Quantum Imaging and Ghost Imaging

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The visuals of this talk will be posted at boydnlo.ca/presentations

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Quantum Imaging Outline

Introduction to Quantum Imaging

Quantum Superresolution

Quantum, Nonlocal Aberration Correction

Quantum Ghost Imaging

And what is quantum?

Quantum Imaging

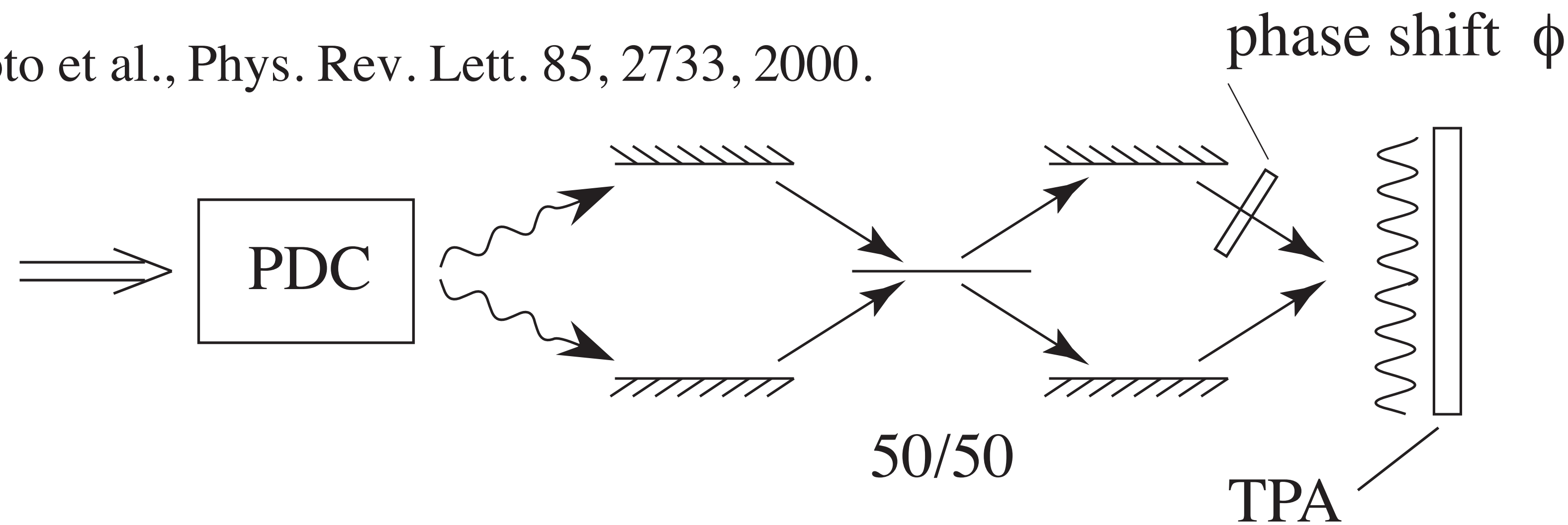
- Goal of quantum imaging is to produce “better” images using quantum methods
  - image with a smaller number of photons
  - achieve better spatial resolution
  - achieve better signal-to-noise ratio
- Alternatively, quantum imaging exploits the quantum properties of the transverse structure of light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

SHARPER IMAGE

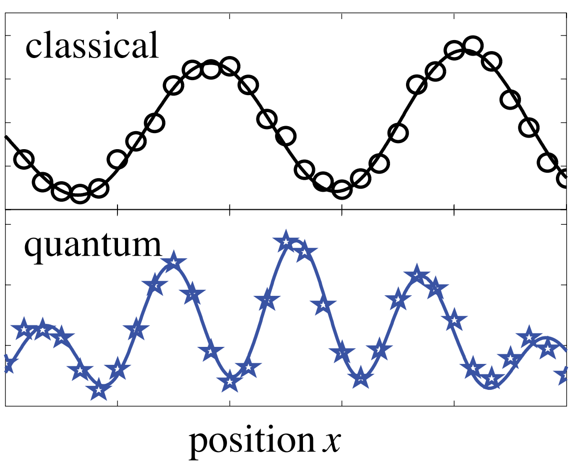
Quantum Lithography: Concept of Jonathan Dowling

- 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).

Quantum Imaging Outline

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Quantum Superresolution

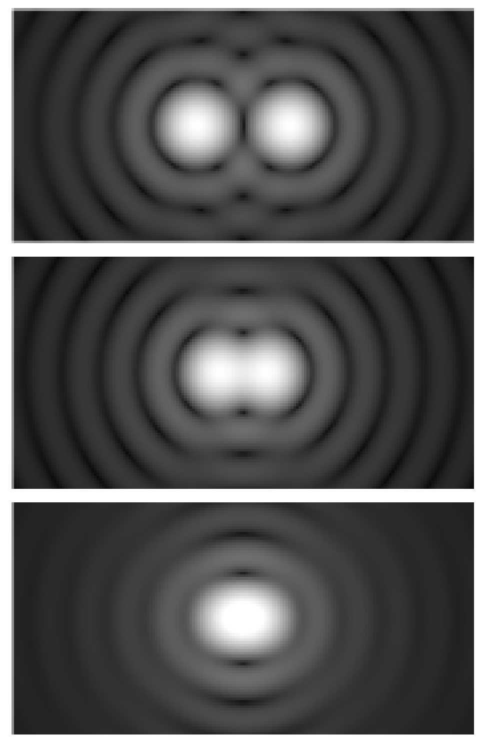
Quantum, Nonlocal Aberration Correction

Quantum Ghost Imaging

Superresolution

- What does quantum mechanics have to say about one's ability to achieve superresesolution?
- And what is superresolution? We will take it to mean achieving spatial resolution in an optical imaging system that exceeds the Rayleigh or Abbe criterion.

  – Rayleigh criterion: the angular separation of two stars must be greater than 1.22 λ / D, where D is the diameter of the collecting aperture.



Resolved

At limit of resolution

Not resolved

Mode Decomposition and Imaging

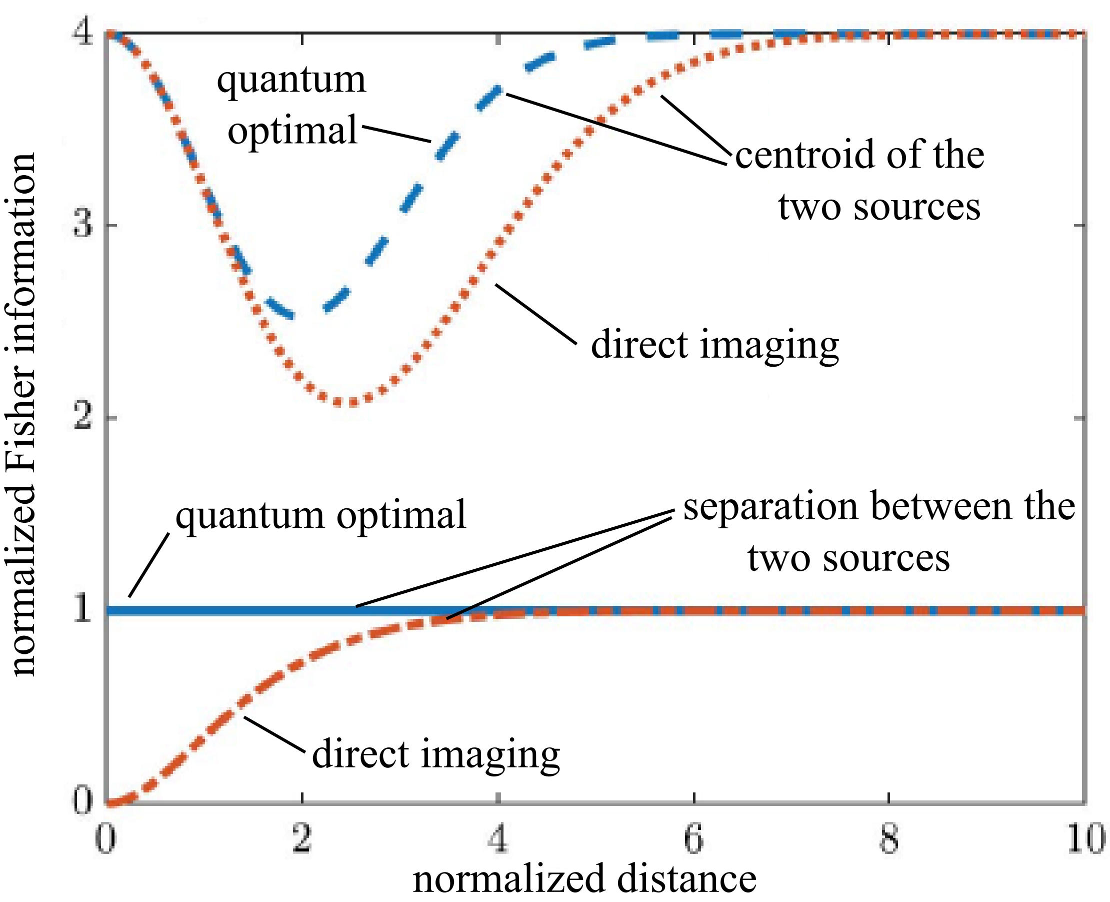
1. It is most natural to perform imaging in coordinate space, that is to measure the intensity $I(x)$ as a fuction of position.

2. However, one can alternatively describe an image by decomposing it into any complete, orthogonal basis set, such as the Hermite-Gauss (HG) or Laguerre-Gauss (LG) modes.

3. There are advantages to describing images in terms of a mode decomposition
   (a) often a small number of parameters can characterize an image
   (b) techniques exist for characterizing and manipulating LG and HG modes
   (c) the mode dcomposition can be used for superresolution

Mankei Tsang and Rayleigh's Curse

- Mankei Tsang and coworkers speak of Rayleigh's curse as the result that angular resolution for incoherent sources is limited to 1.22 λ / D, where D is the diameter of the collecting aperture.
- They show that this limitation is the result of measuring the intensity distribution $I(x)$ of the light in the image plane.
- They also show through quantum measurement theory that there would be no limitation if one were instead to measure the complex field amplitude in the image plane.
- In addition, they show that there is no limitation if one measures the mode amplitudes after performing a mode decomposition of the field.



M. Tsang, R. Nair, and X.-M. Lu, "Quantum theory of superresolution for two incoherent optical point sources," Phys. Rev. X 6, 031033 (2016).

Mankei Tsang and Rayleigh's Curse – II

Mankei Tsang's super-resolution procedure [1] is known as SPADE (SPAtial-mode DEcomposition).

It been confirmed [2-4] for transverse resolution.

What about axial resolution, which is also very important?

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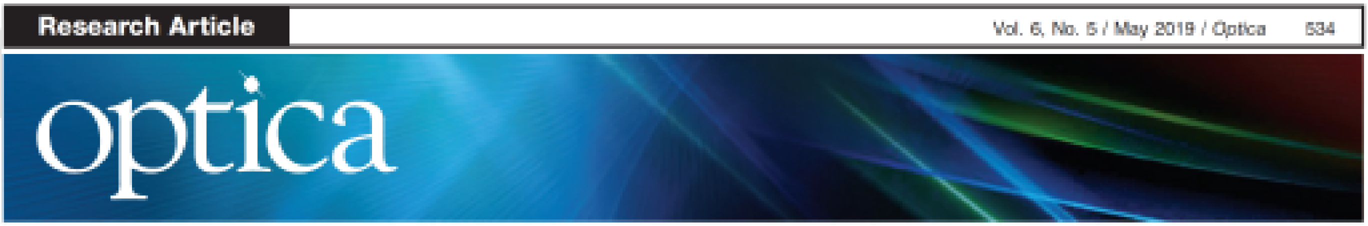
1. M. Tsang, R. Nair, and X.-M. Lu, Phys. Rev. X 6, 031033 (2016).

2. W.-K. Tham, H. Ferretti, and A. M. Steinberg, Phys. Rev. Lett. 118, 070801 (2017).

3. M. Paúr, B. Stoklasa, Z. Hradil, L. L. Sánchez-Soto, and J. Rehacek, Optica 3, 1144 (2016).

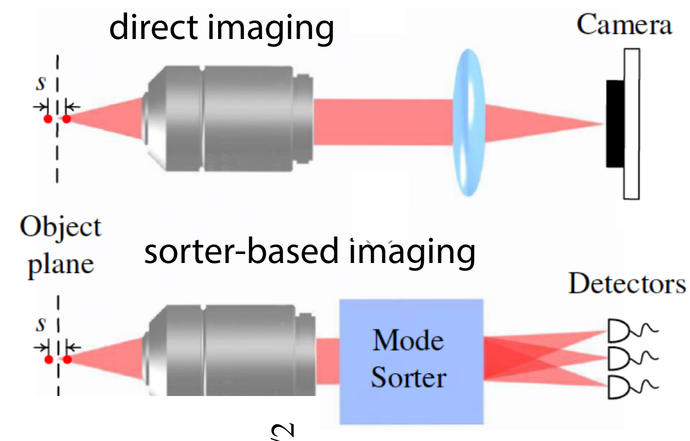
4. F. Yang, A. Tashchilina, E. S. Moiseev, C. Simon, and A. I. Lvovsky, Optica 3, 1148 (2016).


