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, and Mehul Malik

Presented at the Australian National University, July 5, 2007.

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.

Outline for this presentation

- Review of quantum imaging
- Coherence and Indistinguishability in two-photon interference

Quantum Imaging MURI

Major US Initiative in Quantum Imaging

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

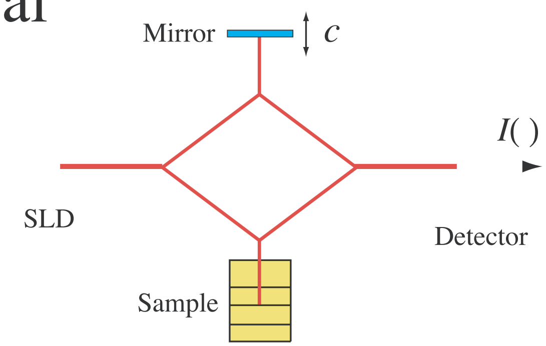
- Quantum Optical Coherence Tomography (QOCT).
- Quantum Coincidence (or Ghost) Imaging.
- Quantum Laser Radar.
- Quantum Lithography.

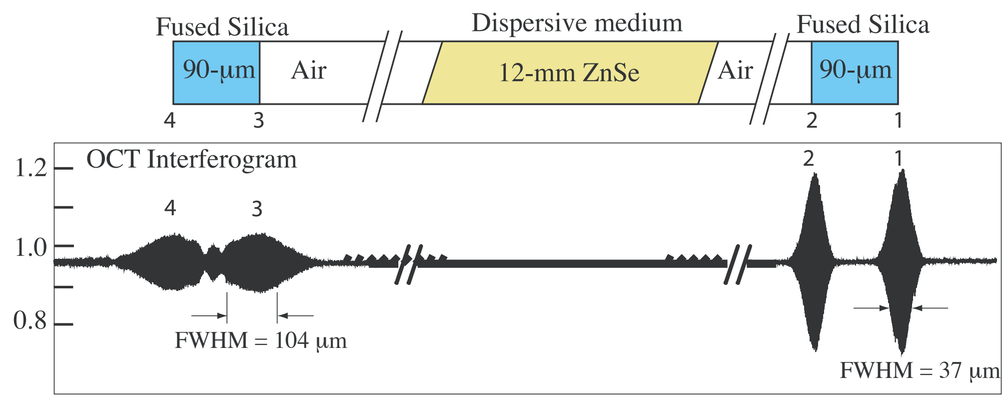
Quantum Imaging Technologies

- 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.

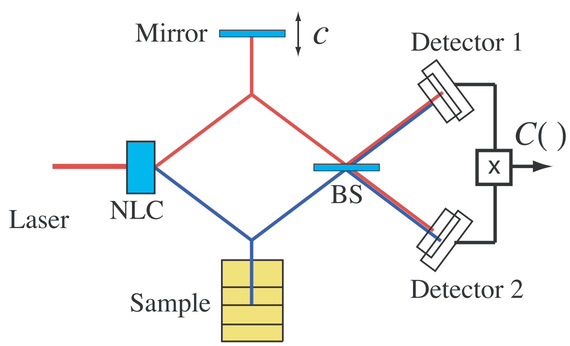
Quantum Optical Coherence Tomography

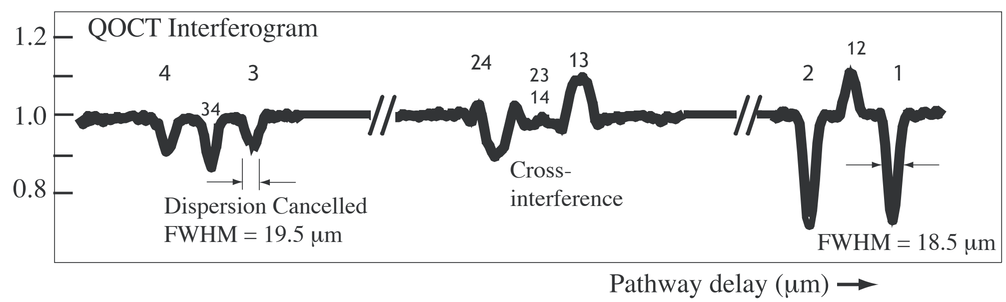
Classical





Quantum





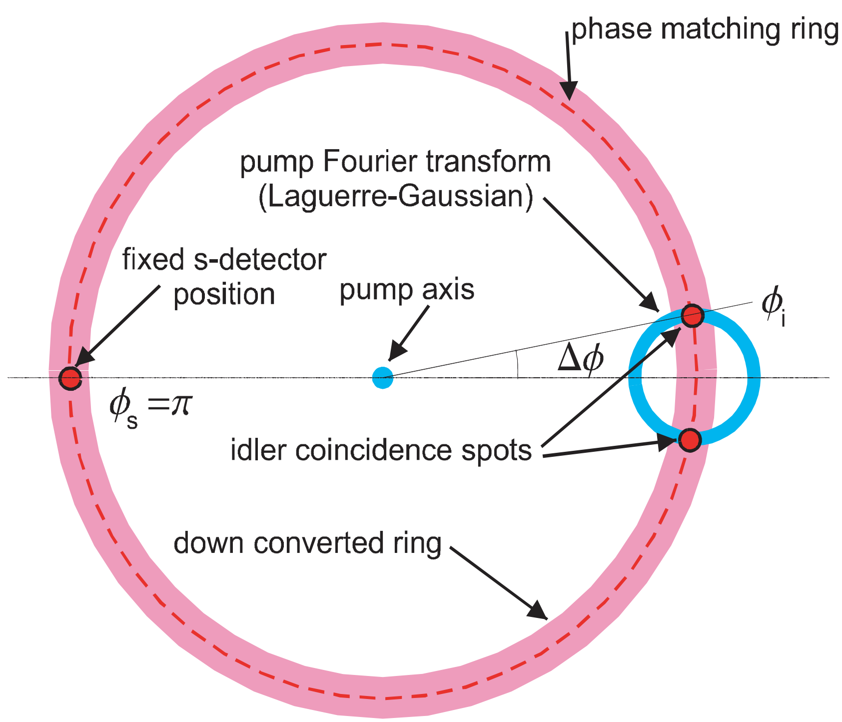
Quantum OCT offers three advantages over classical:

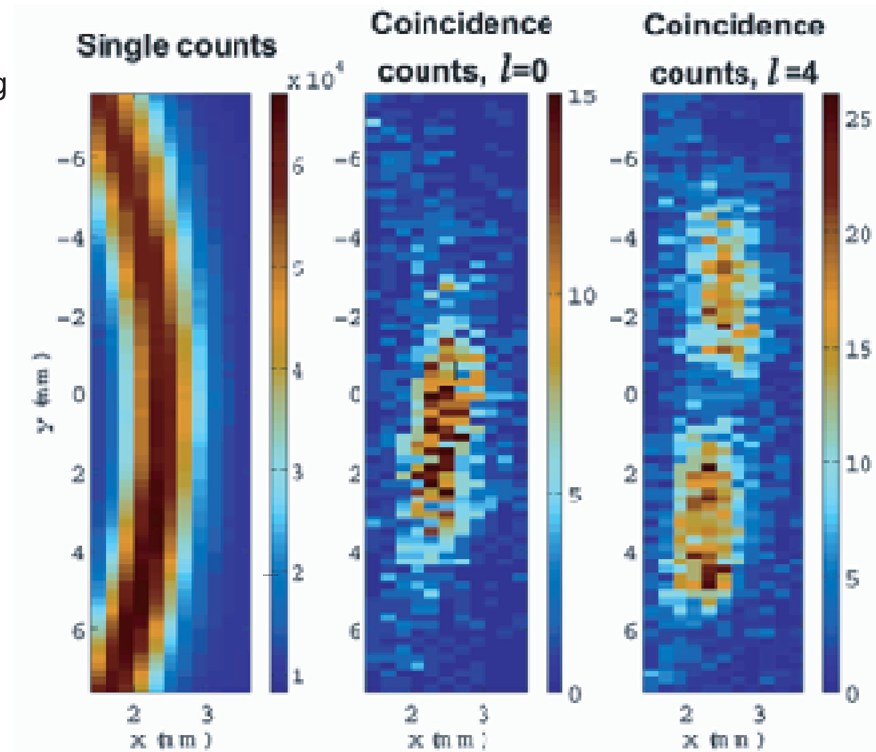
- Factor-of-two better spatial resolution
- Dispersion cancellation
- Cross-interference provides additional information

Boston University

Nasr, Saleh, Sergienko, and Teich, PRL 91 083601 (2003)

Nonlocal Quantum Spatial Correlations Induced by Pump Beams Carrying Orbital Angular Momentum





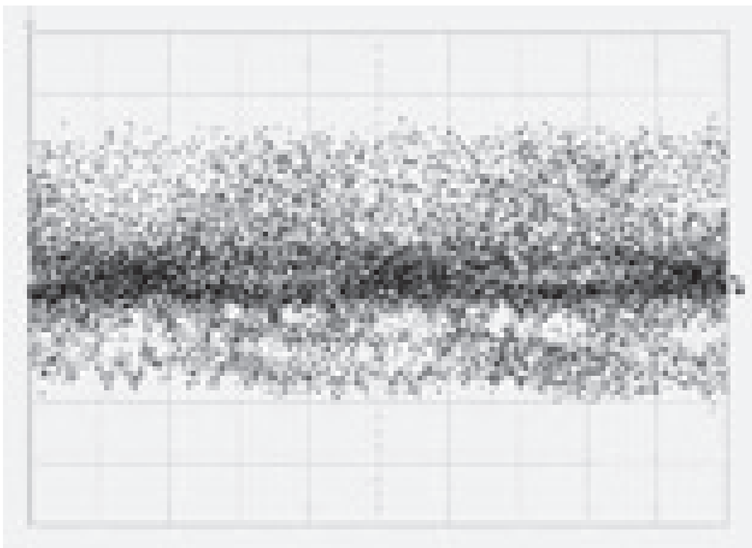
- Image information encoded on pump beam leads to quantum correlations in the down-converted photons.
- Demonstrates entanglement of orbital angular momentum.

NWU

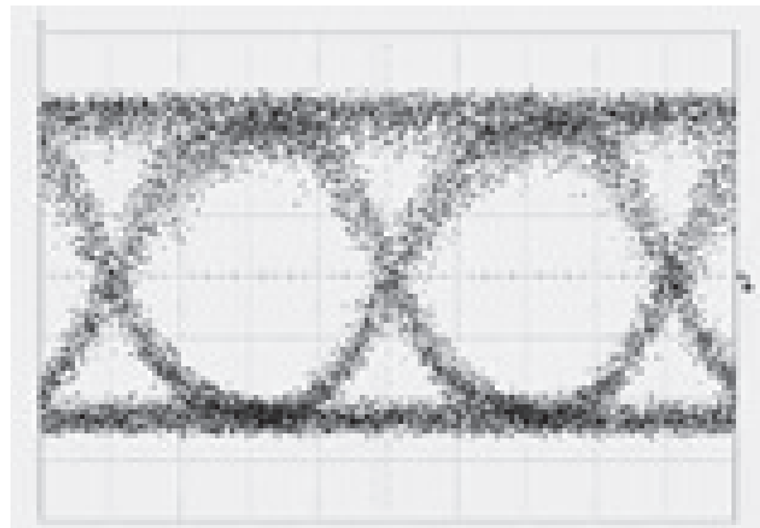
Altman, Kumar, Barbosa, et al., PRL 94 123601 (2005).

Quantum Laser Radar

Primary goal is to use noiseless preamplification (phase sensitive amplification) to increase senstivity of laser radar.



phase-insensitive amplification



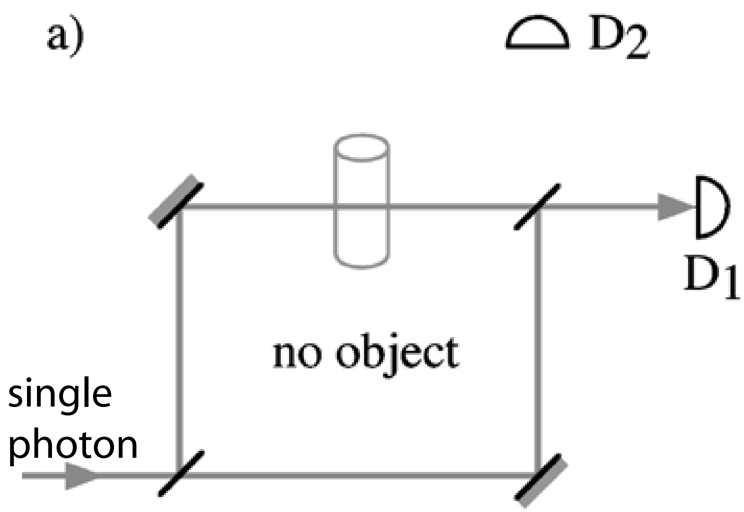
phase-sensitive amplification

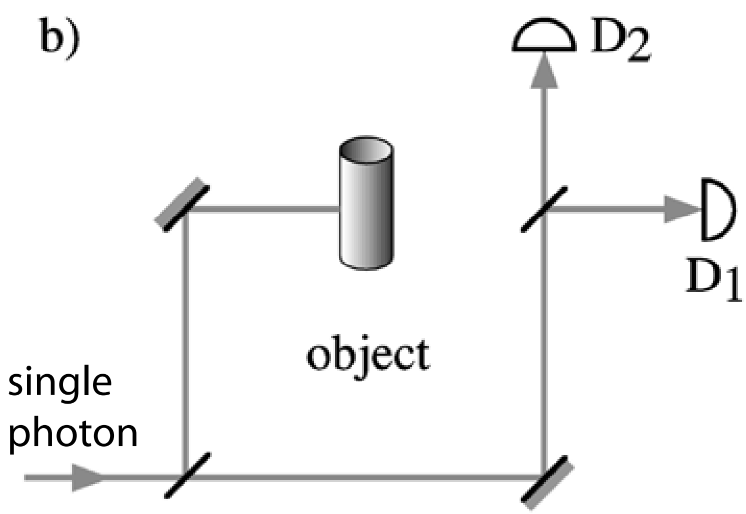
Kumar (Northwestern) and Shapiro (MIT)

