Entangled Light Sources for Quantum Imaging

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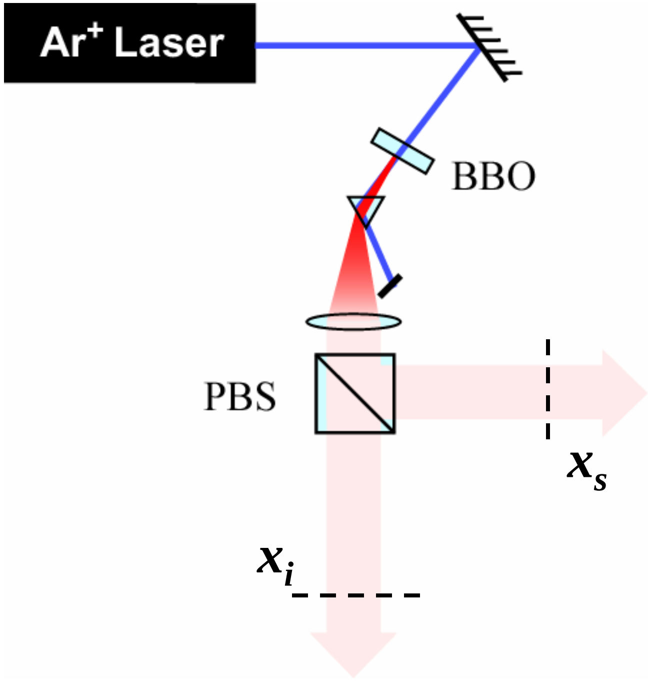
Outline

1. Overview of Quantum Imaging

2. Temporal Coherence in two-photon interference effects

Modification of Quantum States upon Propagation



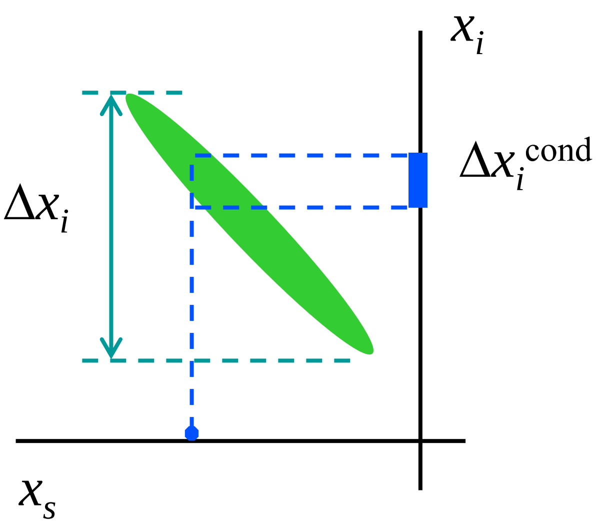
- **Effects of free space propagation on the spatial correlations between photons?**
- **Effects of turbulence on the spatial correlations between photons?**

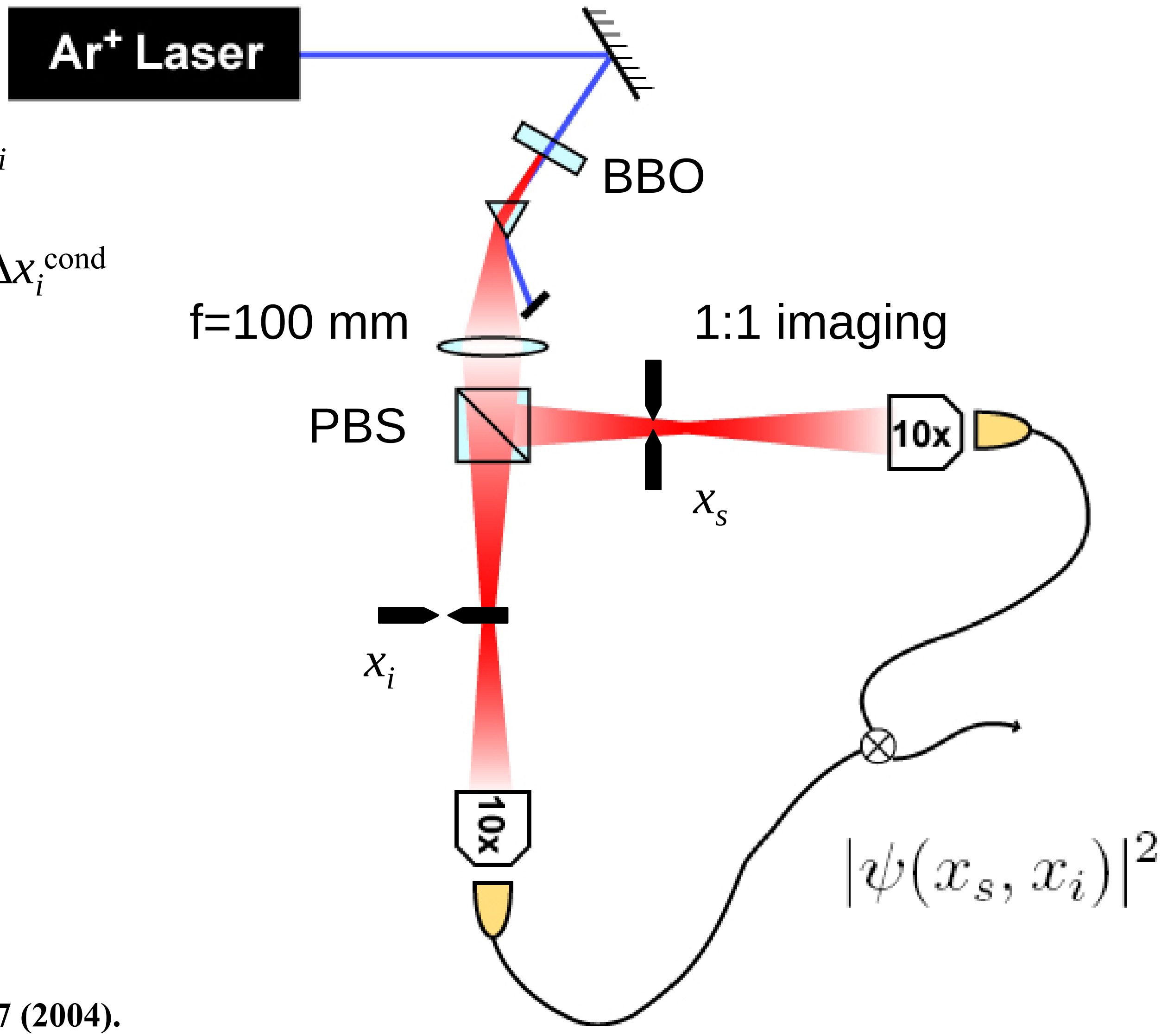
$$\psi(x_s, x_i) \rightarrow N \exp\left[-\frac{B}{2}(x_s - x_i)^2\right] \exp\left[-\frac{A}{2}(x_s + x_i)^2\right]$$

A and *B* are complex quantities

Law & Eberly, PRL 92, 127903 (2004)

