Sharper Images Through Quantum Imaging

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Presented as a Physics Colloquium at McGill University, Montreal QC, Sept. 20, 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

Quantum Imaging Outline

Introduction to Quantum Imaging

Quantum Superresolution

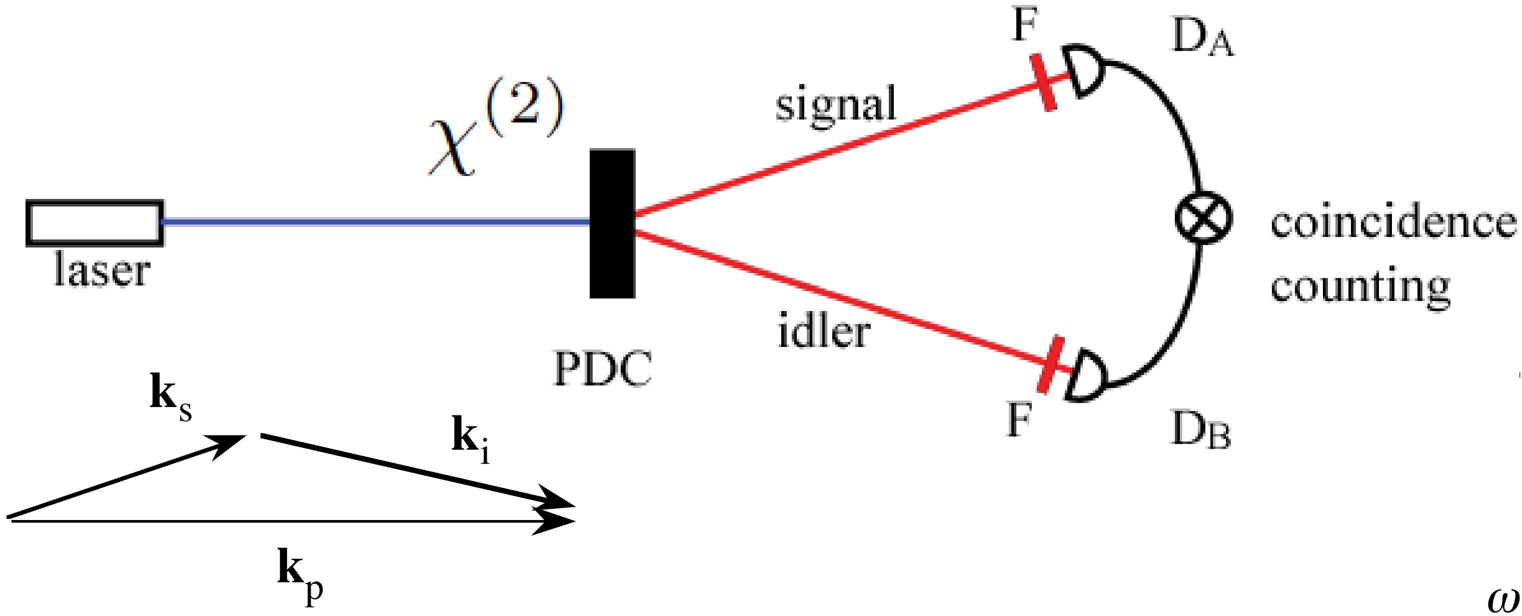
Imaging through Scattering Media

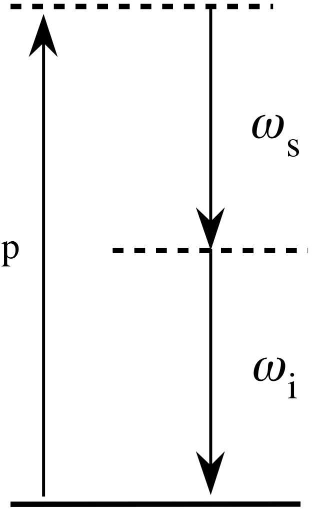
Ghost and Interaction-Free Imaging

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

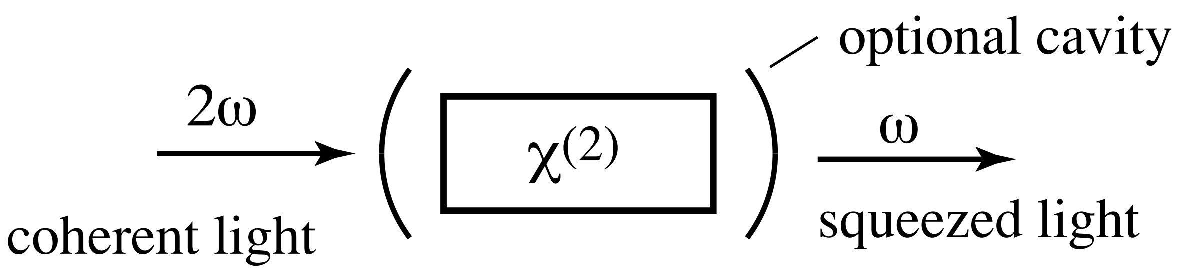
(d) angular position and orbital angular momentum

Entanglement is important for:

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

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

Squeezed Light Generation



2ω

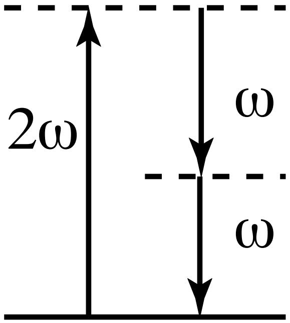
coherent light

$\chi^{(2)}$

optional cavity

ω

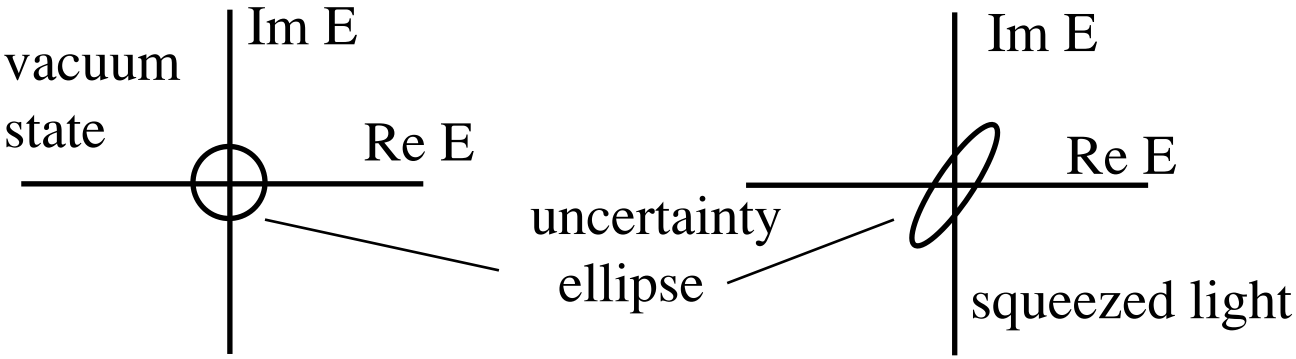
squeezed light



2ω

ω

ω



vacuum state

Im E

Re E

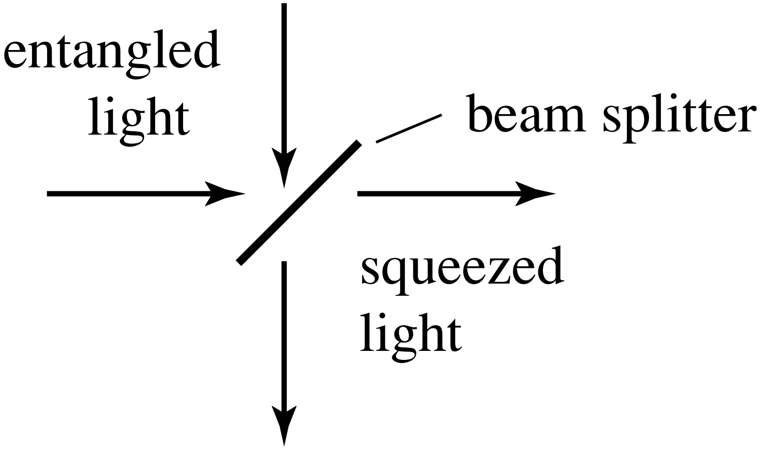
uncertainty ellipse

Im E

Re E

squeezed light

Entanglement and squeezing share a common origin. In fact:



entangled light

beam splitter

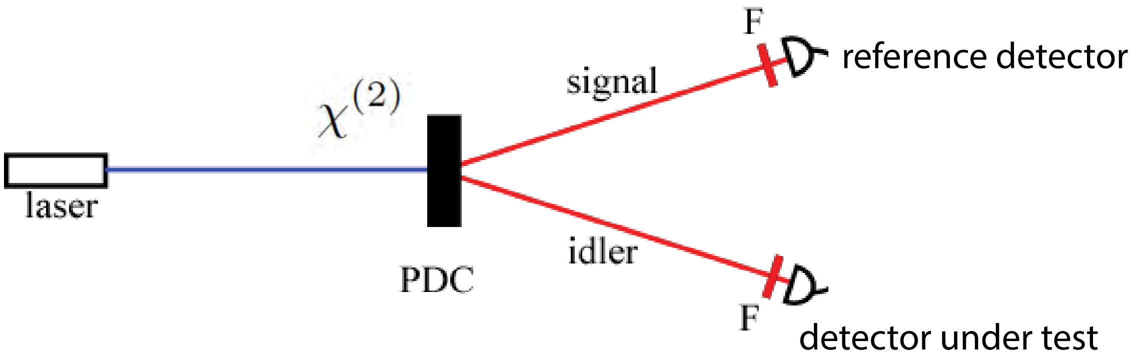
squeezed light

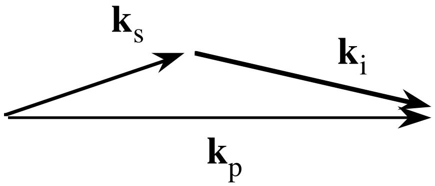
Quantum States of Light

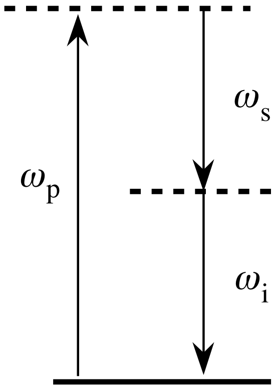
Some examples of applications based on the use of quantum light.

Klyshko's Method for Absolute Calibration of a Photodetector

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



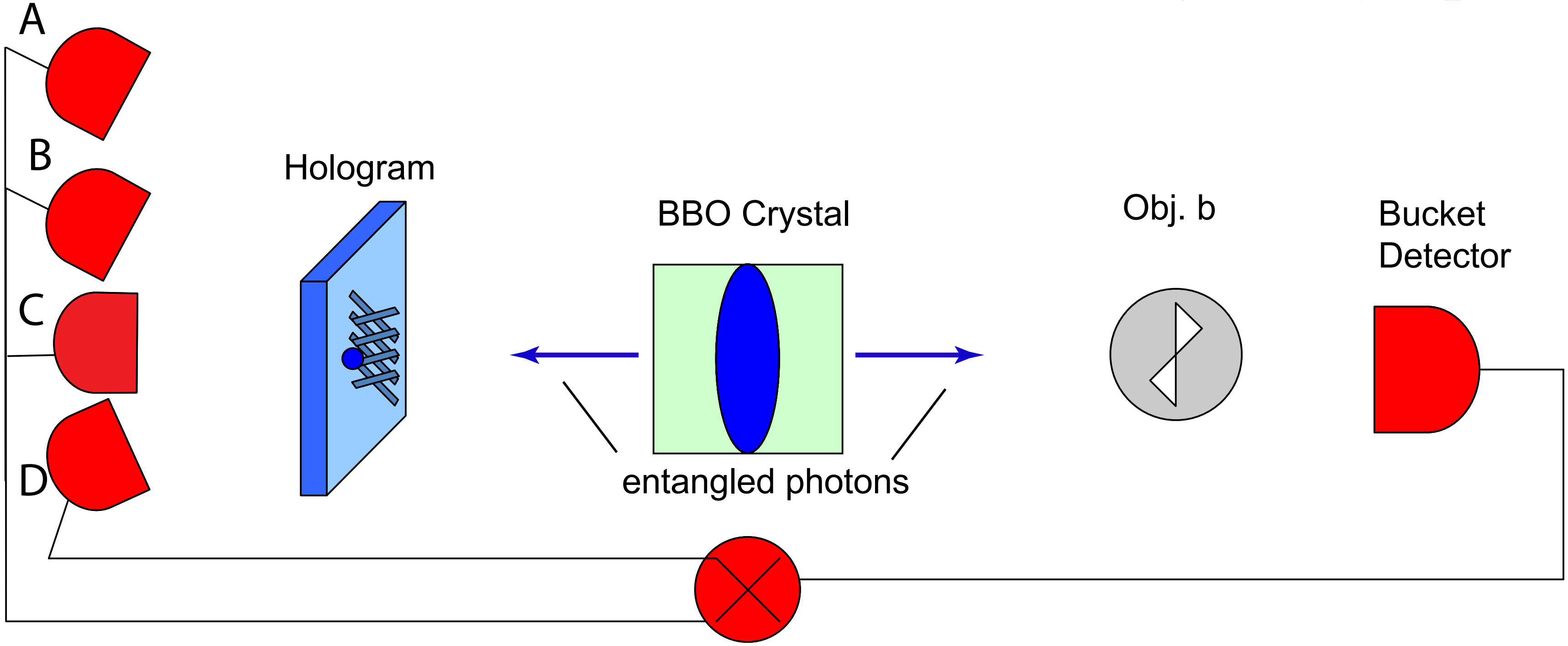




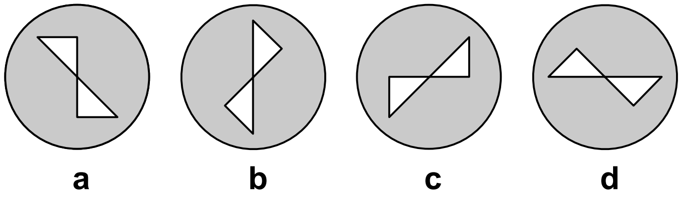
- Earlier work (Klyshko) established that the light produced by spontaneous parametric downconversion (SPDC) can be characterized in terms of the radiometric property known as brightness (or radiance).

