The Promise of Quantum Imaging

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Quantum Imaging

Prospectus

1. Goal of Quantum Imaging
2. Quantum Metrology of Single-Transverse-Mode Fields
3. Quantum Imaging
   (metrology with multi-transverse-mode fields)
4. Ghost Imaging
5. Some Specialty Topics in Quantum Imaging
6. Interaction Free Imaging

Quantum Imaging

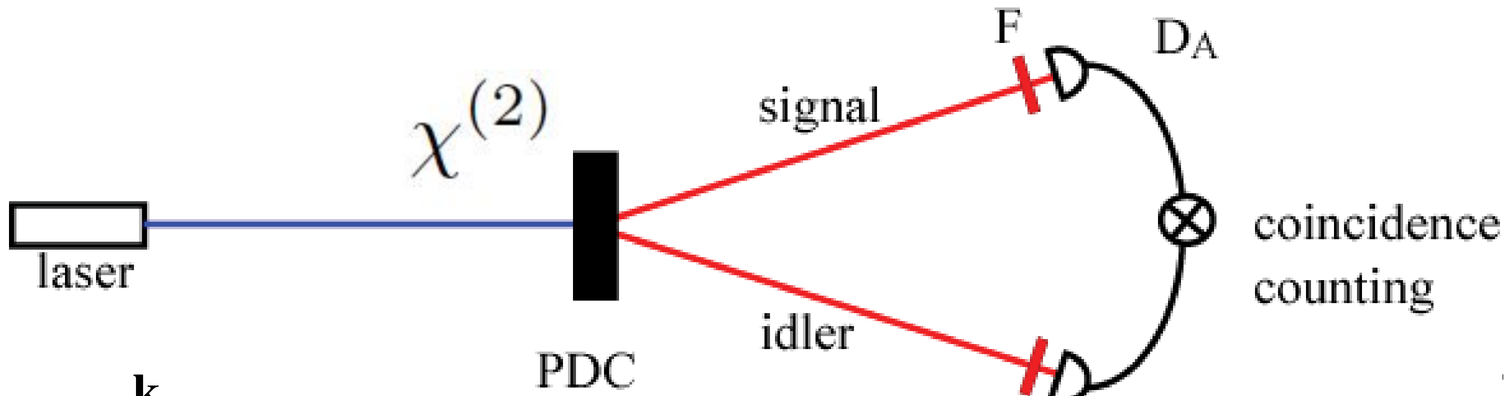
- Goal of quantum imaging is to produce "better" images using quantum methods
  - image with a smaller number of photons
  - achieve better spatial resolution
  - achieve better signal-to-noise ratio
- Alternatively, quantum imaging exploits the quantum properties of the transverse structure of light fields

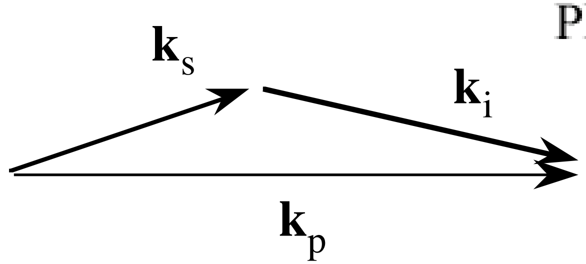
SHARPER IMAGE®

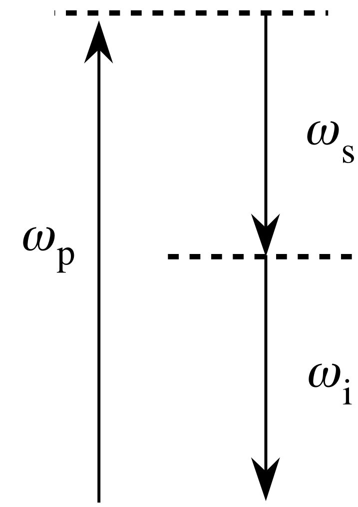
Brief History of Quantum Methods in Metrology

- Let's start by looking at the quantum features of single-transverse-mode fields
  - squeezed light fields (Kimble, many others)
  - twin beams (Fabre, many others)
  - entangled light fields (EPR, quantum cryptography, and quantum teleportation)

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

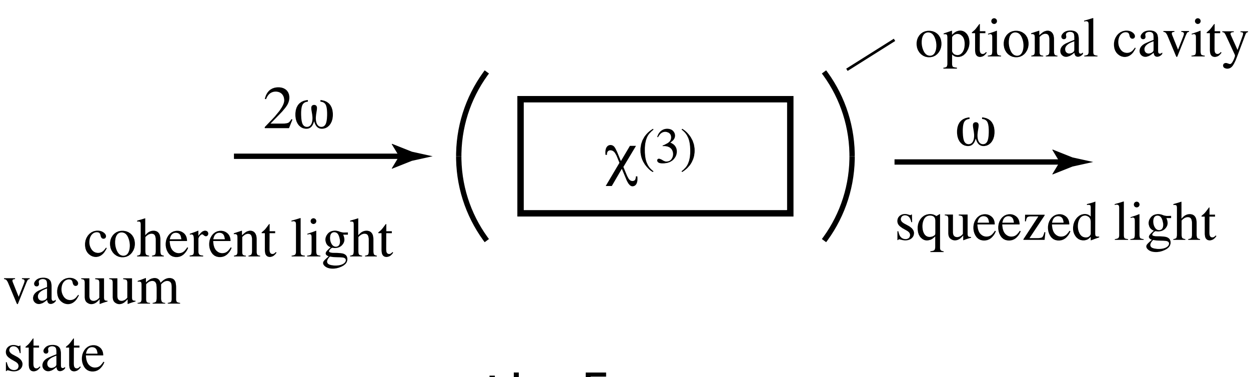
(d) angular position and orbital angular momentum

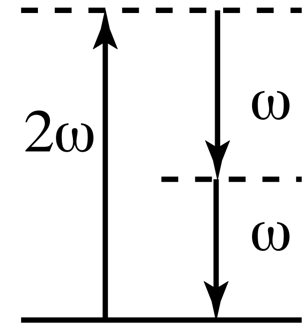
Entanglement is important for:

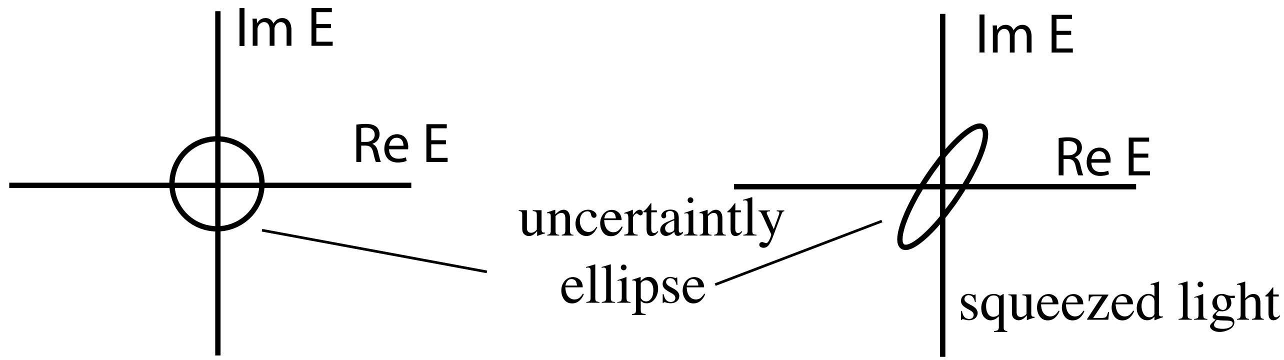
(a) Fundamental tests of QM (e.g., nonlocality)

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

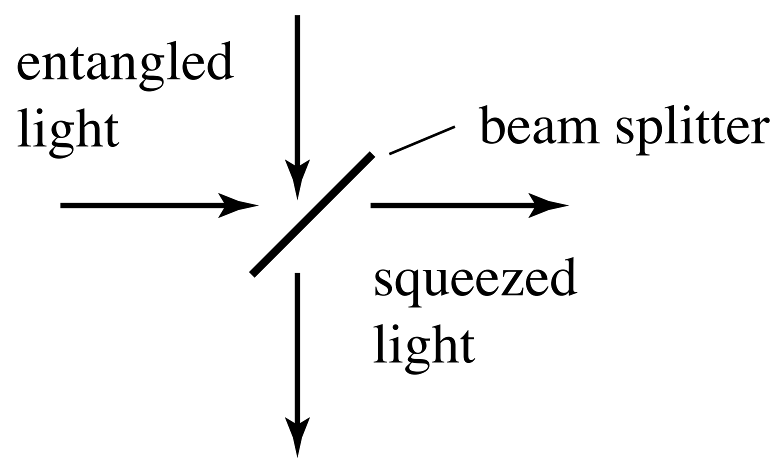
Squeezed Light Generation



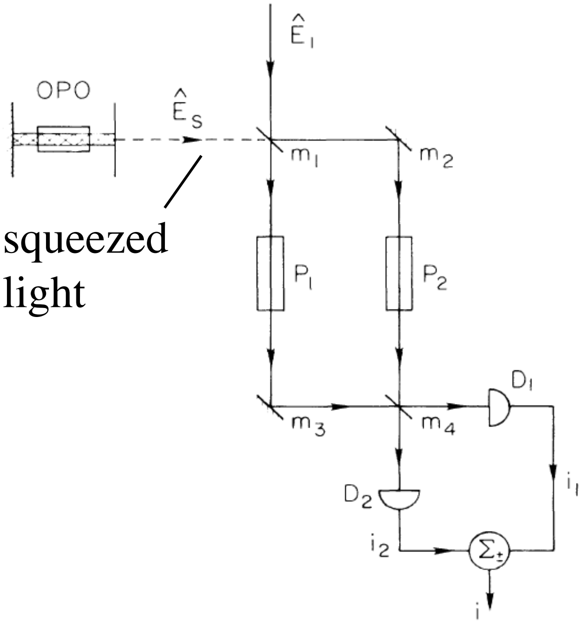




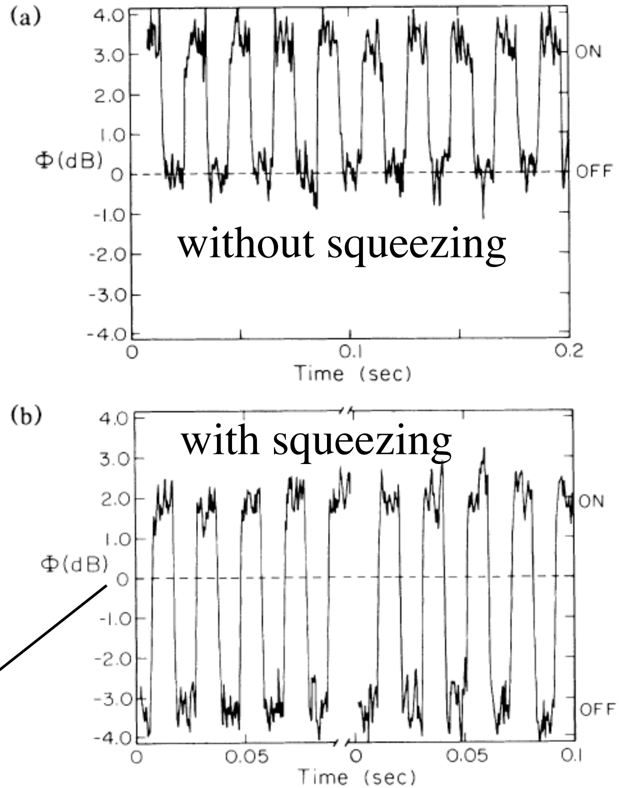
Entanglement and squeezing share a common origin:



Precision Measurement beyond the Shot-Noise Limit



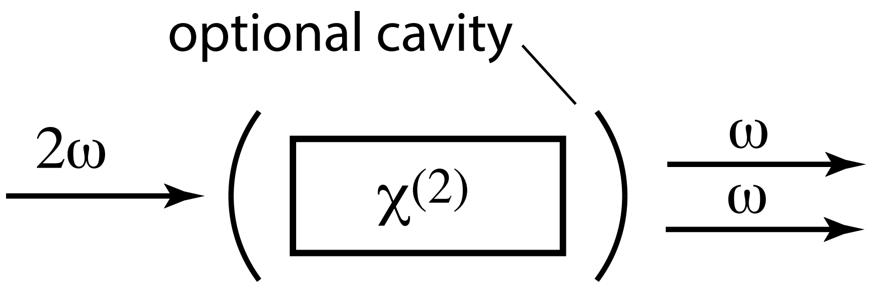
squeezed light



shot-noise limit = standard quantum limit

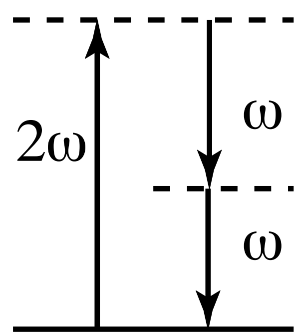
Xiao, M., L. A. Wu, and H. J. Kimble, Phys. Rev. Lett. 59, 278, 1987.

Generation of Twin Beams

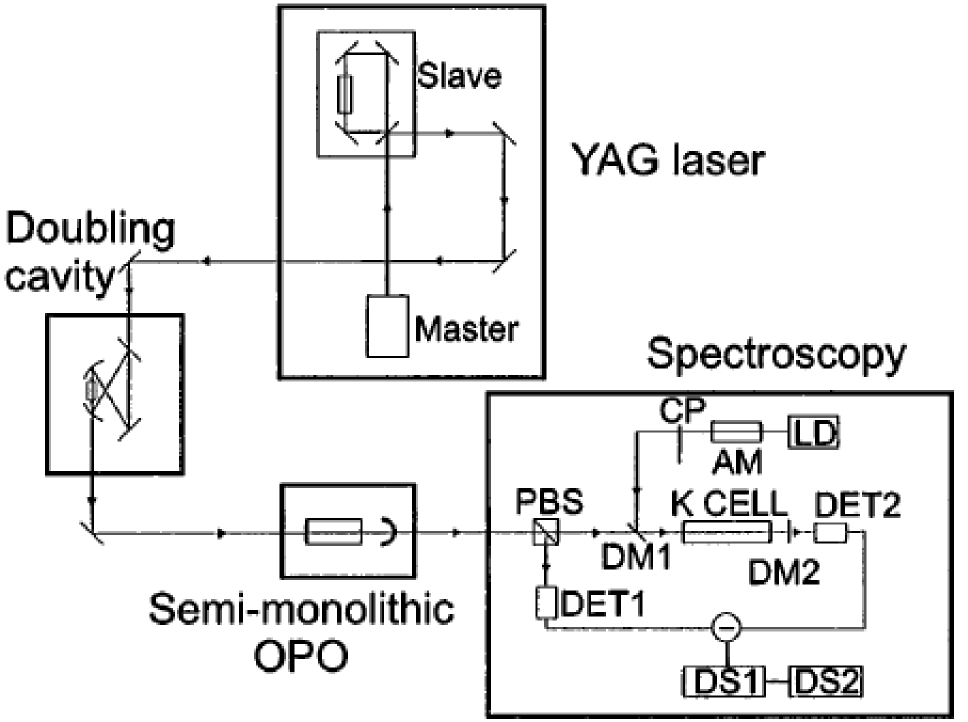


these beams possess identical fluctuations

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

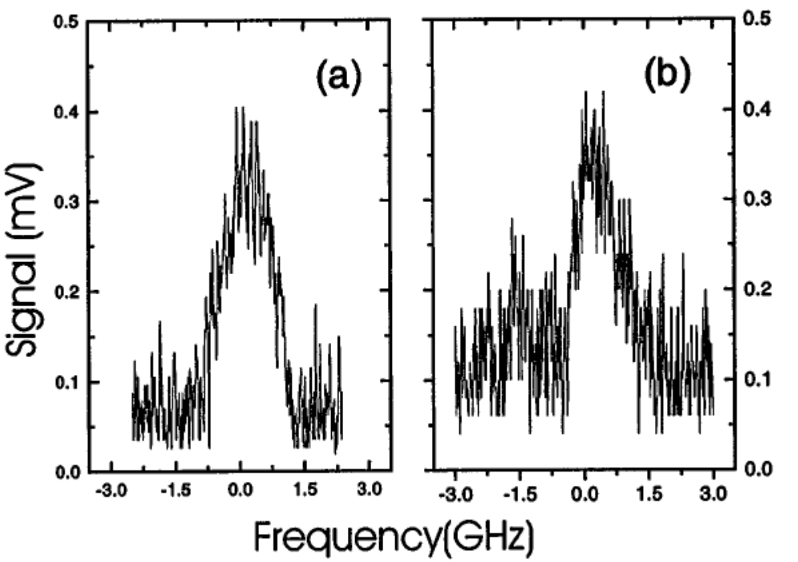


Noise-Reduced Measurement with Twin Beams



spectrum of two-photon absorption of atomic potassium

twin beam   laser light



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

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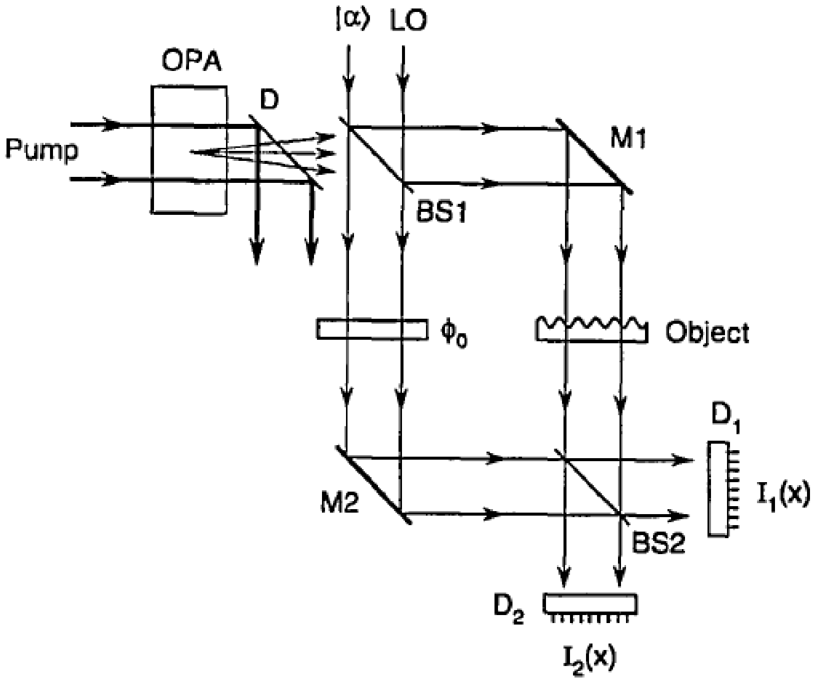
Brief History of Quantum Methods in Metrology

