Quantum Imaging: Enhanced Image Formation Using Quantum States of Light

Robert W. Boyd

Institute of Optics and
Department of Physics and Astronomy
University of Rochester

http://www.optics.rochester.edu/~boyd

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

Presented at the University of Maryland - NIST Joint Quantum Institute, April 14, 2008.

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 MURI

Robert Boyd, John Howell, UR
Sasha Sergienko, Bahaa Saleh, Mal Teich, BU
Jon Dowling, LSU
Jeff Shapiro, MIT
Geraldo Barbosa, Prem Kumar, NWU
Yanhua Shih, Fow-Sen Choa, Morton Rubin, UMBC

International Collaborators

- **Hans Bachor, Australian National University**
- **Claude Fabre, University of Paris**
- **Mikhail Kolobov, University of Lille**
- **Luigi Lugiato, Alessandra Gatti, Como**

Quantum Imaging Research Plan

Quantum Imaging Systems

- Quantum Optical Coherence Tomography (QOCT).
- Quantum Coincidence (or Ghost) Imaging.
- Quantum Laser Radar.
- Quantum Lithography.

Quantum Imaging Technologies

- Intense Sources of Entangled Photons
  - Parametric Downconversion in Periodically Poled Waveguides.
  - Quantum Entangled Sources based on Third-Order Interactions.
  - Entanglement Utilizing Complex Pump Mode Patterns.
- High-Order Entanglement.
- Pixel Entanglement and Secure Transmission of Images.
- Unified Theoretical Framework for Classical and Quantum Imaging.

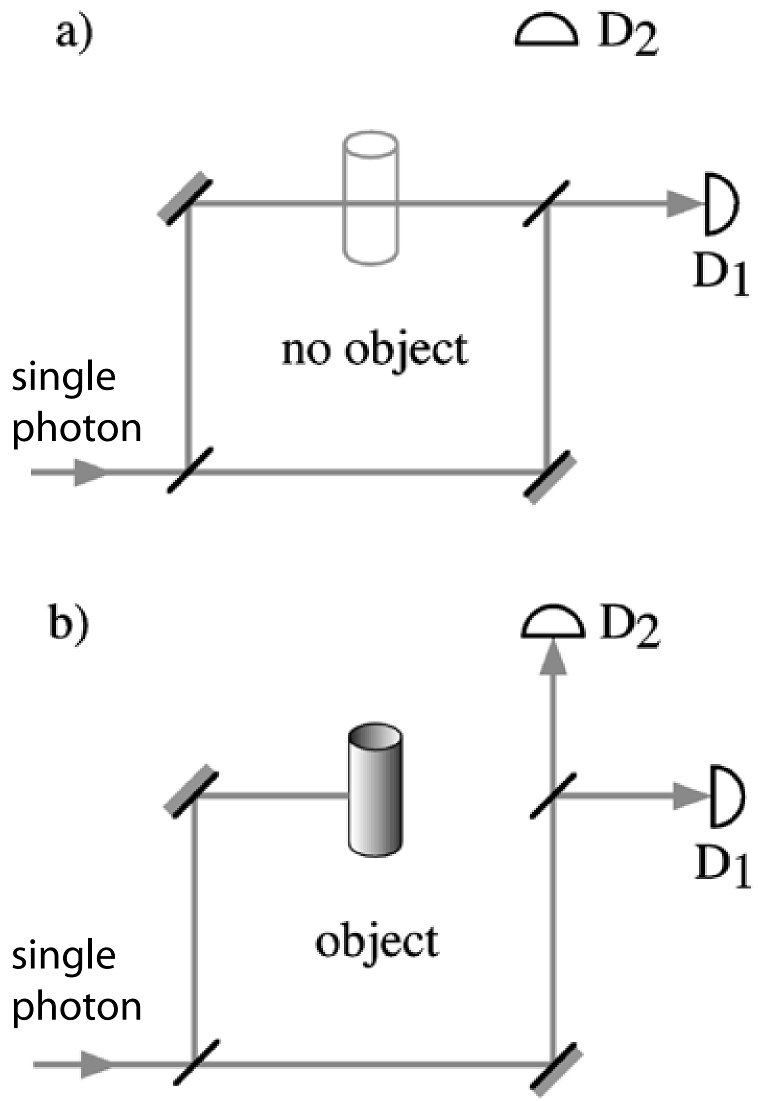
Outline of Presentation

1. Introduction to quantum imaging
   a. "Interaction-free" imaging
   b. Overview of ghost imaging
   c. Overview of quantum lithography
2. Development of technology needed for quantum imaging
   a. Single-photon imaging
   b. Propagation through turbulence
   c. Bayesian analysis of single-photon detectors
3. Conceptual understanding: nature of two-photon interference

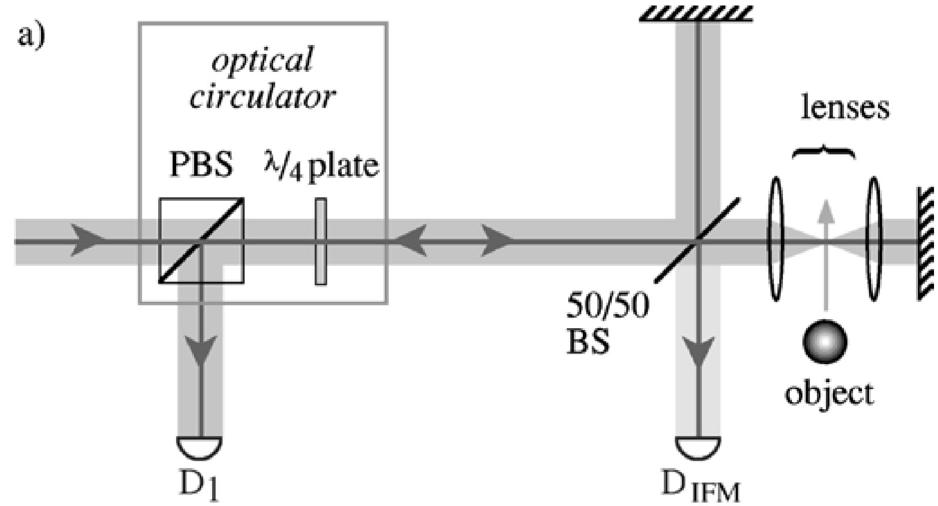
Stealth Imaging

Interaction-Free Imaging and Ghost Imaging

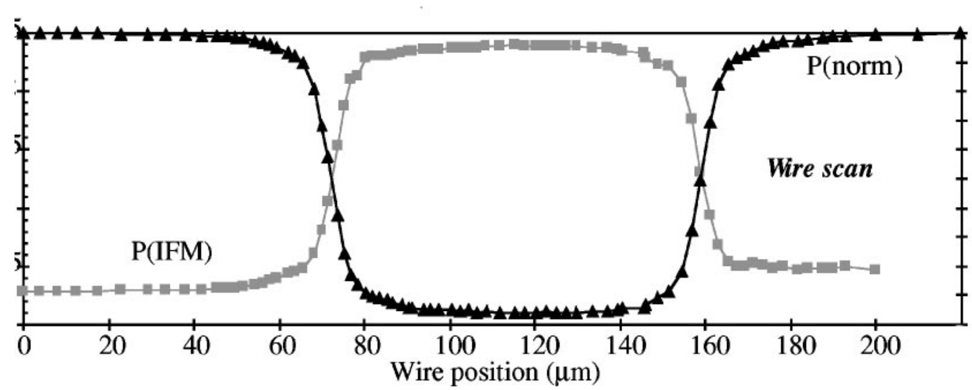
Quantum Imaging by Interaction-Free Measurement



imaging setup



results

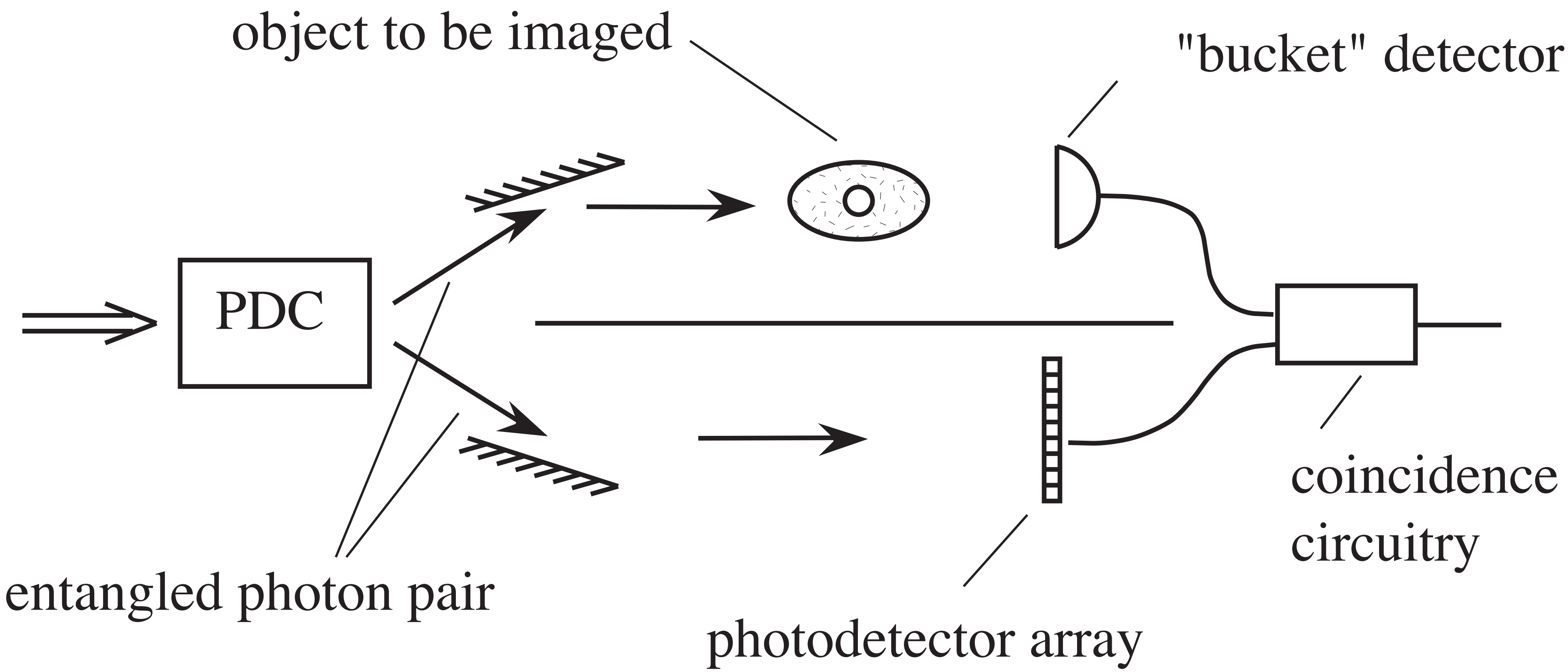


A. Elitzur and L. Vaidman, Foundations of Physics, 23 987 (1993).

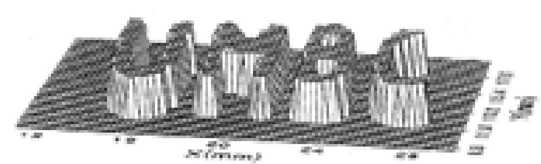
Kwiat, Weinfurter, Herzog, Zeilinger, and Kasevich, Phys. Rev. Lett. 74 4763 1995

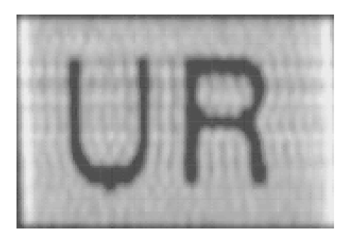
White, Mitchell, Nairz, and Kwiat, Phys. Rev. A58, 605 (1998).

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)



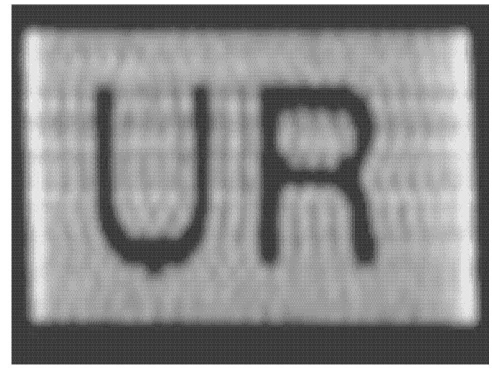


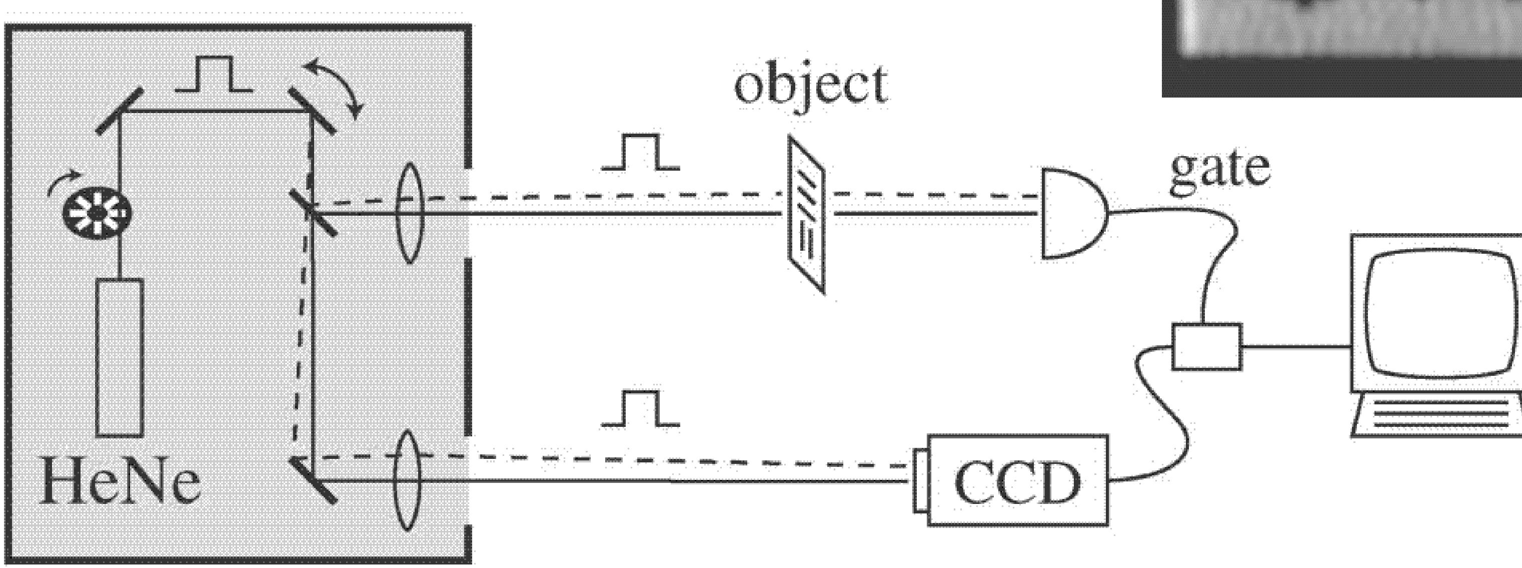
Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).

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)

Classical Coincidence Imaging

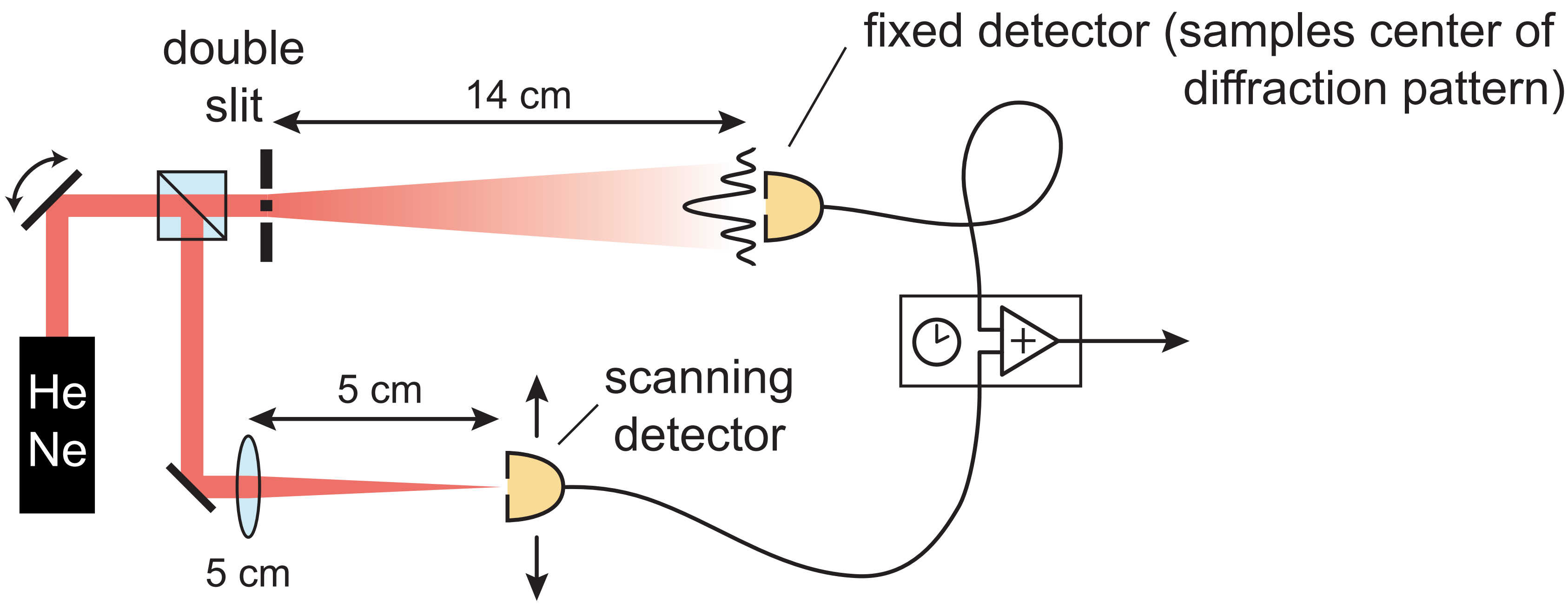
We have performed coincidence imaging with a demonstrably classical source.

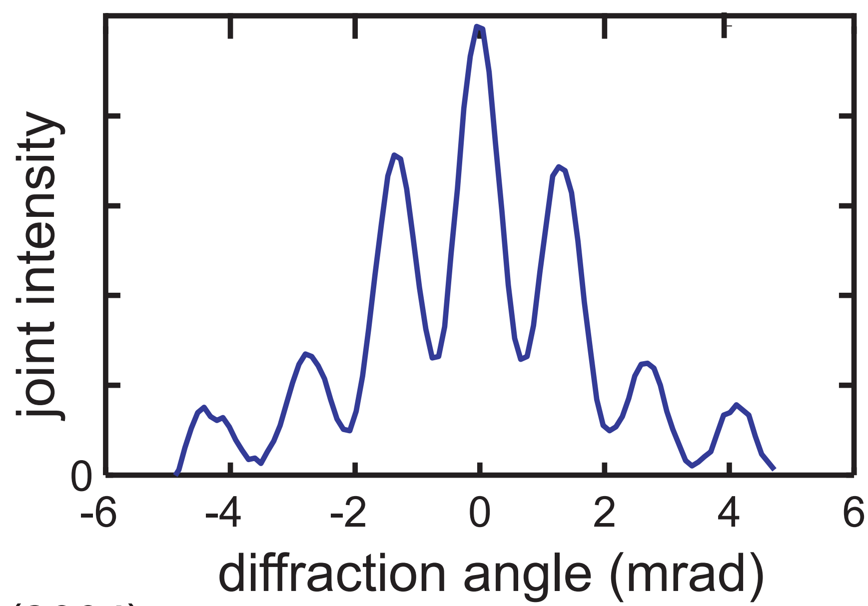




Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601 (2002).

