Top

Left side

TEST

Right side

bottom

Correlation functions in optics and quantum optics, 4

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NIST

The slides of the course are available at:

http://www.physics.umd.edu/rgroups/amo/orozco/results/2018/Results18.htm

Some review papers on this topic:

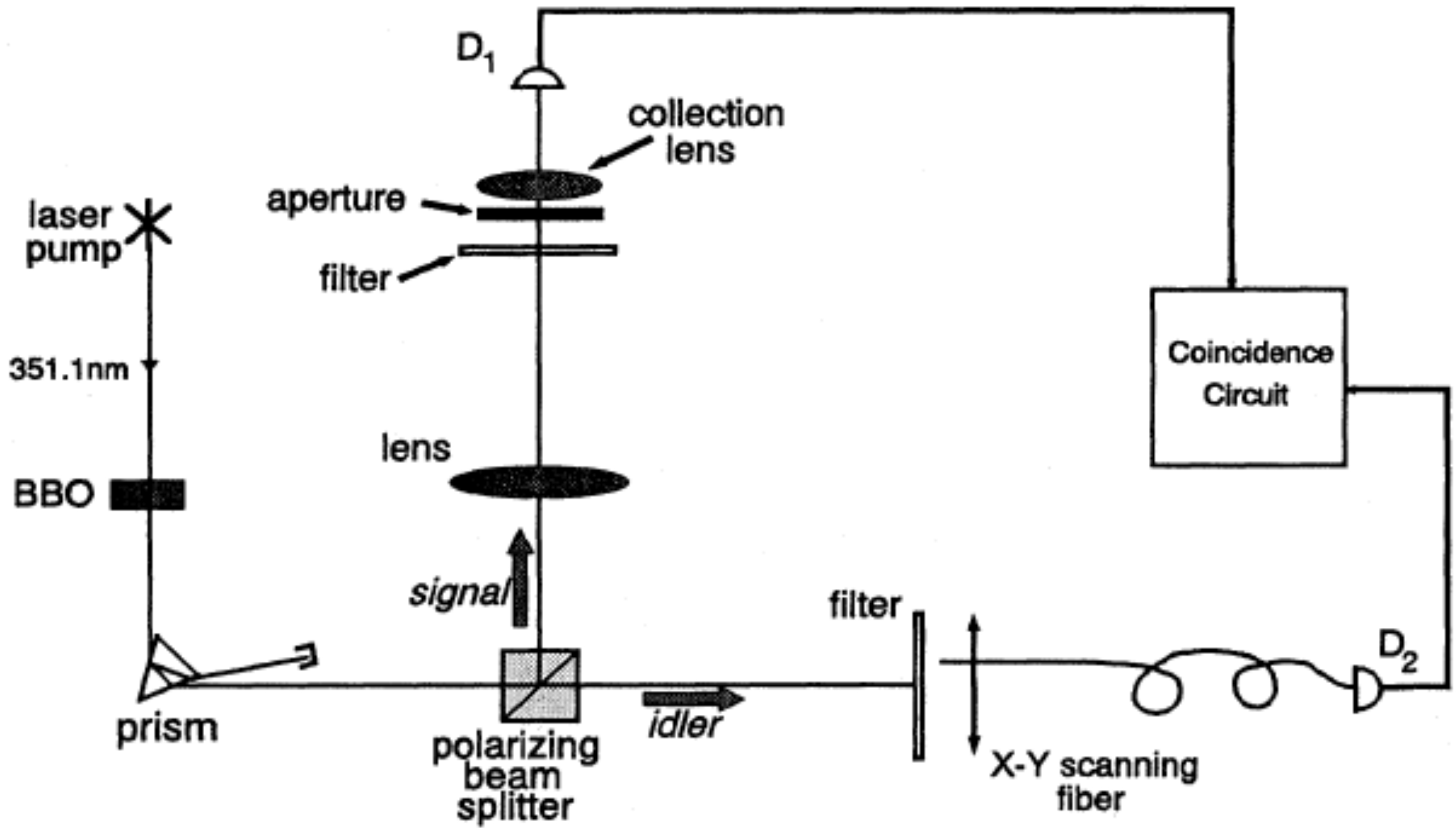
Baris I. Erkmen and Jeffrey H. Shapiro, “Ghost imaging: from quantum to classical to computational,” Advances in Optics and Photonics **2**, 405 (2010). doi:10.1364/AOP.2.000405.

Miles Padgett, Reuben Aspden, Graham Gibson, Matthew Edgar and Gabe Spalding, “Ghost Imaging,” Optics and Photonics News, p. 40, October 2016.

Ghost imaging is also known as Single Pixel Imaging: (Rice University in the 1990’s.) See for exampe: Marco F. Duarte, Mark A. Davenport, Dharmpal Takhar, Jason N. Laska, Ting Sun, Kevin F. Kelly, and Richard G. Baraniuk “Single-Pixel Imaging via Compressive Sampling” IEEE Signal Processing Magazine **25**, 85 (2008) DOI:10.1109/MSP.2007.914730

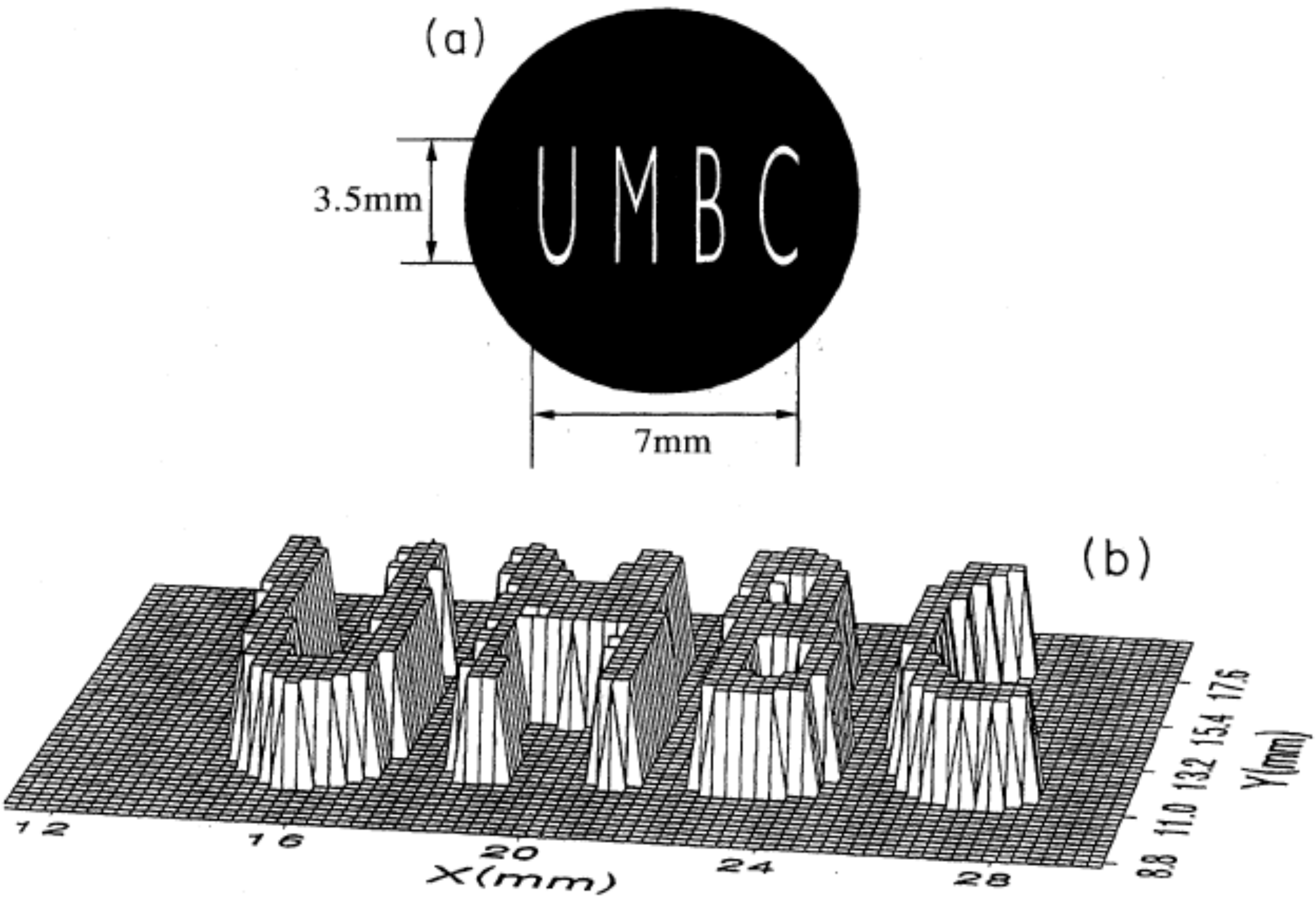
What is ghost imaging?

An experiment:



1. T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko, "Optical imaging by means of two-photon quantum entanglement," Phys. Rev. A **52**, R3429–R3432 (1995).

The image



T. B. Pittman, et al. Phys. Rev. A **52**, R3429 (1995).

Correlated photons

- Source: Spontaneous Parametric Down Conversion [SPDC]: non linear process where the pump frequency at 2ω becomes two beams at frequencies ω_s and ω_i (signal and idler).

- Conservation of energy requires: $2\omega = \omega_s + \omega_i$
- Conservation of momentum requires: $k_{2\omega} = k_s + k_i$
- Conservation of angular momentum requires that the polarization of s and i have to be related.

- The photon pair can be entangled.

Entanglement implies a high correlation between two properties or two particles (please be aware of the recent discussions on classical entanglement).

R. J. C. Spreeuw, “A classical analogy of entanglement,” Found. Phys. 28, 361 (1998).
R. J. C. Spreeuw, “Classical wave-optics analogy of quantum information processing,” Phys. Rev. A 63, 062302 (2001).
F. Töppel, A. Aiello, C. Marquardt, E. Giacobino, and G. Leuchs,“Classical entanglement in polarization metrology,” New J. Phys. 16, 073019 (2014).
X. F. Qian, B. Little, J. C. Howel, J. H. Eberly, “Shifting the quantum-classical boundary: theory and experiment for statistically classical optical fields,” Optica, 2, 611 (2015).

The correlation is independent of the basis used to measure it. Can be generalized for n particles

The state can not be written as an external product.

With two polarizations and two photons: $|H\rangle_1$, $|V\rangle_1$, $|H\rangle_2$, $|V\rangle_2$

$$\Psi=\alpha|H\rangle_1|H\rangle_2+\beta|V\rangle_1|V\rangle_2+\gamma|H\rangle_1|V\rangle_2+\delta|V\rangle_1|H\rangle_2$$

Bell states:

$$\Phi^{\pm} = (|H\rangle_1|H\rangle_2 \pm |V\rangle_1 |V\rangle_2)/(1/2)^{1/2}$$

$$\Psi^{\pm} = (|H\rangle_1 |V\rangle_2 \pm |V\rangle_1|H\rangle_2)/(1/2)^{1/2}$$