Stealth Imaging

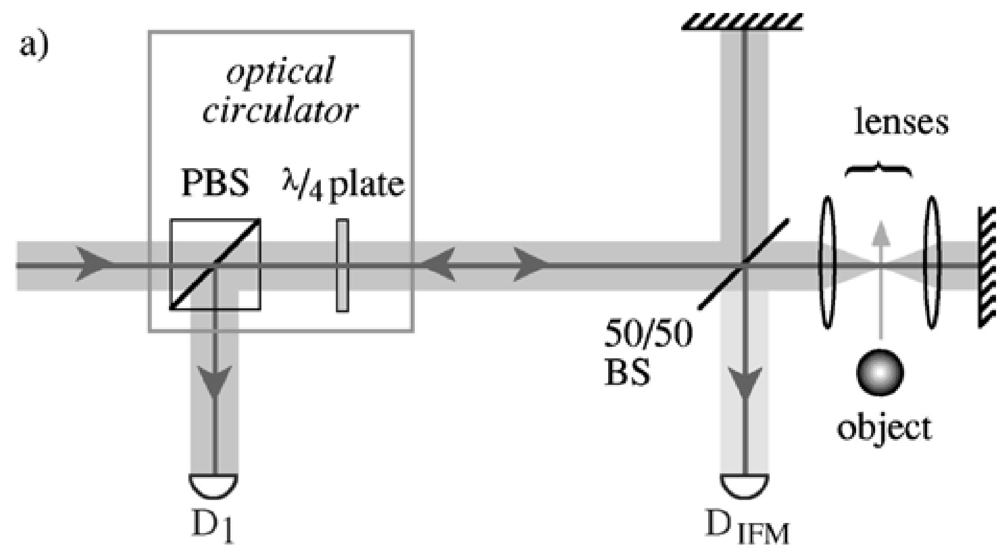
Interaction-Free Imaging and Ghost Imaging

Quantum Imaging by Interaction-Free Measurement



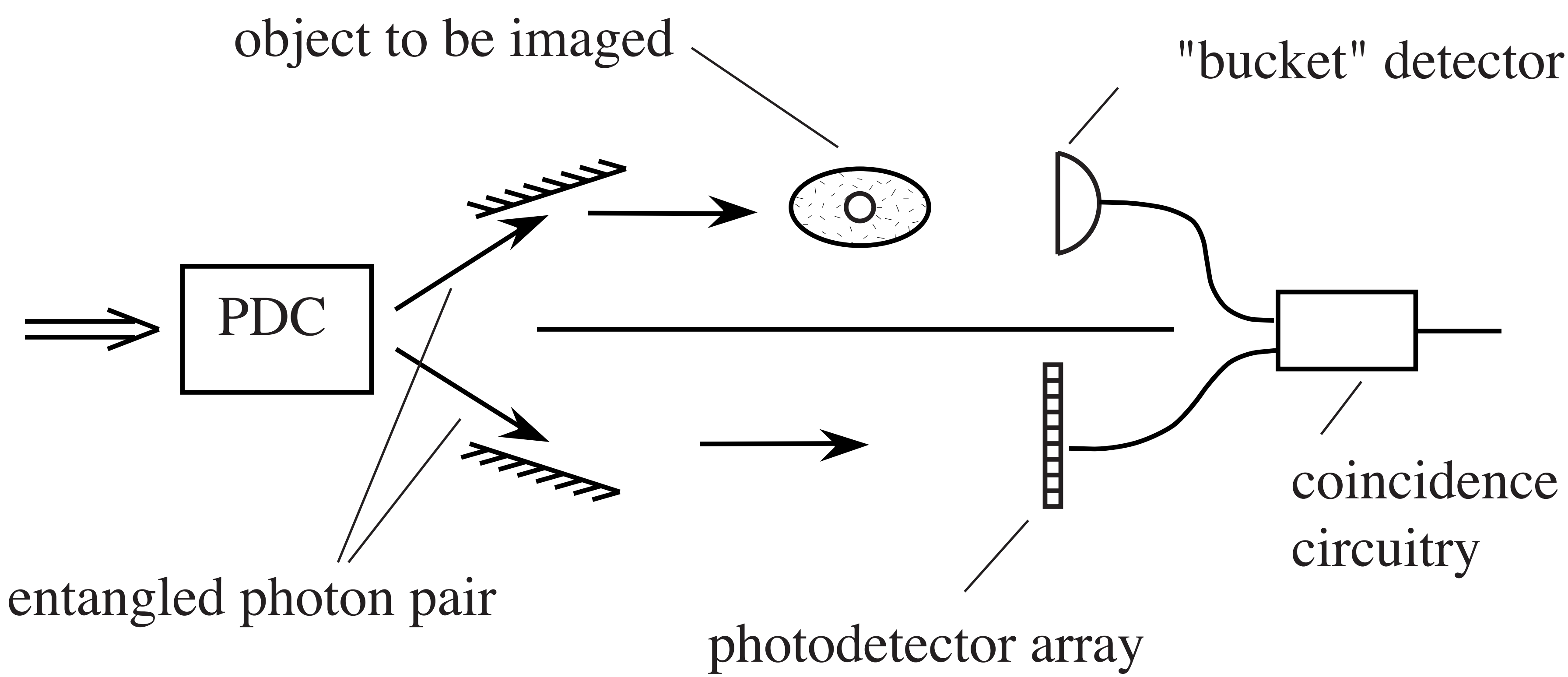


imaging setup



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

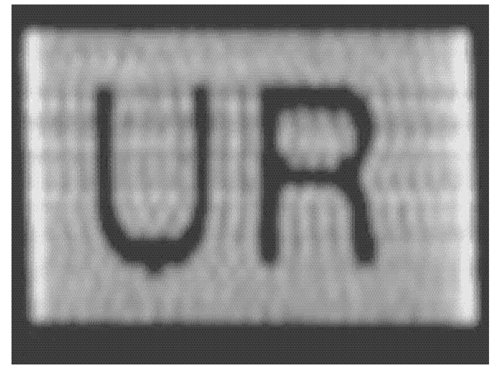


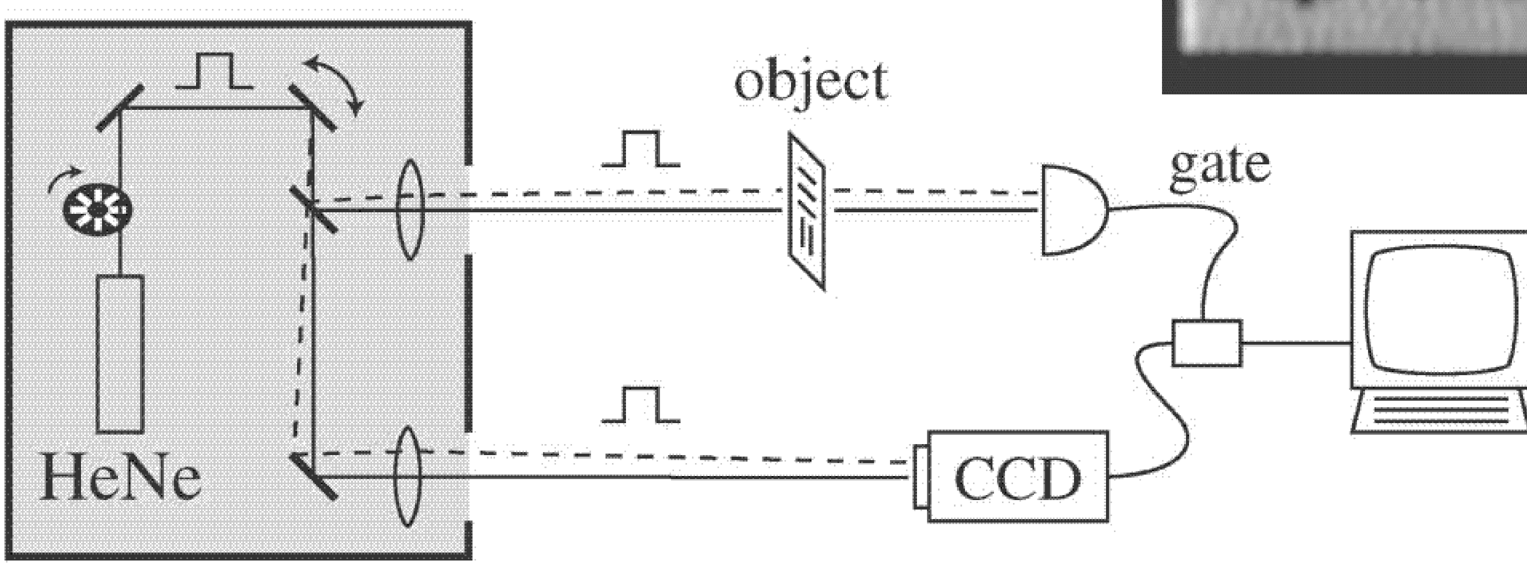
- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process?

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

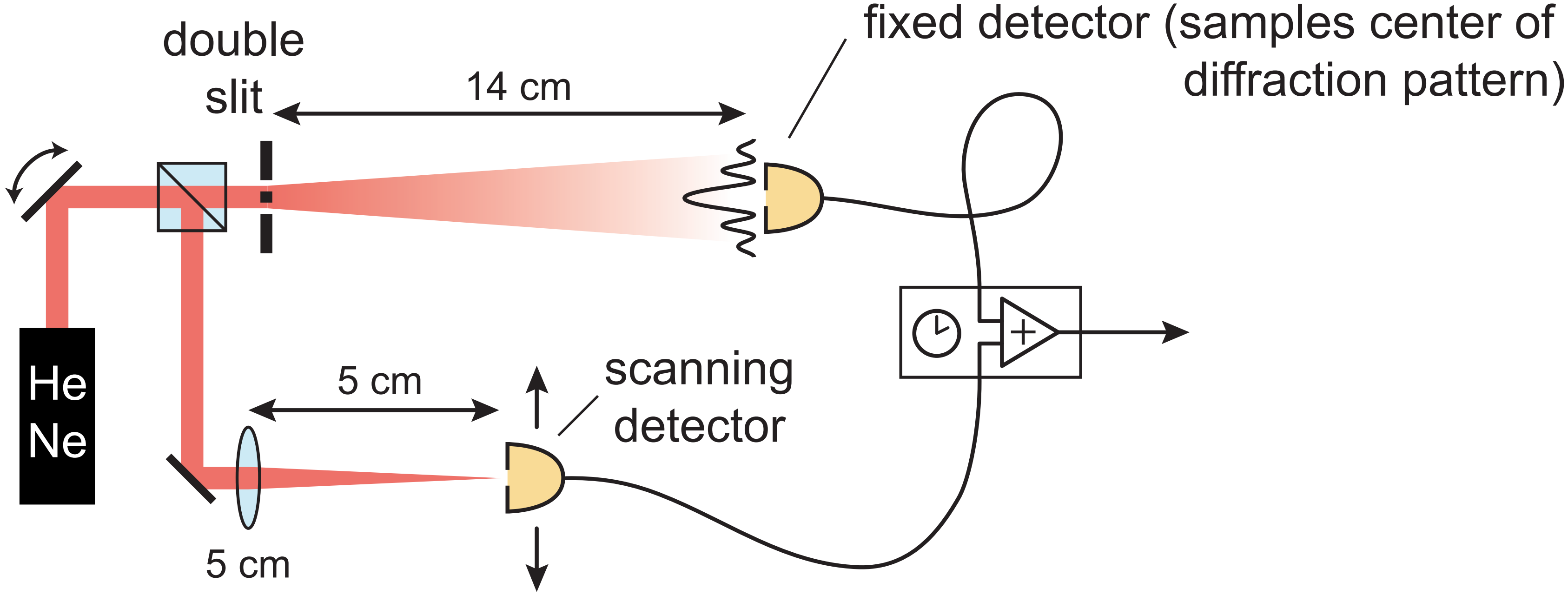
We have performed coincidence imaging with a demonstrably classical source.



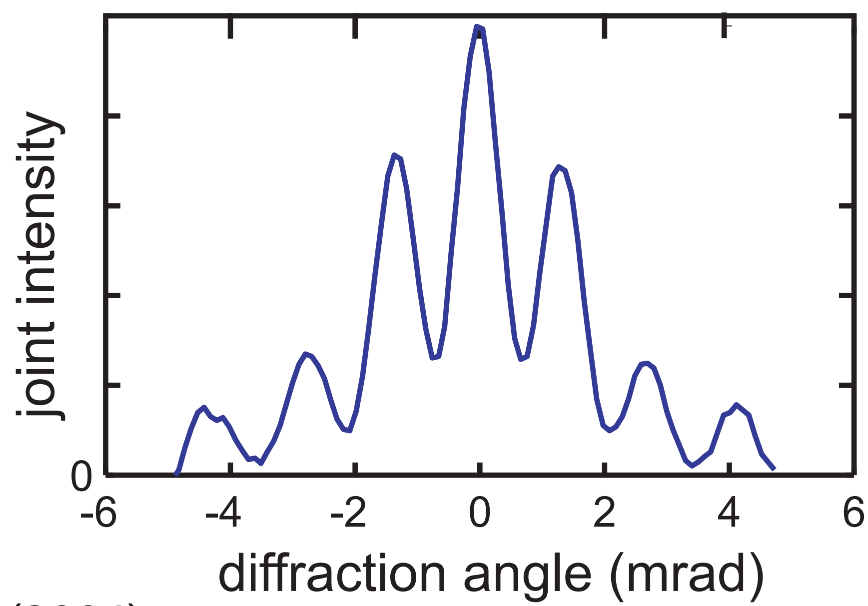


Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601 (2002).

