Quantum Imaging

Robert W. Boyd

Department of Physics
University of Ottawa

The Institute of Optics
University of Rochester

Department of Physics and Astronomy
University of Glasgow

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Quantum Imaging

Introductory remarks
Two-color ghost imaging
Interaction-free ghost imaging
Imaging with “undetected photons”
Imaging using weak values
Imaging with photon-added states

Quantum Imaging

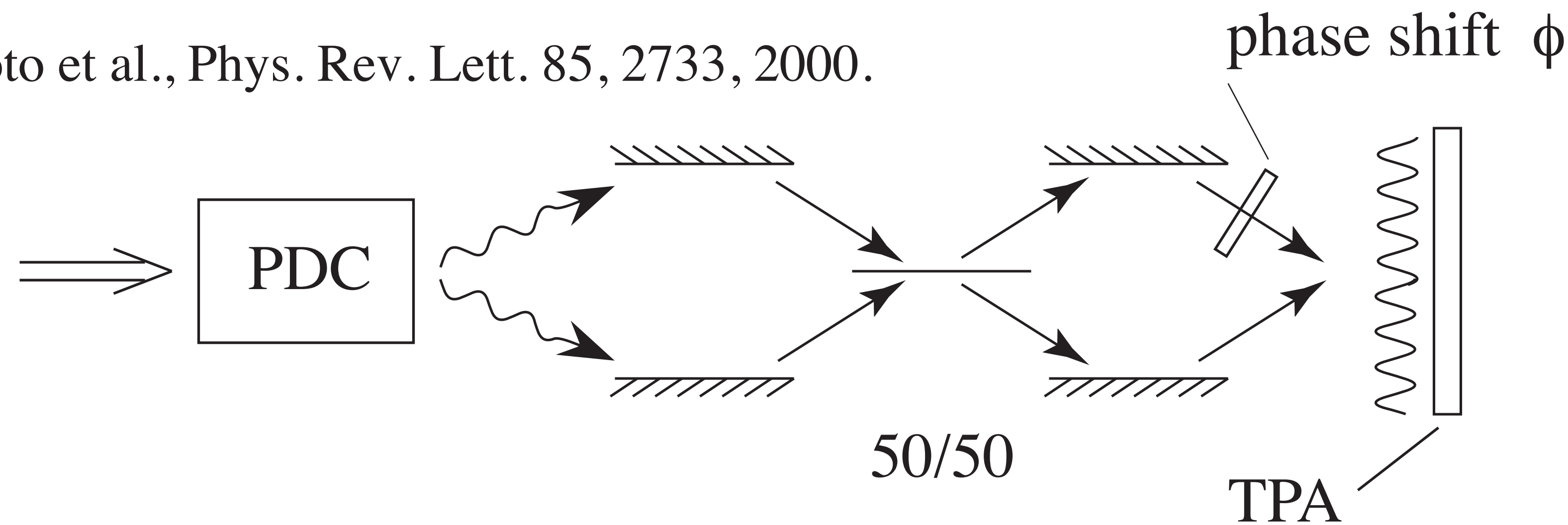
- Goal of quantum imaging is to produce “better” images using quantum methods
  - image with a smaller number of photons
  - achieve better spatial resolution
  - achieve better signal-to-noise ratio
- Alternatively, quantum imaging exploits the quantum properties of the transverse structure of light fields

SHARPER IMAGE

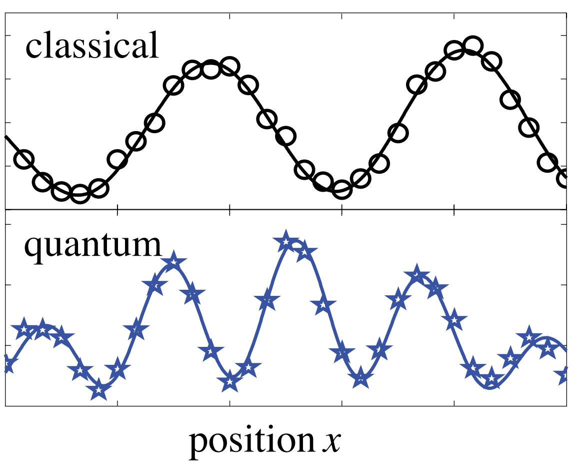
Quantum Lithography: Concept of Jonathan Dowling

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit
- Resolution ≈ $\lambda/2N$, where N = number of entangled photons

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



- No practical implementation to date, but some laboratory results

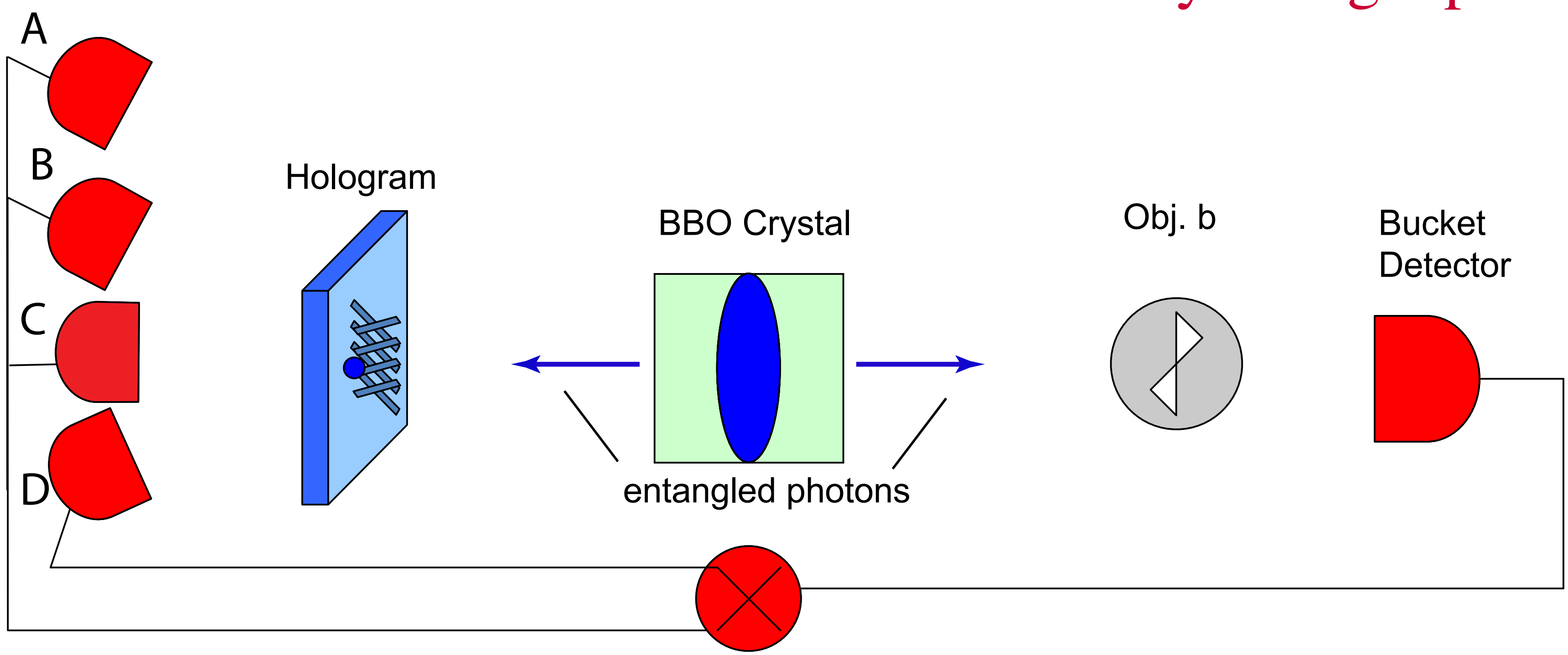


Quantum spatial superresolution by optical centroid measurements, Shin, Chan, Chang, and Boyd, Phys. Rev. Lett. 107, 083603 (2011).