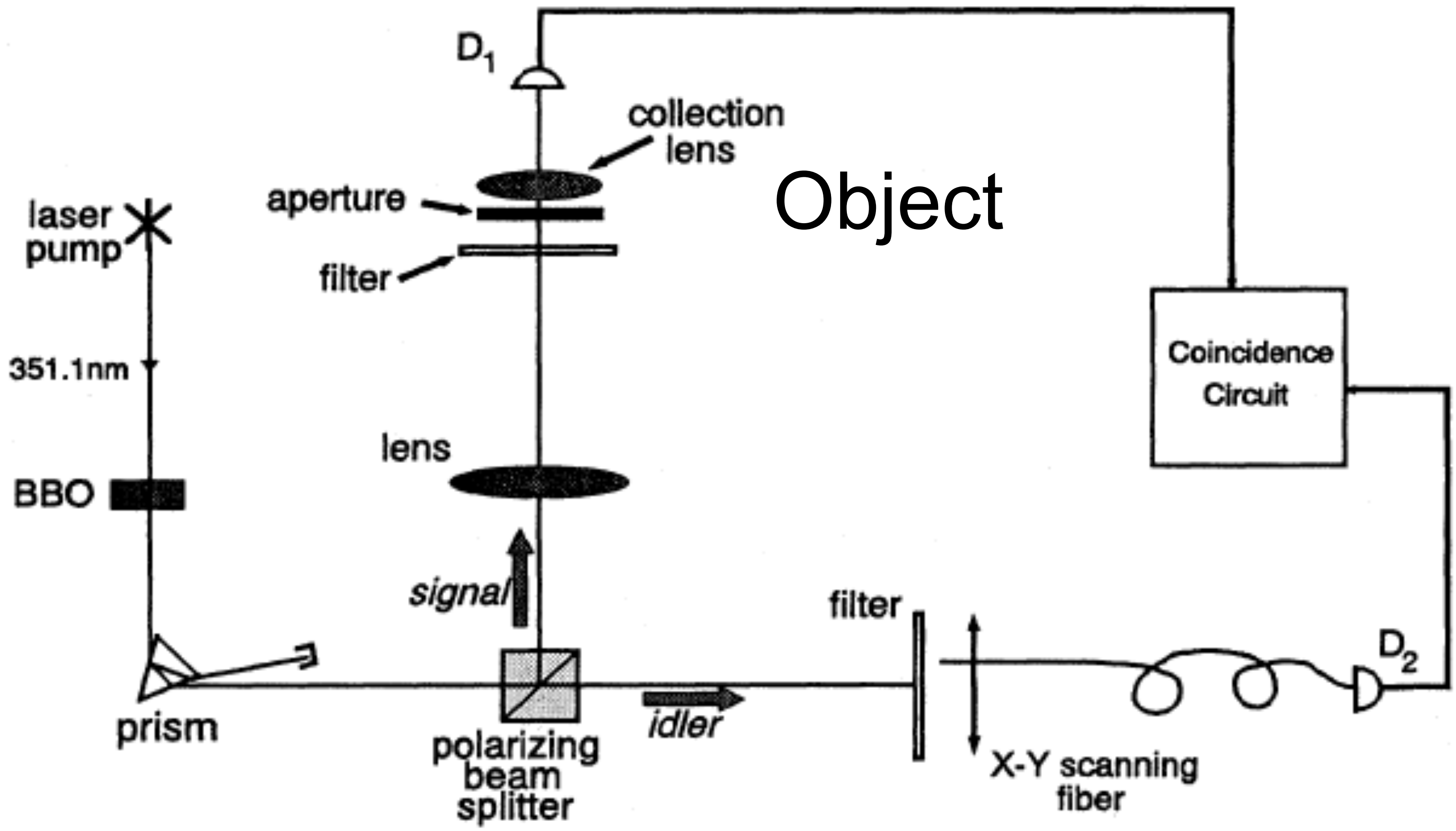
If we know the polarization of one, then we are sure of the polarization of the other.
In the circular basis |+>,|-> the same happens, this is what is strange.

The photon source gives highly correlated photon pairs.
However in each realization the individual result is random.

If we condition the detector of many pixels to detect a single click on the one pixel detector, it is possible to reconstruct the image.

Single pixel detector (bucket)

The lenses are not necessary

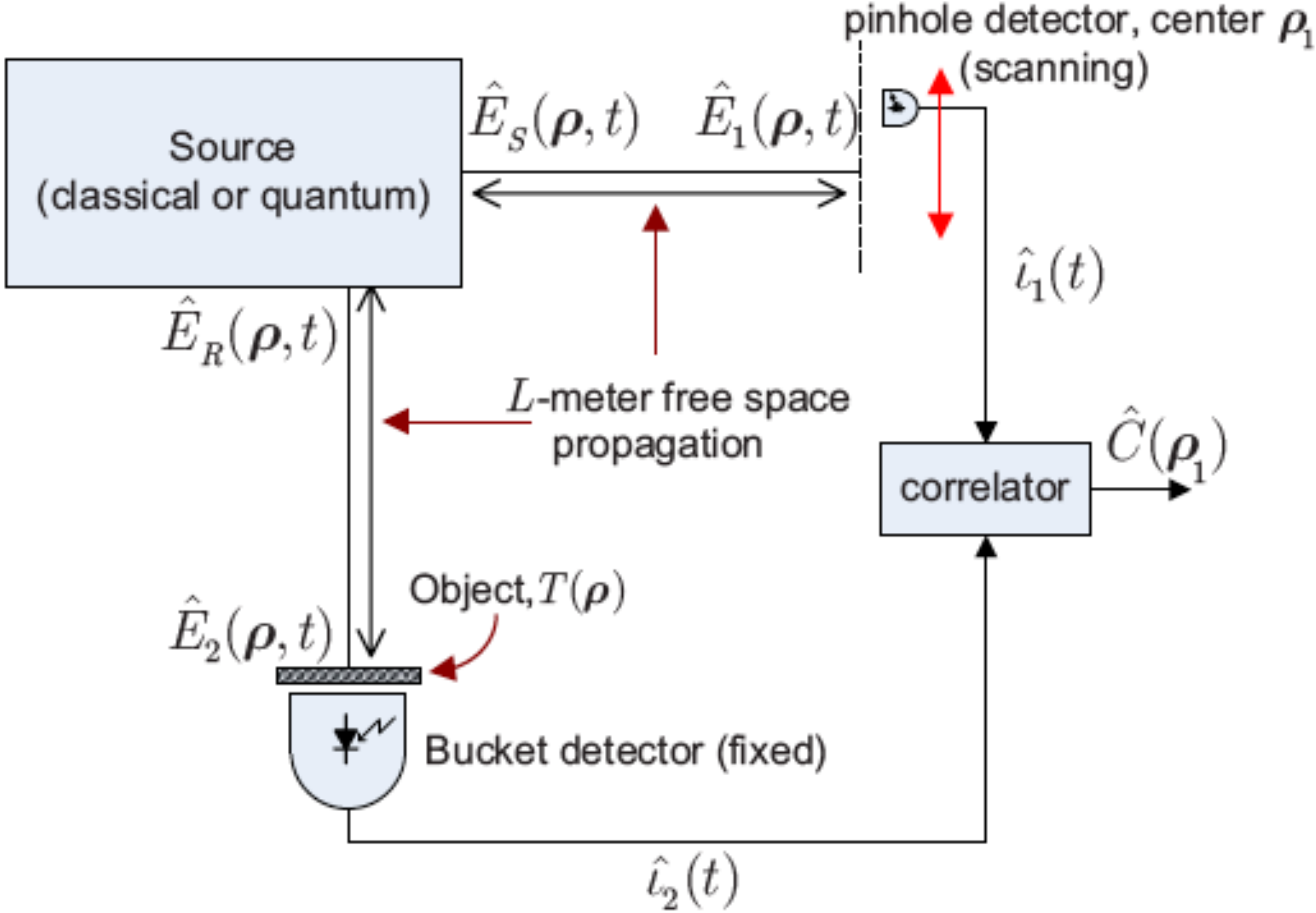


Multi pixel detector (scanning)

Coincidence (correlation, trigger)

T. B. Pittman, et al. Phys Rev. A **52,** R3429 (1995).

A generalization of the apparatus.



Baris I. Erkmen and Jeffrey H. Shapiro, "Ghost imaging: from quantum to classical to computational," Advances in Optics and Photonics **2**, 405–450 (2010).

Is it necessary to have entangled photons?

Correlation on the displacement of a classical beam

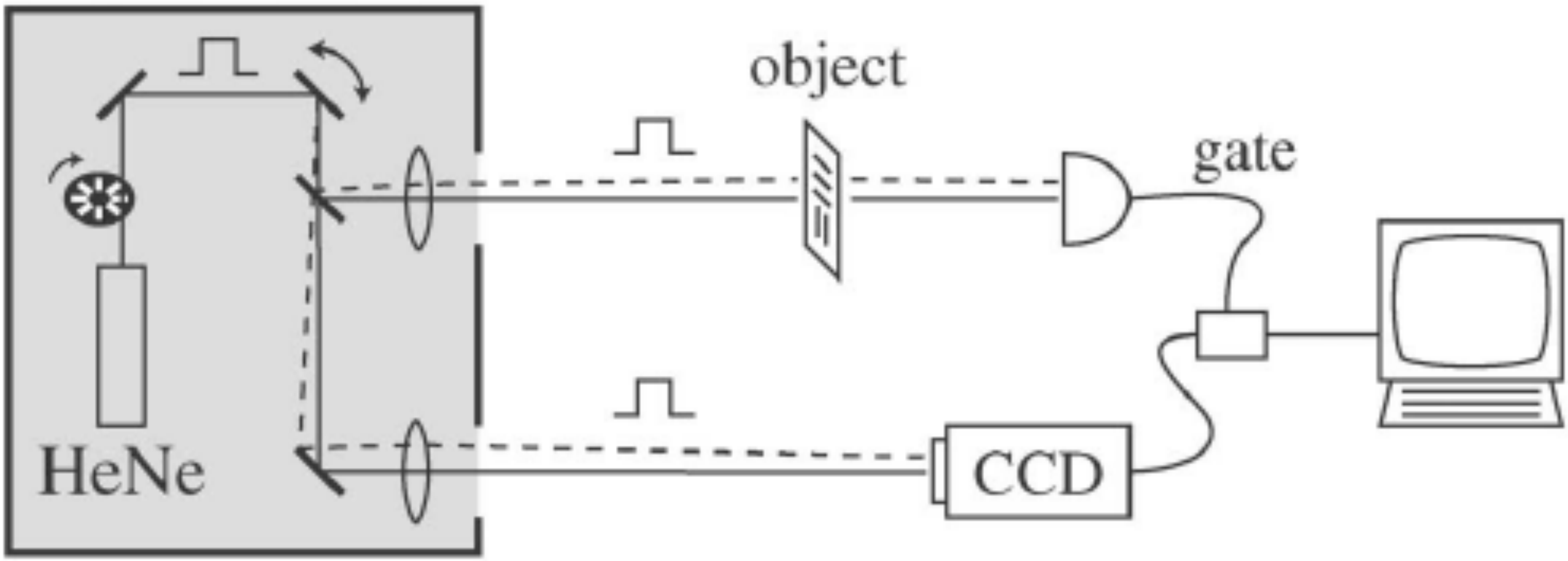


FIG. 2. The experimental setup used to perform coincidence imaging with a classically correlated source (shaded box).

R. S. Bennink, S. J. Bentley, and R. W. Boyd, “Two-photon” coincidence imaging with a classical source,” Phys. Rev. Lett. **89**, 113601 (2002).

