Sharper Images Through Quantum Imaging

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

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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

1. Introduction to Quantum Imaging
2. Quantum Microscopy for Biomedicine
3. Imaging through Strongly Scattering Media
4. Interaction-Free Ghost Imaging
5. Superresolution
6. Imaging with Undetected Photons

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

And what is "quantum"?

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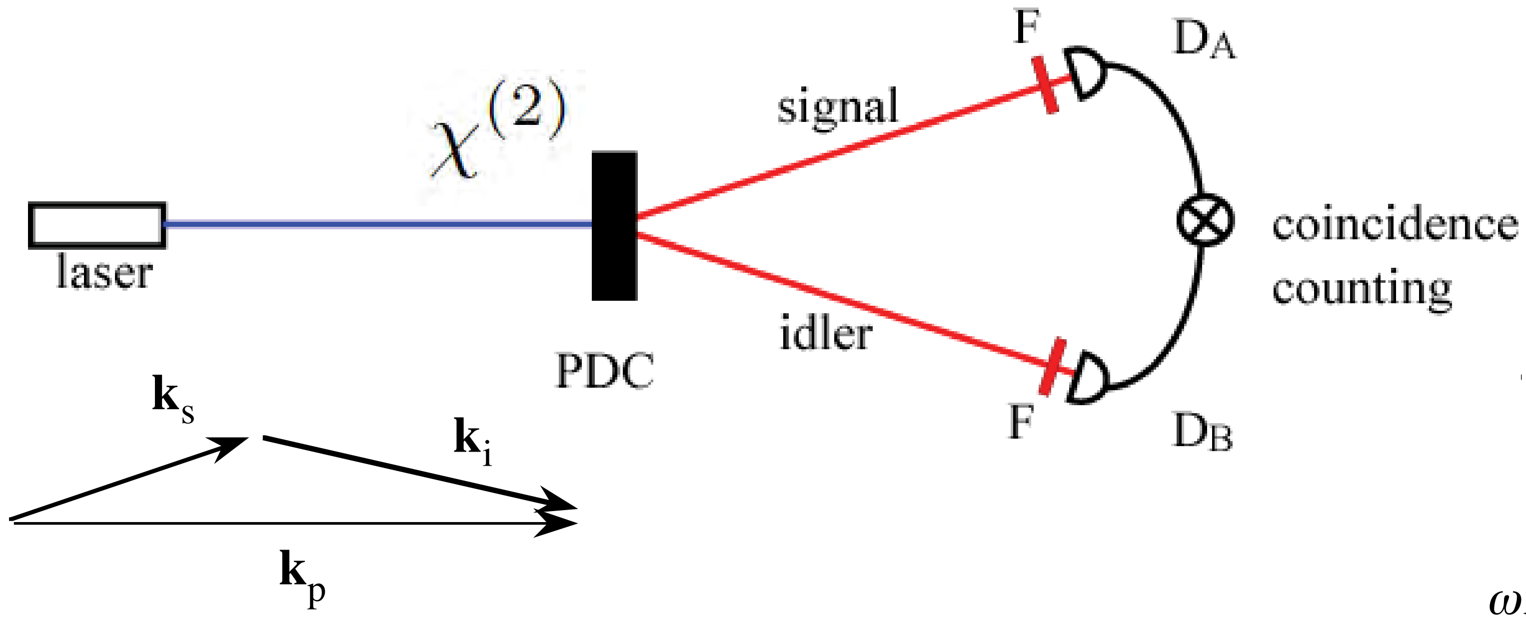
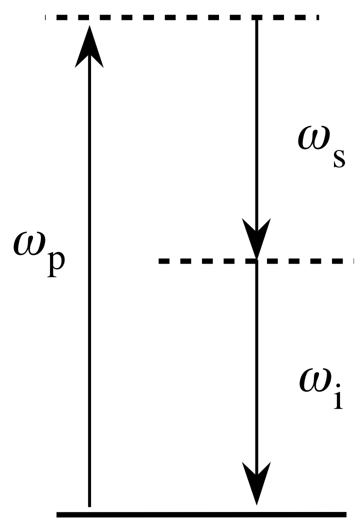
Parametric Downconversion: A Source of Entangled Photons





The signal and idler photons are entangled in:

(a) polarization

(b) time and energy

(c) position and transverse momentum

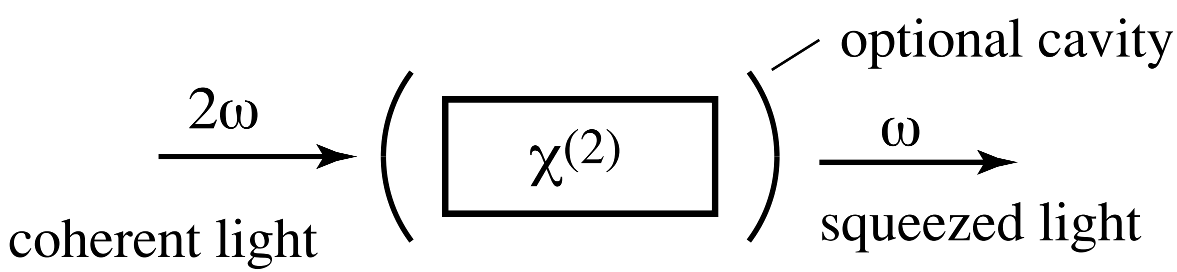
(d) angular position and orbital angular momentum

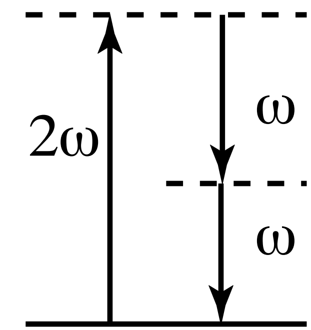
Entanglement is important for:

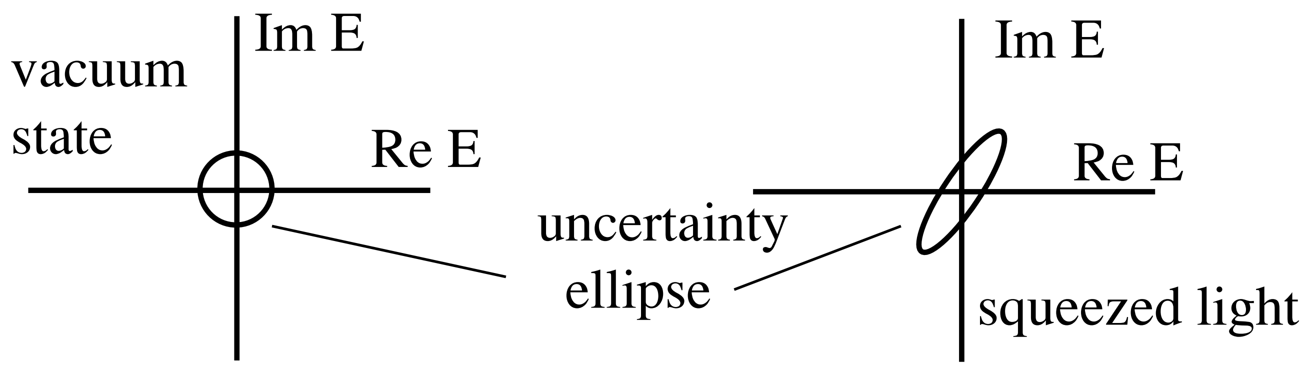
(a) Fundamental tests of QM (e.g., nonlocality)

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

Squeezed Light Generation



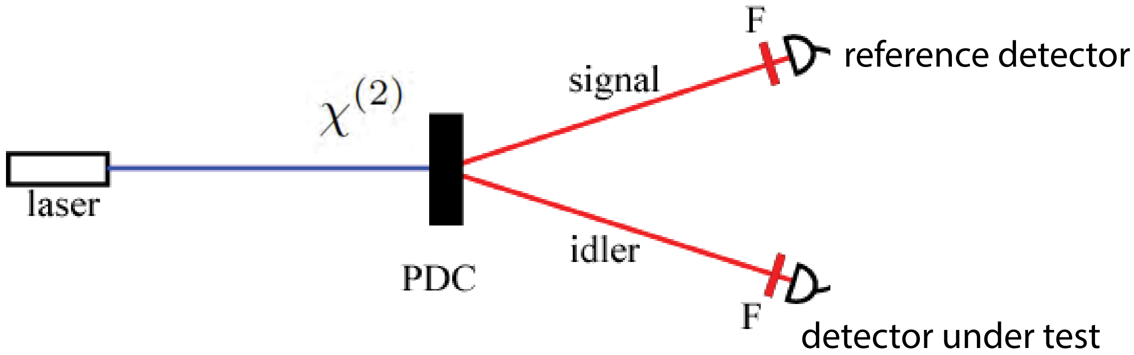


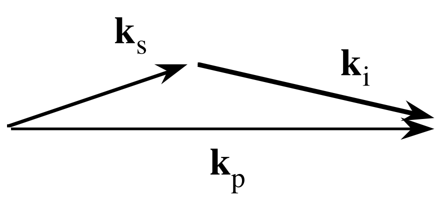


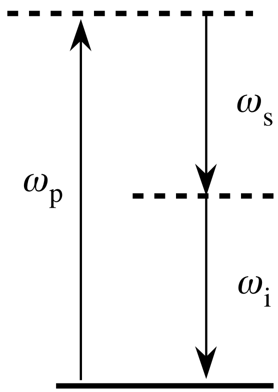
- Note that in both examples nonlinear optics (NLO) plays a key role in producing quantum states of light.
- In fact, NLO is *required*! A linear optical transformation cannot turn classical light into quantum light.

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).

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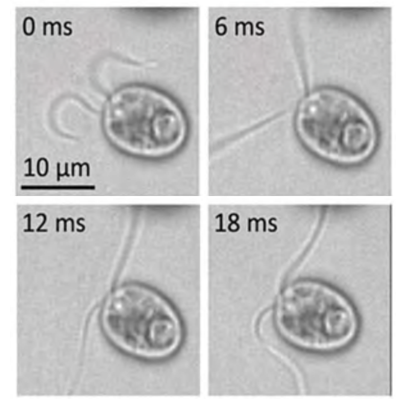
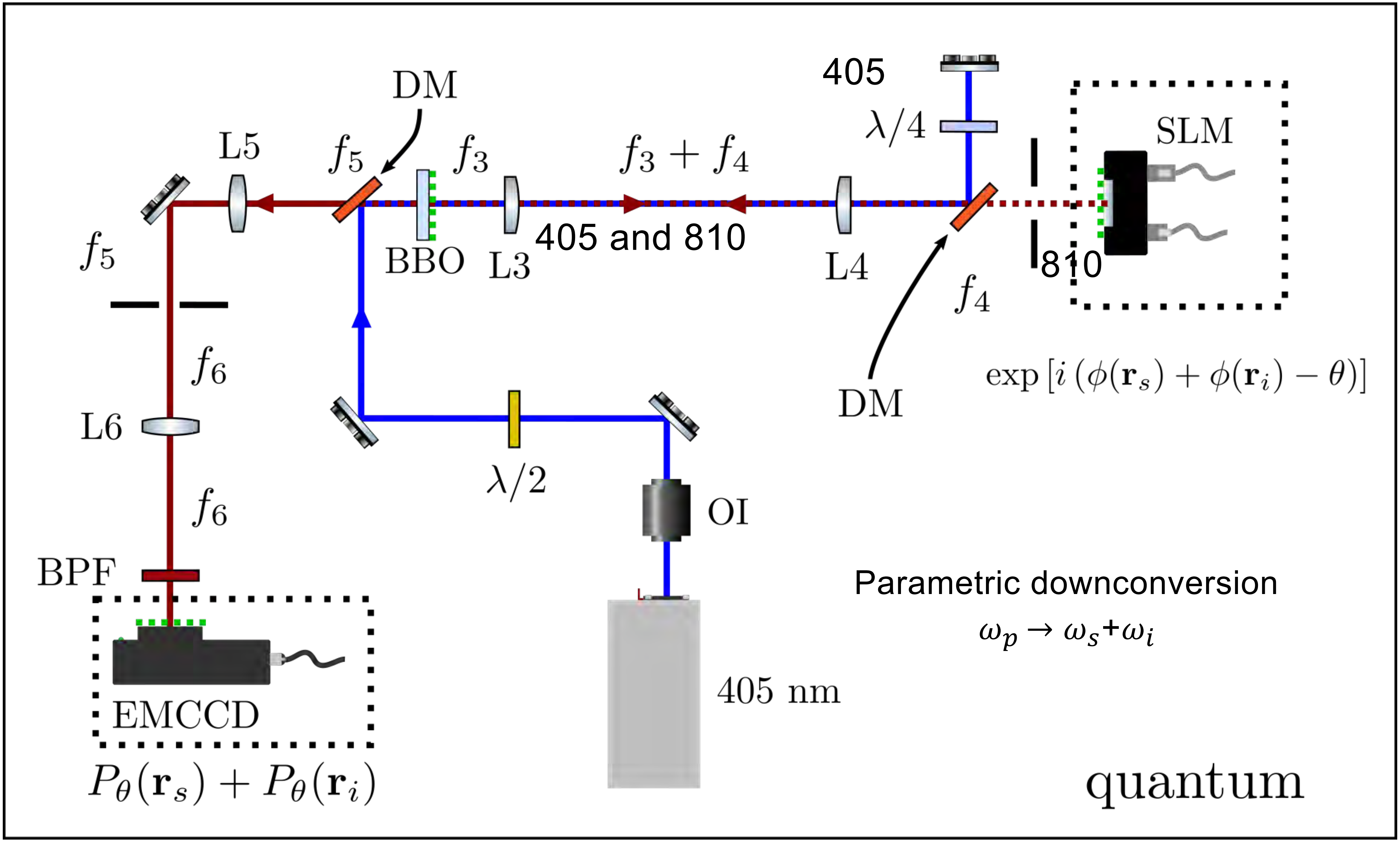
Quantum-Enhanced, Phase-Sensitive Microscope for Biomedical Imaging