Research Article Vol. 6, No. 5 / May 2019 / Optica 534

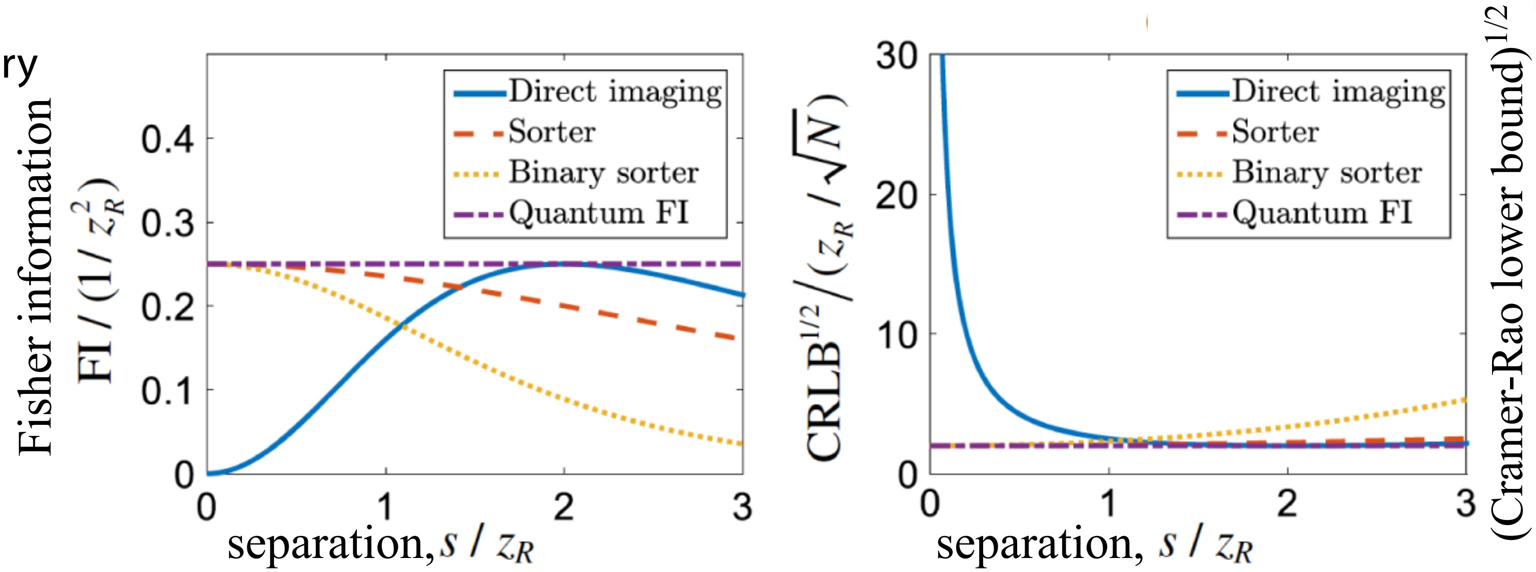
optica

Quantum-limited estimation of the axial separation of two incoherent point sources

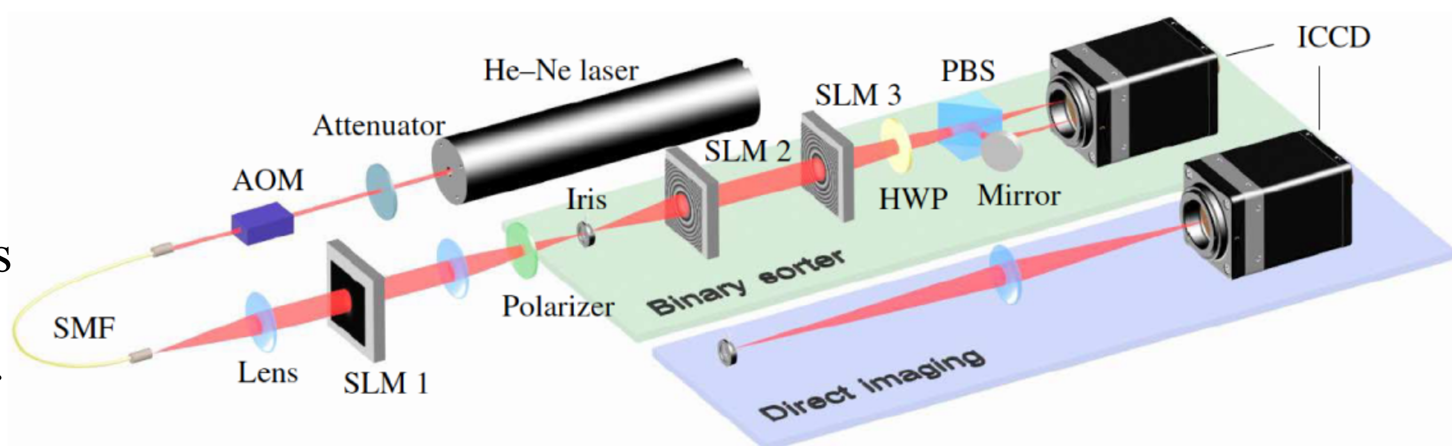
Yiyu Zhou,[1,*] Jing Yang,[2] Jeremy D. Hassett,[1] Seyed Mohammad Hashemi Rafsanjani,[3] Mohammad Mirhosseini,[4] A. Nick Vamivakas,[1,2,5] Andrew N. Jordan,[2,6] Zhimin Shi,[7,9] and Robert W. Boyd[1,2,8,10]



- Theory



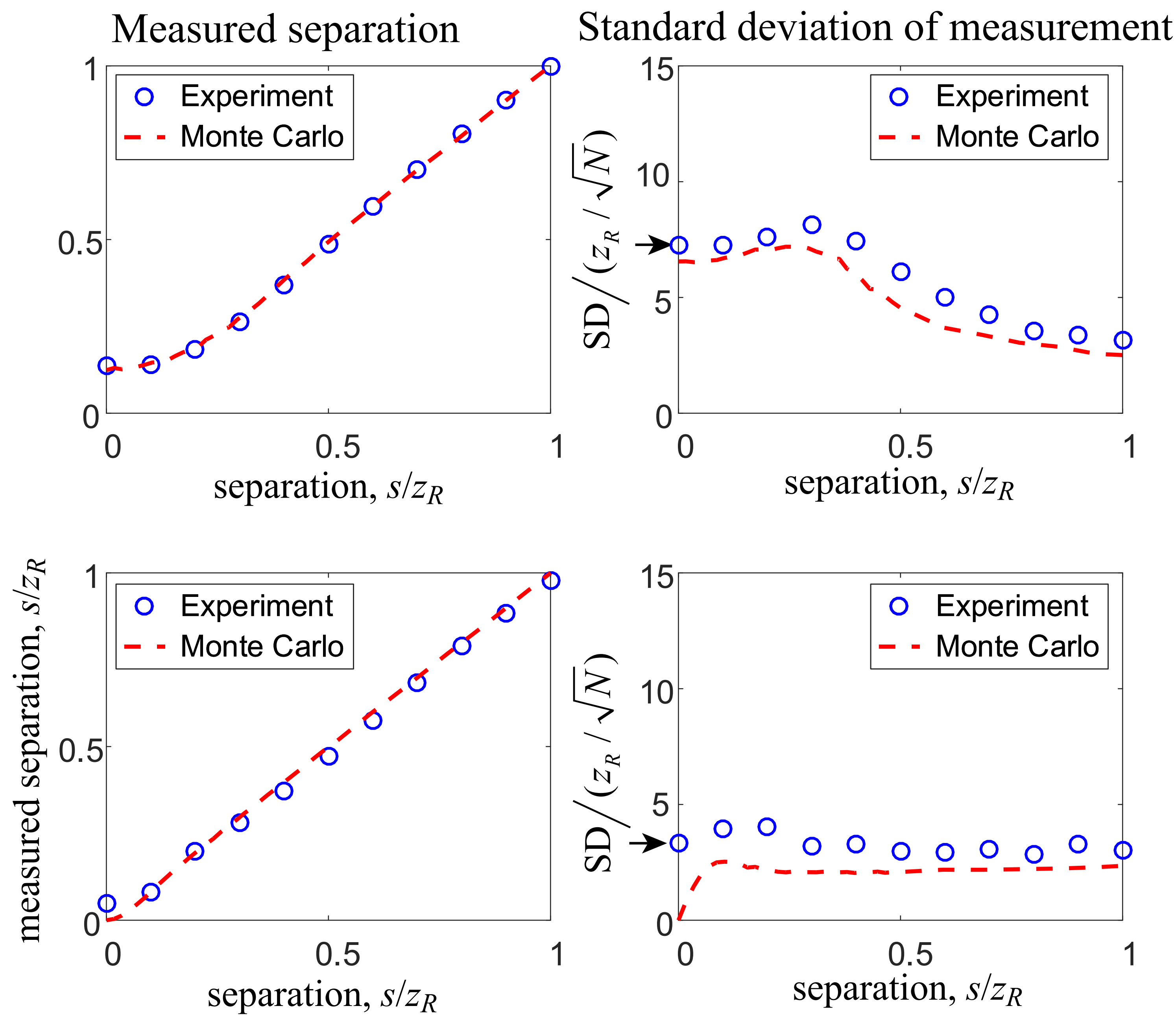
- Laboratory:
  We use a binary sorter:
- Even-order radial modes go to one port and odd-order modes to the other port.



Laboratory Results: Axial Superresolution

Direct imaging

Sorter-based imaging



- Note factor-of-two improvement in standard deviation

Mankei Tsang and Rayleigh's Curse – III

- Mankei Tsang's SPADE method can lead to a factor-of-two increased accuracy in determining the separation of two point sources.

- Can this method be applied to the task of increasing the sharpness of more complicated (natural) images?

Research Article
Vol. 29, No. 8 / 12 April 2021 / *Optics Express* 11784
Optics EXPRESS

Confocal super-resolution microscopy based on a spatial mode sorter

KATHERINE K. M. BEARNE,[1,7] YIYU ZHOU,[2,7,*] BORIS BRAVERMAN,[1] JING YANG,[3] S. A. WADOOD,[2] ANDREW N. JORDAN,[3,4] A. N. VAMIVAKAS,[2,3,5] ZHIMIN SHI,[6] AND ROBERT W. BOYD[1,2,3]