Ghost Diffraction with a Classically Correlated Source





Even diffraction effects are observable with classical coincidence imaging.

Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004)

Further Development

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato

INFM, Dipartimento di Scienze CC.FF.MM., Università dellíInsubria, Via Valleggio 11, 22100 Como, Italy

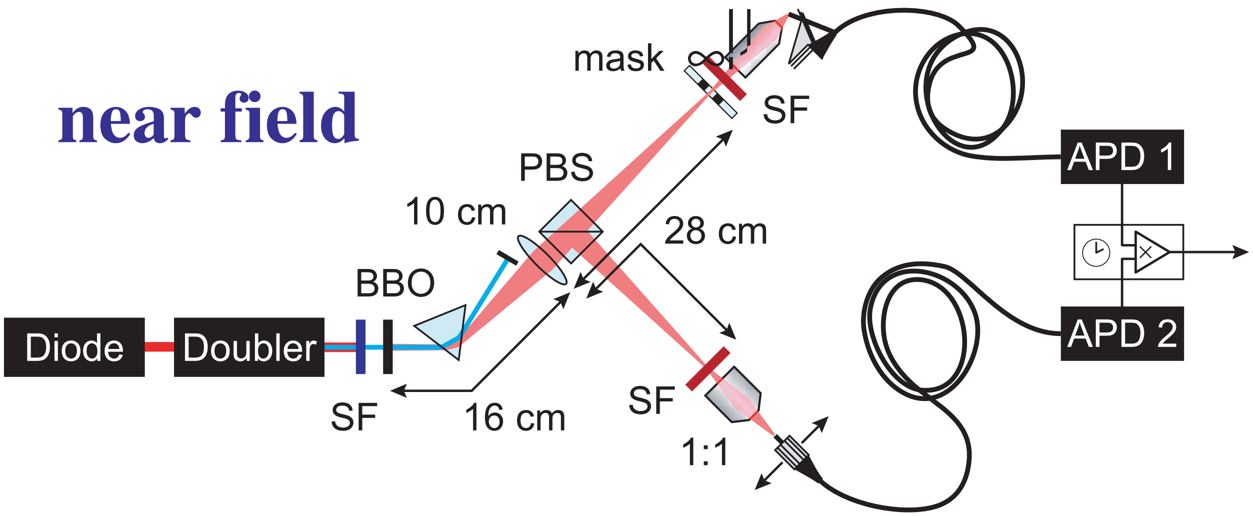
(Received 11 October 2002; published 3 April 2003)

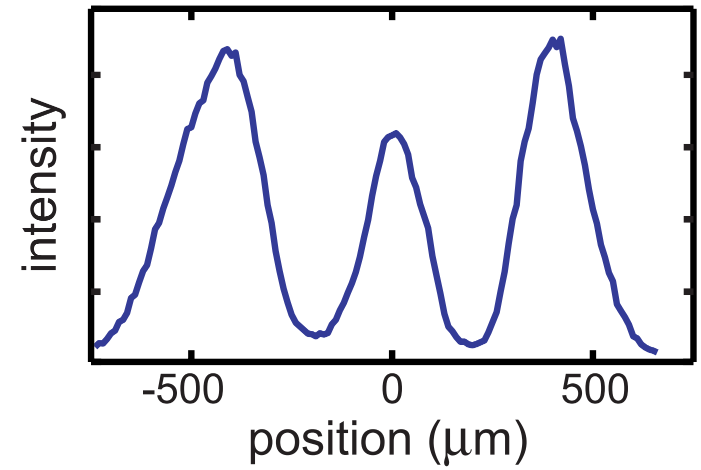
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

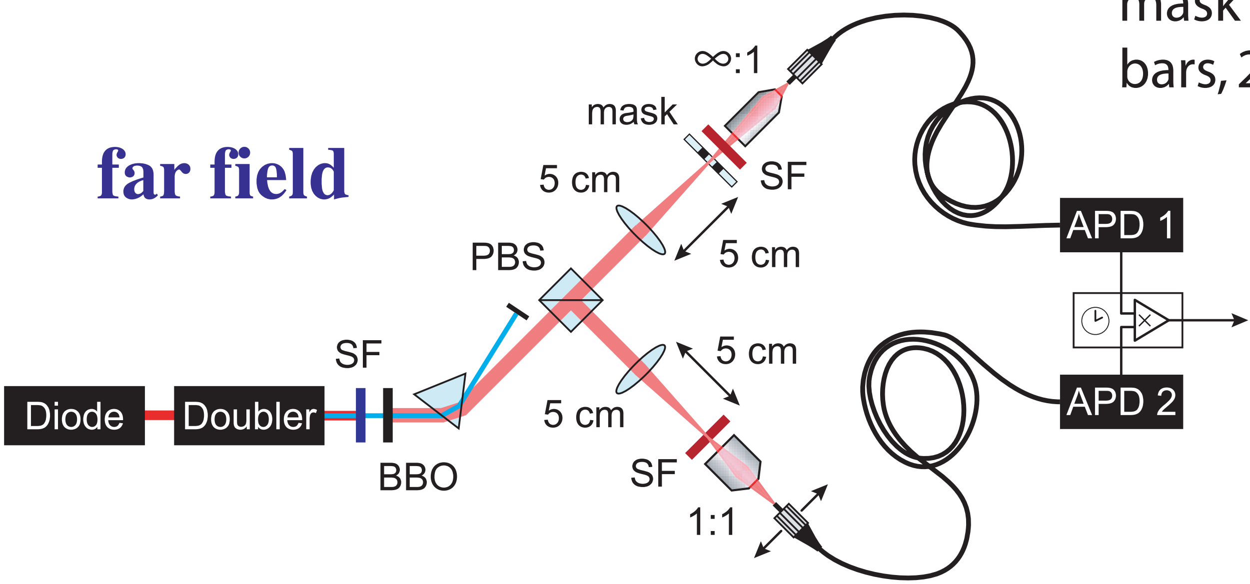
Near- and Far-Field Imaging Using Quantum Entanglement

near field

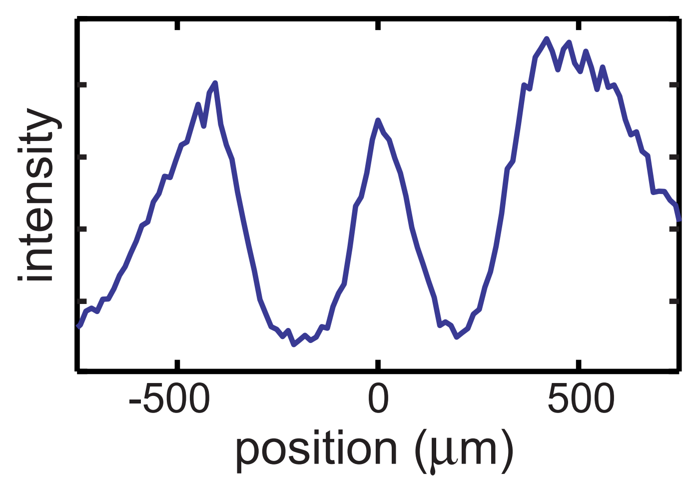




far field



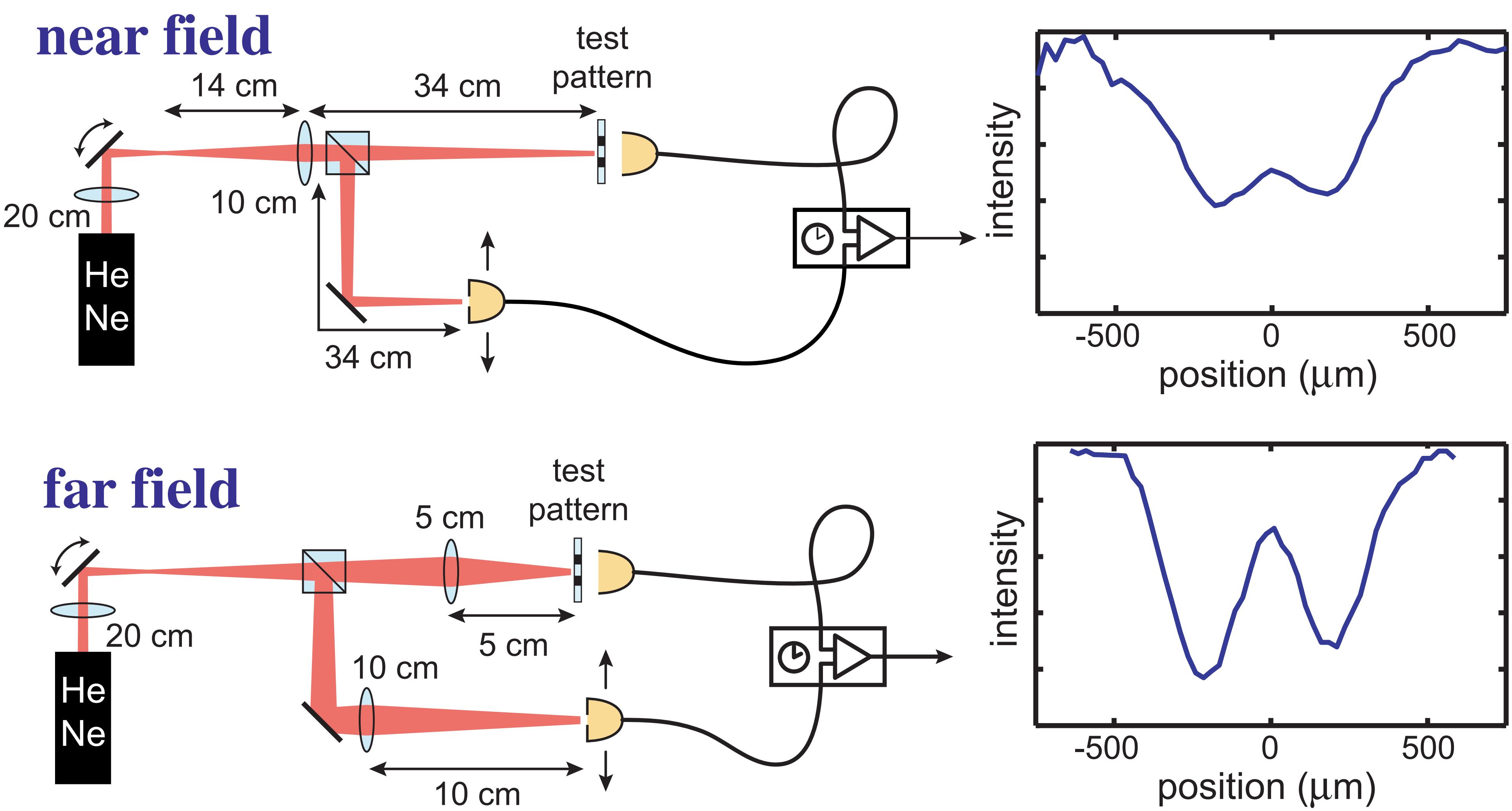
mask (object) is two opaque bars, 200 μm wide



Good imaging observed in both the near and far fields!

Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

Near- and Far-Field Imaging With a Classical Source



- Good imaging can be obtained only in near field **or** far field.
- Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of ten.

Is Entanglement Really Needed for Ghost Imaging with an Arbitrary Object Location?

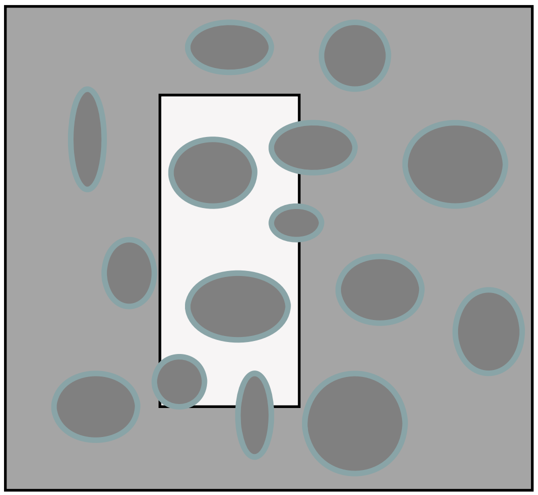
Gatti et al. (PRA and PRL, 2004) argue that thermal sources can mimic the quantum correlations produced by parametric down conversion. (Related to Brown-Twiss effect.)

Experimental confirmation of ghost imaging with thermal sources presented by Como and UMBC groups

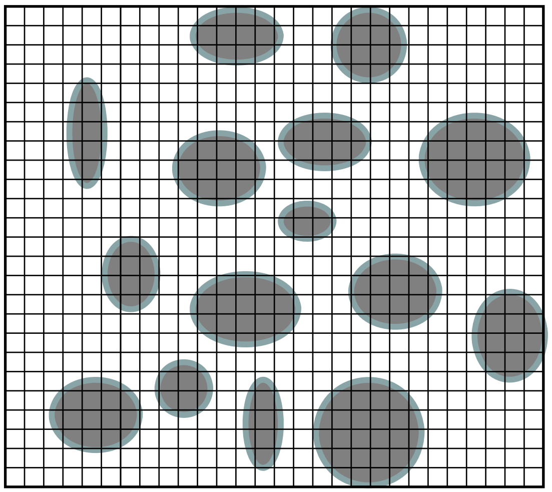
But the contrast of the images formed in this manner is limited to 1/2 or 1/N (depending on the circumstances) where N is the total number of pixels in the image.

Origin of Thermal Ghost Imaging

Create identical speckle patterns in each arm.



object arm
(bucket detector)



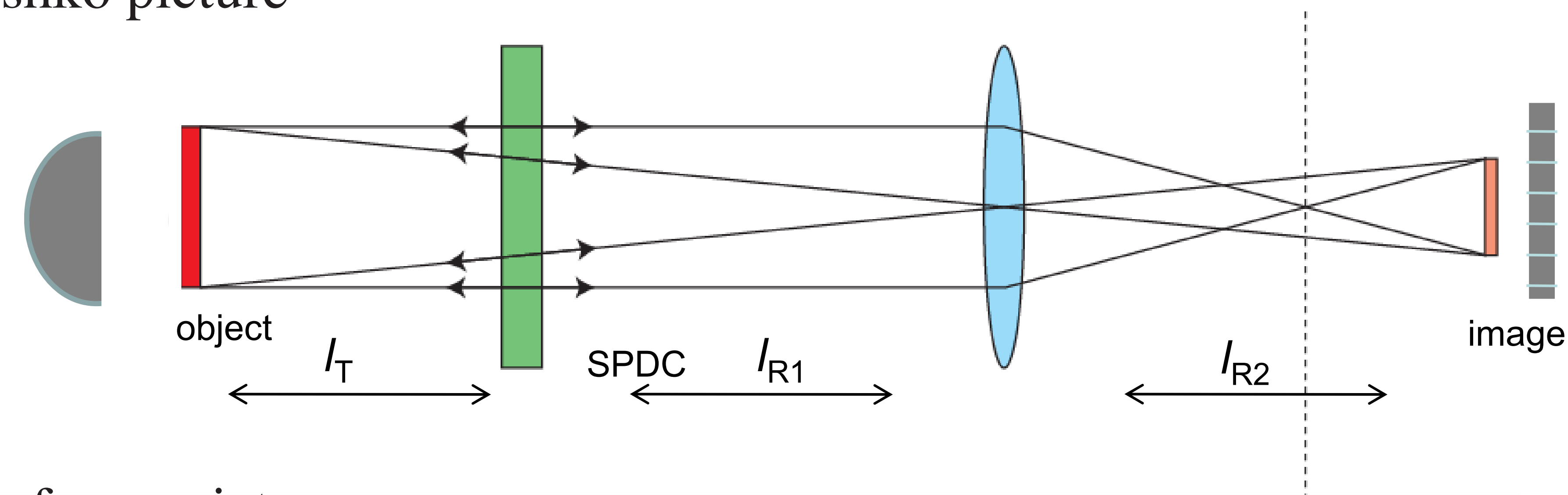
reference arm
(pixelated imaging detector)