- How do you image an object under photon-starved conditions?
- Many biological materials display phase contrast but little intensity contrast..
- Biological materials are damaged by intense laser light, especially at short wavelengths.
- Illuminate sample with entangled photon pairs. Photon wave length is 810 nm, but achieve Abbe-limited resolution of 405 nm.
- Illuminate with a small number of photons to minimize laser damage.



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

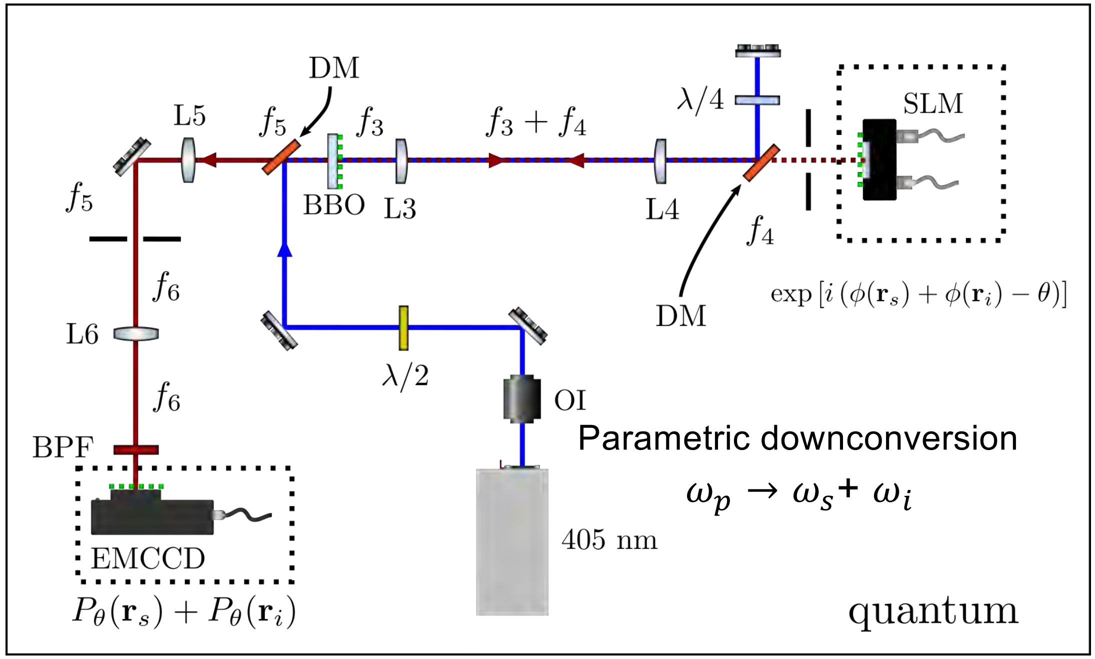
Our phase-sensitive imaging setup:



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).

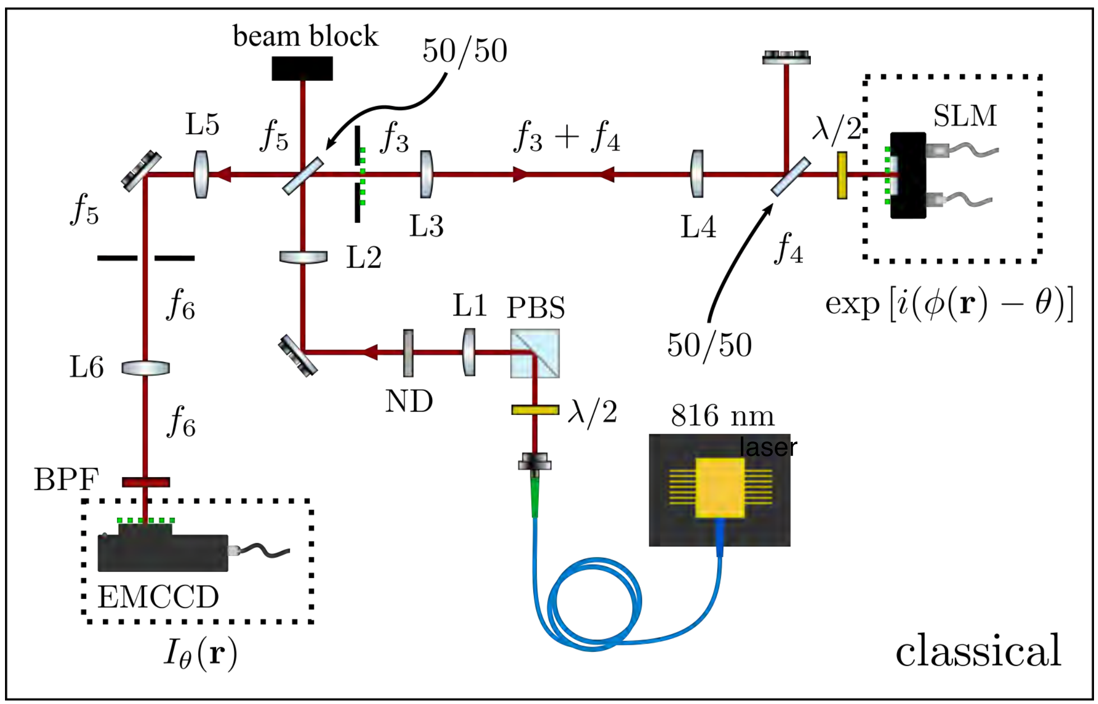
Comparison of Quantum and Classical Imaging Setups

Quantum



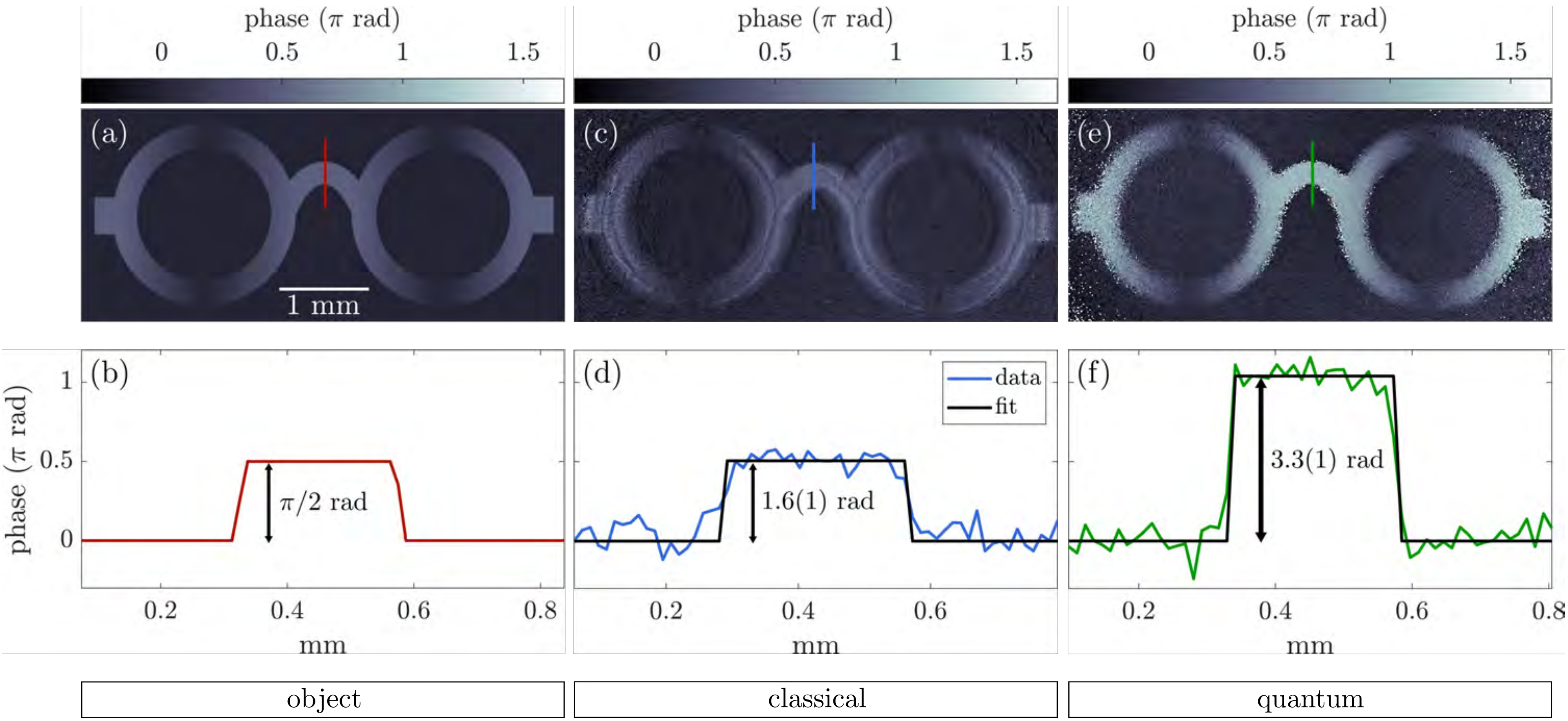
Classical

(with same numerical aperture)



Comparison of classical and quantum phase imaging

Object | Classical image | Quantum image

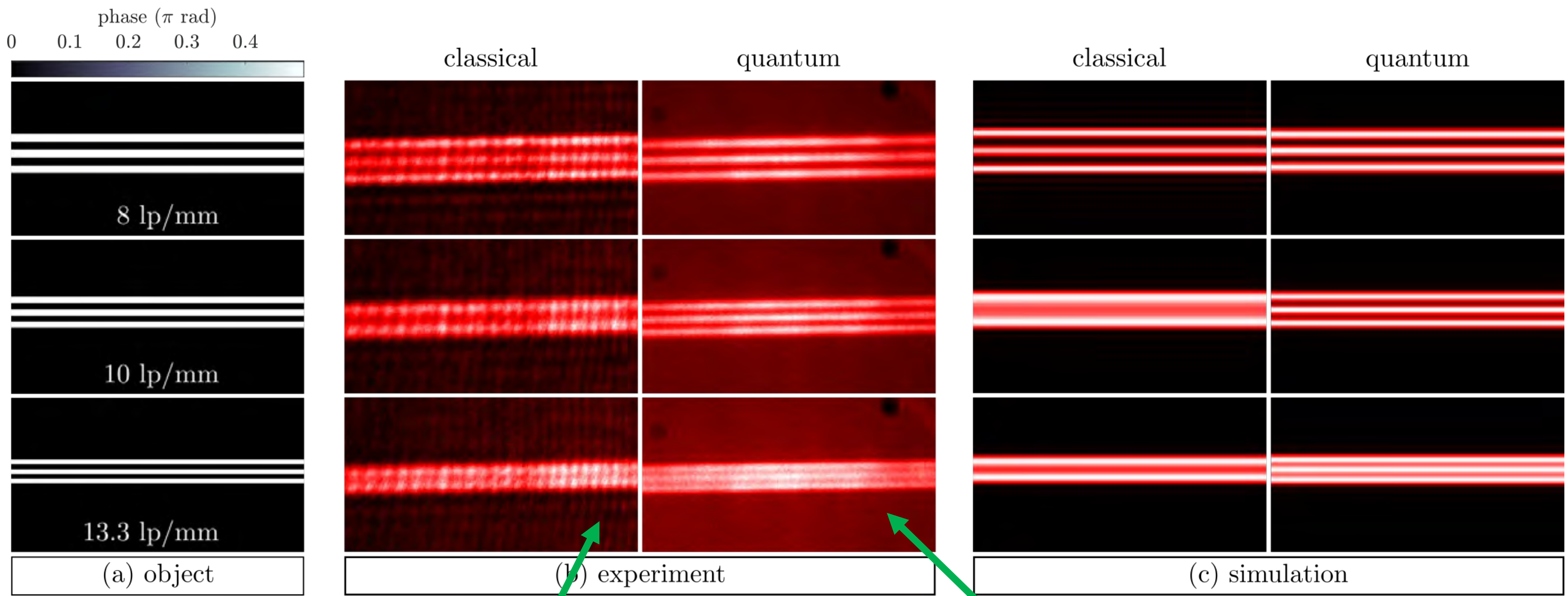


The "object" is a phase object
Written onto an SLM.