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[2] *The Institute of Optics, University of Rochester, Rochester, New York 14627, USA*
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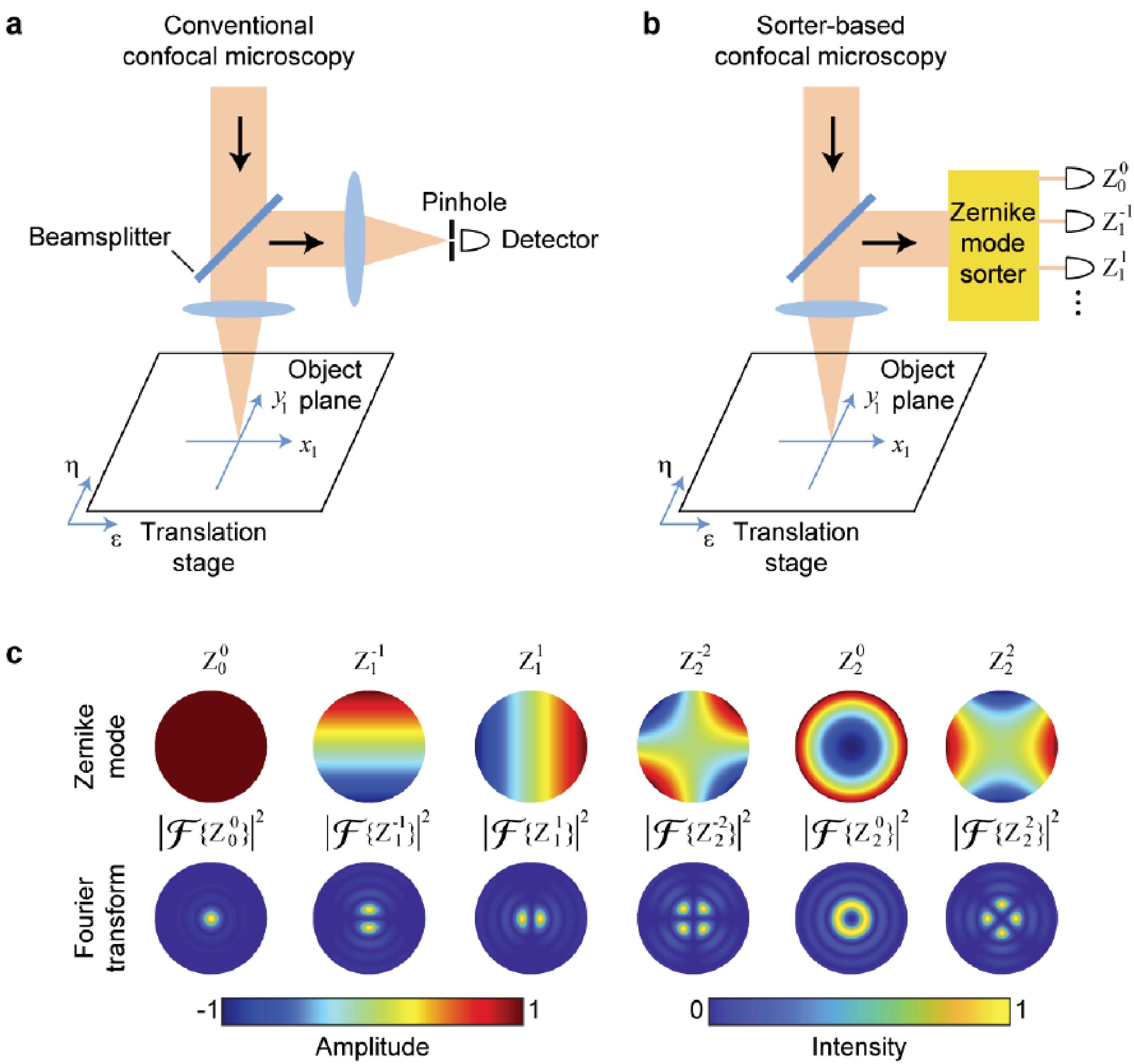
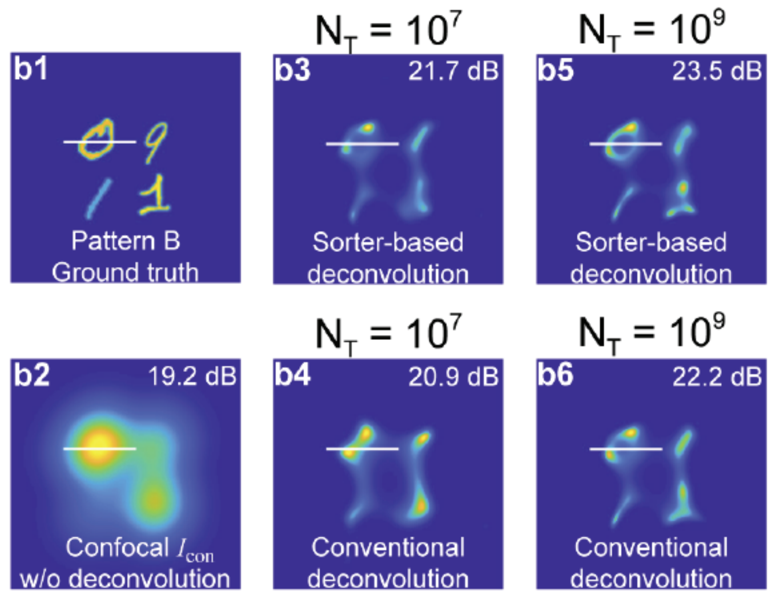
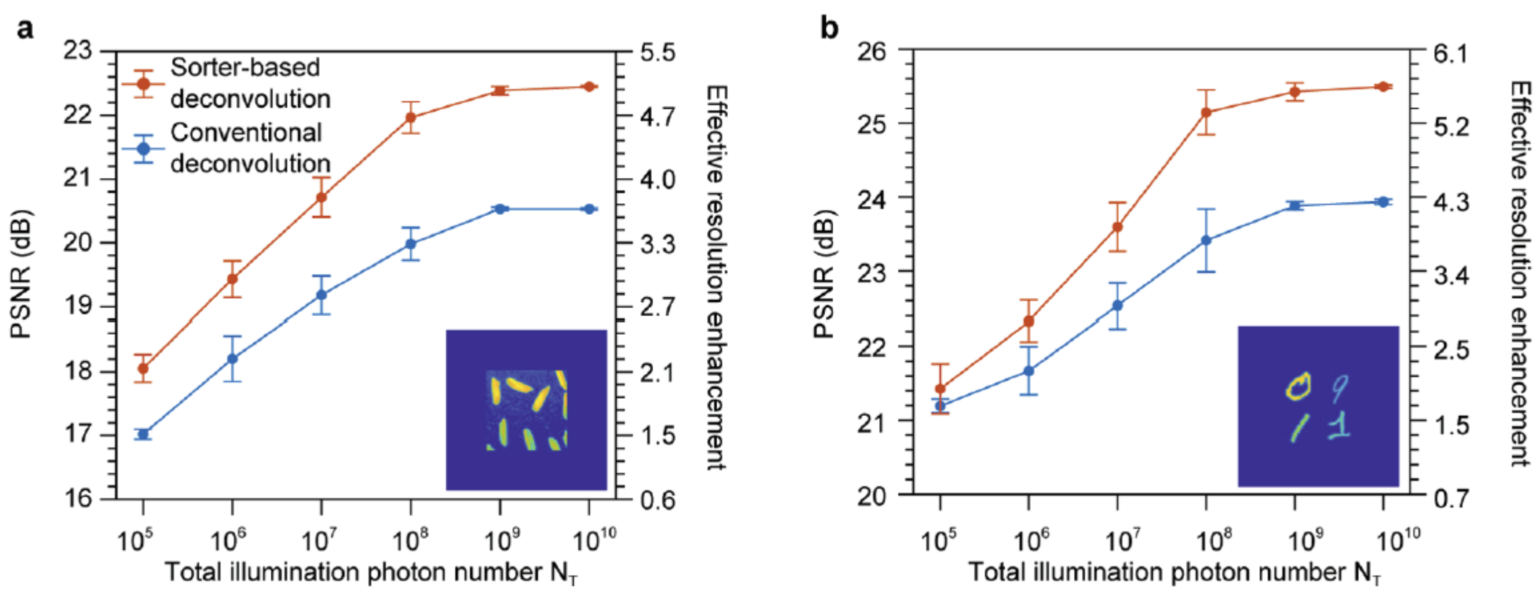
[5] *Materials Science Program, University of Rochester, Rochester, New York 14627, USA*
[6] *Department of Physics, University of South Florida, Tampa, Florida 33620, USA*
[7] *These authors contributed equally*
[*] *yzhou62@ur.rochester.edu*

Our Experimental Procedure



Some Experimental Results





Quantum Imaging Outline

Introduction to Quantum Imaging

Quantum Superresolution

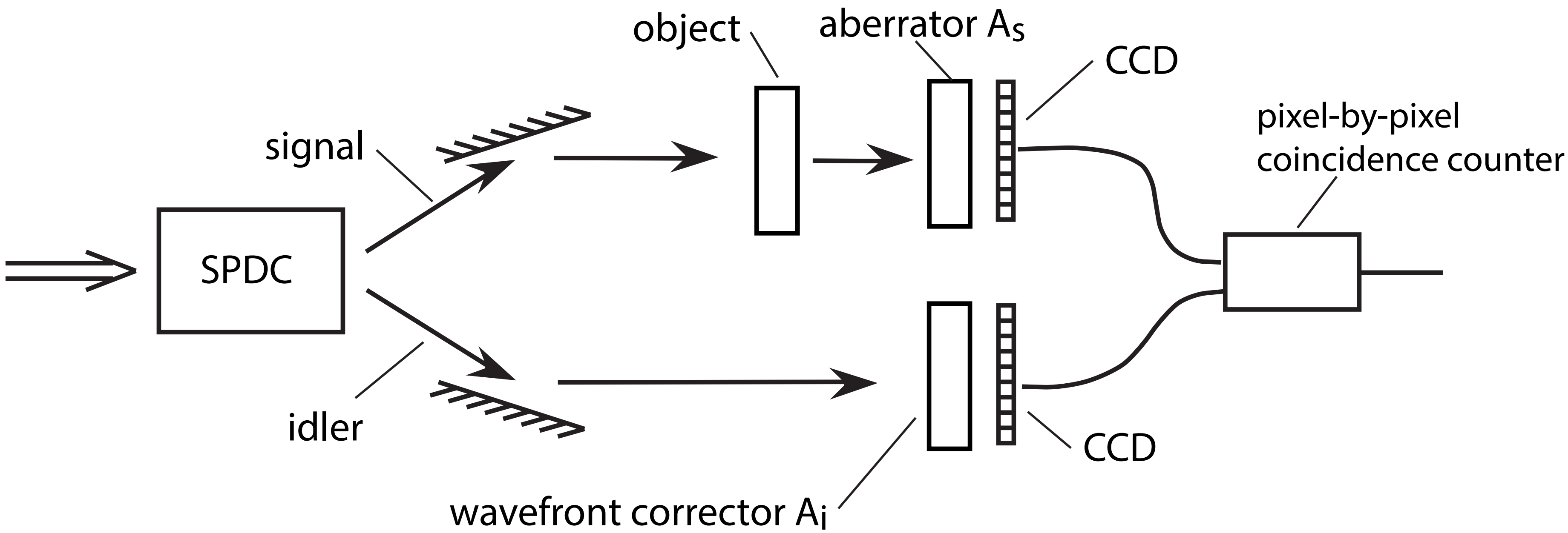
Quantum, Nonlocal Aberration Correction

Quantum Ghost Imaging

Nonlocal Quantum Aberration Correction

- Can a wavefront corrector in the idler path correct for aberrations in the signal path? (When measured in coincidence.)

(This is what we mean by “nonlocal” in the present context.)



Nonlocal Quantum Aberration Correction

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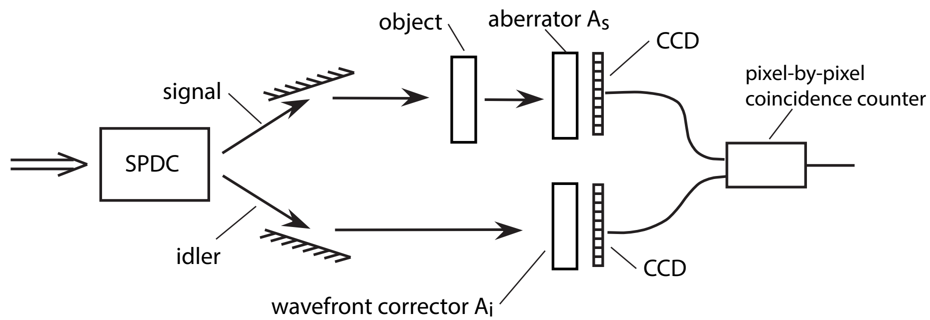


- This situation is reminiscent of Franson's dispersion cancellation, in the time domain.

- Recall strong similarity between time and spatial domains

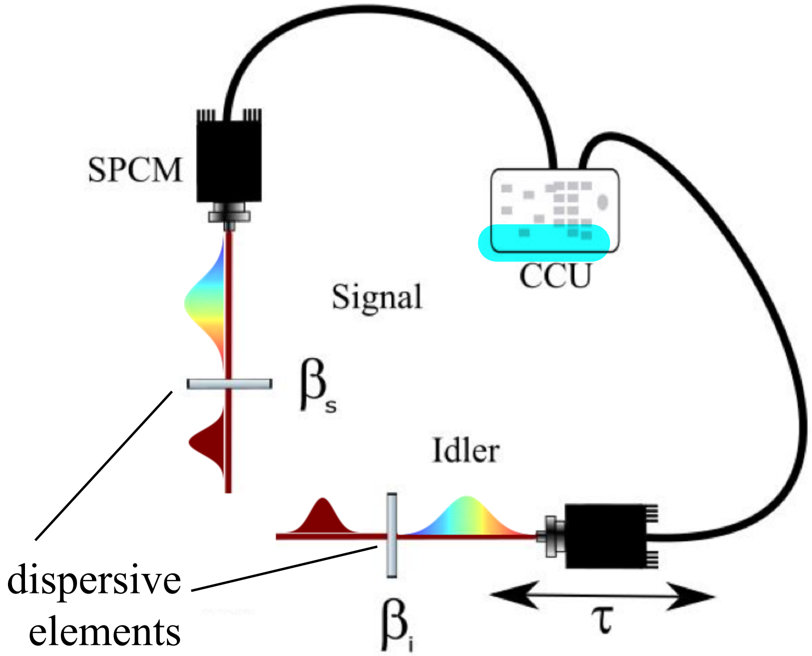
time domain: $$\frac{\partial \tilde{A}_s}{\partial z} + \frac{1}{2} i k_2 \frac{\partial^2 \tilde{A}_s}{\partial \tau^2} = i\gamma |\tilde{A}_s|^2 \tilde{A}_s.$$

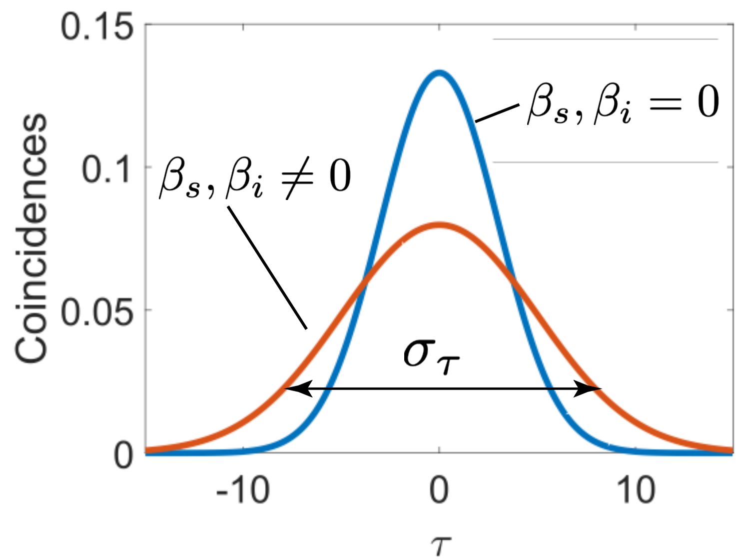
spatial domain: $$2ik_0 \frac{\partial A}{\partial z} + \frac{\partial^2 A}{\partial x^2} = -3\chi^{(3)} \frac{\omega^2}{c^2} |A|^2 A$$

- Let's remind ourselves about Franson's dispersion cancellation.

