JPL Quantum Sensing Seminar Series
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Ghost Imaging
&
Turbulence-free Camera

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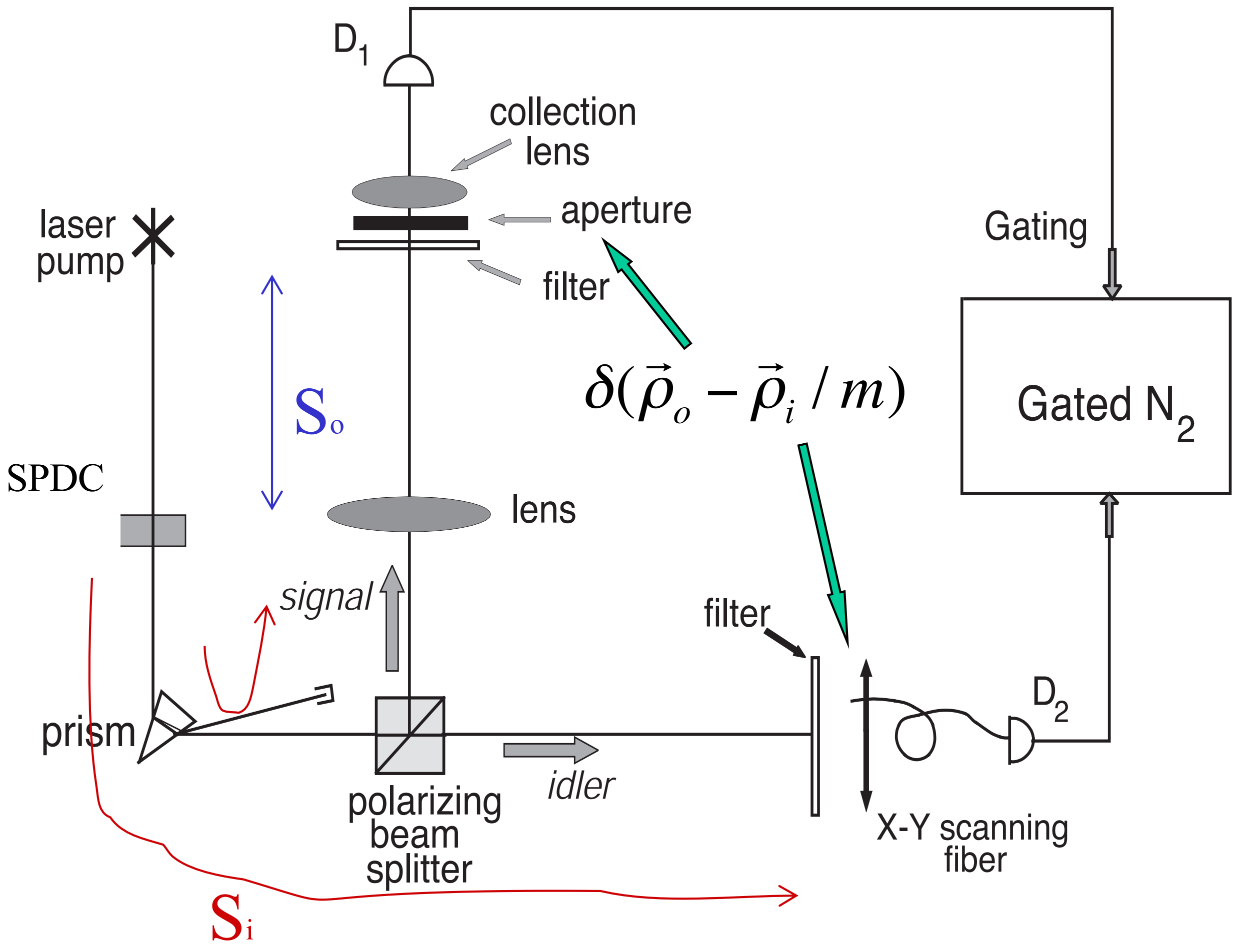
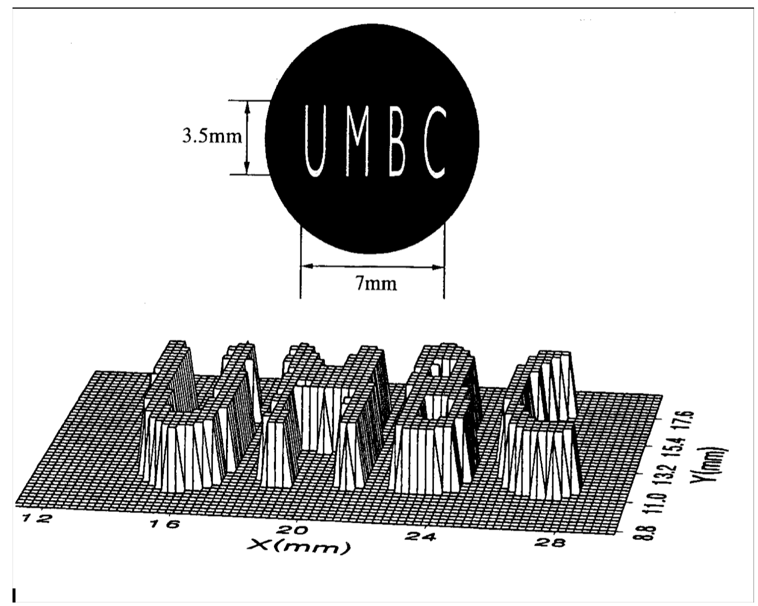
The first “ghost imaging” experiment

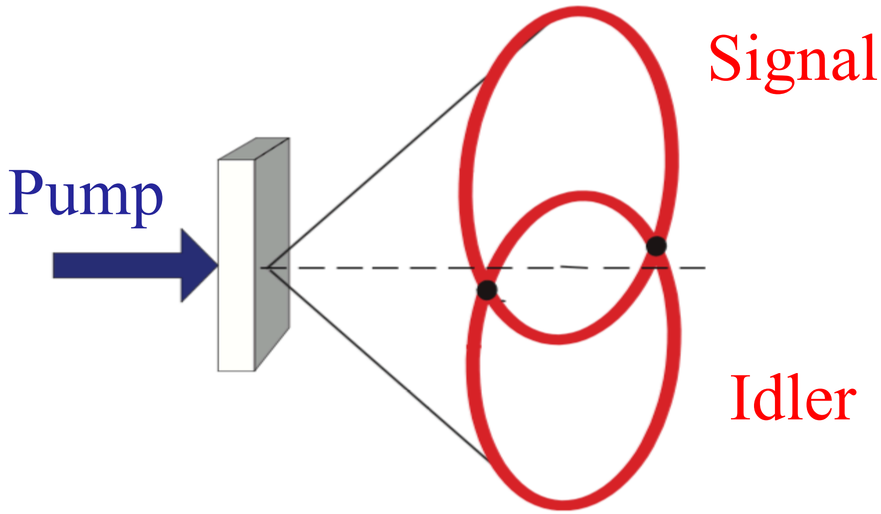




$$\boxed{\frac{1}{S_0} + \frac{1}{S_i} = \frac{1}{f}}$$

Pittman *et al.*, PRA, 52, R3429 (1995); Strekalov *et al.*, PRL, 74, 3600 (1995).

What is so special about entangled biphoton?

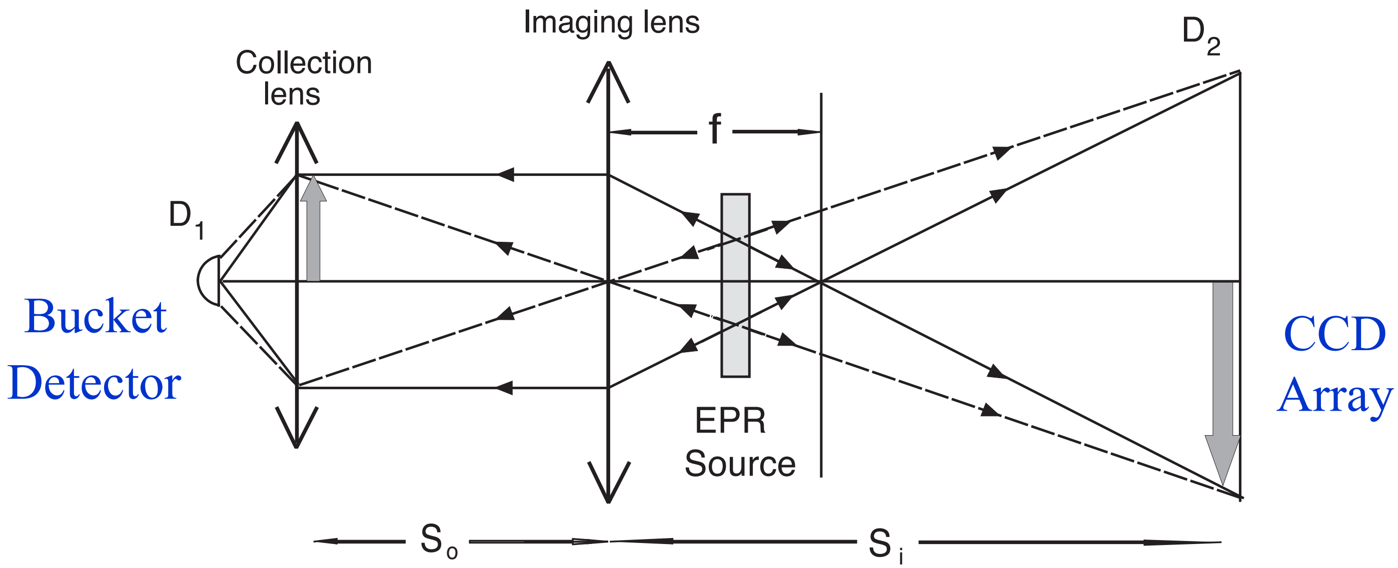


Spontaneous Parametric Down-Conversion (SPDC)

$$|\Psi\rangle = \Psi_0 \int d\mathbf{k}_s d\mathbf{k}_i \, \delta[\omega_p - \omega_s(\mathbf{k}_s) - \omega_i(\mathbf{k}_i)] \delta(\mathbf{k}_p - \mathbf{k}_s - \mathbf{k}_i) a_s^\dagger(\mathbf{k}_s) a_i^\dagger(\mathbf{k}_i)|0\rangle$$

$$\delta(\vec{\rho}_s + \vec{\rho}_i) \Longleftrightarrow \delta(\vec{\kappa}_s + \vec{\kappa}_i)$$

Ghost Imaging: result of self-interference of an entangled photon pair (biphoton)



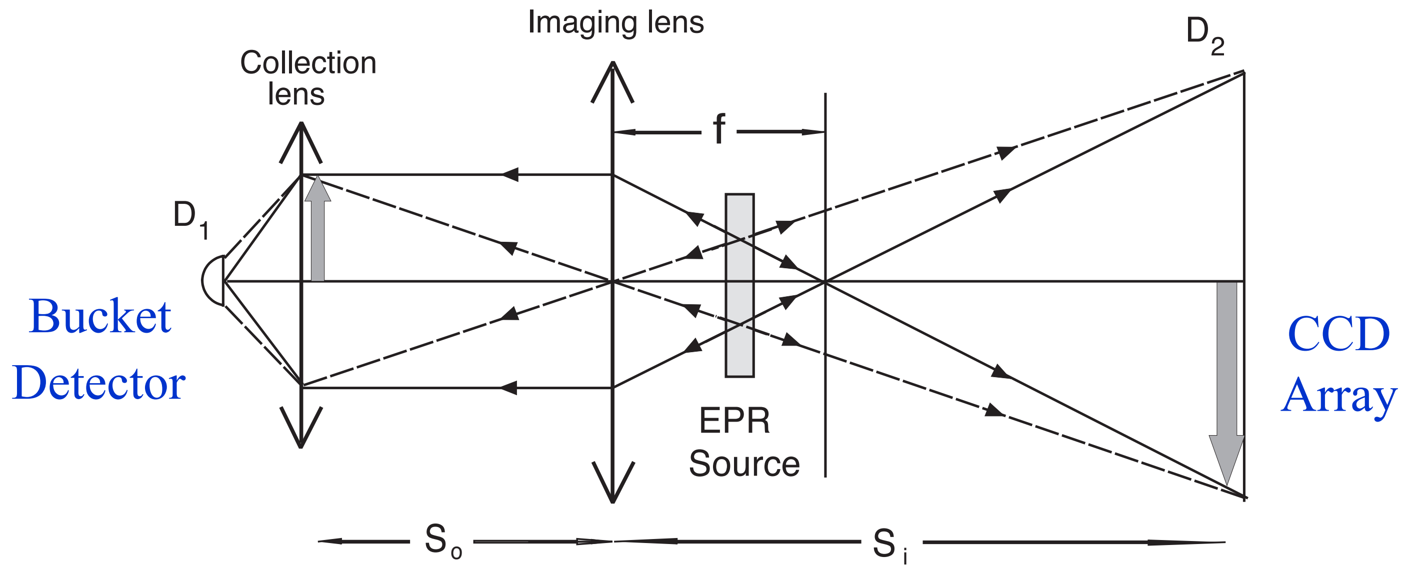
Klyshko's picture of the 1995 Ghost Imaging experiment

$$R_c(\vec{\rho}_i) = \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \left\langle \hat{E}_1^{(-)} \hat{E}_2^{(-)} \hat{E}_2^{(+)} \hat{E}_1^{(+)} \right\rangle$$

$$= \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \boxed{\sum_{j=1}^{\infty} A_j(\vec{\rho}_{s1}, \vec{\rho}_{i2})} = \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \boxed{\delta(\vec{\rho}_o - \vec{\rho}_i / m)}$$

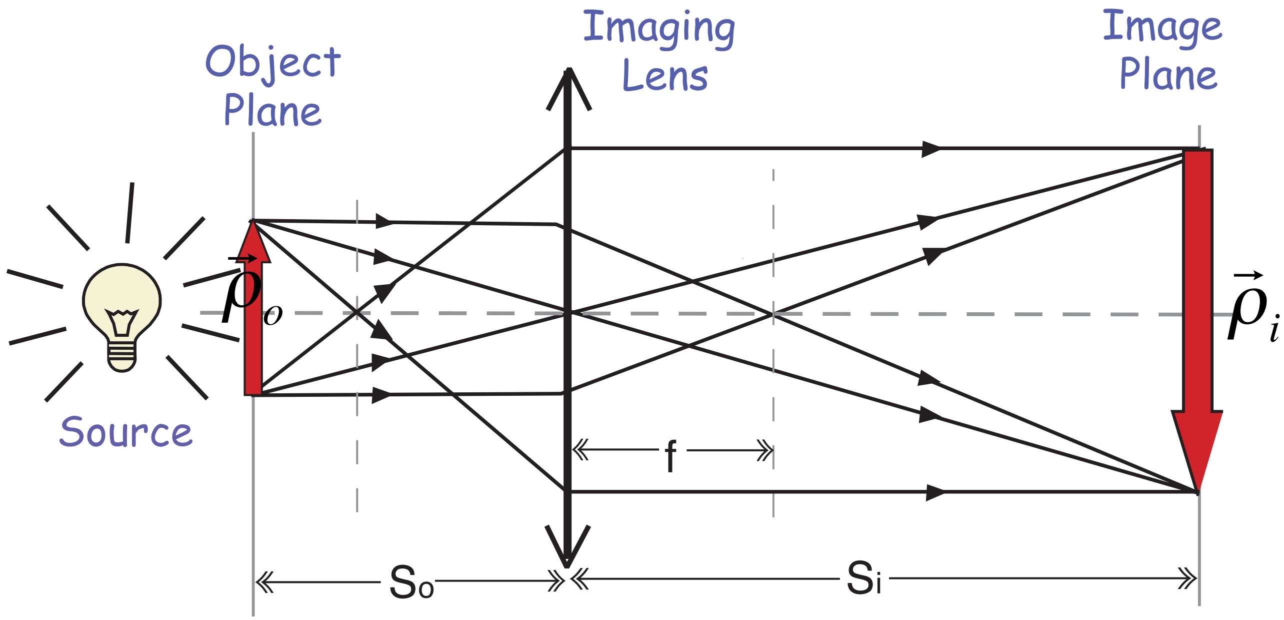
A large number of biphoton amplitudes $A_j(\vec{\rho}_{s1}, \vec{\rho}_{i2})$ superposed constructively at a unique pair of $\vec{\rho}_i$ and $\vec{\rho}_o$, i.e., an object point and its image, and destructively at all other positions in the joint measurement of the pair.

