Sharper Images Through Quantum Imaging

Robert W. Boyd

Department of Physics and
School of Electrical Engineering and Computer Science
University of Ottawa

The Institute of Optics and
Department of Physics and Astronomy
University of Rochester

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Quantum Imaging

- The 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 is research that seeks to exploit the quantum properties of the transverse structure of light fields

Quantum Imaging Outline

Introduction to Quantum Imaging

Quantum Superresolution

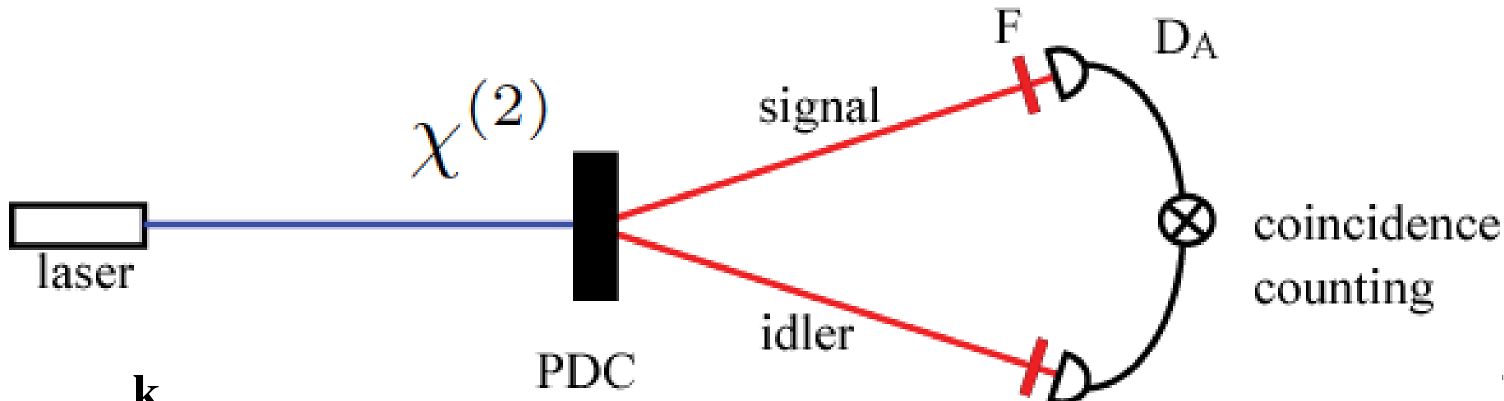
Imaging through Scattering Media

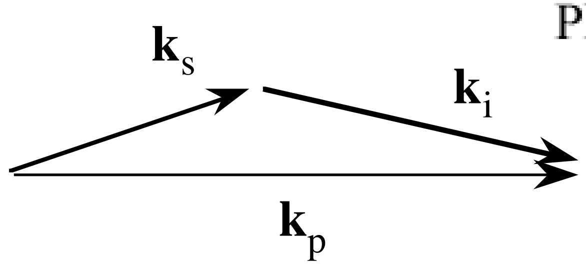
Ghost and Interaction-Free Imaging

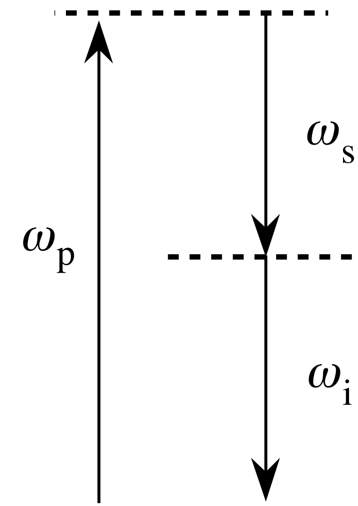
Why do we need quantum? (think of STED, etc.)

And what is "quantum"?

Parametric Downconversion: A Source of Entangled Photons







The signal and idler photons are entangled in:

(a) polarization

(b) time and energy

(c) position and transverse momentum

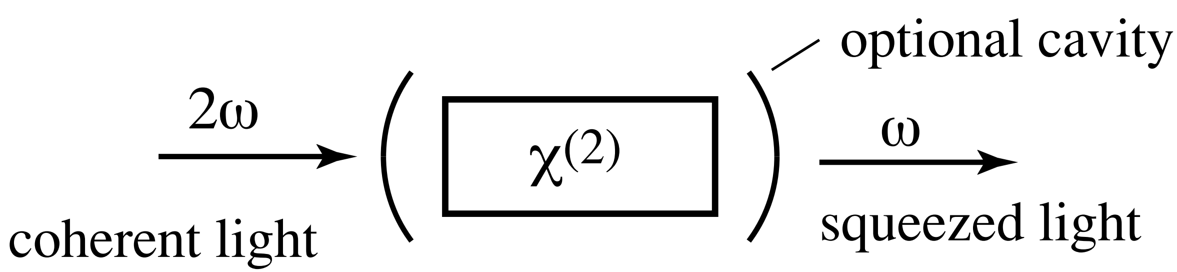
(d) angular position and orbital angular momentum

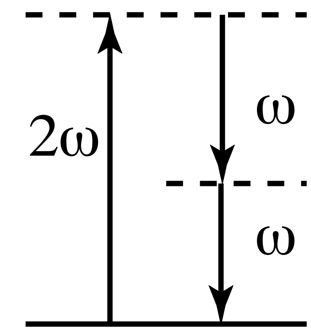
Entanglement is important for:

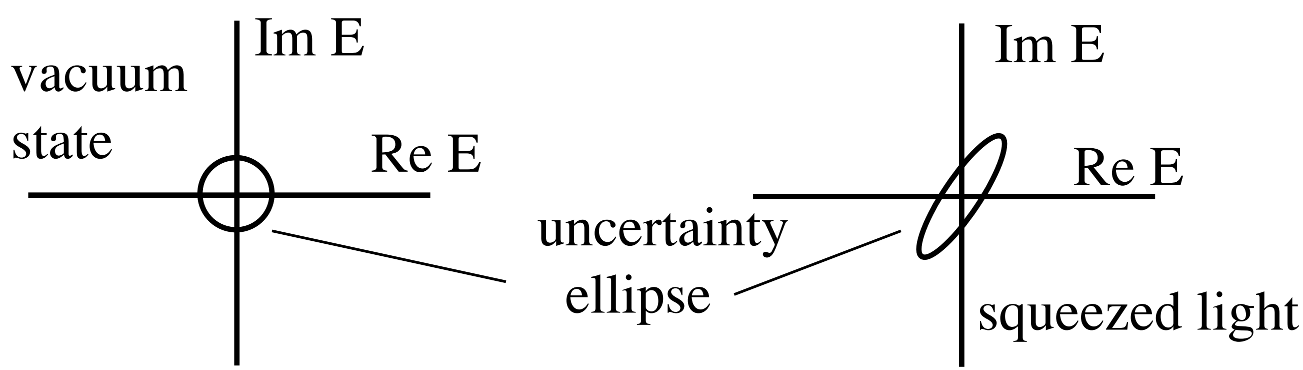
(a) Fundamental tests of QM (e.g., nonlocality)

(b) Quantum technologies (e.g., secure communications)

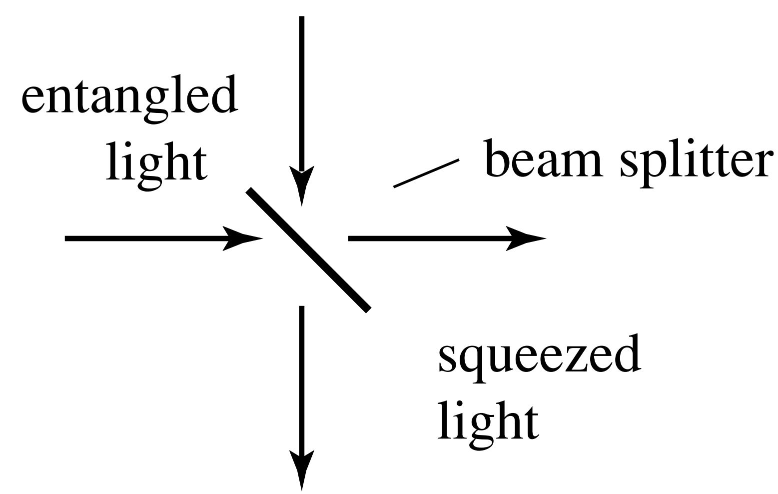
Squeezed Light Generation





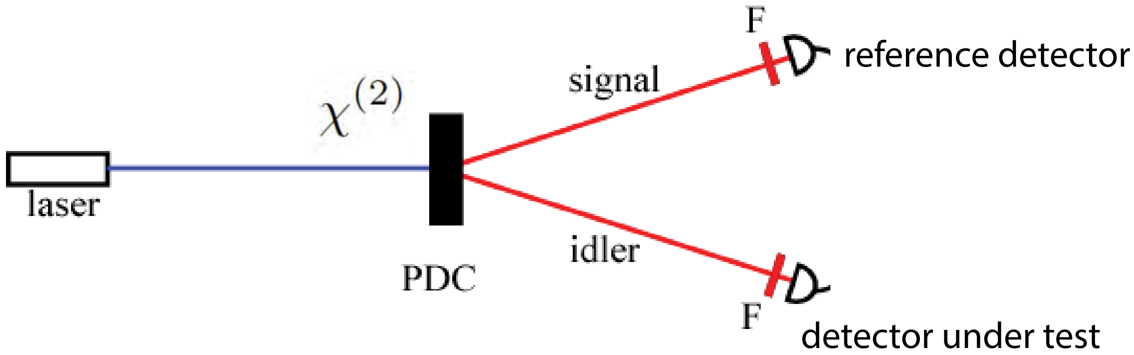


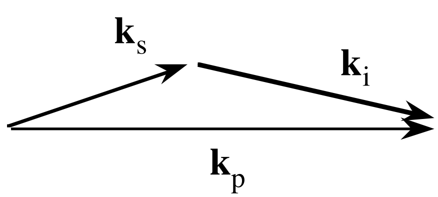
Entanglement and squeezing share a common origin. In fact:

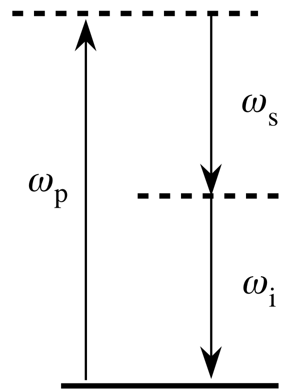


Klyshko's Method for Absolute Calibration of a Photodetector

- Absolute measurement of detector quantum efficiency (Klyshko, Sergienko, Migdall, Polyakov, etc.)





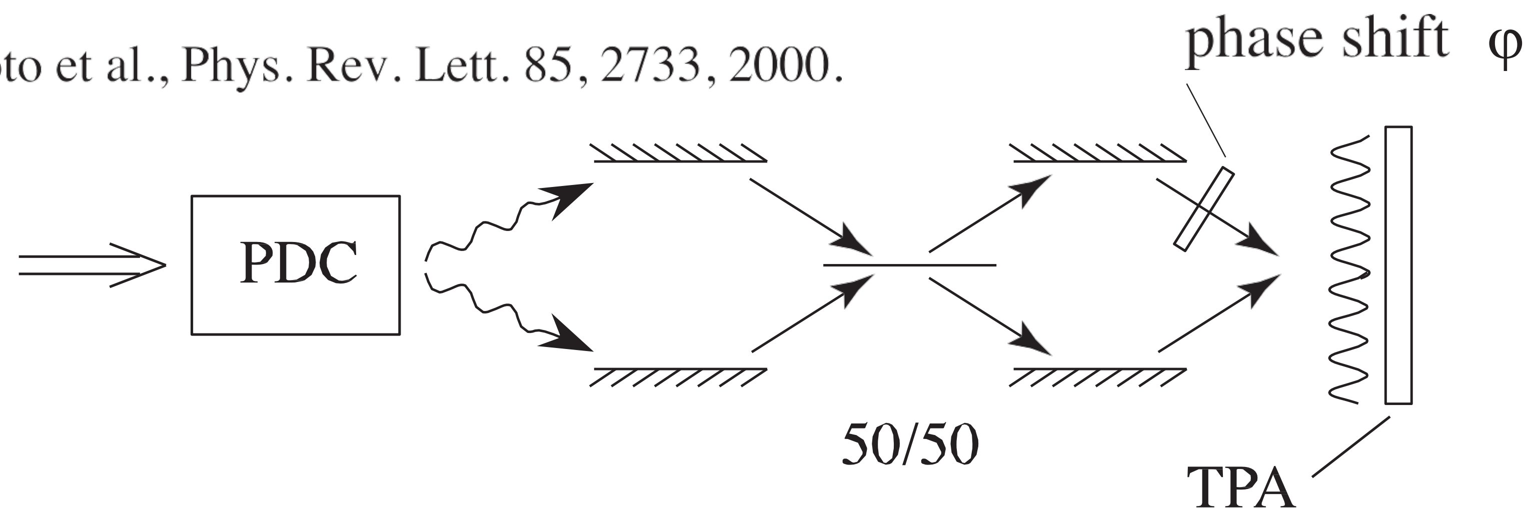


- Earlier work (Klyshko) established that the light produced by spontaneous parametric downconversion (SPDC) can be characterized in terms of the radiometric property known as brightness (or radiance).

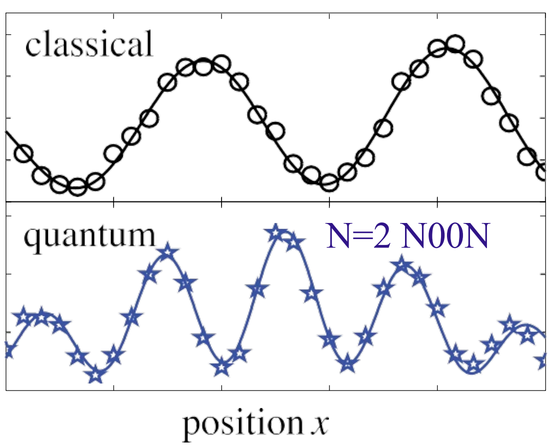
Quantum Lithography: Concept of Jonathan Dowling

- 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). Based on a proposal of M. Tsang, Phys. Rev. Lett. 102, 253601 (2009).