Single-Photon Coincidence Imaging (or rather Sorting)

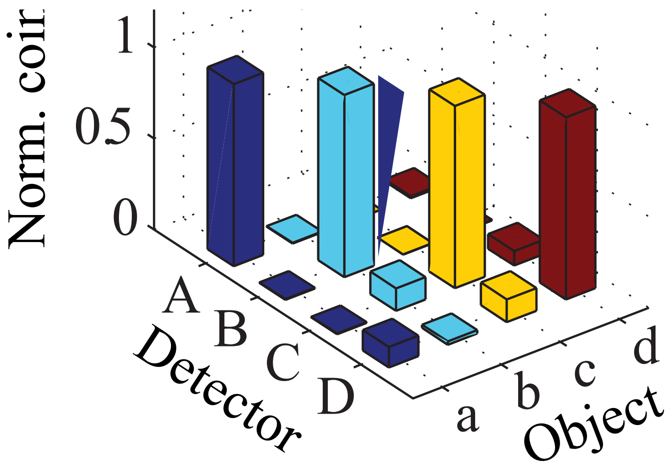
How much information can be carried by a single photon?



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

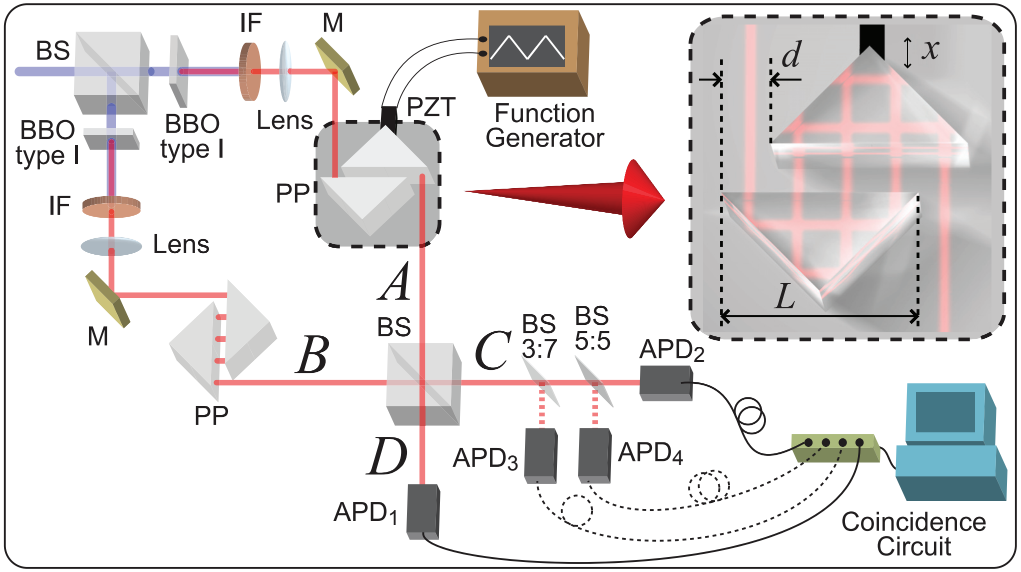


coincidence count rate



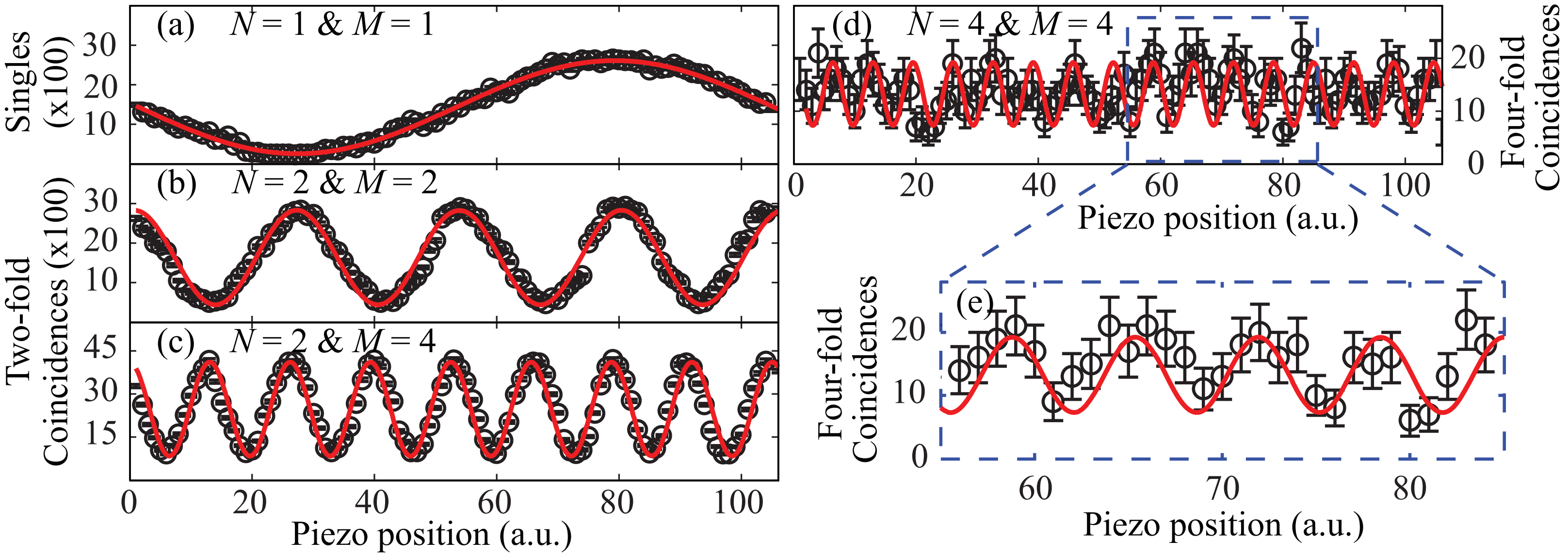
Malik, Shin, O’Sullivan. Zerom, and Boyd, Phys. Rev. Lett. 104, 163602 (2010).

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.



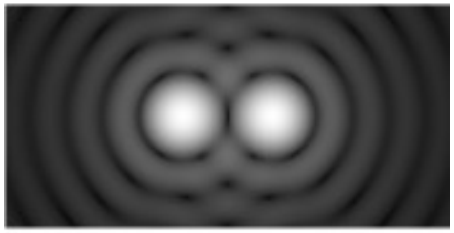
*N*00*N* state, *M* = number of passes though prism pair

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

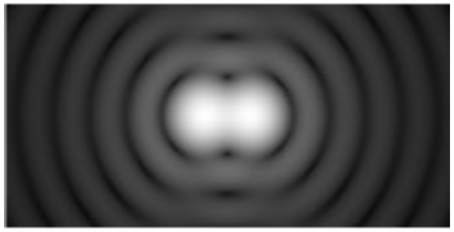
Superresolution

- 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 $1.22\ \lambda / D$, where D is the diameter of the collecting aperture.

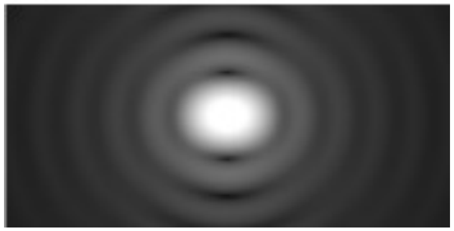
Resolved



At limit of resolution



Not resolved



Mode Decomposition and Imaging

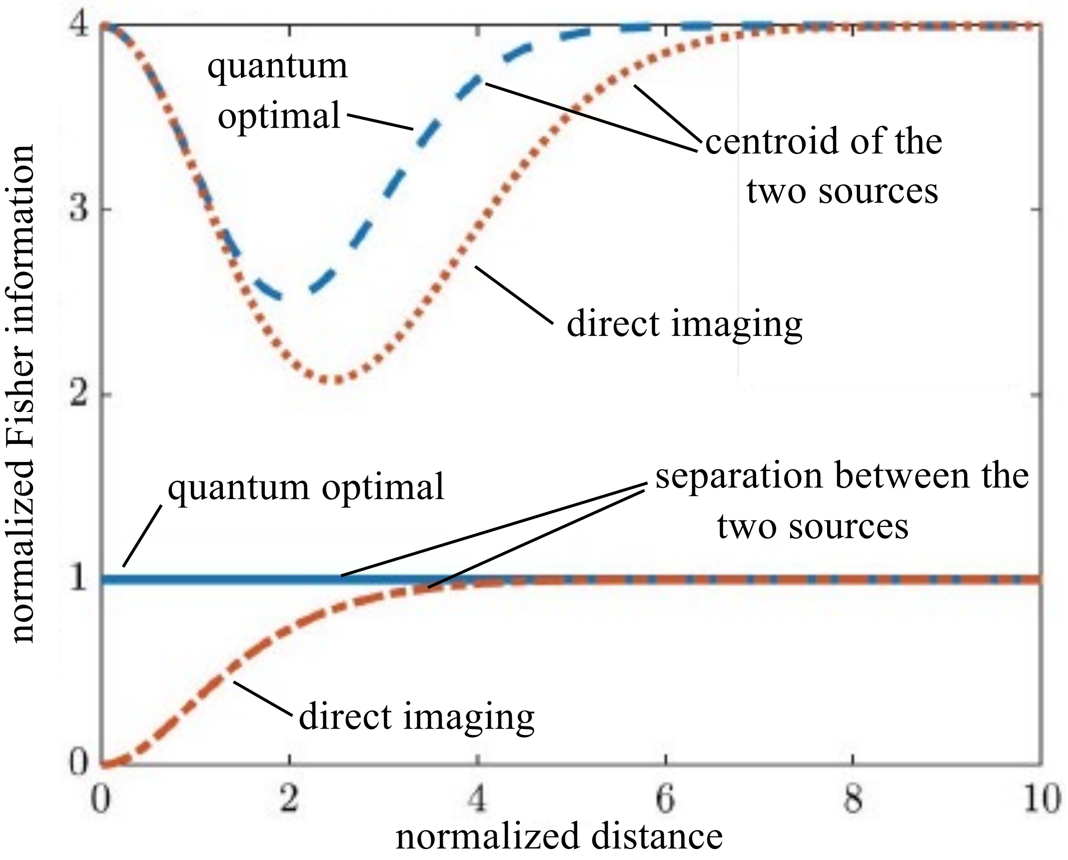
1. It is most natural to perform imaging in coordinate space, that is to measure the intensity *I*(*x*) as a fuction of position *x*.