- Let's start by looking at the quantum features of single-transverse-mode fields

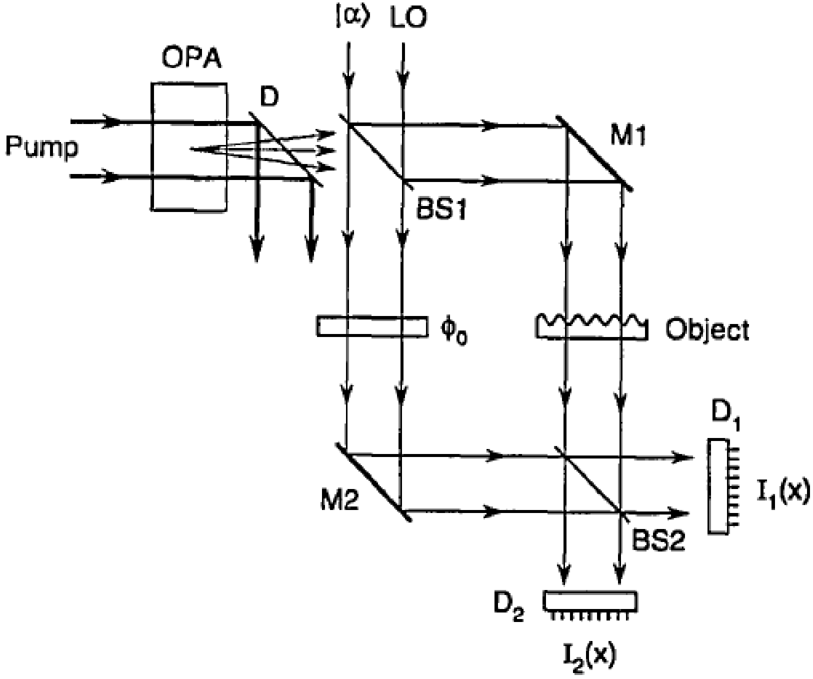
- Quantum Imaging: quantum features of multiple-transverse-mode fields
  - quantum microscopy with squeezed light (Kolobov and Kumar)
  - quantum lithography (Dowling)
  - many other examples: Devaux and Lantz (1997) Kolobov and Lugiato (1995), Choi et al. (1999). quantum laser pointer (Trepps, Fabre, 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).

Application of Multi-Transverse-Mode Squeezed Light

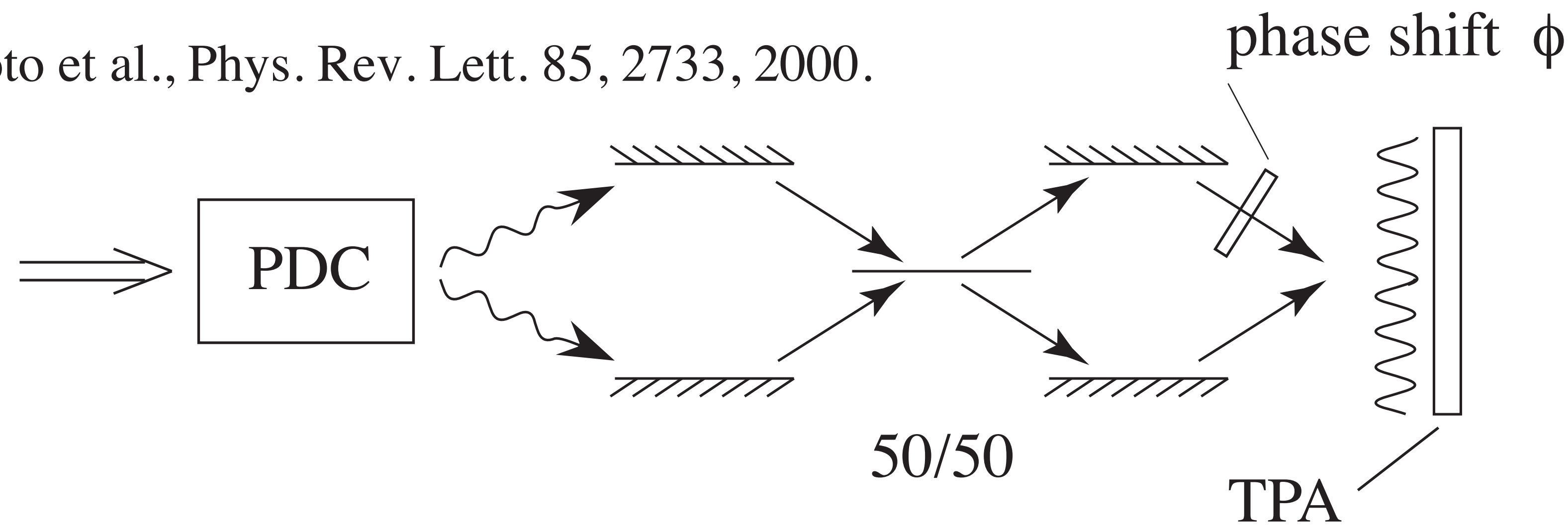


M. Kolobov and P. Kumar, Sub-shot-noise microscopy: imaging of faint phase objects with squeezed light, Optics Letters 18, 849 (1993).

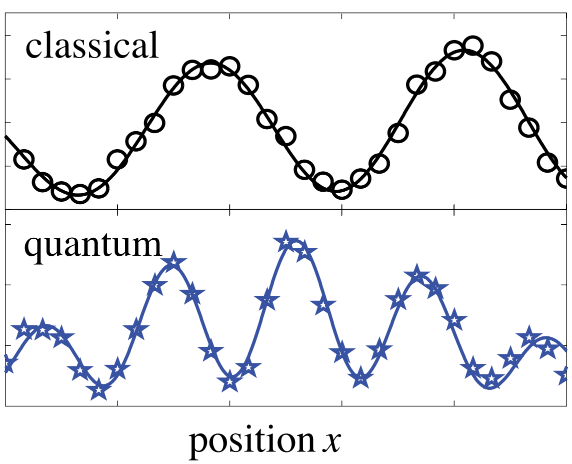
Quantum Lithography: Concept of Jonathan Dowling

- 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).

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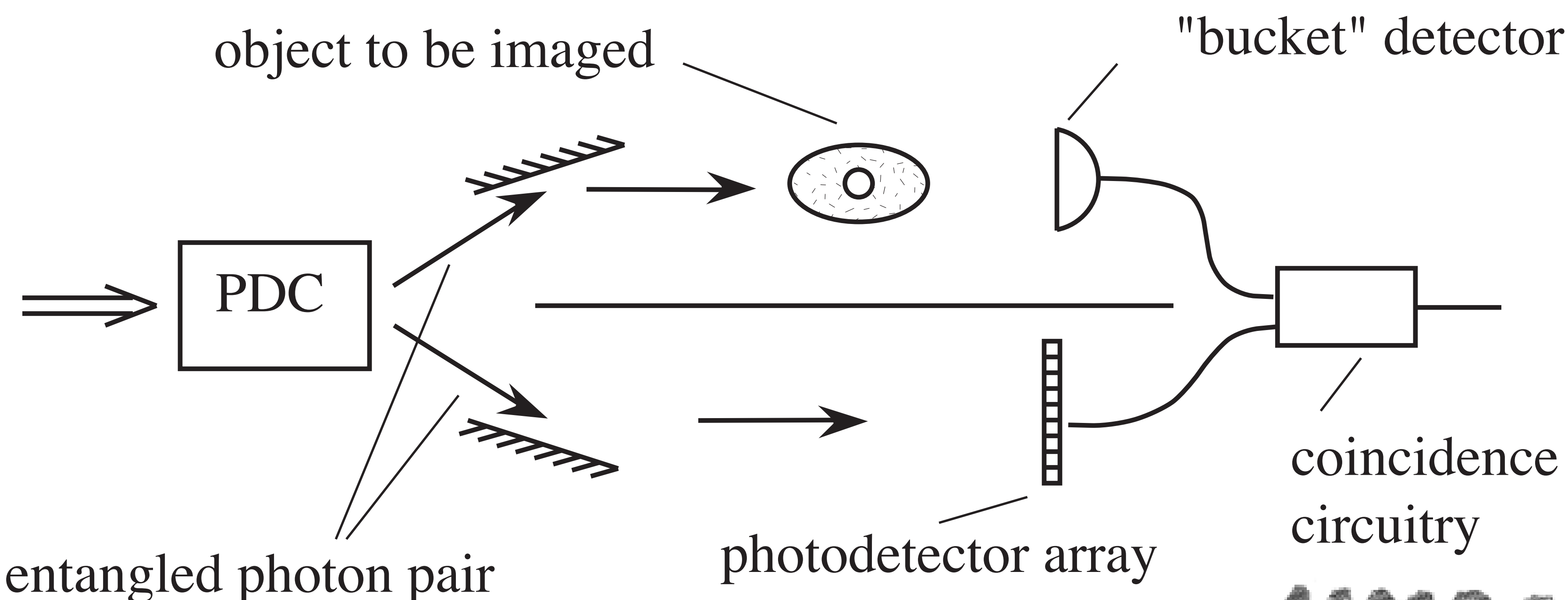
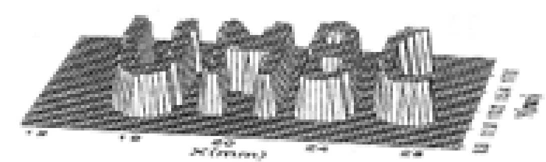
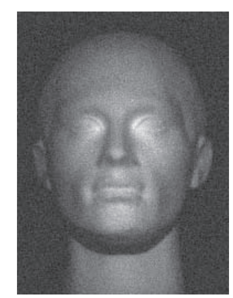
Ghost (Coincidence) Imaging





- 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)

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

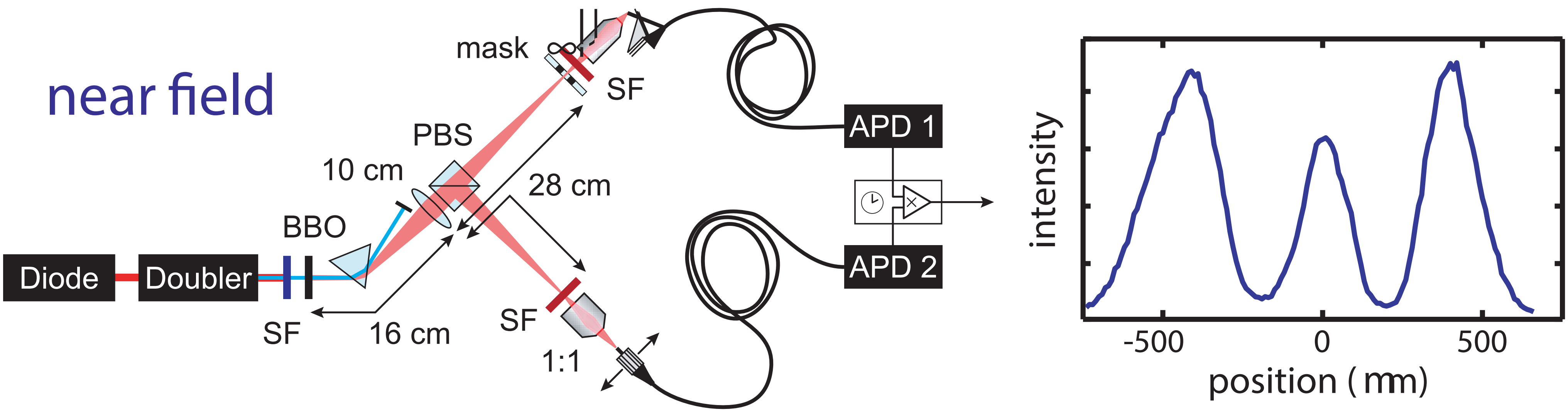
(Received 11 October 2002; published 3 April 2003)

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.

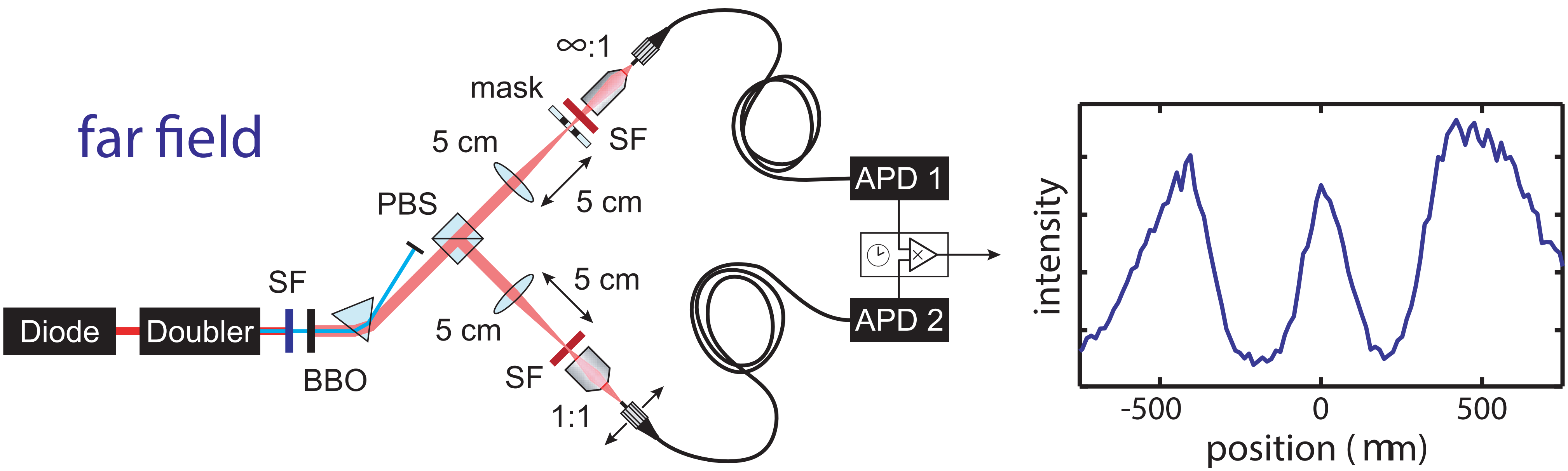
DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