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

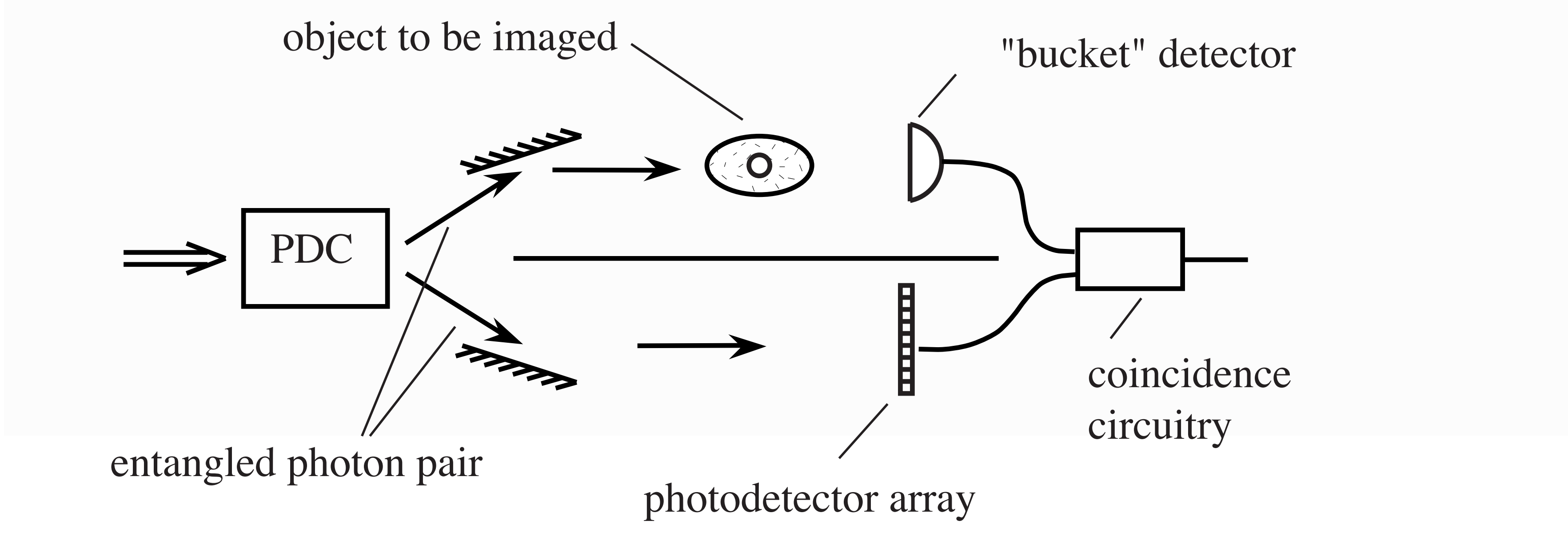
Average over many speckle patterns

Klyshko Picture of Quantum Ghost Imaging

Klyshko picture



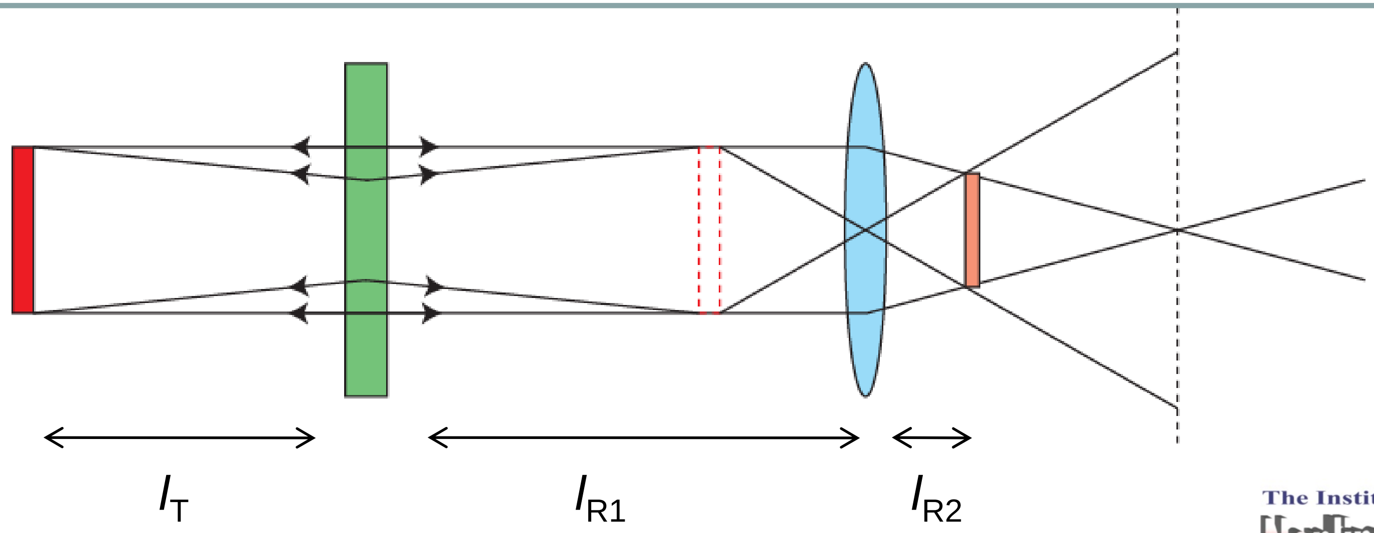
Lab-frame picture



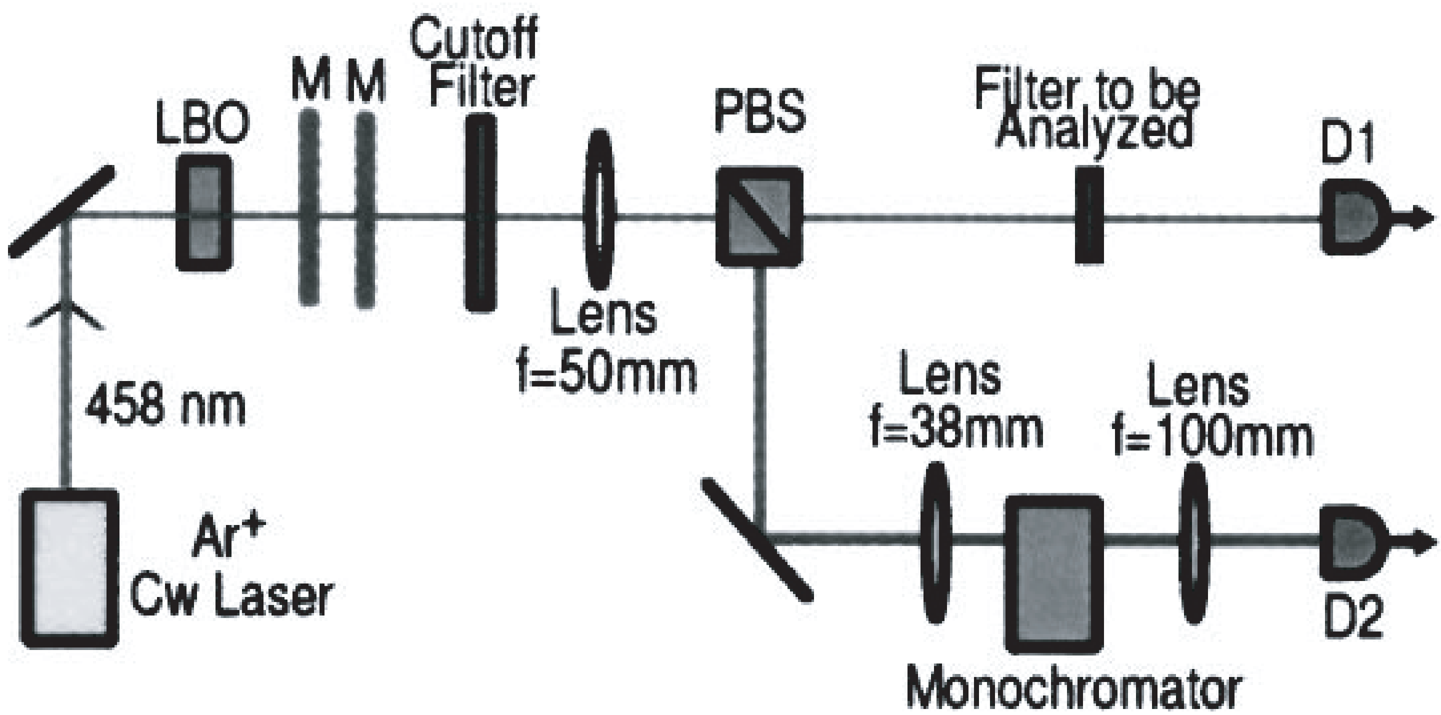
Thermal Ghost Imaging

Imaging condition:

$$\frac{1}{l_{\mathrm{R1}} - l_{\mathrm{T}}} + \frac{1}{l_{\mathrm{R2}}} = \frac{1}{f}$$



Remote (Ghost) Spectroscopy



Can this idea be implemented with thermal light?

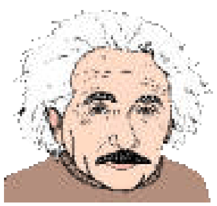
Scarcelli, Valencia, Compers, and Shih, APL 83 5560 2003.

See also the related work of Bellini et al., Phys. Rev. Lett. 90 043602 (2003).

The EPR Paradox

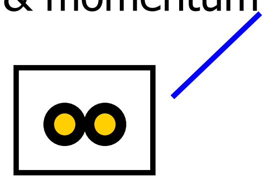
In 1935, Einstein, Podolsky, and Rosen argued that quantum mechanics must be "incomplete."

entangled particles, perfectly correlated in position & momentum



measure x or p

Det. 1



Det. 2

- measure x_1 $\Rightarrow$ know x_2 with certainty ($\Delta x_2 = 0$)
- measure p_1 $\Rightarrow$ know p_2 with certainty ($\Delta p_2 = 0$)
- measurement of particle 1 cannot affect particle 2 (?!)

$\Rightarrow$ $\Delta x_2 = 0$ and $\Delta p_2 = 0$ simultaneously (?!)

in conflict with $\Delta x_2 \Delta p_2 \geq \frac{1}{2}\hbar$

Quantum Imaging and the EPR Effect

- The quantum signature of ghost imaging is simultaneous correlations in both x and k
- EPR thought that simultaneous correlations in both x and p contradicted Heisenberg's uncertainty principle

The criterion for quantum features in coincidence imaging,

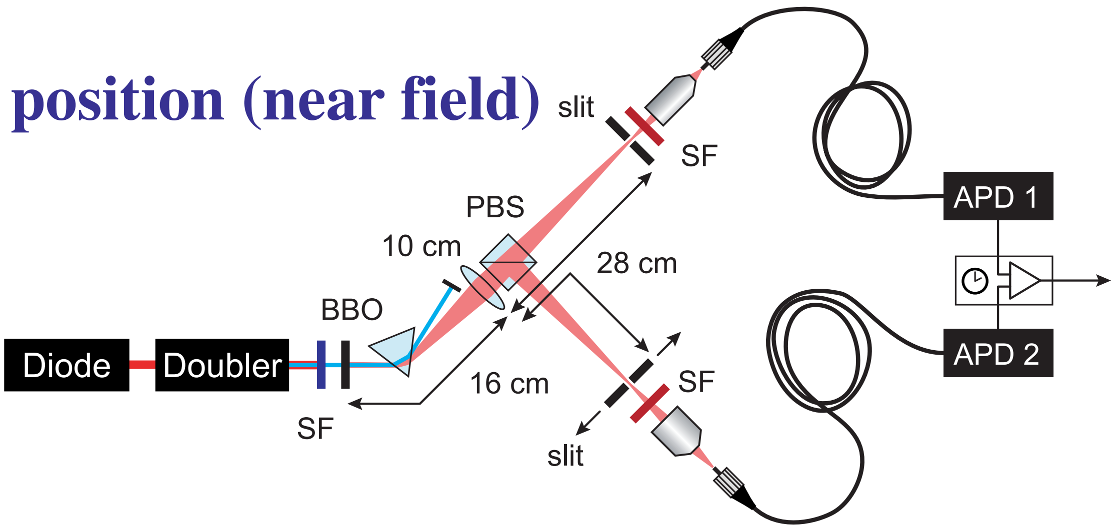
$$\left((\Delta x_2)_{x_1}\right)^2 \left((\Delta k_2)_{k_1}\right)^2 \leq 1$$

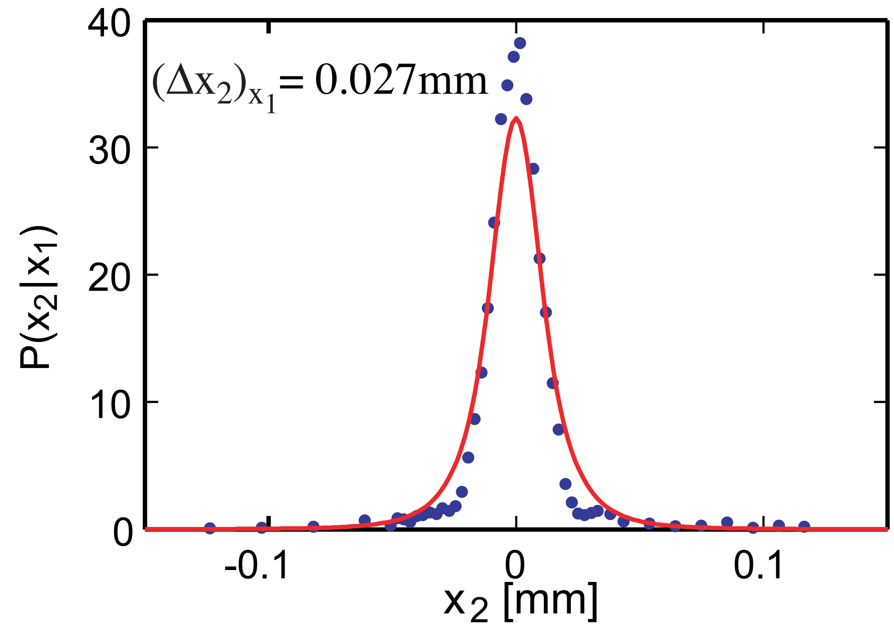
is equivalent to that for violating the EPR hypothesis.

- With entangled photons, one can perfom the original EPR experiment (not Bell's!). EPR were considering continuous variables (momentum and position) not the spin variable.

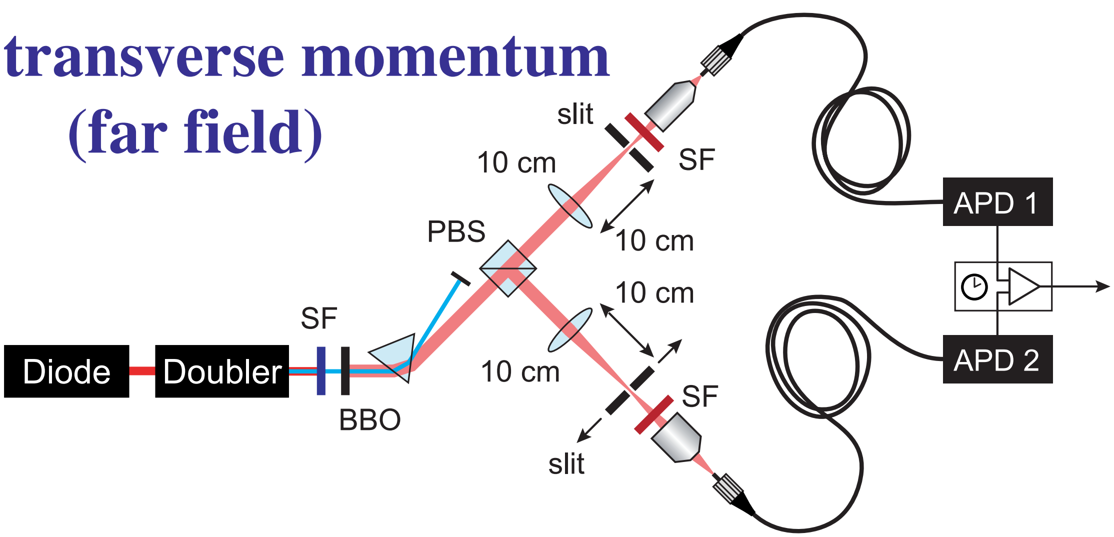
Position-Momentum Realization of the EPR Paradox

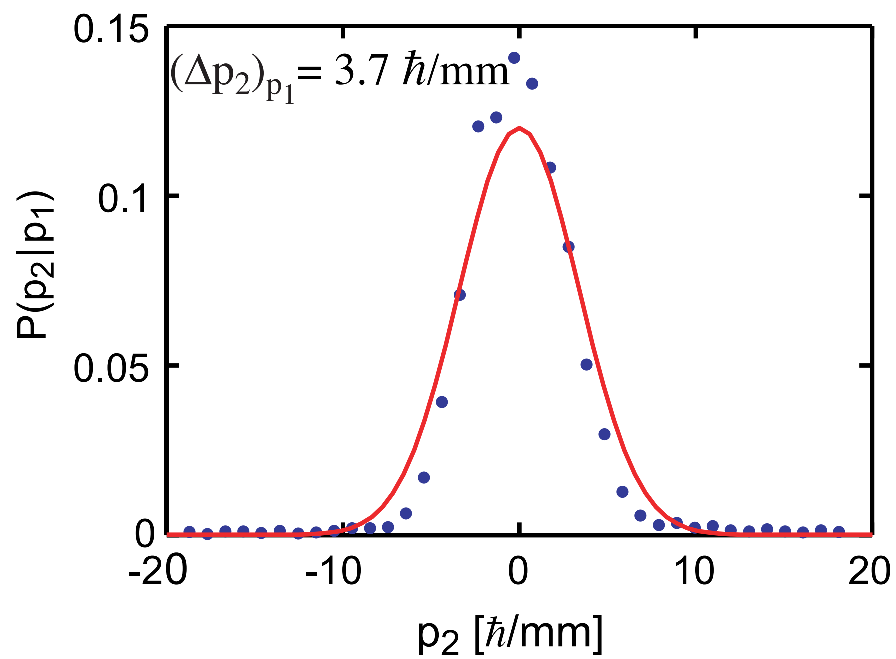
position (near field)





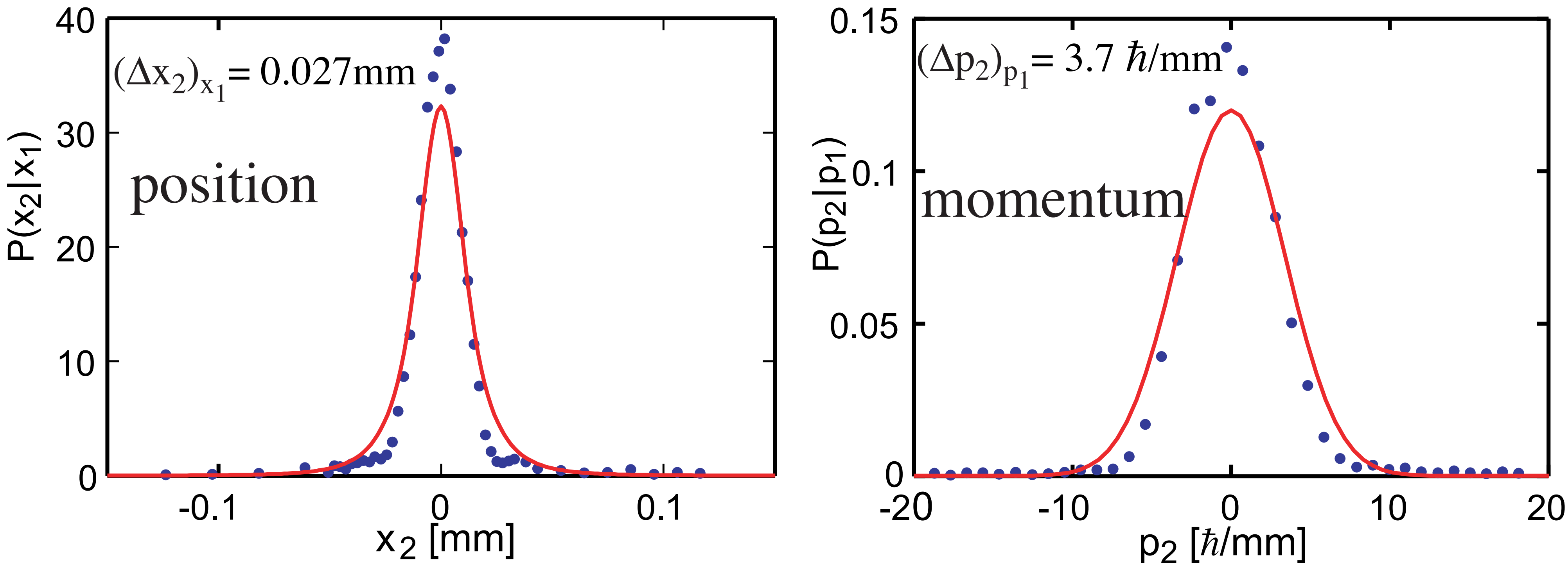
transverse momentum (far field)





- We find that $(\Delta x_2)_{x_1}\,(\Delta p_2)_{p_1} = 0.1\hbar$

Discussion: Position-Momentum Realization of the EPR Paradox



- The spread in *p* is determined by the momentum uncertainty of the pump beam, which is limited by the pump spot size.
- The spread in *x* is determined by the angular bandwidth of the PDC process, which is limited by phase matching requirements.
- We find that $(\Delta x_2)_{x_1}{}^2 \, (\Delta p_2)_{p_1}{}^2 = 0.01\hbar^2$, where according to EPR the product could be no smaller than unity.
- PRL, 92, 210403 (2004).

