Quantum Imaging and Self-Action Effects in Nonlinear Optics

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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

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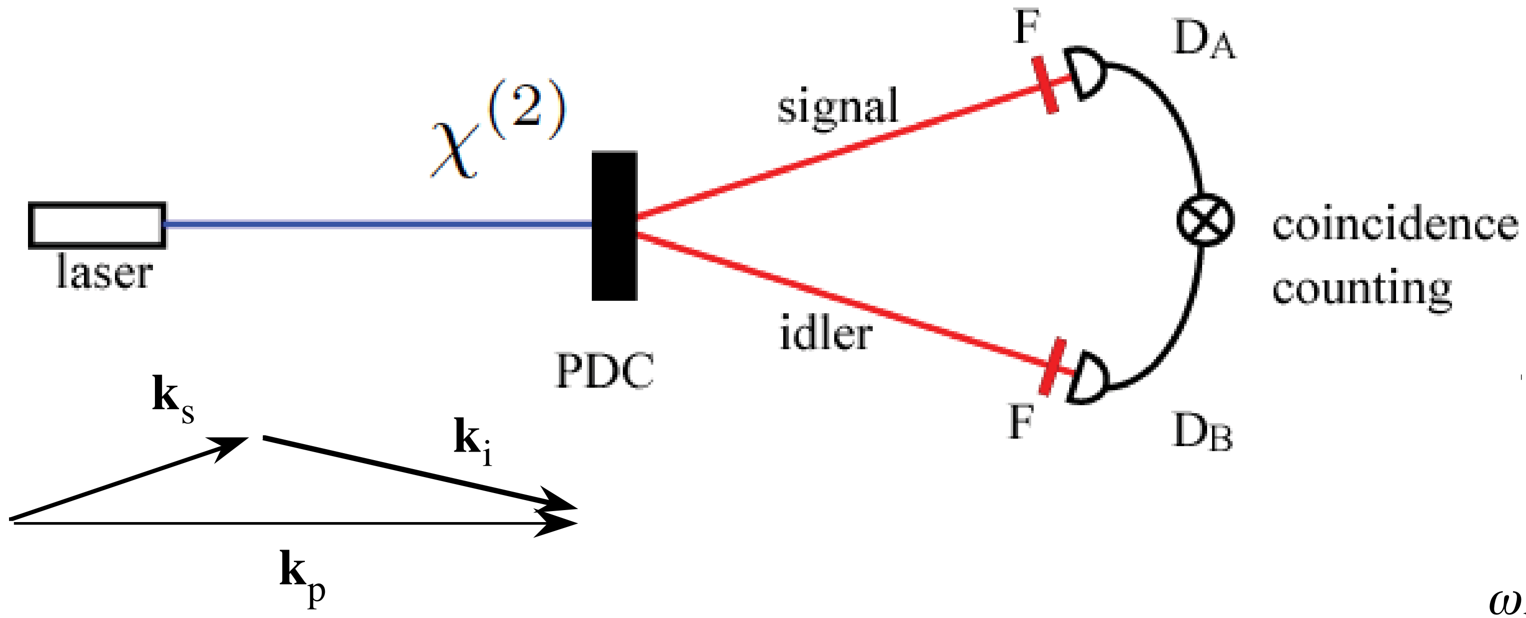
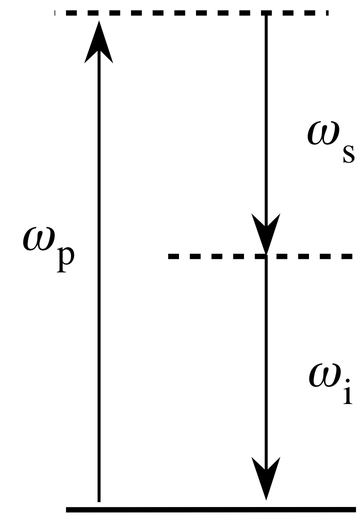
Brief History of Quantum Methods in Metrology

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

  - 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

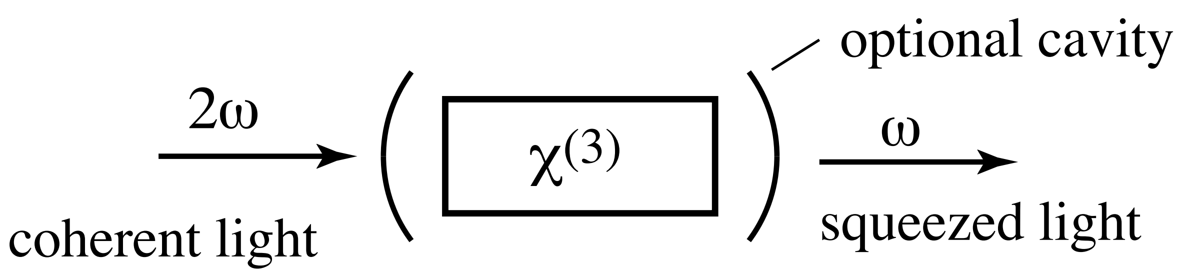
(d) angular position and orbital angular momentum

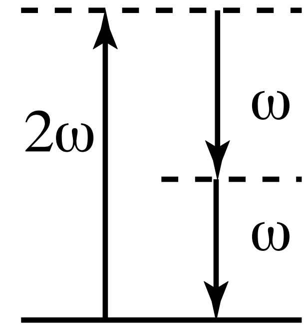
Entanglement is important for:

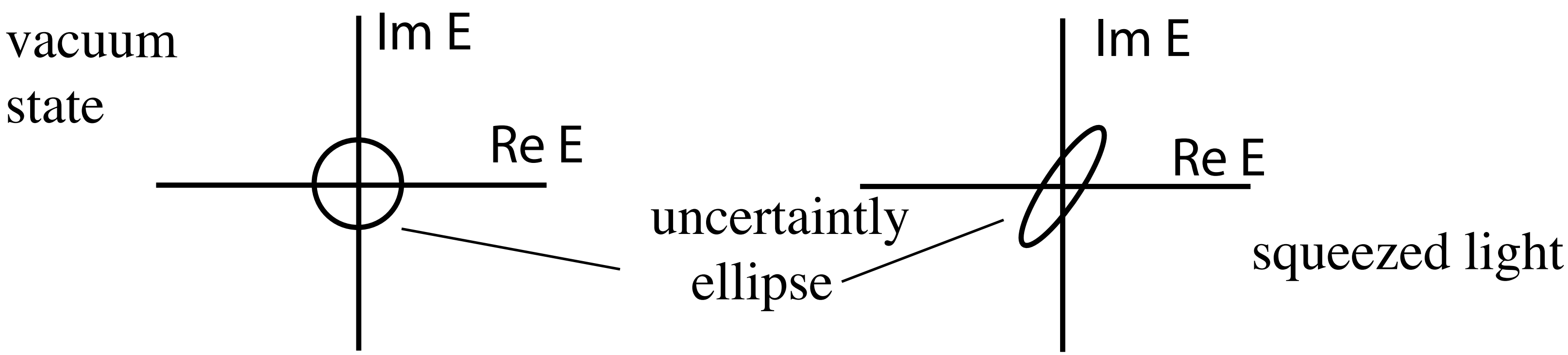
(a) Fundamental tests of QM (e.g., nonlocality)