Effects of free space propagation



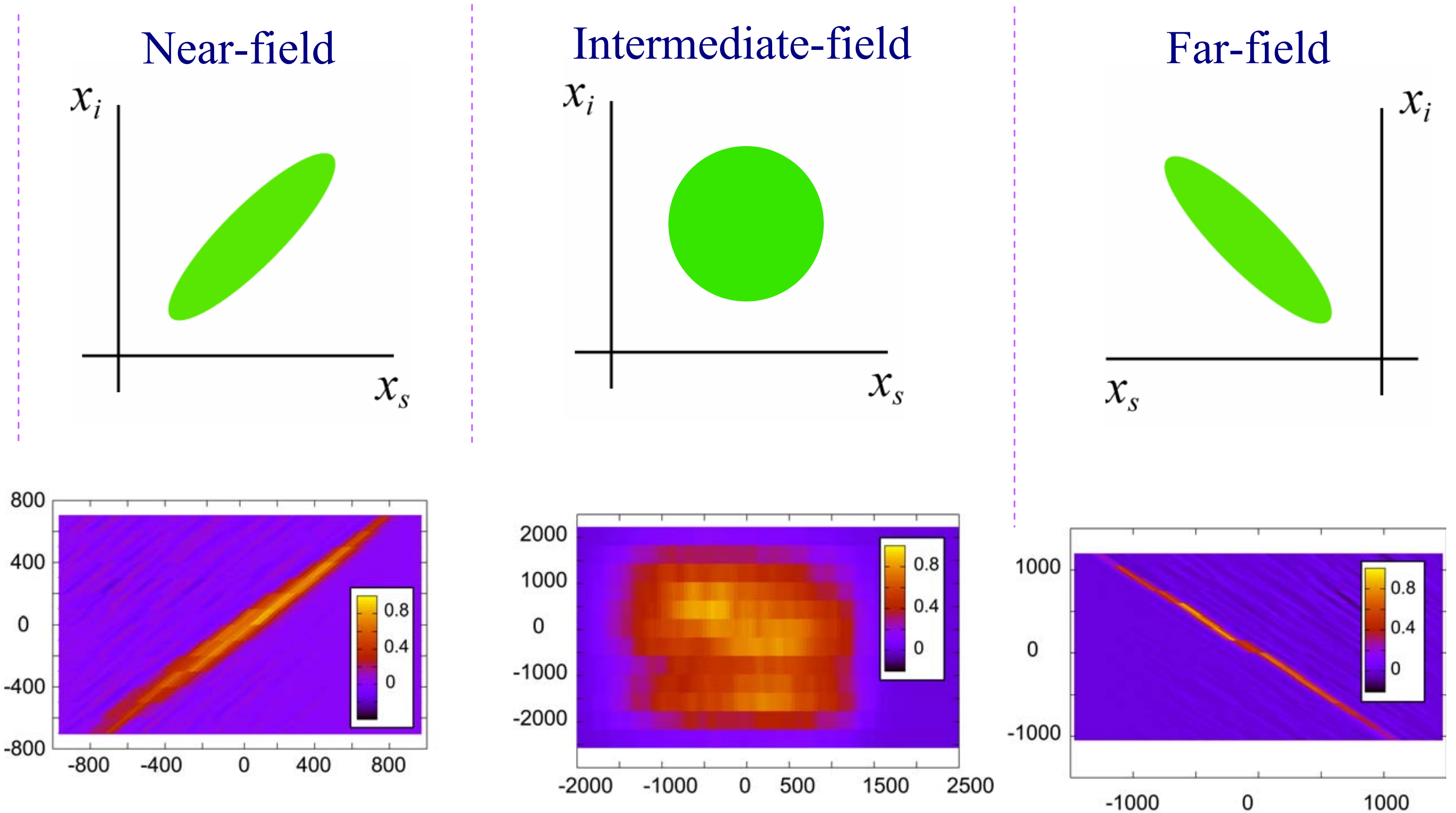


Federov Ratio[1,2]:

$$R_q = \frac{\Delta x_i}{\Delta x_i^{cond}}$$

[1] Fedorov et al., PRA 69, 052117 (2004).
[2] Chan and Eberly, quant-ph/0404093.

