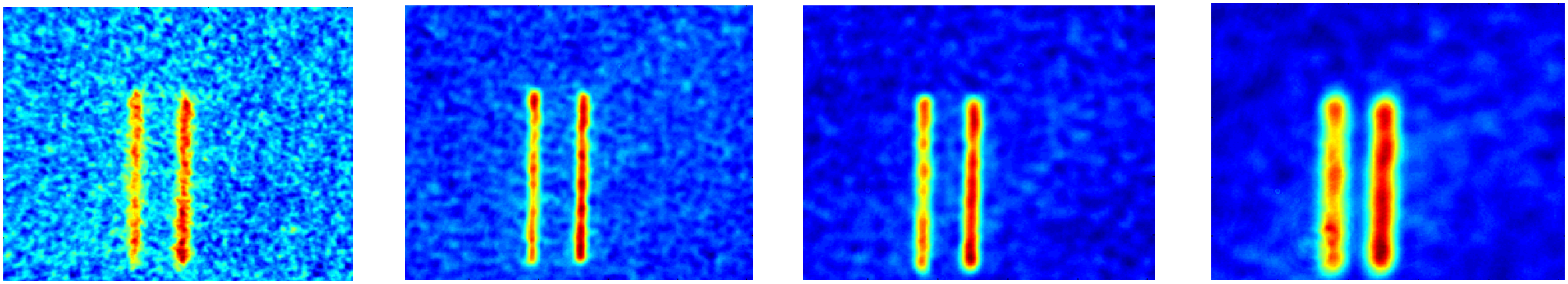
(click within window to play movie)

Influence of Speckle Size on Spatial Resolution

Test object
(stencil)



small speckle → large speckle



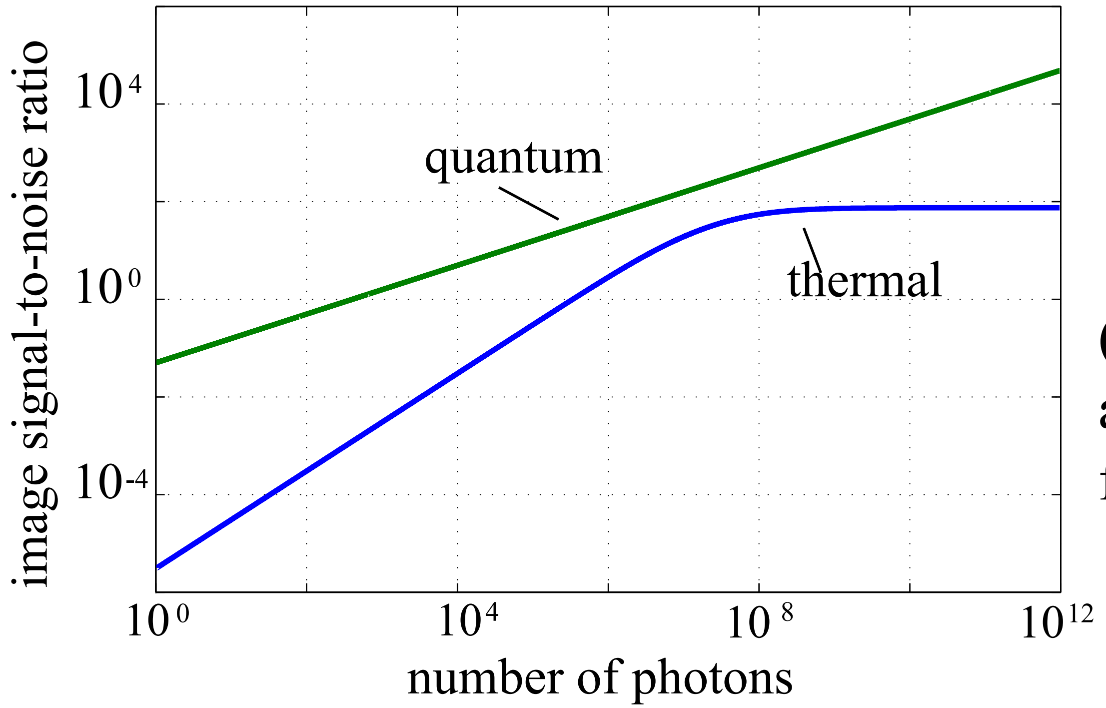
As the speckle size increases, the resolution decreases but the signal-to-noise ratio increases.

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

1. In thermal ghost imaging, image is formed on a background, which adds noise and lowers contrast.
2. But it is easier to get intense thermal light sources than entangled light sources

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



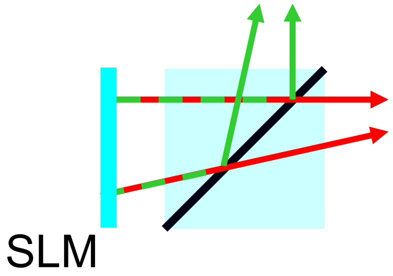
Preliminary result; work still in progress

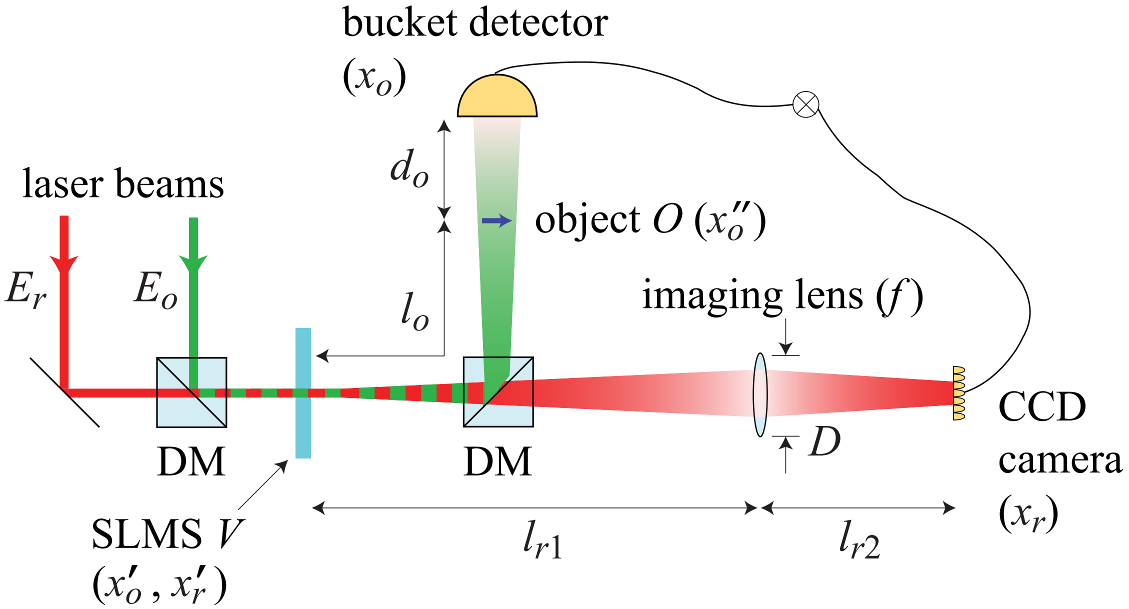
(numerical result assumes 10^6 frames for thermal case)

Two-Color Ghost Imaging

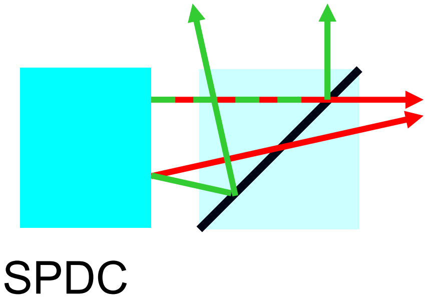
New possibilities afforded by using different colors in object and reference arms

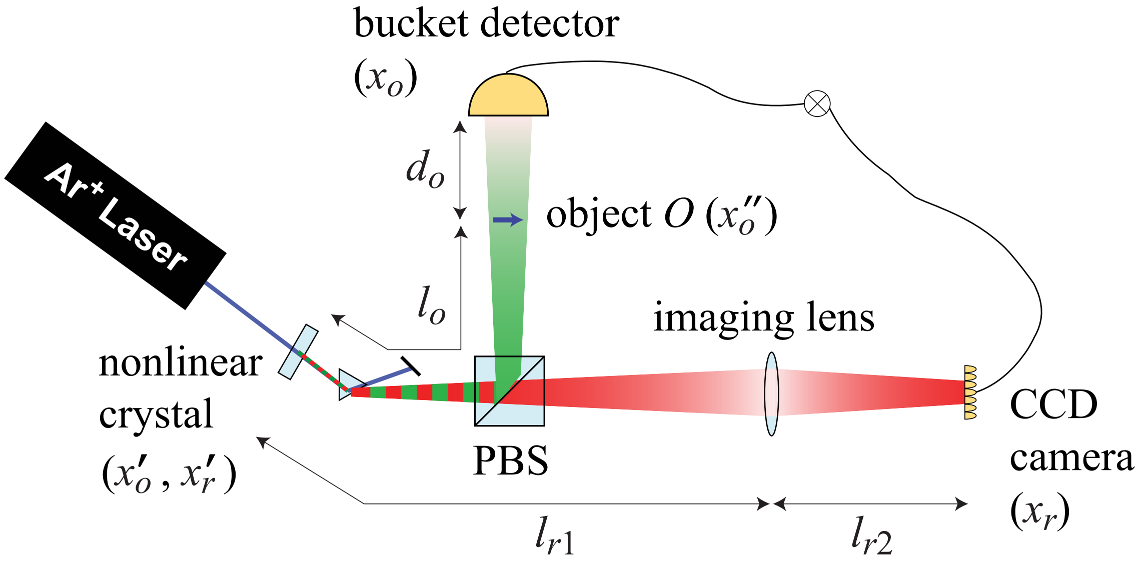
Thermal ghost imaging





Quantum ghost imaging





Chan, O’Sullivan, Boyd, PRA 2009

Two-Color Ghost Imaging: Model

- Classical (thermal): Gaussian-Schell Model

Coherence function

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

- Quantum (PDC): Gaussian approximation

Two-photon wavefunction

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

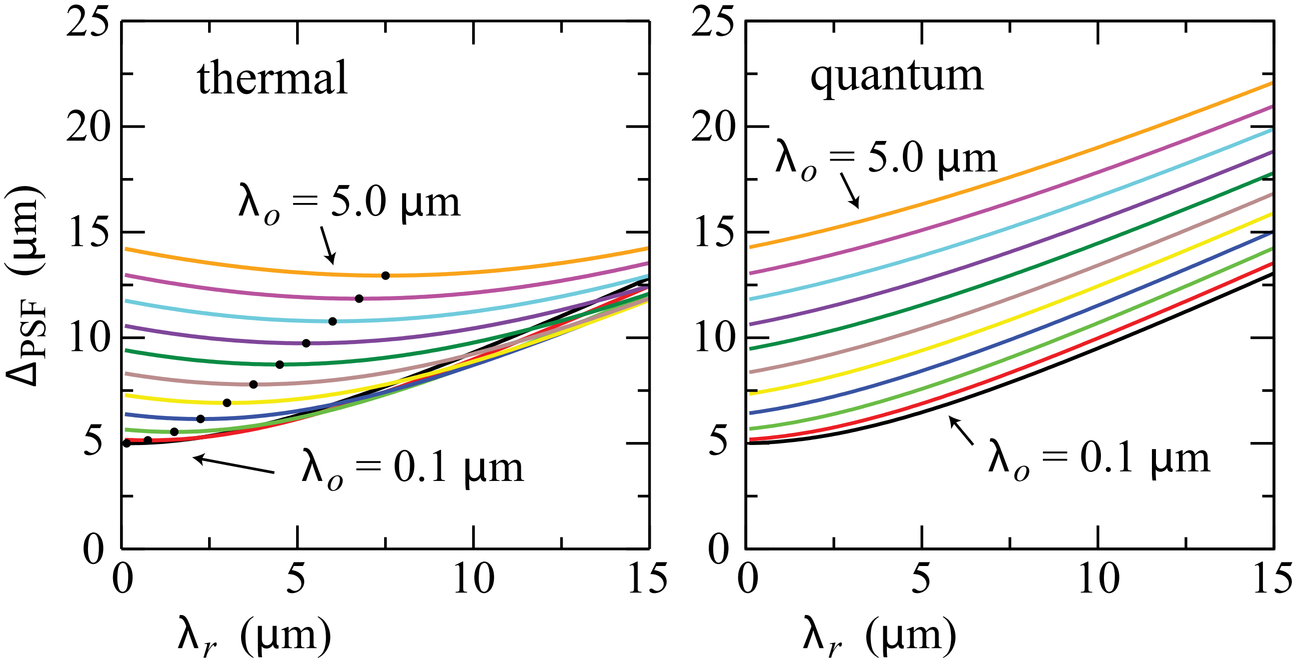
w is the width of the laser beam; σ_x is the correlation distance (speckle size).