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

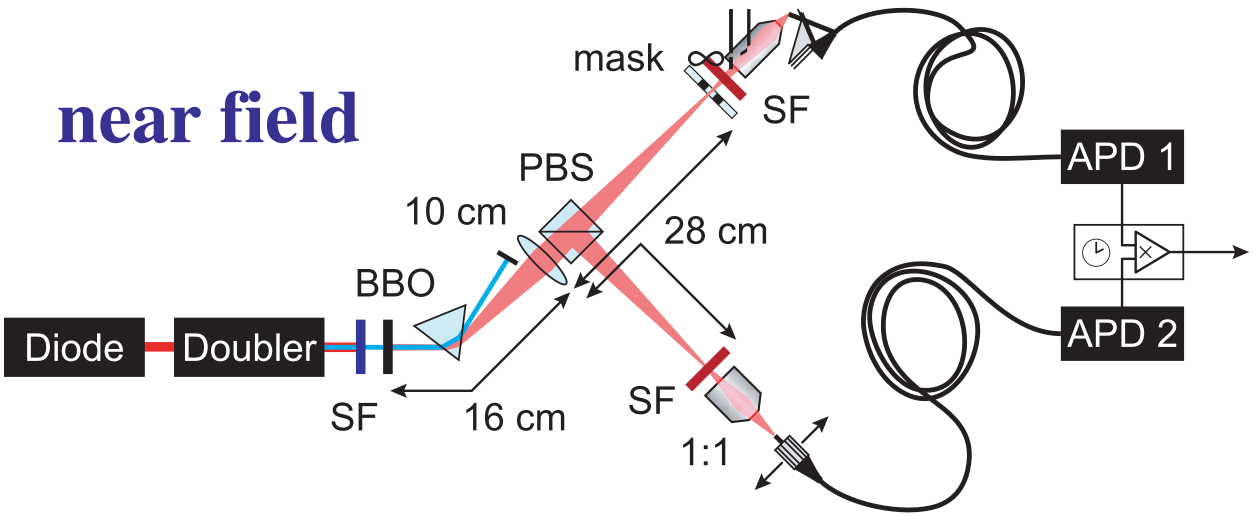
(Received 11 October 2002; published 3 April 2003)

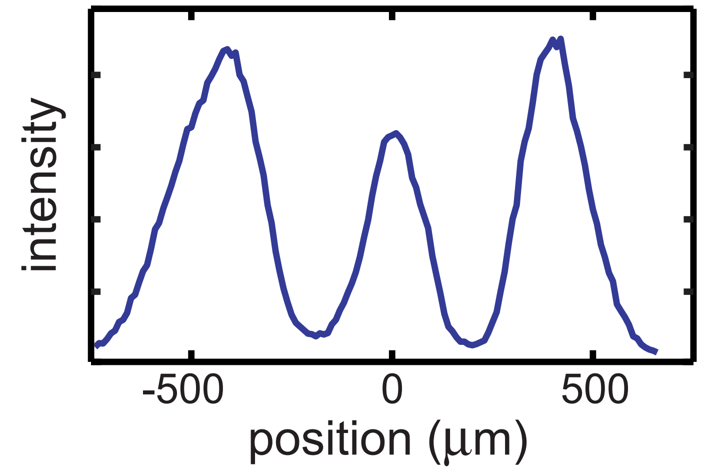
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. 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

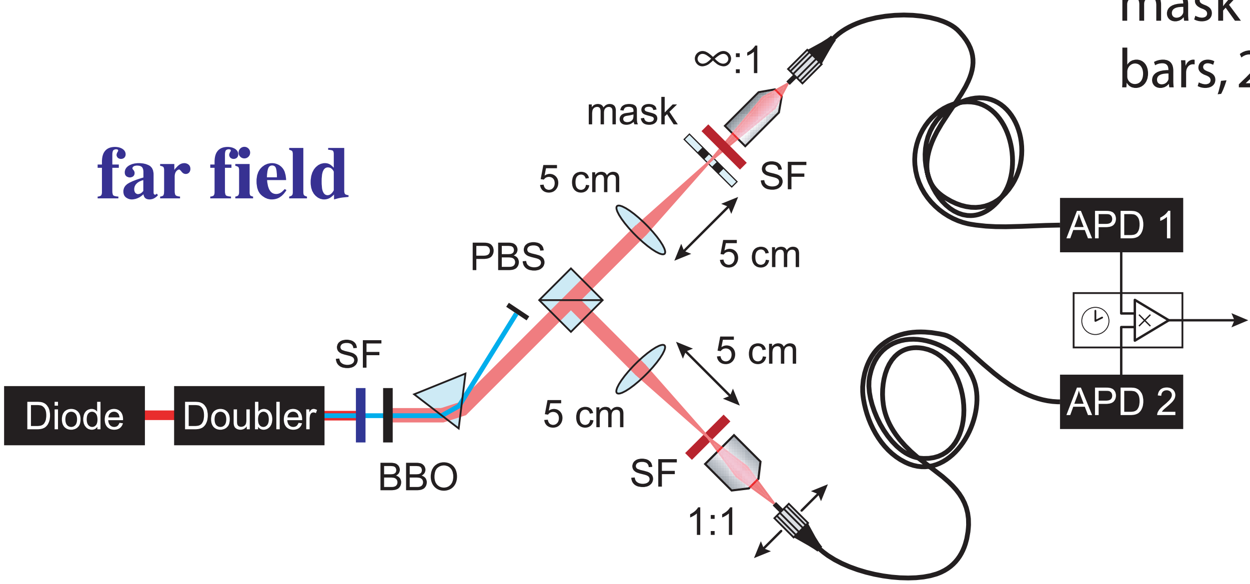
near field

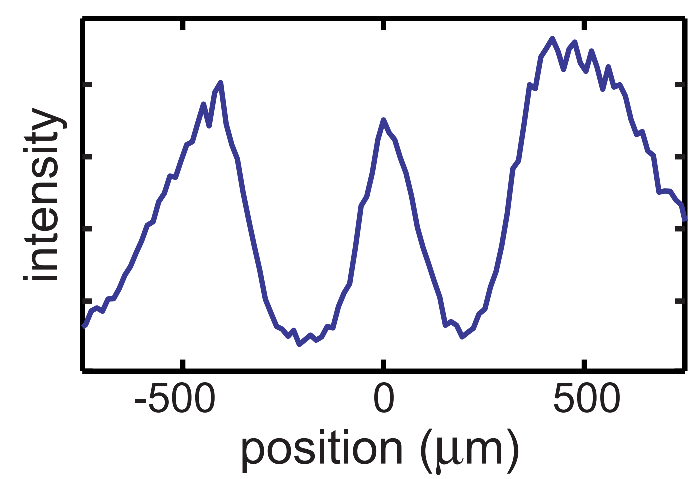




mask (object) is two opaque bars, 200 µm wide

far field



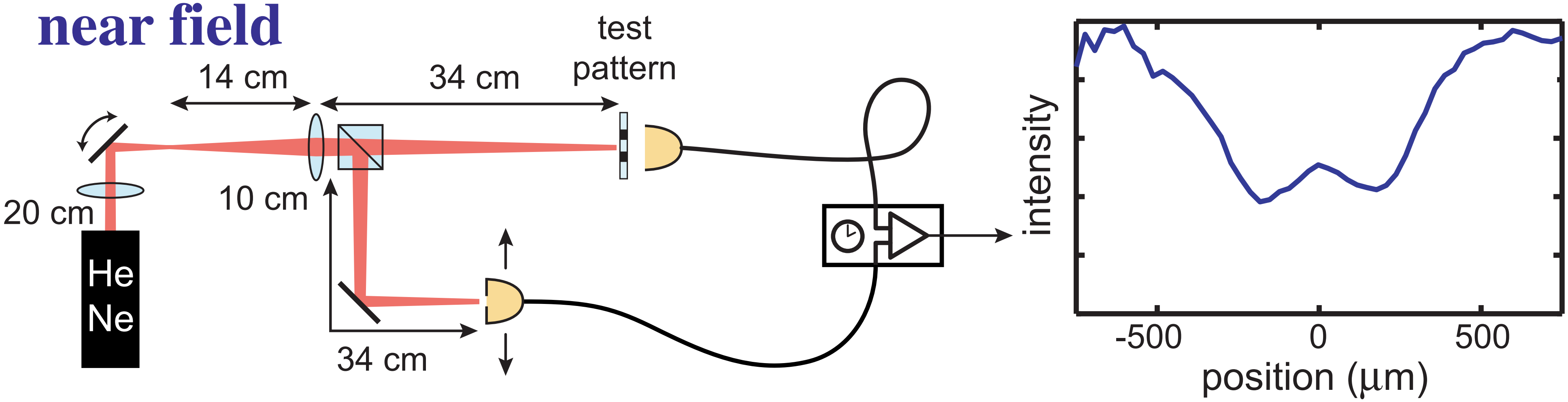


Good imaging observed in both the near and far fields!

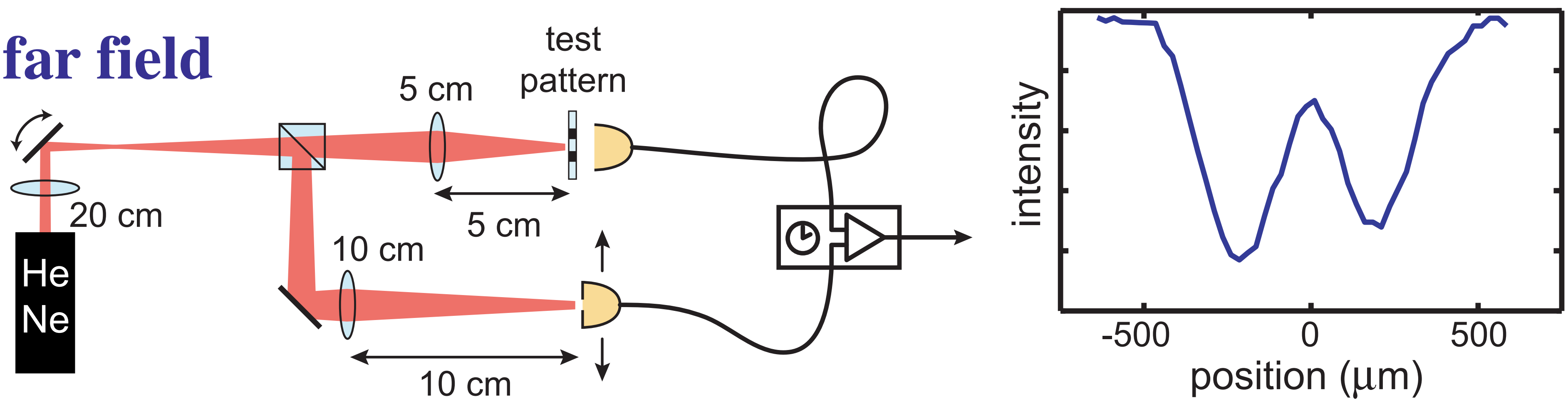
Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

Near- and Far-Field Imaging With a Classical Source

near field



far field



- 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.

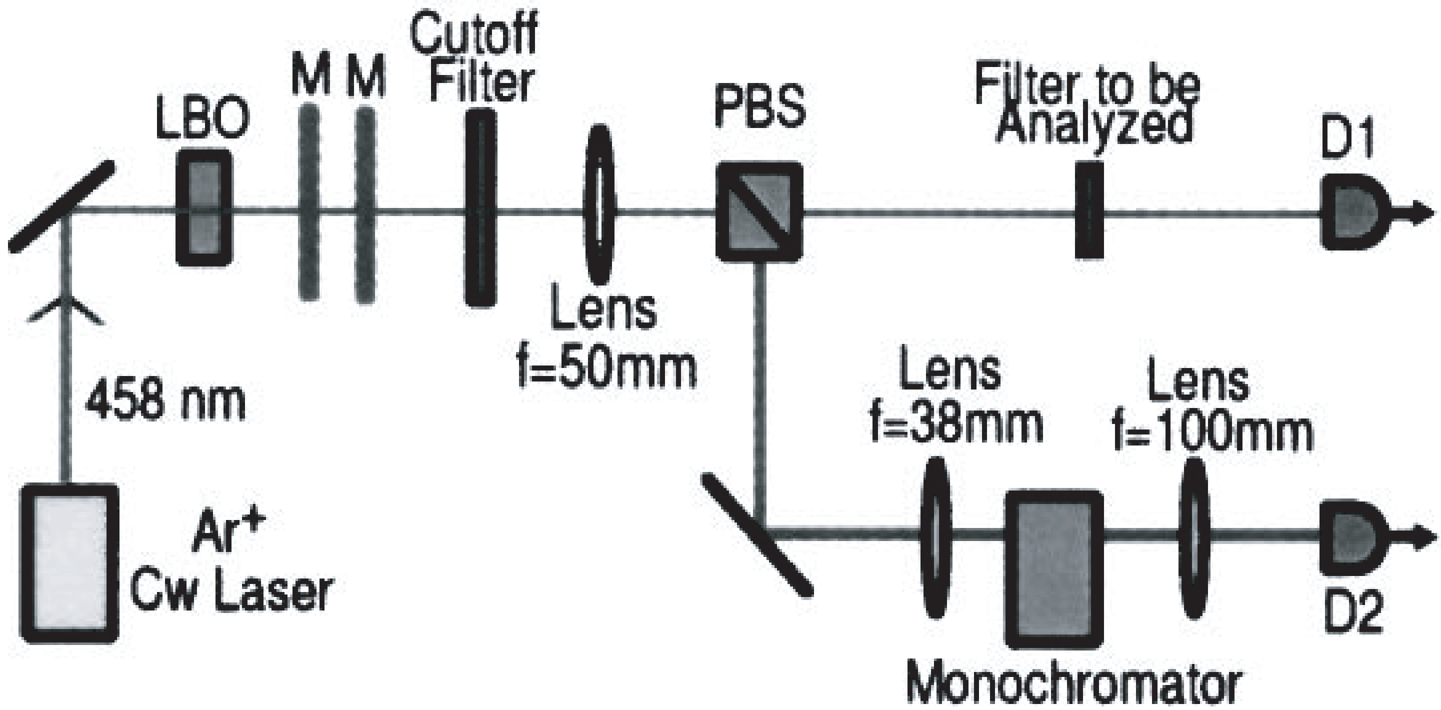
Is Entanglement Really Needed for Ghost Imaging with an Arbitrary Object Location?

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.

Remote (Ghost) Spectroscopy



Can this idea be implemented with thermal light?

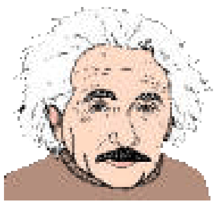
Scarcelli, Valencia, Compers, and Shih, APL 83 5560 2003.

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

The EPR Paradox

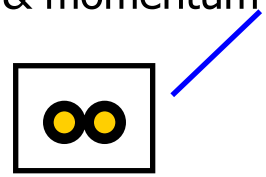
In 1935, Einstein, Podolsky, and Rosen argued that quantum mechanics must be "incomplete."

