Quantum Imaging: Enhanced Image Formation Using Quantum States of Light

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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?

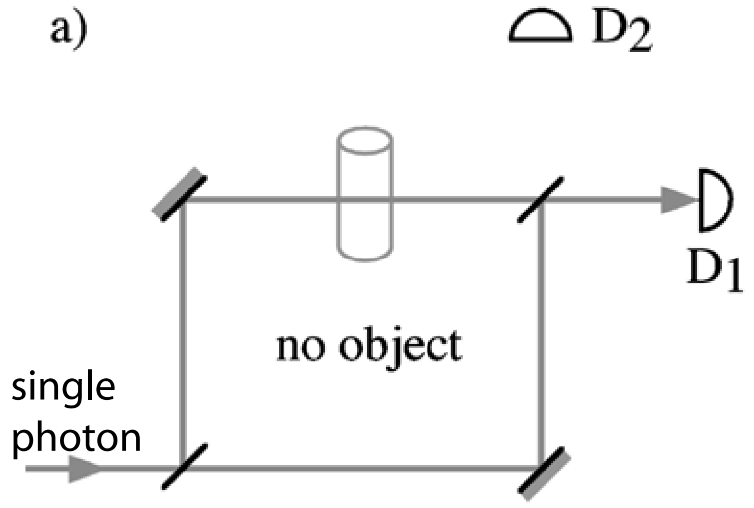
What are the implications of “interaction free” and “ghost” imaging

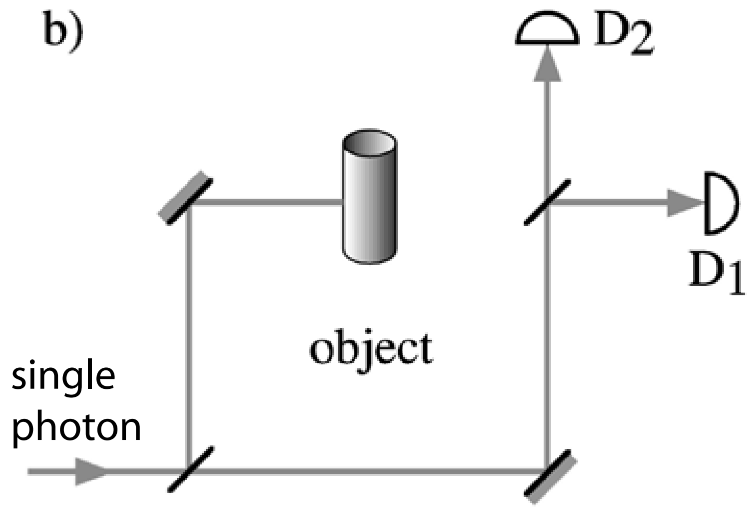
Quantum states of light: For instance, squeezed light or entangled beams of light.

Stealth Imaging

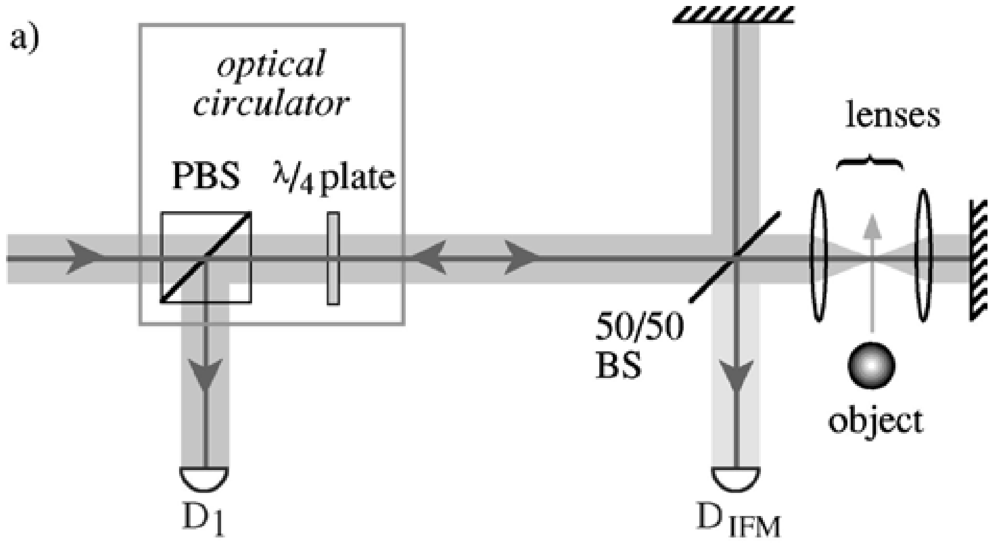
Interaction-Free Imaging and Ghost Imaging

Quantum Imaging by Interaction-Free Measurement





imaging setup

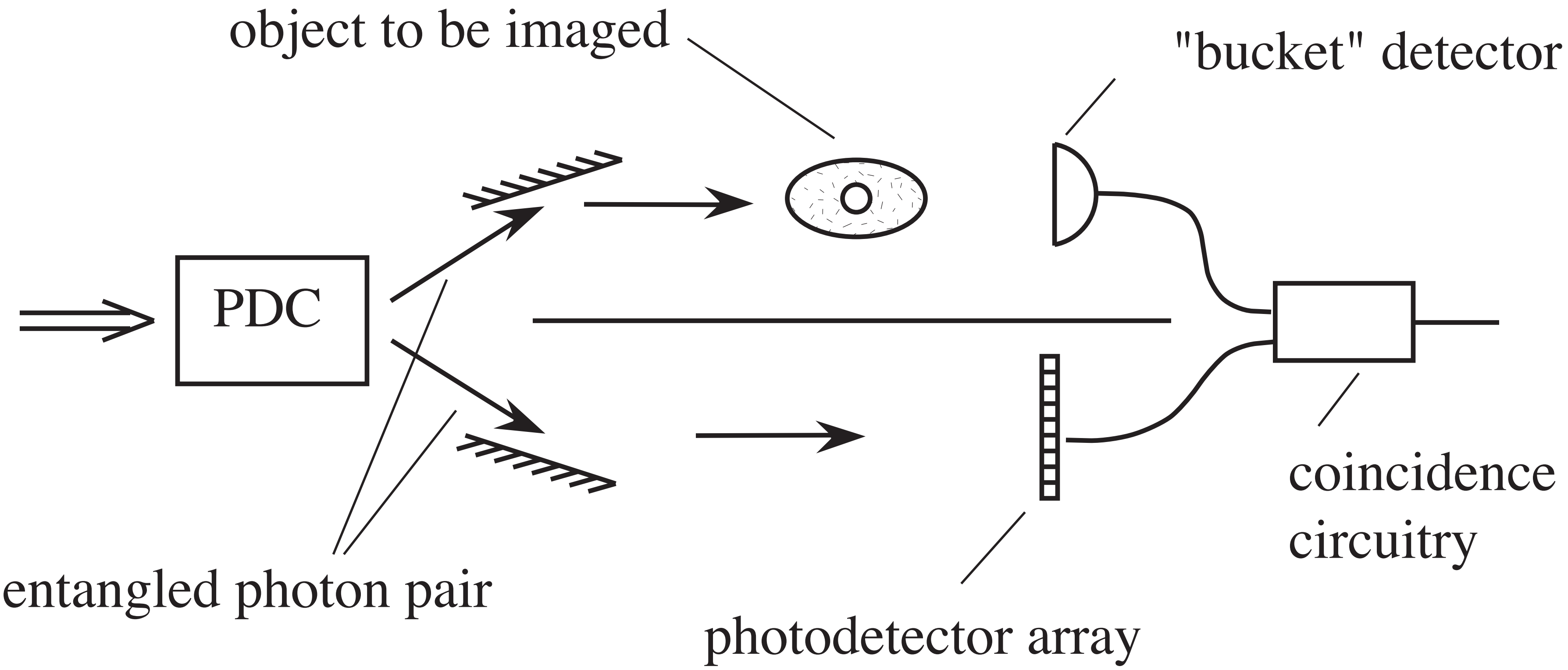


A. Elitzur and L. Vaidman, Foundations of Physics, 23 987 (1993).

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



object to be imaged

"bucket" detector

PDC

entangled photon pair

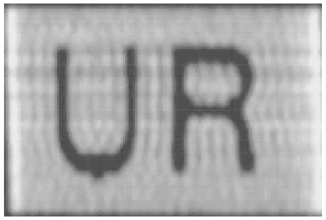
photodetector array

coincidence circuitry

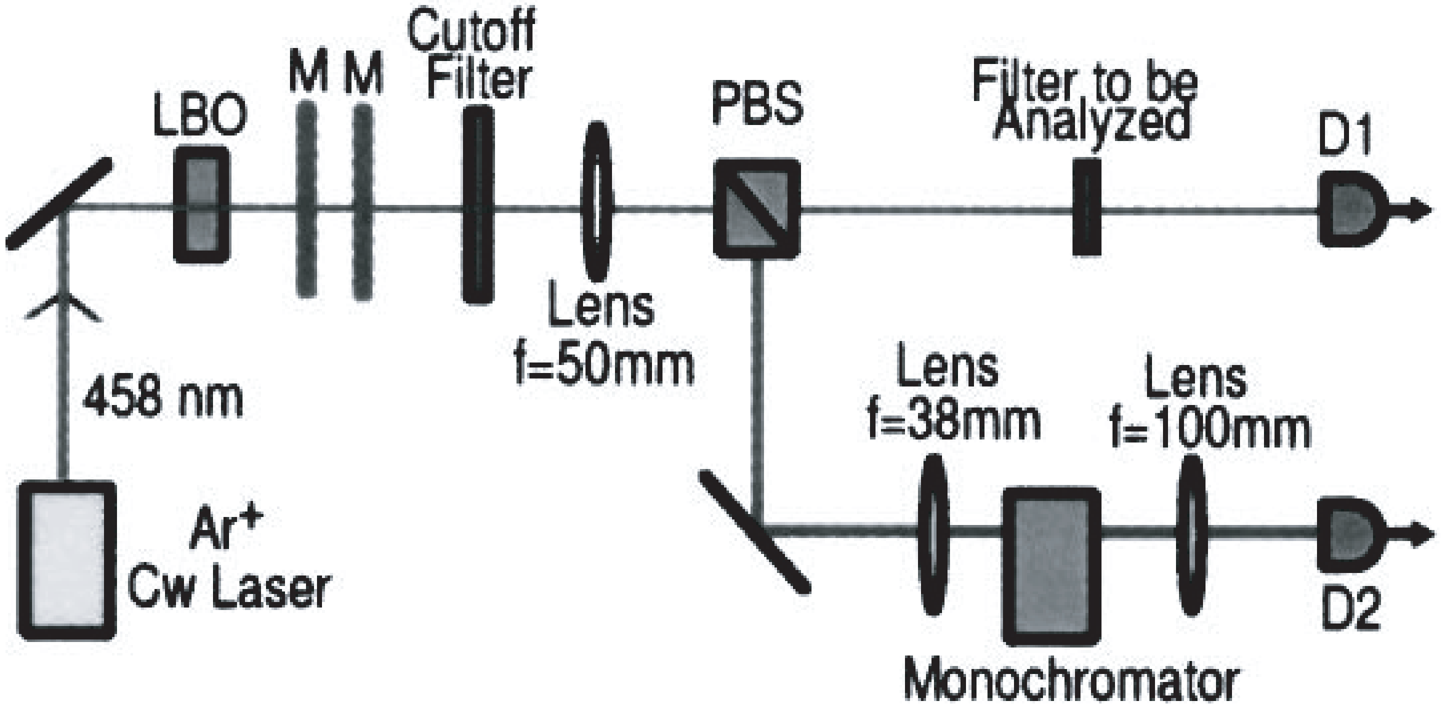
- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)

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)