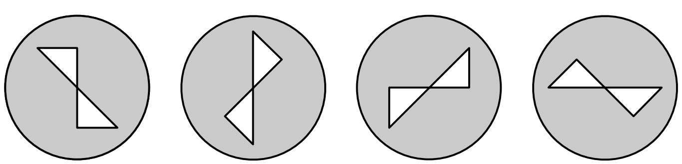
See also, Quantum Lithography: Status of the Field, R.W. Boyd and J.P. Dowling, Quantum Information Processing, 11:891–901 (2012).

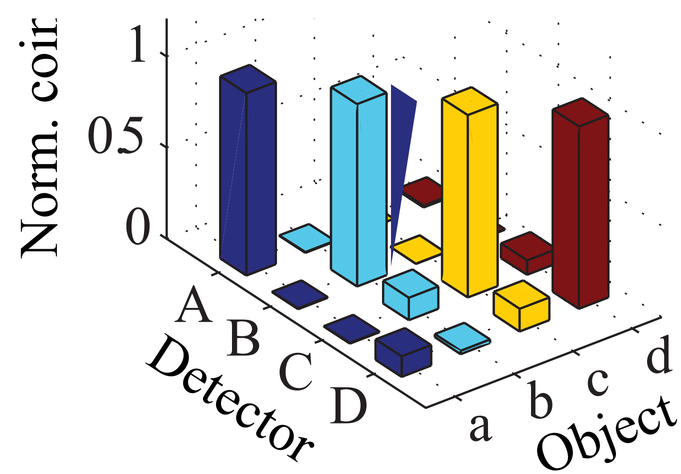
Single-Photon Coincidence Imaging

How much information can be carried by a single photon?



We discriminate among four orthogonal images using single-photon interrogation in a coincidence imaging configuration.





Malik, Shin, O'Sullivan. Zerom, and Boyd, Phys. Rev. Lett. 104, 163602 (2010).

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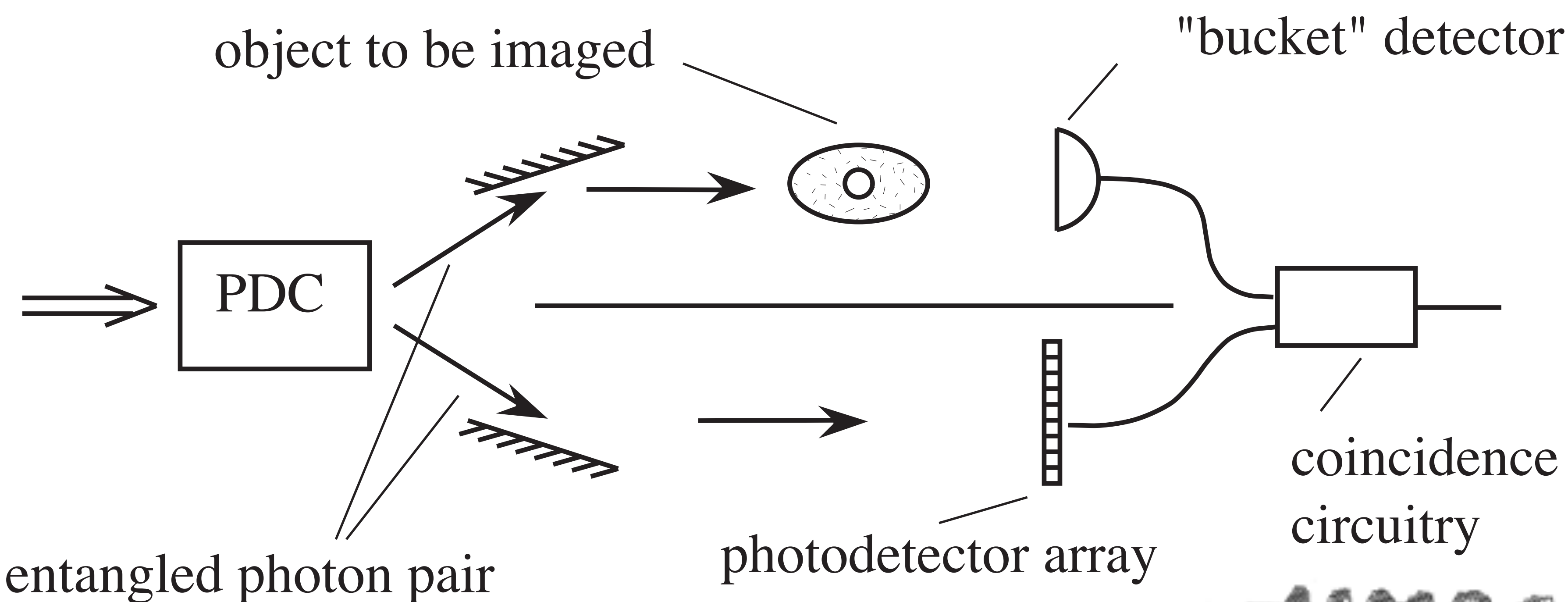
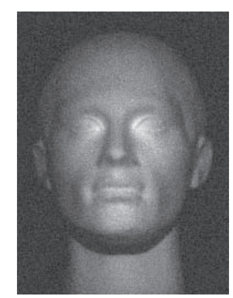
Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing!
  (imaging under adverse situations, bio, two-color, etc.)
- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)



Padgett Group

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)

Is Ghost Imaging a Quantum Phenomenon?

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

(Received 11 October 2002; published 3 April 2003)

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.

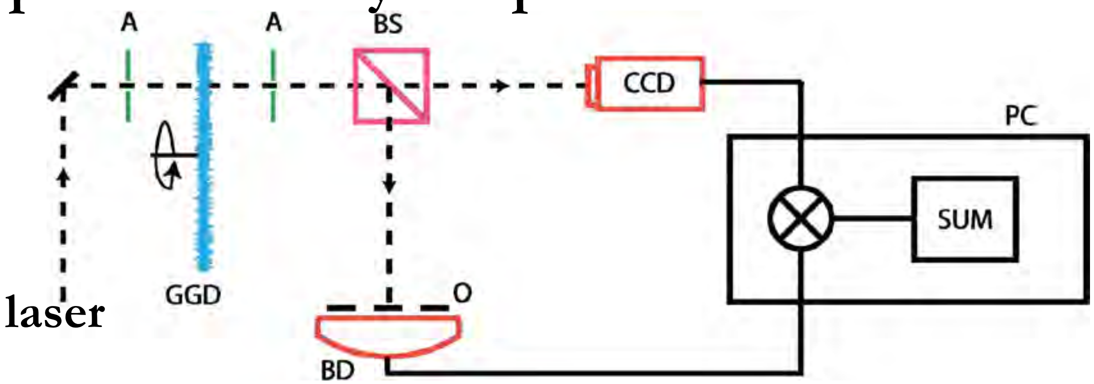
Experimental verification by Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

Thermal Ghost Imaging

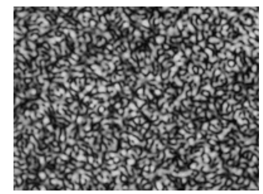
Instead of using entangled photons, one can perform ghost imaging using the (HBT) correlations of thermal (or quasithermal) light.

(Gatti et al., Phys. Rev. Lett. 93, 093602, 2004).