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,

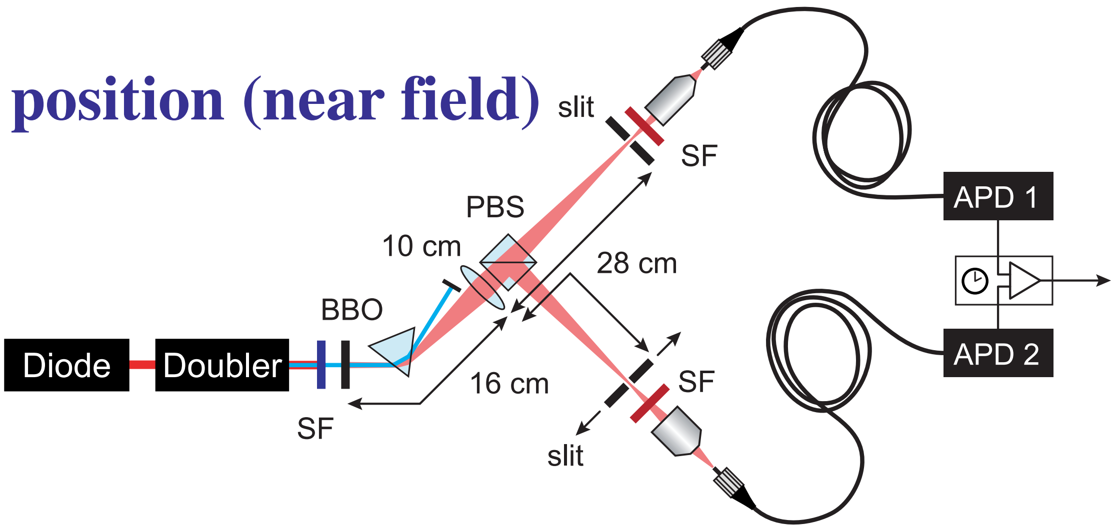
$$\left((\Delta x_2)_{x_1}\right)^2\left((\Delta k_2)_{k_1}\right)^2 \leq 1$$

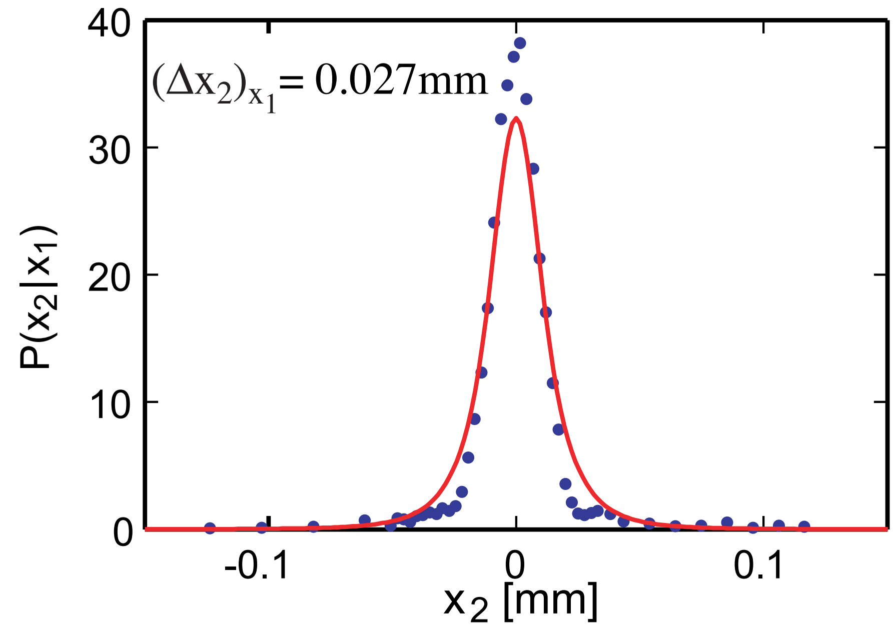
is equivalent to that for violating the EPR hypothesis.

- 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.

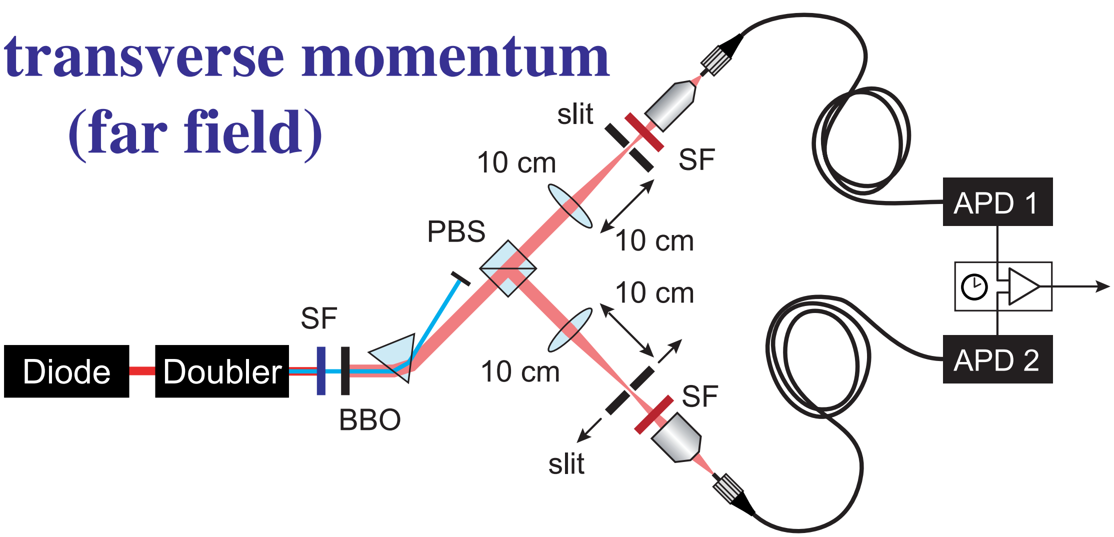
Position-Momentum Realization of the EPR Paradox

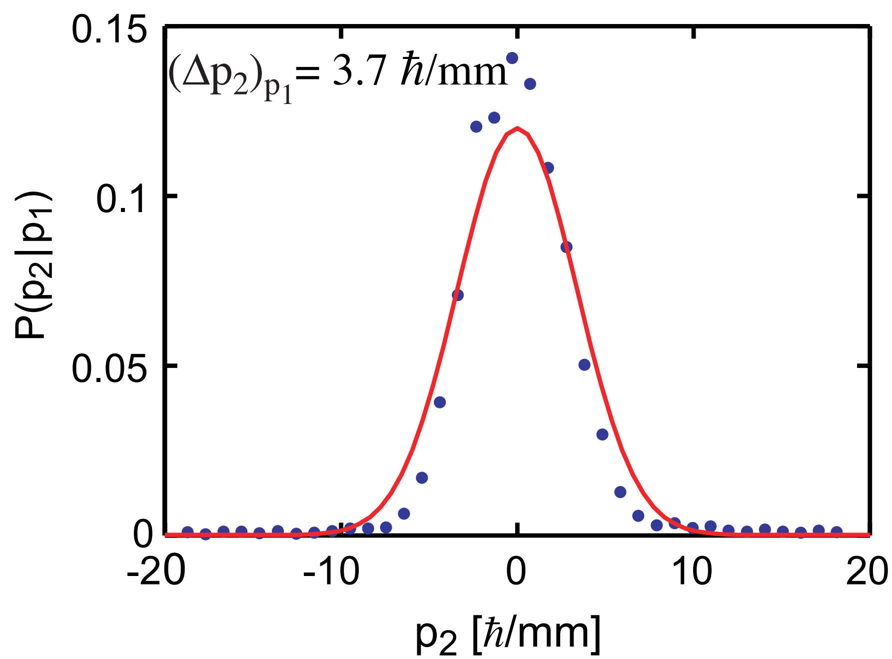
position (near field)





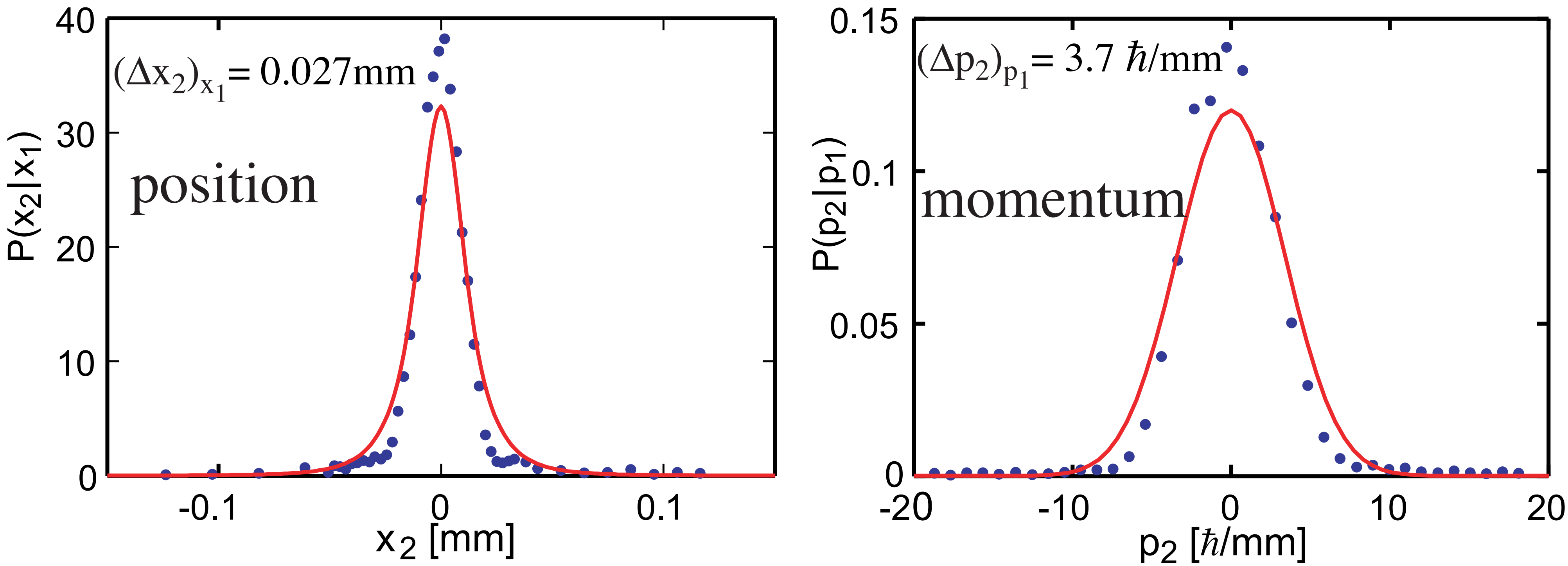
transverse momentum (far field)





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

Discussion: Position-Momentum Realization of the EPR Paradox



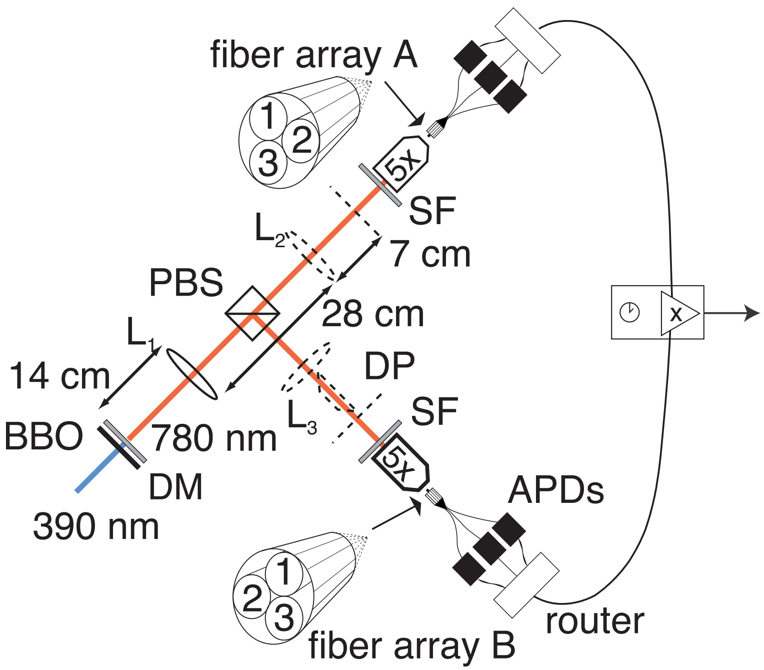
- The spread in *p* is determined by the momentum uncertainty of the pump beam, which is limited by the pump spot size.
- The spread in *x* is determined by the angular bandwidth of the PDC process, which is limited by phase matching requirements.
- We find that $(\Delta x_2)_{x_1}{}^2 \, (\Delta p_2)_{p_1}{}^2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

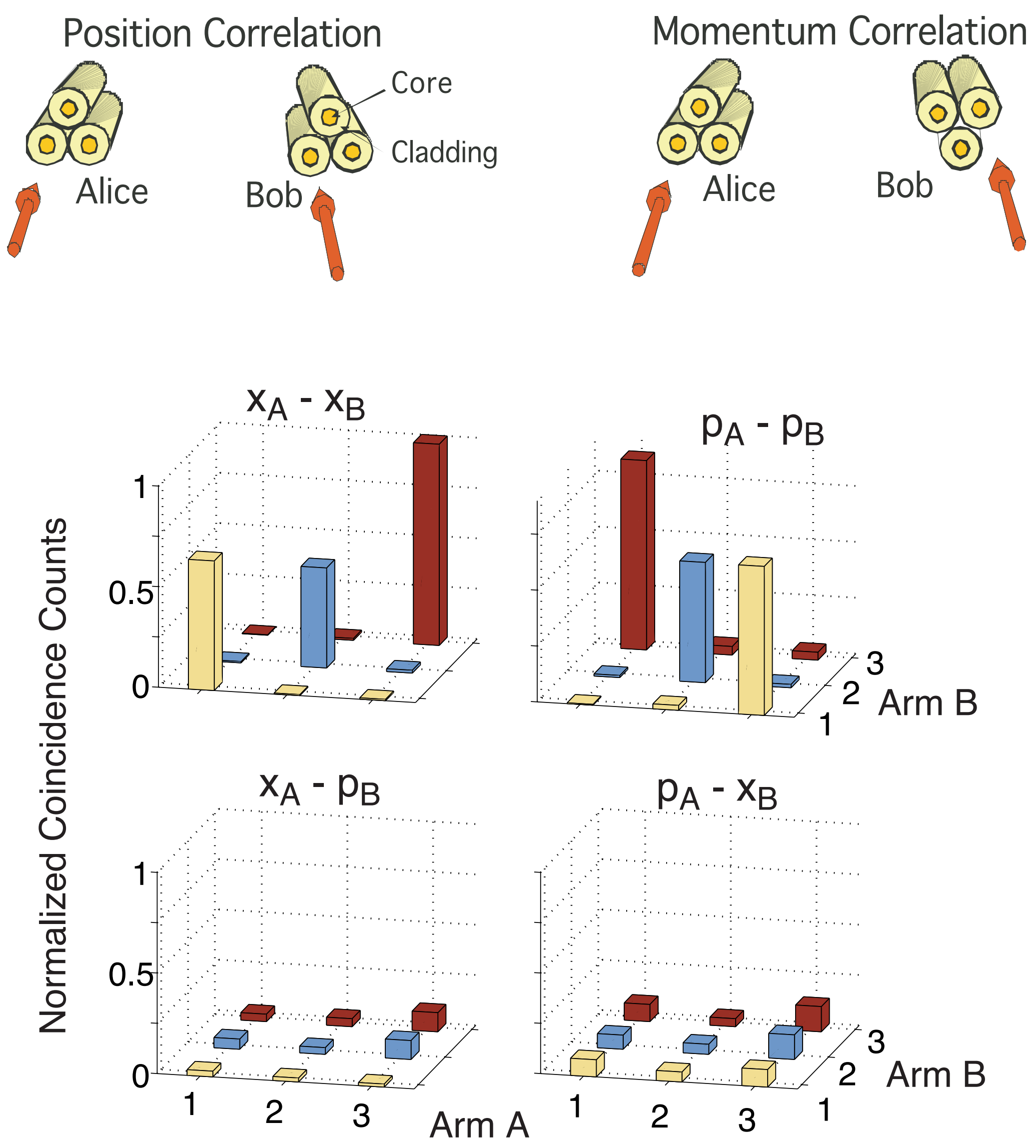
EPR Entanglement: previous work

- 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)

Pixel Entanglement: Entanglement In A Very Large Hilbert Space

Quantum pixel: discrete average of a non-commuting, continuous variable (e.g., x or p).