Entanglement Migration



$$|\psi(x_s, x_i)|^2$$

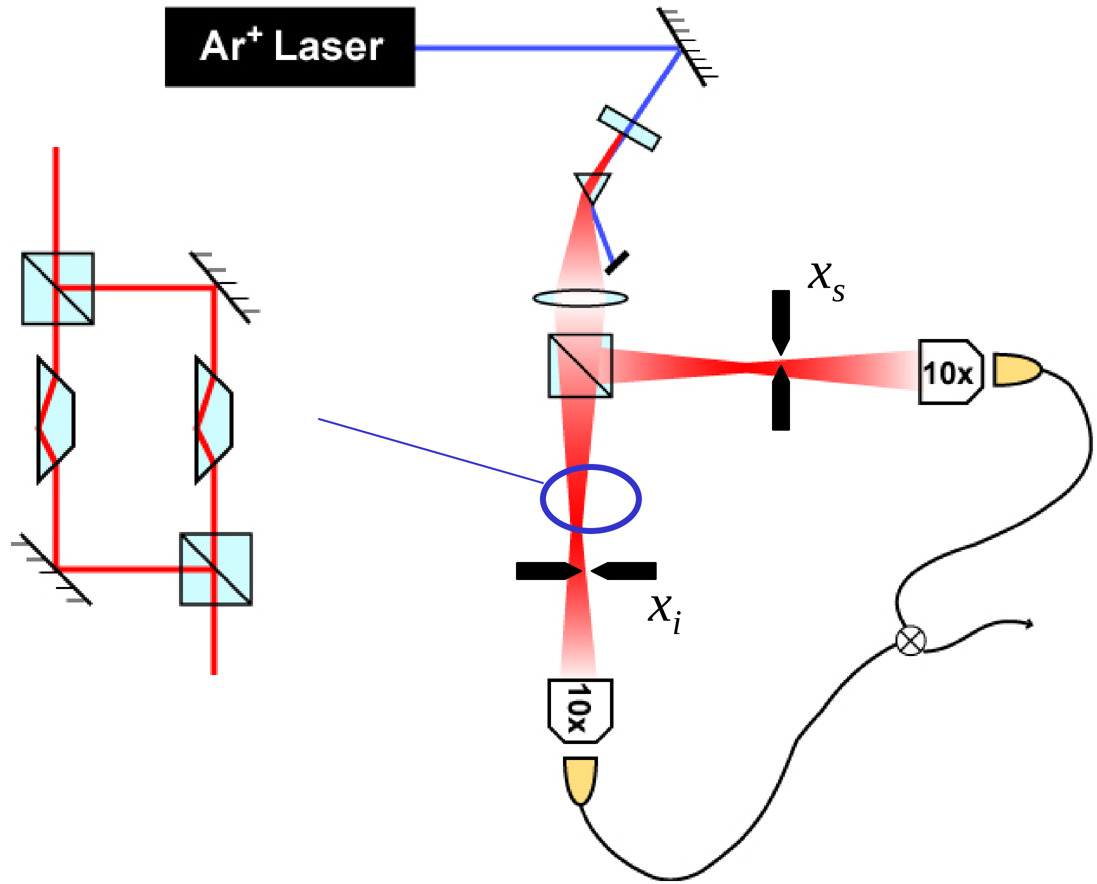
$$|\psi(x_s, x_i)|^2 = f(x_s)g(x_i)$$

$$|\psi(x_s, -x_i)|^2$$

$$\psi(x_s, x_i) = \sqrt{f(x_s)g(x_i)}e^{i\phi(x_s,x_i)}$$

Experiment to detect phase entanglement

A rotational shearing interferometer in idler arm

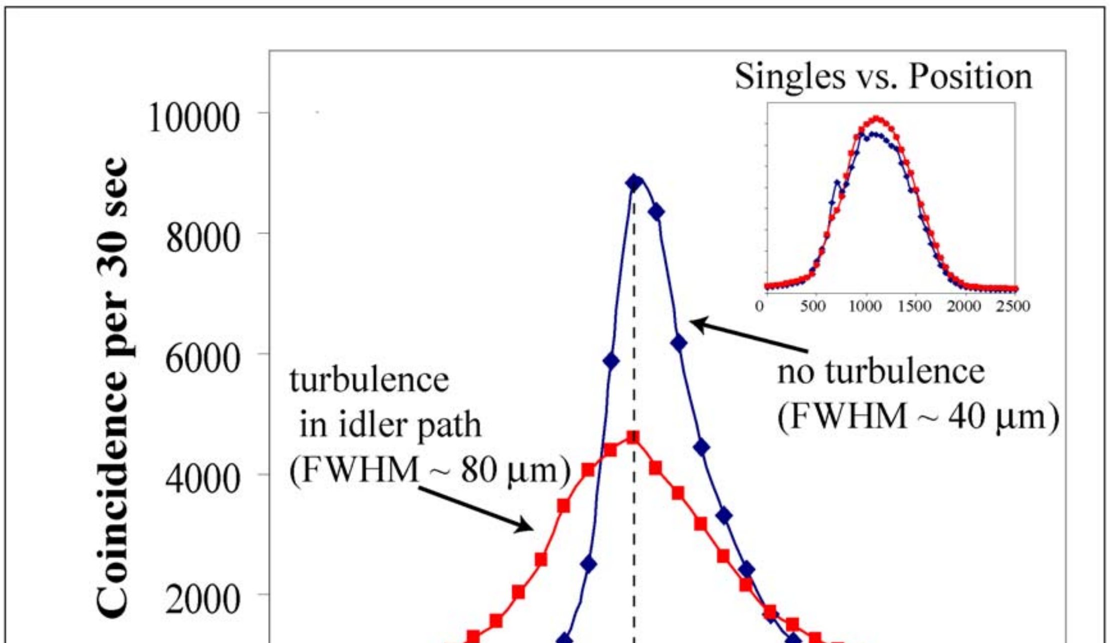


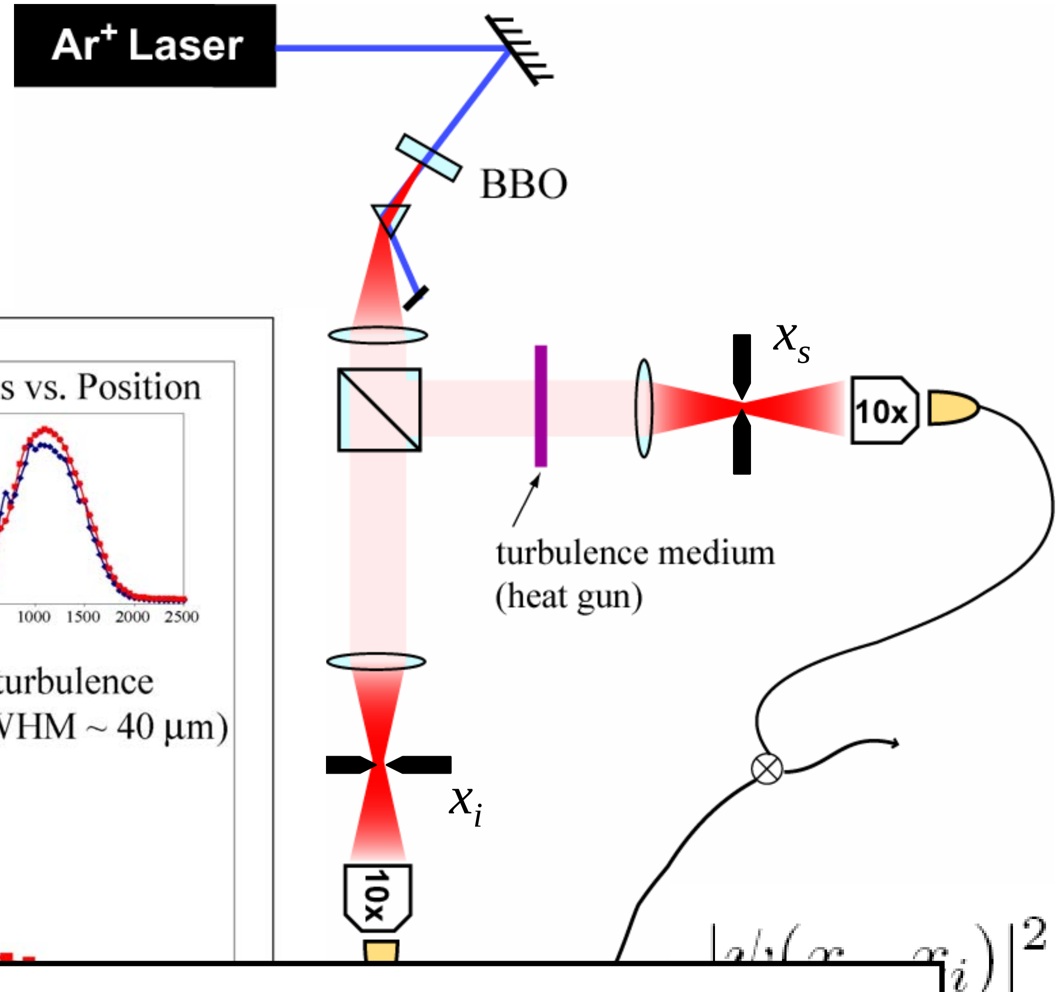
$$|\psi(x_s, x_i) + \psi(x_s, -x_i)|^2$$

Effects of Turbulence

Turbulence medium:

- ☑ heat gun
  (easy to implement)
- ❑ Kolmogorov phase screen

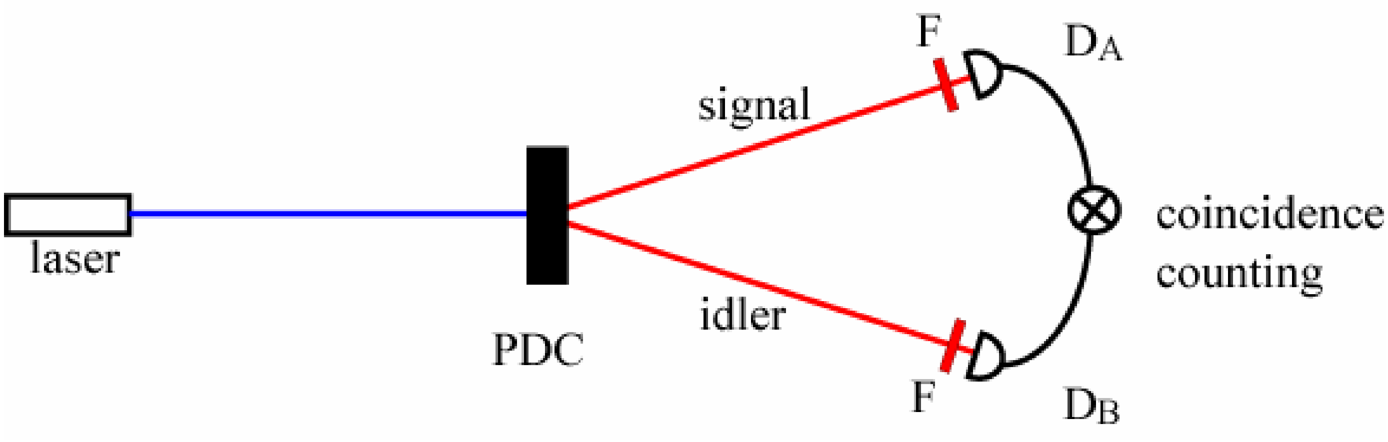


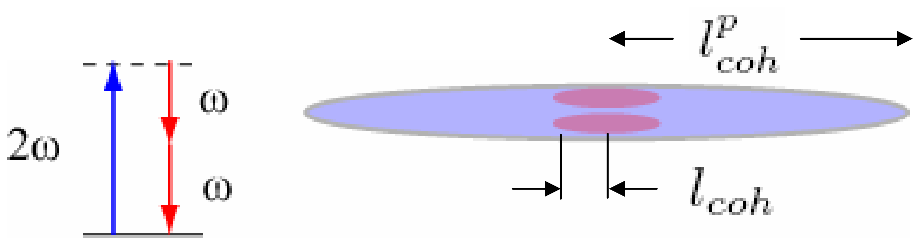


Use adaptive optics to minimize disentanglement

Temporal coherence in two-photon interference effects

Parametric Downconversion





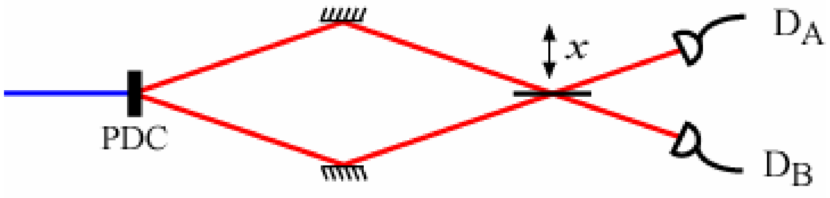
Coherence length of pump laser: l^p_{coh} ~ 10 cm.

