Quantum Imaging

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

Presented at New Directions in Superresolution, Chapman University, April 9, 2024.

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

Research in Quantum Imaging

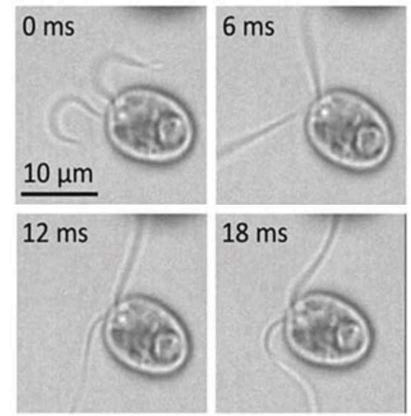
Quantum Imaging or Quantum Imogene?

Sid Caesar and Imogene Coca in 1953

Quantum Phase Imaging

Some biological samples require low illumination intensities and long wavelengths.

- How do you image an object under photon-starved conditions?
  - For example, chlamydomonas reinhardtii, an algae studied for biofuel production, experiences a resetting of its circadian rhythm upon illumination with blue/green and red light[1,2].
- Low-intensity imaging typically suffers from a low SNR due to the presence of stray light and detector noise.
- Imaging with a longer wavelength results in a lower imaging resolution.
- Chlamydomonas reinhardtii has very little intensity contrast. Need to perform phase-sensitive imaging.
- How can we image Chlamydomonas reinhardtii at different times during its circadian cycle at a high SNR and high resolution?



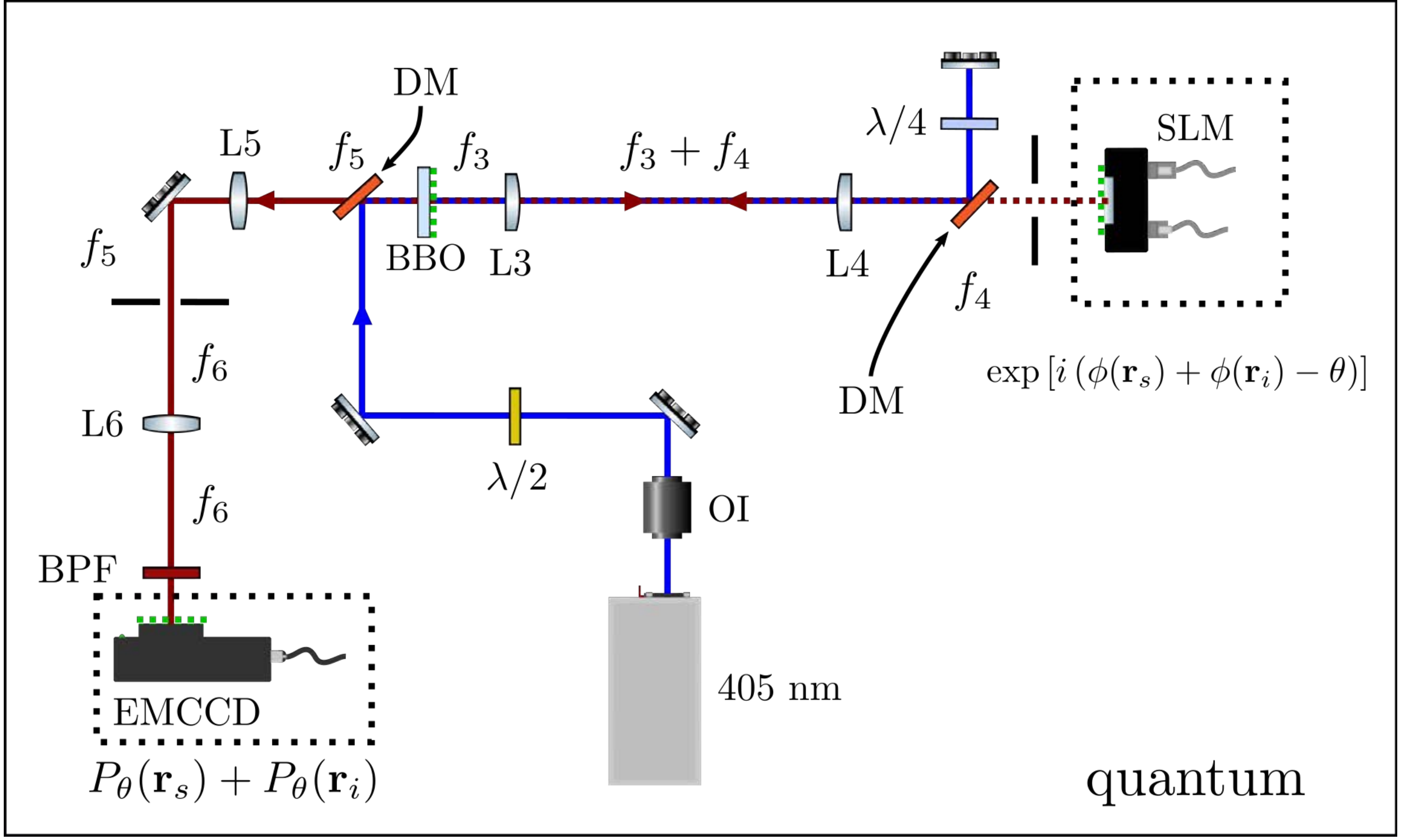
O. Taino et al., Soft Matter **17**, 145-152 (2021).

Solution: Use quantum imaging.

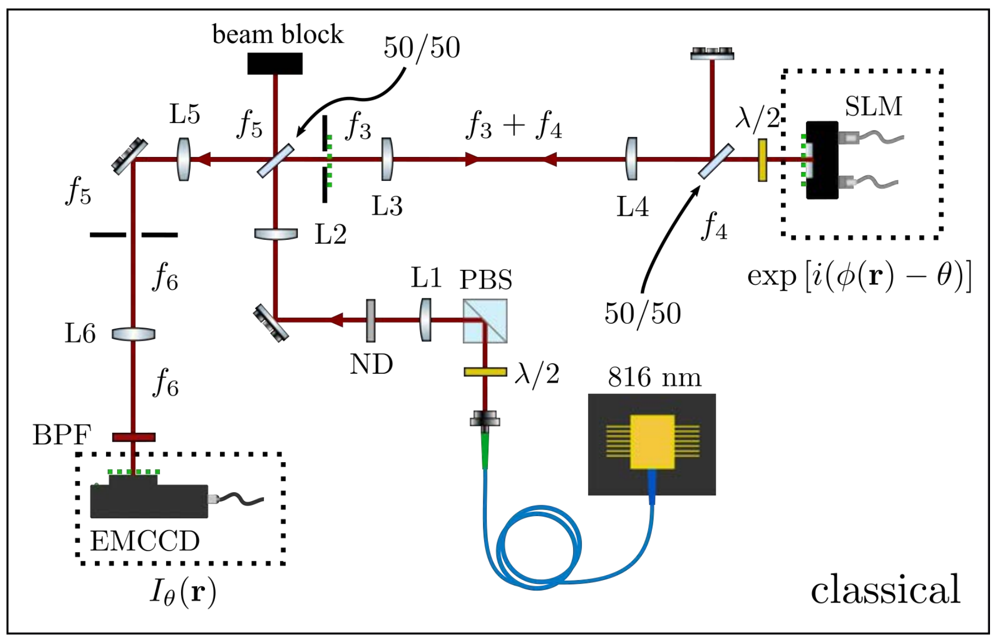
[1] Y. Niwa et al., Proc. National Acad. Sci. **110**, 13666–13671 (2013).
[2] Q. Thommen et al., Front. Genet. **6**, 65 (2015).

Phase-sensitive imaging setups:

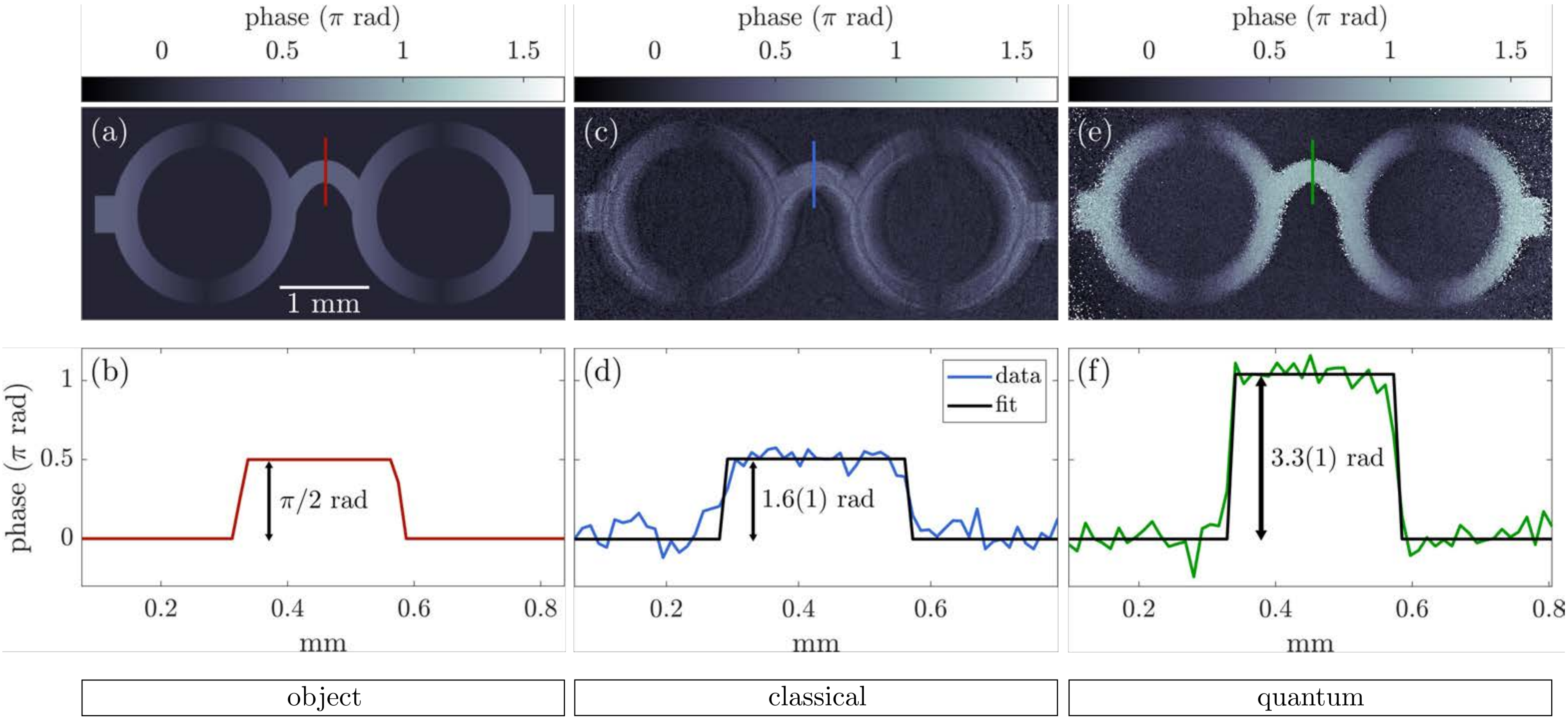
Quantum



Classical
(with same numerical aperture)



Comparing classical and quantum phase imaging



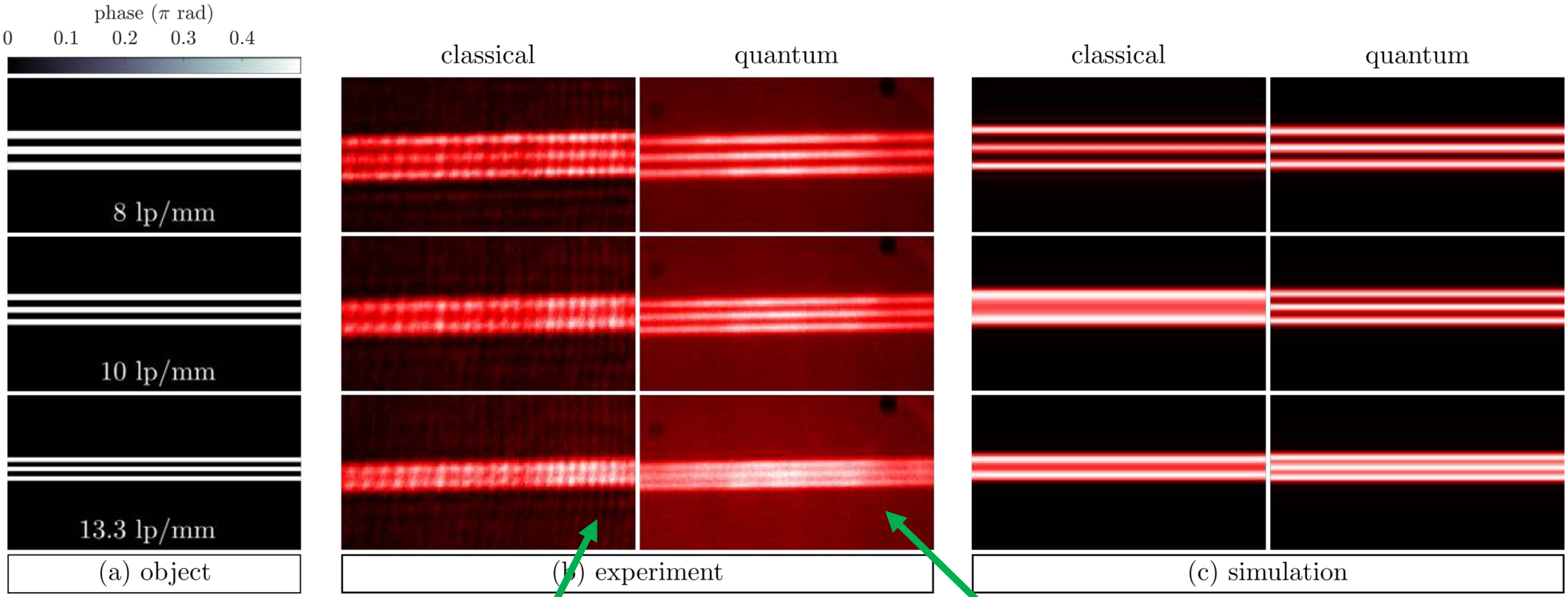
The “object” is a phase object
Written onto an SLM.

photon flux: ~40 photons/s/μm^2

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).