Remote (Ghost) Spectroscopy



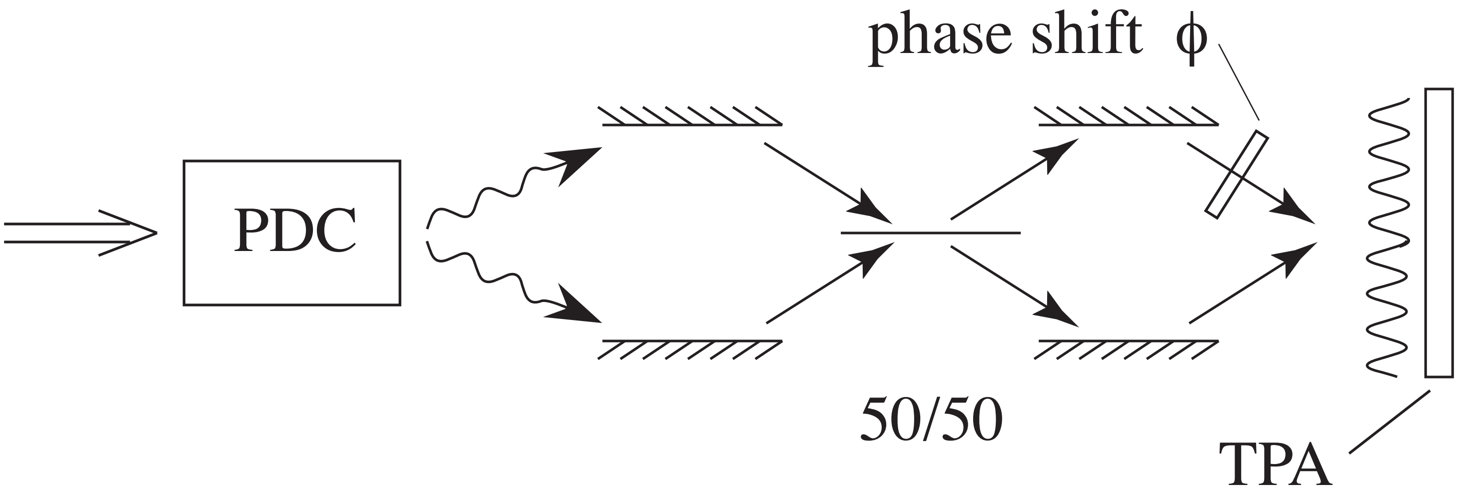
Can this idea be implemented with thermal light?

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

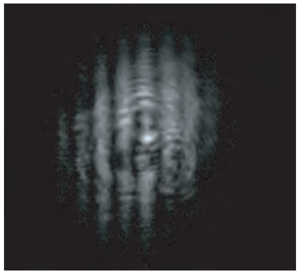
See also the related work of Bellini et al., Phys. Rev. Lett. 90 043602 (2003).

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



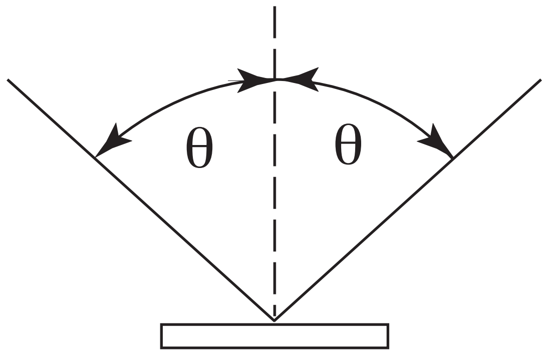
Boto et al., Phys. Rev. Lett. 85, 2733, 2000.



Classical analog

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

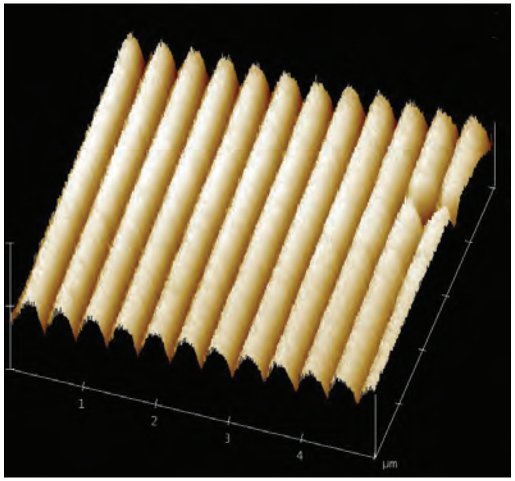
Demonstration of Fringes Written into PMMA



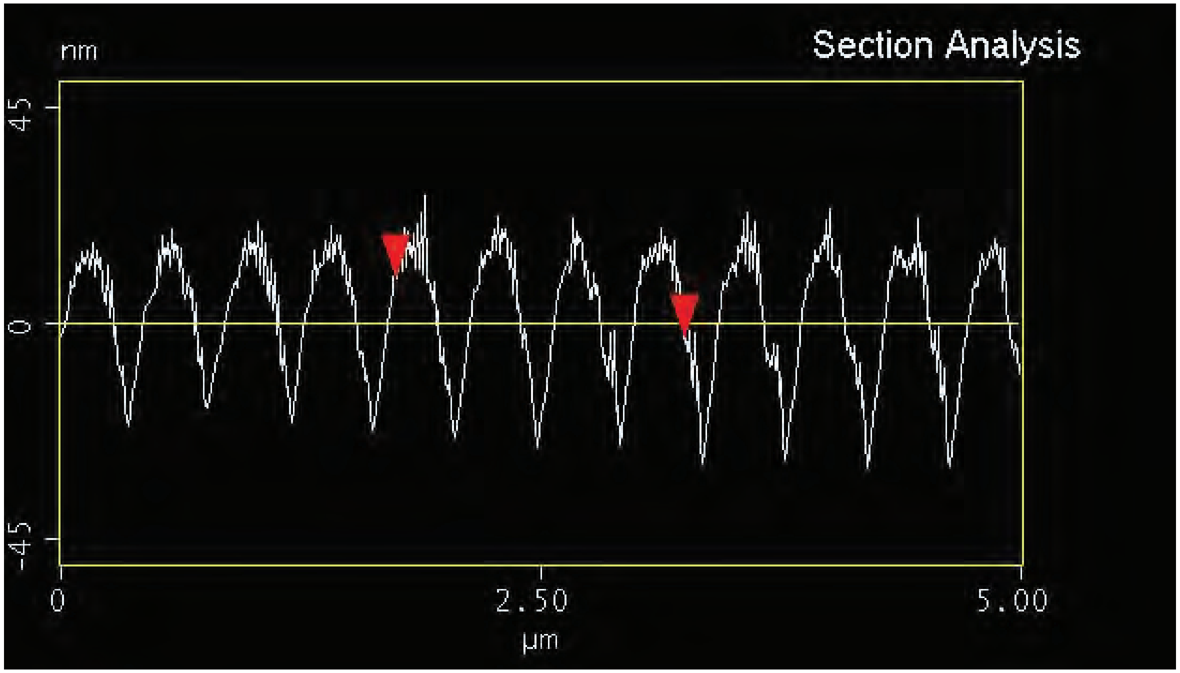
N-photon absorber
(N = 3 ?)

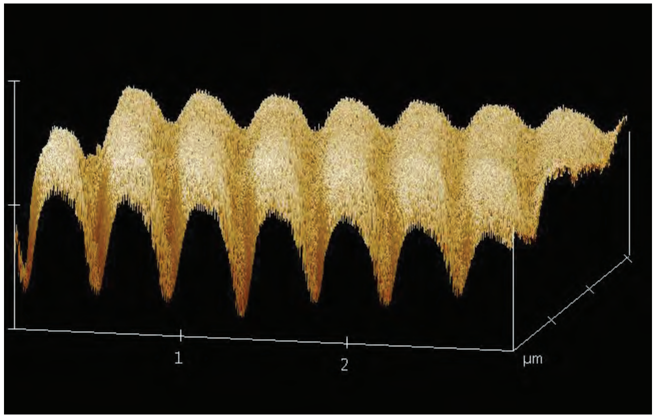
θ = 70 degrees
write wavelength = 800 nm
pulse energy = 130 μJ per beam
pulse duration = 120 fs
period = λ / (2 sin θ) = 425 nm

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).

Boyd Group Research Program

- Single photon imaging (joint with Howell group)
  - full image encoded on a single photon
- Entanglement propagation through turbulence
- Nature of two-photon interference
  - observation of generalized HOM interference
- Development of photon-number-resolving detectors
  - Bayesian analysis can improve performance of TMD
- Quantum lithography
  - careful dosimetry measurements of recording materials

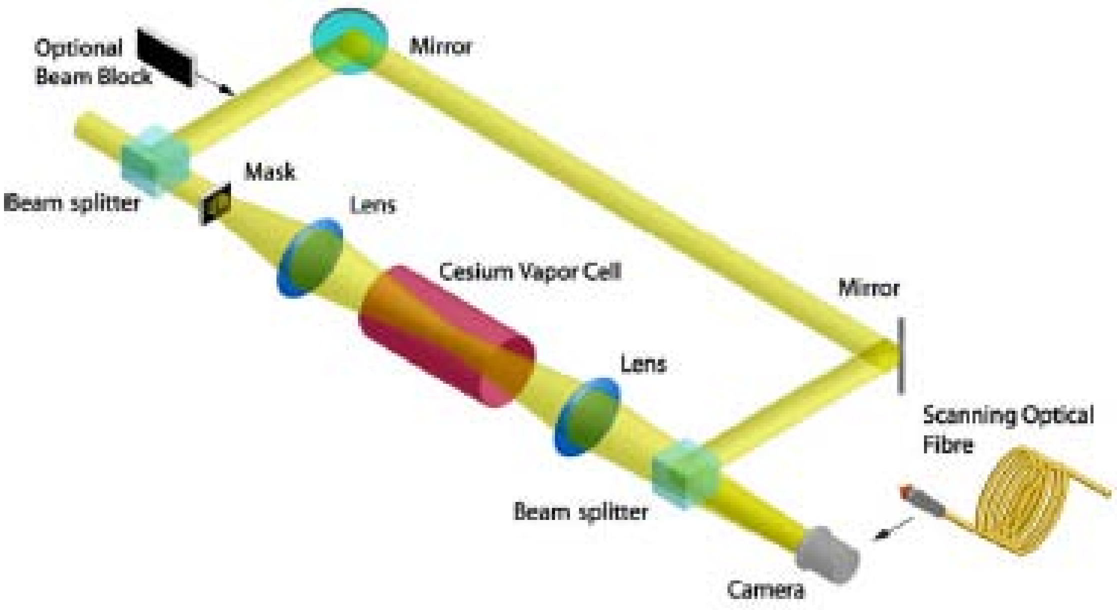
Single-Photon Imaging

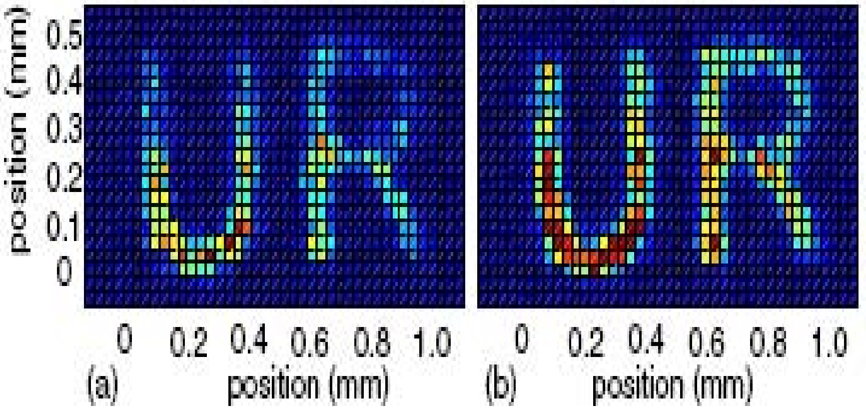
Joint Project: Boyd and Howell Groups

Petros Zerom, Heedeuk Shin, others

- We want to impress an entire image unto a single photo 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)