Possible application: generalization of cryptographic protocols to qudits of higher dimension d.

O'Sullivan-Hale, Khan, Boyd, and Howell, PRL 2005

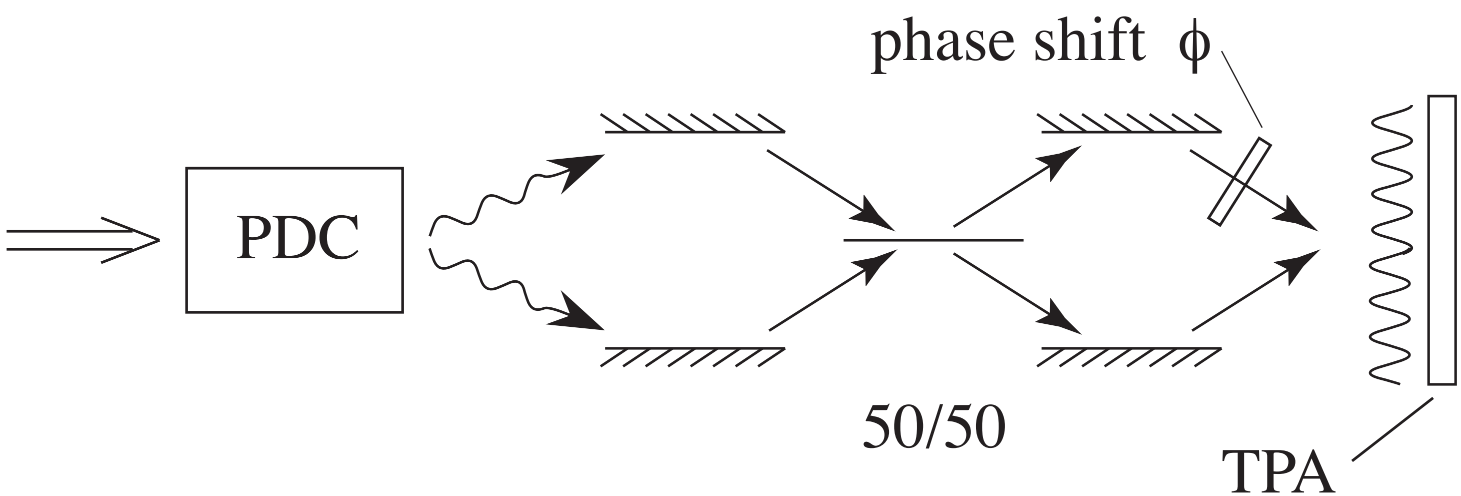
Research in Quantum Imaging

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 $\approx \lambda / 2N$, where N = number of entangled photons



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

("al." includes Jon Dowling)

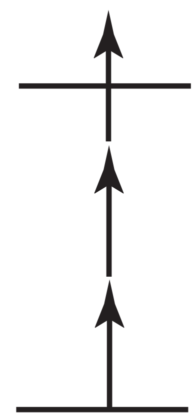
Quantum Lithography: Easier Said Than Done

- 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.



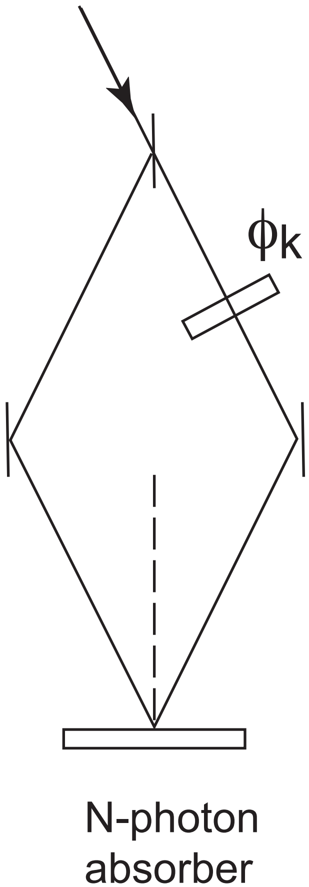
3PA in PMMA breaks chemical bond, modifying optical properties.

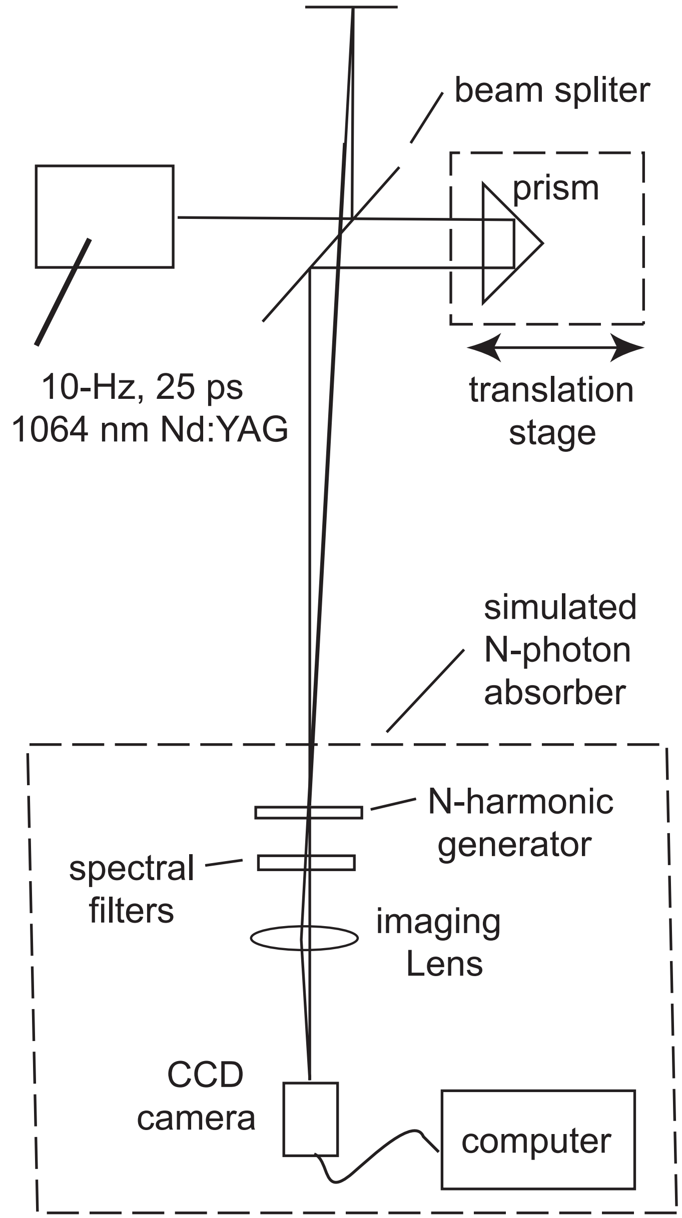
- Need an intense source of individual biphotons (Inconsistency?)

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

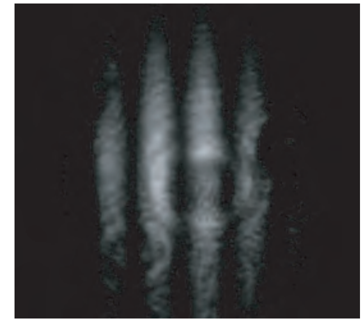
Classically Simulated (Non-Quantum) Quantum Lithography

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

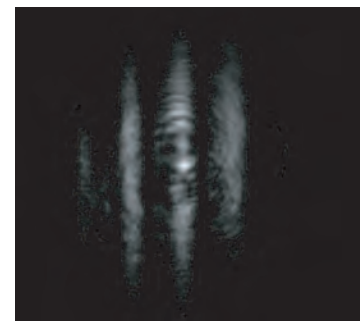




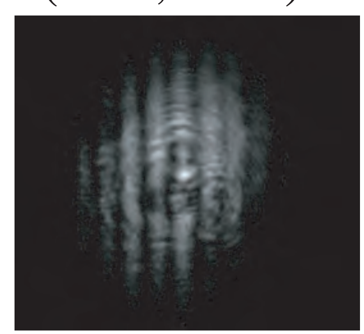
One-photon absorber (N=1, M=1)



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

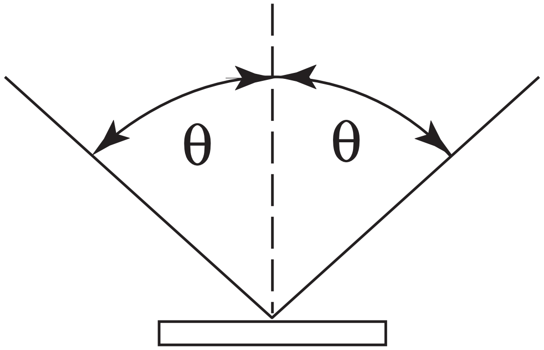


Two-photon absorber two exposures (N=2, M=2)



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

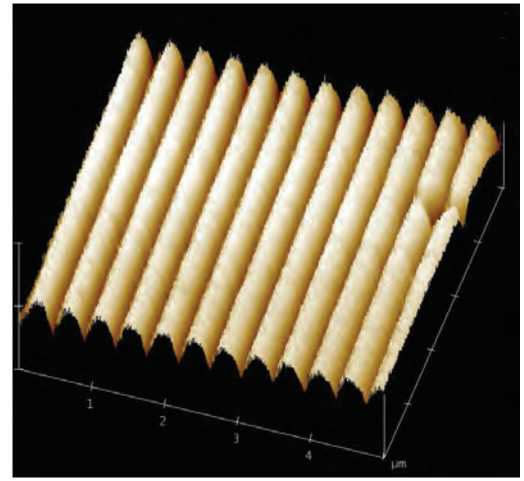
Demonstration of Fringes Written into PMMA



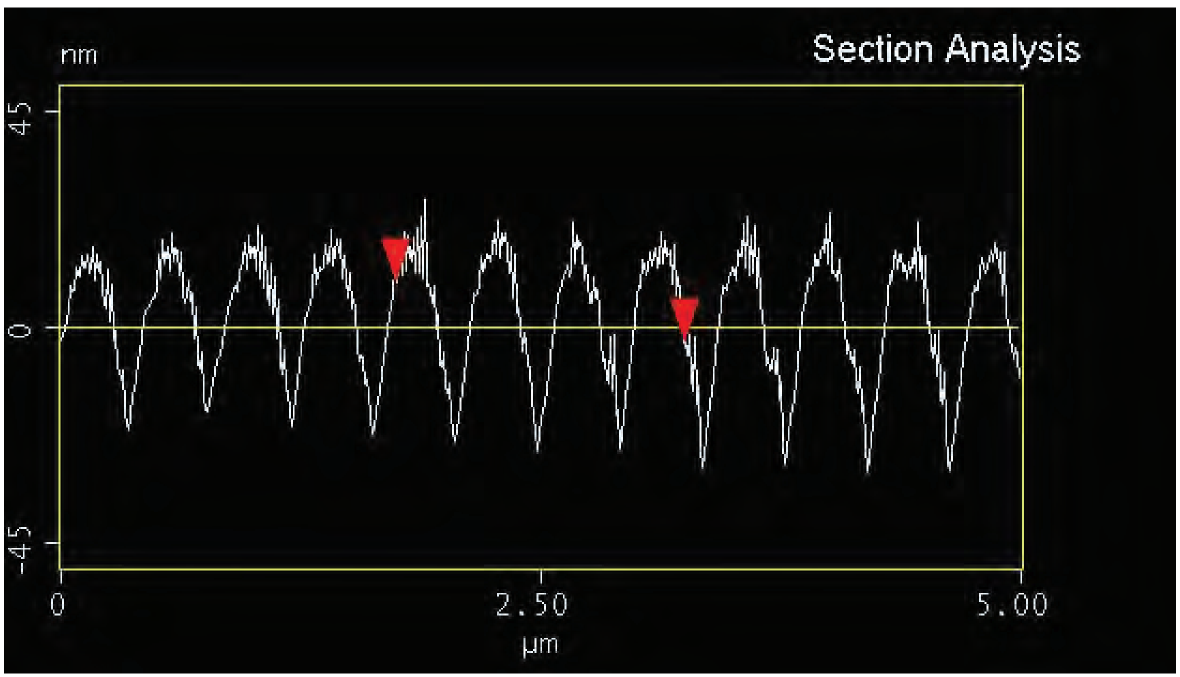
N-photon absorber
(N = 3 ?)

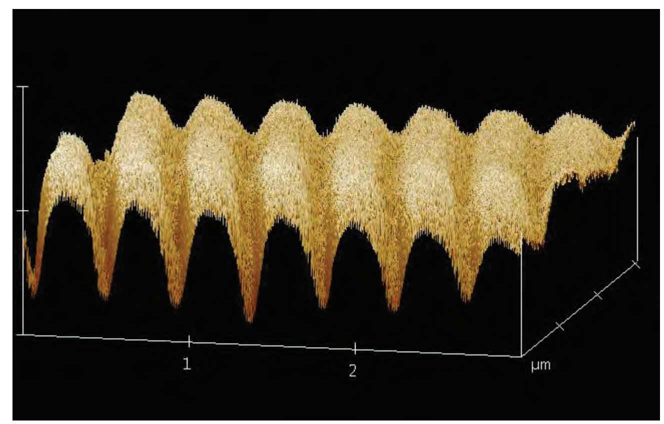
θ = 70 degrees
write wavelength = 800 nm
pulse energy = 130 μJ per beam
pulse duration = 120 fs
period = $\lambda / (2 \sin \theta)$ = 425 nm

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



AFM





PMMA is a standard lithographic material

Coherence and Indistinguishability in Two-Photon Interference

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

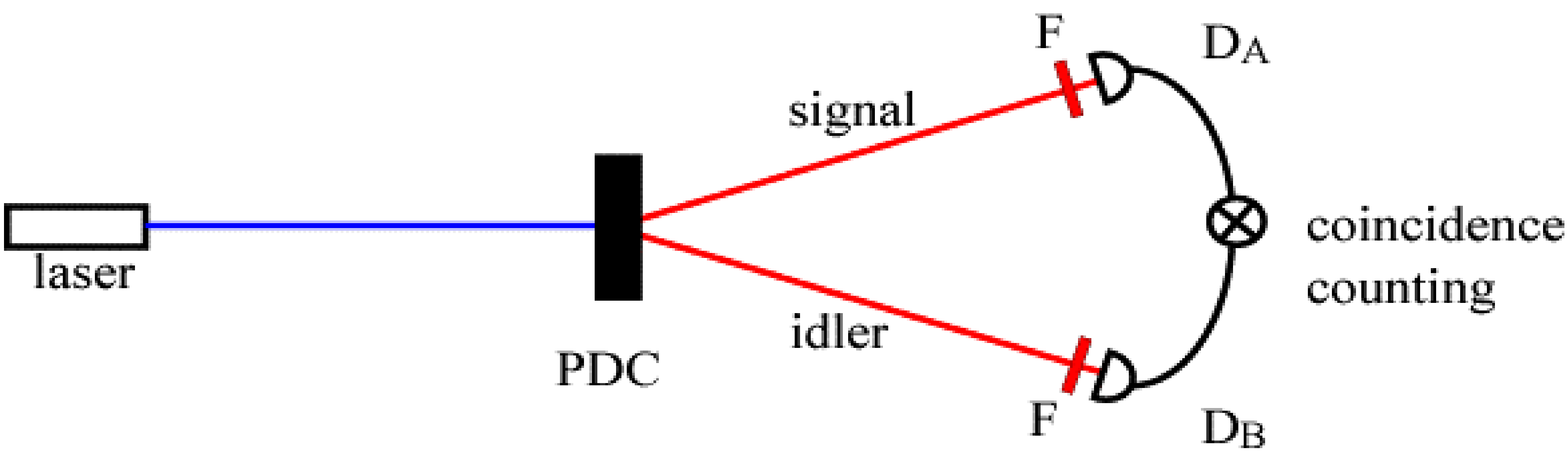
Institute of Optics, University of Rochester

