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

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Outline

1. Overview of quantum imaging

2. The nature of two-photon interference

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?

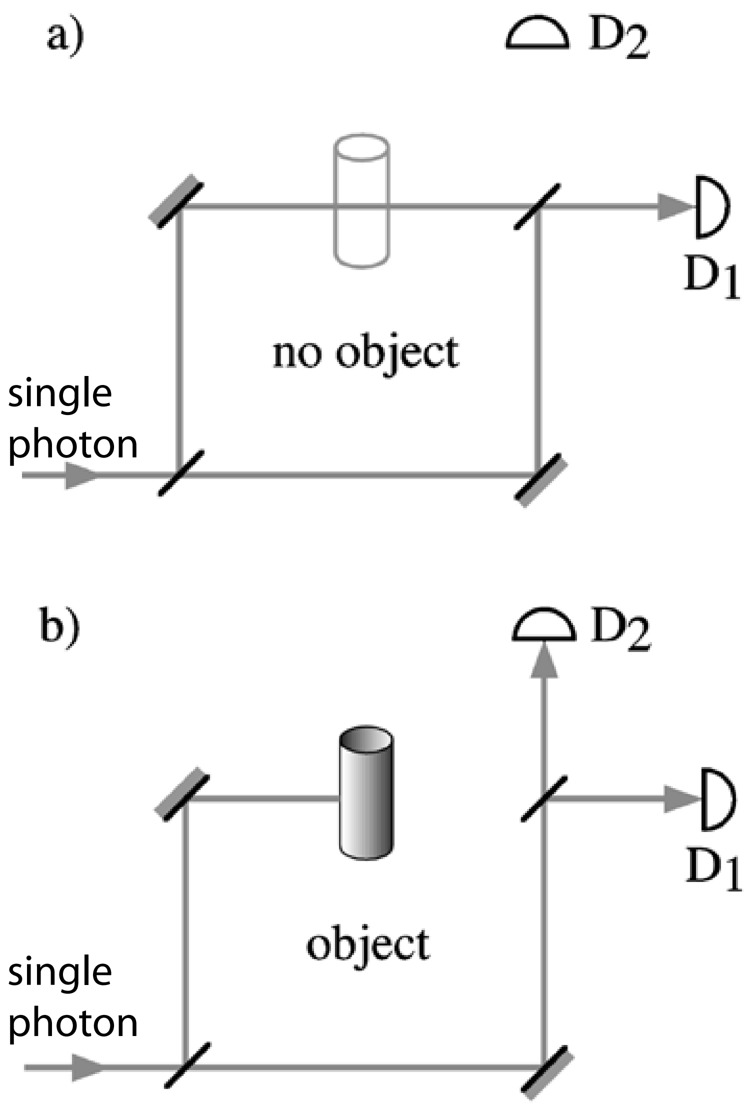
What are the implications of “interaction free” and “ghost” imaging

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

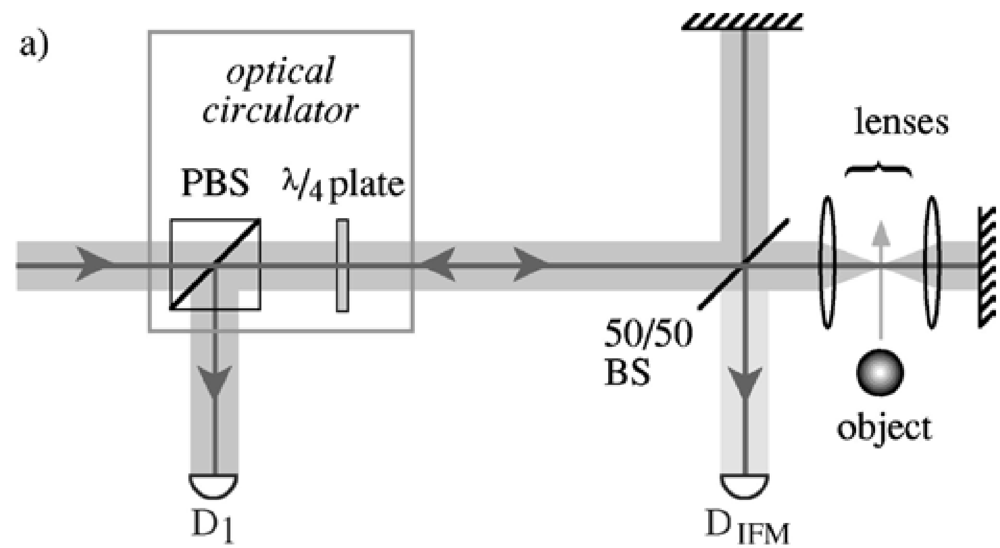
Stealth Imaging

Interaction-Free Imaging and Ghost Imaging

Quantum Imaging by Interaction-Free Measurement

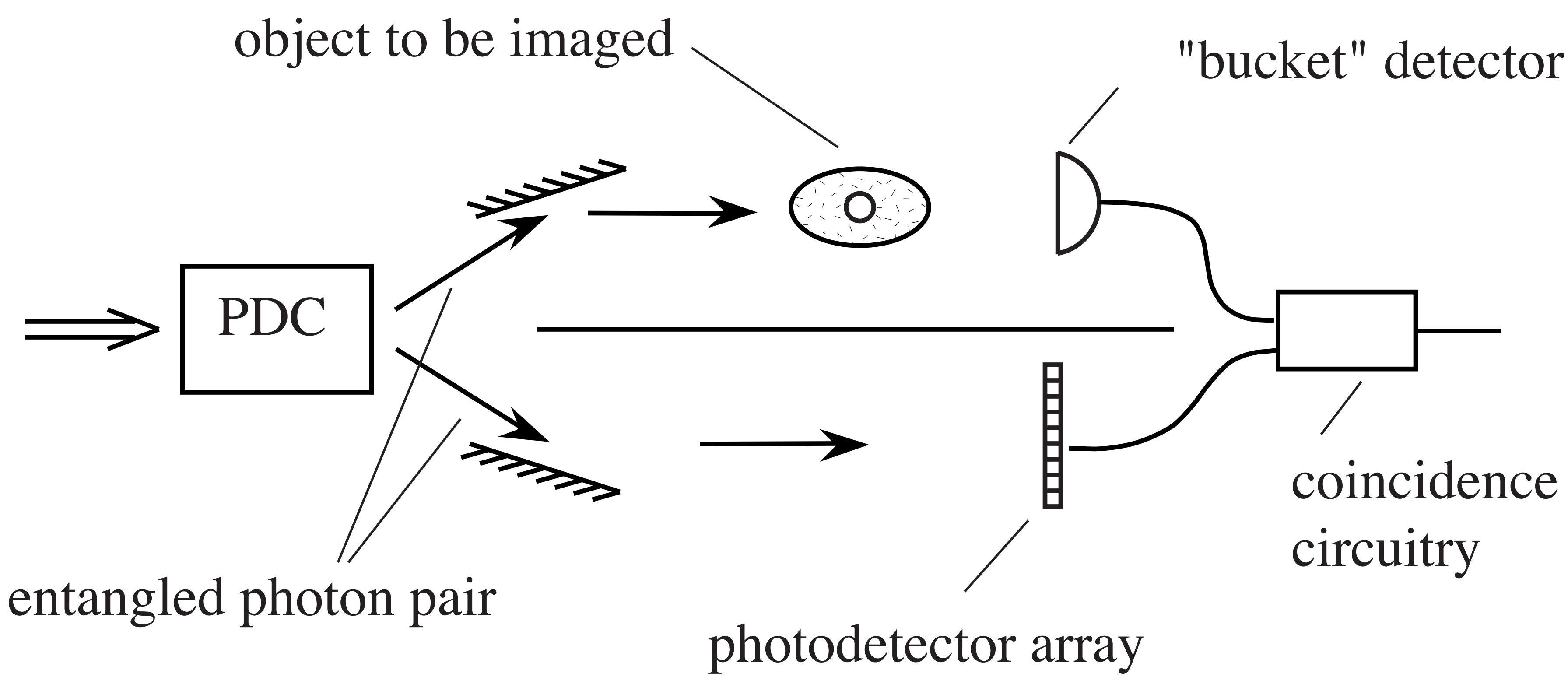


imaging setup



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

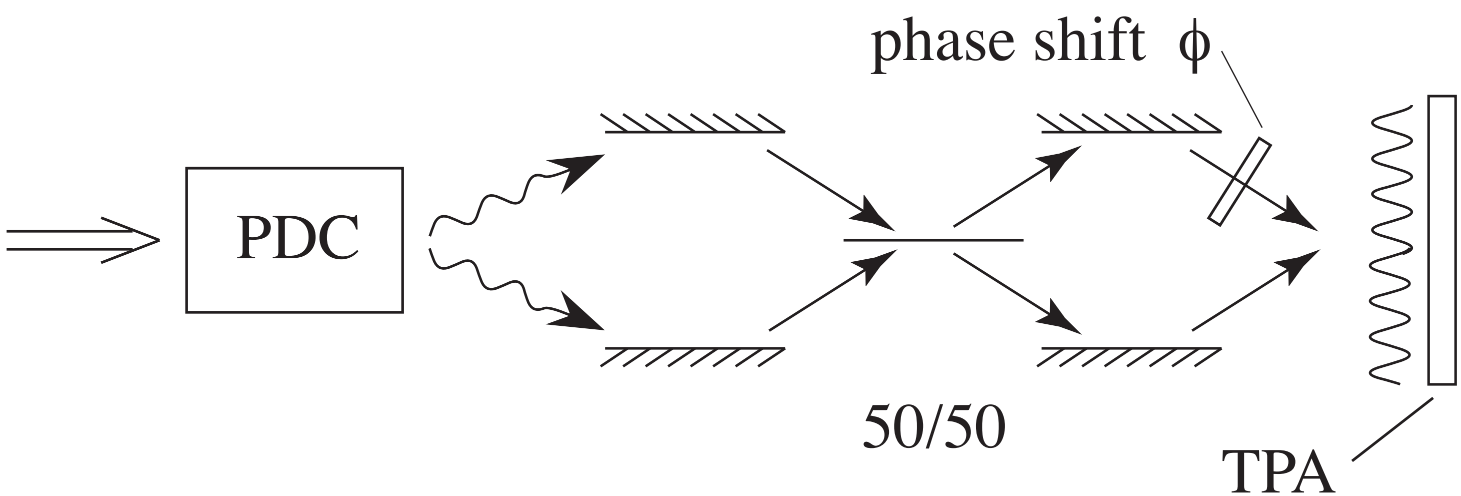


- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process?

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)

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.

("al." includes Jon Dowling)

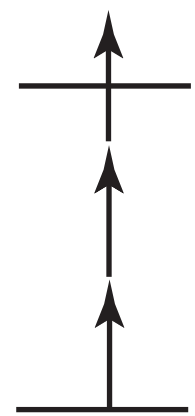
Quantum Lithography: Easier Said Than Done

- 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.