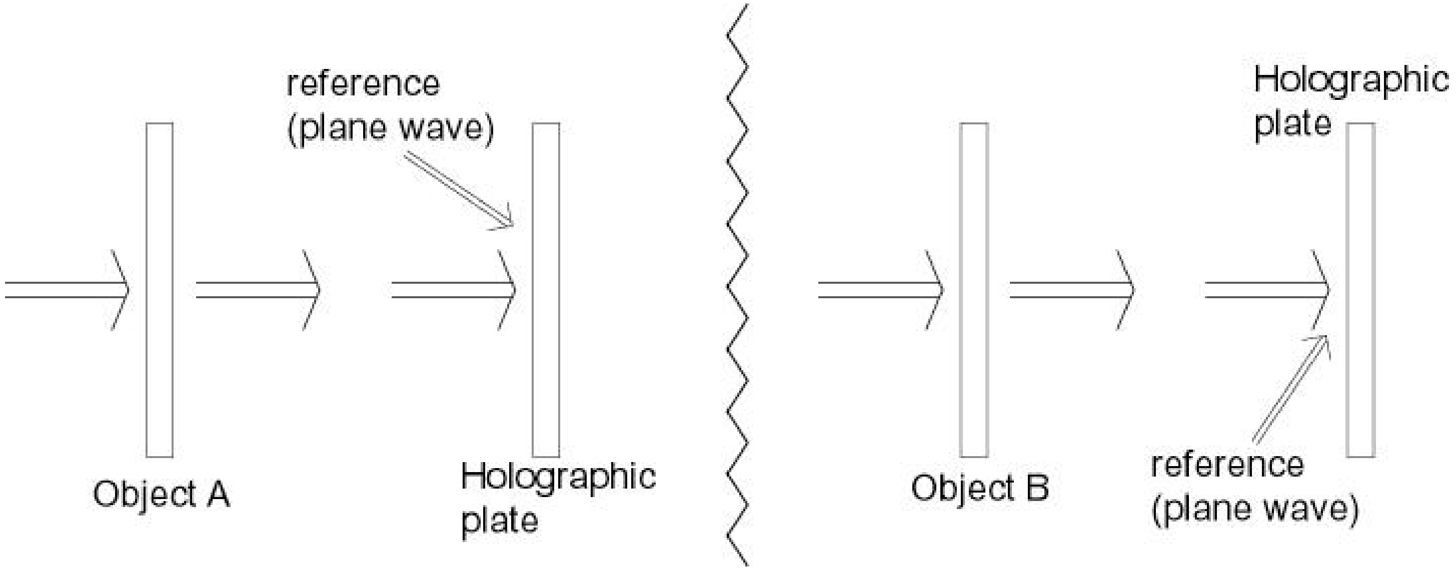
Non-delayed

- 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

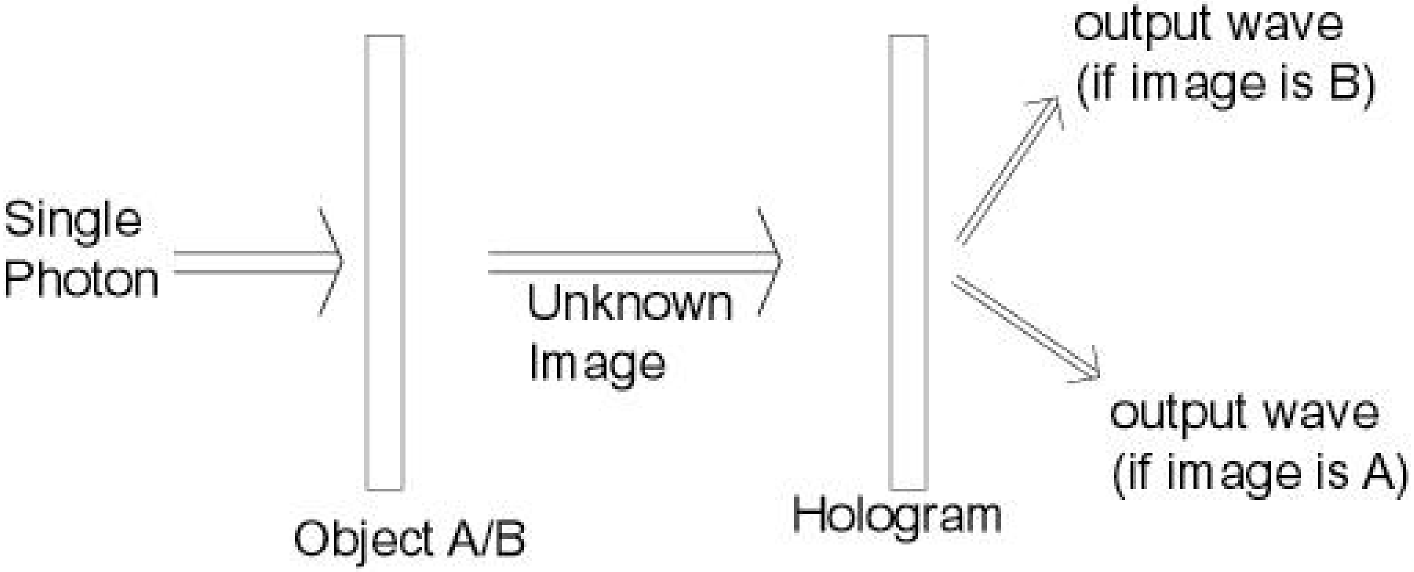
R. M. Camacho, *et al, PRL* ***98****, 043902 (2007)*

Holography, matched filtering, and single-photon Imaging

- Writing the matched filter (a multiple exposure hologram)

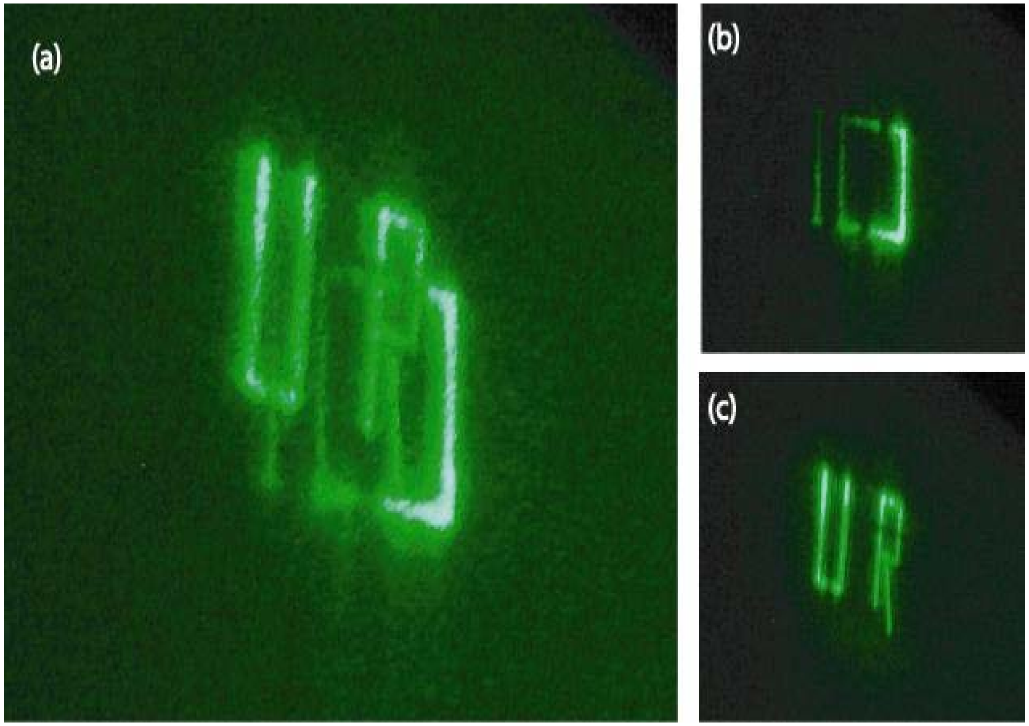


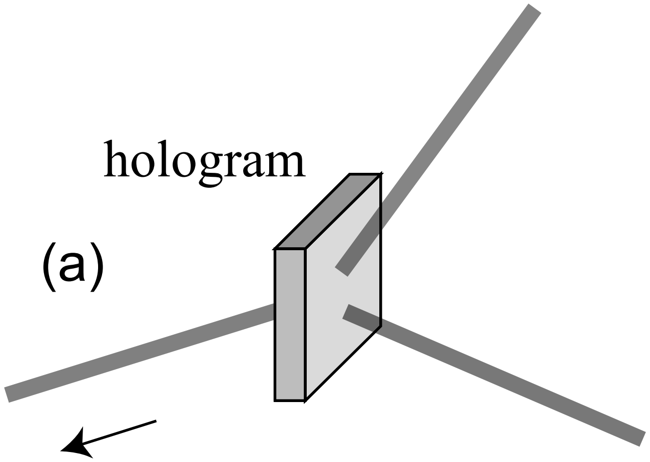
- Reading the hologram (with a single-photon)