Ghost Imaging: result of self-interference of an entangled photon pair



* Biphoton amplitudes interfere constructively at a unique pair of $\vec{\rho}_o$ and $\vec{\rho}_i$ (equal paths) and interfere destructively at all other points;
* The signal and idler may propagate to any points of $\vec{\rho}_o$ and $\vec{\rho}_i$ respectively, however, if the signal is observed at a point of $\vec{\rho}_o$ the idler can only be detected at a unique point of $\vec{\rho}_i$, jointly, due to constructive-destructive biphoton interference.

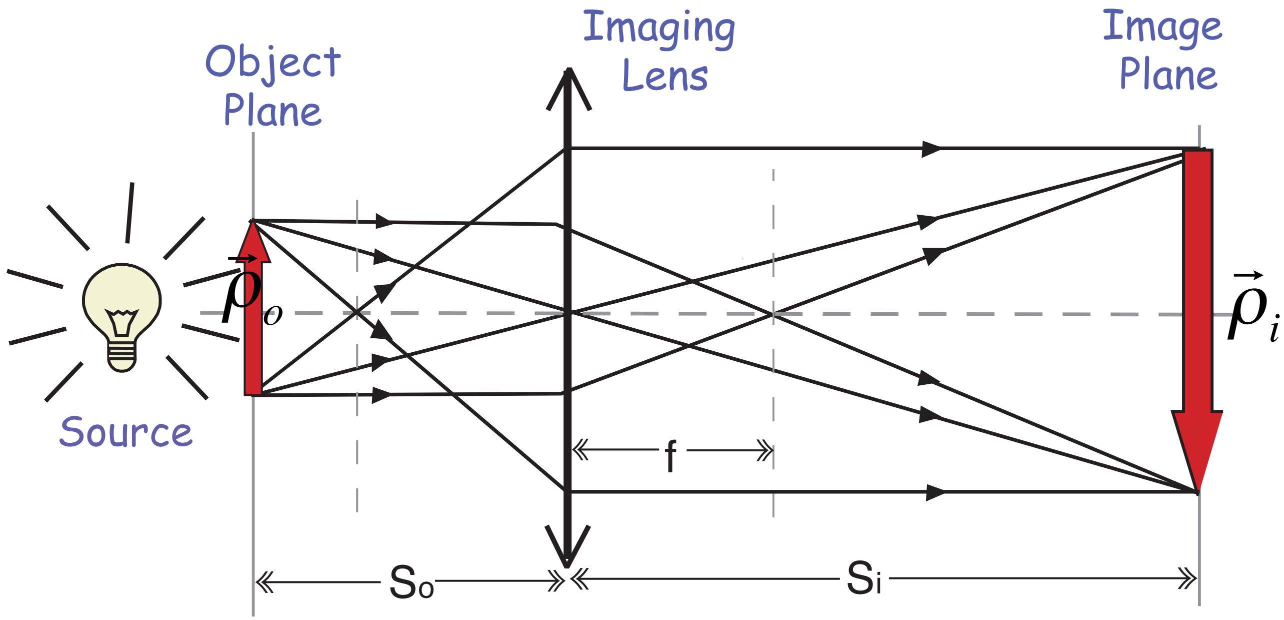
Classical Imaging: result of self-interference of a photon



(1) Radiations from each $\vec{\rho}_o$ interfere constructively at a unique $\vec{\rho}_i$ (equal paths) and interfere destructively at all other points;

(2) Radiations received at $\vec{\rho}_i$ comes from a unique point $\vec{\rho}_o$ due to constructive-destructive interference.

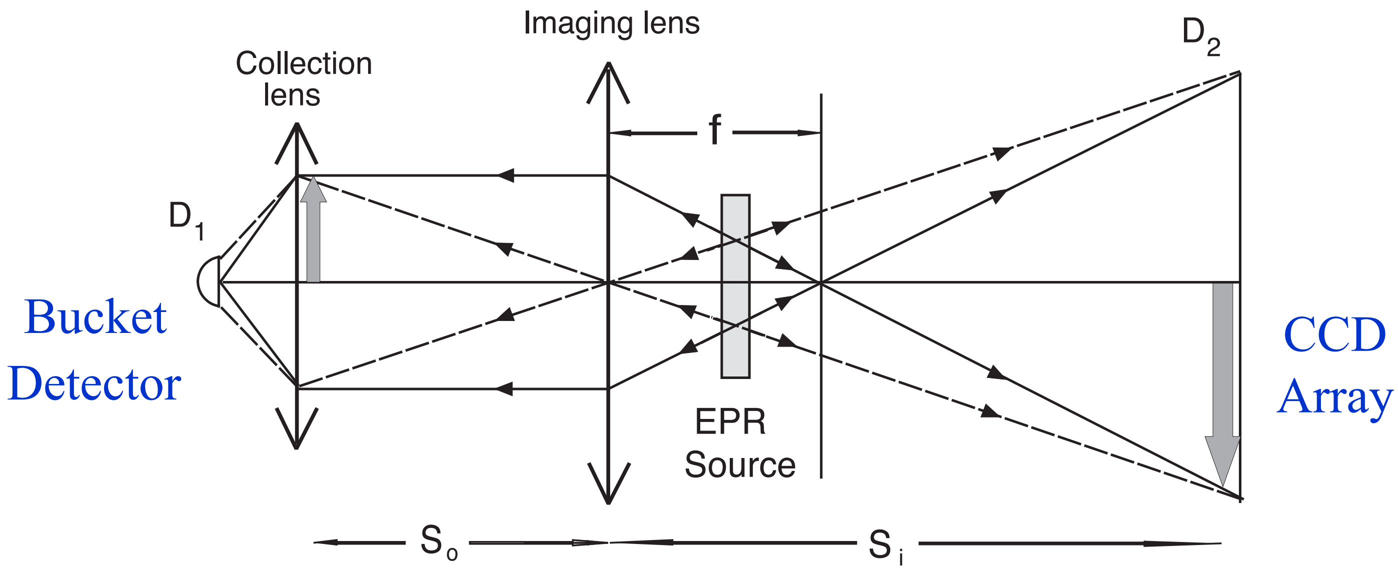
Classical Imaging: result of self-interference of a photon



$$I(\vec{\rho}_i) = \left|E(\vec{\rho}_i)\right|^2 = \sum_{\vec{\rho}_o}\left|A(\vec{\rho}_o)\int d\vec{k}\, E_{\vec{\rho}_o}(\vec{k},\vec{\rho}_i)\right|^2 \cong \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \delta(\vec{\rho}_o - \vec{\rho}_i / m)$$

Classic image is the result of a convolution between the aperture function $A(\rho_o)$ and the image-forming function $\delta(\rho_o - \rho_i/m)$, which is the result of first-order interference: a photon interferes with itself.

Ghost Imaging

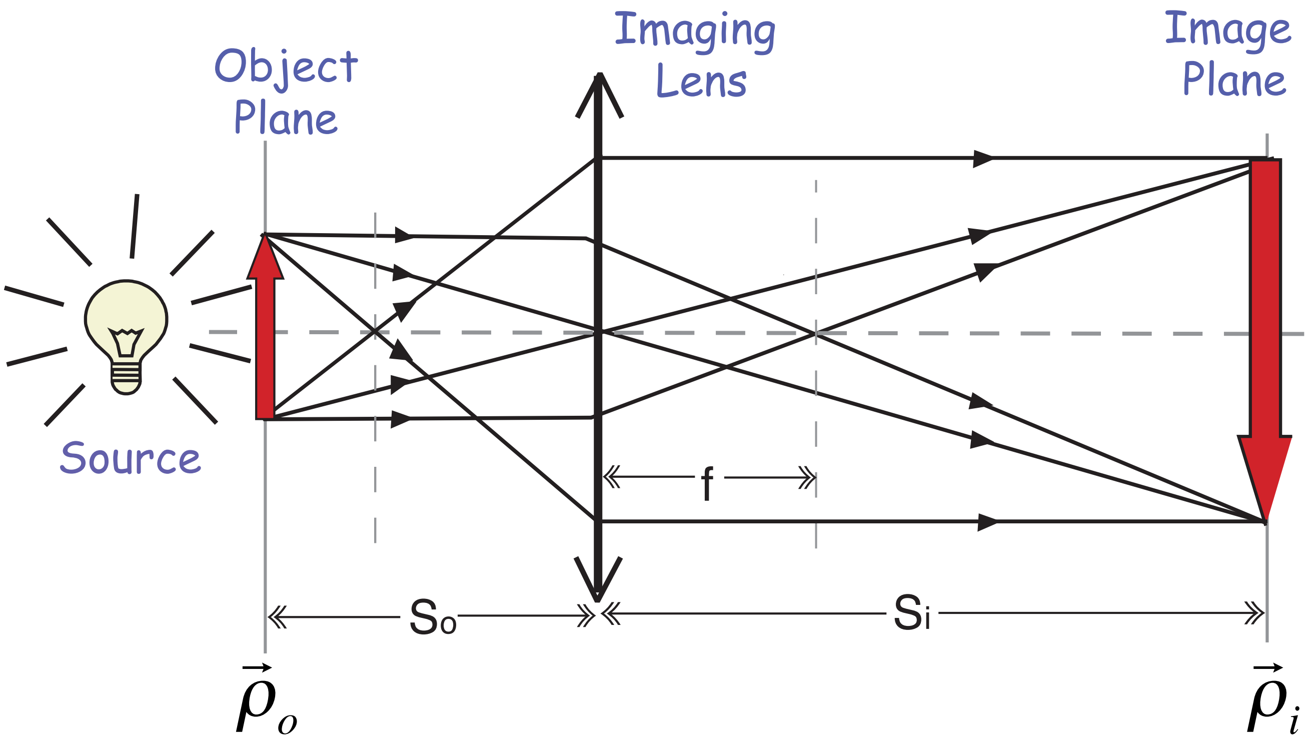


$$R_c(\vec{\rho}_i) = \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \left\langle \hat{E}_1^{(-)}\hat{E}_2^{(-)}\hat{E}_2^{(+)}\hat{E}_1^{(+)} \right\rangle$$

$$= \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \boxed{\sum_{j=1}^{\infty} A_j(\vec{\rho}_{s1}, \vec{\rho}_{i2})} = \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \delta(\vec{\rho}_o - \vec{\rho}_i / m)$$

Ghost image is the result of a convolution between the aperture function $A(\rho_o)$ and the image-forming function $\delta(\rho_o - \rho_i/m)$, which is the result of second-order interference, namely two-photon interference: a biphoton interferes with itself.

Concept of Imaging



$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$$

Gaussian thin lens equation

Imaging: a point-to-point mapping between the object plane and the image plane; all radiations emitted or scattered from a point on the object plane "collapse" to a unique point on the image plane.

From the very beginning of ghost imaging, we started to ask ourselves: Can the self-interference of a randomly paired photons (two randomly created photons are jointly observed by chance) in thermal state produce ghost image?