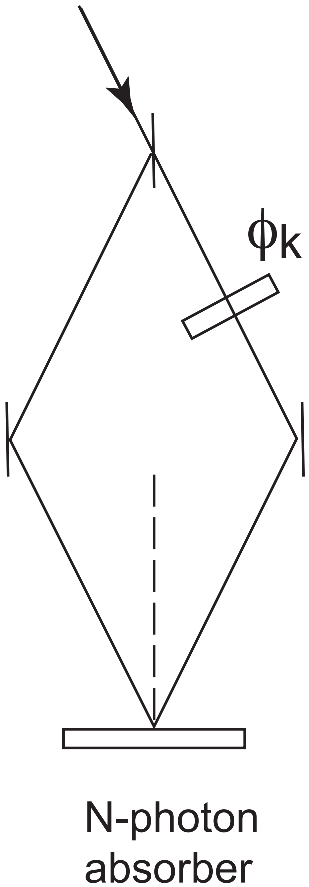
3PA in PMMA breaks chemical bond, modifying optical properties.

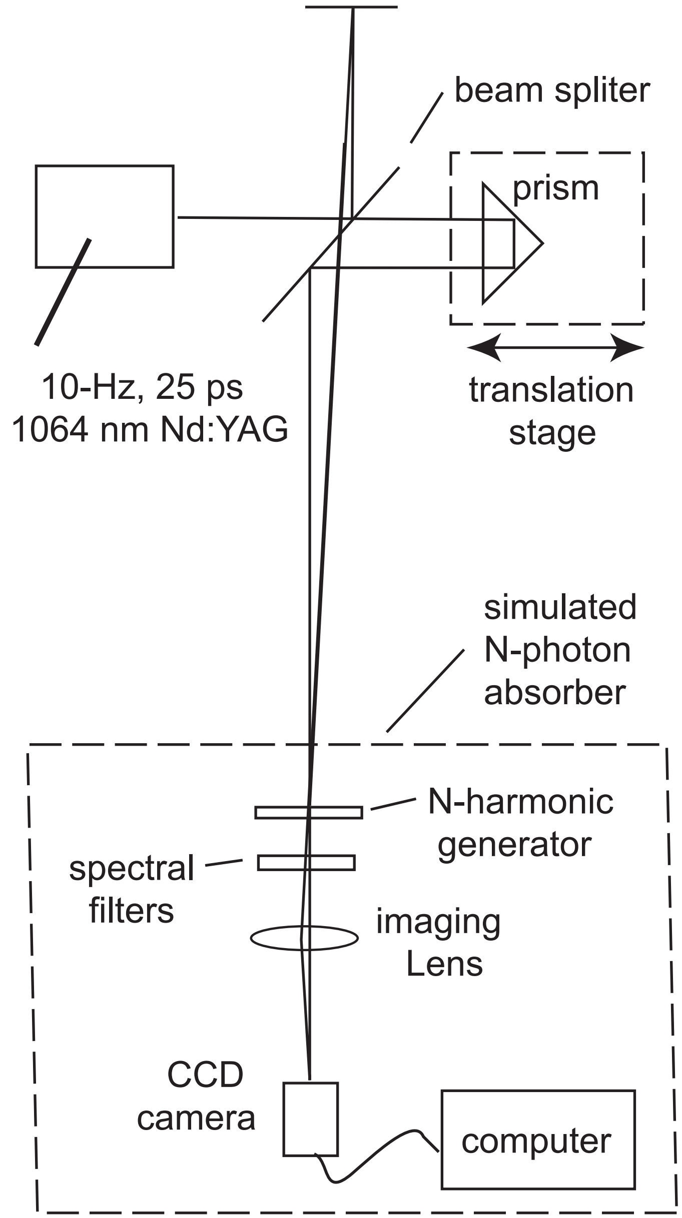
- Need an intense source of individual biphotons (Inconsistency?)

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

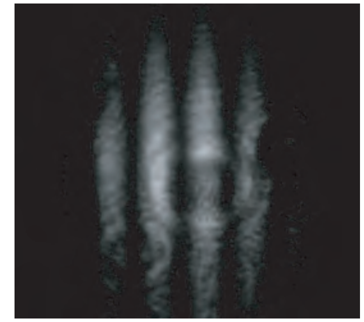
Classically Simulated (Non-Quantum) Quantum Lithography

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

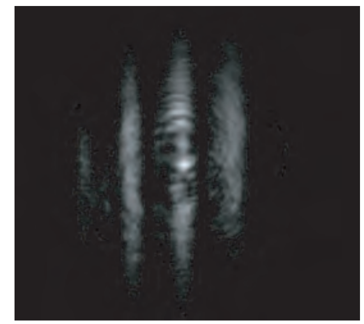




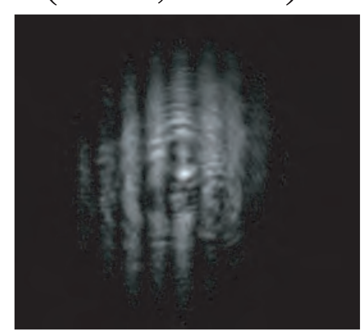
One-photon absorber (N=1, M=1)



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

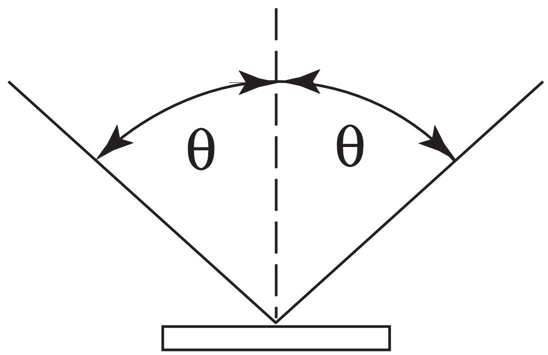


Two-photon absorber two exposures (N=2, M=2)



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

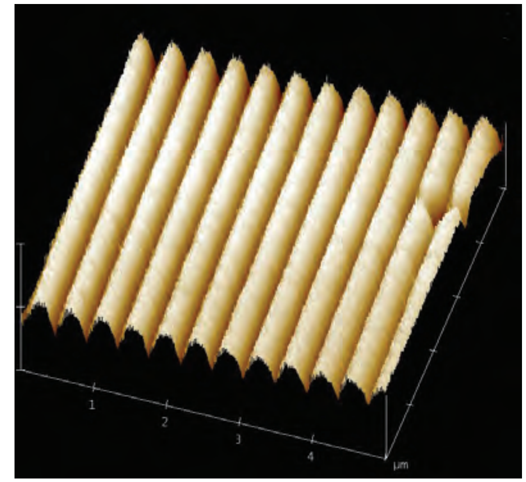
Demonstration of Fringes Written into PMMA



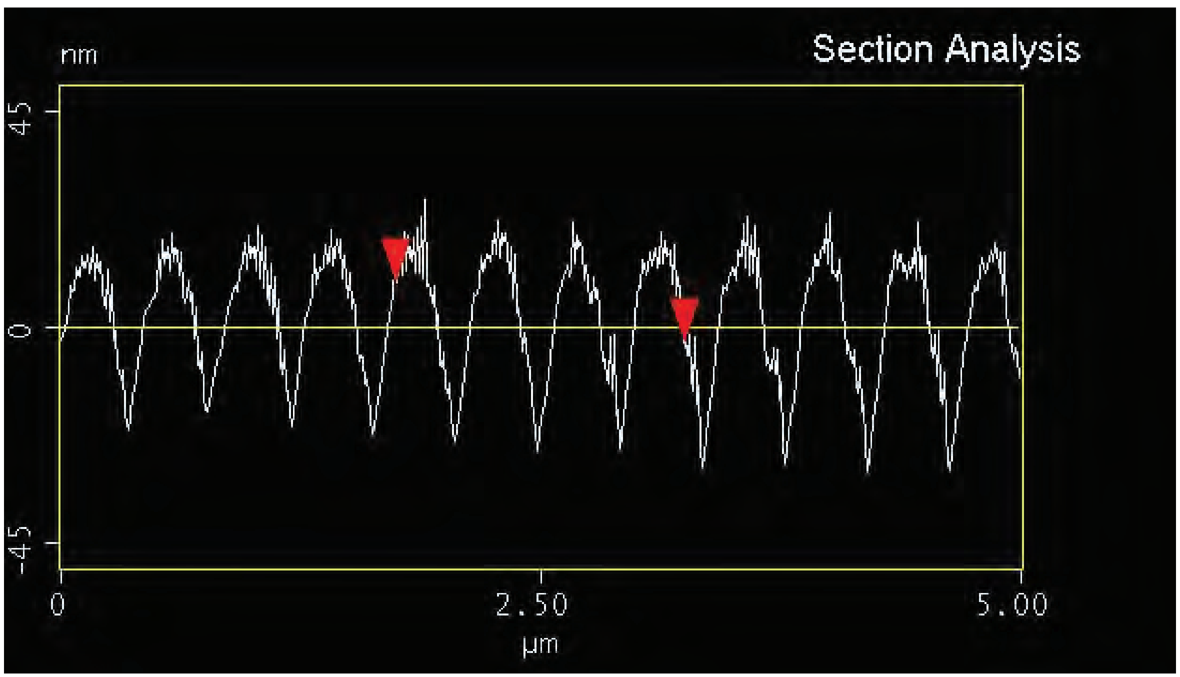
N-photon absorber
(N = 3 ?)

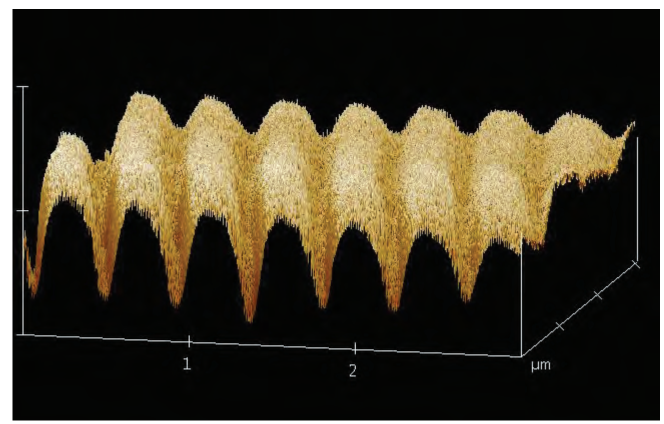
θ = 70 degrees
write wavelength = 800 nm
pulse energy = 130 µJ per beam
pulse duration = 120 fs
period = $\lambda / (2 \sin \theta)$ = 425 nm