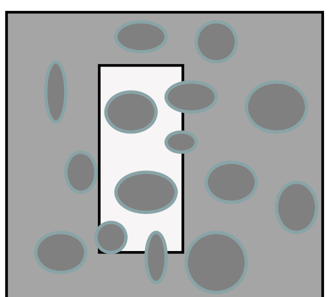
- **Typical laboratory setup**



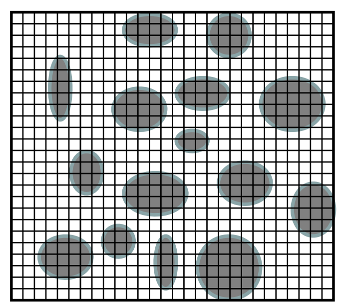
identical speckle patterns in each arm



- **How does this work? (Consider the image of a slit.)**

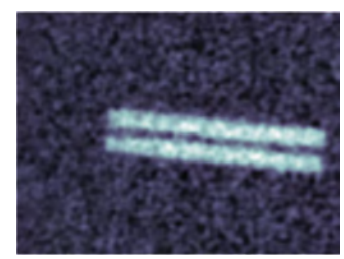


Object arm, bucket detector



Reference arm, CCD

Example ghost image



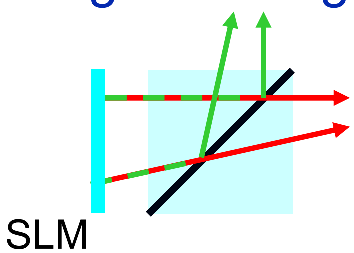
Zerom et al., A 86, 063817 (2012)

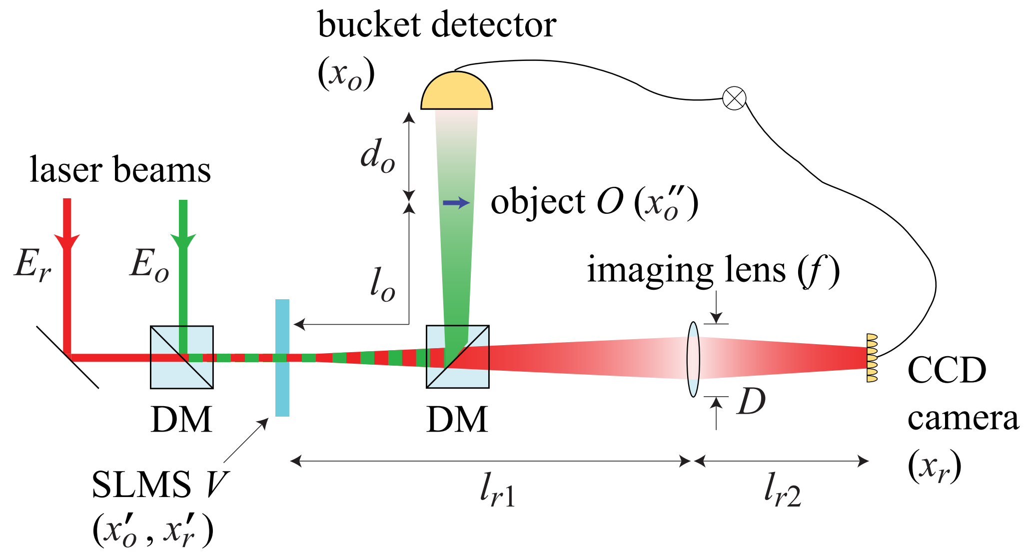
Calculate (total transmitted power) x (intensity at each pixel) and average over many speckle patterns.

Two-Color Ghost Imaging

New possibilities afforded by using different colors in object and reference arms

Thermal ghost imaging





But no obvious way to make identical speckle patterns at two wavelengths

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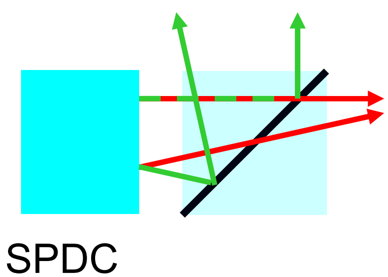
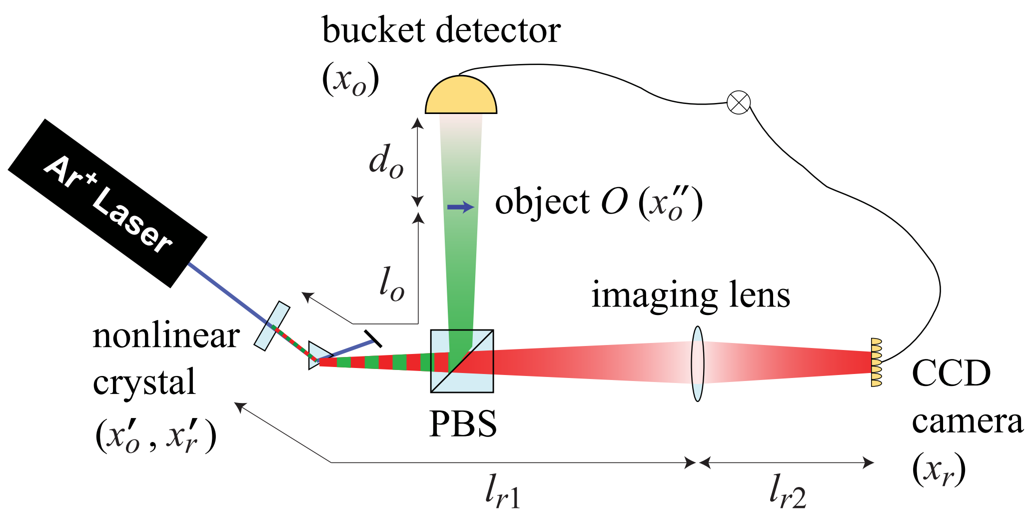
Quantum ghost imaging





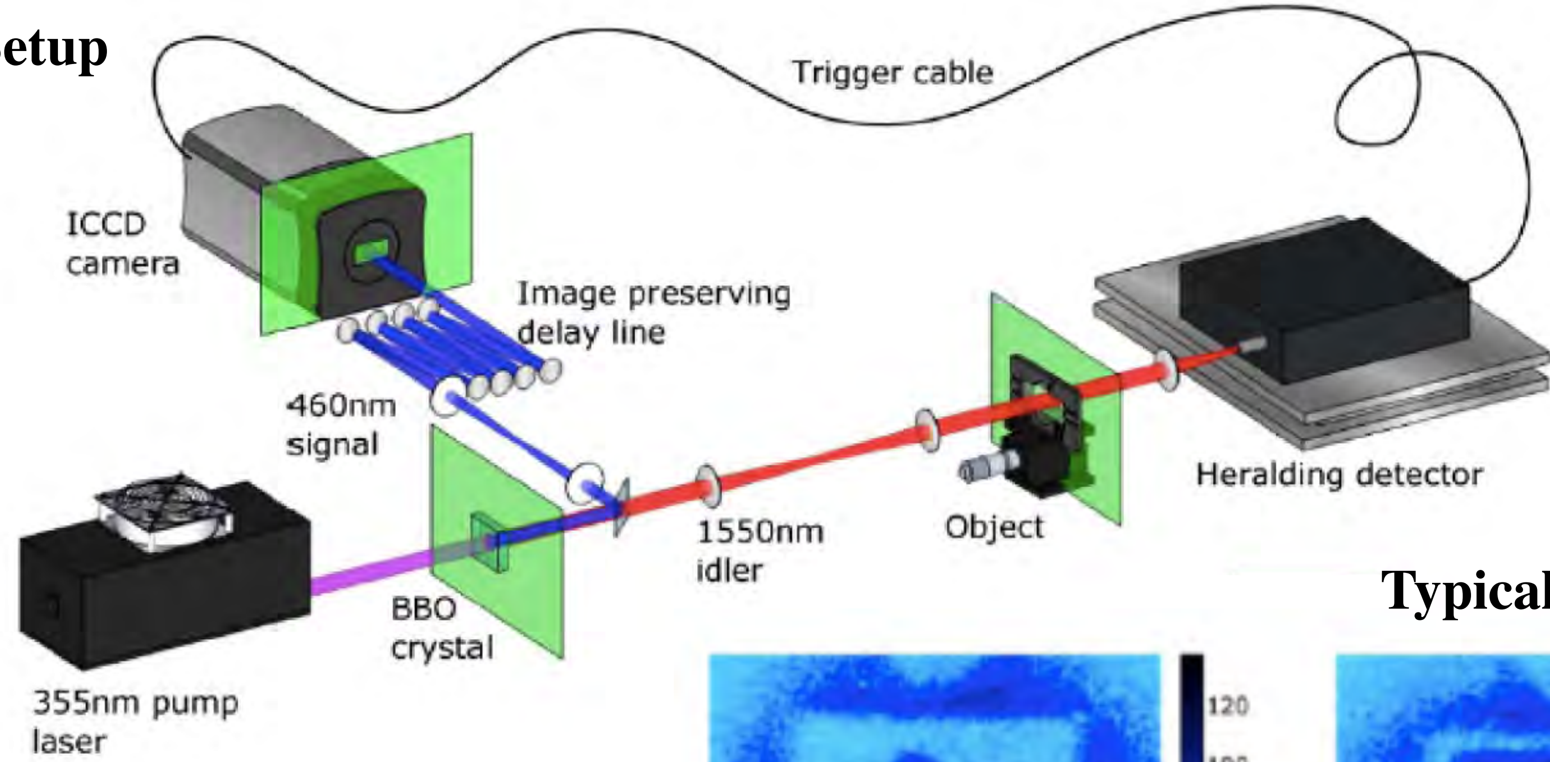
Spatial resolution depends on wavelength used to illuminate object.