Near- and Far-Field Ghost Imaging Using Quantum Entanglement

near field



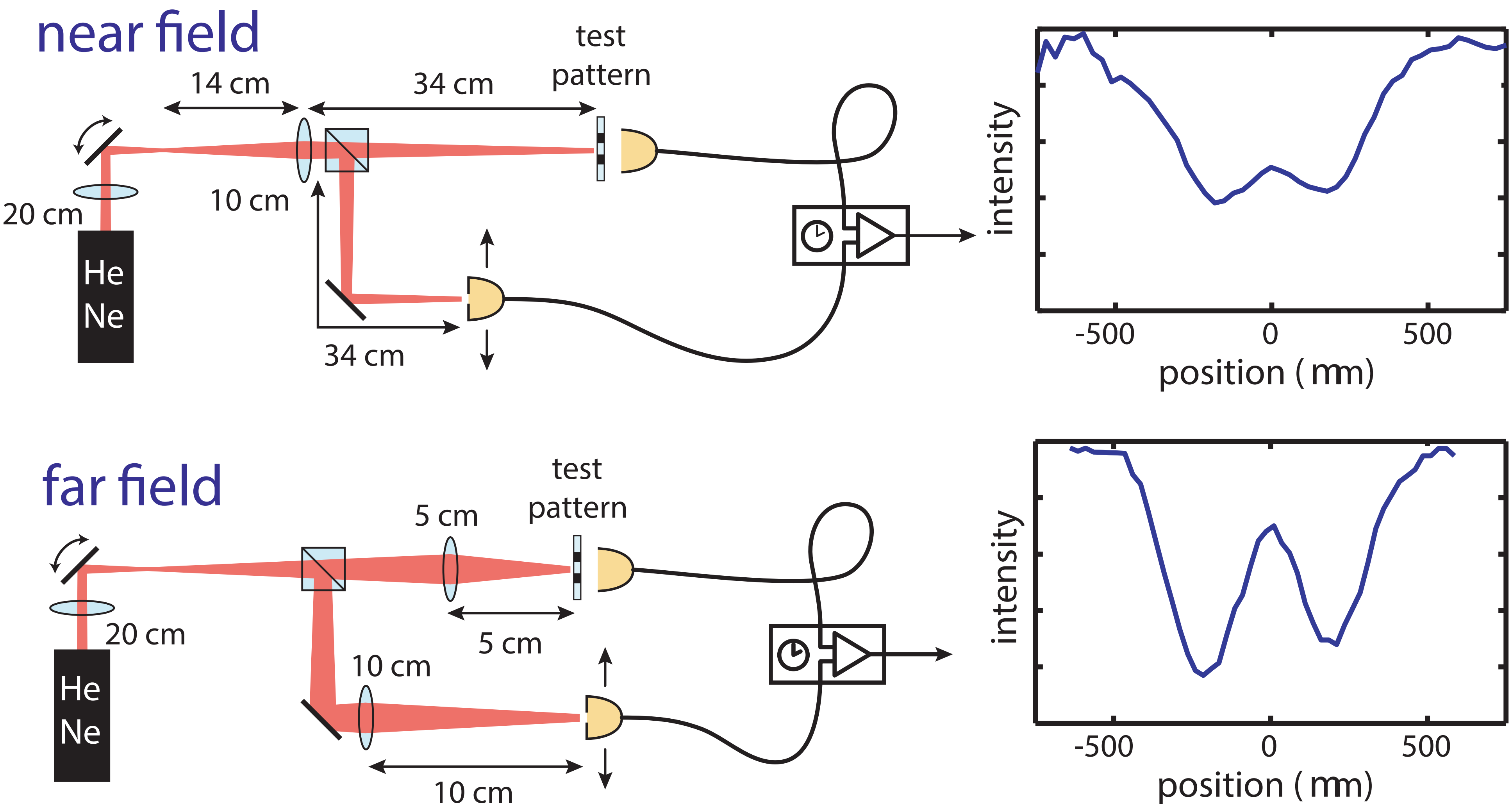
far field



Good imaging observed in both the near and far field

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

Near- and Far-Field Ghost Imaging With a Classical Source

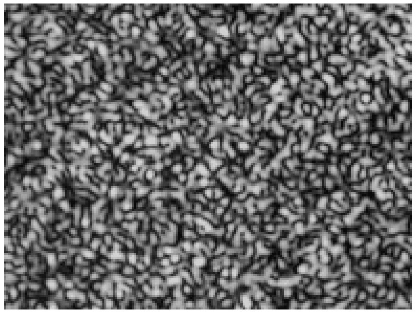


- Good imaging can be obtained only in near field or far field.
- Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of three.

Thermal Ghost Imaging

Instead of using quantum-entangled photons, one can perform ghost imaging using the correlations of a thermal light source, as predicted by Gatti et al. 2004.

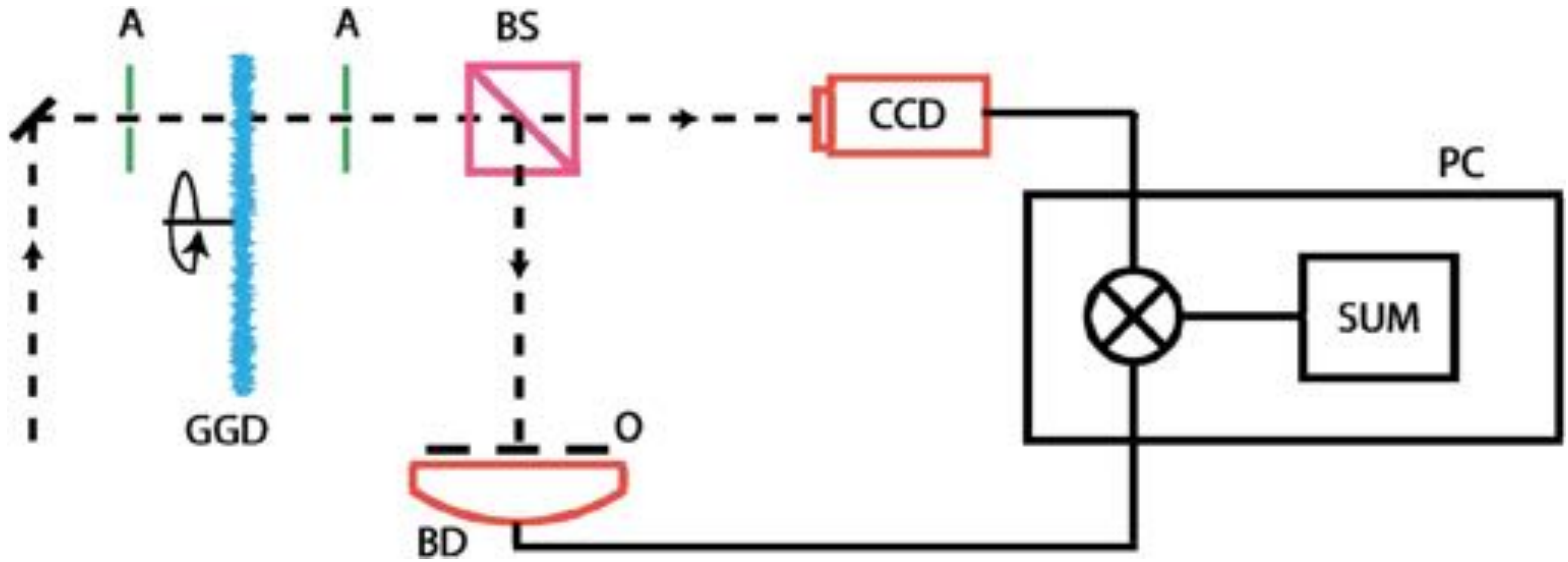
Recall that the intensity distribution of thermal light looks like a speckle pattern.



We use pseudothermal light in our studies: we create a speckle pattern with the same statistical properties as thermal light by scattering a laser beam off a rotating ground glass plate.

A. Gatti, E. Brambilla, M. Bache, and L. A. Lugiato, Phys. Rev. Lett. 93, 093602 (2004).

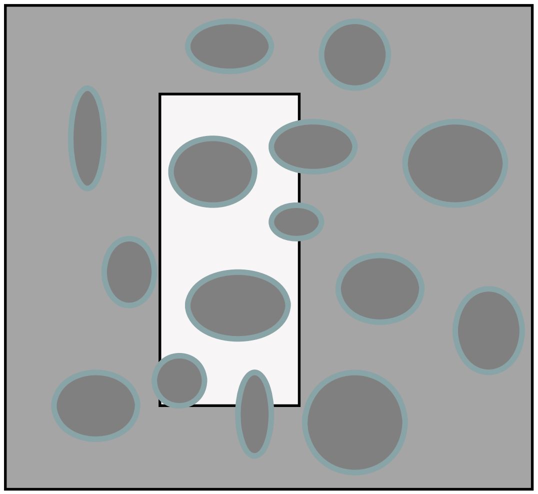
How does thermal ghost imaging work?

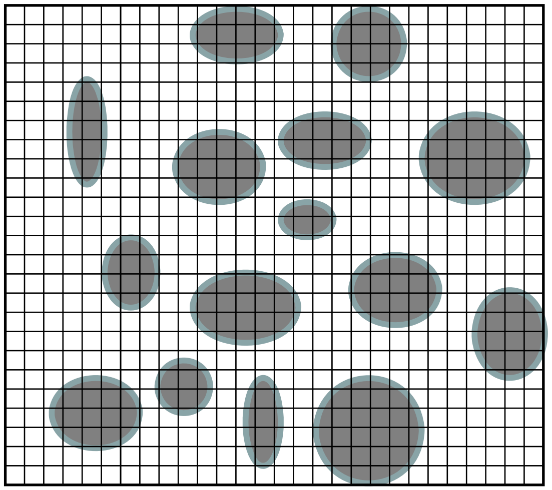


- Ground glass disk (GGD) and beam splitter (BS) create two identical speckle patterns
- Many speckles are blocked by the opaque part of object (O), but some are transmitted, and their intensities are summed by bucket detector (BD)
- CCD camera measures intensity distribution of speckle pattern
- Each speckle pattern is multiplied by the output of the BD
- Results are averaged over a large number of frames.

Origin of Thermal Ghost Imaging

Create identical speckle patterns in each arm.





object arm
(bucket detector)

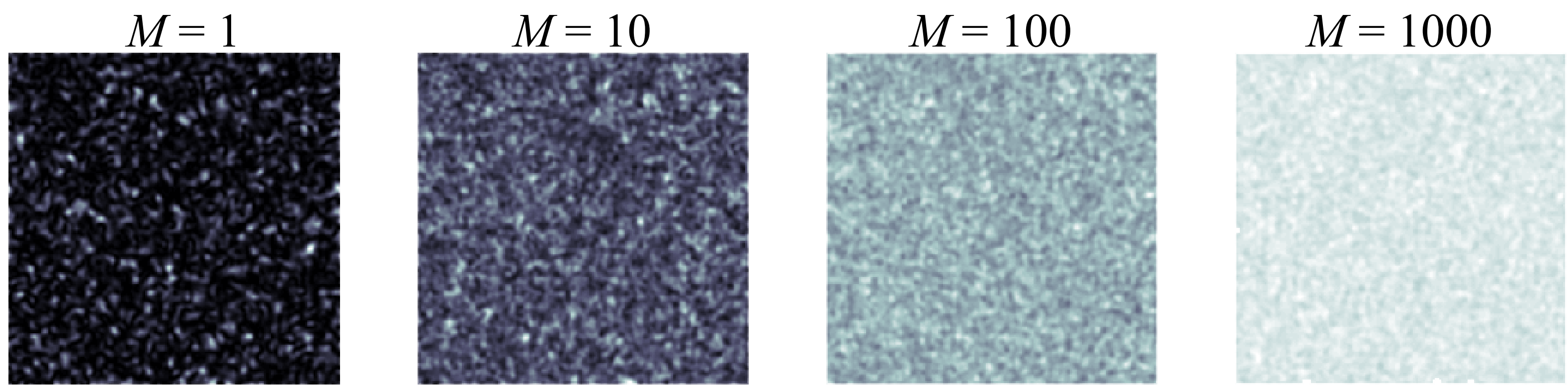
reference arm
(pixelated imaging detector)

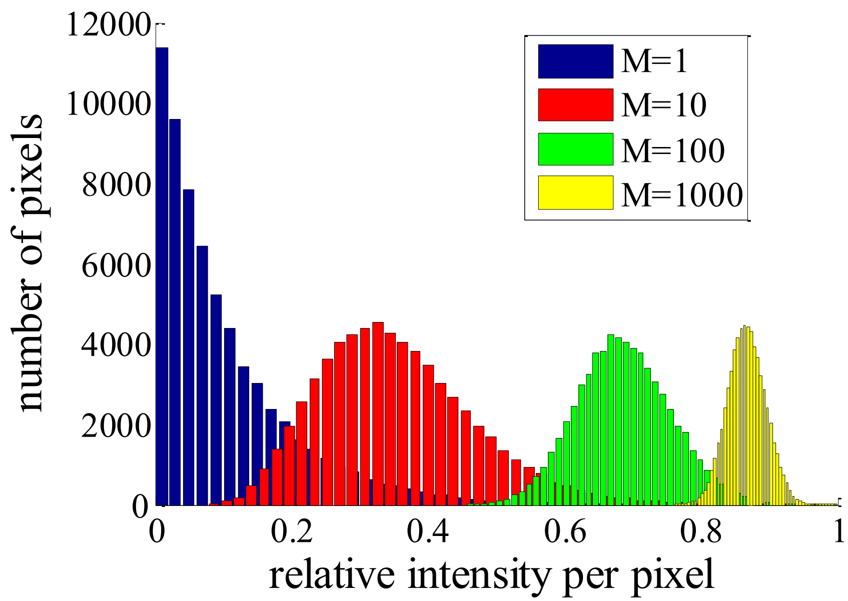
$g_1(x,y)$ = (total transmitted power) x (intensity at each point x,y)

Average over many speckle patterns

Can one Perform Thermal Ghost Imaging With Natural Thermal Light Sources?

- No current detector can time-resolve the rapidly changing speckle pattern of a natural light source.
- Detector sees intensity time-averged averaged speckles; contrast is reduced





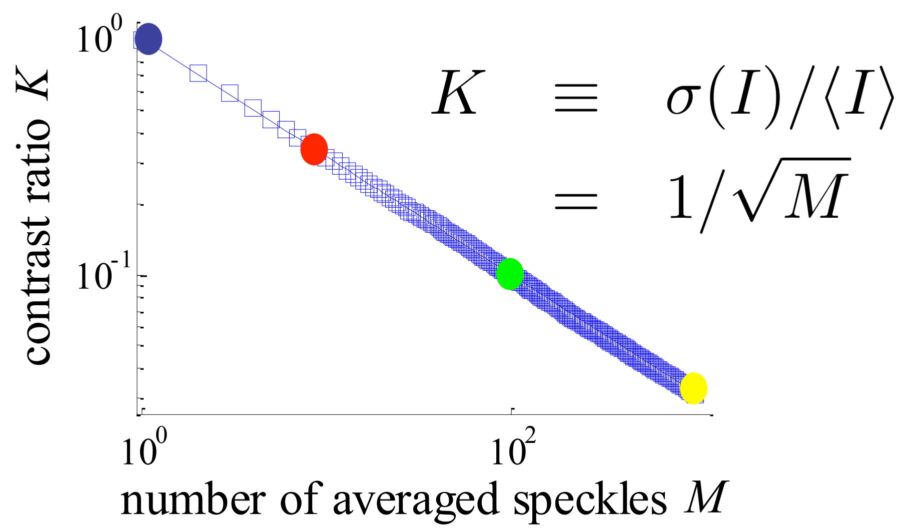
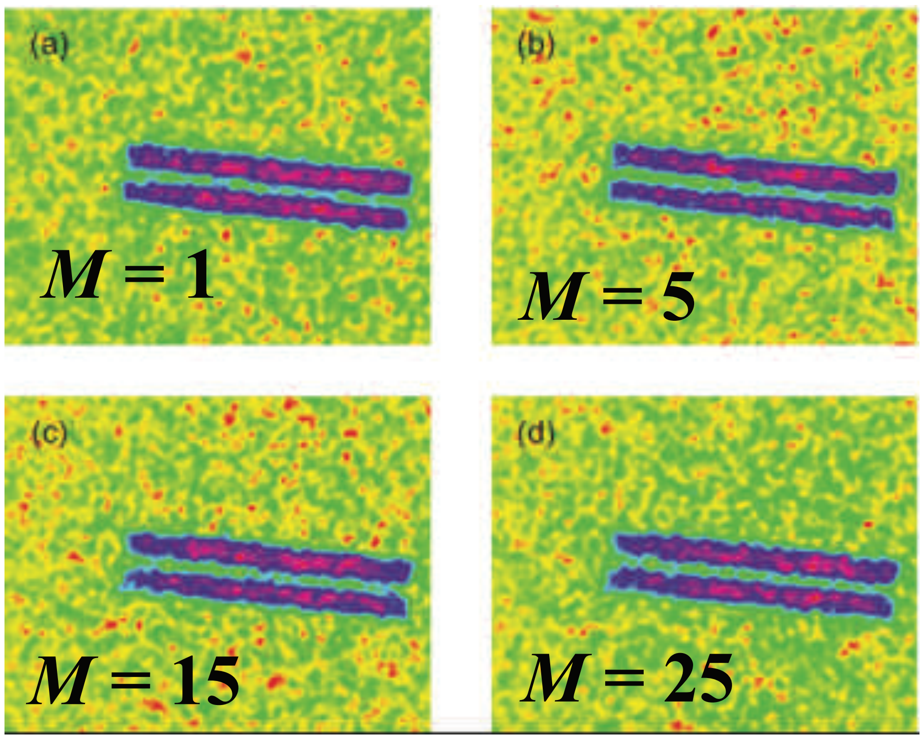
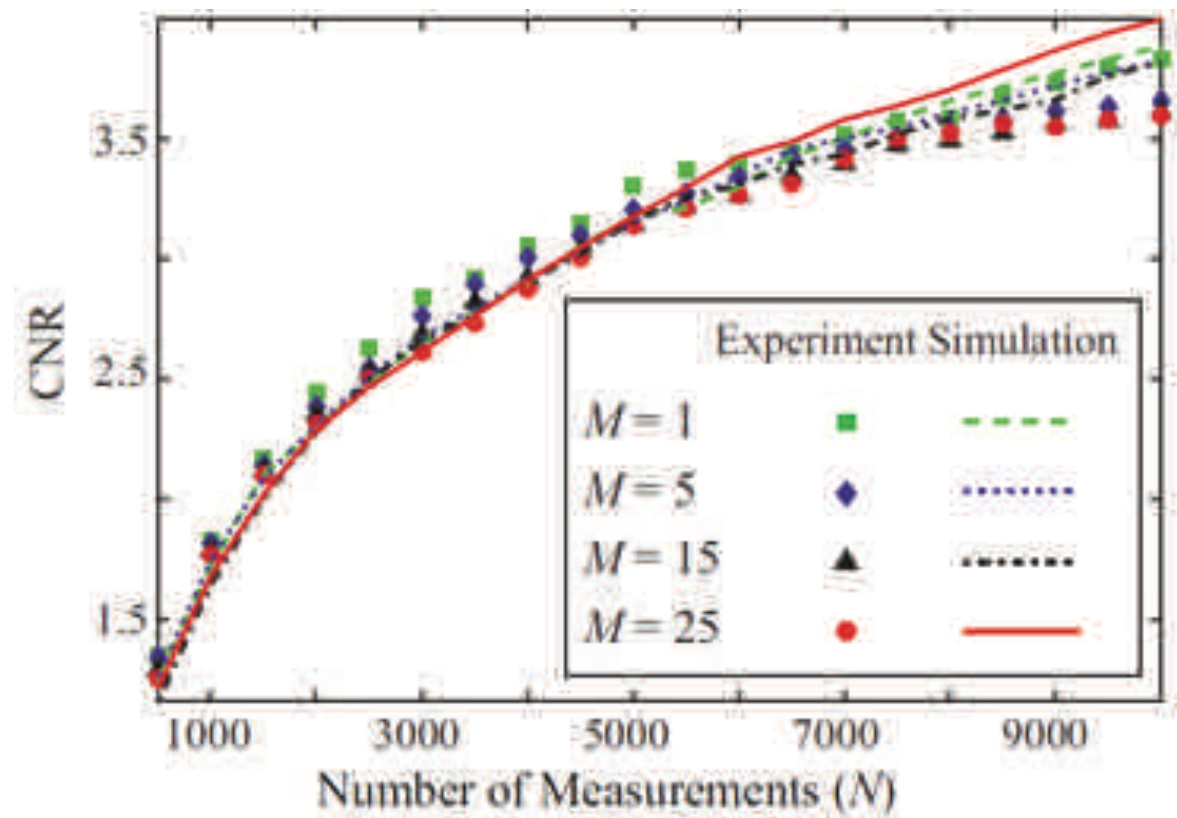


Image Quality is not Degraded through Use of Slow Detectors!