Nonlocal Dispersion Cancellation

- Laboratory setup





$$k_j(\omega) = k_{j,0} + \alpha_j(\omega_j - \omega_0) + \beta_j(\omega_j - \omega_0)^2 + \cdots$$

$1/v_g(\omega_0)$ — GVD parameter, $(d/d\omega)[1/v_g(\omega)]$

classical result

$$\sigma_\tau^2 = \frac{2\,\sigma_0^4 + (\beta_s^2 + \beta_i^2)\,x^2}{\sigma_0^2}$$

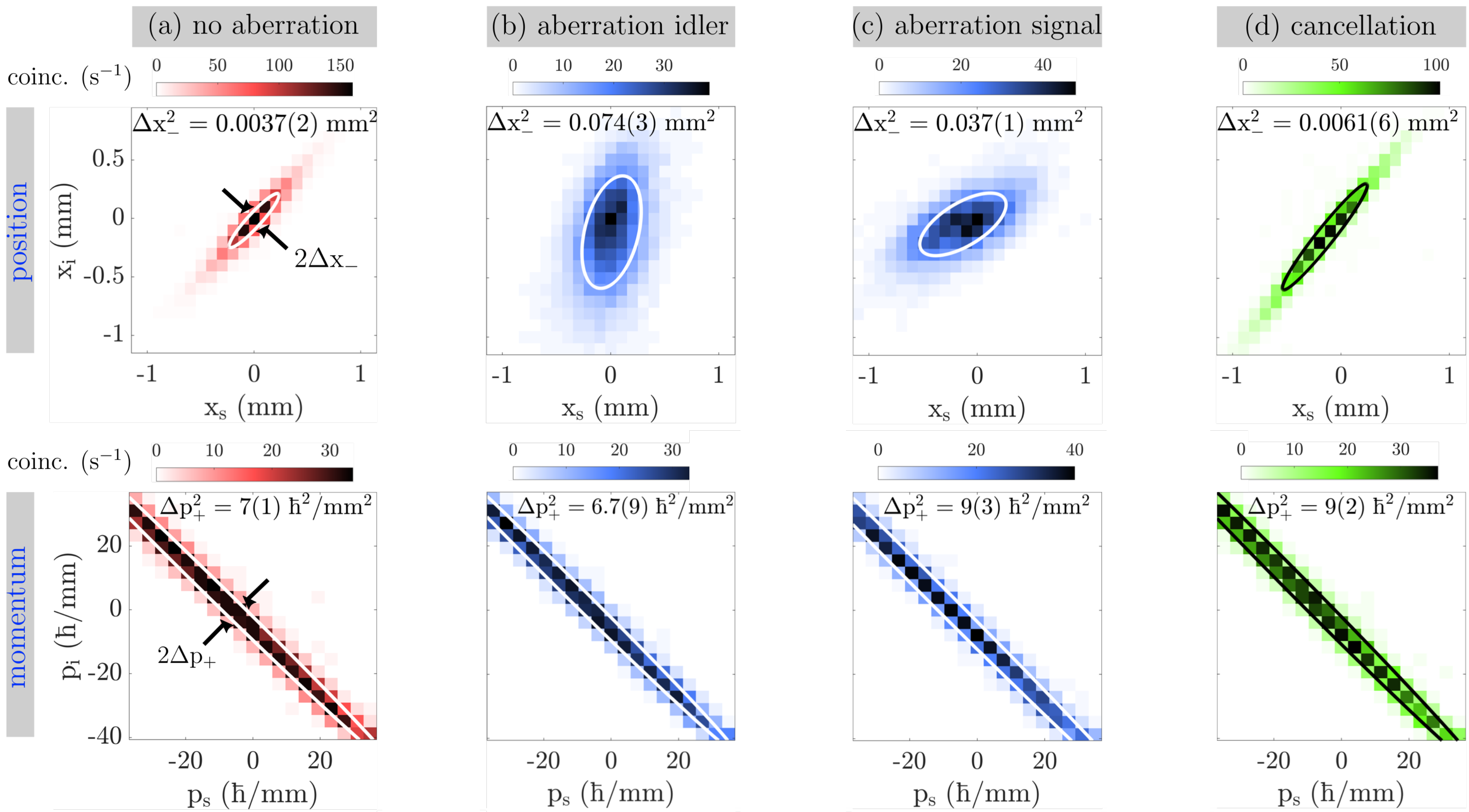
quantum result

$$\sigma_T^2 = \frac{4\,\sigma_0^4 + (\beta_s + \beta_i)^2\,x^2}{2\,\sigma_0^2}$$

- Our experiment is similar, but in the spatial domain.
- We replace the dispersive elements with wavefront aberrators and measure the distortion of the pulse transverse profile.

J. D. Franson, Phys. Rev. A 45, 3126 (1992).

Laboratory Results

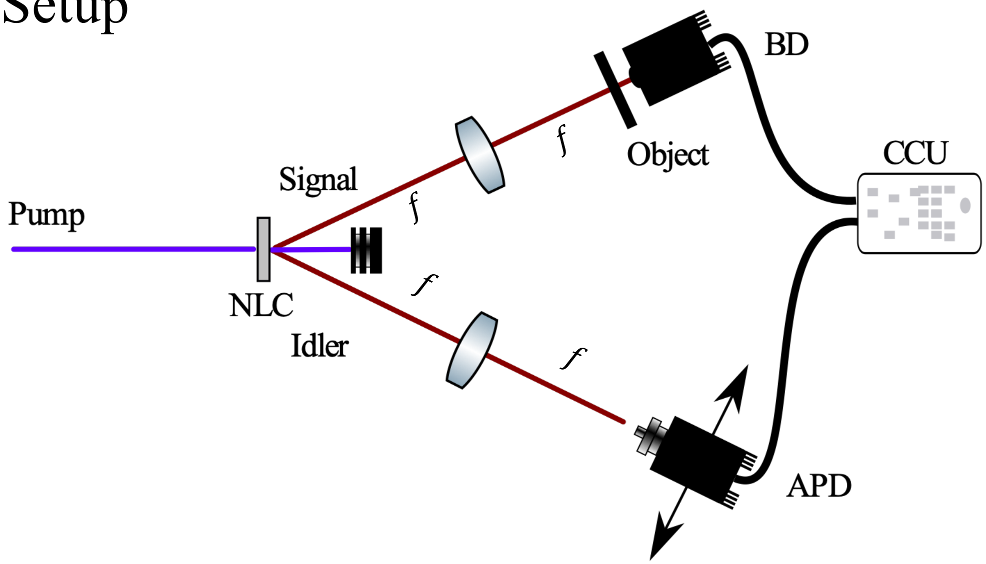


	(a)	(b)	(c)	(d)
$\phi_s''(0)$	0	0	0.0104 mm^2	0.0104 mm^2
$\phi_i''(0)$	0	-0.0104 mm^2	0	-0.0104 mm^2
$\Delta x_-^2 \Delta p_+^2$	0.026(4) $\hbar^2$	0.50(7) $\hbar^2$	0.3(1) $\hbar^2$	0.05(1) $\hbar^2$

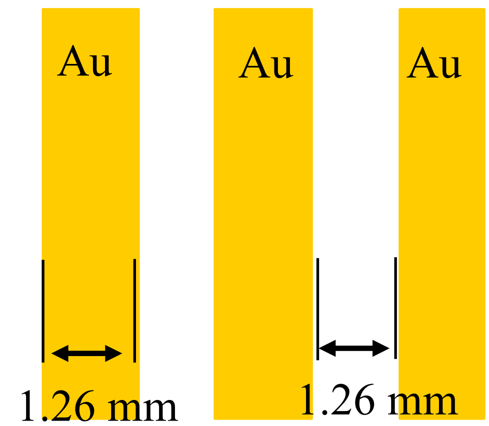
$(\Delta x_-)^2(\Delta p_+)^2 < \hbar^2/4$ Mancini criterion for entanglement (PRL 88, 120401 (2002)).

Nonlocal Aberration Cancellation for a Real Object

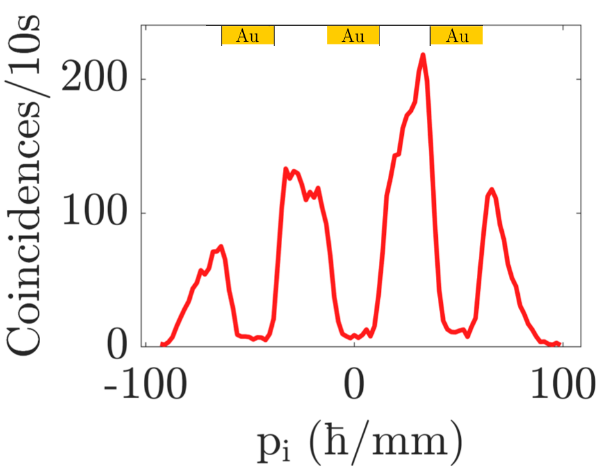
Setup



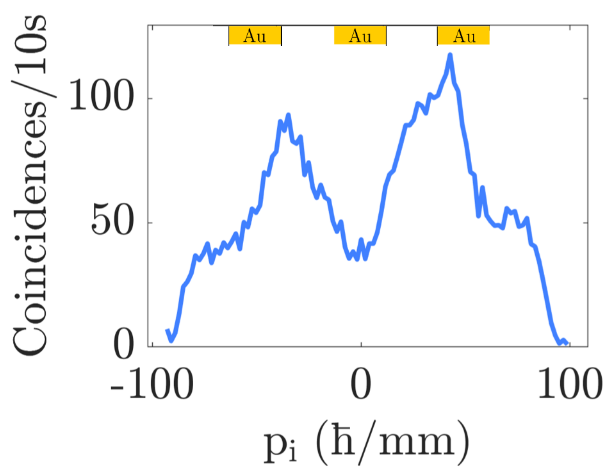
Object:



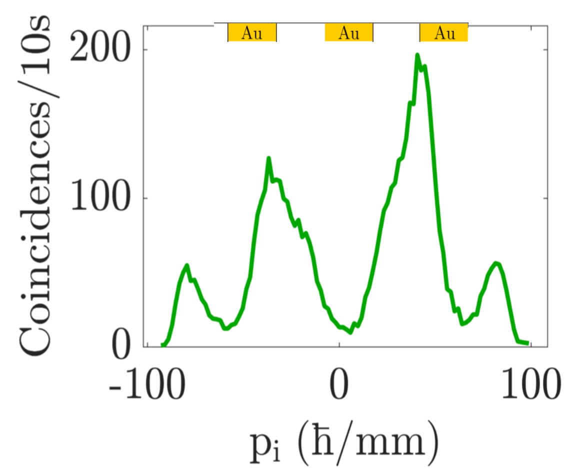
No aberrations



Aberrations in signal beam only



Aberrations compen-sated by idler beam



Earlier Work on Aberration Correction

PRL **101**, 233603 (2008) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2008

Even-Order Aberration Cancellation in Quantum Interferometry

Cristian Bonato,[1,2] Alexander V. Sergienko,[1,3] Bahaa E. A. Saleh,[1] Stefano Bonora,[2] and Paolo Villoresi[2]
[1]*Department of Electrical & Computer Engineering, Boston University, Boston, Massachusetts 02215, USA*
[2]*CNR-INFM LUXOR, Department of Information Engineering, University of Padova, Padova, Italy*
[3]*Department of Physics, Boston University, Boston, Massachusetts 02215, USA*
(Received 18 July 2008; published 2 December 2008)

→ Local, even-order only

PHYSICAL REVIEW A **84**, 043817 (2011)

Nonlocal compensation of pure phase objects with entangled photons

Simone Cialdi*
Dipartimento di Fisica dell' Università degli Studi di Milano, I-20133 Milano, Italy and INFN, Sezione di Milano, I-20133 Milano, Italy

→ Explored polarization entanglement

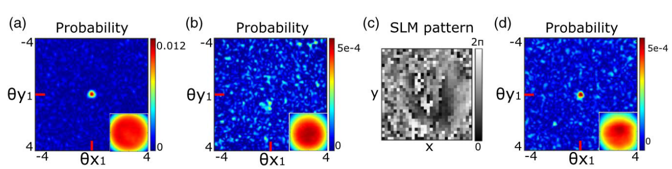
Experimental observation of aberration cancellation in entangled two-photon beams

