Nonlinear Optics and Quantum Imaging

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

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Quantum Sensing and Quantum Imaging

Quantum Sensing refers to the use of quantum methods to increase the sensitivity of optical measurements.

One is often interested in increasing the sensitivity to beyond the *standard quantum limit*, a very strange and misleading name, because it is the limiting sensitivity attainable with classical measurements

One is sometimes interested in achieving the seemingly best possible sensitivity using quantum methods, which is called the *Heisenberg limit*. This name is also misleading. The Heisenberg limit presumably refers to the *Fourier transform limit*, but we know that superoscillations can exceed this limit.

A specific example of Quantum Sensing is *Quantum Imaging*.

Quantum Imaging

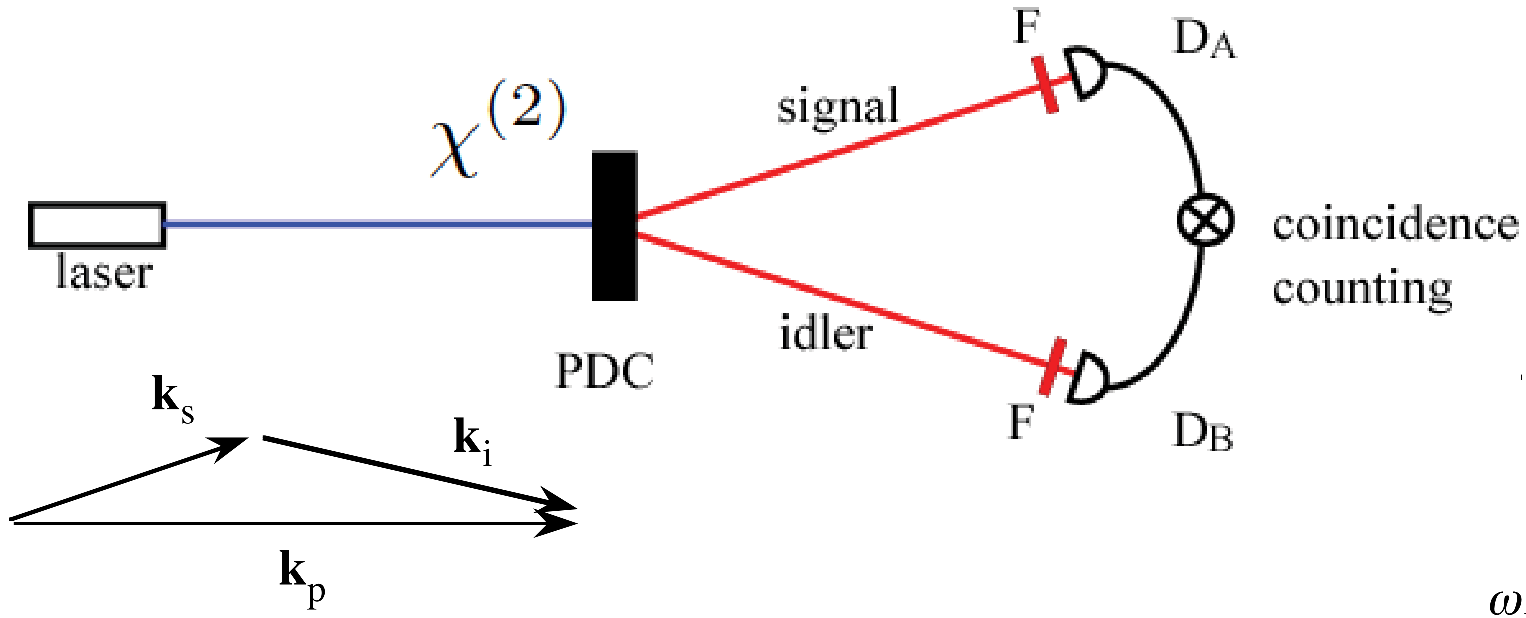
- The goal of quantum imaging is to produce “better” images using quantum methods
  - image with a smaller number of photons
  - achieve better spatial resolution
  - achieve better signal-to-noise ratio
- Alternatively, quantum imaging is research that seeks to exploit the quantum properties of the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

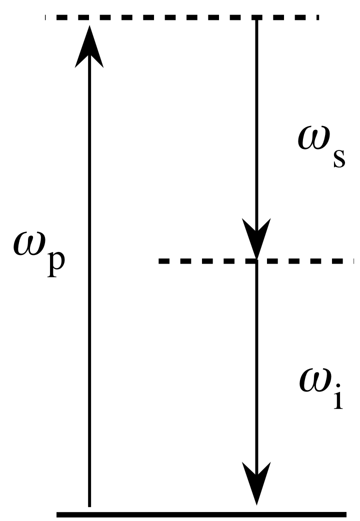
Quantum Imaging Outline

1. Introduction to Quantum Imaging
2. Quantum Microscopy for Biomedicine
3. Imaging through Strongly Scattering Media
4. Interaction-Free Ghost Imaging

Introduction to Quantum Imaging

Parametric Downconversion: A Source of Entangled Photons





The signal and idler photons are entangled in:

(a) polarization

(b) time and energy (note different format of name)

(c) position and transverse momentum

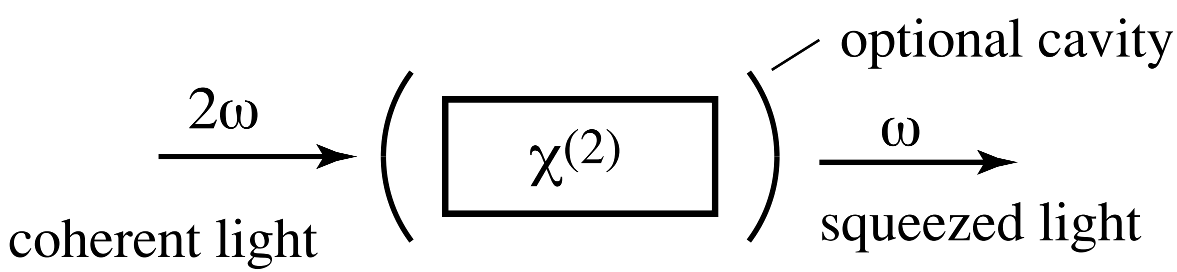
(d) angular position and orbital angular momentum

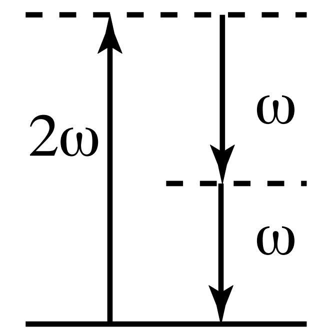
Entanglement is important for:

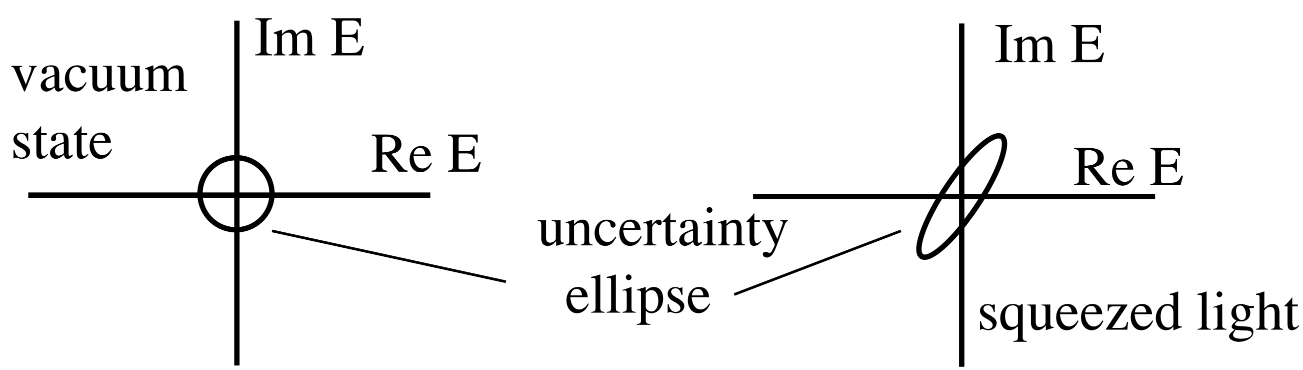
(a) Fundamental tests of QM (e.g., nonlocality)

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

Squeezed Light Generation



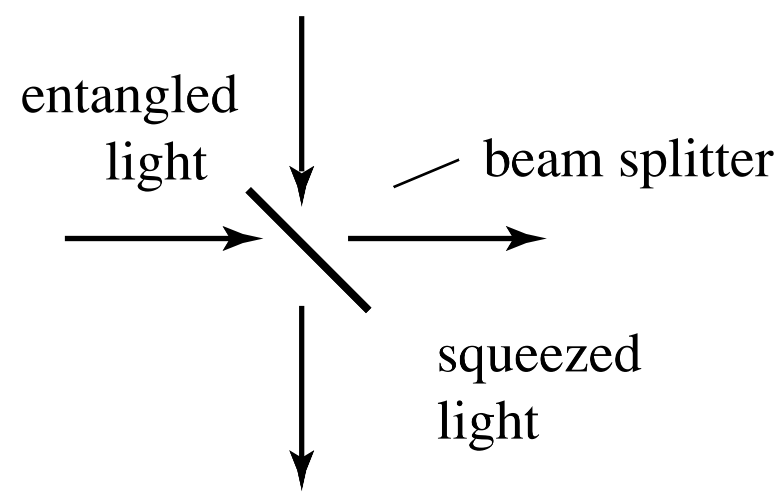




Entanglement and squeezing share a common origin.

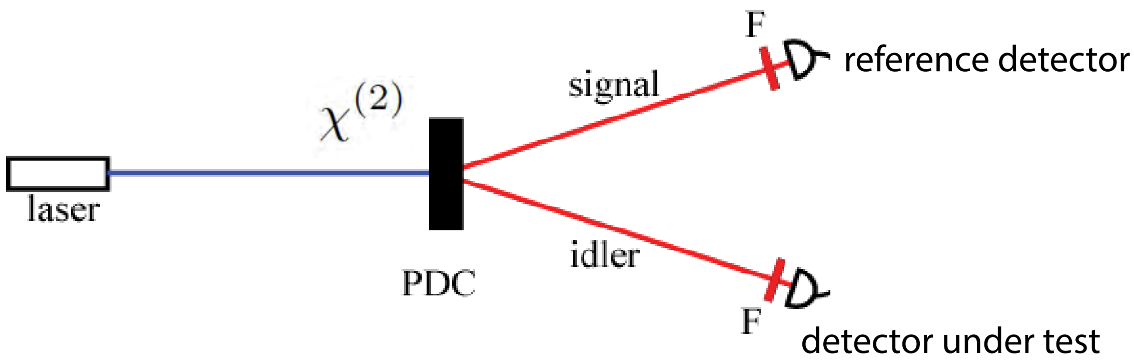
NLO required to transform classical light into quantum light.

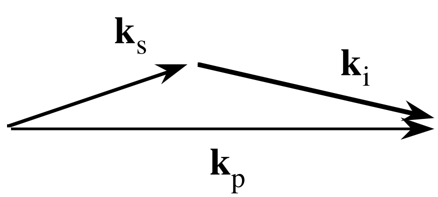
Need NLO to mix a and $a^\dagger$

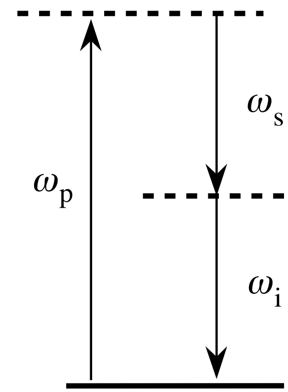


Klyshko's Method for Absolute Calibration of a Photodetector

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

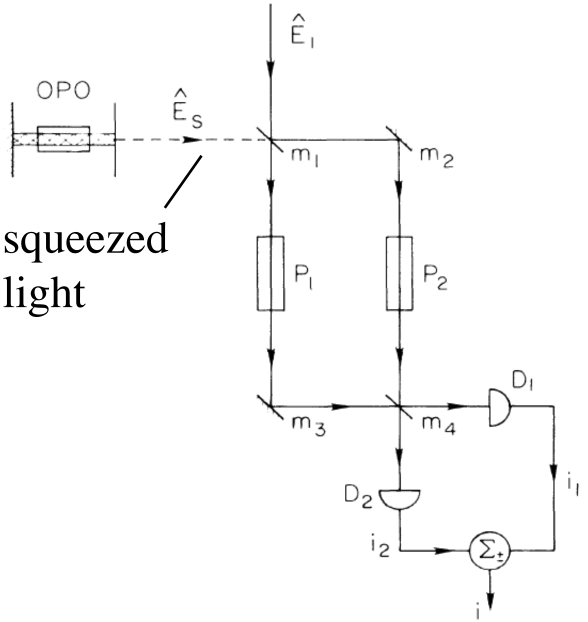




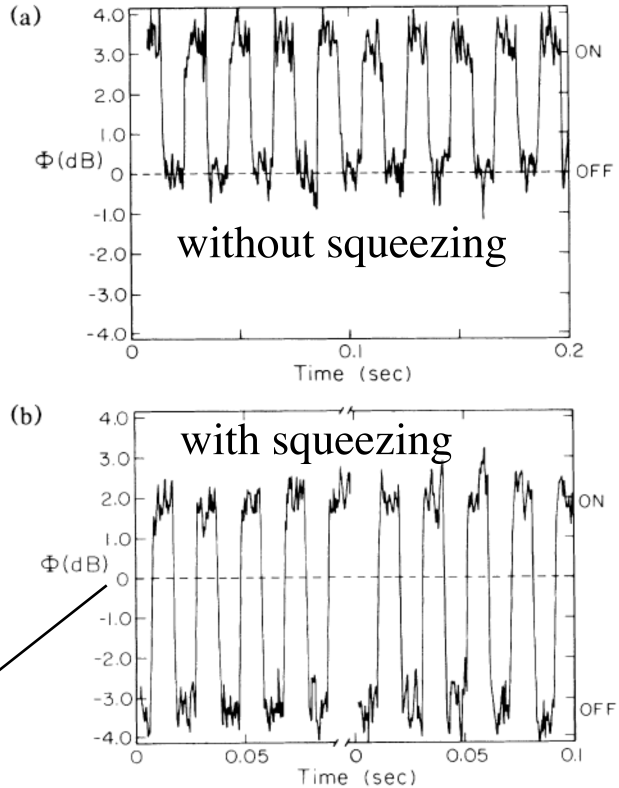


- Earlier work (Klyshko) established that the light produced by spontaneous parametric downconversion (SPDC) can be characterized in terms of the radiometric property known as brightness (or radiance).