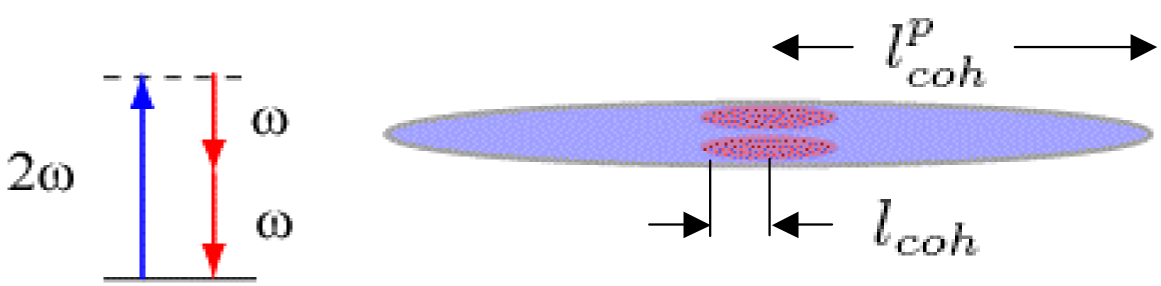
http://www.optics.rochester.edu/~boyd

What are the relevant degrees of freedom of a biphoton?

What are the generic features of two-photon interference?

Biphotons Are Created by Parametric Downconversion (PDC)





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

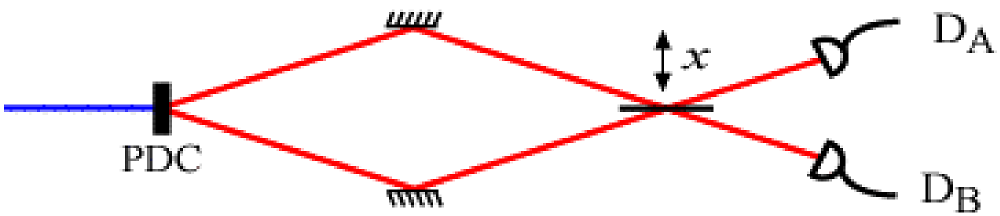
Coherence length of signal/idler photons ~ c/Δω ~ 100 μm.

Individual photons are entangled and can be made indistinguishable.

Two-Photon Interference -- How to Understand?

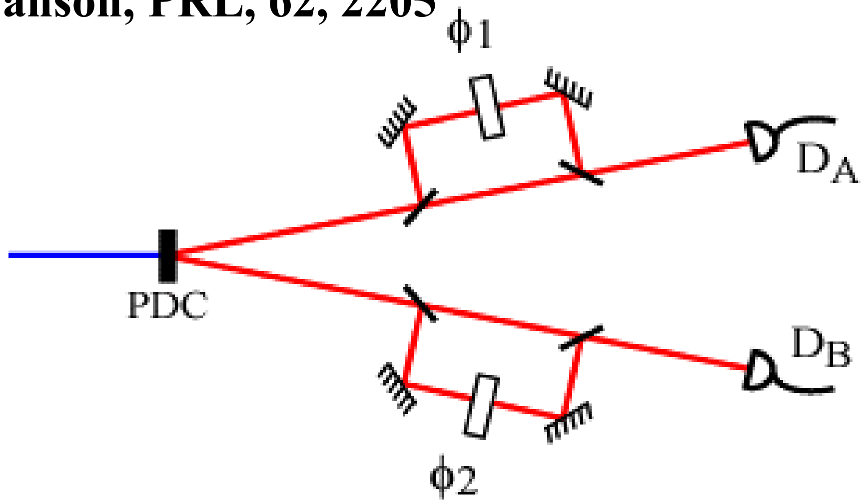
- **Hong-Ou-Mandel effect (1987)**

PRL, 59, 2044



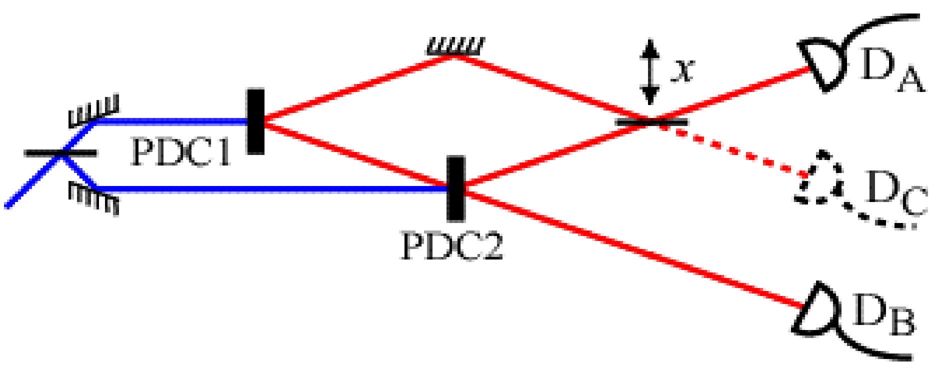
- **Bell Inequality for position and time (1989)**

Franson, PRL, 62, 2205



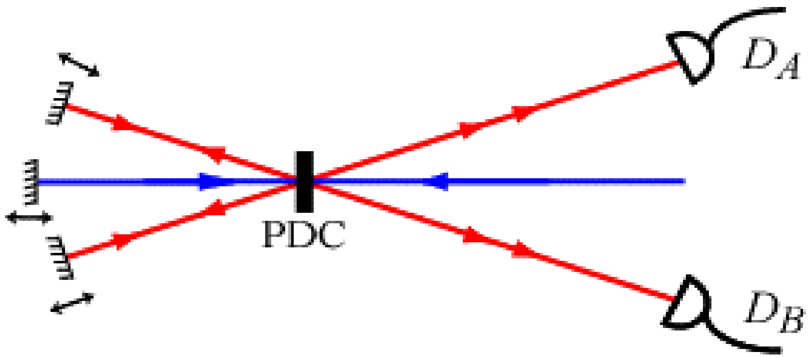
- **Induced Coherence (1991)**

Zou et al. PRL, 67, 318

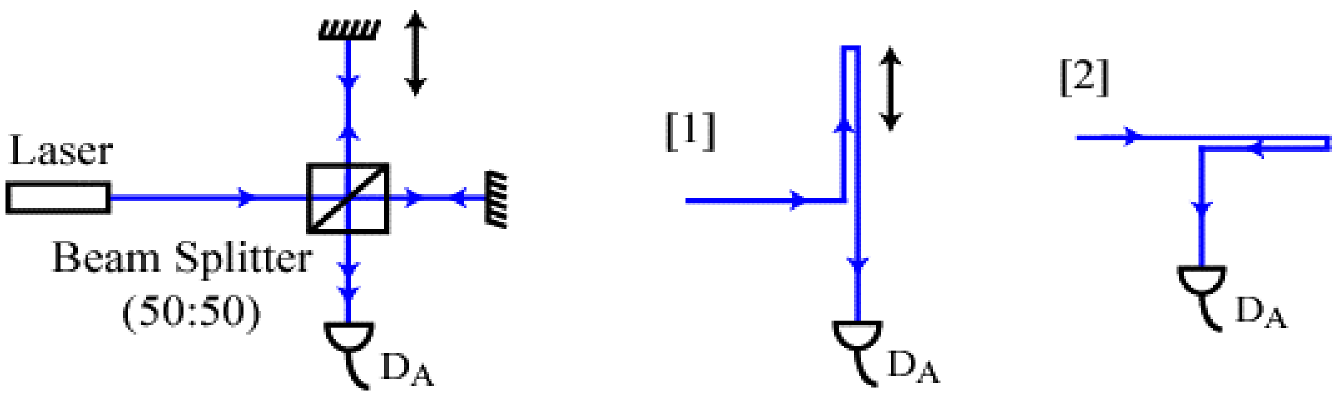


- **Frustrated two-photon creation (1994)**

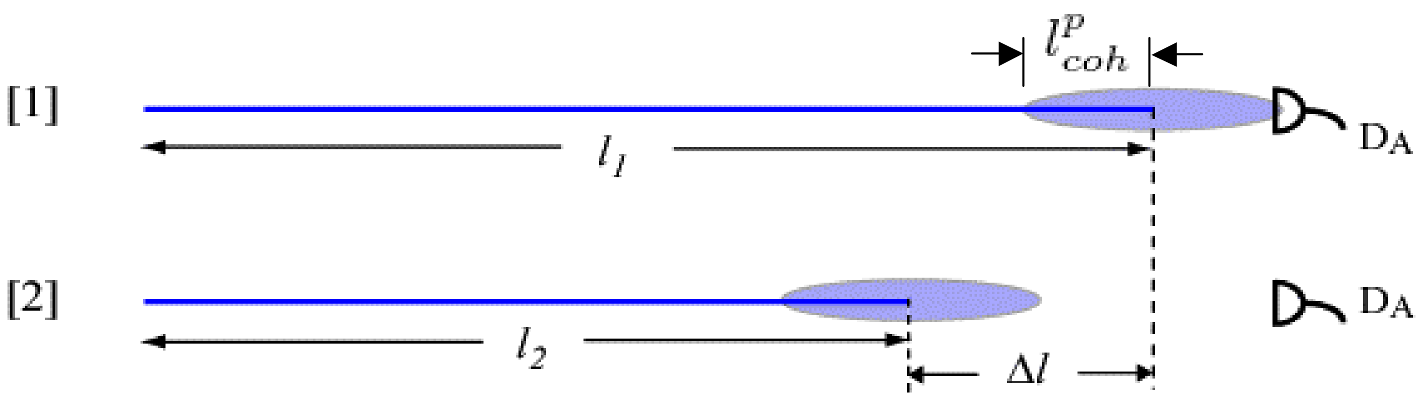
Herzog et al. PRL, 72, 629



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



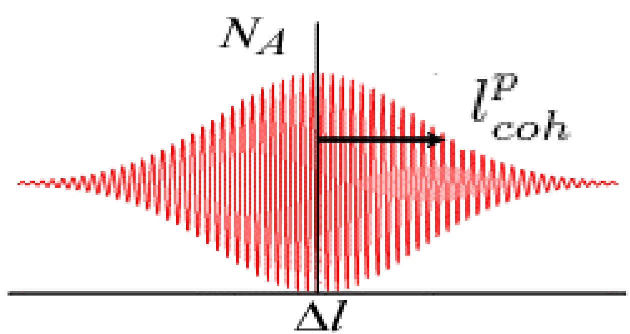
Add probability amplitudes for alternative pathways [1] and [2]



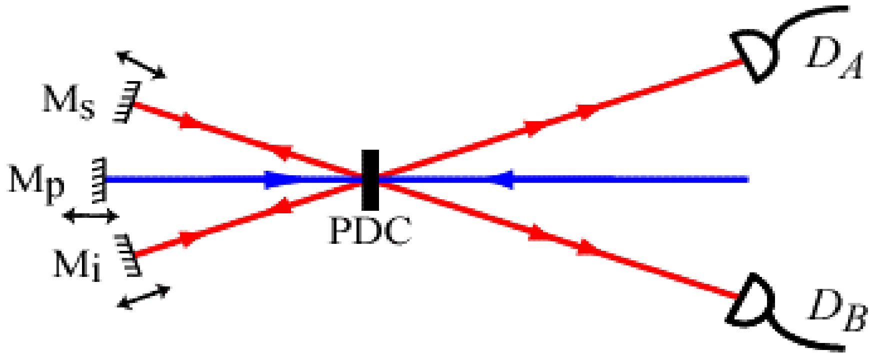
(unfolded paths)

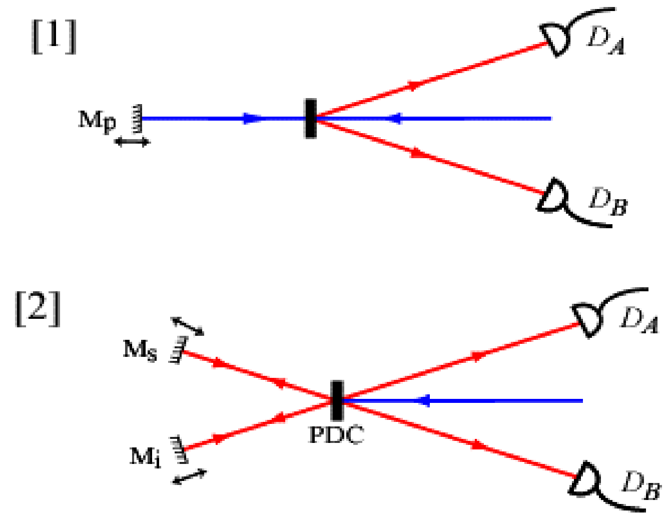
Necessary condition for one-photon interference

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

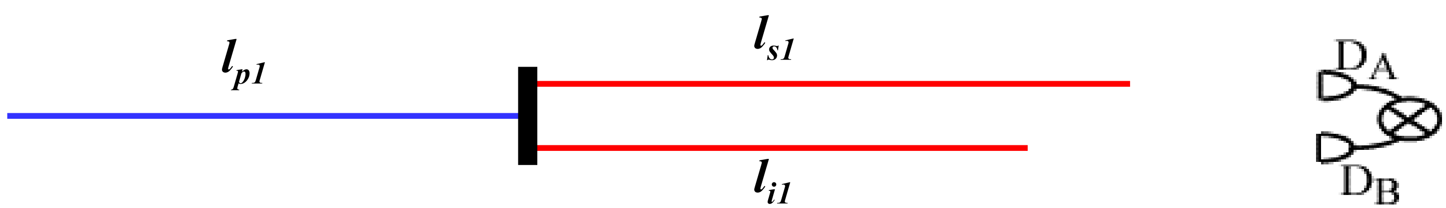


What about biphoton interference? (Generic setup)