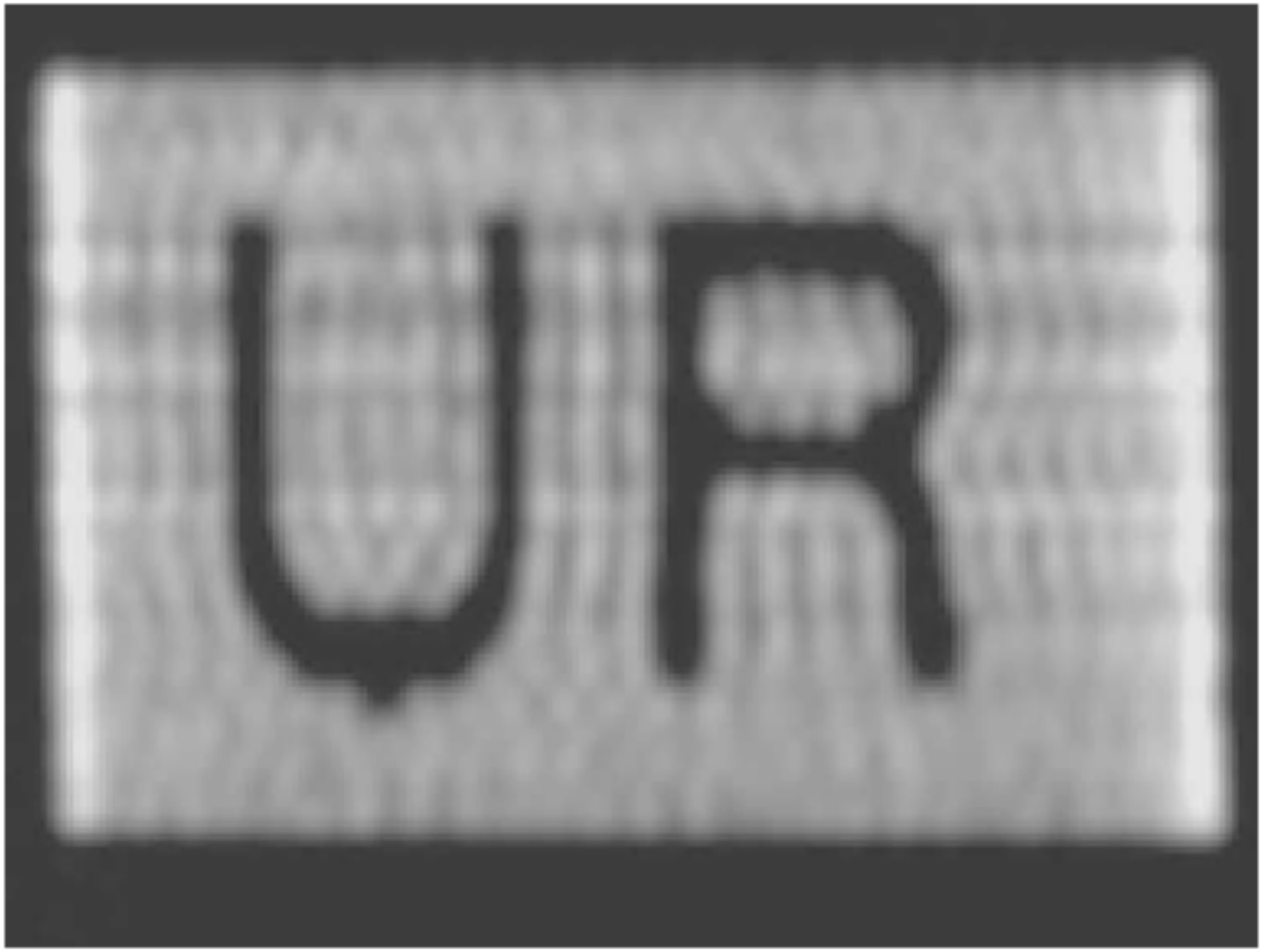


FIG. 3. The image formed in the reference arm when gated by the detector in the test arm. Such an image corresponds to the marginal probability distribution.

R. S. Bennink, S. J. Bentley, and R. W. Boyd, "Two-photon" coincidence imaging with a classical source," Phys. Rev. Lett. **89**, 113601 (2002).

Generalization as a probability problem.

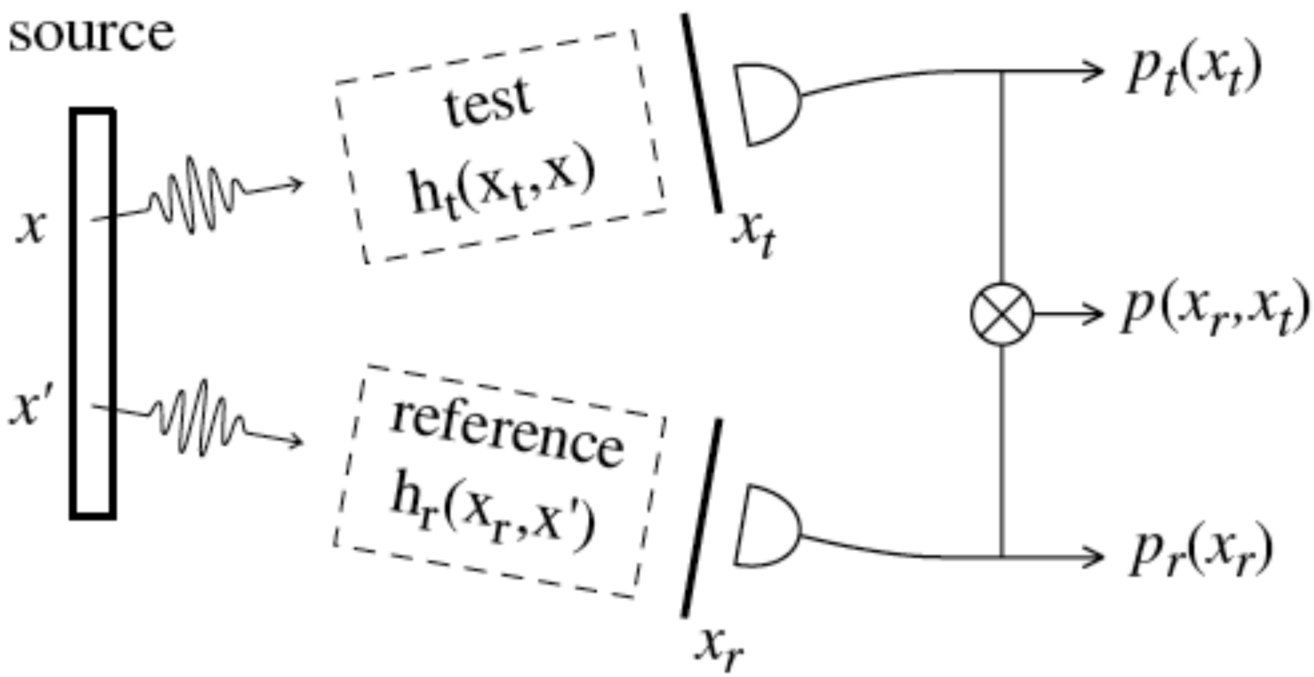


FIG. 1. (adapted from [12]) Two-photon coincidence imaging. The transfer function of the test system is to be obtained from the joint detection statistics using knowledge of the reference system.

R. S. Bennink, S. J. Bentley, and R. W. Boyd, "Two-photon" coincidence imaging with a classical source," Phys. Rev. Lett. **89**, 113601 (2002).

The probabilities given the source distribution

$$p_t(x_t) = \int dx' \left| \int dx h_t(x_t, x) \varphi(x, x') \right|^2,$$

$$p_r(x_r) = \int dx \left| \int dx' h_r(x_r, x') \varphi(x, x') \right|^2,$$

$$p(x_t, x_r) = \left| \int dx dx' h_t(x_t, x) h_r(x_r, x') \varphi(x, x') \right|^2,$$

h is the appropriate transfer function and it is crucial ϕ has correlations

- The correlation functions satisfy the same wave equation (including diffraction) that the appropriate electromagnetic wave.

Classical sources have (random interference) speckle

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optica

Tabletop x-ray ghost imaging with ultra-low radiation

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[4]*e-mail: wula@aphy.iphy.ac.cn*
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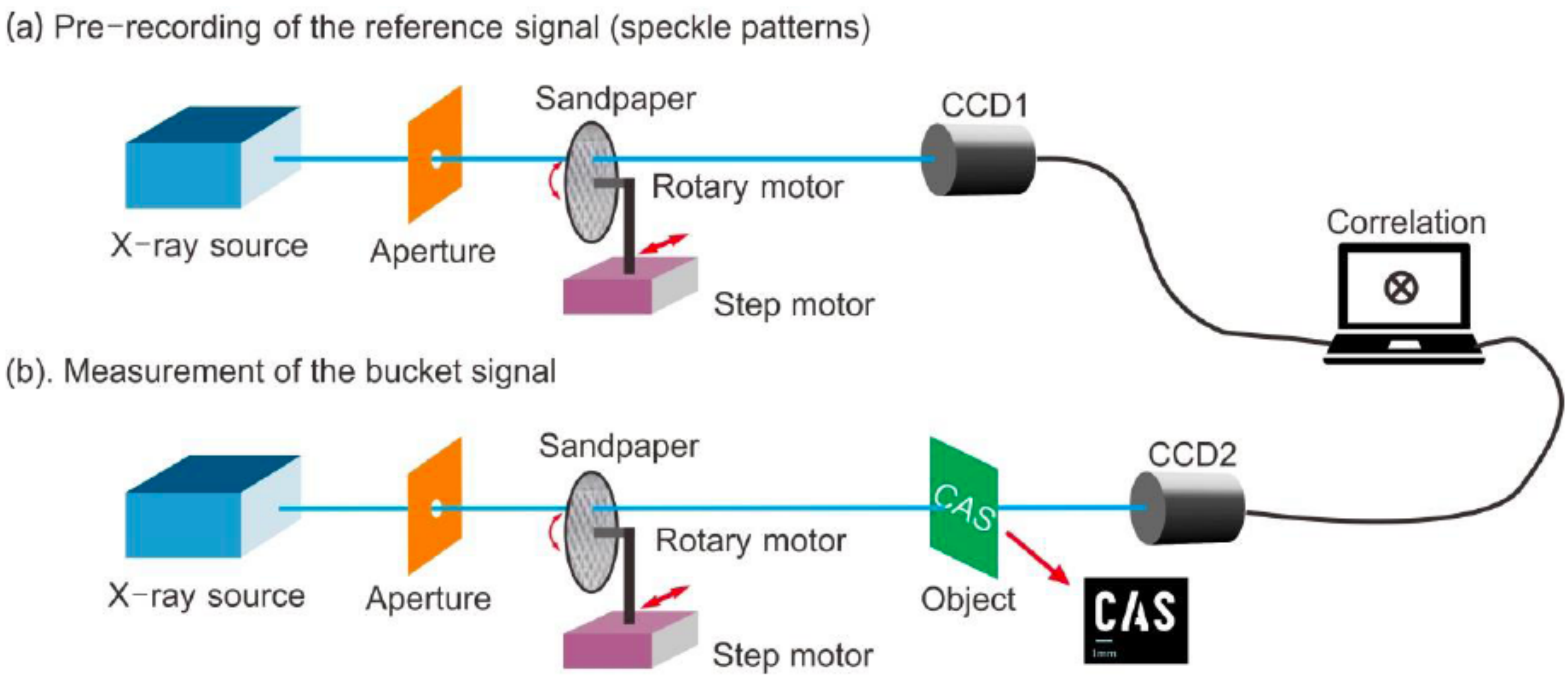


Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation” Optica, 5, 374 (2018).