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

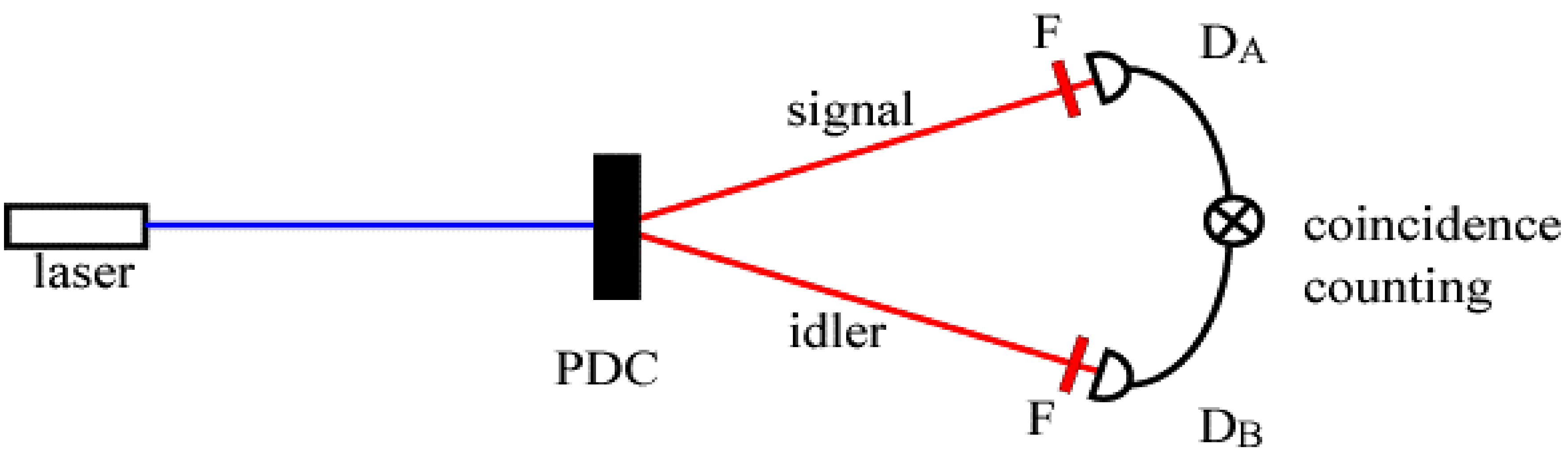
Institute of Optics, University of Rochester

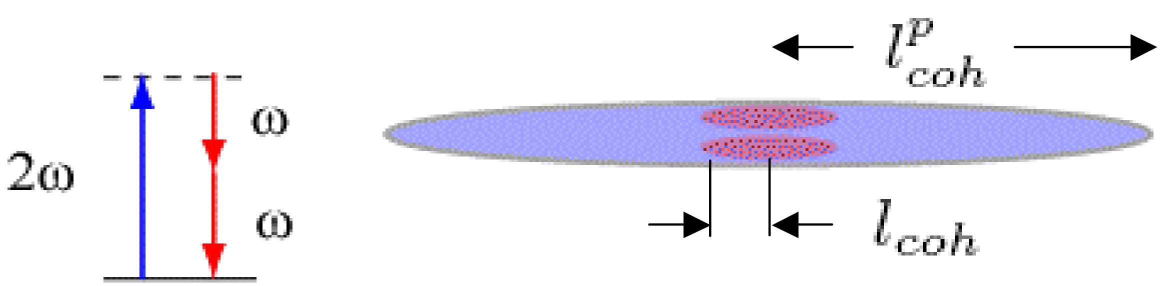
http://www.optics.rochester.edu/~boyd

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

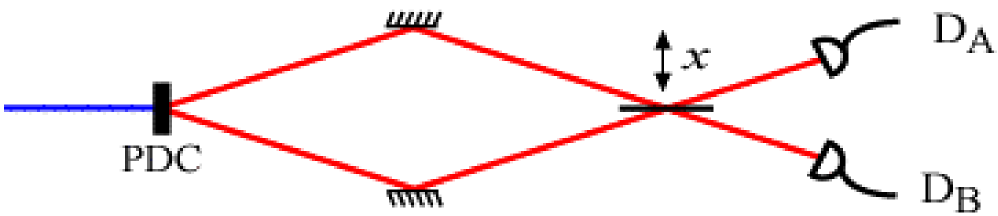
Coherence length of signal/idler photons ~ c/Δω ~ 100 μm.

Individual photons are entangled and can be made indistinguishable.

Two-Photon Interference -- How to Understand?

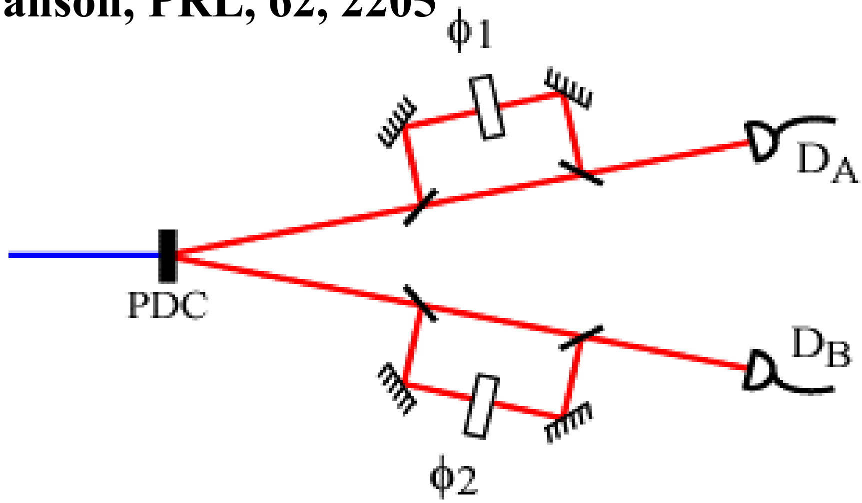
- **Hong-Ou-Mandel effect (1987)**

PRL, 59, 2044



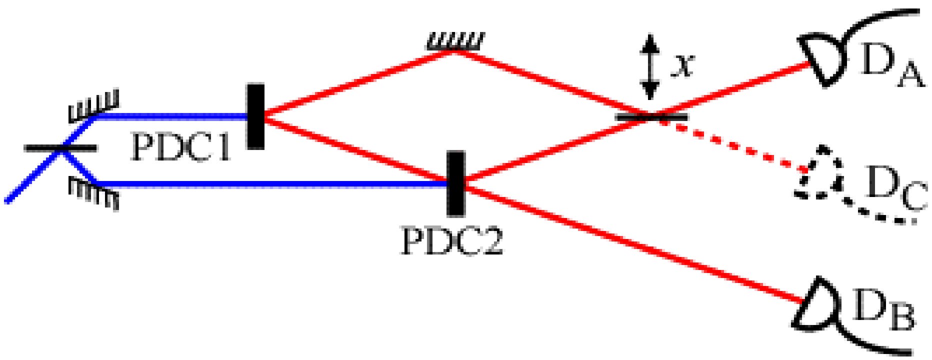
- **Bell Inequality for position and time (1989)**

Franson, PRL, 62, 2205



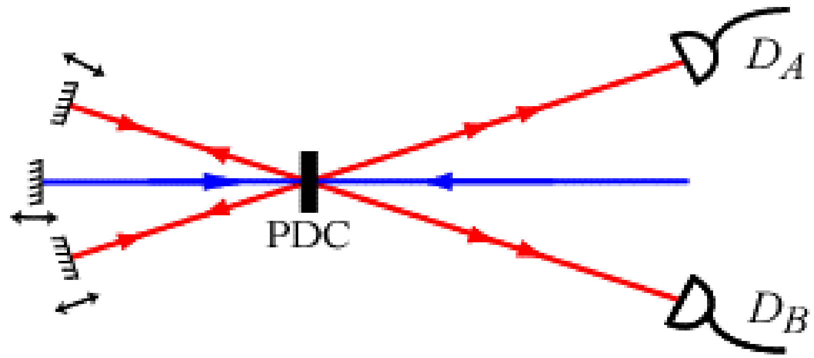
- **Induced Coherence (1991)**

Zou et al. PRL, 67, 318

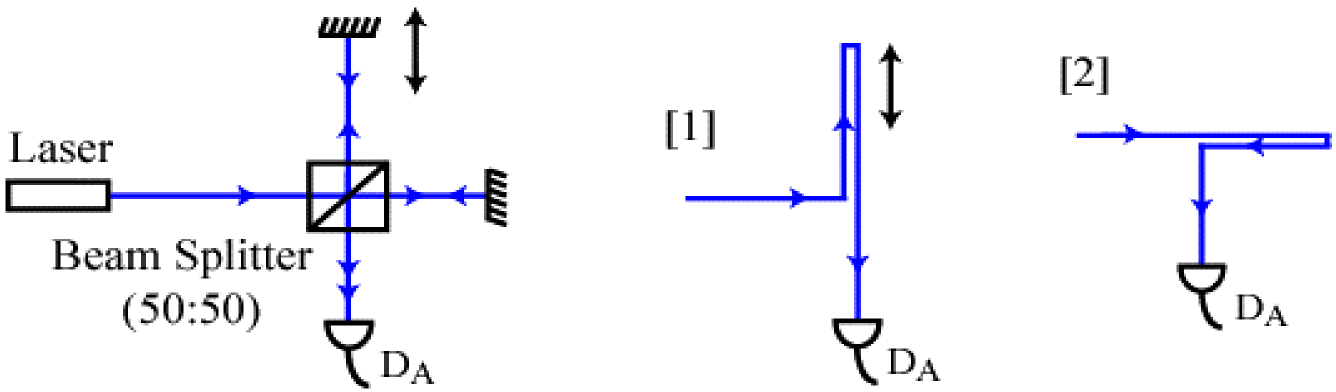


- **Frustrated two-photon creation (1994)**

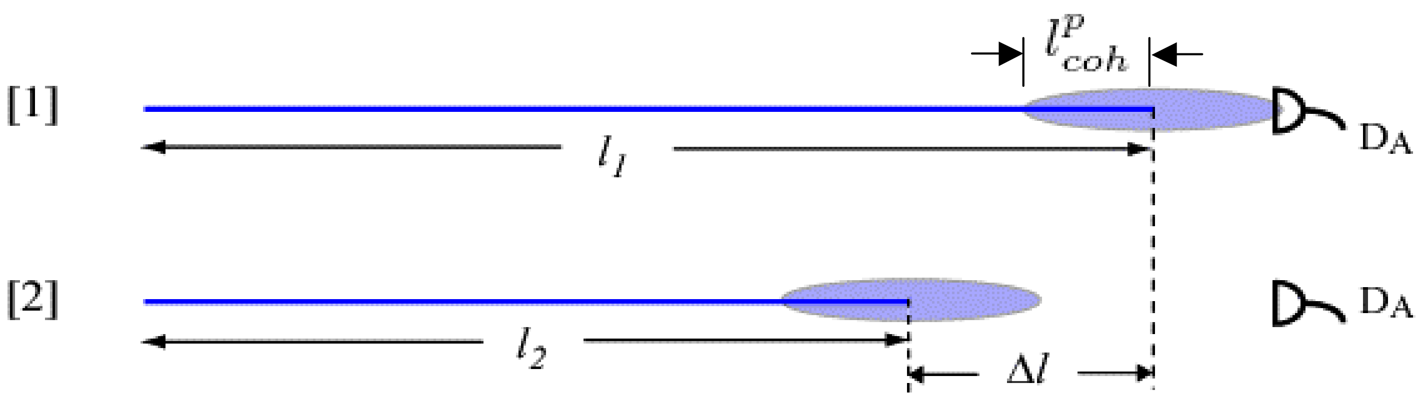
Herzog et al. PRL, 72, 629



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



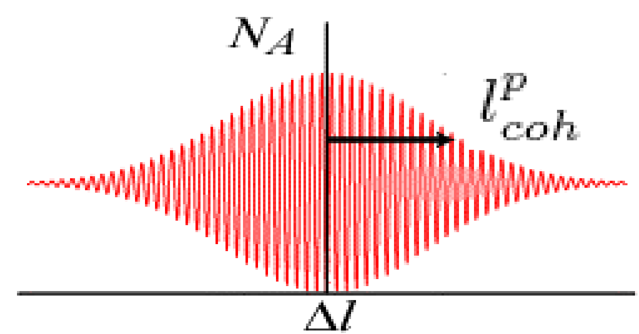
Add probability amplitudes for alternative pathways [1] and [2]