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

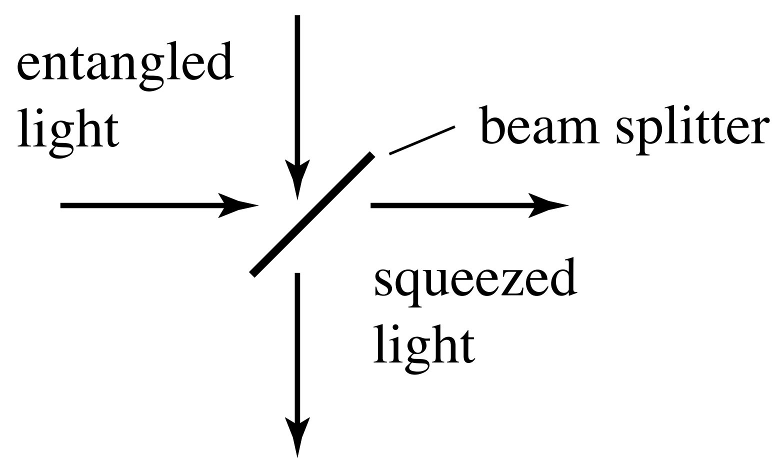
Squeezed Light Generation



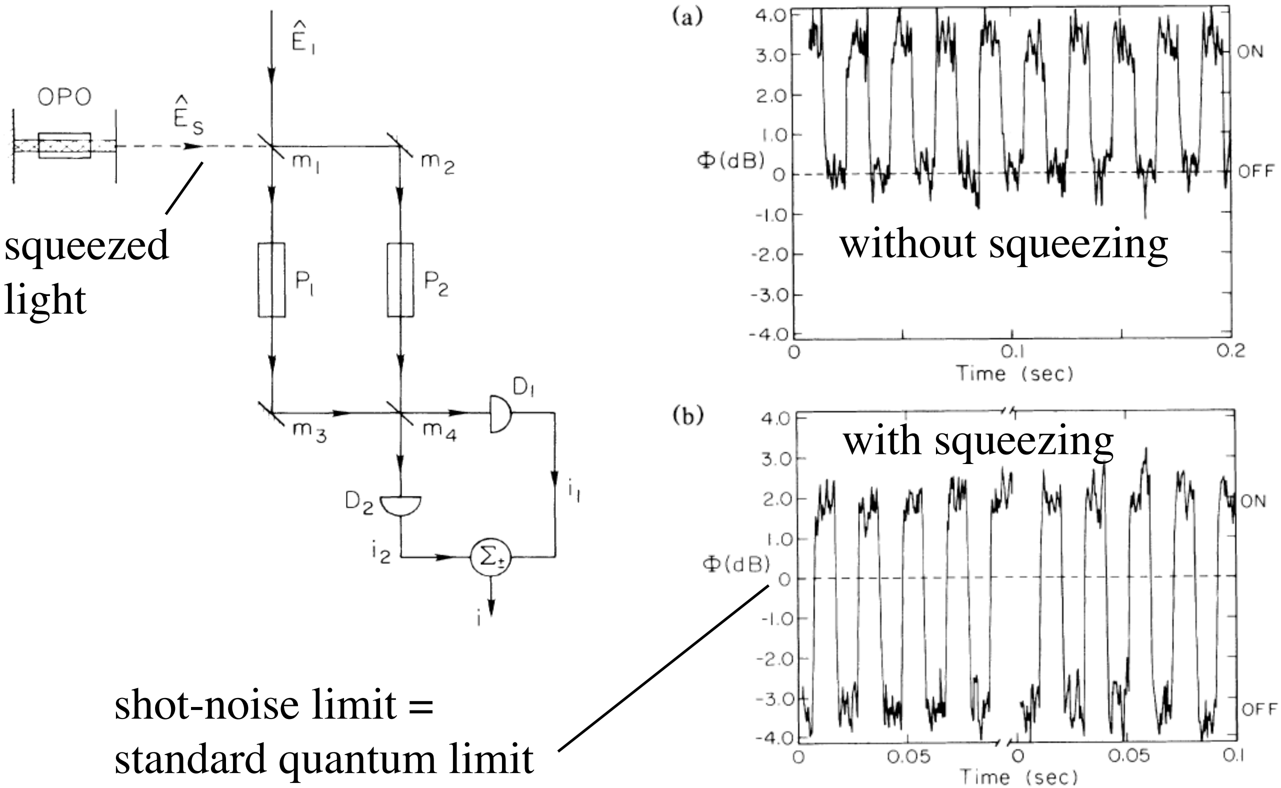




Entanglement and squeezing share a common origin:

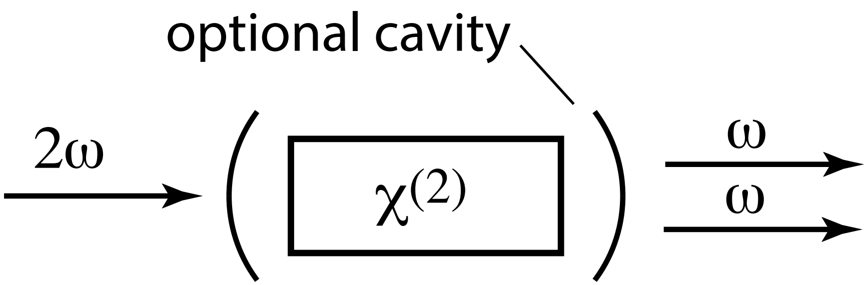


Precision Measurement beyond the Shot-Noise Limit



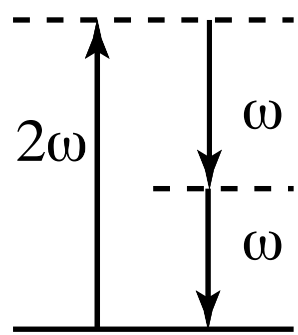
Xiao, M., L. A. Wu, and H. J. Kimble, Phys. Rev. Lett. 59, 278, 1987.

Generation of Twin Beams

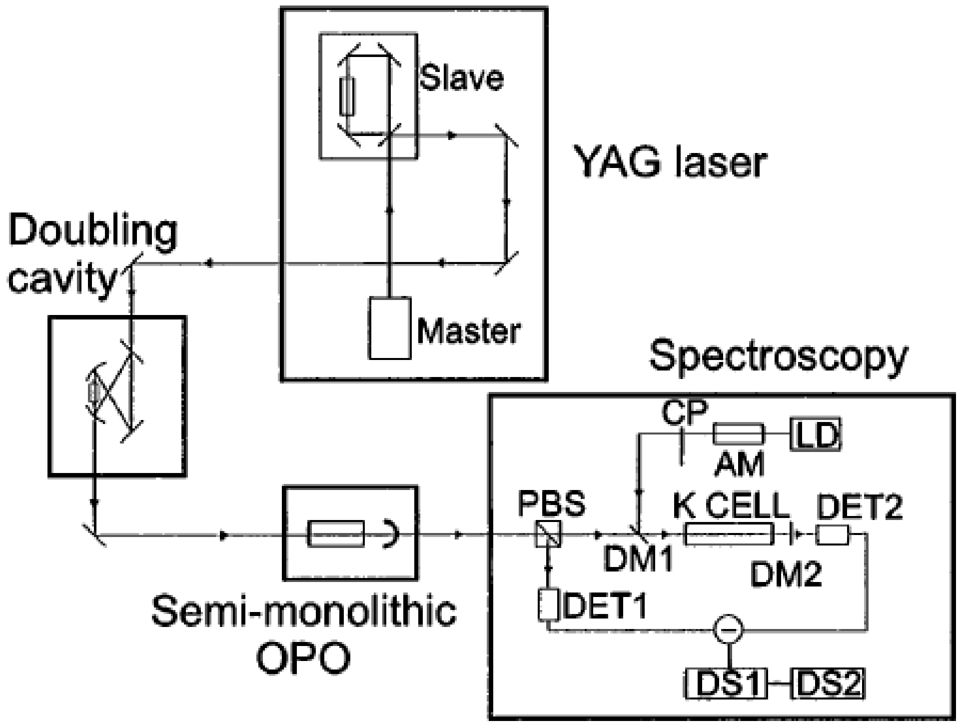


these beams possess identical fluctuations

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

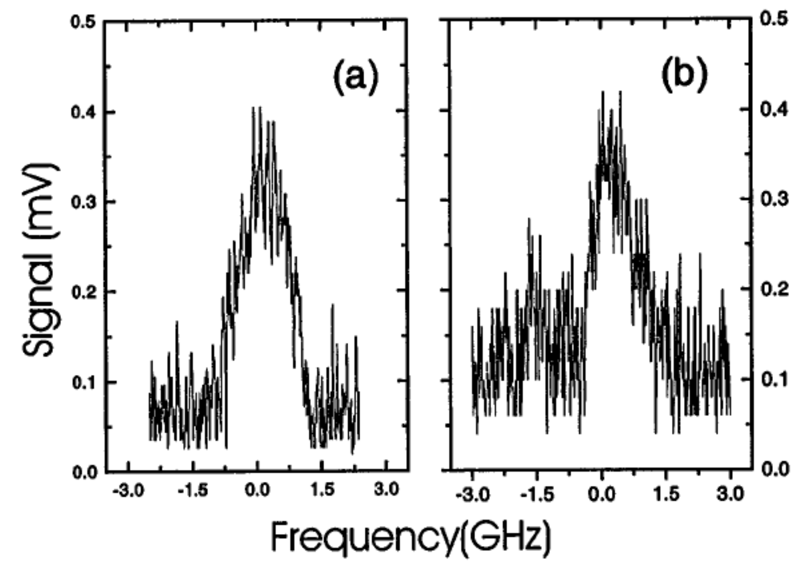


Noise-Reduced Measurement with Twin Beams



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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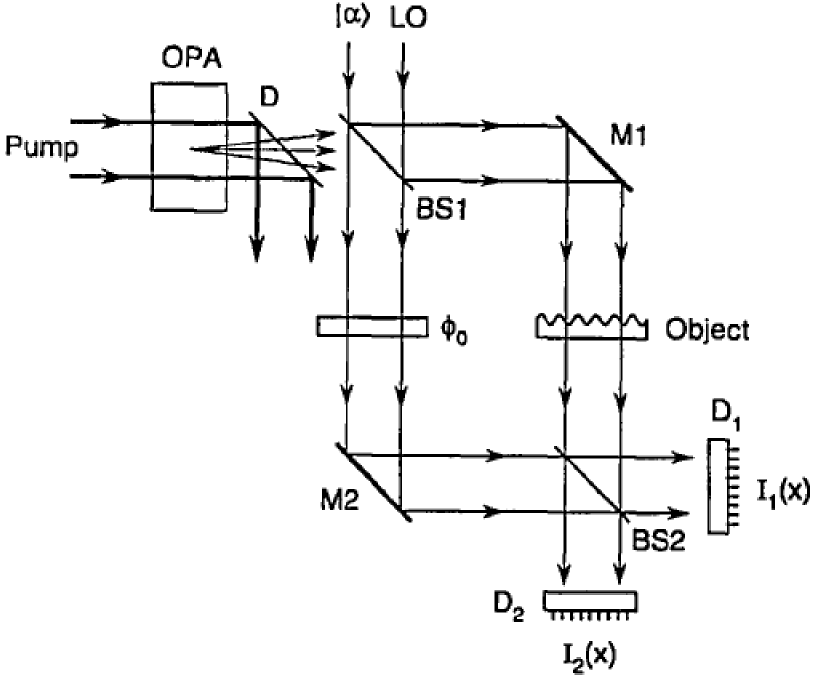
Brief History of Quantum Methods in Metrology