- M = number of speckle patterns averaged together
- 10,000 measurements with four different values of M
- All images qualitatively similar



- Contrast-to-noise ratio increases with mumber of measurements, and does not decrease with M



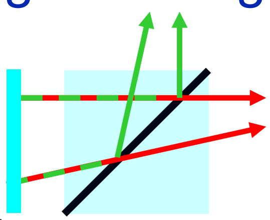
- Results suggest that ghost imaging can be performed with natural light sources

Thermal ghost imaging with averaged speckle patterns, P. Zerom, Z. Shi, M.N. O'Sullivan, K.W.C. Chan, M.Krogstad, J.H. Shapiro, and R.W. Boyd, Phys. Rev. A 86, 063817 (2012)

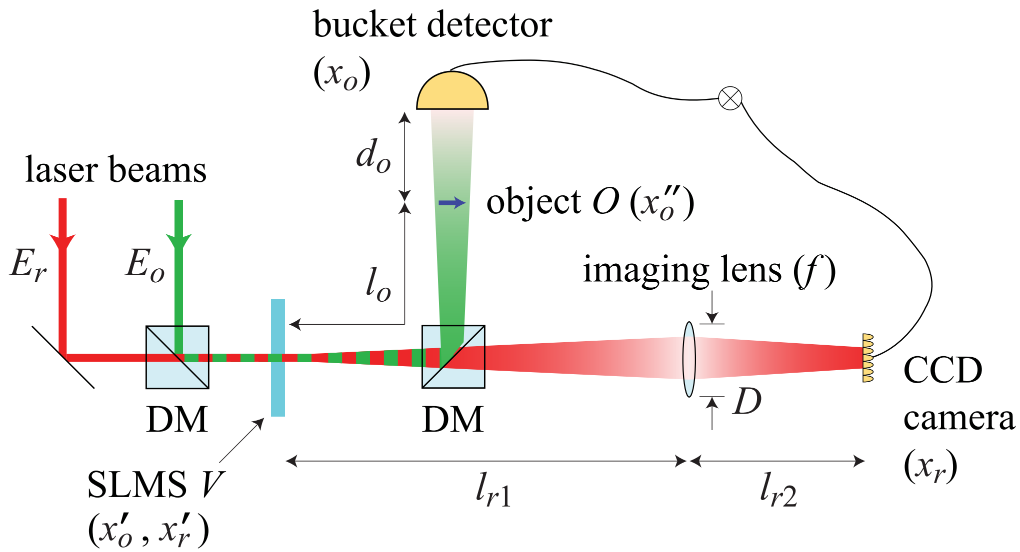
Two-Color Ghost Imaging

New possibilities afforded by using different colors in object and reference arms

Thermal ghost imaging

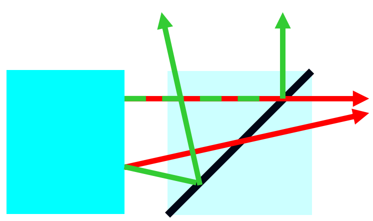


SLM

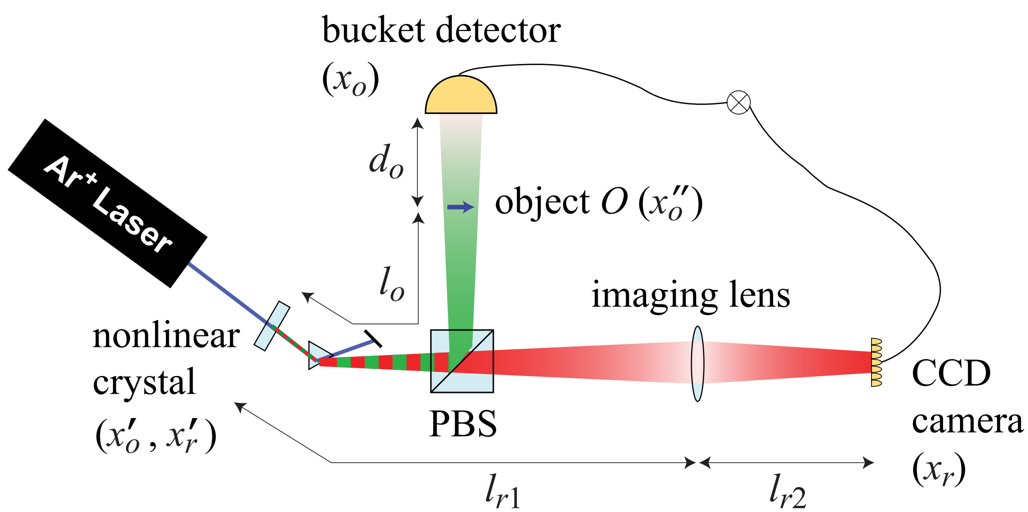


But no obvious way to make identical speckle patterns at two wavelengths

Quantum ghost imaging



SPDC



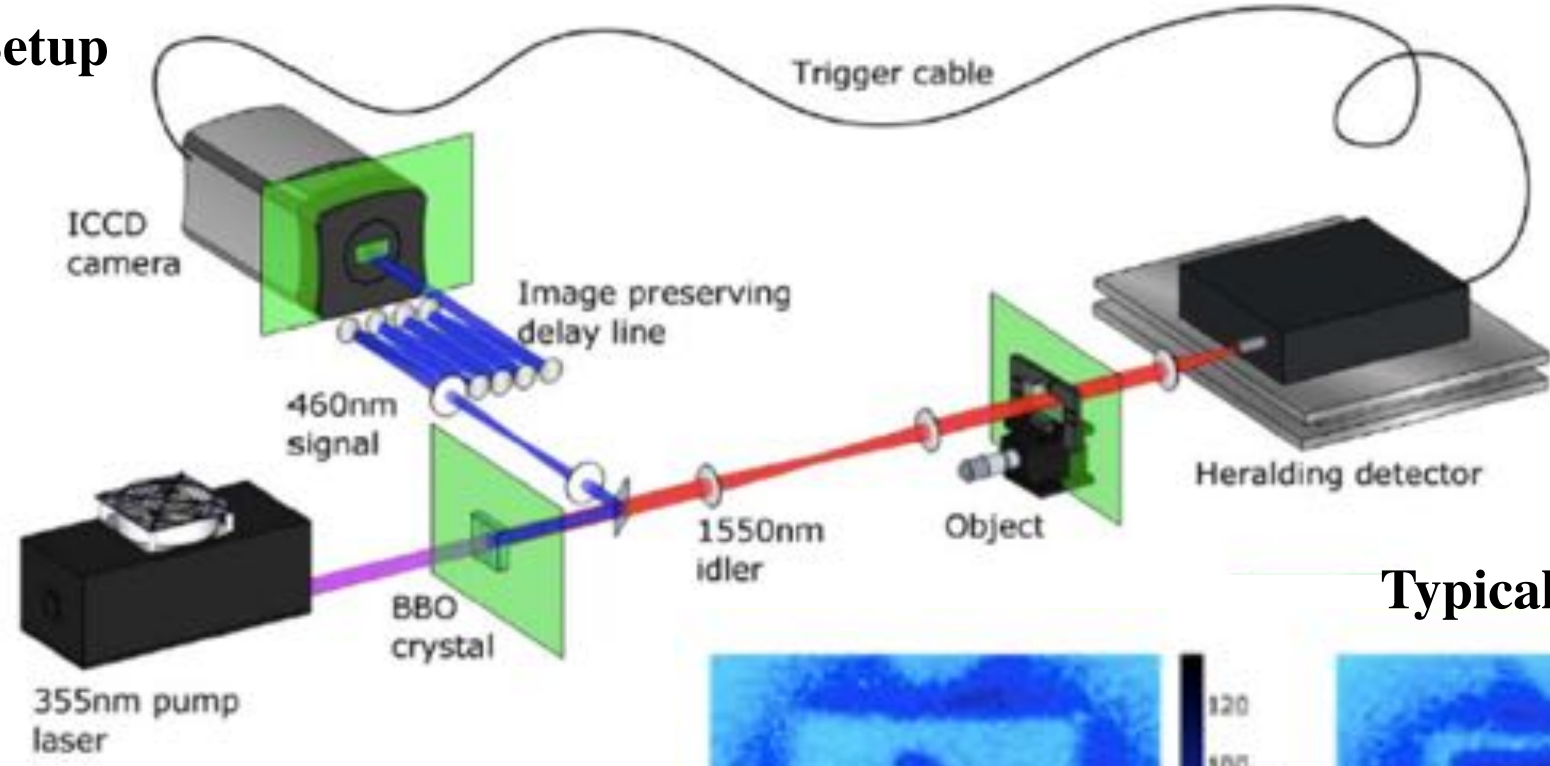
Spatial resolution depends on wavelength used to illuminate object.

Two-Color Ghost Imaging, K.W.C. Chan, M.N. O'Sullivan, and R.W. Boyd, Phys. Rev. A 79, 033808 (2009).

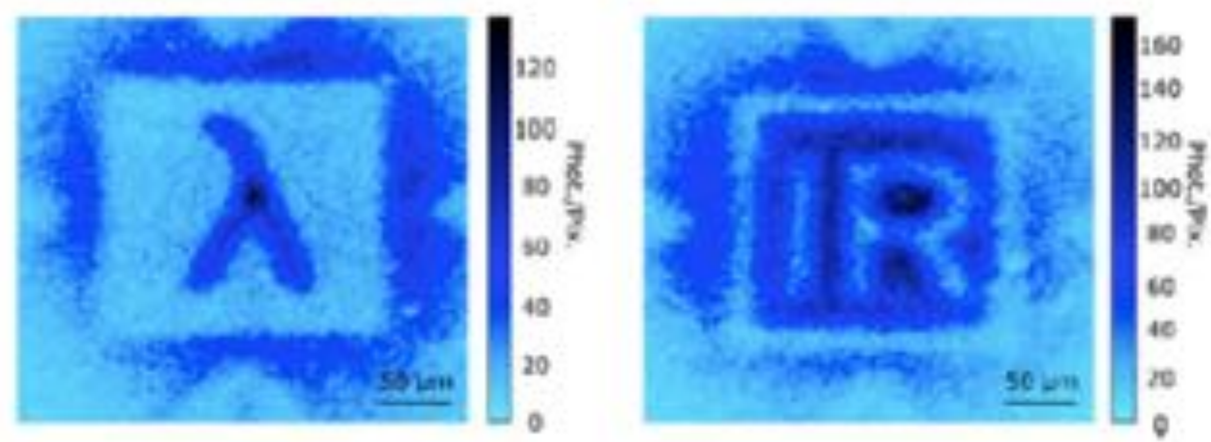
Wavelength-Shifted (Two-Color Ghost) Microscopy

- 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



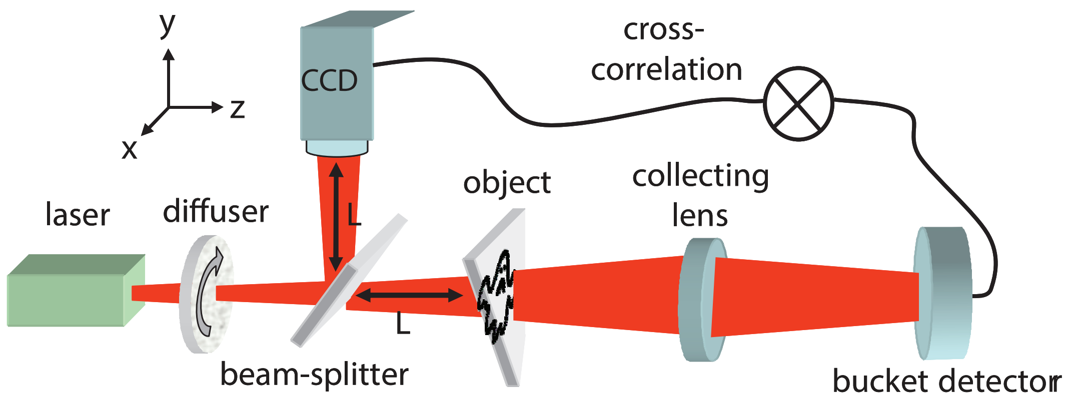
Typical images



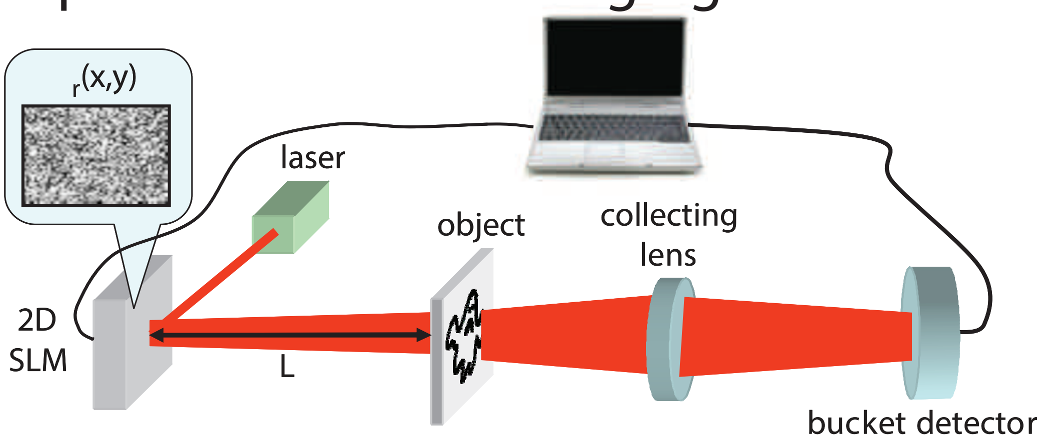
Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

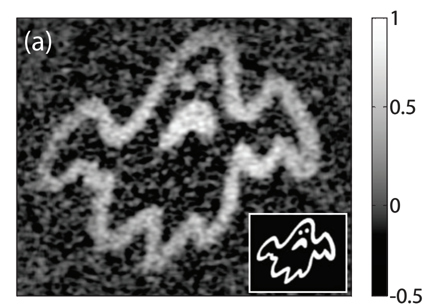
Computational Ghost Imaging

- Conventional Ghost Imaging



- Computational Ghost Imaging





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B. I. Erkmen and J. H. Shapiro, Advances in Optics and Photonics 2, 405–450 (2010)

Trying to Give Credit

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Quantum Imaging

Prospectus

1. Goal of Quantum Imaging
2. Quantum Metrology of Single-Transverse-Mode Fields
3. Quantum Imaging
   (metrology with multi-transverse-mode fields)
4. Ghost Imaging
5. Some Specialty Topics in Quantum Imaging
6. Interaction Free Imaging

Nearly "ideal" CCD cameras are now commercially available!