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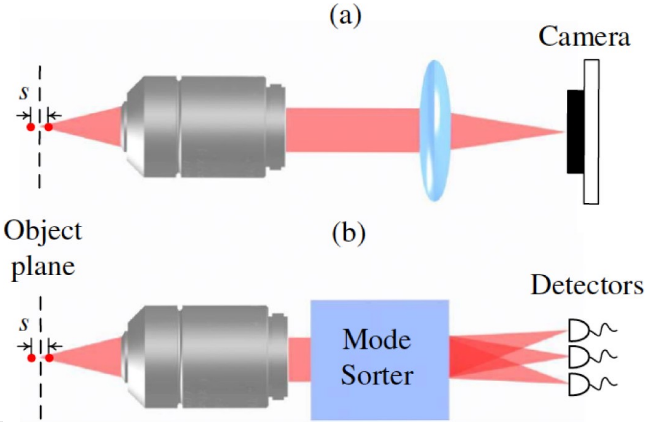
1. M. Tsang, R. Nair, and X.-M. Lu, Phys. Rev. X 6, 031033 (2016).
2. W.-K. Tham, H. Ferretti, and A. M. Steinberg, Phys. Rev. Lett. 118, 070801 (2017).
3. M. Paúr, B. Stoklasa, Z. Hradil, L. L. Sánchez-Soto, and J. Rehacek, Optica 3, 1144 (2016).
4. F. Yang, A. Tashchilina, E. S. Moiseev, C. Simon,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

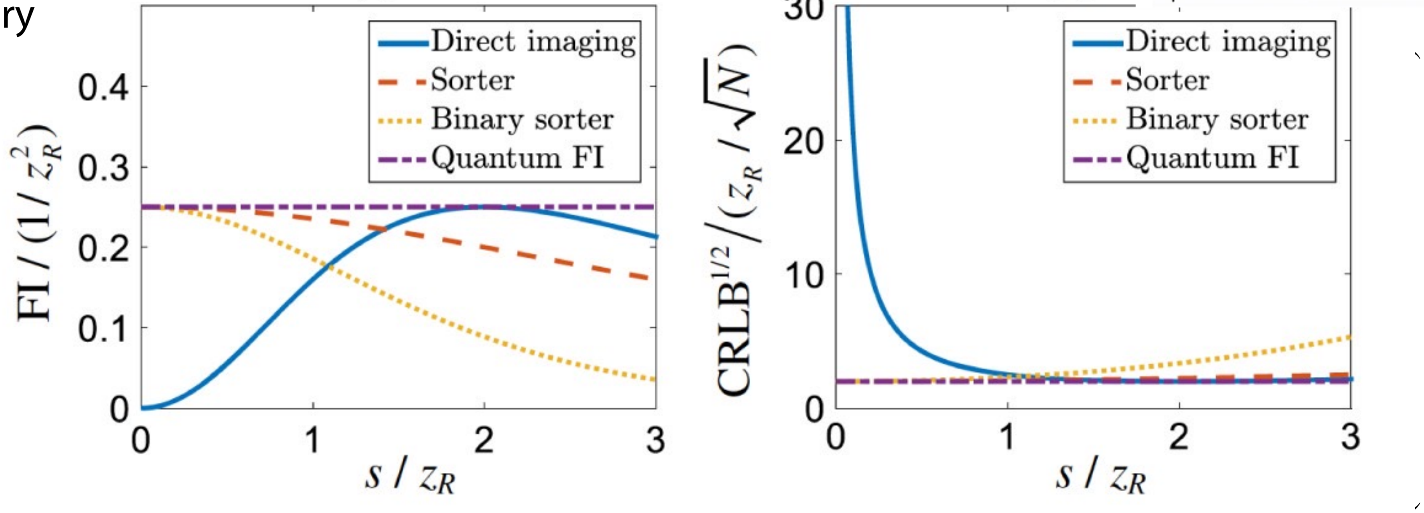

optica

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]



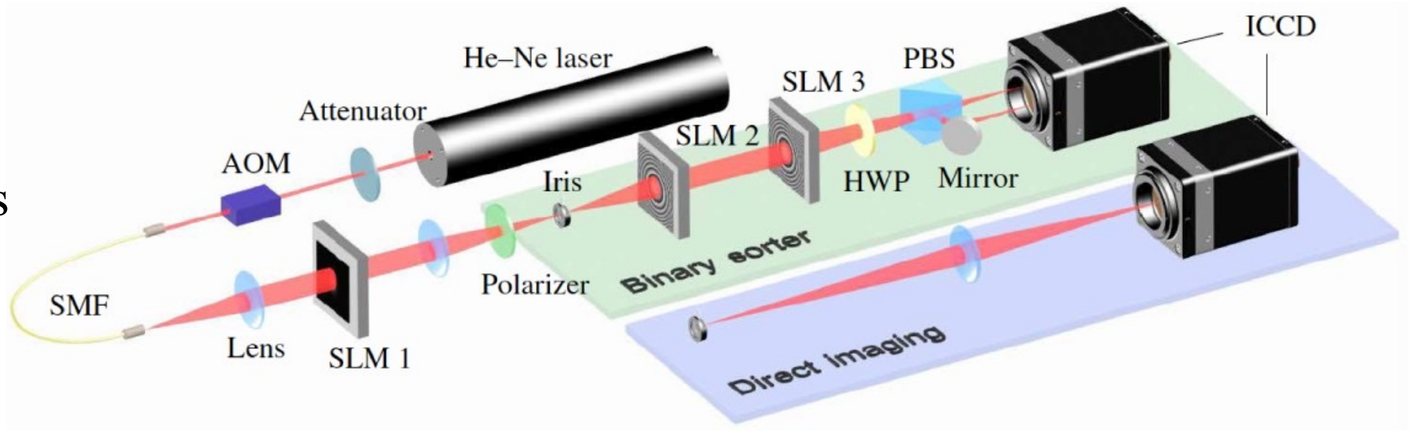
- Theory



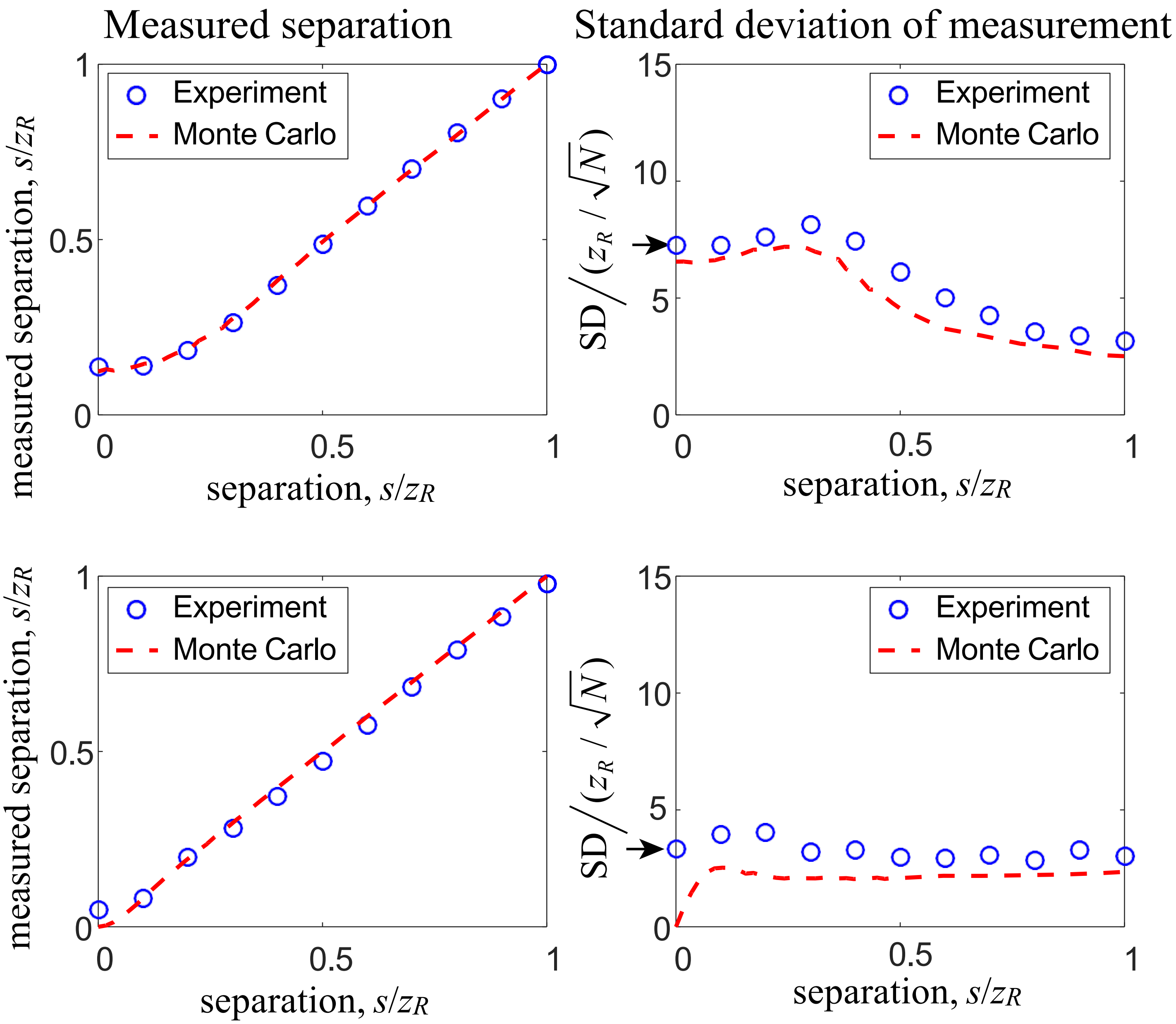
CRLB = Cramer-Rao lower bound = reciprocal of Fisher information

- 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



Direct imaging

Sorter-based imaging

- Note factor-of-two improvement in standard deviation

Mankei Tsang’s SPADE Method – 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?

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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[6] Department of Physics, University of South Florida, Tampa, Florida 33620, USA
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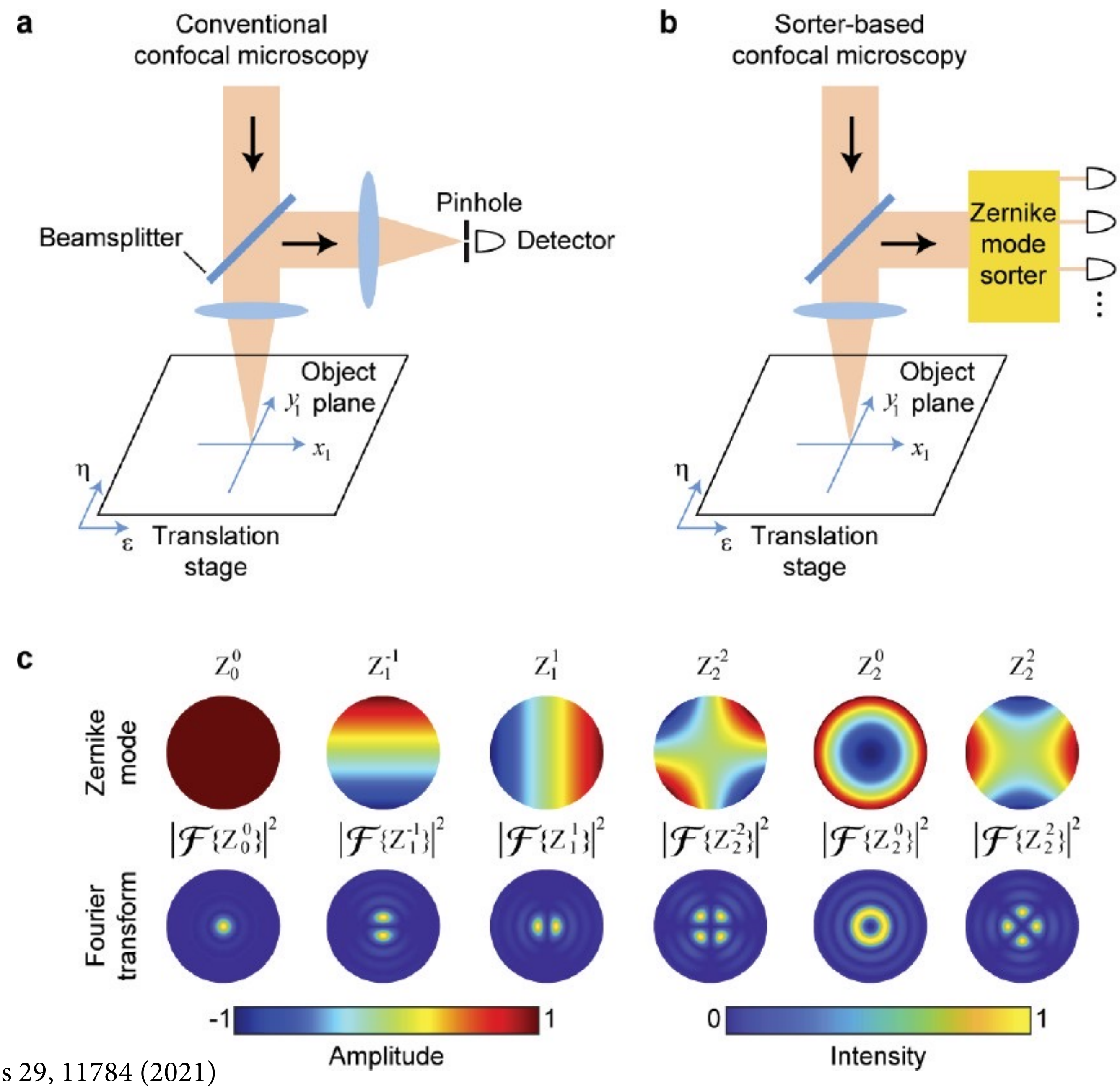
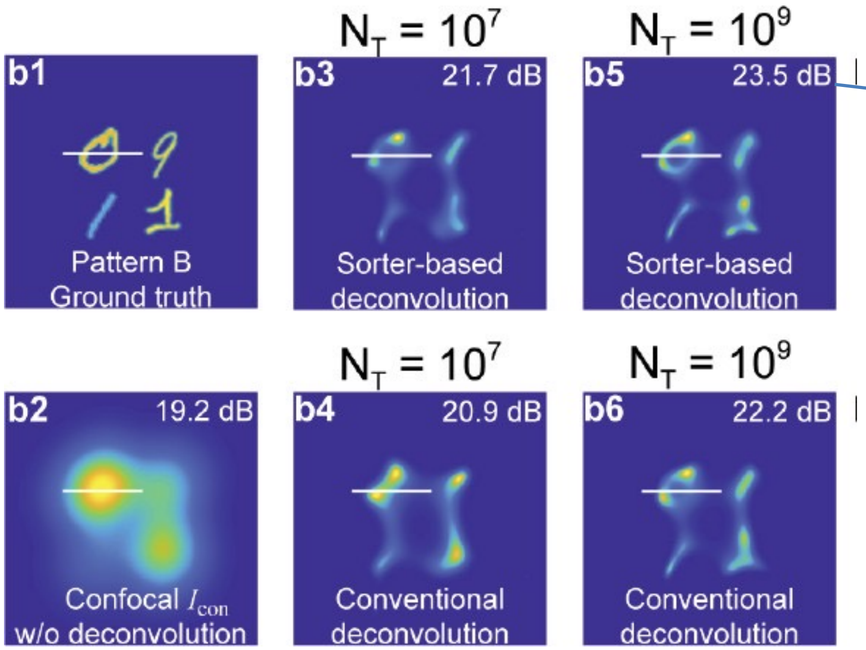
Our Experimental Procedure