めがね之碑
眼鏡がはるかに海を越え我が日本に渡来したのは四百二十余年前のことであります 文化の発達につれてめがねの需要も増大し 文化政治経済に貢献した役割は誠に大なるものがありますその間業界先覚者の研鑽努力により今日の発展をみるに至ったことを回想し明治百年を記念してその功績を顕彰し慈眼大師ゆかりの地上野不忍池畔にこの碑を建立し感謝の念を新たにするものであります

Compare quantum and classical 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 resolution.

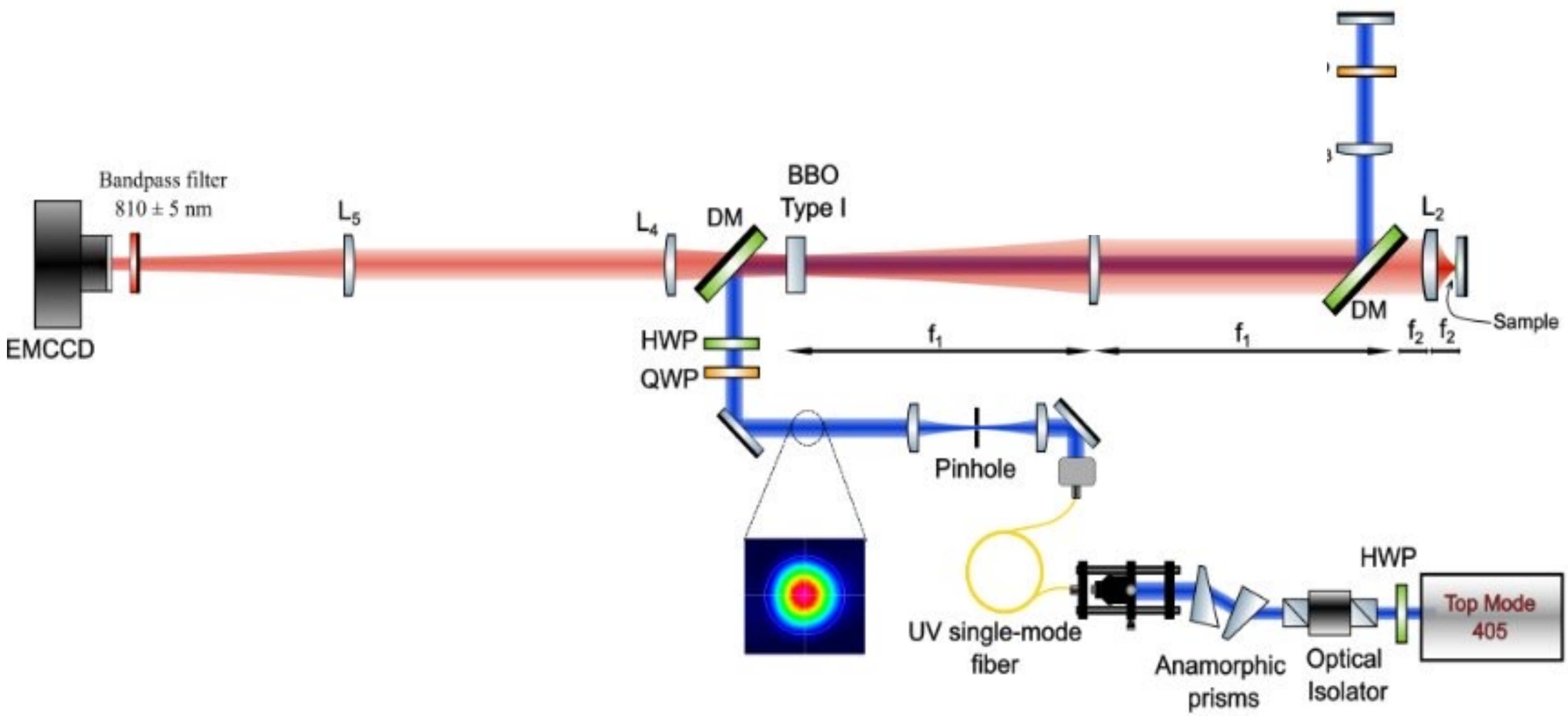
A. Nicholas Black, Long D. Nguyen, Boris Braverman, Kevin T. Crampton, James E. Evans, and Robert W. Boyd, "Quantum-enhanced phase imaging without coincidence counting," Optica 10, 952-958 (2023).

Quantum-enhanced phase microscopy - next steps

- **Modify previous setup to work at a higher numerical aperture**

- Earlier work used an NA of only 0.02
- Change to an aspheric lens (NA = 0.63) as objective lens.

Magnification: 20X
Expected resolution: 400 nm



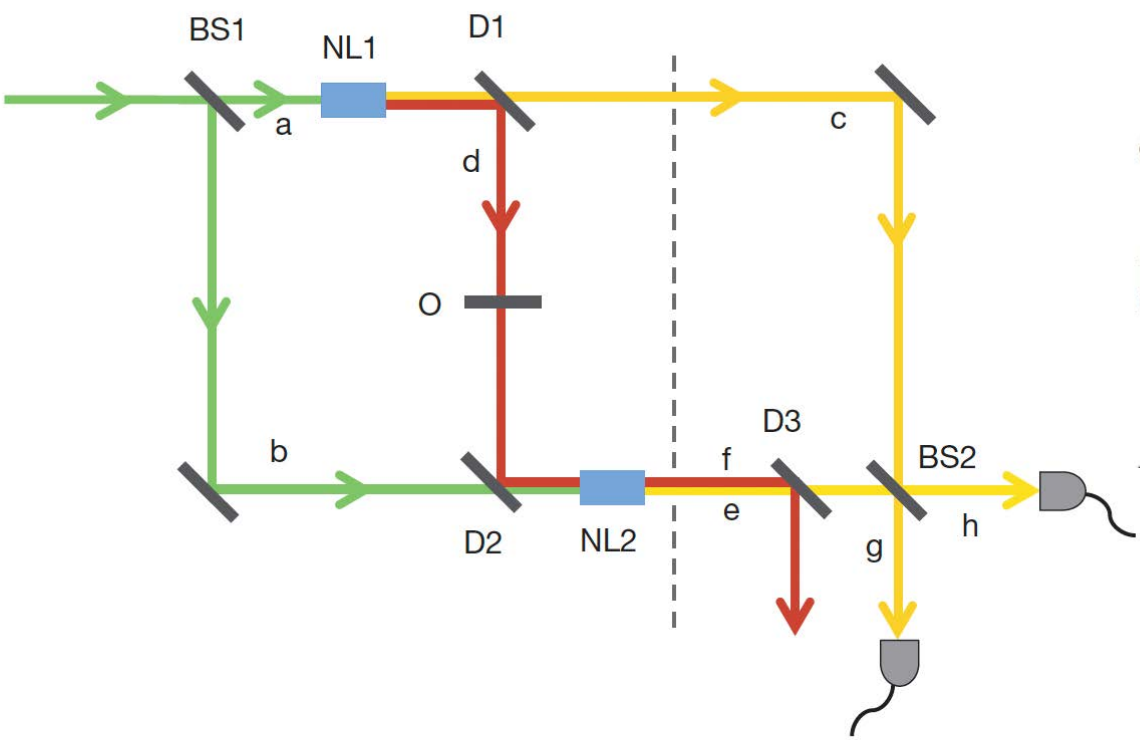
Quantum Imaging with Undetected Photons

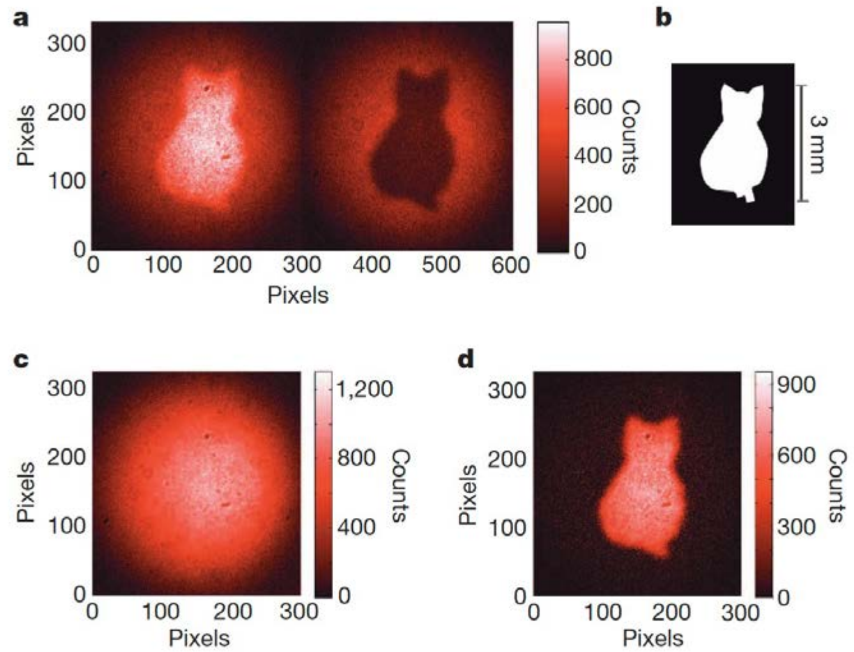
Quantum imaging with undetected photons

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?



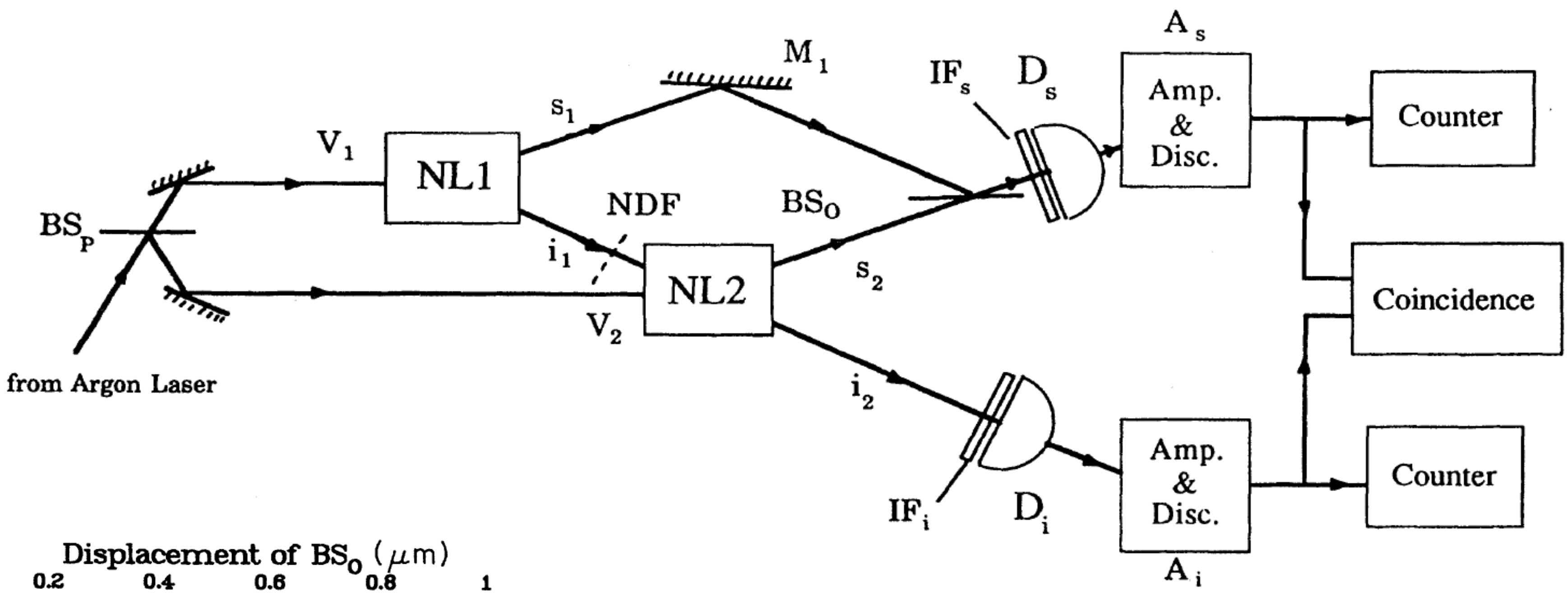


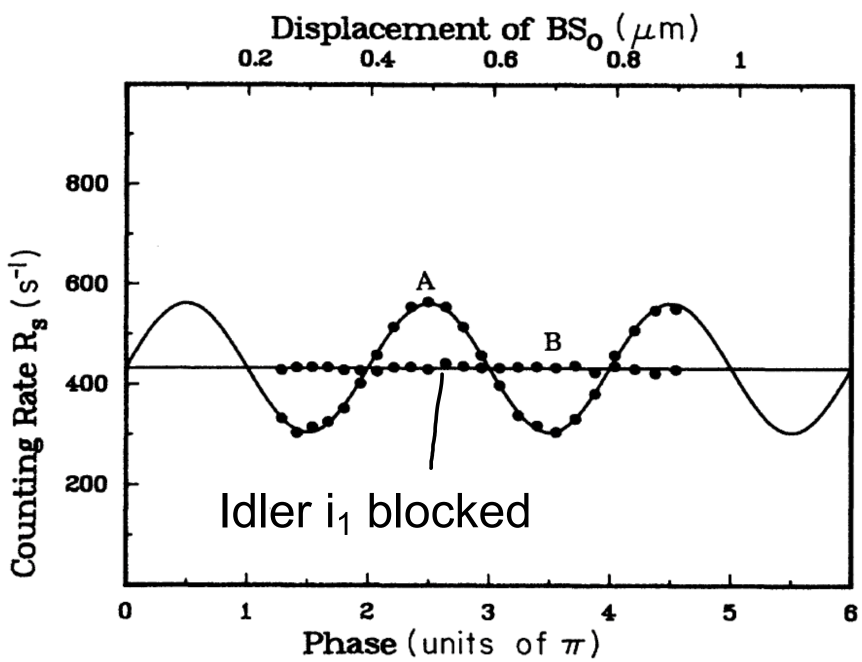
Very famous paper. Can we improve image quality?