assume that $w \gg \sigma_x$

- Let D be the diameter of the imaging lens

Chan, O'Sullivan, Boyd, PRA 2009

Two-Color Ghost Imaging: Results



$\sigma_x = 5\,\mu\text{m}$

$w = 10\,\text{mm}$

$D = 20\,\text{mm}$

$l_{r1} = 100\,\text{mm}$

$l_o = 150\,\text{mm}$

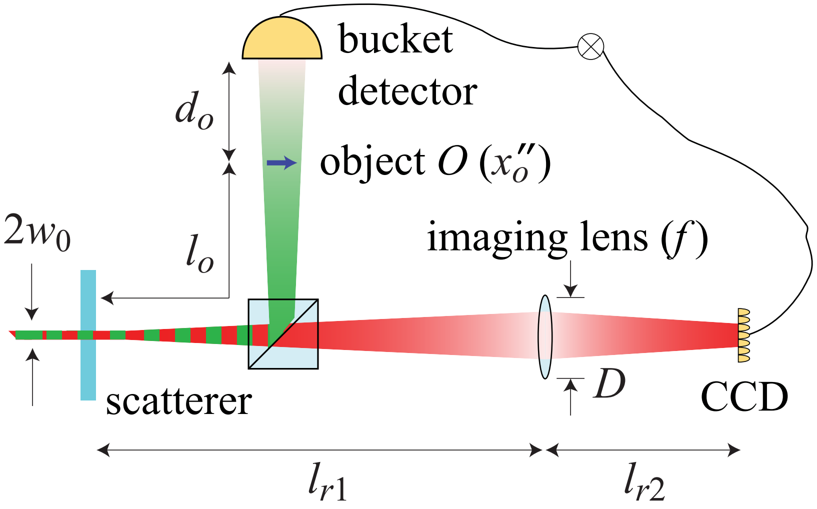
thermal:

$$\Delta_{\rm PSF} = \sqrt{\sigma_x^2 + \left(\frac{\lambda_o l_o}{2\pi w}\right)^2 + \frac{(\lambda_r l_{r1} - \lambda_o l_o)^2}{(\lambda_r l_{r1}/w)^2 + (2\pi D)^2}}.$$

quantum:

$$\Delta_{\rm PSF} = \sqrt{\sigma_x^2 + \left(\frac{\lambda_o l_o}{2\pi w}\right)^2 + \frac{(\lambda_r l_{r1} + \lambda_o l_o)^2}{(\lambda_r l_{r1}/w)^2 + (2\pi D)^2}}.$$

In many practical situations, this term dominates.



Chan, O'Sullivan, Boyd, PRA 2009

Single-Photon Imaging

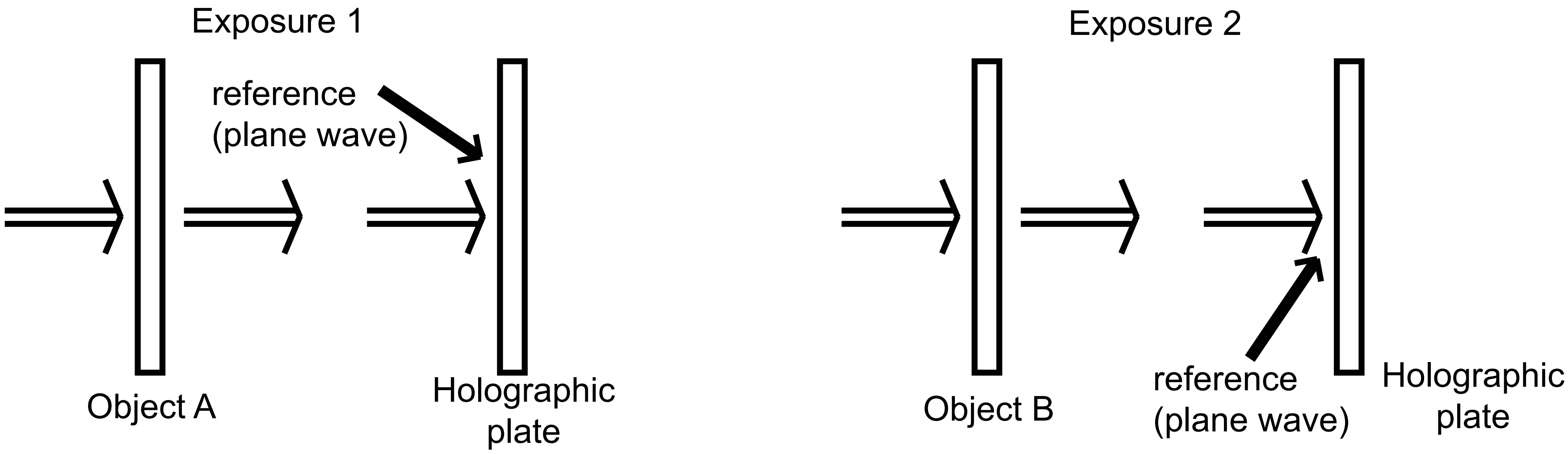
Joint Project: Boyd and Howell Groups

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

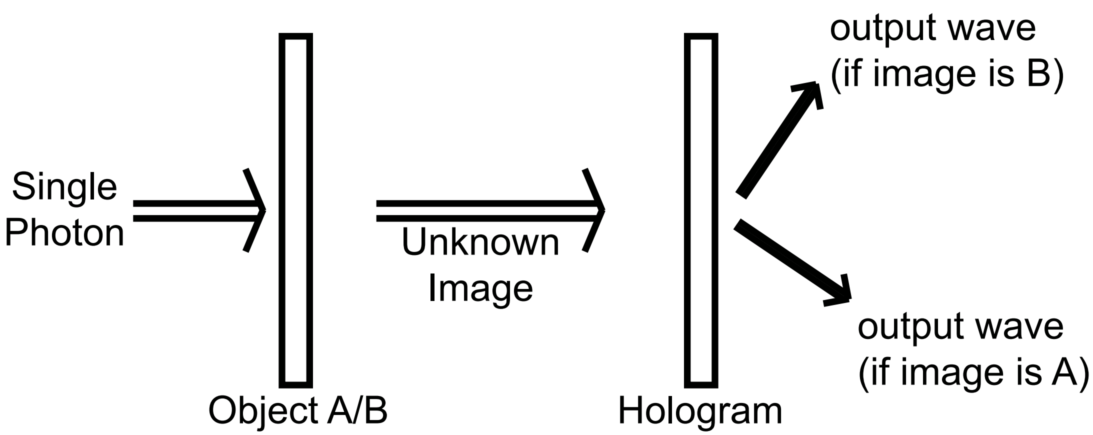
Exposure 2

Object B

reference
(plane wave)

Holographic
plate

- Reading the hologram (with a single-photon)



output wave
(if image is B)

Single
Photon

Unknown
Image

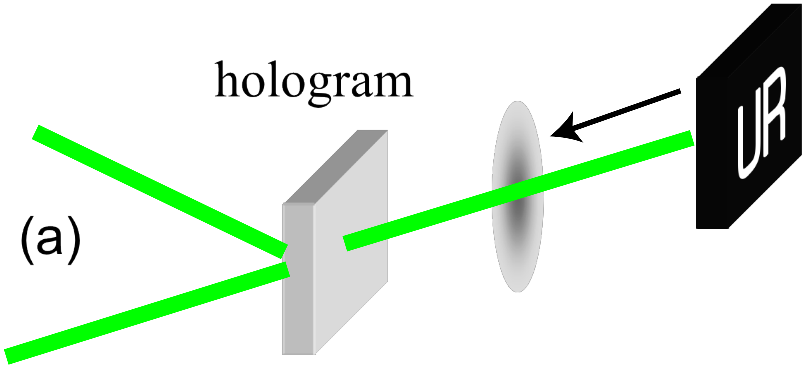
output wave
(if image is A)

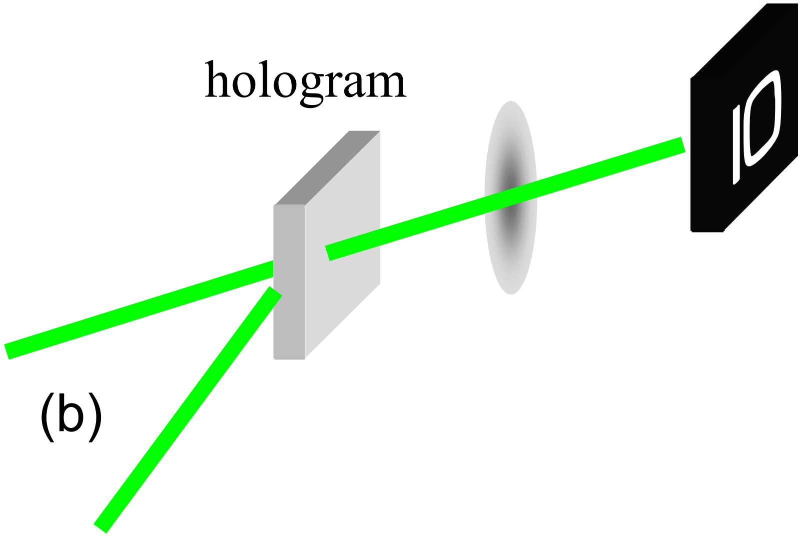
Object A/B

Hologram

Reconstruction - with structured reference beam

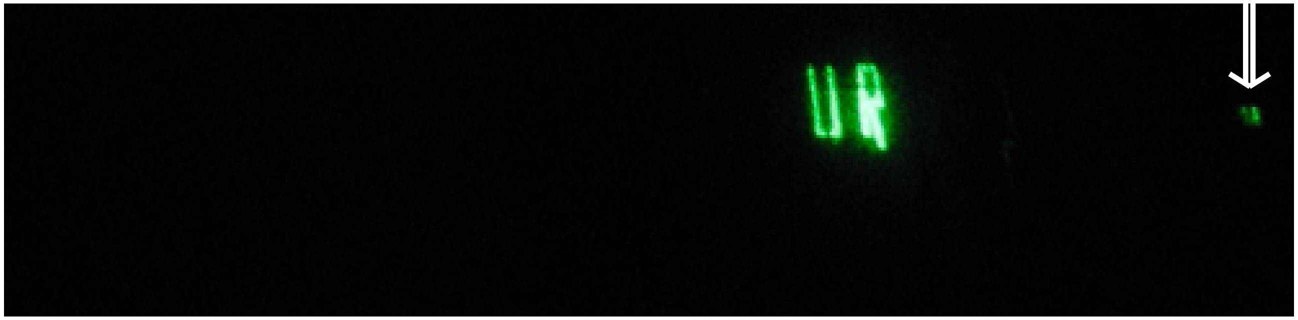
- Very little cross-talk (less than 1%)





Single-Photon Imaging - Results

- 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**

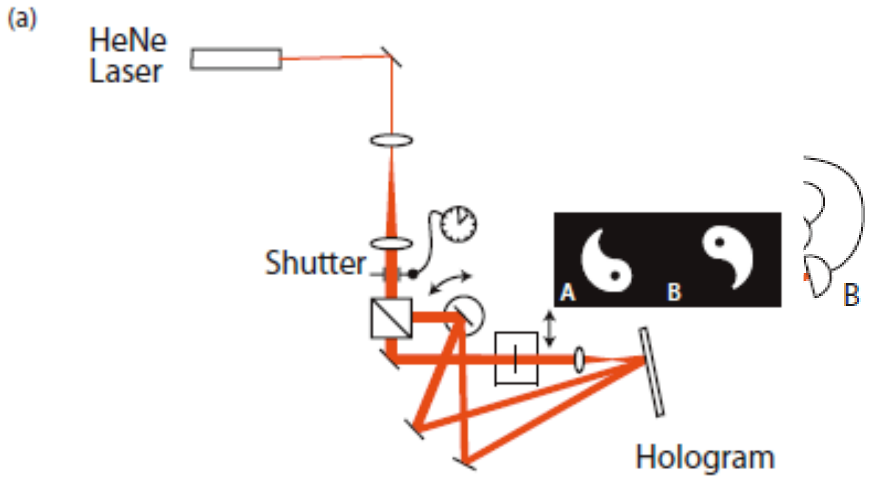
High light level

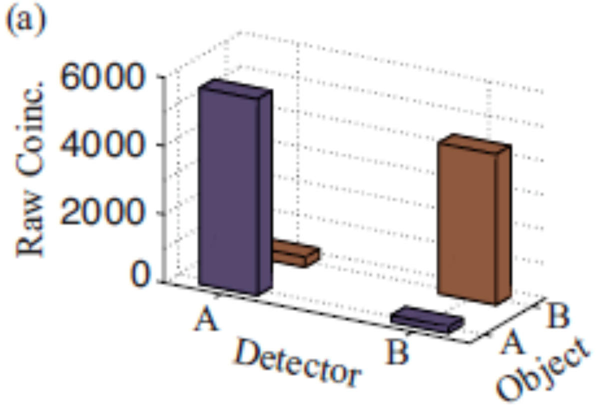
Low light level

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

Broadbent et al. PRA **79**, 033802 2009.