Precision Measurement beyond the Shot-Noise Limit



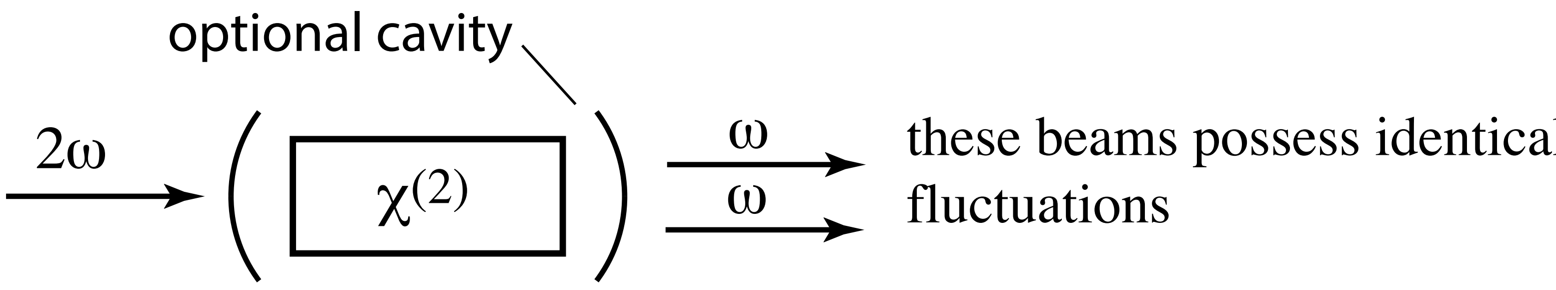
squeezed light



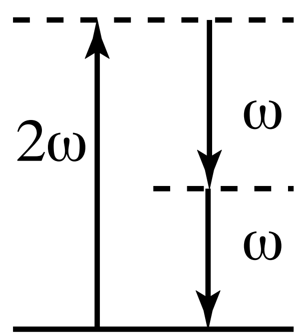
shot-noise limit = standard quantum limit

Xiao, M., L. A. Wu, and H. J. Kimble, Phys. Rev. Lett. 59, 278, 1987.

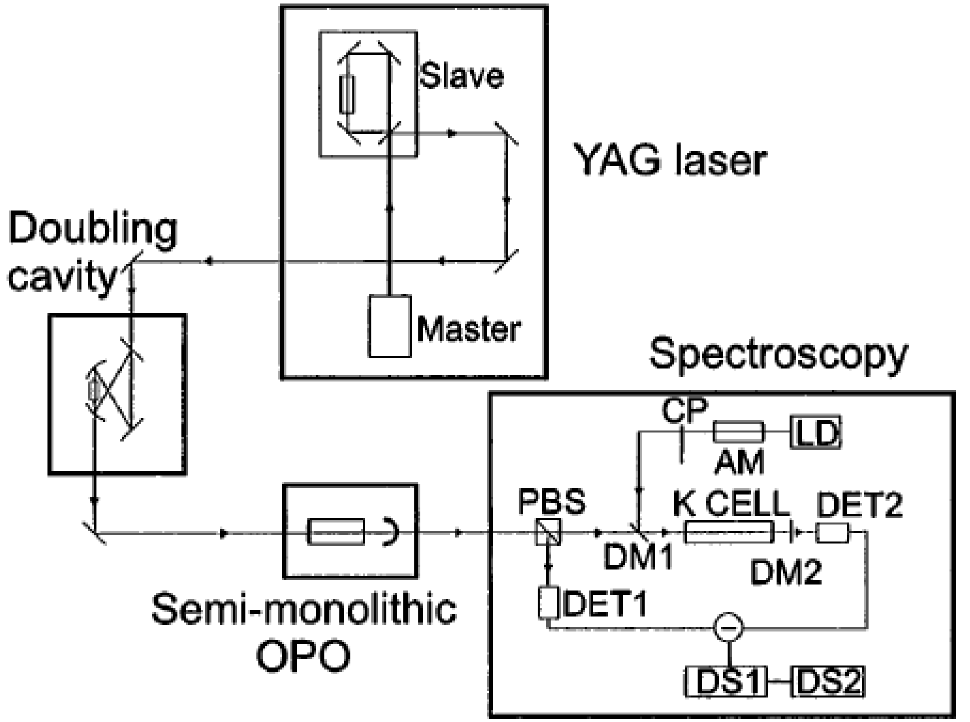
Generation of Twin Beams



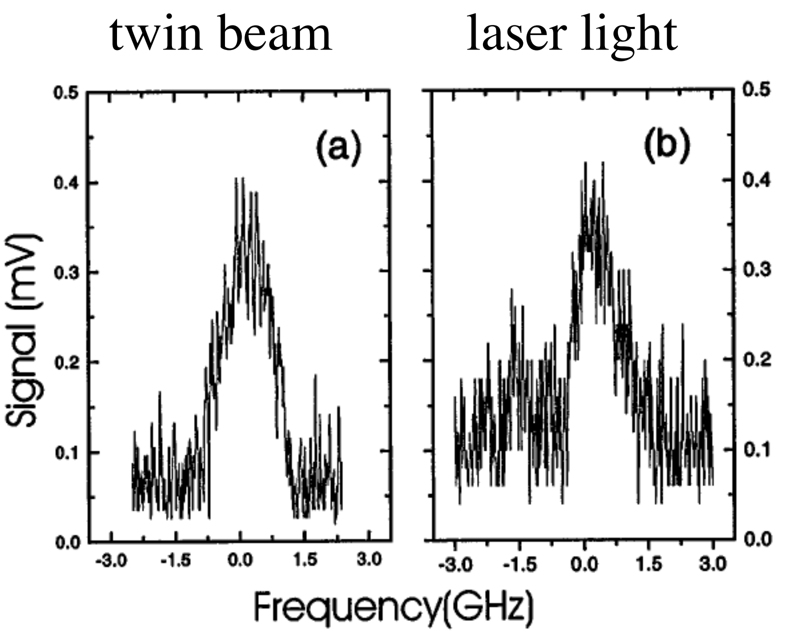
Even though each beam separetely shows intensity fluctuations, there is no fluctuation in the intensity difference.



Noise-Reduced Measurement with Twin Beams



spectrum of two-photon absorption of atomic potassium



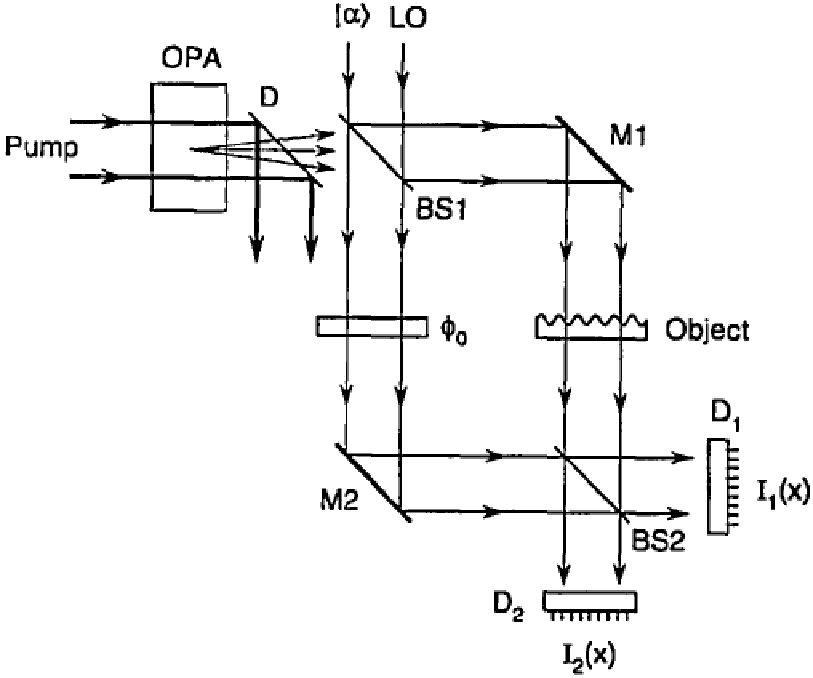
twin beam leads to 1.9 dB reduction in noise

Souto Ribeiro, P. H., C. Schwob, A. Maître, and C. Fabre, Sub-shot-noise high-sensitivity spectroscopy with optical parametric oscillator twin beams, Opt. Lett. 24, 1893, 1997

Early Work in Quantum Imaging

- Quantum Imaging: quantum features of multiple-transverse-mode fields
  - quantum microscopy with squeezed light (theory) (Kolobov and Kumar)
  - quantum lithography (Dowling)
  - many other examples: Kolobov and Lugiato (1995), Choi et al. (1999). Quantum laser pointer (Trepps, Fabre, Bachor) Imaging with entangled photons (Pádua)

Application of Multi-Transverse-Mode Squeezed Light

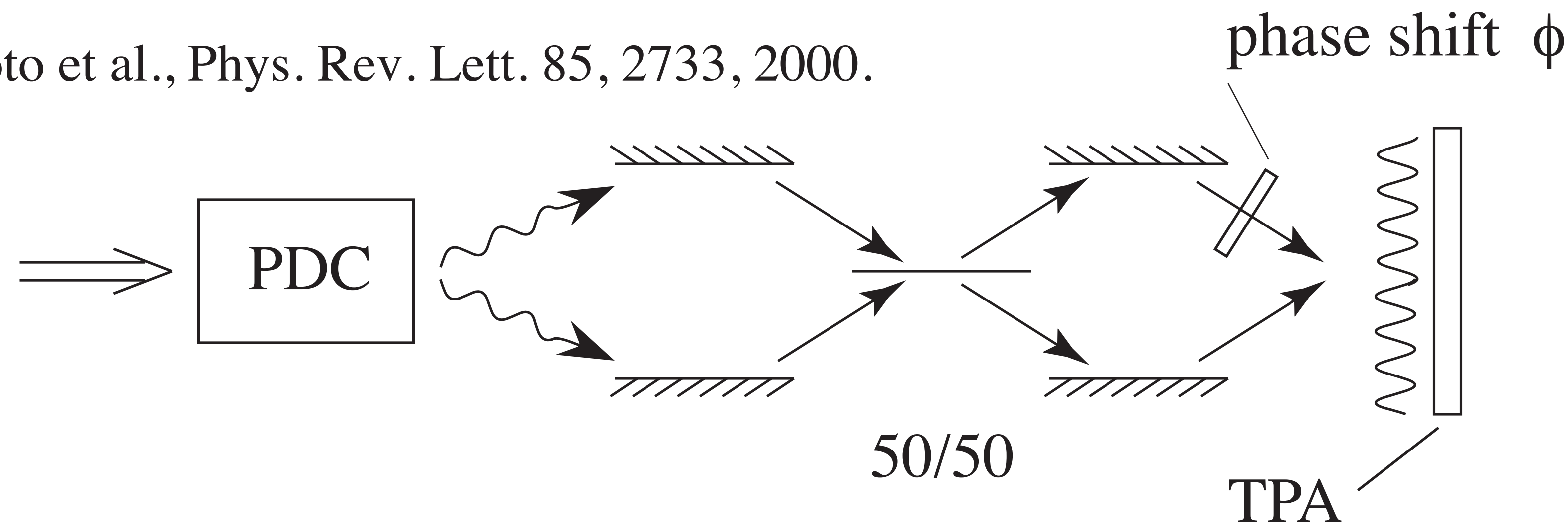


M. Kolobov and P. Kumar, Sub-shot-noise microscopy: imaging of faint phase objects with squeezed light, Optics Letters 18, 849 (1993).

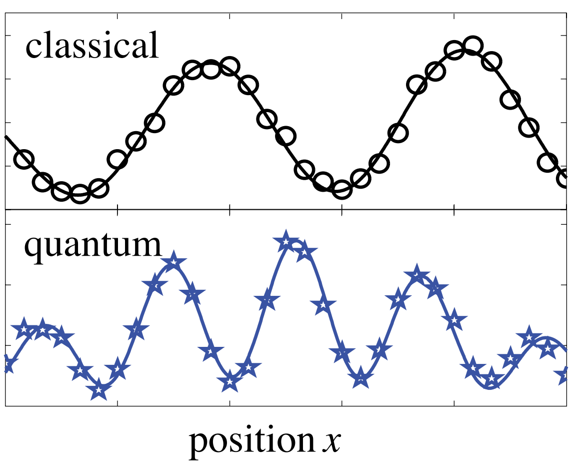
Quantum Lithography: Concept of Jonathan Dowling

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit
- Resolution ≈ $\lambda/2N$, where N = number of entangled photons

Boto et al., Phys. Rev. Lett. 85, 2733, 2000.



- No practical implementation to date, but some laboratory results



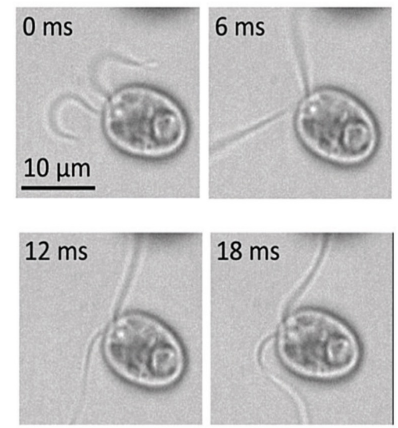
Quantum spatial superresolution by optical centroid measurements, Shin, Chan, Chang, and Boyd, Phys. Rev. Lett. 107, 083603 (2011).

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

Quantum Microscopy for Biomedicine

Many biological samples require low illumination intensities , long wavelengths, and phase imaging

- Many biological materials suffer structural damage when exposed to strong laser light, especially at short wavelengths.
- Problem: Low-intensity imaging typically leads to a low SNR.
- Problem: Imaging with long wavelengths results in lower spatial resolution.
- Many biological materials display very low intensity contrast. Need to perform phase-sensitive imaging.