Induced coherence without induced emission

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

INDUCED COHERENCE WITHOUT INDUCED EMISSION





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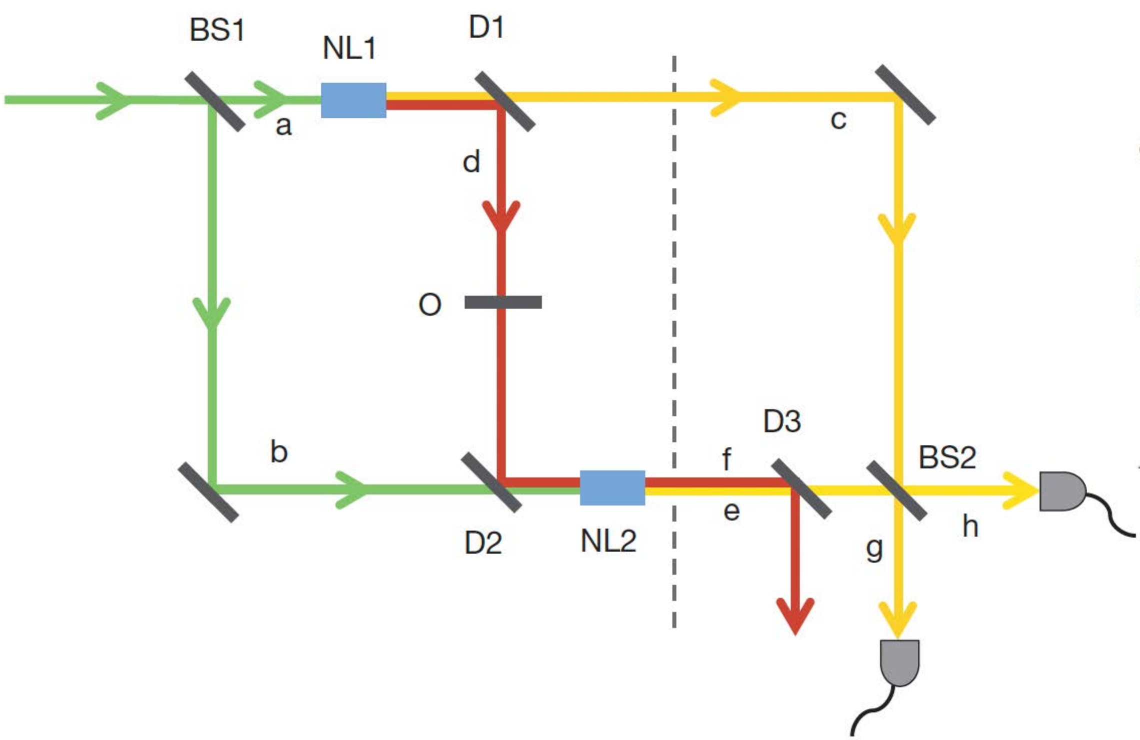
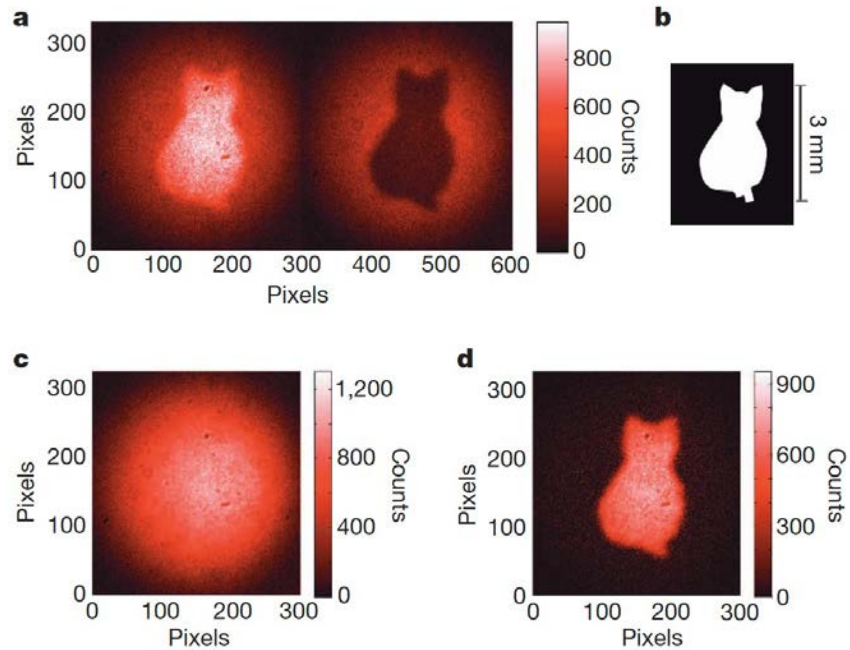




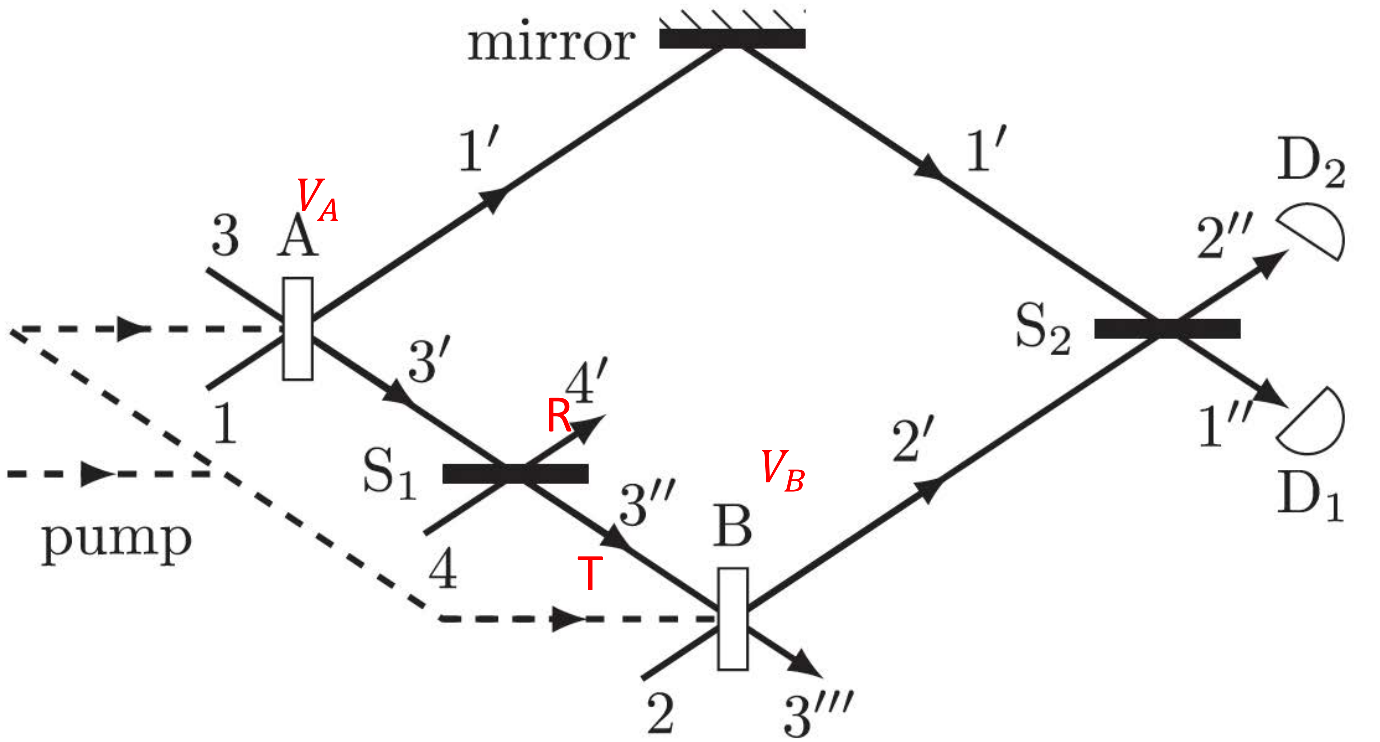
Very famous paper. Can we improve image quality?

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

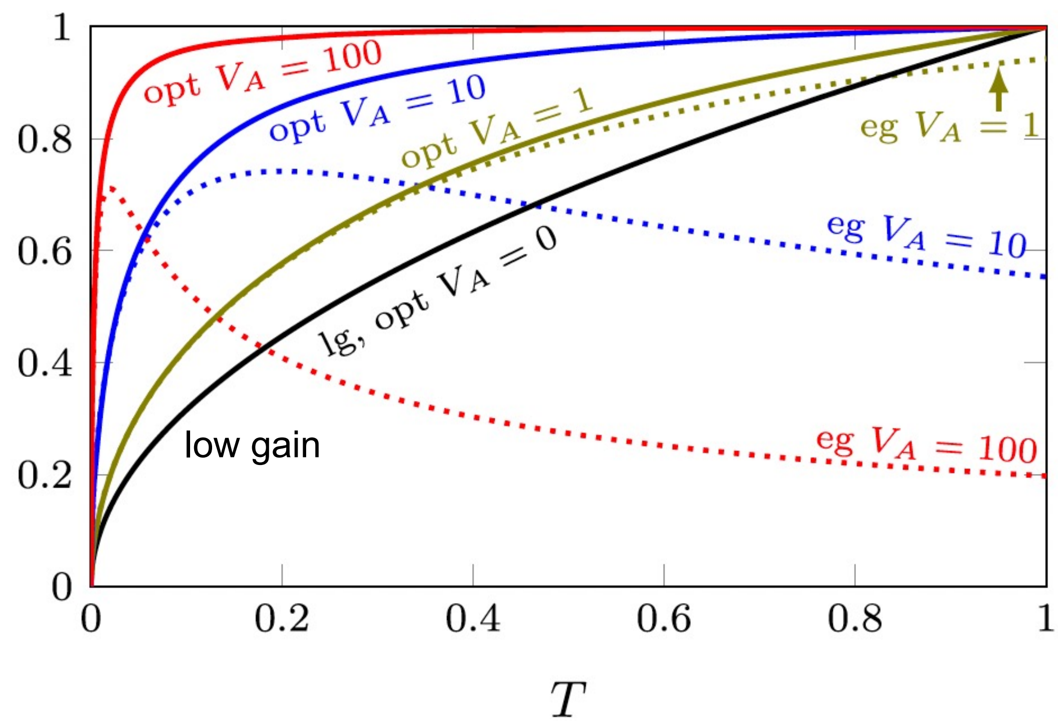


- How are visibility and SNR of the quantum interference influenced by working in the high-gain limit (V_A and V_B greater than unity) of parametric down-conversion?
- Here V_A and V_B are the parametric gains of NL crystals A and B.
- We also study imbalanced pumping, V_A not equal to V_B

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

We also find a higher signal-to-noise ratio (SNR) by working in the high-gain limit

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	$V_A \gg 1,\ V_B << 1$	$\mathcal{V}^{(hgs)} = 2\sqrt{V_B T} \ll 1$
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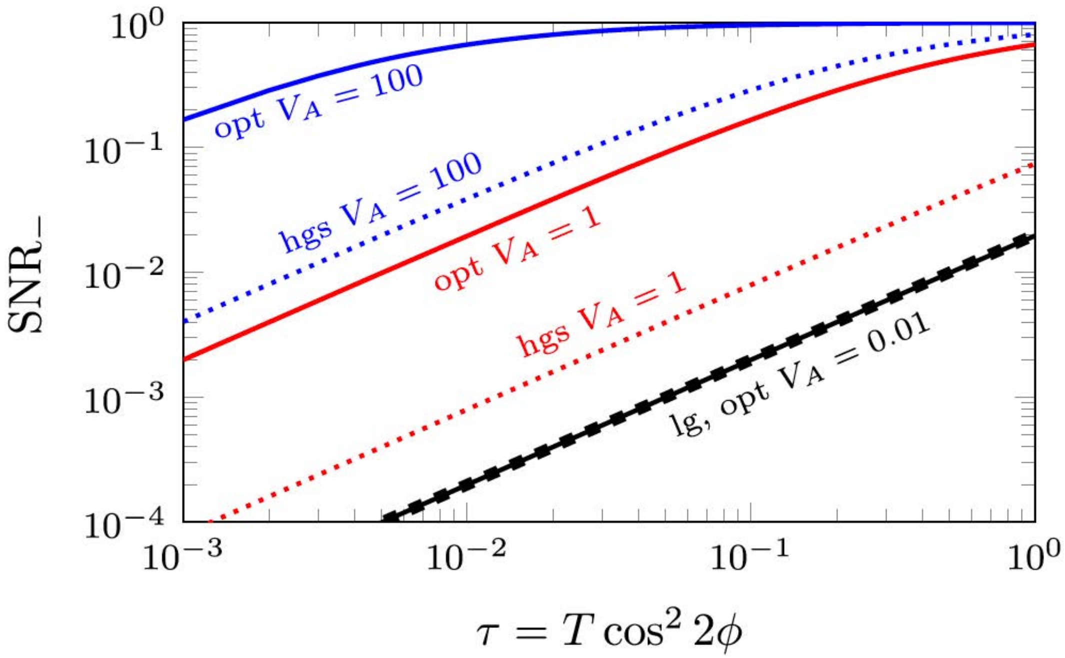