Coherence length of signal/idler field: l_{coh} ~ c/Δω ~ 100 μm.

Two-Photon Interference

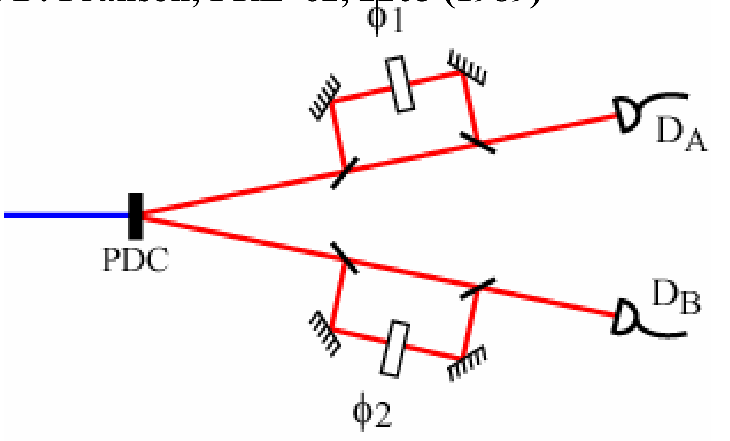
- **HOM effect**

C. K. Hong et al., PRL 59, 2044 (1987)



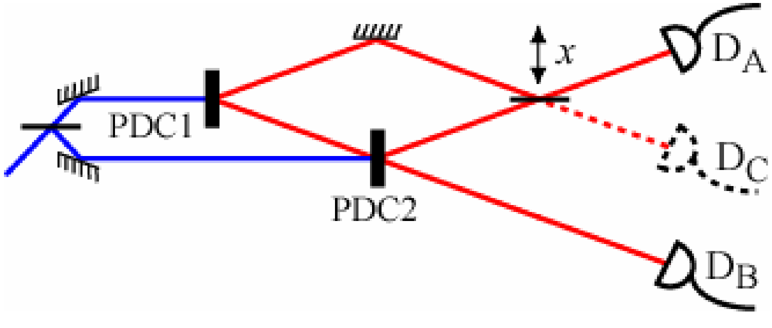
- **Bell Inequality for position and time**

J. D. Franson, PRL 62, 2205 (1989)



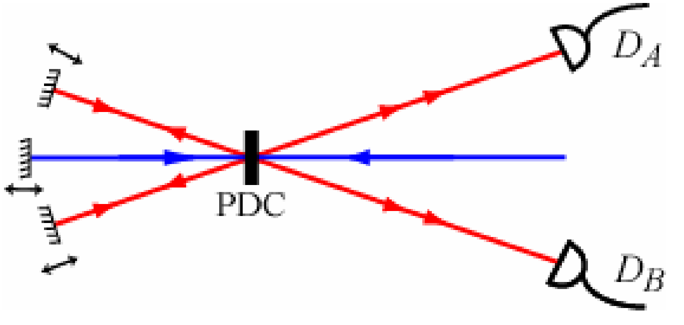
- **Induced Coherence**

X. Y. Zou et al., PRL 67, 318 (1991)

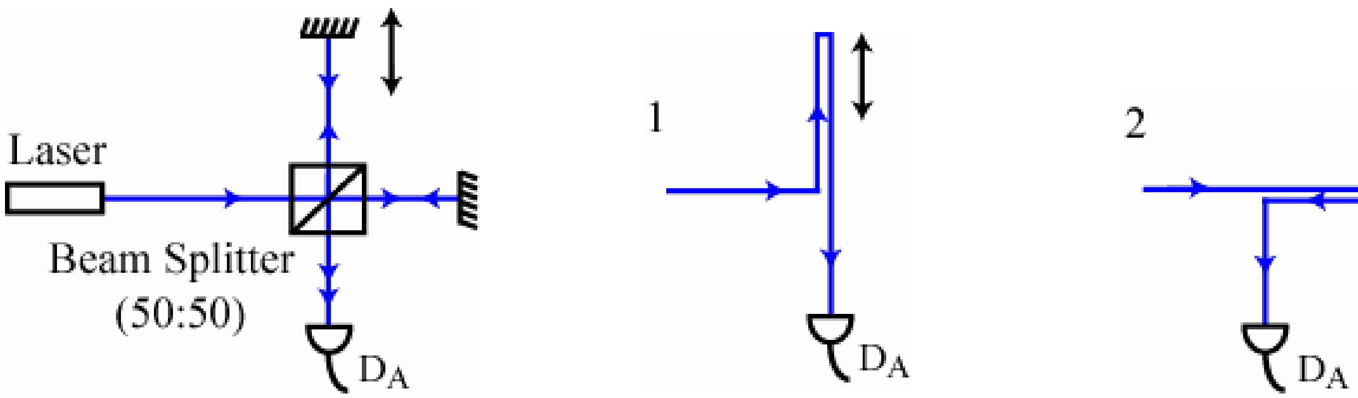


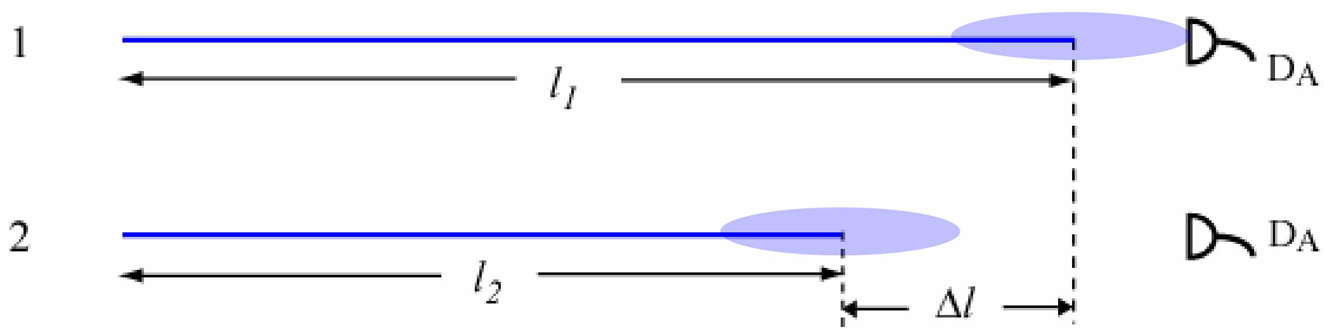
- **Frustrated two-photon Creation**

T. J. Herzog et al., PRL 72, 629 (1994)



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





(unfolded paths)