Two-Color Ghost Imaging, K.W.C. Chan, M.N. O'Sullivan, and R.W. Boyd, Phys. Rev. A 79, 033808 (2009).

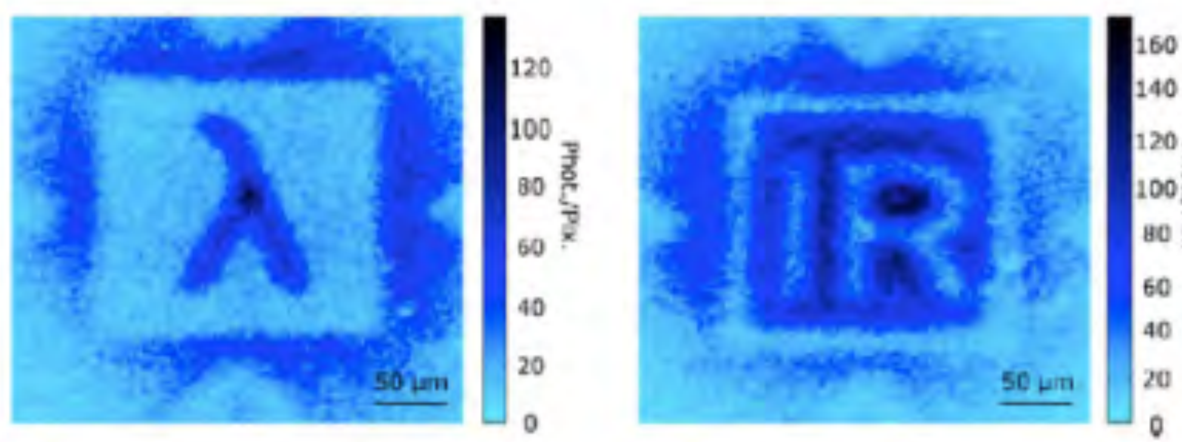
Wavelength-Shifted (Two-Color) Ghost Microscopy

- Pump at 355 nm produces signal at 460 nm and idler at 1550 nm
- Object is illuminated at 1550 nm, but image is formed (in coincidence) at 460 nm
- Wavelength ratio of 3.4 is the largest yet reported.

Setup



Typical images



Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

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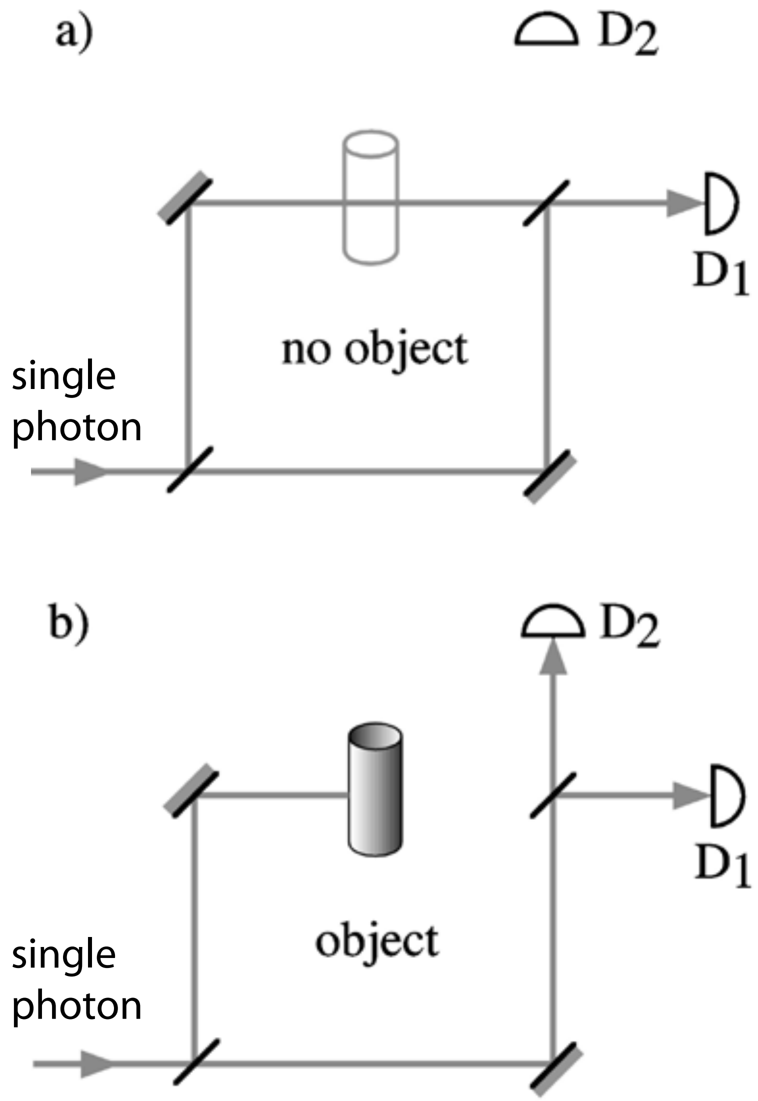
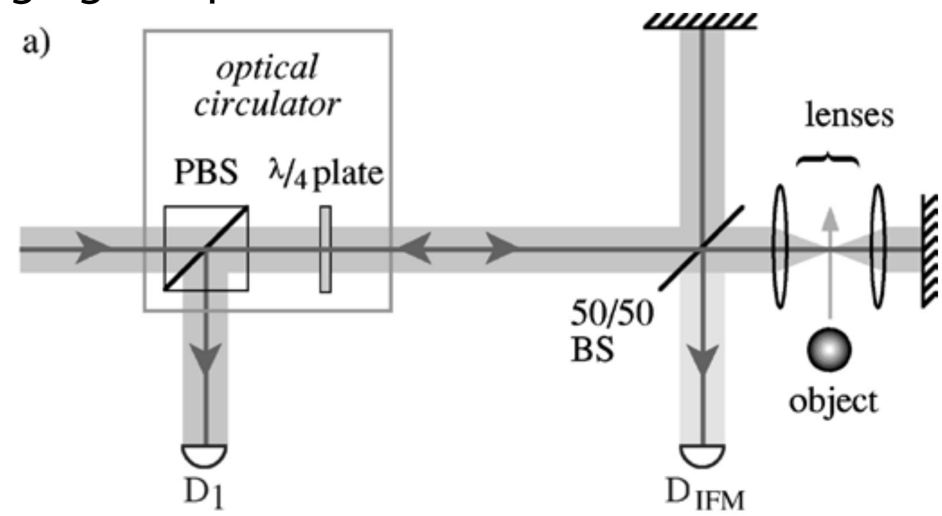
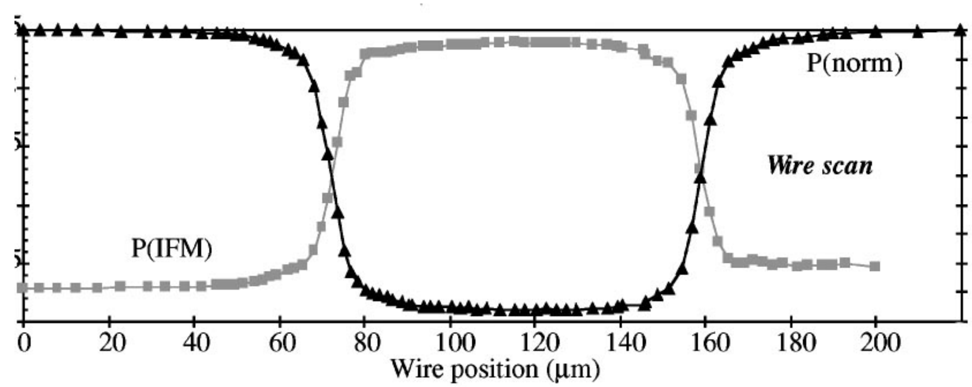
Quantum Imaging by Interaction-Free Measurement