(An ideal camera would have 100% detection quantum efficiency and a vanishing dark-count rate.)

The fine print (or, if you prefer, the details).

- Intensified CCD (ICCDs) cameras have a detection quantum efficiency of only about 20%, but can be gated in such a way that there are essentially no dark counts in an integration time.

- Electron multiplied CCD (EMCCDs) cameras have a detection quantum efficiency of about 90%, but have a background dark-count rate of about 0.02 counts per pixel per readout. This is almost (but not quite) good enough.

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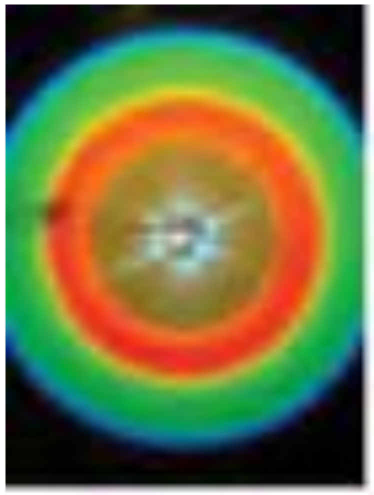
Imaging high-dimensional spatial entanglement with a camera

M.P. Edgar, D. S. Tasca, F. Izdebski, R.E. Warburton, J. Leach, M. Agnew, G. S. Buller, R.W. Boyd & M.J. Padgett



Large number of entangled modes in PDC field

But we can access them only one mode at a time using APDs

Need a camera with unit quantum efficieny and no dark signal

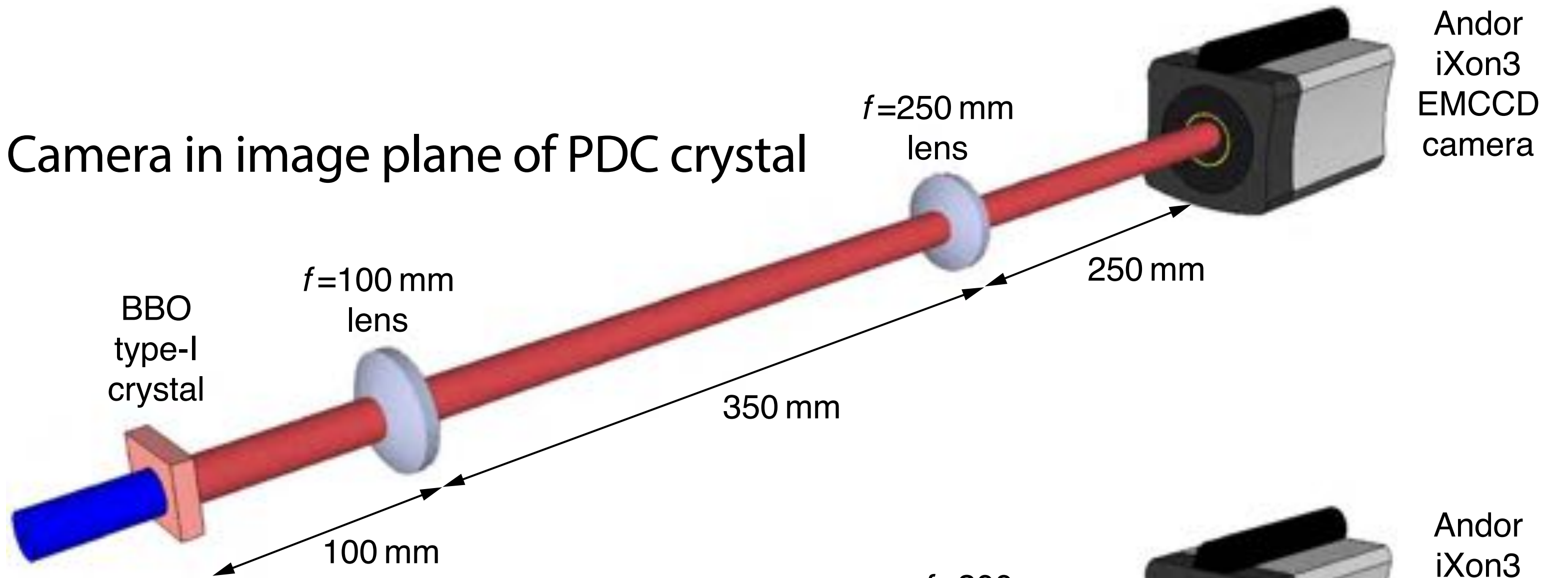
Modern EMCCD cameras provide a close approximation

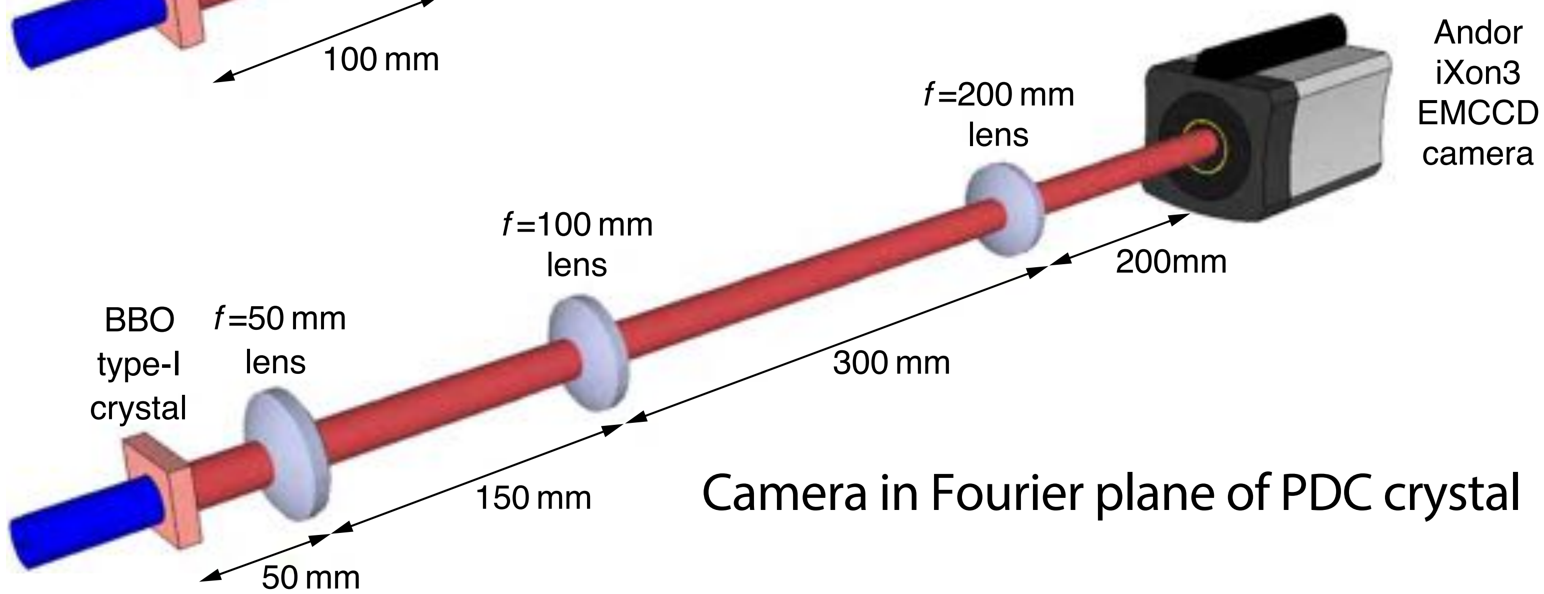
Andor iXon3:

90% quantum efficiency

dark signal of 0.02 events per pixel per readout

This performance is adequate for studies in quantum information.



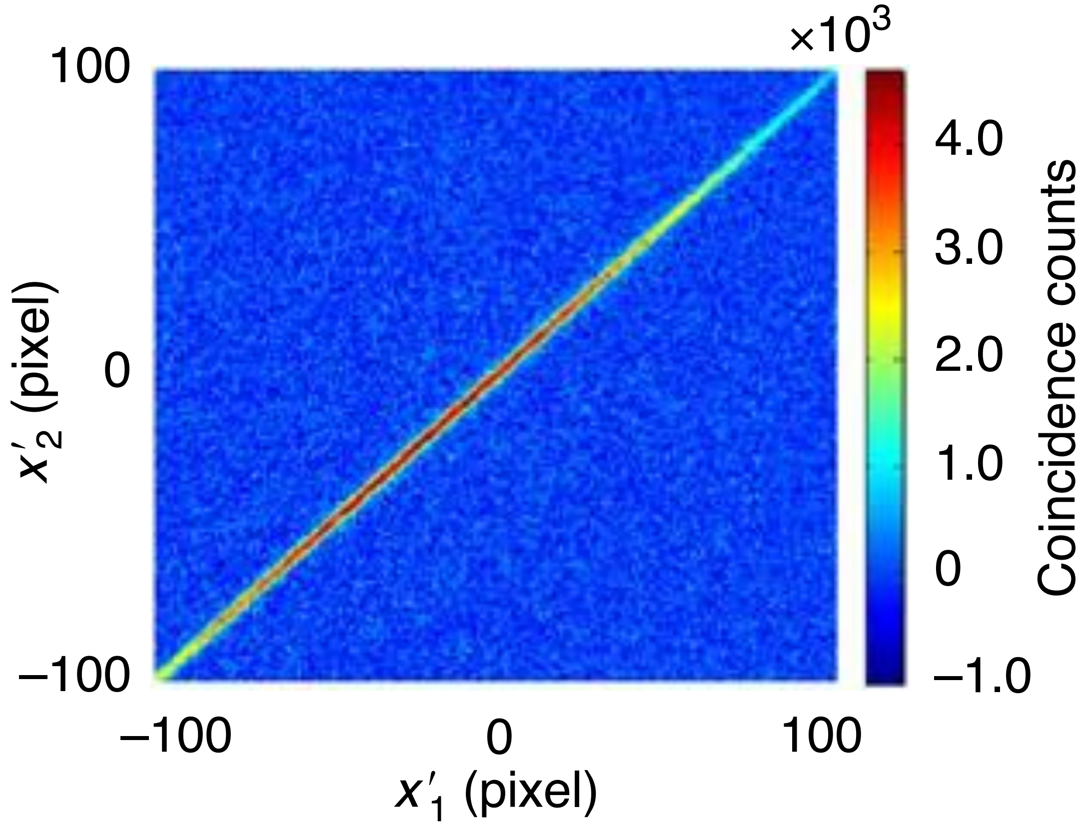


See also, e.g., Zhang, L., Neves, L., Lundeen, J. S. & Walmsley, I. A. J. Phys. B 42, 114011 (2009).

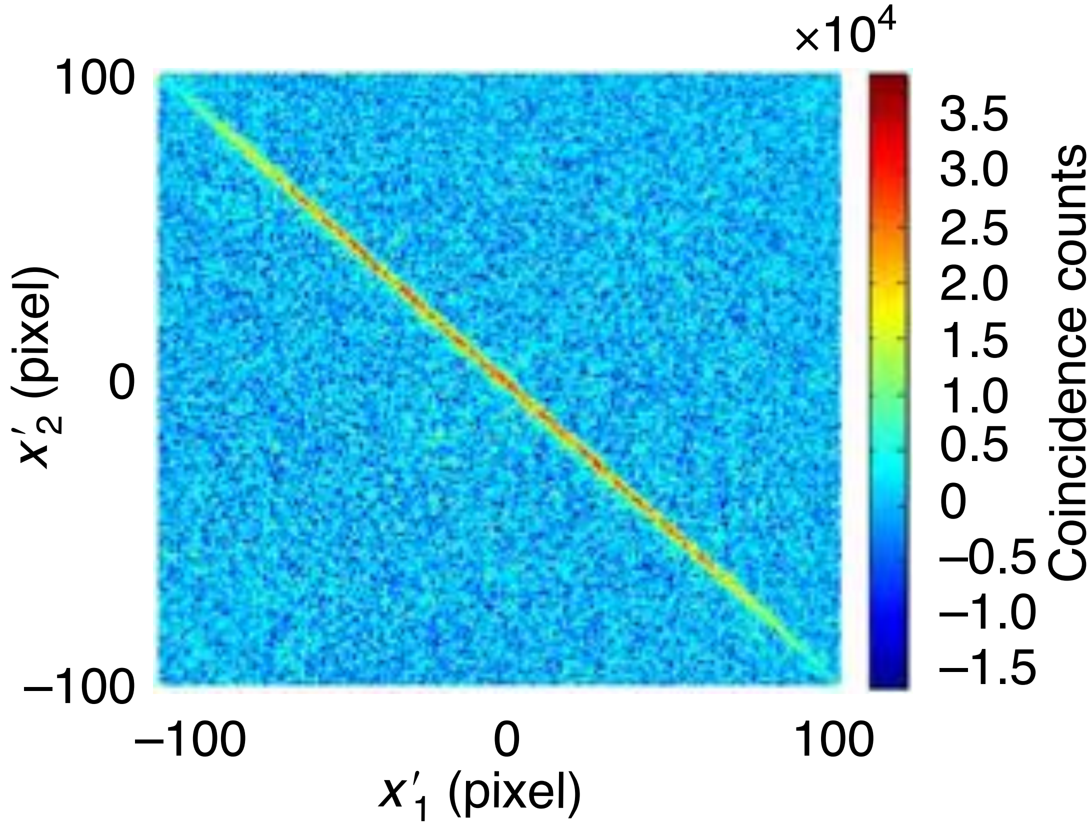
Imaging high-dimensional spatial entanglement with a camera

- Correlations:

near-field (position)



far-field (momentum)



2500 spatial modes are entangled!

- Our data shows violations of the Reid EPR criterion

$$\Delta^2_{\min}(x_1 \mid x_2)\Delta^2_{\min}(p_{x_1} \mid p_{x_2}) = (6.6 \pm 1.0)\times 10^{-4}\hbar^2,$$

$$\Delta^2_{\min}(x_2 \mid x_1)\Delta^2_{\min}(p_{x_2} \mid p_{x_1}) = (6.2 \pm 0.9)\times 10^{-4}\hbar^2,$$

New Journal of Physics
The open access journal for physics

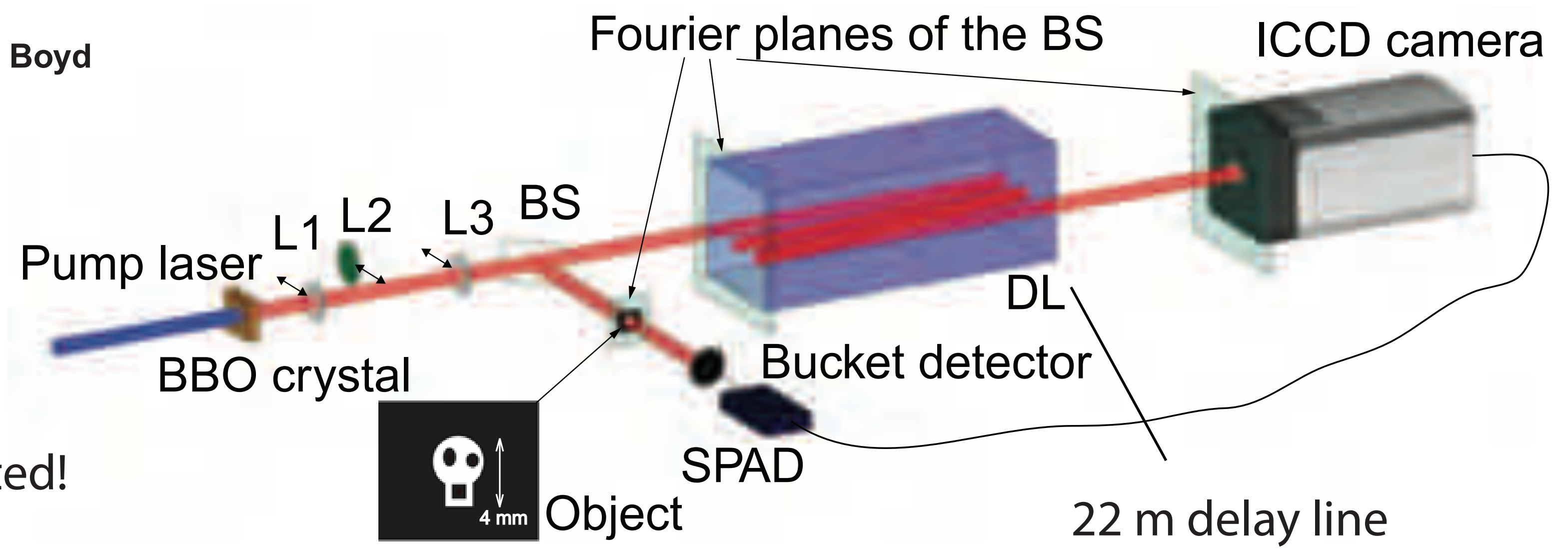
EPR-based ghost imaging using a single-photon-sensitive camera