EPR Entanglement: previous work

- Squeezed light fields (quadrature squeezed correlations)
  - Reid and Drummond, PRL 60, 2731 (1988)
  - Ou et al, PRL 68, 3663 (1992)
  - Silberhorn et al, PRL 86, 4267 (2001)
  - Bowen et al, PRL 89, 253601 (2002)
- Collective atomic spin variables (spin observables)
  - Julsgaard, Nature 413, 400 (2001)
- Modern rephrasing of continuous entanglement
  - Duan et al, PRL 84, 2722 (2000)
  - Simon, PRL 84, 2726 (2000)
  - Mancini et al, PRL 88, 120401 (2002)

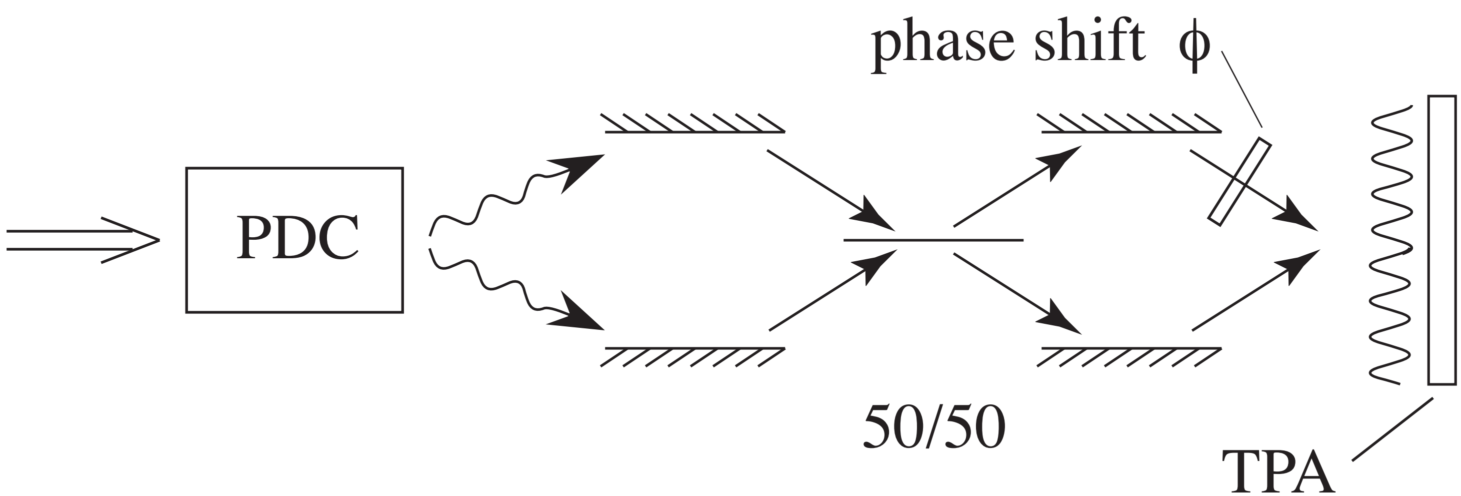
Research in Quantum Imaging

Quantum Imaging or Quantum Imogene?

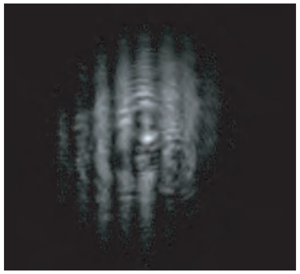
Sid Caesar and
Imogene Coca in 1953

Quantum Lithography

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit
- Process "in reverse" performs sub-Rayleigh microscopy, etc.
- Resolution ≈ $\lambda / 2N$, where N = number of entangled photons



Boto et al., Phys. Rev. Lett. 85, 2733, 2000.



Classical analog

S. J. Bentley and R.W. Boyd, Optics Express, 12, 5735 (2004).

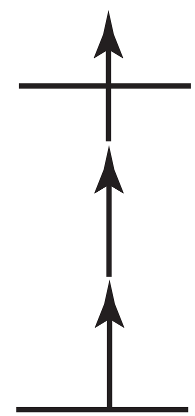
Quantum Lithography: Easier Said Than Done

- Need an *N*-photon recording material

  For proof-of-principle studies, can use *N*-th-harmonic generator, correlation circuitry, *N*-photon photodetector.

  For actual implementation, use ????

  Maybe best bet is UV lithographic material excited in the visible or a broad bandgap material such as PMMA excited by multiphoton absorption.

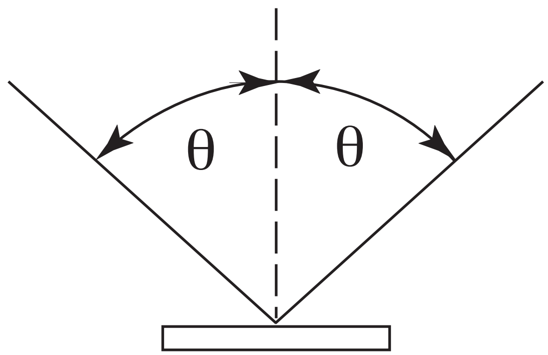


3PA in PMMA breaks chemical bond, modifying optical properties.

- Need an intense source of individual biphotons (Inconsistency?)

  Maybe a high-gain OPA provides the best tradeoff between high intensity and required quantum statistics

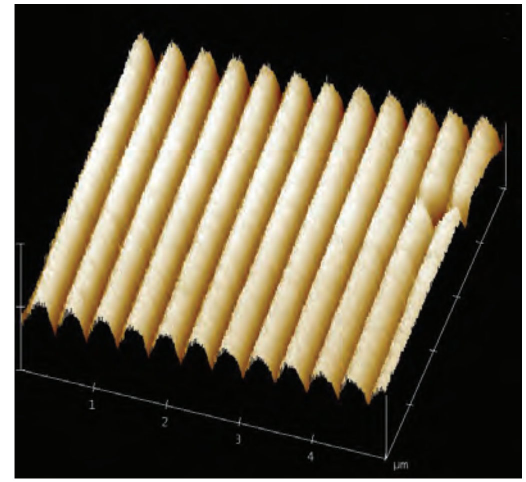
Demonstration of Fringes Written into PMMA



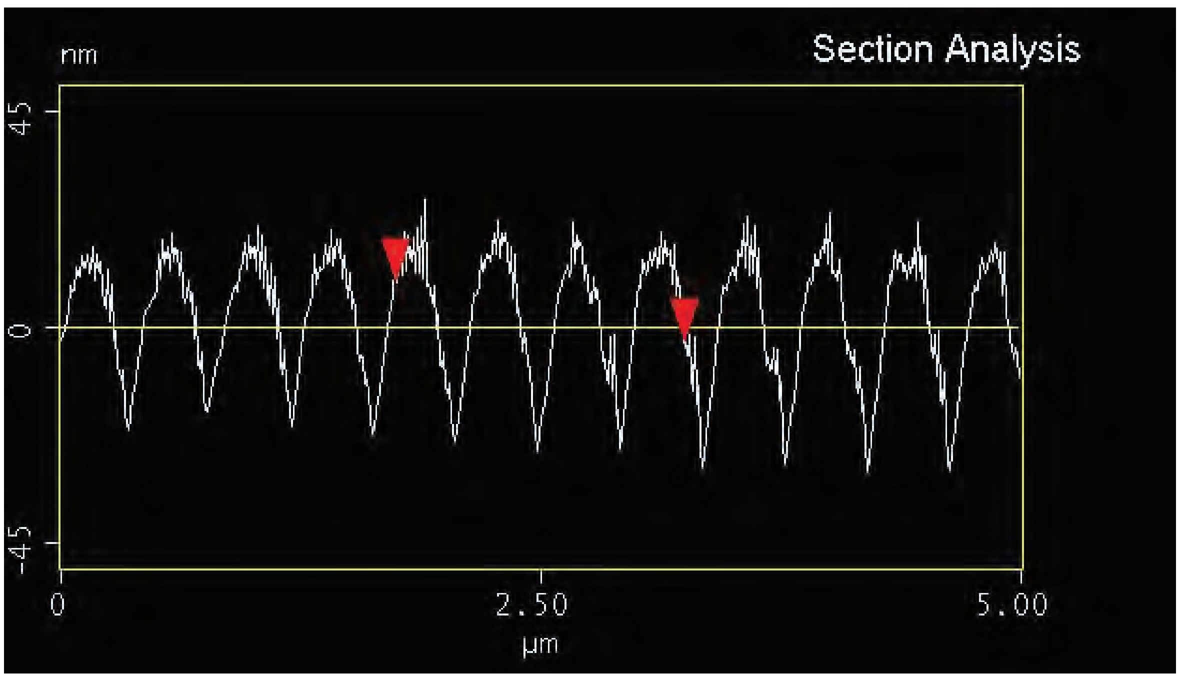
N-photon absorber
(N = 3 ?)

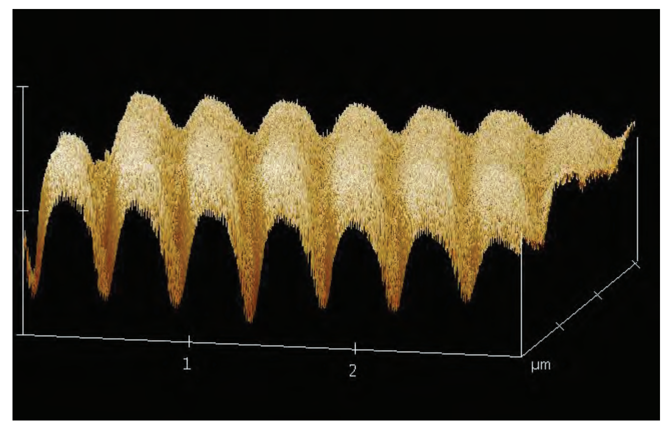
θ = 70 degrees
write wavelength = 800 nm
pulse energy = 130 μJ per beam
pulse duration = 120 fs
period = λ / (2 sin θ) = 425 nm

PMMA on glass substrate
develop for 10 sec in MBIK
rinse 30 sec in deionized water



AFM





PMMA is a standard lithographic material

H. J. Chang, H. Shin, M. N. O'Sullivan-Hale, and R. W. Boyd, J. Mod. Optics, 53, 10-20 (2006).

Significance of PMMA Grating Results

- Provides an actual demonstration of sub-Rayleigh resolution by the phase-shifted grating method
- Demonstrates an N-photon absorber with adequate resolution to be of use in true quantum lithography

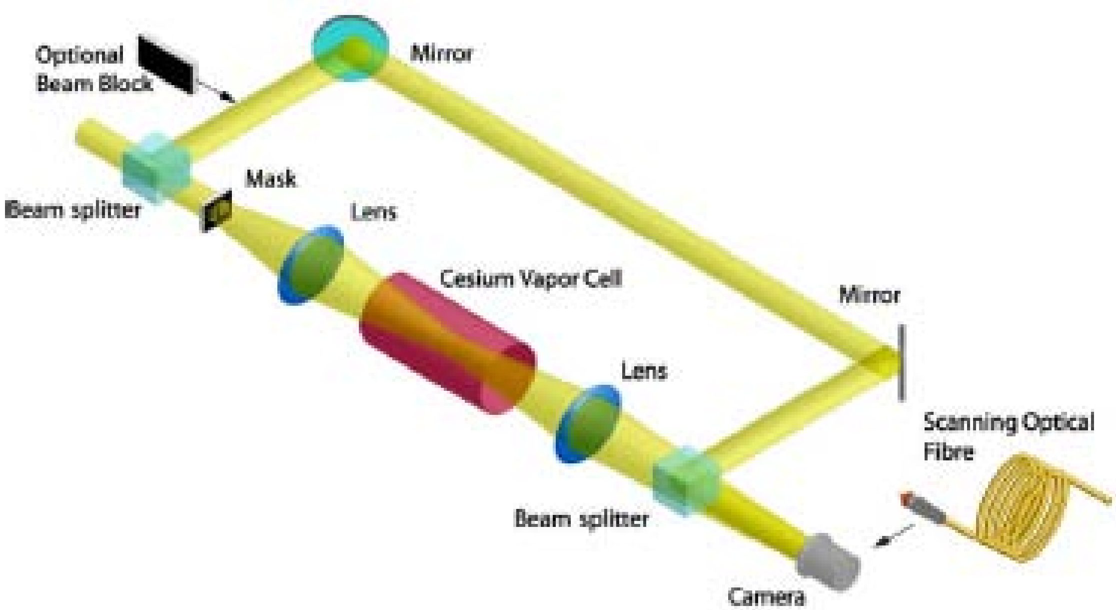
Single-Photon Imaging

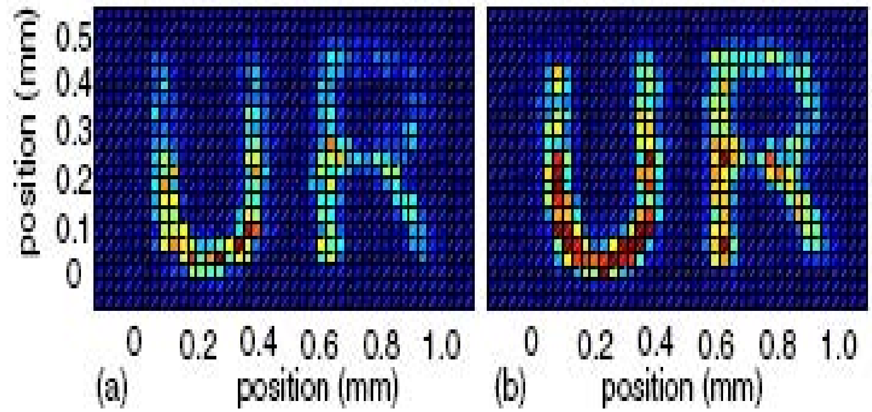
Joint Project: Boyd and Howell Groups

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

Prior Work - Howell Group





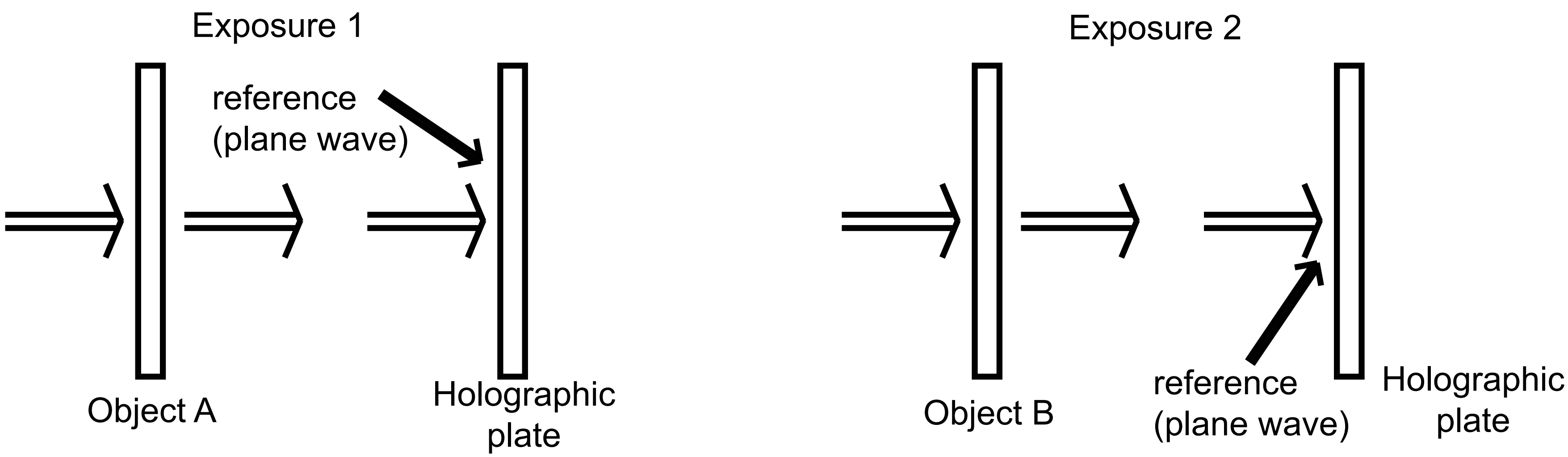
Delayed (9 ns) **Non-delayed**

- 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

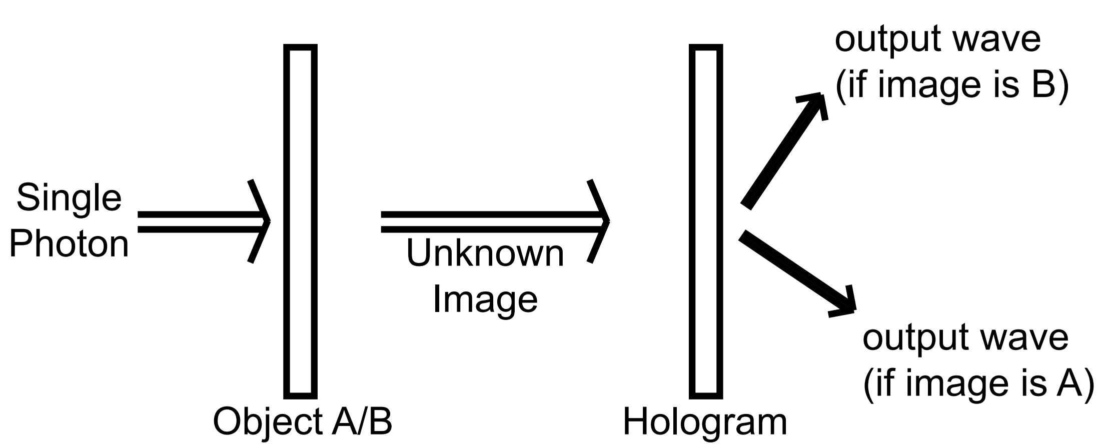
R. M. Camacho, *et al, PRL* ***98****, 043902 (2007)*

Holography, matched filtering, and single-photon Imaging

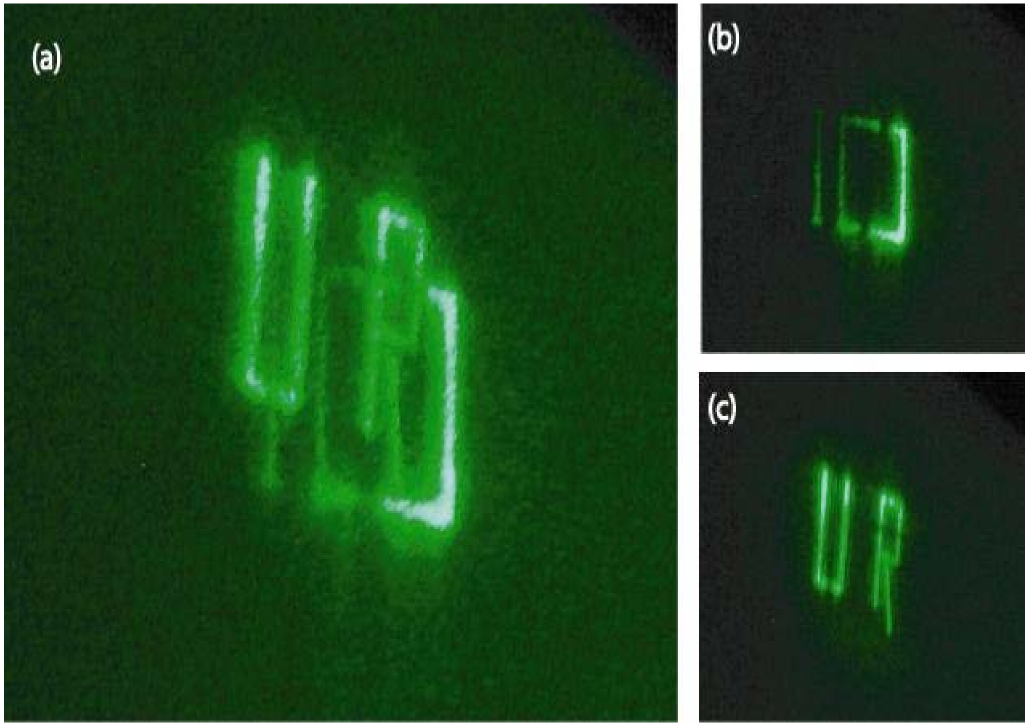
- Writing the matched filter (a multiple exposure hologram)