- 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

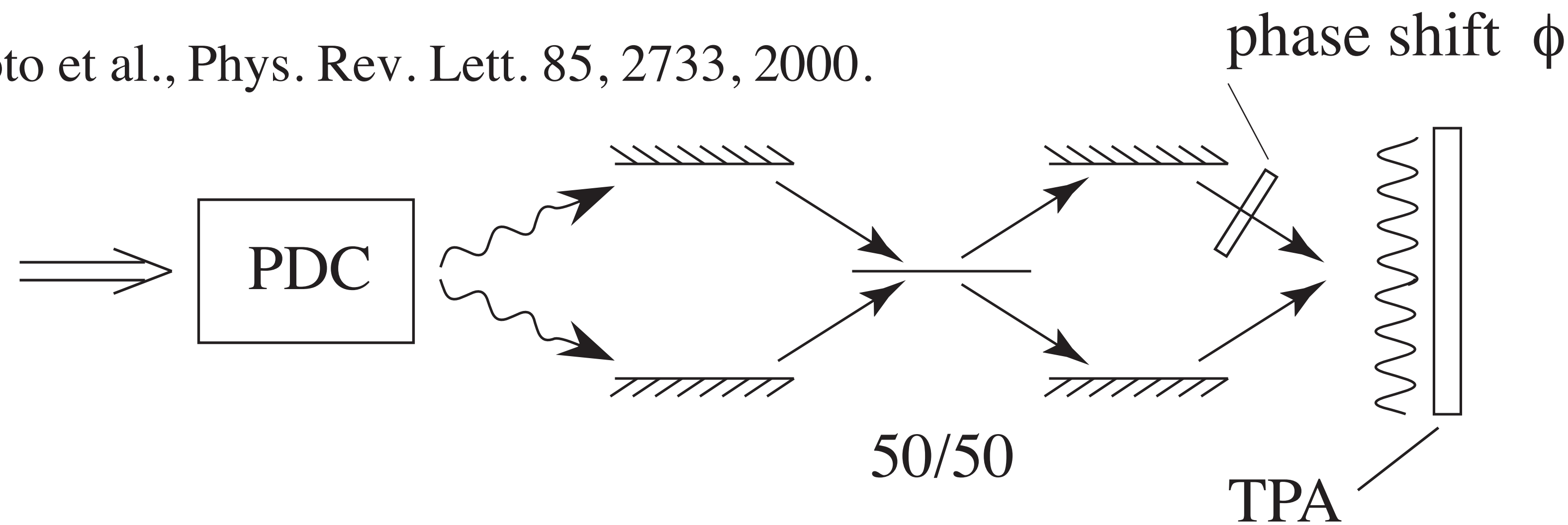


M. Kolobov and P. Kumar, Sub-shot-noise microscopy: imaging of faint phase objects with squeezed light, Optics Letters 18, 849 (1993).

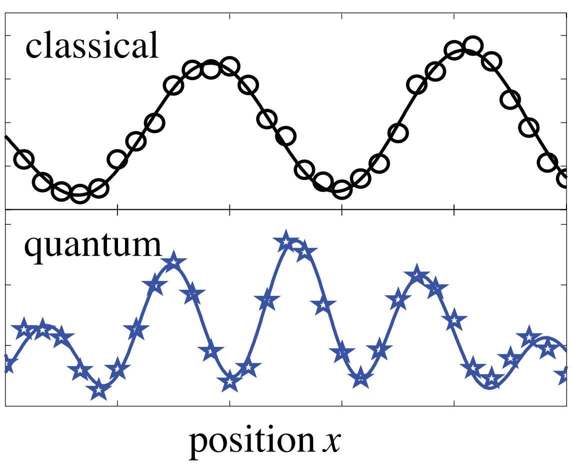
Quantum Lithography: Concept of Jonathan Dowling

- 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

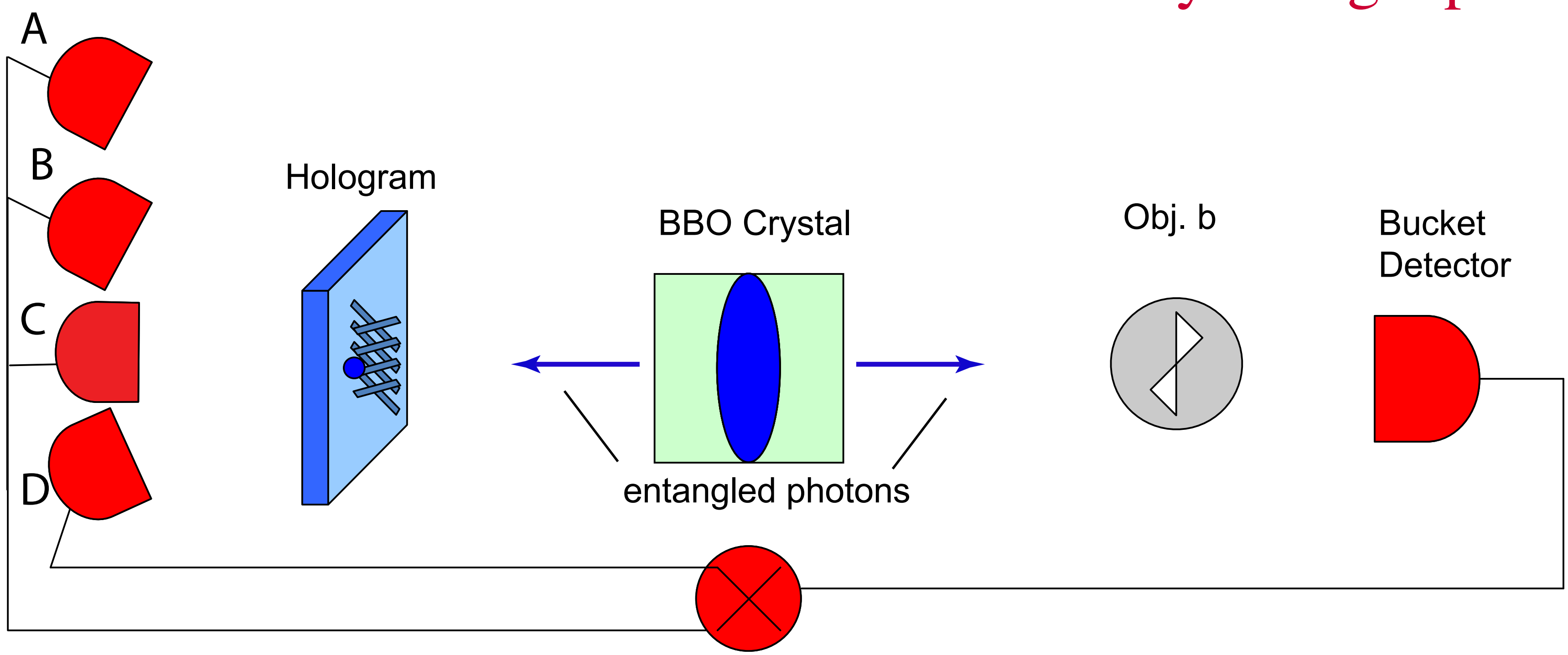


Quantum spatial superresolution by optical centroid measurements, Shin, Chan, Chang, and Boyd, Phys. Rev. Lett. 107, 083603 (2011).

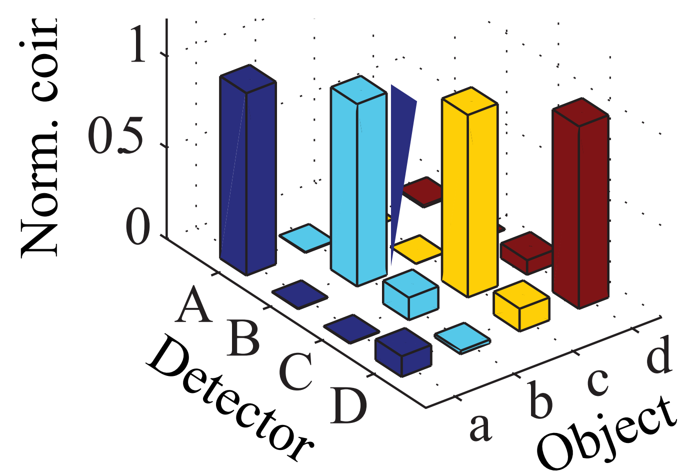
See also, Quantum Lithography: Status of the Field, R.W. Boyd and J.P. Dowling, Quantum Information Processing, 11:891–901 (2012).

Single-Photon Coincidence Imaging

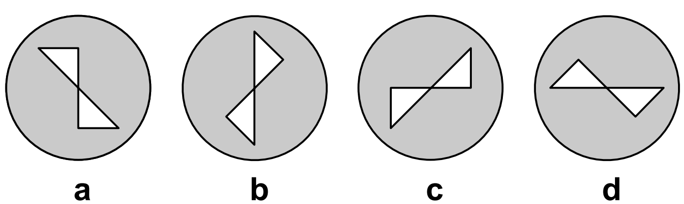
How much information can be carried by a single photon?



coincidence count rate



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).