imaging setup

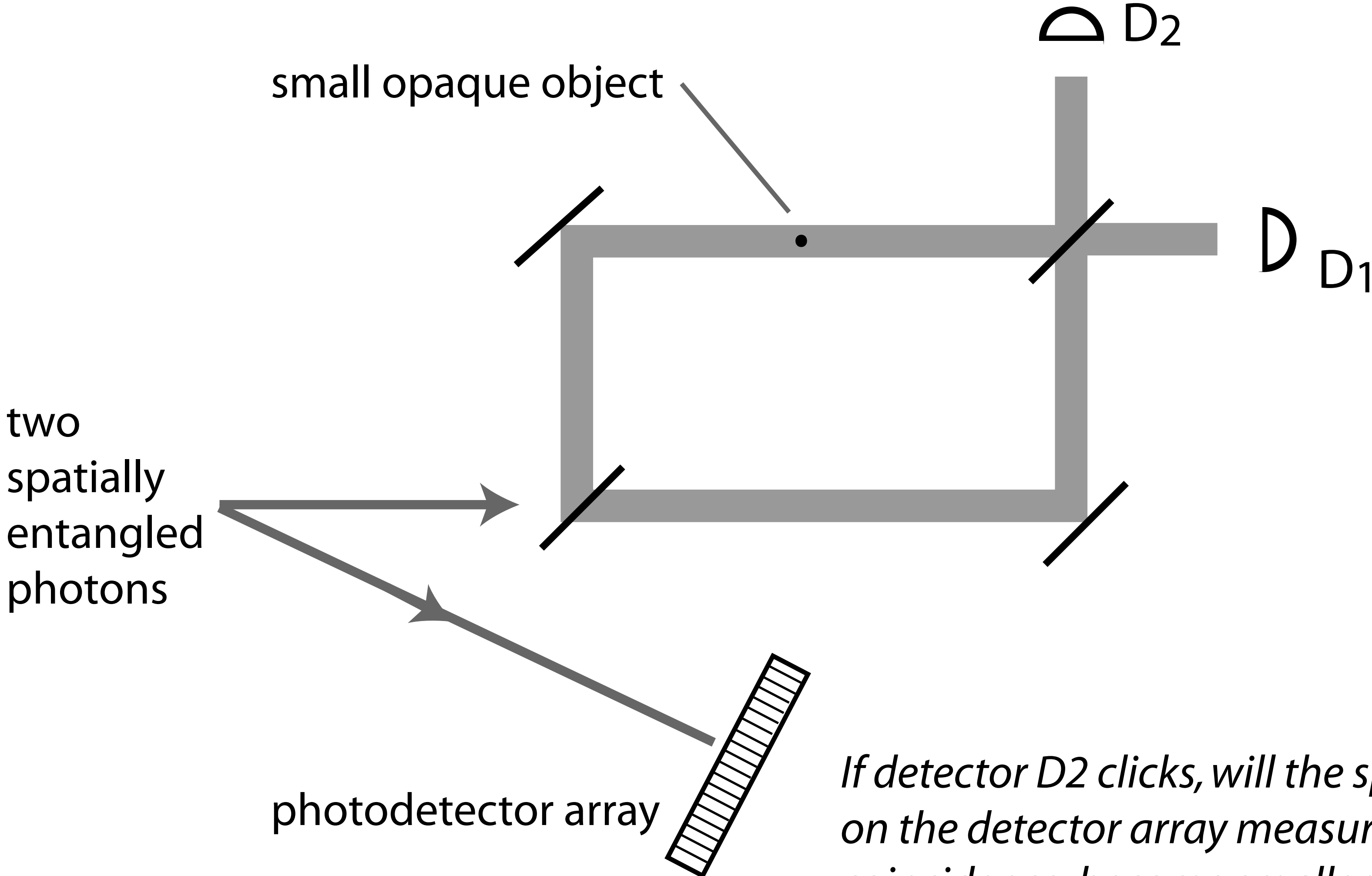


results



M. Renninger, Z. Phys. 15S, 417 (1960).
R. H. Dicke, Am. J. Phys. 49, 925 (1981).
A. Elitzur and L. Vaidman, Found. Phys. 23, 987 (1993).
L. Vaidman, Quant. Opt. 6, 119 (1994).
P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, Phys. Rev. Lett. 74, 4763 (1995)
A. G. White, J. R. Mitchell, O. Nairz, and P. G. Kwiat, Phys. Rev. A 58, 605 (1998).

Interaction-Free Measurements and Entangled Photons



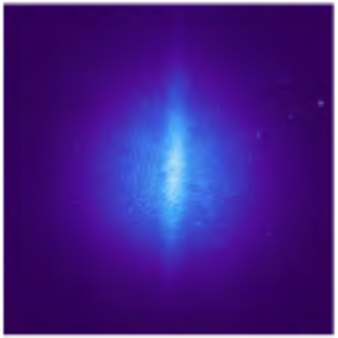
If detector D2 clicks, will the spot size on the detector array measured in coincidence become smaller?

- Does an interaction-free measurement constitute a "real" measurement?
- Does it lead to the collapse of the wavefunction of its entangled partner?
- More precisely, does the entire two-photon wavefunction collapse?

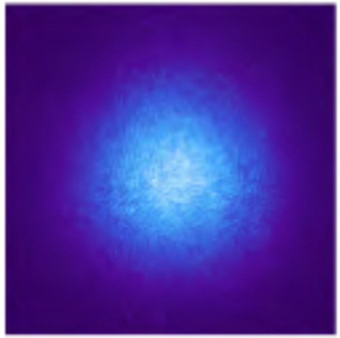
Experimental Results

Interaction-free ghost image of a straight wire

coincidence counts



singles counts



- Note that the interaction-free ghost image is about five times narrower than full spot size on the ICCD camera
- This result shows that interaction-free measurements lead to wavefunction collapse, just like standard measurements.

With Frédéric Bouchard, Harjaspreet Mand, and Ebrahim Karimi,

Is interaction-free imaging useful?

Interaction-free imaging allows us to see what something looks like *in the dark*!

Could be extremely useful for biophysics. What does the retina look like when light does not hit it?

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VOLUME 60, NUMBER 14 PHYSICAL REVIEW LETTERS 4 APRIL 1988

How the Result of a Measurement of a Component of the Spin of a Spin-$\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman
Physics Department, University of South Carolina, Columbia, South Carolina 29208, and School of Physics and Astronomy, Tel-Aviv University, Ramat Aviv 69978, Israel
(Received 30 June 1987)

We have found that the usual measuring procedure for preselected and postselected ensembles of quantum systems gives unusual results. Under some natural conditions of weakness of the measurement, its result consistently defines a new kind of value for a quantum variable, which we call the weak value. A description of the measurement of the weak value of a component of a spin for an ensemble of preselected and postselected spin-$\frac{1}{2}$ particles is presented.