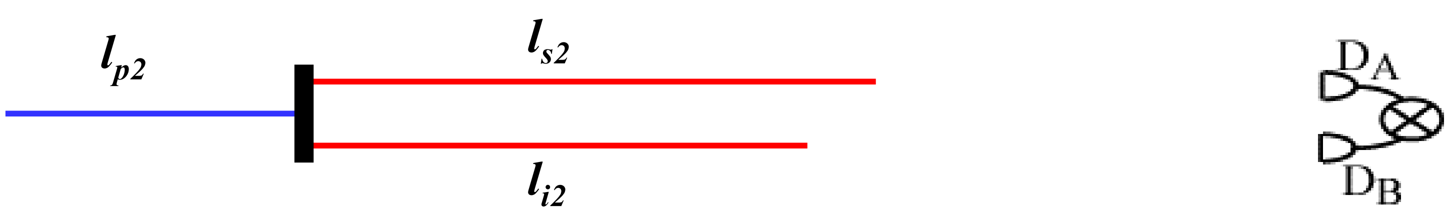




[1]

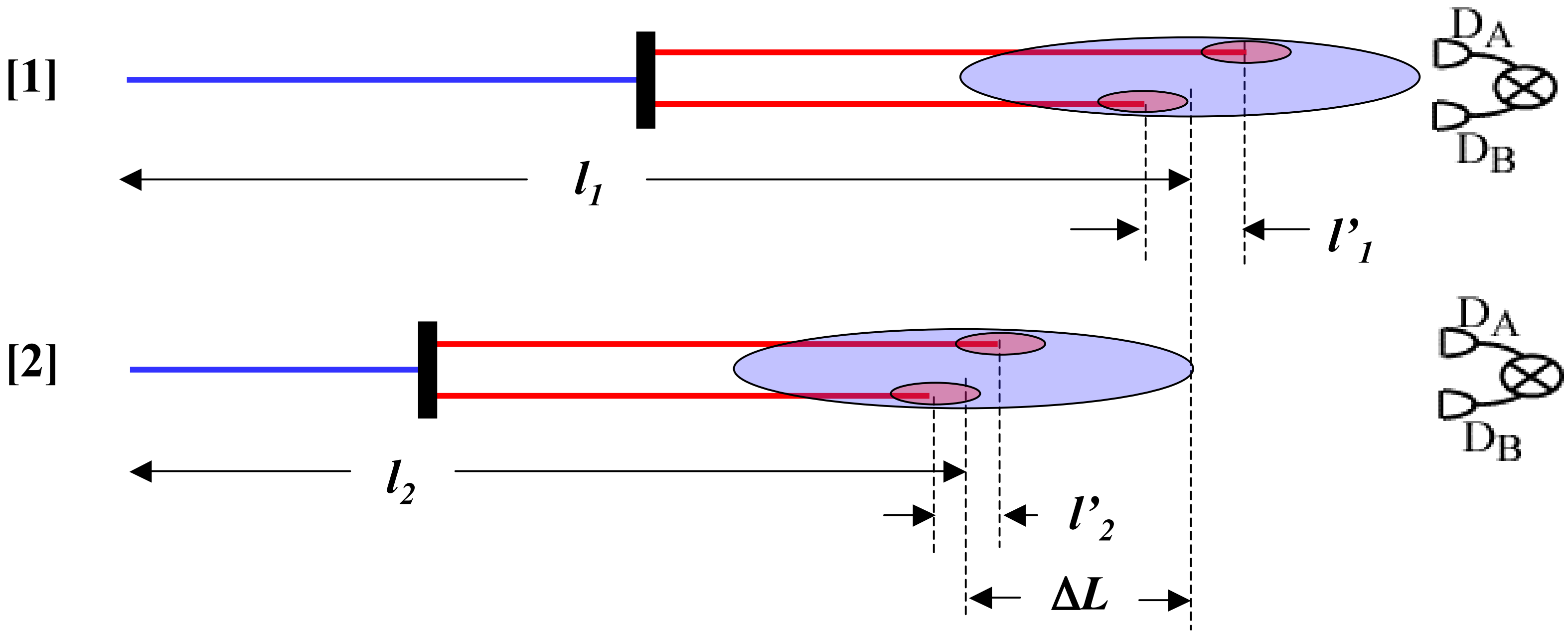


[2]



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**

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

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

Conditions for two-photon interference:

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

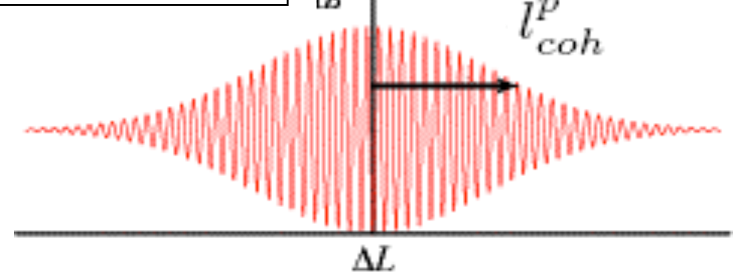
$$\Delta L' \; < \; l_{coh}$$

Two-Photon Interference (two special cases)

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

<u>**Cases I : Δ*L'* = 0**</u>

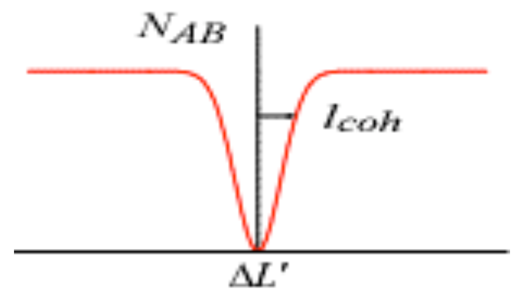
$$N_{AB} \propto \quad 1 - \gamma\left(\Delta L\right)\cos\left(k_0 \Delta L\right)$$



- **Δ*L* plays the same role in two-photon interference as Δ*l* does in one-photon interference**

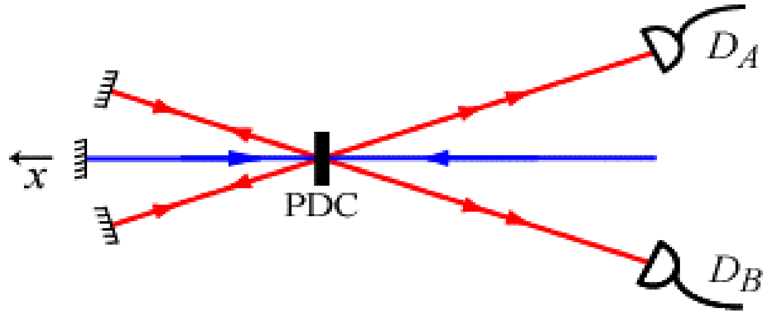
<u>**Cases II : Δ*L* = 0**</u>

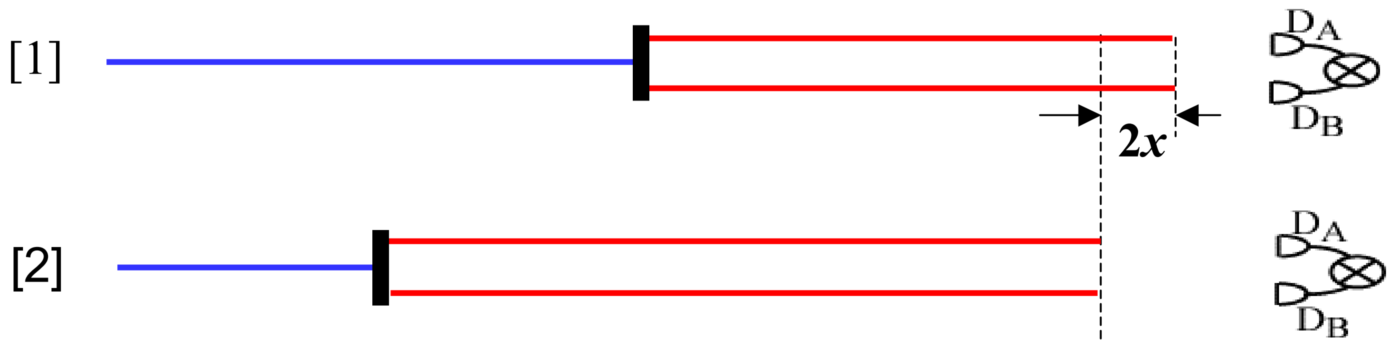
$$N_{AB} \propto \quad 1 - \gamma'\left(\Delta L'\right) = 1 - e^{-\frac{1}{2}\left(\frac{\Delta L'}{l_{coh}}\right)^2}$$



- **Δ*L'* has no one-photon analogue**
- **The curve show how coherence is lost due to an increase in the biphoton path-length asymmetry difference Δ*L'***

Two-Photon Interference (Procedure 1)

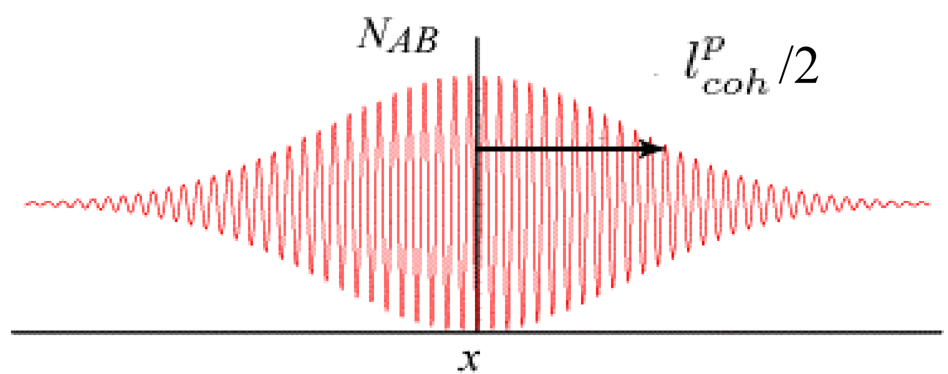




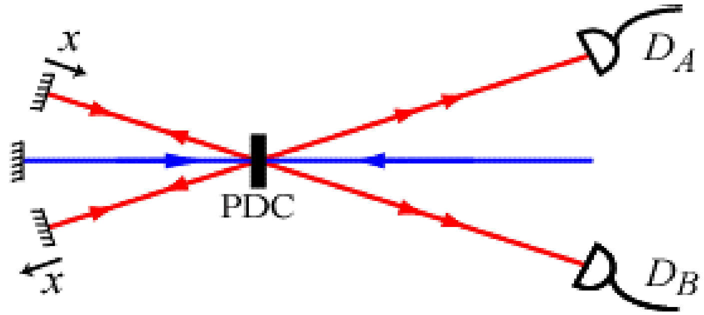
$\Delta L = 2x$
$\Delta L' = 0$

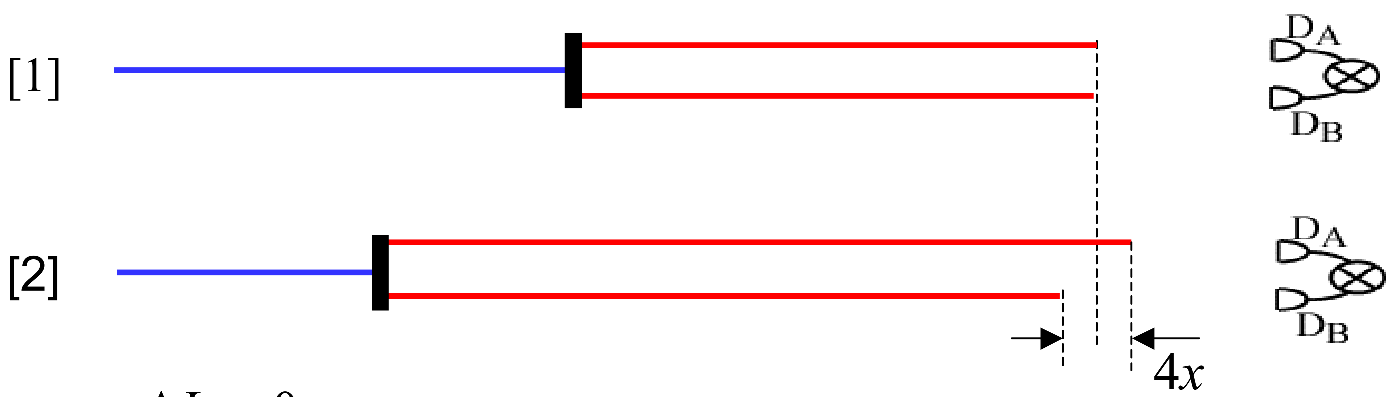
$$N_{AB} \propto \quad 1 - \gamma'\left(\Delta L'\right)\gamma\left(\Delta L\right)\cos\left(k_0 \Delta L\right)$$

$$N_{AB} \propto \quad 1 - \gamma\left(2x\right)\cos\left(k_0 2x\right)$$



Two-Photon Interference (Procedure 2)



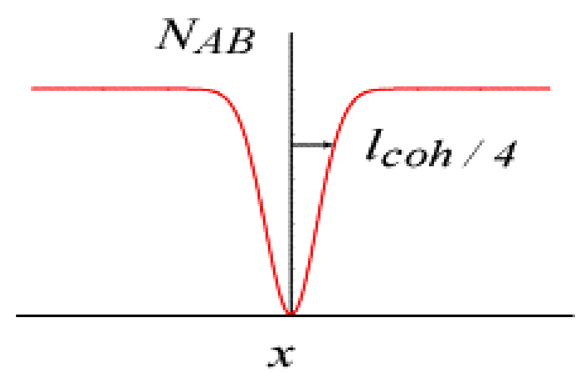


$\Delta L = 0$

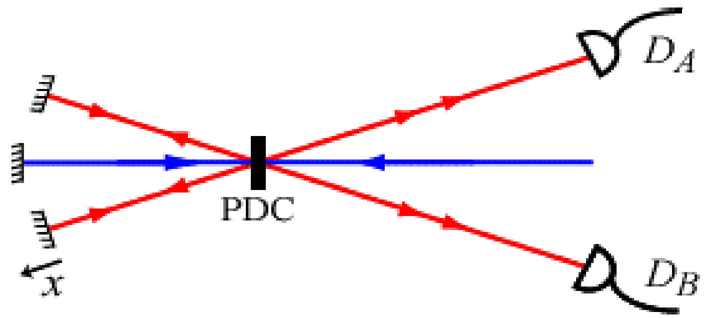
$\Delta L' = 4x$

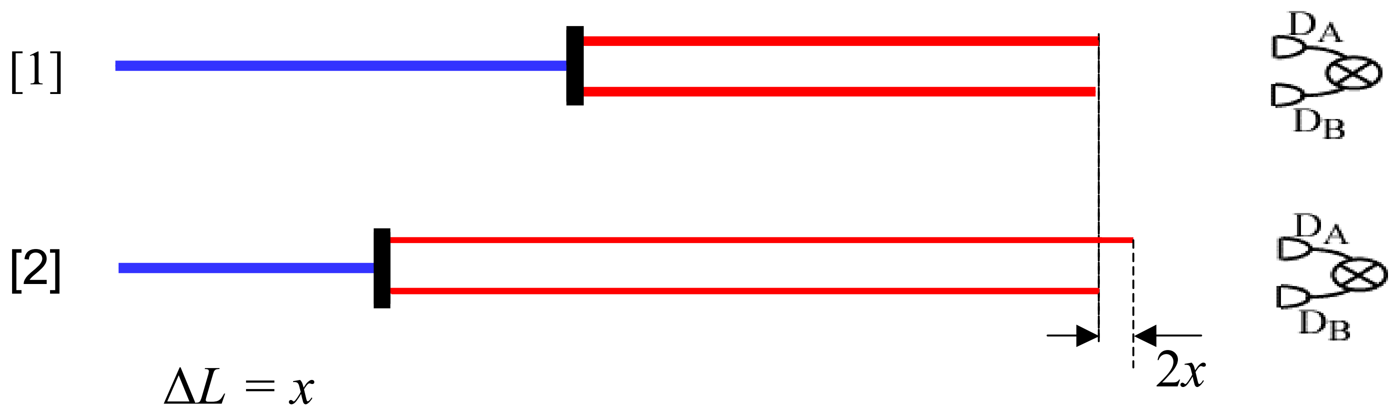
$$N_{AB} \propto \quad 1 - \gamma'\left(\Delta L'\right)\gamma\left(\Delta L\right)\cos\left(k_0 \Delta L\right)$$

$$N_{AB} \propto \quad 1 - \gamma'\left(4x\right)$$



Two-Photon Interference (Procedure 3)