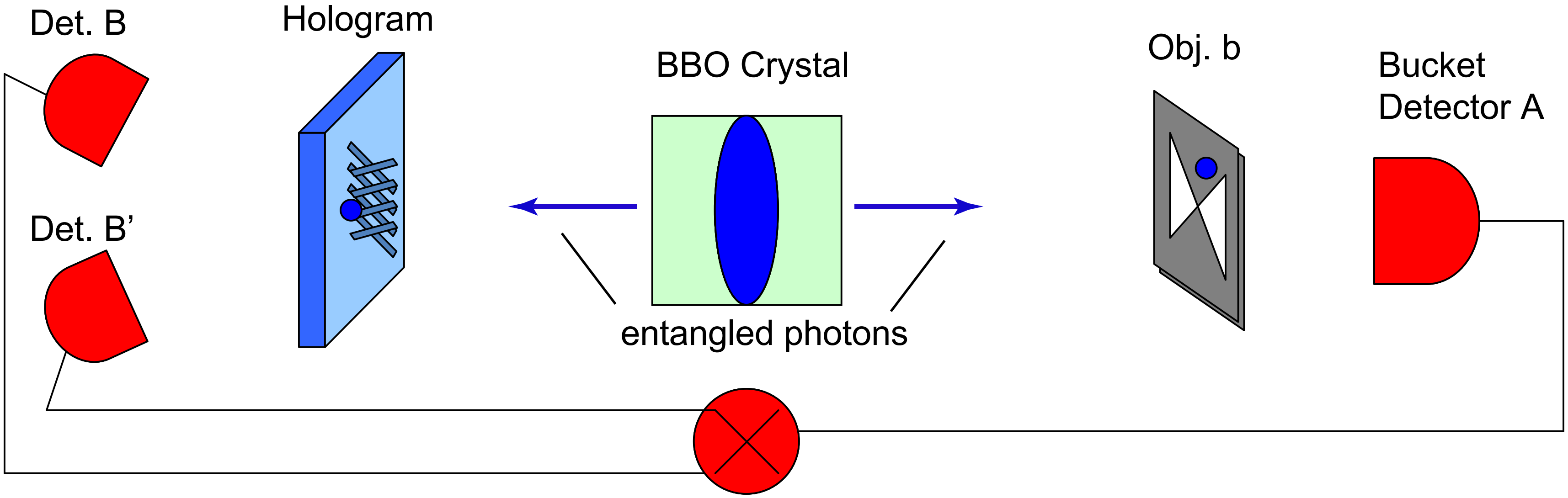
SINGLE PHOTON IMAGING III



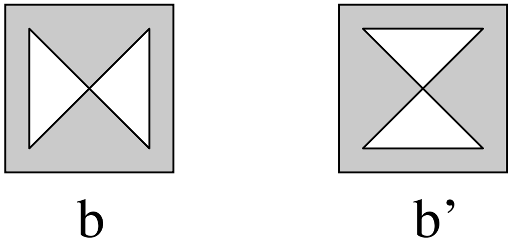


- Discriminating Orthogonal Single-Photon Images, Broadbent et al., PRA 79, 033802 (2009)
- Multiplexed hologram made with classical light (HeNe)
- Yin/Yang image impressed on heralded single photons
- Sorted using holographic filter
- Yin can be distinguished from Yang with a confidence level of 96.8%
- Proves that a **single photon** can carry a whole image
- Information can be retrieved for a **pre-established basis set**

Single-Photon Ghost Imaging

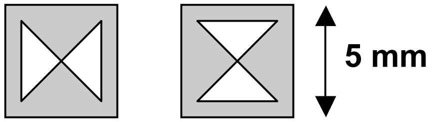


We discriminate between two orthogonal images, b and b', at the single-photon level in a ghost imaging configuration.

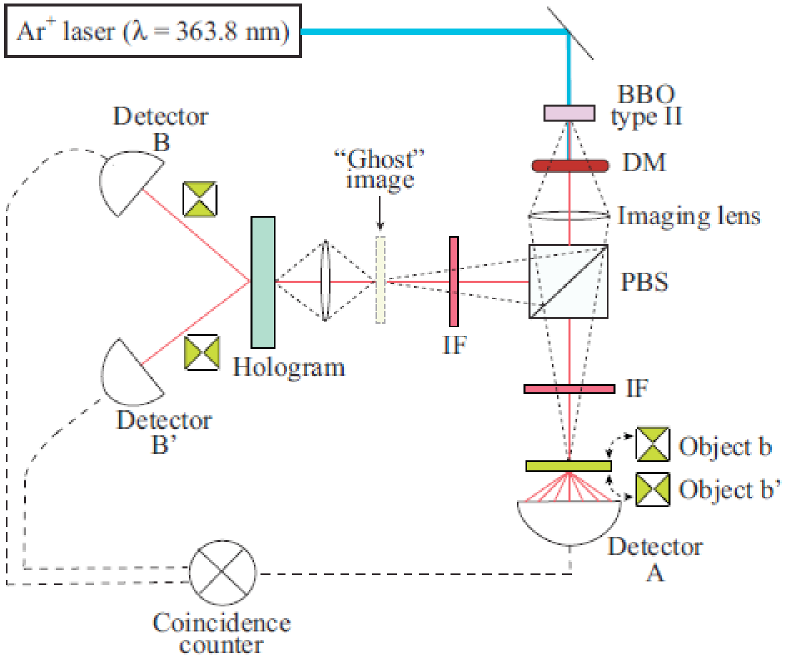


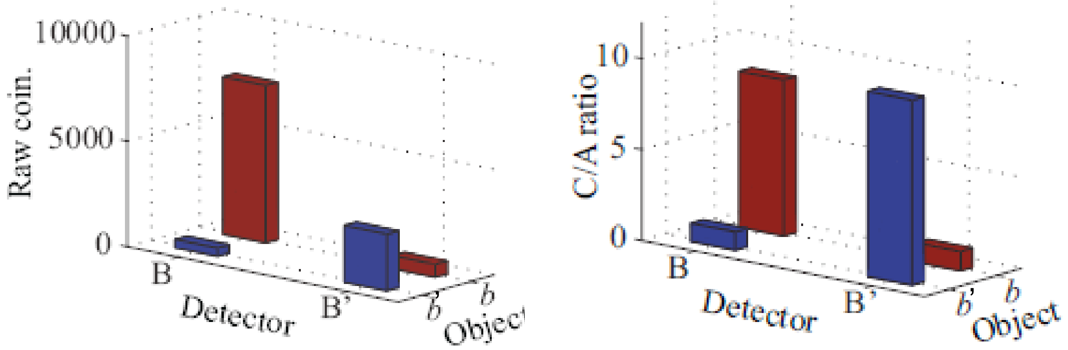
SINGLE PHOTON QUANTUM GHOST IMAGING II

- Experimental setup
- 2 orthogonal objects:



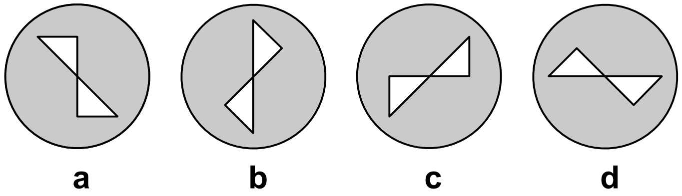
- Hologram made with HeNe (633 nm)
- Read-out with down-converted single photons at 727.6 nm
- Can distinguish b’ from b with 95% confidence factor



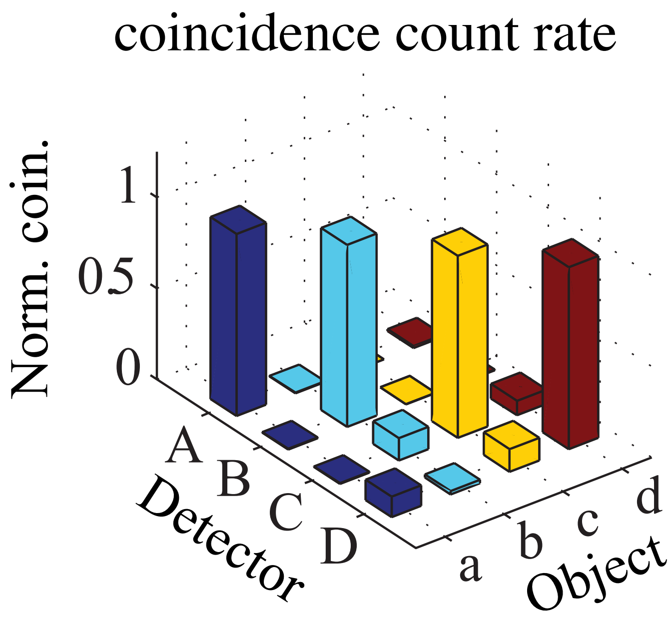


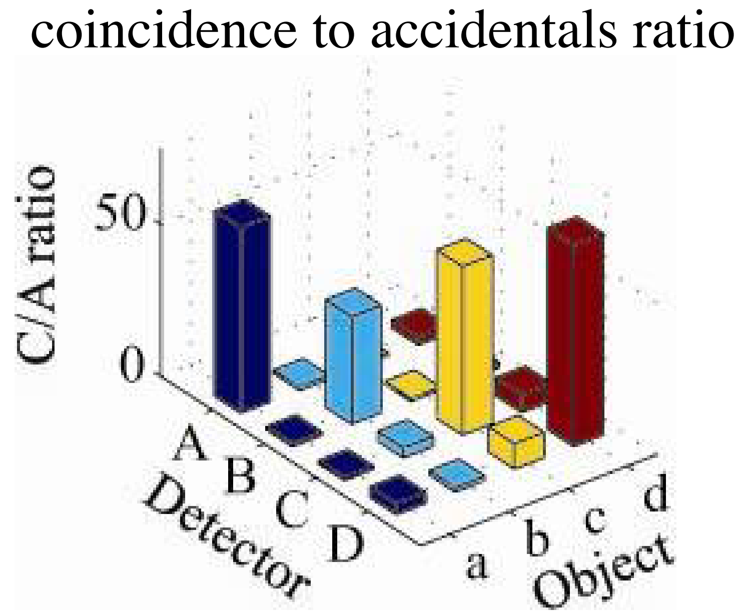
Single-Photon Ghost Imaging

Now try this with a larger object space (four orthogonal objects)