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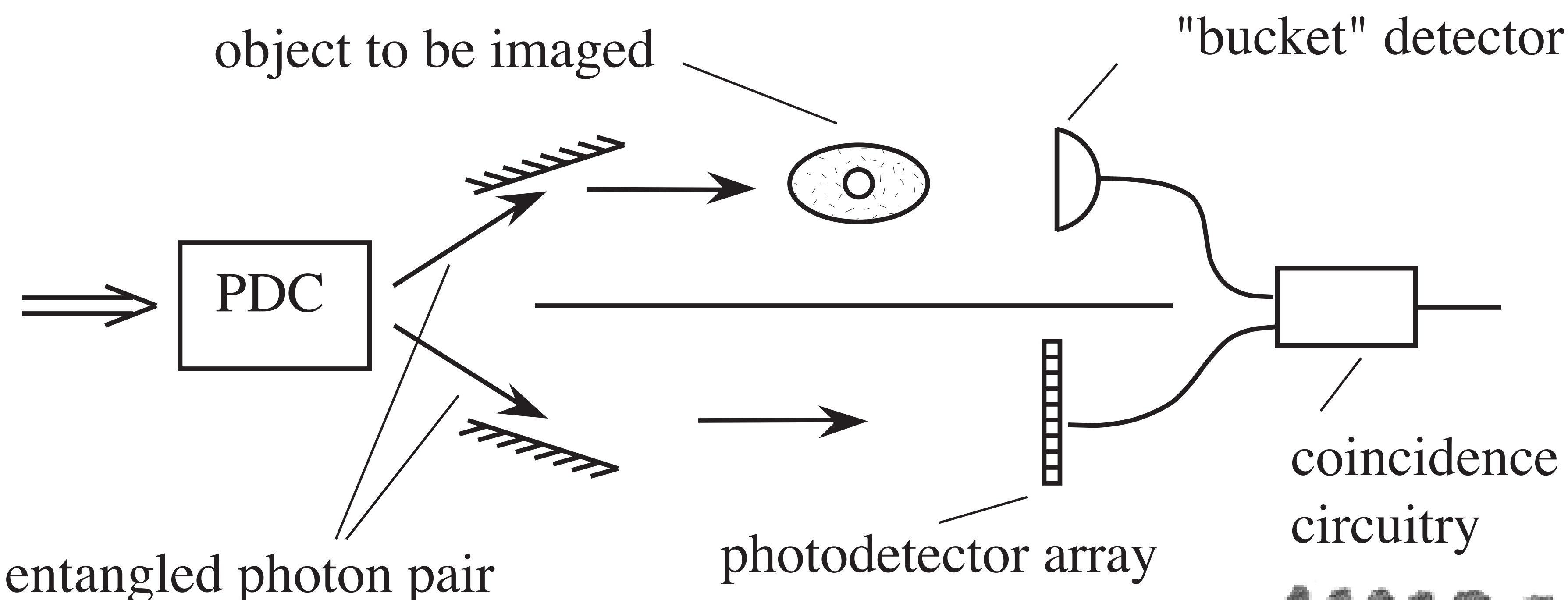
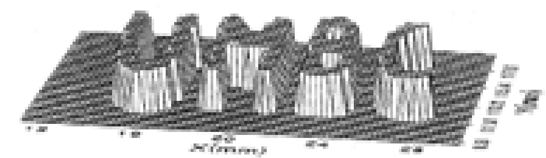
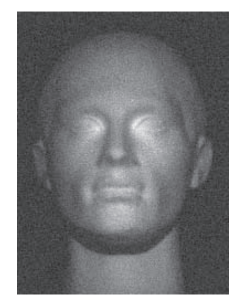
Ghost (Coincidence) Imaging





- 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

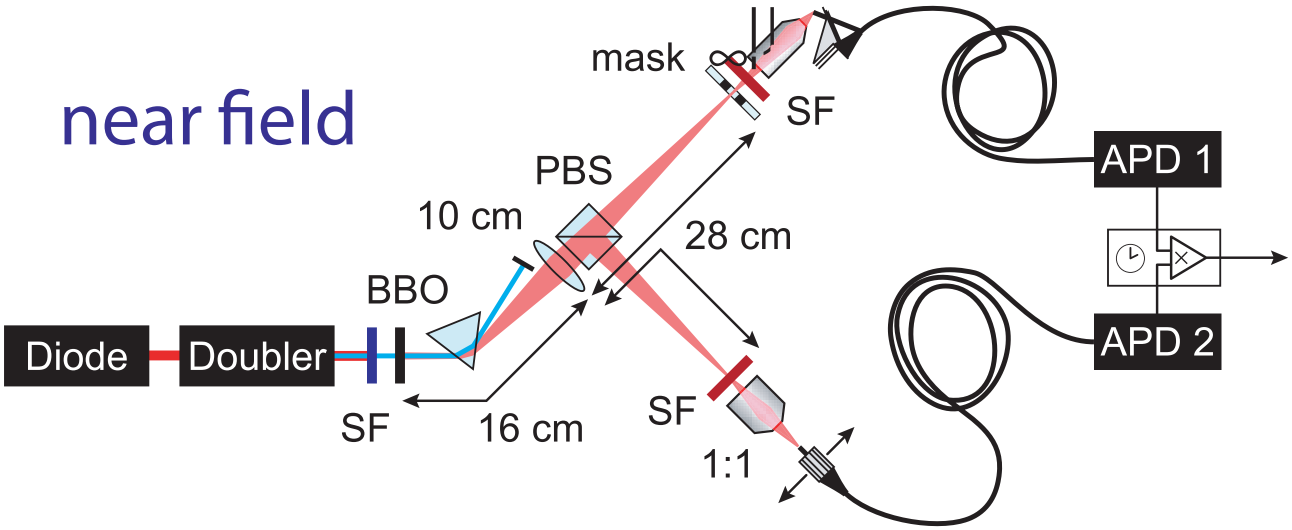
(Received 11 October 2002; published 3 April 2003)

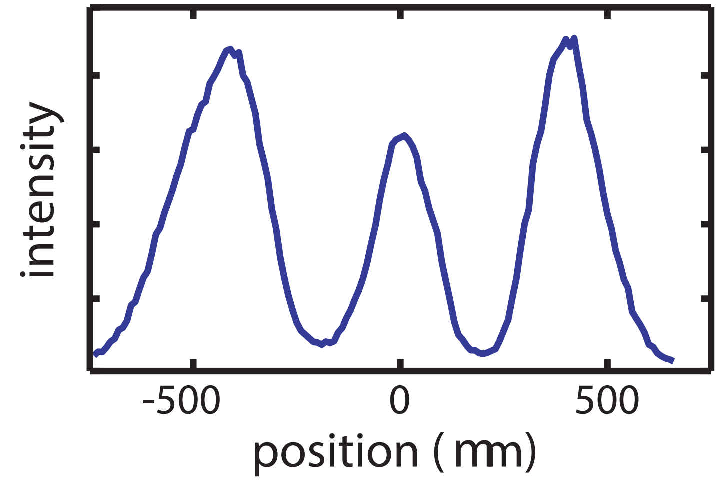
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. 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

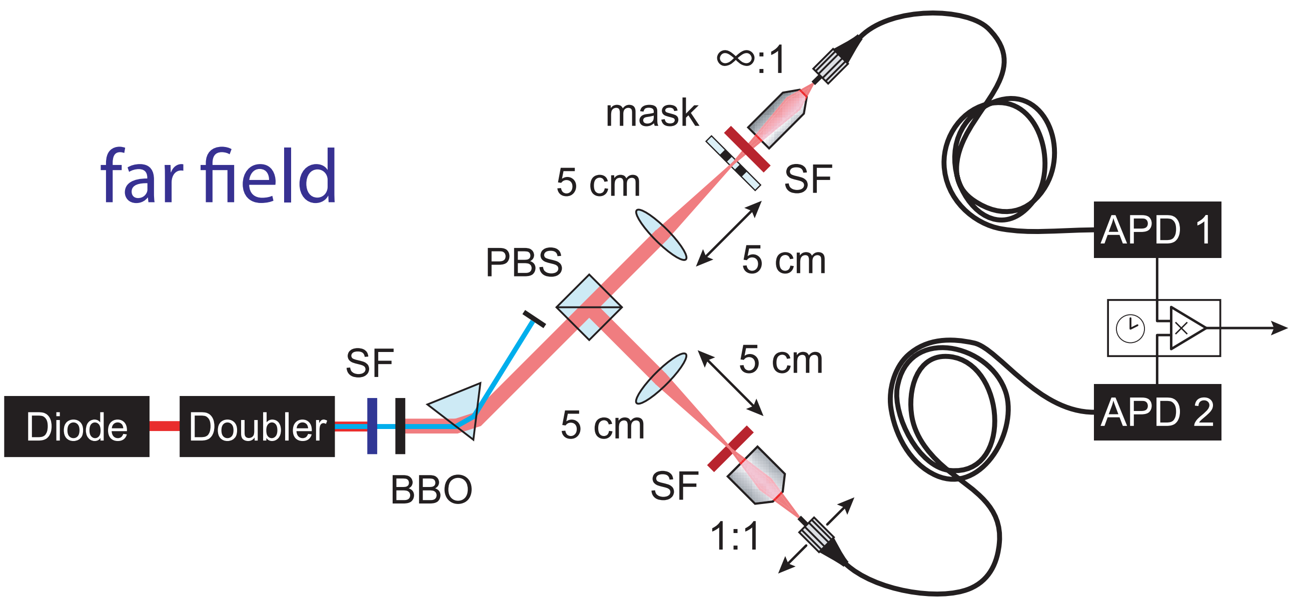
Near- and Far-Field Ghost Imaging Using Quantum Entanglement