For $T \neq 0$, $SNR_-^{eg} \gg SNR_-^{opt}$

ϕ = phase of the interference fringes

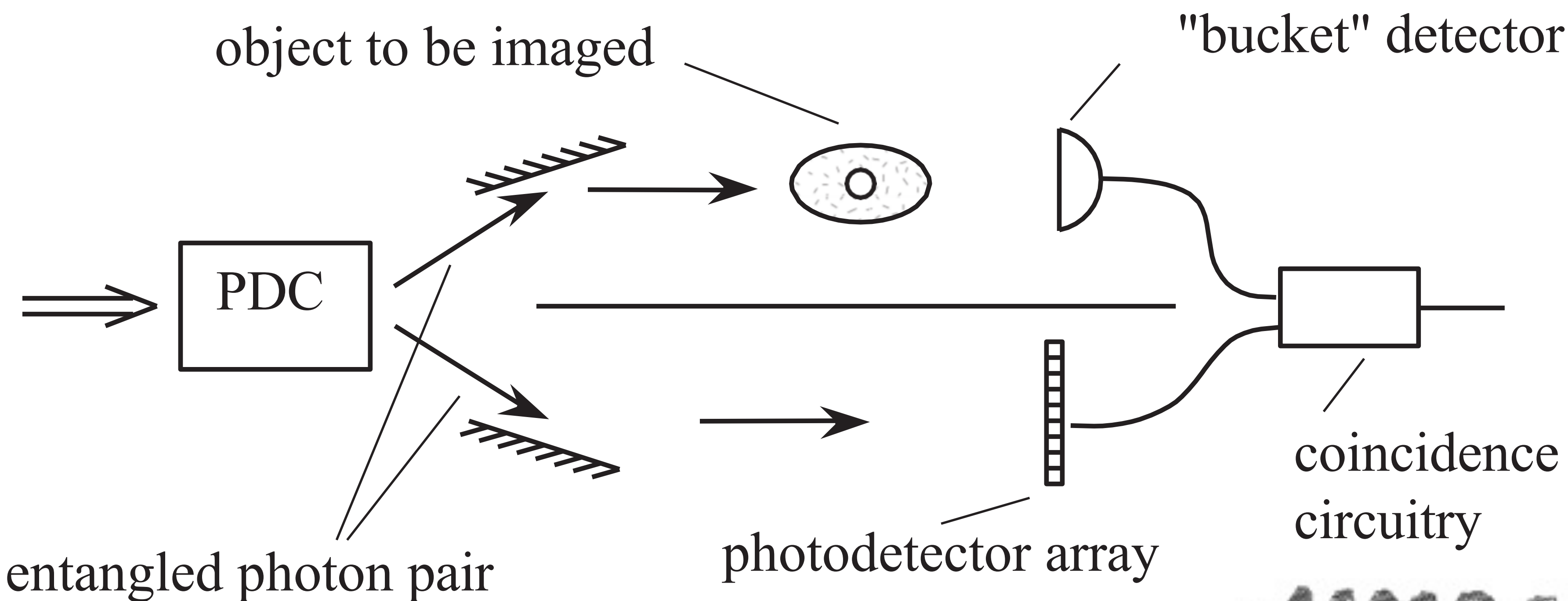
We plot the SNR per laser pulse.

Experiments are being planned.

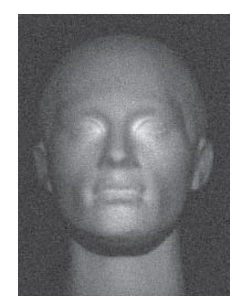
Kolobov et al., J. Opt. 19 (2017) 054003

Interaction-Free 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)

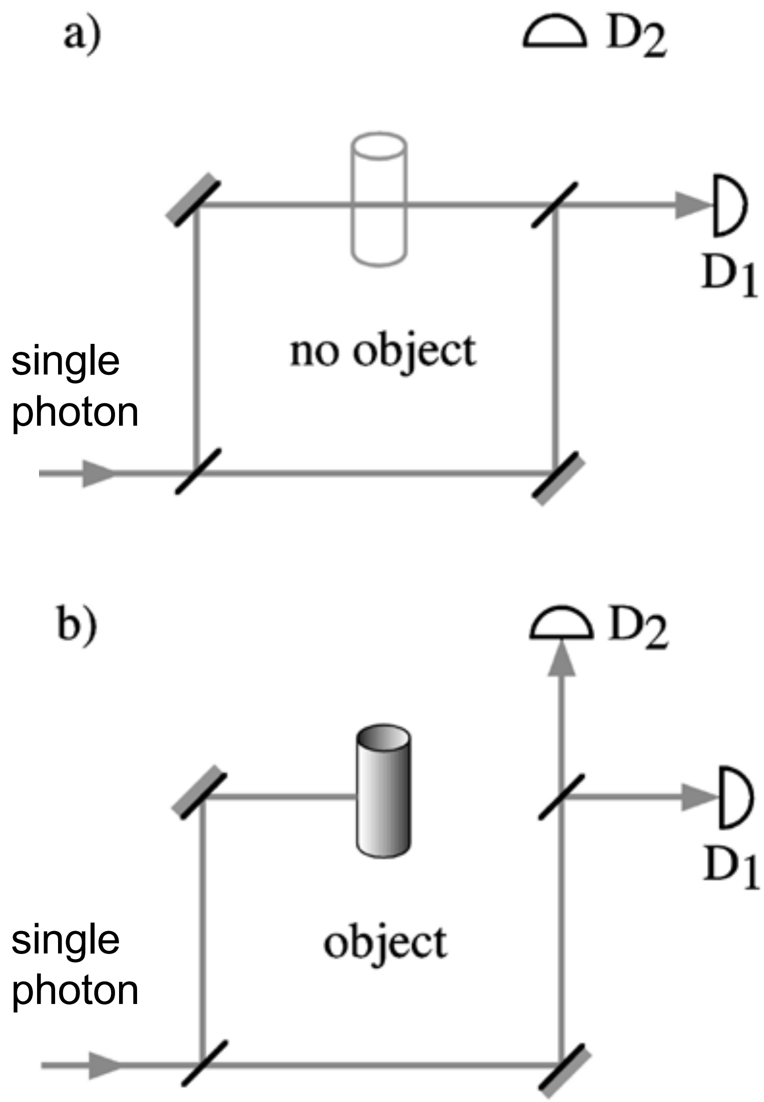


Padgett Group

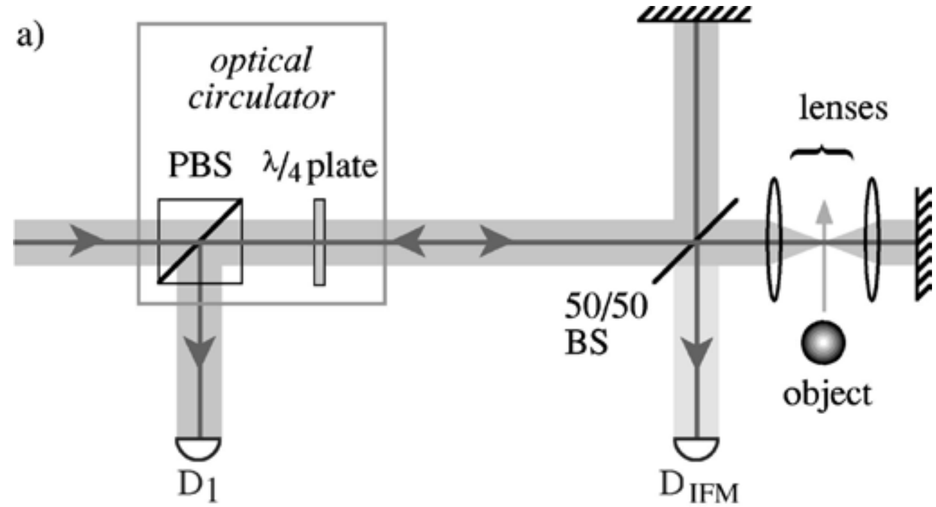
Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).

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)

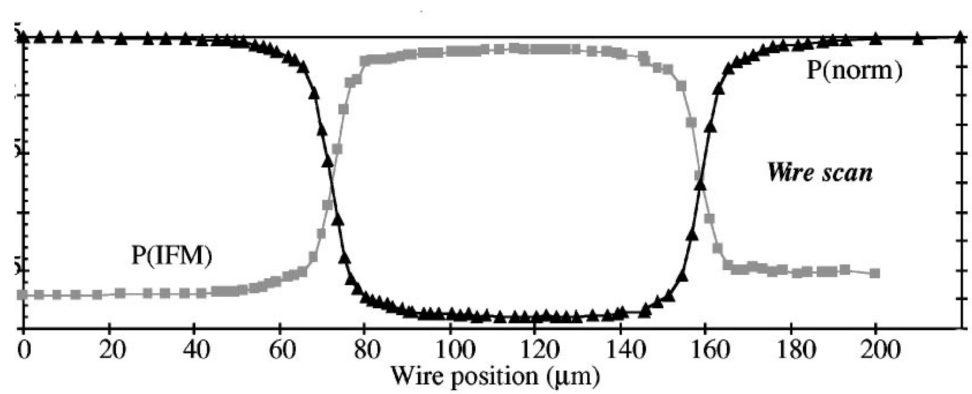
Quantum Imaging by Interaction-Free Measurement



imaging setup

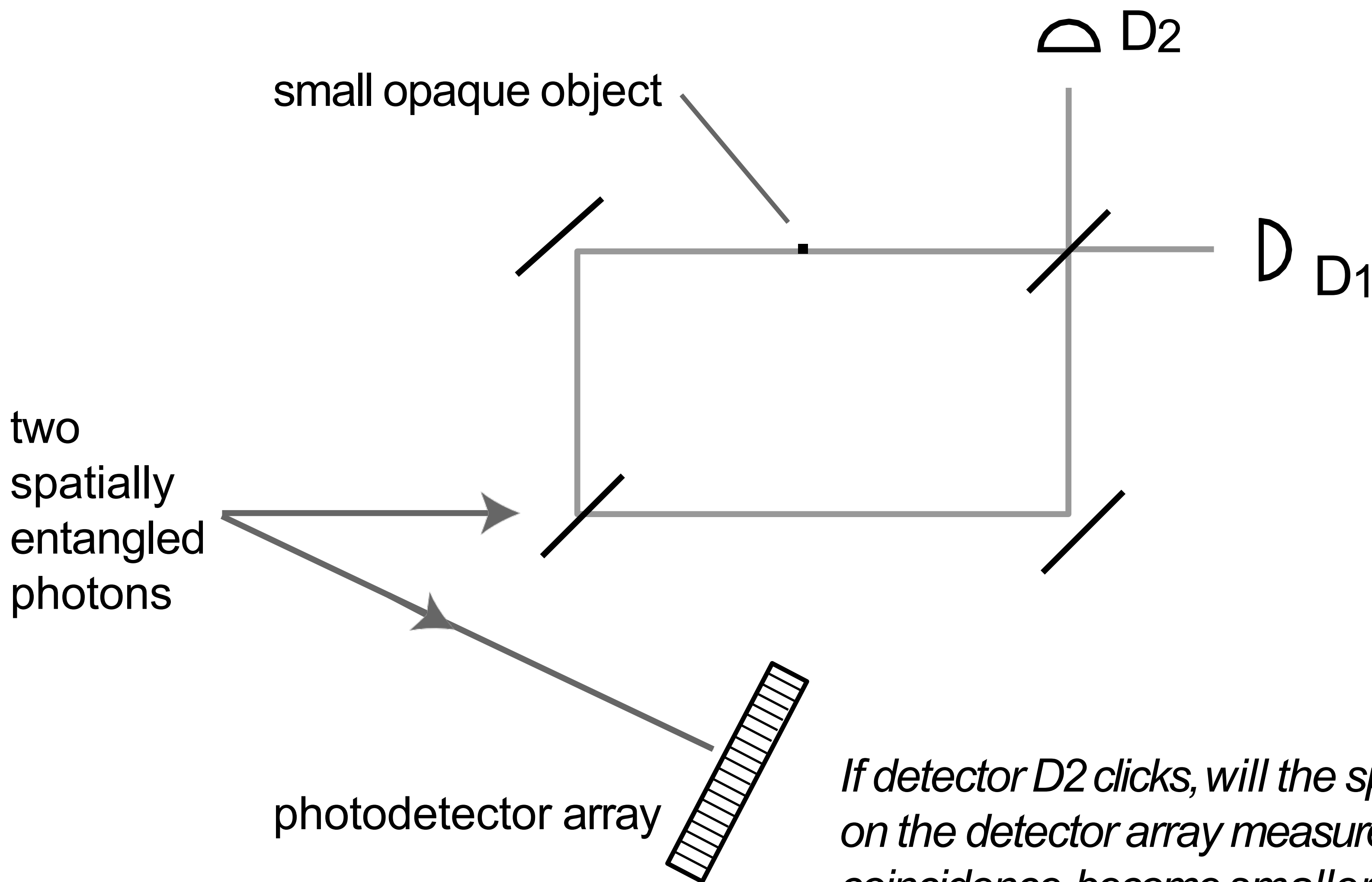


results



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?

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?

Quantum Superresolution

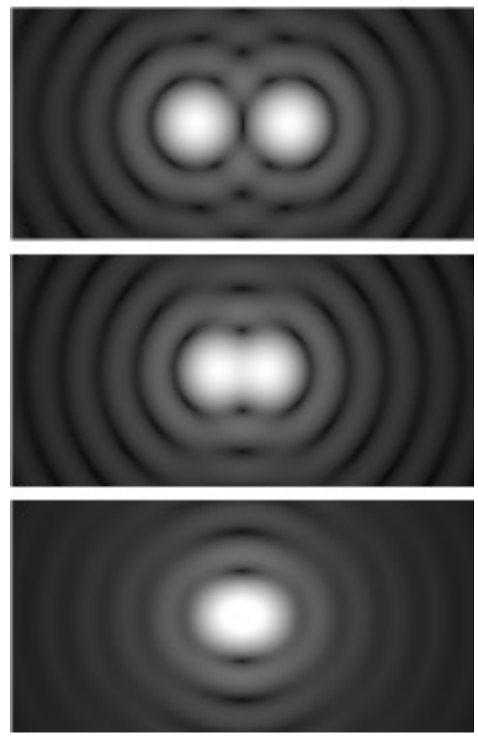
Superresolution

- 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 x.