Reuben S Aspden, Daniel S Tasca , Robert W Boyd and Miles J Padgett

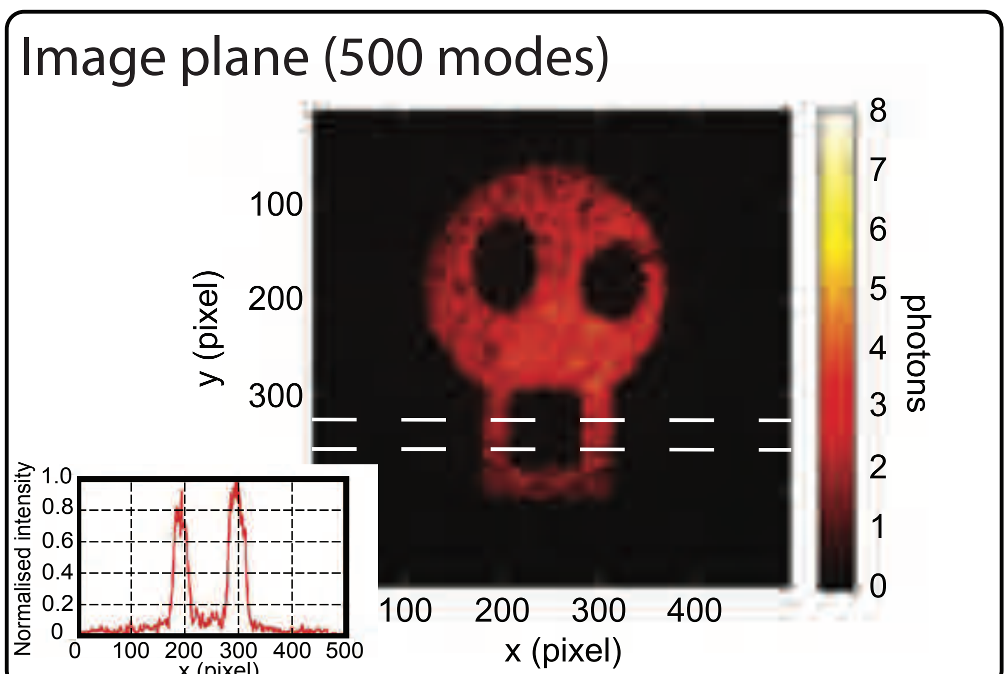
New Journal of Physics **15** (2013) 073032 (11pp)

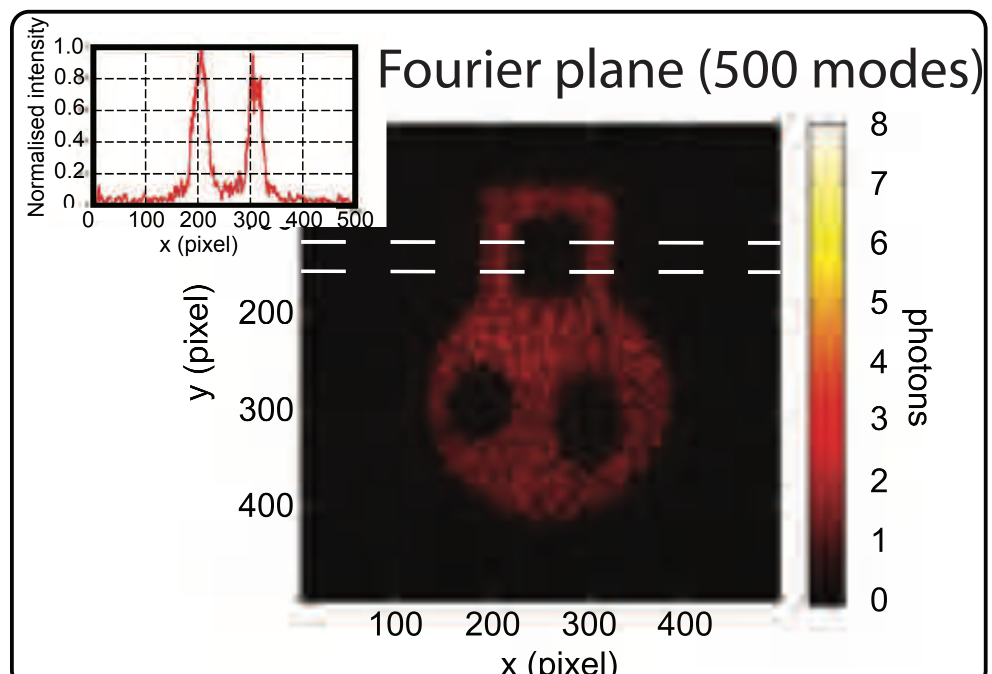
Essentially “ideal” cameras now are available!

When time gated, essentially all background noise is eliminated!



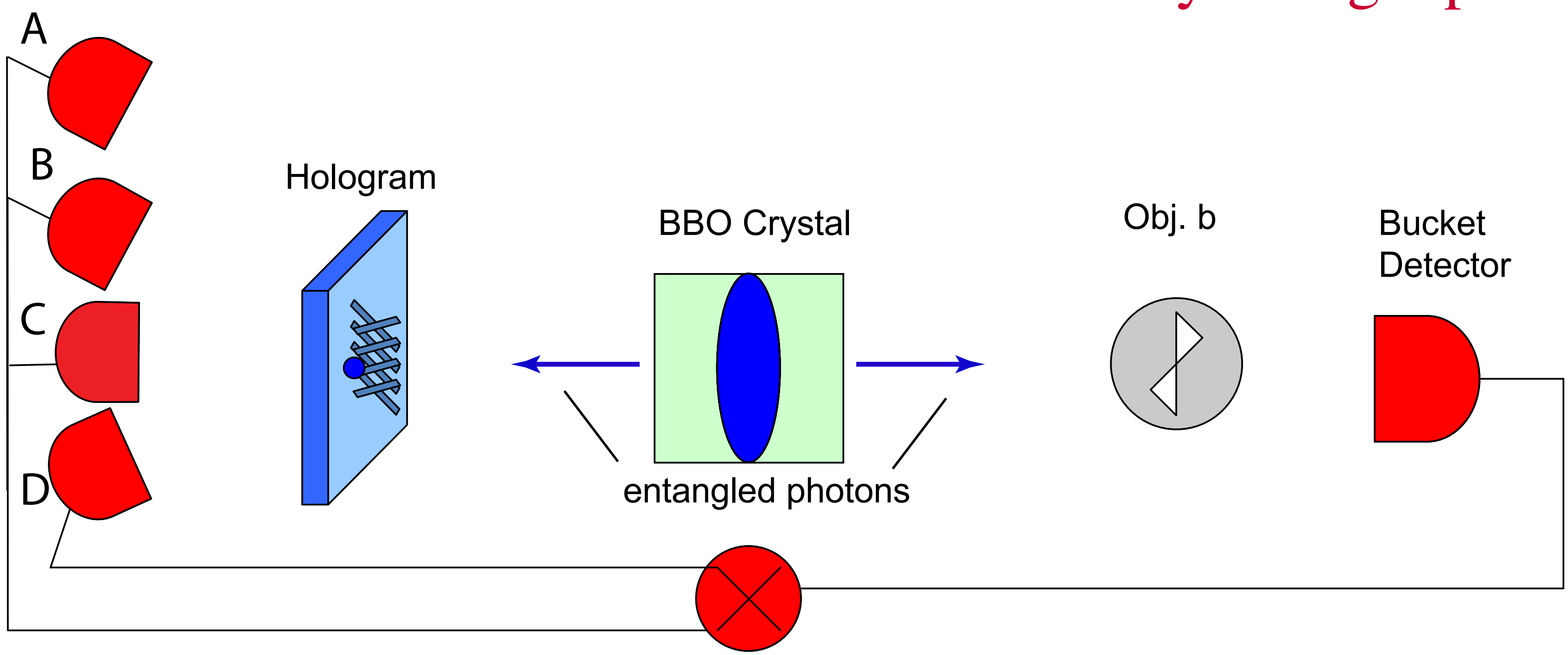
Edgar M P, Tasca D S, Izdebski F, Warburton R E, Leach J, Agnew M, Buller G S, Boyd R W and Padgett M J 2012 Imaging high-dimensional spatial entanglement with a camera Nature Commun. 3 984



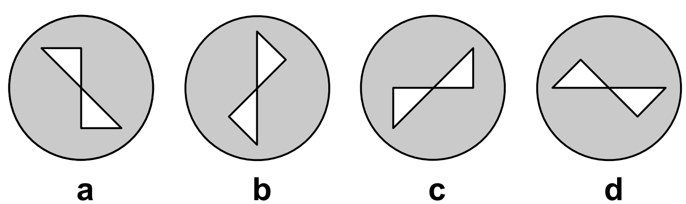


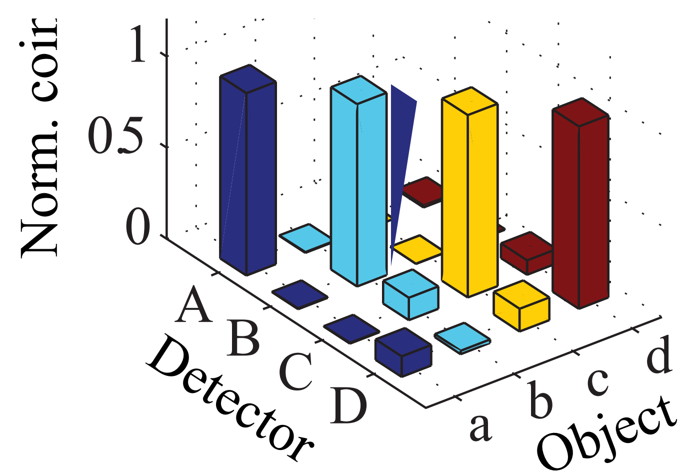
Single-Photon Coincidence Imaging

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.





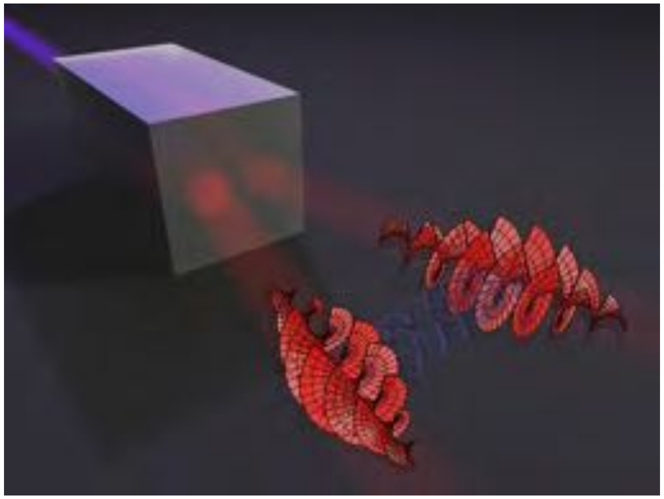
Malik, Shin, O'Sullivan. Zerom, and Boyd, Phys. Rev. Lett. 104, 163602 (2010).

Use of Quantum States for Secure Optical Communication

- The celebrated BB84 protocol for quantum key distribution (QKD) transmits one bit of information per received photon

- We have built a QKD system that can carry more than one bit per photon.
  - Note that in traditional telecom, one uses many photons per bit!

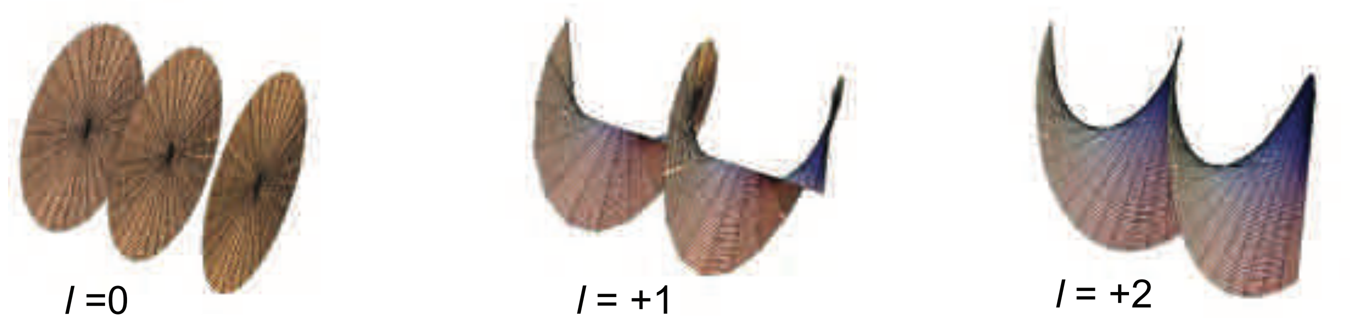
- Our procedure is to encode using beams that carry orbital angular momentum (OAM), such as the Laguerre-Gauss states, which reside in an infinite dimensional Hilbert space.



What Are the Orbital Angular Momentum (OAM) States of Light?

- Light can carry spin angular momentum (SAM) by means of its circular polarization.
- Light can also carry orbital angular momentum (OAM) by means of the phase winding of the optical wavefront.
- A well-known example are the Laguerre-Gauss modes. These modes contain a phase factor of $\exp(il\varphi)$ and carry angular momentum of $\hbar k$ per photon. (Here φ is the azimuthal coordinate.)

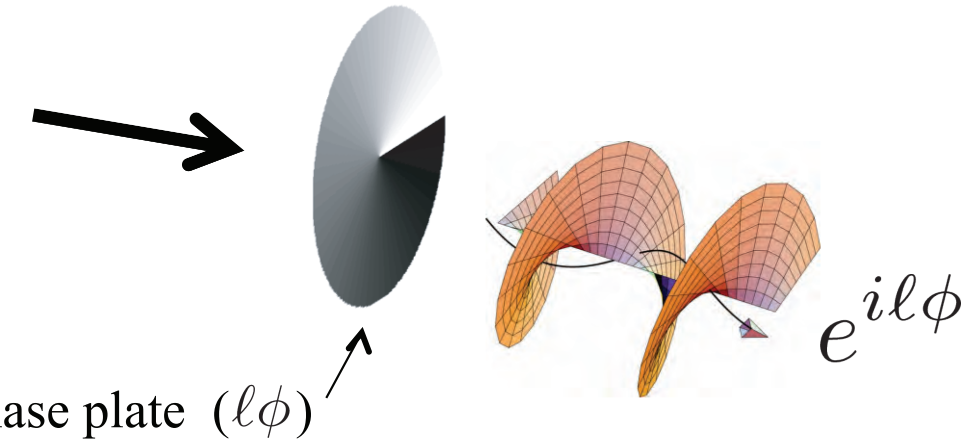
Phase-front structure of some OAM states



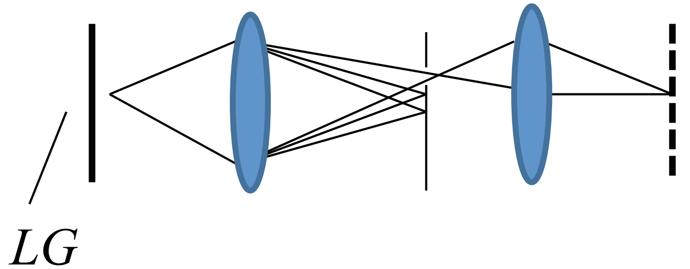
See, for instance, A.M. Yao and M.J. Padgett, Advances in Photonics 3, 161 (2011).

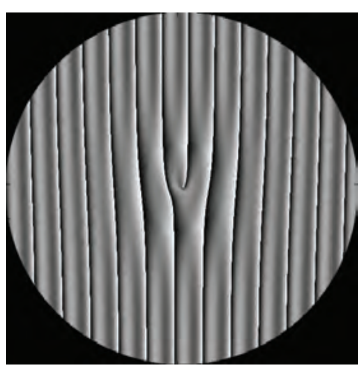
How to create a beam carrying orbital angular momentum?

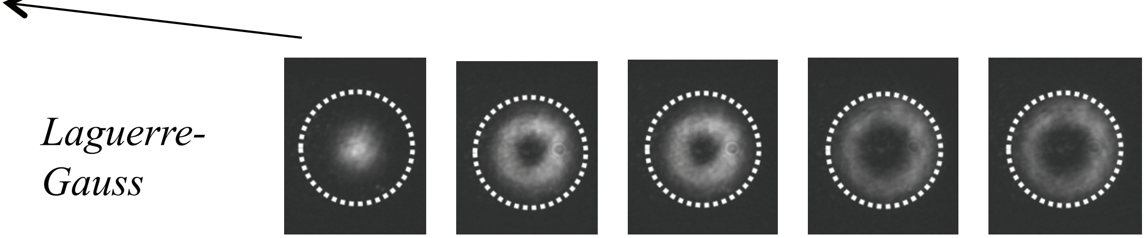
Pass beam through a spiral phase plate



Use a spatial light modulator acting as a computer generated hologram (more versatile)







Exact solution to simultaneous intensity and phase masking with a single phase-only hologram, E. Bolduc, N. Bent, E. Santamato, E. Karimi, and R. W. Boyd, Optics Letters 38, 3546 (2013).