PACS numbers: 03.65.Bz

standard expectation value: $< A >=< \Psi|\hat{A}|\Psi >$

weak value: $A_w \equiv \langle \psi_f | A | \psi_{\text{in}} \rangle / \langle \psi_f | \psi_{\text{in}} \rangle.$

Why are weak values important?

can lead to amplification of small signals

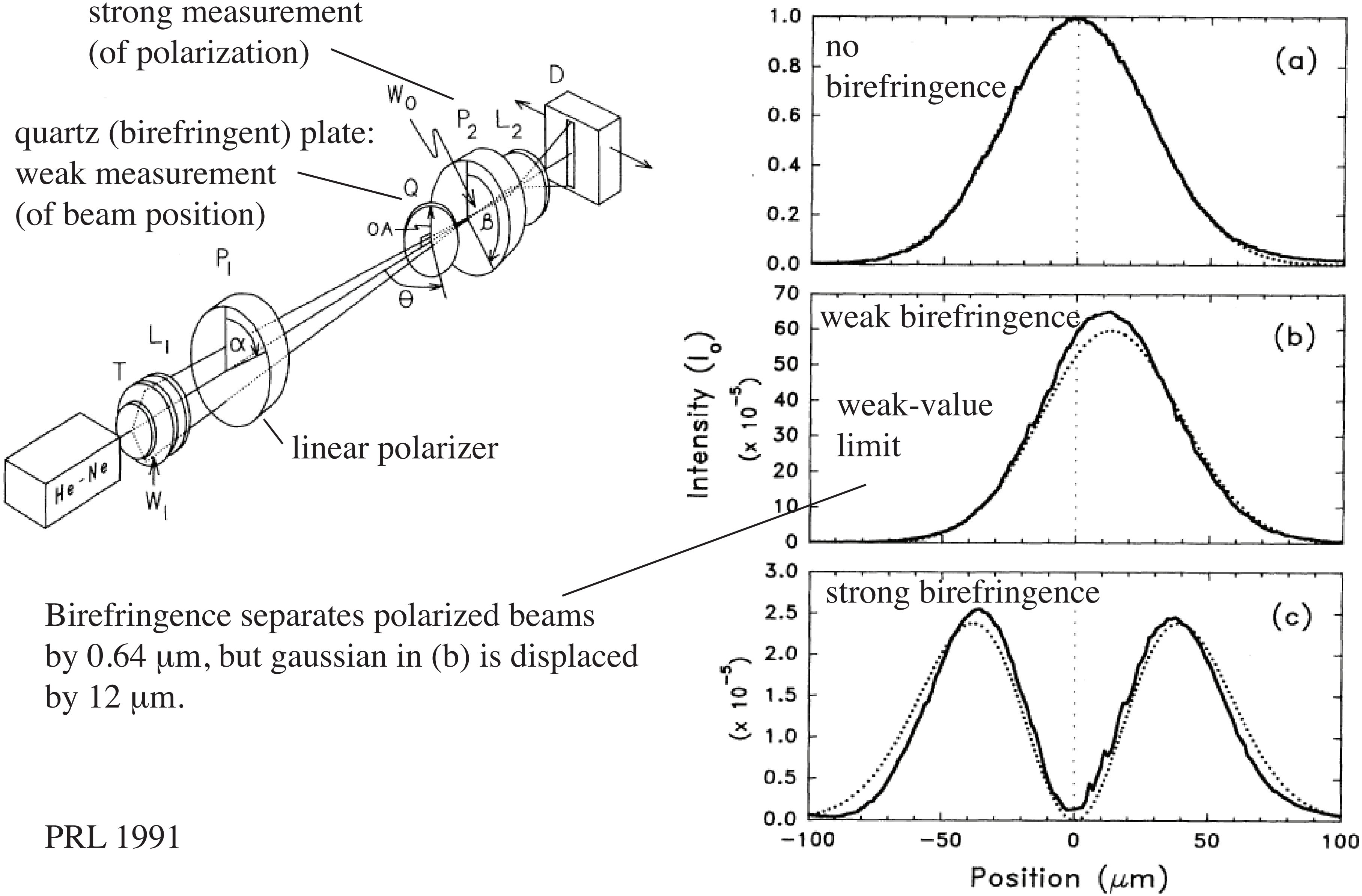
can lead to direct measurement of the quantum wavefunction

Realization of a Measurement of a "Weak Value"

N. W. M. Ritchie, J. G. Story, and Randall G. Hulet
Department of Physics and Rice Quantum Institute, Rice University, Houston, Texas 77251-1892
(Received 7 December 1990)

linear polarizer:
strong measurement
(of polarization)

quartz (birefringent) plate:
weak measurement
(of beam position)



Birefringence separates polarized beams by 0.64 μm, but gaussian in (b) is displaced by 12 μm.

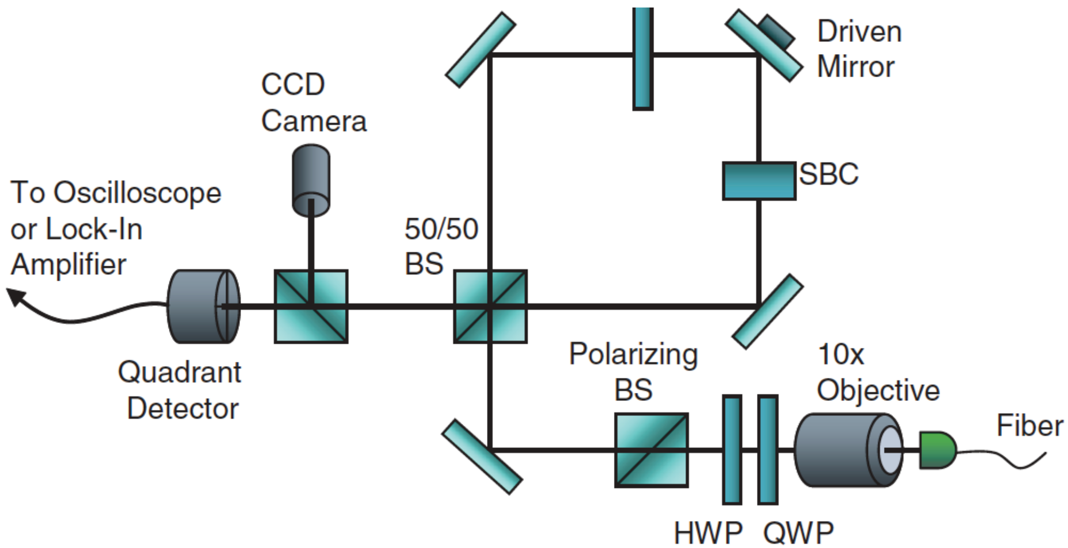
PRL 1991

Selected for a Viewpoint in *Physics*
PRL **102,** 173601 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification

P. Ben Dixon, David J. Starling, Andrew N. Jordan, and John C. Howell
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA
(Received 12 January 2009; published 27 April 2009)

We report on the use of an interferometric weak value technique to amplify very small transverse deflections of an optical beam. By entangling the beam's transverse degrees of freedom with the which-path states of a Sagnac interferometer, it is possible to realize an optical amplifier for polarization independent deflections. The theory for the interferometric weak value amplification method is presented along with the experimental results, which are in good agreement. Of particular interest, we measured the angular deflection of a mirror down to 400 $\pm$ 200 frad and the linear travel of a piezo actuator down to 14 $\pm$ 7 fm.



LETTER

doi:10.1038/nature10120

Direct measurement of the quantum wavefunction

Jeff S. Lundeen[1], Brandon Sutherland[1], Aabid Patel[1], Corey Stewart[1] & Charles Bamber[1]

$$\langle A\rangle_W = \frac{\langle c|A|\Psi\rangle}{\langle c|\Psi\rangle}$$

Returning to our example of a single particle, consider the weak measurement of position ($A = \pi_x \equiv |x\rangle\langle x|$) followed by a strong measurement of momentum giving $P = p$. In this case, the weak value is:

$$\langle\pi_x\rangle_W = \frac{\langle p|x\rangle\ \langle x|\Psi\rangle}{\langle p|\Psi\rangle} \tag{2}$$