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

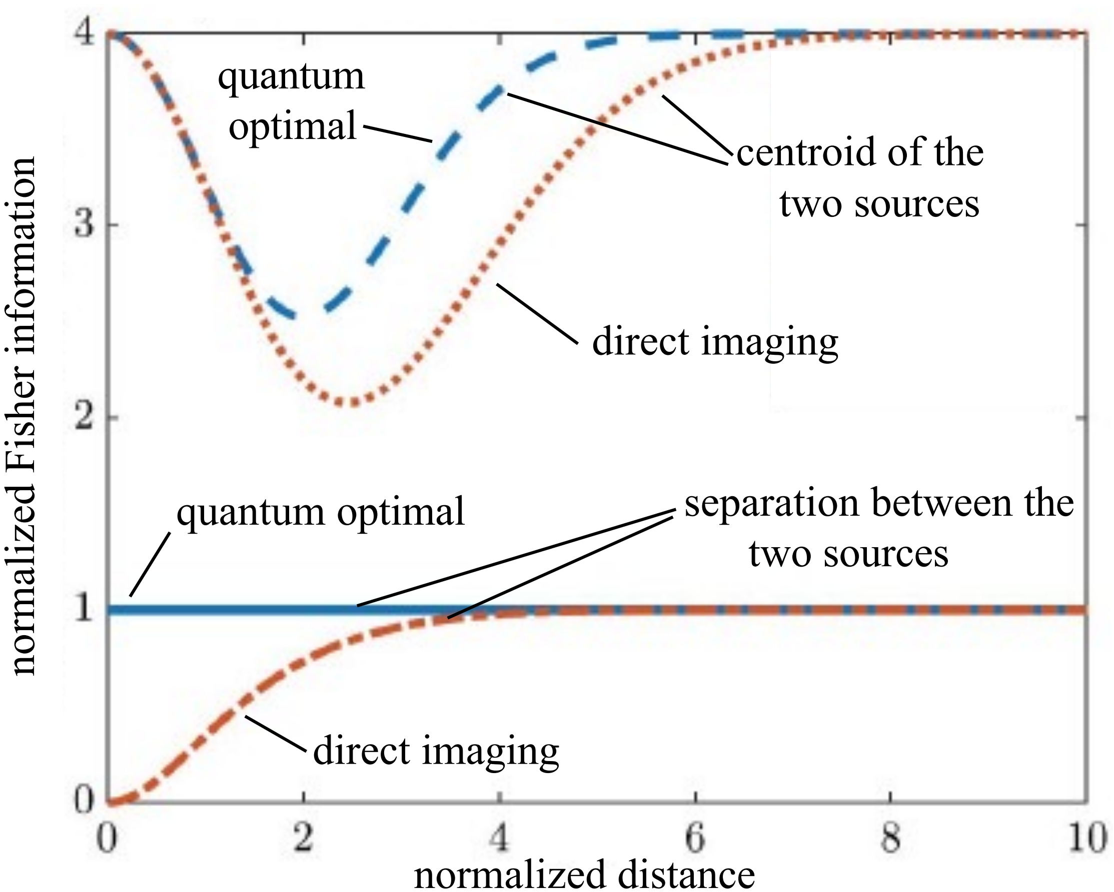
   (a) often a small number of parameters can characterize an image

   (a) techniques exit for characterizing and manipulating LG and HG modes

4. 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 $1.22\, \lambda / D$, 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?

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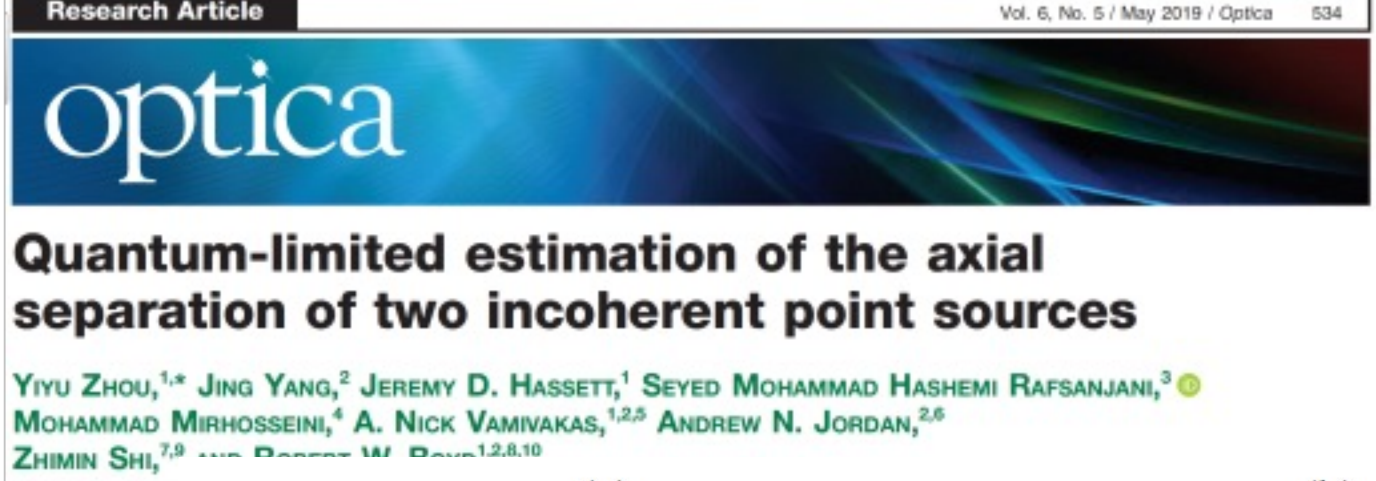
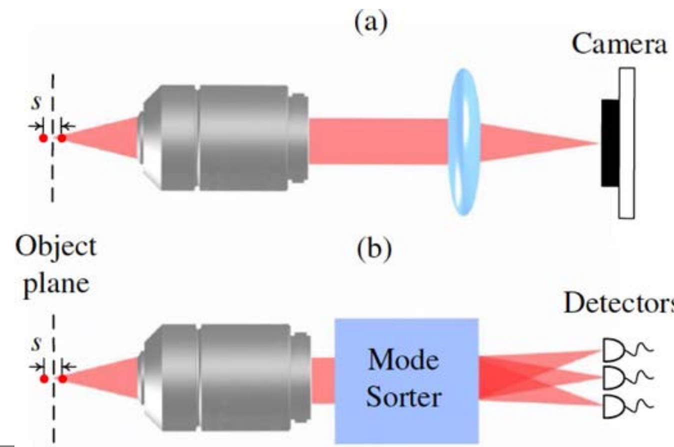
1. M. Tsang, R. Nair, and X.-M. Lu, Phys. Rev. X 6, 031033 (2016).
2. W.-K. Tham, H. Ferretti, and A. M. Steinberg, Phys. Rev. Lett. 118, 070801 (2017).
3. M. Paúr, B. Stoklasa, Z. Hradil, L. L. Sánchez-Soto, and J. Rehacek, Optica 3, 1144 (2016).
4. F. Yang, A. Tashchilina, E. S. Moiseev, C. Simon, and A. I. Lvovsky, Optica 3, 1148 (2016).


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

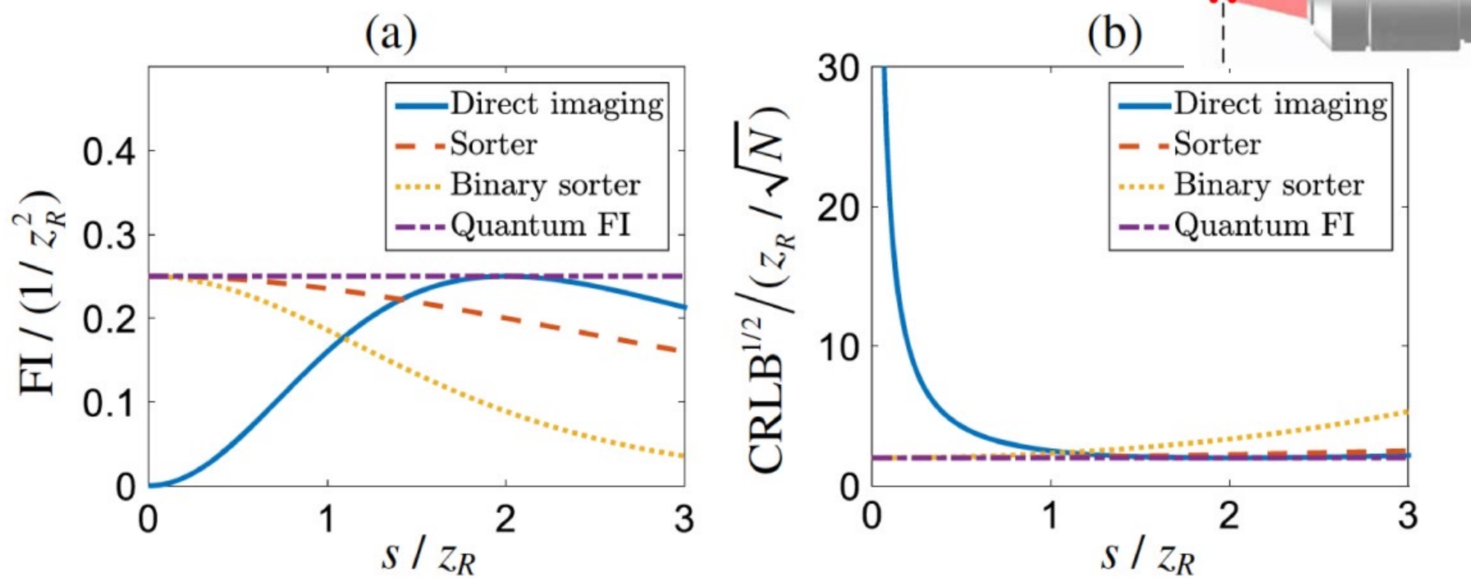
optica

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]

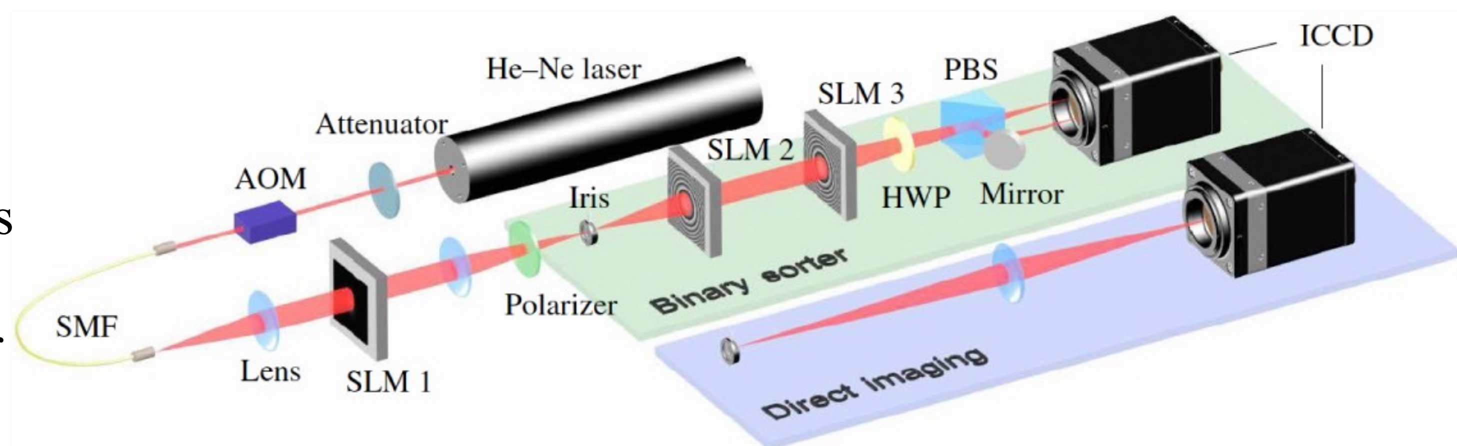


• Theor

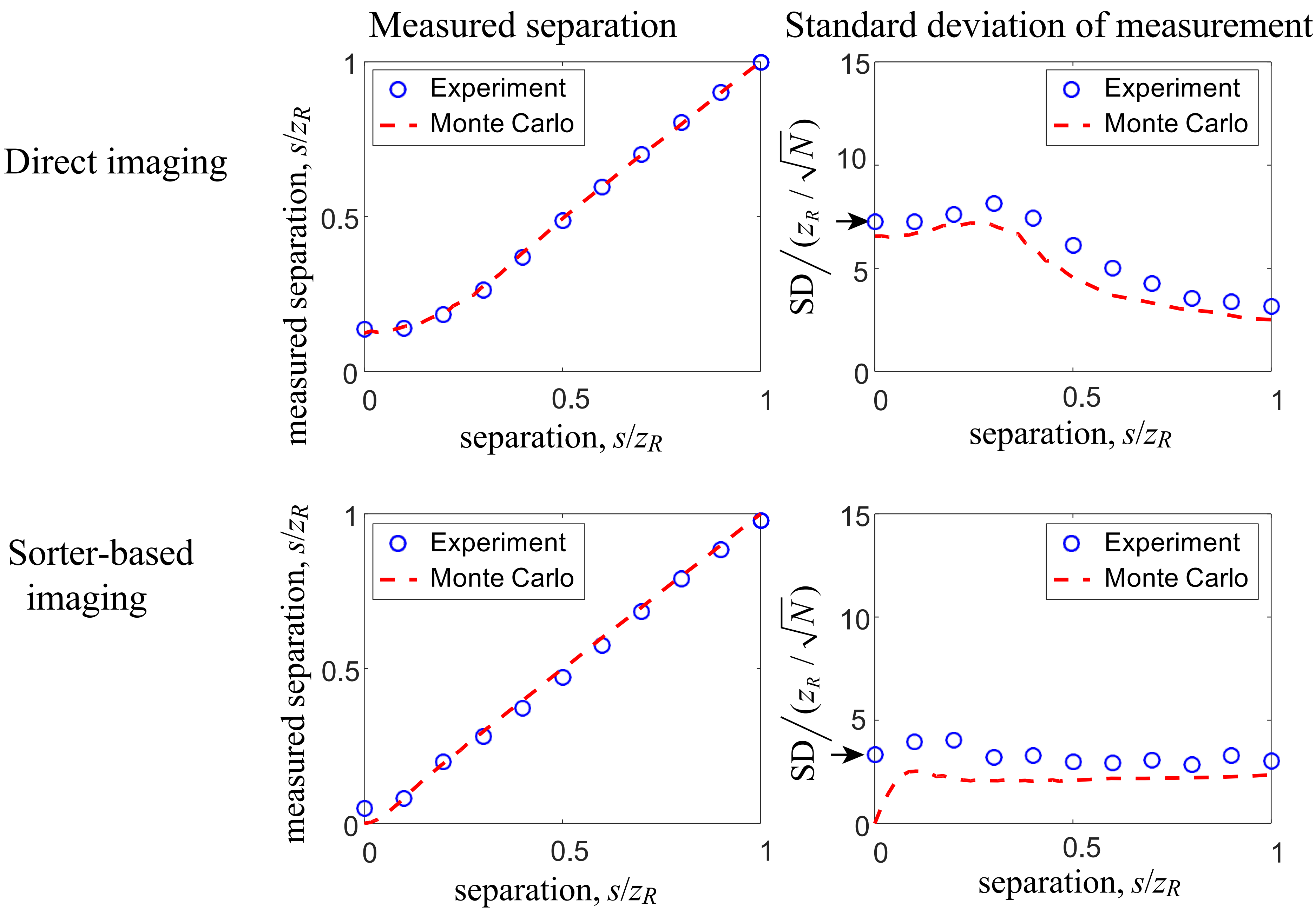


CRLB = Cramer-Rao lower bound = reciprocal of Fisher information

- 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

Mankei Tsang -- Comments

- 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?