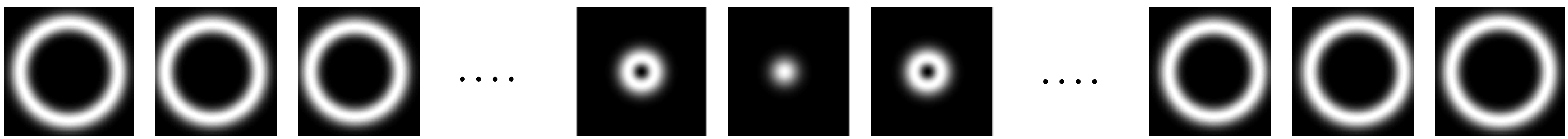
High Capacity QKD Protocol

We are developing a free-space quantum key distribution system that can carry many bits per photon (think about it!).

We encode either in the Laguerre-Gauss modes or in their linear superpositions (or in other transverse modes).

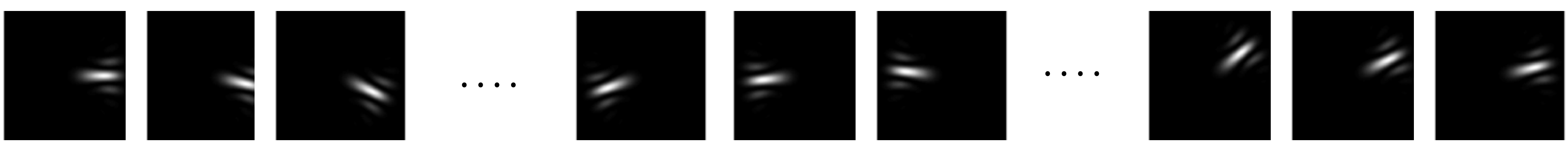
We are developing means to mitigate the influence of atmospheric turbulence

Laguerre-Gaussian Basis $\ell = -13, \ldots, 13$



0 1 2 12 13 14 25 26 27

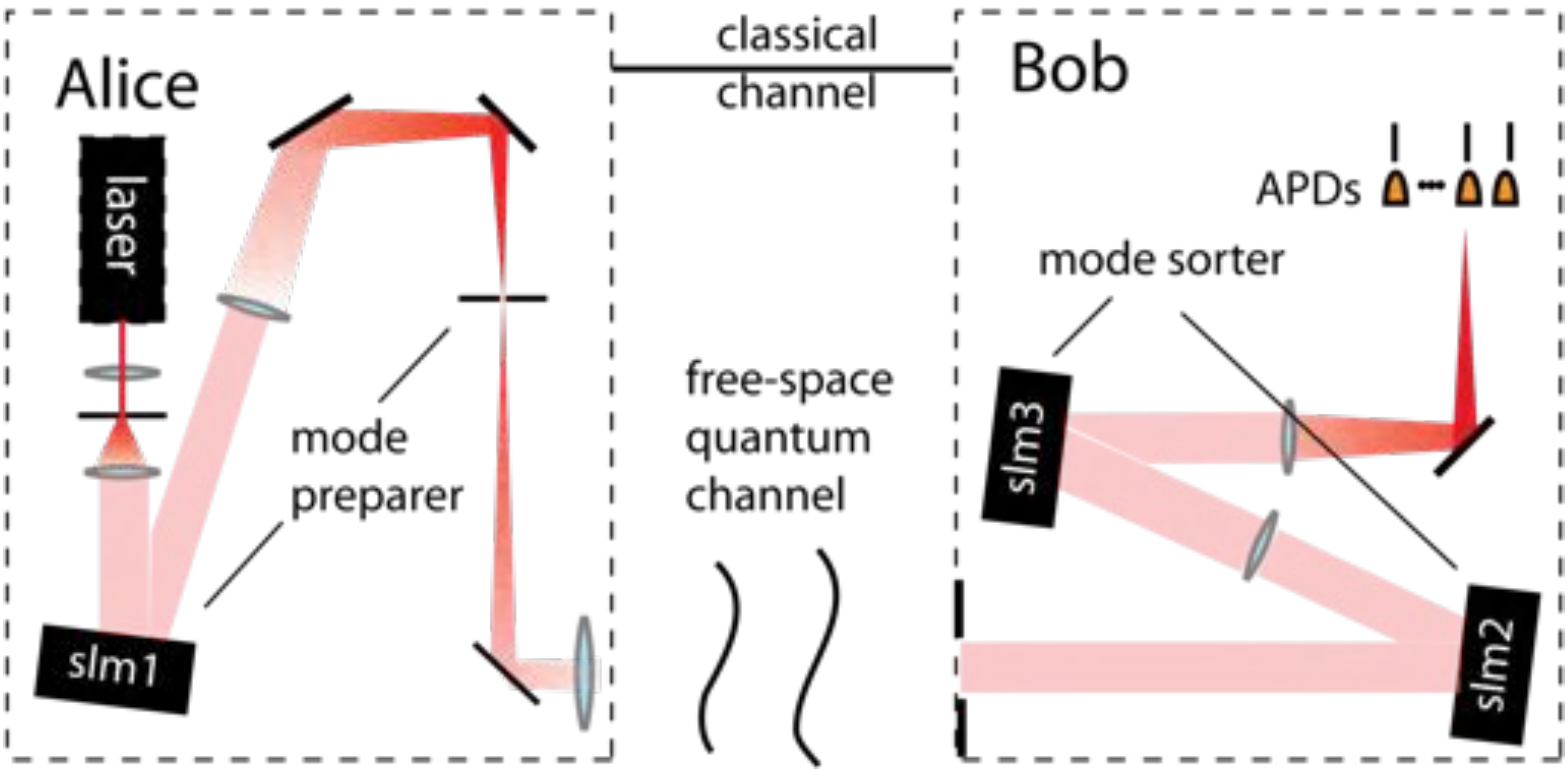
"Angular" Basis (mutually unbiased with respect to LG)



0 1 2 12 13 14 25 26 27

$$\Psi_{AB}^{N} = \frac{1}{\sqrt{27}} \sum_{l=-13}^{13} \mathrm{LG}_{l,0} \exp\left(i2\pi N l/27\right)$$

Spatially Based QKD System



<u>Source</u>

Weak Coherent Light

Heralded Single Photon

<u>Protocol</u>

Modified BB84 as discussed

<u>Challenges</u>

1. State Preparation
2. State Detection
3. Turbulence

Laboratory Results - OAM-Based QKD

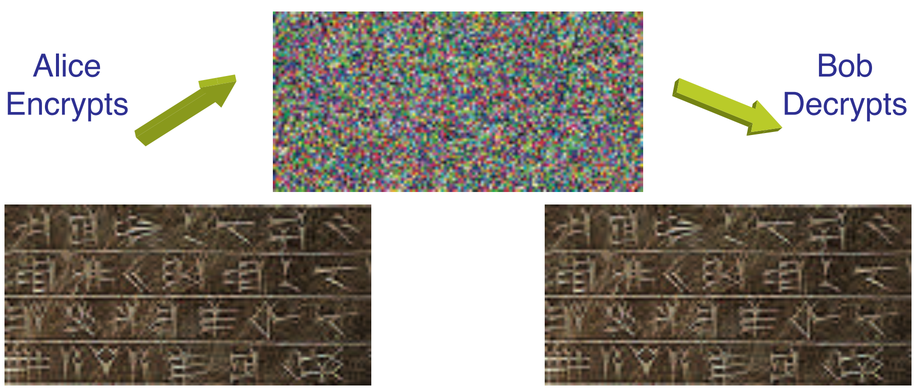
Alice	Bob
063133602132045444456141026645 545050363603025261643215524164 230146602513401613222451551026	063033601132021444456141026645 545022353603025261643215524164 230146602515403613422451551026

Error Correction

0000 0100 0111 0100 0101 0001 1100 0010 1100 1001 0010 0100 1101 0001 0000 0001 0011 0100 0000 0100 0010 0001 0001 0011 0000 0101 0010 0111 1000 0101 1101 0011 0001 1001 1011 0101 0000 0100 0111 0100 0011 0110 0101 0000 1101 0101 0010 1111 1010 1111 0010 1000

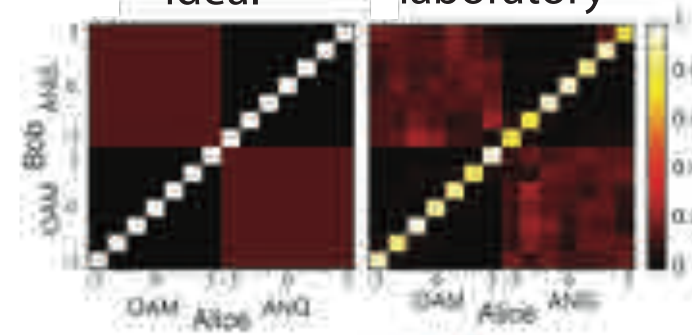
Privacy Amplification

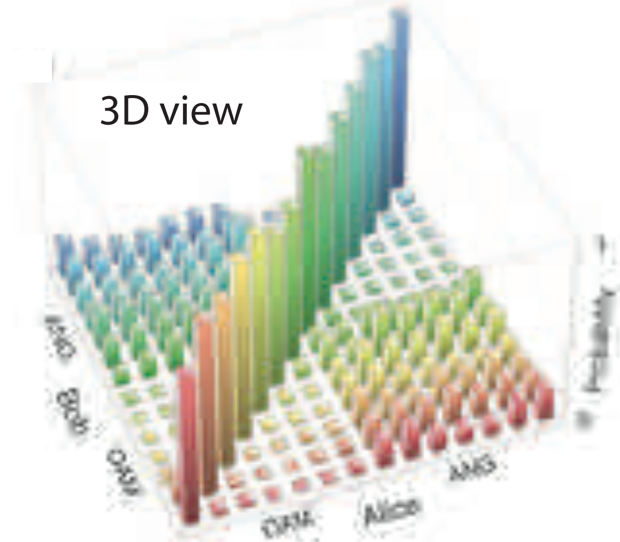
0001 0100 1011 1111 1111 1010 1010 0111 1010 1011 1111 0001 0000 1101 1111 1110 1110 1101 1110 0001 0011 1000 0101 1101 1100 0011 0111 1101 0001 1001 0100 0110 1011 0000 0110 1010 1



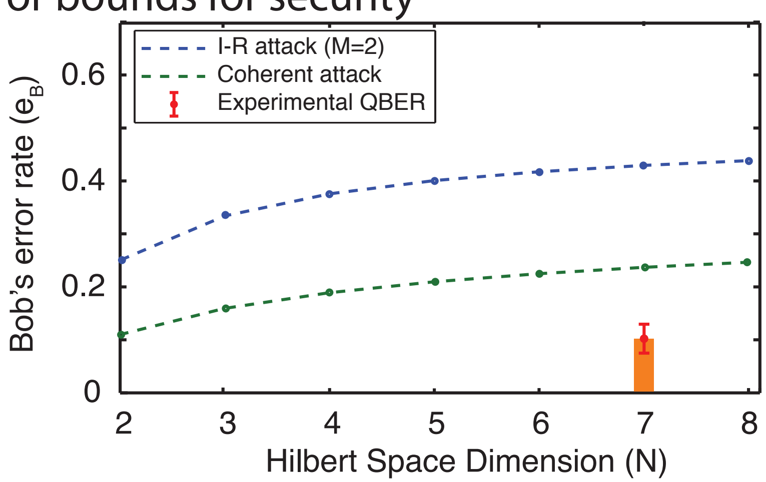
cross-talk matrices

ideal laboratory





- error bounds for security



We use a 7-letter alphabet, and achieve a channel capacity of 2.1 bits per sifted photon.

We do not reach the full 2.8 bits per photon for a variety of reasons, including dark counts in our detectors and cross-talk among channels resulting from imperfections in our sorter.

Nonetheless, our error rate is adequately low to provide full security,

Quantum Imaging

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6. Interaction Free Imaging

Interaction-Free Ghost Imaging

Frédéric Bouchard, Harjaspreet Mand, Ebrahim Karimi,
and Robert W. Boyd*

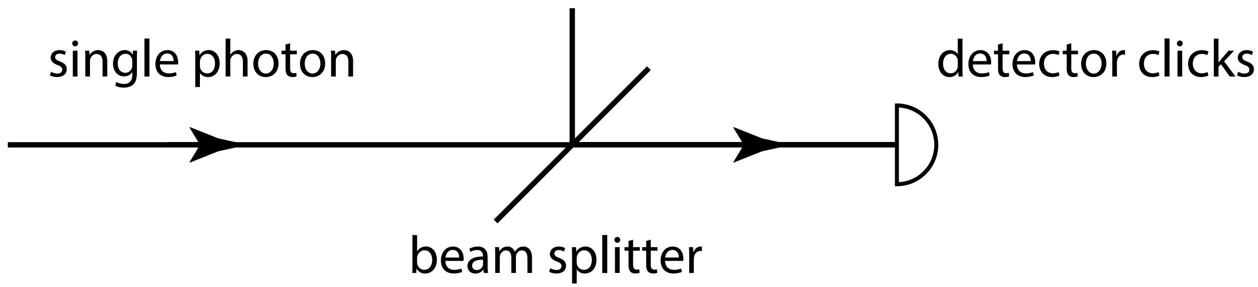
Department of Physics and
Max-Planck Centre for Extreme and Quantum Photonics
University of Ottwa

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

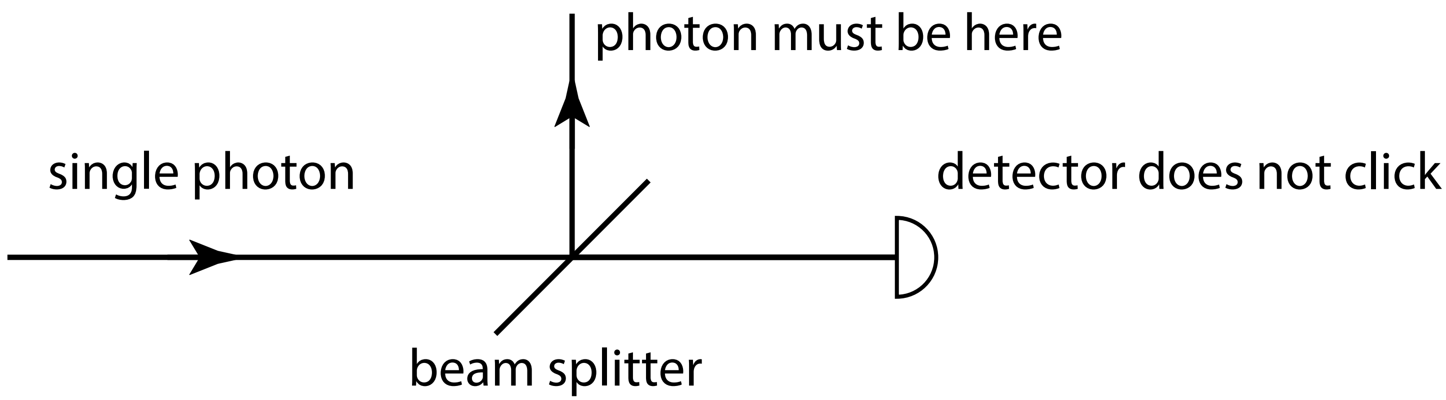
*Department of Physics and Astronomy
University of Glasgow

What Constitutes a Quantum Measurement?