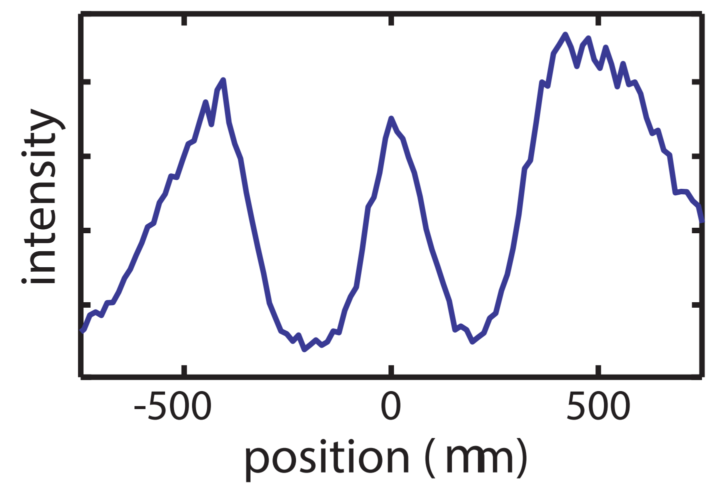
near field





far field

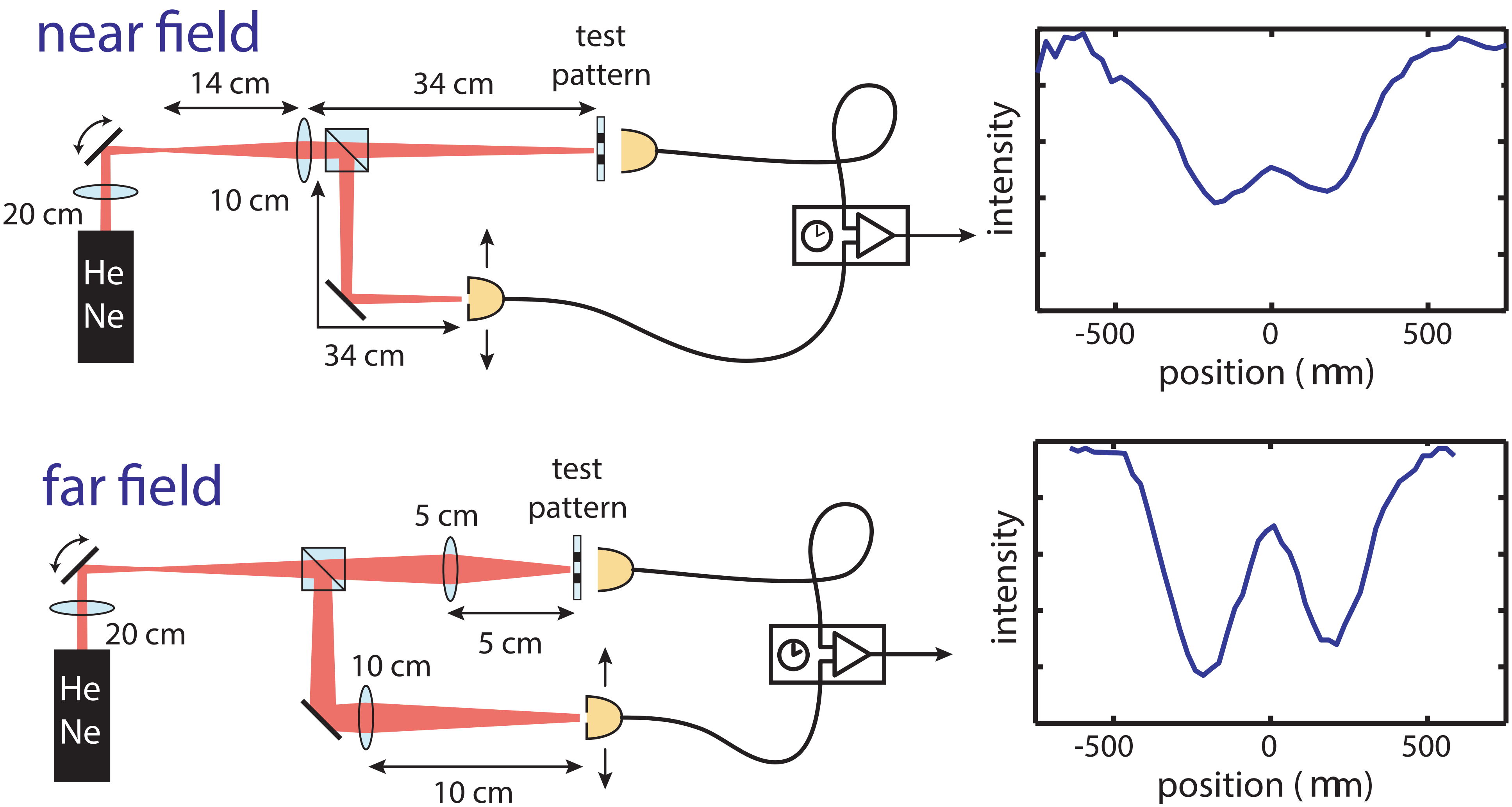




Good imaging observed in both the near and far field

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

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

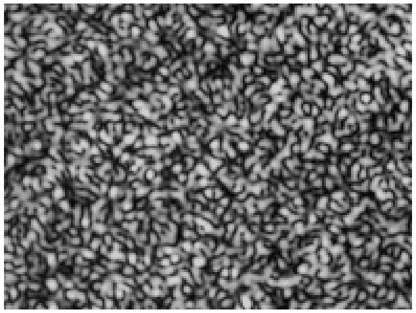


- Good imaging can be obtained only in near field or far field.
- Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of three.

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.

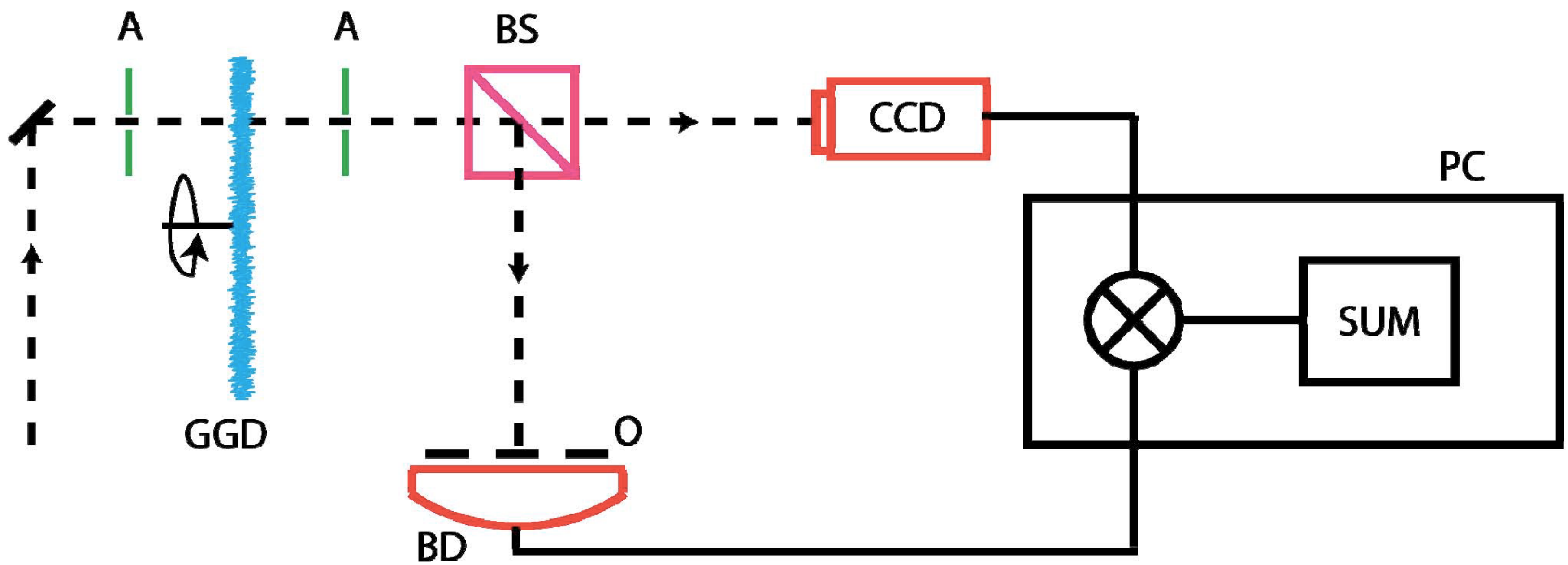
Recall that the intensity distribution of thermal light looks like a speckle pattern.



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).

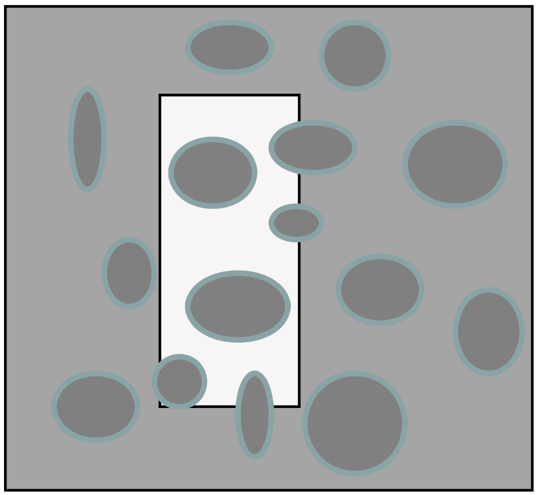
How does thermal ghost imaging work?

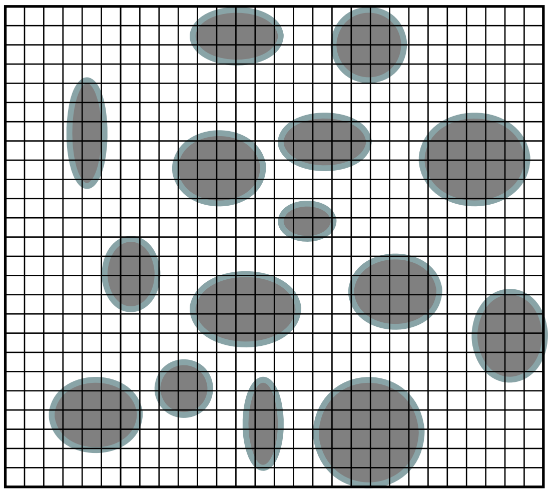


- Ground glass disk (GGD) and beam splitter (BS) create two identical speckle patterns
- Many speckles are blocked by the opaque part of object (O), but some are transmitted, and their intensities are summed by bucket detector (BD)
- CCD camera measures intensity distribution of speckle pattern
- Each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

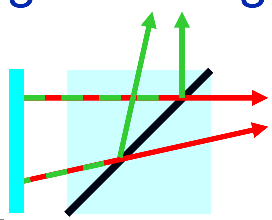
$g_1(x,y)$ = (total transmitted power) x (intensity at each point x,y)