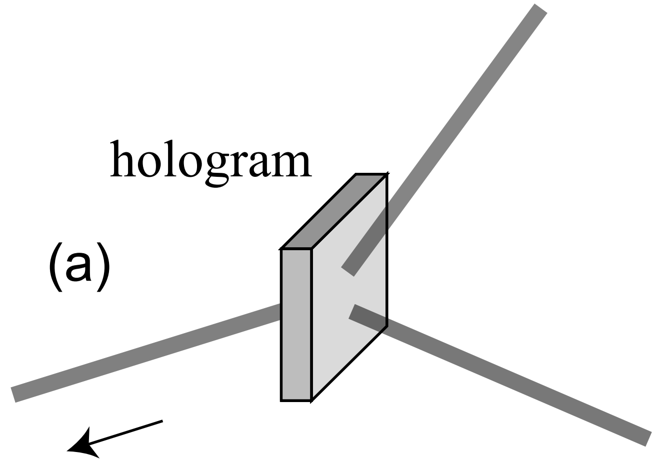


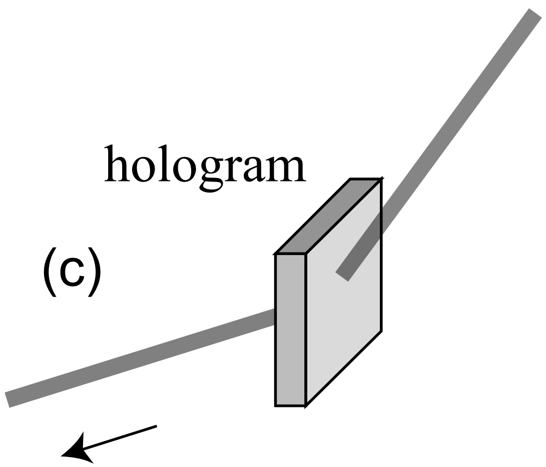
- Reading the hologram (with a single-photon)

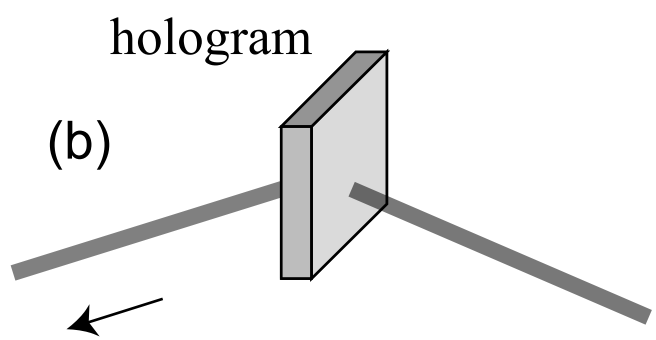


Reconstruction - with plane-wave reference beam

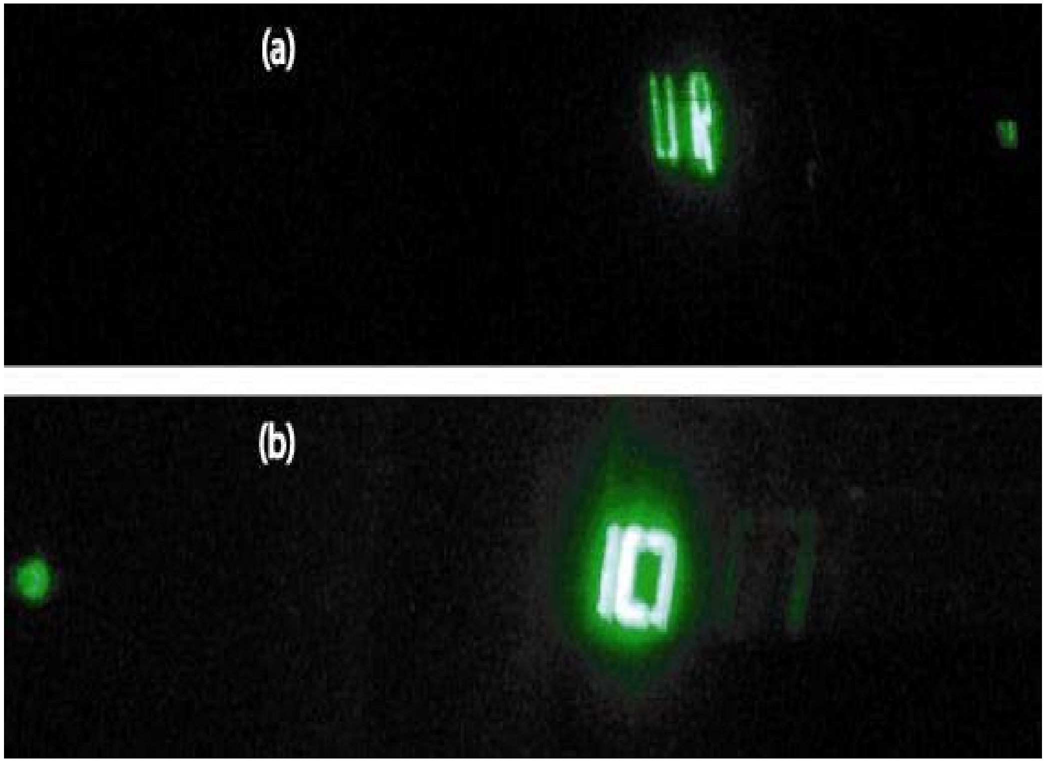


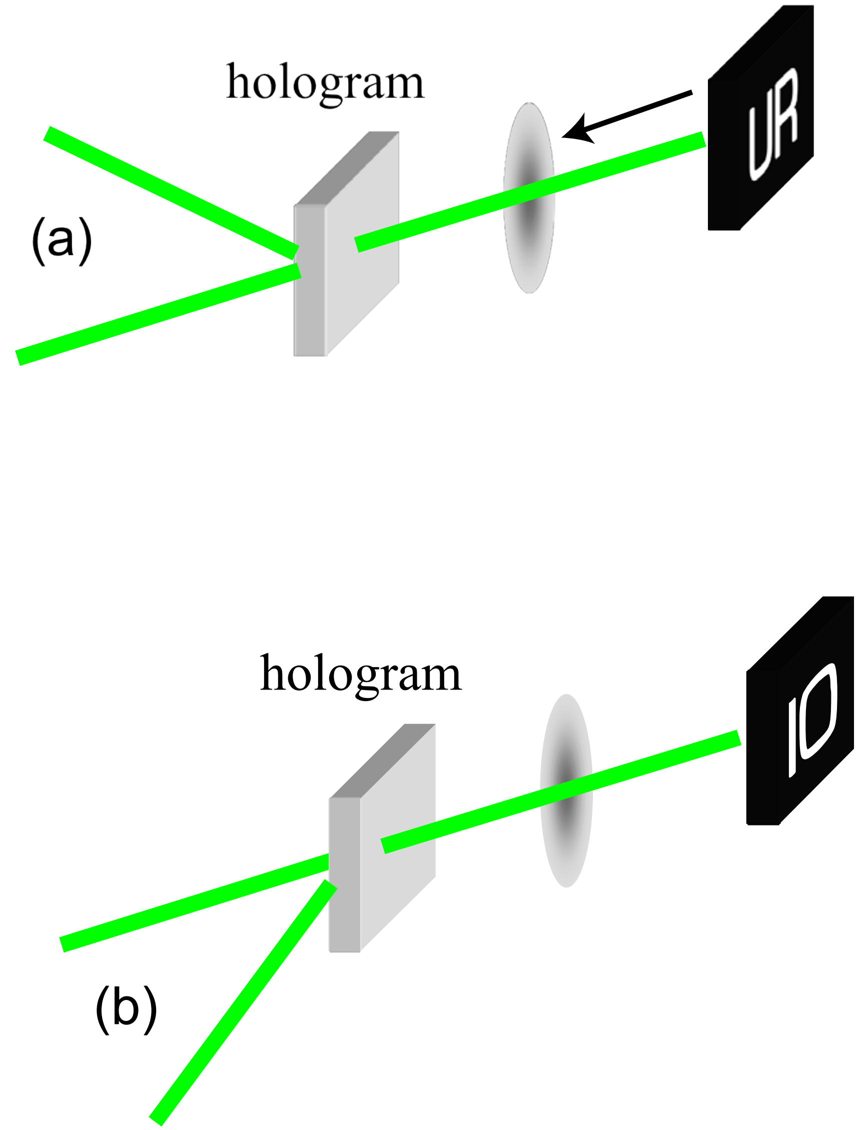






Reconstruction - with structured reference beam





- 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**

Coherence and Indistinguishability in Two-Photon Interference

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

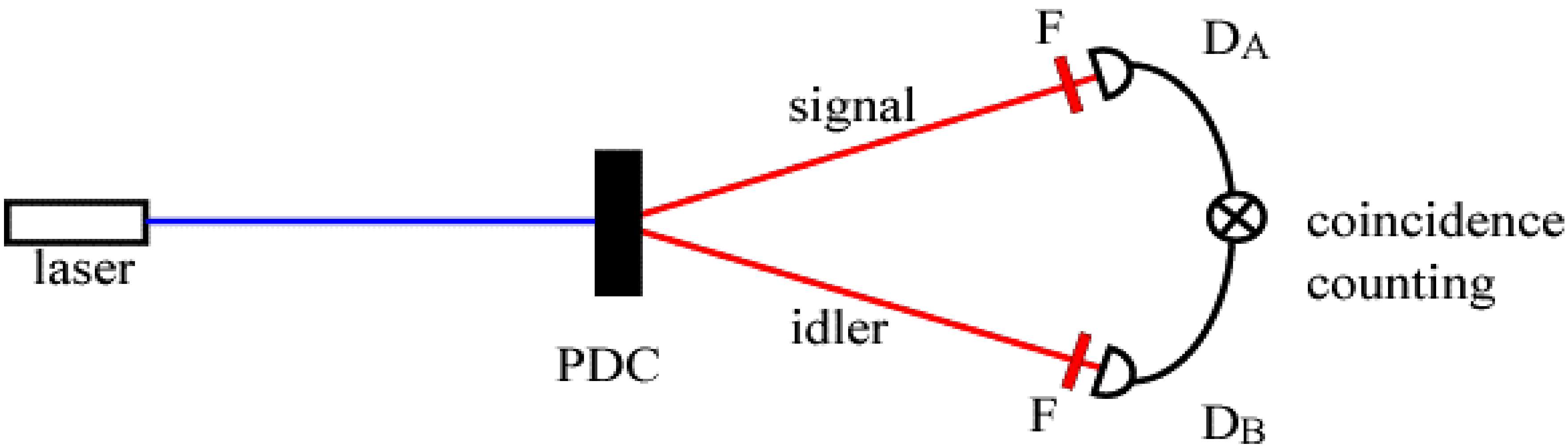
Institute of Optics, University of Rochester

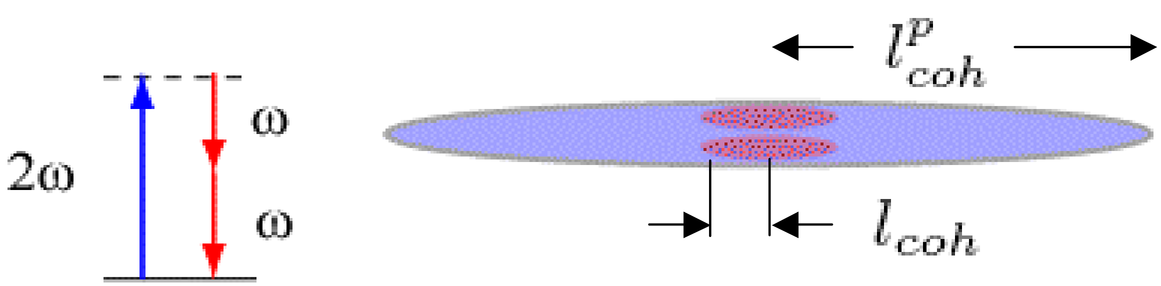
What are the relevant degrees of freedom of a biphoton?

What are the generic features of two-photon interference?

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

Biphotons Are Created by Parametric Downconversion (PDC)





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

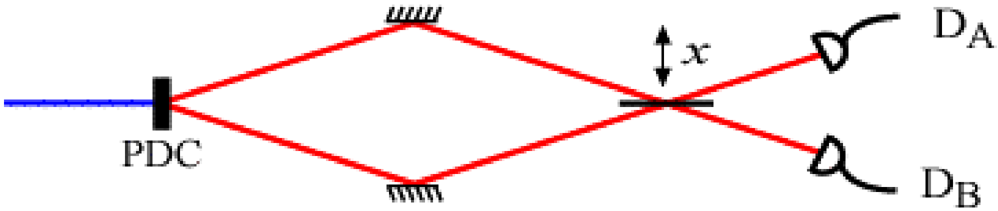
Coherence length of signal/idler photons ~ c/Δω ~ 100 μm.

Individual photons are entangled and can be made indistinguishable.

Two-Photon Interference -- How to Understand?

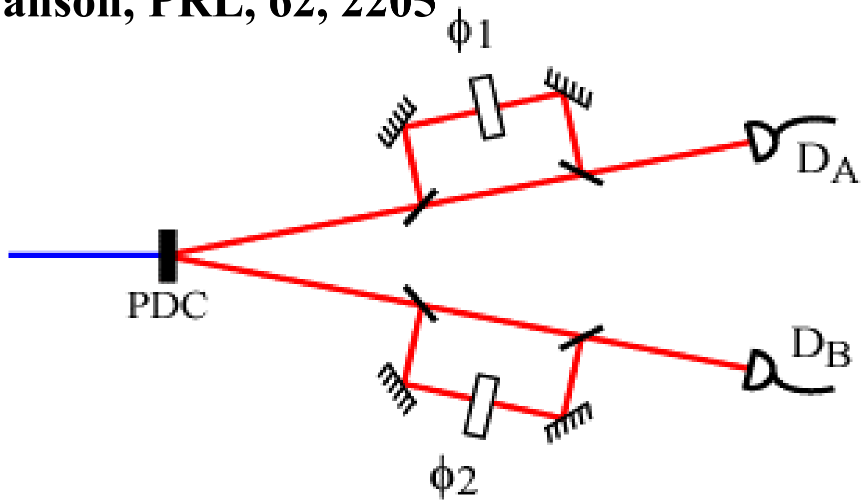
- **Hong-Ou-Mandel effect (1987)**

PRL, 59, 2044



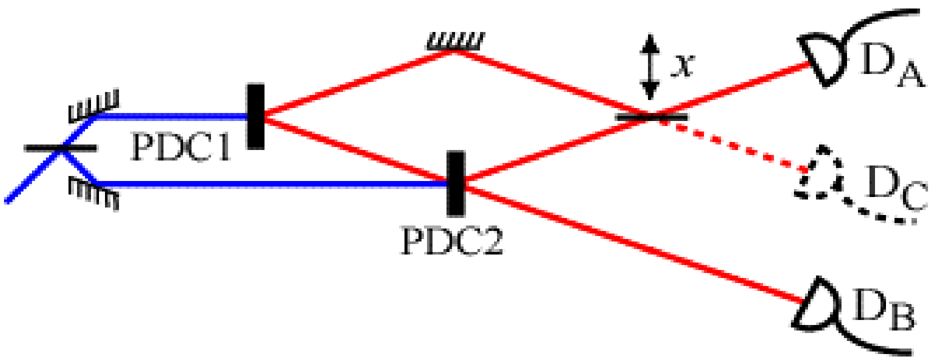
- **Bell Inequality for position and time (1989)**

Franson, PRL, 62, 2205



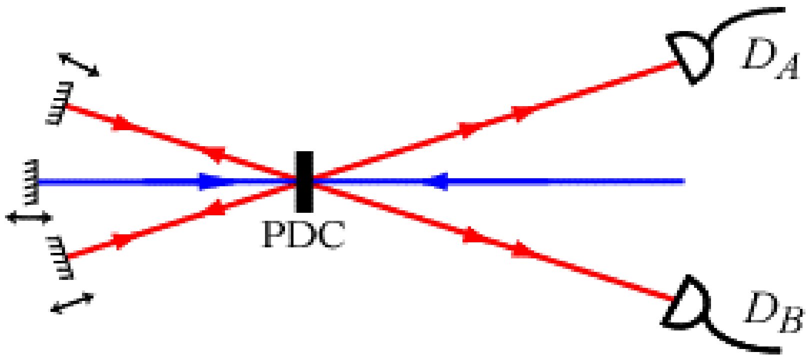
- **Induced Coherence (1991)**

Zou et al. PRL, 67, 318

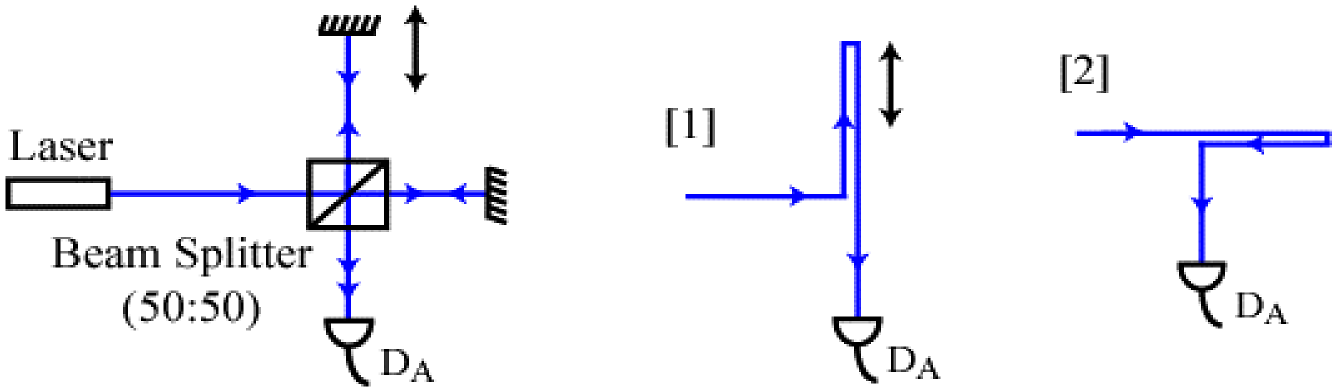


- **Frustrated two-photon creation (1994)**

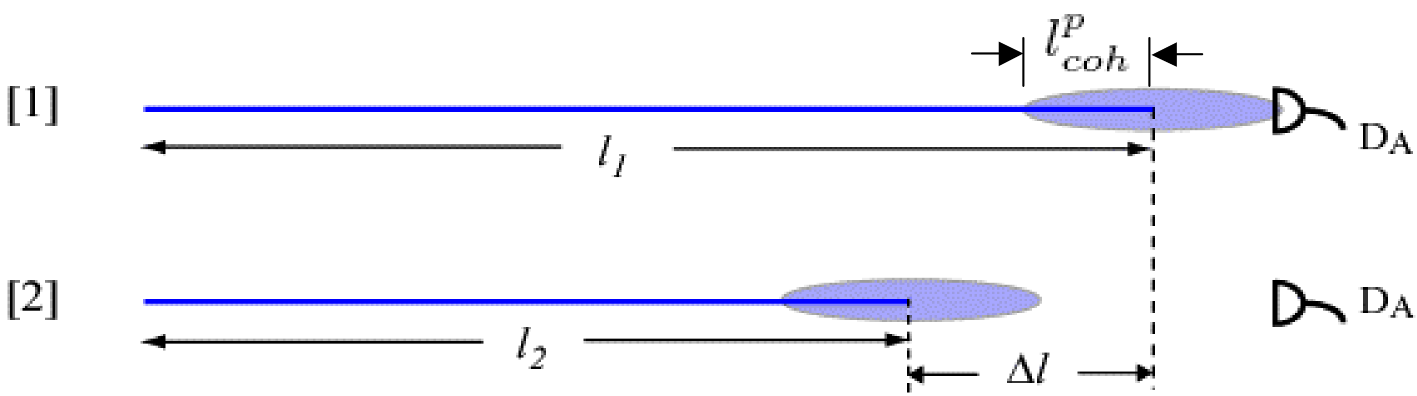
Herzog et al. PRL, 72, 629



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



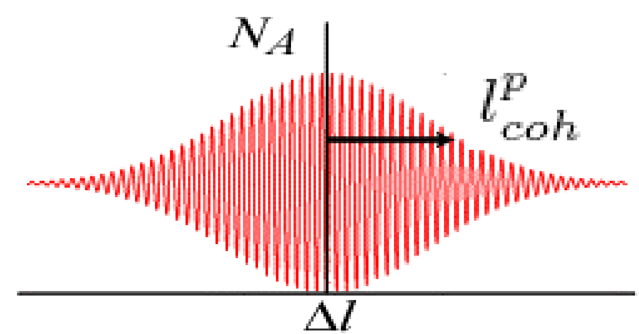
Add probability amplitudes for alternative pathways [1] and [2]