Optics Express 29, 11784 (2021)

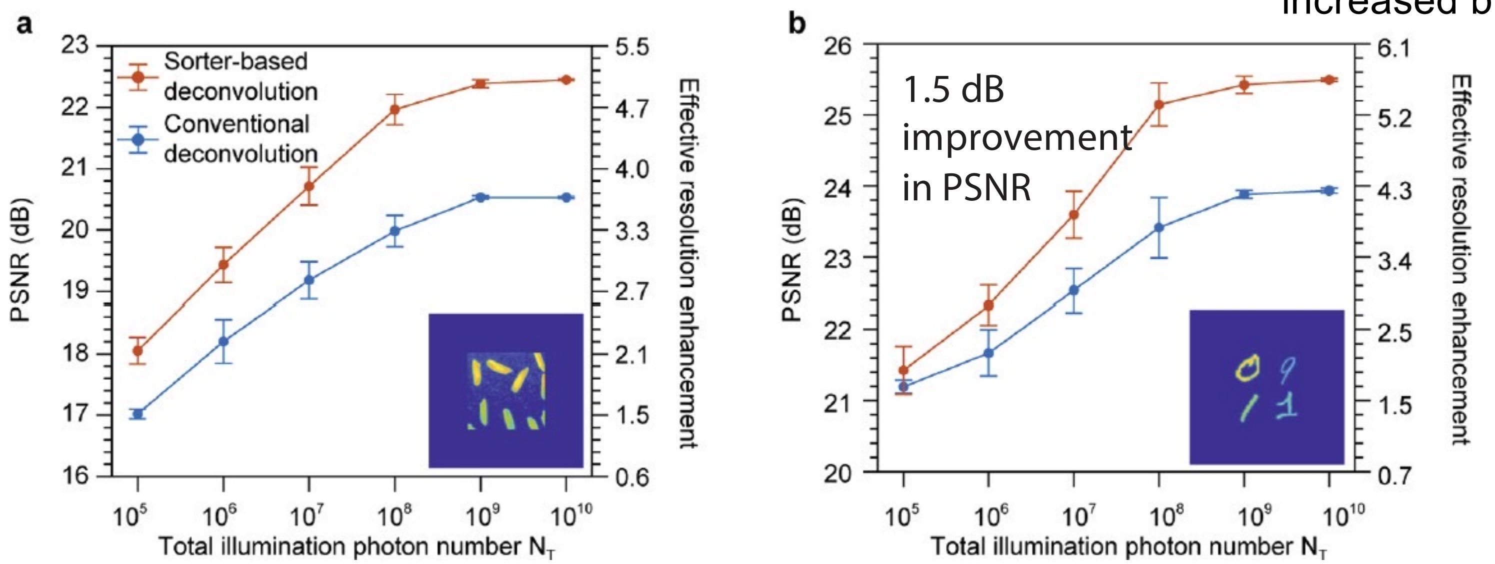
Some Numerical Results



PSNR = peak signal-to-noise ratio

- We use the Richardson-Lucy deconvolution algorithm

resolution enhancement increased by 30%



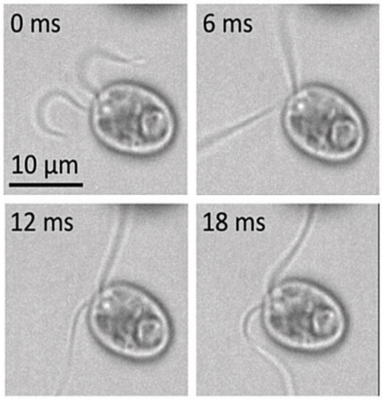
1.5 dB improvement in PSNR

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

Optics Express 29, 11784 (2021)

Many biological materials 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 phase imaging.

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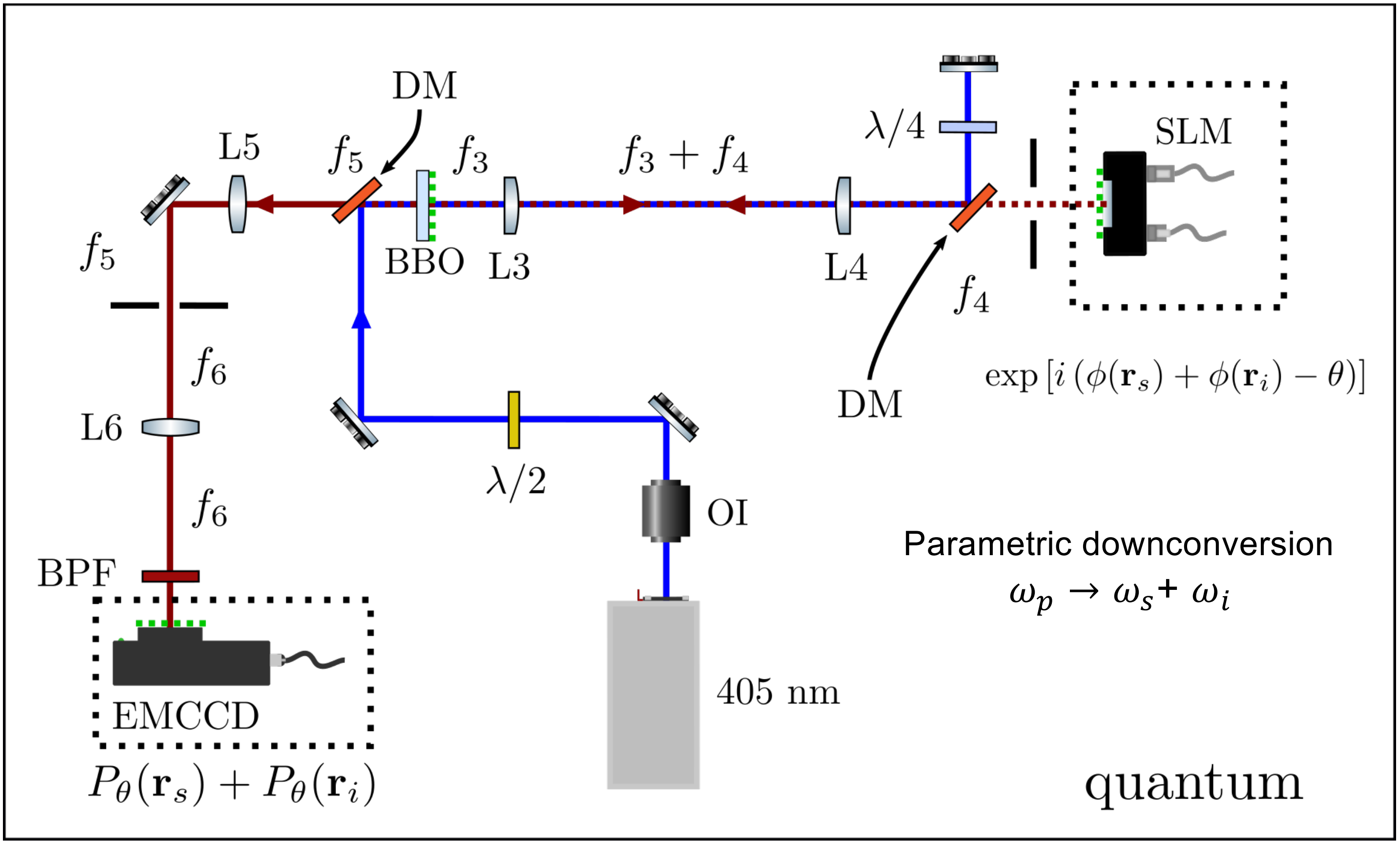
[1] Y. Niwa et al., Proc. National Acad. Sci. **110**, 13666–13671 (2013).

[2] Q. Thommen et al., Front. Genet. **6**, 65 (2015).

Our phase-sensitive imaging setups:

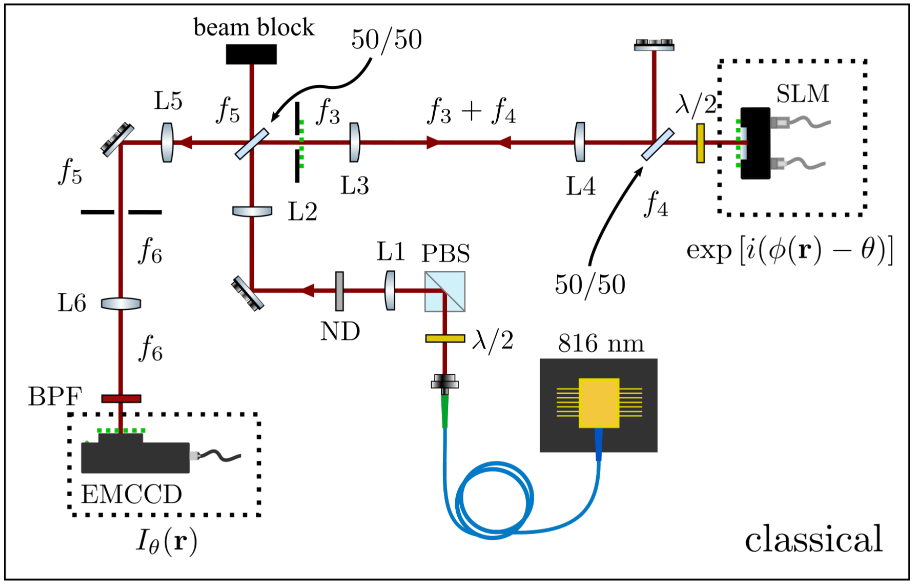
Quantum



Parametric downconversion

$\omega_p \rightarrow \omega_s + \omega_i$

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

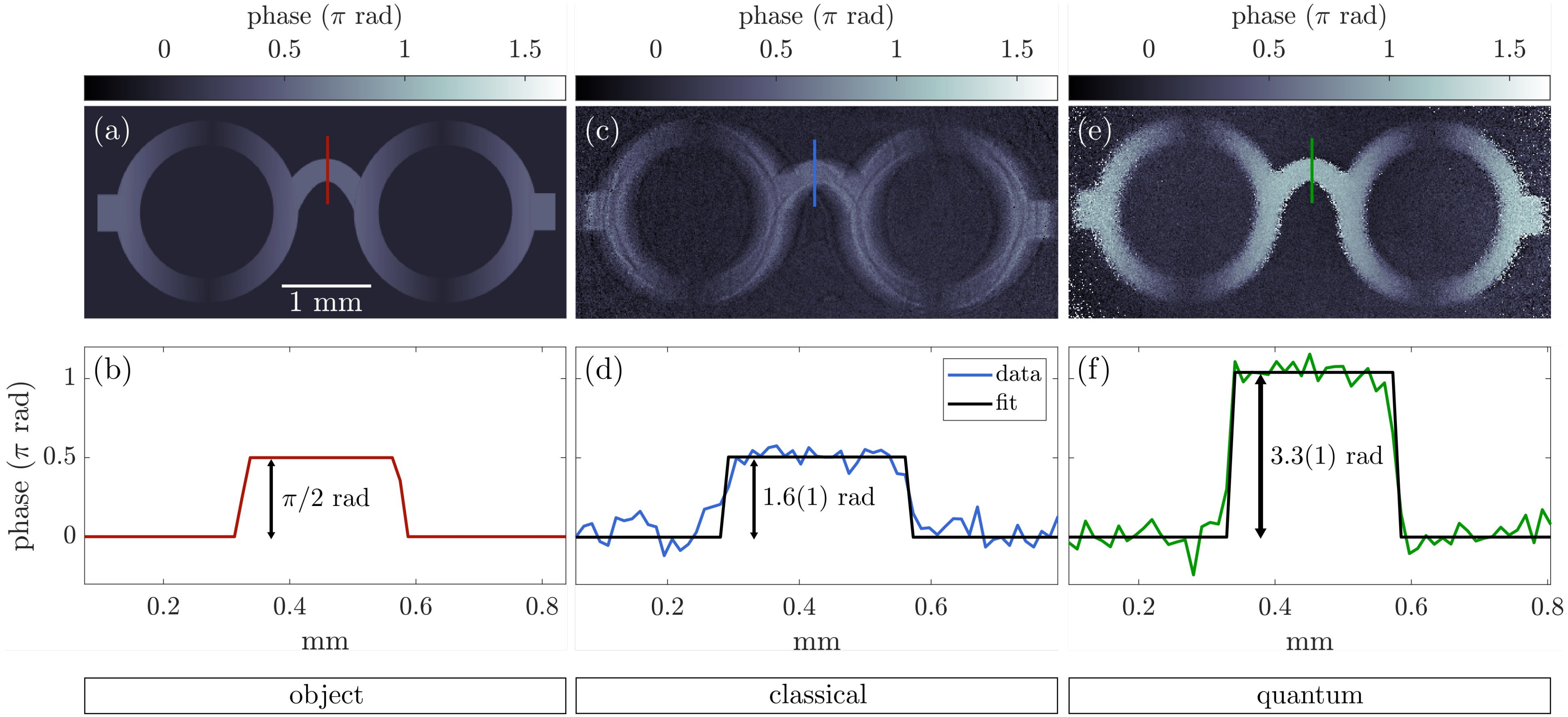
眼鏡がはるかに海を越え我が日本に渡来したのは四百二十余年前のことであります　文化の発達につれて　めがねの需要も増大し　文化政治経済に貢献した役割は誠に大なるものがあります　その間業界先覚者の研鑽努力により今日の発展をみるに至ったことを回想　明治百年を記念してその功績を顕彰し　慈眼大師ゆかりの地上野不忍池畔にこの碑を建立し感謝の念を新たにするものであります

Comparison of classical and quantum phase imaging

Object

Classical image

Quantum image

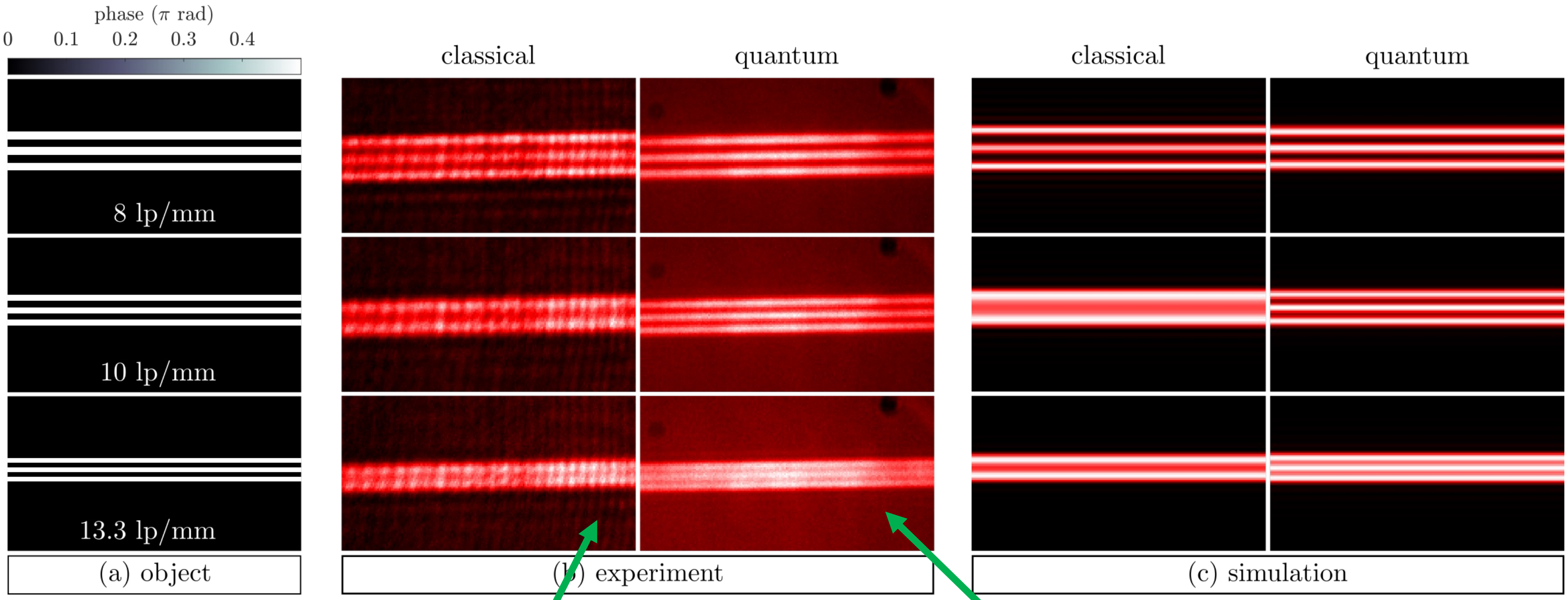


The “object” is a phase object
Written onto an SLM.

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



(a) object (b) experiment (c) simulation

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).

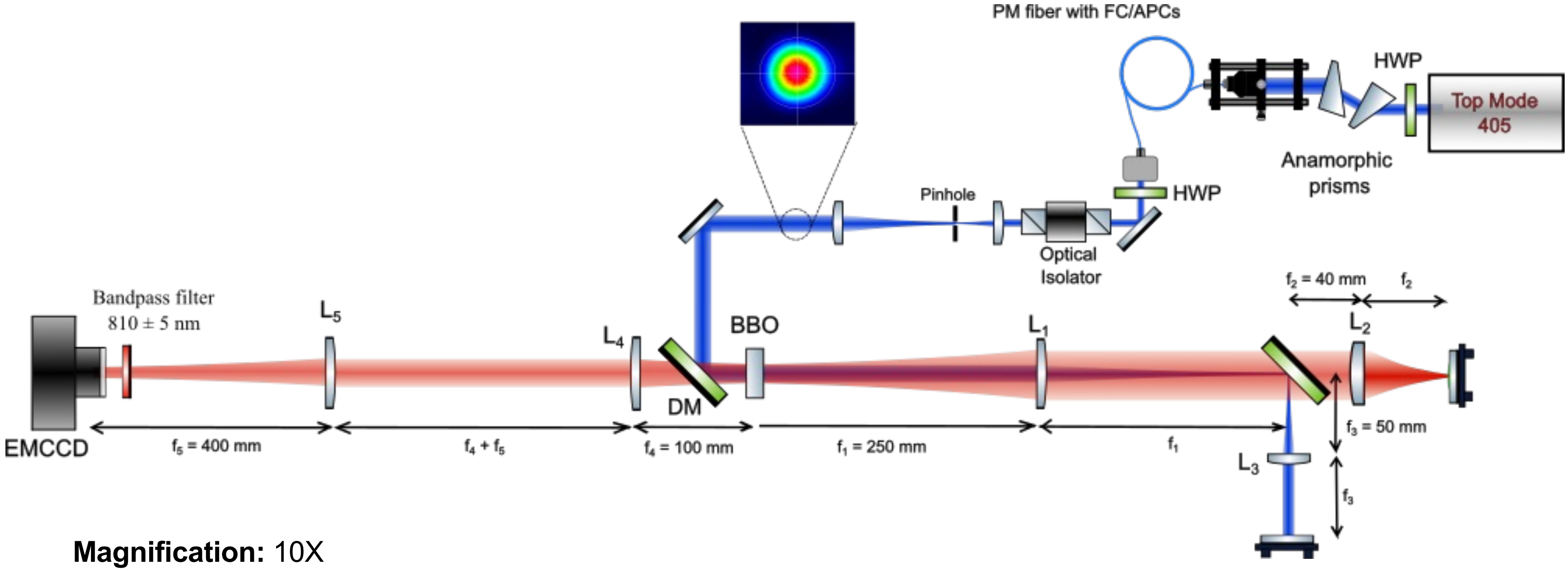
Current Project: Quantum-enhanced phase microscopy

- **Modify previous setup by using a higher numerical aperture:**

- Use an aspheric lens (NA = 0.75) as objective lens.
- Separate pump and SPDC photons at the Fourier plane L1 to reduce aberrations due to the dichroic mirror (tilted plane-parallel plate).

- **Additional improvements:**

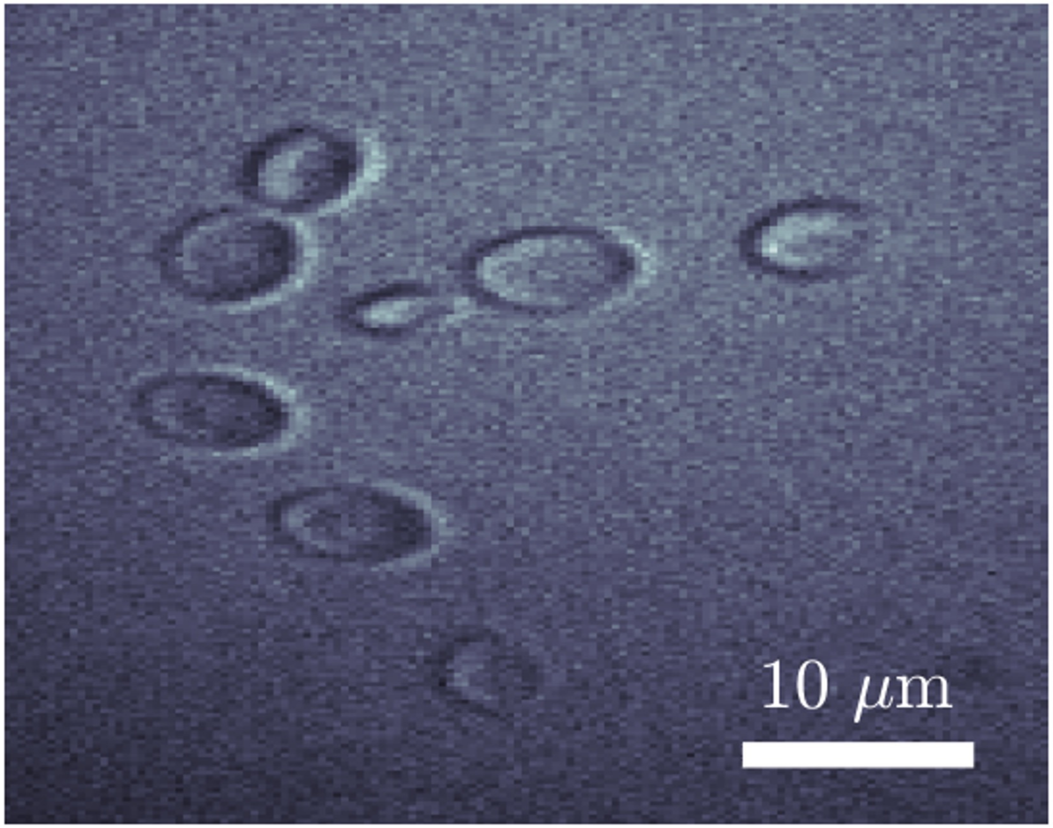
- Improve pump beam's spatial profile with single mode fiber coupling and pinhole spatial filtering.
- Reduce background fluorescence by using nonfluorescent lenses.
- Automate the alignment with motorized/piezo actuators .