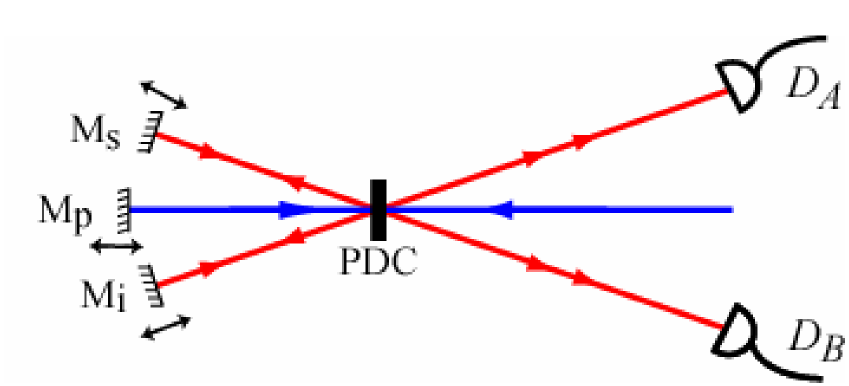
Probability amplitudes for alternatives 1 and 2 add to produce one-photon interference

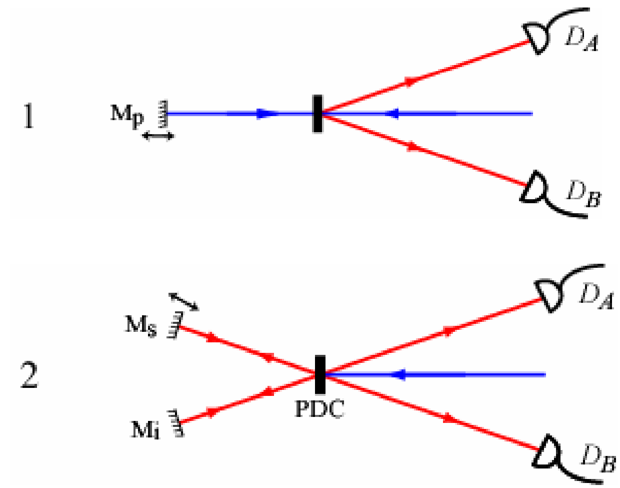
$$R \;\propto\; 1 + \gamma(\Delta l)\cos(k_0 \Delta l)$$

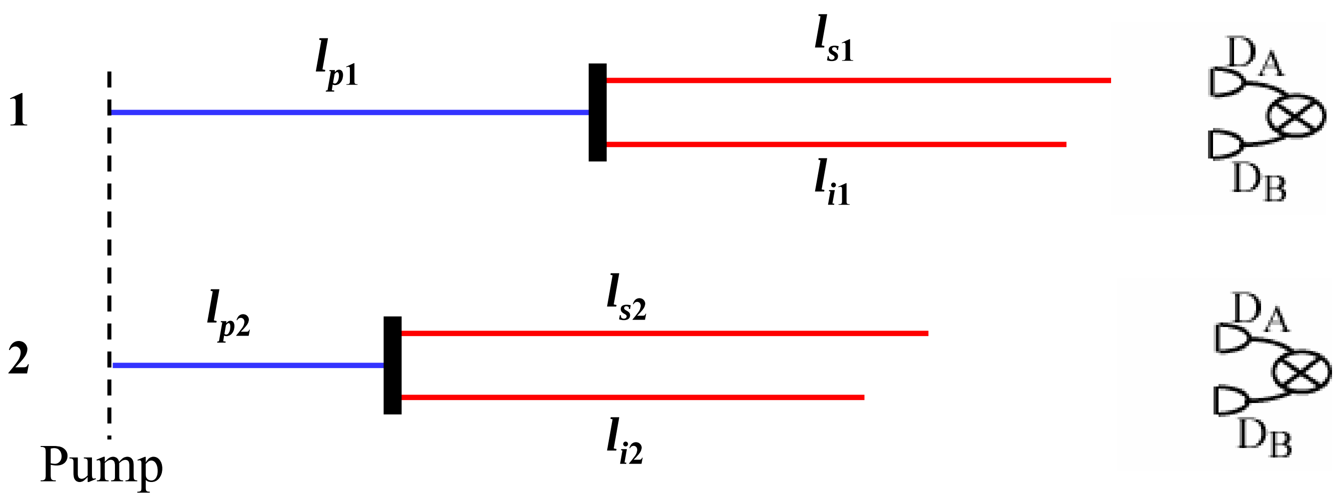
Necessary condition for one-photon interference:

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

What about two-photon interference?



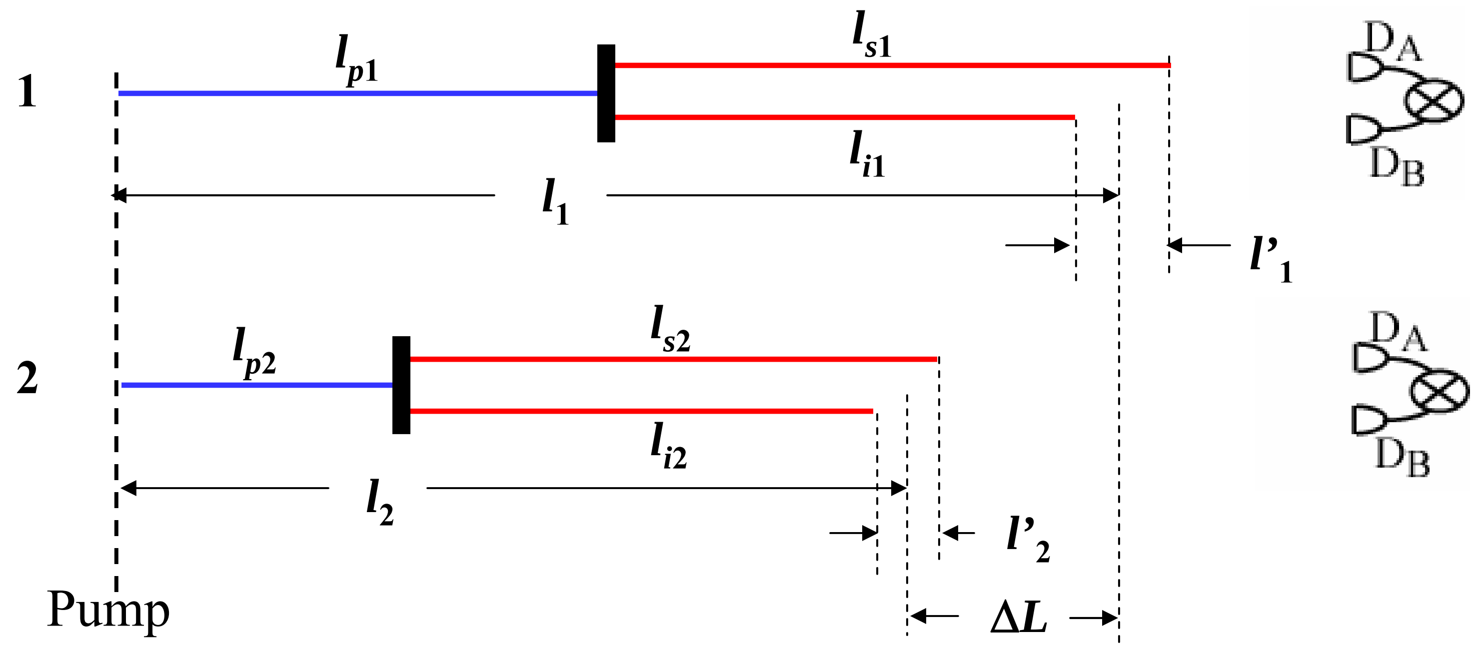




(unfolded paths)

Probability amplitudes for alternatives 1 and 2 add to produce two-photon interference