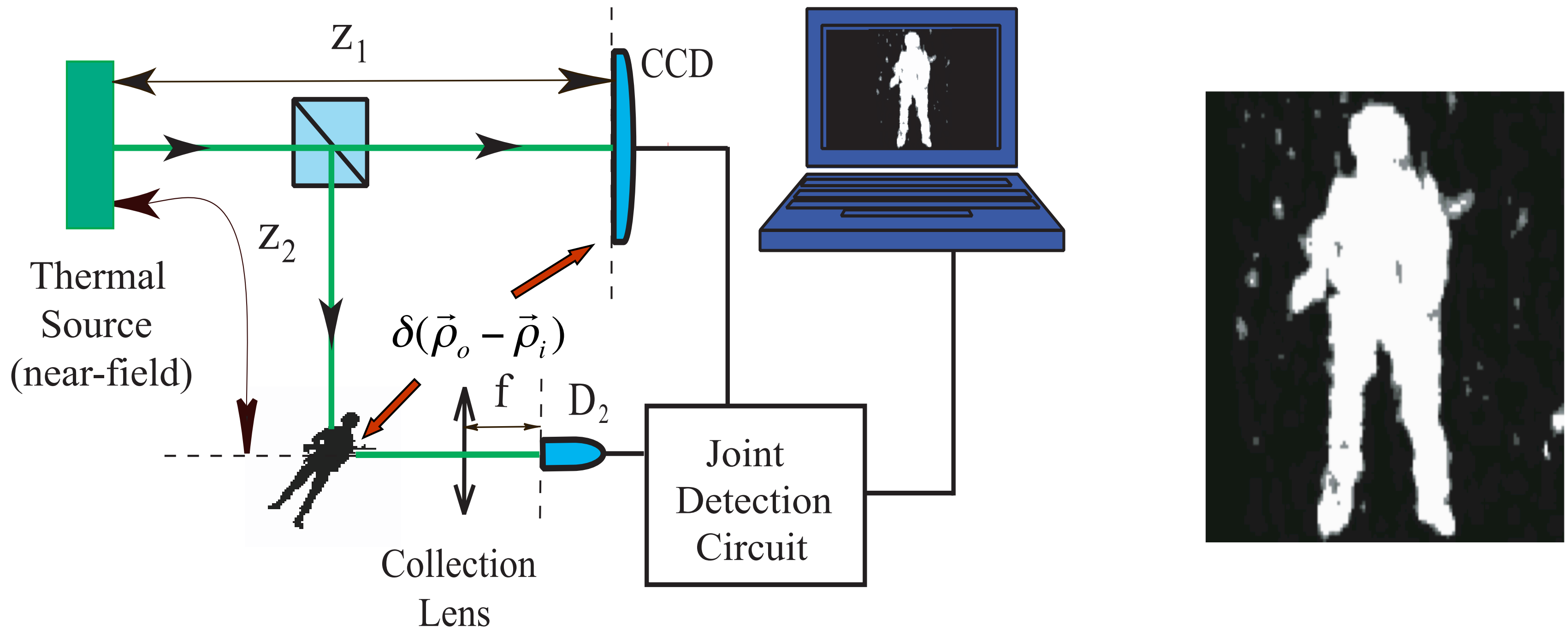
In our 1995 ghost imaging paper (PRA, 52, R3429), we concluded:

"… indeed it is possible to imagine some type of classical source that could partially emulate this behavior…"

It took us 10 years to figure out how to experimentally observe ghost image from self-interference of two randomly created and randomly paired photons in thermal state; a lensless ghost imaging experiment was successfully demonstrated in 2005.

A. Valencia, G. Scarcelli, M. D'Angelo and Y.H. Shih, PRL, 94, 063601 (2005).

The lensless thermal light Ghost Imaging

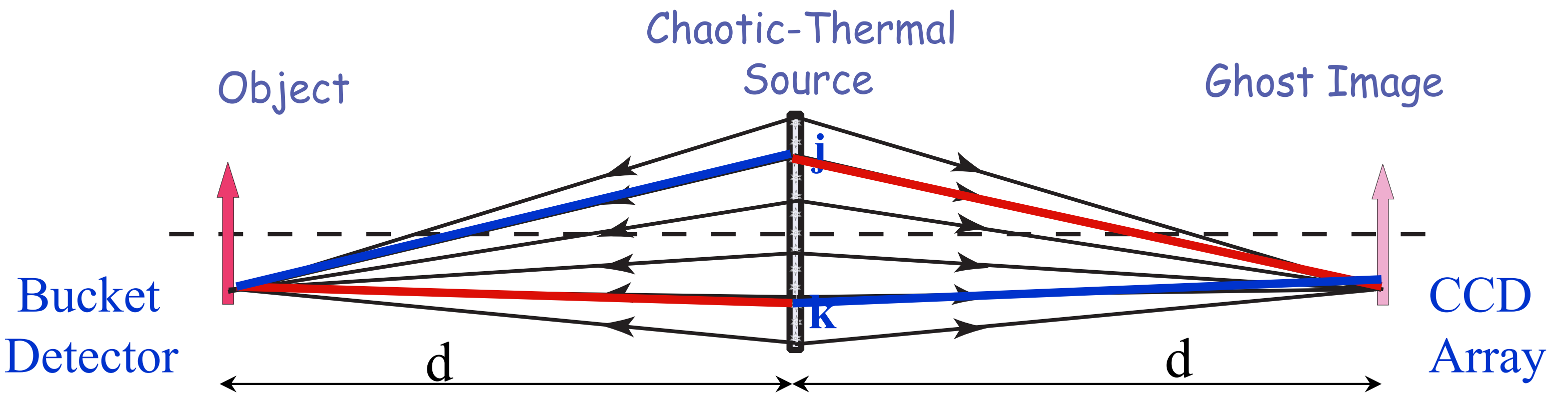


A photon counting detector, D_2, is used to collect and to count all the photons that are randomly scattered-reflected from the toy soldier. A CCD array (2D) was facing the light source instead of the object. An image of the soldier was observed in the measurement of photon number fluctuation correlation of D_2 and the CCD.

R. Myers, K.S. Deacon, and Y.H. Shih, Phys. Rev, A77, R041801 (2008).

Lensless thermal light Ghost Imaging

- Result of self-interference of a random pair of photons



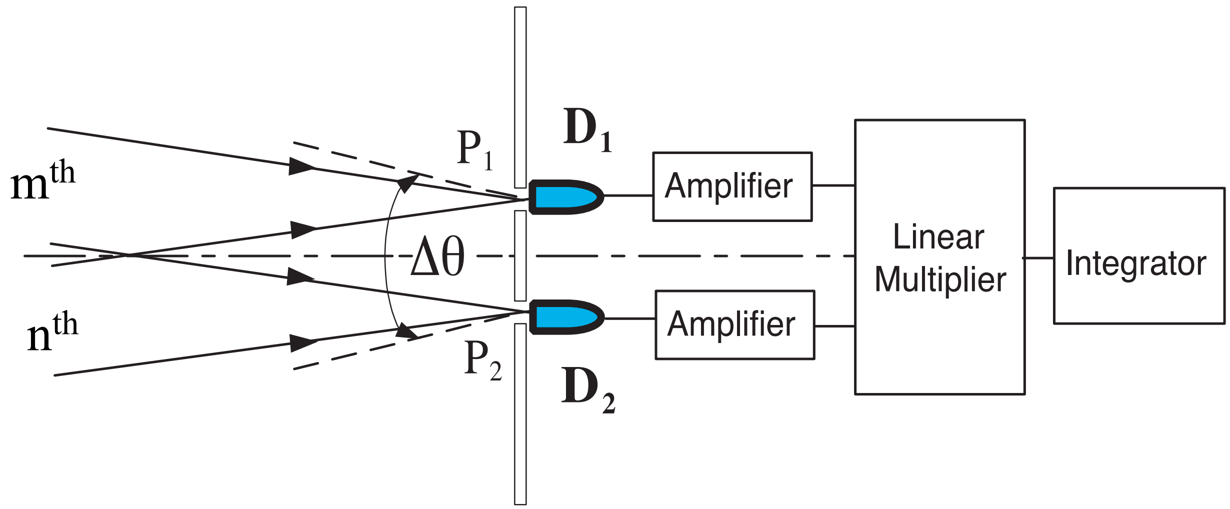
Klyshko's picture of the thermal light Ghost Imaging experiment

$$R_c(\vec{\rho}_i) = \int d\vec{\rho}_o |A(\vec{\rho}_o)|^2 \langle \Delta I(\vec{\rho}_o) \Delta I(\vec{\rho}_i) \rangle$$

$$= \int d\vec{\rho}_o |A(\vec{\rho}_o)|^2 \sum_{j \neq k} \left| \boxed{A(r_{j1}, r_{k2})} + \boxed{A(r_{k1}, r_{j2})} \right|^2 = \int d\vec{\rho}_o |A(\vec{\rho}_o)|^2 \mathrm{somb}^2 [\frac{\pi \Delta\theta}{\lambda} |\vec{\rho}_1 - \vec{\rho}_2|]$$

A large number of randomly distributed and randomly paired subfields superposed constructively at $\vec{\rho}_o = \vec{\rho}_i$, and destructively at all other transverse coordinates $\vec{\rho}_o \neq \vec{\rho}_i$ in the intensity fluctuation correlation measurement.

HBT interferometer
- second-order spatial coherence-correlation



Schematic of a HBT interferometer. The interferometer is similar to the Young's double-pinhole interferometer and the Michelson stellar interferometer, except two analog photodetectors are placed behind the pinholes for joint-detection of the radiations.

$$\Gamma^{(2)}_{mn}(\vec{\rho}_1, z_1; \vec{\rho}_2, z_2)$$
$$= I^2_{mn} \Big| \frac{1}{\sqrt{2}} \big[g_m(\vec{\rho}_1, z_1)\, g_n(\vec{\rho}_2, z_2) + g_m(\vec{\rho}_2, z_2)\, g_n(\vec{\rho}_1, z_1) \big] \Big|^2$$

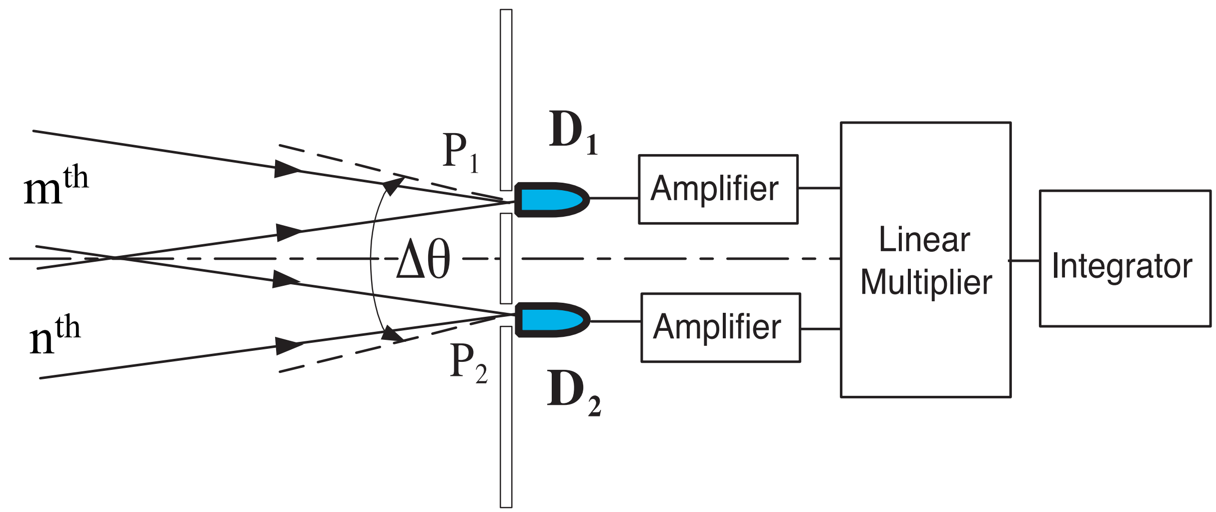
Einstein's picture

$$
\begin{aligned}
&\Gamma^{(2)}(\vec{\rho}_1, z_1; \vec{\rho}_2, z_2) \\
&= \sum_{m,n} \Big| \frac{1}{\sqrt{2}} \big[E_m(\vec{\rho}_1, z_1) E_n(\vec{\rho}_2, z_2) + E_n(\vec{\rho}_1, z_1) E_m(\vec{\rho}_2, z_2) \big] \Big|^2 \\
&= \sum_{m,n} \Gamma^{(2)}_{mn}(\vec{\rho}_1, z_1; \vec{\rho}_2, z_2),
\end{aligned}
$$

$$
\begin{aligned}
&\Gamma^{(2)}_{mn}(\vec{\rho}_1, z_1; \vec{\rho}_2, z_2) \\
&= I^2_{mn} \Big| \frac{1}{\sqrt{2}} \big[g_m(\vec{\rho}_1, z_1)\, g_n(\vec{\rho}_2, z_2) + g_m(\vec{\rho}_2, z_2)\, g_n(\vec{\rho}_1, z_1) \big] \Big|^2
\end{aligned}
$$

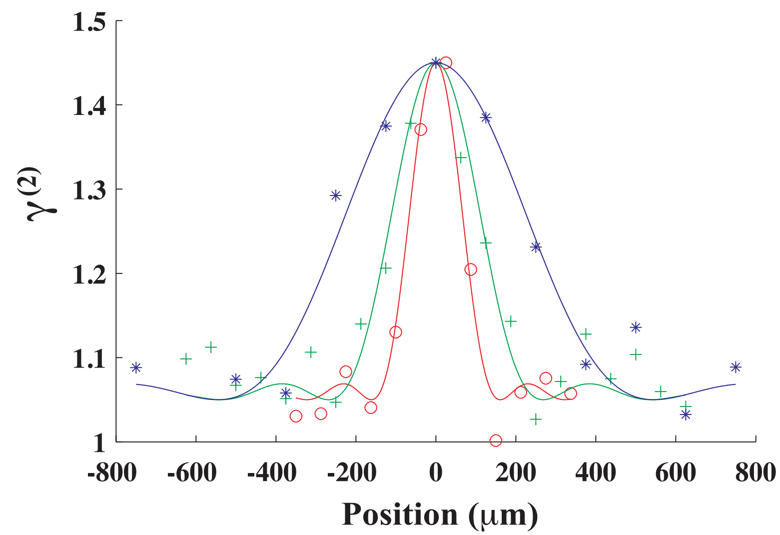
$$
g_m(\vec{\rho}_j, z_j) = \frac{c_o}{z_j} e^{i \frac{\omega z_j}{c}} e^{i \frac{\omega}{2 c z_j} |\vec{\rho}_j - \vec{\rho}_m|^2}
$$

HBT interferometer
- second-order spatial coherence-correlation



$$\Gamma^{(2)}(\vec{\rho}_1, \vec{\rho}_2) = I_0^2 \left[1 + \mathrm{somb}^2\left(\frac{\pi\Delta\theta}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|\right)\right]$$

$$\gamma^{(2)}(\vec{\rho}_1, \vec{\rho}_2) = 1 + \mathrm{somb}^2\left(\frac{\pi\Delta\theta}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|\right)$$