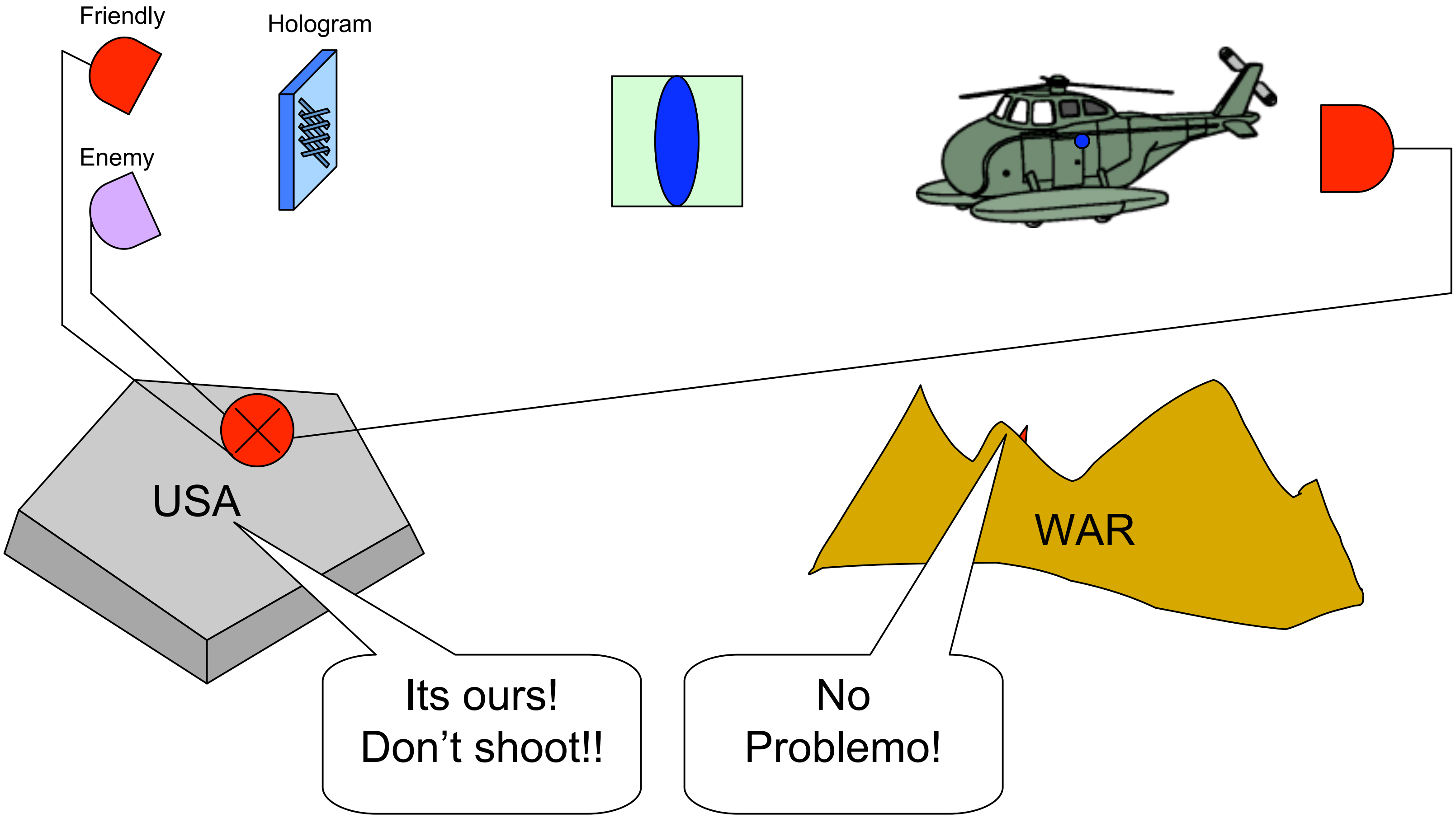
We still find very good discrimination, although with lower count rates because of lower diffration efficiency.





Possible Applications!?

[Remote Sensing at low light levels]



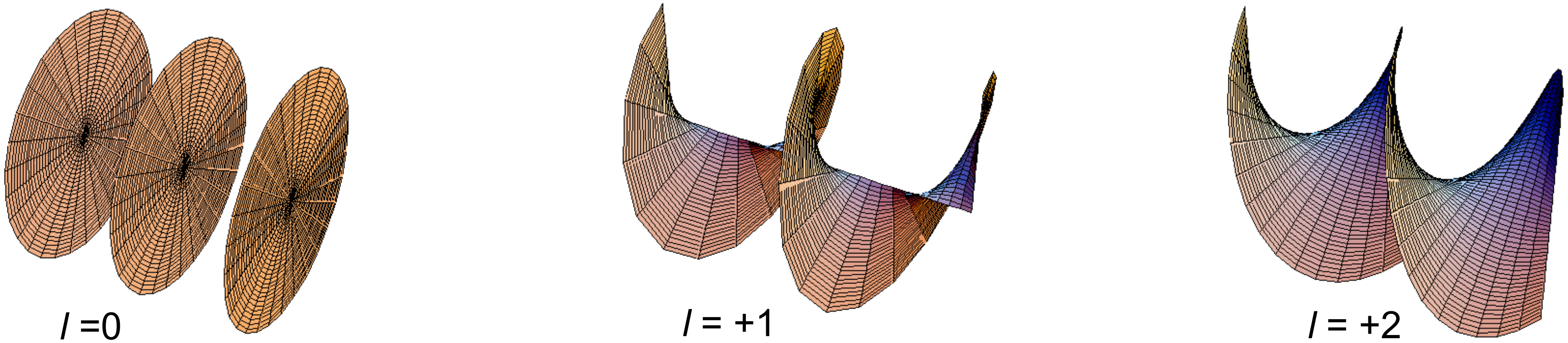
Use of the Orbital Angular Momentum of Light to Carry Quantum Information

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?

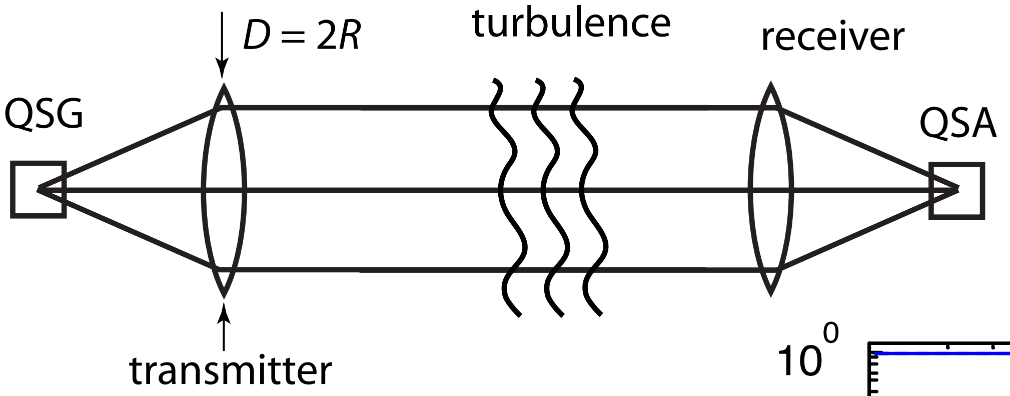
Phase-front structure of some OAM states



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).

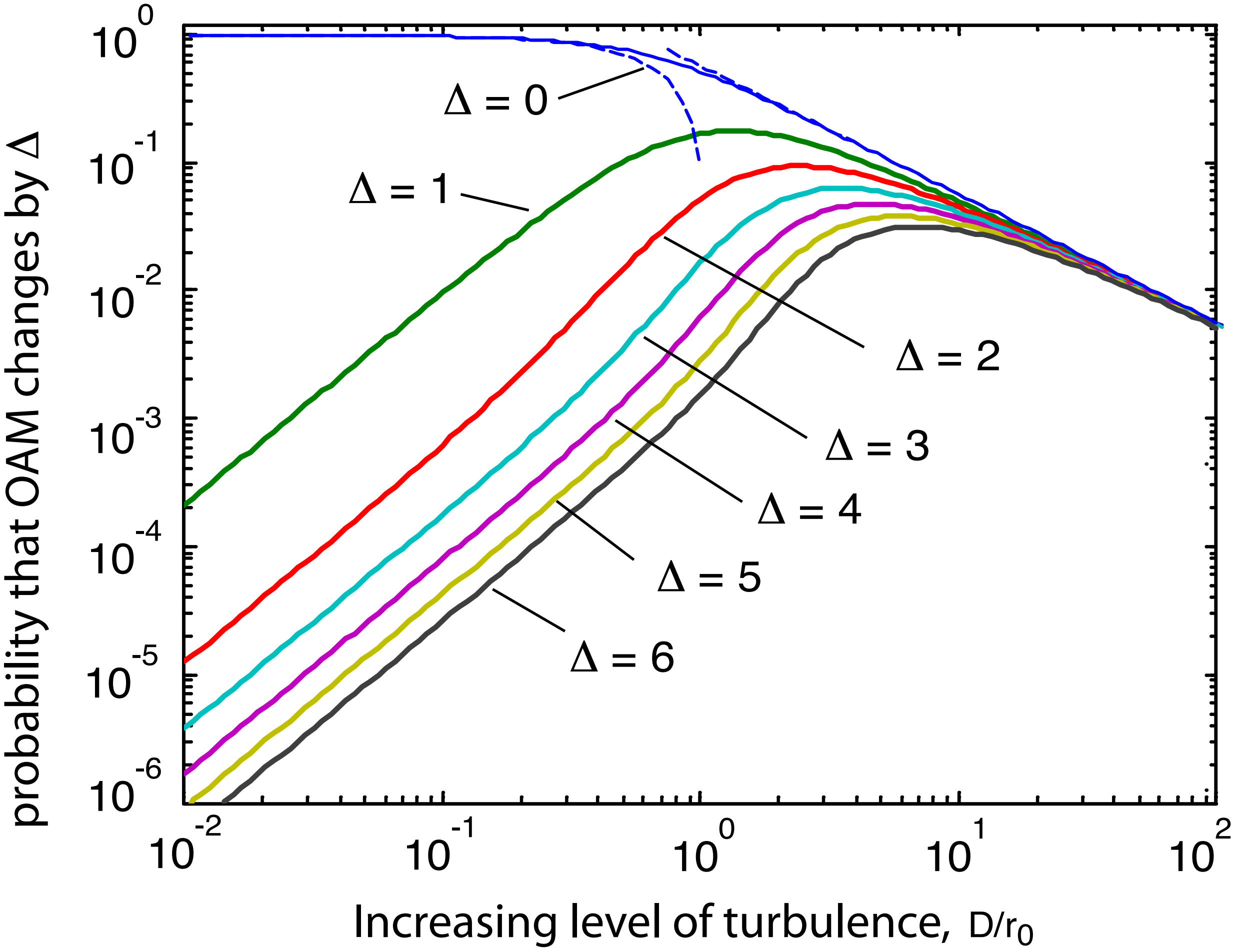
Influence of Atmospheric Turbulence on the Propagation of Quantum States of Light Carrying Orbital Angular Momentum



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).