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

Superresolution

Superresolution

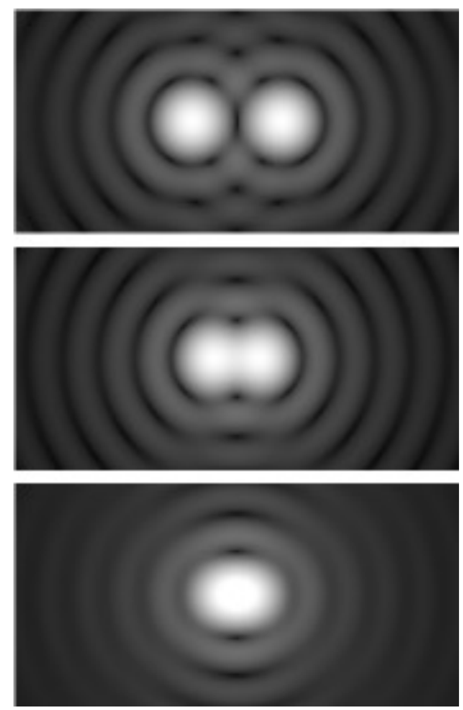
- What does quantum mechanics have to say about one's ability to achieve superresesolution?
- And what is superresolution? We will take it to mean achieving spatial resolution that exceeds the Rayleigh or Abbe criterion.

  – 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

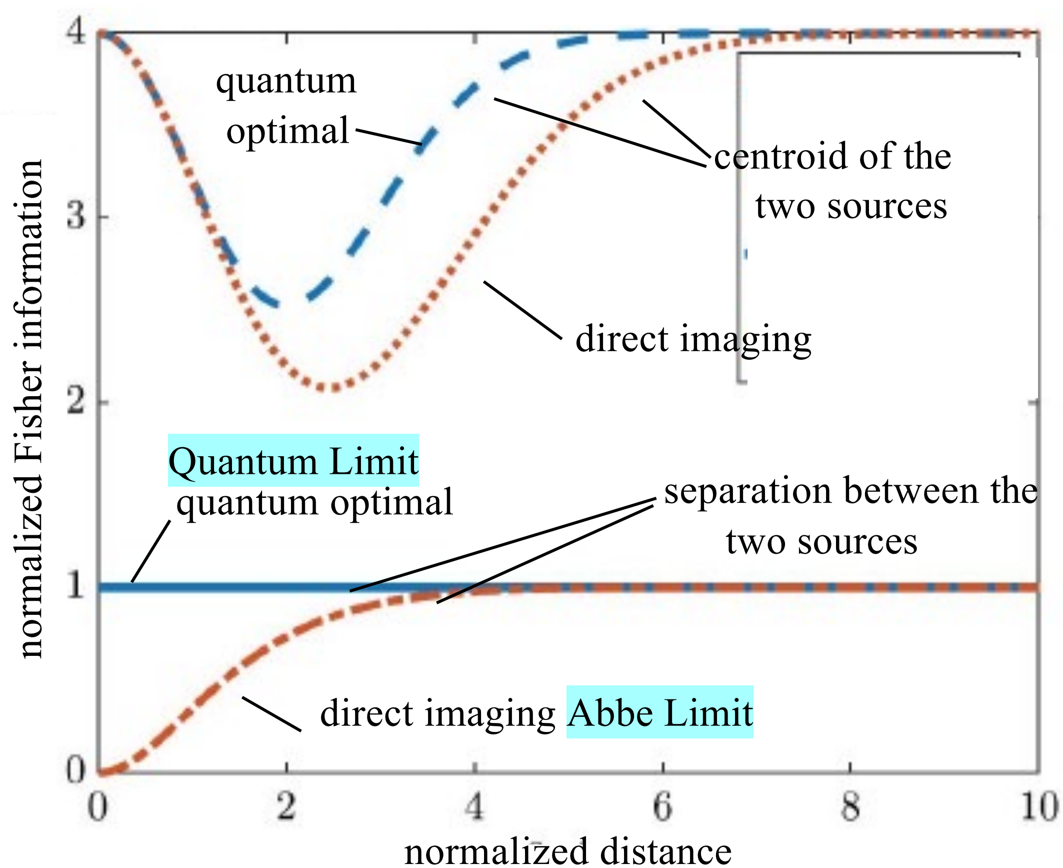
1. It is most natural to perform imaging in coordinate space, that is to measure the intensity $I(x)$ as a fuction of position.

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 (as in jpg)
   (b) techniques exist for characterizing and manipulating LG and HG modes
   (c) the mode dcomposition can be used to implement superresolution

Mankei Tsang and Rayleigh's Curse

- Mankei Tsang and coworkers speak of Rayleigh's curse as the belief that the 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 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.

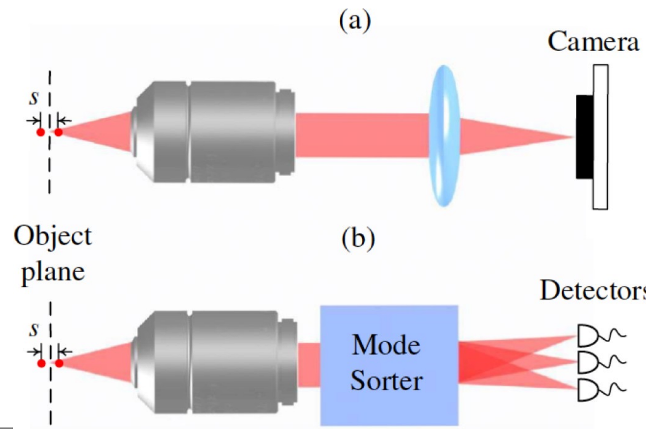
What about axial resolution, which is also very important?

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).

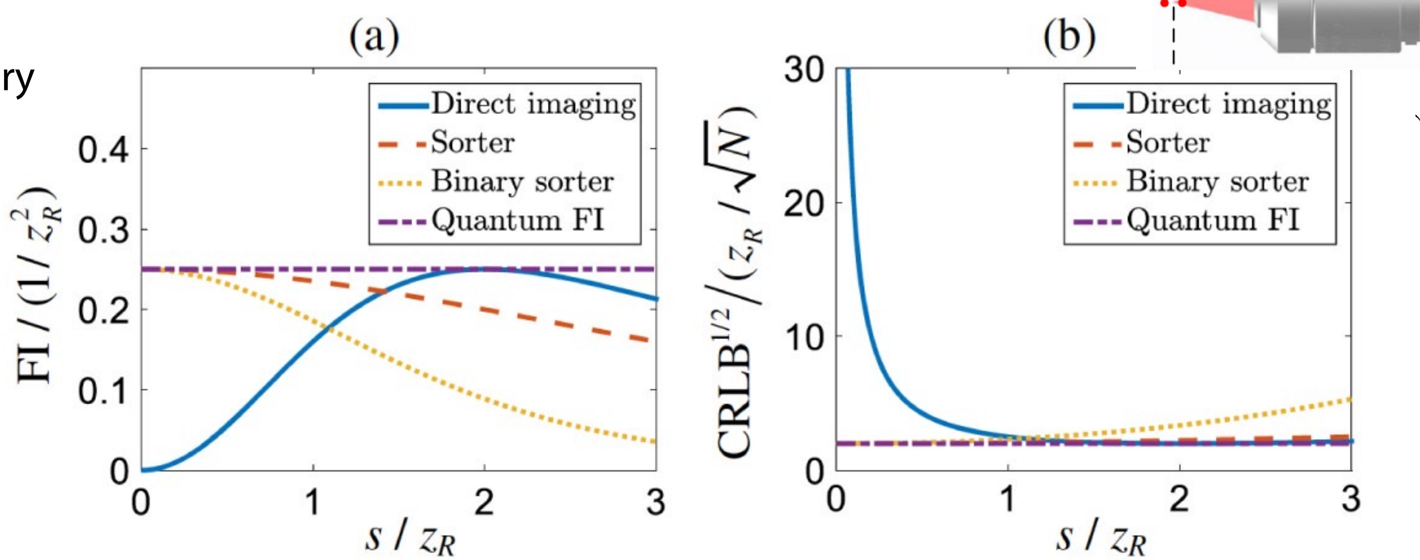
optica

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]

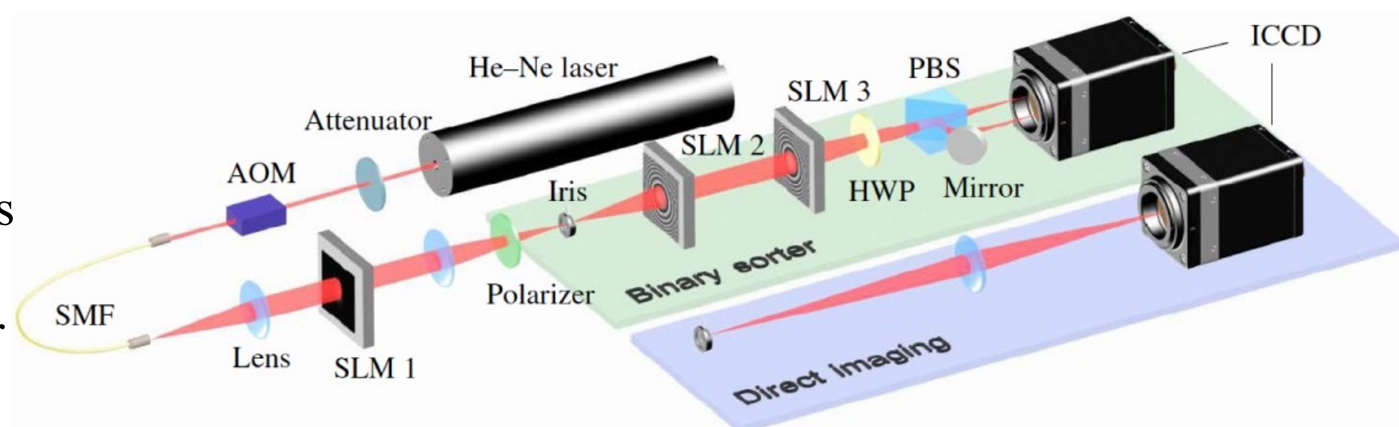


- Theory

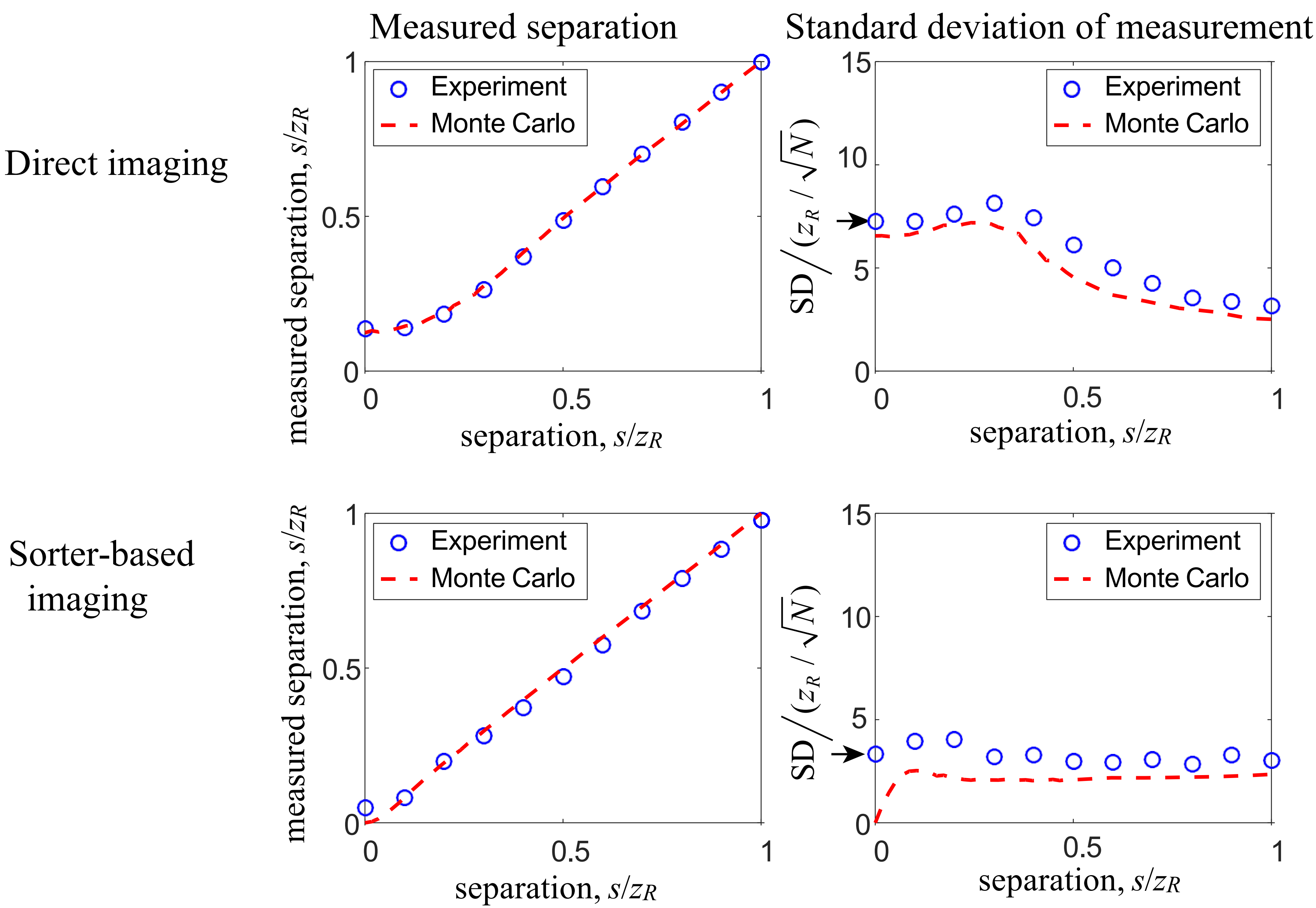


CRLB = Cramer-Rao lower bound = reciprocal of Fisher information

- 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



- Note factor-of-two improvement in standard deviation
- Can this method be applied to natural images, not just two point sources?