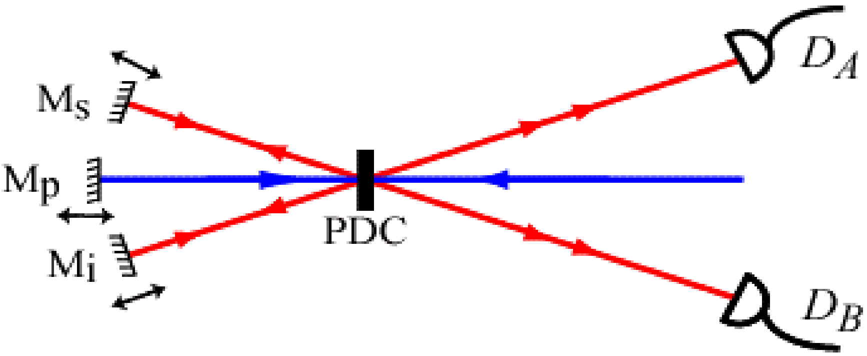
(unfolded paths)

Necessary condition for one-photon interference

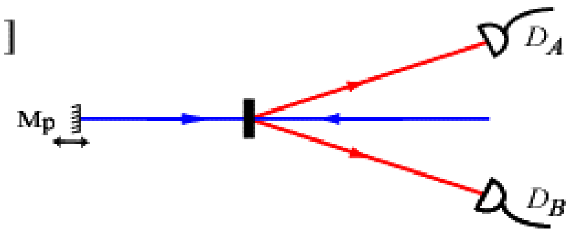
$$\Delta l \; < \; l^p_{coh}$$



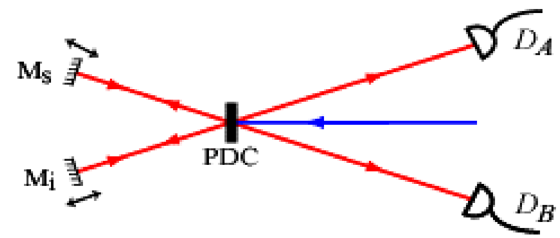
What about biphoton interference? (Generic setup)



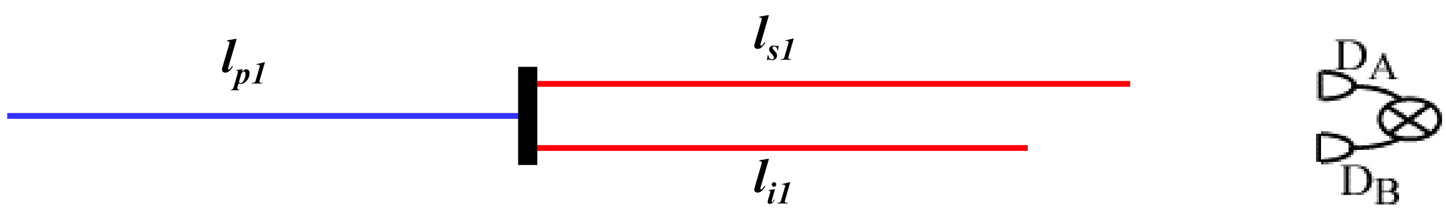
[1]



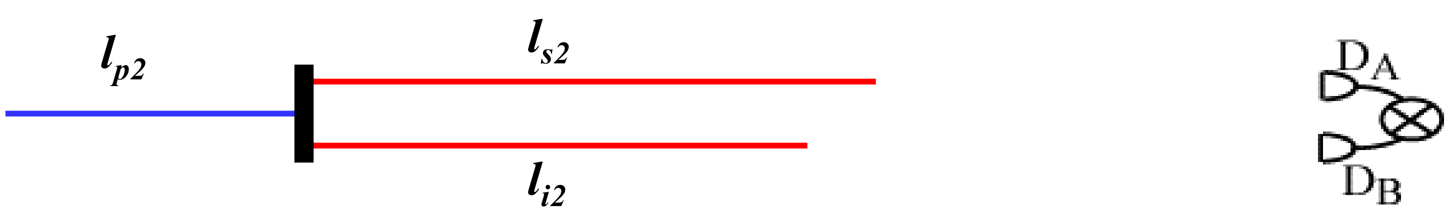
[2]



[1]

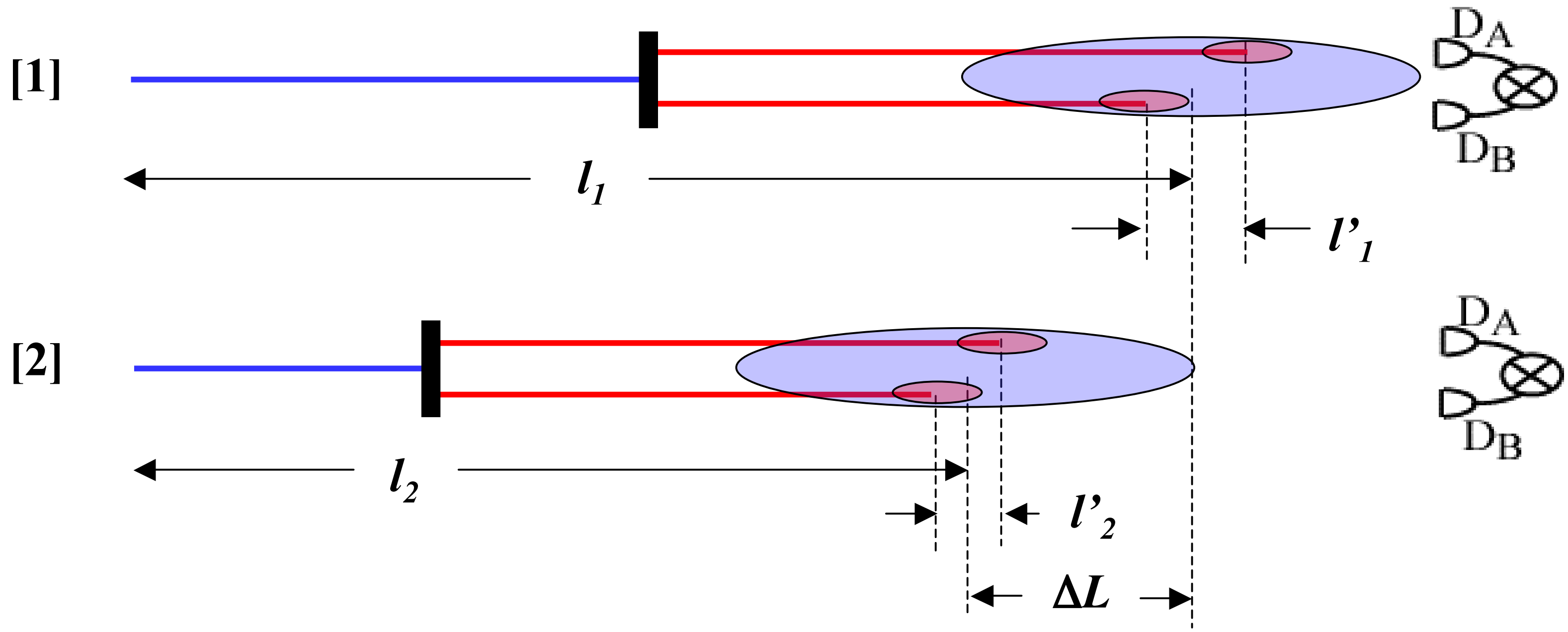


[2]



Probability amplitudes for pathways [1] and [2] add to produce interference.

Biphotons Can Interfere Only If They Are Indistinguishable



$\Delta L = l_1 - l_2$ ≡ **Biphoton path-length difference**

$\Delta L' = l'_1 - l'_2$ ≡ **Biphoton path-length asymmetry difference**

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

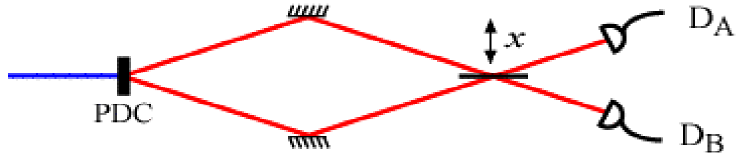
$$\gamma(\Delta L) = \exp\left[-\frac{1}{2}\left(\frac{\Delta L}{l^p_{coh}}\right)^2\right] \qquad \gamma'(\Delta L') = \exp\left[-\frac{1}{2}\left(\frac{\Delta L'}{l_{coh}}\right)^2\right]$$

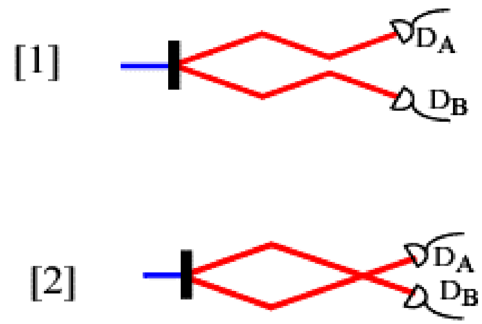
Conditions for two-photon interference:

$$\Delta L < l^p_{coh}$$

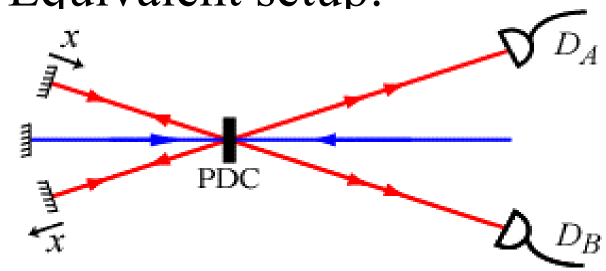
$$\Delta L' < l_{coh}$$

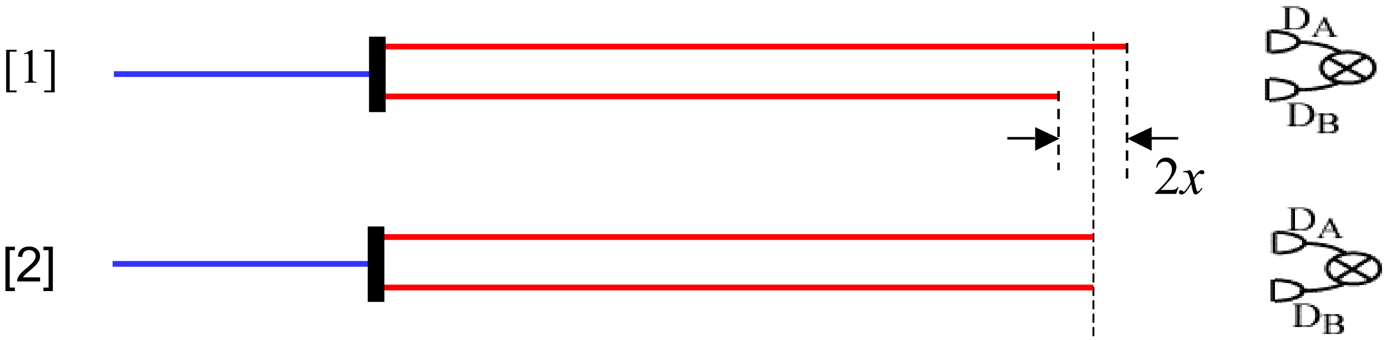
Hong-Ou-Mandel Experiment





Equivalent setup:

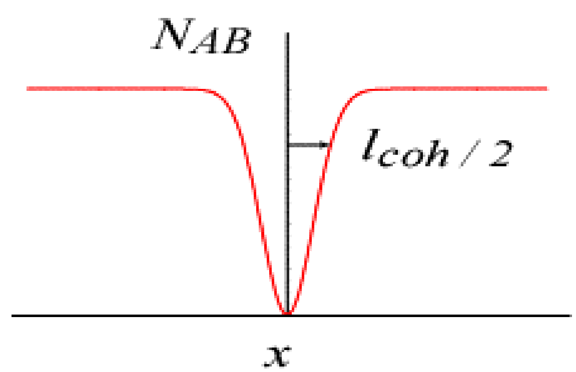




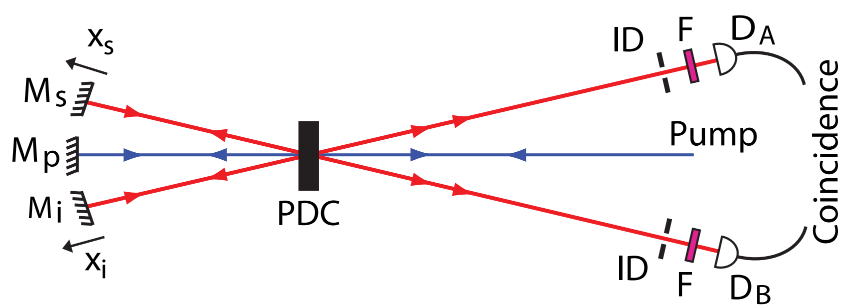
$\Delta L = 0 \qquad \Delta L' = 2x$

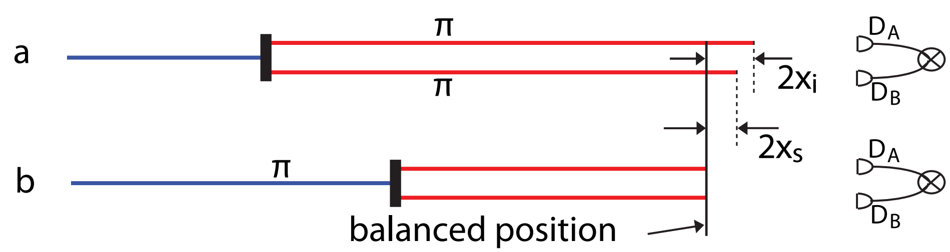
$$N_{AB} \propto \; 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

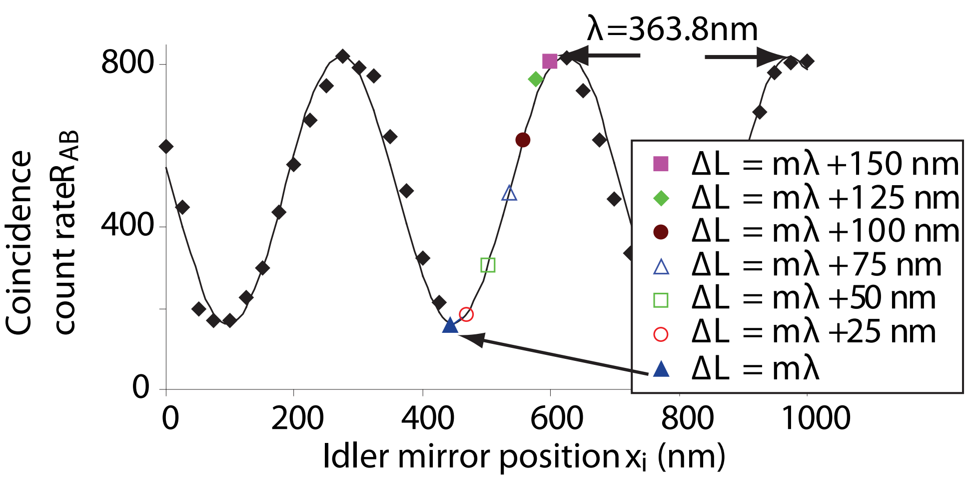
$$N_{AB} \propto \; 1 - \gamma'(2x)$$

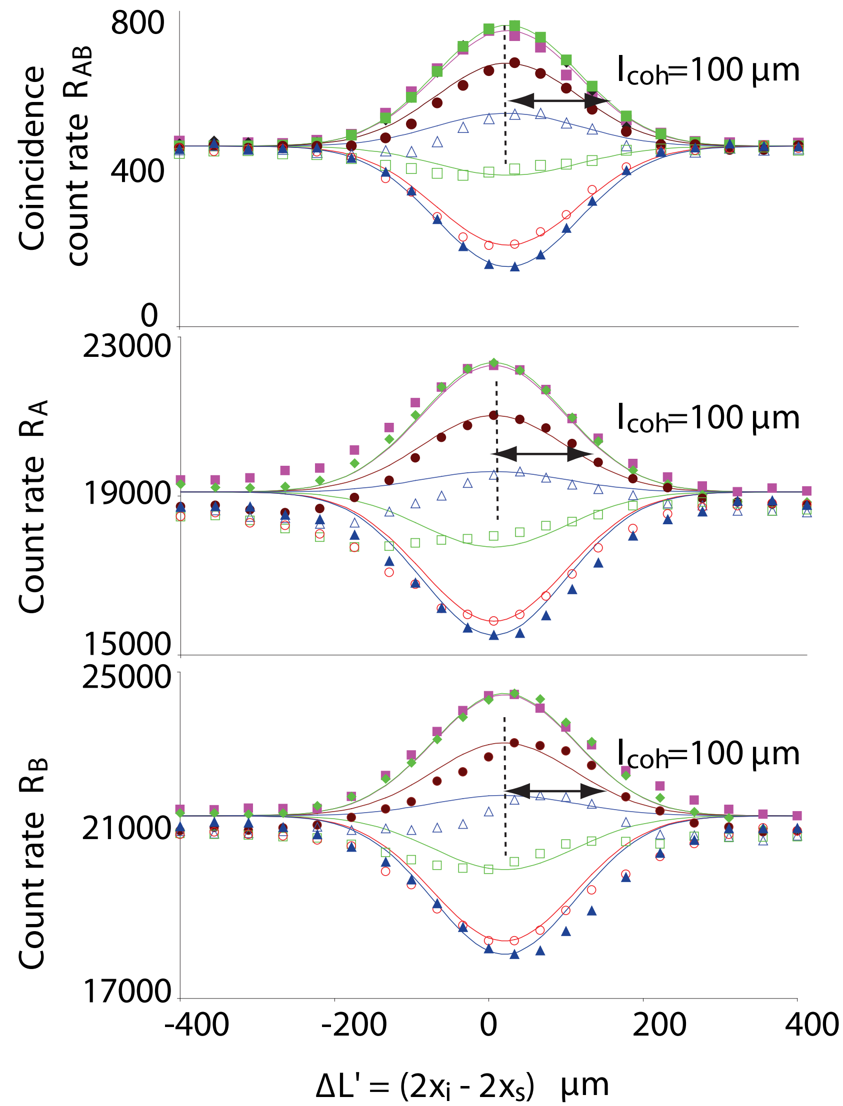


Our Experiment: Generalization of the Hong-Ou-Mandel Effect









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 $\Delta L'$.