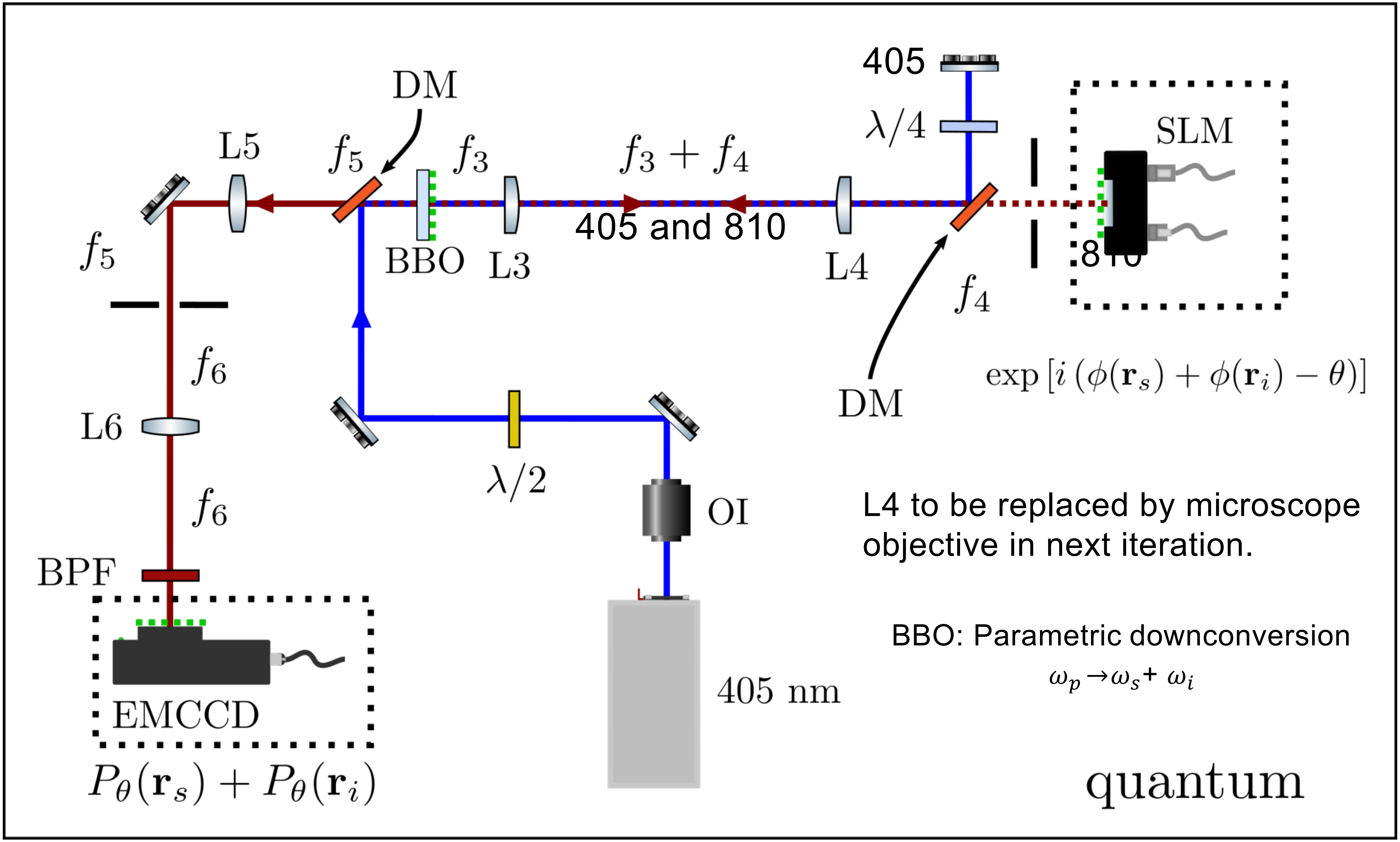


O. Taino et al., Soft Matter **17**, 145-152 (2021).

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).

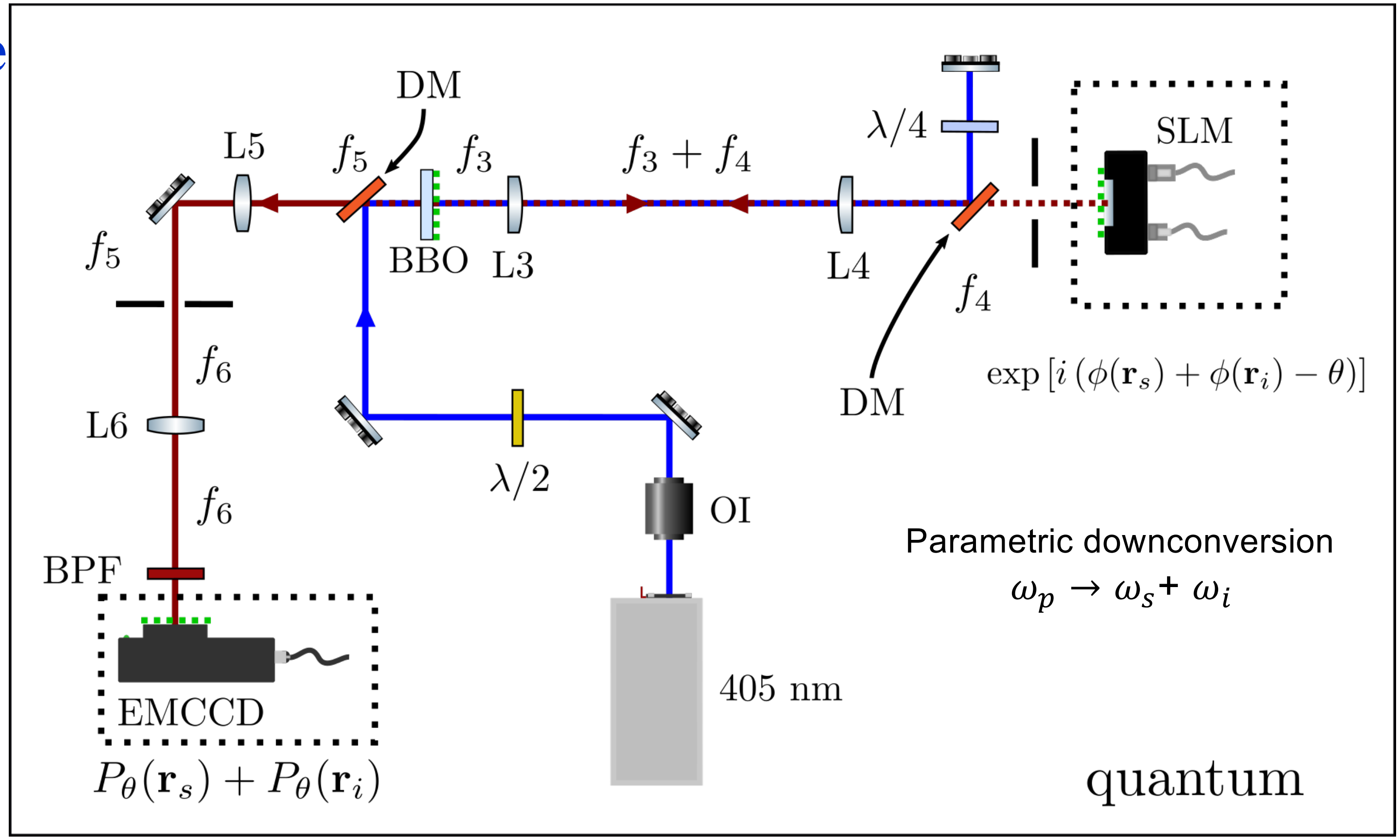
Phase-Sensitive Quantum Imaging Setup:



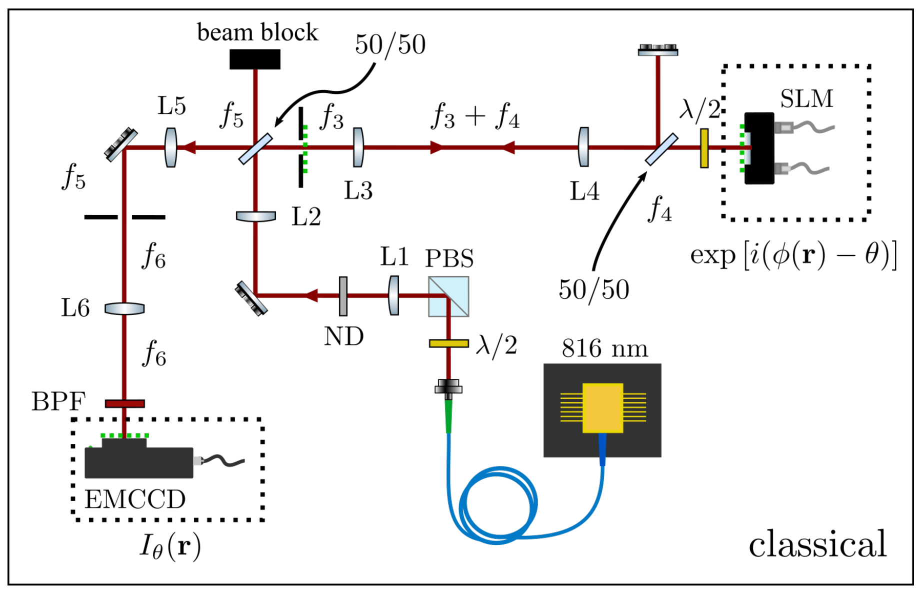
A. Nicholas Black, Long D. Nguyen, Boris Braverman, Kevin T. Crampton, James E. Evans, and Robert W. Boyd, "Quantum-enhanced phase imaging without coincidence counting," Optica 10, 952-958 (2023).

Our phase-sensitive imaging setups:

Quantum

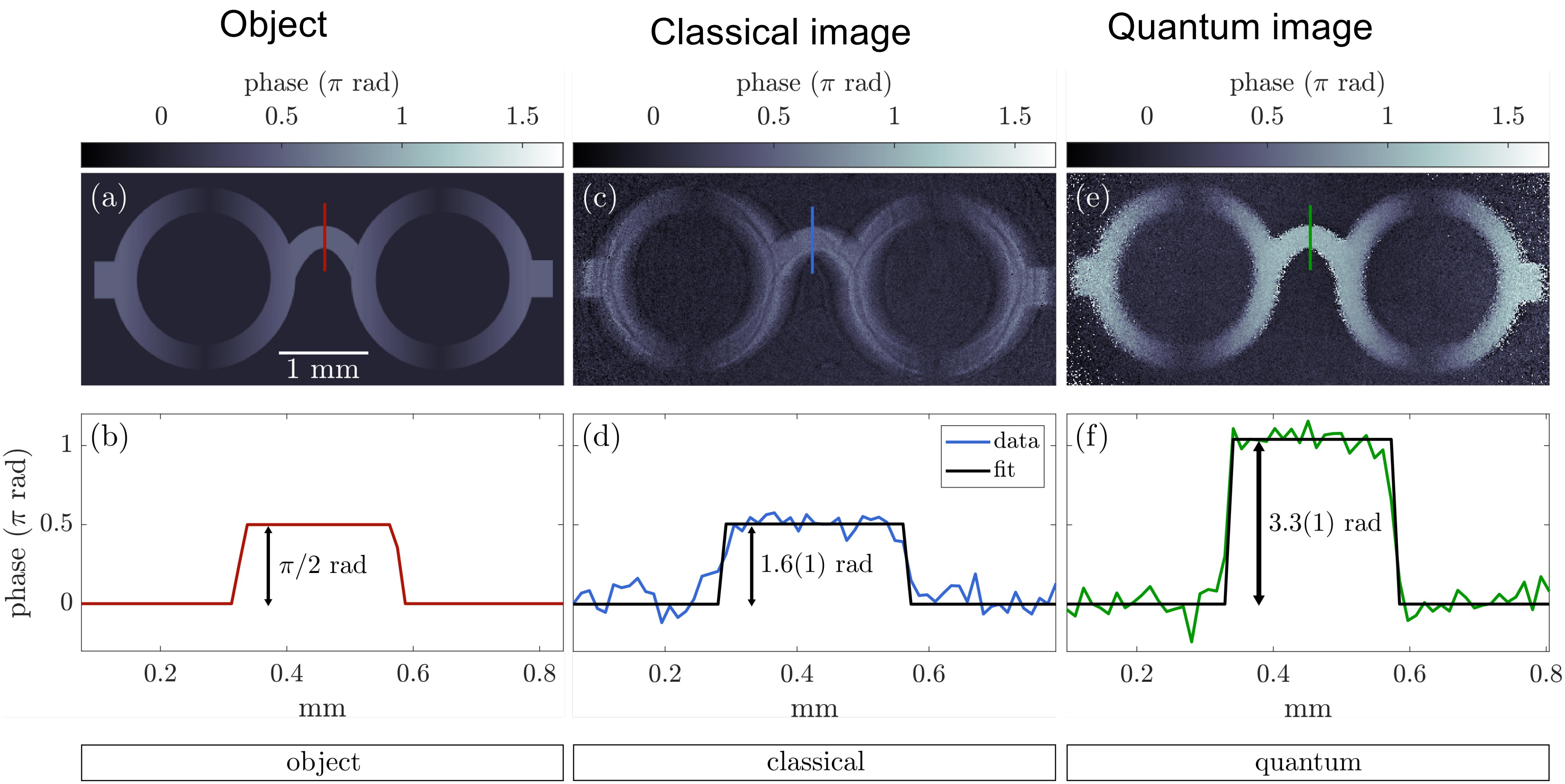


Classical
(with same numerical
aperture)



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).

Comparison of classical and quantum phase imaging



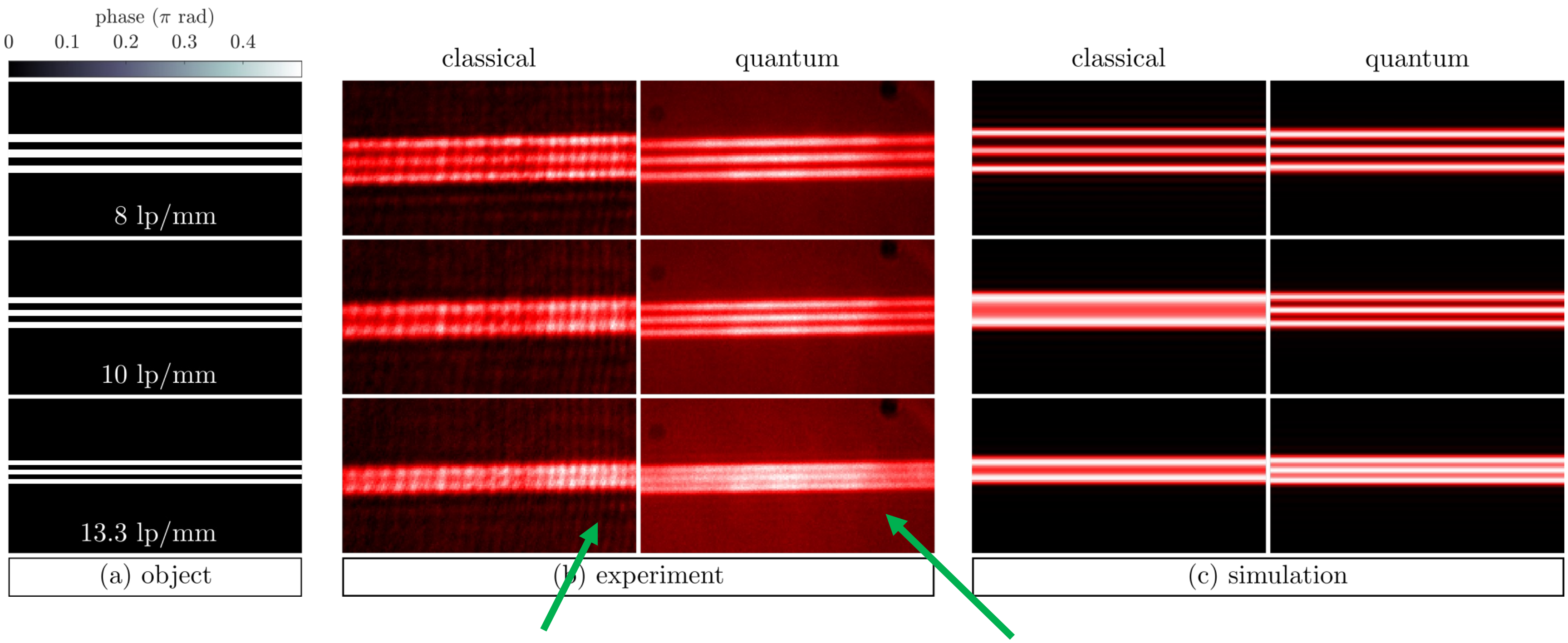
The "object" is a phase object written onto an SLM.
Photon flux: ~40 photons/s μm^2

Signal twice as large in quantum setup
Image is 1.7-times sharper in quantum 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).