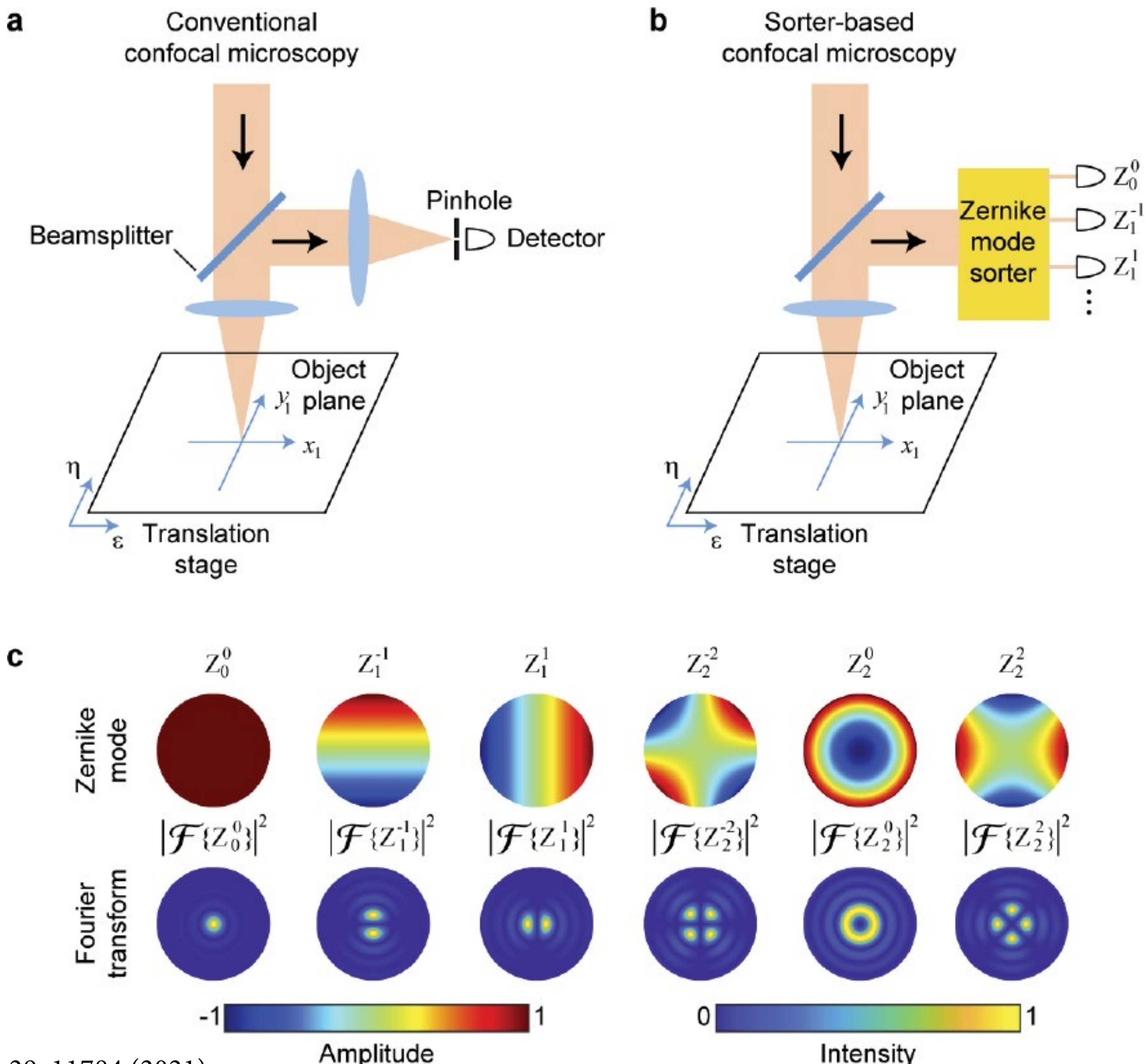
Optics EXPRESS

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]

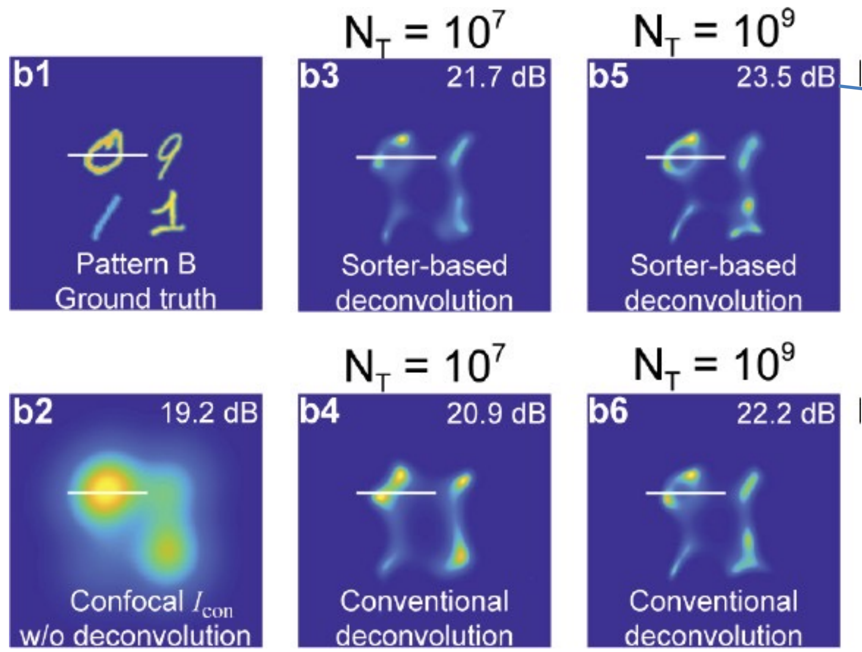
[1]Department of Physics, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada
[2]The Institute of Optics, University of Rochester, Rochester, New York 14627, USA
[3]Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA
[4]Institute for Quantum Studies, Chapman University, Orange, California 92866, USA
[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



Optics Express 29, 11784 (2021)

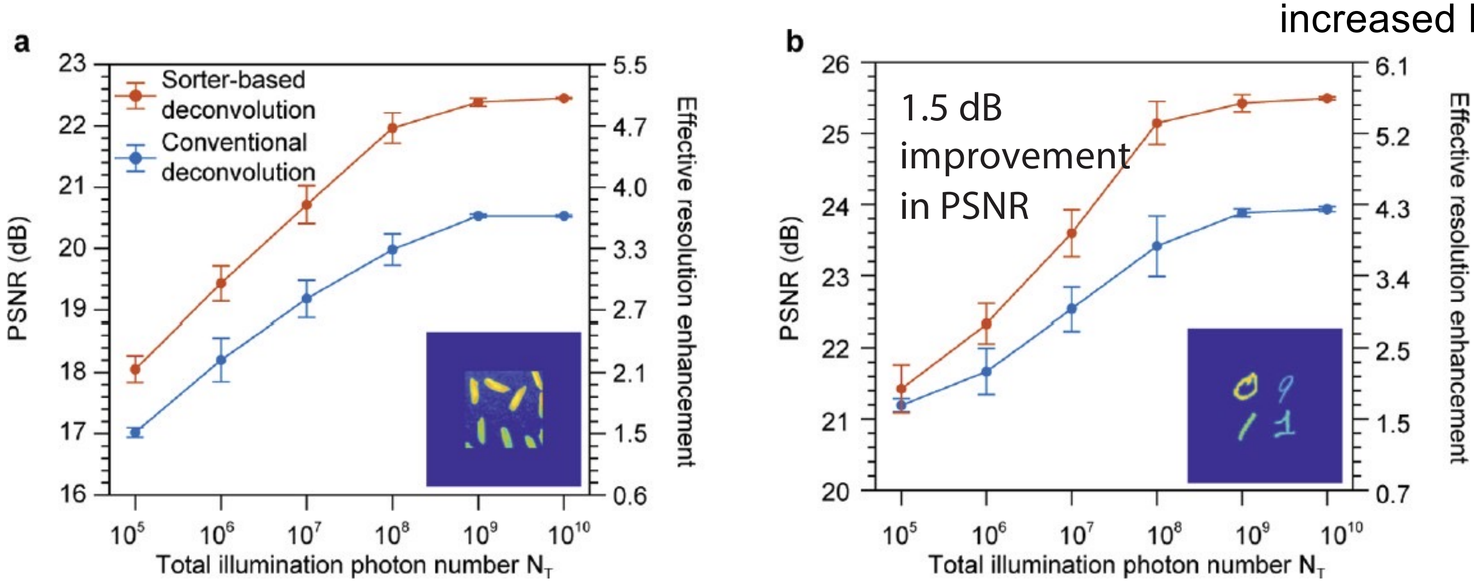
Some Numerical Results



PSNR = peak signal-to-noise ratio

- We use the Richardson-Lucy deconvolution algorithm

resolution enhancement increased by 30%



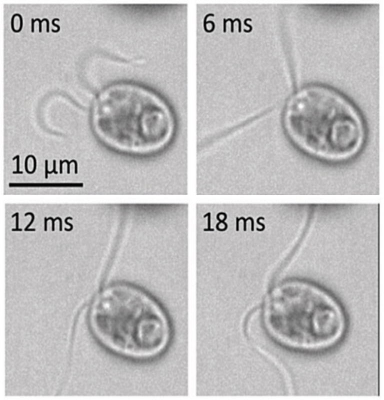
- Improvement in resolution is real, but it is not a significant improvement. Can we do better?

Optics Express 29, 11784 (2021)

Quantum Microscopy for Biomedicine

Some biological samples require low illumination intensities and long wavelengths.

- How do you image an object under photon-starved conditions?
- Many biological materials suffer structural damage when exposed to strong laser light, especially at short wavelengths.
- Low-intensity imaging typically leads to a low SNR due to the presence of stray light and detector noise.
- Imaging with a longer wavelength results in a lower image resolution.
- Many biological materials (such as Chlamydomonas reinhardtii) present very low intensity contrast. Need to perform phase-sensitive imaging.
- How can we image these materials at different times during their circadian cycle at a high SNR and high resolution?

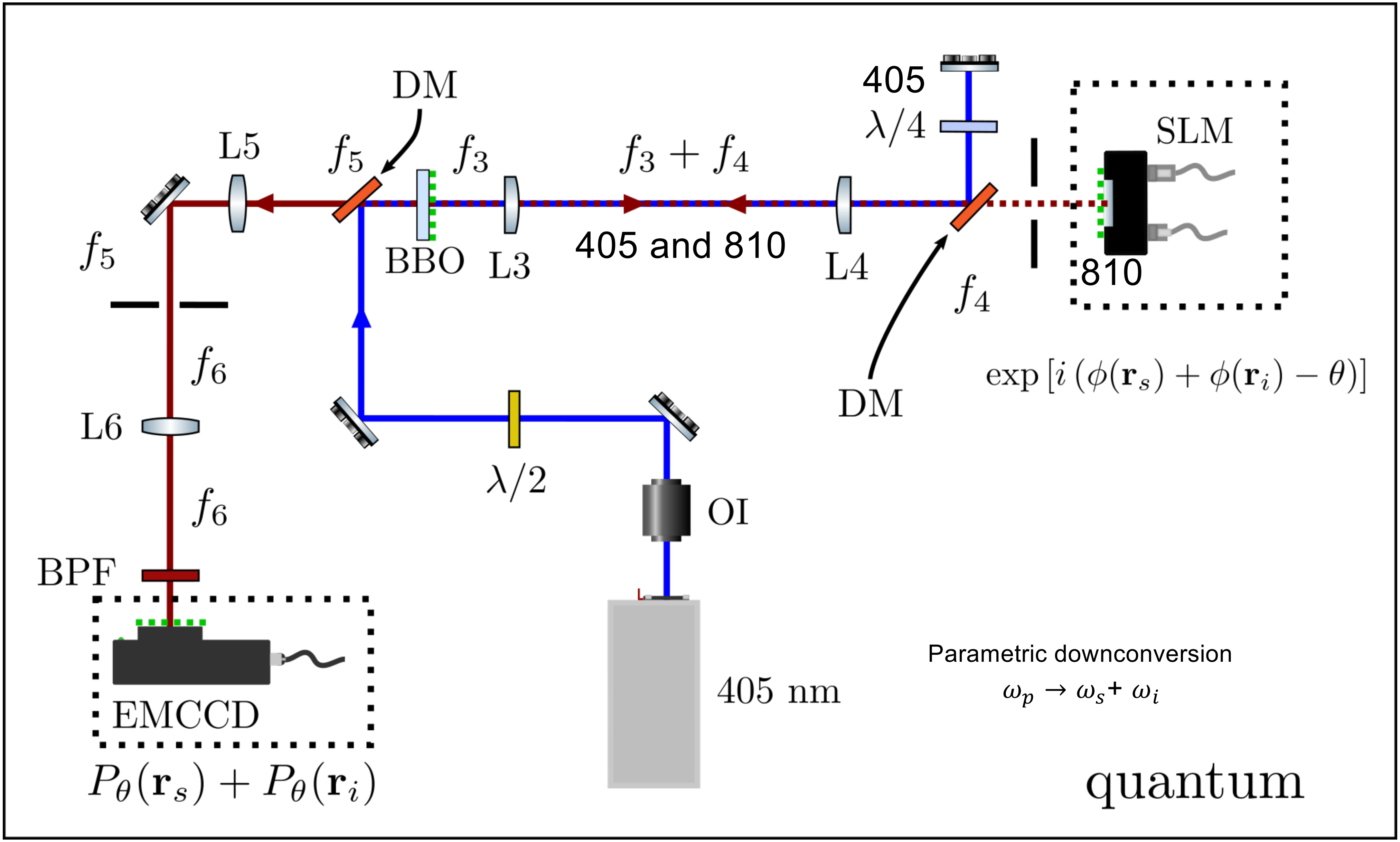


O. Taino et al., Soft Matter **17**, 145-152 (2021).

Solution:
Use quantum imaging.