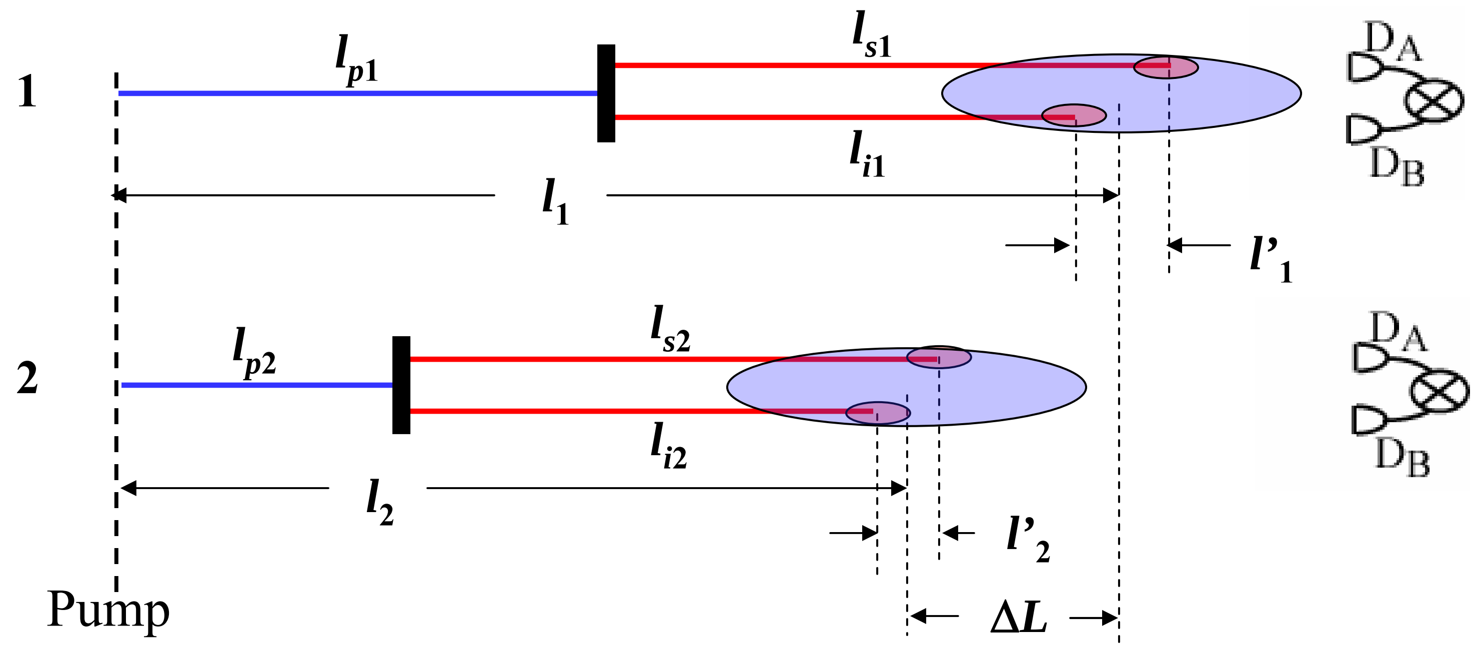
Two-Photon Path Diagram



$$\Delta L \equiv l_1 - l_2 = \left(\frac{l_{s1} + l_{i1}}{2} + l_{p1} \right) - \left(\frac{l_{s2} + l_{i2}}{2} + l_{p2} \right)$$ **Biphoton path-length difference**

$$\Delta L' \equiv l'_1 - l'_2 = (l_{s1} - l_{i1}) - (l_{s2} - l_{i2})$$ **Biphoton path-length asymmetry difference**

Two-Photon Path Diagram



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

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

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

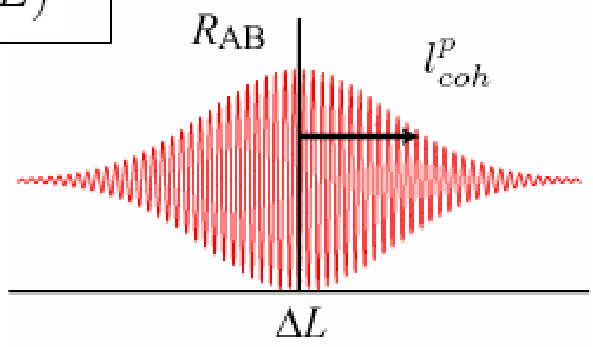
Necessary conditions for two-photon interference:

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

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

Two-Photon Interference (Two special cases)

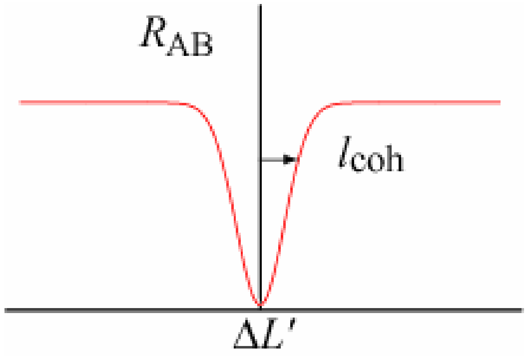
$$R_{\mathrm{AB}} \propto 1-\gamma'(\Delta L')\,\gamma(\Delta L)\cos(k_0 \Delta L)$$



Case I : $\Delta L' = 0$

$$R_{\mathrm{AB}} \propto 1-\gamma(\Delta L)\cos(k_0 \Delta L)$$

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

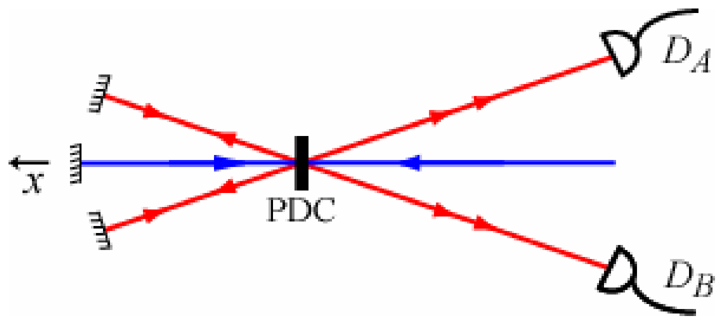


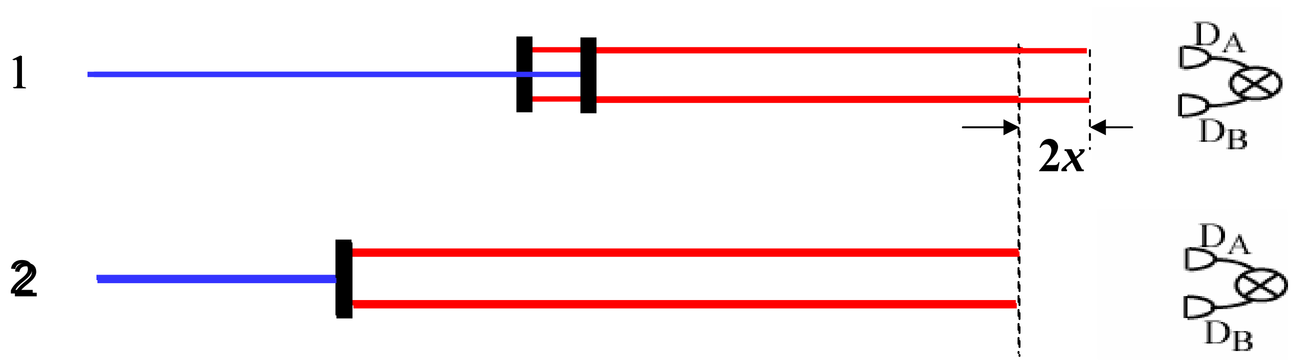
Case II : $\Delta L = 0$

$$R_{\mathrm{AB}} \propto 1-\gamma'(\Delta L')$$

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

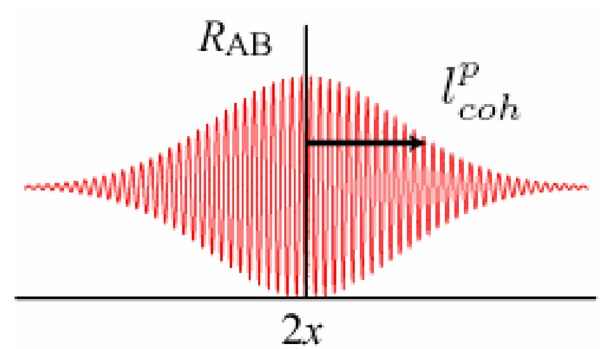
Two-Photon Interference (Case I: $\Delta L' = 0$)