Average over many speckle patterns

Two-Color Ghost Imaging

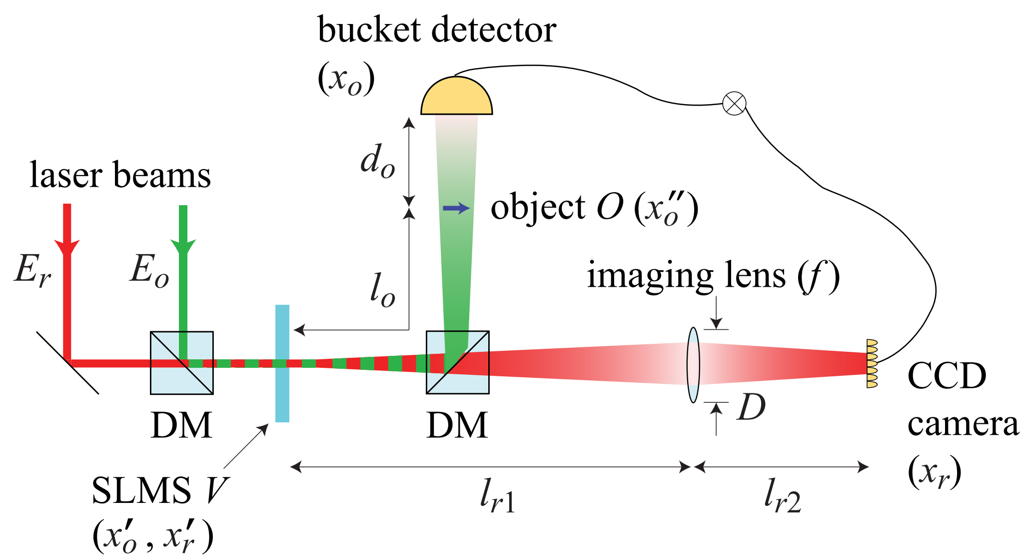
New possibilities afforded by using different colors in object and reference arms

Thermal ghost imaging

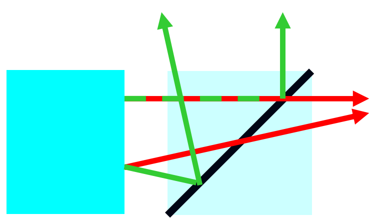


SLM

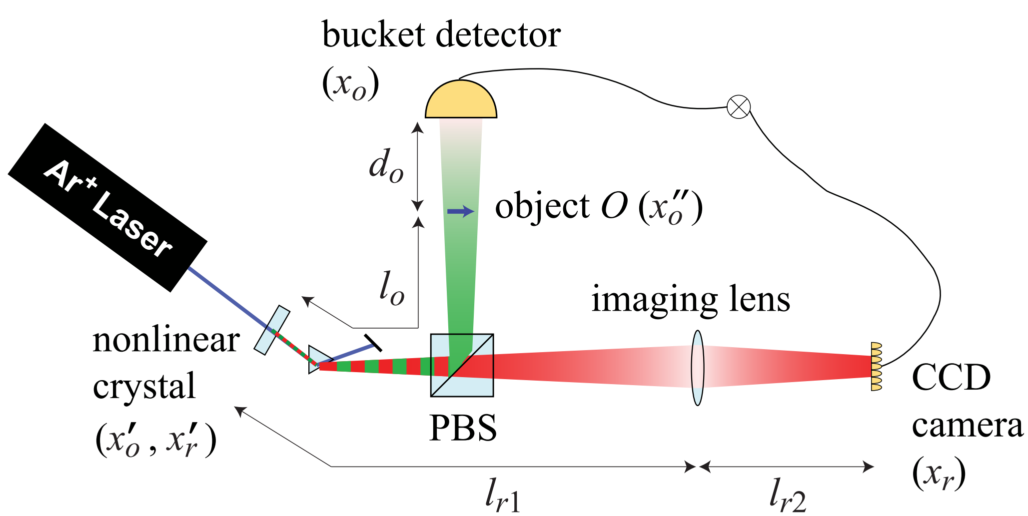
But no obvious way to make identical speckle patterns at two wavelengths



Quantum ghost imaging



SPDC



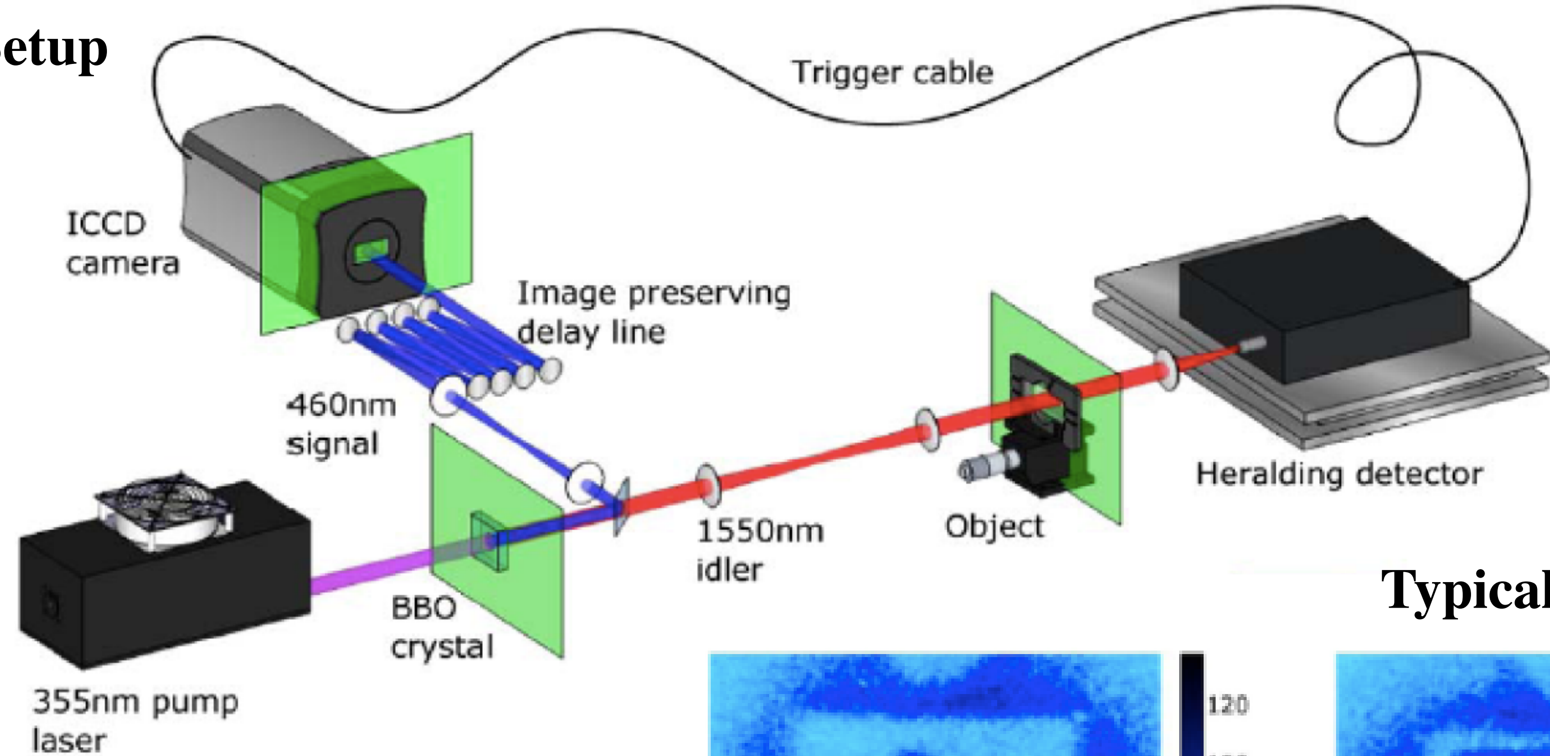
Spatial resolution depends on wavelength used to illuminate object.

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

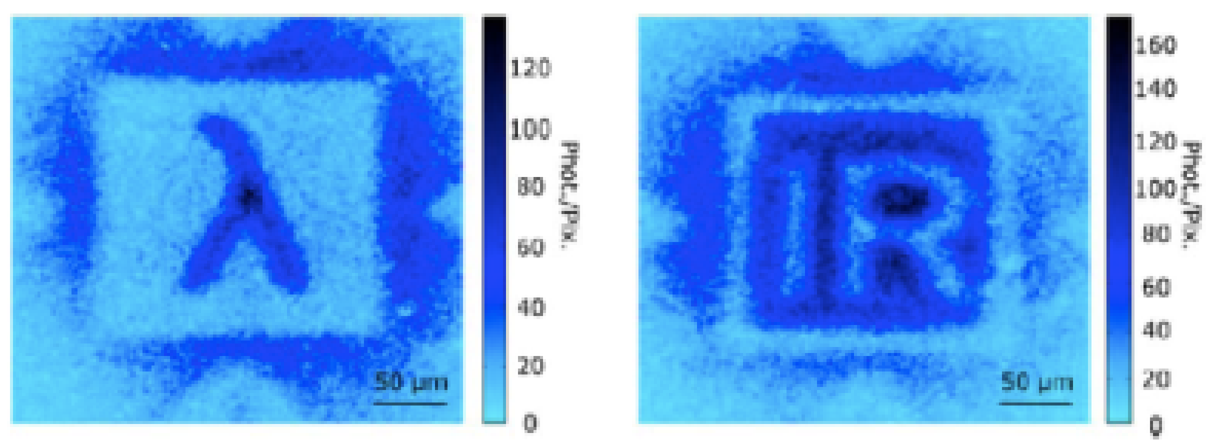
Wavelength-Shifted (Two-Color Ghost) Microscopy

- 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).