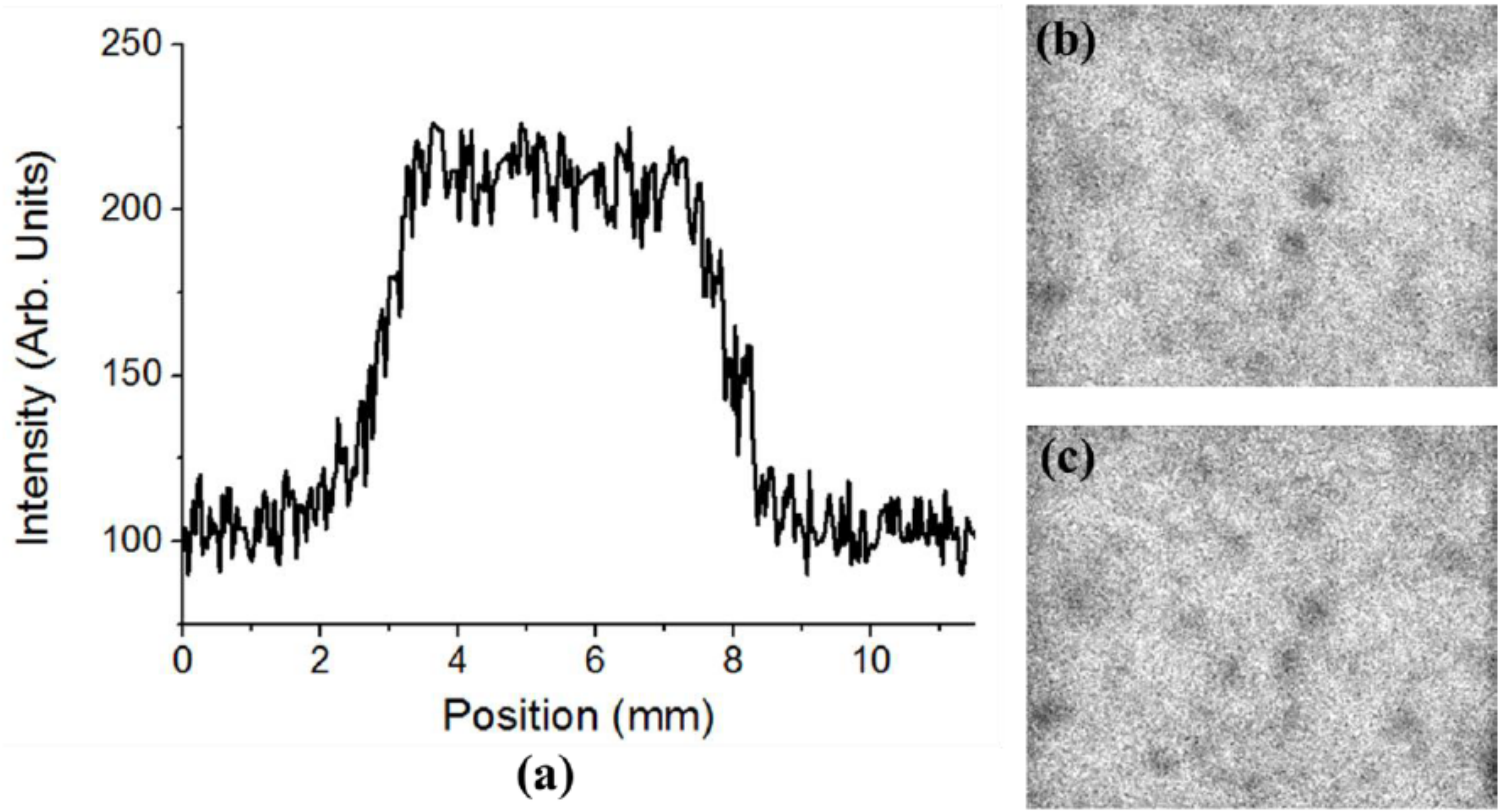
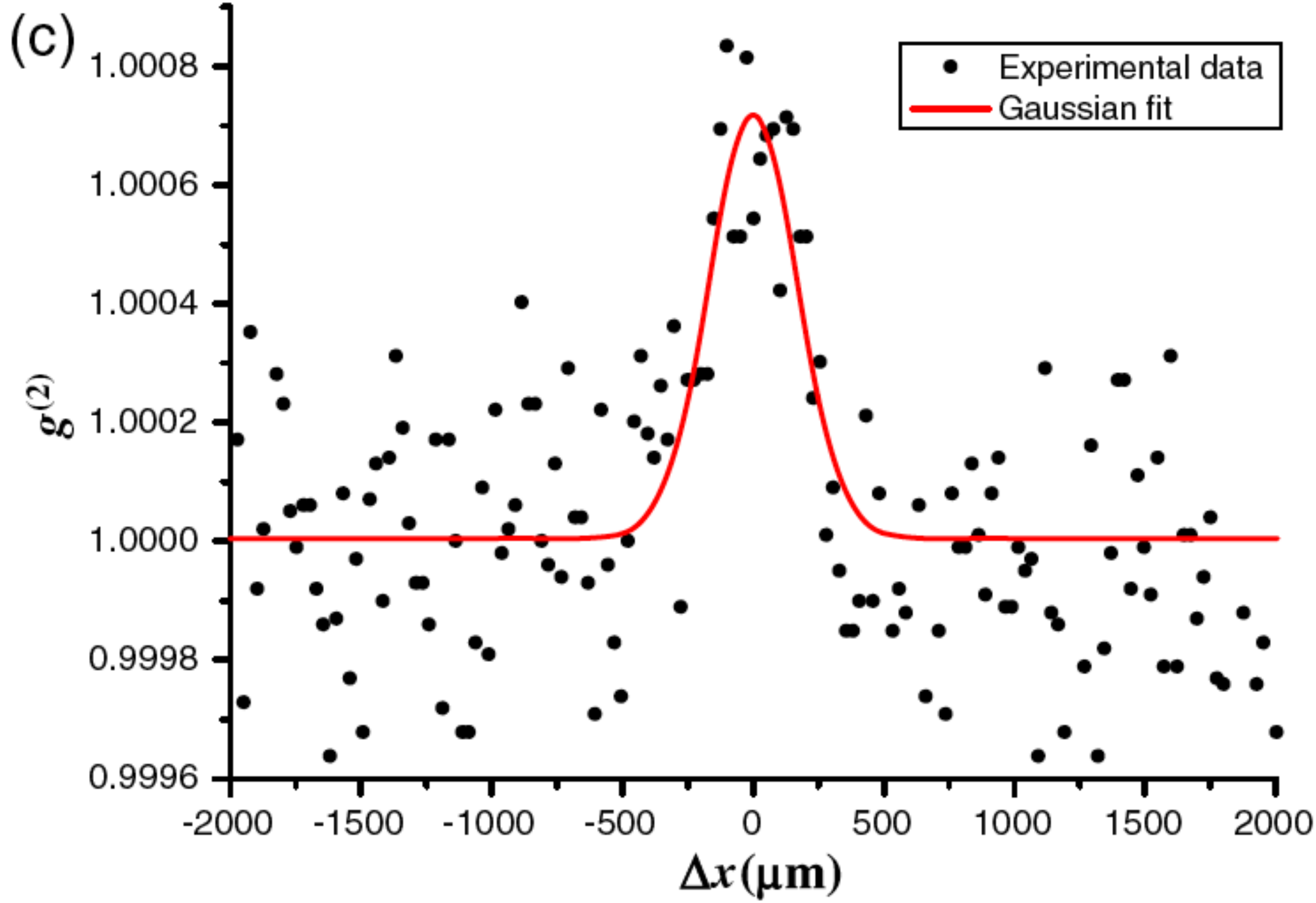
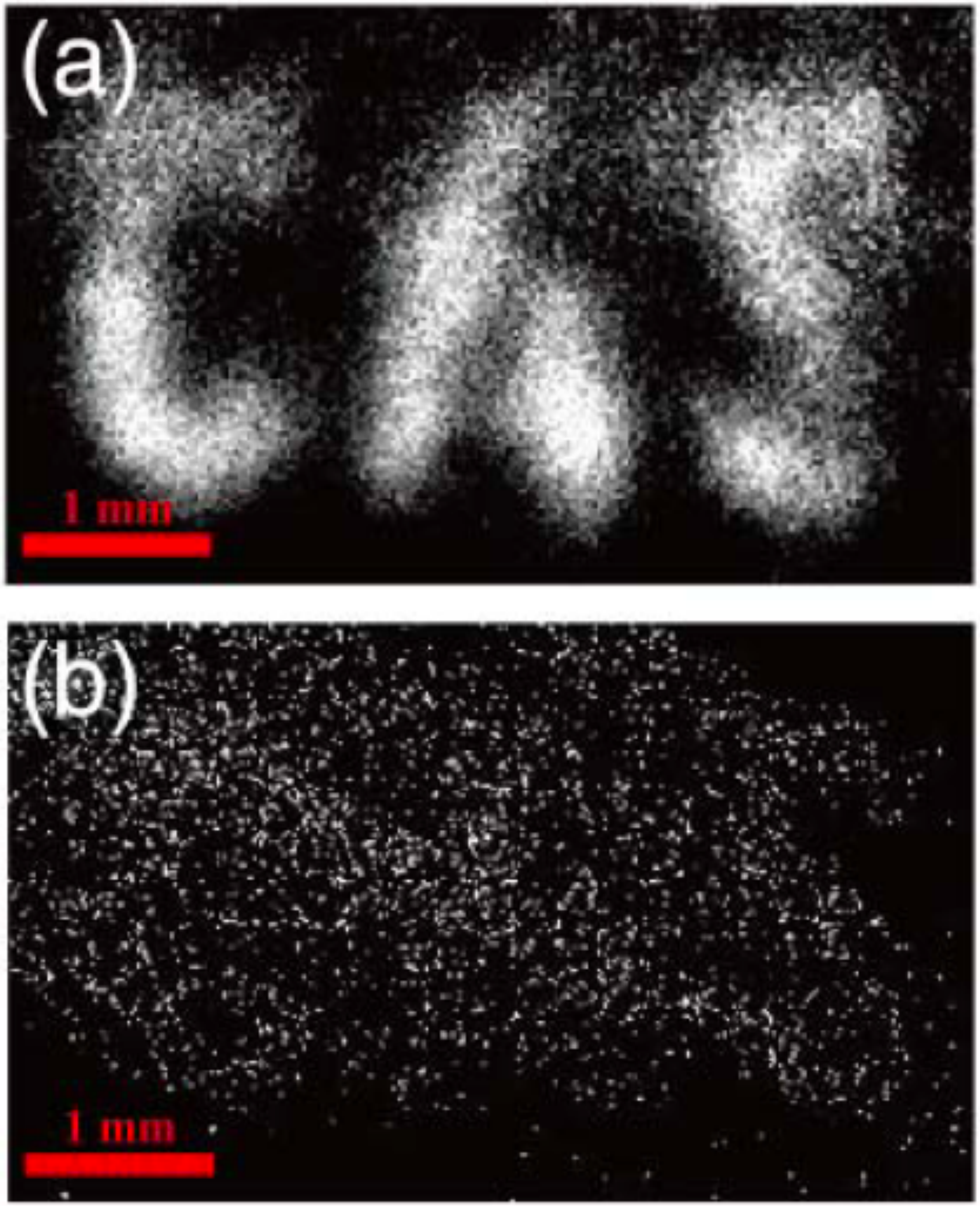


Fig. 2(a) Intensity profile of the direct x-ray beam; (b) Pre-recorded speckle pattern I_1; (c) Speckle pattern I_1' in the second series of positions.

Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation” Optica, 5, 374 (2018).



Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation” Optica, 5, 374 (2018).



Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation” Optica, 5, 374 (2018).