L. A. P. Filpi, M. V. da Cunha Pereira, and C. H. Monken*
Departamento de Física, Universidade Federal de Minas Gerais, Caixa Postal 702, Belo Horizonte, MG 30123-970, Brazil

Received 5 Nov 2014; revised 18 Jan 2015; accepted 23 Jan 2015; published 9 Feb 2015
23 Feb 2015 | Vol. 23, No. 4 | DOI:10.1364/OE.23.003841 | OPTICS EXPRESS 3841

→ Local, odd-order only

H. Defienne et al., PRL, **121**, 233601 (2018)



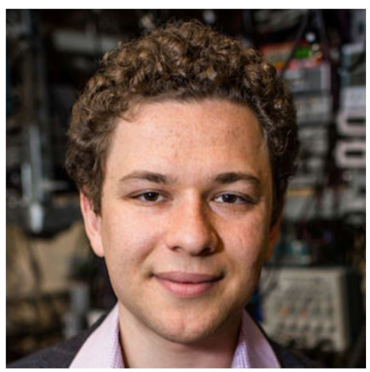
→ Local, all orders

Conclusions

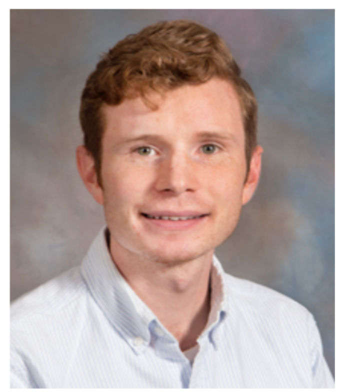
- Demonstrated effect of aberrations on transverse entanglementof photons.
- Observed simultaneous even- and odd-order nonlocal aberration cancellation.
- Quantum Nonlocal Aberration Cancellation, A. N. Black, E. Giese, B. Zollo, S. M. Barnett, and R. W. Boyd, Phys. Rev. Lett. 123, 143603(2019).

— My coauthors

Enno Giese



Boris Braverman



Nick Black

Stephen Barnett

Nicholas Zollo (not pictured)

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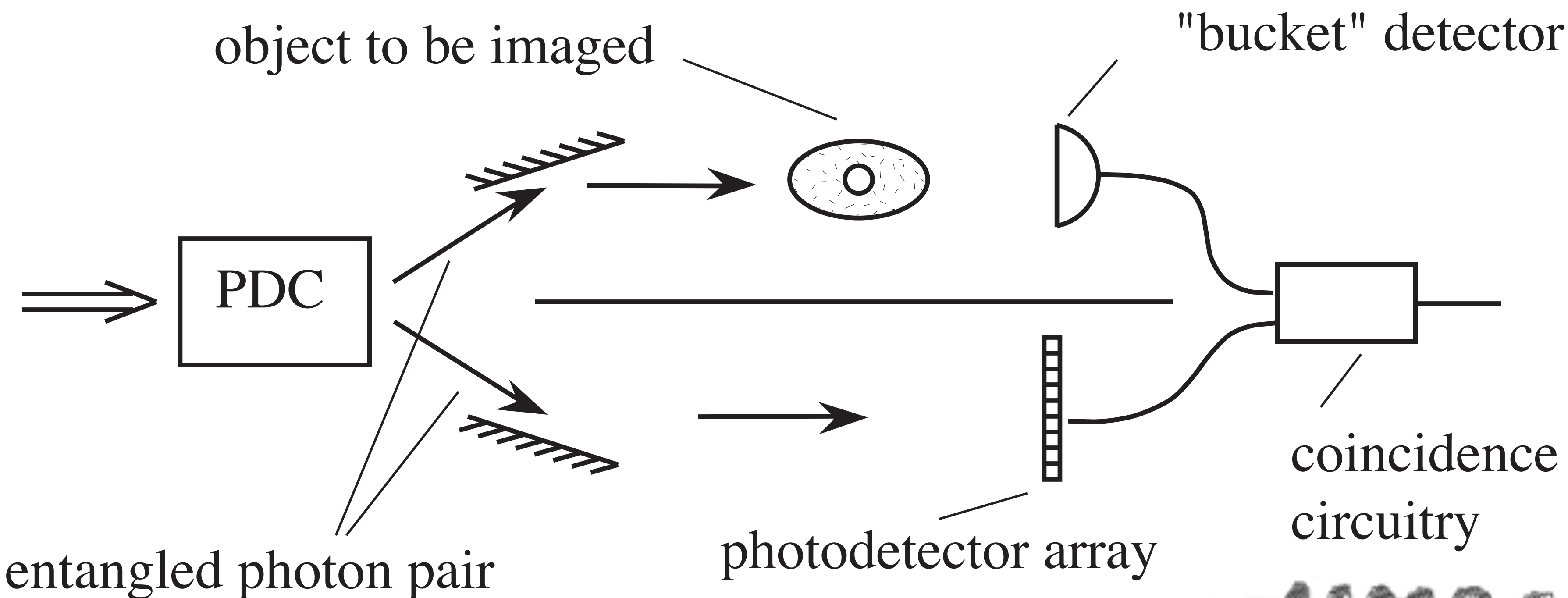
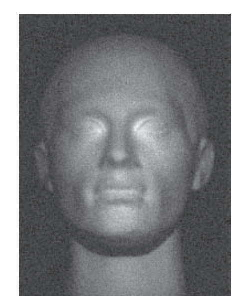
Ghost (Coincidence) Imaging



- 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

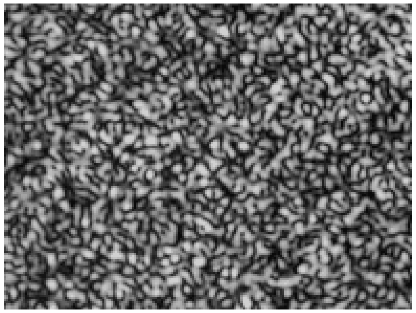
Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).

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)

Thermal Ghost Imaging

Instead of using quantum-entangled photons, one can perform ghost imaging using the correlations of a thermal light source, as predicted by Gatti et al. 2004.

Recall that the intensity distribution of thermal light looks like a speckle pattern.

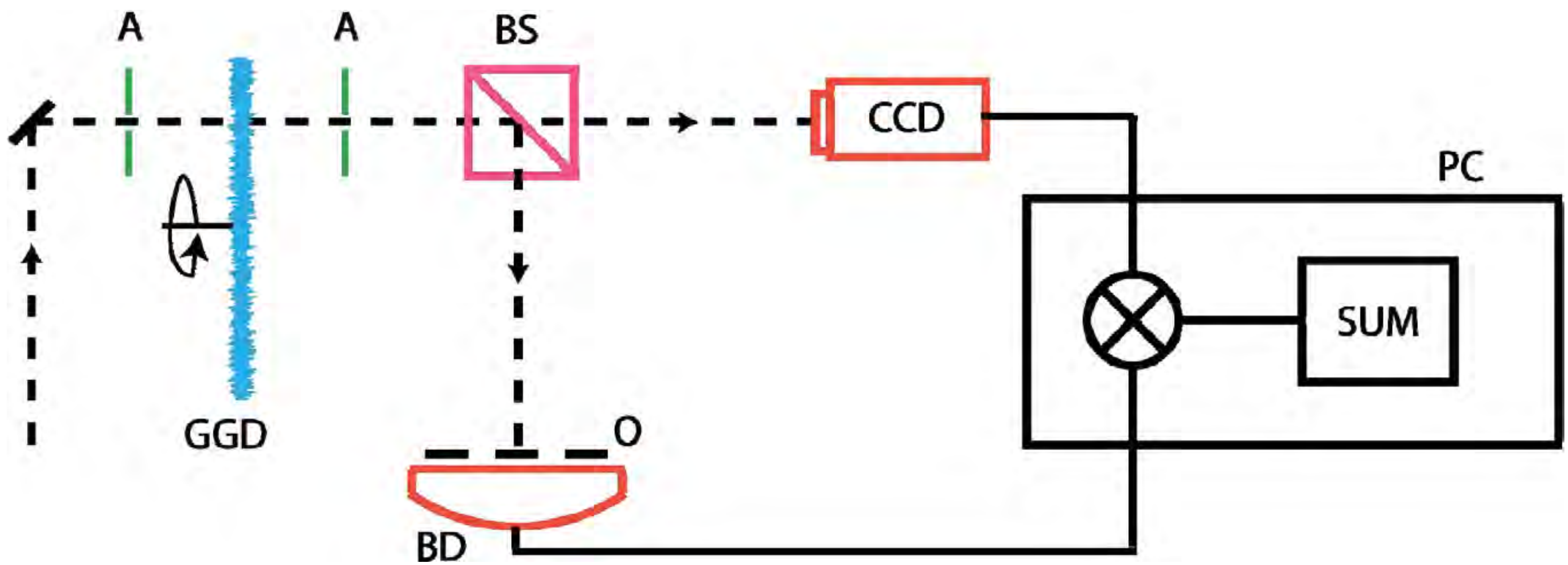


We use pseudothermal light in our studies: we create a speckle pattern with the same statistical properties as thermal light by scattering a laser beam off a rotating ground glass plate.

Thermal ghost imaging has been observed previously by several groups; our interest is in performing careful studies of its properties.

A. Gatti, E. Brambilla, M. Bache, and L. A. Lugiato, Phys. Rev. Lett. 93, 093602 (2004).

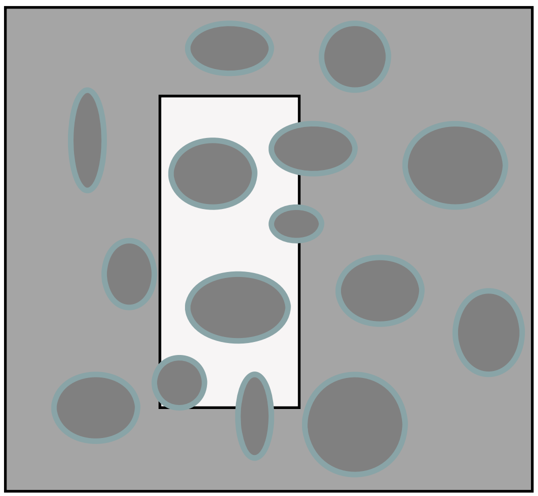
How does thermal ghost imaging work?

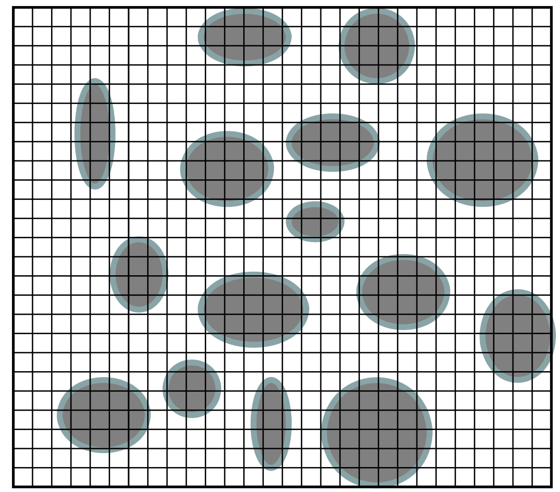


- Ground glass disk (GGD) and beam splitter (BS) create two identical speckle patterns
- Many speckles are blocked by the opaque part of object, but some are transmitted, and their intensities are summed by BD
- CCD camera measures intensity distribution of speckle pattern
- Each speckle pattern is multiplied by the output of the BD
- Results are averaged over a large number of frames.

Origin of Thermal Ghost Imaging

Create identical speckle patterns in each arm.