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



Vertical fringing is from back reflections.

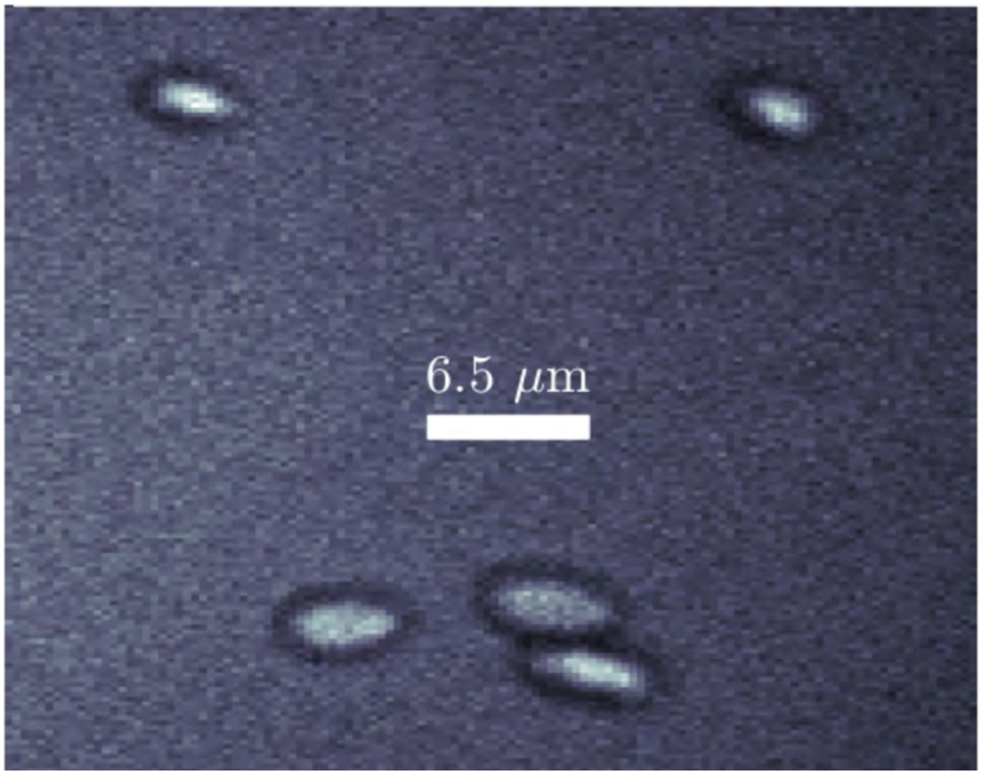
Fringing from back reflections not present in quantum experiment because back reflections are not mode matched.

The quantum experiment achieves ~1.7 times better spatial resolution.

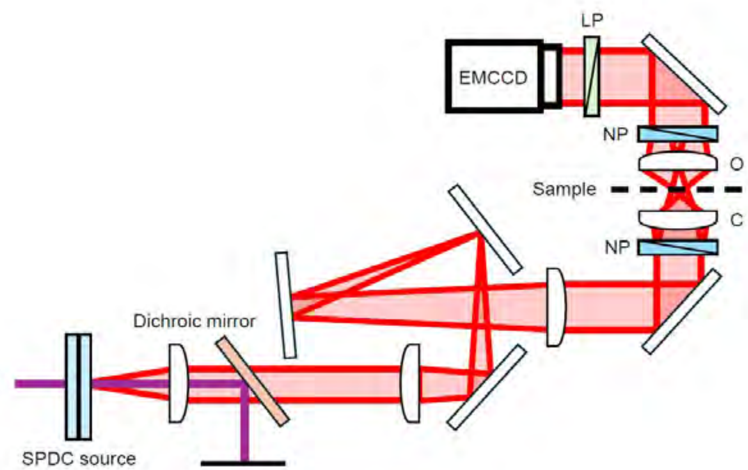
A. Nicholas Black, Long D. Nguyen, Boris Braverman, Kevin T. Crampton, James E. Evans, and Robert W. Boyd, "Quantum-enhanced phase imaging without coincidence counting," Optica 10, 952-958 (2023).

Latest Lab Result: Quantum Phase Microscopy

- Living yeast cells imaged by entangled photons at 710 nm.
- Image is near the Abbe limit of resolution



Quantum Nomarsky microscope



Objective: 40x magnification, NA = 0.75

Collaboration with DoE Pacific Northwest National Laboratory

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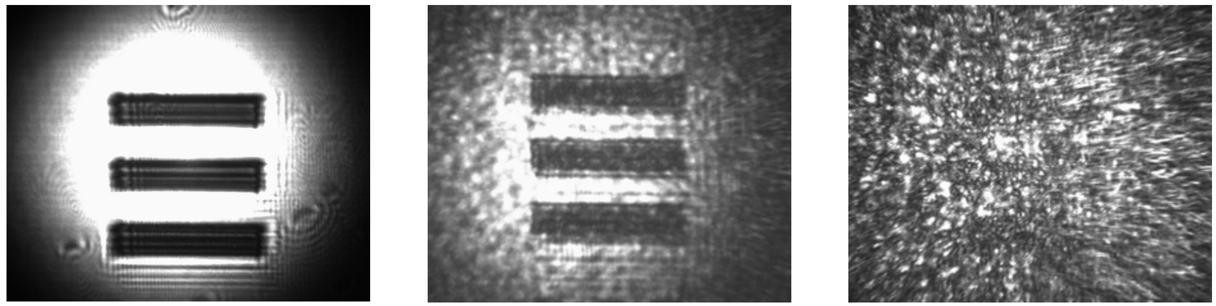
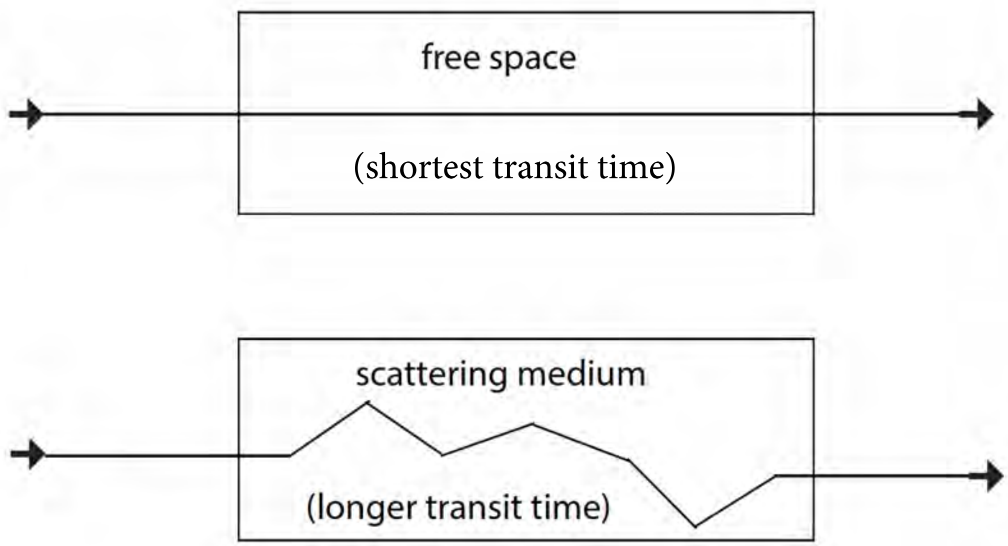
How to transmit an image through a strongly scattering medium

No scattering | Weak scattering | Strong scattering

Direct image



- Example: How do we look through skin and flesh to see what is inside human body?
- Solution: Use time-gating to reject all but the unscattered, first-arriving photons.
- Need material with a strong, fast nonlinear optical response to construct the time gate.
- Use material such as ITO with a strong NL response at its epsilon-near zero wavelength



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

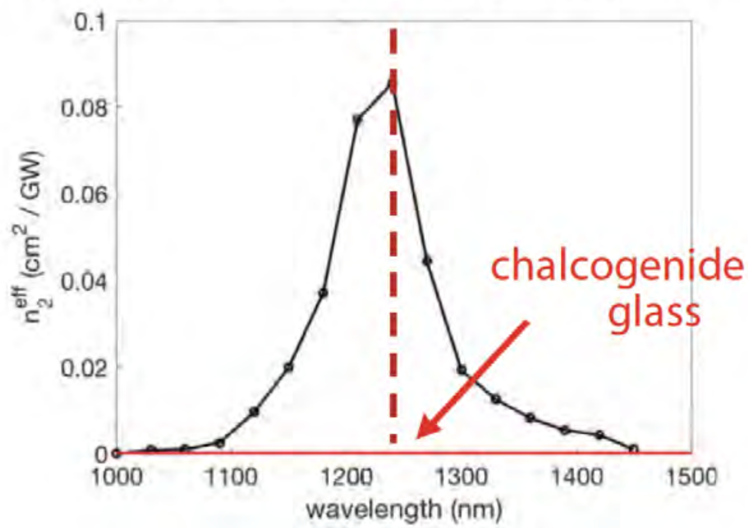
$$n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 c\, n_0 \,\mathrm{Re}(n_0)}$$

- 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.

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



Footnote:

Standard notation for perturbative NLO

$$P = \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots$$

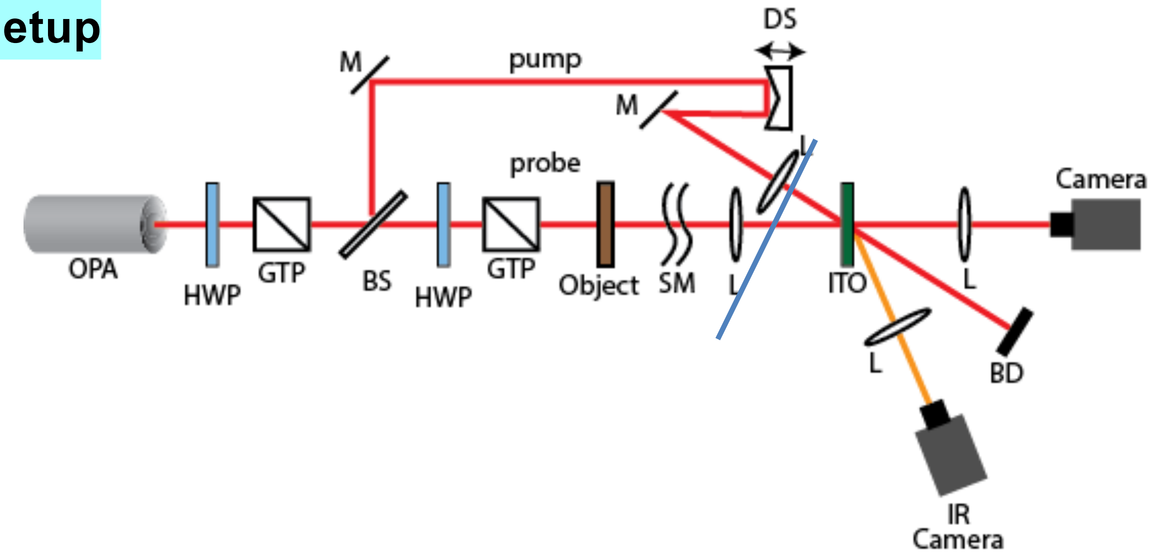
P is the induced dipole moment per unit volume and E is the field amplitude.