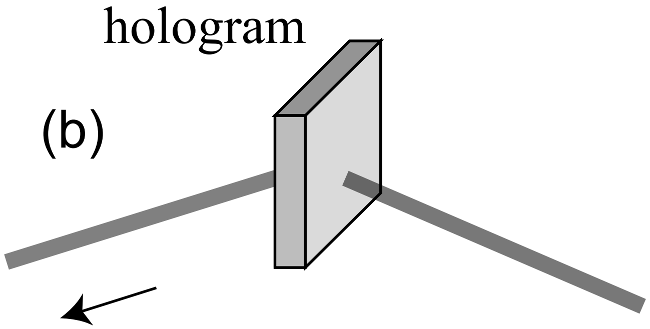


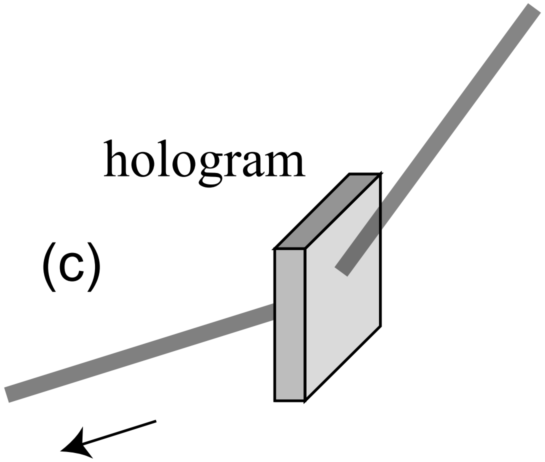
- Generalize to N-exposures

Reconstruction - with plane-wave reference beam

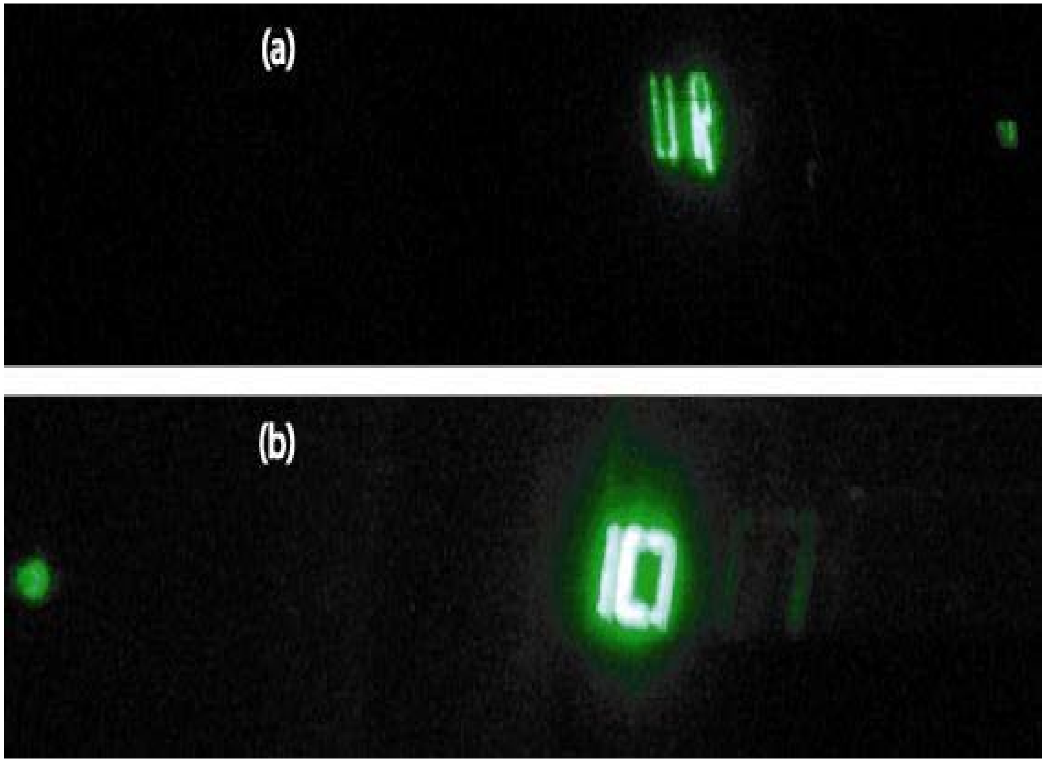


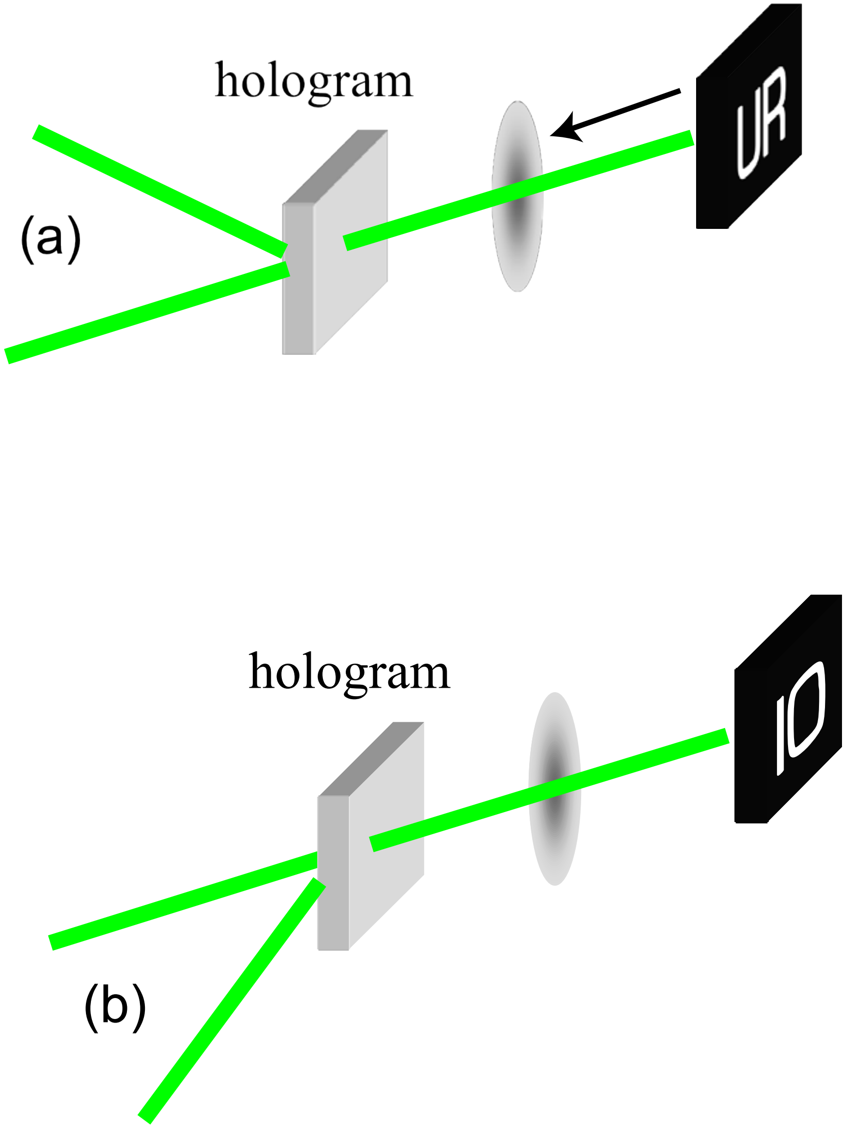






Reconstruction - with structured reference beam





- 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

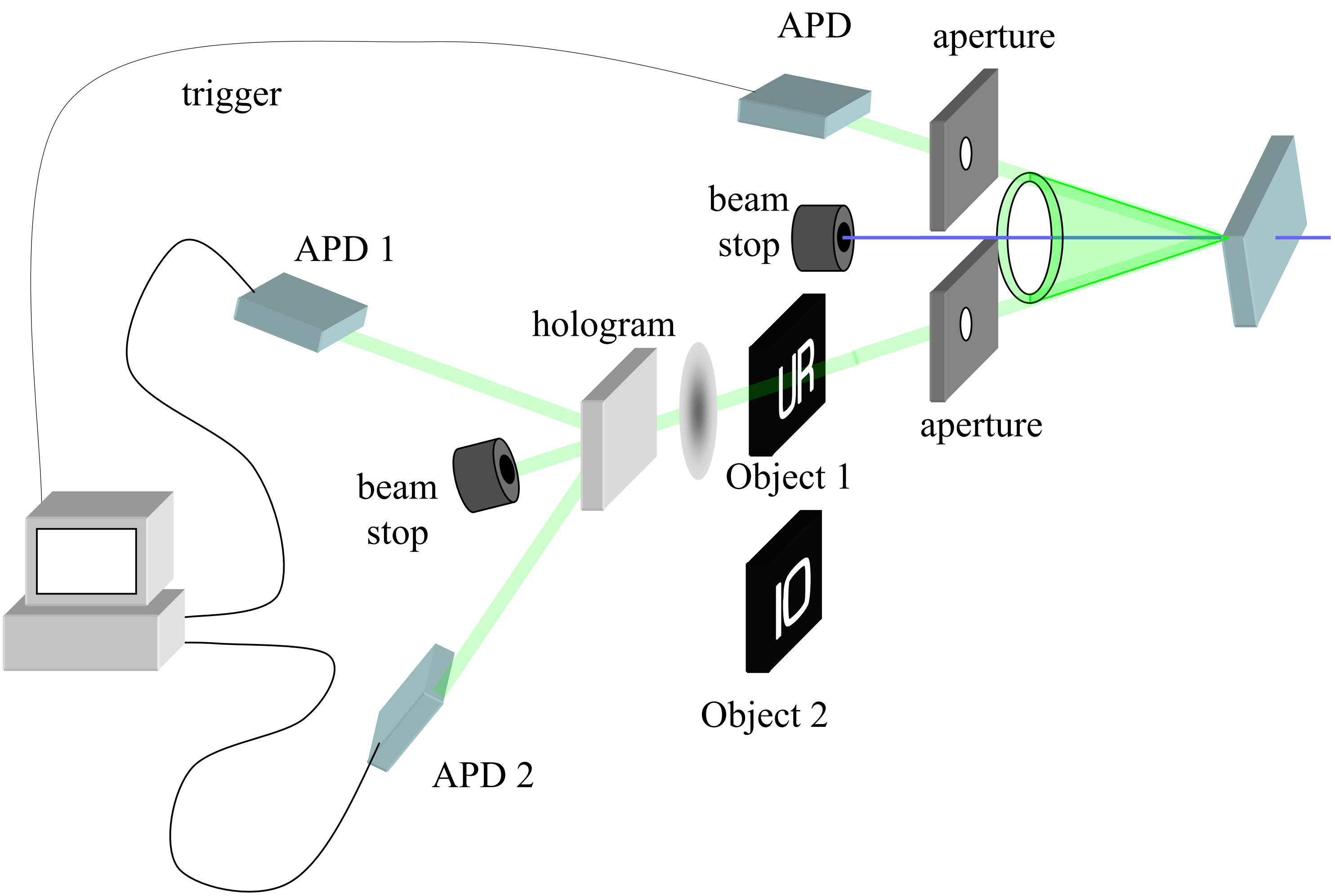
Count rate (1/s) **146** **24506**

High light level

Low light level

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

Next step: use heralded single photons



Possible Applications:

Automatic traget recognition at the single photon level

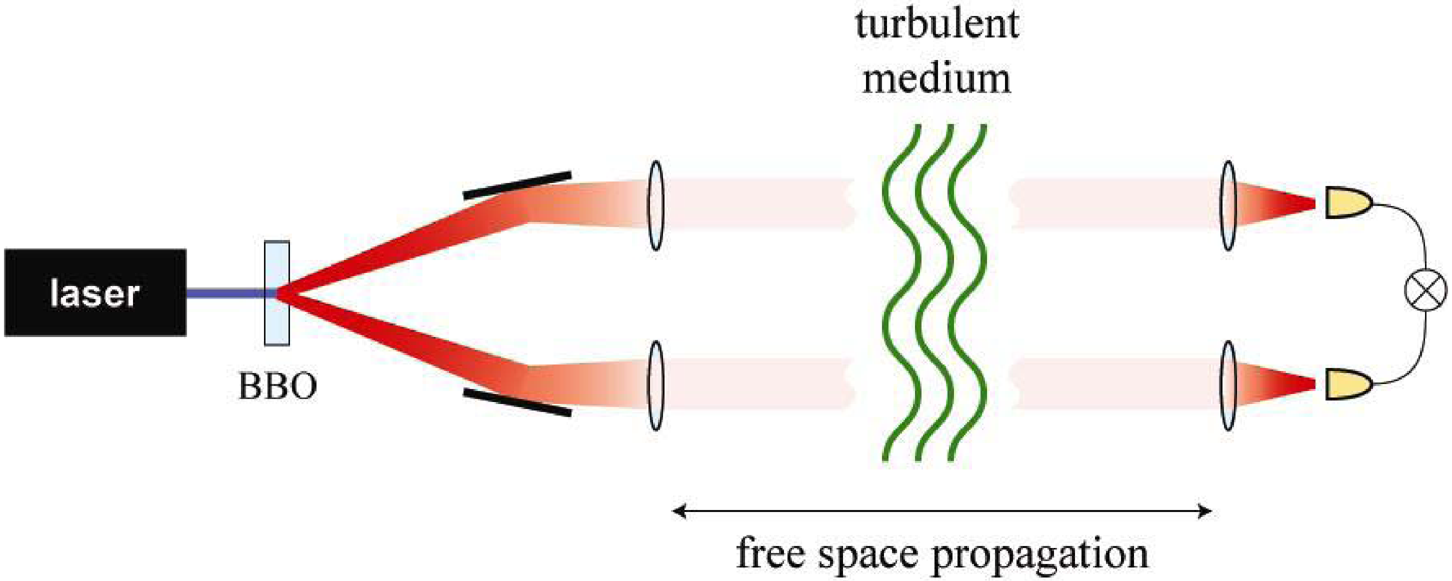
"Dense coding" of quantum information

Entanglement Propagation

Goal

To understand and develop the tools to study how the transverse spatial correlations between photons produced in SPDC change as the photons propagate:

- through free-space (develop formalism, merit functions, experimental techniques)
- through distorting and turbulent media
  help with theory from Glenn Tyler and Jeff Shapiro



Theory of Propagation through Turbulence

The propagated field in a turbulent medium is given by

$$\hat{E}^{(+)}(\vec{x},z) = e^{ikz}\int d\vec{x}'\ h(\vec{x},\vec{x}',z)e^{i\phi(\vec{x}')}\hat{E}^{(+)}(\vec{x}',0)$$

Note:

1. Turbulent medium is described by the statistical character of $\phi(\vec{x}')$.
2. The medium is replaced by a single "phase screen" accounting for all the phase fluctuation incurred in the propagation to z, i.e., $\phi(\vec{x}') = k\int_0^z n(\vec{x}',z')dz'$
3. Fluctuating phase: $\overline{e^{i[\phi(\vec{x}')-\phi(\vec{y}')]}} = e^{-(1/2)D_s(|\vec{x}'-\vec{y}'|)}$
   Phase structure function $D_s(|\vec{x}'-\vec{y}'|) = \alpha|\vec{x}'-\vec{y}'|^{5/3}$ (Kolmogorov)

Now take ensemble average when calculating four-point correlation function:

$$G(\vec{x}_s,\vec{y}_s;\vec{x}_i,\vec{y}_i) \equiv \langle\Psi|\overline{\hat{E}^{(-)}(\vec{y}_i,z_i)\hat{E}^{(-)}(\vec{y}_s,z_s)\hat{E}^{(+)}(\vec{x}_s,z_s)\hat{E}^{(+)}(\vec{x}_i,z_i)}|\Psi\rangle$$

Quantification of Entanglement

Biphoton density matrix - approximate r^(5/3) dependence of D by r^(6/3)

$$G_0(\vec{x}_s,\vec{y}_s;\vec{x}_i,\vec{y}_i) = e^{-\frac{1}{2}\mathcal{D}_s(|\vec{x}_s-\vec{y}_s|)}e^{-\frac{1}{2}\mathcal{D}_i(|\vec{x}_i-\vec{y}_i|)}\Psi(\vec{x}_s,\vec{x}_i)\Psi^*(\vec{y}_s,\vec{y}_i)$$

with $$\Psi(\vec{x}_s,\vec{x}_i) = N\exp\left[-\frac{B}{2}(\vec{x}_s-\vec{x}_i)^2\right]\exp\left[-\frac{A}{2}(\vec{x}_s+\vec{x}_i)^2\right]$$

$$D_s(r) = 3.44\left(\frac{r}{r_0}\right)^{6/3}$$

r_0 – the length scale of turbulence structure

For continuous variable entanglement

The second moments of the variables provide useful information about the degree of entanglement. #

Measures of entanglement (these are mixed states; can't use Schmidt and Fedorov)

1. EPR uncertainty
2. Entanglement of formation

Hyllus & Eisert, New J. Phys. **8**, 51 (2006)

Effect of Turbulence on Entanglement

EPR uncertainty

$$\Delta = \sqrt{\Delta^2(x_s - x_i) + \Delta^2(p_s + p_i)}$$

Gaussian state: $\Delta < 1$ entangled

$\Delta \geq 1$ disentangled

We find #

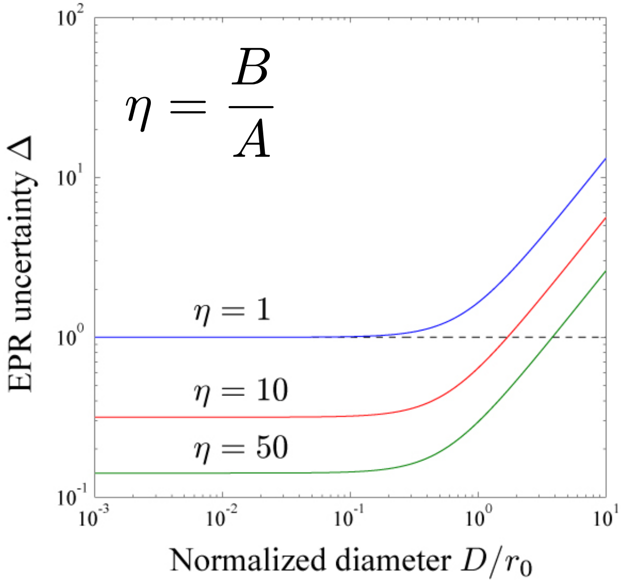
$$\Delta = \sqrt{\frac{(1+\eta^{-1}) + 3.44(D/r_0)^2}{1+\eta}}$$

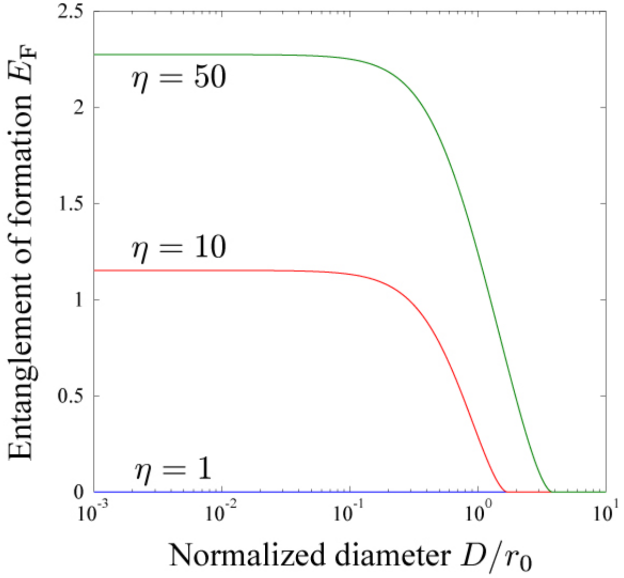
Entanglement of formation for Gaussian states

– how much entanglement is needed to construct the state

$$E_F = c_+ \log c_+ - c_- \log c_-$$

where $c_\pm = \frac{1}{4}\left(\Delta^{-1/2} \pm \Delta^{1/2}\right)^2$



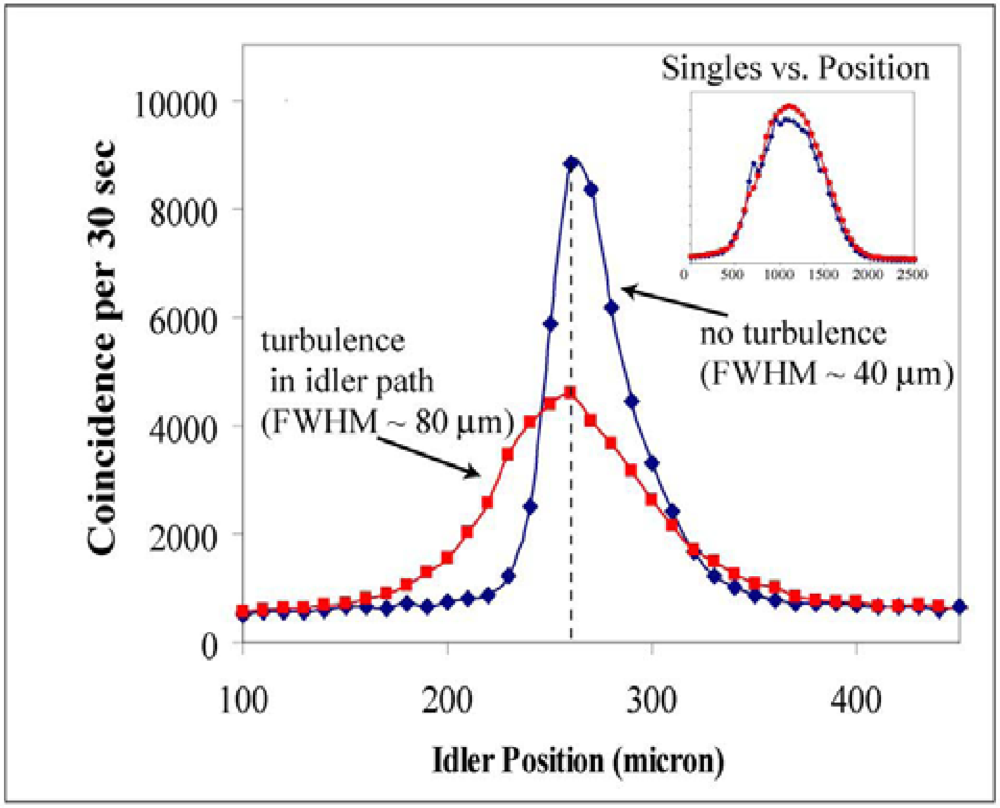


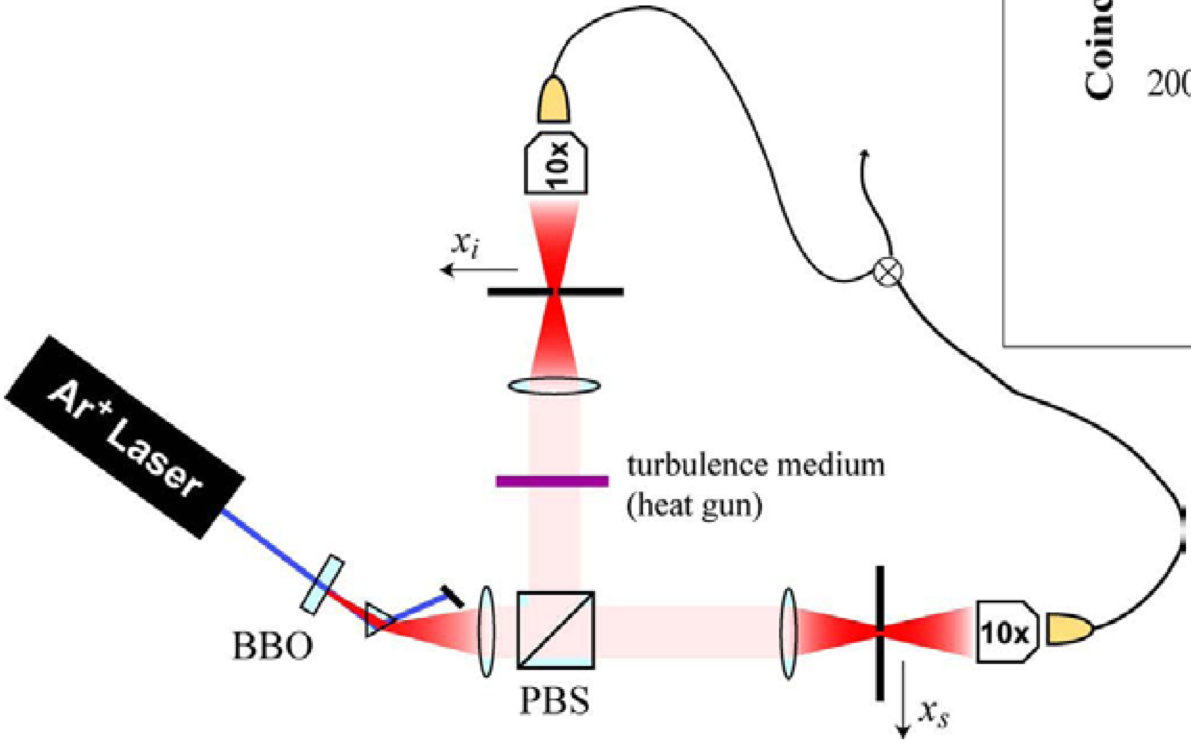
Giedke *et al*., PRL **91**, 107901 (2003)

Preliminary Results

Turbulence medium:

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





Next: Can we use adaptive optics to prevent the loss of entanglement due to turbulence?