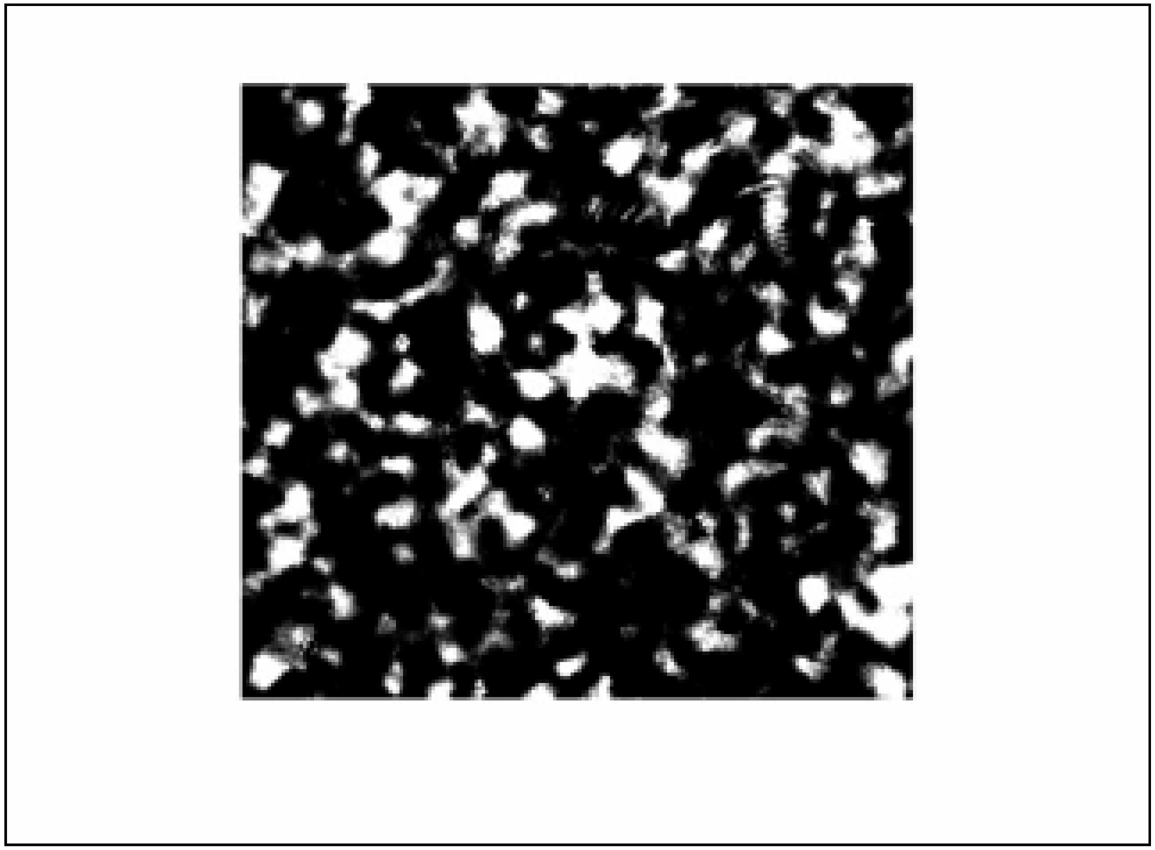
object arm
(bucket detector)

reference arm
(pixelated imaging detector)

$g_1(x,y)$ = (total transmitted power) x (intensity at each point x,y)

Average over many speckle patterns

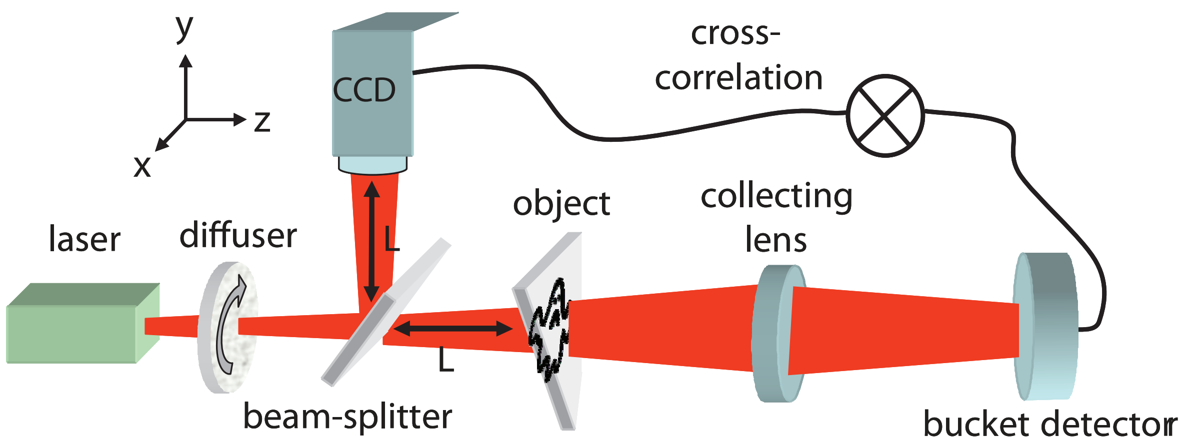
Demonstration of Image Buildup in Thermal Ghost Imaging



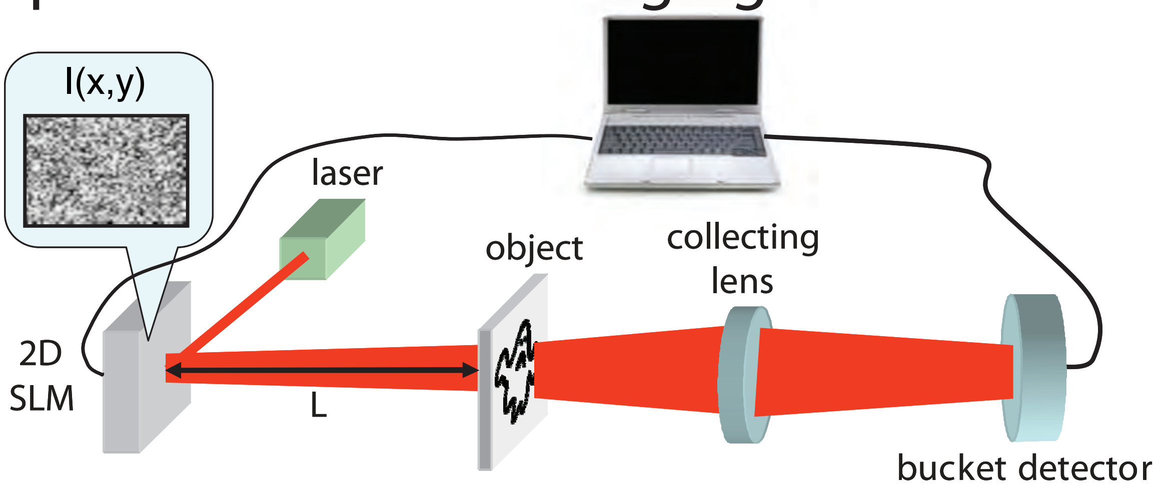
(click within window to play movie)

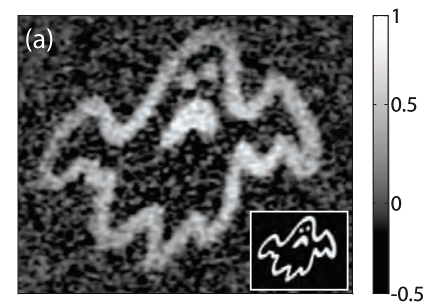
Computational Ghost Imaging

Conventional Ghost Imaging



Computational Ghost Imaging





J. H. Shapiro, Phys. Rev. A 78, 061802(R) (2008).

Y. Bromberg, O. Katz, and Y. Silberberg, Phys. Rev. A 79, 053840 (2009).

B. I. Erkmen and J. H. Shapiro, Advances in Optics and Photonics 2, 405–450 (2010)

Research in Quantum Imaging

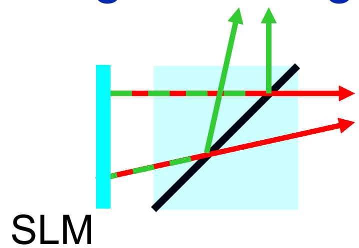
Quantum Imaging or Quantum Imogene?

Sid Caesar and
Imogene Coca in 1953

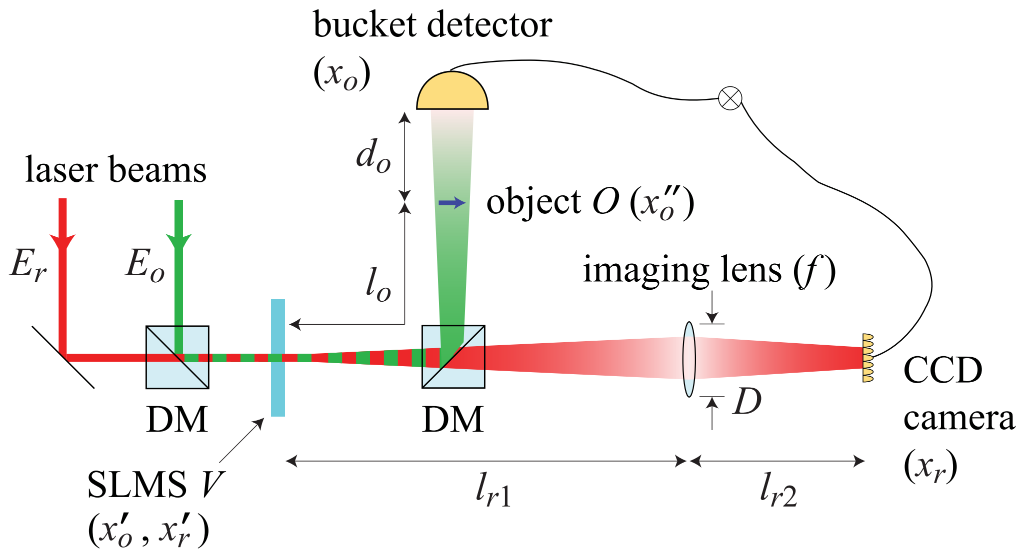
Two-Color Ghost Imaging

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

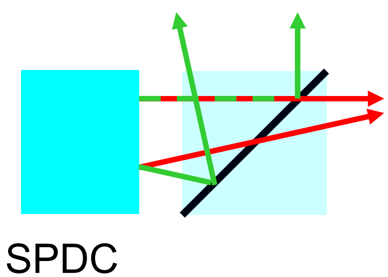
Thermal ghost imaging

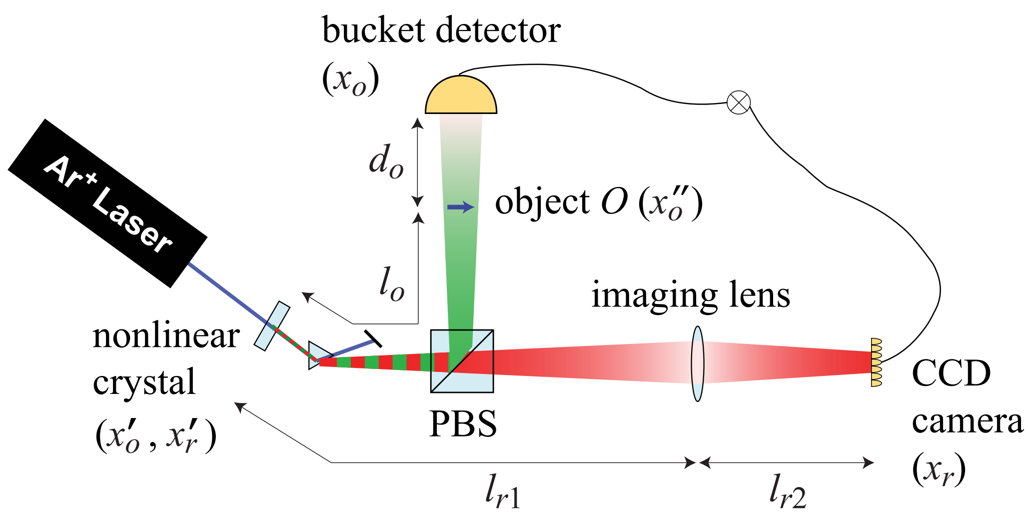


But no obvious way to make identical speckle patterns at two wavelengths



Quantum ghost imaging





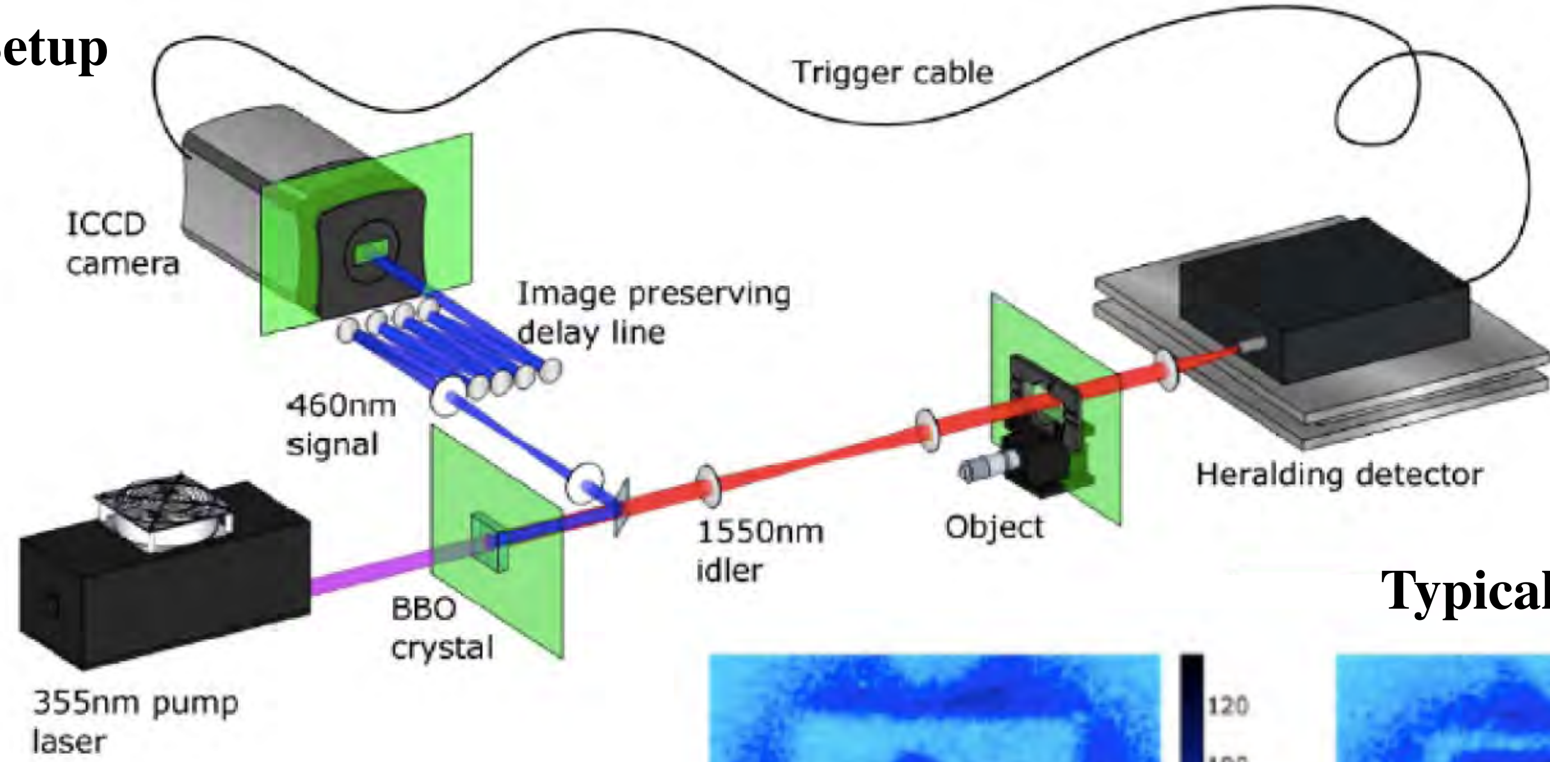
Spatial resolution depends on wavelength used to illuminate object.