Magnification: 10X
Expected resolution: 800 nm

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 Strongly Scattering Media Using Four-Wave Mixing (FWM) in Indium Tin Oxide (ITO)

With Yang Xu and Saumya Choudhary

What can we do to see though highly scattering materials?

Example: Imaging through thick biological materials.

Materials for Quantum (and Classical) Photonics

- 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 $n \cong 0$. (This is the ENZ, epsilon-near-zero, condition.)

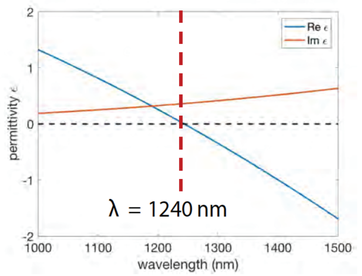
$$n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 c\, n_0\, \mathrm{Re}(n_0)}$$

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

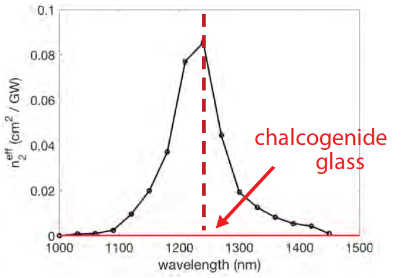
$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

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

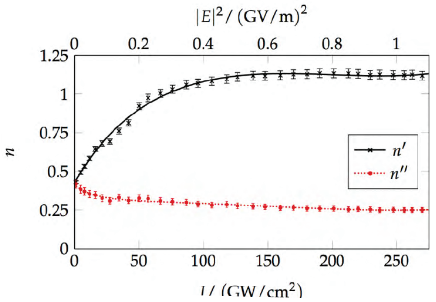
- ellipsometry



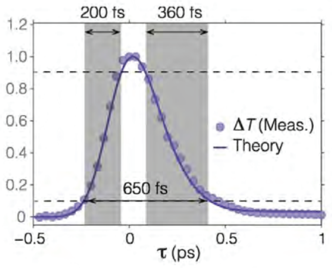
- n2 can be 3.4 x10^5 times larger than that of silica glass



- overall change in refractive index of 0.8



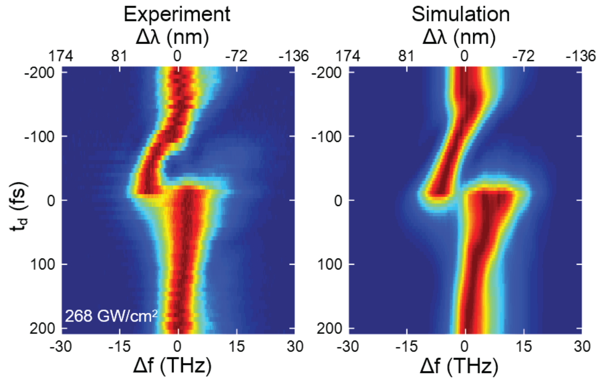
- sub picosecond reponse time



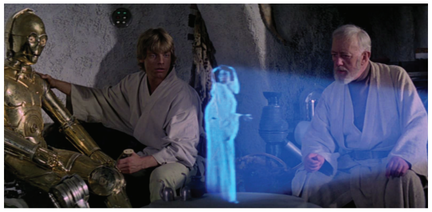
M. Z. Alam et al., Science 352, 795-797 (2016)

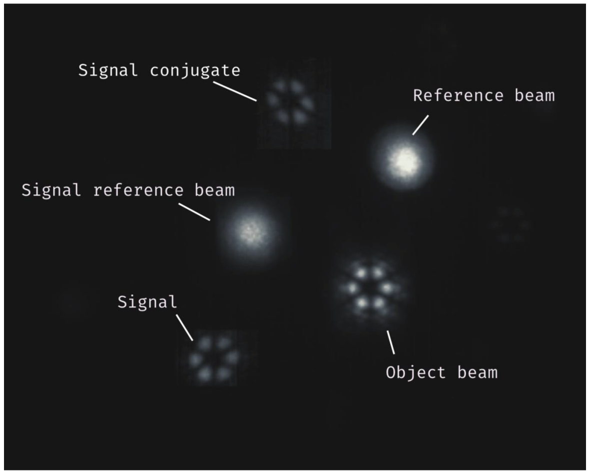
- Application: Adiabatic wavelength conversion
  - We can controllably shift the carrier wavelength of a data-encoded light field by as much as 100 nm.

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



- Application: Ultrafast real-time holography





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

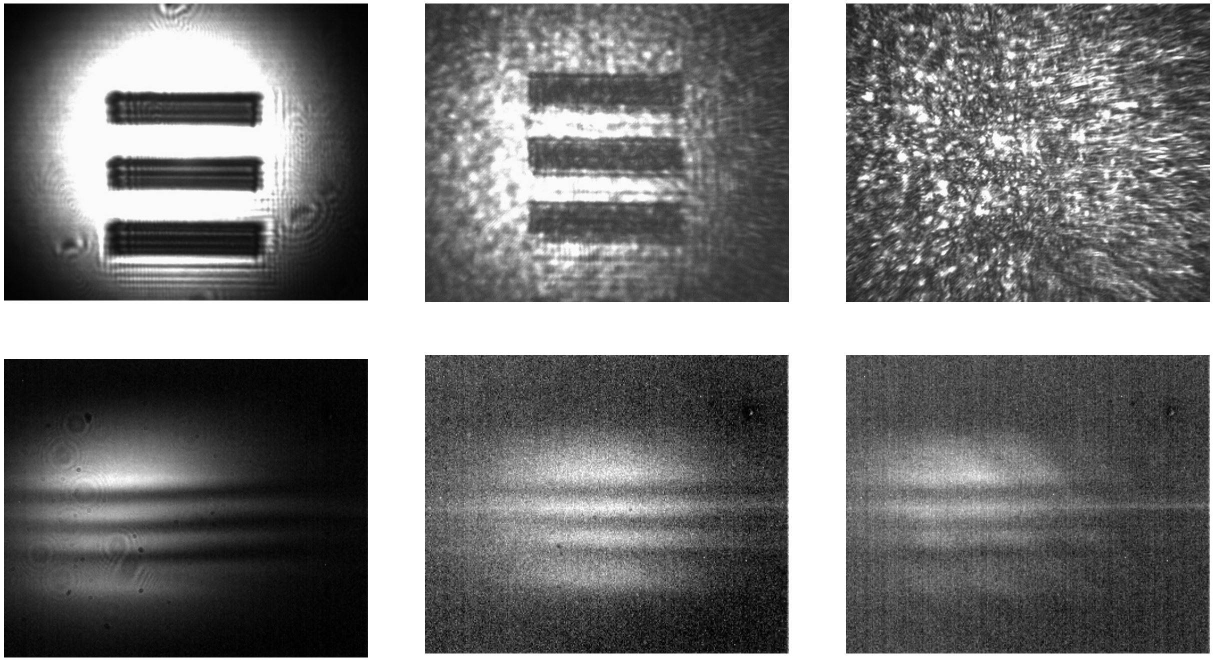
No scattering

Weak scattering

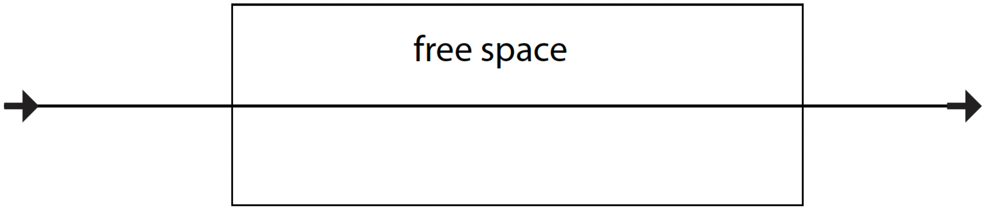
Strong scattering

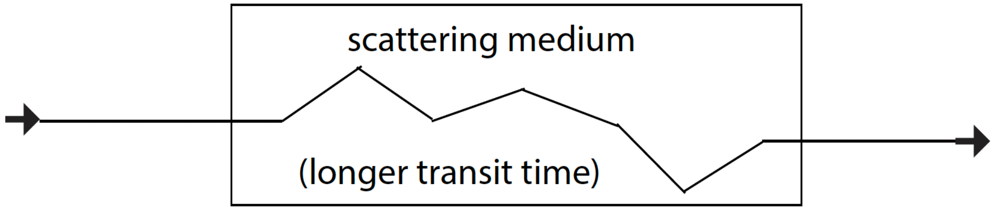
Direct image

Time-gated image



Compare!



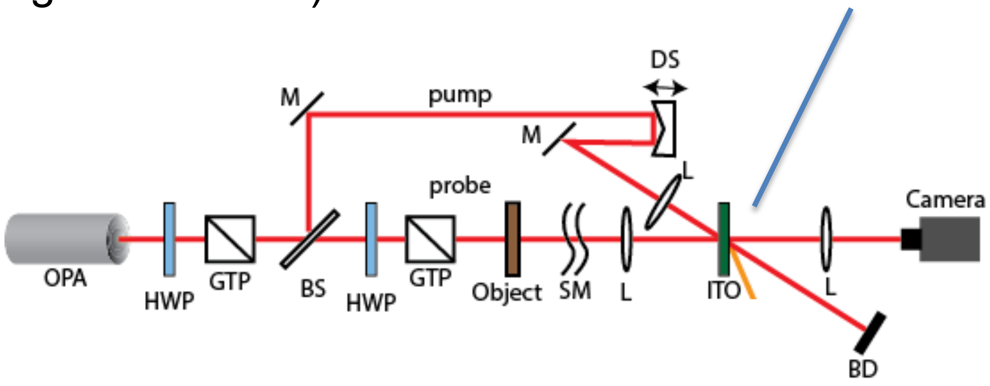


See also Wang et al (Alfano group), Science 253, 769 (1991).

Experiment Setups

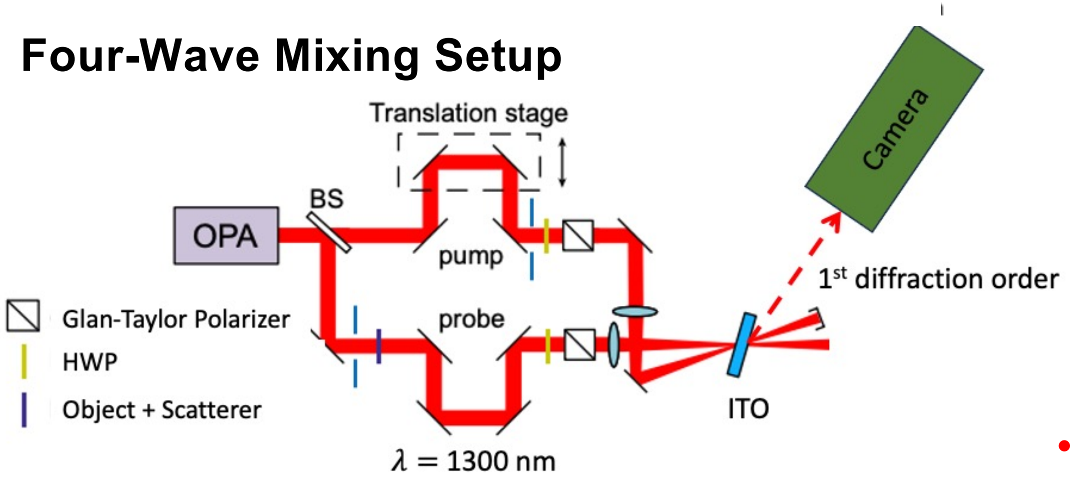
Nonlinear Transmission Setup
(using a Kerr Gate)