Why is interference seen in single-detector count rate?

Path-length difference is much larger than single-photon coherence length; this is not conventional (Young's) interference!

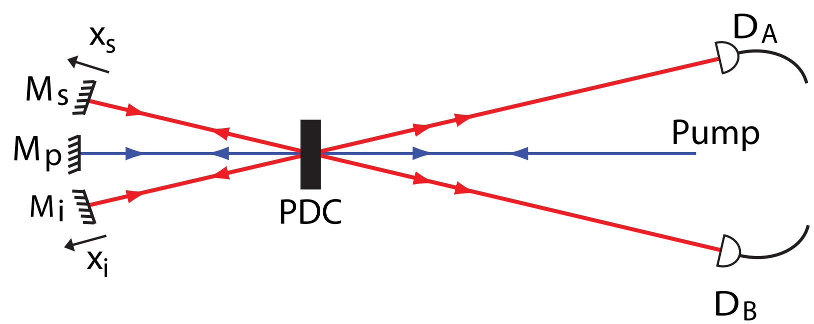
Note that: $$R_{\mathrm{X}} = \sum_i R_{\mathrm{XY}_i}$$

R_{X} = single detector count rate $\quad$ R_{XY_i} = coincidence count rate

But for our setup, the twin of the photon detected at A can end up only at B.

Thus:

$$R_{\mathrm{A}} = R_{\mathrm{AB}}$$

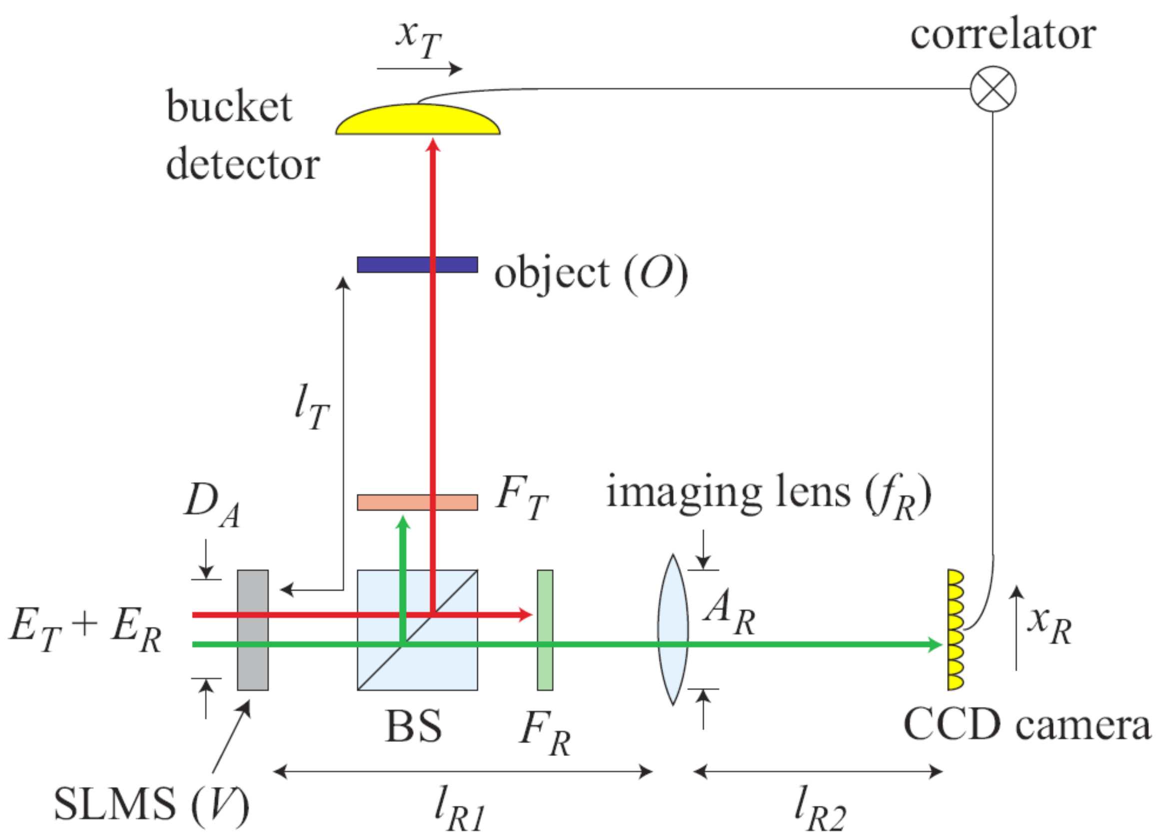


Work in Progress

Some very brief reports.

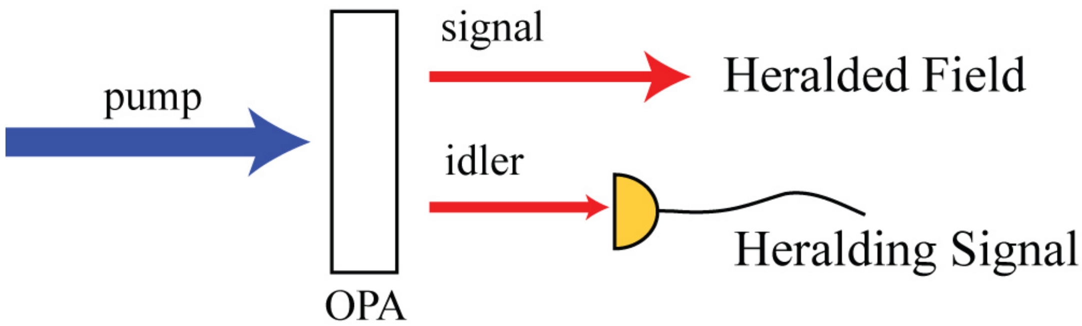
Two-Color Ghost Imaging

- Could be very useful to use different wavelengths in each arm.
- Fix wavelength used in object arm. How does resolution depend on wavelength of the CCD arm?



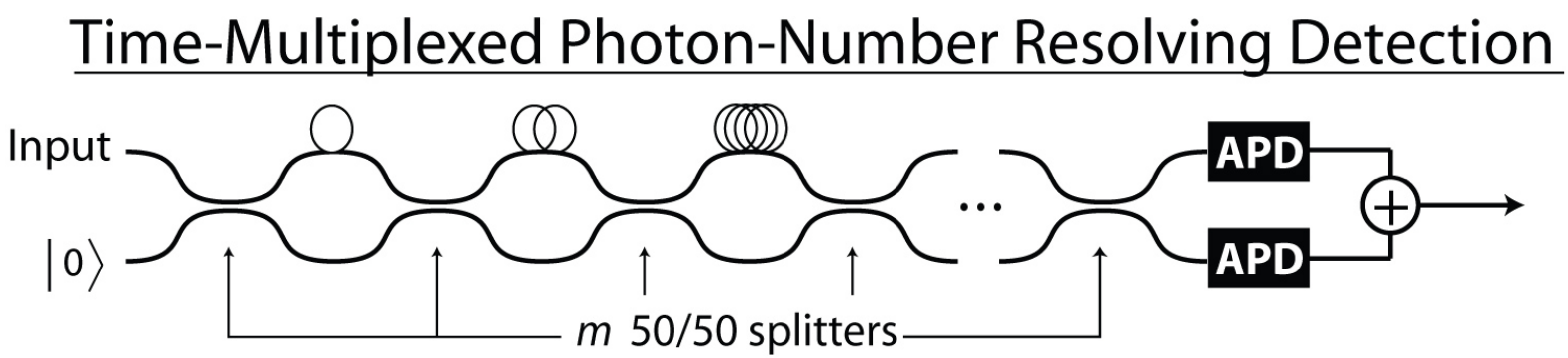
Heralded Photon-Number States

Scheme for producing heralded photon-number states



(Signal and idler contain same number of photons)

Need a photon-number-resolving detector for idler field.
One possibility:

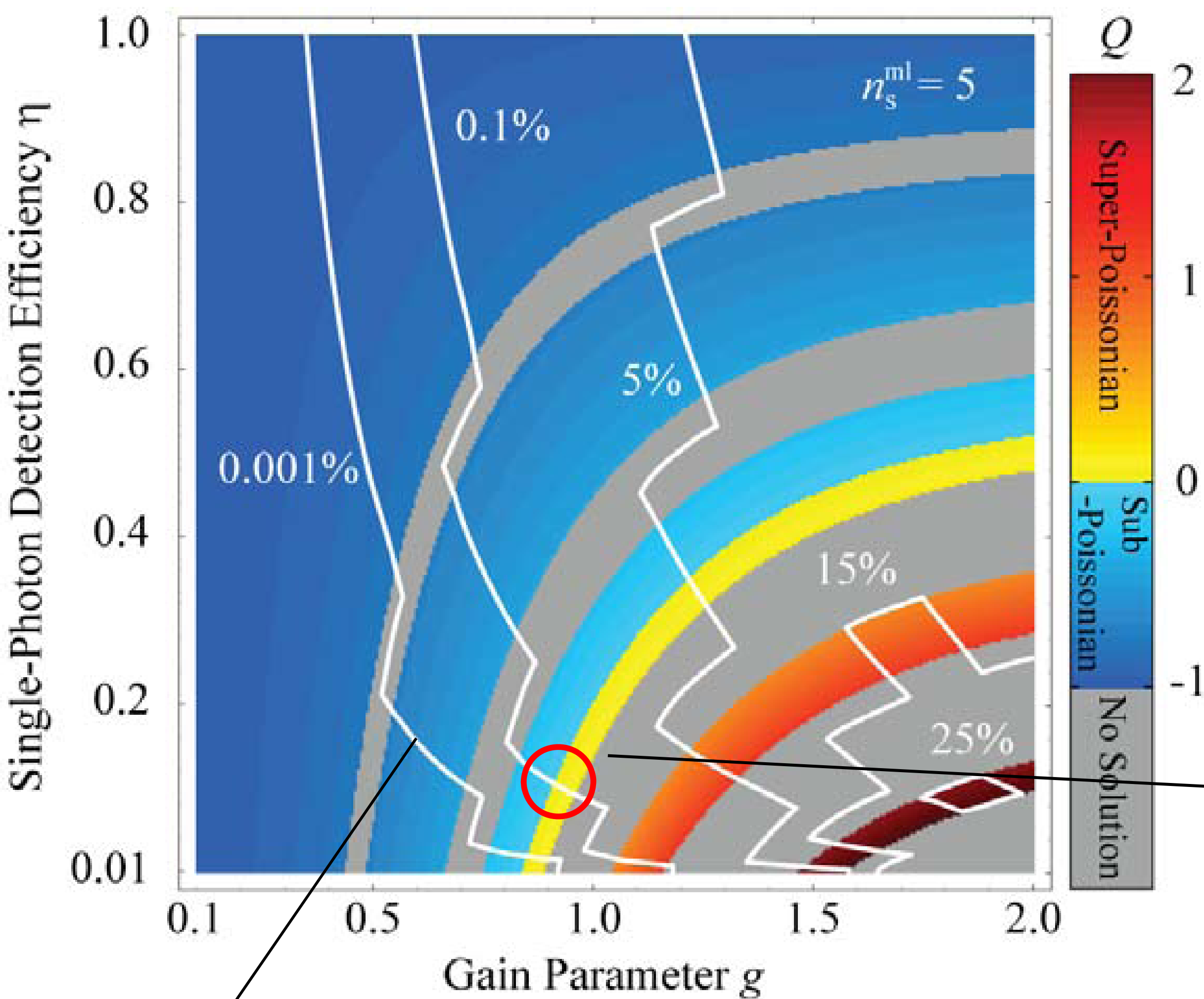


TMDs do not provide perfect photon-number-resolving capabilities (but are easy to implement in the lab) because of loss, etc.

Under what conditions will this method work?

Results

Using Bayes' theorem and *a priori* knowledge of the statistics of the OPA (characterized by gain *g*), we calculate the Mandel's *Q*-parameter to characterize the resulting heralded state for various detector parameters.



white lines – efficiency of creating the heralded state

Example

Create a 5-photon heralded state

Use a TMD with 5 beam splitters and detection efficiency η.

Trade-offs between purer Fock states and

- heralding efficiency (determined by *g*)
- TMD detection efficiency η

But, for detector efficiency as low as η ~ 10%, sub-Poissionian states can be created with reasonable efficiency.

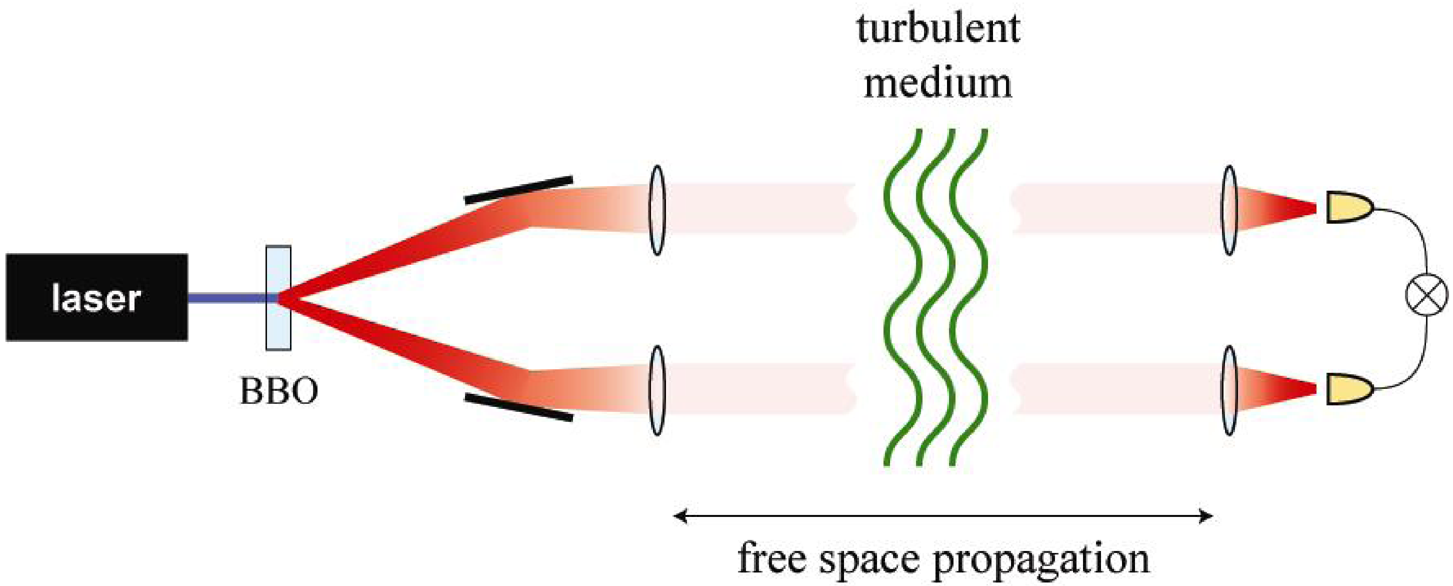
O'Sullivan et al., Phys. Rev. A (2008)

Propagation of Entanglement

How do entanglement and other quantum correlations become modified as light propagates?

– changes occur even for free-space propagation because of diffraction effects (entanglement migration; Chan and Eberly)

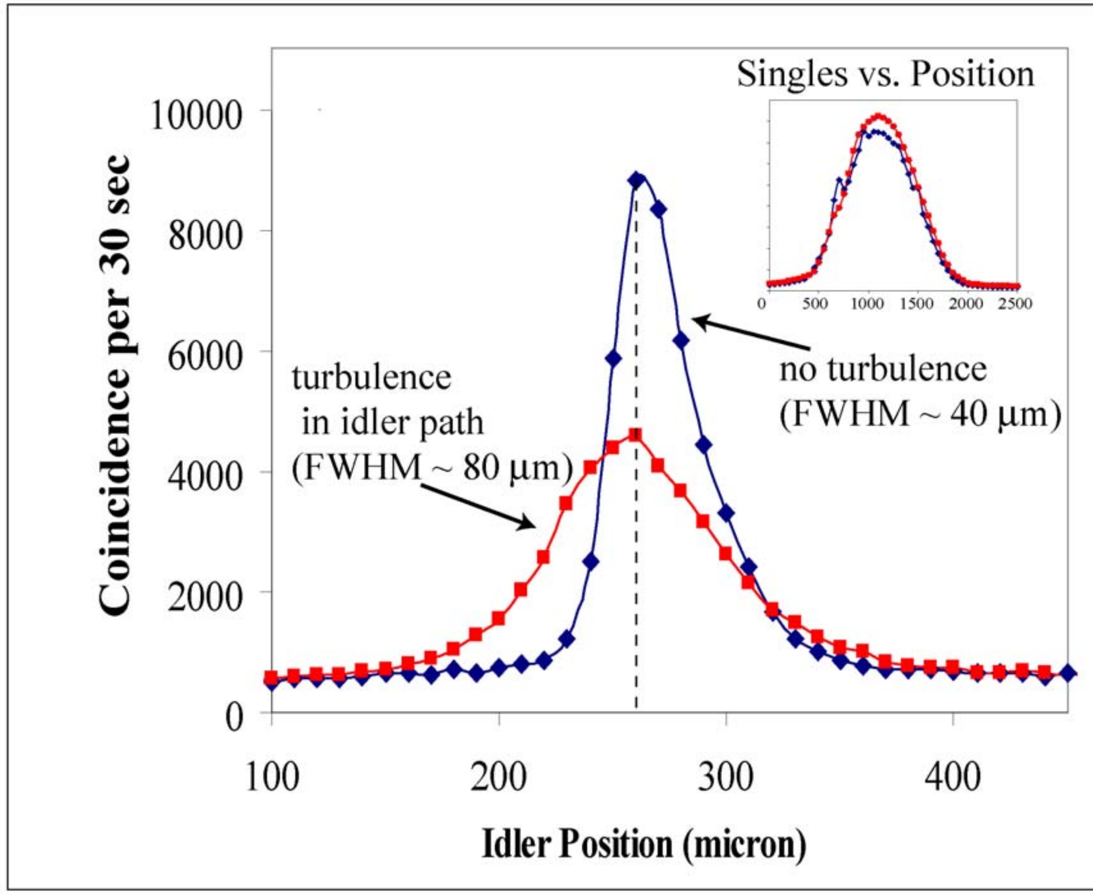
– more pronounced changes occur for propagation through atmospheric turbulence (Paterson)