[1] Y. Niwa et al., Proc. National Acad. Sci. **110**, 13666–13671 (2013).
[2] Q. Thommen et al., Front. Genet. **6**, 65 (2015).

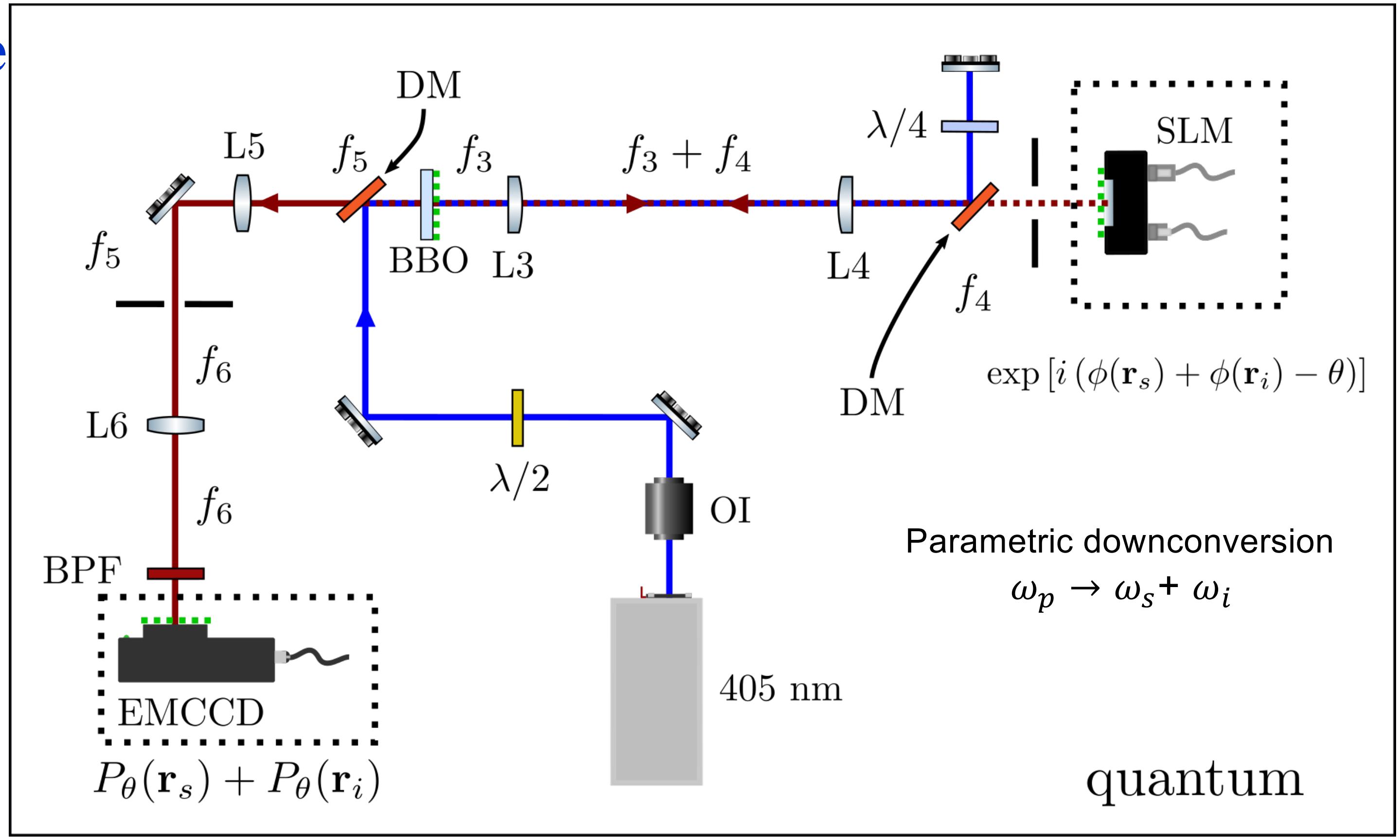
Our phase-sensitive imaging setup:



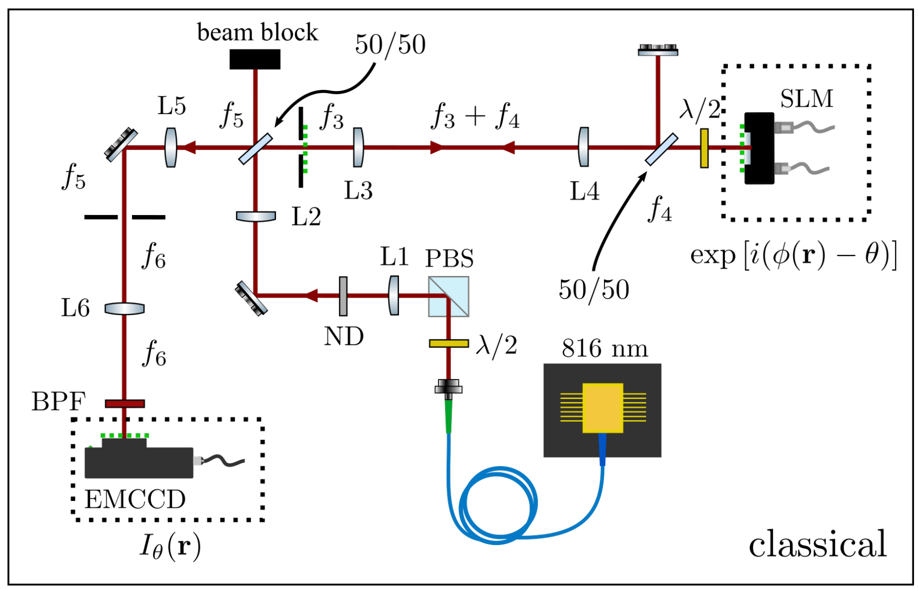
A. Nicholas Black, Long D. Nguyen, Boris Braverman, Kevin T. Crampton, James E. Evans, and Robert W. Boyd, "Quantum-enhanced phase imaging without coincidence counting," Optica 10, 952-958 (2023).

Our phase-sensitive imaging setups:

Quantum



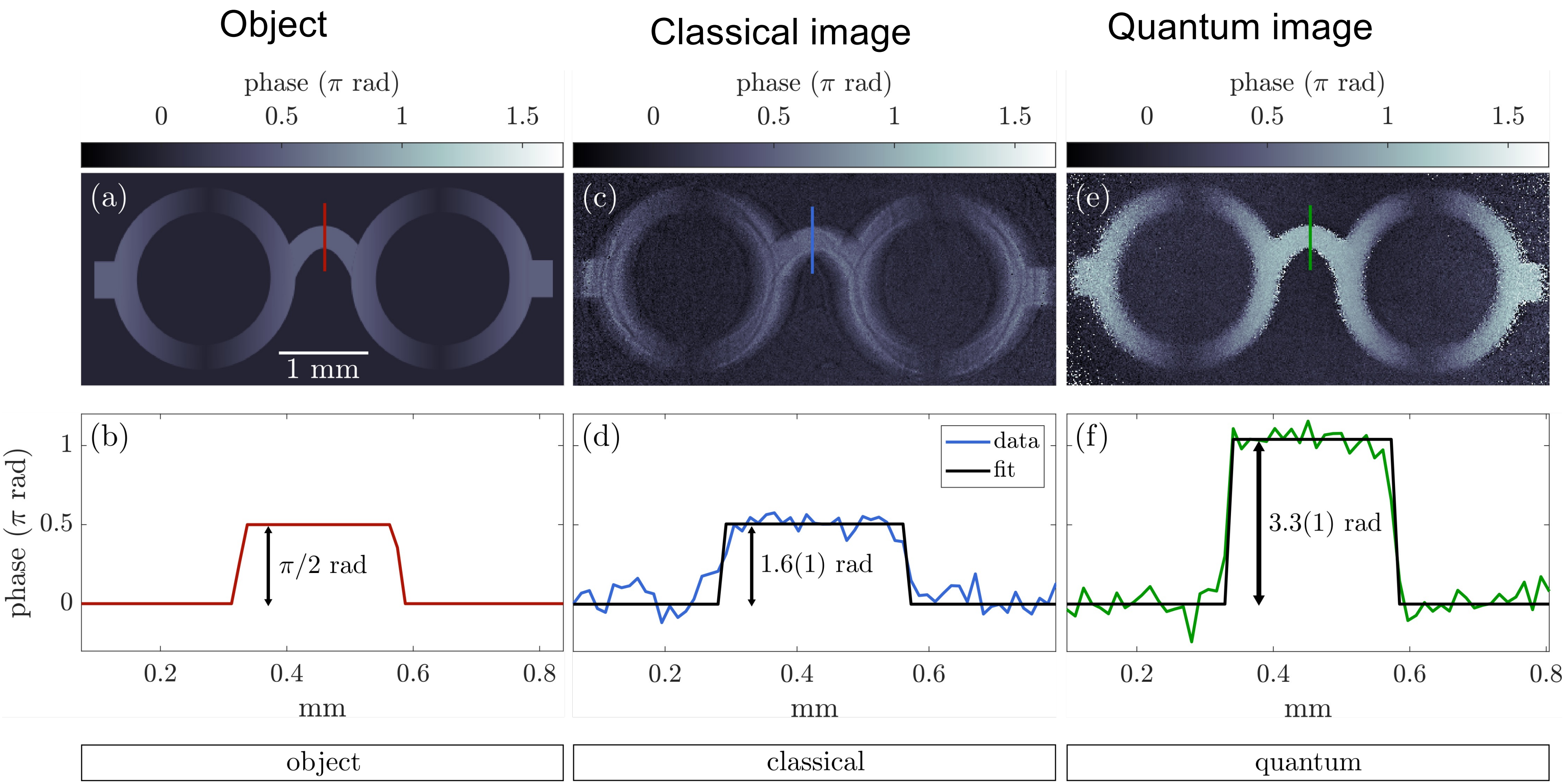
Classical
(with same numerical aperture)



A. Nicholas Black, Long D. Nguyen, Boris Braverman, Kevin T. Crampton, James E. Evans, and Robert W. Boyd, "Quantum-enhanced phase imaging without coincidence counting," Optica 10, 952-958 (2023).

Monument In Tokyo, Japan

Comparison of classical and quantum phase imaging

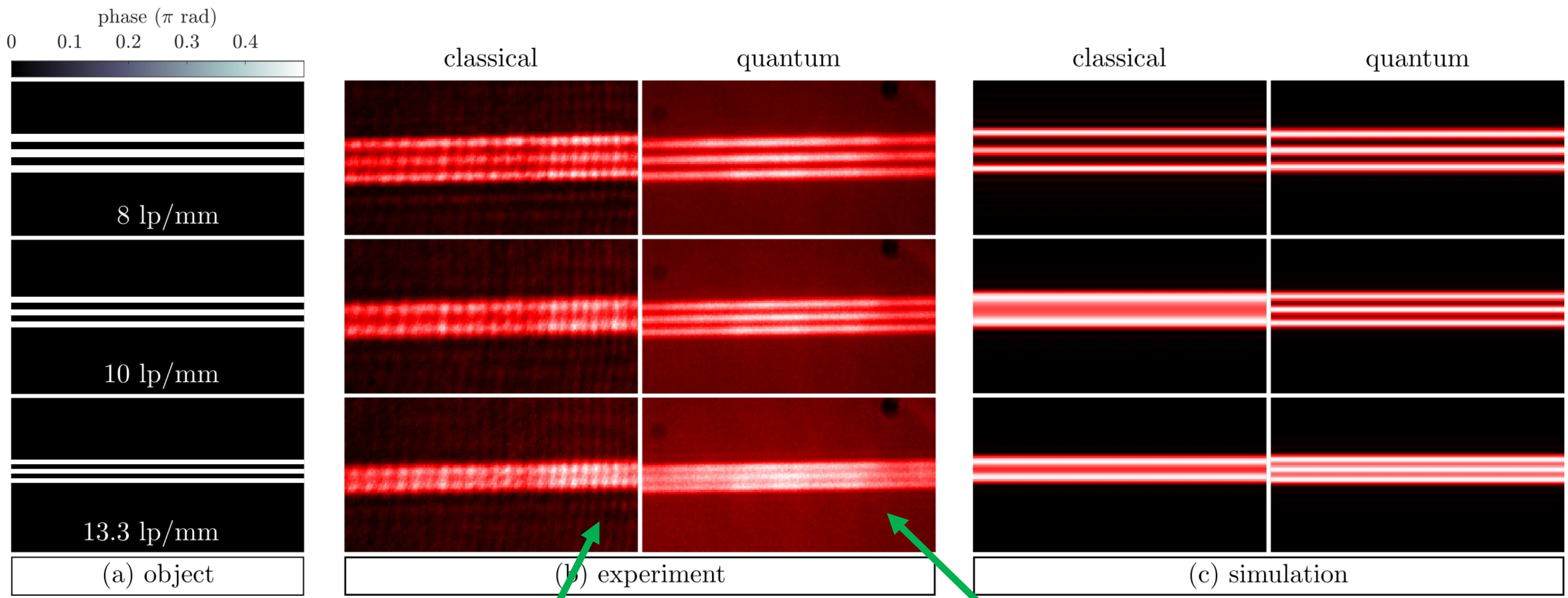


The “object” is a phase object
Written onto an SLM.