Also, the refractive index changes according to

$$n = n_0 + n_2 I + n_4 I^2 + \ldots$$

Experiment Setups

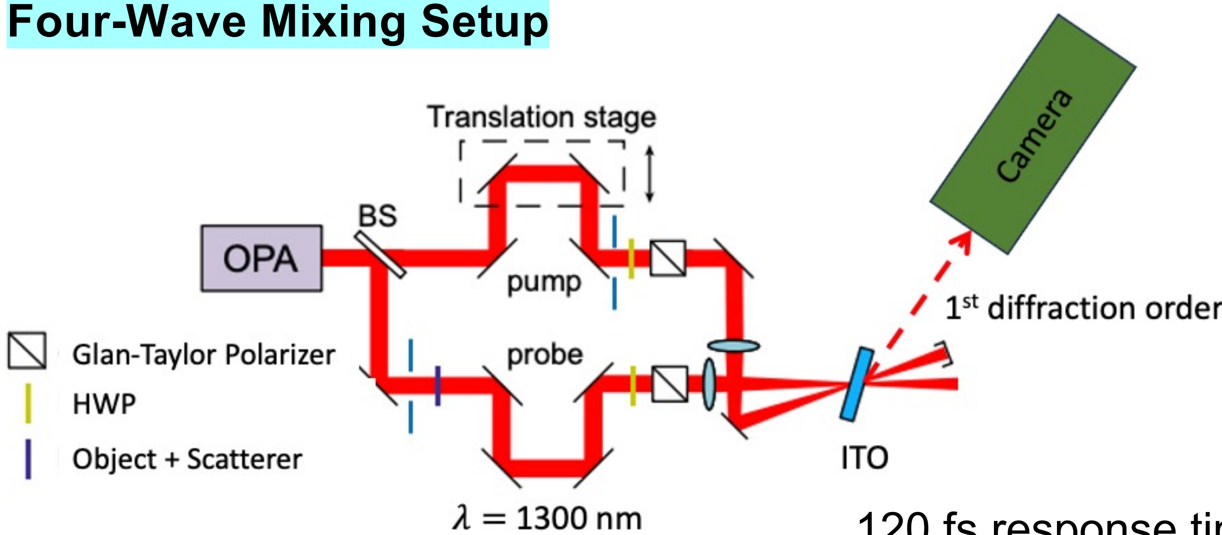
Kerr Gate Setup



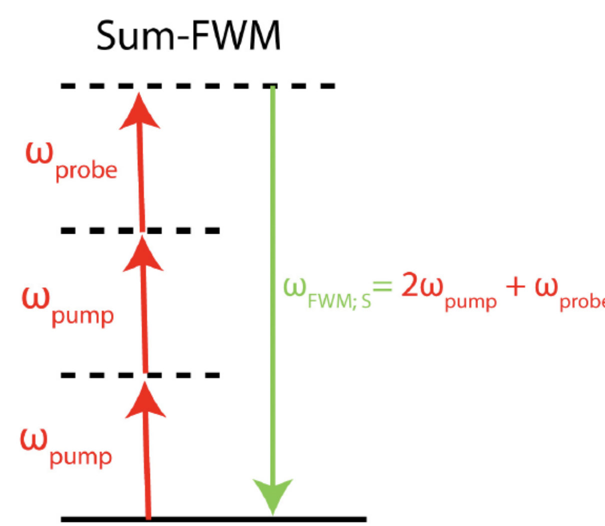
Probe transmission shuttered by pump pulse in a “Kerr gate.”

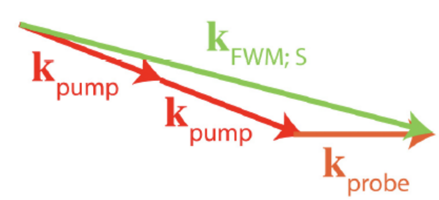
300 fs response time

Four-Wave Mixing Setup



120 fs response time

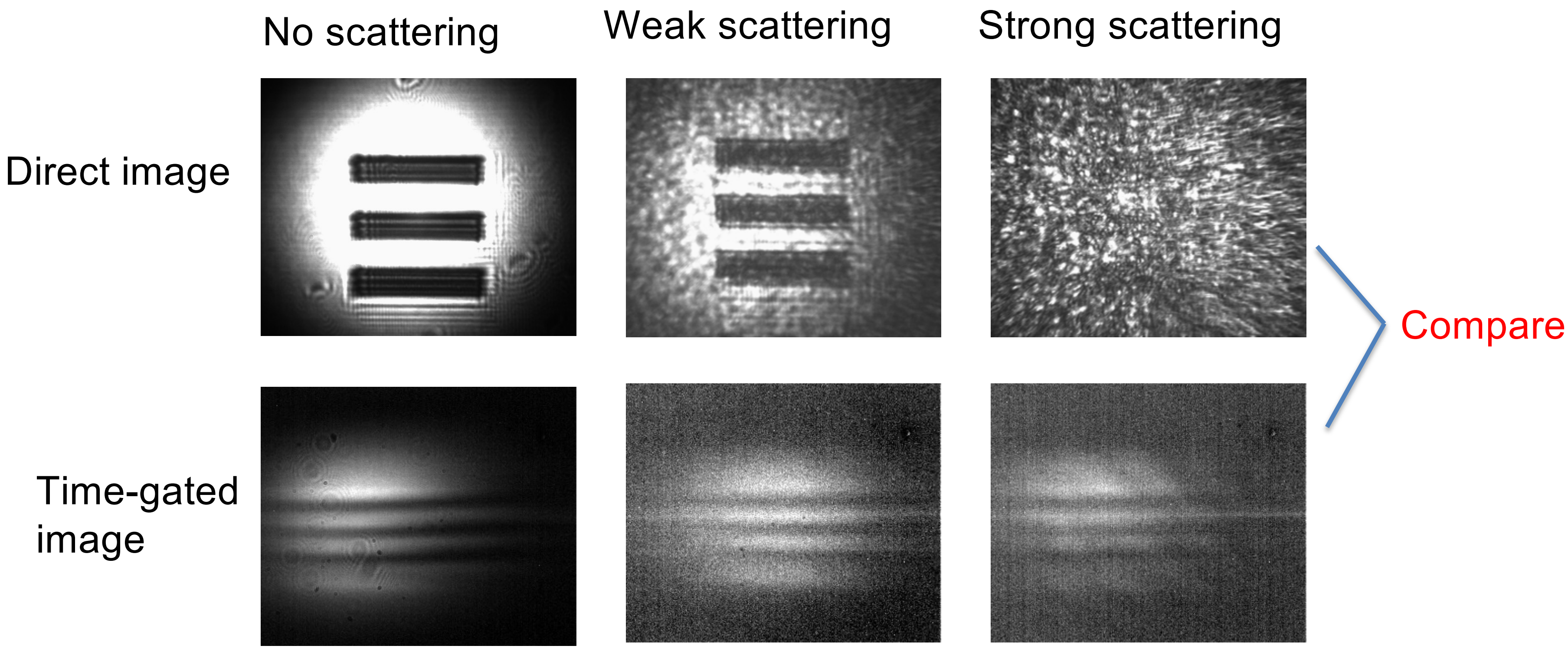




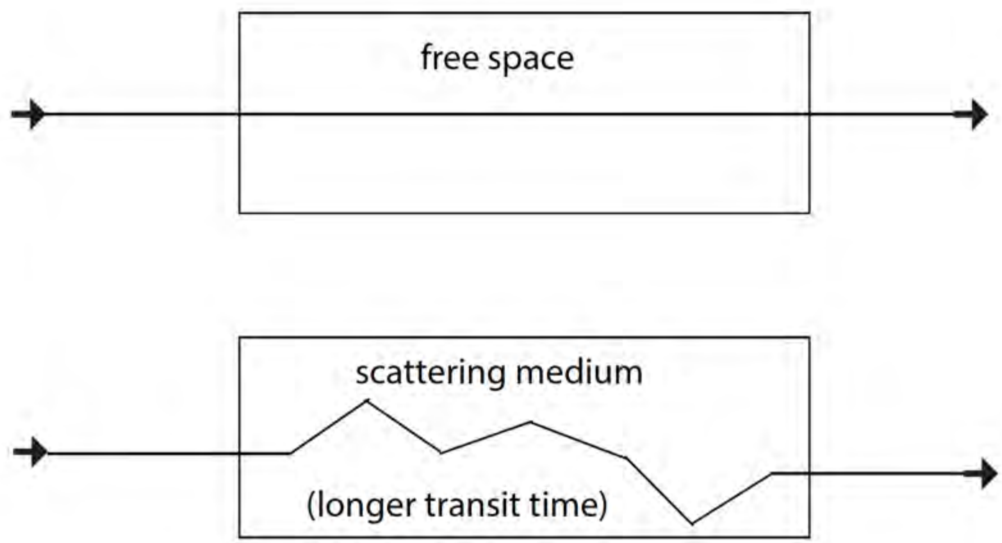
We use the four-wave mixing setup because it gives a shorter gating time and better suppresses background.

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

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.



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

Imaging through a Strongly Scattering Medium

We have demonstrated an imaging method that

- Preserves the spatial resolution of the object
- Is background free
- Converts image to a desirable wavelength

Our approach involves time-gating using a highly nonlinear ENZ material

- Time-gate transmits only the unscattered photons, which contain the image information

Useful for

- Non-invasive biomedical imaging and tomography
- Optical (including OAM-based optical) communication through atmospheric turbulence

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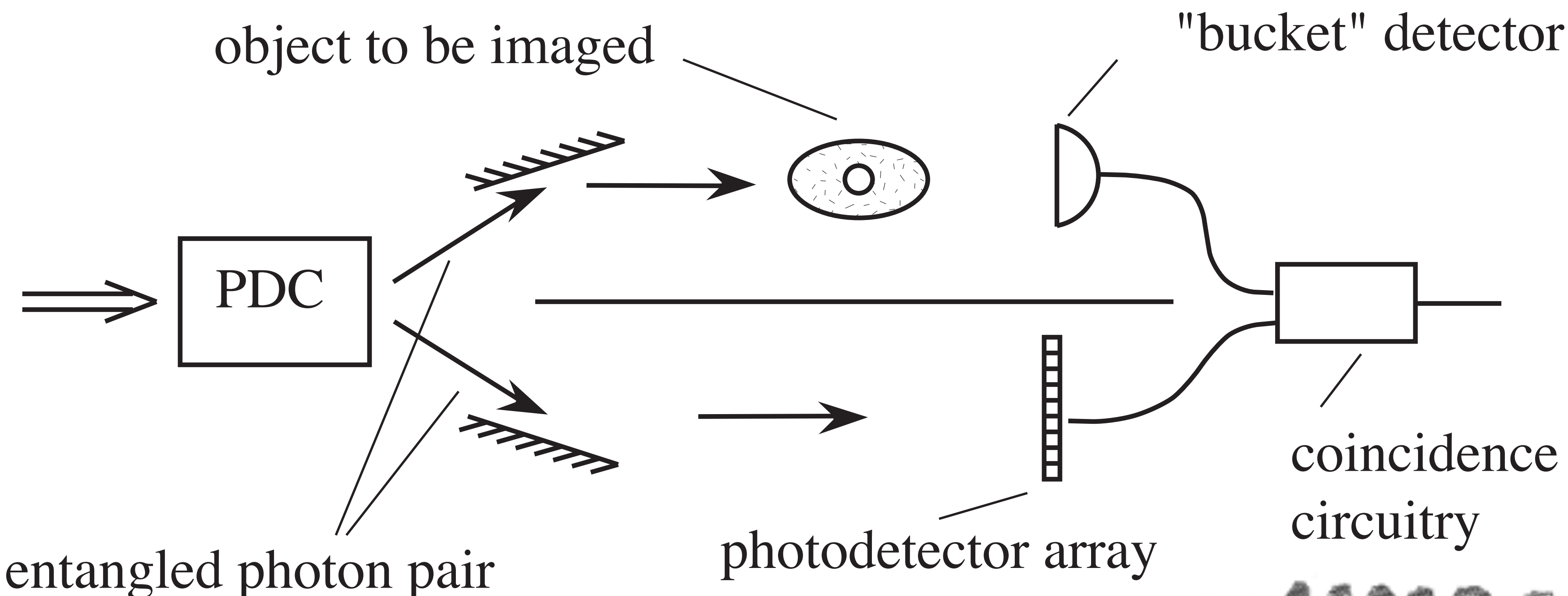
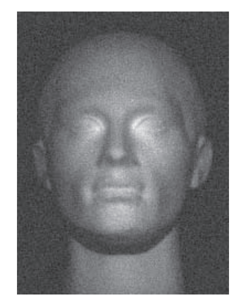
Ghost (Coincidence) Imaging