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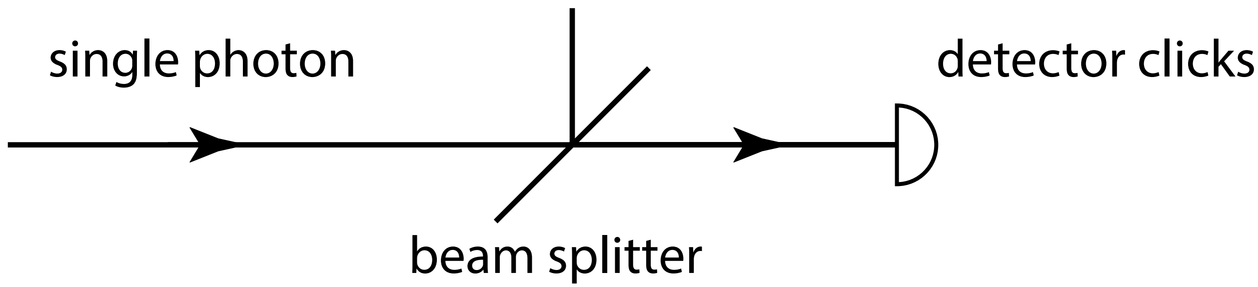
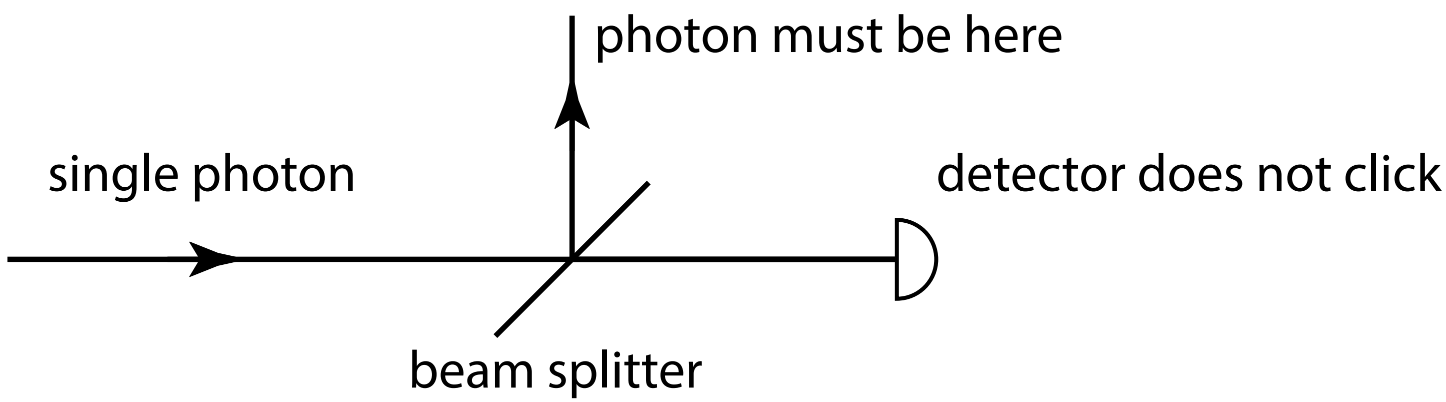
What Constitutes a Quantum Measurement?

• Situation 1

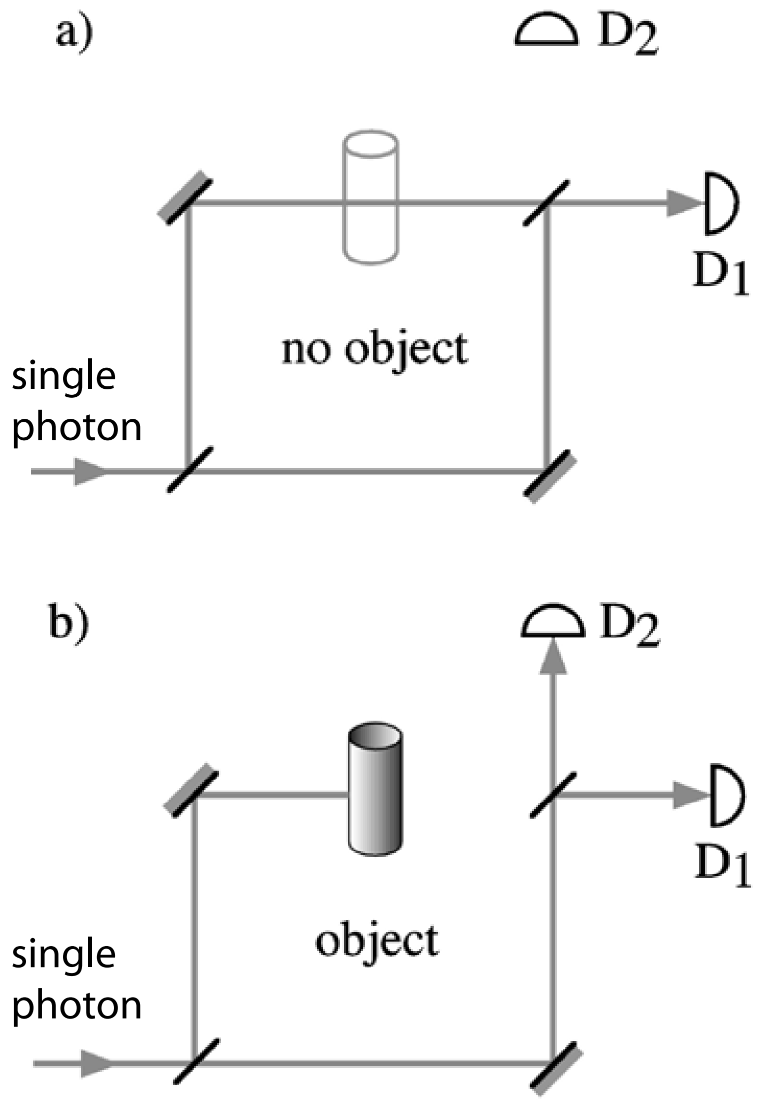


• Situation 2

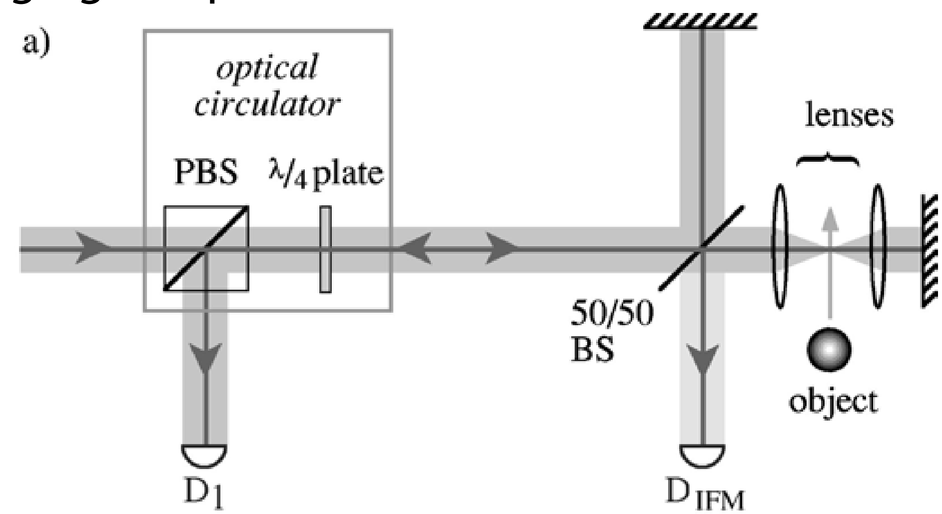


M. Renninger, Z. Phys. 15S, 417 (1960).
R. H. Dicke, Am. J. Phys. 49, 925 (1981).

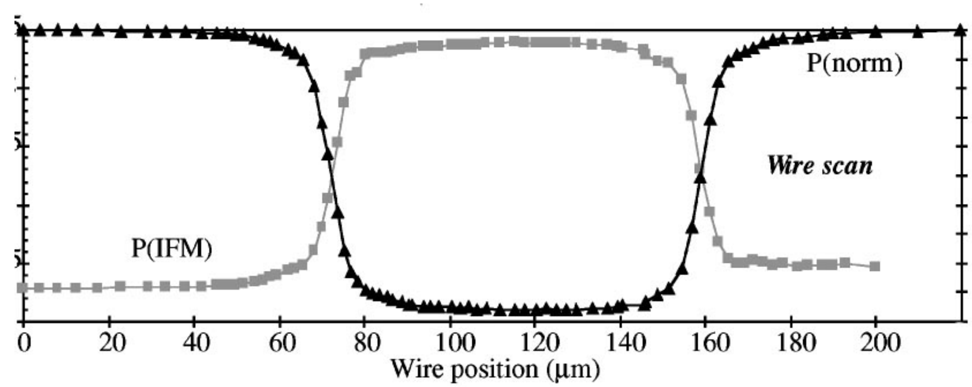
Quantum Imaging by Interaction-Free Measurement