Monument In Tokyo, Japan

Comparison of quantum to classical spatial resolution



Vertical fringing is from back reflections.

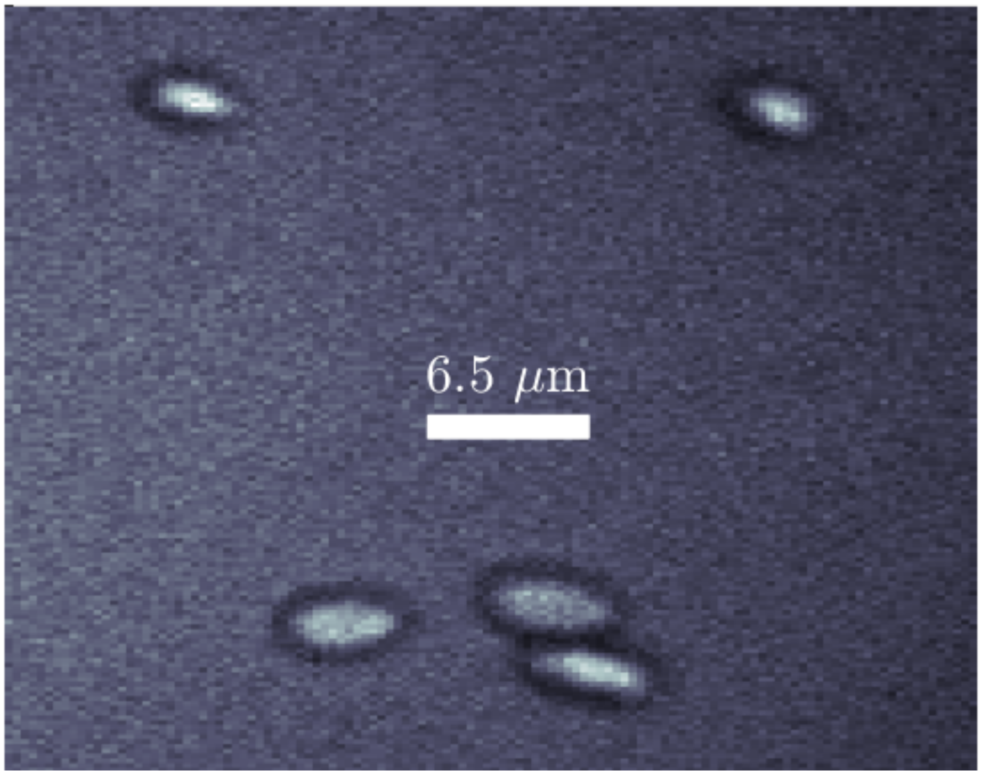
Fringing from back reflections not present in quantum experiment because back reflections are not mode matched.

The quantum experiment achieves ~1.7 times better spatial resolution.

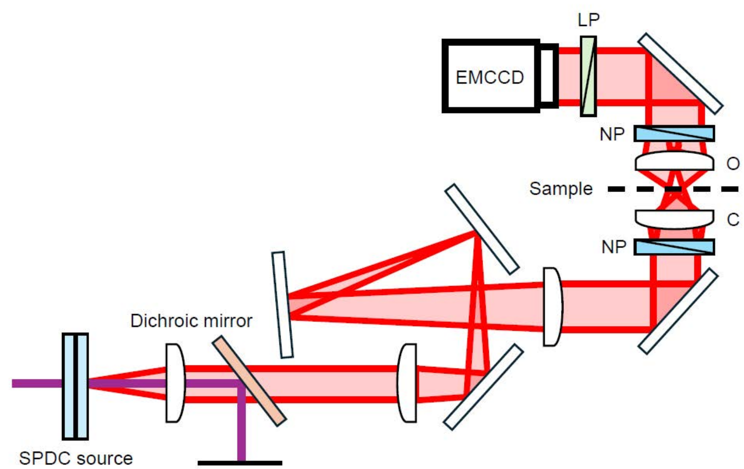
A. Nicholas Black, Long D. Nguyen, Boris Braverman, Kevin T. Crampton, James E. Evans, and Robert W. Boyd, "Quantum-enhanced phase imaging without coincidence counting," Optica 10, 952-958 (2023).

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



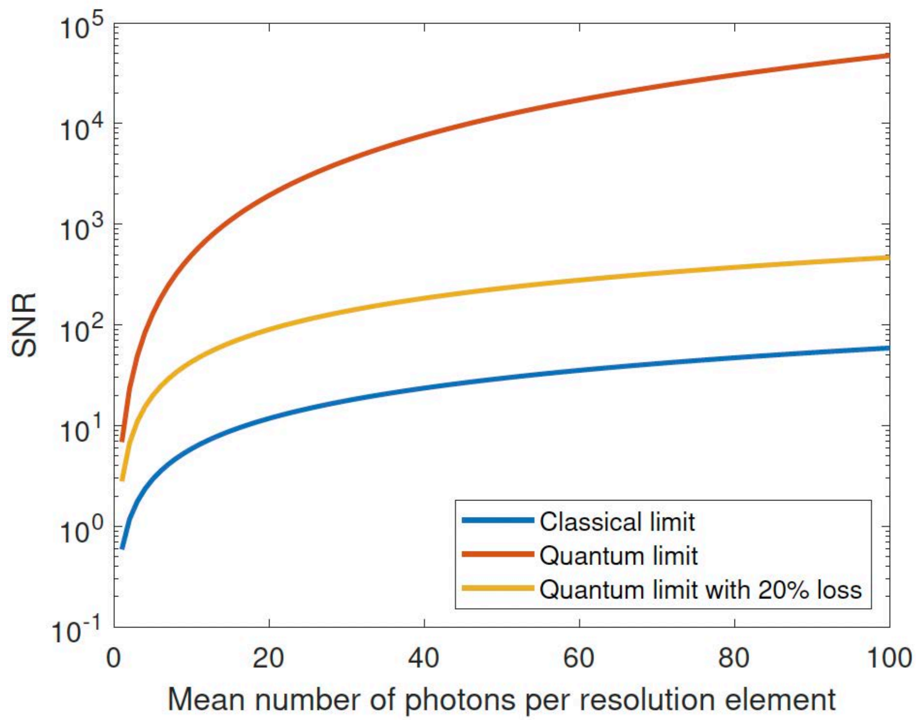
Objective: 40x magnification, NA = 0.75

Progress is financially-limited.

Collaboration with US DOE Pacific Northwest National Laboratory

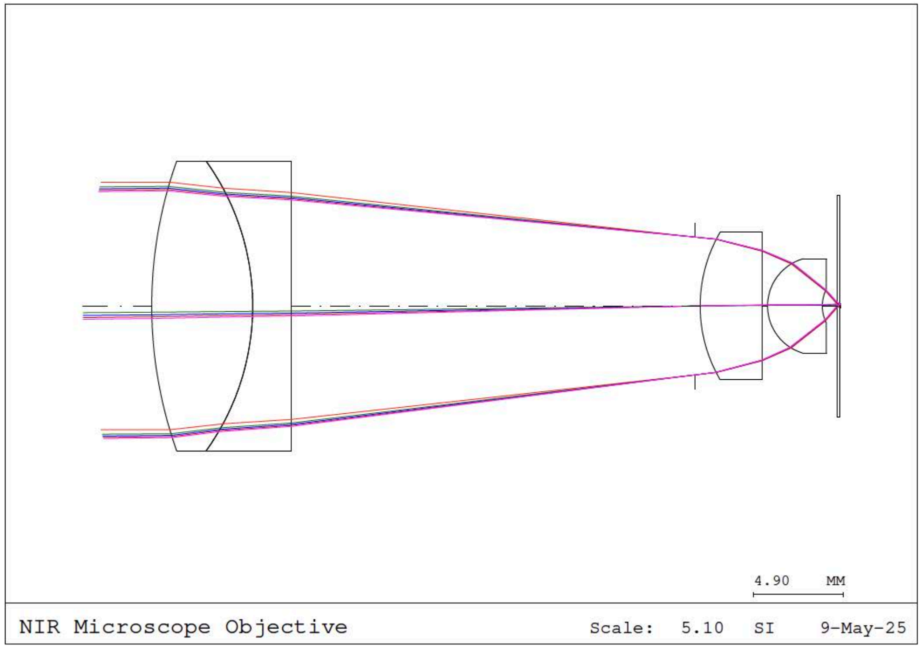
Next Step: Design and Acquire Custom Microscope Objective

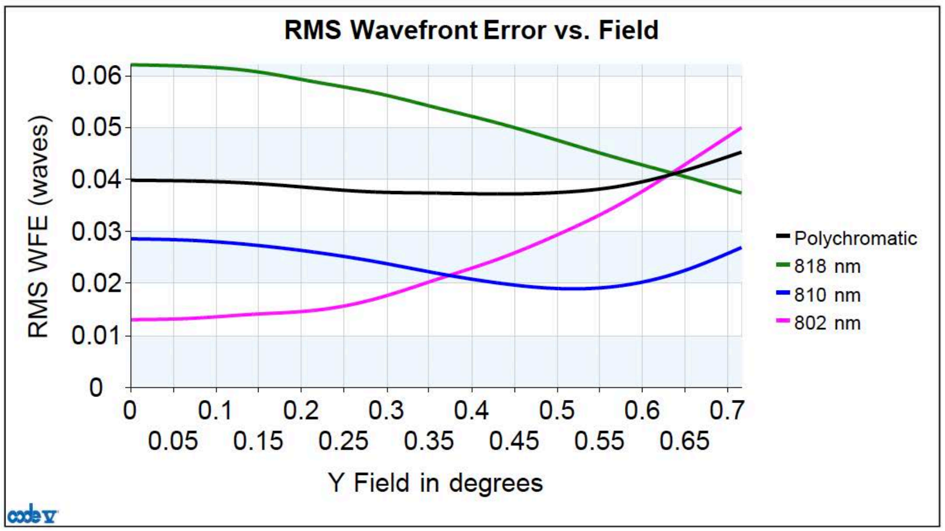
- SNR of quantum microscope is much higher than for classical microscope but decreases rapidly with transmission loss
- Design uses small number of elements (4) to achieve high throughput.



J. Li et al., Phys. Rev. A 97, 052127 (2018).

- Design is well corrected against wavefront aberrations.



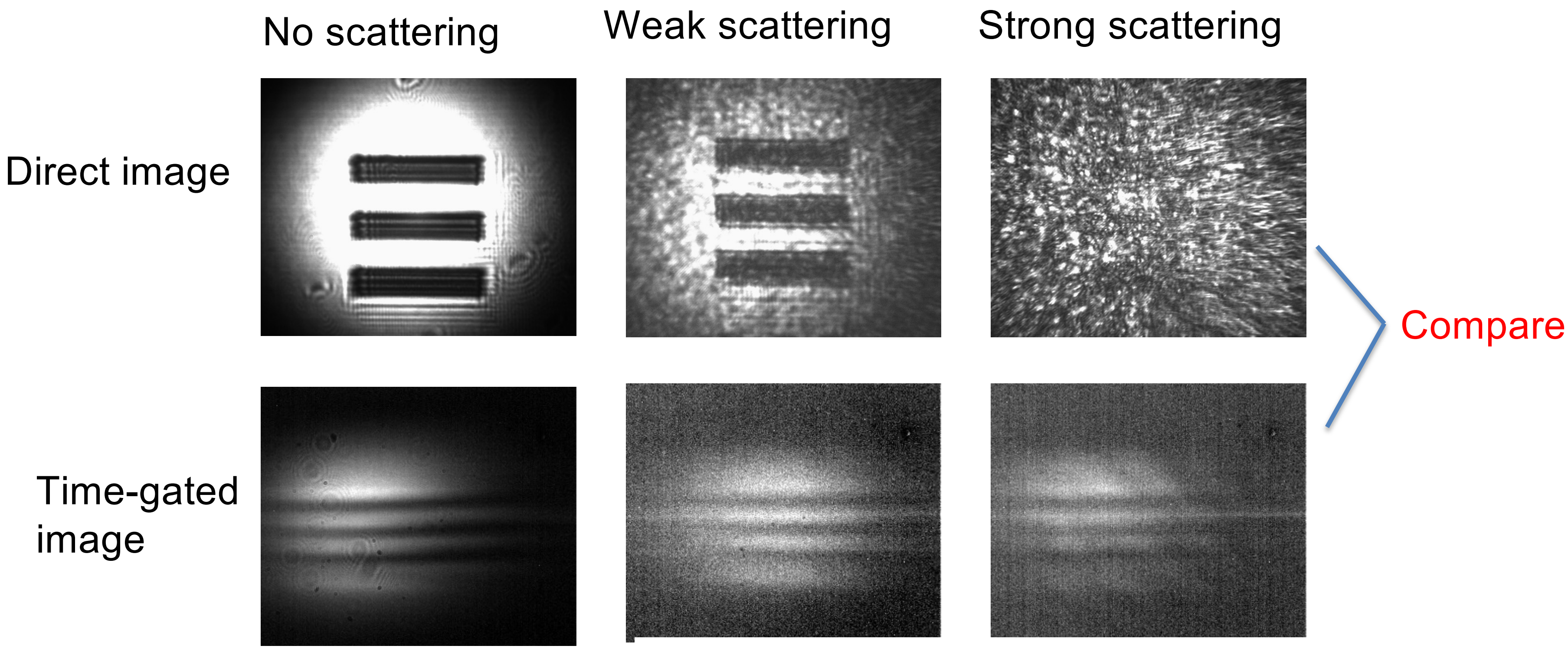


3. Imaging through a Strongly Scattering Medium

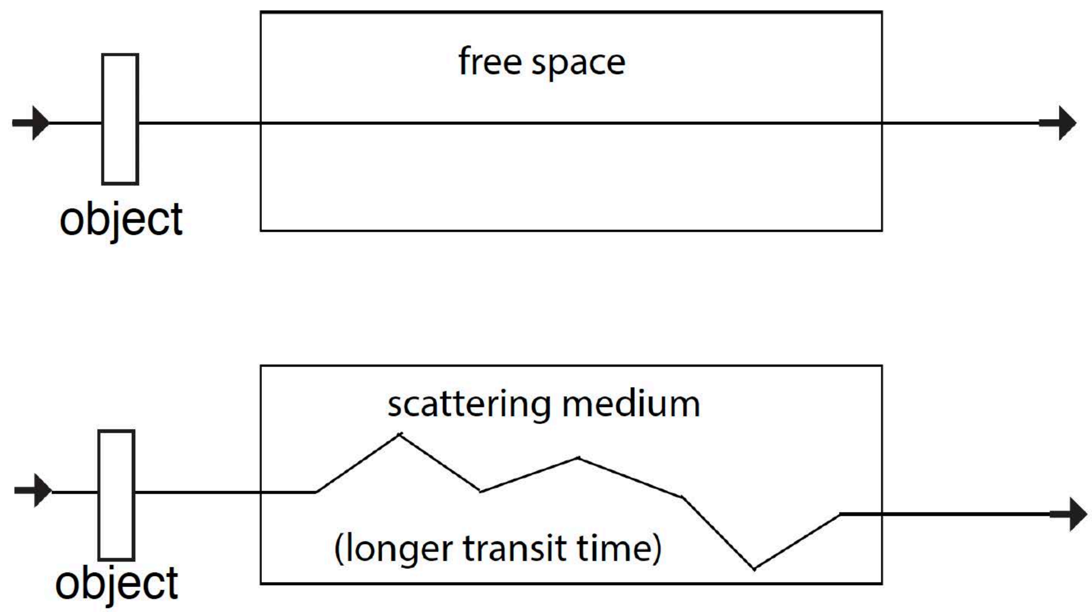
Not really quantum.