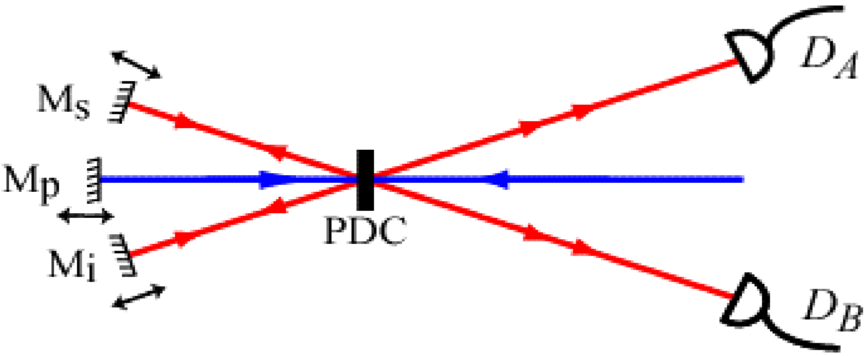
(unfolded paths)

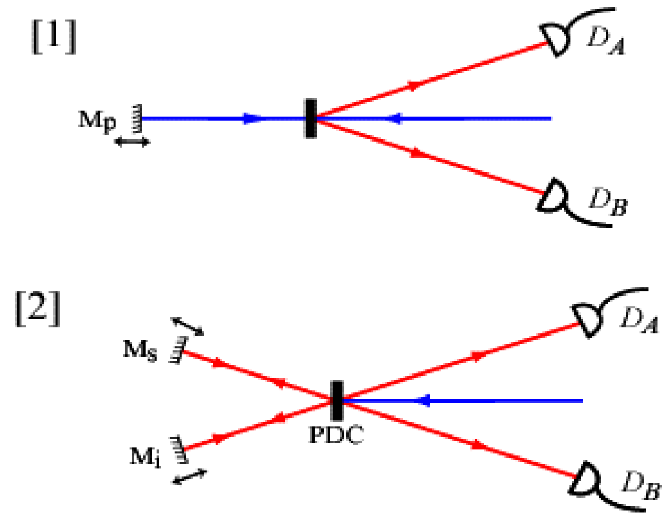
Necessary condition for one-photon interference

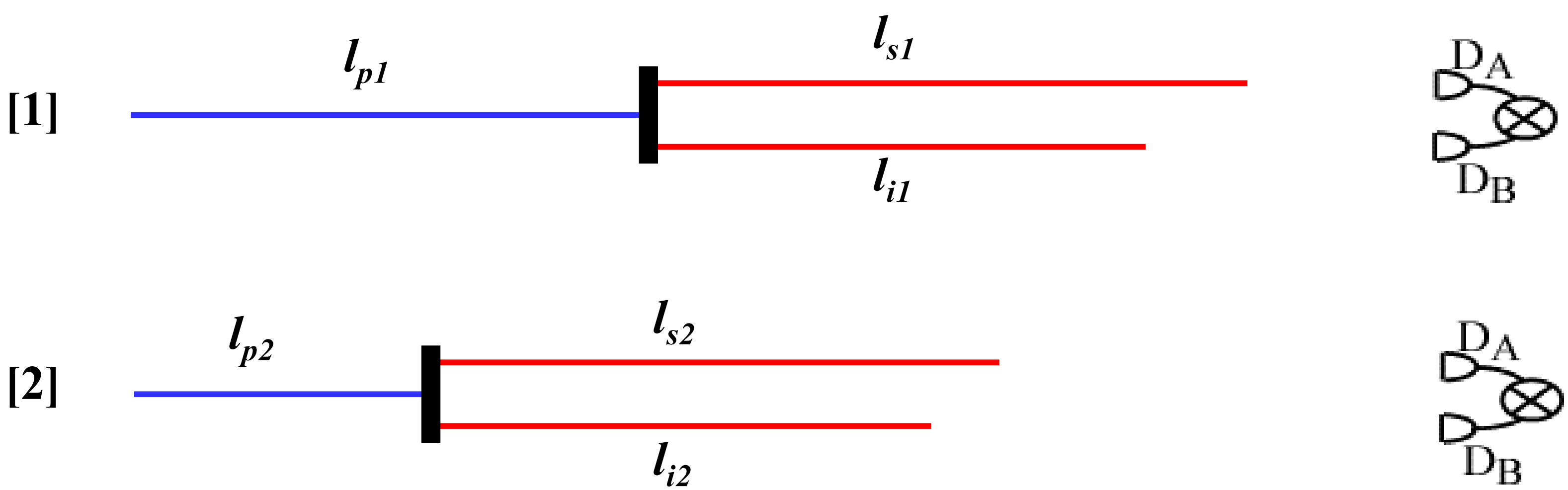
$$\Delta l < l^{p}_{coh}$$



What about biphoton interference? (Generic setup)

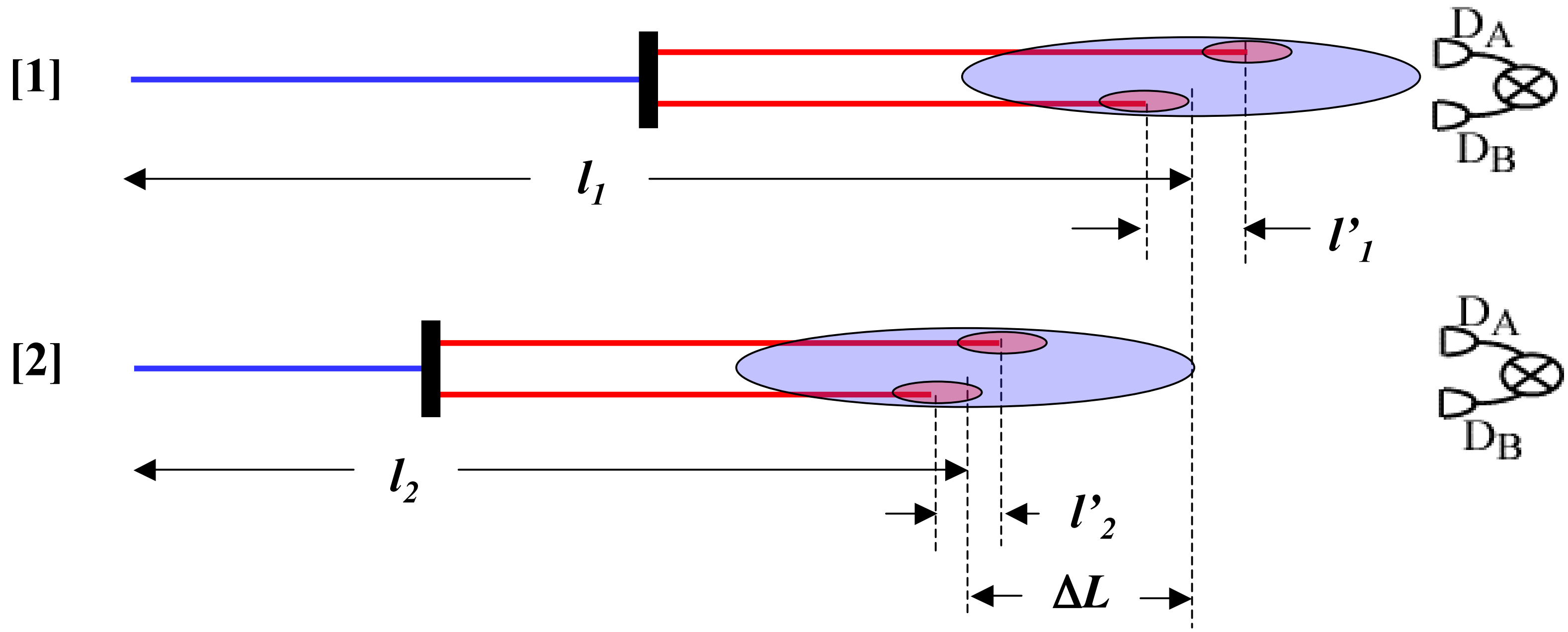






Probability amplitudes for pathways [1] and [2] add to produce interference.

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:

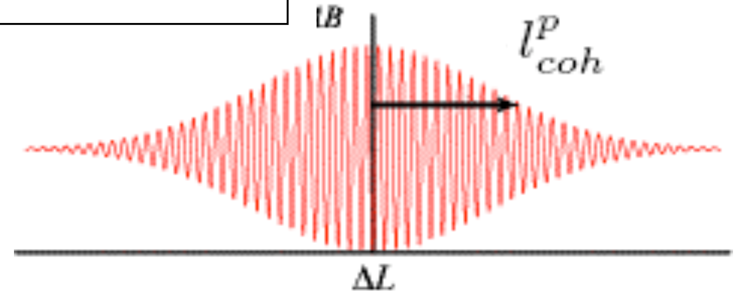
$$\Delta L \; < \; l^p_{coh}$$

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

Two-Photon Interference (two special cases)

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

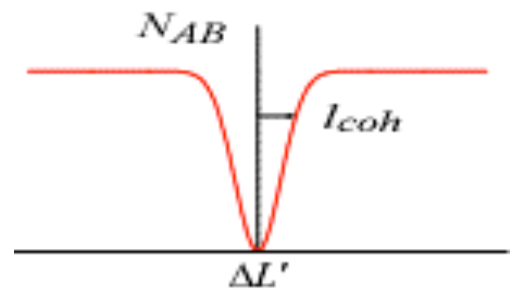
Cases I : $\Delta L' = 0$



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

- **ΔL plays the same role in two-photon interference as Δl does in one-photon interference**