$$= \frac{e^{ipx/\hbar}\Psi(x)}{\Phi(p)} \tag{3}$$

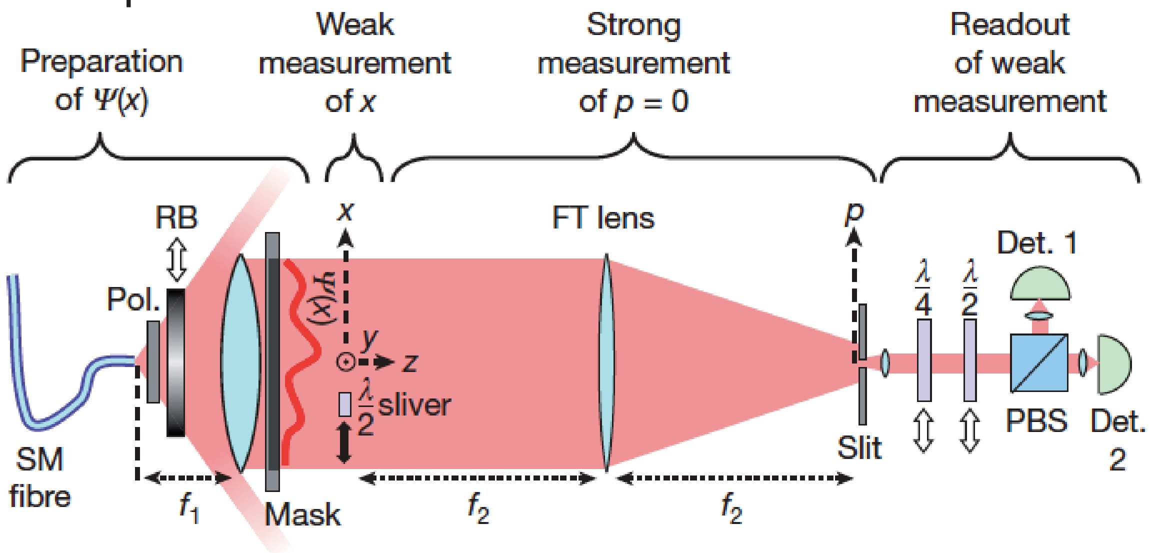
In the case $p = 0$, this simplifies to

$$\langle\pi_x\rangle_W = k\Psi(x) \tag{4}$$

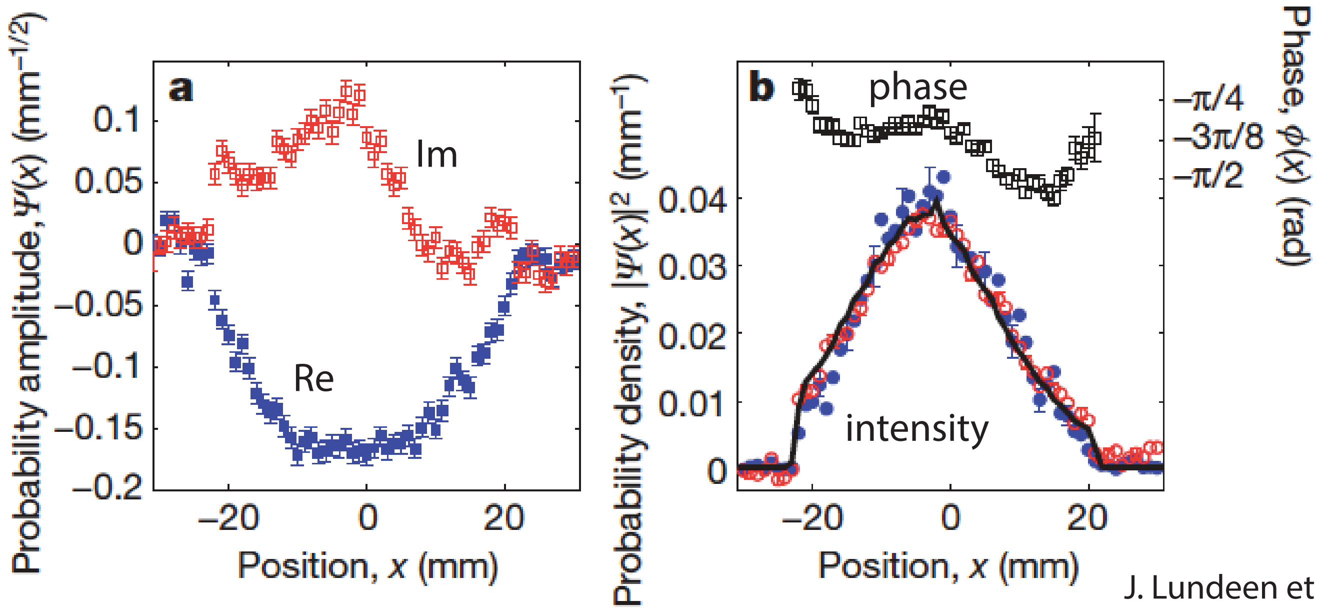
where $k = 1/\Phi(0)$ is a constant (which can be eliminated later by normalizing the wavefunction). The average result of the weak mea-

Direct Measurement of the Photon "Wavefunction"

Measurement setup



Typical results



J. Lundeen et al., Nature 474, 188 (2011)

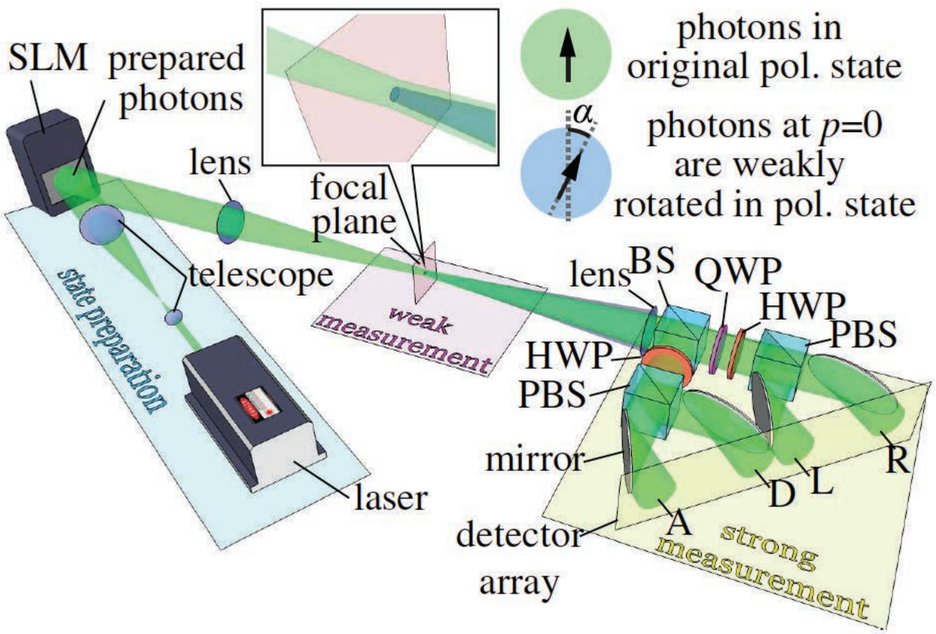
Research Article Vol. 2, No. 4 / April 2015 / Optica 388

optica

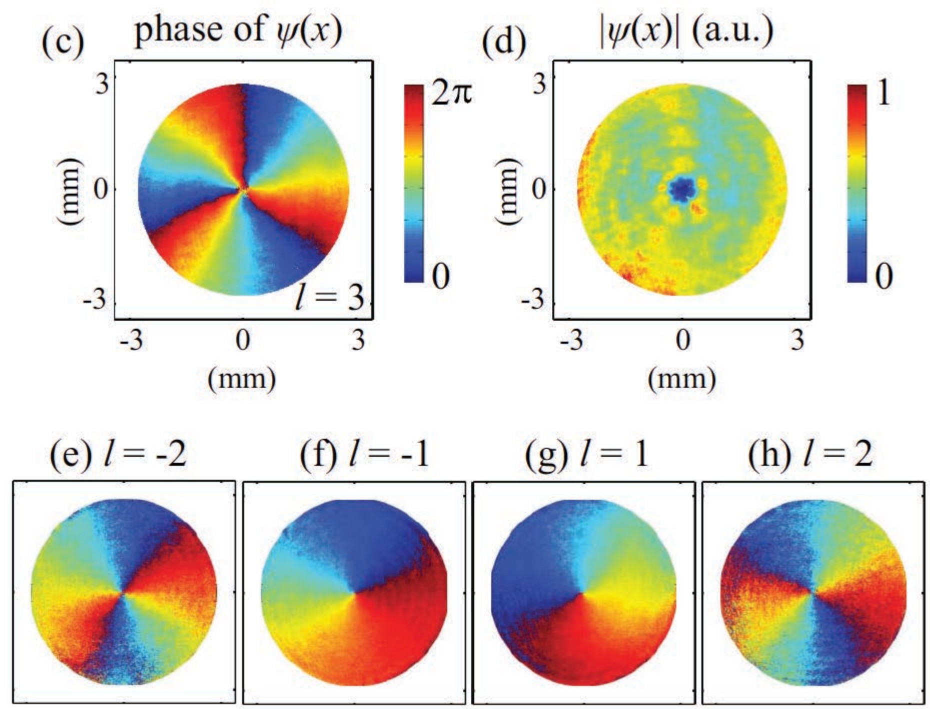
Scan-free direct measurement of an extremely high-dimensional photonic state