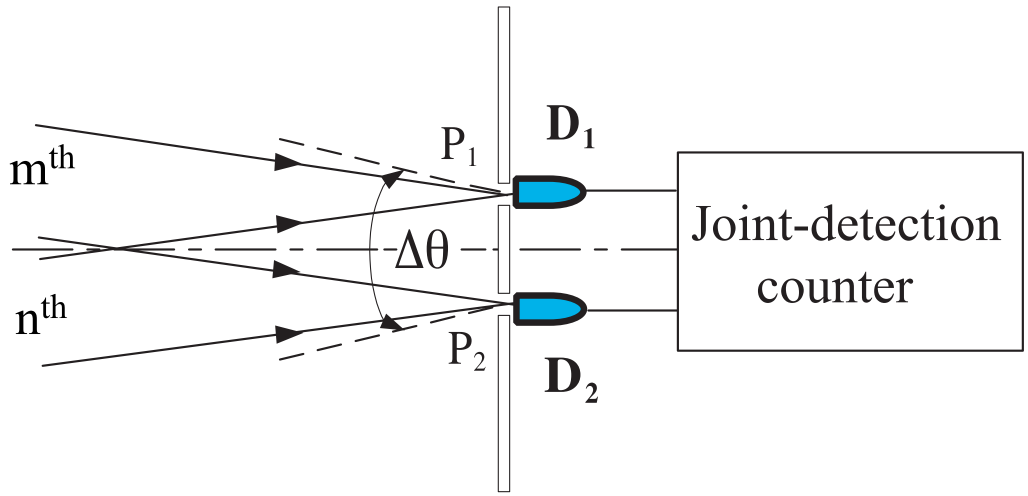
Quantum mechanical picture

$$G^{(2)}(\vec{\rho}_1, z_1; \vec{\rho}_2, z_2)$$
$$= \sum_{m,n} \Big| \frac{1}{\sqrt{2}} \big[\psi_{mn}(\vec{\rho}_1, z_1; \vec{\rho}_2, z_2) + \psi_{nm}(\vec{\rho}_1, z_1; \vec{\rho}_2, z_2)\big] \Big|^2$$
$$= \sum_{m,n} \Big| \frac{1}{\sqrt{2}} \big[\psi_m(\vec{\rho}_1, z_1)\psi_n(\vec{\rho}_2, z_2) + \psi_n(\vec{\rho}_1, z_1)\psi_m(\vec{\rho}_2, z_2)\big] \Big|^2$$

$$G^{(2)}_{mn}(\vec{\rho}_1, z_1; \vec{\rho}_2, z_2)$$
$$= \Big| |\alpha_{mn}|^2 \frac{1}{\sqrt{2}} \big[g_m(\vec{\rho}_1, z_1)\, g_n(\vec{\rho}_2, z_2) + g_n(\vec{\rho}_1, z_1)\, g_m(\vec{\rho}_2, z_2)\big] \Big|^2$$
$$g_m(\vec{\rho}_j, z_j) = \frac{c_o}{z_j} e^{i\frac{\omega z_j}{c}} e^{i\frac{\omega}{2cz_j}|\vec{\rho}_j - \vec{\rho}_m|^2}$$

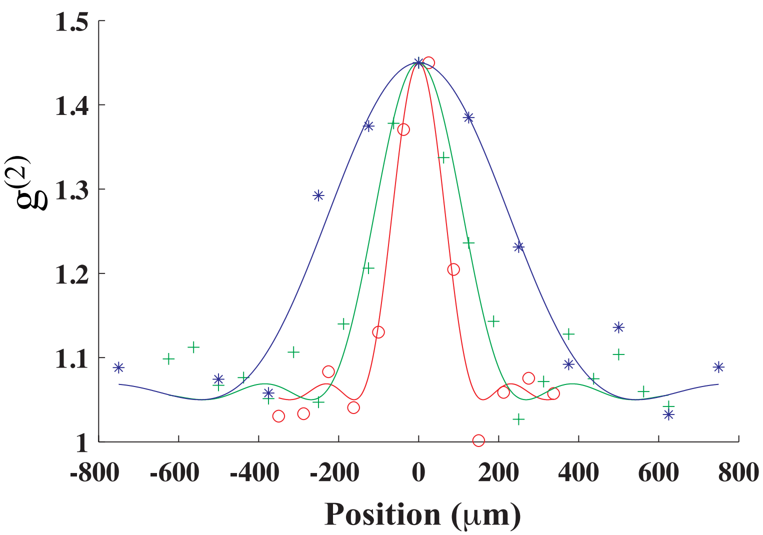
$$G^{(2)}(\vec{\rho}_1, \vec{\rho}_2) = G_0^2 \left[1 + \mathrm{somb}^2\Big(\frac{\pi\Delta\theta}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|\Big)\right]$$
$$g^{(2)}(\vec{\rho}_1, \vec{\rho}_2) = 1 + \mathrm{somb}^2\Big(\frac{\pi\Delta\theta}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|\Big)$$

HBT interferometer
- second-order spatial coherence-correlation



$$G^{(2)}(\vec{\rho}_1, \vec{\rho}_2) = G_0^2\left[1 + \mathrm{somb}^2\left(\frac{\pi\Delta\theta}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|\right)\right]$$

$$g^{(2)}(\vec{\rho}_1, \vec{\rho}_2) = 1 + \mathrm{somb}^2\left(\frac{\pi\Delta\theta}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|\right)$$



Photon number fluctuation correlation

$$\langle \Delta n_1(\vec{\rho}_1)\Delta n_2(\vec{\rho}_2)\rangle \propto \mathrm{somb}^2\big(\frac{\pi\Delta\theta}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|\big)$$

(1) The correlation is nonlocal;

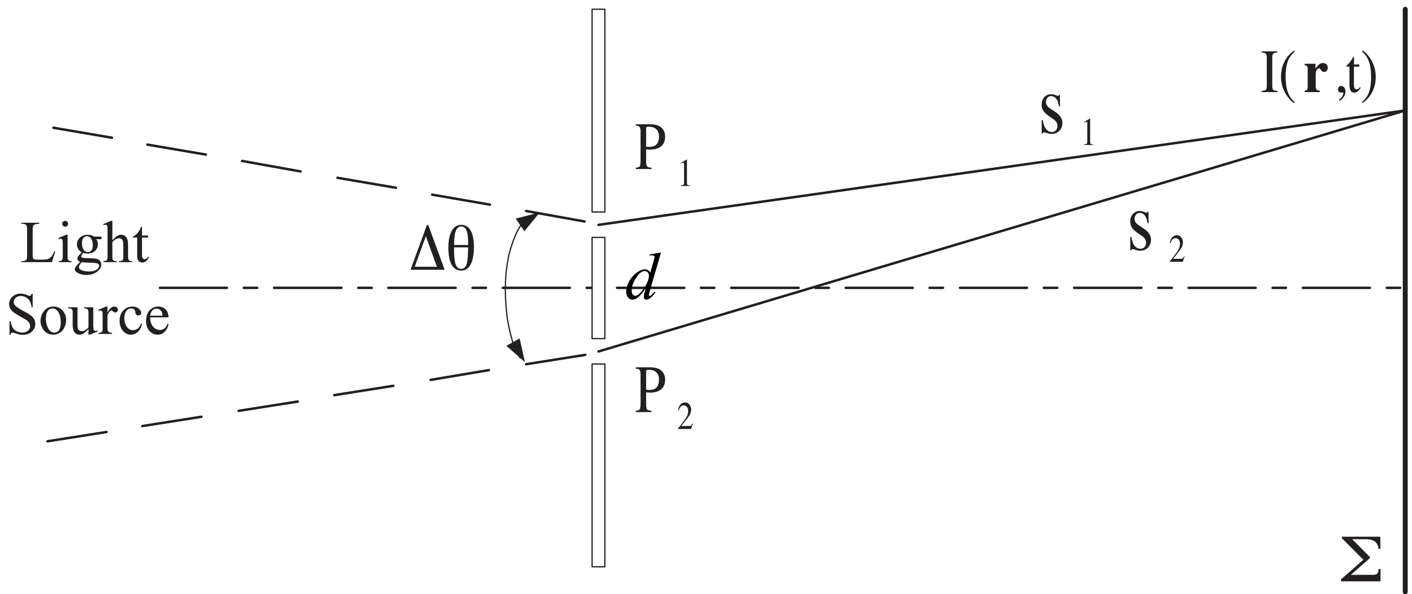
(2) The correlation is turbulence-free;

(3) Its resolution is determined by the angular size of the source.

It is possible to obtain a turbulence-free point-to-spot correlation in the measurement of intensity fluctuation correlation on earth from sunlight. The angular diameter of sun is about 0.5-degree: spatial resolution ~150μm for any position on earth. To achieve 150μm resolution at 10km from a classical imaging system, ~92m diameter imaging lens is required. For a large sized source the somb-function can be approximated to a δ-function.

Two-photon interference can be turbulence-free.

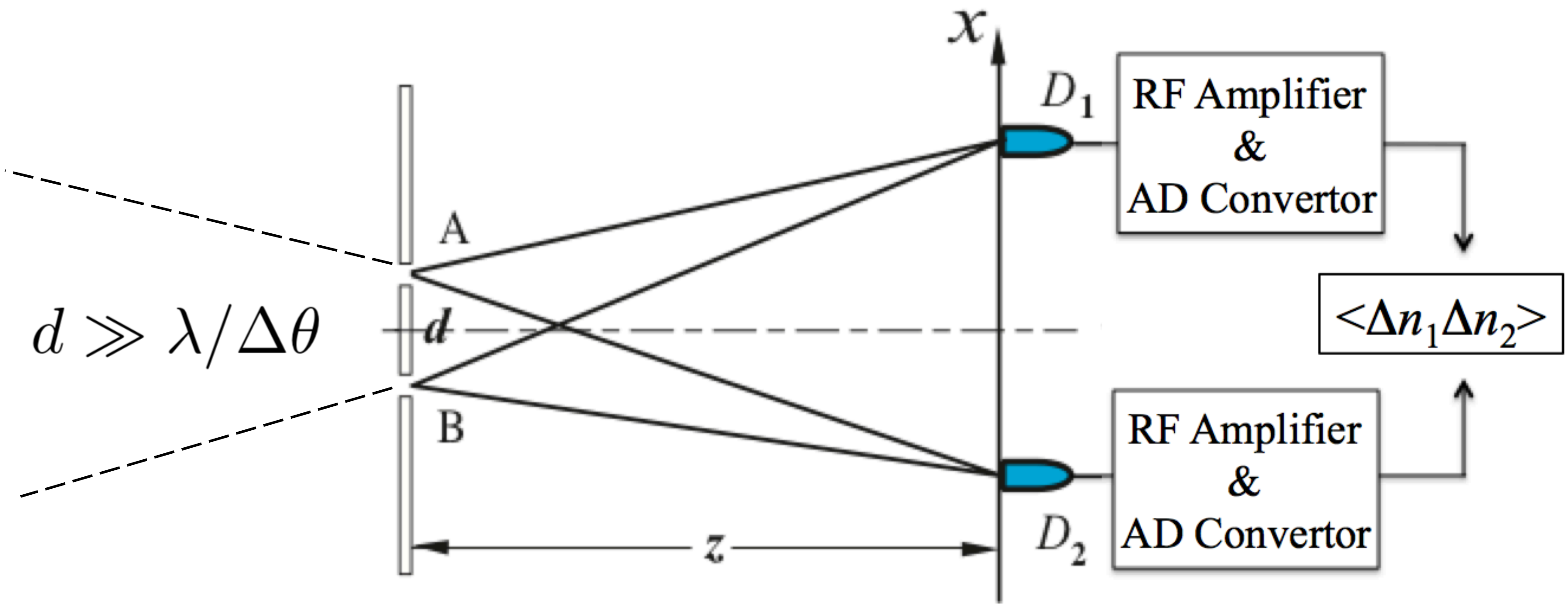
Young's Double-slit interferometer



$$\langle I(x)\rangle = I_0[1 + \mathrm{sinc}\frac{\pi d\Delta\theta}{\lambda}\cos\frac{2\pi d}{\lambda z}x]$$

$\boxed{\mathrm{sinc}(x) = \sin(x)/x = 0, \text{ when } d > \lambda/\Delta\theta}$ $\boxed{l_c \equiv \lambda/\Delta\theta}$

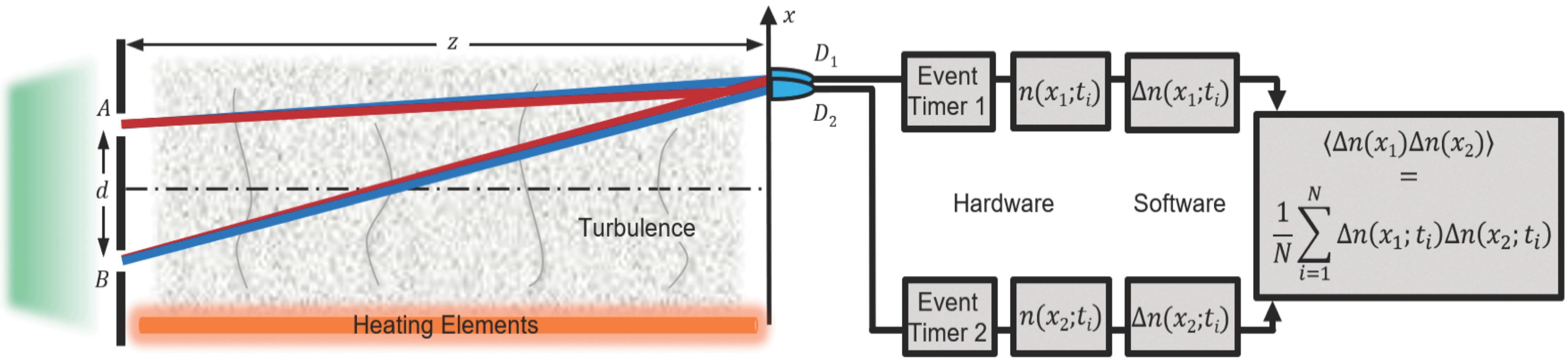
Two-photon Young's double-slit interferometer



$$\langle \Delta I(x_1) \Delta I(x_2) \rangle = I_0^2 \left[1 + \cos \frac{2\pi d}{\lambda z}(x_1 - x_2) \right]$$