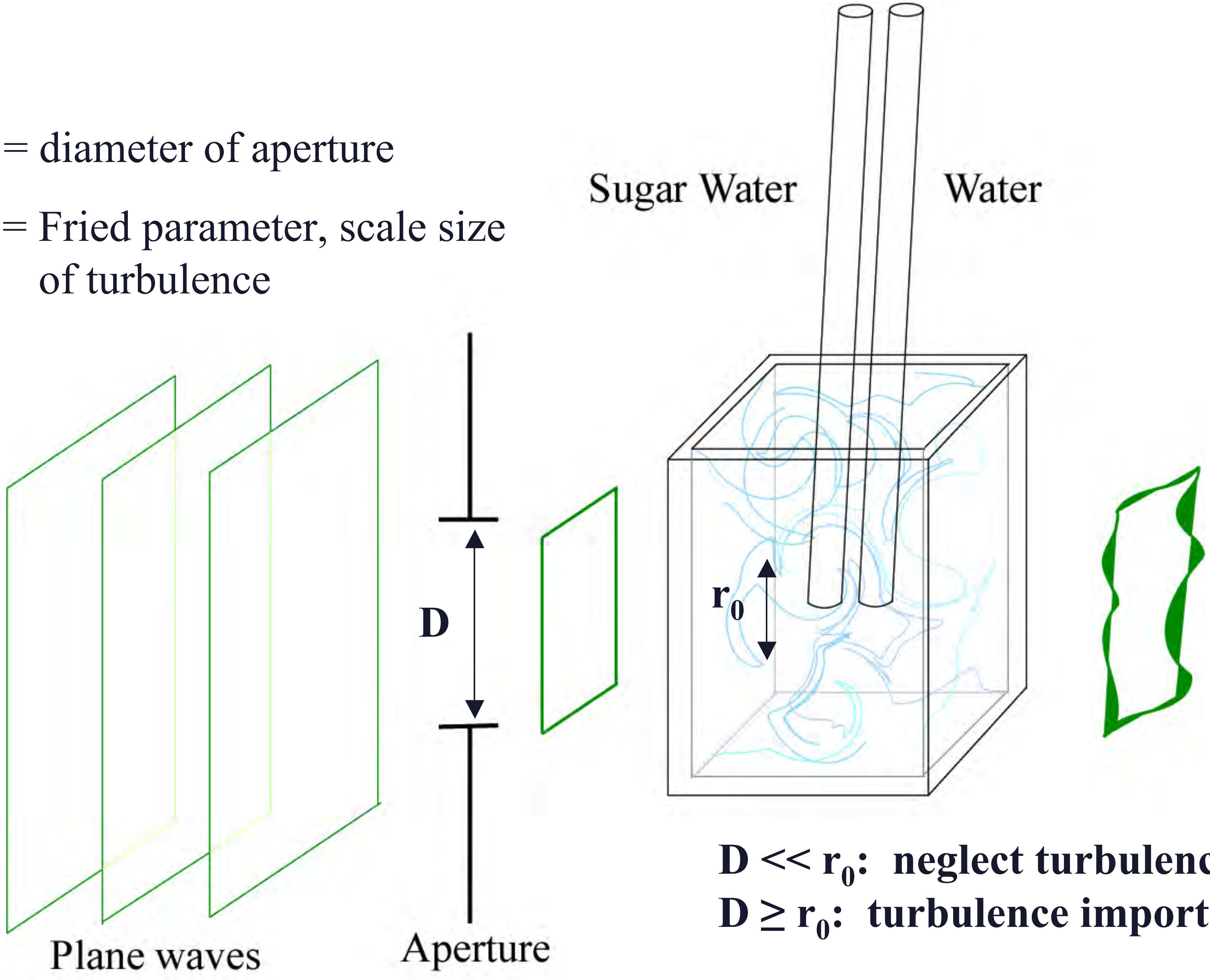
G. A. Tyler and R. W. Boyd, Opt Lett (2009).

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

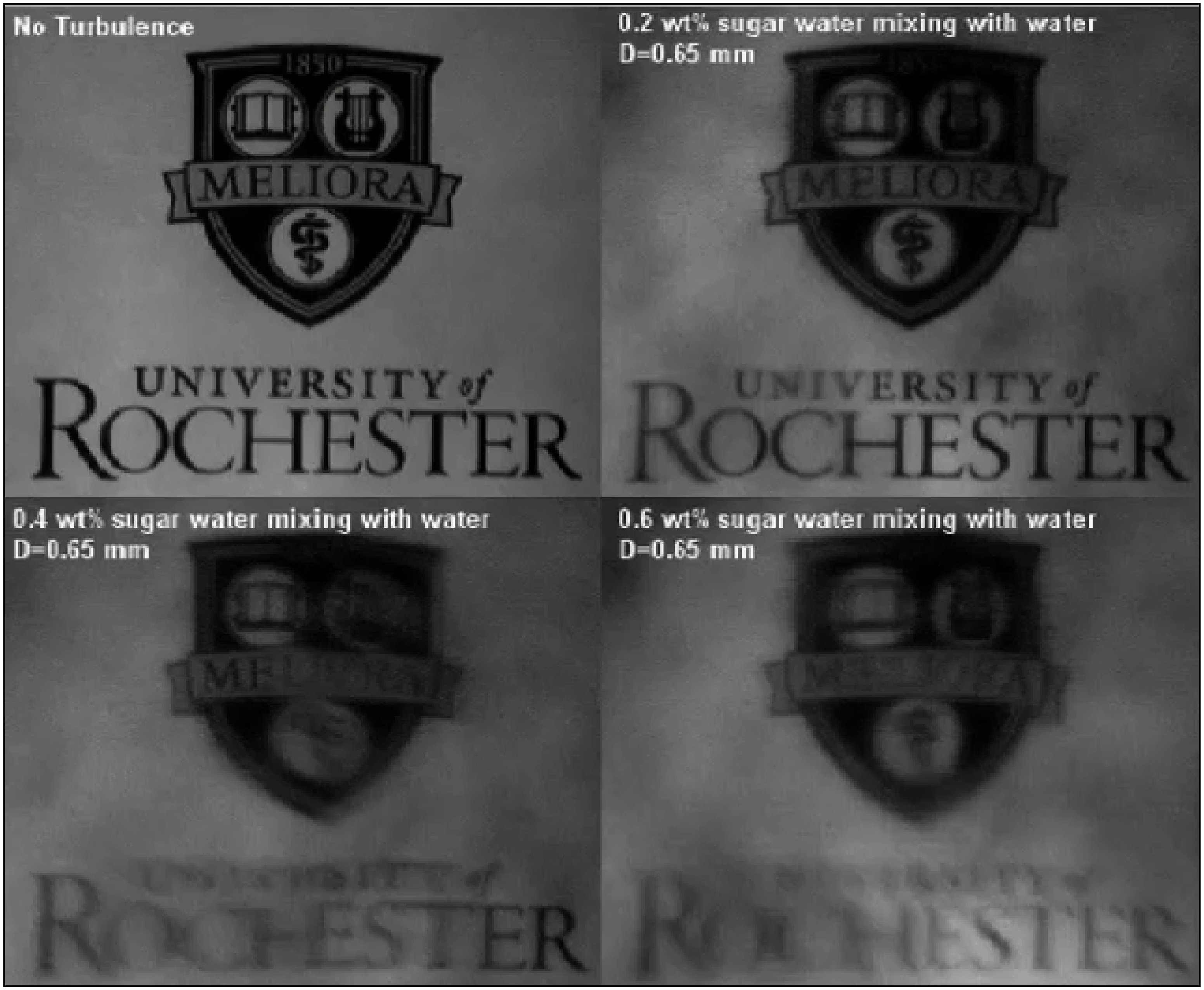
r_0 = Fried parameter, scale size of turbulence



$D \ll r_0$: neglect turbulence

$D \geq r_0$: turbulence important

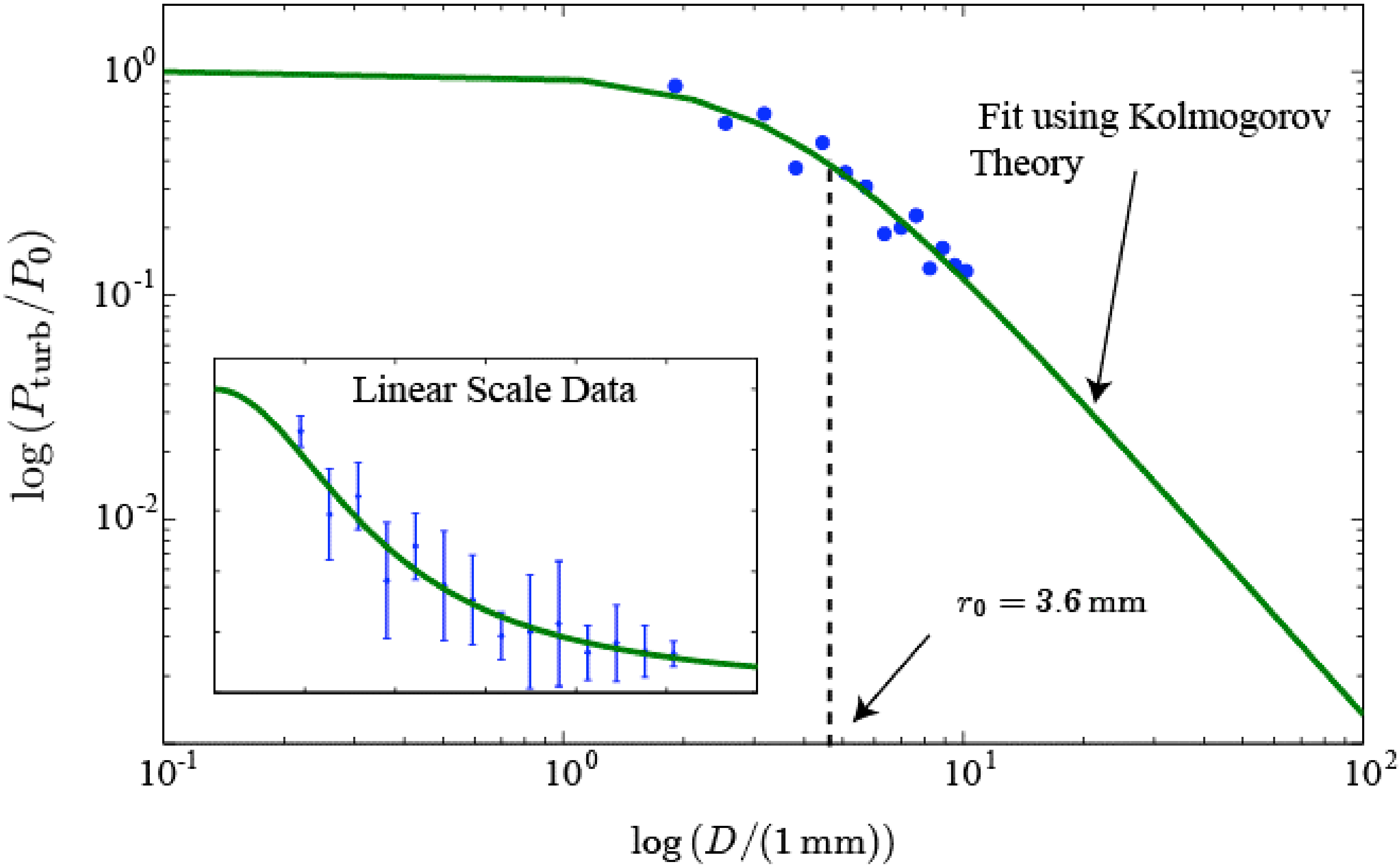
Demonstration of the Operation of the Turbulence Cell



(click within window to play movie)

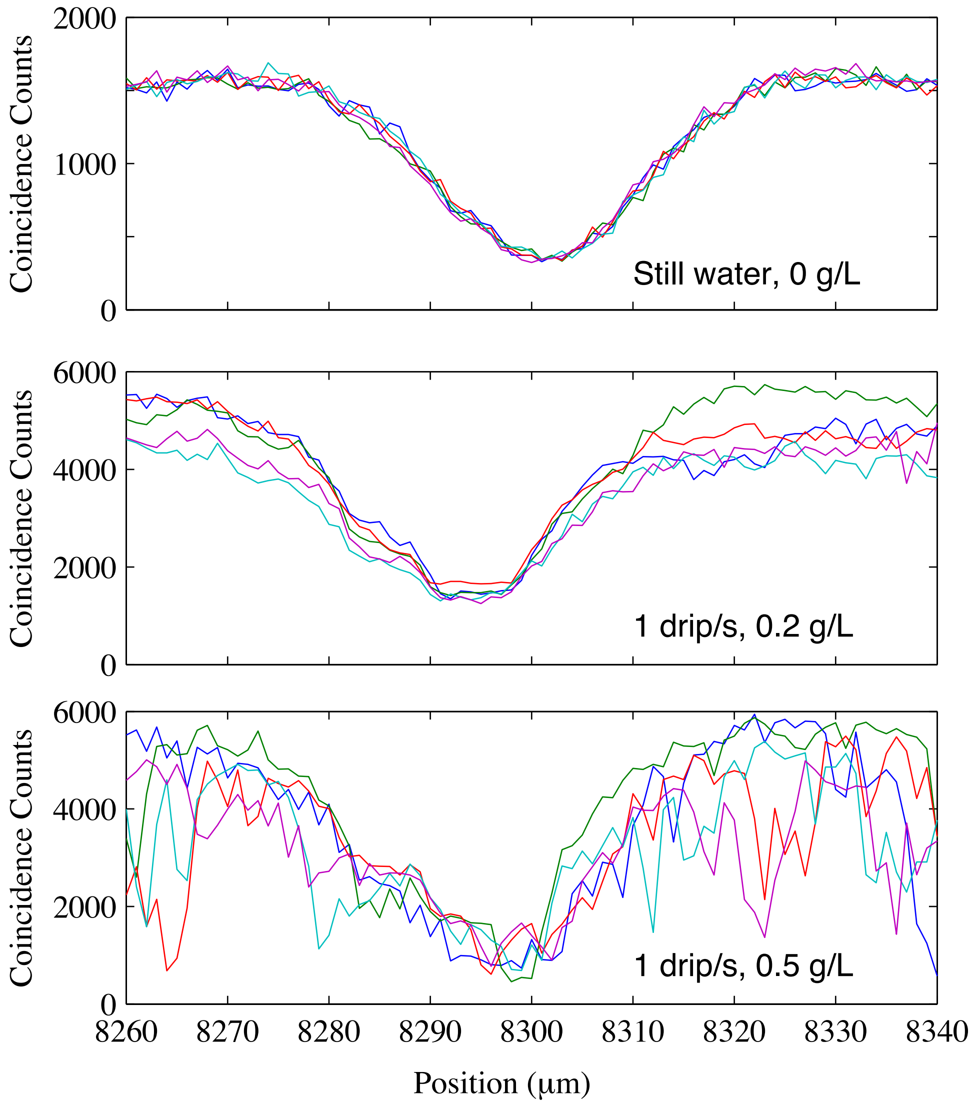
Influence of Atmospheric Turbulence on the Quantum States of Light