Zhimin Shi,[1,*] Mohammad Mirhosseini,[2] Jessica Margiewicz,[1] Mehul Malik,[2,3] Freida Rivera,[1] Ziyi Zhu,[1] and Robert W. Boyd[2,4]

Laboratory setup



Laboratory results for OAM beams



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Photon-Added and Photon-Subtracted States

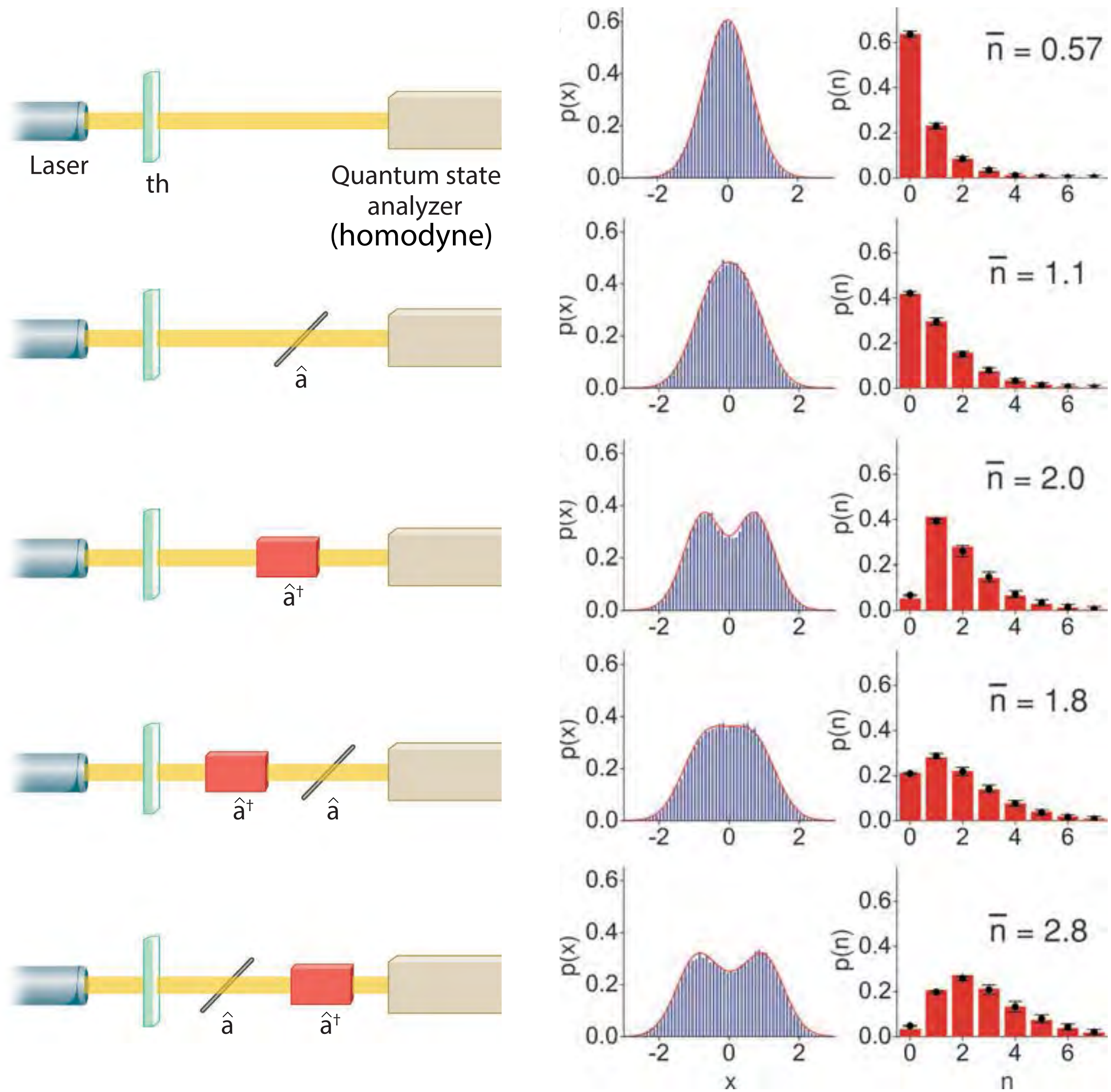
original thermal state

photon-subtracted

photon-added

photon-added and then subtracted

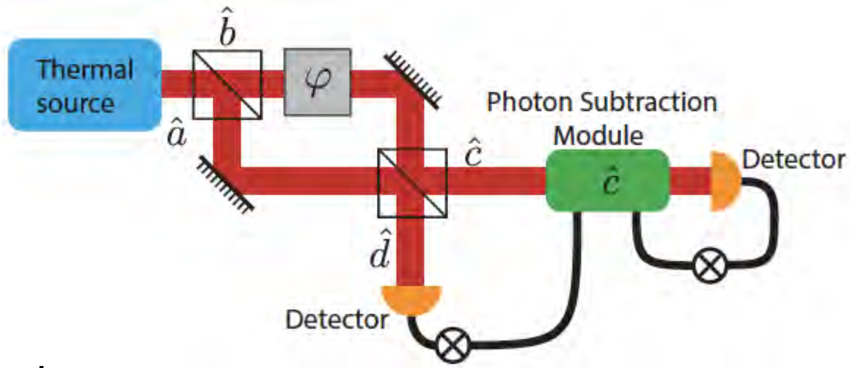
photon-subtracted and then added



Note!

V. Parigi, A. Zavatta, M. Kim, M. Bellini, Science 317,1890 (2007).

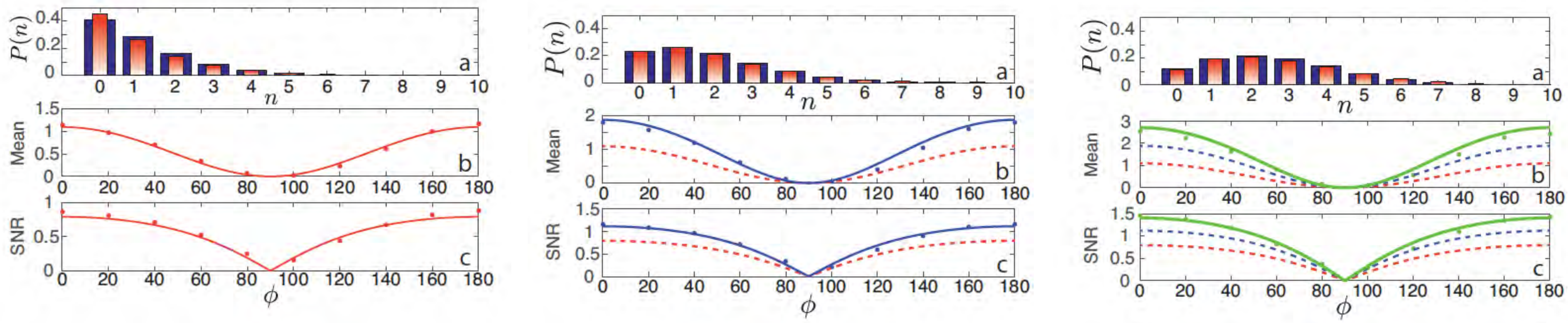
Enhanced Interferometry with Photon-Subtracted Thermal Light



Can we measure the phase ϕ more accurately by using photon-subtracted states?

- Results

without photon subtraction | with one-photon subtraction | with two-photon subtraction



- We find that the signal-to-noise ratio (SNR) is increased through use of photon-subtracted states!
- However, in the present setup, photon-subtraction occurs probabilistically and only a small fraction of the time
- Is there a means to obtain photon-addition and photon-subtraction deterministically?
- Can we use this method to perform quantum imaging with improved SNR?

Rochester, Boeing, LSU, Lehman collaboration

Thank you for your attention!