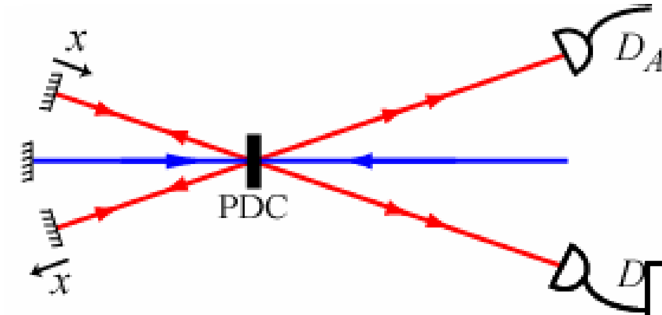
$\Delta L = 2x$; $\Delta L' = 0$

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

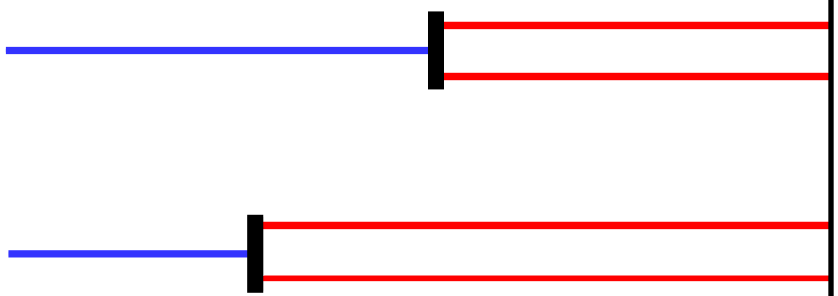


T. J. Herzog et al., PRL 72, 629 (1994)

Two-Photon Interference (Case II: $\Delta L = 0$)