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



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

Four-Wave Mixing Setup

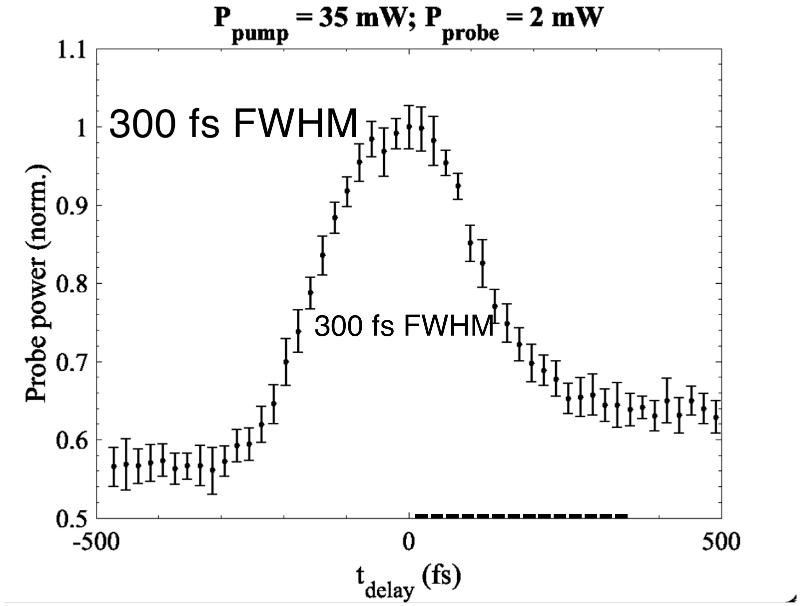


Pump and probe are both centered at the ENZ wavelength (1240 nm) of the 310-nm-thick ITO plate

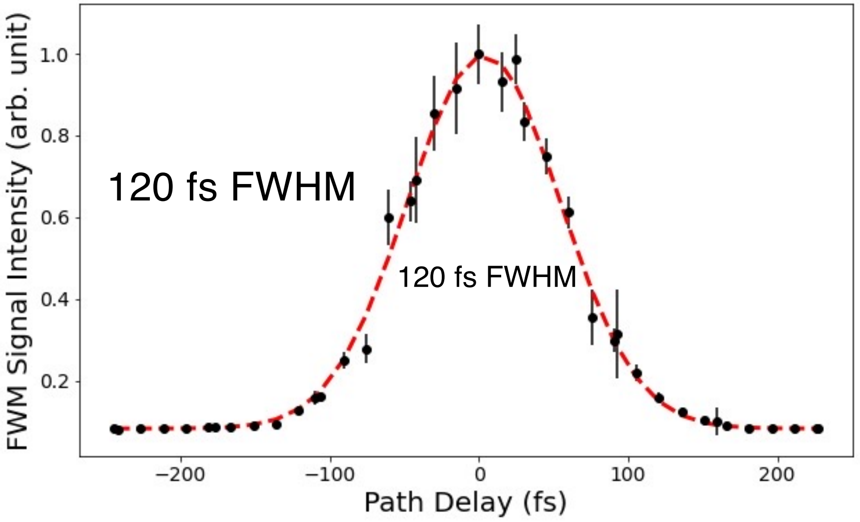
- We use the four-wave mixing setup because it gives a shorter gating time.

Shorter Gate Time Using Four-Wave Mixing in ITO

Nonlinear Probe Transmittance vs Delay
(“slow” nonlinearity)



FWM Intensity vs Delay
(“fast” nonlinearity)



FWM response is symmetric (has no tails). The width of the pulse autocorrelation is much shorter than the characteristic time of the nonlinear refractive index change.

A shorter gating time allows a more accurate selection of ballistic photons. This means we are more robust against scattering.

Summary - Imaging through Scattering Media

We demonstrate the first, to our best knowledge, ultrafast spatiotemporal gating based on spontaneous four-wave mixing (FWM) in ITO to image small objects hidden behind strong scattering media.

FWM on ITO has a shorter gating time (120 fs, more than a factor of 2 shorter) than the traditional method of optical Kerr gating (OKG), which uses polarization rotation (refractive index change). We thus obtain cleaner images.

Thanks to the large nonlinearity of ITO at its ENZ wavelength, we obtain efficient FWM signals even with this ultrashort gating time.

In theory, it is easy for ITO to achieve both good resolution and good scattering rejection at the same time. This is usually not possible for traditional Kerr gating. Given proper engineering of optics and detectors, our proof-of-principle experiment suggests an ideal solution to the long-standing problem of imaging through turbidity.

Quantum Imaging Outline

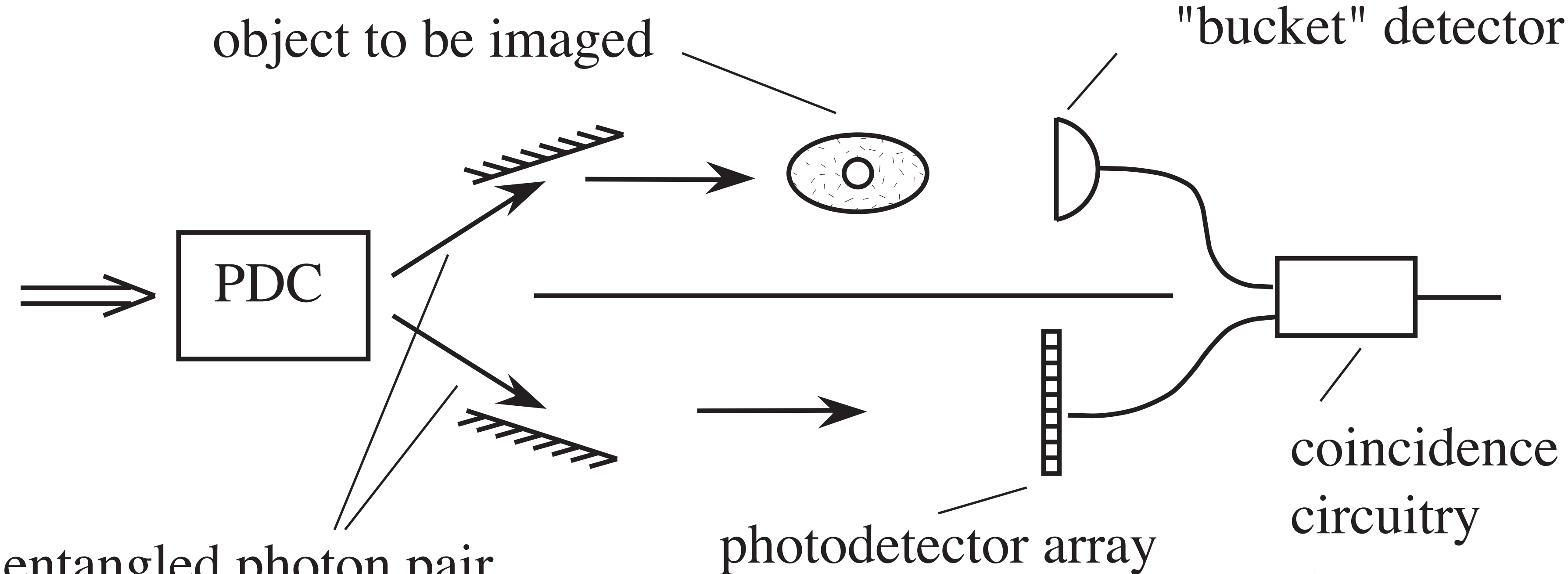
Introduction to Quantum Imaging Quantum

Superresolution

Quantum, Nonlocal Aberration Correction

Quantum Interaction-Free Ghost Imaging

Ghost (Coincidence) Imaging



object to be imaged

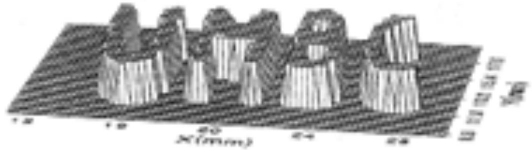
"bucket" detector

PDC

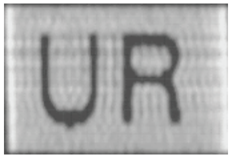
coincidence circuitry

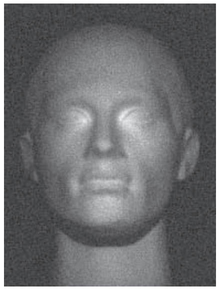
entangled photon pair

photodetector array



- 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)





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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)
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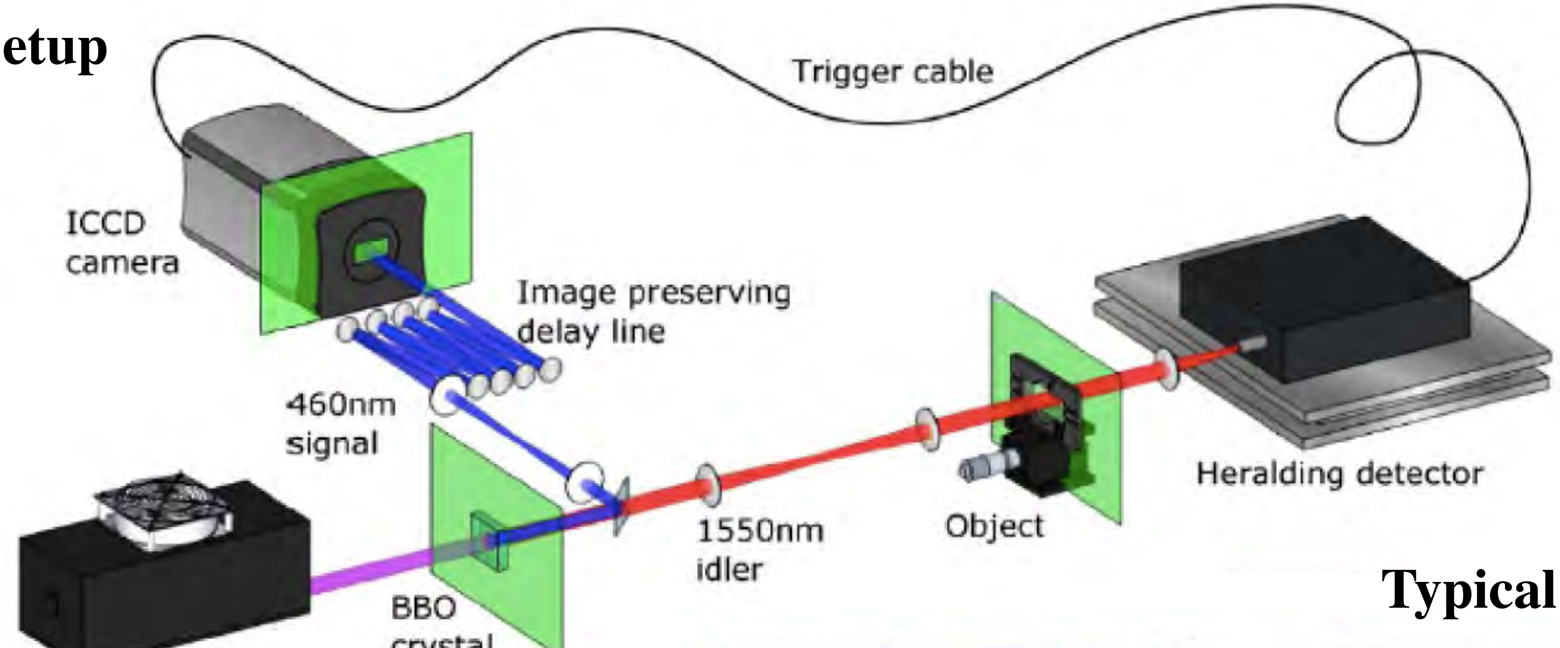
Gatti, Brambilla, Bache, and Lugiato, PRL 93 093602 (2003)

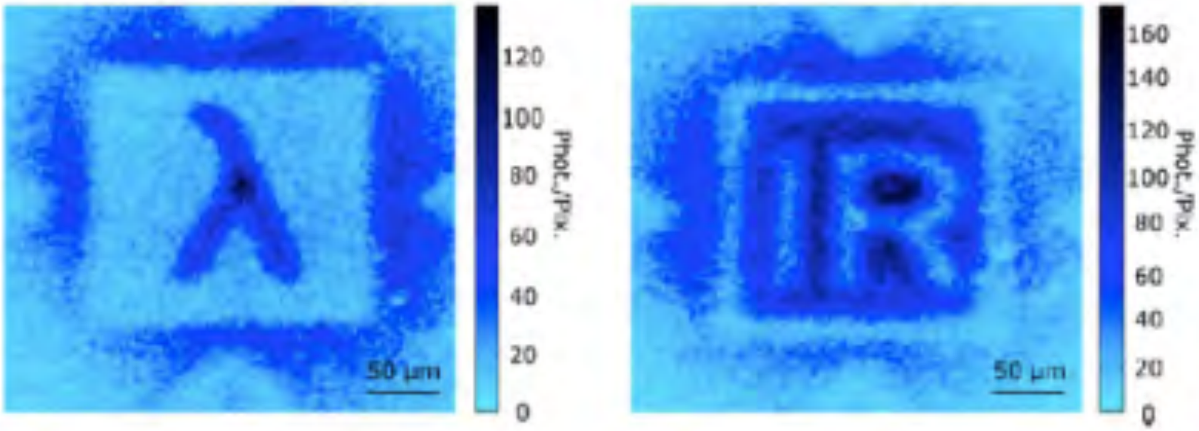
Wavelength-Shifted (Two-Color) Ghost Microscopy