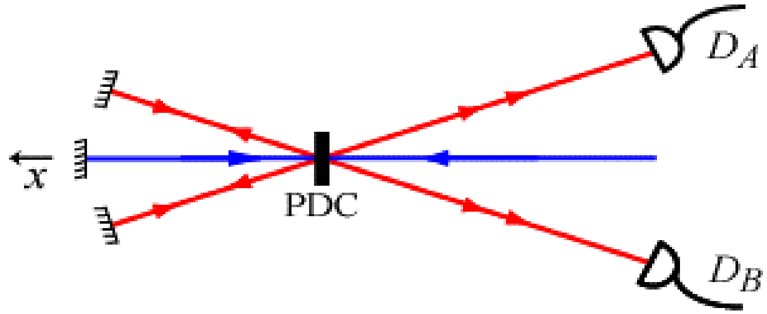
Cases II : $\Delta L = 0$

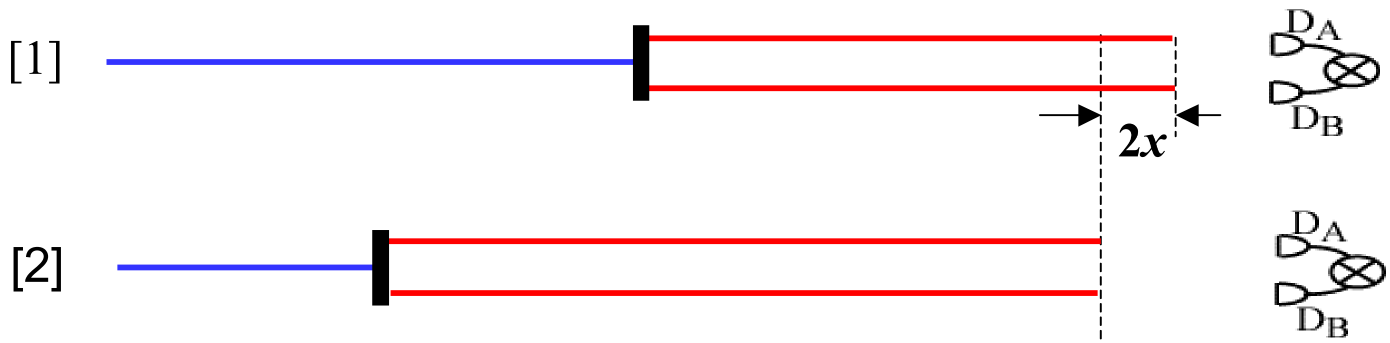


$$N_{AB} \propto \quad 1-\gamma'\left(\Delta L'\right) = 1 - e^{-\frac{1}{2}\left(\frac{\Delta L'}{l_{coh}}\right)^2}$$

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

Two-Photon Interference (Procedure 1)

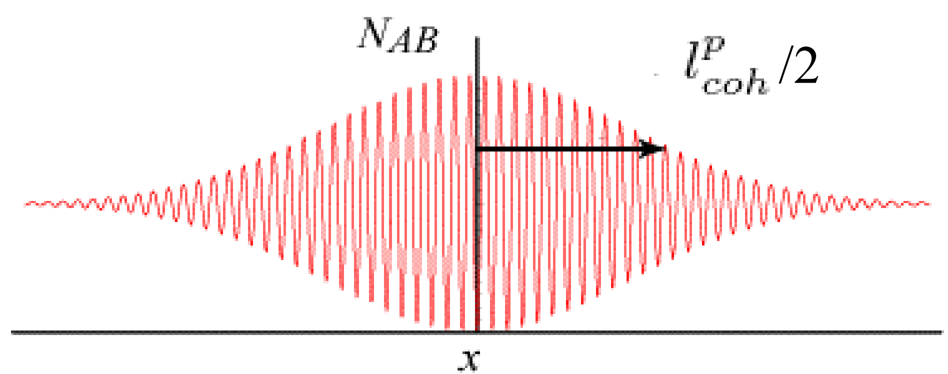




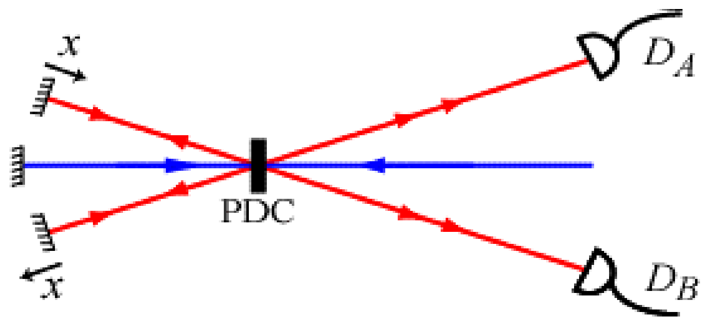
$\Delta L = 2x$
$\Delta L' = 0$

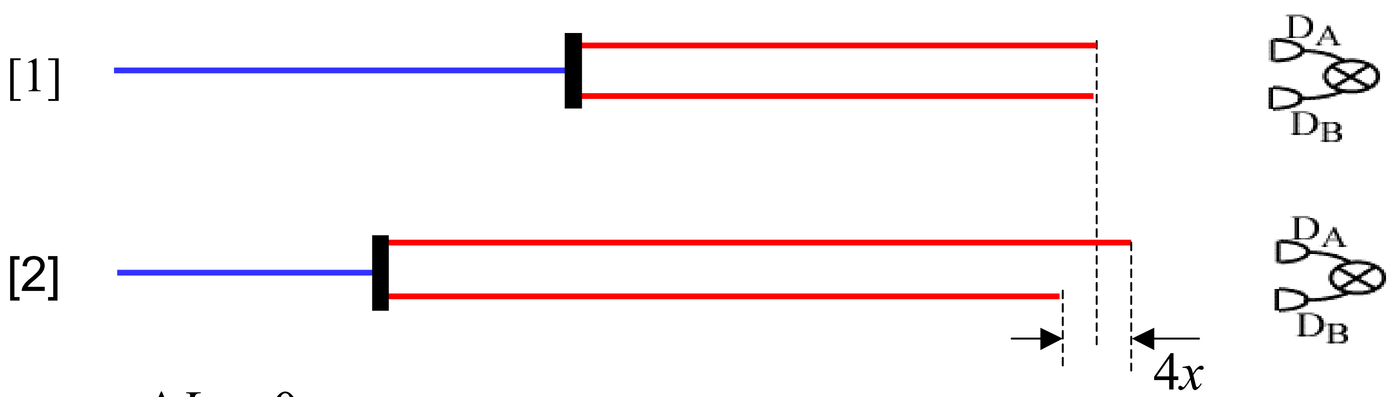
$$N_{AB} \propto \quad 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

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



Two-Photon Interference (Procedure 2)



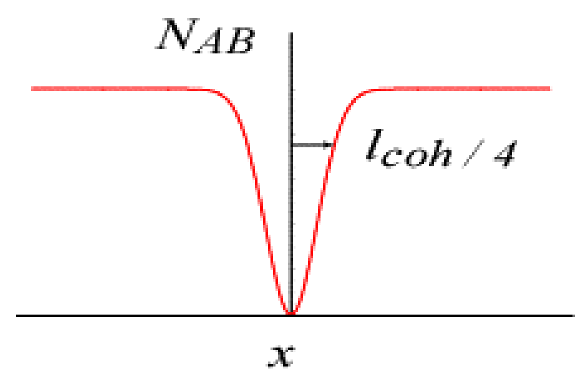


$\Delta L = 0$

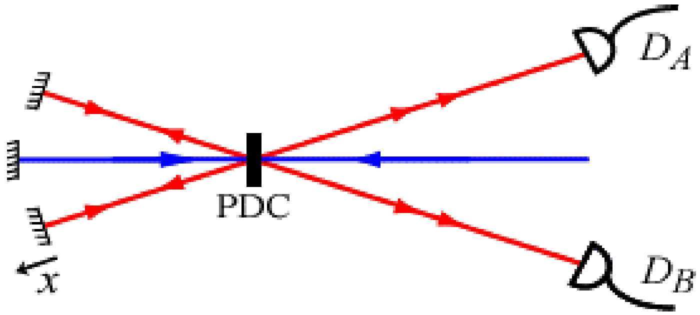
$\Delta L' = 4x$

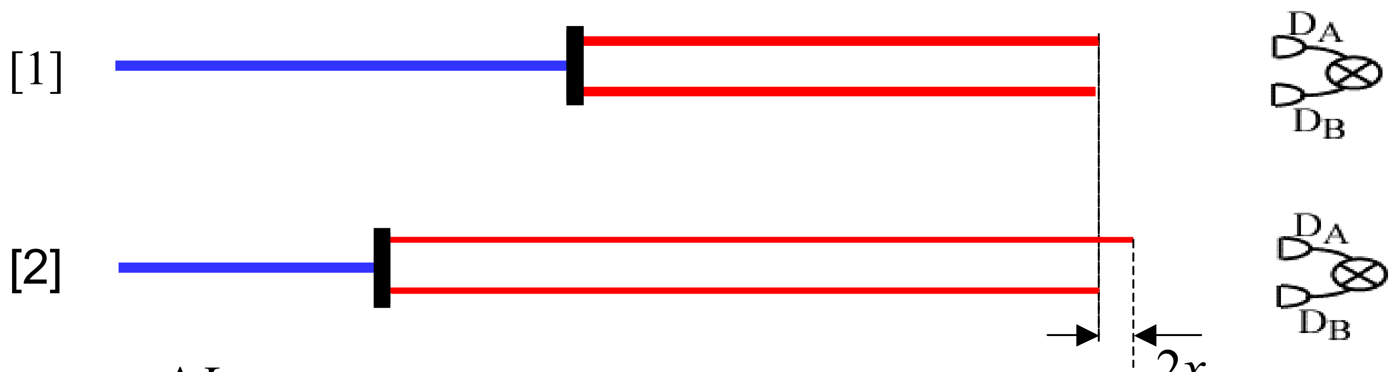
$$N_{AB} \propto \quad 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

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



Two-Photon Interference (Procedure 3)



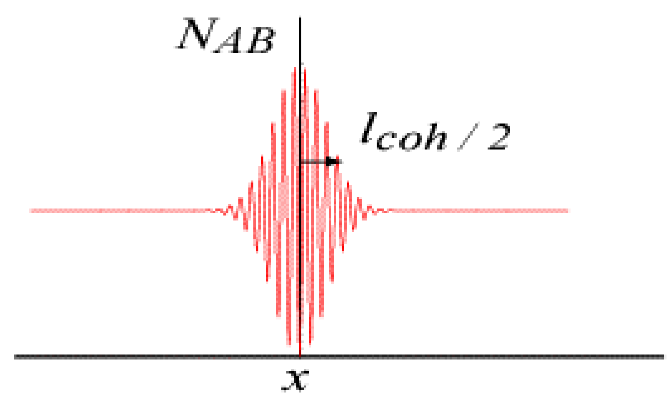


$\Delta L = x$

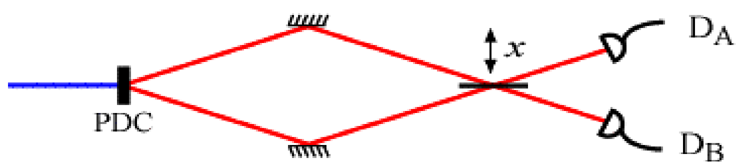
$\Delta L' = 2x$

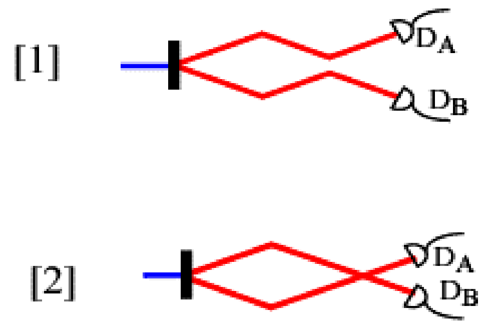
$$N_{AB} \propto \ 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