Photon flux: ~40 photons/s/μm^2
Signal is twice as large
Image is 1.7-times sharper

A. Nicholas Black, Long D. Nguyen, Boris Braverman, Kevin T. Crampton, James E. Evans, and Robert W. Boyd,
"Quantum-enhanced phase imaging without coincidence counting," Optica 10, 952-958 (2023).

Comparison of quantum to classical spatial resolution



Vertical fringing is from back reflections.

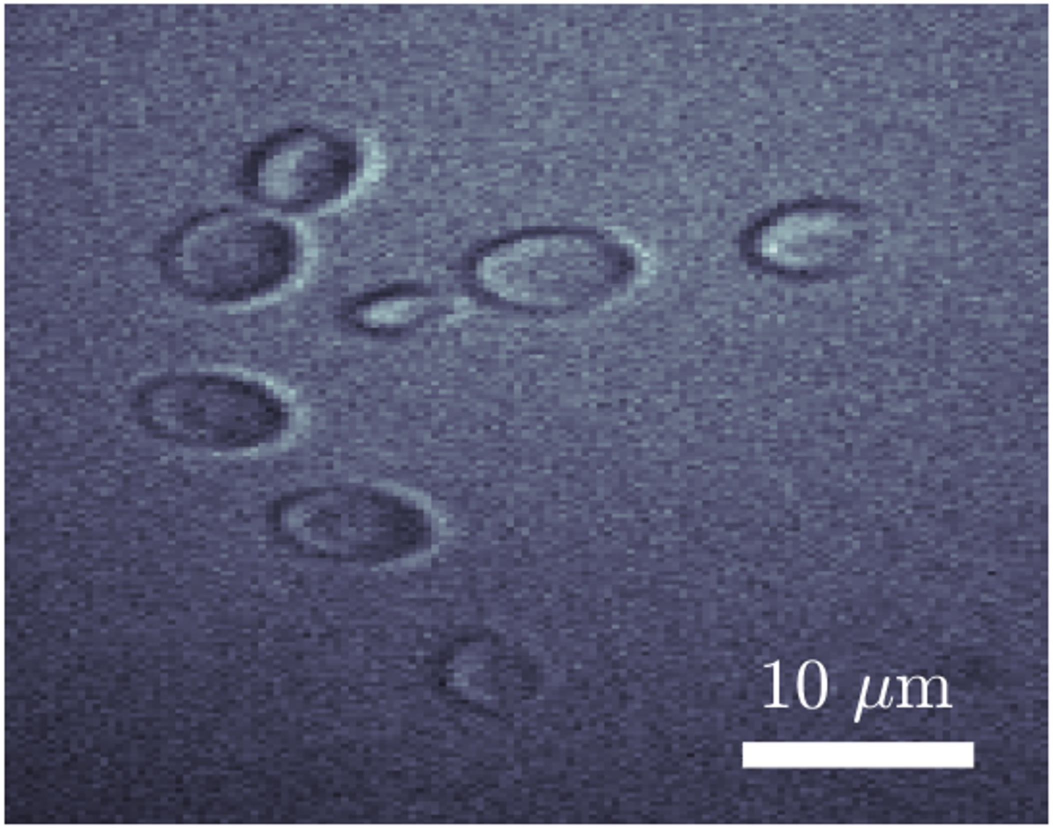
Fringing from back reflections not present in quantum experiment because back reflections are not mode matched.

The quantum experiment achieves ~1.7 times better spatial resolution.

A. Nicholas Black, Long D. Nguyen, Boris Braverman, Kevin T. Crampton, James E. Evans, and Robert W. Boyd, "Quantum-enhanced phase imaging without coincidence counting," Optica 10, 952-958 (2023).

Latest Lab Result: Quantum Phase Microscopy

Living yeast cells imaged by entangled photons at 710 nm.

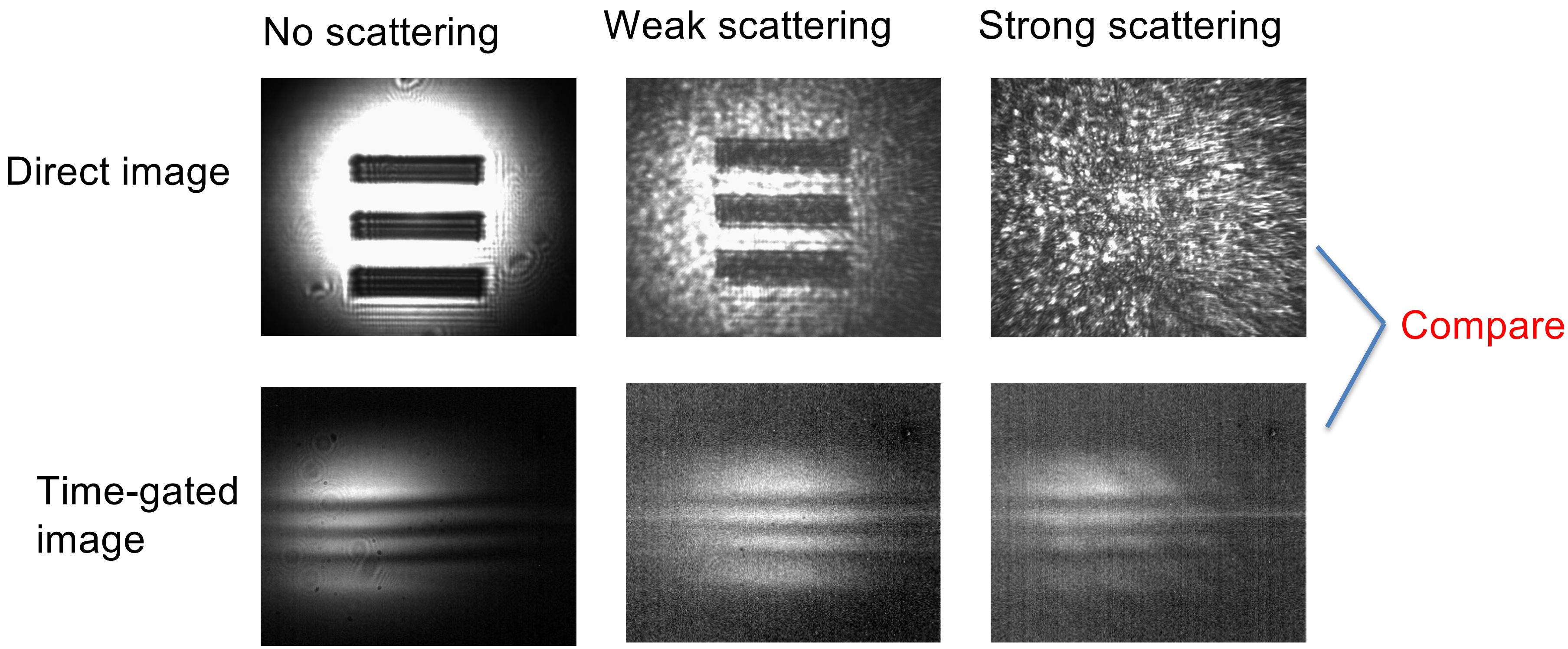


Objective: 40x magnification, NA = 0.75

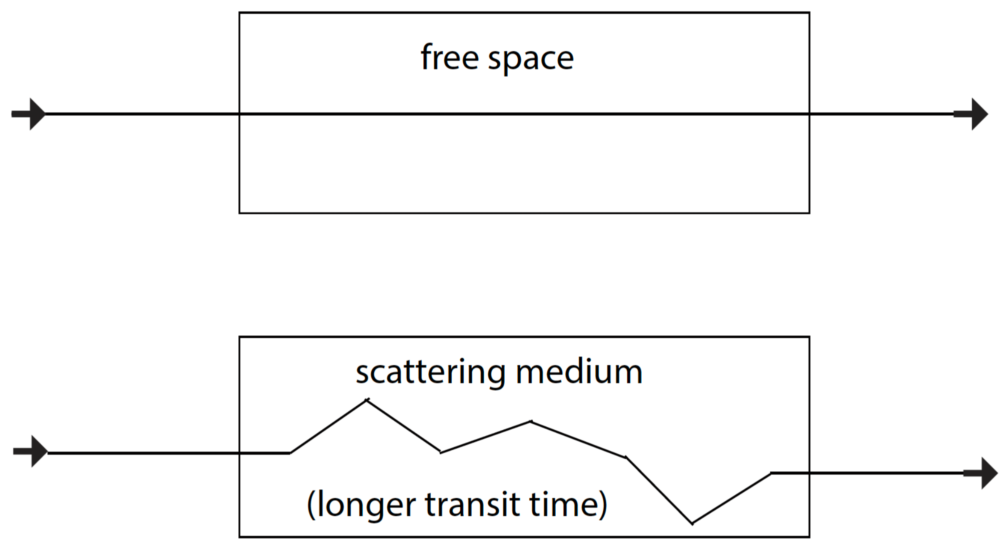
Lead investigator: PhD student Saleem Iqbal

Imaging through a Strongly Scattering Medium

We use time-gating to measure only the first-arriving photons



Need material with a strong, fast nonlinear optical response to construct gate. Use ITO.



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See also Wang et al (Alfano group) Science 253, 769 (1991),

Huge Nonlinear Optical Response of Indium Tim Oxide (ITO) at ENZ

- We need highly nonlinear, low-loss materials for optical switches and gates. (Ideally, we want the control field to contain at most several photons.)
- Note that optical nonlinearities are strongly enhanced at wavelengths for which n ≅ 0. (This is the ENZ, epsilon-near-zero, condition.)

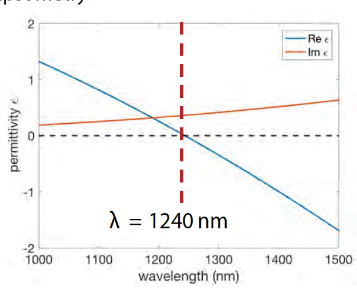
$$n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 c\, n_0\, \mathrm{Re}(n_0)}$$

- Note further that for any conductor Re ε =0 at the reduced plasma frequency :

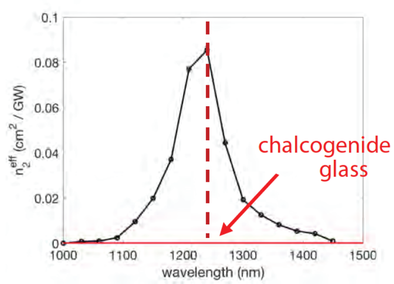
$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

- For indium tin oxide (ITO), Re ε =0 at λ = 1.24 μm.

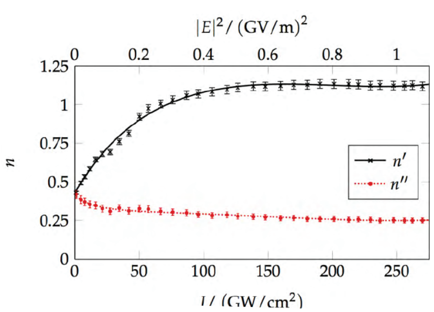
• ellipsometry



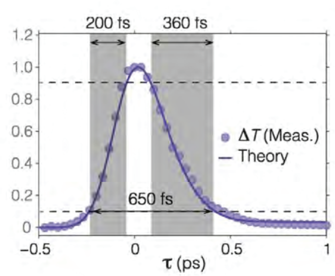
• n_2 can be 3.4 x10^5 times larger than that of silica glass



• overall change in refractive index of 0.8



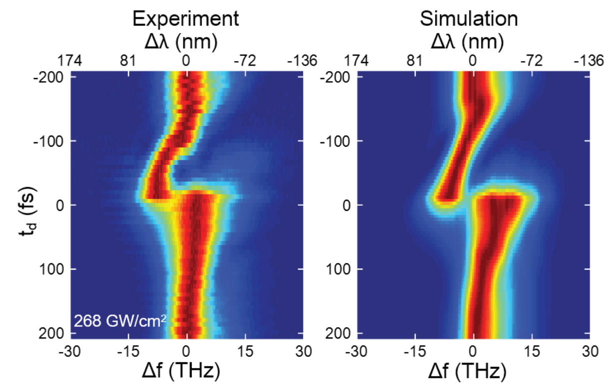
• sub picosecond reponse time



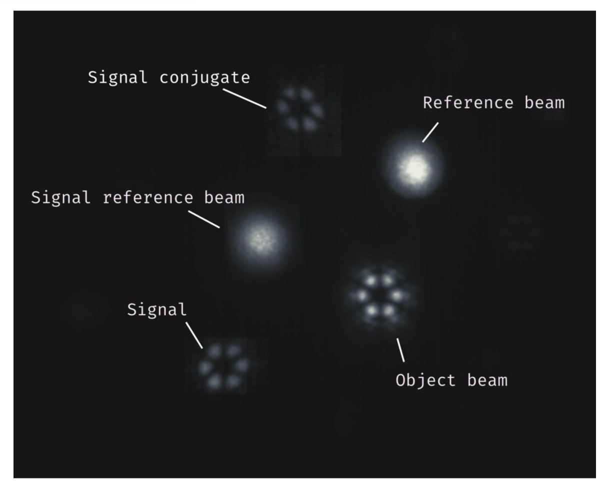
M. Z. Alam et al., Science 352, 795-797 (2016)

- Application: Adiabatic wavelength conversion
  - We can controllably shift the carrier wavelength of a data-encoded light field by as much as 100 nm.