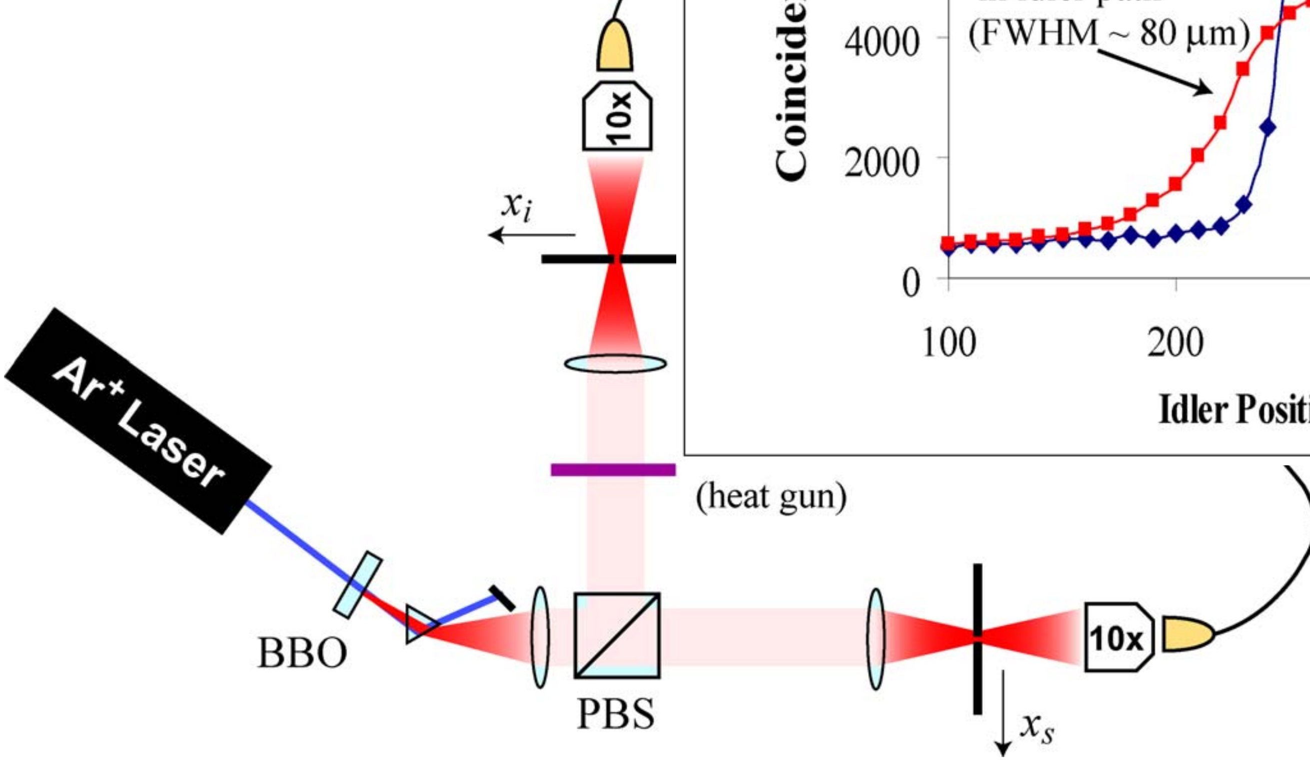


Preliminary Results

Turbulence medium:

- ✓ ❑ heat gun
  (easy to implement)
- ❑ Kolmogorov phase screen
  (quantitative degree of turbulence)

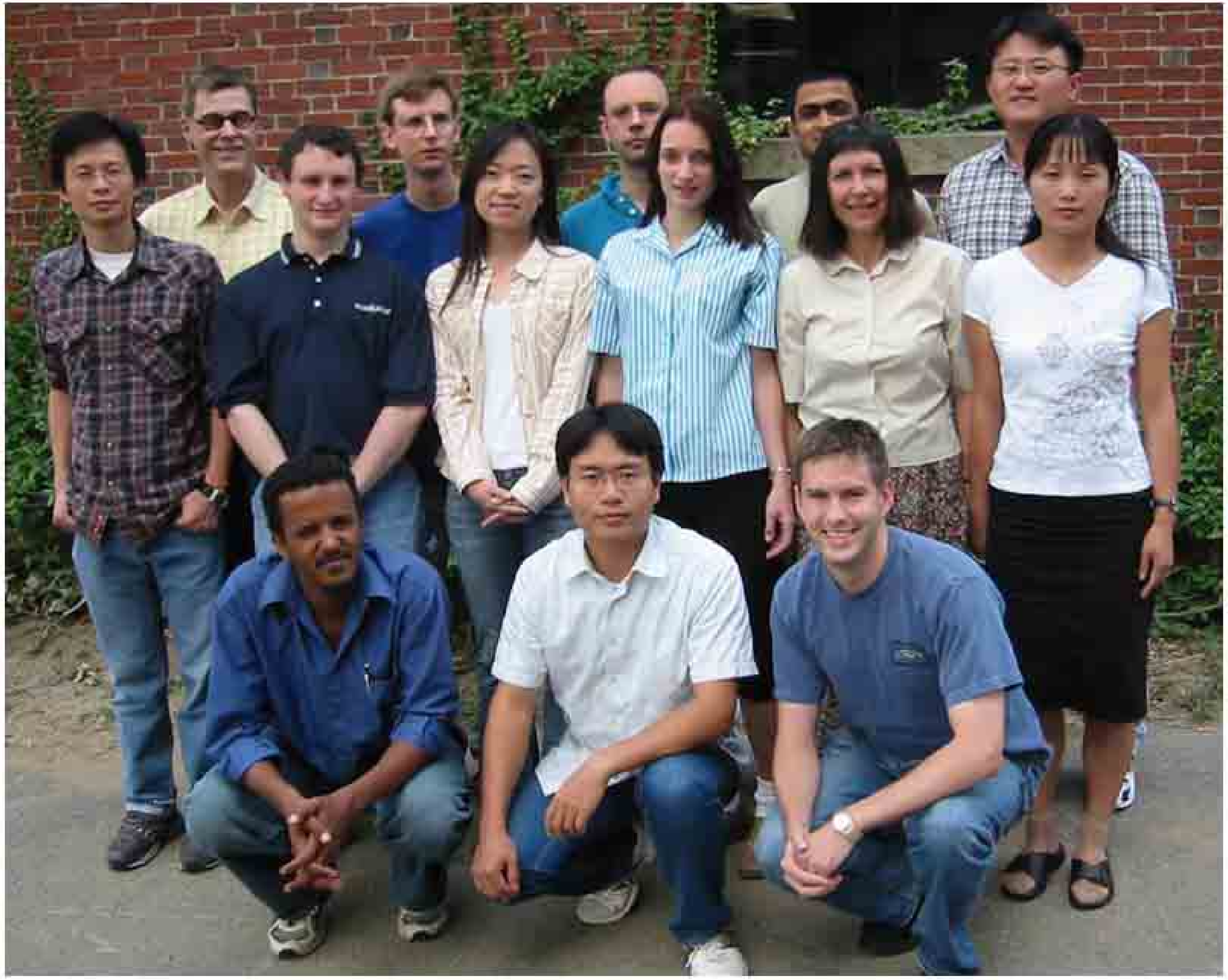




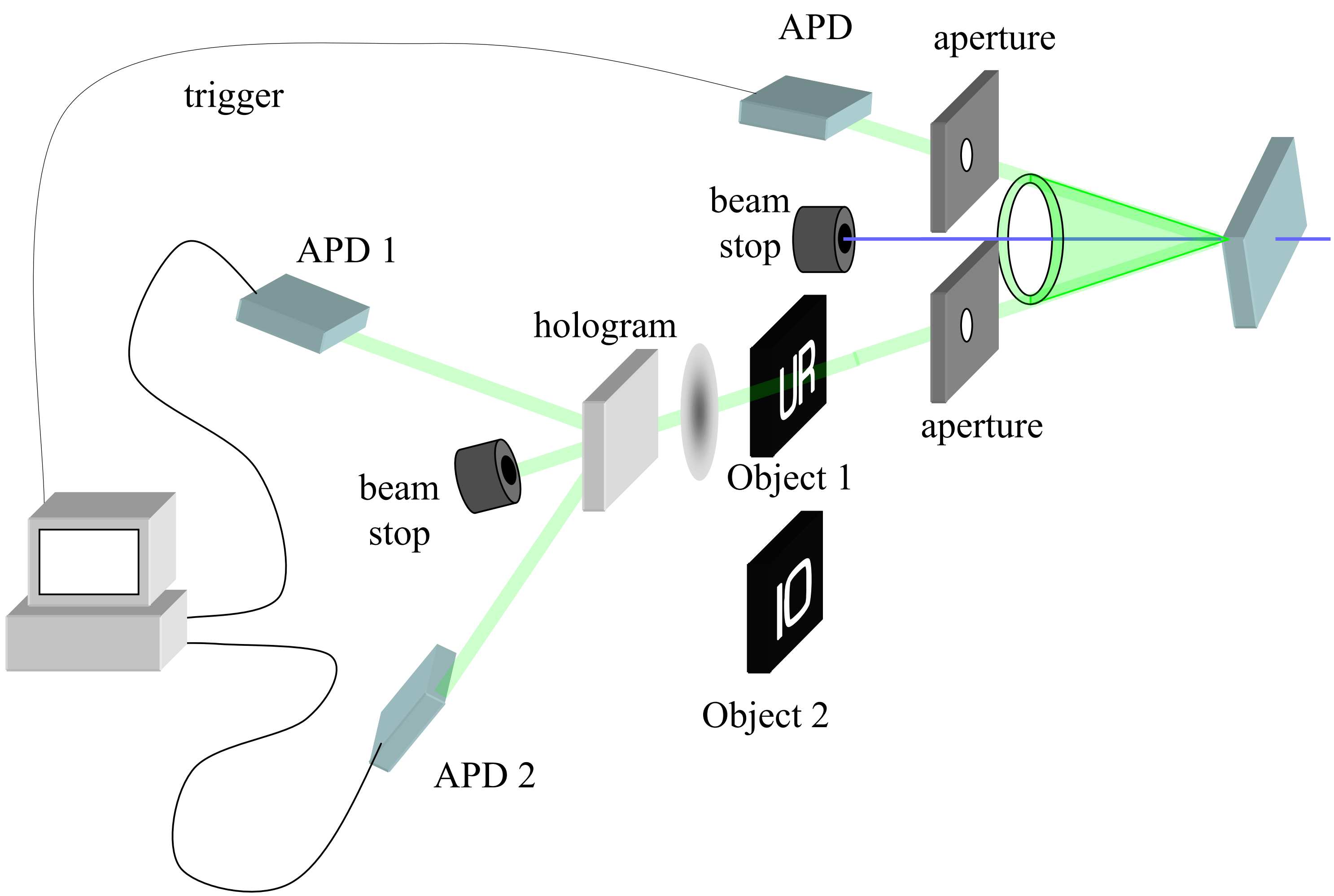
Propagation of Entanglement

- A Movie!

Special Thanks to My Students and Research Associates



Next step: use heralded single photons



Possible Applications:

Automatic traget recognition at the single photon level

"Dense coding" of quantum information

Physics is all about asking the right questions

Just ask

Evelyn **Hu**

Watt Webb (or James **Watt**)

Michael **Ware**

Wen I Wang

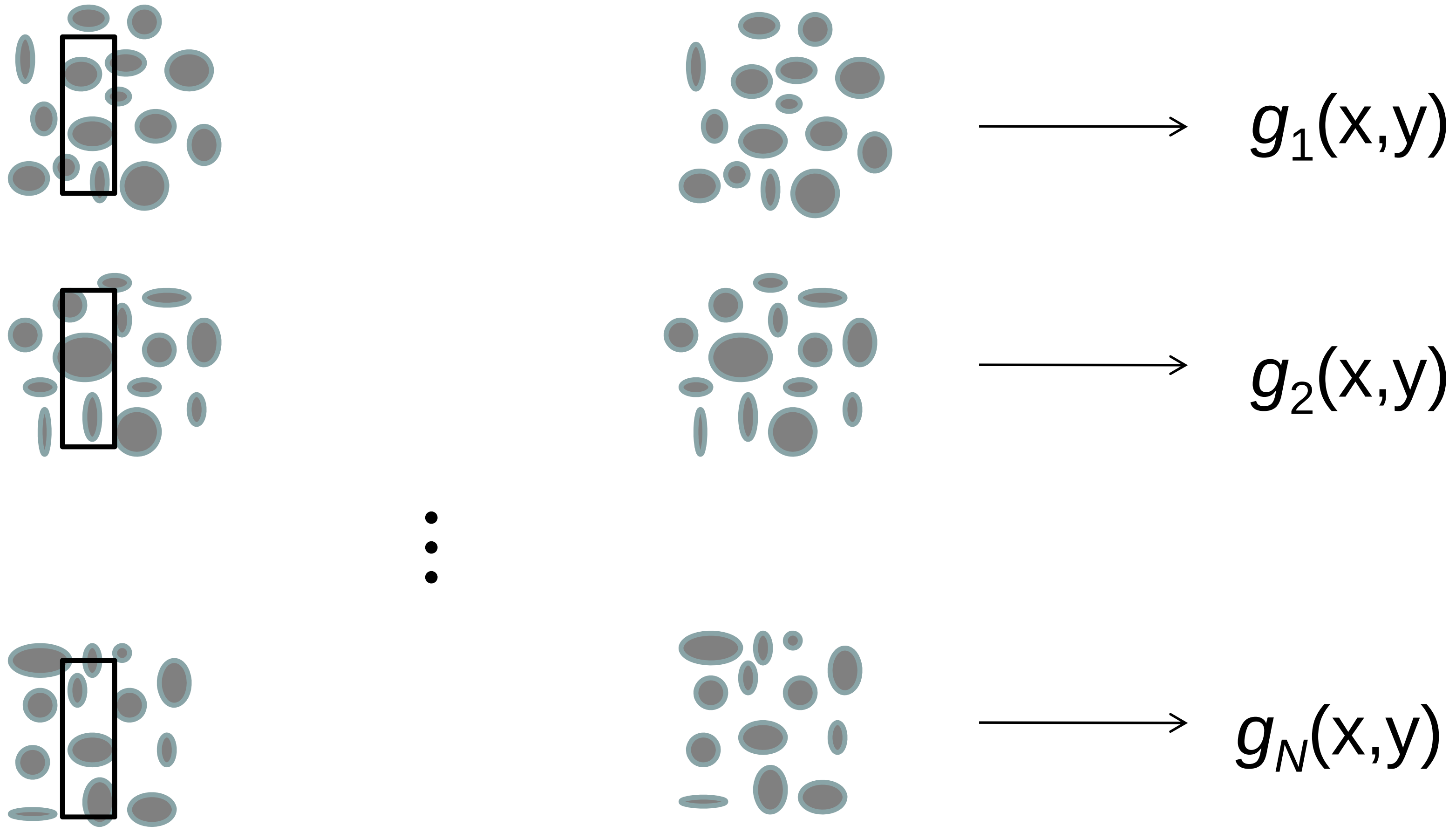
Kam **Wai** Chan

Not to mention

Lene **Hau**

Thermal Ghost Imaging

object plane image plane

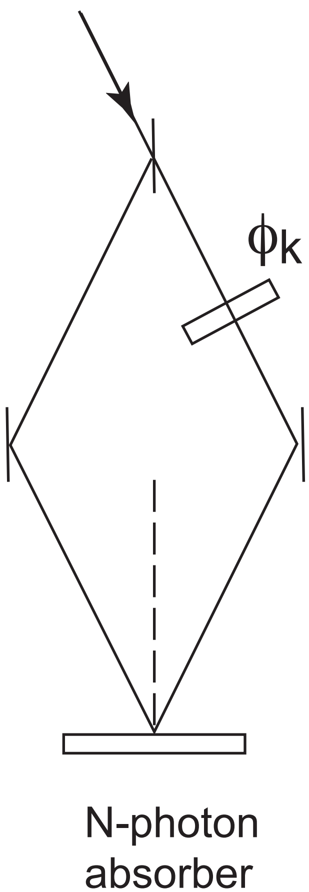


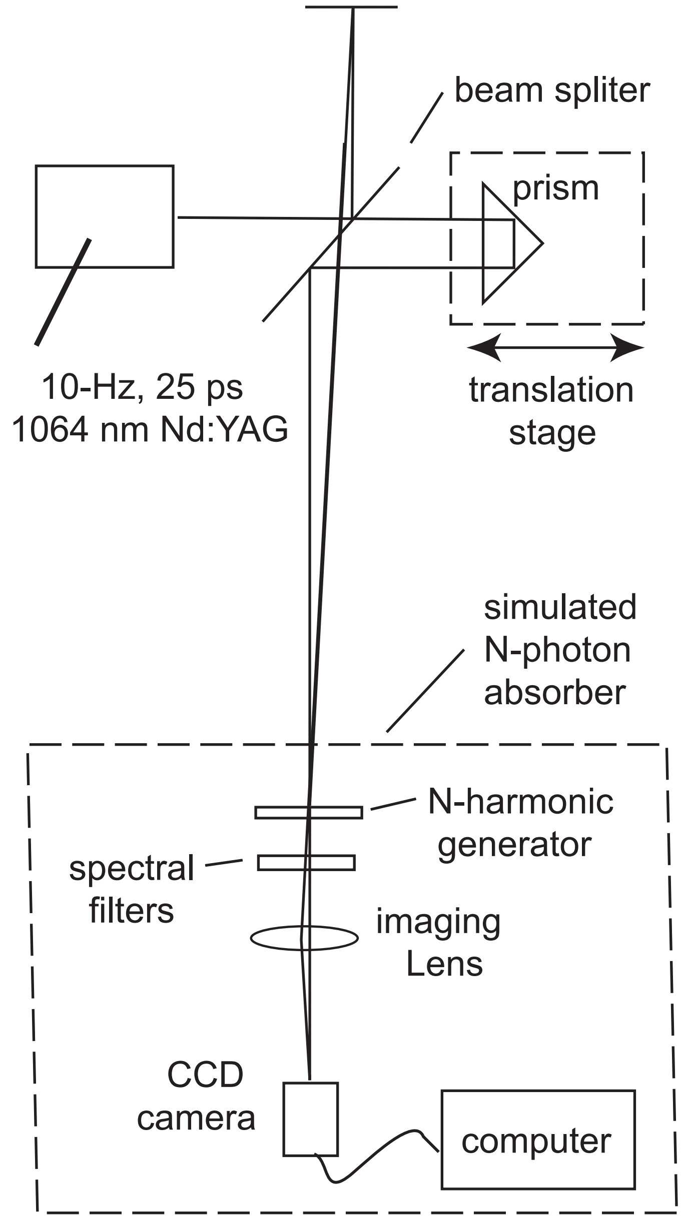
$$\text{Image} = \Sigma\, g_i /N = T(x,y) \langle I^2 \rangle + \alpha \langle I \rangle^2$$

The Institute of Optics
Nonlinear Optics
University of Rochester

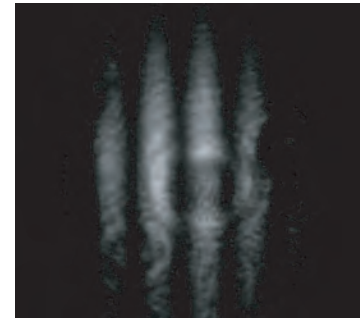
Classically Simulated (Non-Quantum) Quantum Lithography

Concept: average M shots with the phase of shot k given by $2\pi k/M$

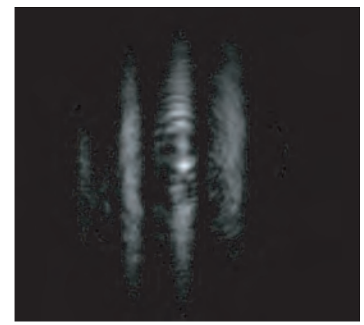




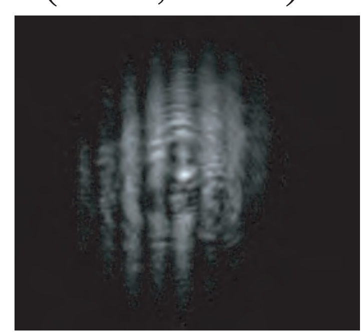
One-photon absorber (N=1, M=1)



Two-photon absorber (N=2, M=1)



Two-photon absorber two exposures (N=2, M=2)



S. J. Bentley and R.W. Boyd, Optics Express, 12, 5735 (2004).