Imaging Through a Strongly Scattering Medium

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



- Need a material with a strong, fast nonlinear optical response to construct time-gate (shutter).
- We use indium tin oxide (ITO), a transparent conducting oxide (TCO) with a strong, fast response.



.

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 switches and gates. (Ideally we want to be able to use weak control beams.)

- Note that optical nonlinearities are strongly enhanced at wavelengths for which n ≅ 0. (This is the ENZ, epsilon-near-zero, condition.)

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

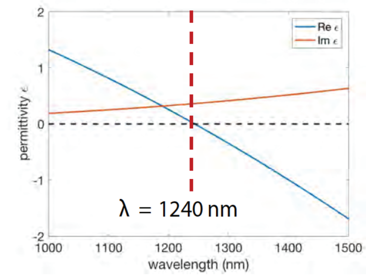
- Note further that for any conductor Re $\varepsilon = 0$ at the reduced plasma frequency :

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

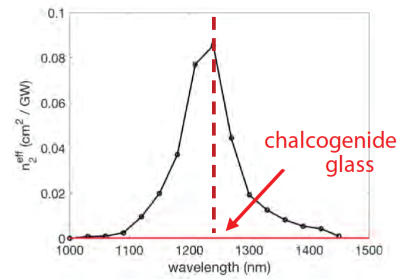
- For indium tin oxide (ITO), Re ε=0 at λ = 1.24 μm.

Characterization of ITO

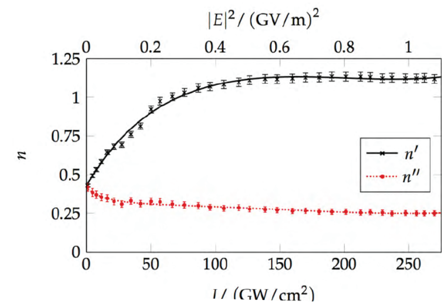
- ellipsometry



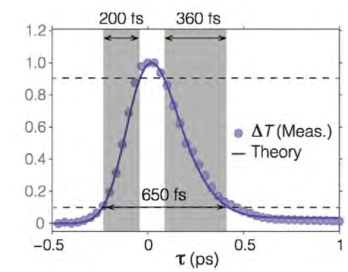
- n_2 can be 3.4 x10^5 times larger than that of silica glass



- overall change in refractive index of 0.8



- sub picosecond reponse time



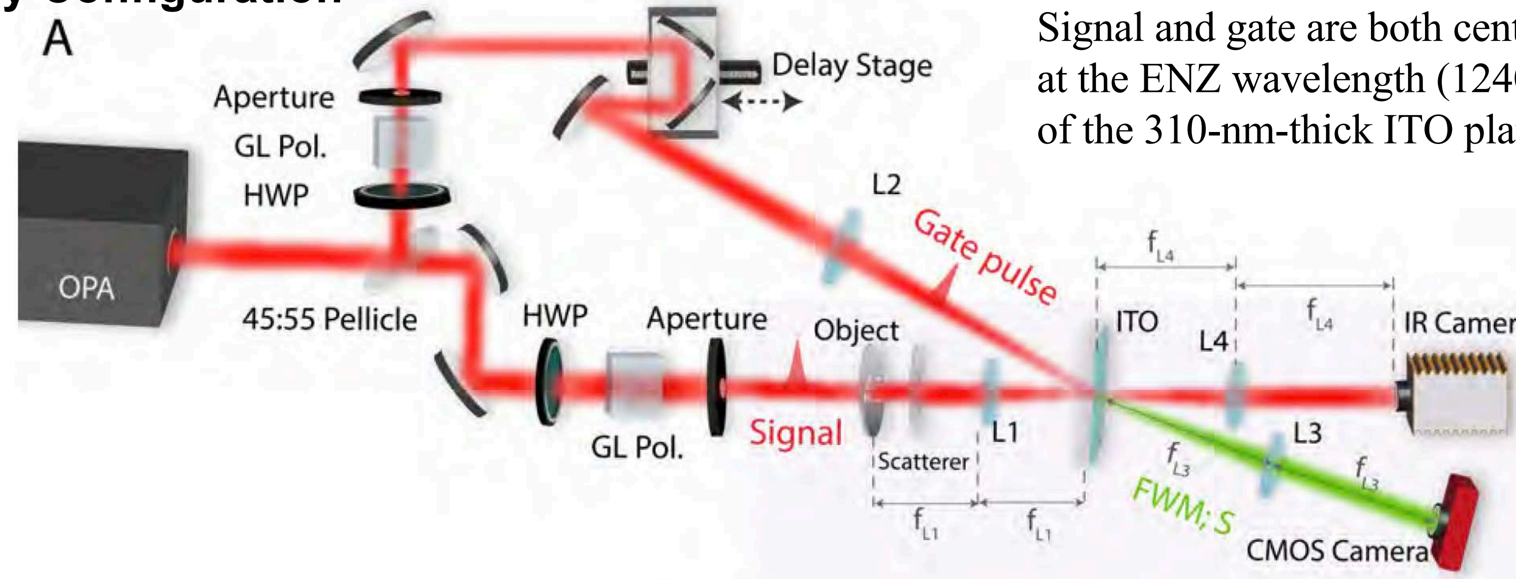
M. Z. Alam et al., Science 352, 795-797 (2016)

n_2 is approximately 300,000 times larger than that of silica glass

M.Z. Alam, I. De Leon, and RWB, Science 352, 795 (2016).

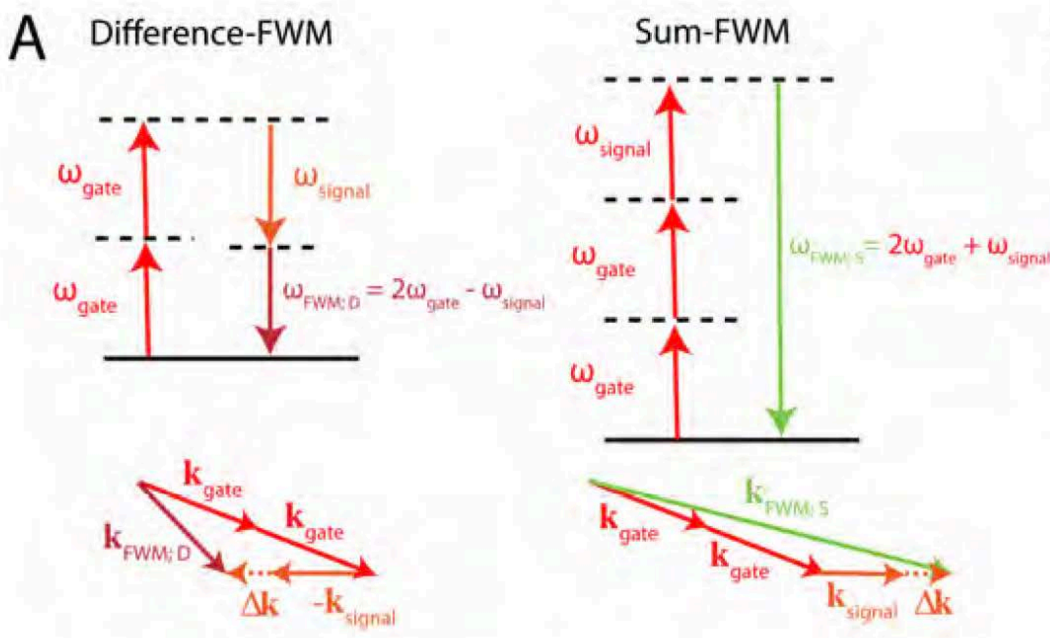
Four-Wave-Mixing Optical Time-Gating

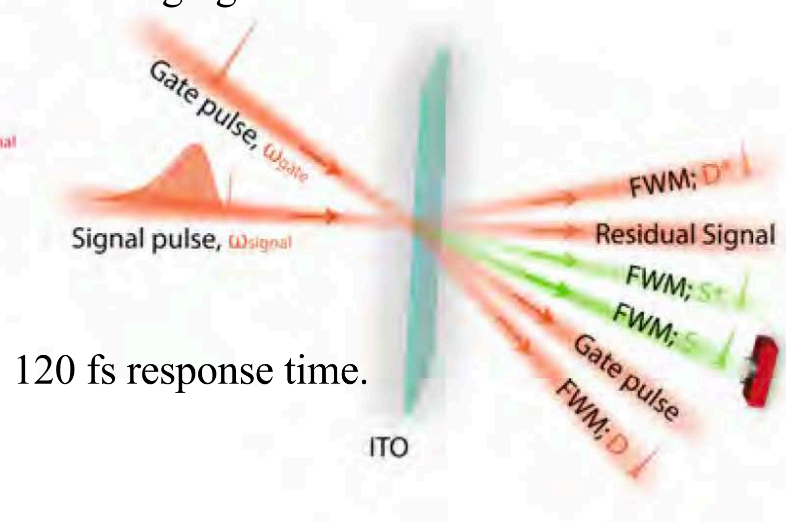
Laboratory Configuration



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

Nonlinear Interaction





Sum four-wave mixing interaction shifts the signal from the IR to the visible where imaging detectors are more sensitive.

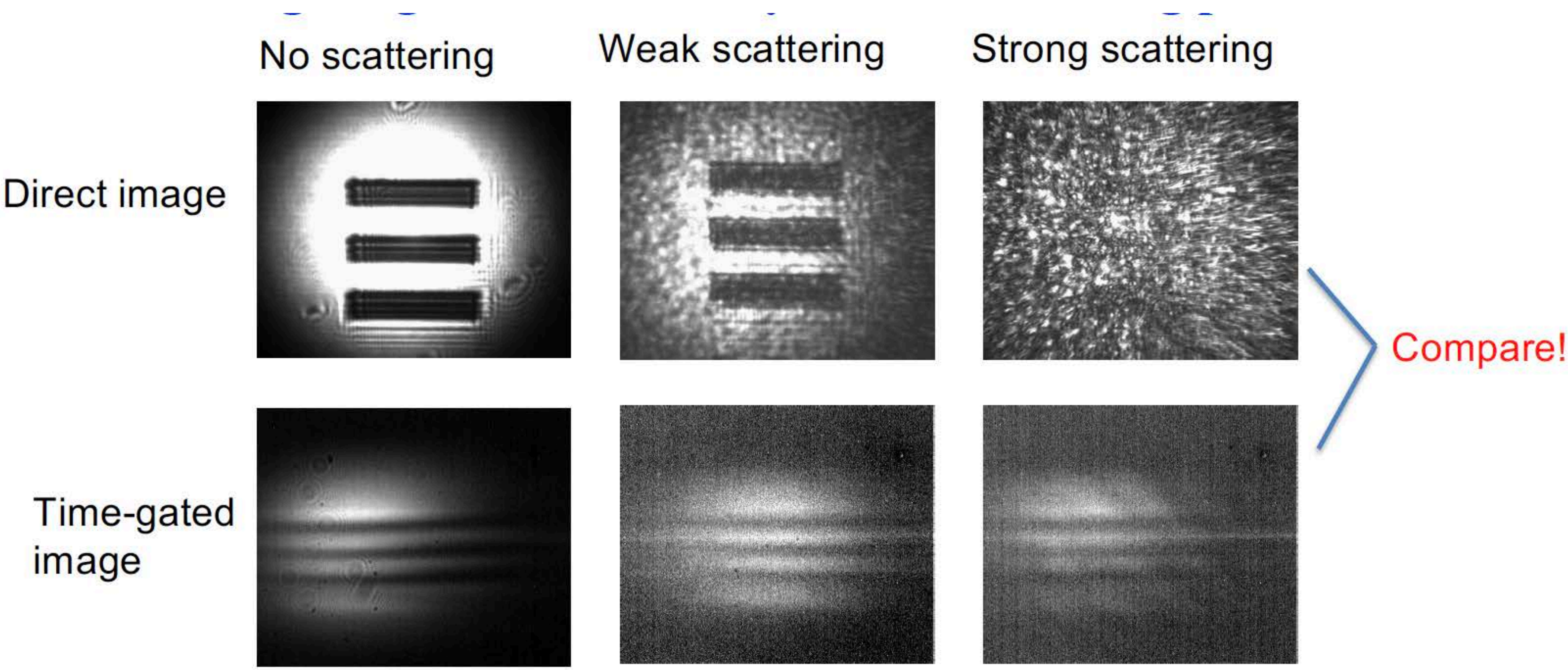
120 fs response time.

Summary: 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

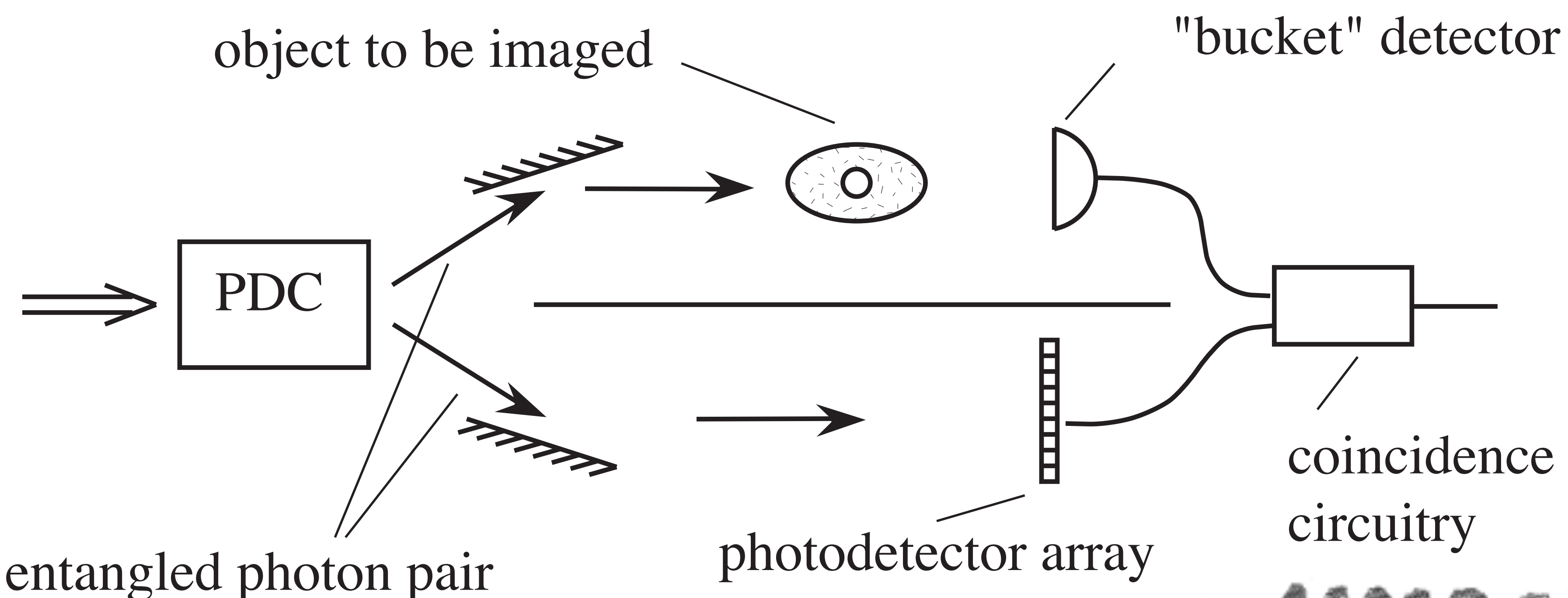
Our approach involves time-gating using a highly nonlinear ENZ material
- Time-gate transmits only the unscattered photons, which contain the image information

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

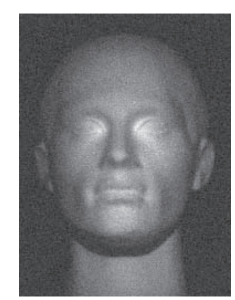


Interaction-Free and Ghost Imaging

Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing!
  (imaging under adverse situations, bio, two-color, etc.)
- Is this a purely quantum mechanical process?
- 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)

Is Ghost Imaging a Quantum Phenomenon?