$$\delta\omega(t) = \frac{d}{dt}\phi_{\mathrm{NL}} = \frac{d}{dt}[n_2 I(t)\omega/c]$$



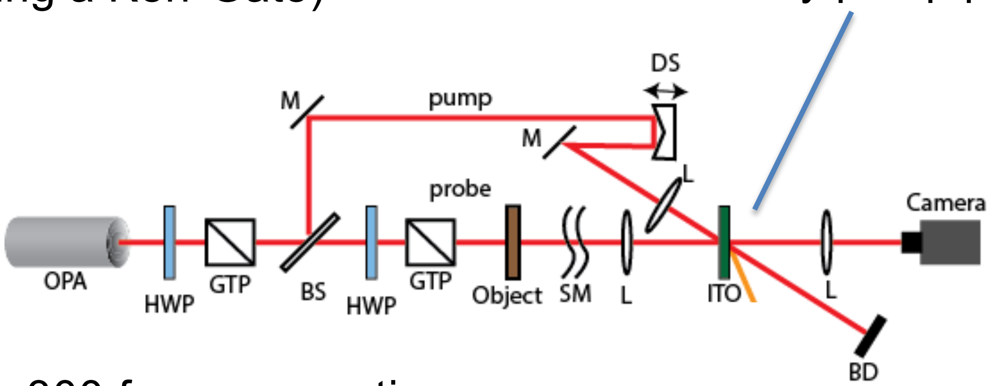
- Application: Ultrafast real-time holography



Experiment Setups

Nonlinear Transmission Setup
(using a Kerr Gate)

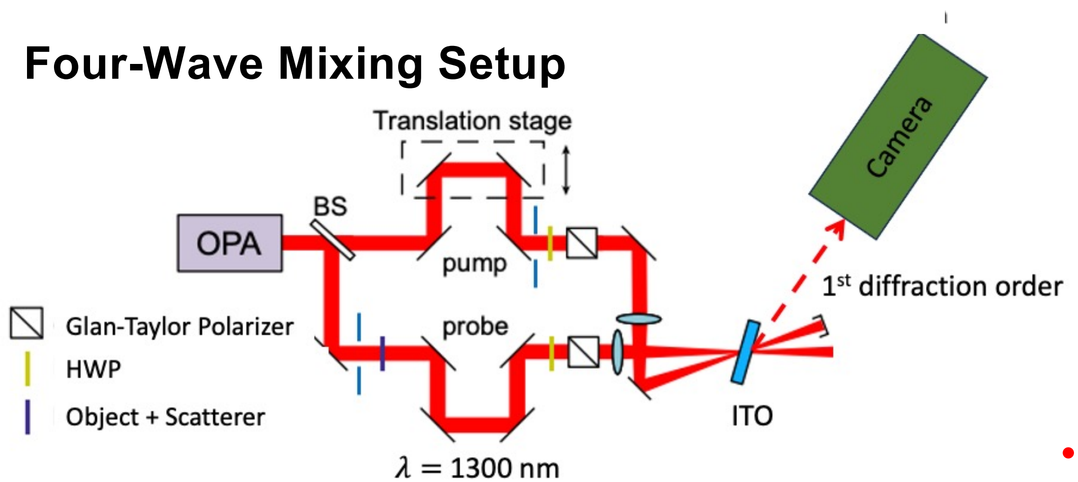
Probe transmission shuttered
by pump pulse in a “Kerr gate.”



300 fs response time

GTP: Glan-Taylor polarizer
SM: scattering media
BS: beam splitter
BD: beam dump
DS: delay stage
L: lens
M: mirror

Four-Wave Mixing Setup



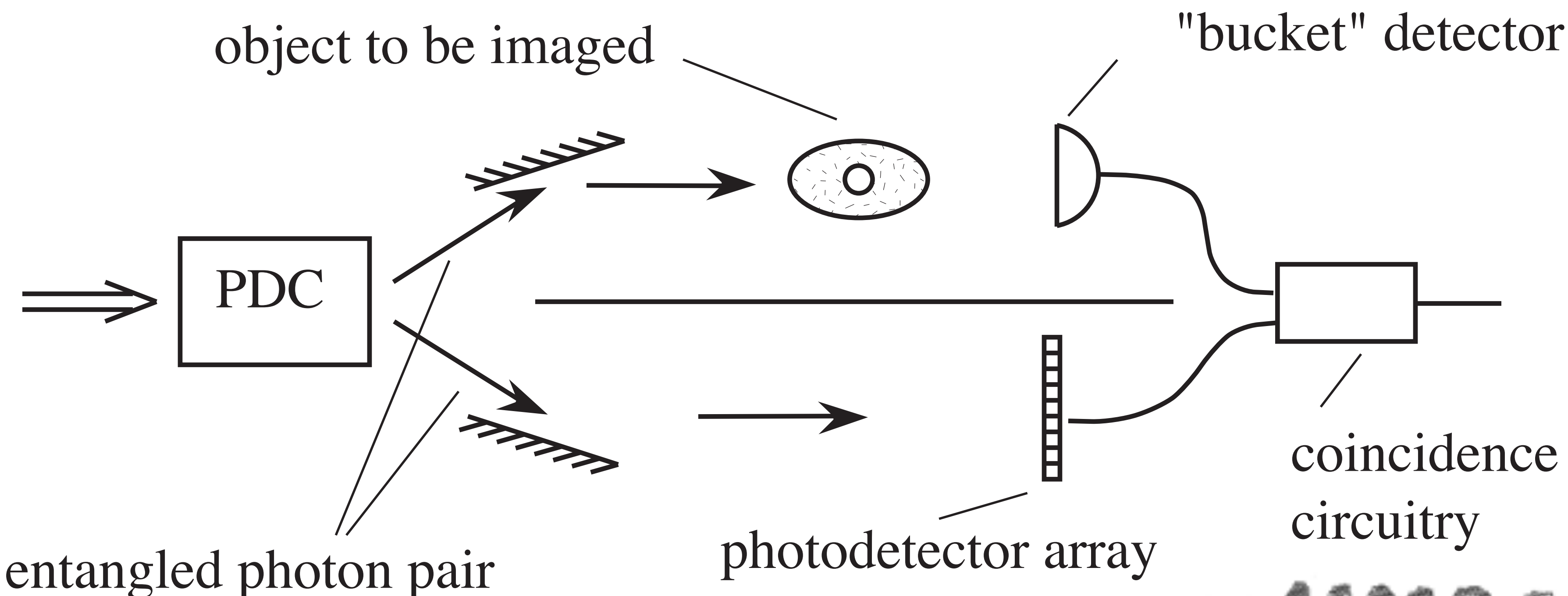
120 fs response time

Pump and probe are both centered at the ENZ wavelength (1240 nm) of the 310-nm-thick ITO plate

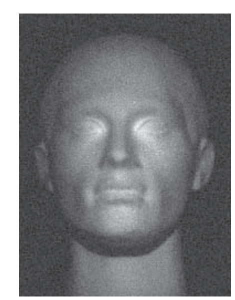
- We use the four-wave mixing setup because it gives a shorter gating time.

Interaction-Free and Ghost Imaging

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)



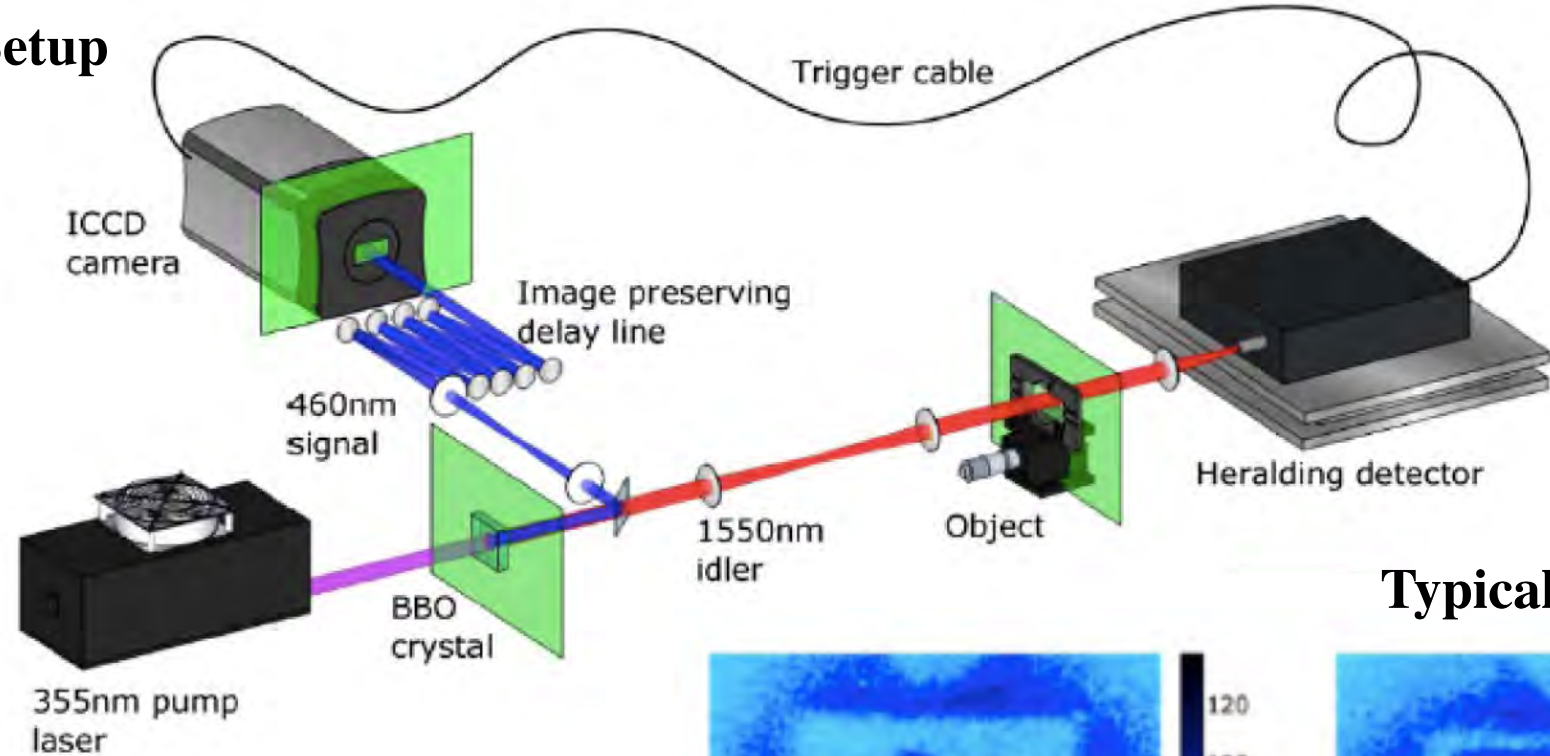
Padgett Group

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)

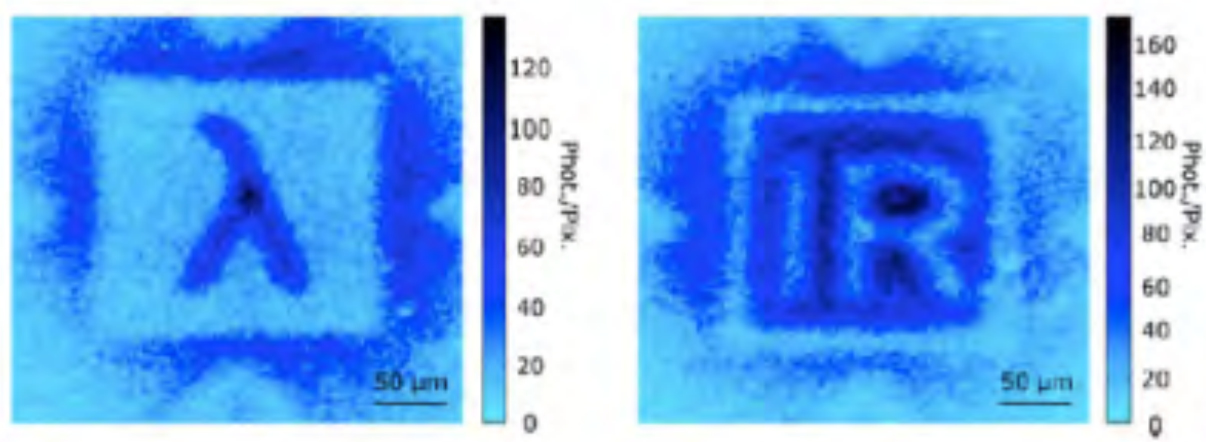
Wavelength-Shifted (Two-Color) Ghost Microscopy