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

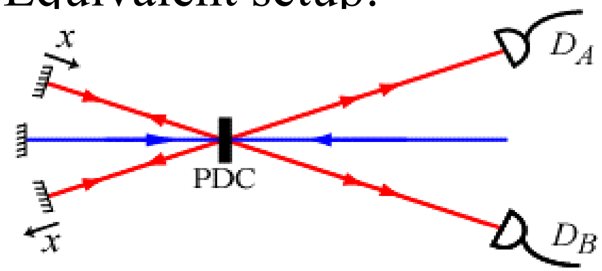


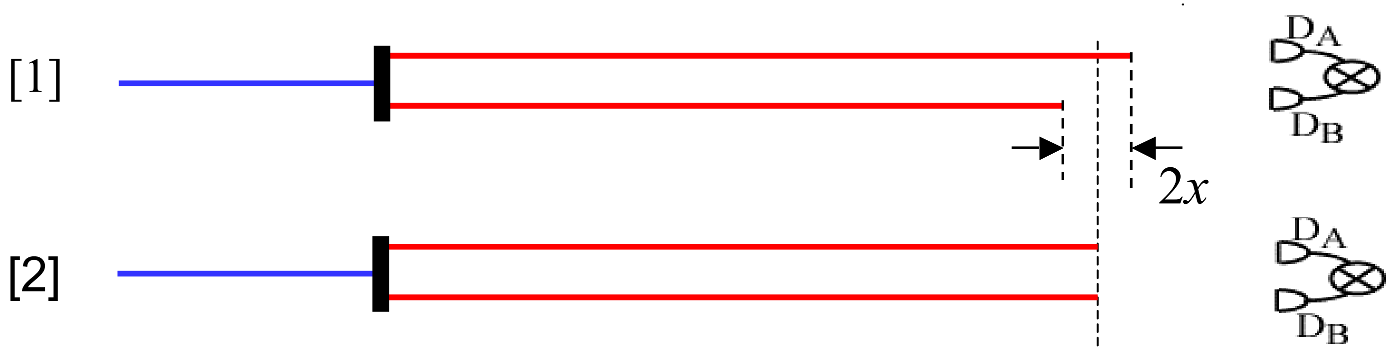
Hong-Ou-Mandel Experiment



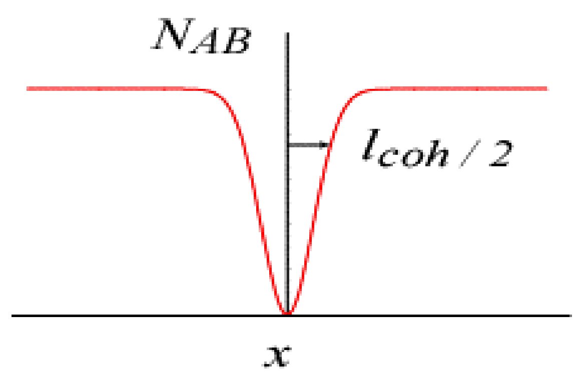


Equivalent setup:





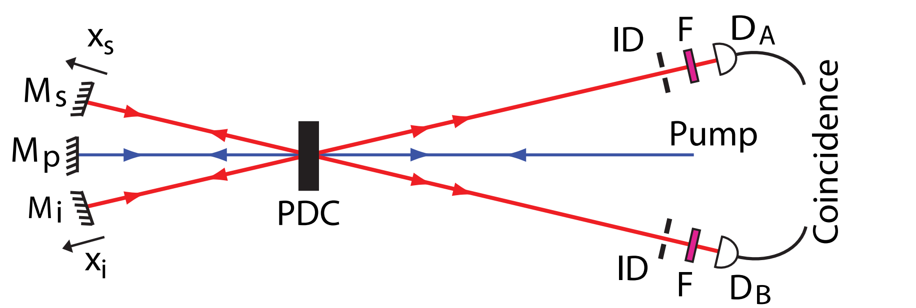
$\Delta L = 0 \qquad \Delta L' = 2x$

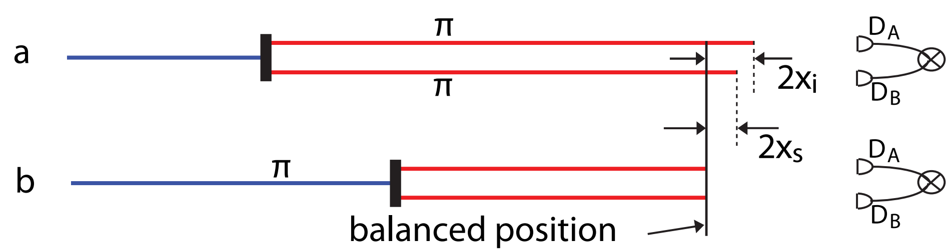


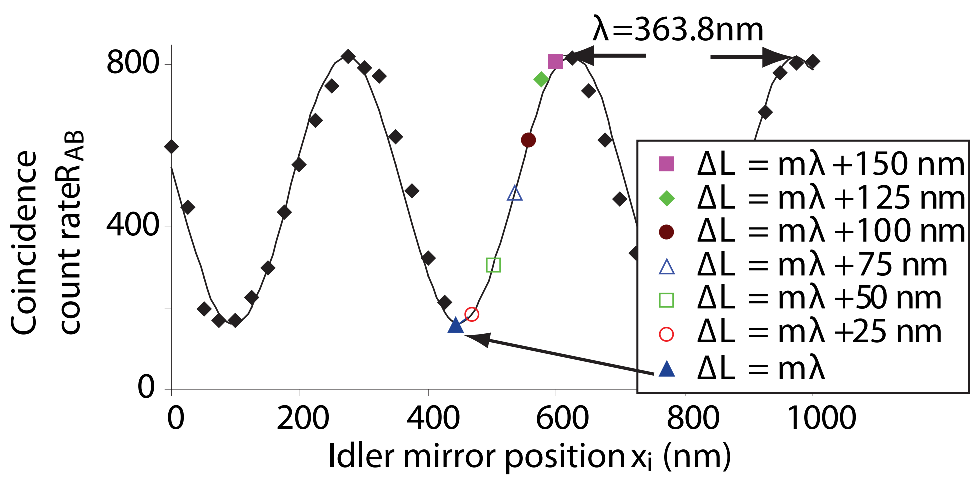
$$N_{AB} \propto \; 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

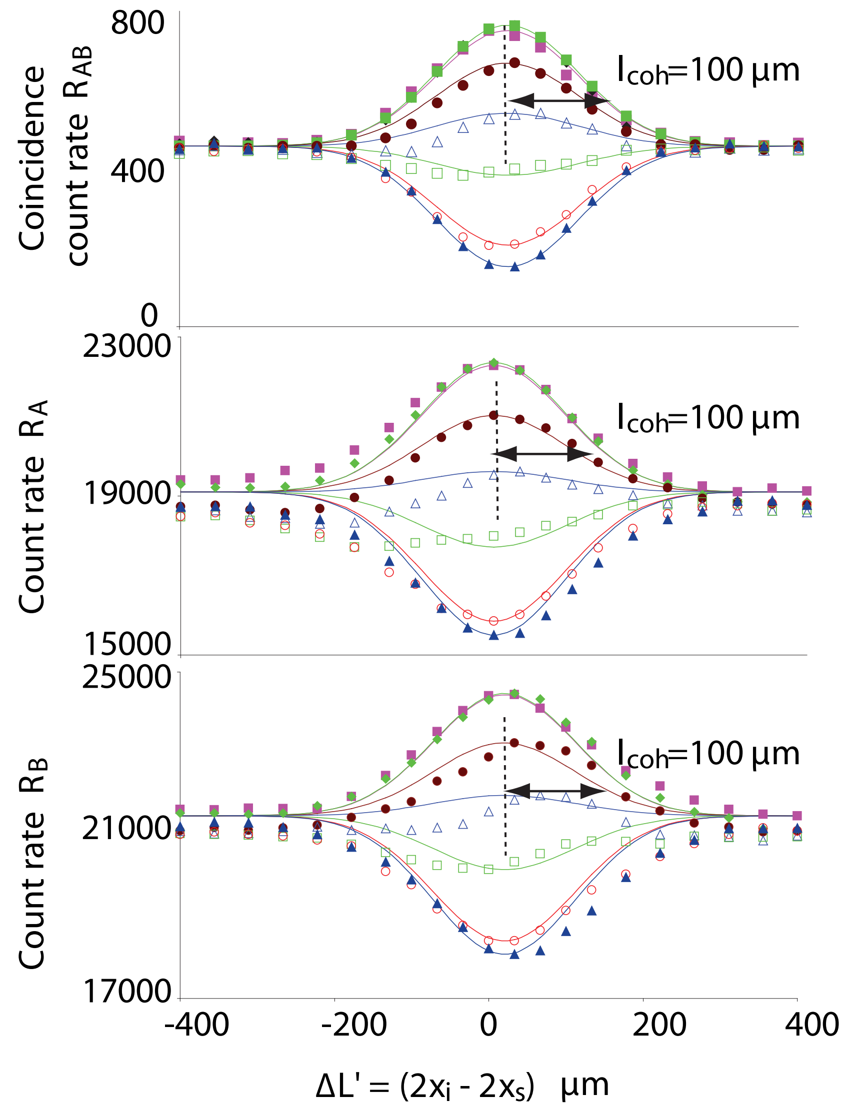
$$N_{AB} \propto \; 1 - \gamma'(2x)$$

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!