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato

INFM, Dipartimento di Scienze CC.FF.MM., Università dellíInsubria, Via Valleggio 11, 22100 Como, Italy

(Received 11 October 2002; published 3 April 2003)

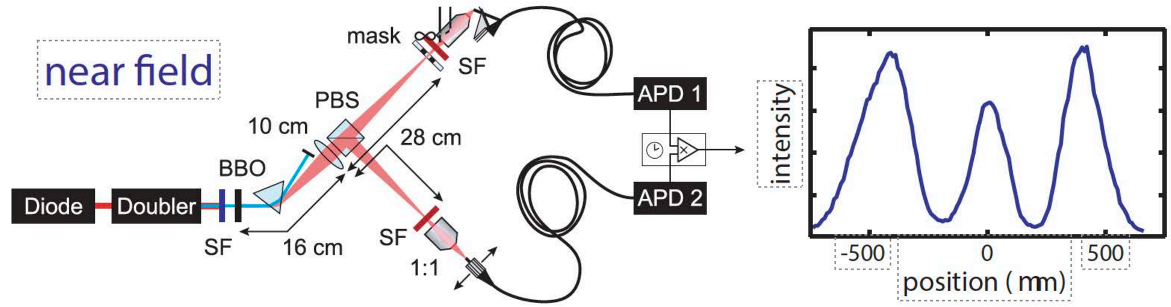
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

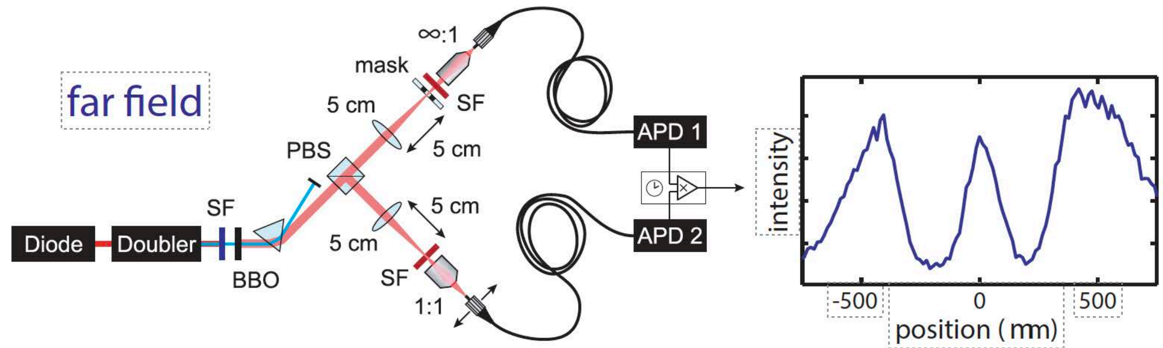
DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

Near- and Far-Field Ghost Imaging

Quantum-Entangled Source

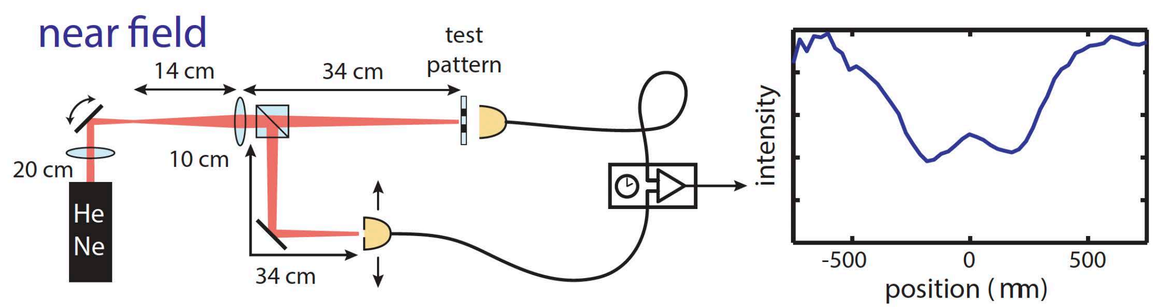
Good imaging observed in both near and far fields.

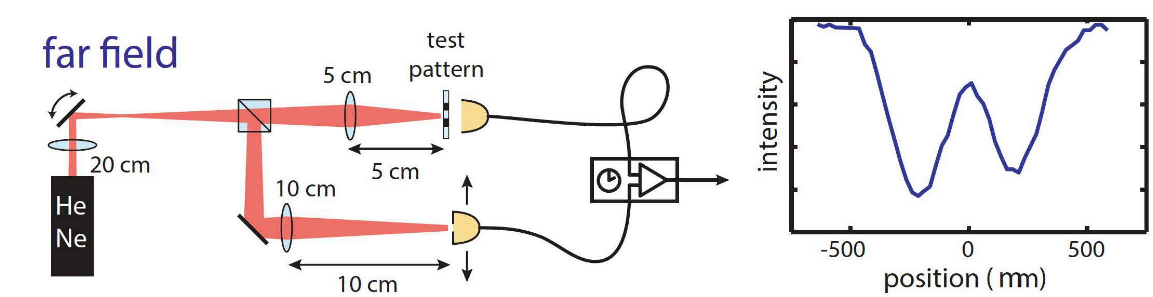




Classical Source

Good imaging can be obtained only in far field (as shown) or in near field.



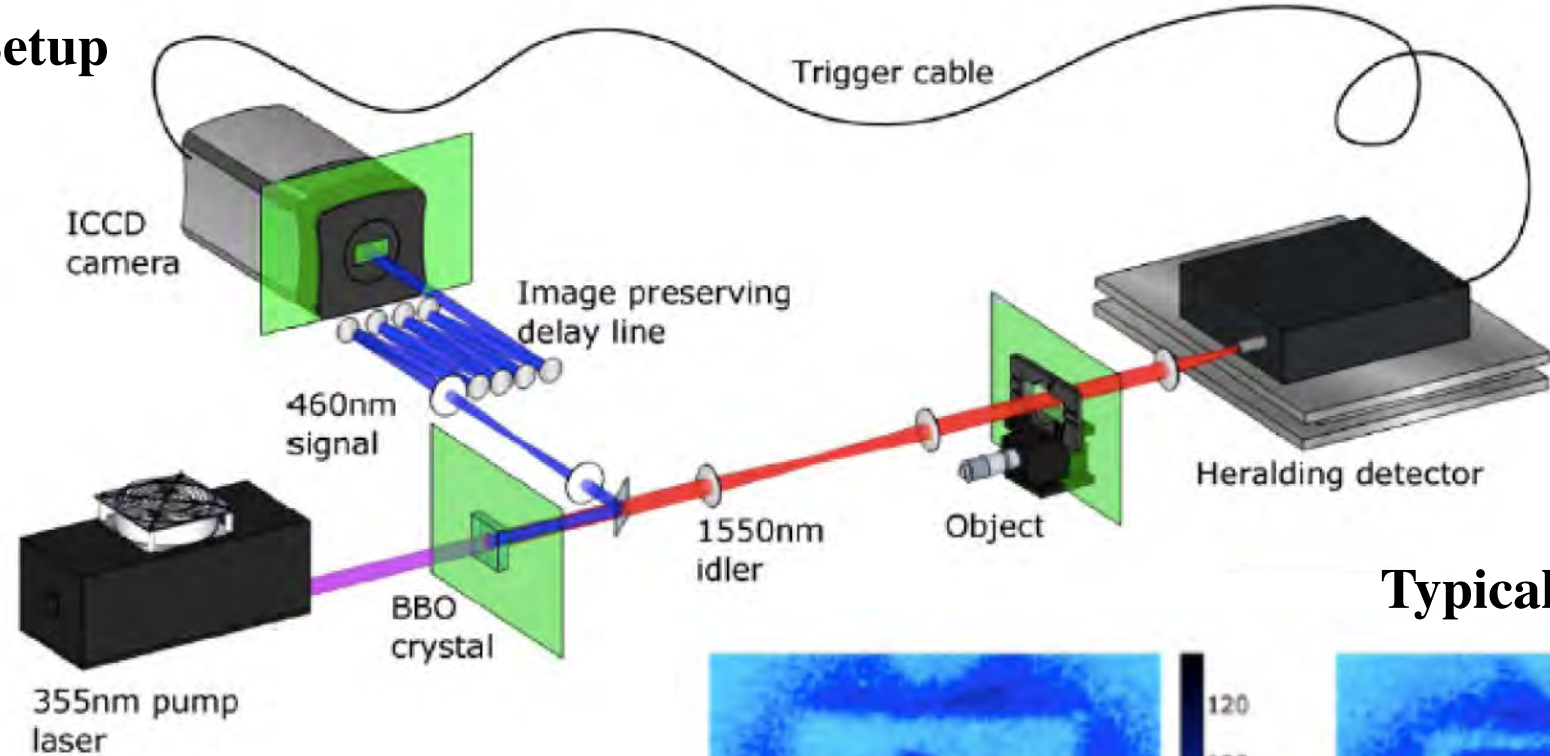


Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

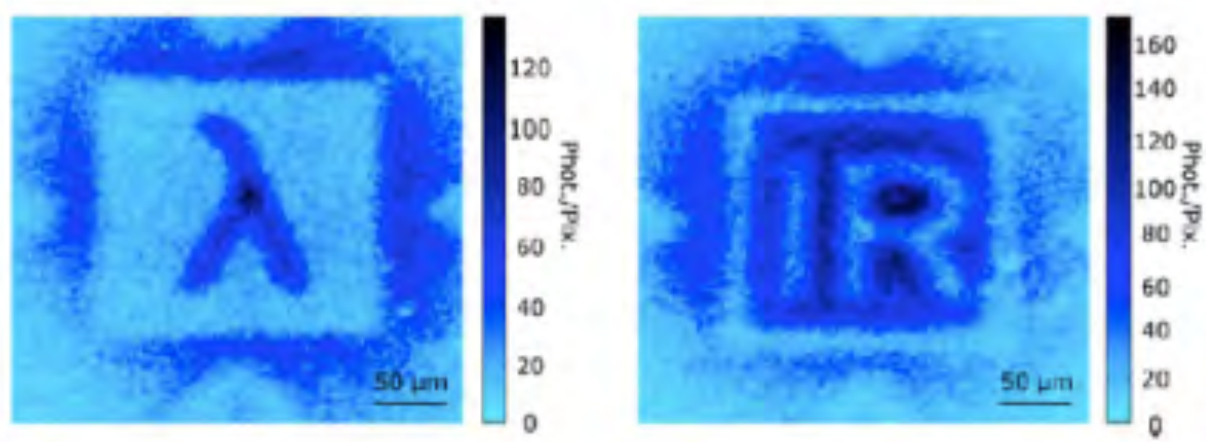
Wavelength-Shifted (Two-Color) Ghost Microscopy

- 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



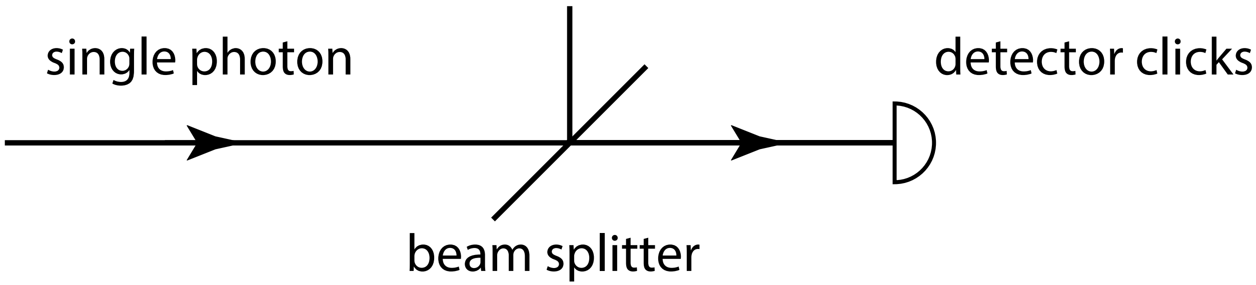
Typical images



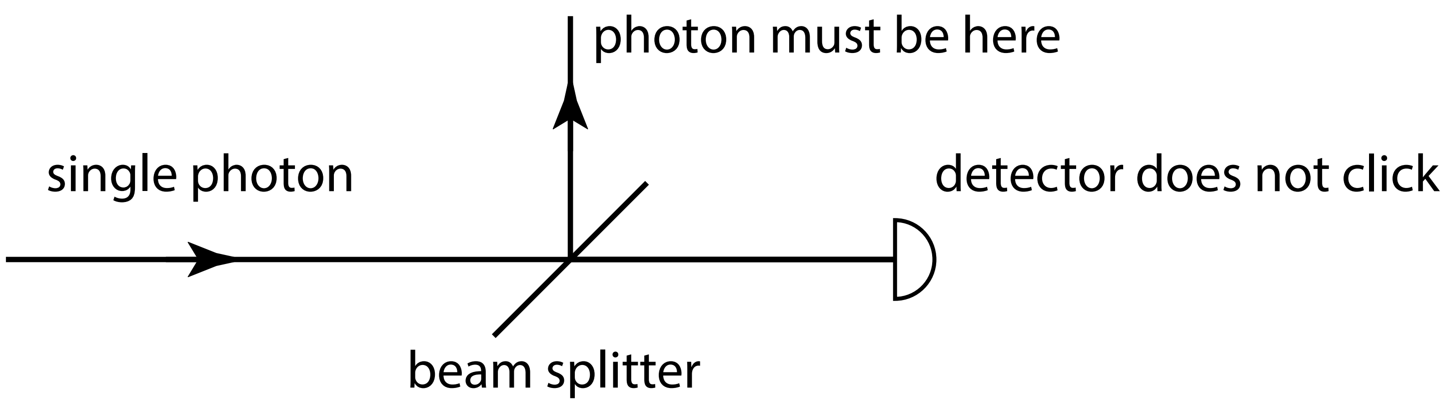
Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

What Constitutes a Quantum Measurement?