- 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)



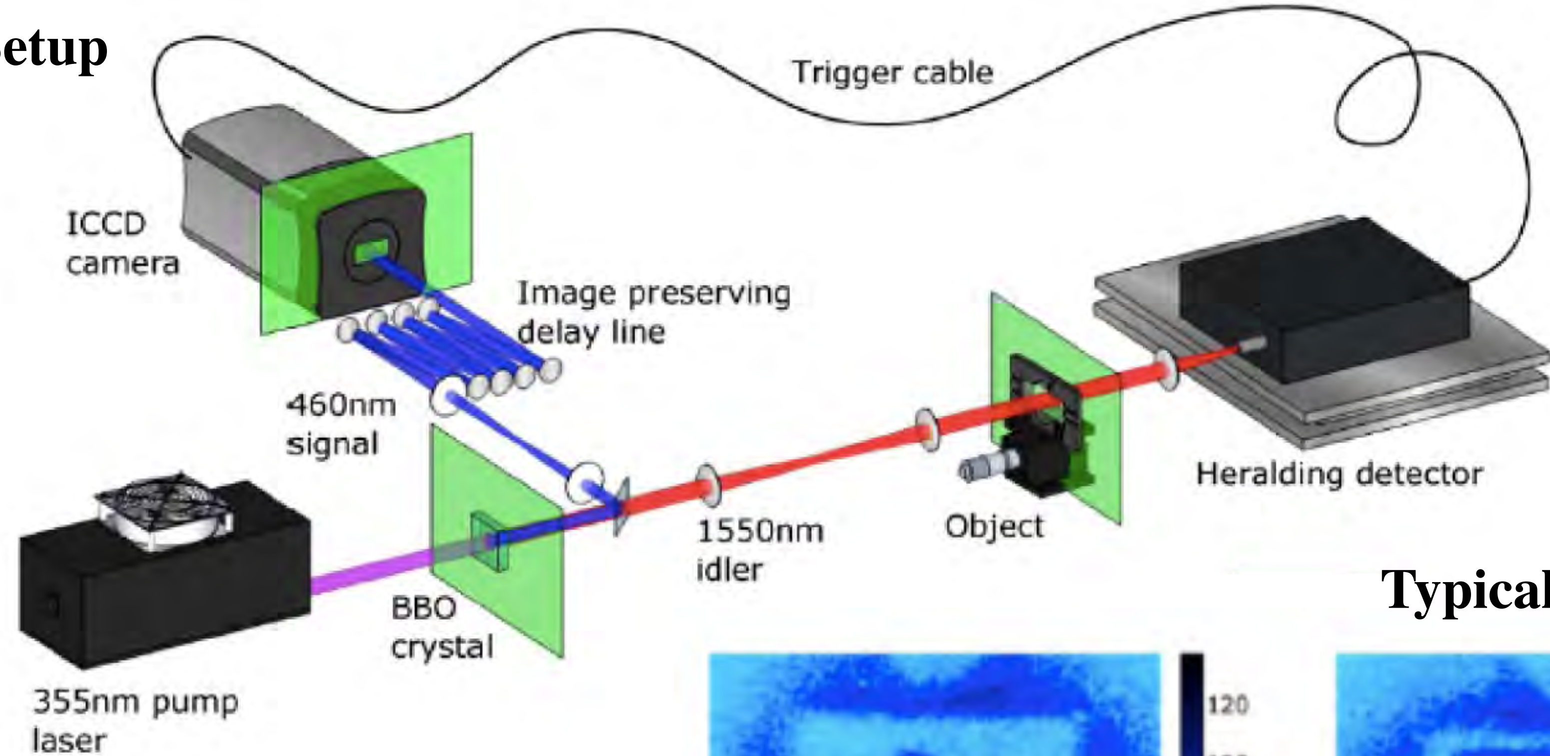
Padgett Group

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)

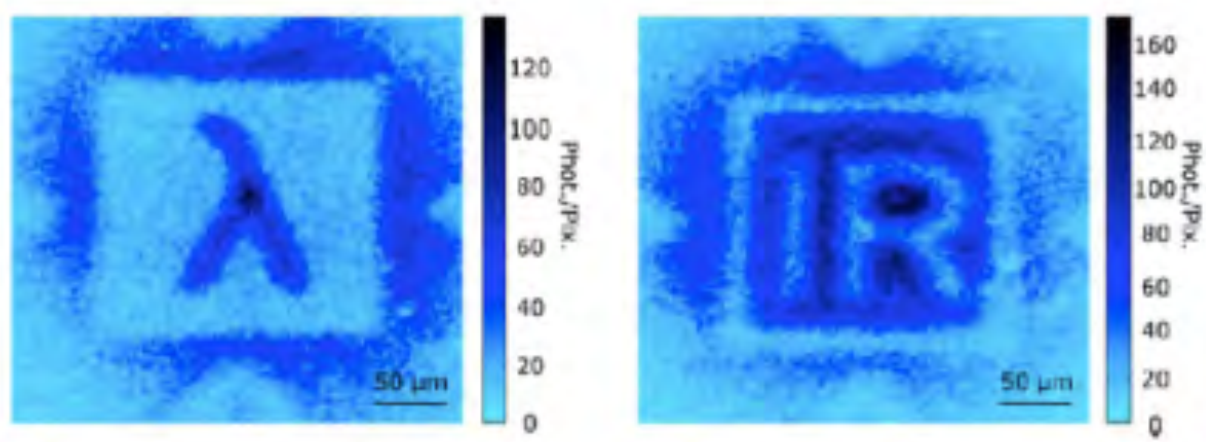
Wavelength-Shifted (Two-Color) Ghost Microscopy

- 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

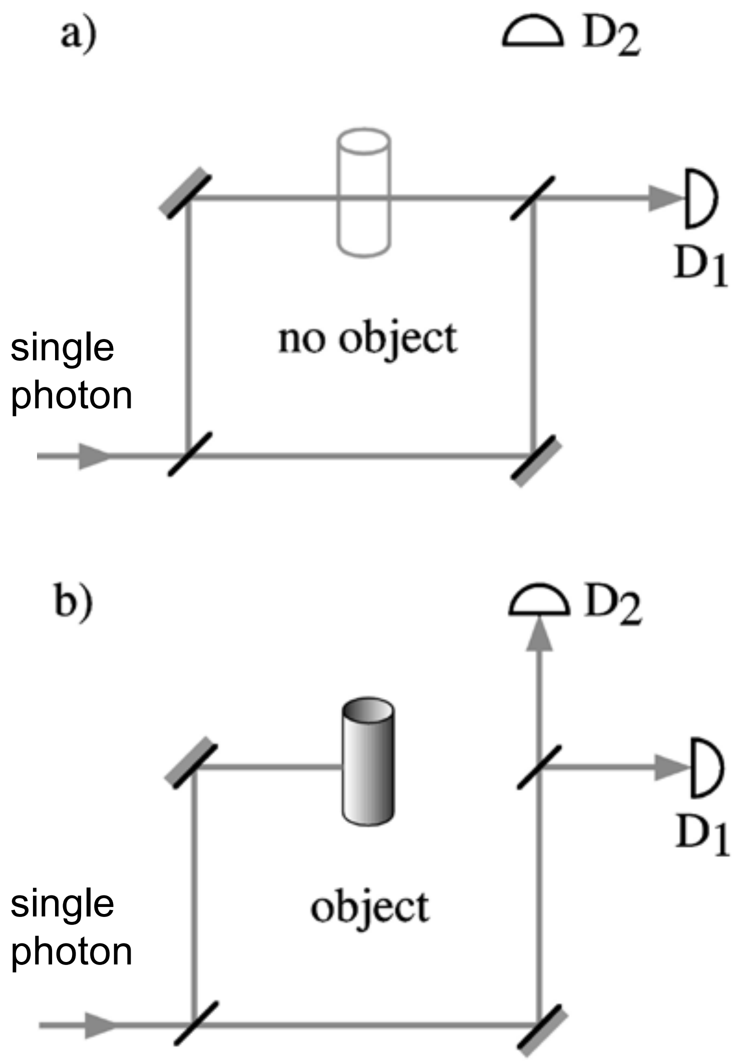


Typical images

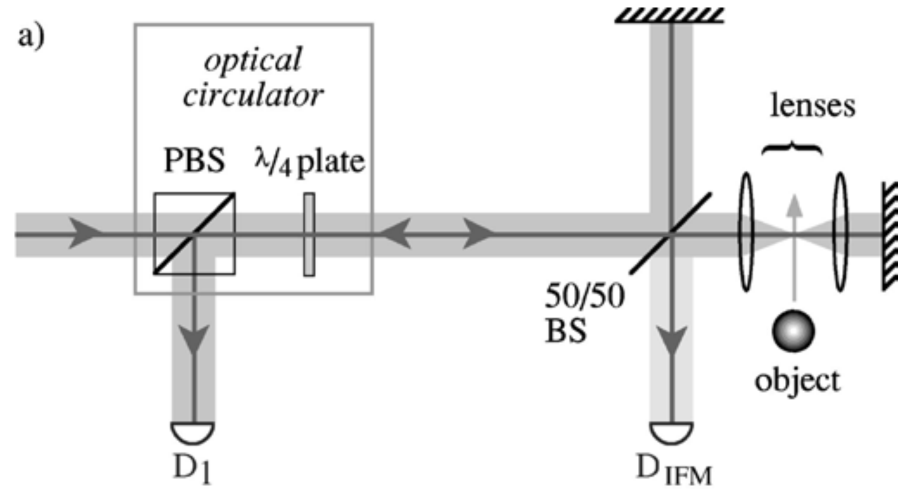


Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

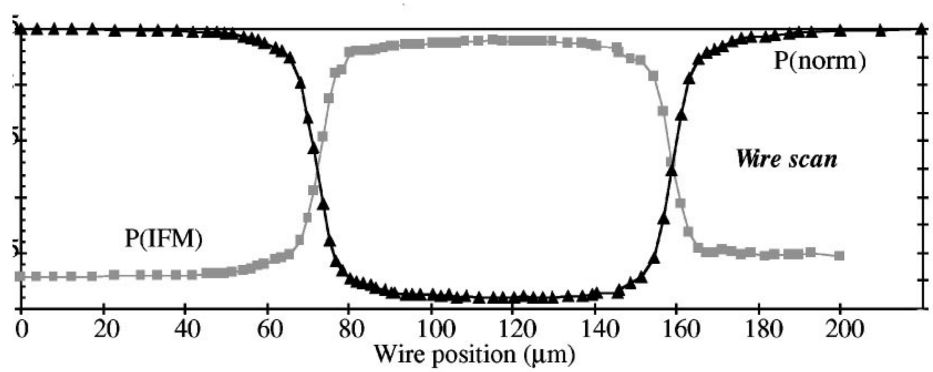
Quantum Imaging by Interaction-Free Measurement