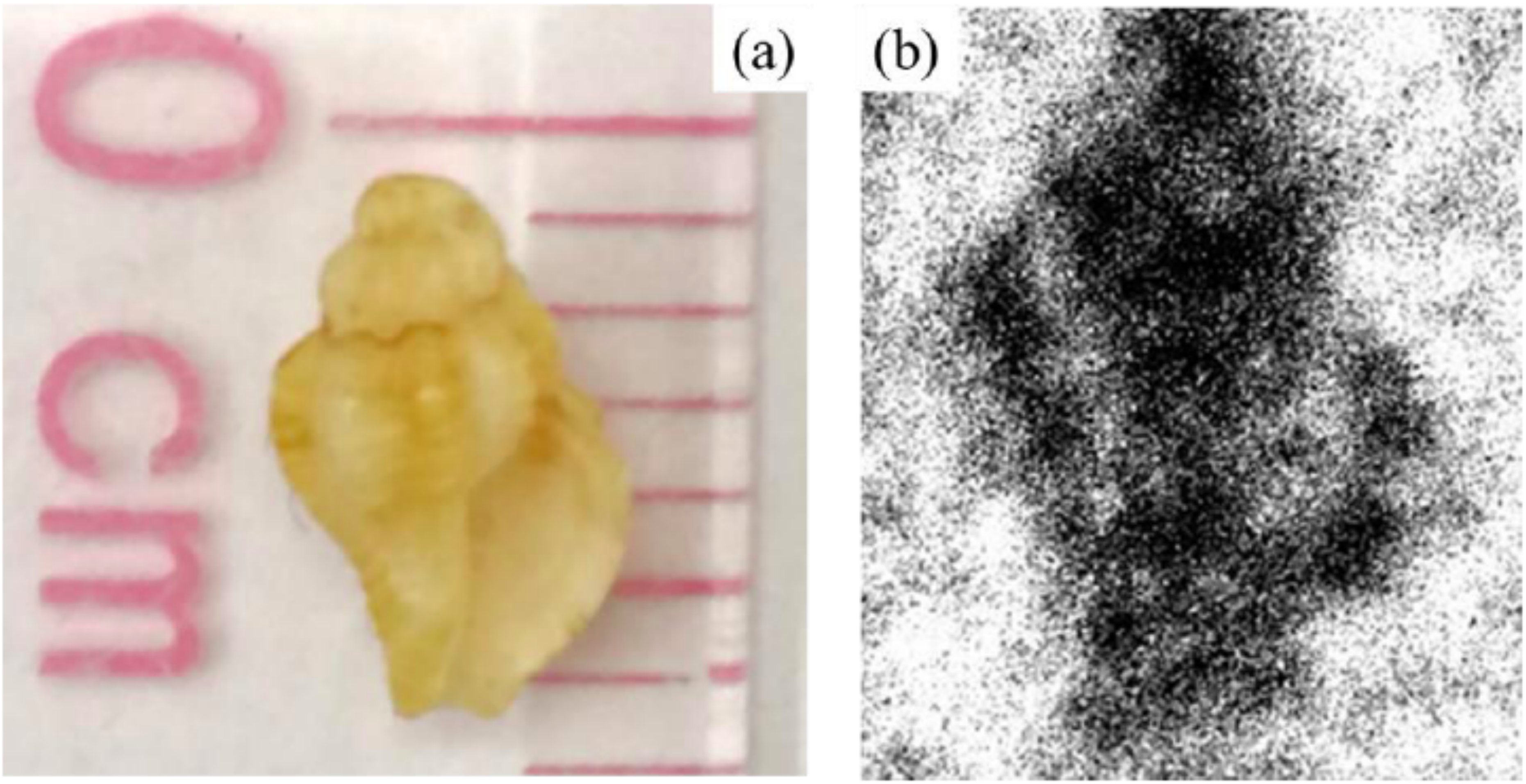
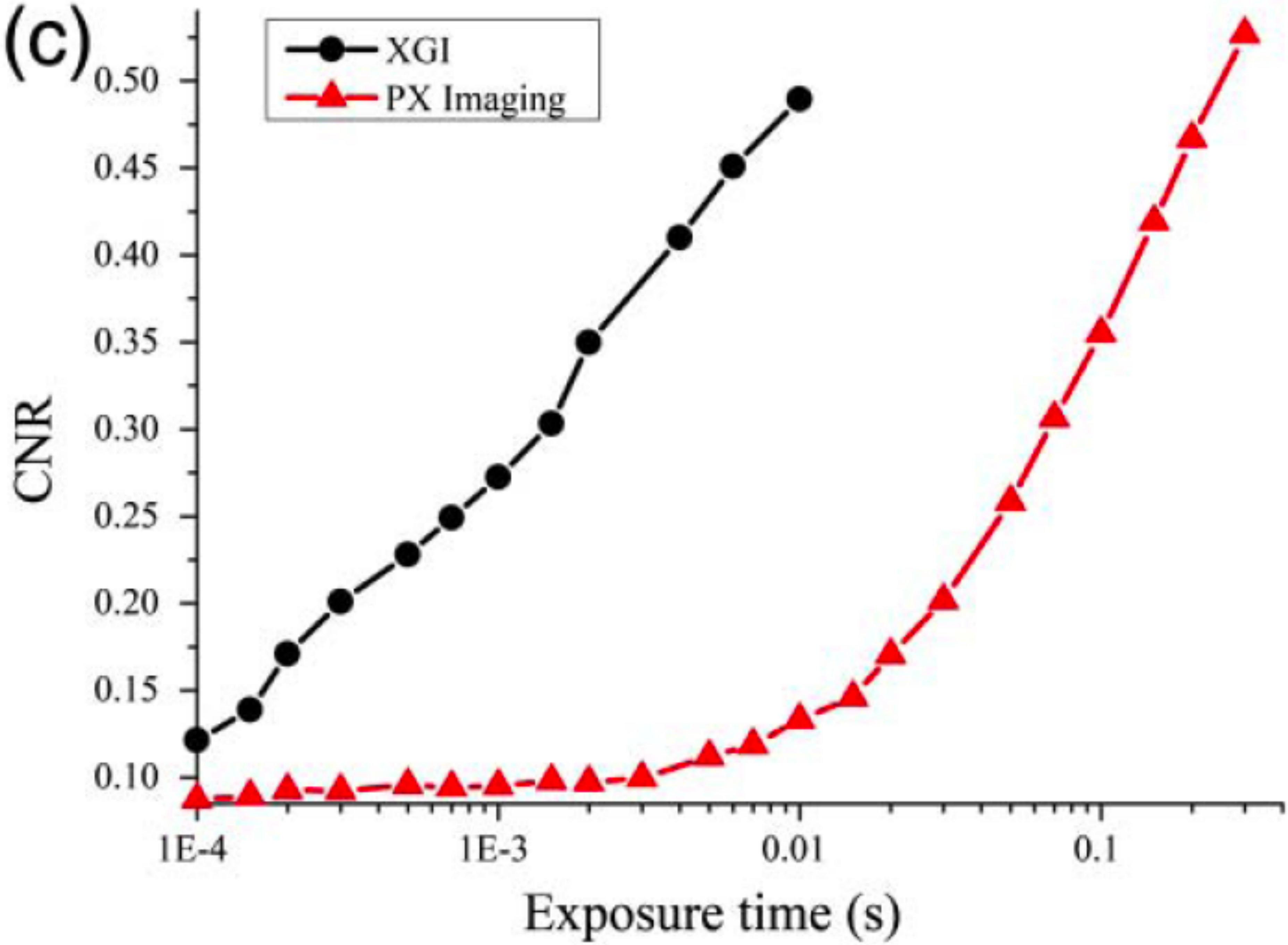
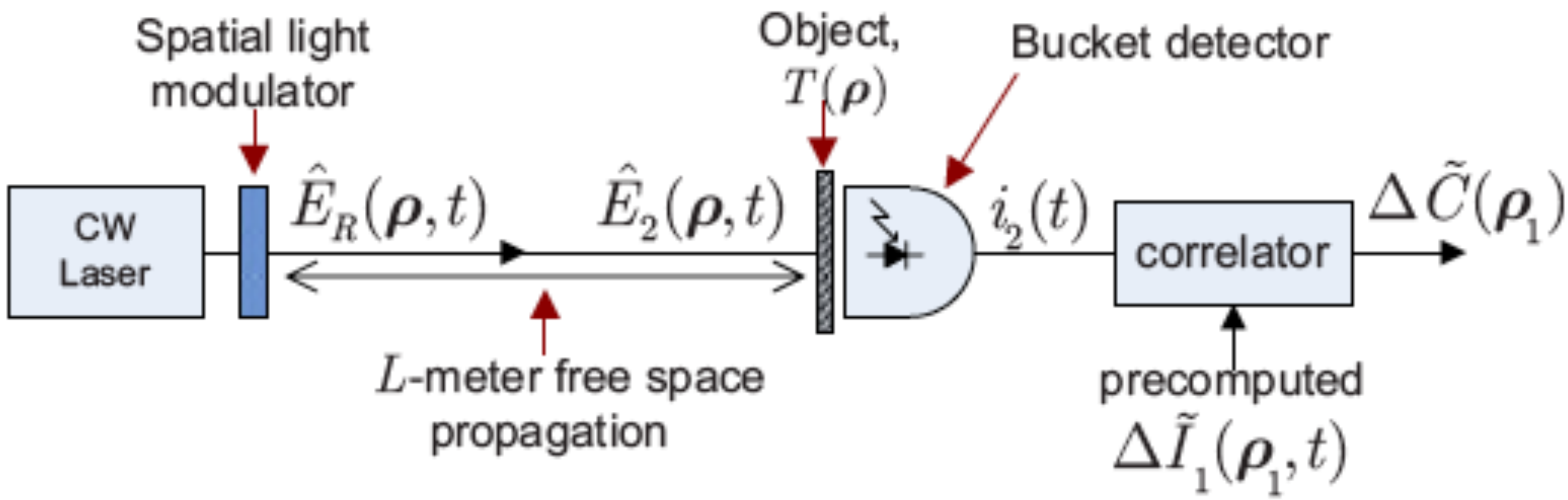


Fig. 4. (a) Ordinary photo of the shell; (b) XGI gray-scale transmission image.

Ai-Xin Zhang, Yu-Hang He, Ling-An Wu, Li-Ming Chen, Bing-Bing Wang, “Table-topX-ray Ghost Imaging with Ultra-Low Radiation” Optica, 5, 374 (2018).


(c)
XGI
PX Imaging
CNR
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
1E-4
1E-3
0.01
0.1
Exposure time (s)

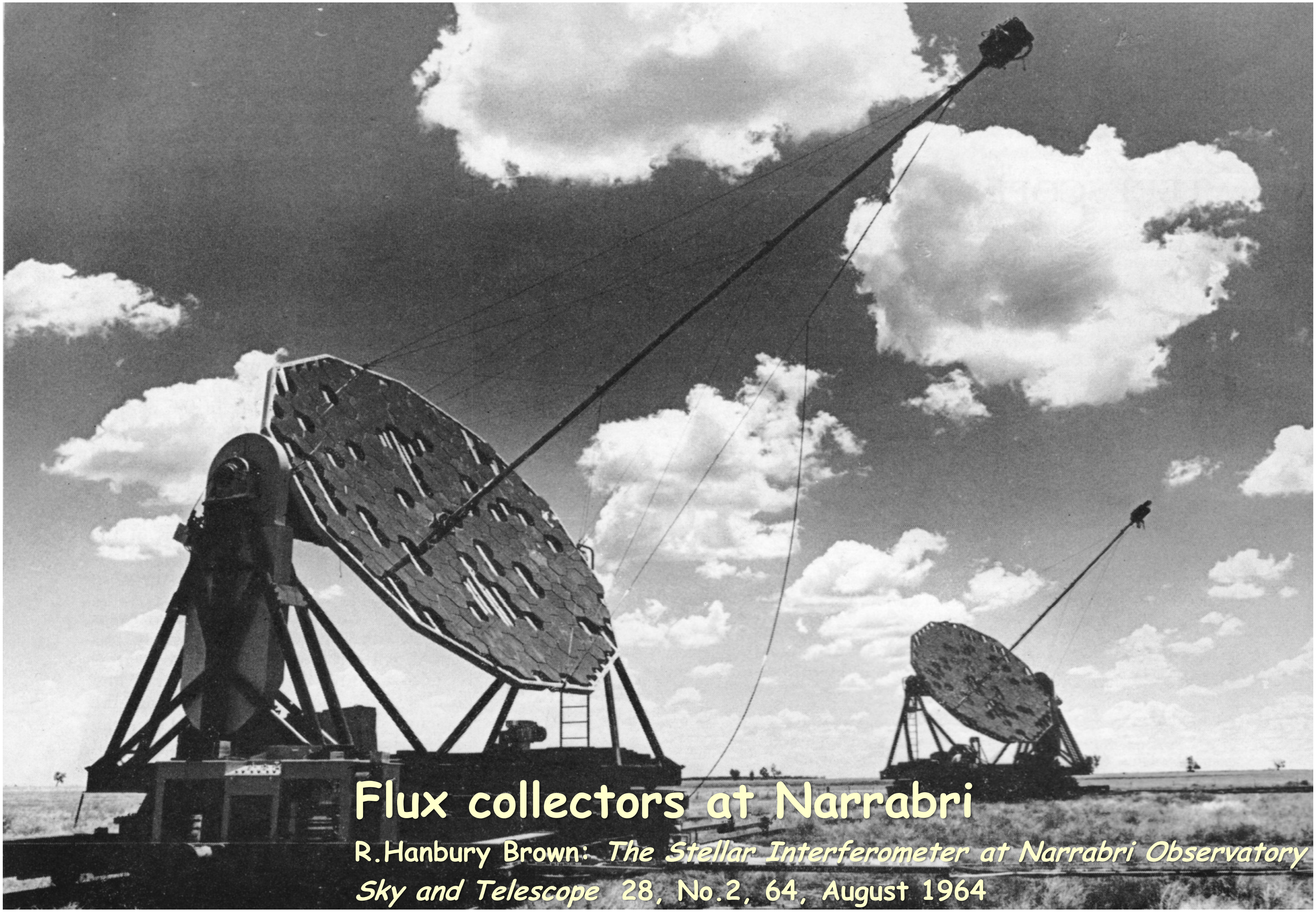


Computational ghost-imaging setup.

There is no lens, only one source.