• Situation 1

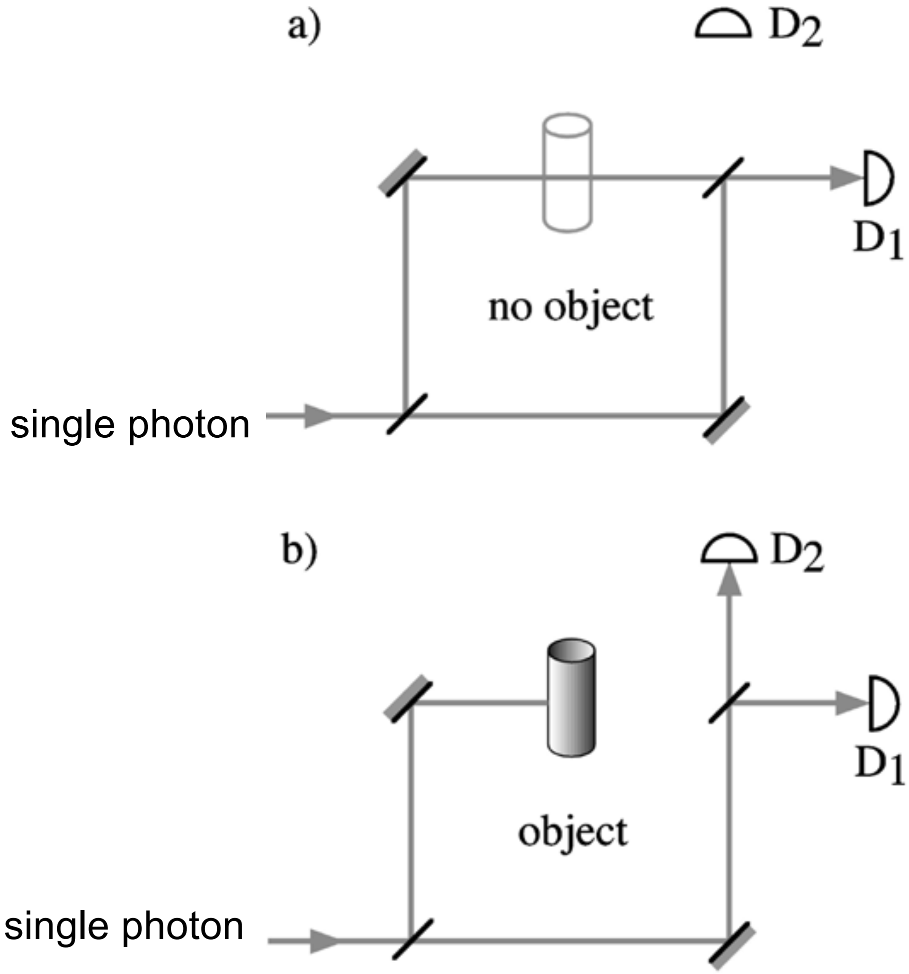


• Situation 2

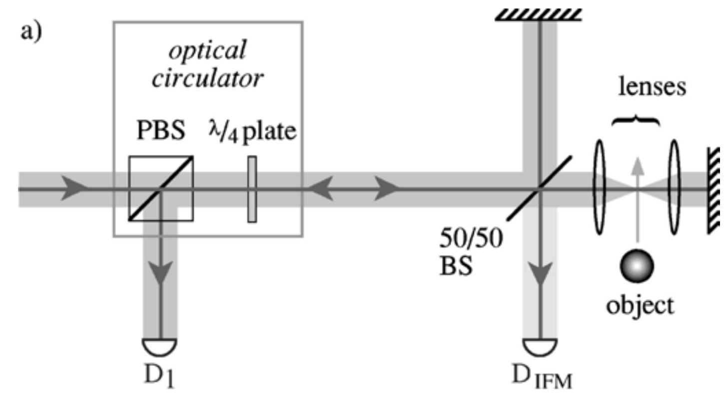


M. Renninger, Z. Phys. 15S, 417 (1960).
R. H. Dicke, Am. J. Phys. 49, 925 (1981).

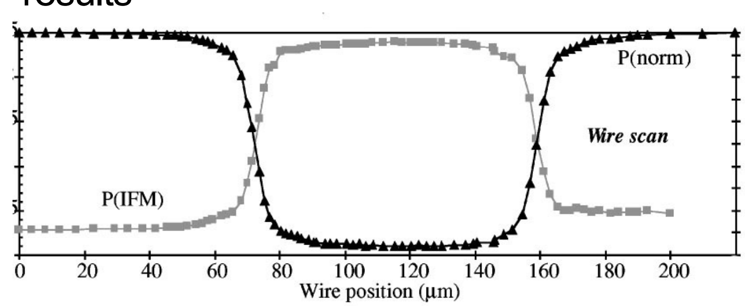
Quantum Imaging by Interaction-Free Measurement



imaging setup



results

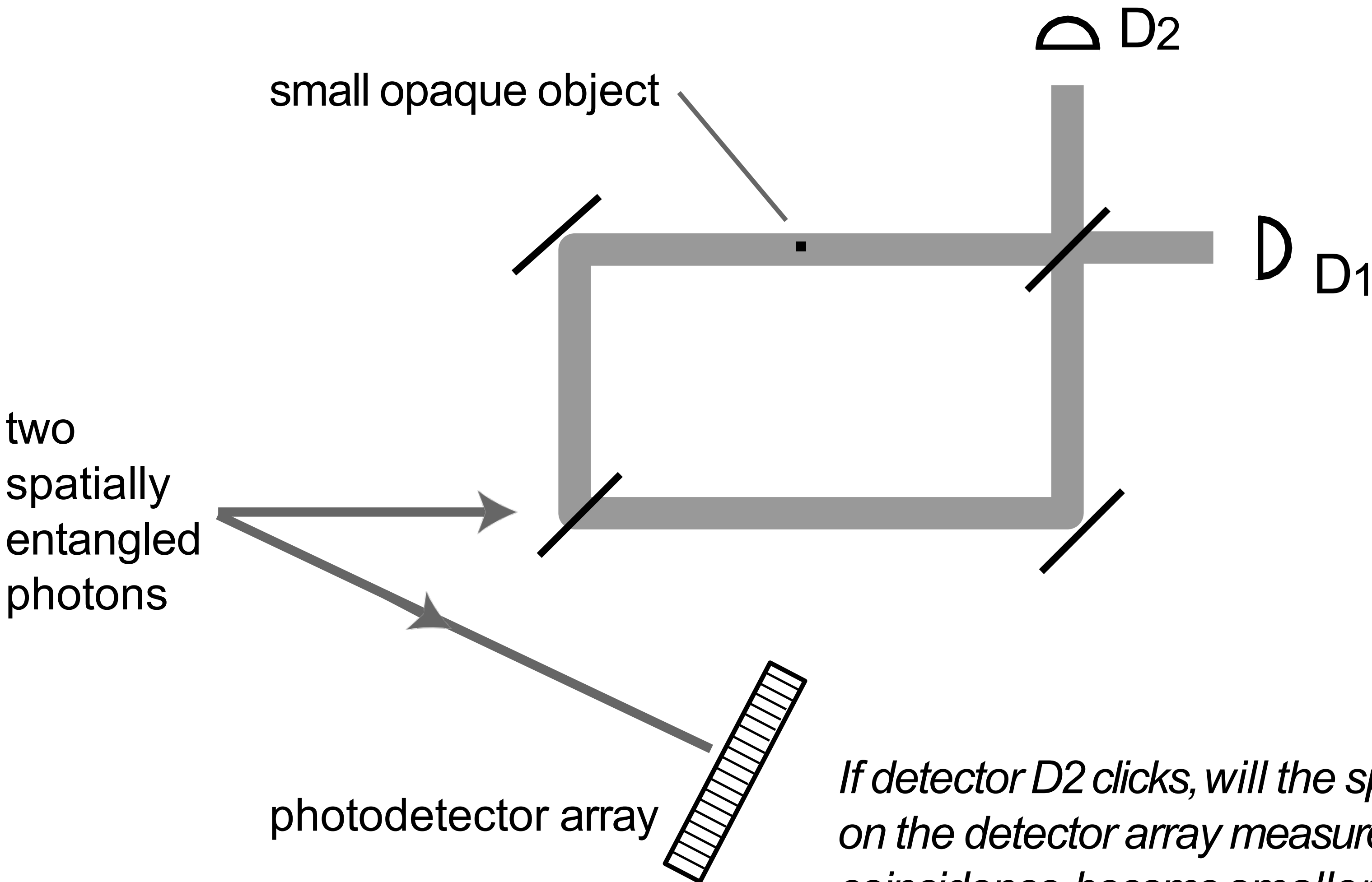


As shown, the object is detected by an interaction-free measurement (that is, D2 registers a photon) 25% of the time. There are other (Zeno) configurations that can lead to a 100% success rate.
Predicted by Elitzur and Vaidman and confirmed by White et al.

White et al. later showed that interaction-free measurements (IFMs) could be used in an imaging configuration to determine the diameter of a wire using only photons that did not physically interact with the wire.

A. Elitzur and L. Vaidman, Found. Phys. 23, 987 (1993).
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



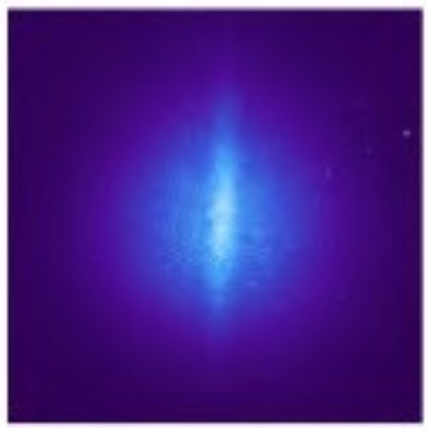
If detector D2 clicks, will the spot size on the detector array measured in coincidence become smaller?

- 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, for example:

What does the retina of the eye look like when light does not hit it?

Similarly, what does the green alga Chlamydomonas reinhardtii (which is a common reference organism in the study of photosynthesis) look like when light does not hit it.

Was this experiment even worth doing?

We could instead have simply answered the question theoretically (of whether interaction-free measurements lead to wavefunction collapse).

My response: Physics is an experimental science. Theoretical models are developed to explain the results of experiment, and not vice versa.

In their mathematical treatment of interaction-free measurements, Elitzur and Vaidman state: "*Assuming* that detectors cause the collapse of the quantum state . . ." (Emphasis mine.)

Foundations of Physics 23, 987 (1993).

Summary

- Laboratory results show that an "interaction-free" measurement of one member of an entangled two-photon state leads to the collapse of the entire two-photon state.

- As such, it is possible to combine *ghost imaging* with *interaction- free imaging* to produce *interaction-free ghost imaging*.

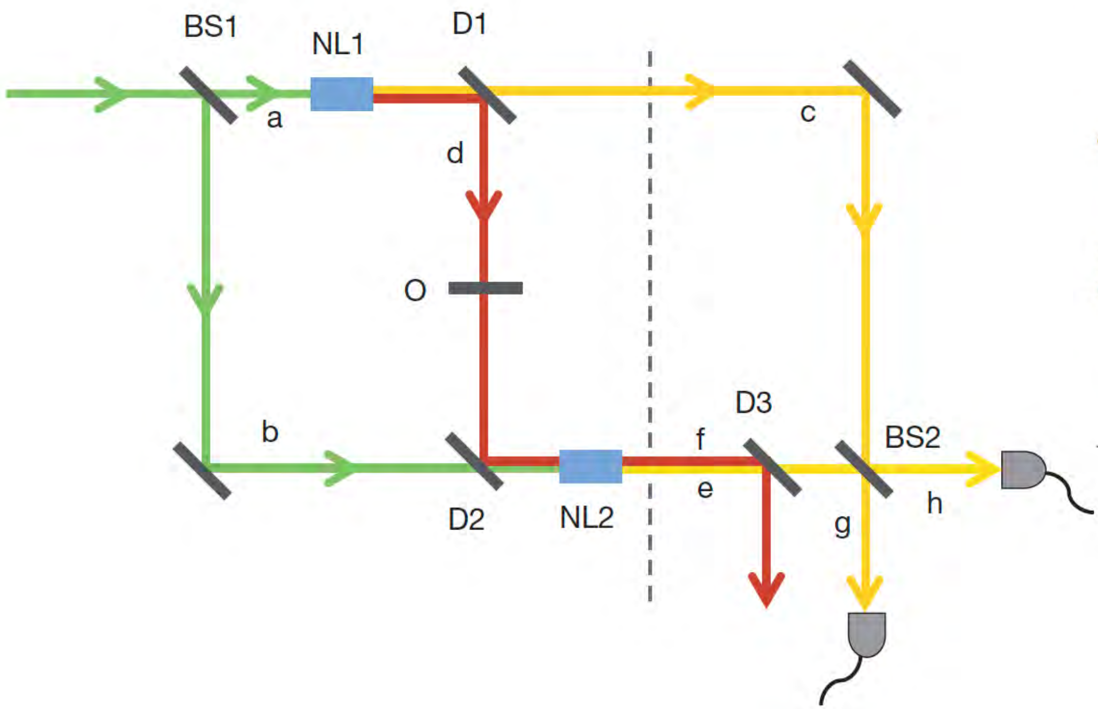
- Interaction-free ghost imaging holds promise for "imaging in the dark," with important implications for biophotonics and surveillance for national security.

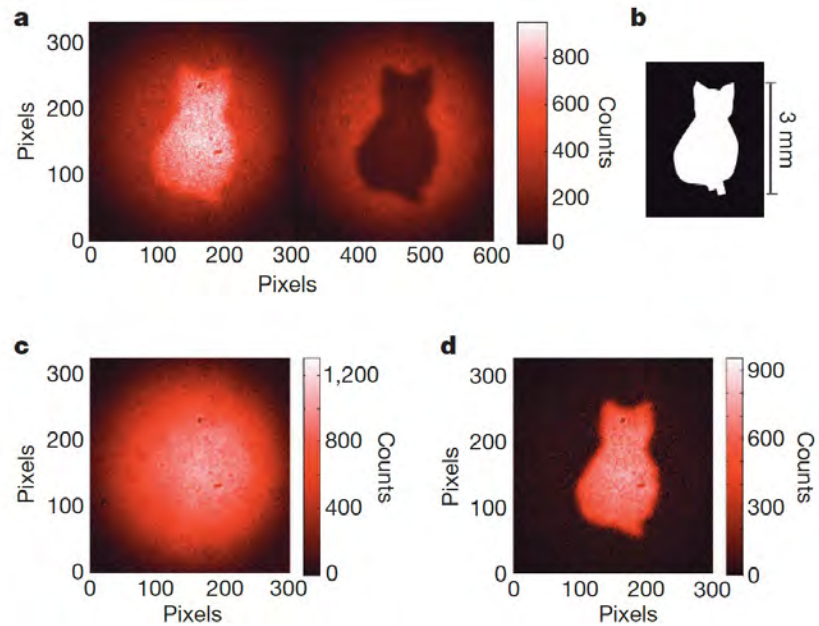
Quantum imaging with undetected photons

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?