imaging setup

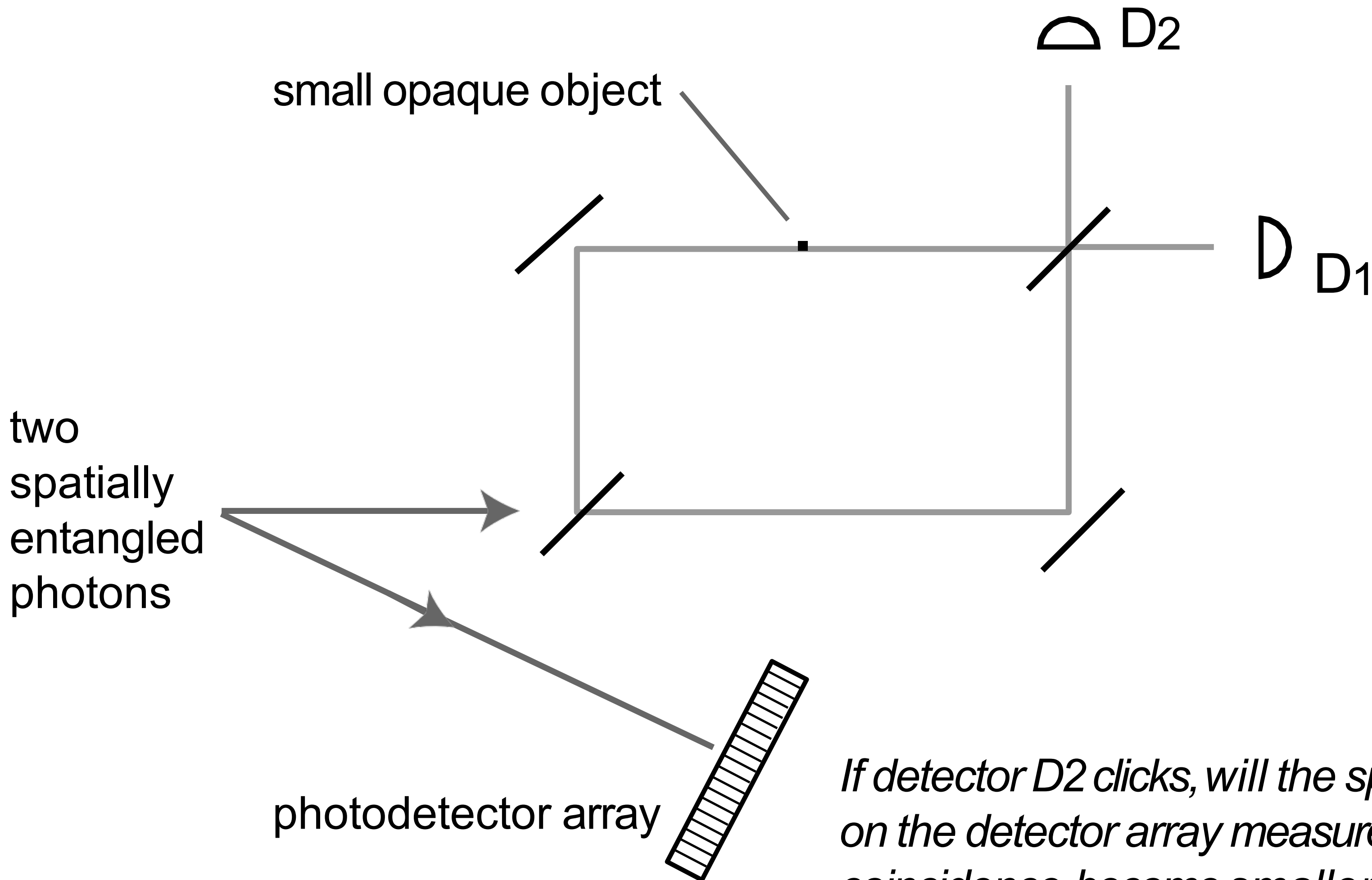


results



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?

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

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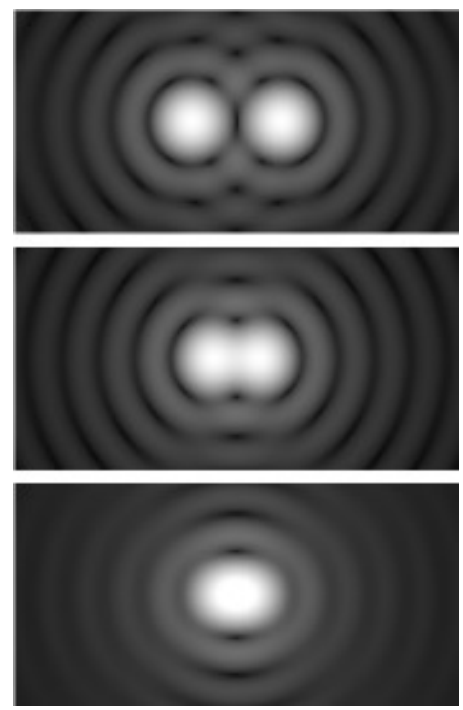
Superresolution

- 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

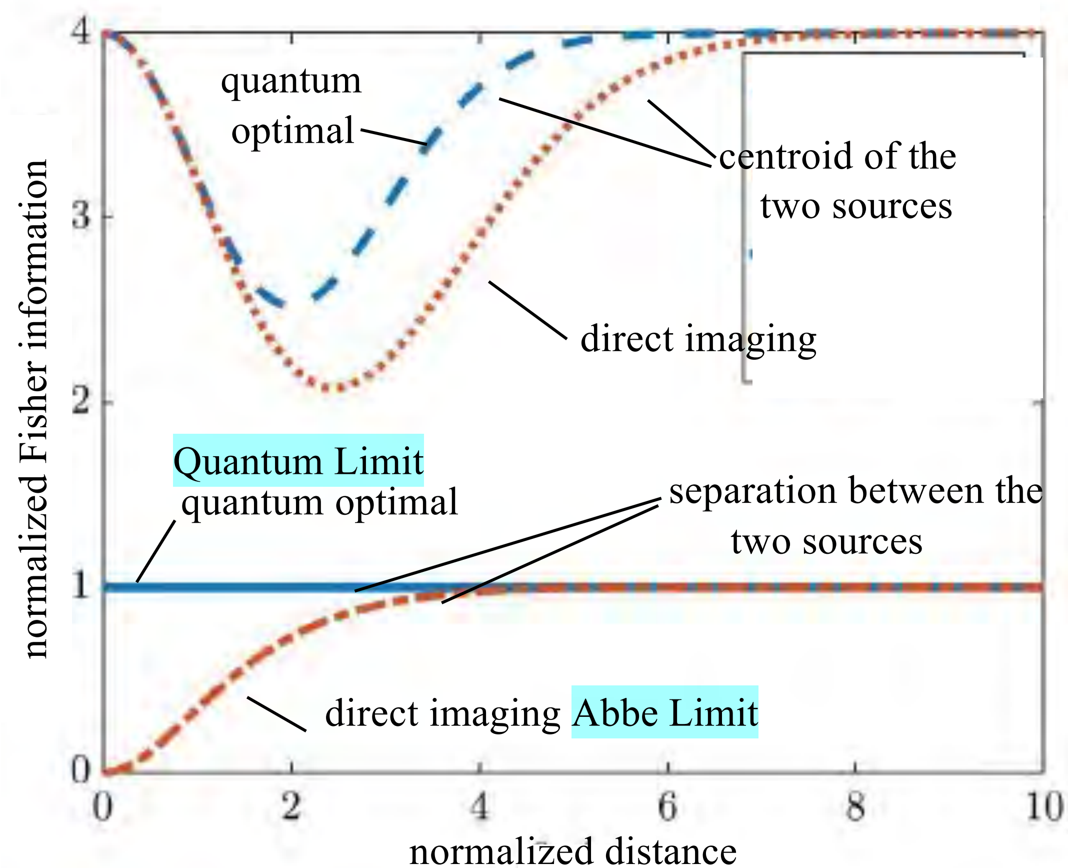
1. It is most natural to perform imaging in coordinate space, that is to measure the intensity $I(x)$ as a fuction of position.

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.

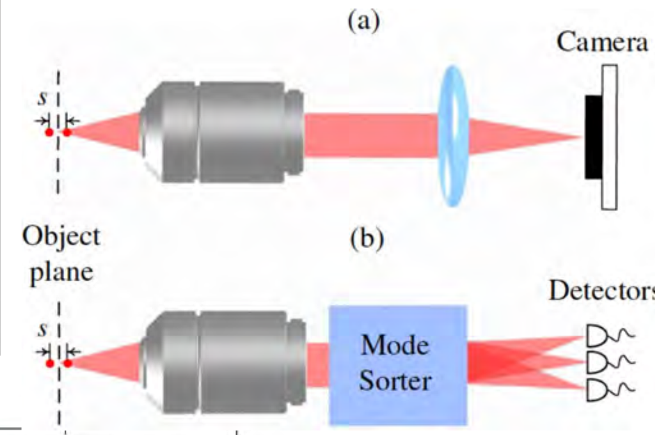
What about axial resolution, which is also very important?

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).

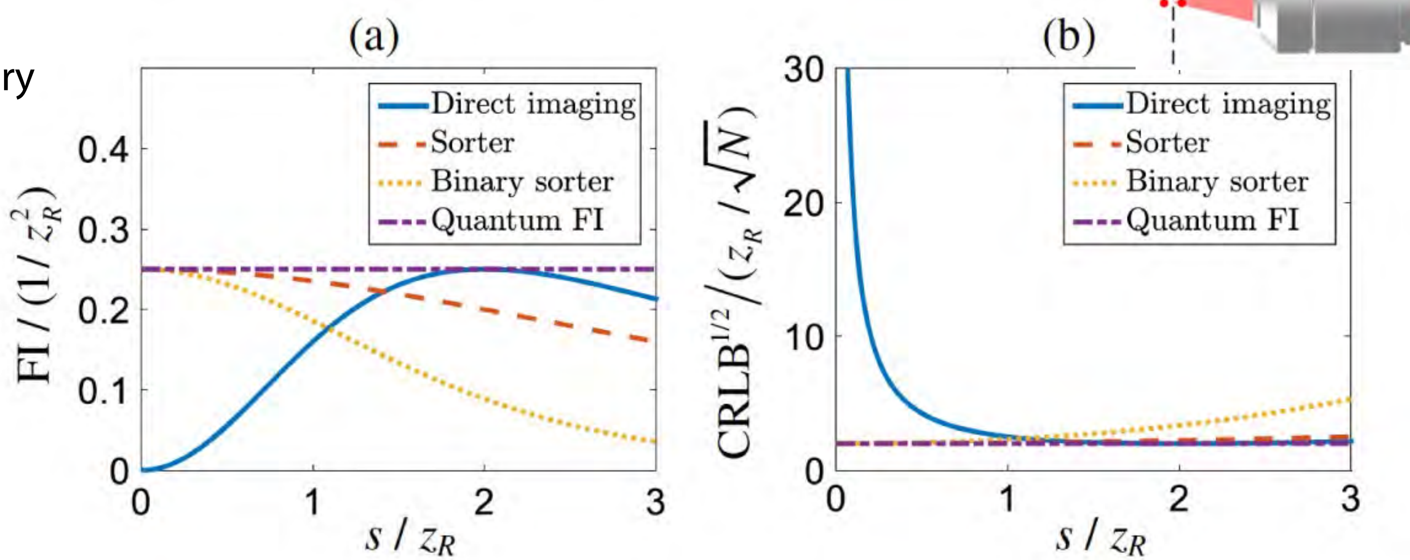
optica

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]