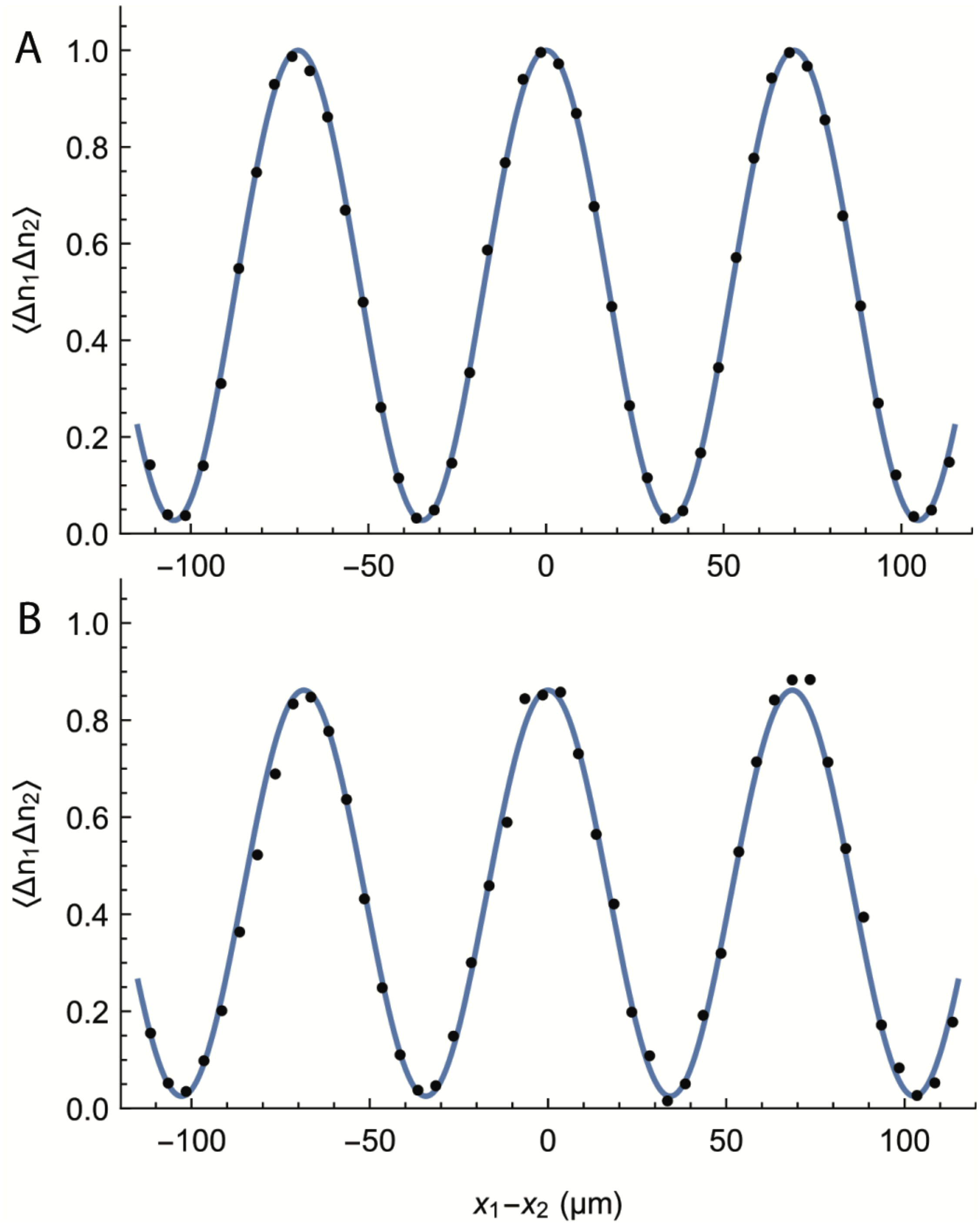
It is turbulence-free !

A Turbulence-free Double-slit Interferometer



This interferometer has two types of output (1) Mean intensity or photon umber, and (2) Intensity fluctuation or photon number fluctuation correlation. Due to the experimental condition of $d >> lc$, no interferences are observable from the mean intensity measurement of D_1 and D_2, respectively. A turbulence-free interference with 100% visibility is observed from the intensity fluctuation correlation measurement D_1 and D_2, jointly. The observed interference is a two-photon phenomenon: a random pair of photons interfering with the pair itself.

Thomas A. Smith and Yanhua Shih, PRL, 120, 063606 (2018).



$$\langle \Delta n(x_1)\Delta n(x_2)\rangle$$

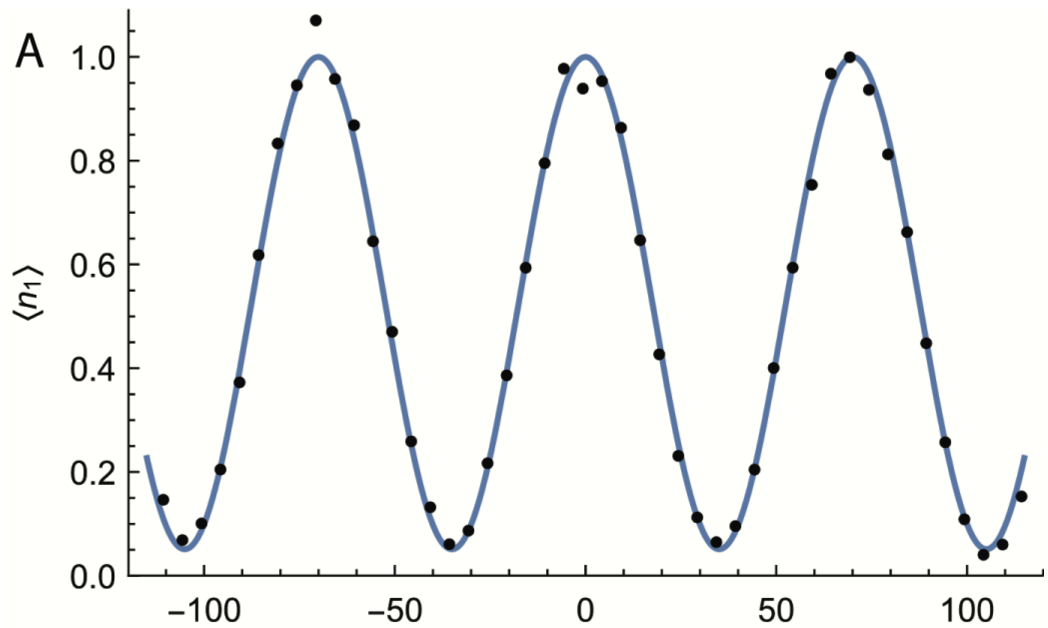
$$d \gg \lambda/\Delta\theta$$

No turbulence

$$\langle \Delta n(x_1)\Delta n(x_2)\rangle$$

$$d \gg \lambda/\Delta\theta$$

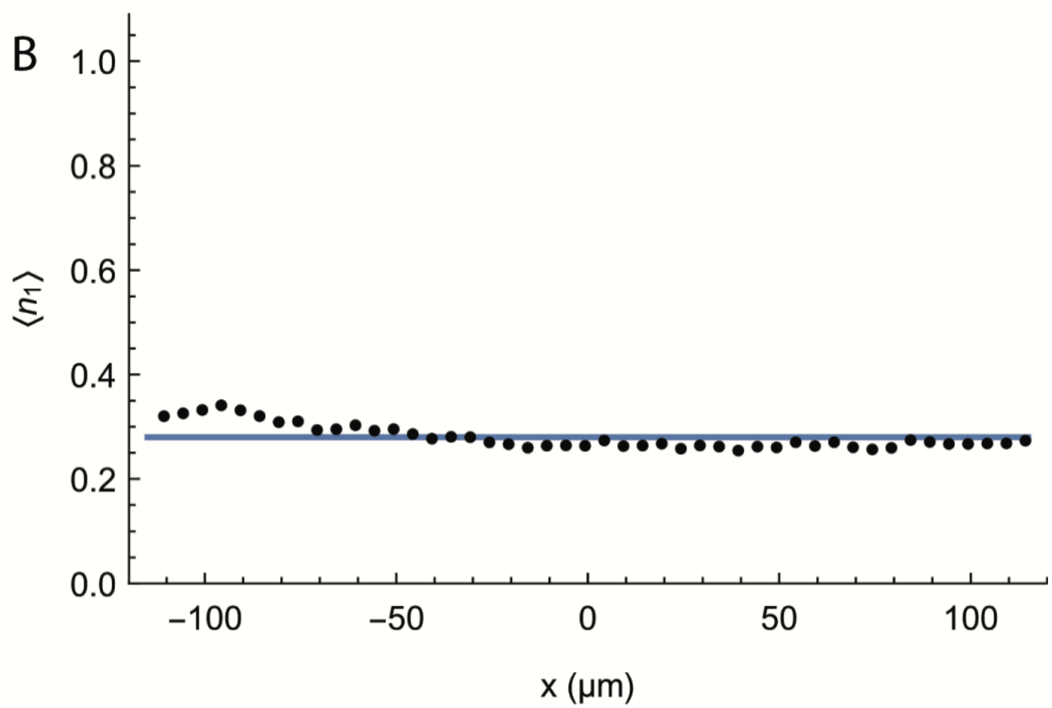
Strong turbulence



$$\langle I(x_1)\rangle$$

$$l_c > d$$

No turbulence



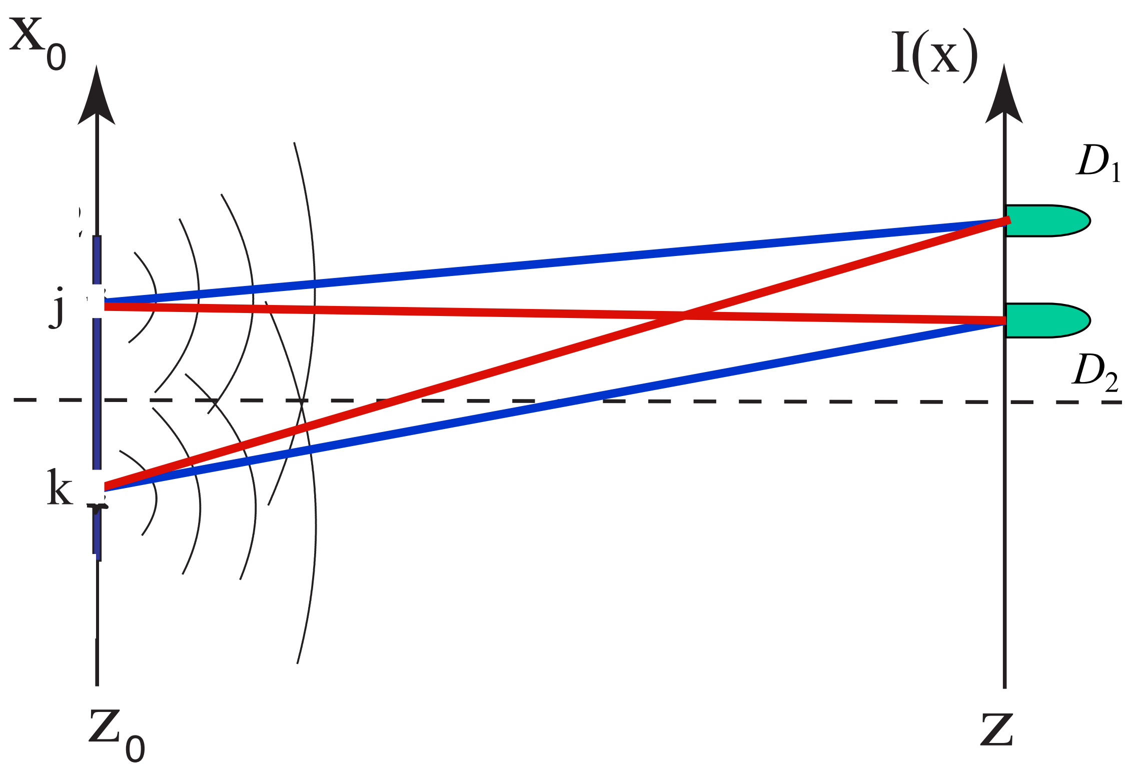
$$\langle I(x_1)\rangle$$

$$l_c > d$$

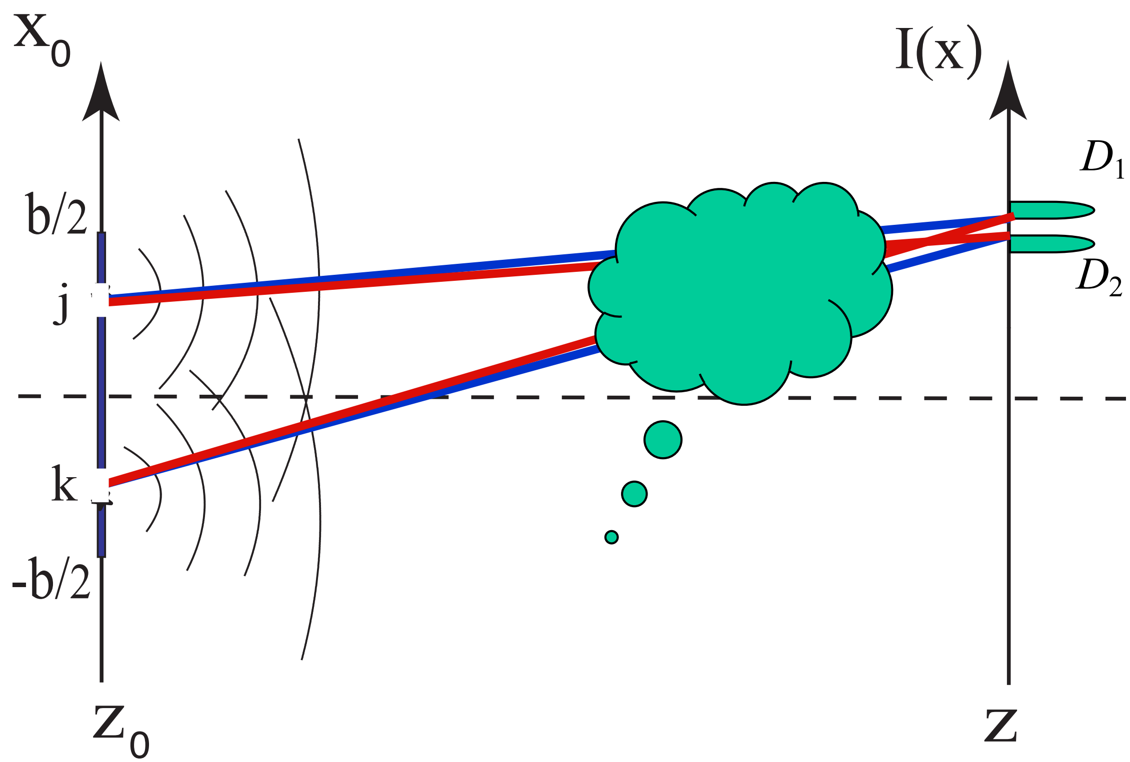
Strong turbulence

Why is it turbulence free?