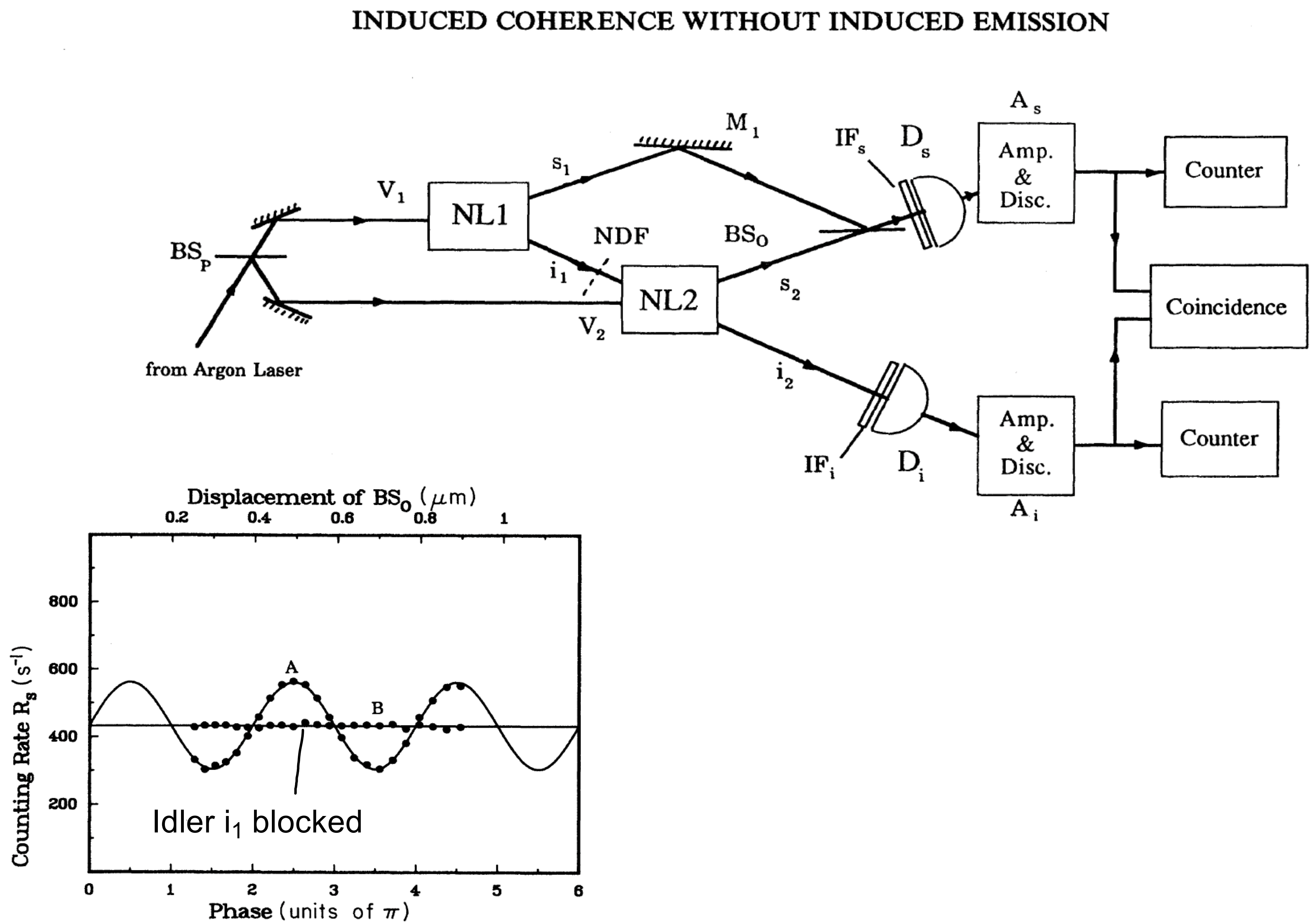




Very famous paper. Can we improve image quality?

Induced coherence without induced emission

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



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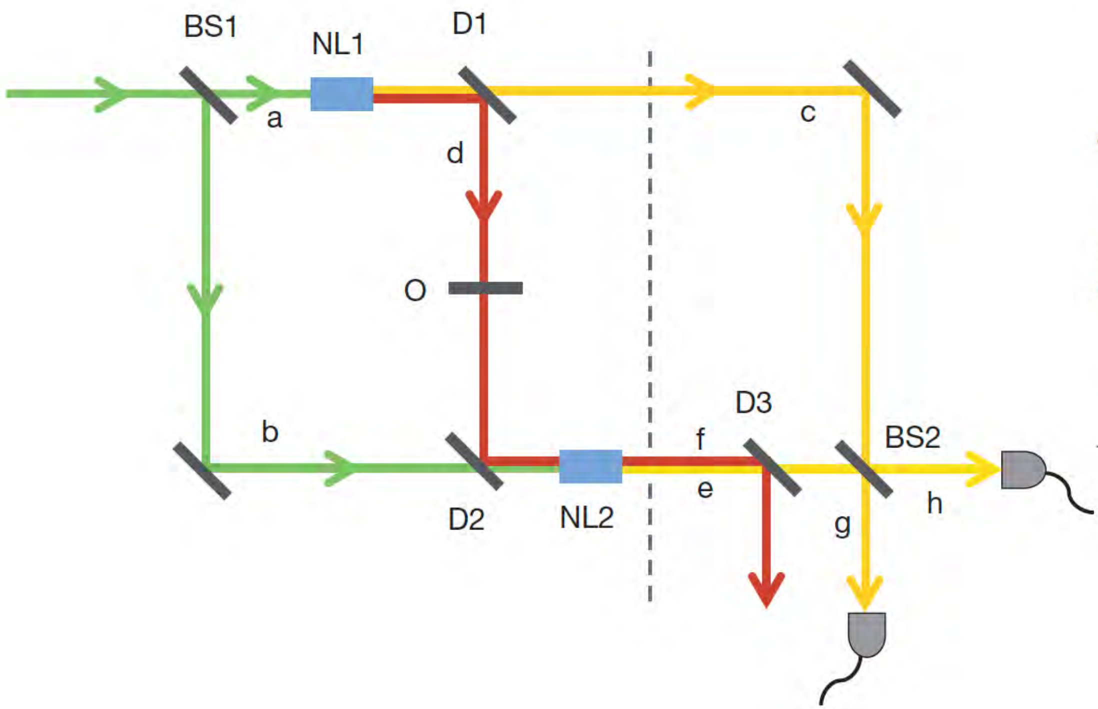

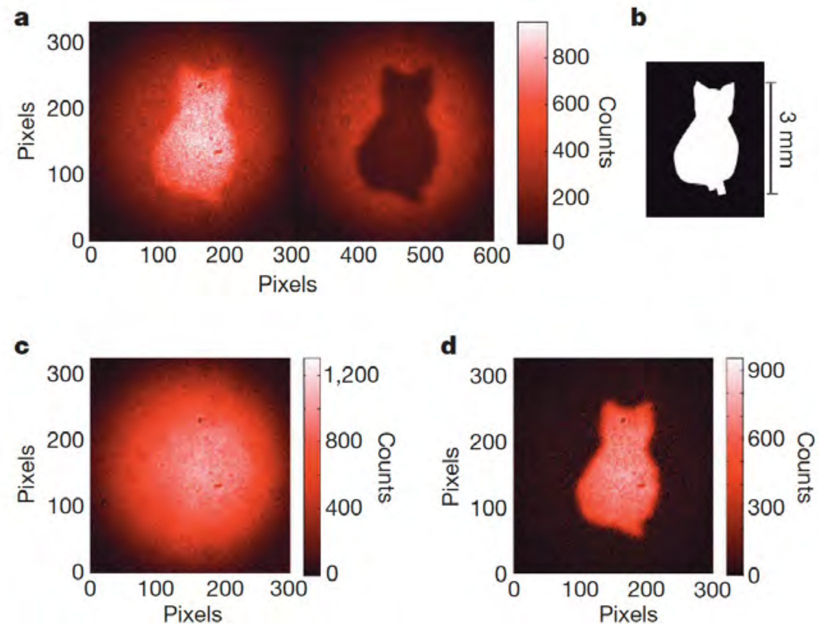

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J. Opt. 19 (2017) 054003 (8pp) https://doi.org/10.1088/2040-8986/aa64a2

Controlling induced coherence for quantum imaging

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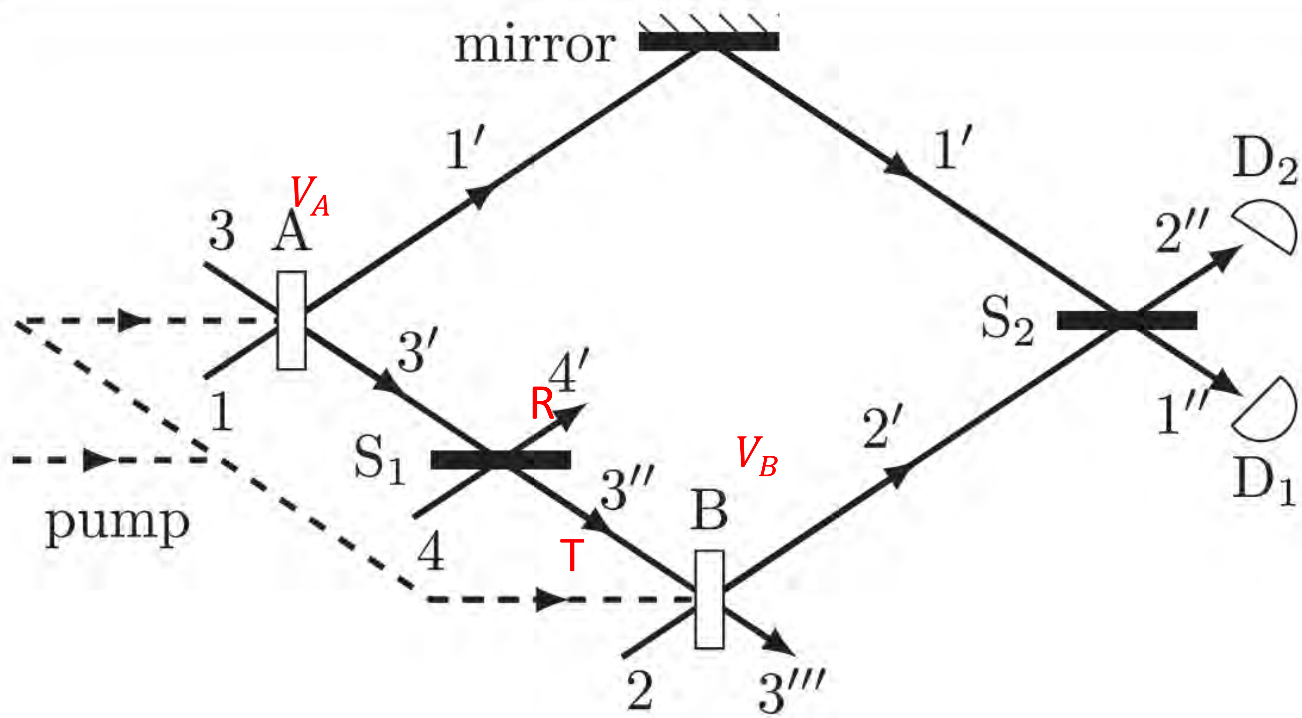
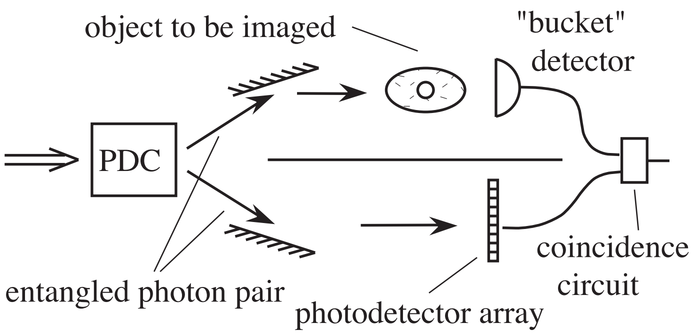
[2] Department of Physics, University of Ottawa, 25 Templeton Street, Ottawa, Ontario K1N 6N5, Canada
[3] Institute of Optics, University of Rochester, Rochester, NY 14627, United States of America



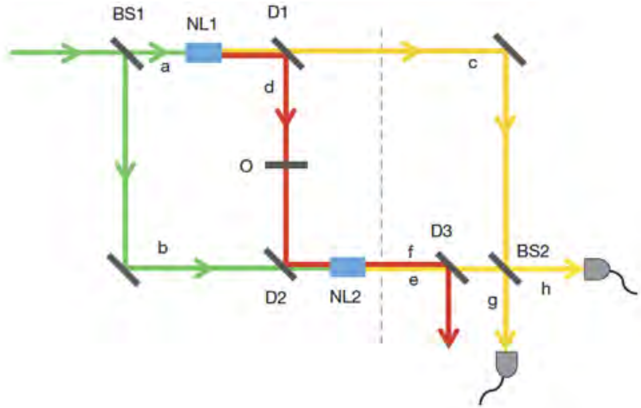
- How are visibility and SNR of the quantum interference influenced by working in the high-gain limit (V_A and V_B greater than unity) of parametric down-conversion?
- Here V_A and V_B are the parametric gains of NL crystals A and B.
- We also study imbalanced pumping, V_A not equal to V_B

Quantum Imaging Overview

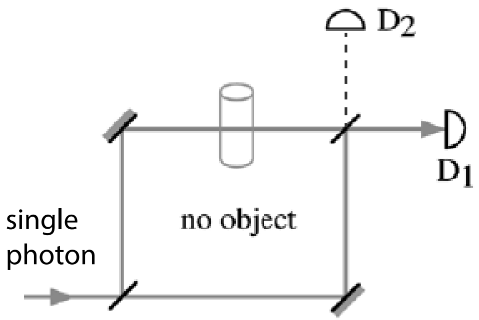
Ghost Imaging (Shih)



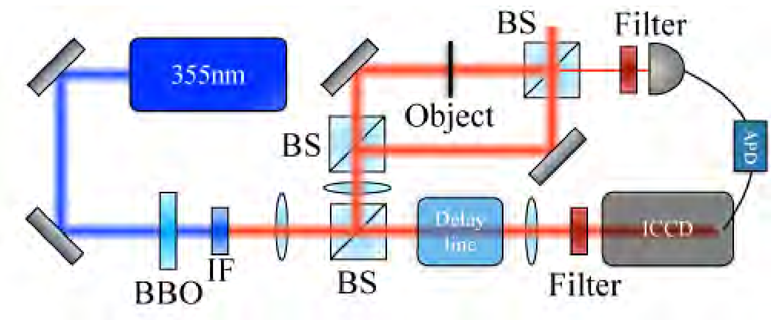
Imaging with Undetected Photons (Zeilinger)



Interaction-Free Imaging (White)



Interaction-Free Ghost Imaging



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