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

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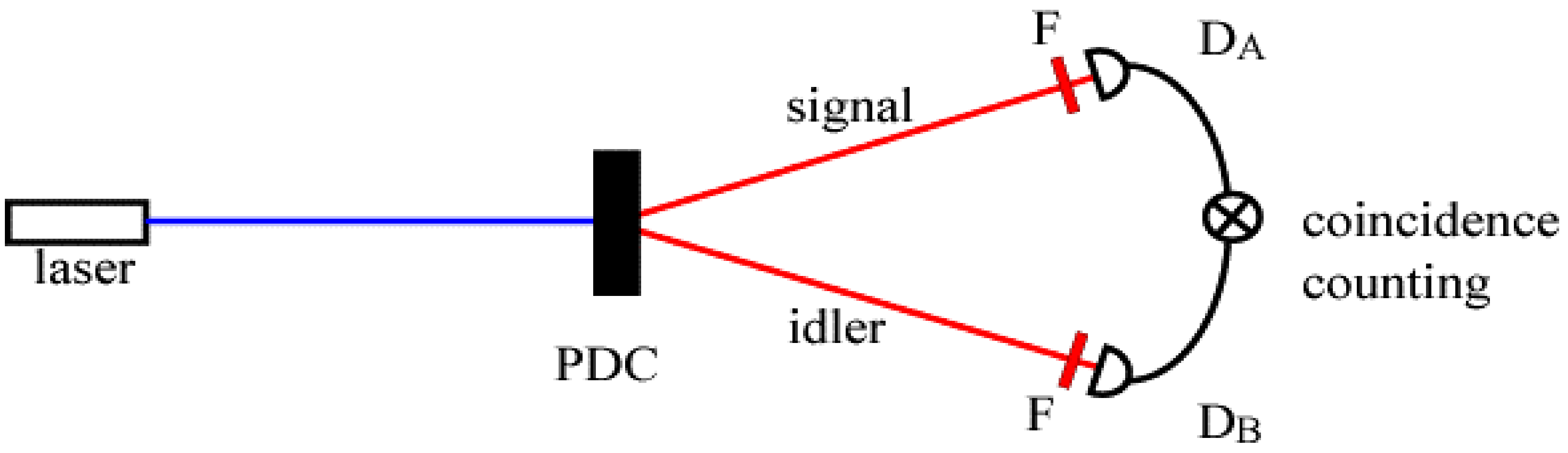
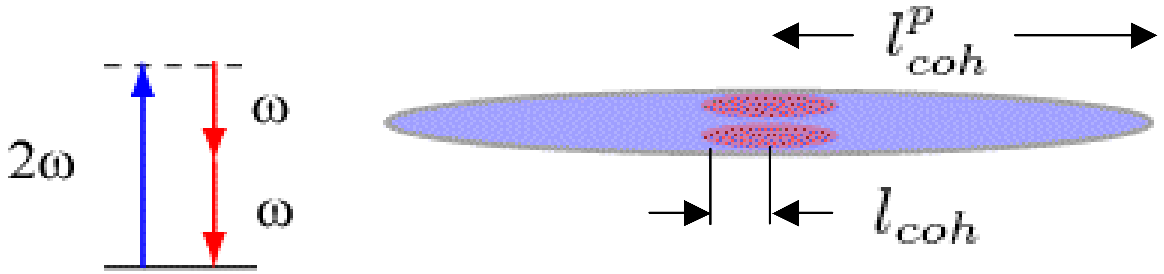
What are the relevant degrees of freedom of a biphoton?

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

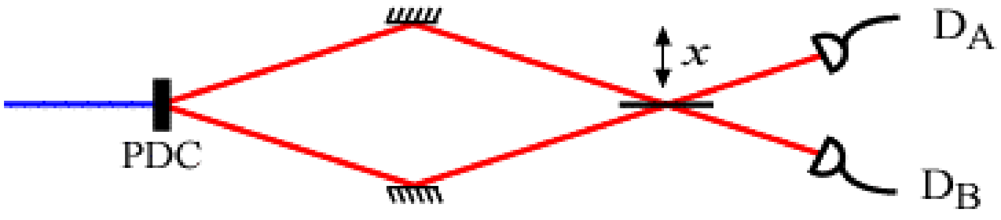
Coherence length of signal/idler photons ~ $c/\Delta\omega$ ~ 100 μm.

Individual photons are entangled and can be made indistinguishable.

Two-Photon Interference -- How to Understand?

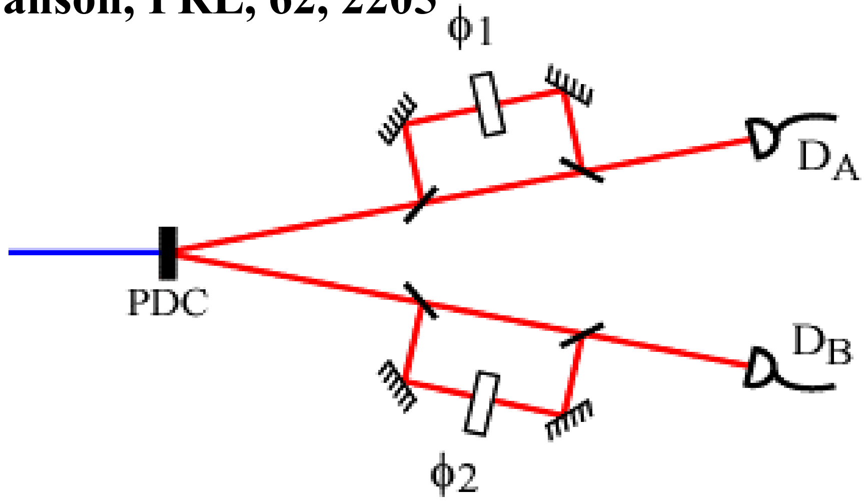
- **Hong-Ou-Mandel effect (1987)**

PRL, 59, 2044



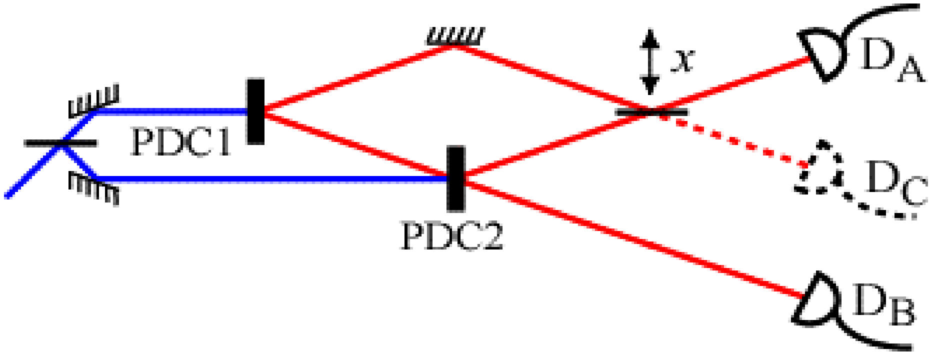
- **Bell Inequality for position and time (1989)**

Franson, PRL, 62, 2205



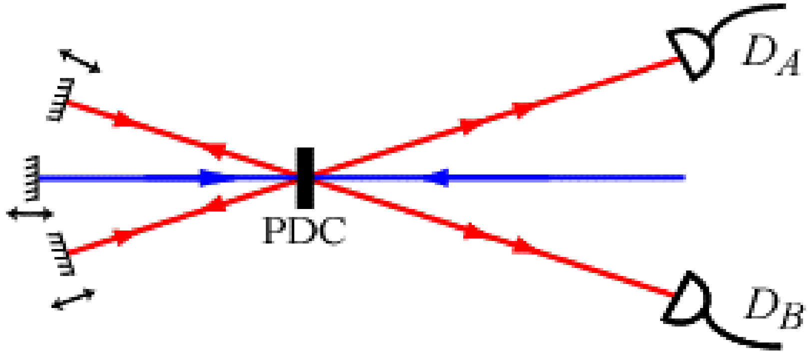
- **Induced Coherence (1991)**

Zou et al. PRL, 67, 318

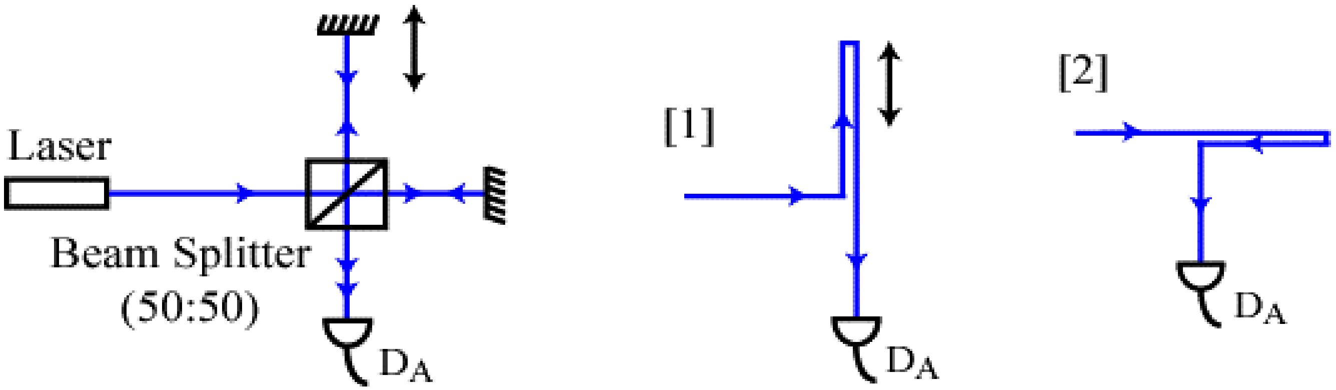


- **Frustrated two-photon creation (1994)**

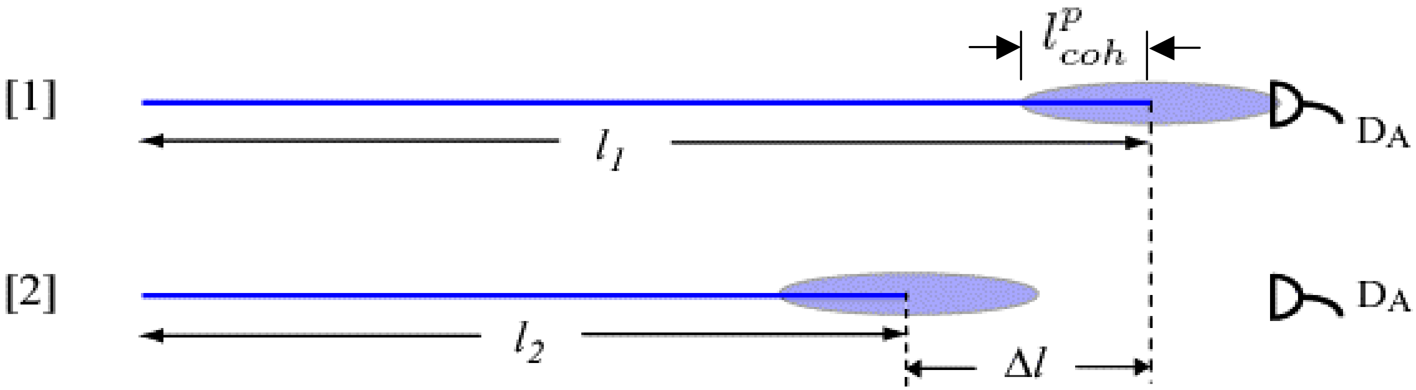
Herzog et al. PRL, 72, 629



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



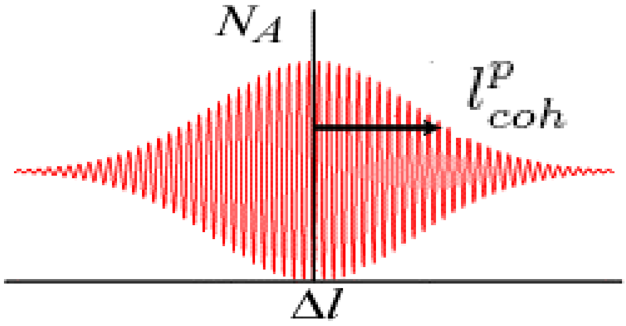
Add probability amplitudes for alternative pathways [1] and [2]