- Situation 1

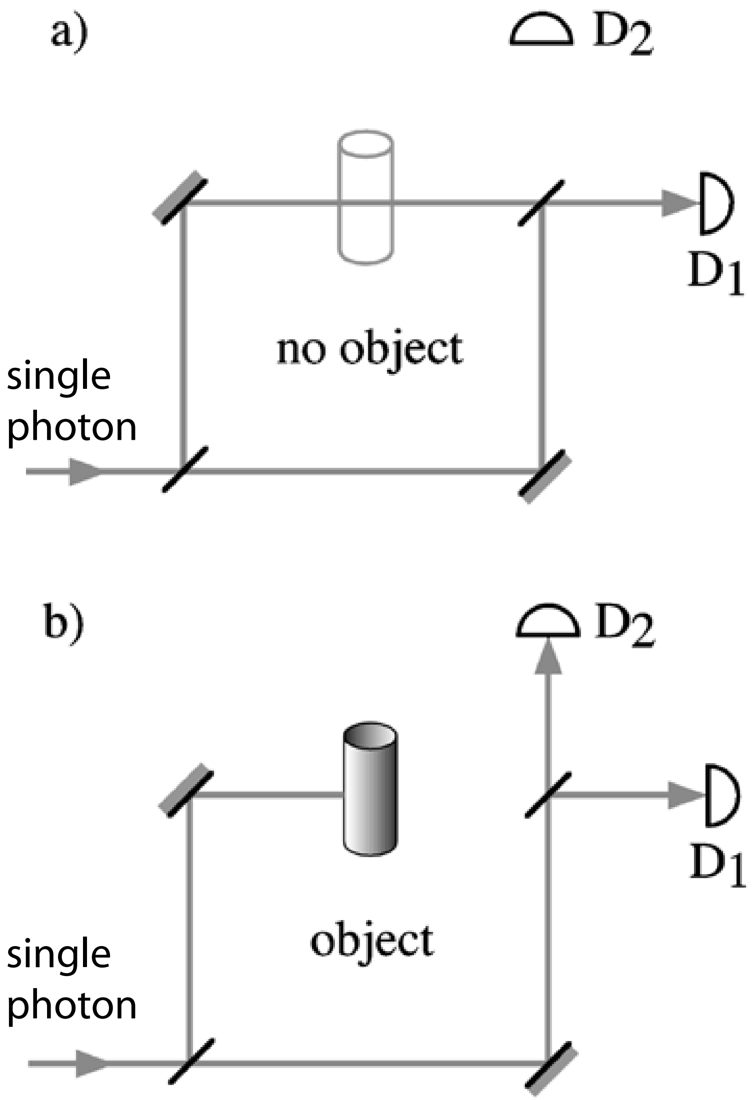


- Situation 2

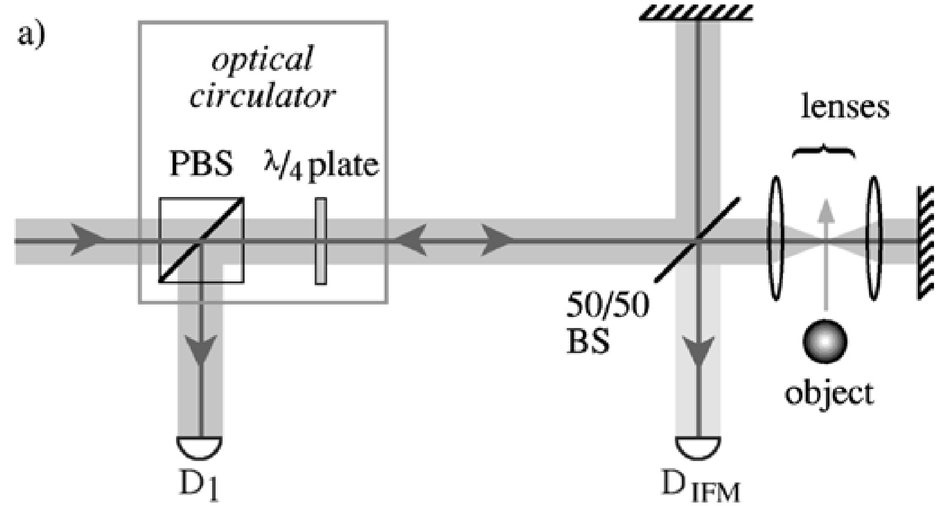


M. Renninger, Z. Phys. 15S, 417 (1960).
R. H. Dicke, Am. J. Phys. 49, 925 (1981).

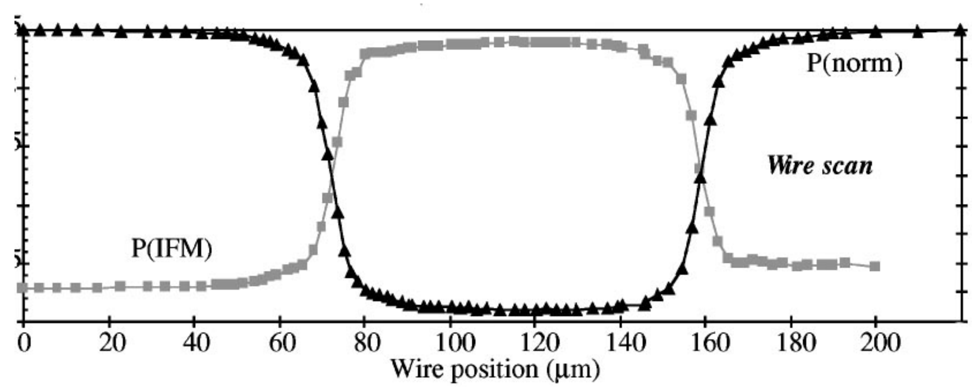
Quantum Imaging by Interaction-Free Measurement



imaging setup

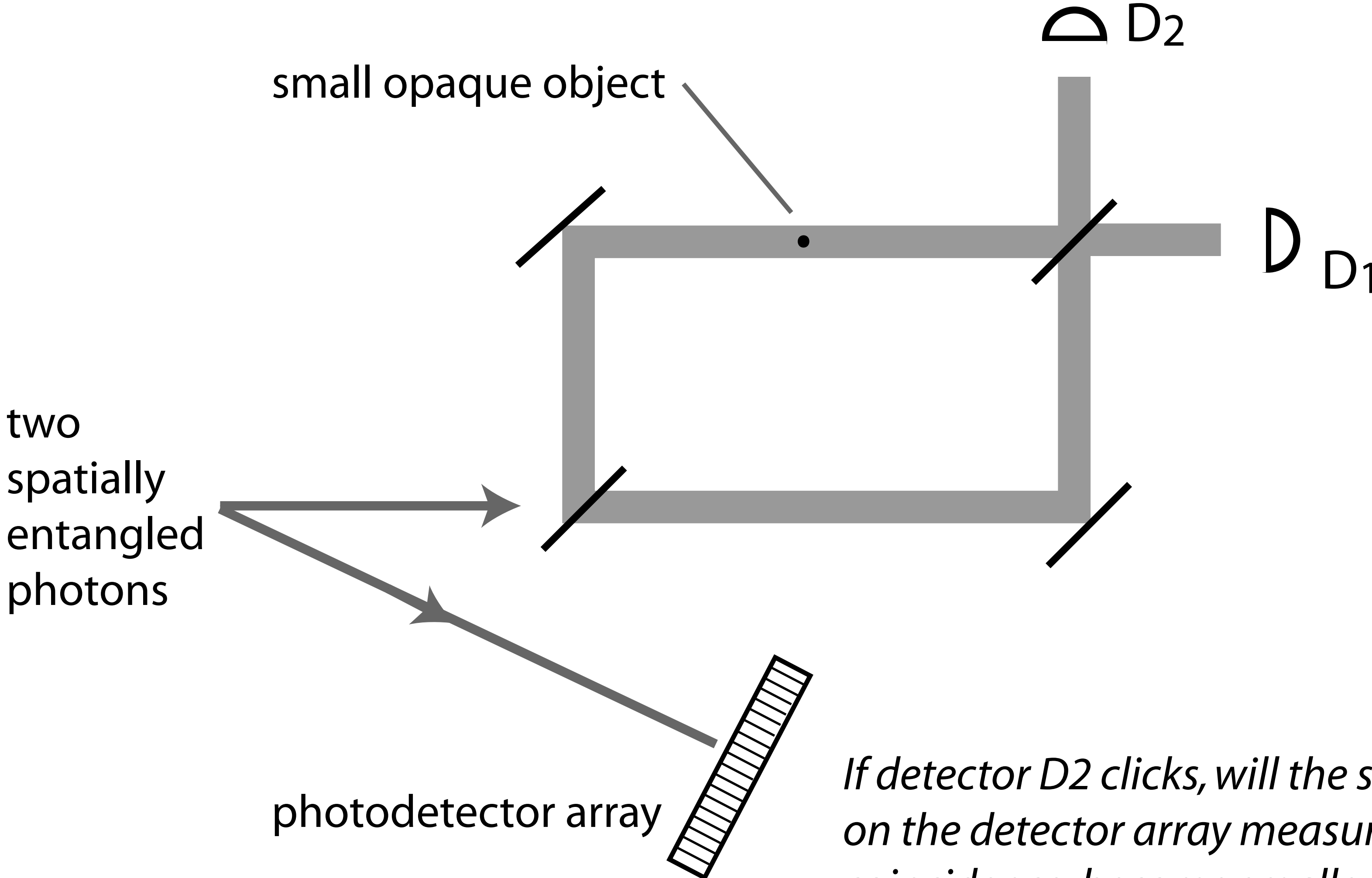


results



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).

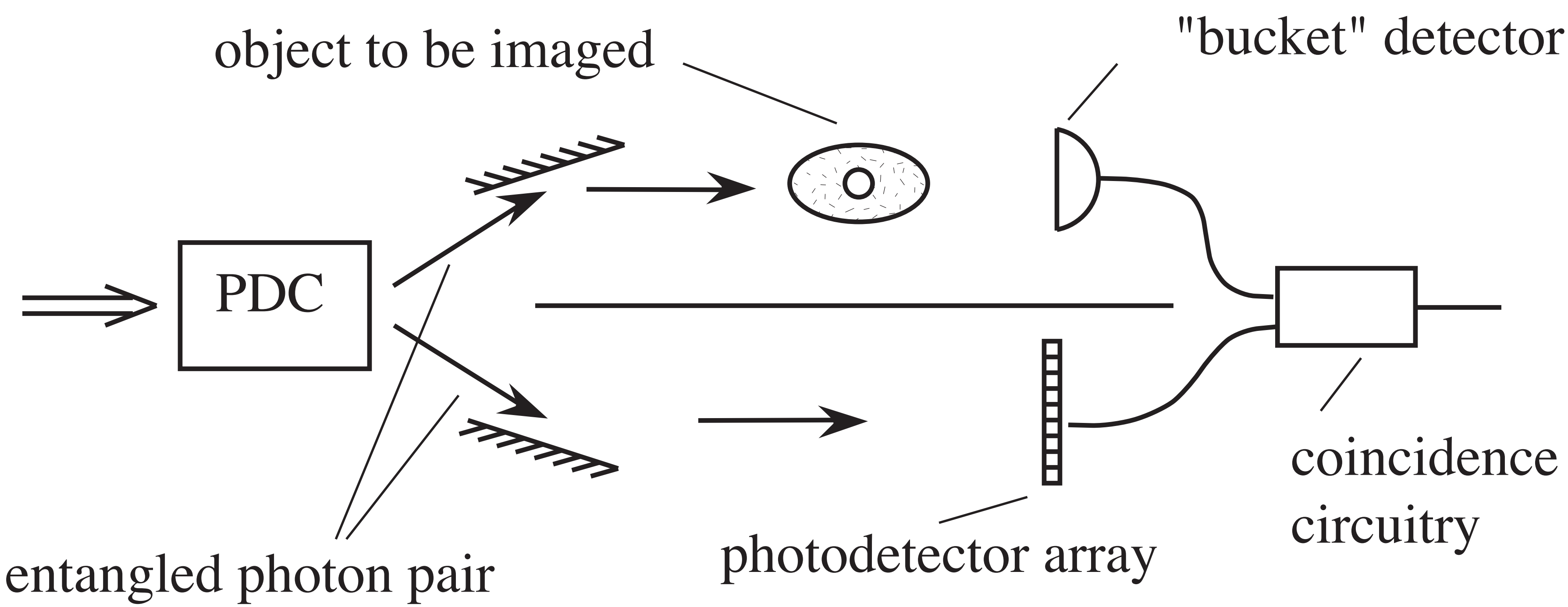
Interaction-Free Measurements and Entangled Photons



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

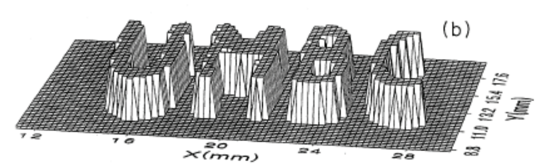
- Does an interaction-free measurement constitute a "real" measurement?
- Does it lead to the collapse of the wavefunction of its entangled partner?
- More precisely, does the entire two-photon wavefunction collapse?

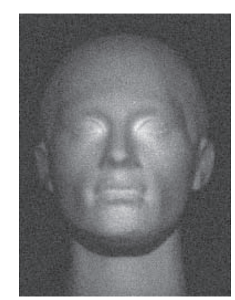
Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing!
  (imaging under adverse situations, bio, two-color, etc.)

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)

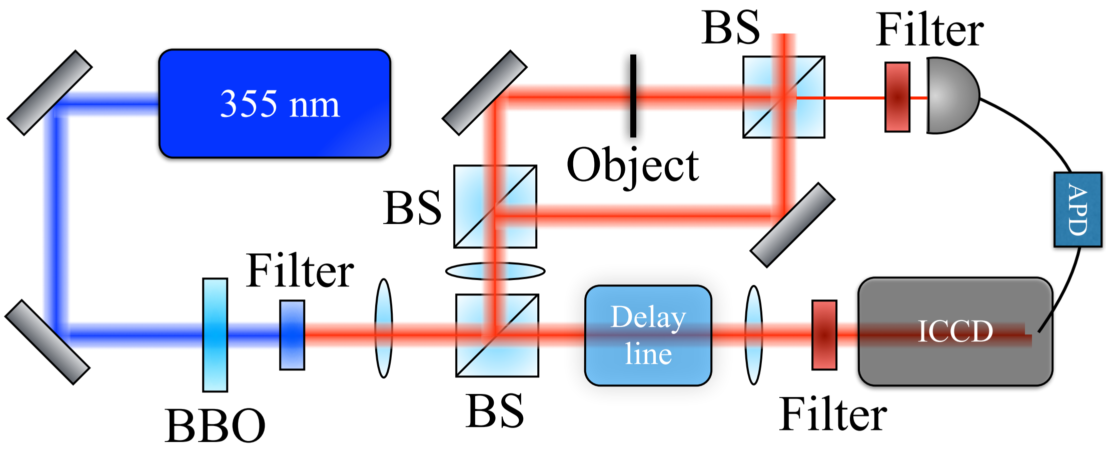




Padgett Group

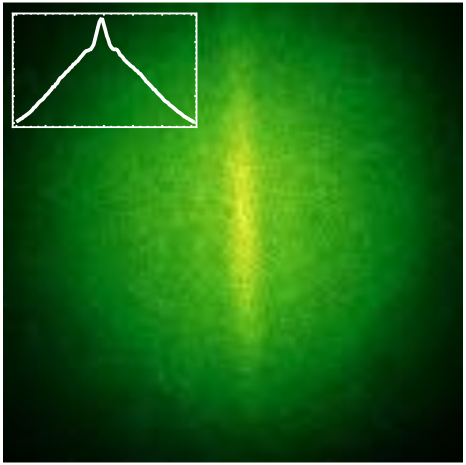
Interaction-Free Ghost Imaging

Experimental Setup



Experimental Results

Interaction-free ghost image of a straight wire



- Note that the interaction-free ghost image is about ten 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.

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).

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?

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.

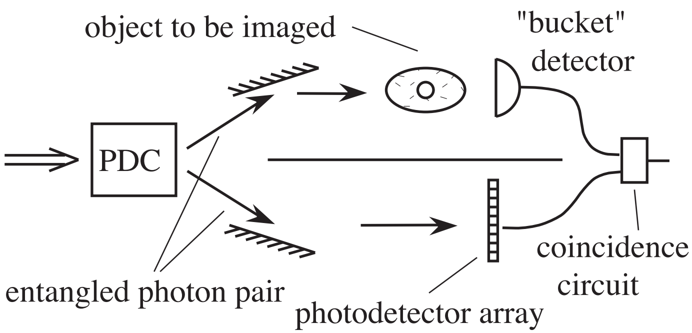
- As such, it is possible to combine *ghost imaging* with *interaction-free imaging* to produce *interaction-free ghost imaging*.

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

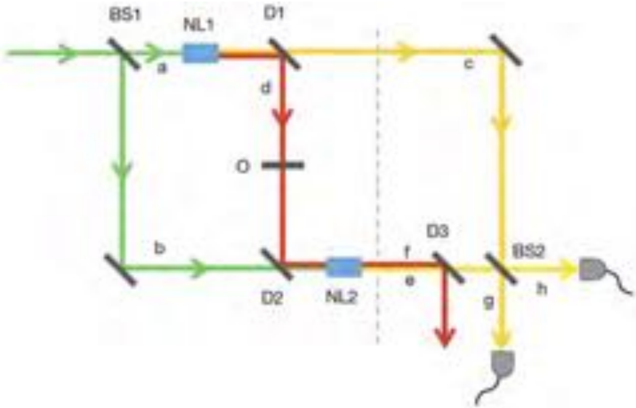
- Work is ongoing to achieve greater transverse spatial resolution.

Quantum Imaging Overview

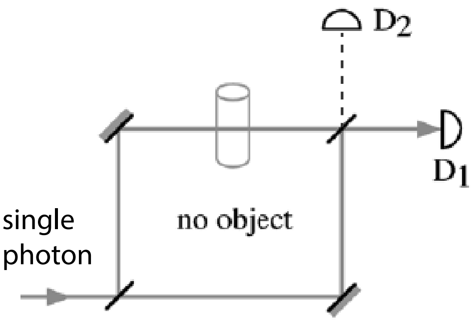
Ghost Imaging (Shih)



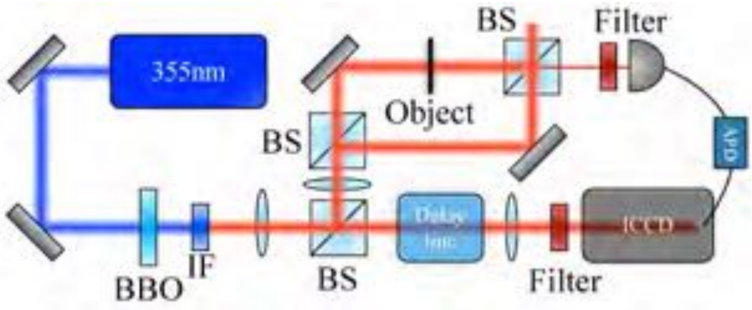
Imaging with Undetected Photons (Zeilinger)



Interaction-Free Imaging (White)



Interaction-Free Ghost Imaging (this talk)



Speaking of Imaging: Why We Shouldn't Trust Google