Two-photon interference of thermal field



$$\left\langle \Delta n_1 \Delta n_2 \right\rangle = \sum_{j \neq k} \left| \boxed{A(r_{j1}, t_{j1}; r_{k2}, t_{k2})} + \boxed{A(r_{k1}, t_{k1}; r_{j2}, t_{j2})} \right|^2$$



$$\boxed{\vec{\rho}_1 \approx \vec{\rho}_2}$$

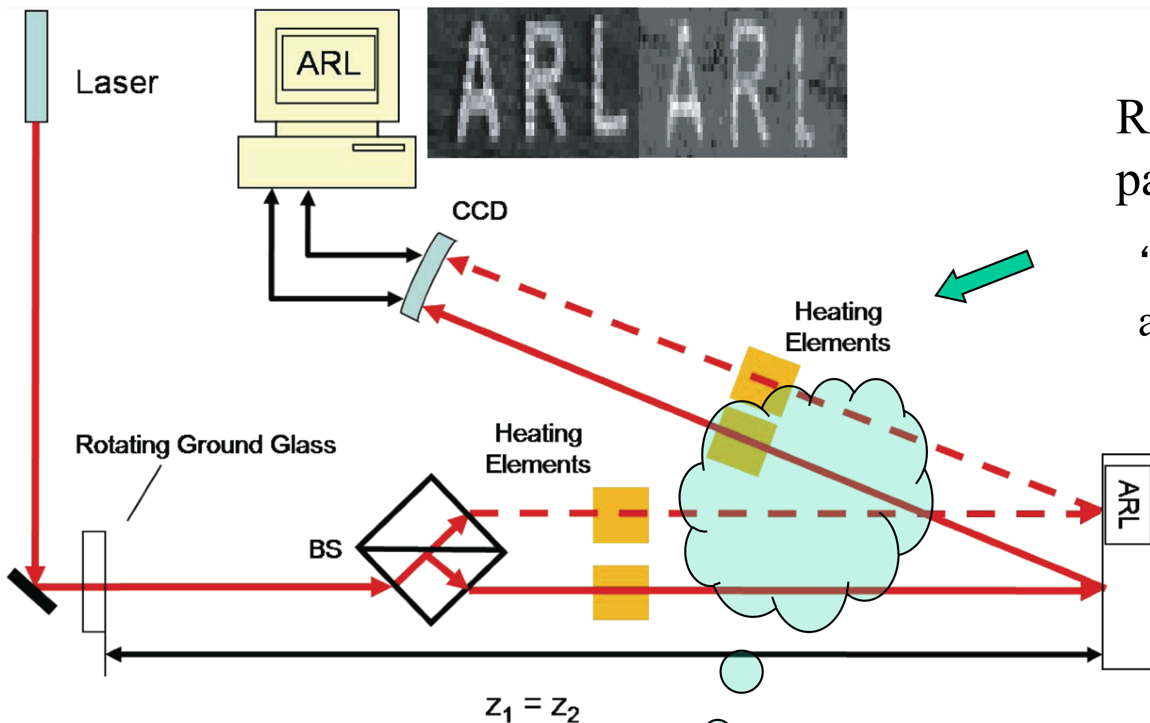
$$\left| e^{i\varphi(r_{j1},r_{k2})} \boxed{A(r_{j1},r_{k2})} + e^{i\varphi(r_{k1},r_{j2})} \boxed{A(r_{k1},r_{j2})} \right|^2 = \left| e^{i\varphi} \boxed{A(r_{j1},r_{k2})} + e^{i\varphi} \boxed{A(r_{k1},r_{j2})} \right|^2$$

The blue and red two-photon amplitudes experience the same turbulence with the same phase variation when $\boxed{\vec{\rho}_1 \approx \vec{\rho}_2}$.

$$\langle \Delta n_1 \Delta n_2 \rangle = \sum_{j \neq k} \left| e^{i\Delta\varphi} \boxed{A_{j1,k2}} + e^{i\Delta\varphi} \boxed{A_{k1,j2}} \right|^2$$

Lensless ghost image, which is produced from two-photon interference, is turbulence-free.

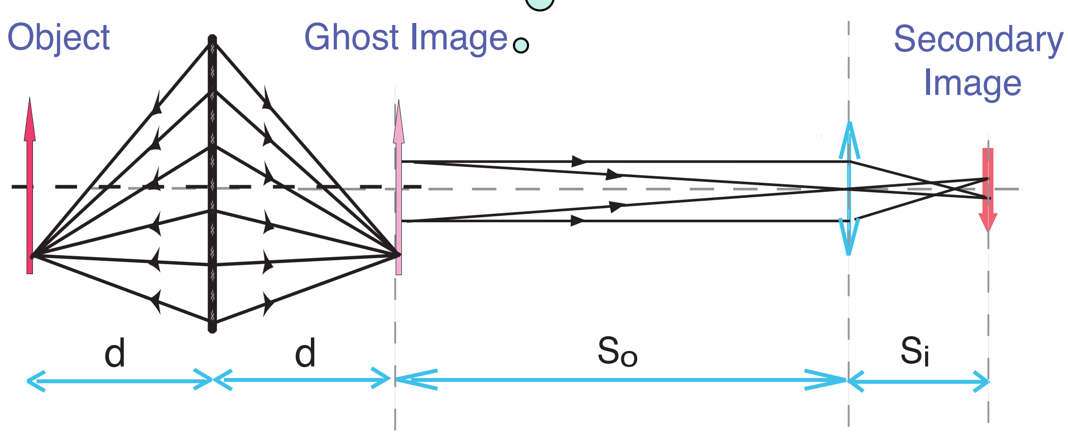
Lensless Ghost Imaging: Turbulence-free



Refractive index structure parameter: $C_n^2 = 1.2 \times 10^{-12}$

"…extremely high level of atmospheric turbulence…"

Classical images are "blurred" out.



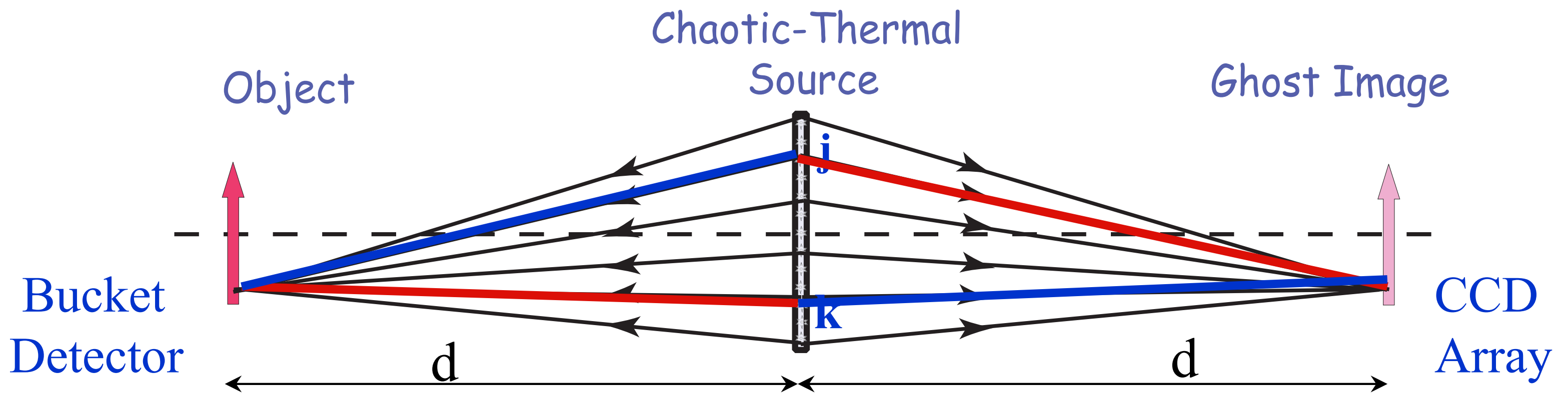
Turbulence-free Image observed from

$$\langle \Delta n(\vec{\rho}_1) \Delta n(\vec{\rho}_2) \rangle$$

R. Meyers, K.S. Deacon, Y.H. Shih, Applied Phys. Lett., 98, 111115 (2011).

Lensless thermal light Ghost Imaging

- Result of self-interference of a random photon pair

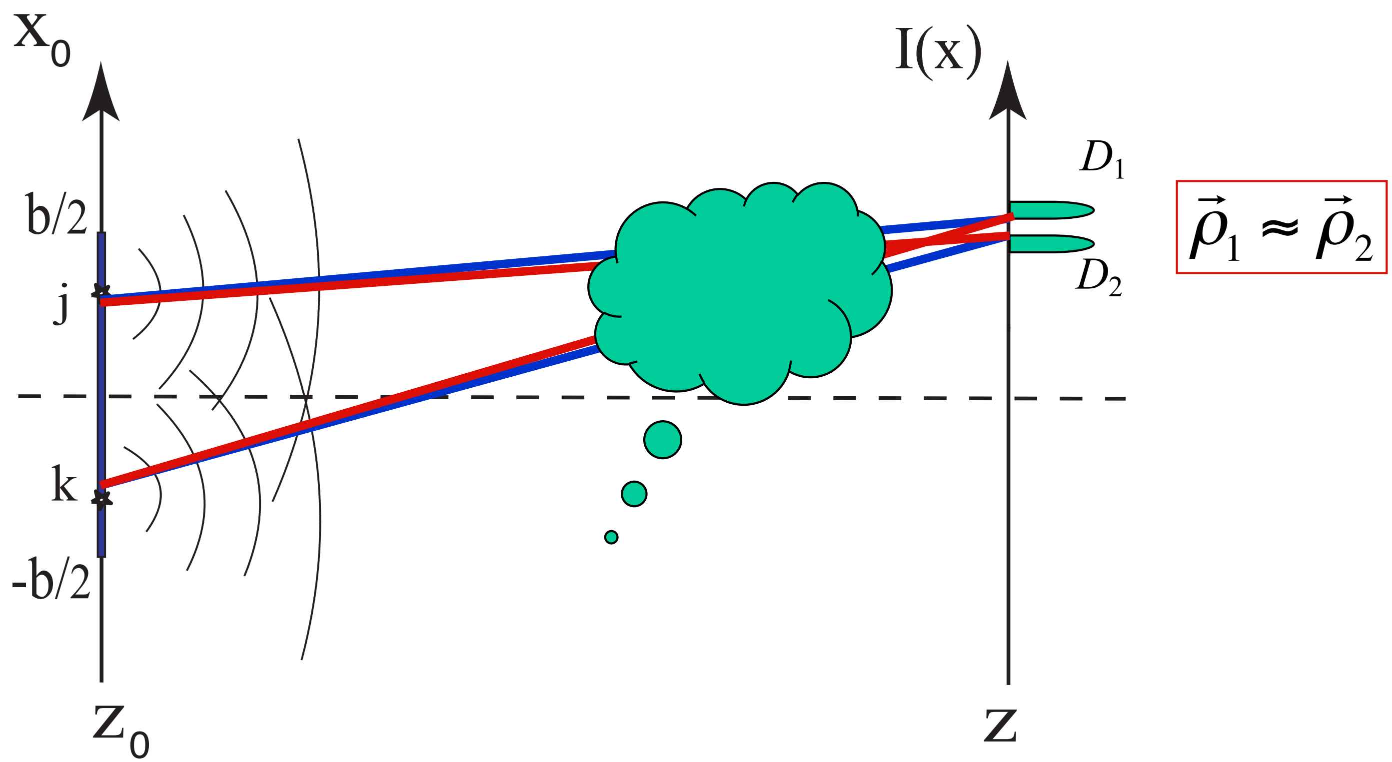


Klyshko's picture of the thermal light Ghost Imaging experiment

$$R_c(\vec{\rho}_i) = \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \langle \Delta I(\vec{\rho}_o)\Delta I(\vec{\rho}_i)\rangle$$

$$= \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \sum_{j\neq k} \left|\boxed{A(r_{j1}, r_{k2})} + \boxed{A(r_{k1}, r_{j2})}\right|^2 = \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \mathrm{somb}^2[\frac{\pi\Delta\theta}{\lambda}|\vec{\rho}_1 - \vec{\rho}_2|]$$

A large number of randomly distributed and randomly paired subfields superposed constructively at $\vec{\rho}_o = \vec{\rho}_i$, and destructively at all other transverse coordinates $\vec{\rho}_o \neq \vec{\rho}_i$ in the intensity fluctuation correlation measurement.



$$\left| e^{i\varphi(r_{j1},r_{k2})} \boxed{A(r_{j1},r_{k2})} + e^{i\varphi(r_{k1},r_{j2})} \boxed{A(r_{k1},r_{j2})} \right|^2 = \left| e^{i\varphi} \boxed{A(r_{j1},r_{k2})} + e^{i\varphi} \boxed{A(r_{k1},r_{j2})} \right|^2$$

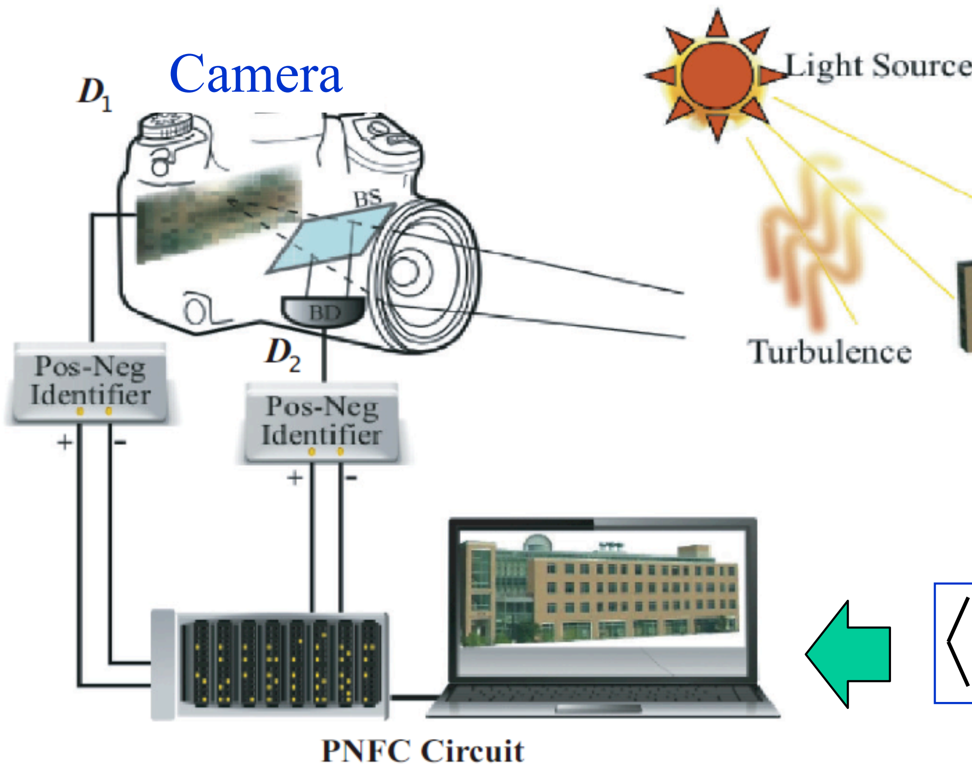
The blue and red two-photon amplitudes experience the same turbulence with the same phase variation when $\boxed{\vec{\rho}_1 \approx \vec{\rho}_2}$.

$$\langle \Delta n_1 \Delta n_2 \rangle = \sum_{j \neq k} \left| e^{i\Delta\varphi} A_{j1,k2} + e^{i\Delta\varphi} A_{k1,j2} \right|^2 \propto \mathrm{somb}^2 \frac{\pi \Delta\theta}{\lambda} (|\vec{\rho}_1 - \vec{\rho}_2|)$$

Is a turbulence-free imaging practically useful?