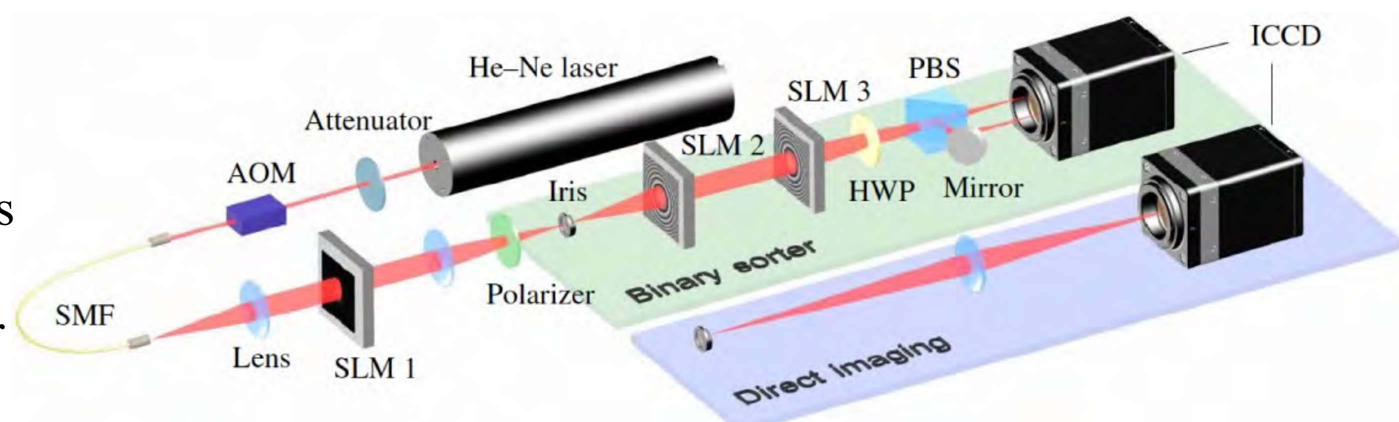
- Theory



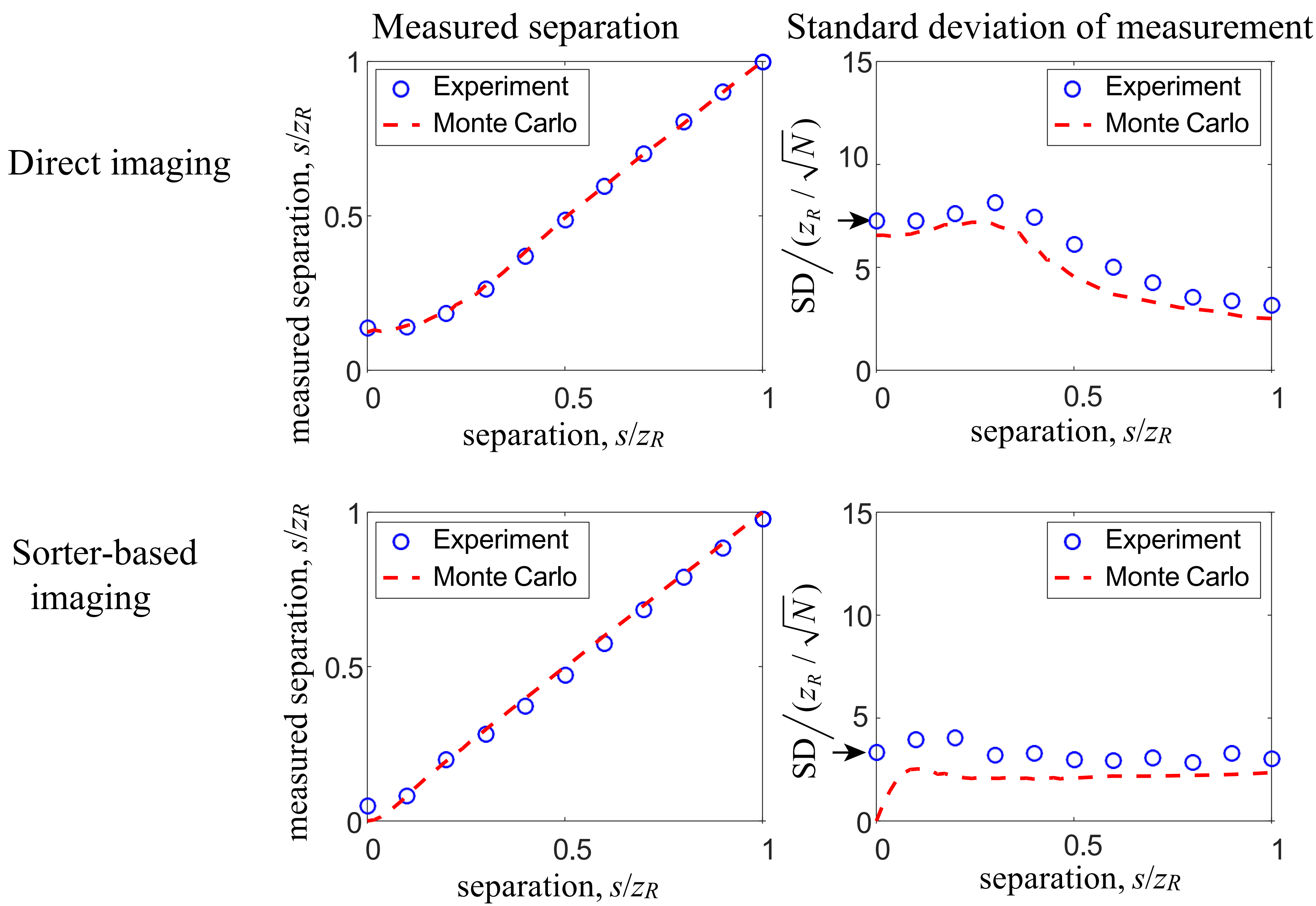
CRLB = Cramer-Rao lower bound = reciprocal of Fisher information

- 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?

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]

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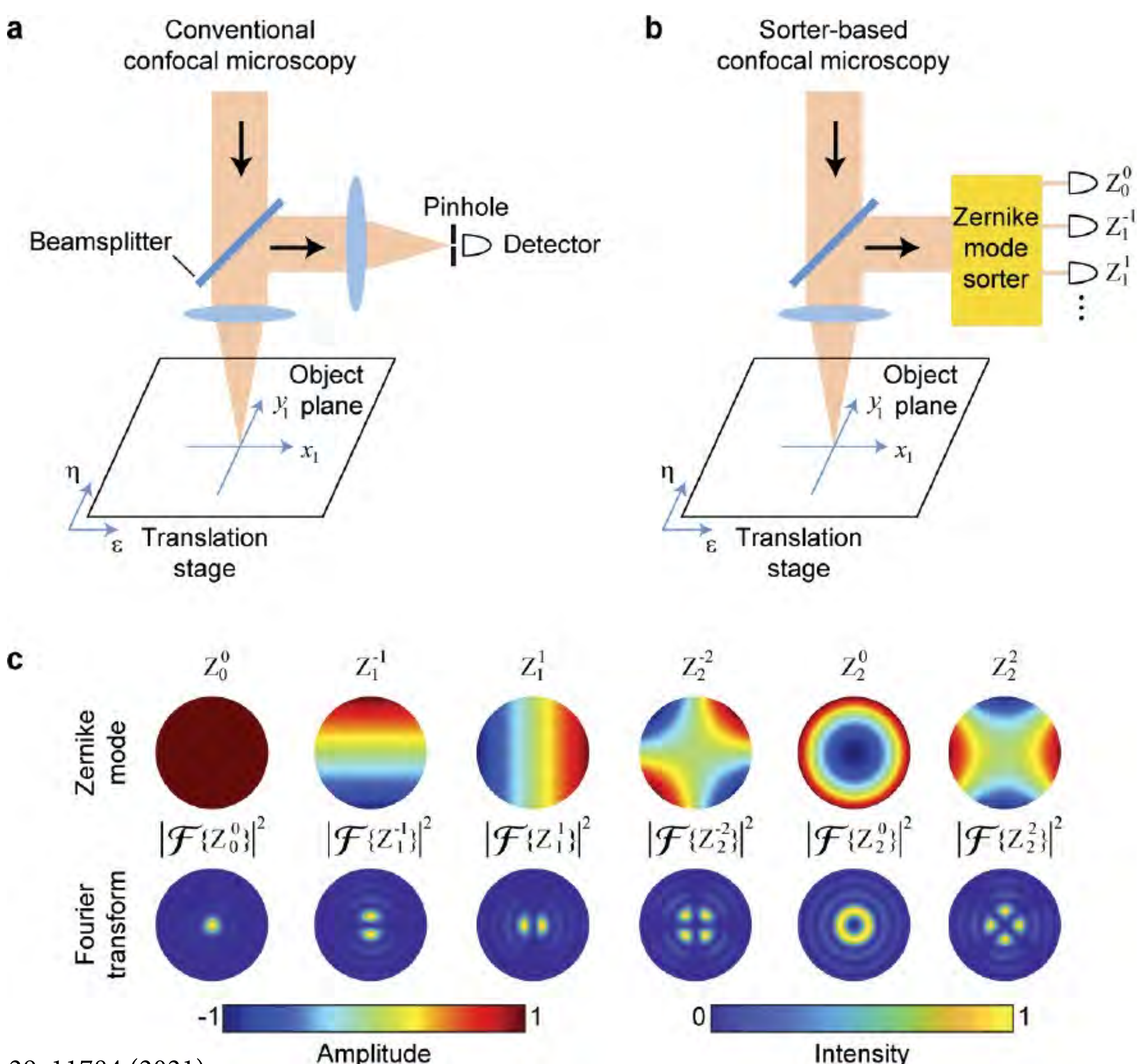
Our Experimental Procedure



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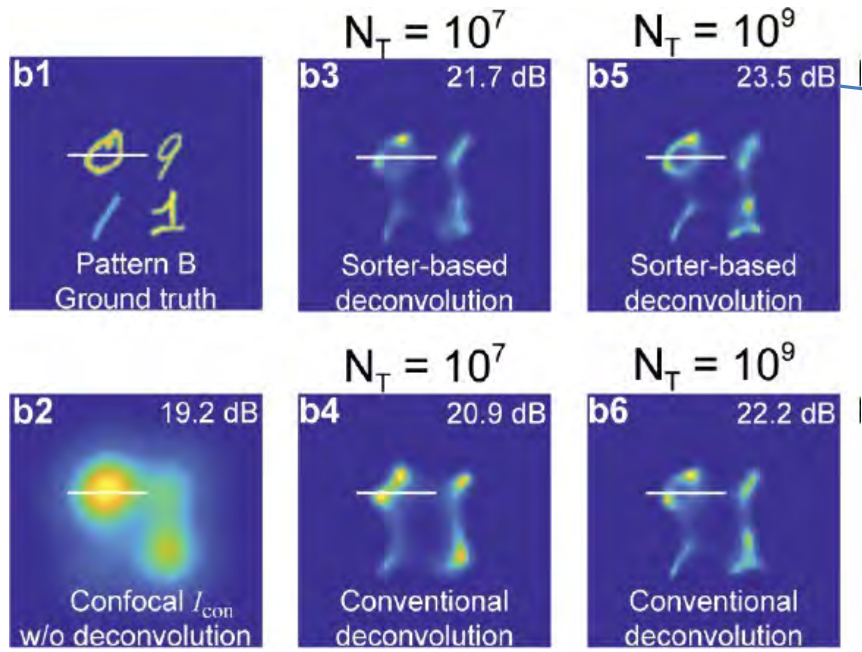
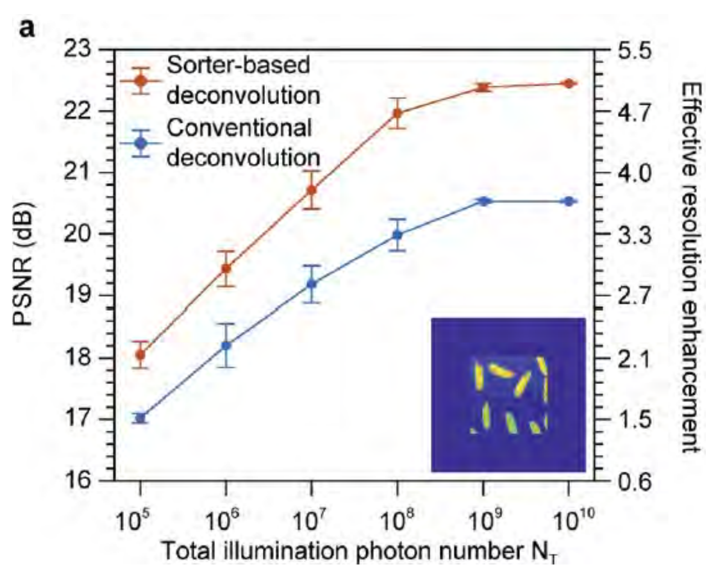
Some Numerical Results

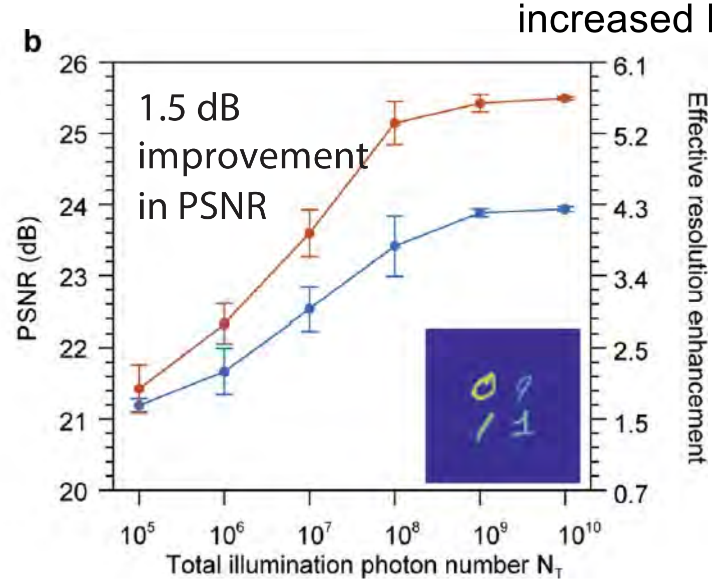


PSNR = peak signal-to-noise ratio

- 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)