- 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



Influence of Atmospheric Turbulence on Quantum States of Light

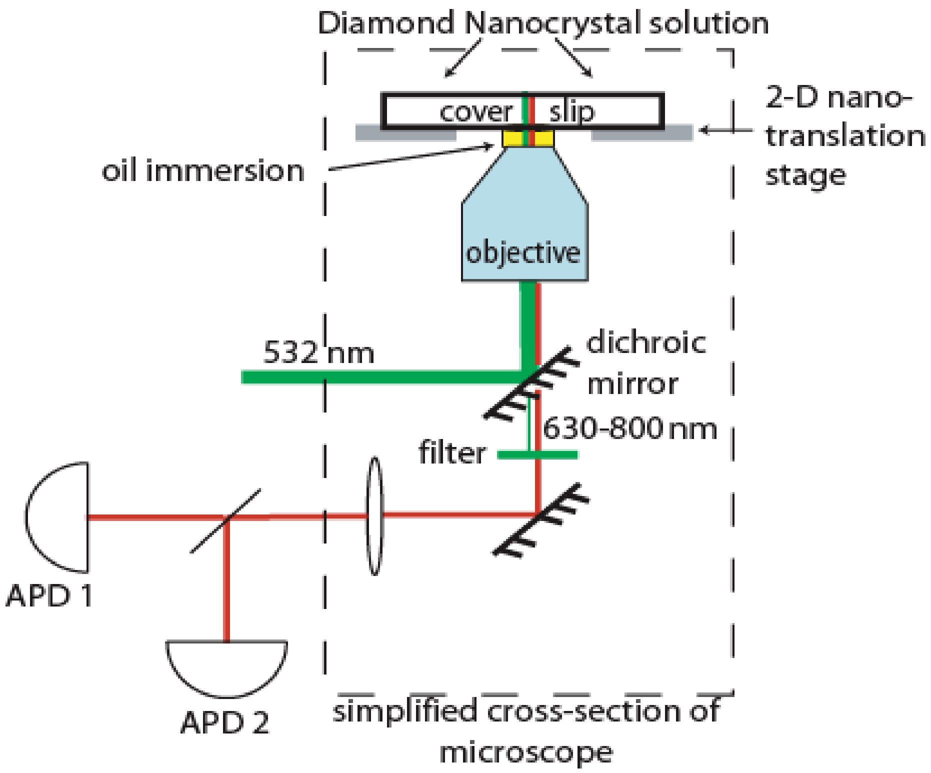
- Recent result: How is the Hong-Ou-Mandel effect influenced by turbulence?
- Recall: The Hong-Ou-Mandel effect depends on the indistinguishability of the two interfering photons.
- Procedure: Place turbulence cell in one arm of Hong-Ou-Mandel interferometer



Tentative conclusion: turbulence leads to a loss of signal to noise ratio of the HOM effect, but does not influence the width or the depth of the Mandel dip.

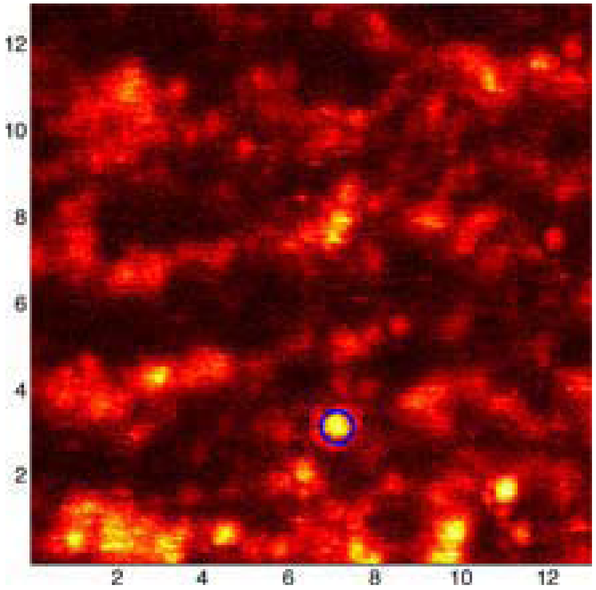
An On-Demand Source of Single Photons

- Single-photon sources are crucial for many quantum-information protocols
- We make use of fluoresence from a single NV color center in diamond
- Our long-term goal is to embed the NV centers into chiral-nematic liquid crsytals
  - Fluorescence then can occur into only one polarization state

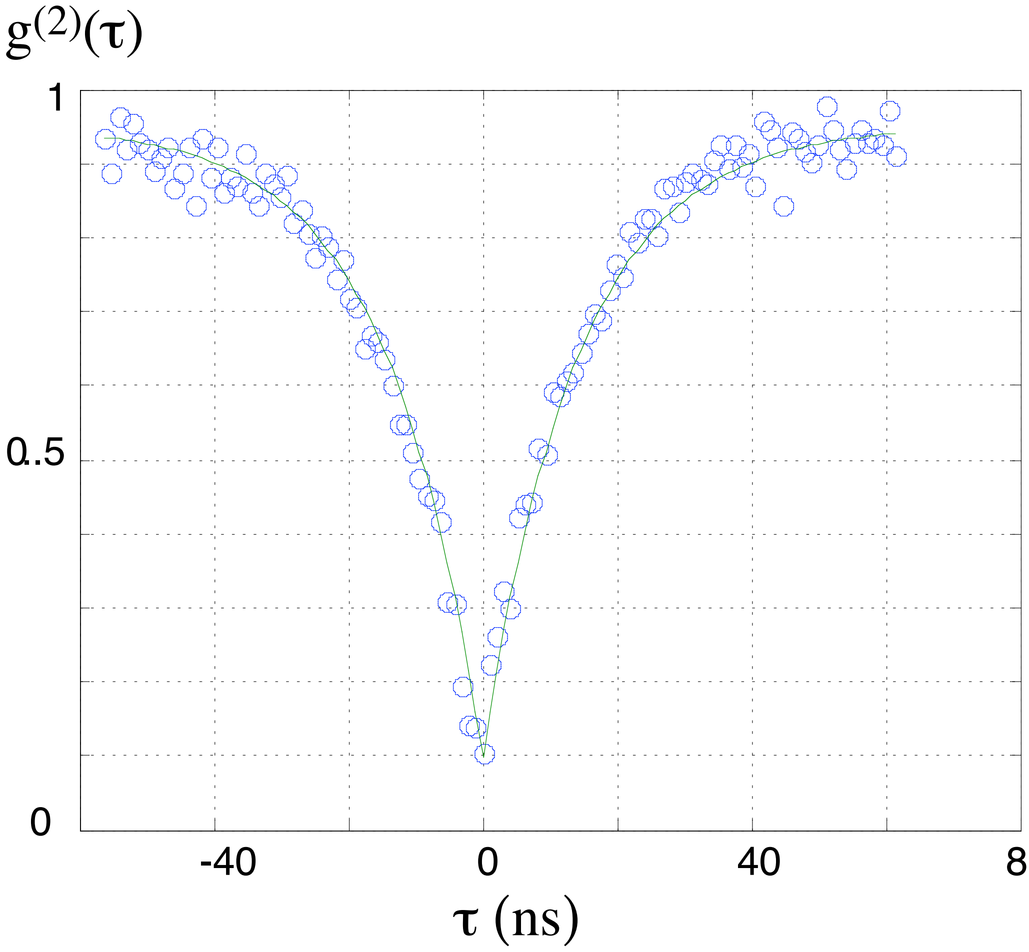


Joint project with S.Lukishova, P. Zerom, L. Bissell, and C. Stroud

Fluorescence antibunching of NV-color centers in nanodiamonds



diamond nanocrystals
approximately 25 nm
in diameter



Data show that photons are emitted one at a time!

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?

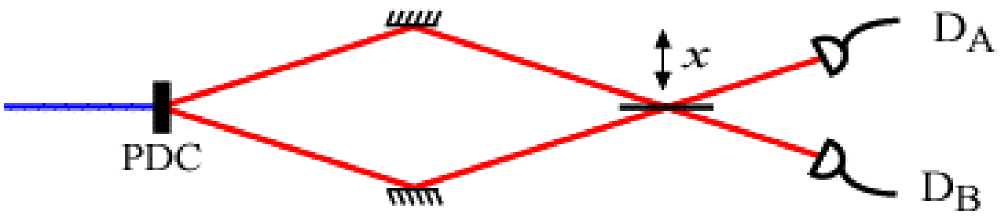
What are the generic features of two-photon interference?

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

Two-Photon Interference -- How to Understand?

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

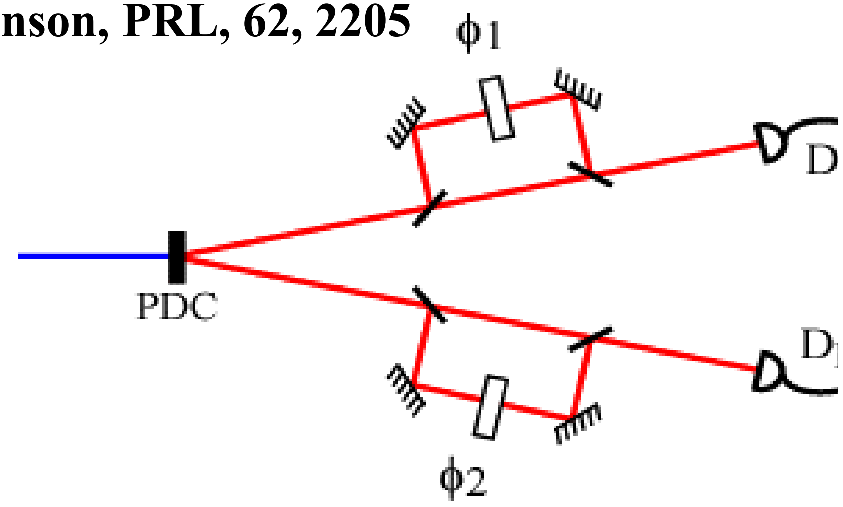
PRL, 59, 2044



Anti-bunching of indistinguishable photons

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

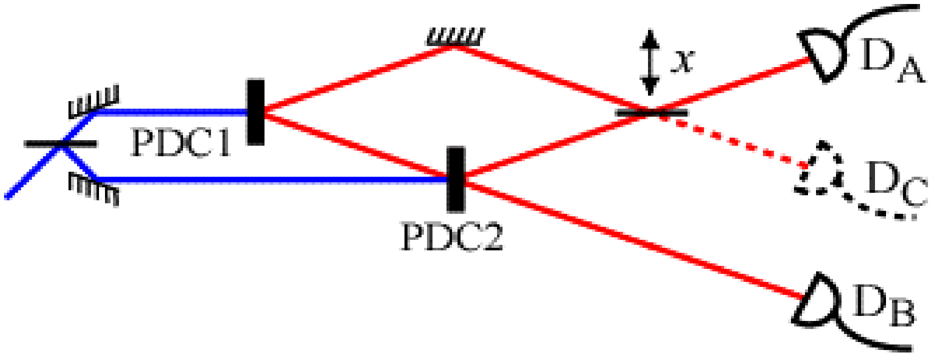
Franson, PRL, 62, 2205



Time-energy entanglement

- **Induced Coherence (1991)**

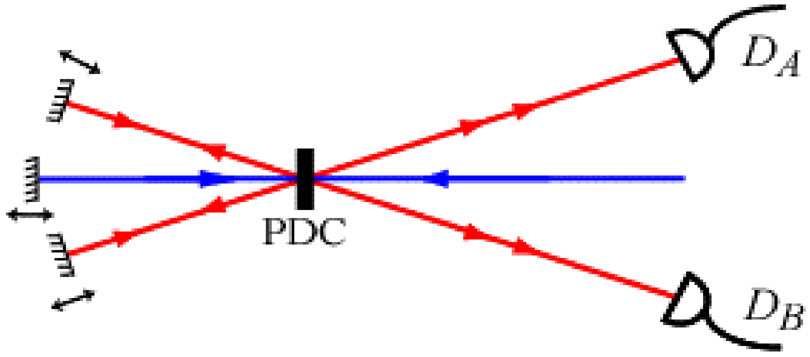
Zou et al. PRL, 67, 318



“mind-boggling”