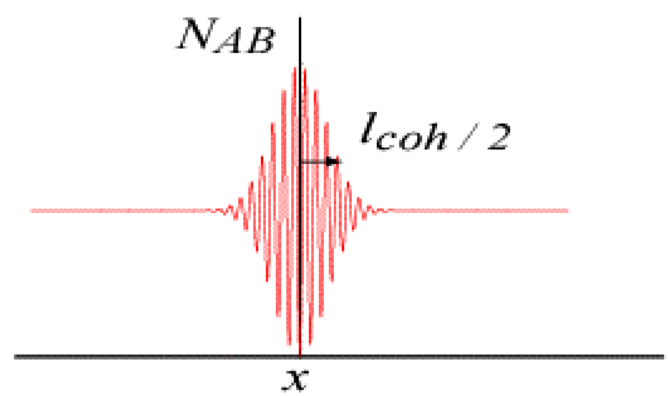


$\Delta L = x$

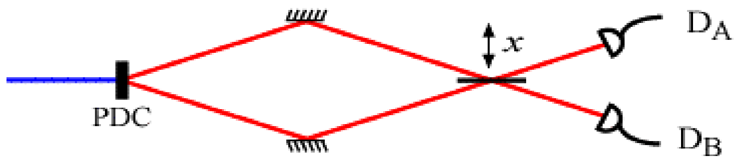
$\Delta L' = 2x$

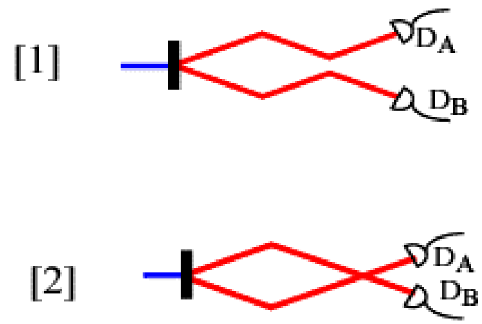
$$N_{AB} \propto \; 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

$$N_{AB} \propto \; 1 - \gamma'(2x)\,\gamma(x)\cos(k_0 x)$$

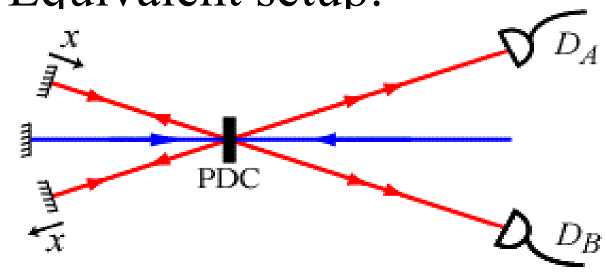


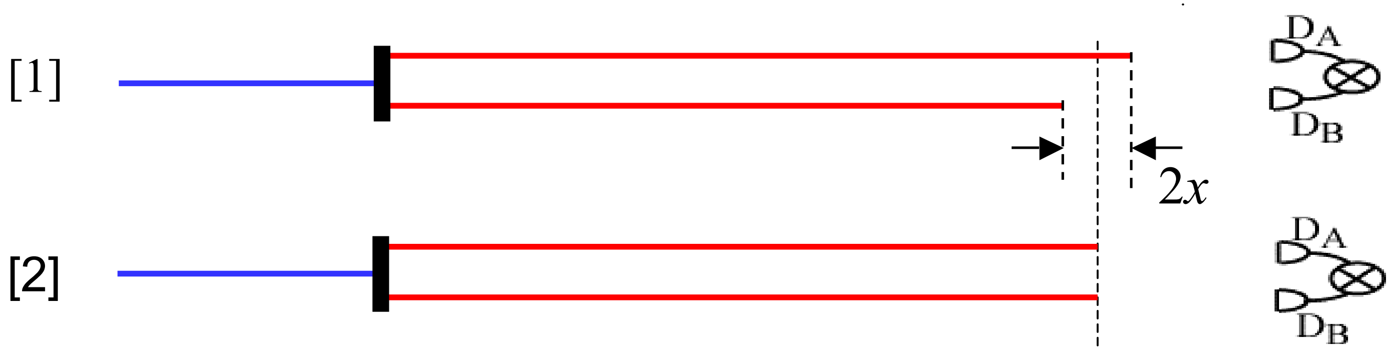
Hong-Ou-Mandel Experiment





Equivalent setup:

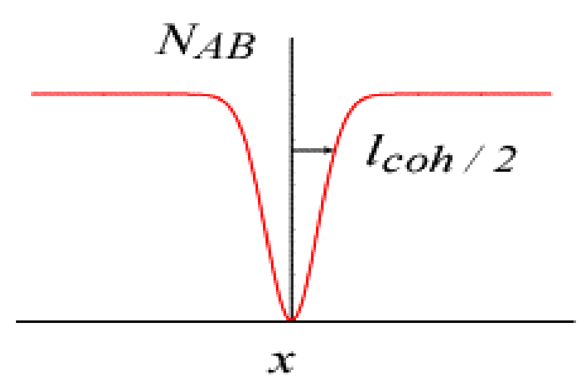




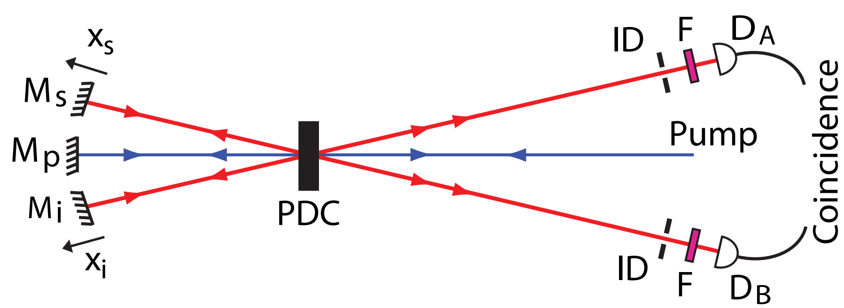
$\Delta L = 0 \qquad \Delta L' = 2x$

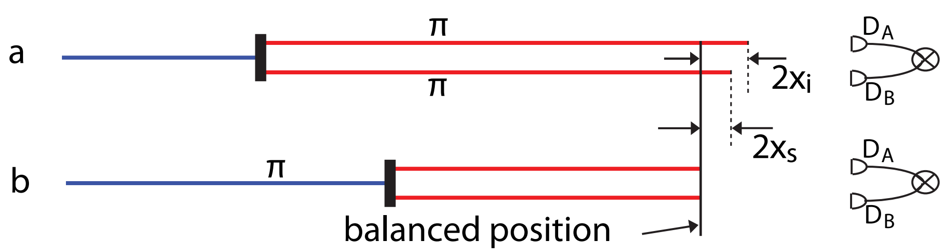
$$N_{AB} \propto \ 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

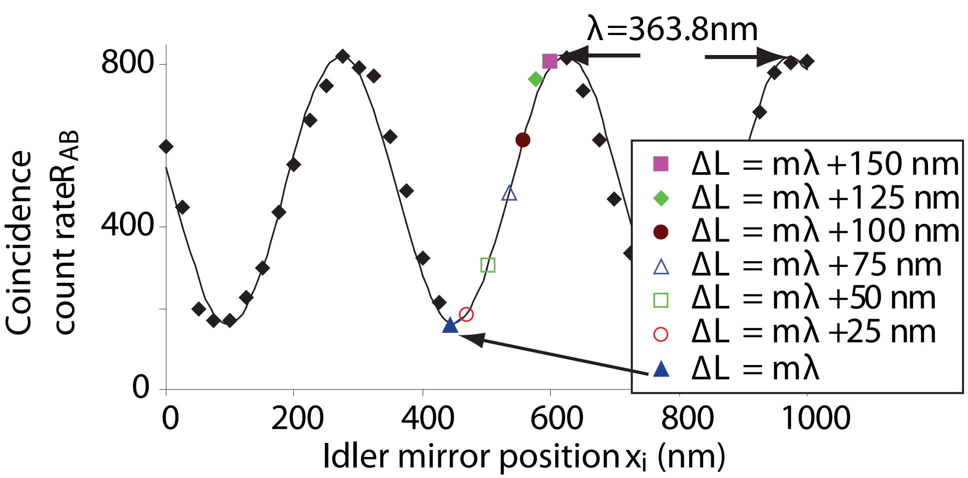
$$N_{AB} \propto \ 1 - \gamma'(2x)$$

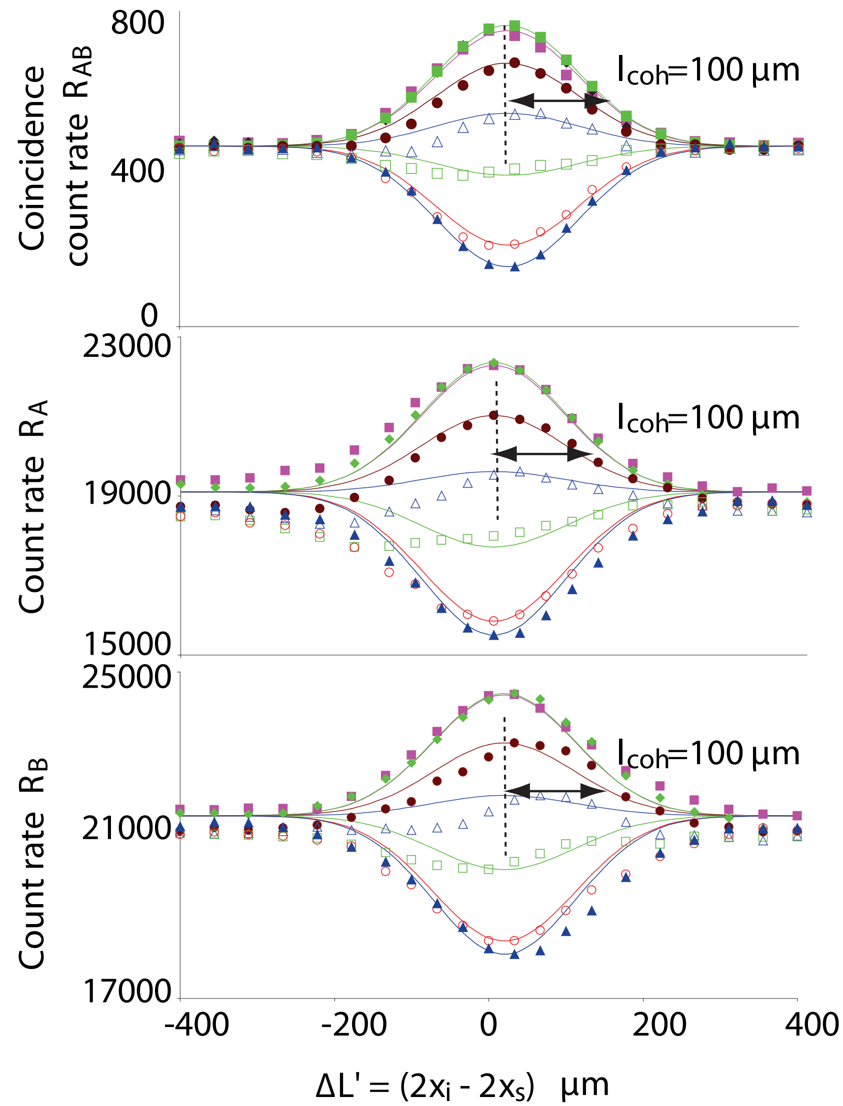


Our Experiment: Generalization of the Hong-Ou-Mandel Effect









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!

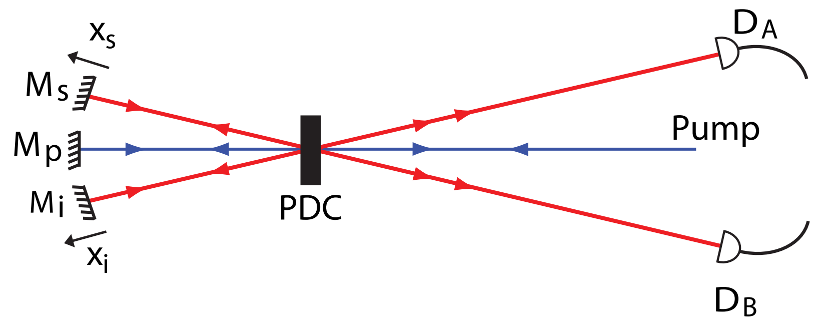
Note that: $$R_{\mathrm{X}} = \sum_i R_{\mathrm{XY}_i}$$

$R_{\mathrm{X}} = \text{single detector count rate}$ $R_{\mathrm{XY}_i} = \text{coincidence count rate}$

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

Thus:

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



Conclusions

One-photon interference

- A photon interferes only with itself
- Condition for interference:

(i) $\Delta l < l^{p}_{coh}$

Two-photon interference

- A bi-photon interferes only with itself
- Condition for interference:

(i) $\Delta L < l^{p}_{coh}$

(ii) $\Delta L' < l_{coh}$

One-photon fringes in two-photon experiments

- Fringes are the sum of two-photon interference profiles observed at a detection point.

Special Thanks: ARO MURI and AFOSR STTR

Thank you for your attention!

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**

Special Thanks to My Students and Research Associates