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

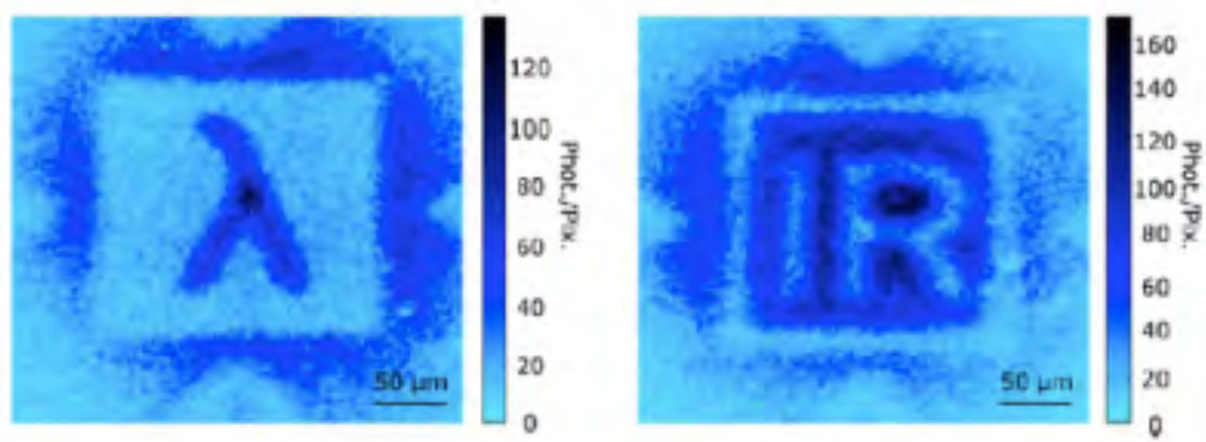
Wavelength-Shifted (Two-Color) Ghost Microscopy

- 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

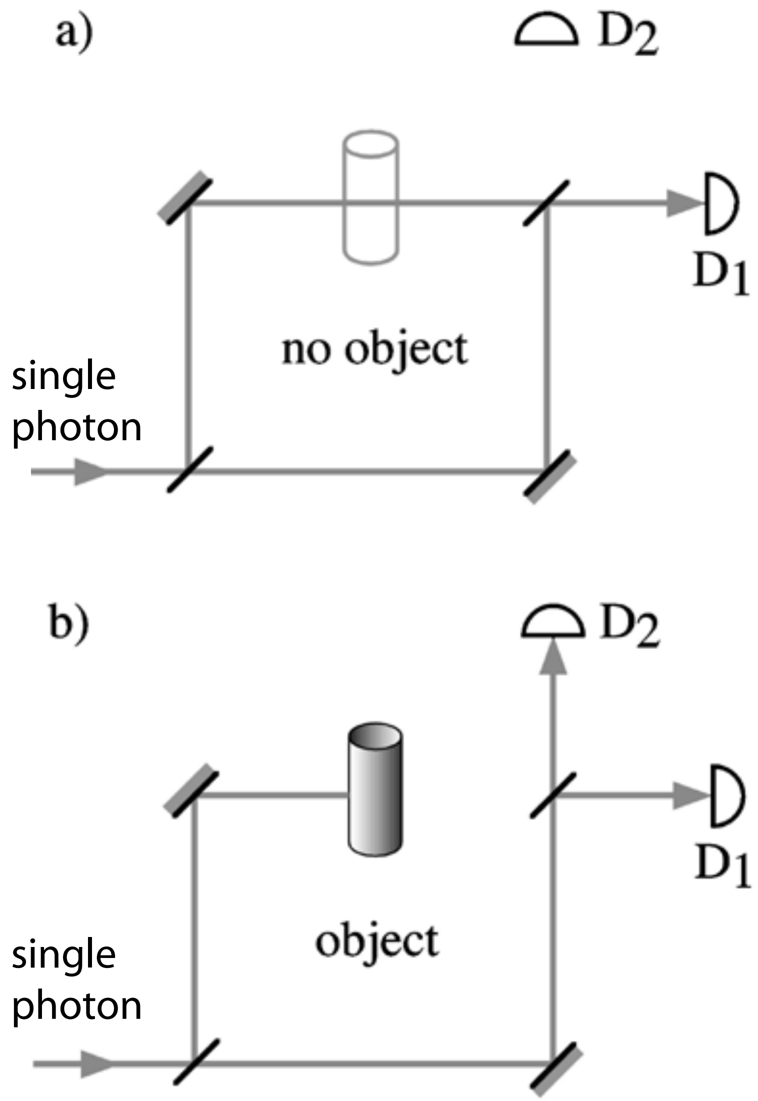


Typical images

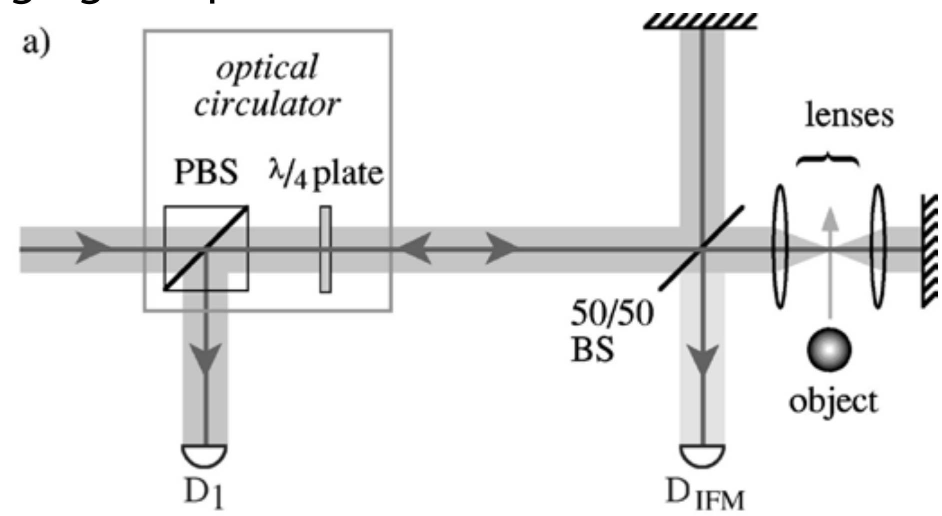


Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

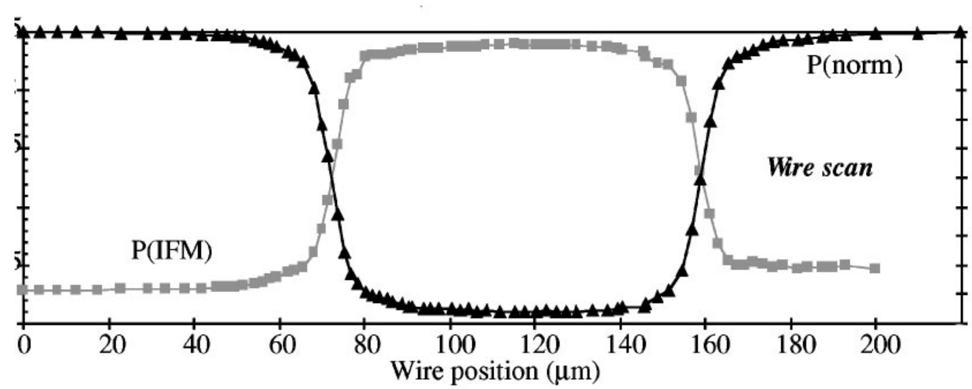
Quantum Imaging by Interaction-Free Measurement



imaging setup

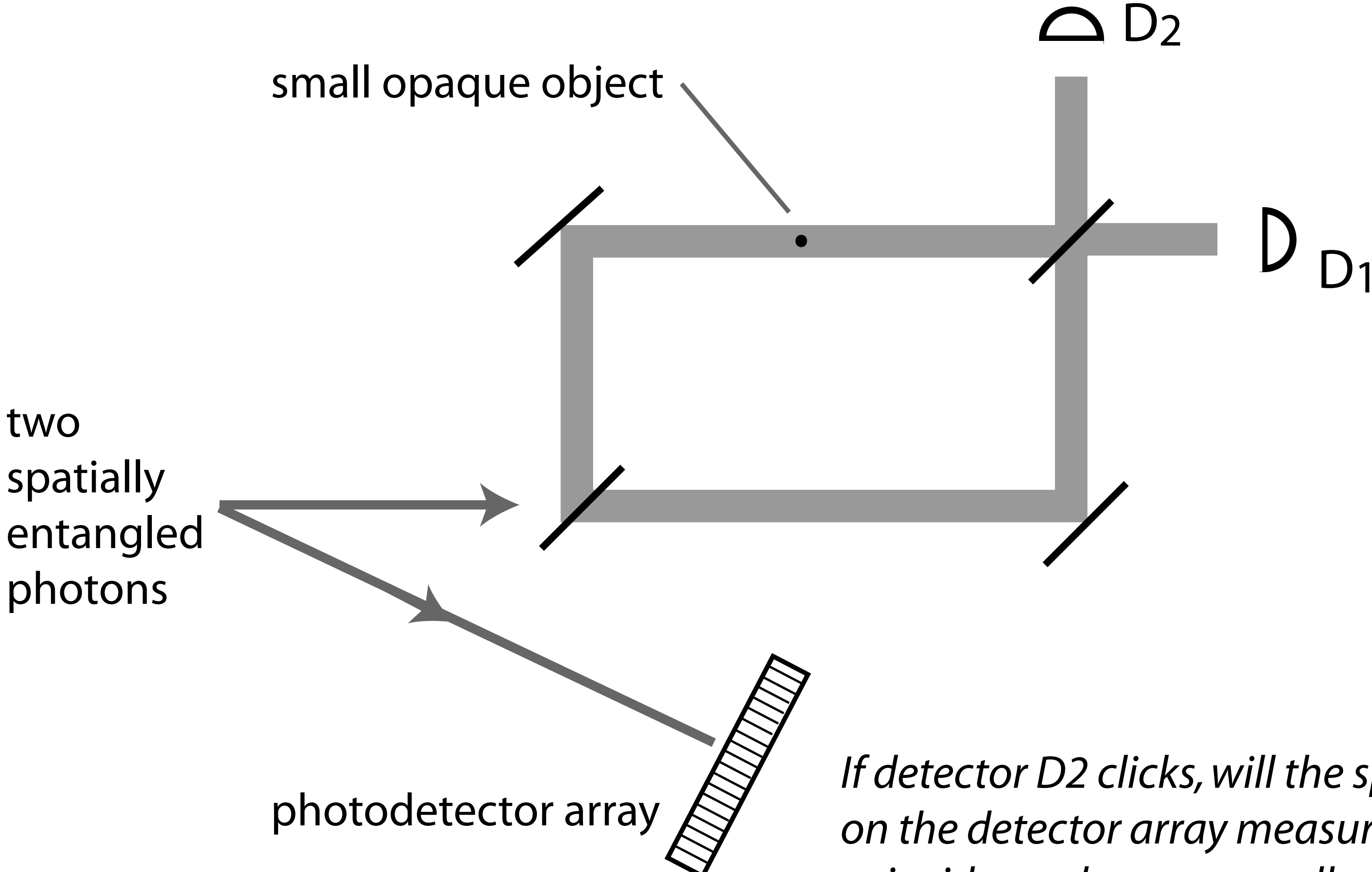


results



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



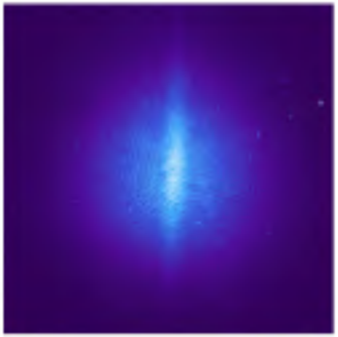
If detector D2 clicks, will the spot size on the detector array measured in coincidence become smaller?