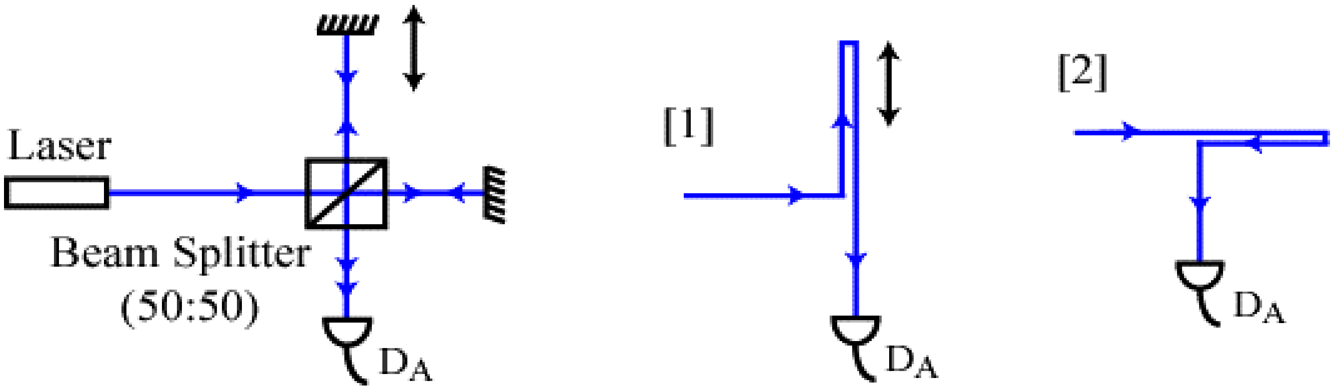
- **Frustrated two-photon creation (1994)**

Herzog et al. PRL, 72, 629

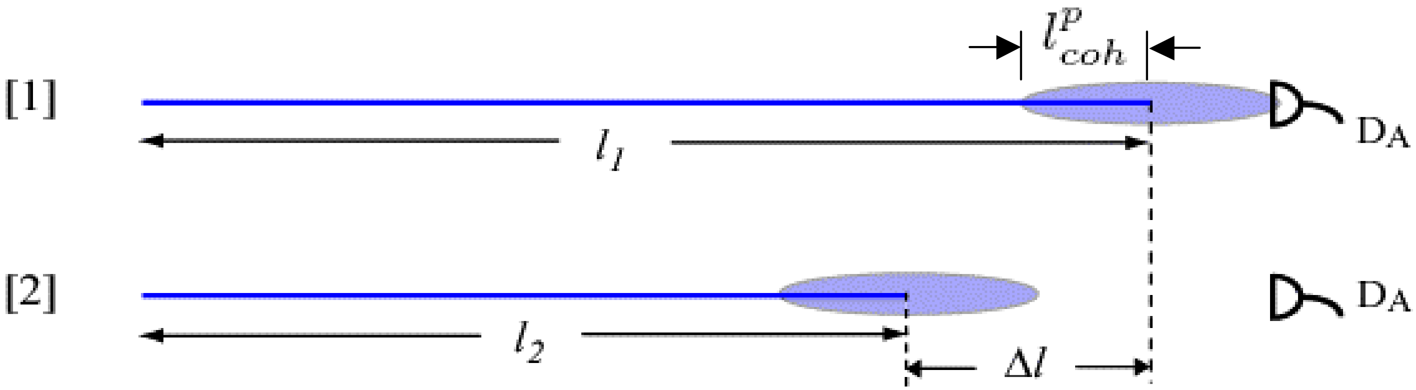


Quantum eraser

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



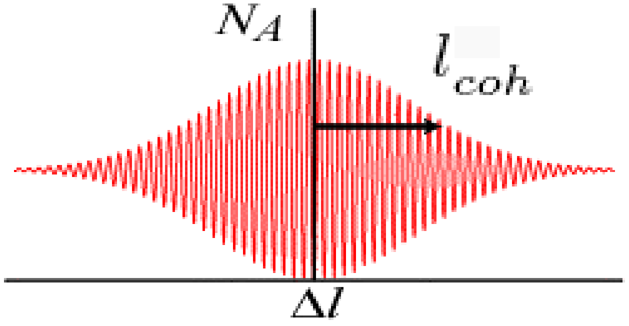
Add probability amplitudes for alternative pathways [1] and [2]



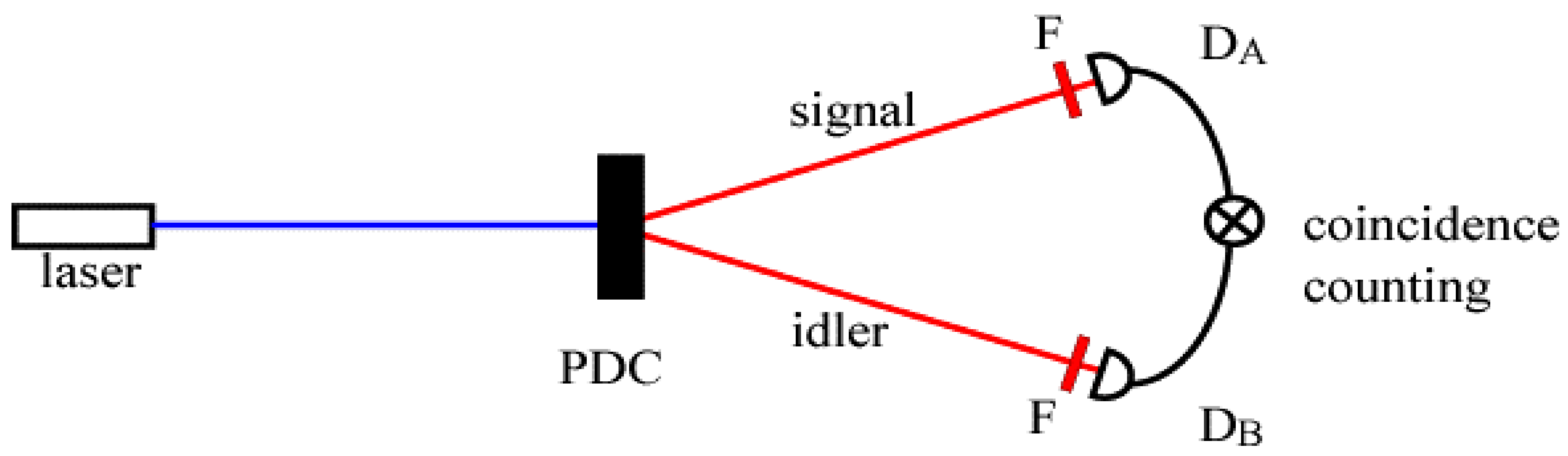
(unfolded paths)

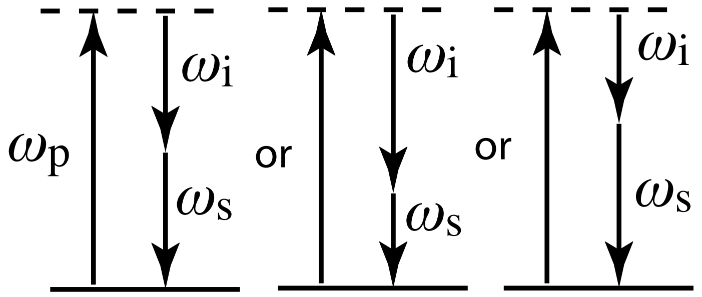
Necessary condition for one-photon interference

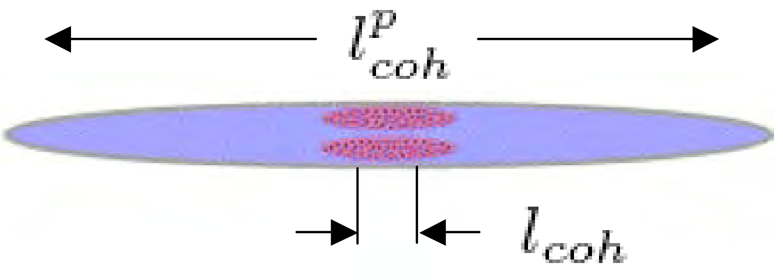
$$\boxed{\Delta l \;<\; l^{p}_{coh}}$$



Biphotons Are Created by Parametric Downconversion (PDC)







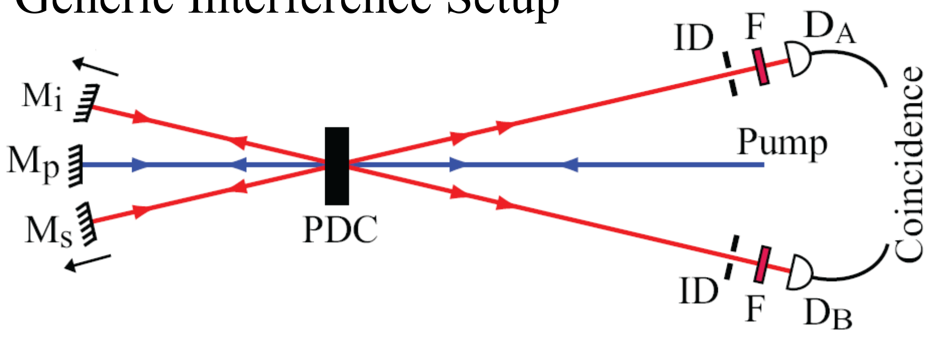
Length of two-photon wavepacket ~ coherence length of pump laser ~ 10 cm

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

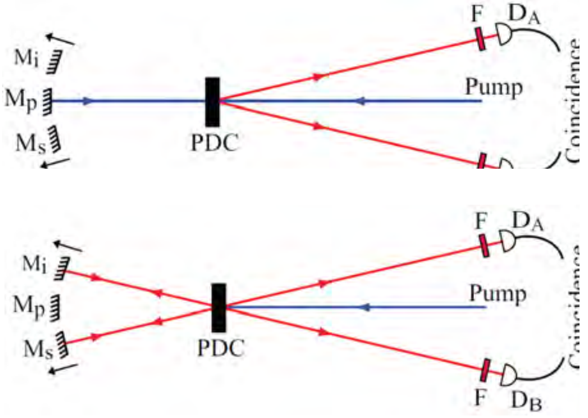
These photons are time-energy entangled!