Check for updates

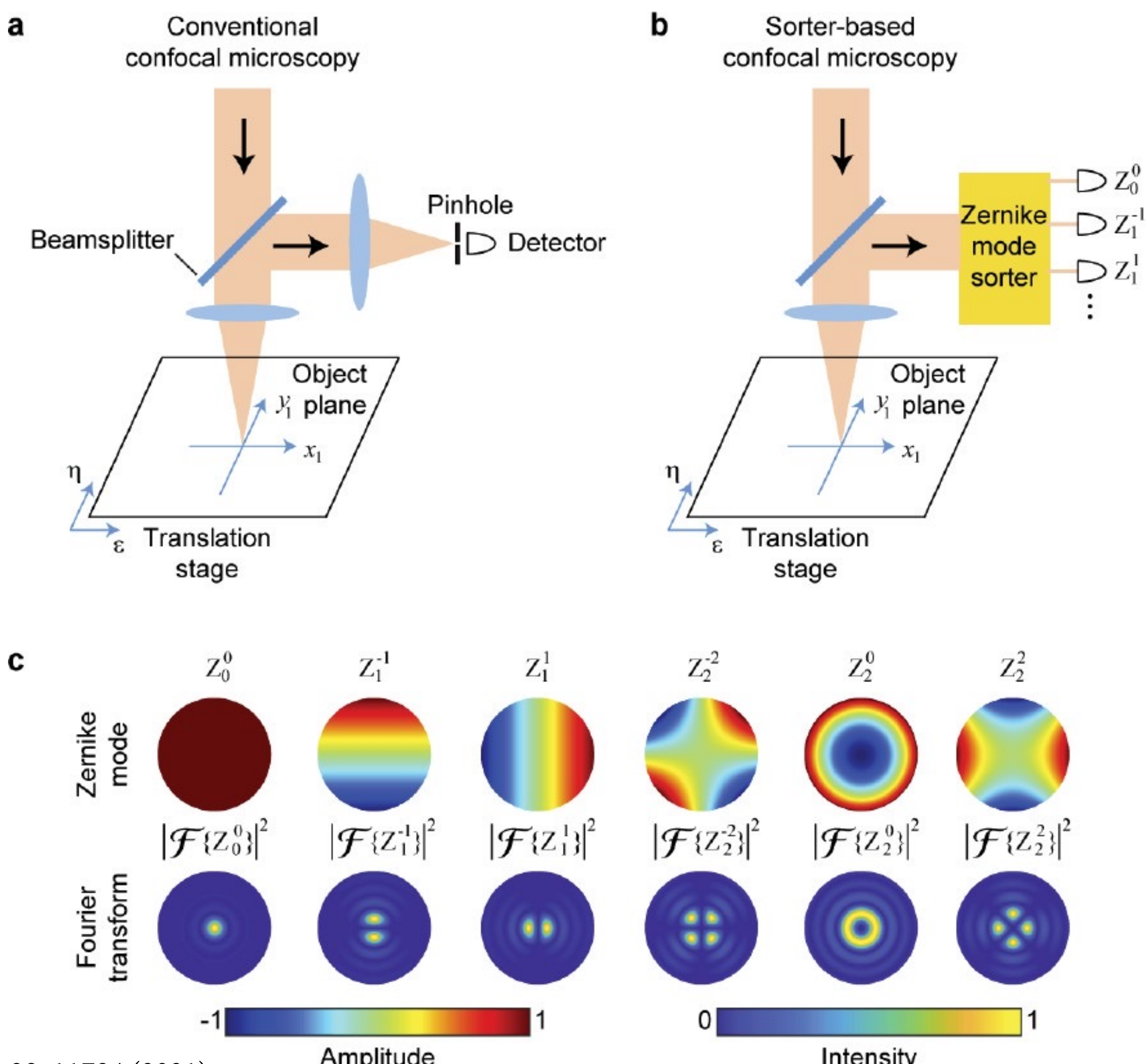
Optics EXPRESS

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]

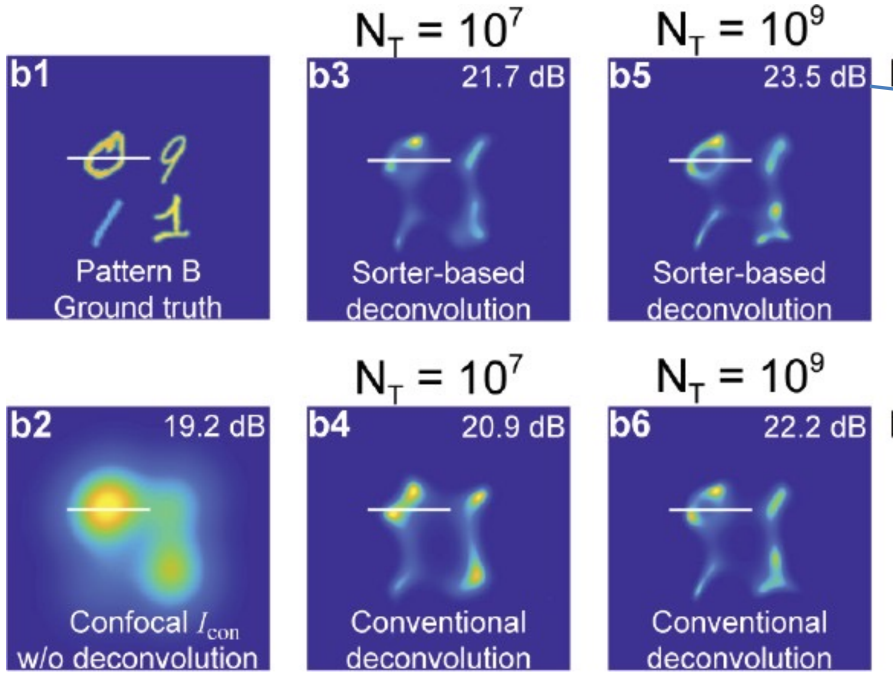
[1]Department of Physics, University of Ottawa, Ottawa, Ontario KIN 6N5, Canada
[2]The Institute of Optics, University of Rochester, Rochester, New York 14627, USA
[3]Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA
[4]Institute for Quantum Studies, Chapman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

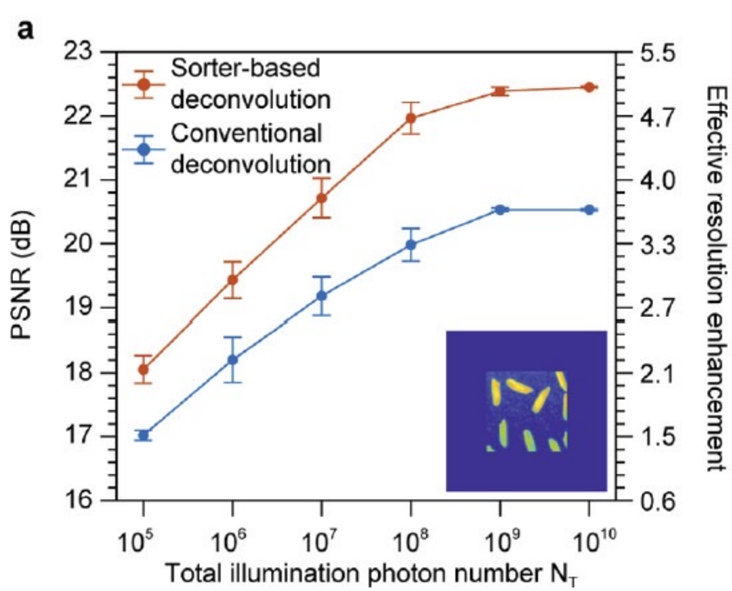
Some Experimental Results

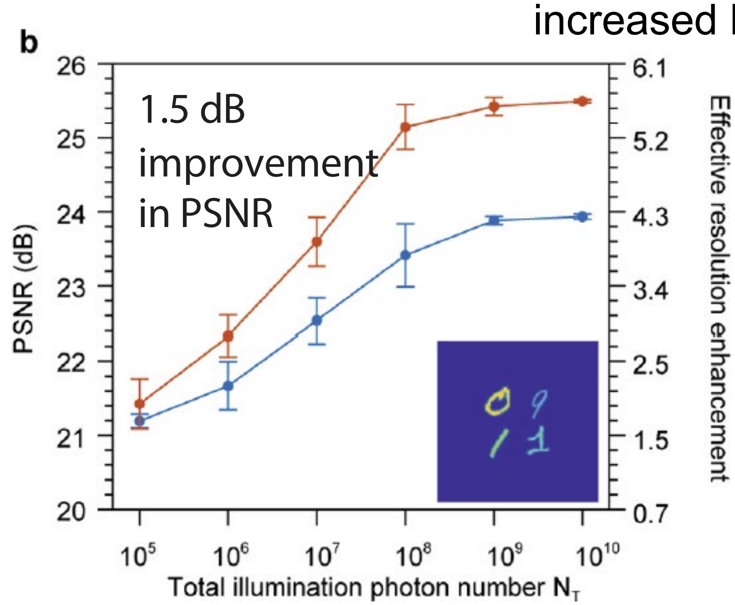


PSNR = peak signal-to-noise ratio

- 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?

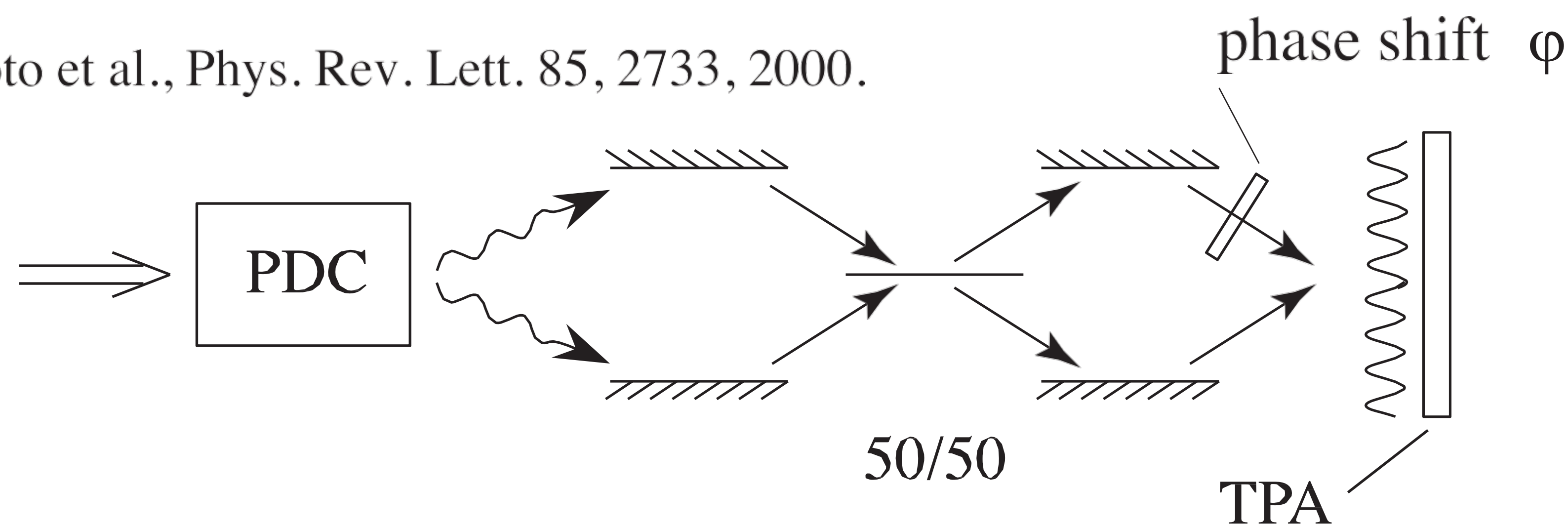
Optics Express 29, 11784 (2021)

Quantum Lithography

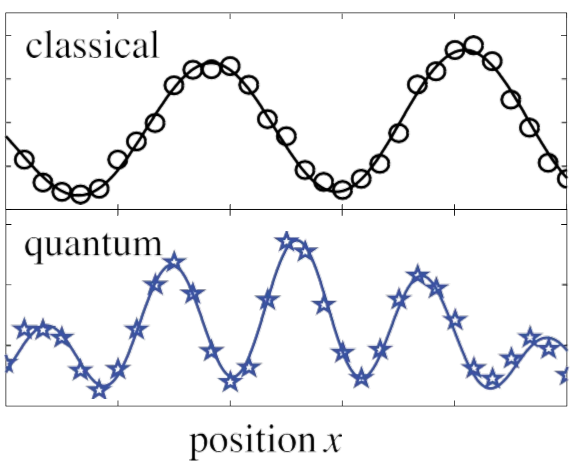
Quantum Lithography: Concept of Jonathan Dowling

- 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).