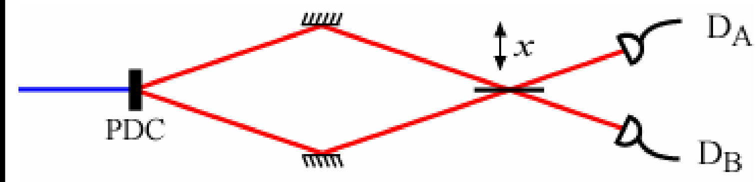
1
2



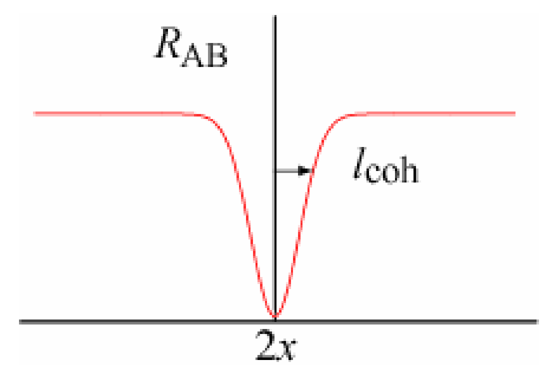
$\Delta L = 0$; $\Delta L' = 4x$

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

Hong-Ou-Mandel Effect

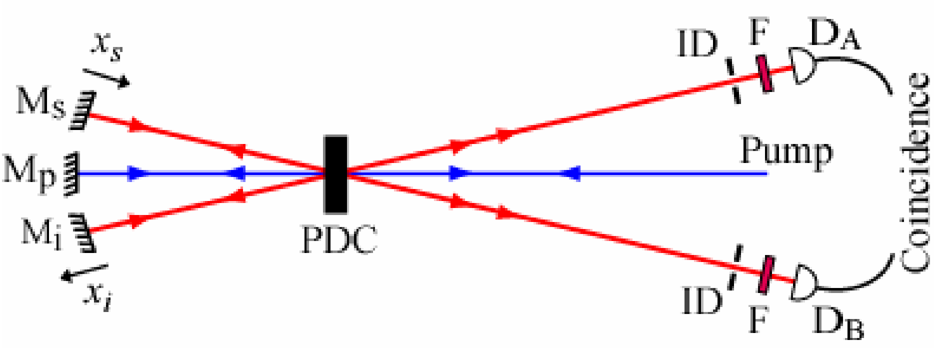


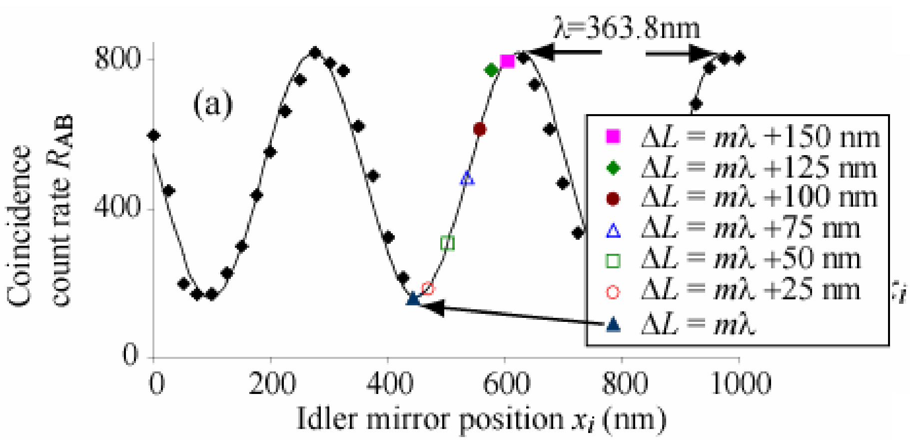
$\Delta L = 0$; $\Delta L' = 2x$

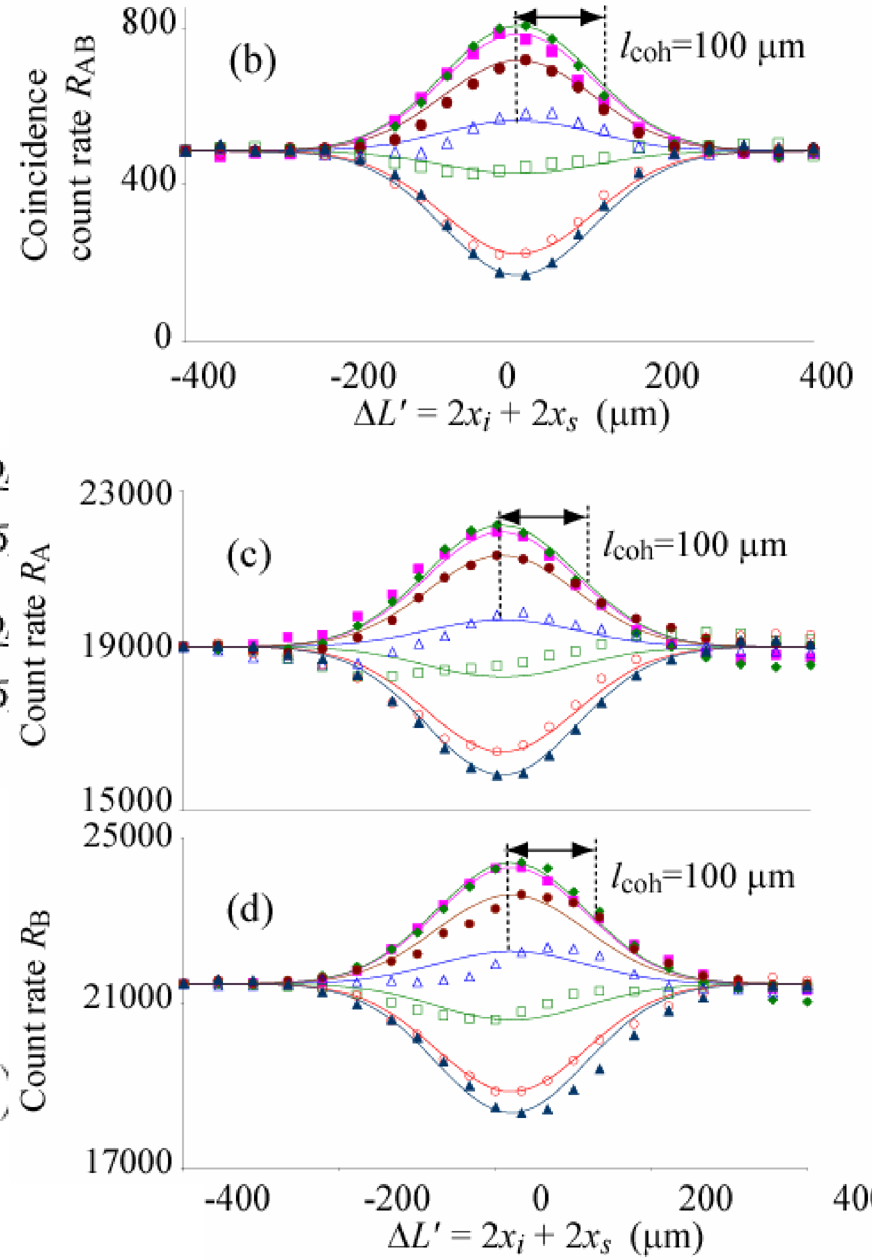


C. K. Hong et al., PRL 59, 2044 (1987)

Experimental Setup



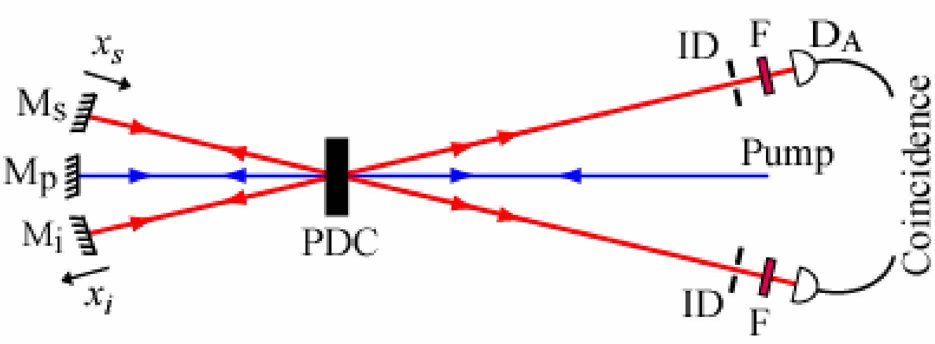




$\Delta L = x_i - x_s$, $\Delta L' = 2x_i + 2x_s$

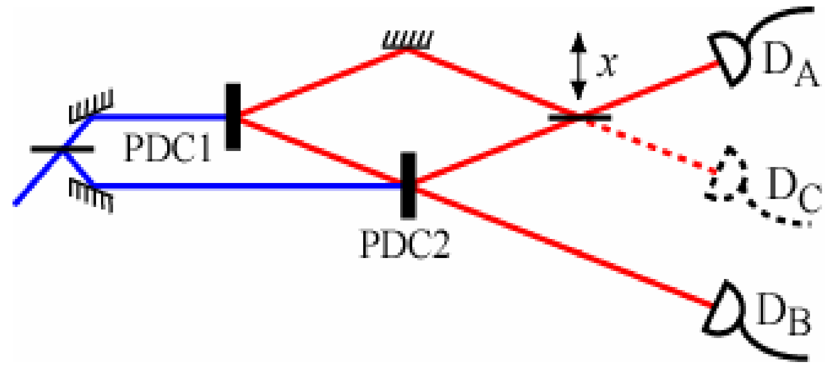
$$R_{AB} \propto 1 - \gamma'(2x_i + 2x_s)\cos[k_0(x_i - x_s)$$

One-photon effects in two-photon experiments



- **Frustrated two-photon Creation**

T. J. Herzog et al., PRL 72, 629 (1994)



- **Induced Coherence**

X. Y. Zou et al., PRL 67, 318 (1991)

One-photon interference profile is the sur
observed at a detection point

$$R_X = \sum_i R_{XY_i}$$

R_X = single detector count rate

R_{XY_i} = coincidence count rate

$$R_A = R_B = R_{AB}$$

Conclusions

One-photon interference

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

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

Two-photon interference

- A two-photon interferes only with itself
- Condition for coherence:

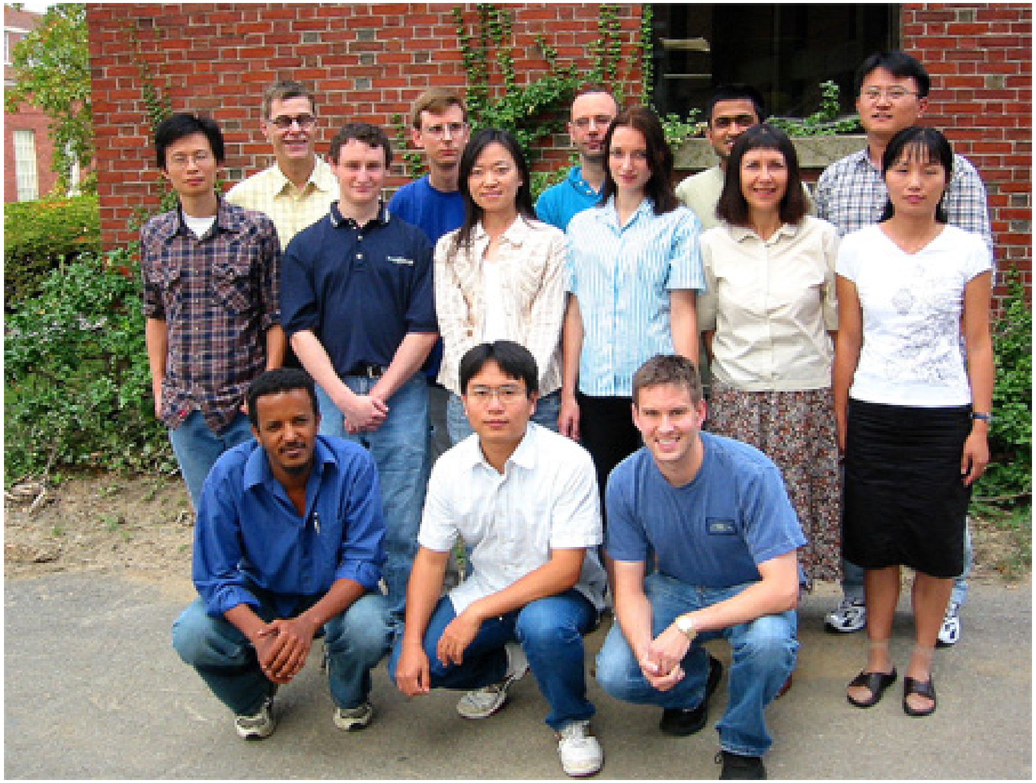
(i) $\Delta L < l^{p}_{coh}$

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

One-photon effect in two-photon experiments

- Interference profile is the sum of two-photon interference profiles observed at a detection point.

Acknowledgements



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- ARO MURI and AFOSR STTR