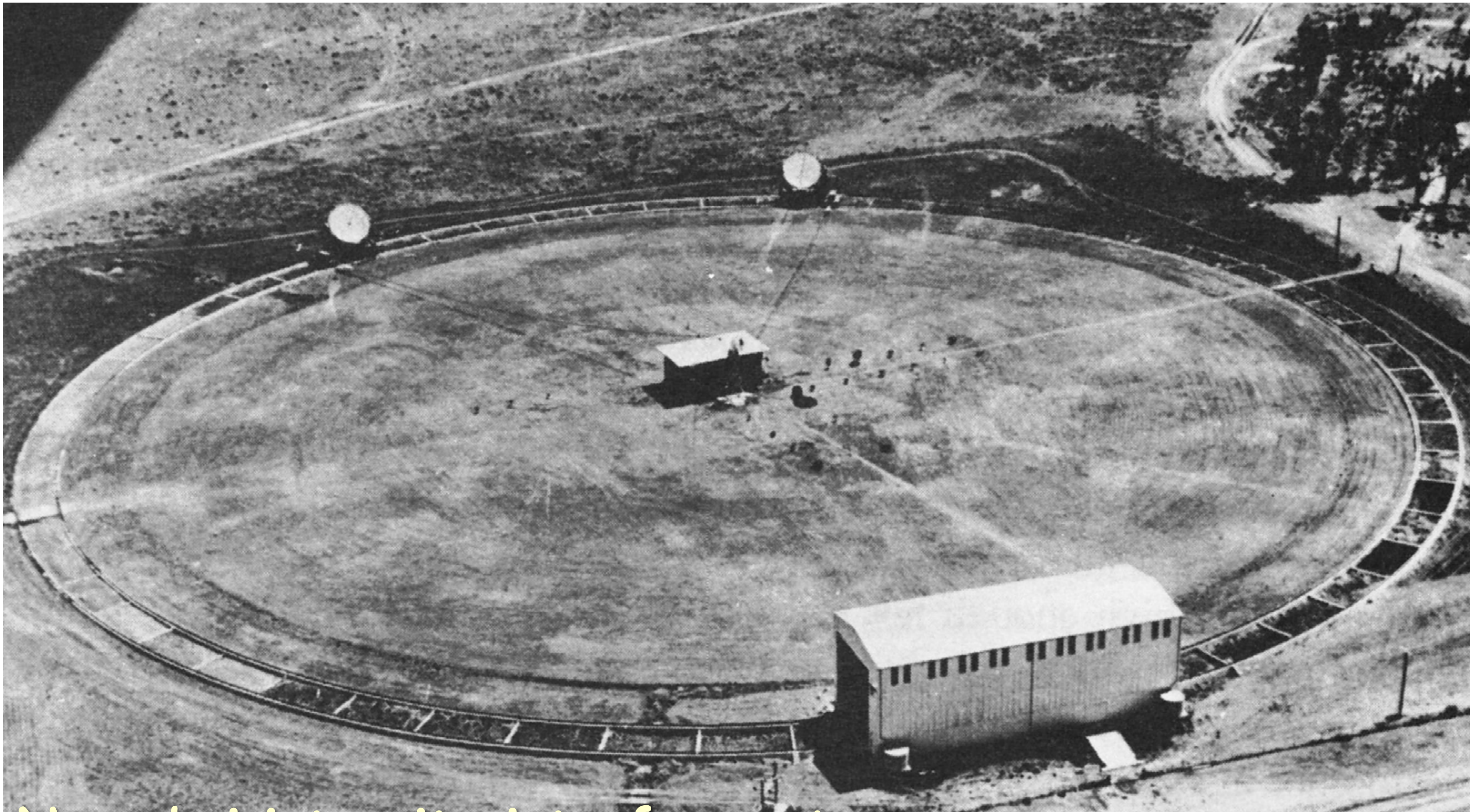
Baris I. Erkmen and Jeffrey H. Shapiro, “Ghost imaging: from quantum to classical to computational,” Advances in Optics and Photonics **2**, 405–450 (2010).

Handbury Brown and Twiss



Flux collectors at Narrabri

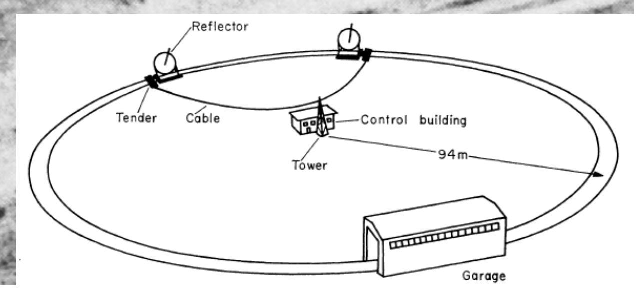
R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*
Sky and Telescope 28, No.2, 64, August 1964

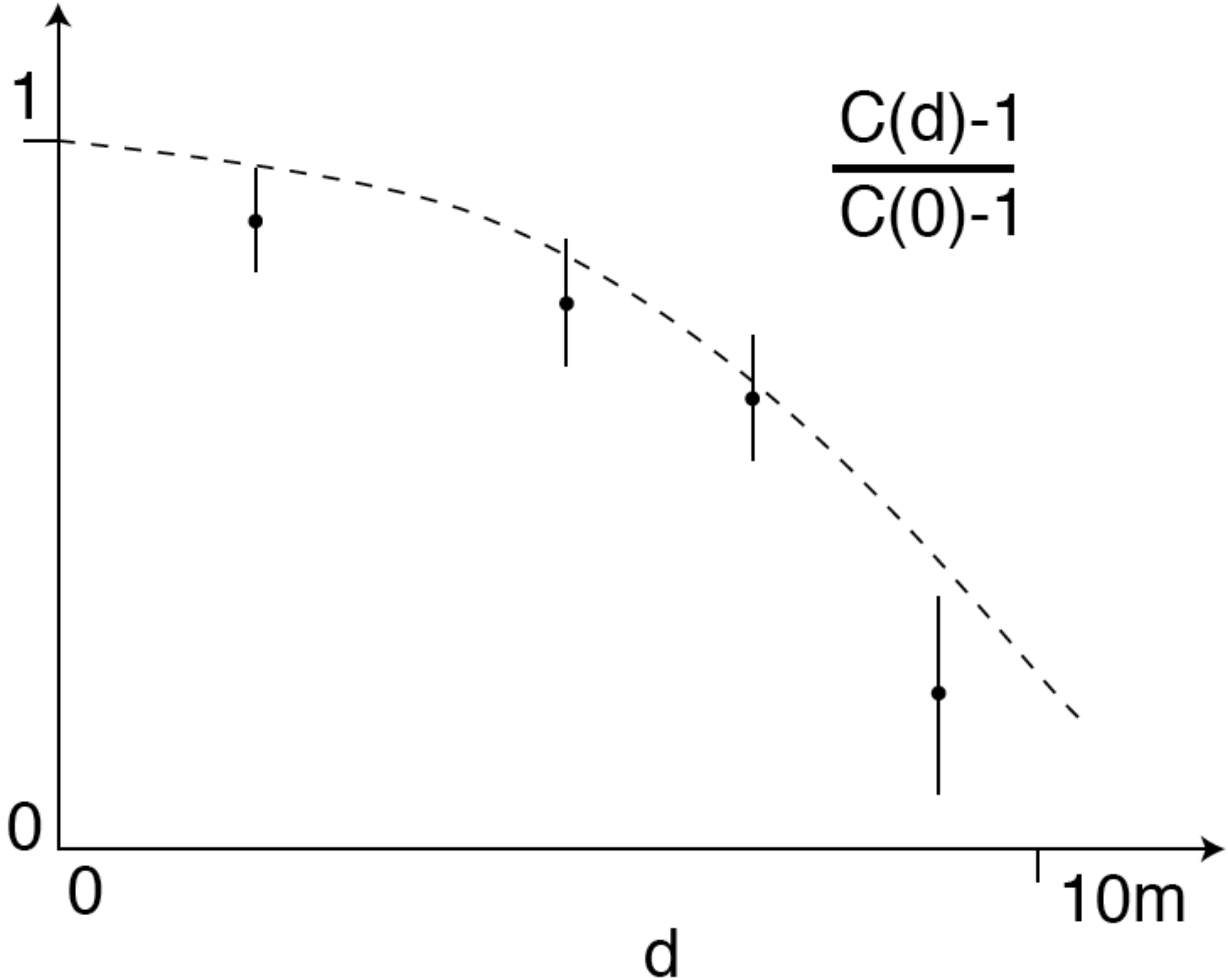


Narrabri intensity interferometer

with its circular railway track

R.Hanbury Brown: *BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics* (1991)





Measurement of the angular diameter of Sirius by HBT in Australia.

A solution to the question on classical vs quantum

PHYSICAL REVIEW A **79**, 033835 (2009)

Hanbury Brown–Twiss effect and thermal light ghost imaging: A unified approach

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[2]*Department of Physics, Chinese University of Hong Kong, Shatin, N. T., Hong Kong*
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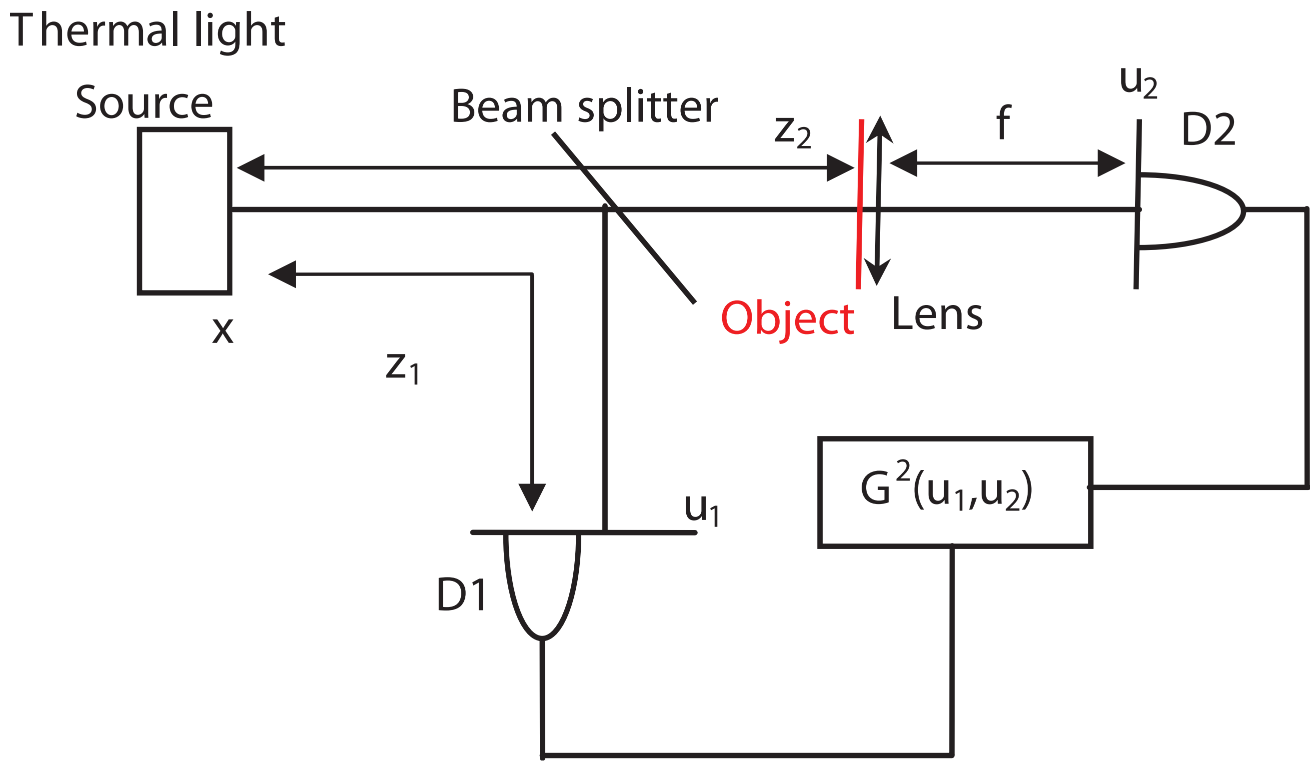
[4]*Department of Physics and Institute for Quantum Studies, Texas A&M University, College Station, Texas 77843-4242, USA*
(Received 14 September 2008; revised manuscript received 1 January 2009; published 24 March 2009)