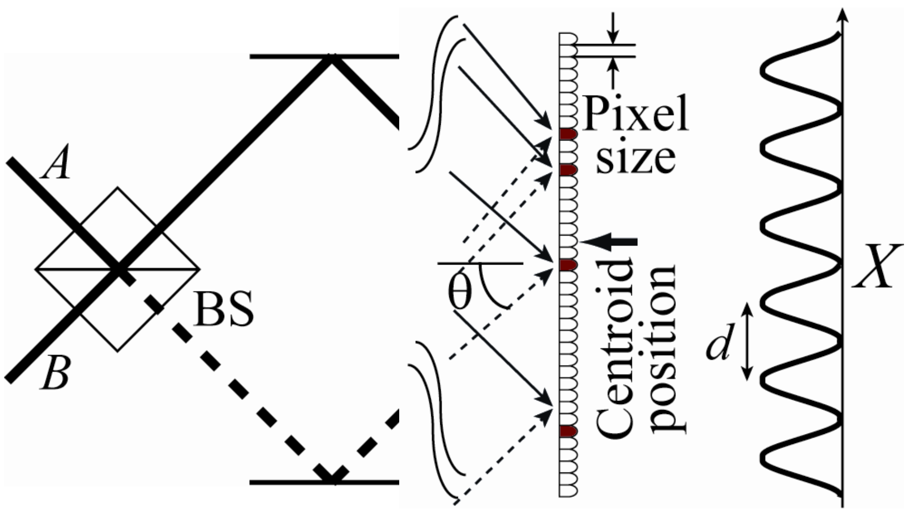
See also, Quantum Lithography: Status of the Field, R.W. Boyd and J.P. Dowling, Quantum Information Processing, 11:891-901 (2012).

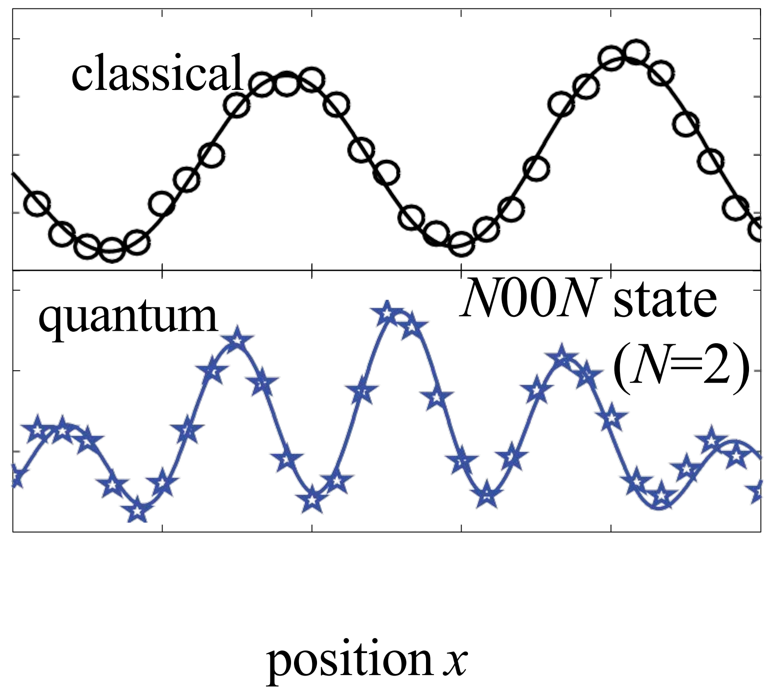
Optical Superresolution based on Entanglement

Entangled photons can be used to write (or read) an image showing increased spatial resolution

Demonstration for a simple interference pattern

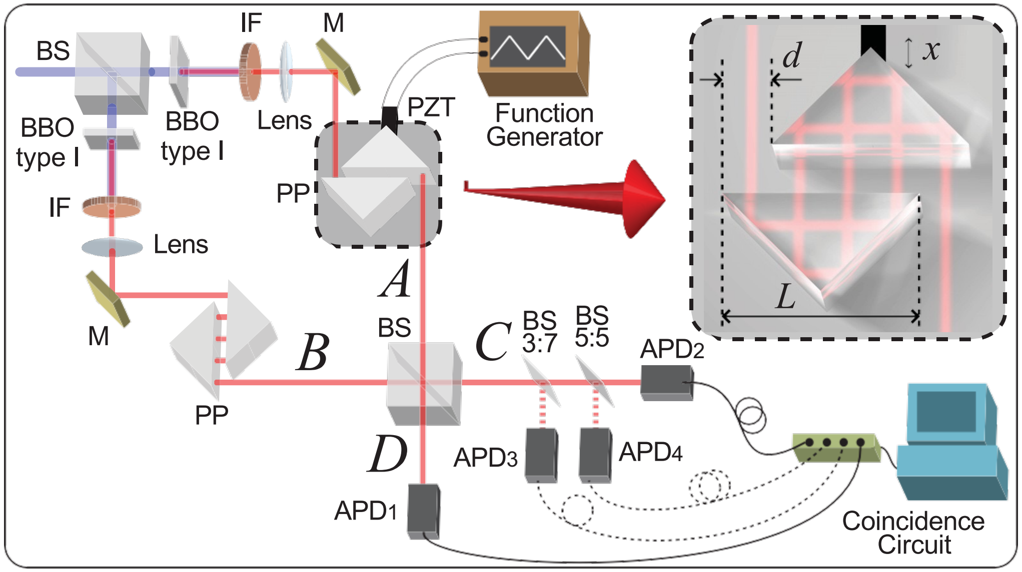
Based on M. Tsang's optical centroid method (PRL, 2009)





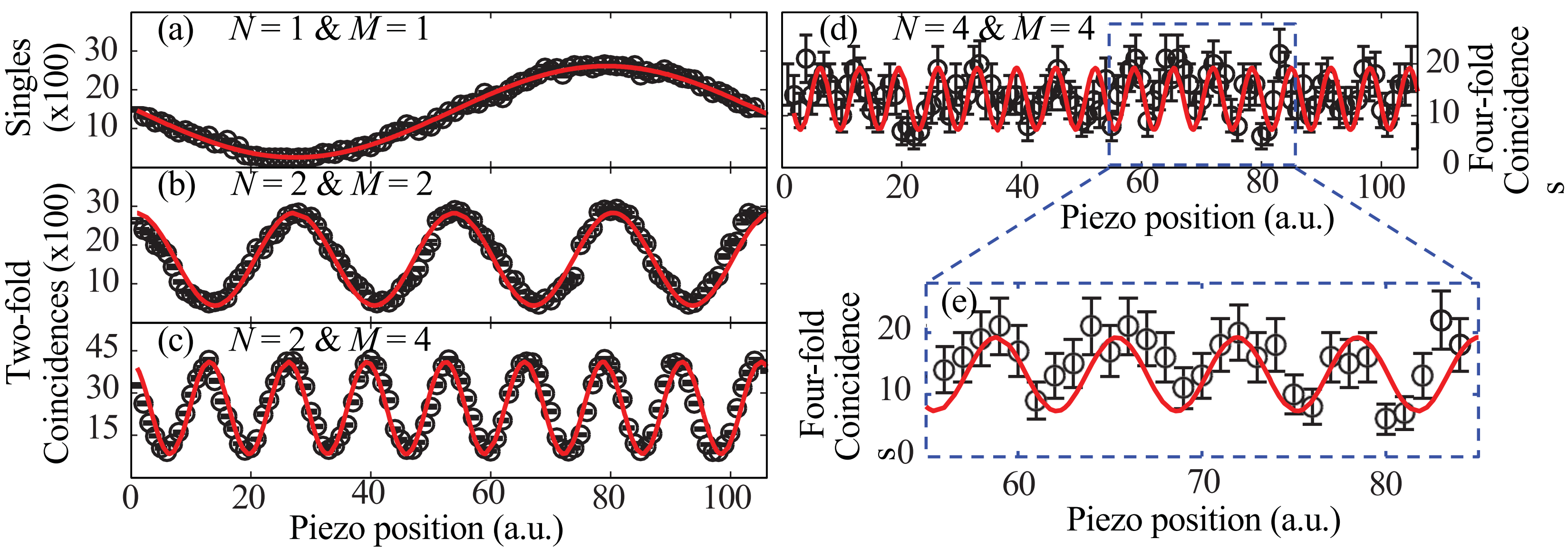
Shin, Chan, Chang, and Boyd, Phys. Rev. Lett. 107, 083603 (2011).

16-fold Increase in the Resolution of a Phase Measurement



PZT changes the separation of the two prisms. How accurately can we measure the resulting phase shift?

We demonstrated superresolution, not supersensitivity.



*N*00*N* state, *M* = number of passes though prism pair

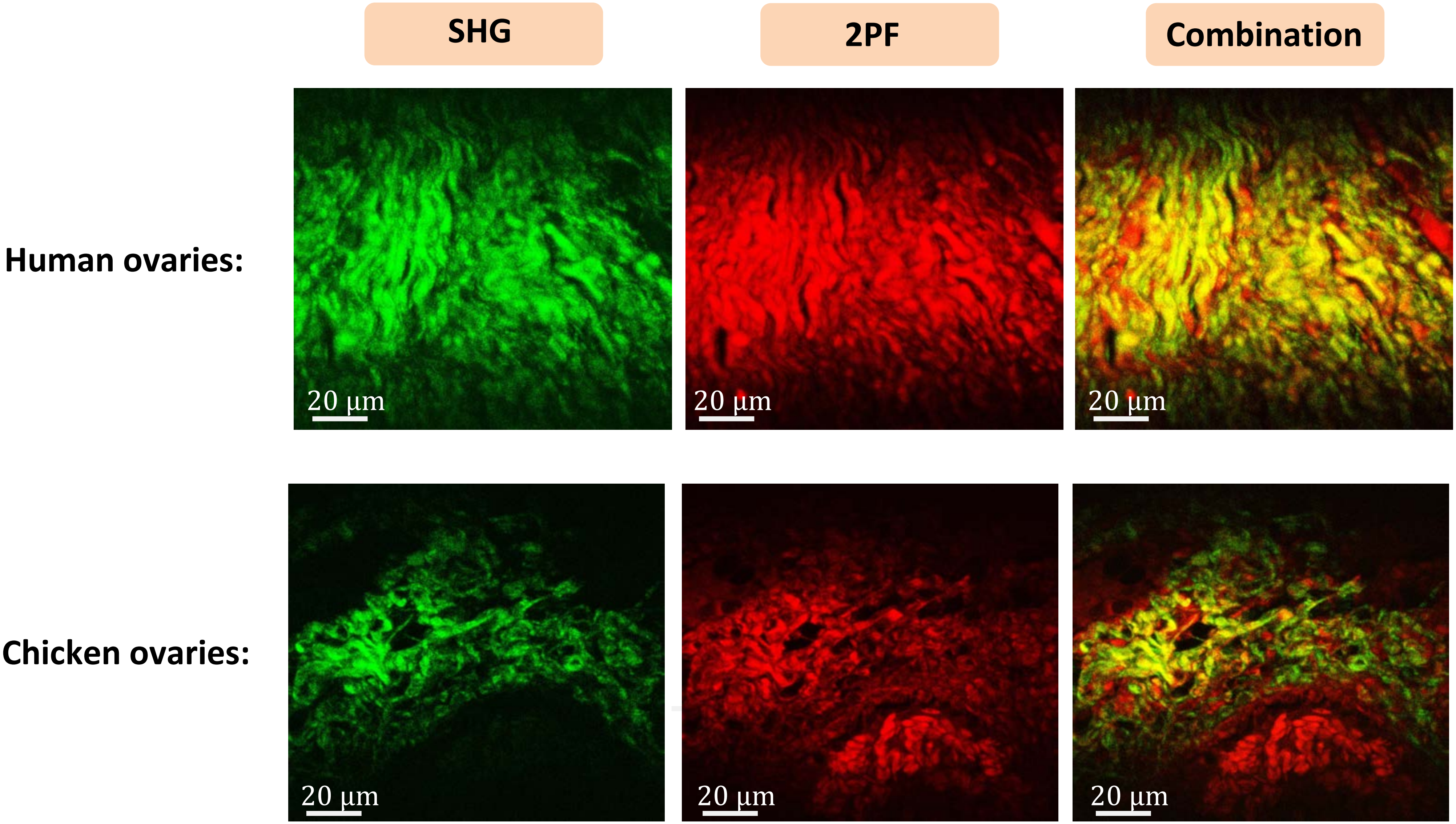
Shin et al., Optics Express 21, 2816 (2013)

Eclipse Photo

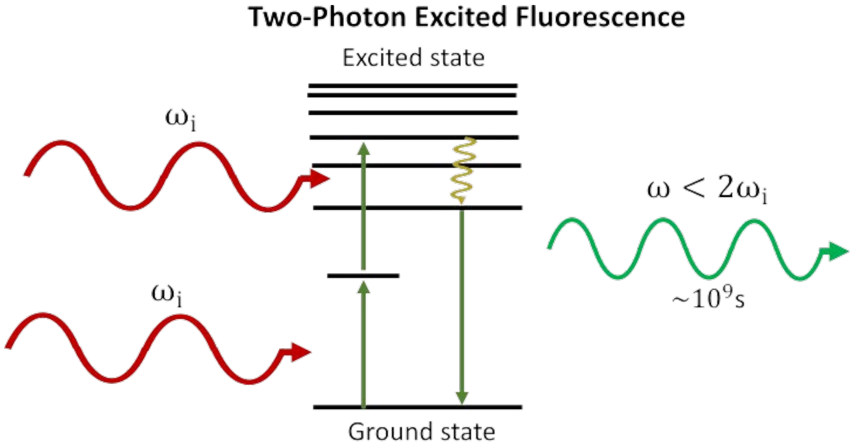
Rochester During the Eclipse

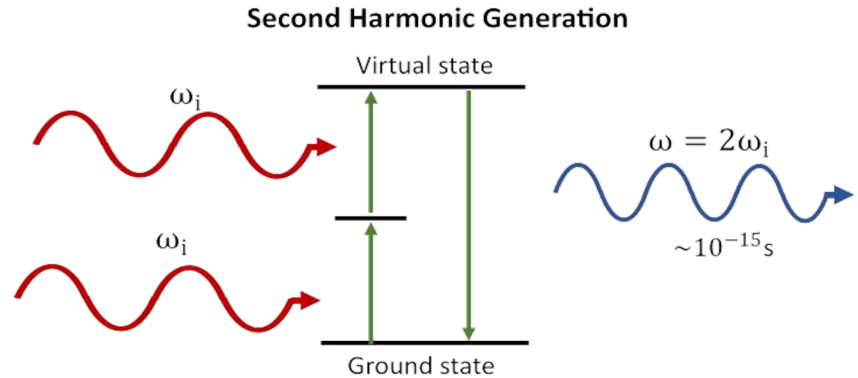
Nonlinear Microscopy for Biomedicine

Nonlinear Optics Can Reveal Structure Not Available Through Linear Optics.