- 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?

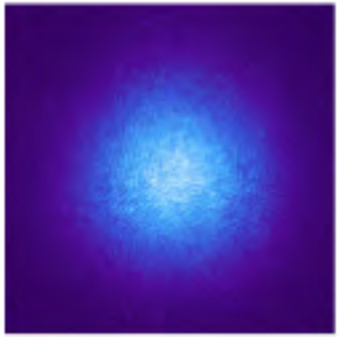
Experimental Results

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.

Zhang, Sit, Bouchard, Larocque, Grenapin, Cohen, Elitzur, Harden, Boyd, and Karimi, Optics Express 27, 2212-2224 (2019).

Is interaction-free imaging useful?

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

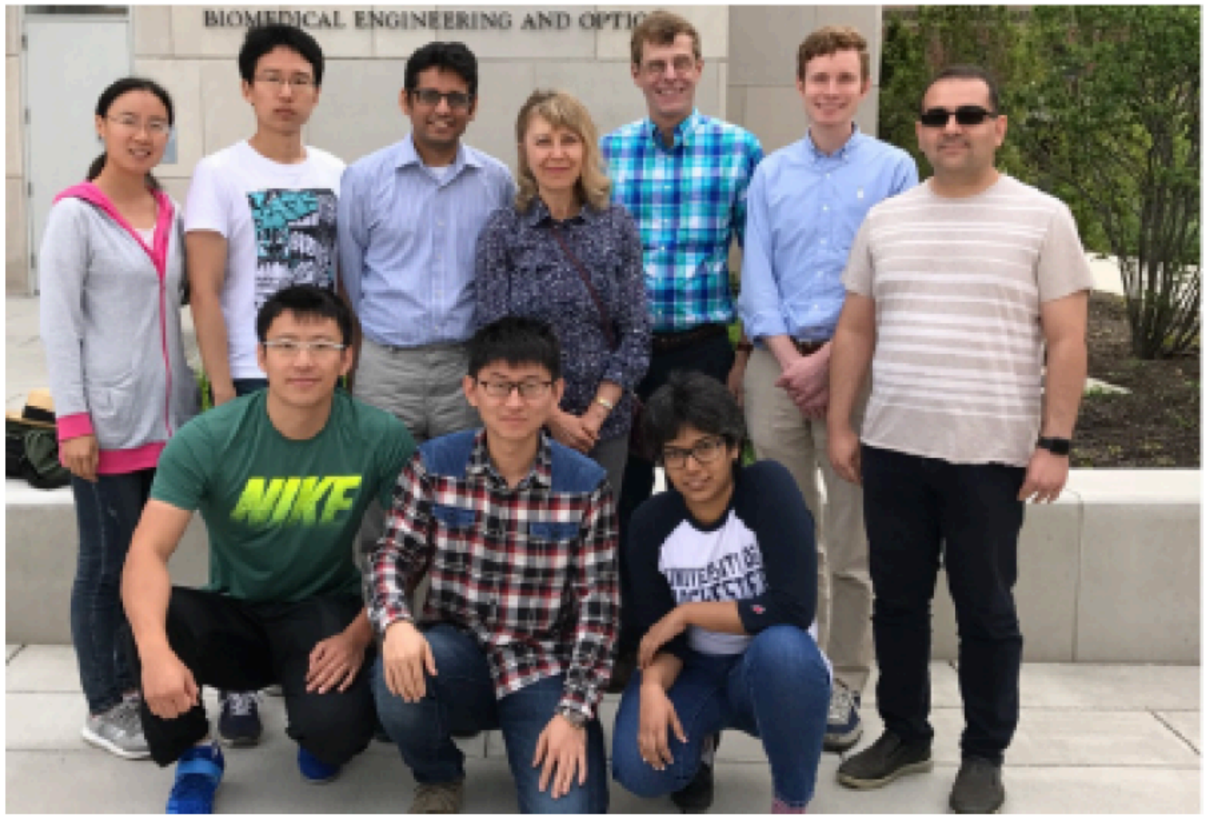
Could be extremely useful for biophysics. What does the retina look like when light does not hit it?

Thank you for your attention!

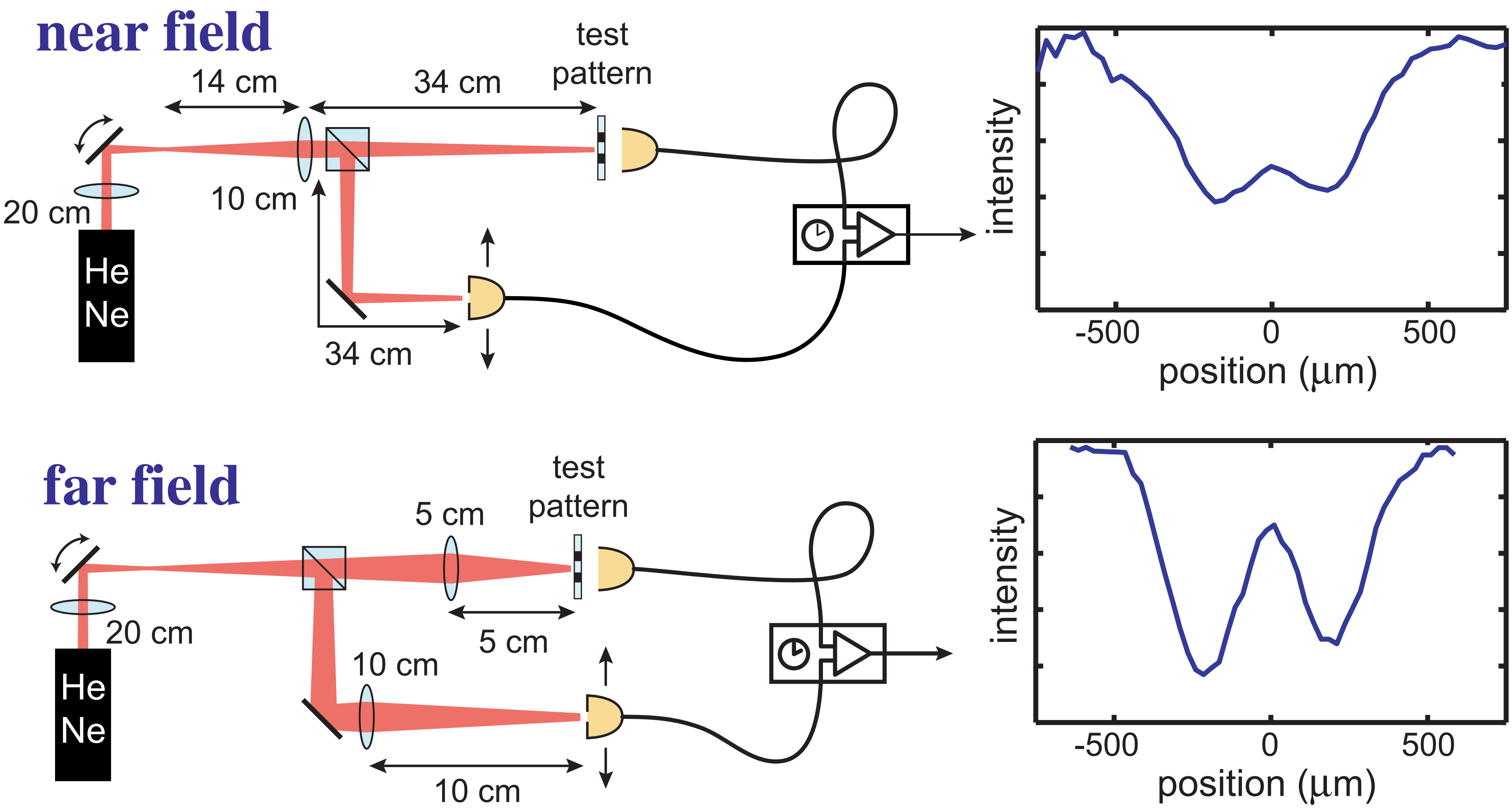
Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group



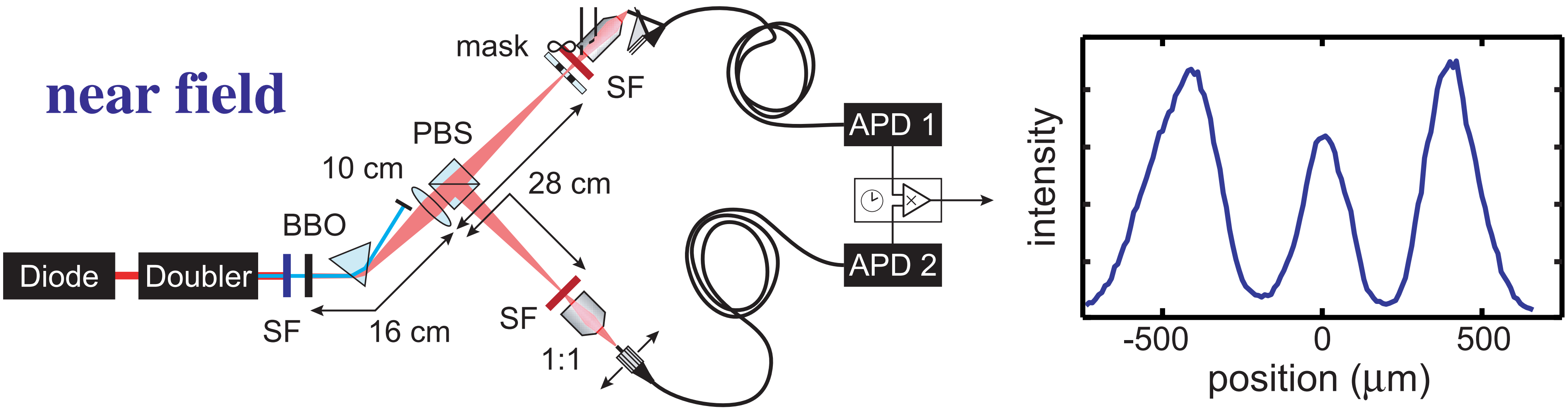
Near- and Far-Field Imaging With a Classical Source



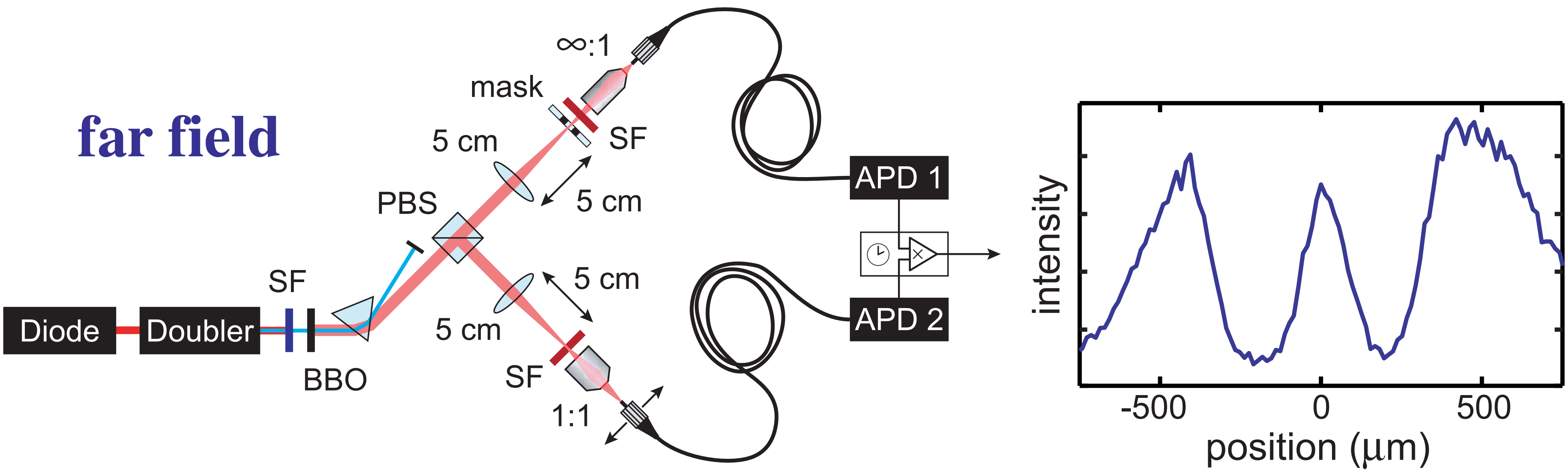
- Good imaging can be obtained only in near field **or** far field.
- Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of three.

Near- and Far-Field Imaging Using Quantum Entanglement

near field



far field



Good imaging observed in both the near and far fields.

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