- 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

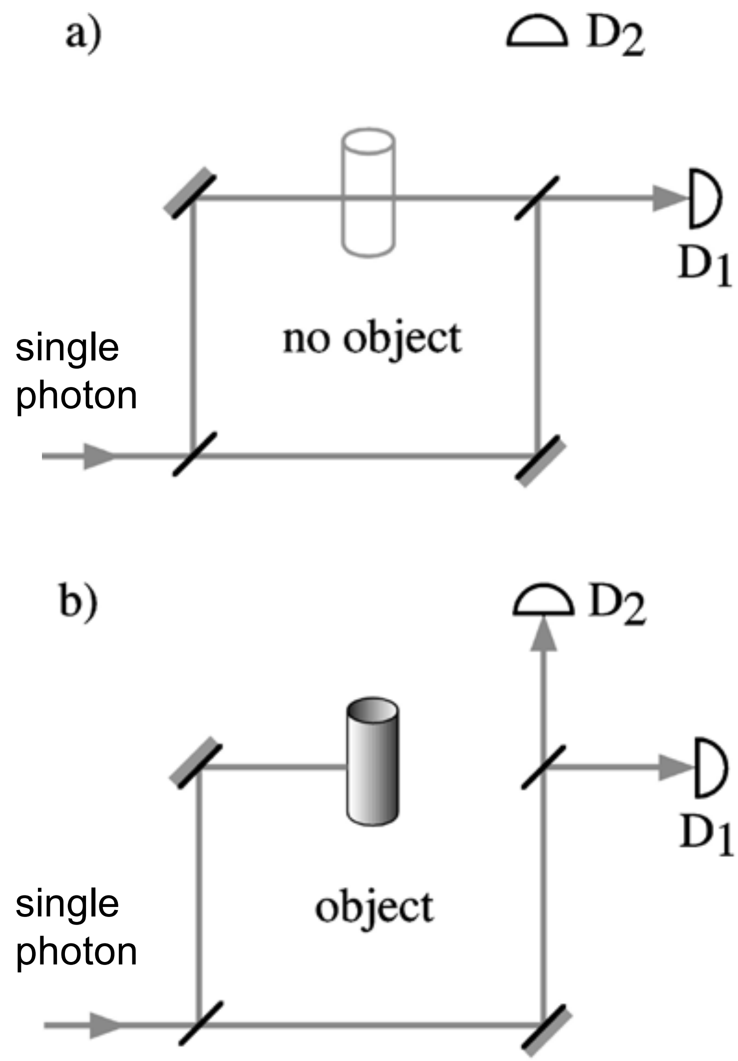


Typical images

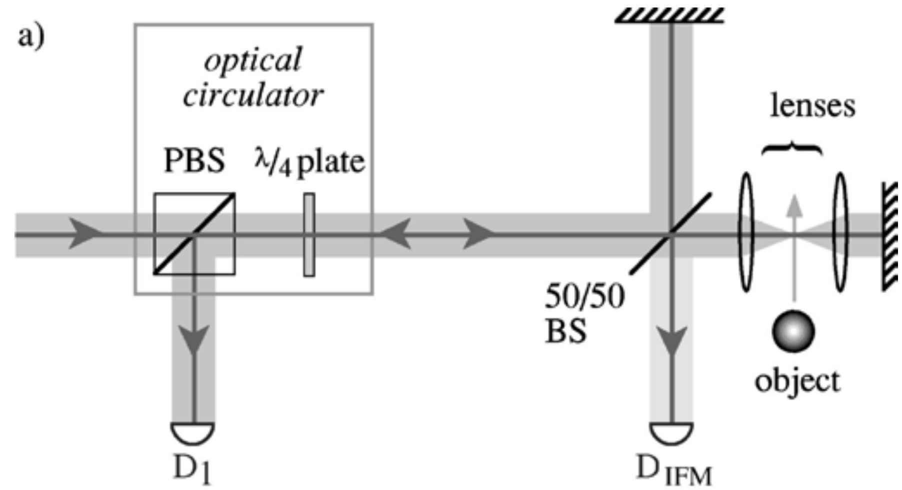


Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

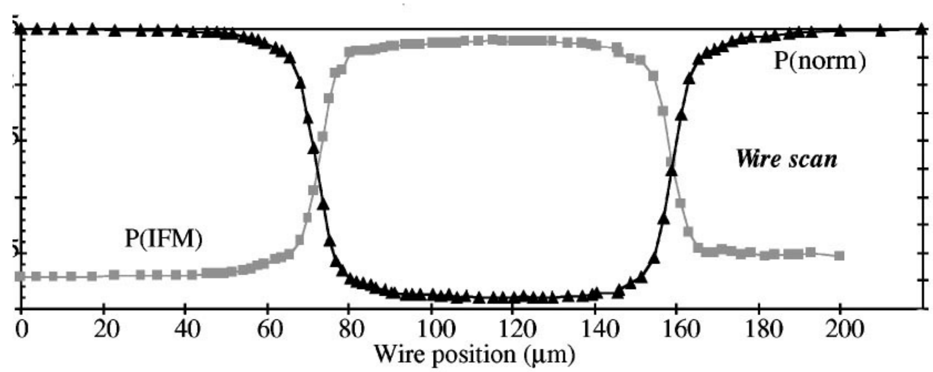
Quantum Imaging by Interaction-Free Measurement



imaging setup



results



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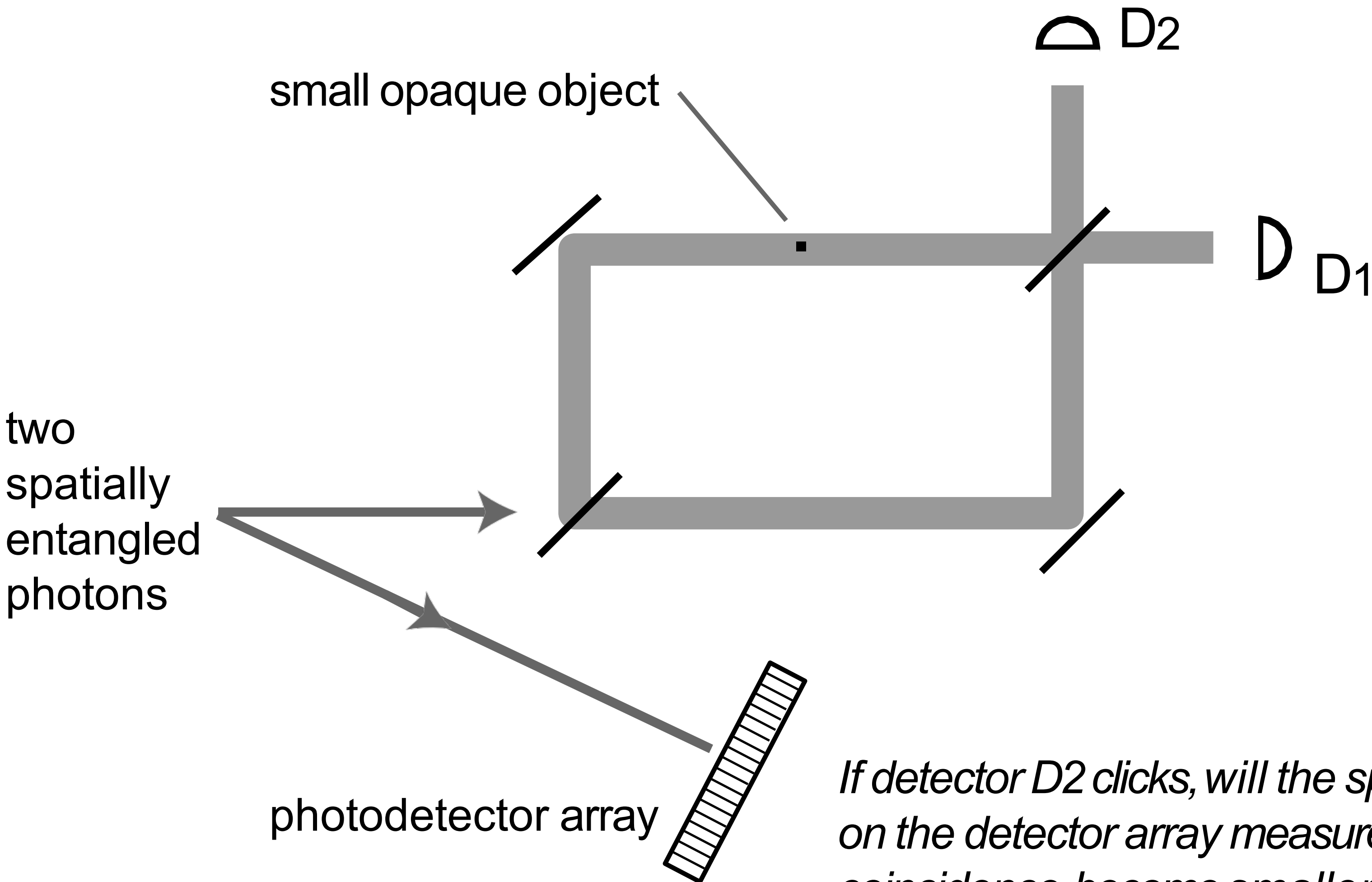
Interaction-Free Measurements and Entangled Photons



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?

Laboratory 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?

Research in Quantum Imaging

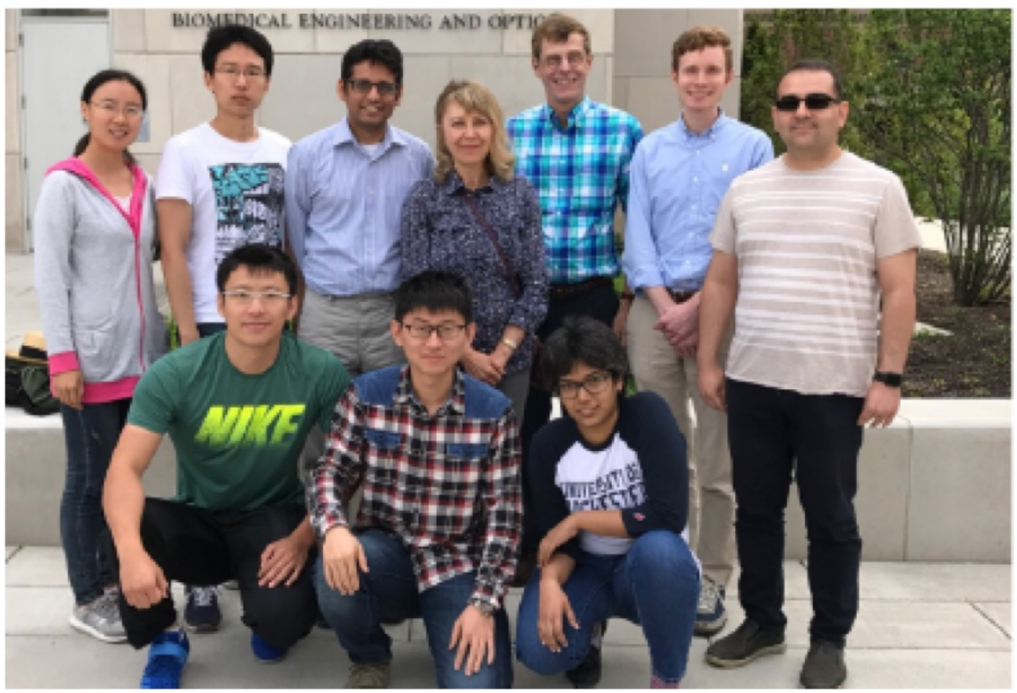
Quantum Imaging or Quantum Imogene?

Sid Caesar and
Imogene Coca in 1953

Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group

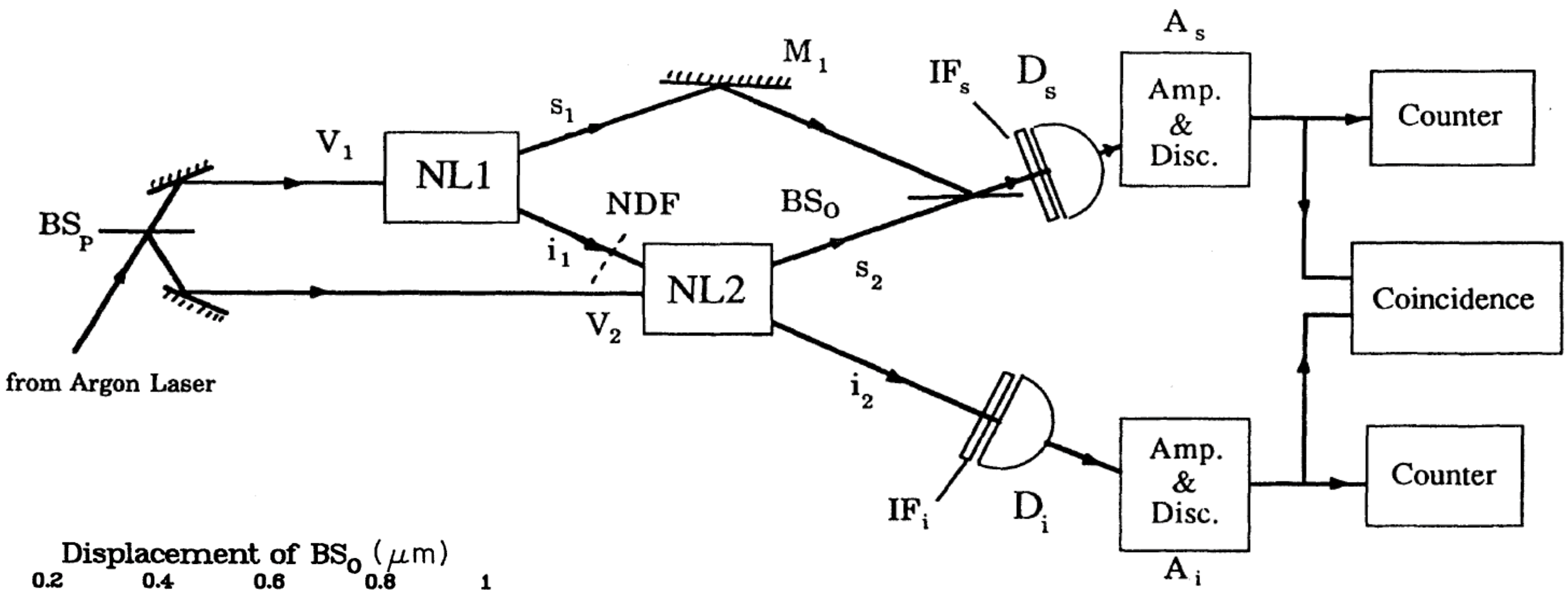


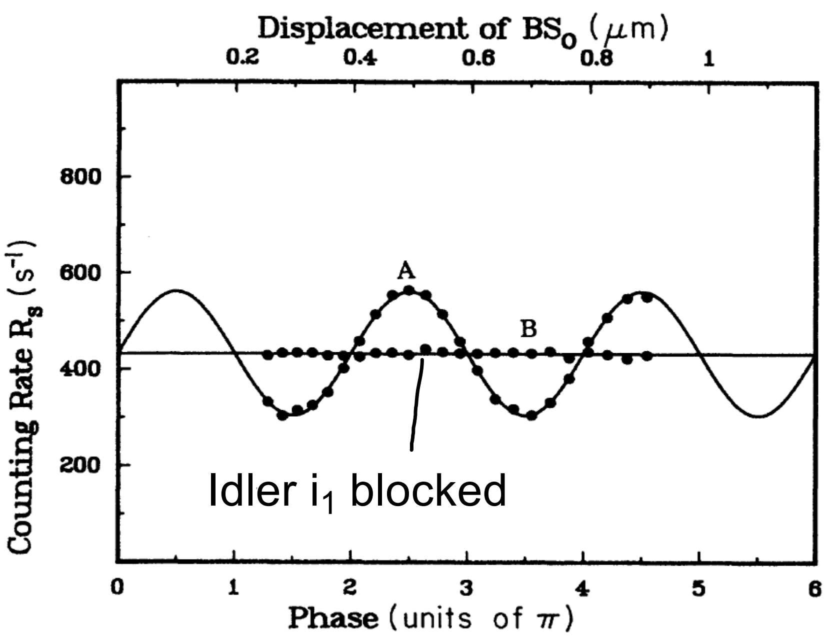
Quantum Imaging with Undetected Photons

Induced coherence without induced emission

Wang, Zou, Mandel, Phys Rev A 44, 4614 (1991).