Turbulence-free Camera

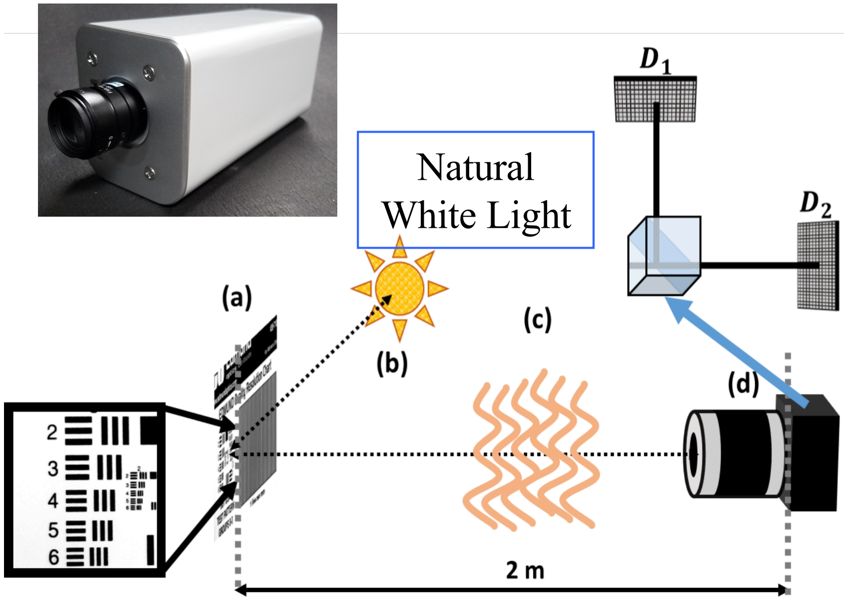
A CCD camera that is able to take video and still pictures of target objects, and is insensitivity to atmospheric turbulence or other types of turbulence - especially useful for satellite imagery.

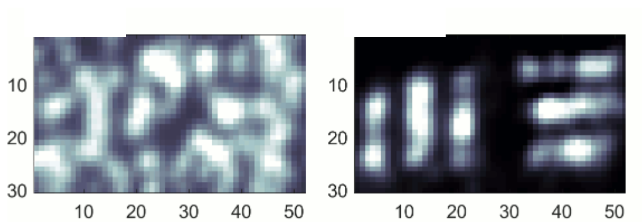


$$\boxed{\langle \Delta n(\vec{\rho}_1)\Delta n(\vec{\rho}_2)\rangle}$$

$$R_c(\vec{\rho}_i) = \int d\vec{\rho}_o \left|A(\vec{\rho}_o)\right|^2 \langle \Delta I(\vec{\rho}_o)\Delta I(\vec{\rho}_i)\rangle$$

Turbulence-free Camera





Tarsier Camera: turbulence-free with resolution beyond classical limit

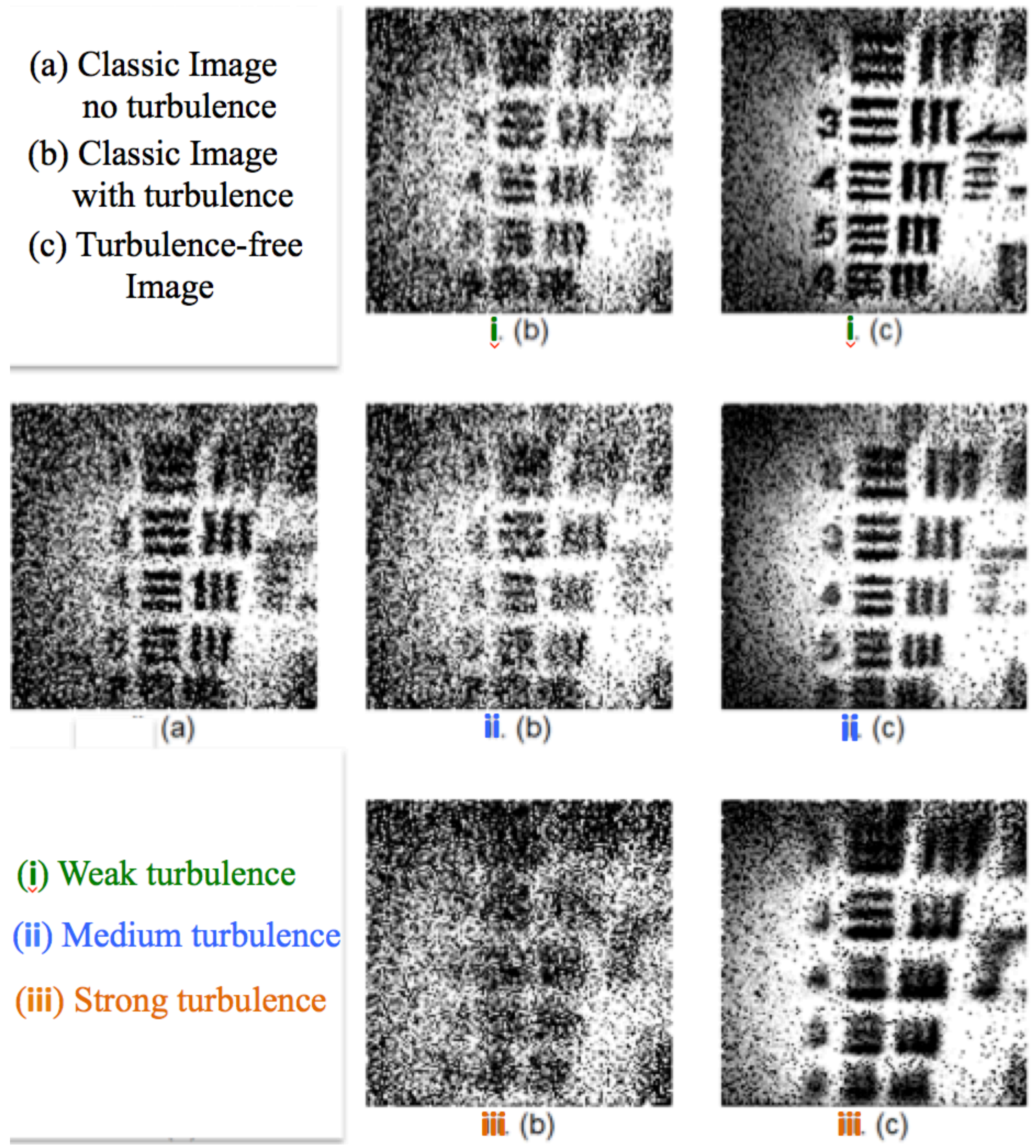
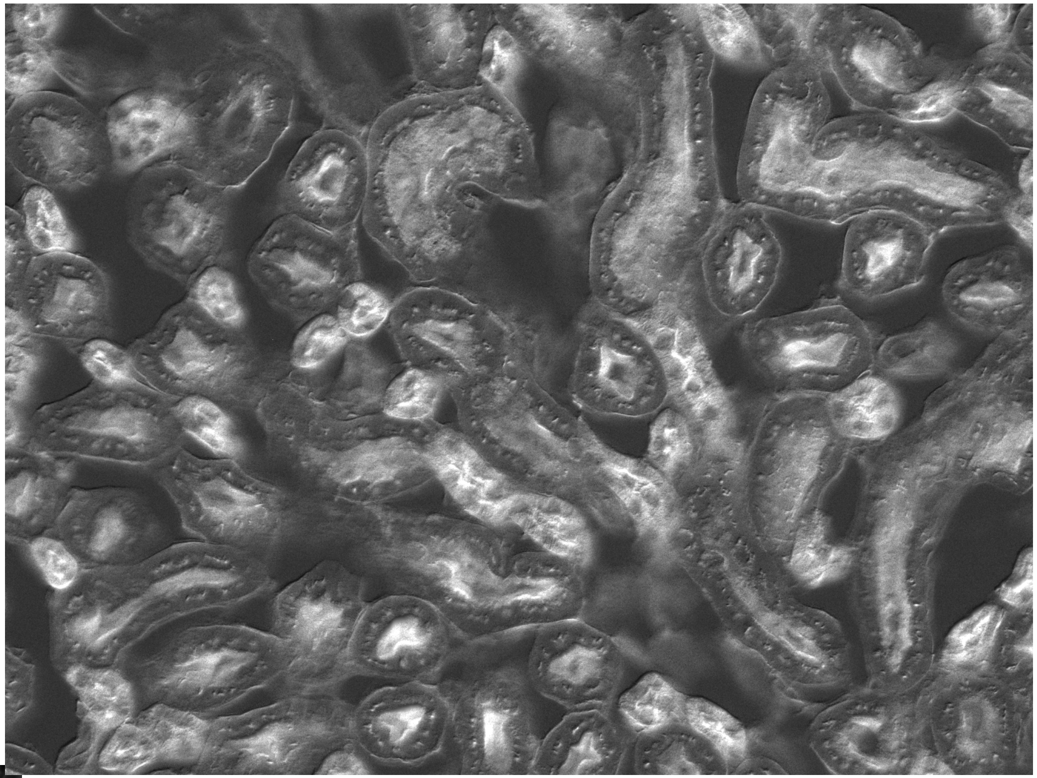
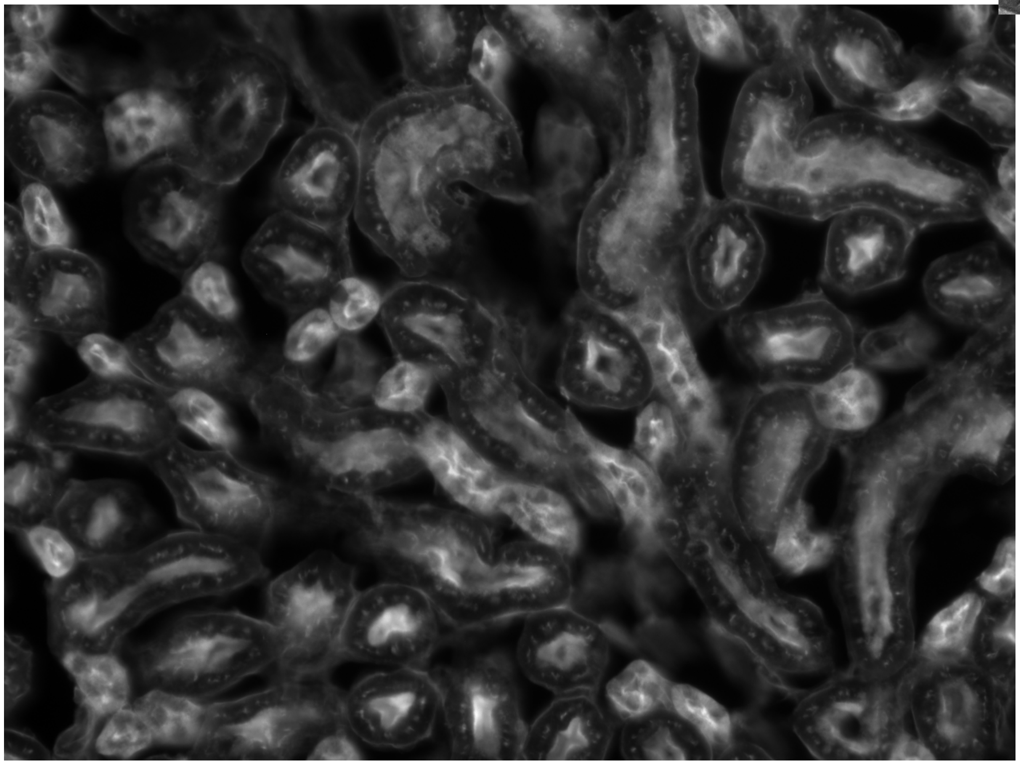


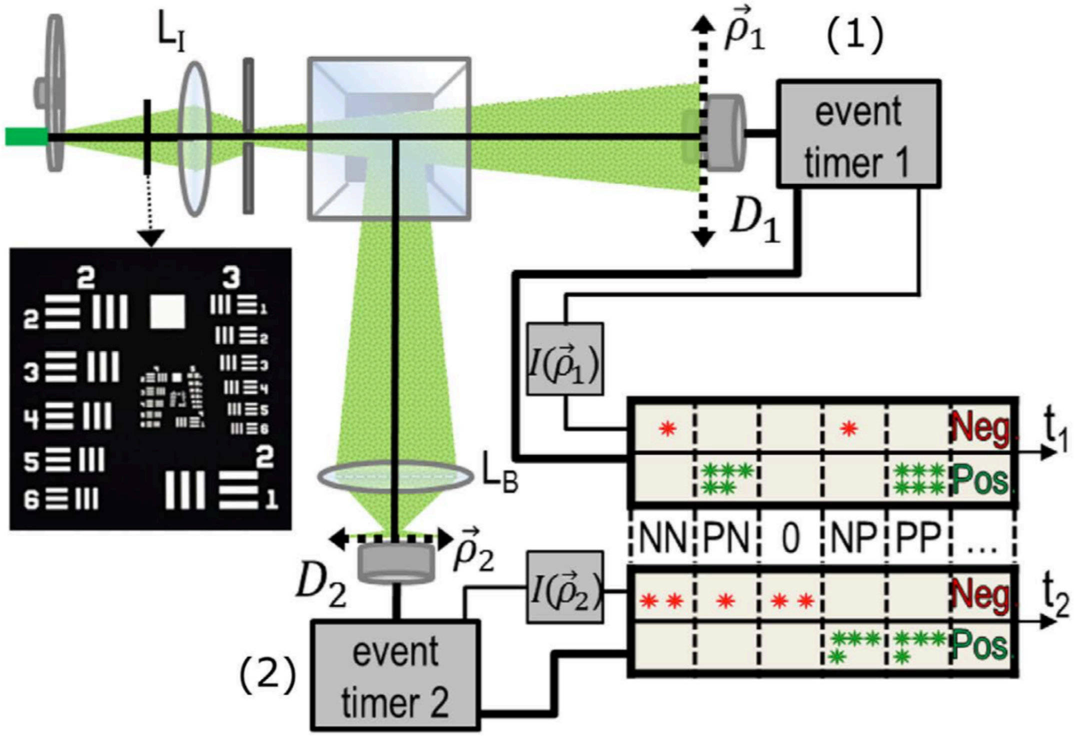
Image of kidney cells from a turbulence-free microscope