Two-Photon Interference

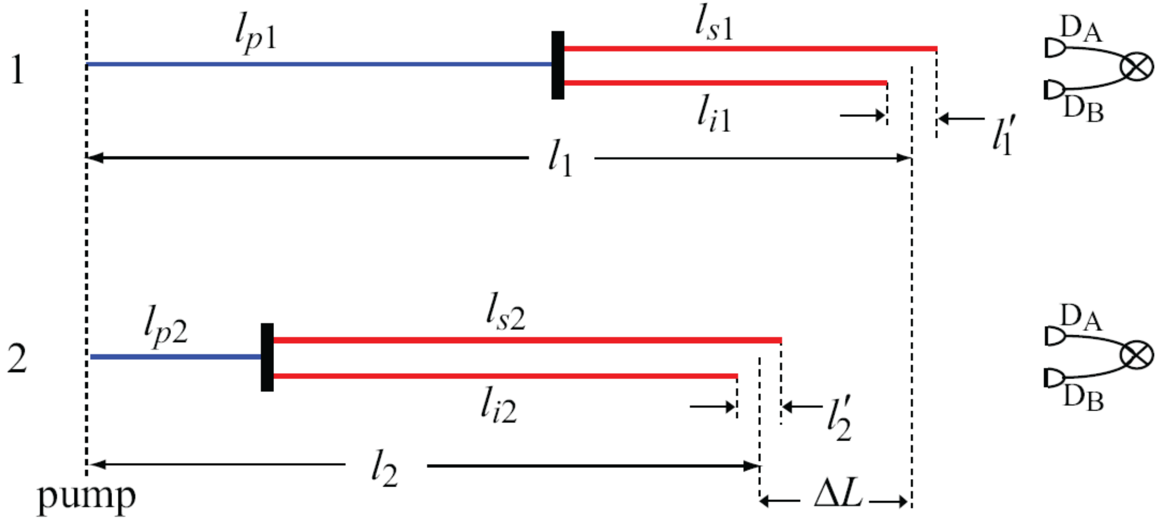
Generic Interference Setup



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)

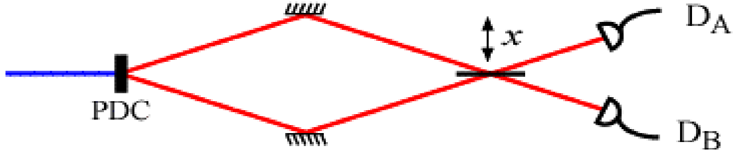
Necessary conditions for two-photon interference:

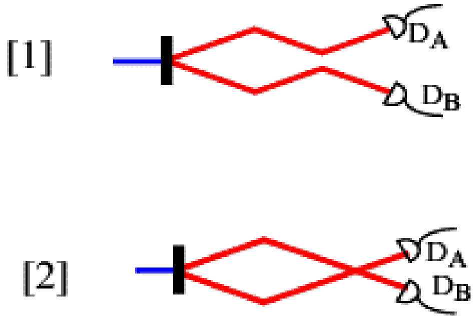
$$\boxed{\begin{array}{l} \Delta L < l^p_{\mathrm{coh}} \\ \Delta L' < l_{\mathrm{coh}} \end{array}}$$

$$l^p_{\mathrm{coh}} \sim 10\ \mathrm{cm}$$

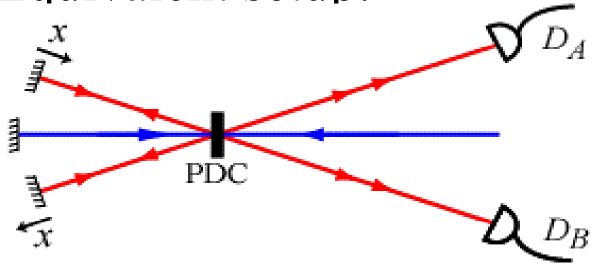
$$l_{\mathrm{coh}} = \frac{c}{\Delta\omega} \sim 100\ \mu\mathrm{m}$$

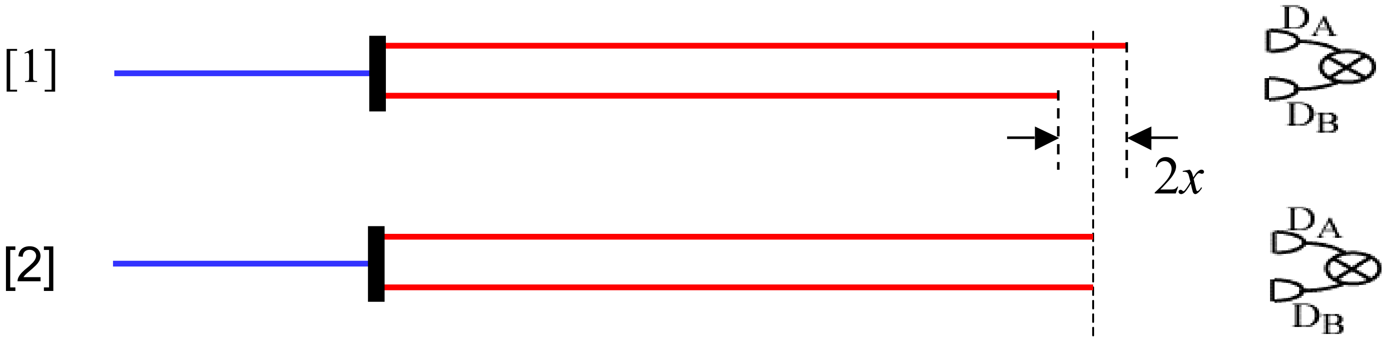
Hong-Ou-Mandel Experiment





Equivalent setup:

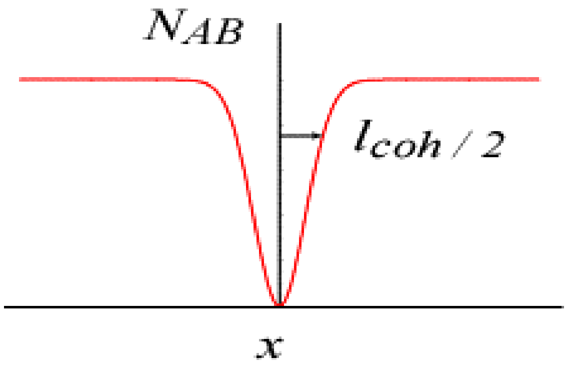




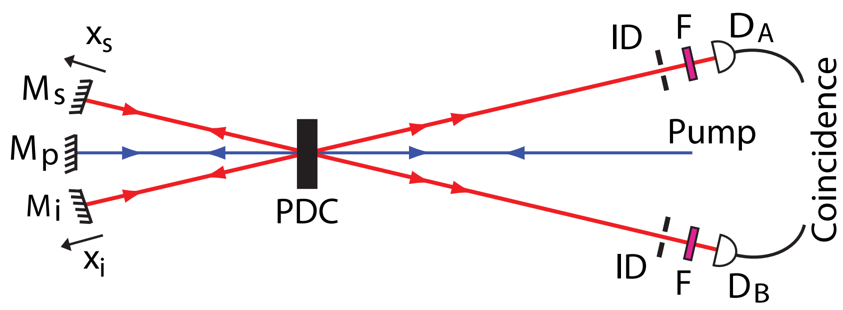
$\Delta L = 0 \qquad \Delta L' = 2x$

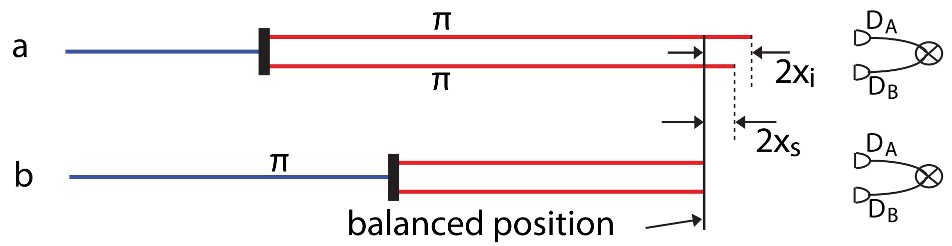
$$N_{AB} \propto \; 1 - \gamma'\left(\Delta L'\right)\gamma\left(\Delta L\right)\cos\left(k_0 \Delta L\right)$$

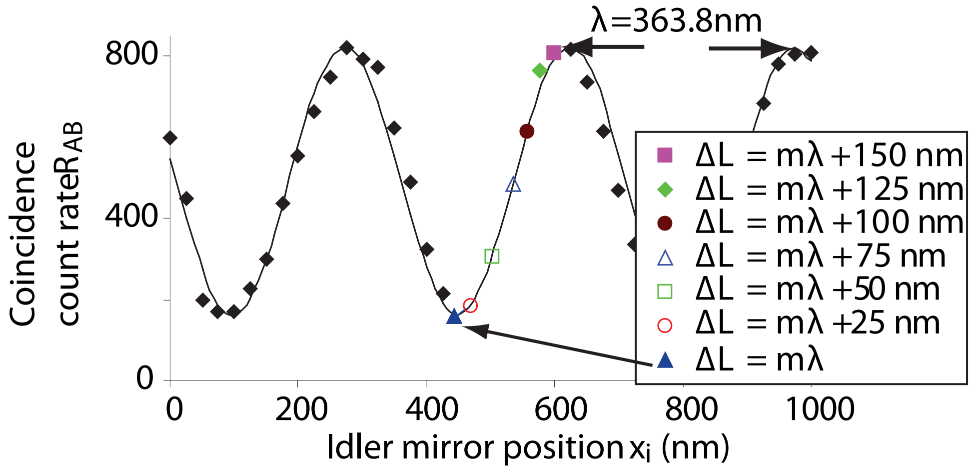
$$N_{AB} \propto \; 1 - \gamma'\left(2x\right)$$

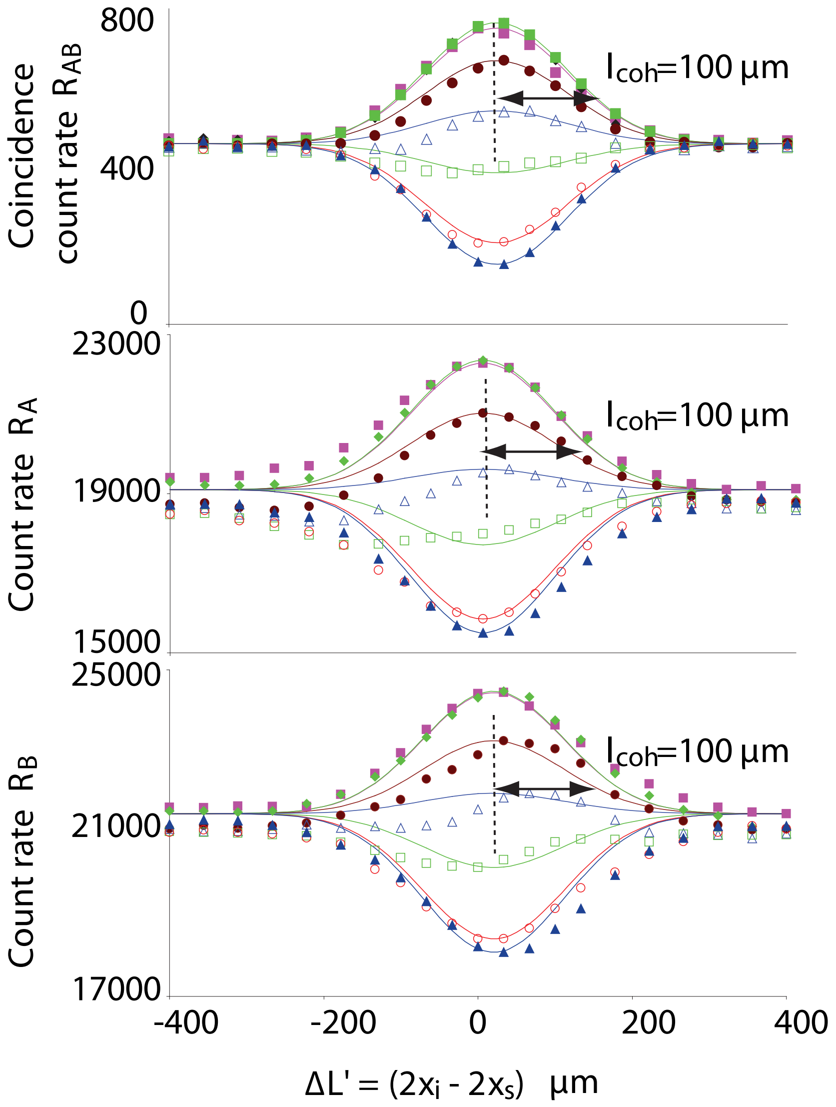


Our Experiment: Generalization of the Hong-Ou-Mandel Effect









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 $\Delta L'$.

Special Thanks to My Students and Research Associates