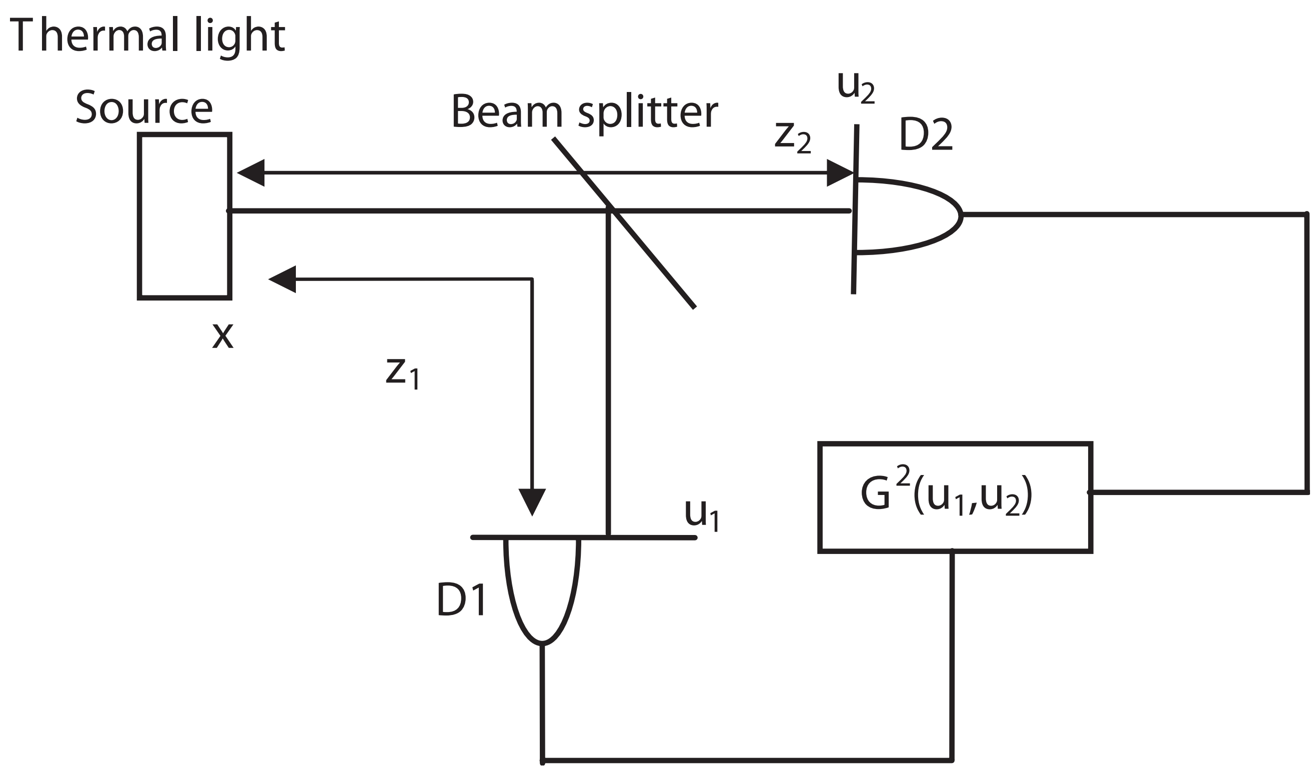
We compare the Hanbury Brown–Twiss (HBT) and the thermal light ghost imaging schemes in both near and far fields. Both effects arise as a result of the intensity fluctuations of the thermal light and we find that the essential physics behind the two effects is the same. The difference however is that, in the ghost imaging, large number of bits information of an object needs to be treated together, whereas, in the HBT, there is only one bit information required to be obtained. In the HBT experiment far field is used for the purpose of easy detection, while in the ghost image experiment near (or not far) field is used for good quality image.

DOI: 10.1103/PhysRevA.79.033835 PACS number(s): 42.50.Ar, 42.50.Dv, 42.50.St

Ghost Image setup



HBT setup



They look almost equal:

- Ghost Imaging there is a lens and the detector is at the focal point.
- Handbury Brown and Twiss is far field, the detector located where the object was.
- We have to propagate the correlations appropriately.
- We demand only one bit of information on HBT and many bits of information on GI to have a good image.

The intensity correlation of thermal light:

The result depends only on the first order correlation, the coherence (linewidth) of the source only.

$$G^2(u_1,u_2) = \langle I_1 I_2 \rangle = \langle I(u_1)\rangle\langle I(u_2)\rangle + |\Gamma(u_1,u_2)|^2$$

$$\Gamma(u_1,u_2) = \langle E^+(u_1)E(u_2)\rangle$$

Gaussian Schell model, σ_i intensity deviation, σ_g correlation length.

$$\langle E_s^+(x_1)E_s(x_2)\rangle = G_0 \exp\left[-\frac{x_1^2+x_2^2}{4\sigma_I^2} - \frac{(x_1-x_2)^2}{2\sigma_g^2}\right]$$

Propagation of correlations:

$$\Gamma(u_1,u_2) = \langle E^{+}(u_1)E(u_2)\rangle$$
$$= \int\int \langle E_s^{+}(x_1)E_s(x_2)\rangle h_1^{*}(x_1,u_1)h_2(x_2,u_2)dx_1dx_2,$$

Where $h_i(x_i,u_i)$ is the appropriate propagation functions of the correlation from the source to the detectors along path I which depend on the optical elements of the paths. given the setup.

h_1 is the same for both setups

$$h_1^{\mathrm{H,G}}(x,u_1) = \left(-\frac{i}{\lambda z_1}\right)^{1/2} \exp\left[-\frac{i\pi}{\lambda z_1}(x^2 - 2xu_1 + u_1^2)\right]$$

h_2 is different for both setups

$$h_2^{\mathrm{H}}(x,u_2) = \left(-\frac{i}{\lambda z_2}\right)^{1/2} \exp\left[-\frac{i\pi}{\lambda z_2}(x^2 - 2xu_2 + u_2^2)\right],$$

$$h_2^{\mathrm{G}}(x,u_2) = \left(-\frac{i}{\lambda f}\right)^{1/2}\left(-\frac{i}{\lambda z_2}\right)^{1/2}\int dv H(v)$$
$$\times \exp\left[-\frac{i\pi}{\lambda z_2}(x^2 - 2xv + v^2) - \frac{i\pi}{\lambda f}(-2vu_2 + u_2^2)\right],$$

$u_1 \neq 0$ and $u_2 = 0$ (transverse HBT)

$$\mathrm{HBT}(\bar{u}_1, 0) = \exp\left(- \frac{\bar{u}_1^2}{\bar{\sigma}_g^2 + \dfrac{\bar{z}^2}{4\pi^2 \bar{\sigma}_I^2}} \right)$$

$\bar{u}_1^2$, $\bar{z}$, and $\bar{\sigma}_{I,g}$ are in units of λ

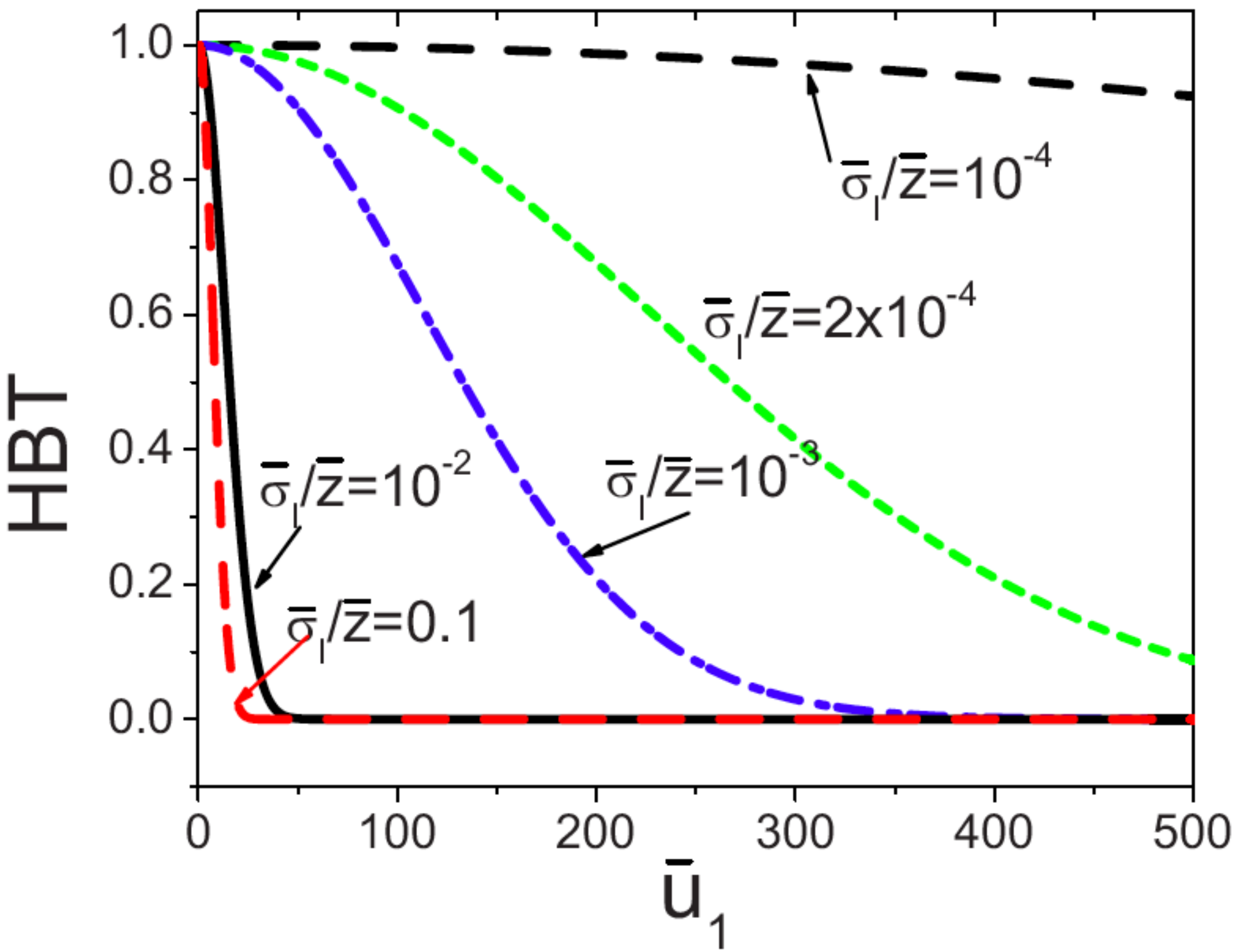


FIG. 2. (Color online) HBT effect for different $\bar{\sigma}_I/\bar{z}=10^{-4}$, $2\times10^{-4}, 10^{-3}, 10^{-2}$, and 0.1 (from top to below), with $\bar{\sigma}_g=10$ and $\bar{z}=10^5$.

For Ghost Imaging (numerical calculation necessary)

$$\Gamma(u_1,0) = \frac{4\pi G_0 \exp\left(\dfrac{i\pi}{\bar{z}_1}\bar{u}_1^2\right)}{\bar{f}^{1/2}\bar{\xi}^{1/2}} \int d\bar{v} H(\bar{v}) \exp\left(-\frac{i\pi}{\bar{z}_1}\bar{v}^2\right)$$
$$\times \exp\left\{-\frac{4\pi^2[(\bar{\sigma}_g^2 + 2\bar{\sigma}_I^2)\bar{u}_1^2 - 4\bar{\sigma}_I^2\bar{u}_1\bar{v} + (\bar{\sigma}_g^2 + 2\bar{\sigma}_I^2)\bar{v}^2 - i4\pi\bar{\sigma}_g^2\bar{\sigma}_I^2(\bar{v}^2 - \bar{u}_1^2)/\bar{z}_1]}{\bar{\sigma}_g^2\bar{\sigma}_I^2\bar{\xi}}\right\}$$