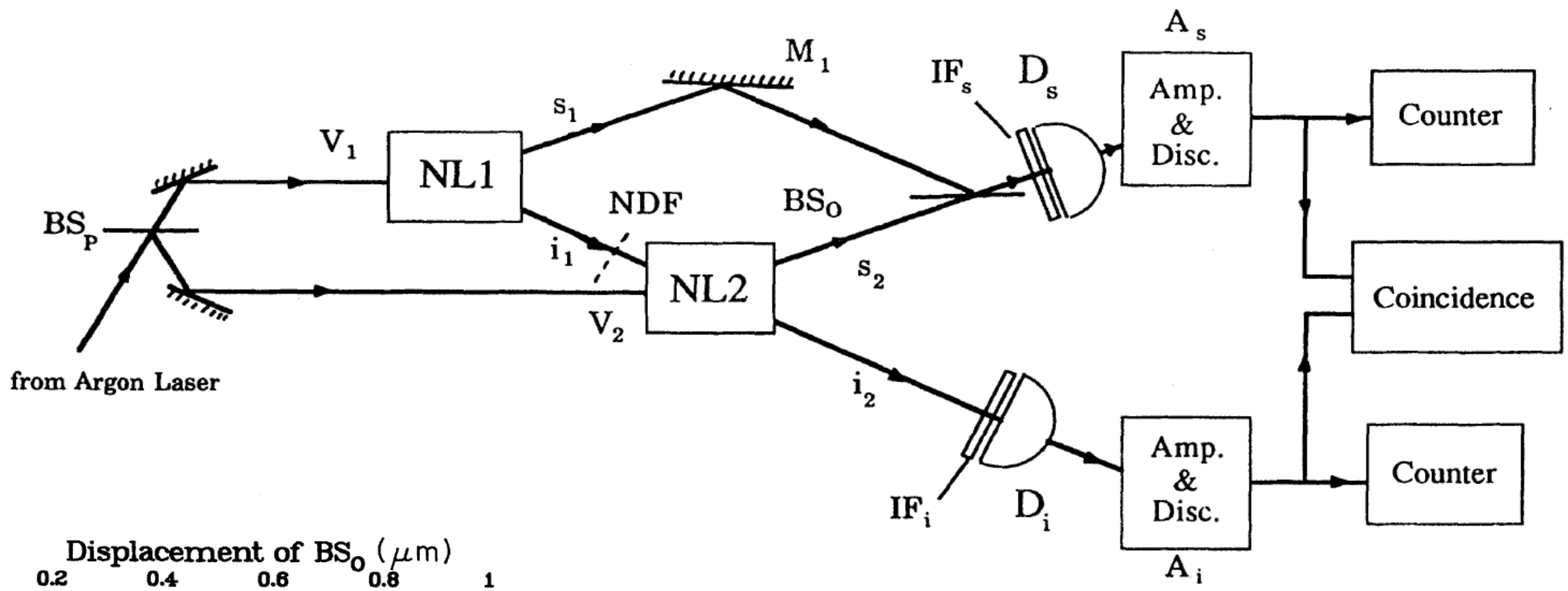
Quantum Imaging Outline

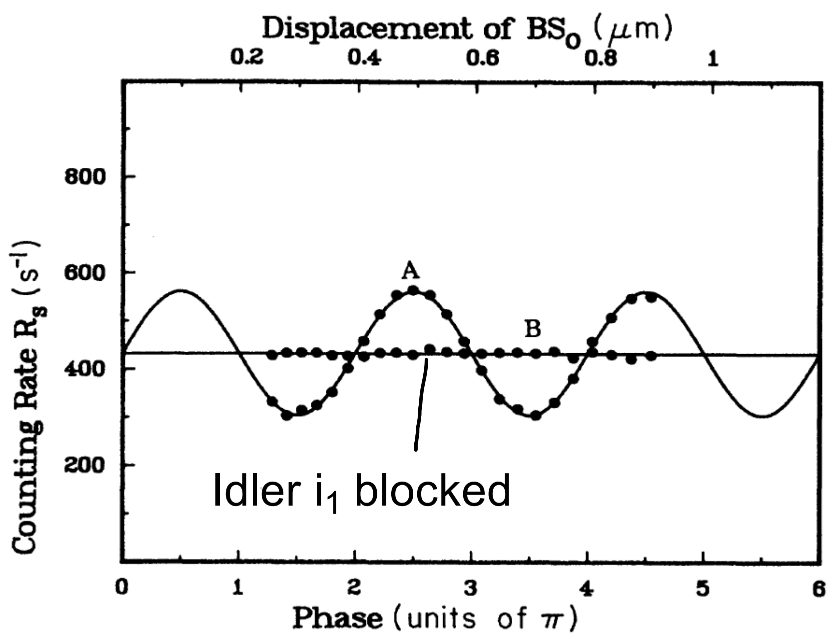
1. Introduction to Quantum Imaging
2. Quantum Microscopy for Biomedicine
3. Imaging through Strongly Scattering Media
4. Interaction-Free Ghost Imaging
5. Superresolution
6. **Imaging with Undetected Photons**

Induced coherence without induced emission

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

INDUCED COHERENCE WITHOUT INDUCED EMISSION



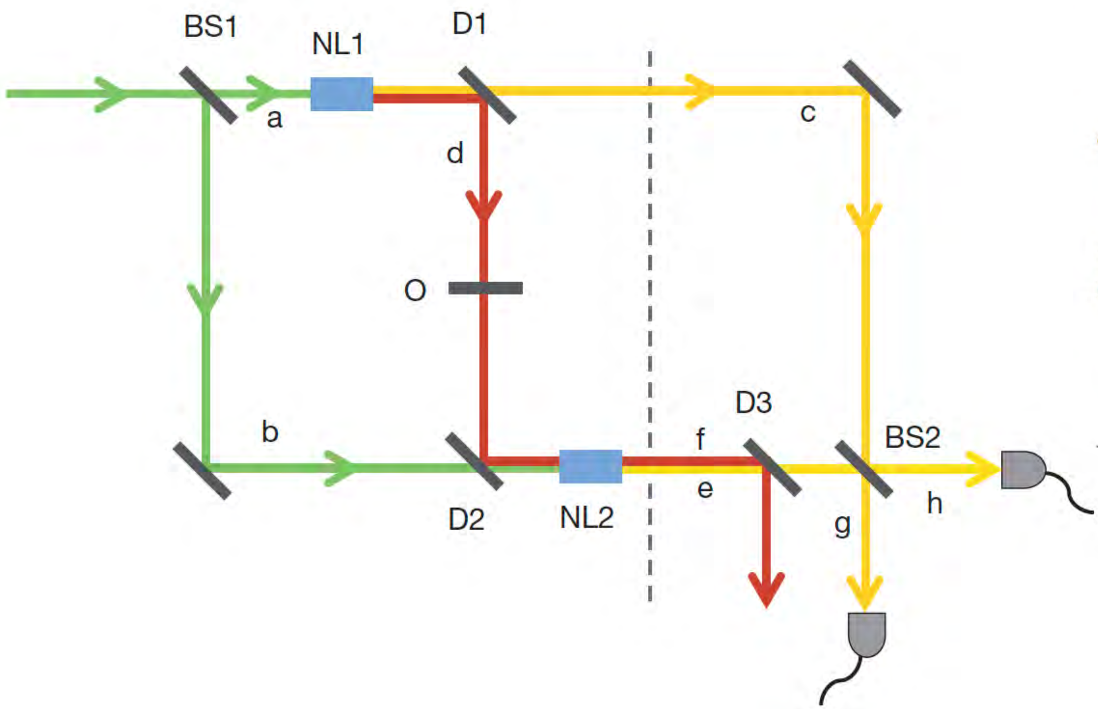


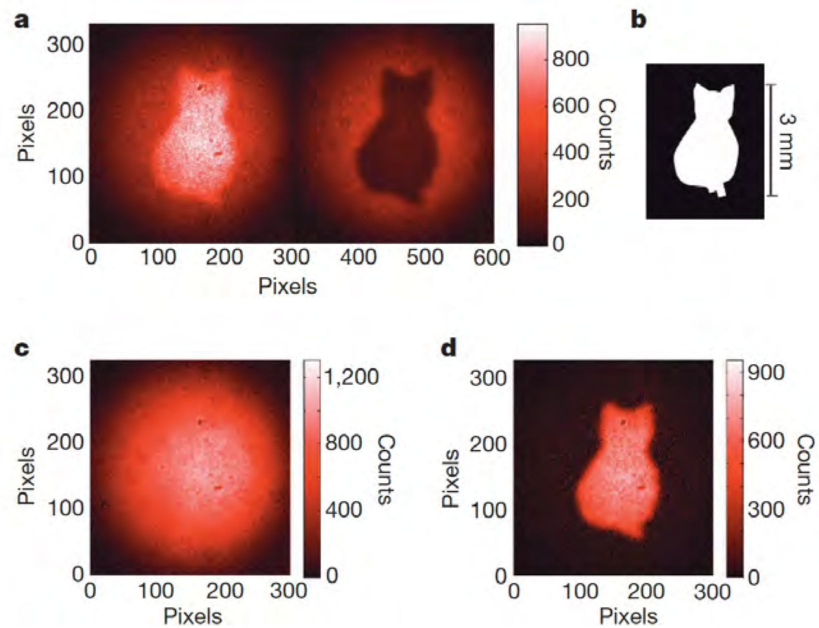
Quantum imaging with undetected photons

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]

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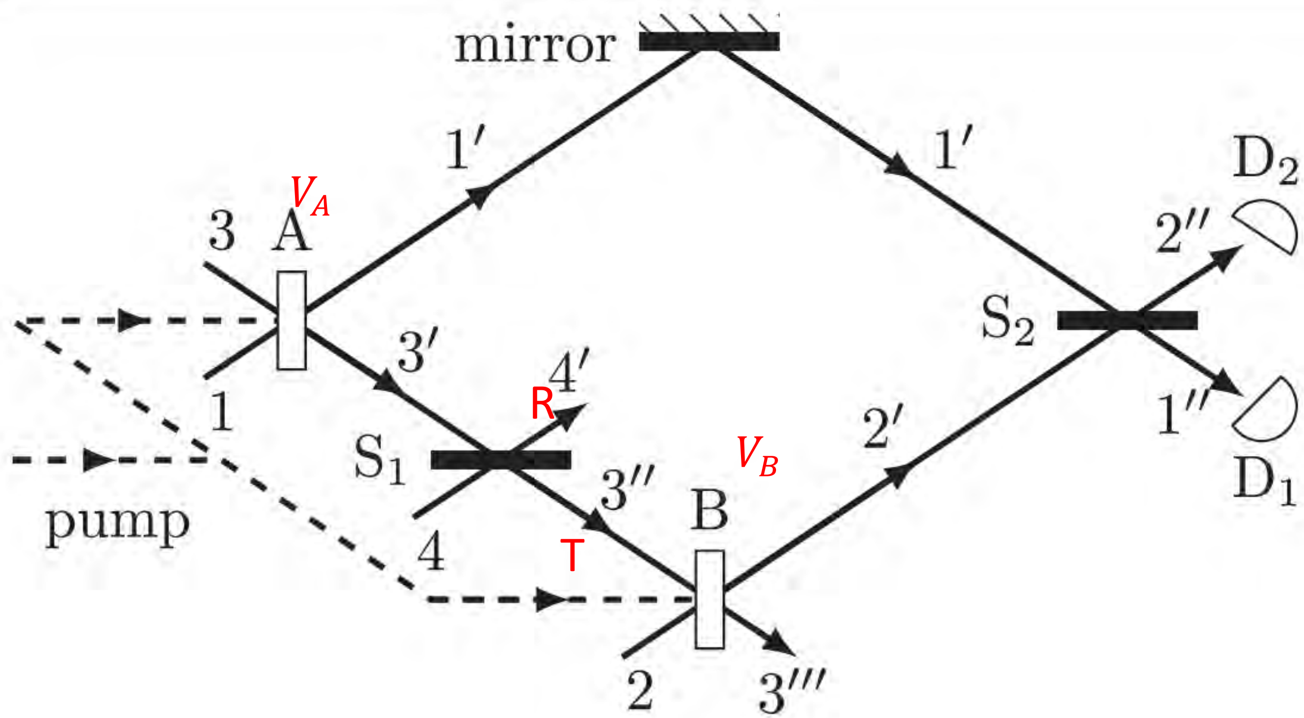

- How are visibility and SNR of the quantum interference influenced by working in the high-gain limit (V_A and V_B greater than unity) of parametric down-conversion?
- Here V_A and V_B are the parametric gains of NL crystals A and B.
- We also study imbalanced pumping, V_A not equal to V_B

Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group