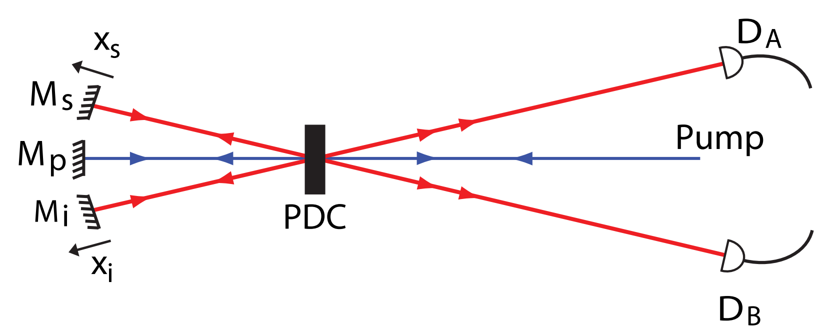
Note that: $$R_{\mathrm{X}} = \sum_i R_{\mathrm{XY}_i}$$

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

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

Thus:

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



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**

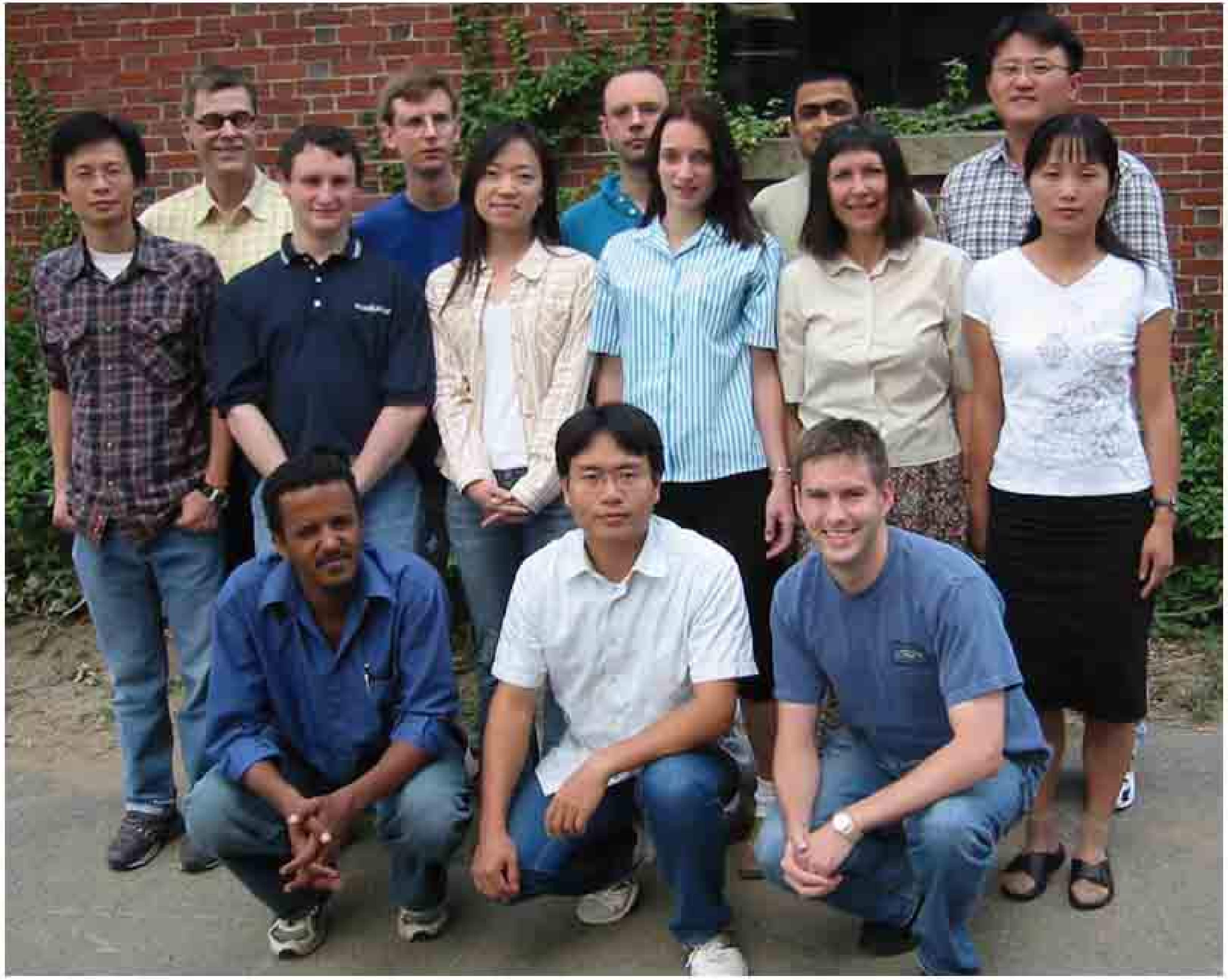
Wen I Wang

Kam **Wai** Chan

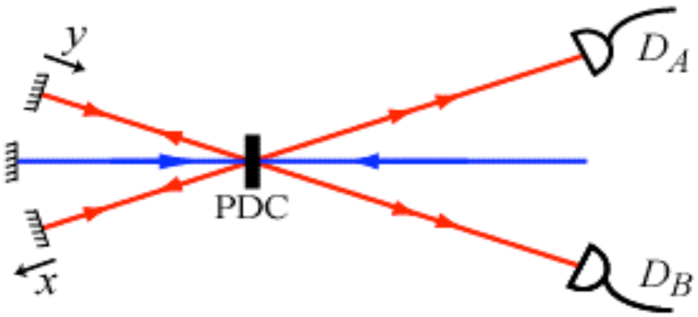
Not to mention

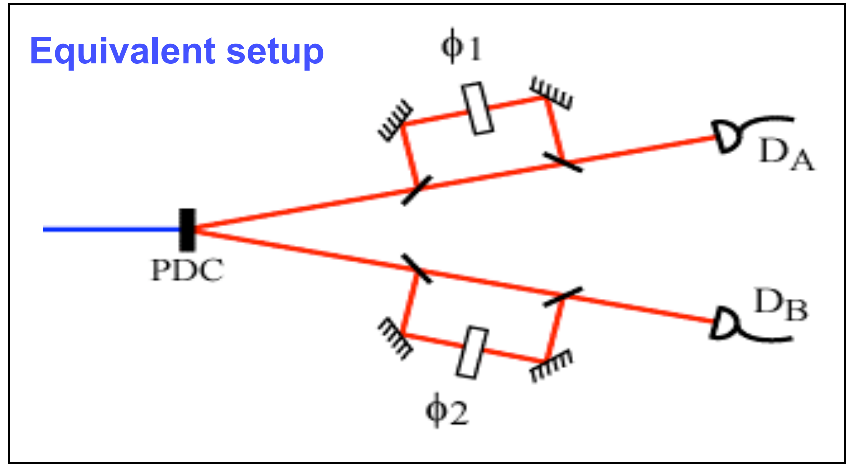
Lene **Hau**

Special Thanks to My Students and Research Associates



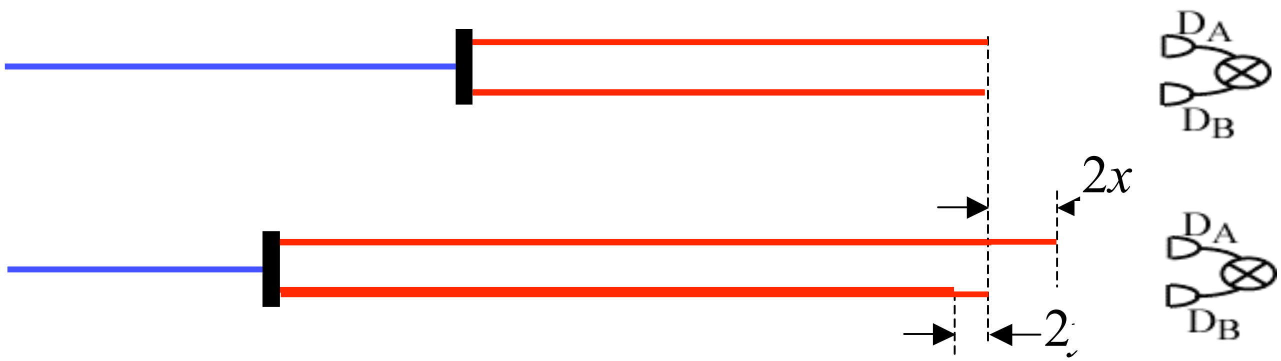
Bell's Inequality for Position and Time





[1]

[2]



$\Delta L = x\text{-}y \qquad \Delta L' = 2x+2y$

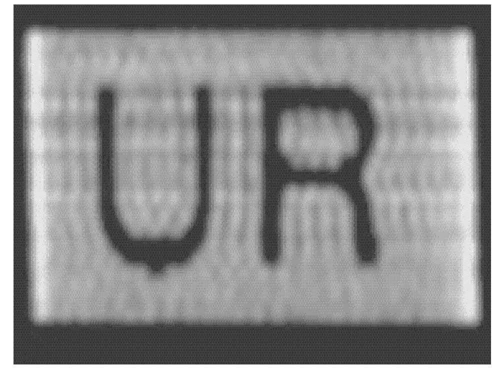
$x, y << \quad l^{p}_{coh} \quad l_{coh}$

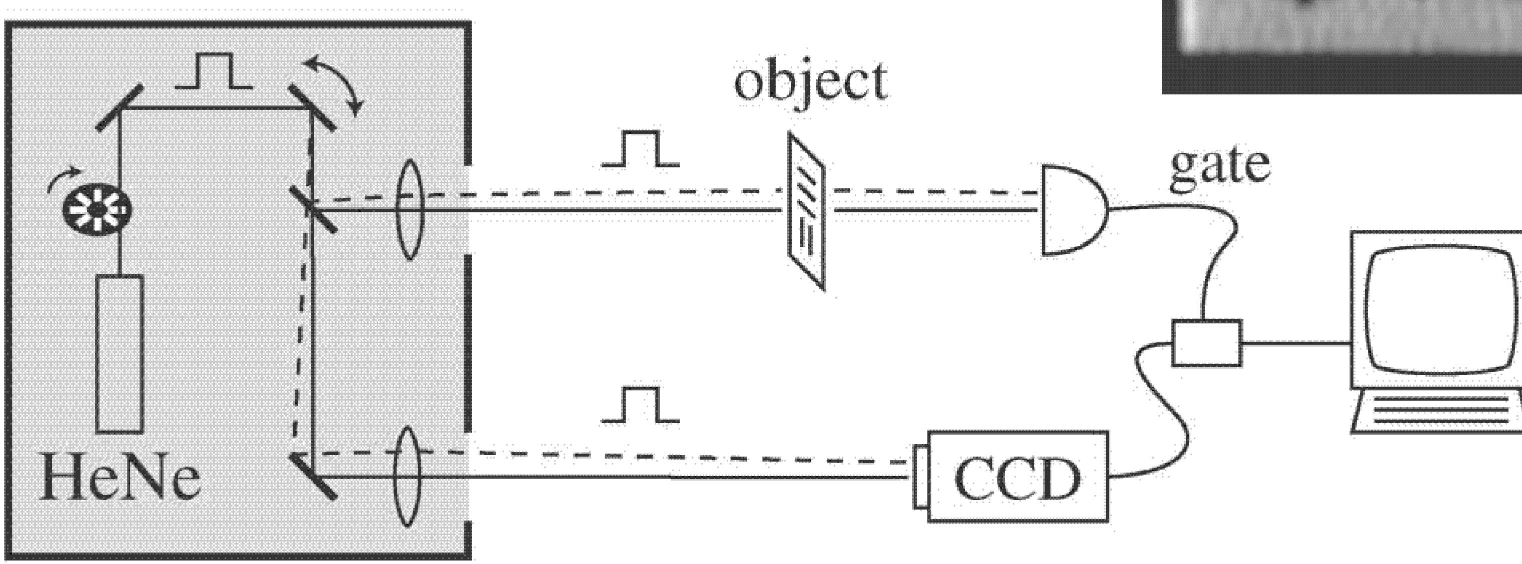
$$N_{AB} \propto \quad 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

$$N_{AB} \propto \quad 1 - \cos[k_0(x-y)]$$

Classical Coincidence Imaging

We have performed coincidence imaging with a demonstrably classical source.