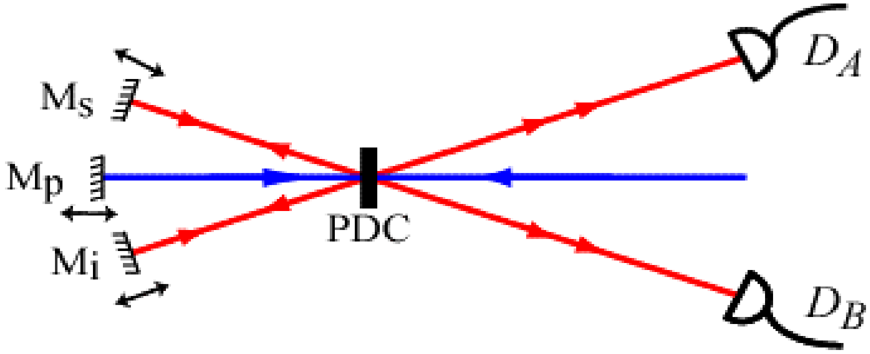
(unfolded paths)

Necessary condition for one-photon interference

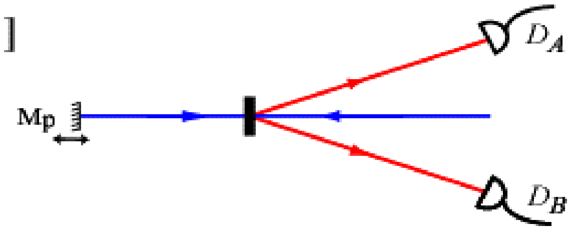
$$\boxed{\Delta l \; < \; l^p_{coh}}$$



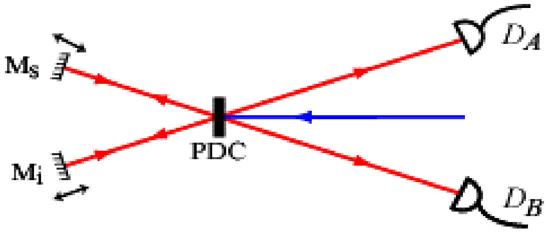
What about biphoton interference? (Generic setup)



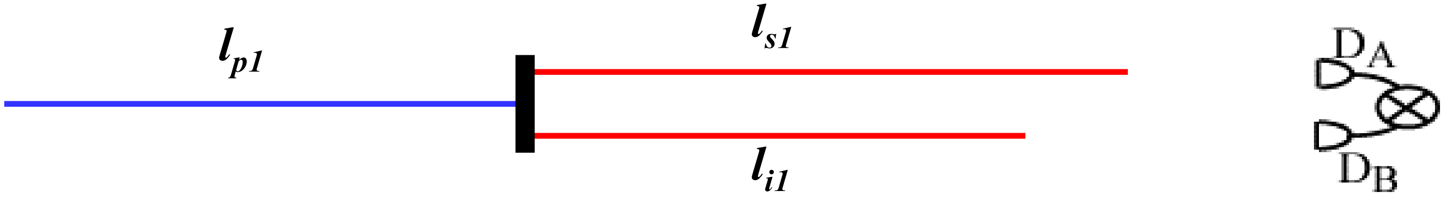
[1]



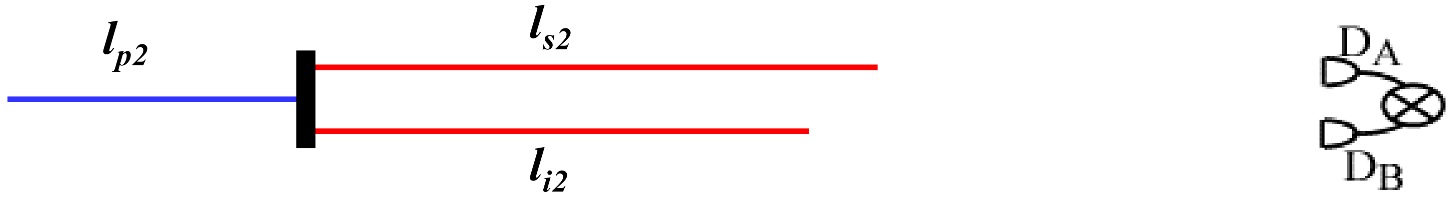
[2]



[1]

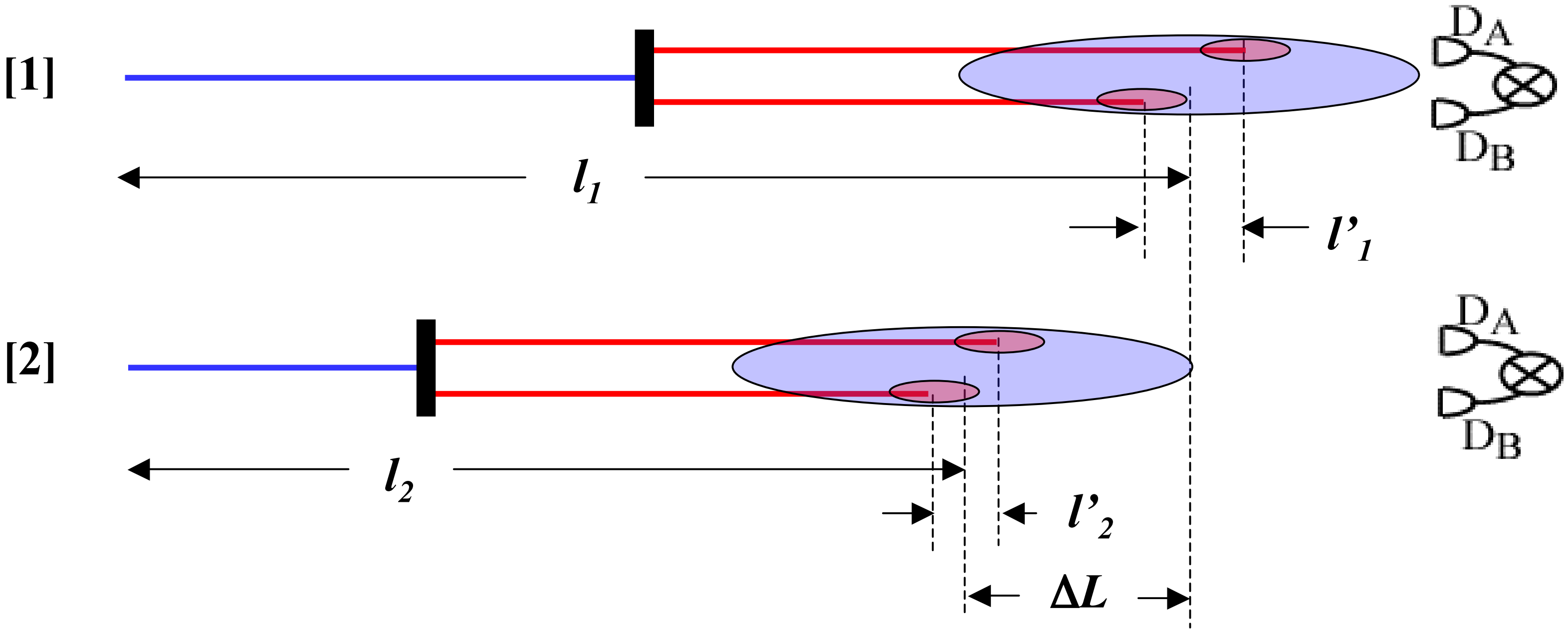


[2]



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**

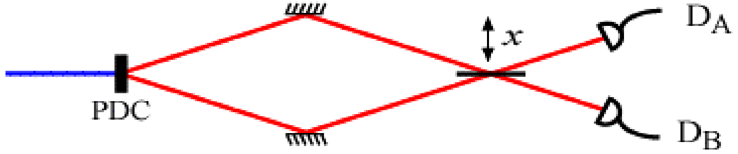
$$N_{AB} \propto \quad 1 - \gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$

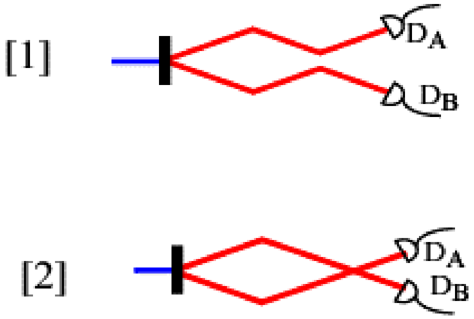
$$\gamma(\Delta L) = \exp\left[-\frac{1}{2}\left(\frac{\Delta L}{l^p_{coh}}\right)^2\right] \qquad \gamma'(\Delta L') = \exp\left[-\frac{1}{2}\left(\frac{\Delta L'}{l_{coh}}\right)^2\right]$$

Conditions for two-photon interference:

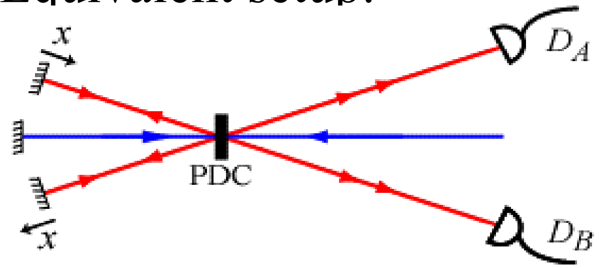
$$\boxed{\begin{array}{l} \Delta L \;<\; l^p_{coh} \\ \Delta L' \;<\; l_{coh} \end{array}}$$

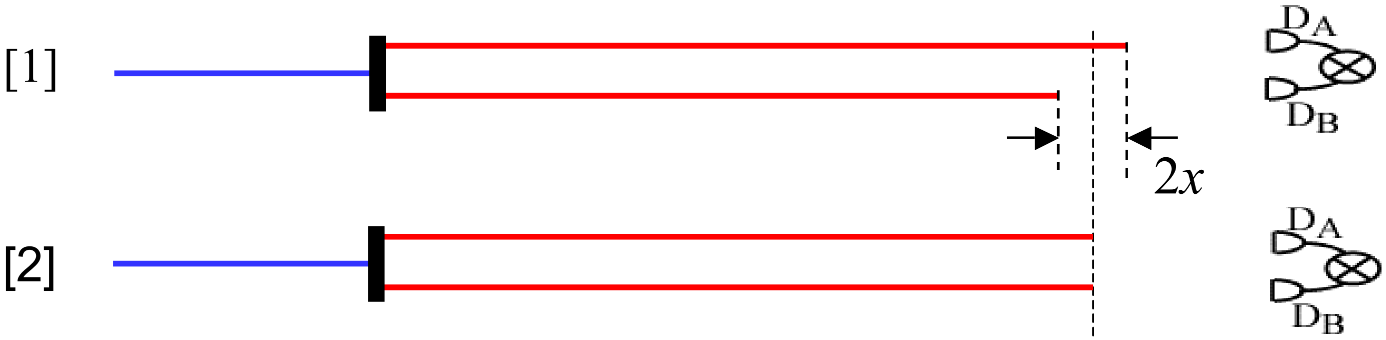
Hong-Ou-Mandel Experiment





Equivalent setup:

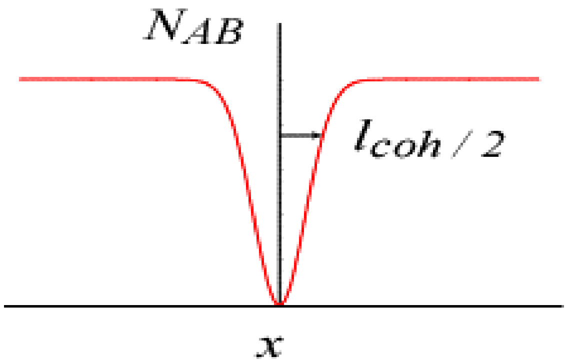




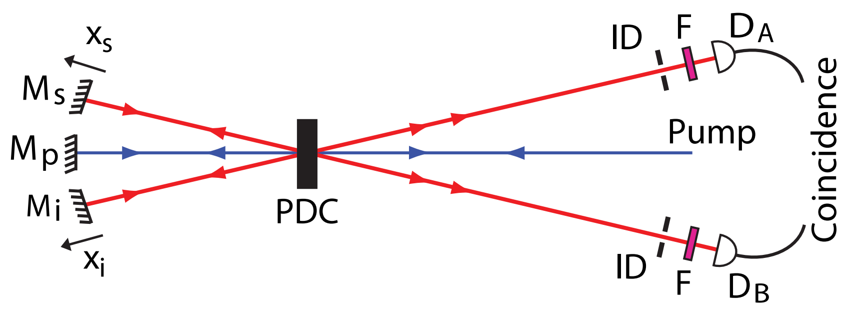
$\Delta L = 0 \qquad \Delta L' = 2x$

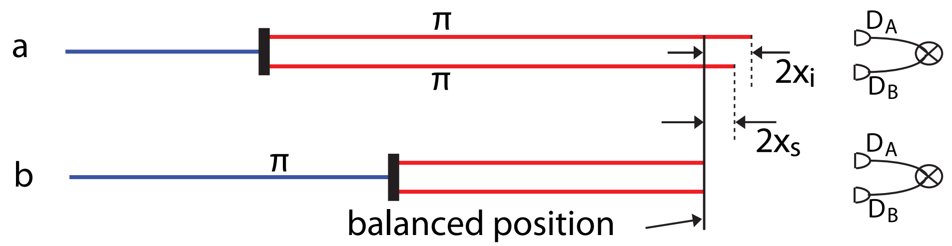
$$N_{AB} \propto \; 1 - \gamma'\left(\Delta L'\right)\gamma\left(\Delta L\right)\cos\left(k_0 \Delta L\right)$$

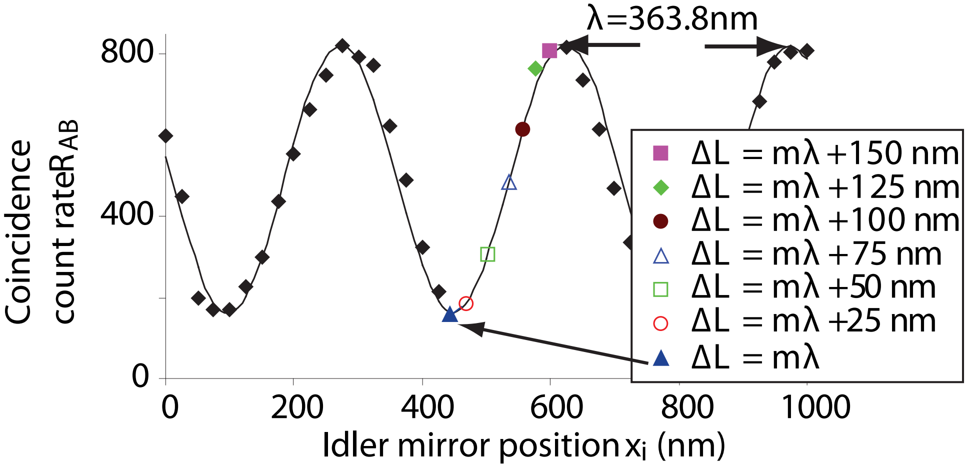
$$N_{AB} \propto \; 1 - \gamma'\left(2x\right)$$

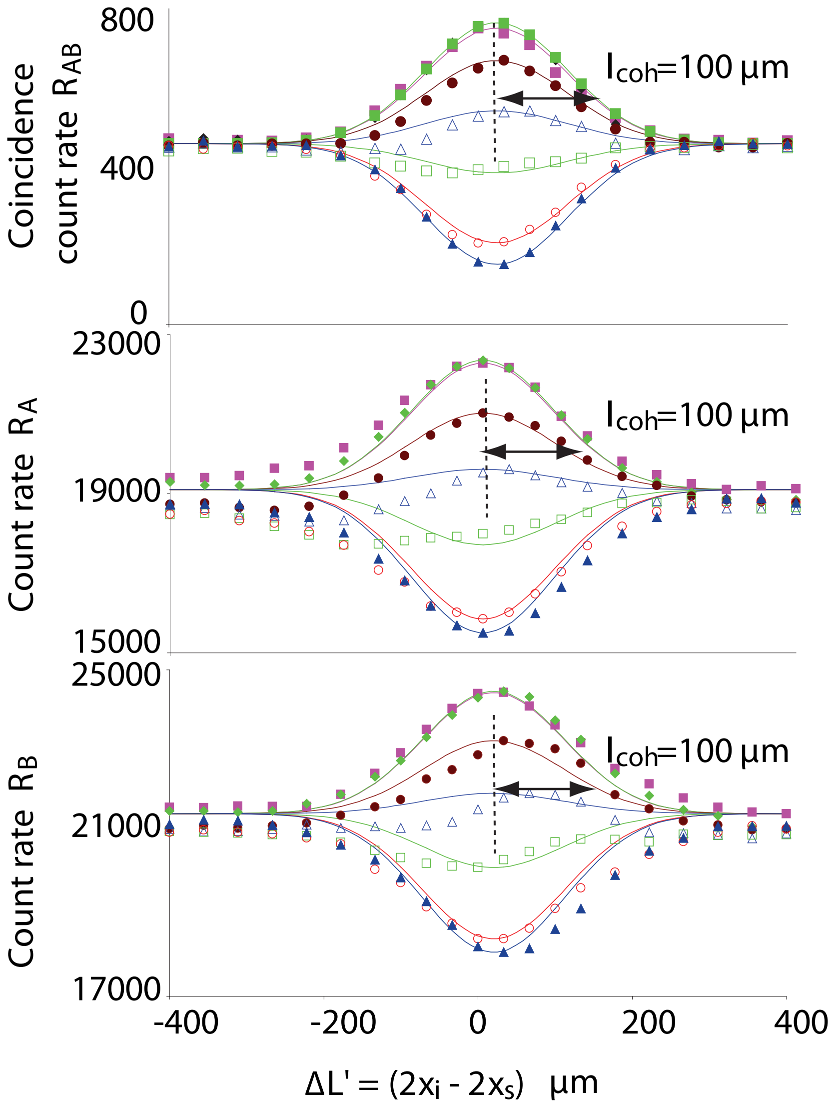


Our Experiment: Generalization of the Hong-Ou-Mandel Effect









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

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!

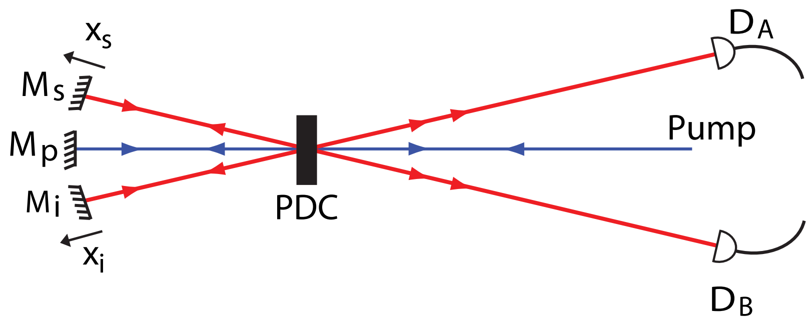
Note that: $$R_{\mathrm{X}} = \sum_i R_{\mathrm{XY}_i}$$

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

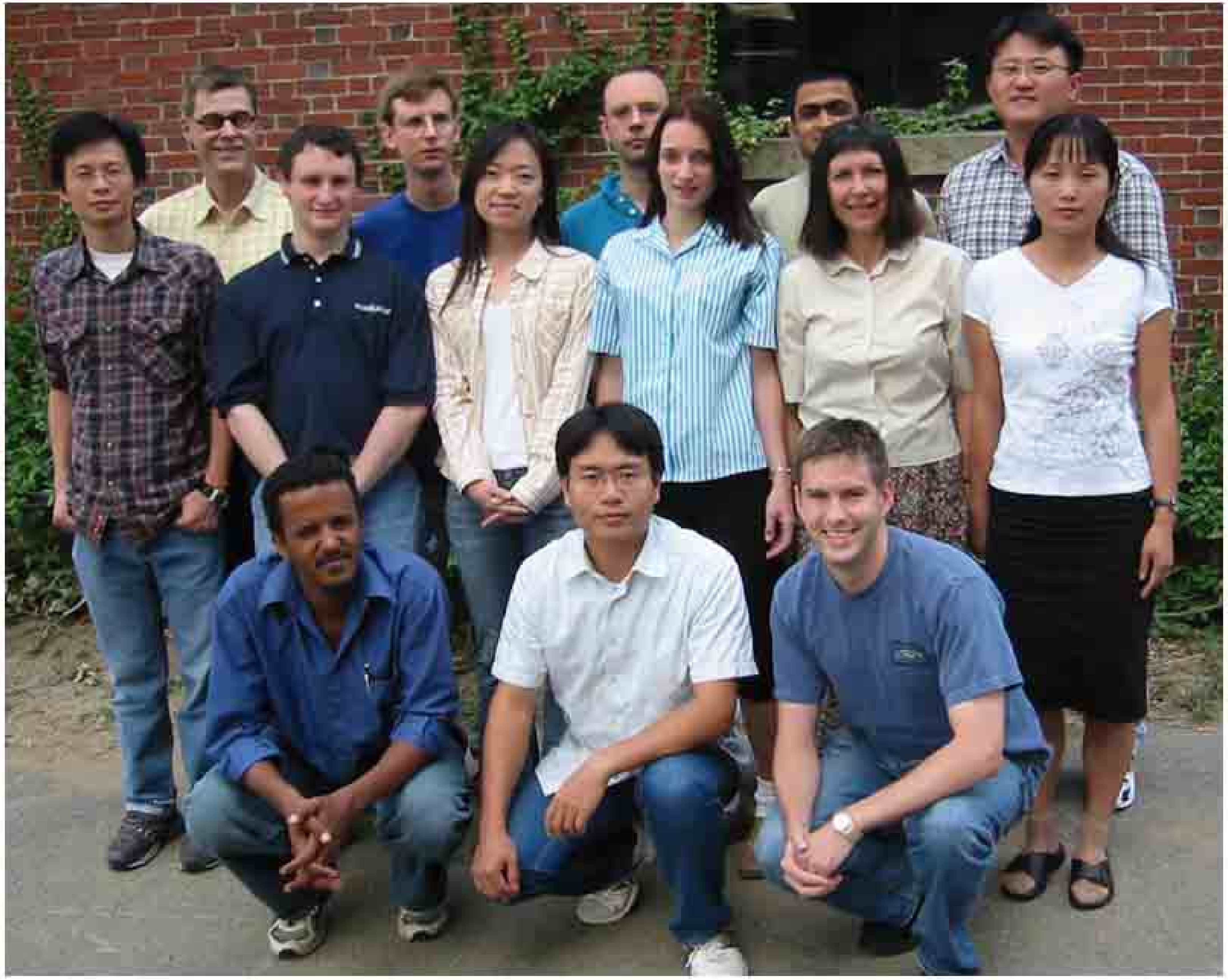
But for our setup, the twin of the photon detected at A can end up only at B.

Thus:

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



Special Thanks to My Students and Research Associates



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**