For an object with three slits

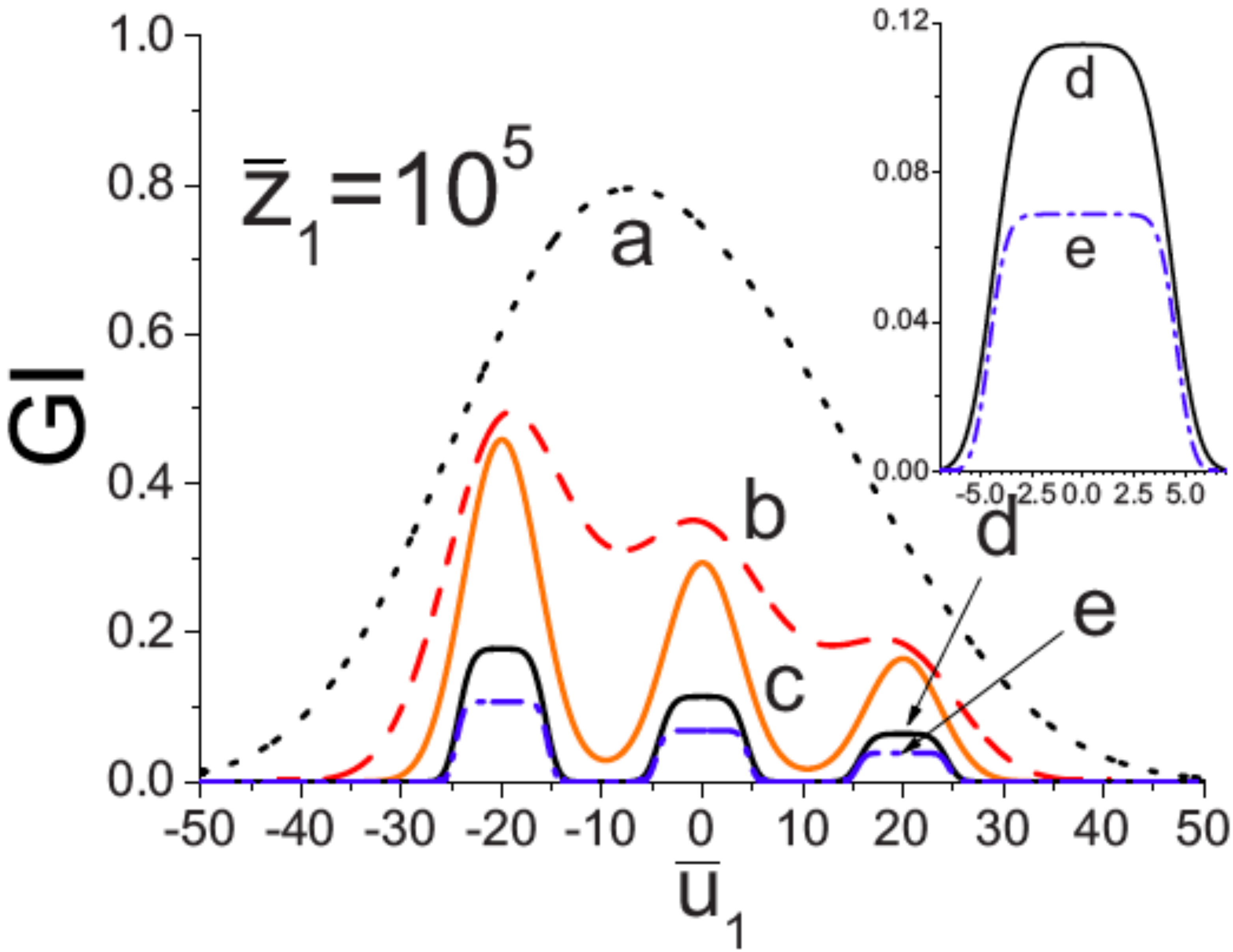
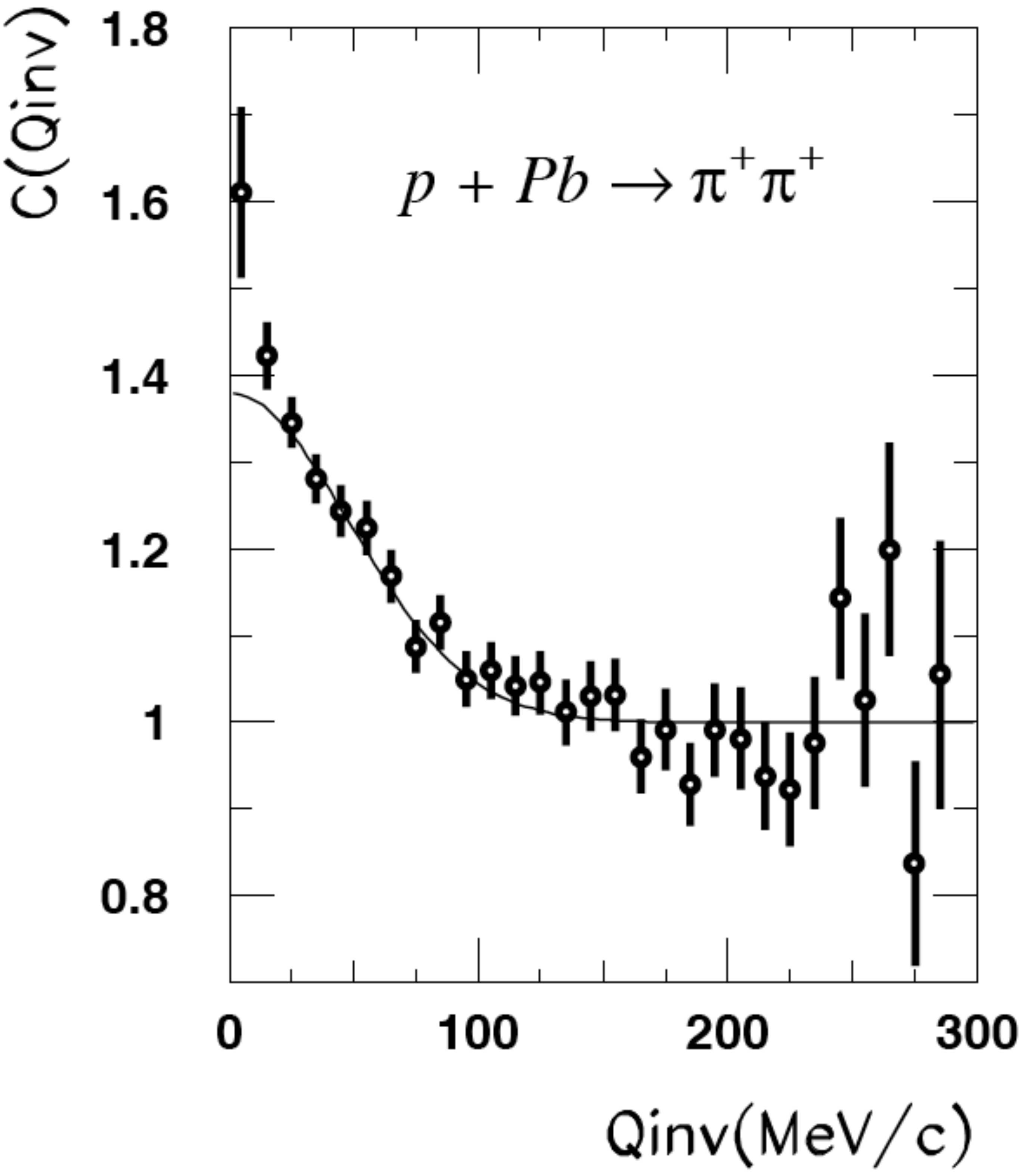


FIG. 3. (Color online) The ghost image of three slits, (a) $\bar{\sigma}_I/\bar{z}_1=10^{-2}$, (b) $\bar{\sigma}_I/\bar{z}_1=2.5\times10^{-2}$, (c) $\bar{\sigma}_I/\bar{z}_1=0.2$, with $\bar{\sigma}_g=4$, (d) $\bar{\sigma}_I/\bar{z}_1=0.2$ and $\bar{\sigma}_g=1$, and (e) $\bar{\sigma}_I/\bar{z}_1=0.2$ and $\bar{\sigma}_g=0.1$.

- Large size of the source results in good quality image, while large size of the object (a large amount of bits) leads to low visibility.
- The physics behind the thermal light ghost imaging and the HBT experiment is the same, the intensity fluctuations.
- The difference between the GI and the HBT experiments is the information that is required to be obtained: large amount for GI and a small amount for HBT large number of bits versus one bit.
- In the HBT experiment the far field is used for the purpose of easy detection, while in the GI experiment the near field not-far field is used for good quality image at the expense of low visibility.

Correlations in high energy physics to measure size



$$\frac{\hbar}{\Delta Q} \approx 4\, fm$$

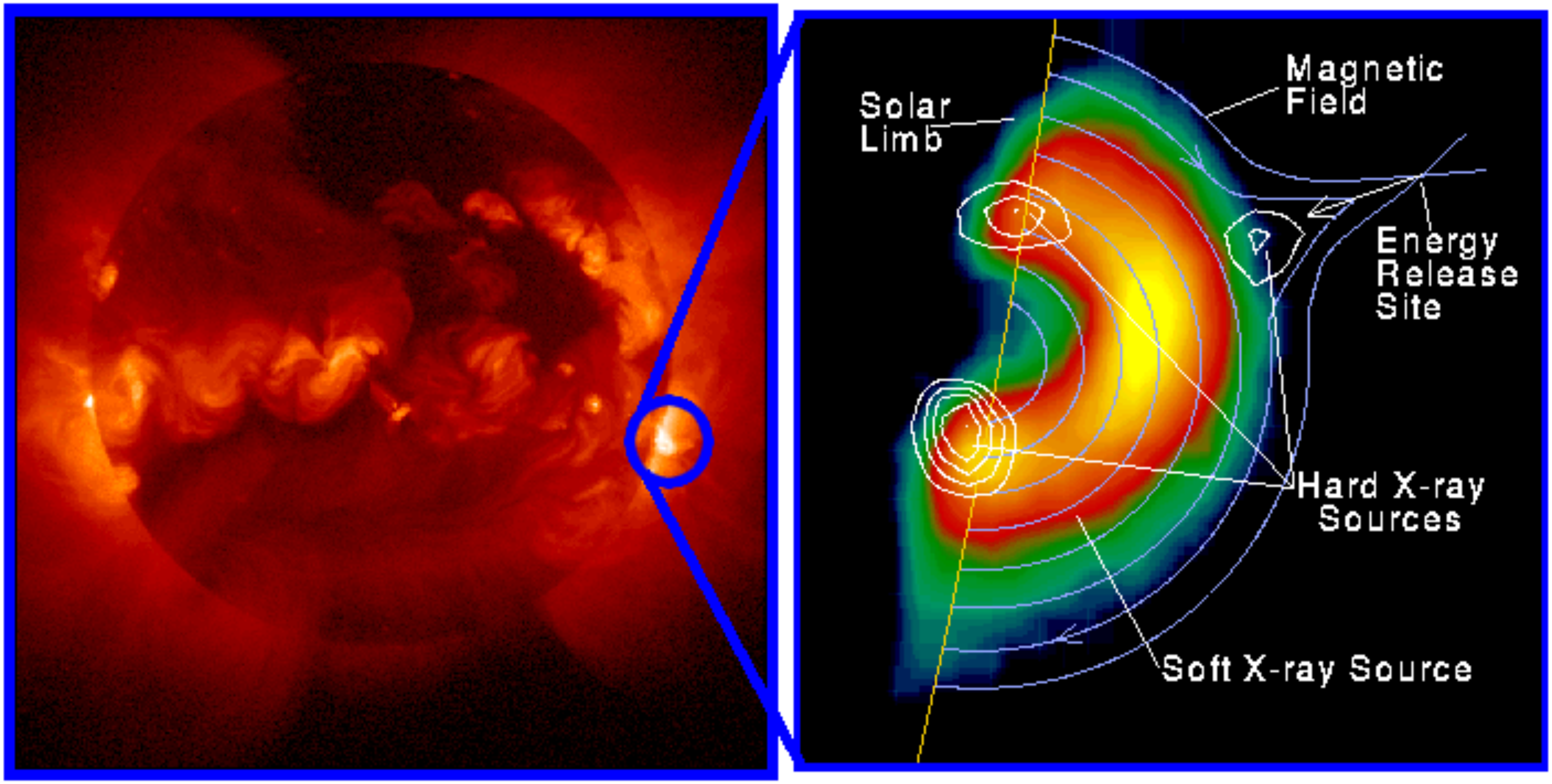
The technique of Hanbury Brown and Twiss, which was first developed to measure astronomical object of sizes at least 10^{12} cm, has, as we have seen, turned into a valuable tool to measure subatomic phenomena on the quite opposite scale of 10^{-12} cm.

RHESSI mission

- How to create an image with a single pixel detector?

- Rotational Modulation Collimators
- 1975 Minoru Oda

- Take a sample (counting) with an aperture to know the amplitude of a certain Fourier Component. Change the shape of the aperture (filter) to obtain enough Fourier Components to reconstruct the image.



Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

Questions:

- Could one use the correlation $h_\theta(\tau)$ (Field-Intensity) to get an image of both the intensity and the phase?
- Which kind of spectral analysis could be done with this images?

Use correlations

Thanks