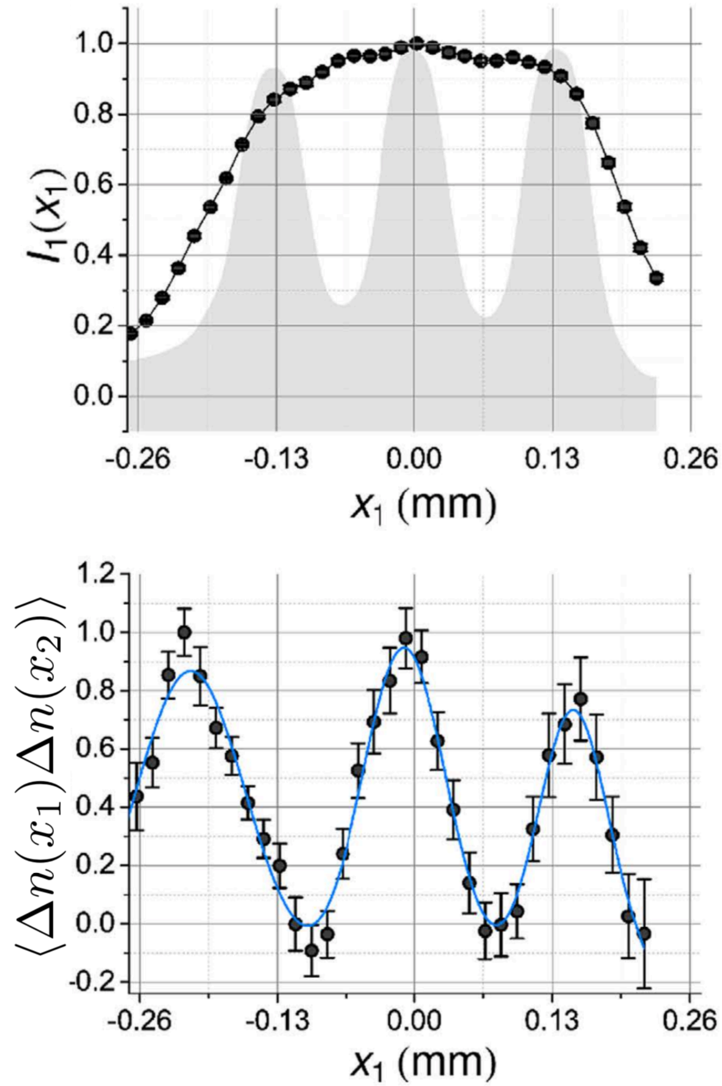




With and without spatial-frequency selection

Sub-Rayleigh imaging





J. Sprigg, T. Peng, and Y.H. Shih, Nature Sci. Rep., 6, 38077 (2017).

Two-photon interference

vs

Speckle-to-speckle correlation

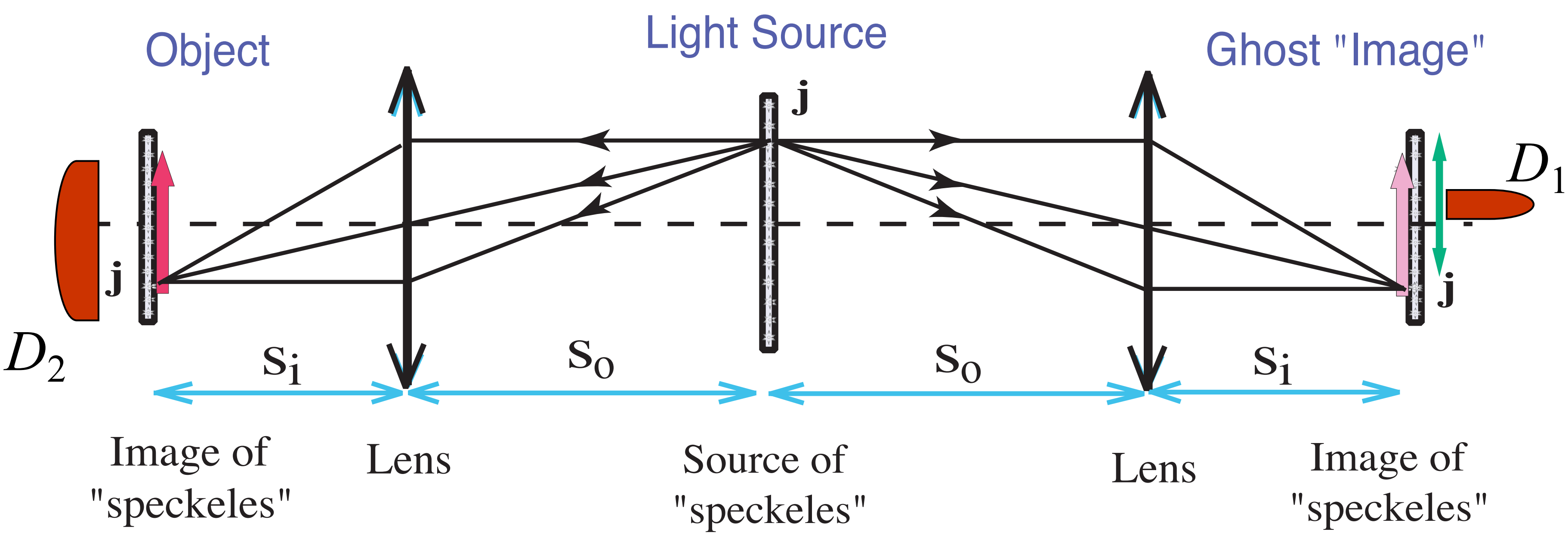
Can two-photon correlation of thermal light be considered as correlation of intensity fluctuation?

We also concluded that HBT effect is the result of two-photon interference: two randomly created and randomly paired photons in thermal state interfering with the pair itself.

The two-photon coherent effects are *observed from* the intensity fluctuations, however, they are *not caused by* the pre-prepared correlation of intensity fluctuations of the source.

G. Scarcelli, V. Berardi and Y.H. Shih, Phys. Rev. Lett., 96, 063602 (2006).

Classical simulation of ghost imaging - speckle-to-speckle correlation

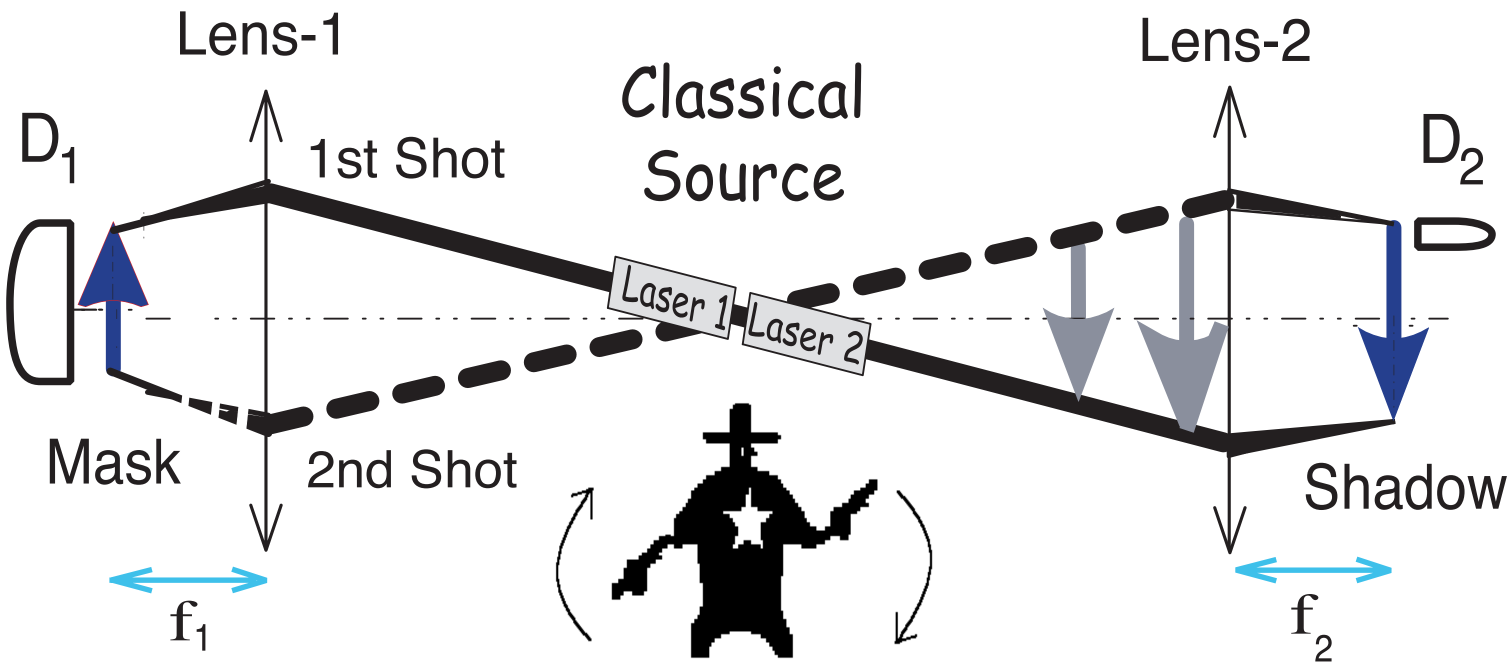


$$G^{(2)}(\vec{\rho}_1,\vec{\rho}_2) = \delta(\vec{\rho}_0 - \vec{\rho}_1/m)\,\delta(\vec{\rho}_0 - \vec{\rho}_2/m)$$

$$R_C(\vec{\rho}_1) \propto \int d\vec{\rho}_2\; A^2(\vec{\rho}_2)\, G(\vec{\rho}_1,\vec{\rho}_2)]$$

A. Gatti, *et al.*, Phys. Rev. Lett. **90**, 133603 (2003).

Classical simulation of ghost imaging
- speckle-to-speckle correlation



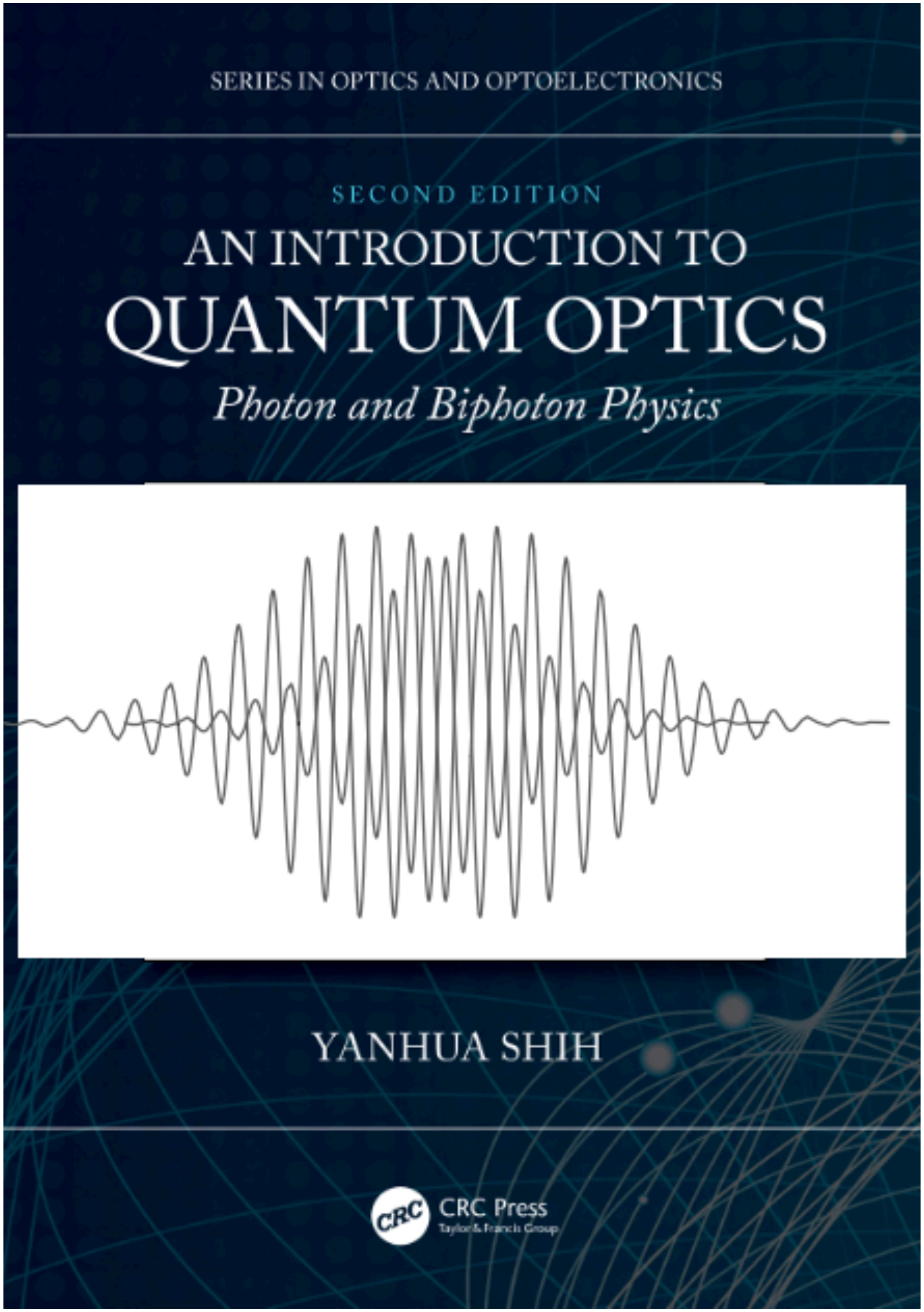
The point-to-point correlation is made shot by shot by two co-rotating laser beams. A ghost shadow can be made in coincidences by "blocking-unblocking" of the correlated laser beams, or simply by "blocking-unblocking" two correlated gun shots.

R.S. Bennink, S.J. Bentley, and R.W. Boyd, Phys. Rev. Lett. **89**, 113601 (2002).

Summary

Physics: ghost imaging and turbulence-free camera are the results of two-photon interference: a pair of photons, either in entangled state or in thermal state, interfering with the pair itself.

Engineering: commercial turbulence-free, sub-Rayleigh camera and microscope are on the way.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Thank you!