- 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

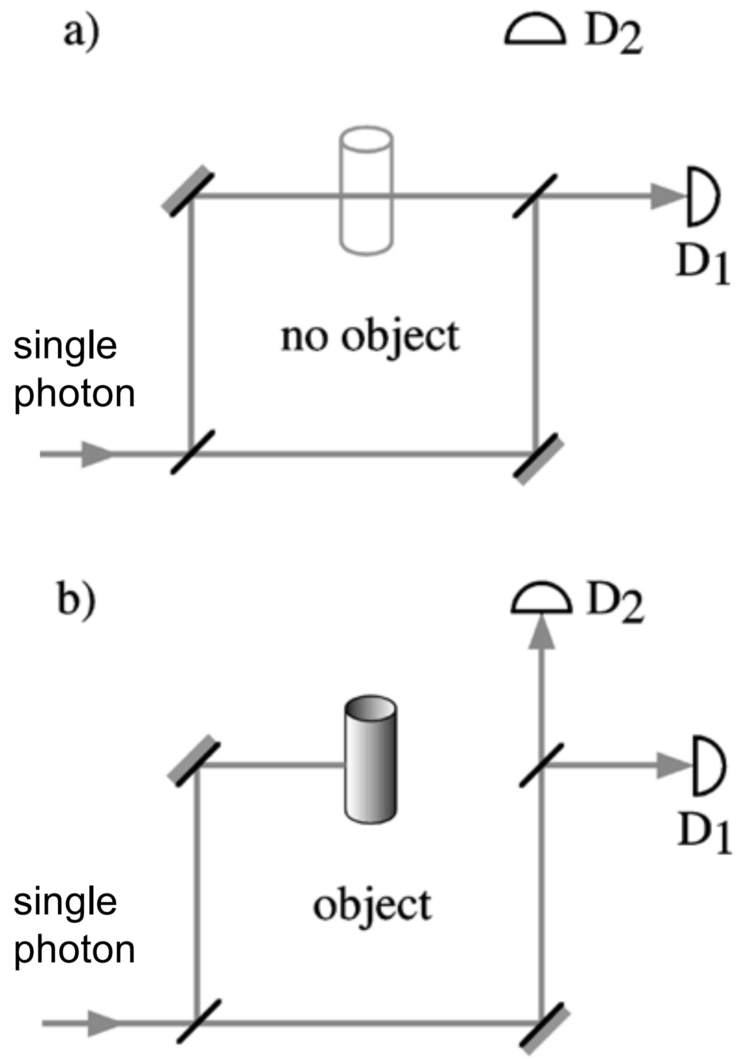


Typical images

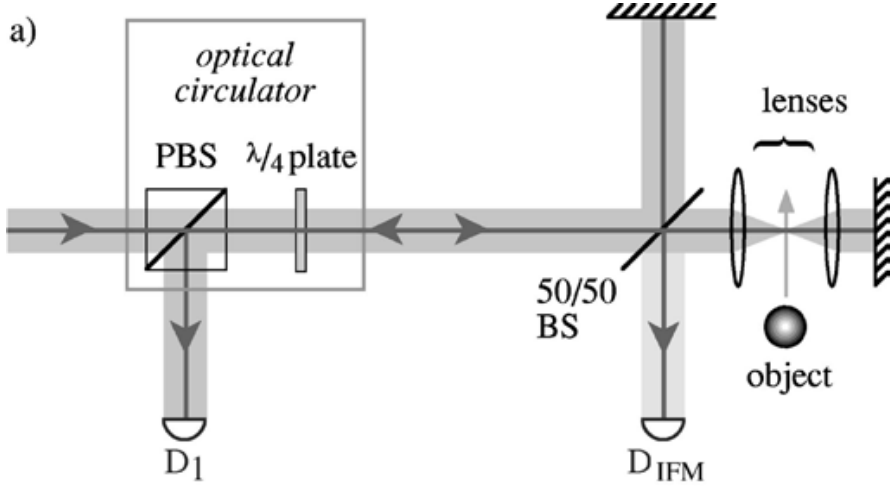


Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

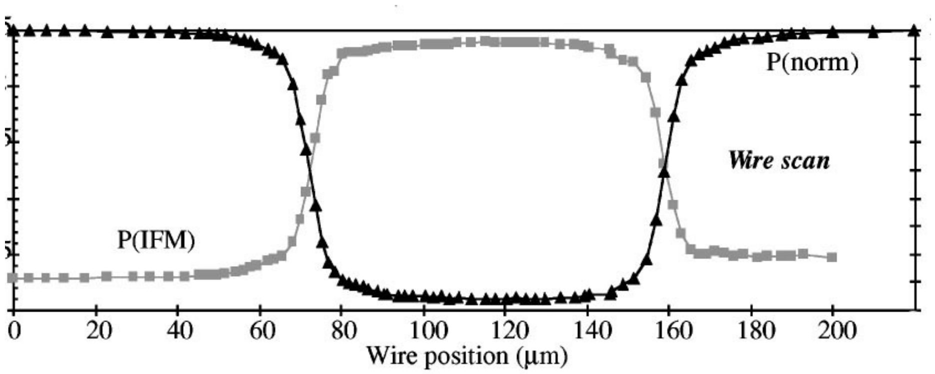
Quantum Imaging by Interaction-Free Measurement



imaging setup



results



M. Renninger, Z. Phys. 15S, 417 (1960).
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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)
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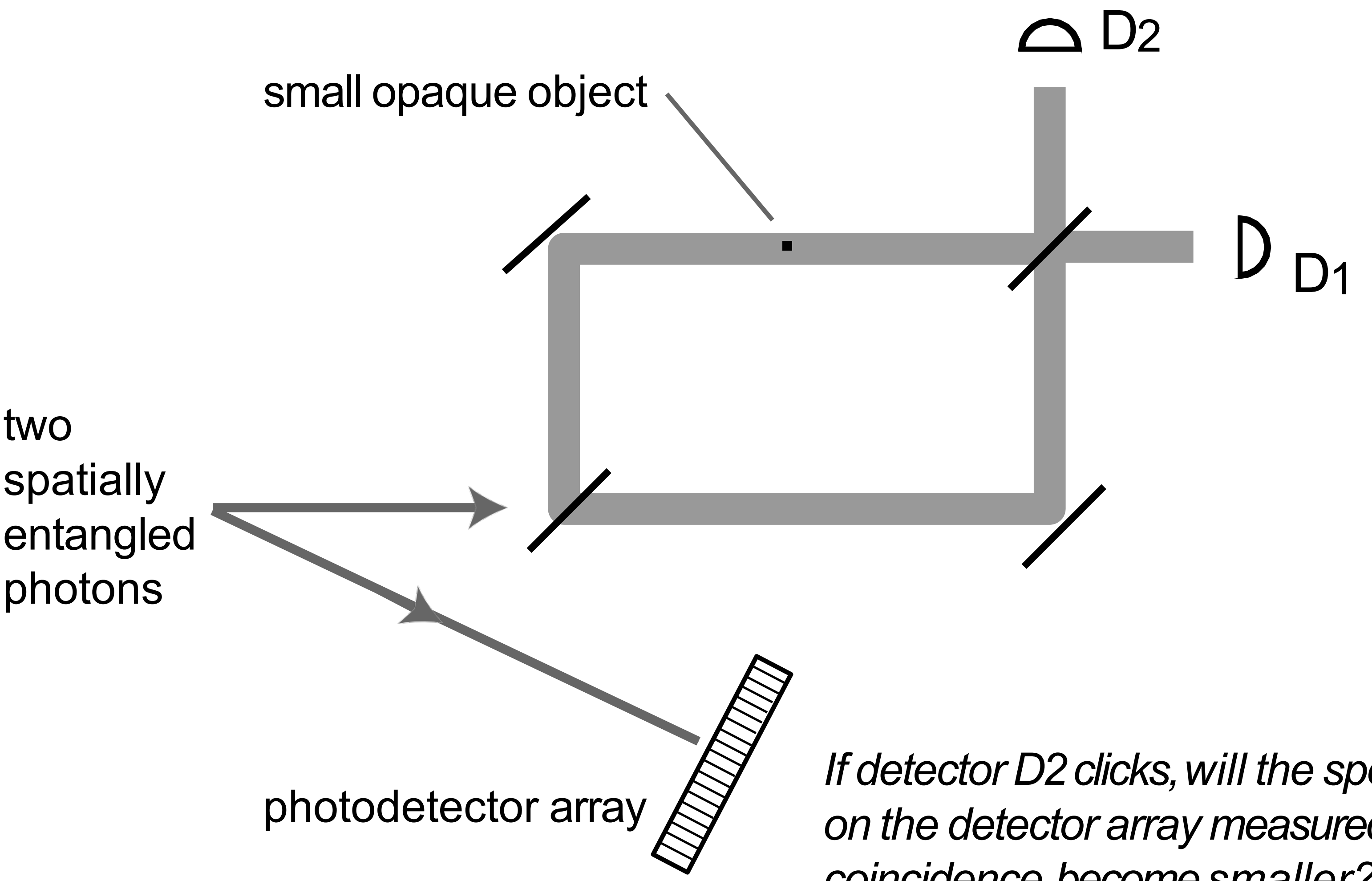
Interaction-Free Measurements and Entangled Photons



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?

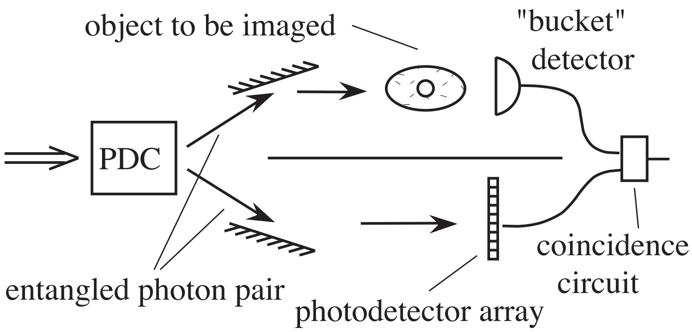
Research in Quantum Imaging

Quantum Imaging or Quantum Imogene?

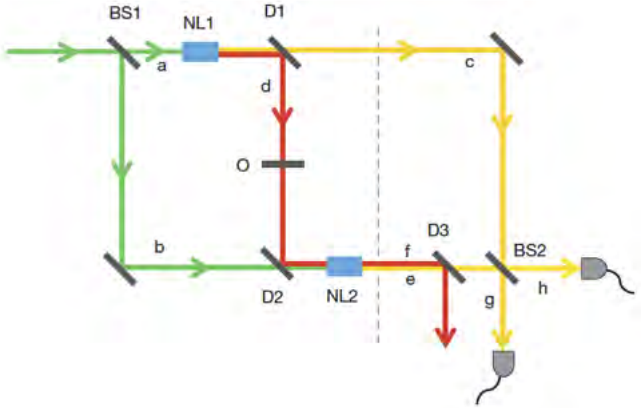
Sid Caesar and Imogene Coca in 1953

Quantum Imaging Overview

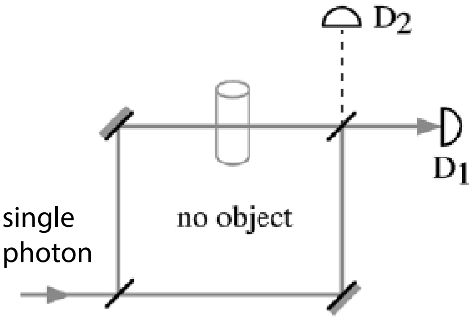
Ghost Imaging (Shih)



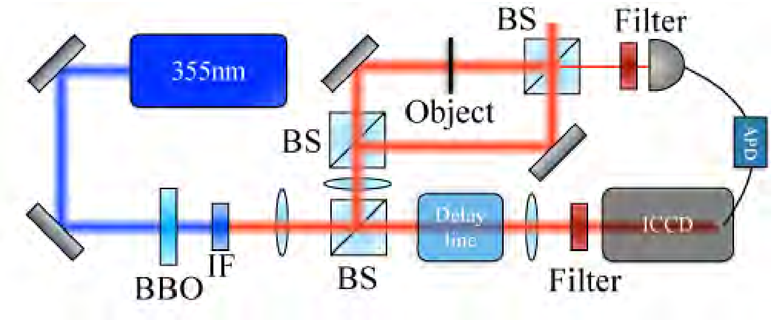
Imaging with Undetected Photons (Zeilinger)



Interaction-Free Imaging (White)



Interaction-Free Ghost Imaging (this talk)



Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group