NL microscopic images from chicken and human ovaries





Polarization dependence of collagen's nonlinearity:

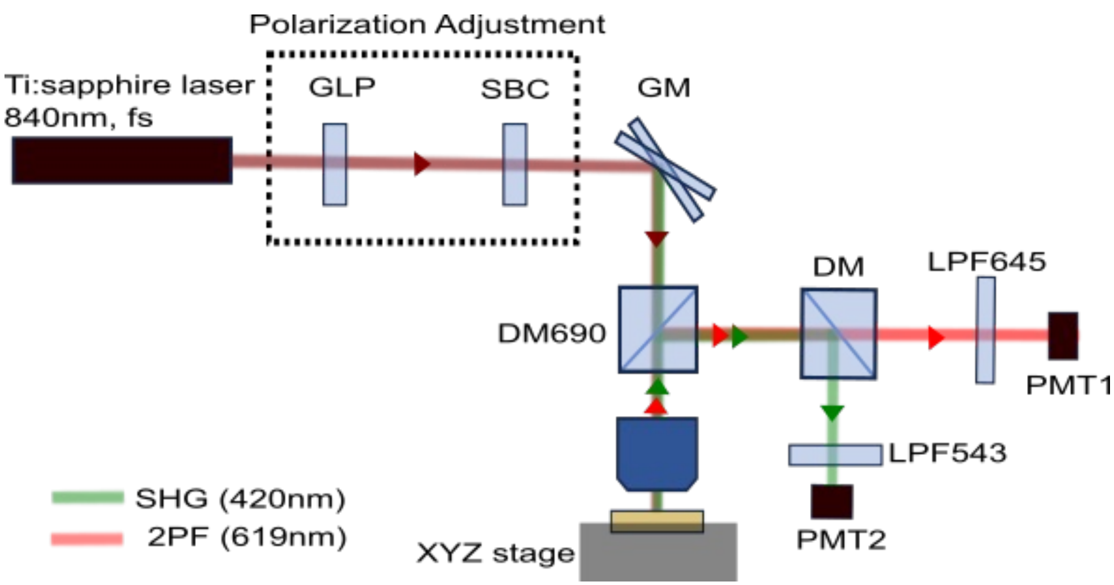
- ✓ Anisotropic Structure
- ✓ Molecular Hyperpolarizability
- ✓ Dichroism and Birefringence
- ✓ Phase-Matching Conditions
- ✓ Optical Alignment and Tissue Organization

Experimental properties:

- ✓ Ti:sappirer, 10 fs, 80 MHz
- ✓ Polarization: Circular
- ✓ Power: 28 mW
- ✓ Excitation wavelength: 840 nm
- ✓ Emission wavelength of SHG: 420 nm
- ✓ Emission wavelength of two-photon excited fluorescent: 619 nm

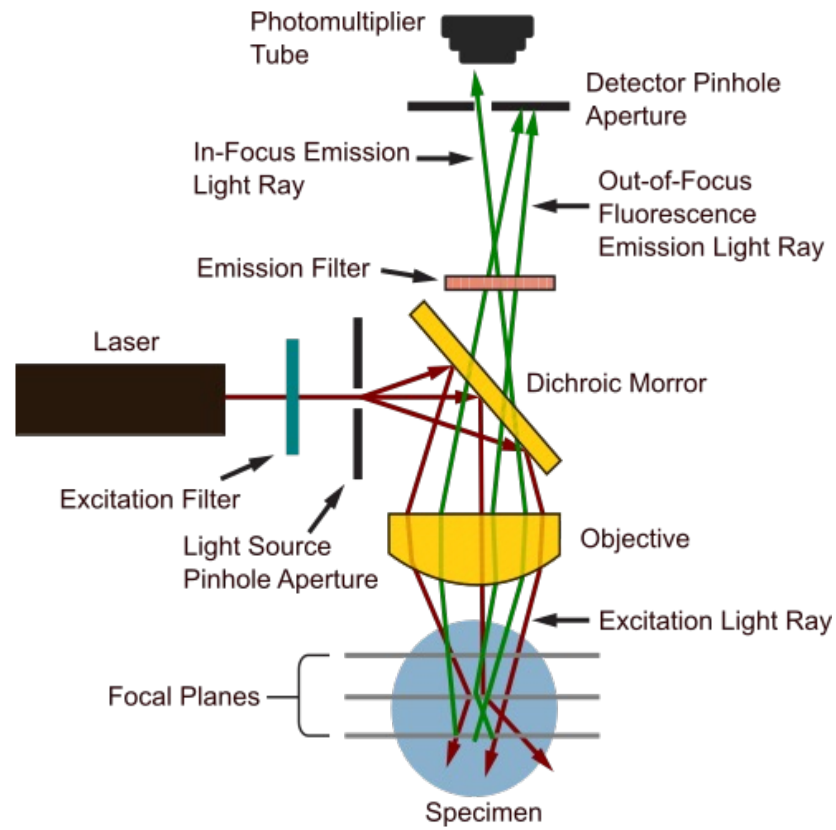
System Layouts

NL microscope



GLP: Glan Laser polarizer
SBC: Soleil-Babinet Compensator
GM: Galvo Mirror
DM690: Dichroic Mirror reflecting 690 nm
LPF645: High-pass filter transferring below 645nm
LPF543: Low-pass Filter transferring below 543 nm

Confocal Microscope



Nonlinear Optical Microscopy

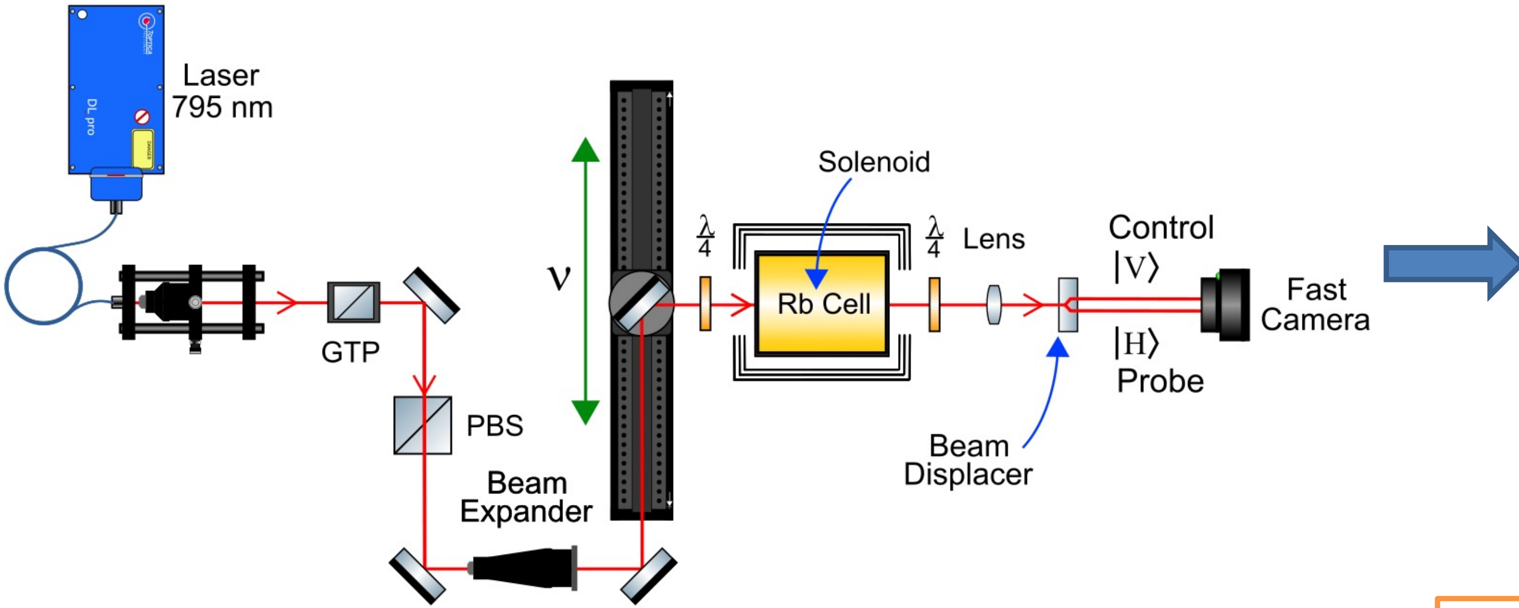
An important application of harmonic generation is nonlinear microscopy.
One motivation for using nonlinear effects and in particular harmonic generation in microscopy is to provide enhanced transverse and longitudinal resolution.
Resolution is enhanced because nonlinear processes are excited
most efficiently in the region of maximum intensity of a focused laser beam. Microscopy based on harmonic generation also offers the advantage that the signal is far removed in frequency from unwanted background light that results from linear scattering of the incident laser beam. Moreover, light at
a wavelength sufficiently long that it will not damage biological materials can be
used to achieve a resolution that would normally require a much shorter wavelength.
Harmonic-generation microscopy can make use either
of the intrinsic nonlinear response of biological materials or can be used with materials that are labeled with nonlinear optical chromophores. Microscopy
based on second-harmonic generation in the configuration of a confocal microscope and excited by femtosecond laser pulses was introduced by Curley et al. (1992).
Also, harmonic-generation microscopy can be used to form images of transparent (phase) objects, because the phase matching condition of nonlinear optics depends sensitively on the refractive index variation within the sample being imaged (Muller et al., 1998).

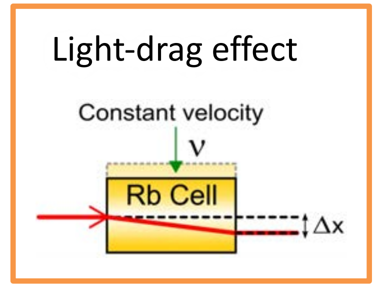
Boyd, NLO, Subsection 2.7.1

Caution!

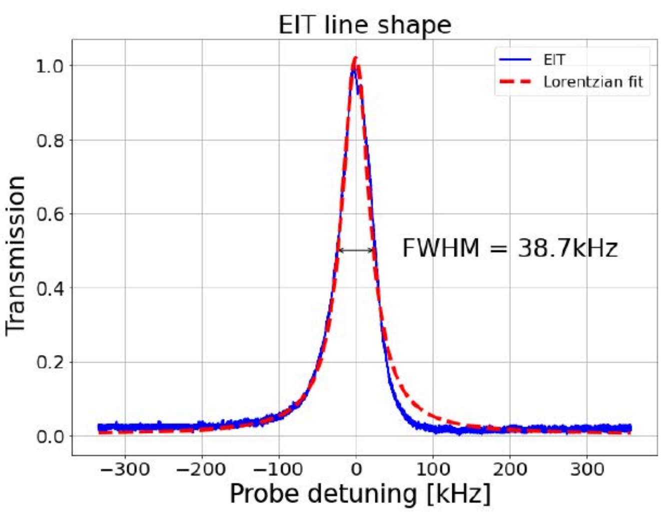
Curley et al., not Curly et al.

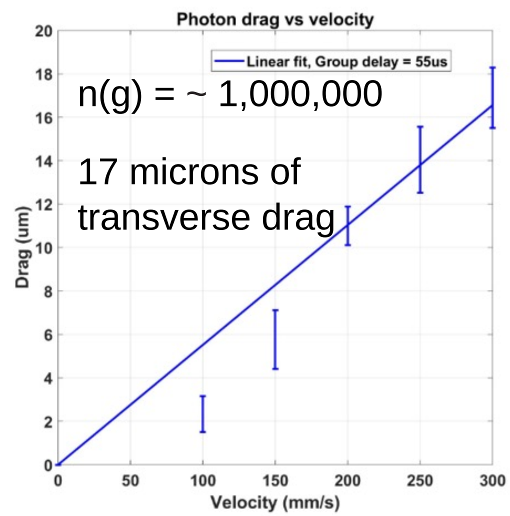
Photon Drag in Slow-Light Media to Create Velocity Meters and Accelerometers



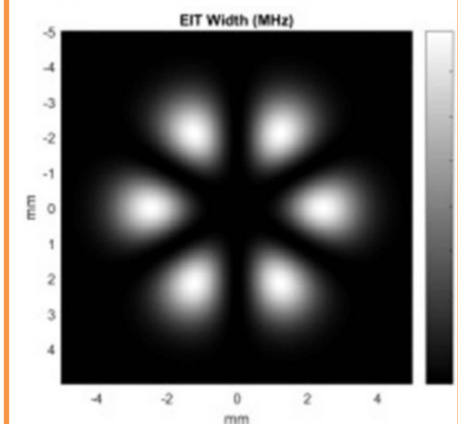


$$\Delta x = \frac{L v n_g}{c}$$





NEXT: Using Structured beams instead of Gaussian beams, we'll be able to measure drag at each point



[1] Solomons, Y., Banerjee, C., Smartsev, S., Friedman, J., Eger, D., Firstenberg, O. and Davidson, N., 2020. Transverse drag of slow light in moving atomic vapor. Optics Letters, 45(13), pp.3431-3434.

[2] Chauhan VS, Kumar R, Manchaiah D, Kumar P, Easwaran RK. Narrowing of electromagnetically induced transparency by using structured coupling light in 85Rb atomic vapor medium. Laser Physics. 2020 May 6;30(6):065203.

Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group