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

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

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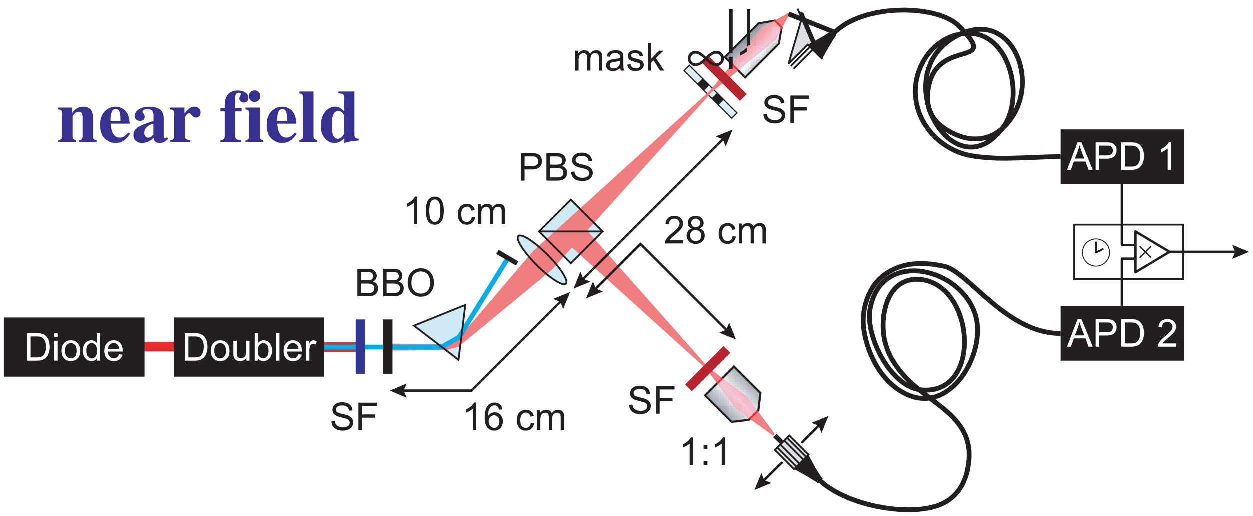
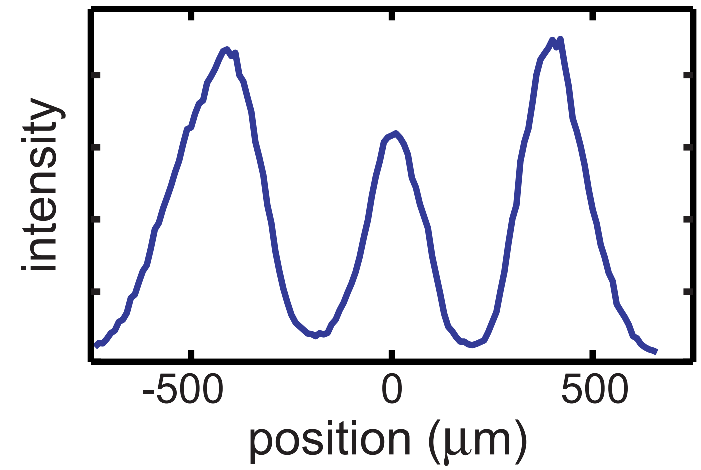
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain.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

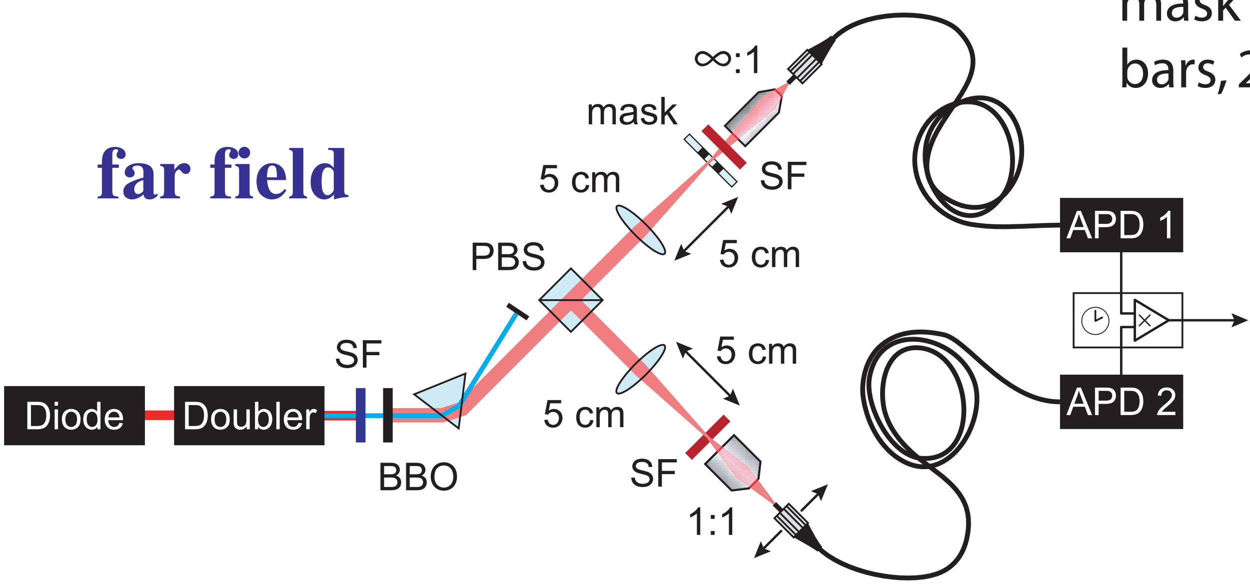
near field

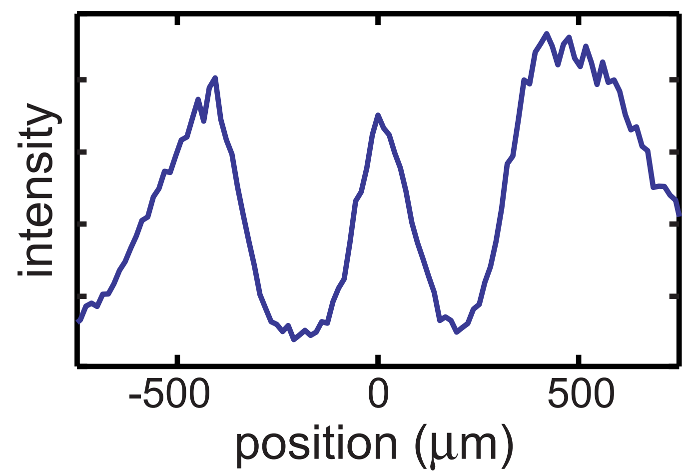




mask (object) is two opaque bars, 200 μm wide

far field



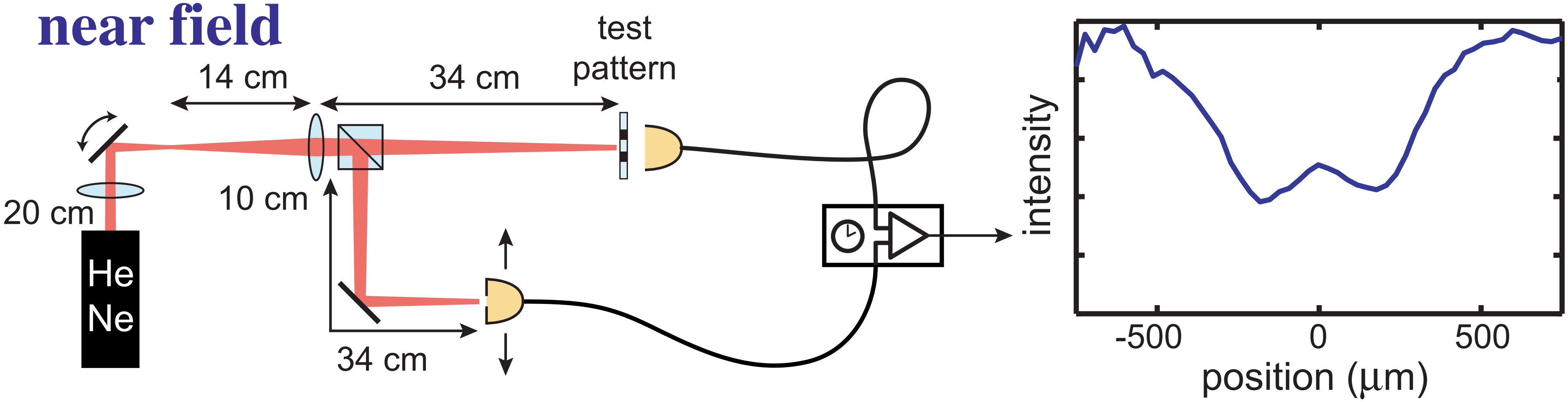


Good imaging observed in both the near and far fields!

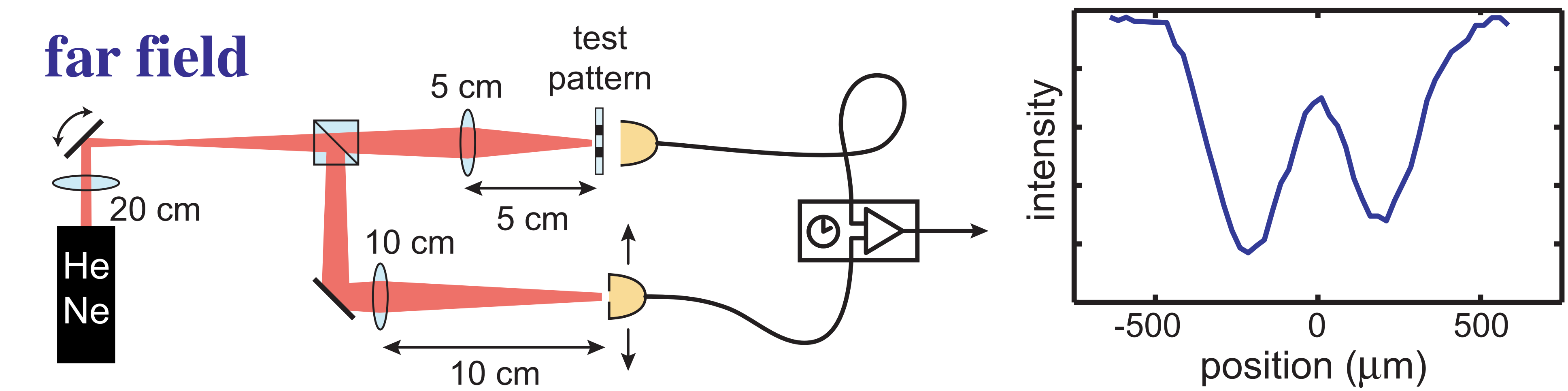
Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

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.