INDUCED COHERENCE WITHOUT INDUCED EMISSION



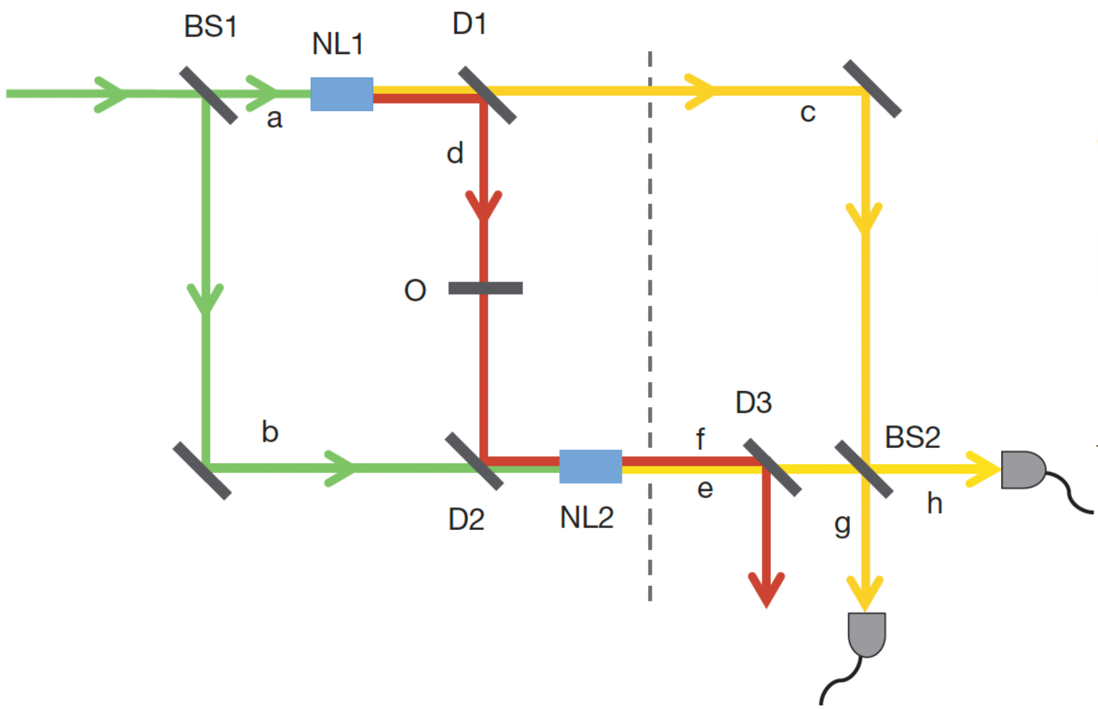


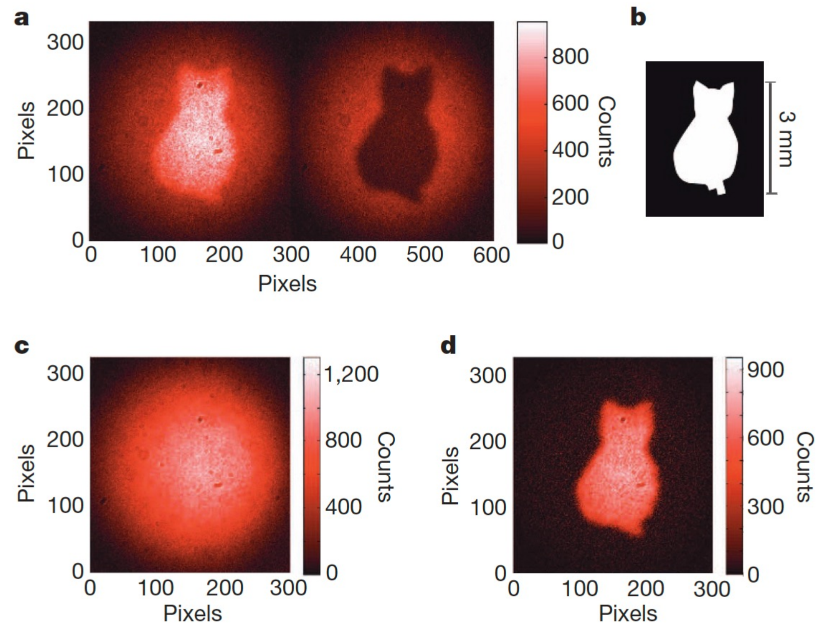
Quantum imaging with undetected photons

Gabriela Barreto Lemos[1,2], Victoria Borish[1,3], Garrett D. Cole[2,3], Sven Ramelow[1,3]†, Radek Lapkiewicz[1,3] & Anton Zeilinger[1,2,3]

Nature 512, 409 (2014).

Works by quantum interference. Are photon pairs created in NL1 or NL2?





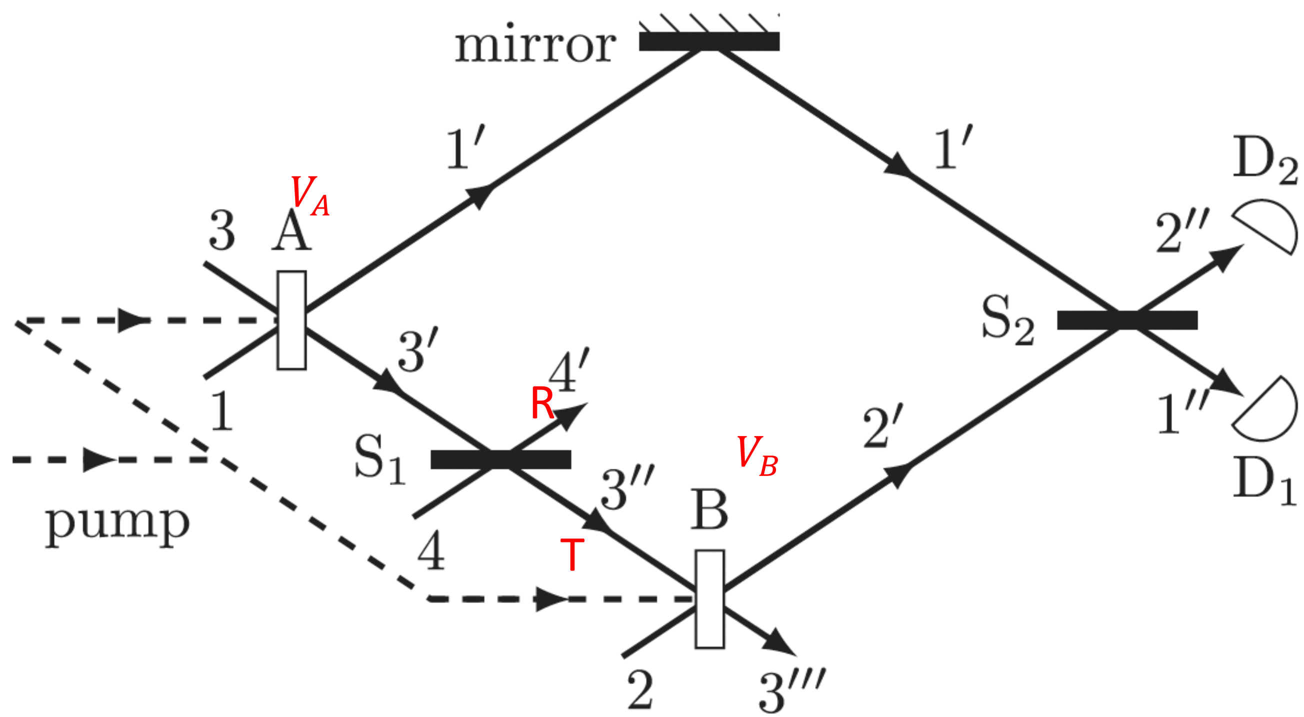
Very famous paper. Can we improve image quality?

IOP Publishing Journal of Optics
J. Opt. 19 (2017) 054003 (8pp) https://doi.org/10.1088/2040-8986/aa64a2

Controlling induced coherence for quantum imaging

Mikhail I Kolobov[1], Enno Giese[2], Samuel Lemieux[2], Robert Fickler[2] and Robert W Boyd[2,3]

[1] Univ. Lille, CNRS, UMR 8523—PhLAM—Physique des Lasers Atomes et Molécules, F-59000 Lille, France
[2] Department of Physics, University of Ottawa, 25 Templeton Street, Ottawa, Ontario K1N 6N5, Canada
[3] Institute of Optics, University of Rochester, Rochester, NY 14627, United States of America

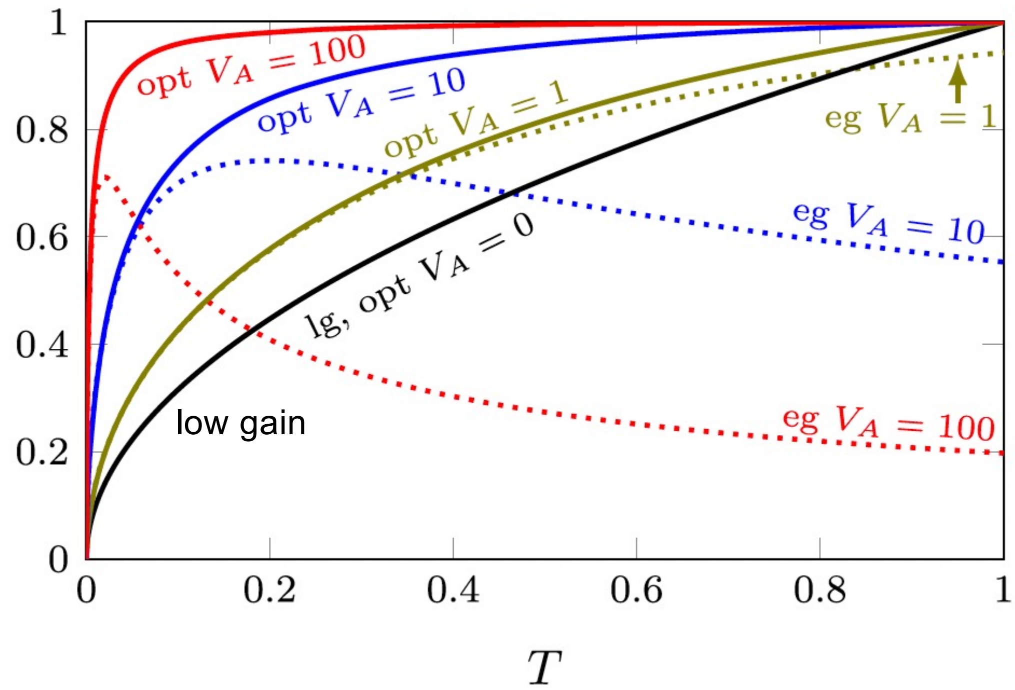


- How are visibility and SNR of the quantum interference influenced by working in the high-gain limit (V_A and V_B greater than unity) of parametric down-conversion?
- Here V_A and V_B are the parametric gains of NL crystals A and B.
- We also study imbalanced pumping, V_A not equal to V_B

Theoretical Results

- We find that the mutual coherence $g^{(1)}$ is given by $\gamma_{12} = \sqrt{T\frac{1+V_A}{1+TV_A}}$
- We find that the visibility is given by $\mathcal{V} = 2\frac{\sqrt{(1+V_A)V_A V_B T}}{V_A + V_B + V_A V_B T}.$

Regime	V_A and V_B	Visibility
Both Low gain	$V_A = V_B << 1$	$\mathcal{V}^{(lg)} = \sqrt{T} = \gamma_{12}$
A High gain, B Low gain	$V_A \gg 1,\ V_B << 1$	$\mathcal{V}^{(hgs)} = 2\sqrt{V_B T} \ll 1$
Both High gain	$V_A = V_B >> 1$	$\mathcal{V}^{(eg)} = 2\frac{\sqrt{(1+V_A)T}}{2+V_A T}$
Optimized case	$V_A, V_B >> 1$ $V_B = \frac{V_A}{1+V_A T}$	$\mathcal{V}^{(opt)} = \sqrt{T\frac{1+V_A}{1+TV_A}} = \gamma_{12}$



We can obtain higher fringe visibility by working in the high-gain limit!

*Controlling induced coherence for quantum imaging; Mikhail I Kolobov, Enno Giese, Samuel Lemieux, Robert Fickler and Robert W Boyd J. Opt. 19 (2017) 054003