imaging setup

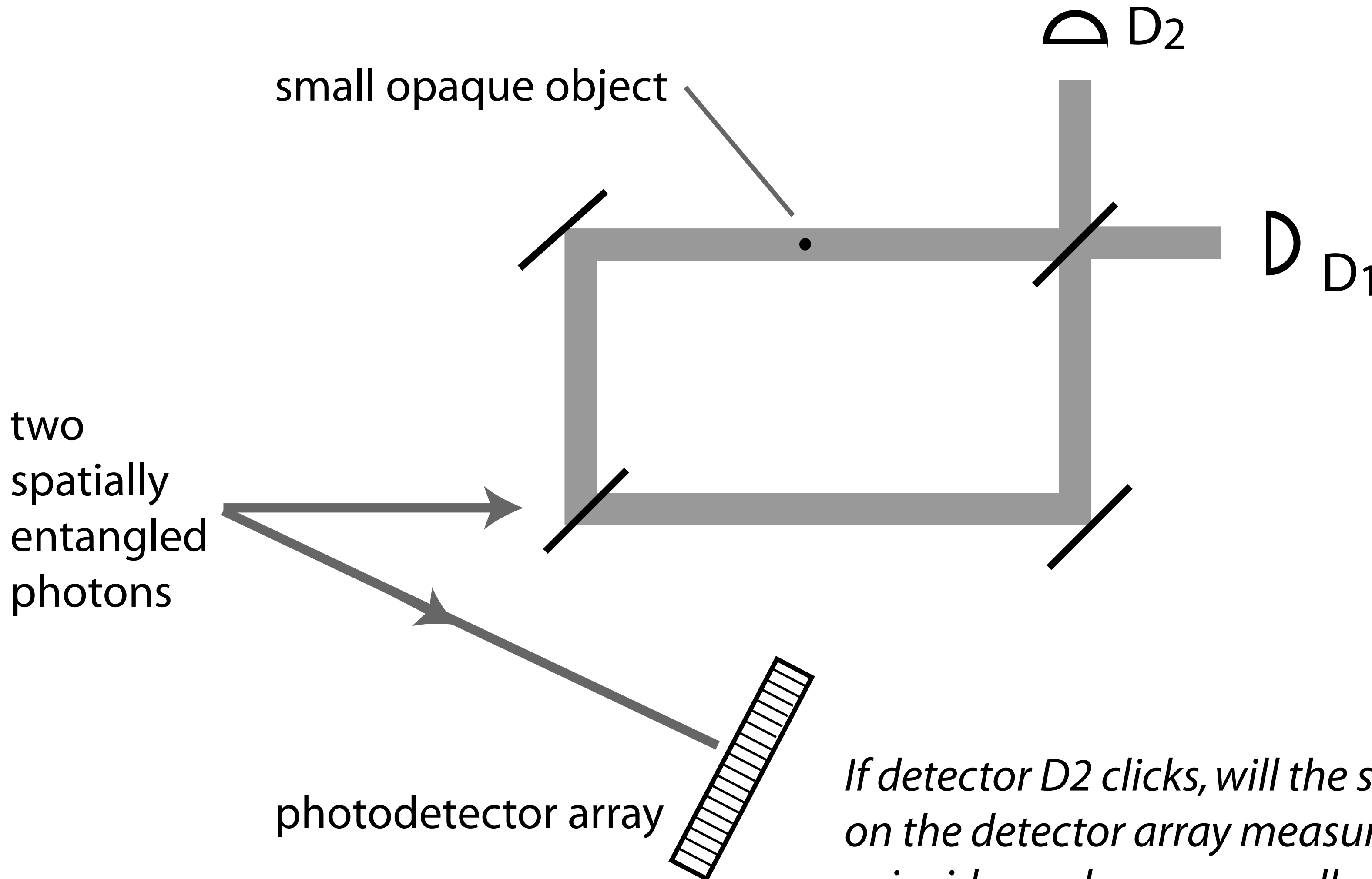


results



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



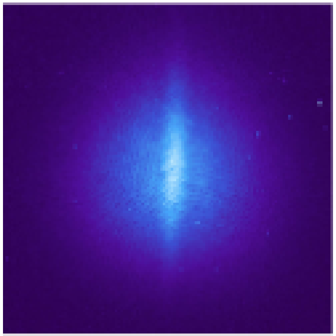
If detector D2 clicks, will the spot size on the detector array measured in coincidence become smaller?

- 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?

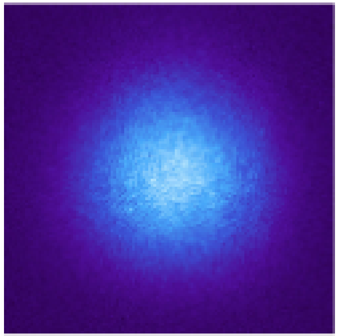
Experimental Results

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.

With Frédéric Bouchard, Harjaspreet Mand, and Ebrahim Karimi,

Is interaction-free imaging useful?

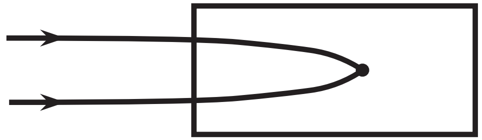
Interaction-free imaging allows us to see what something looks like *in the dark*!

Could be extremely useful for biophysics. What does the retina look like when light does not hit it?

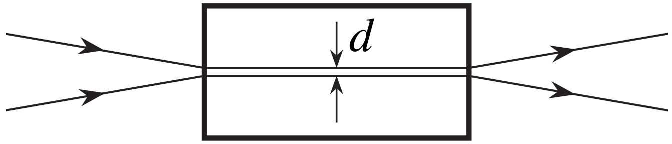
Self Action Effects in Nonlinear Optics

Self-action effects: light beam modifies its own propagation

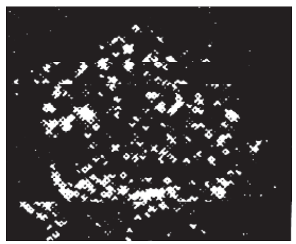
self focusing



self trapping



small-scale filamentation

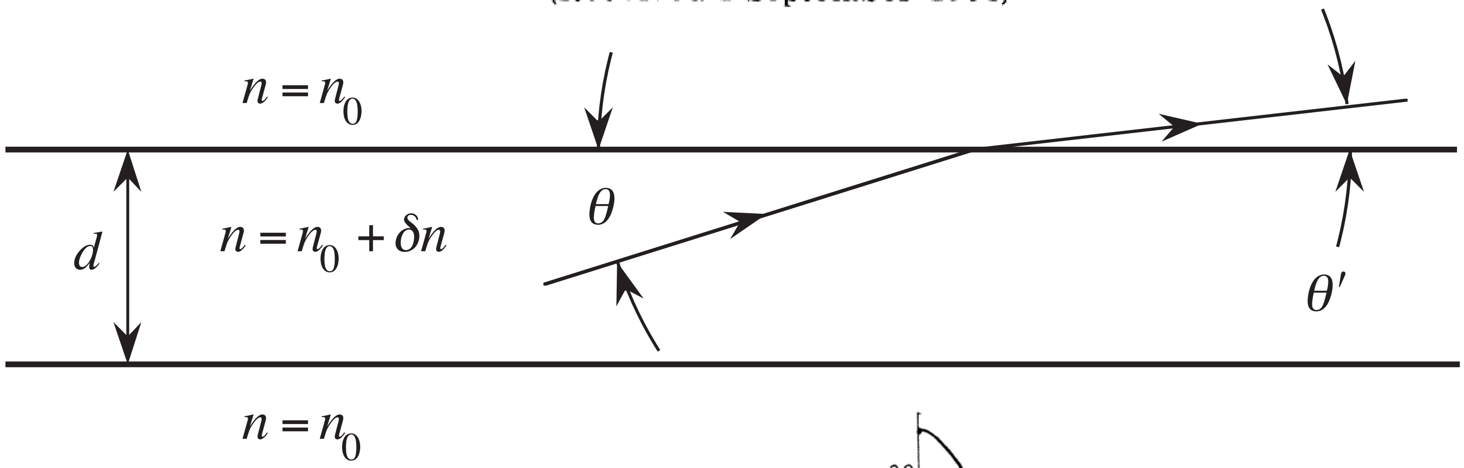


Prediction of Self Trapping

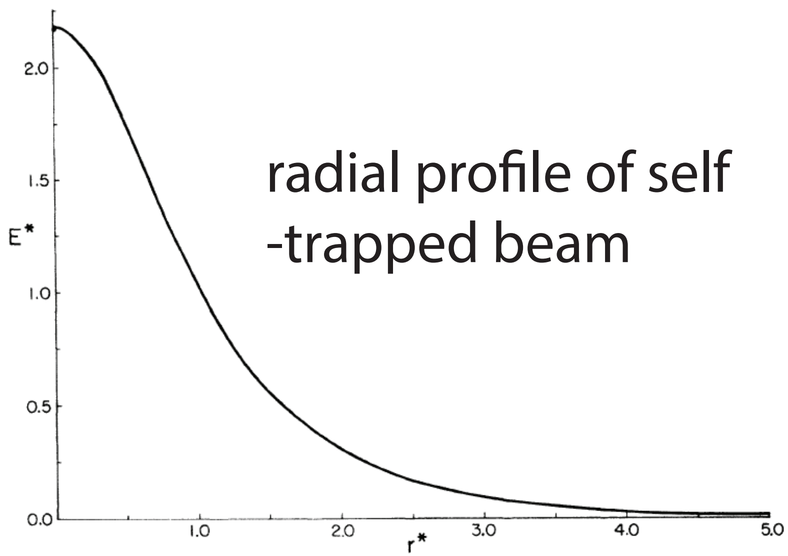
VOLUME 13, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1964

SELF-TRAPPING OF OPTICAL BEAMS*

R. Y. Chiao, E. Garmire, and C. H. Townes
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 1 September 1964)



$$P_{\mathrm{cr}} = \frac{\pi (0.61)^2 \lambda_0^2}{8 n_0 n_2}$$



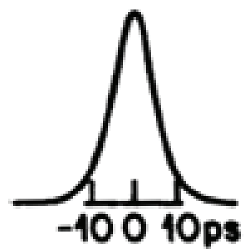
radial profile of self
-trapped beam

Optical Solitons

Field distributions that propagate without change of form

Temporal solitons (nonlinearity balances gvd)

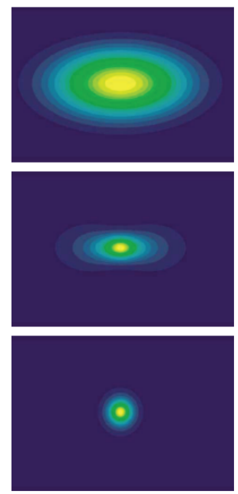
$$\frac{\partial \tilde{A}_s}{\partial z} + \frac{1}{2} i k_2 \frac{\partial^2 \tilde{A}_s}{\partial \tau^2} = i\gamma |\tilde{A}_s|^2 \tilde{A}_s.$$



1973: Hasegawa & Tappert
1980: Mollenauer, Stolen, Gordon

Spatial solitons (nonlinearity balances diffraction)

$$2ik_0 \frac{\partial A}{\partial z} + \frac{\partial^2 A}{\partial x^2} = -3\chi^{(3)} \; \frac{\omega^2}{c^2} \, |A|^2 A$$



1964: Garmire, Chiao, Townes
1974: Ashkin and Bjorkholm (Na)
1985: Barthelemy, Froehly (CS2)
1991: Aitchison et al. (planar glass waveguide
1992: Segev, (photorefractive)

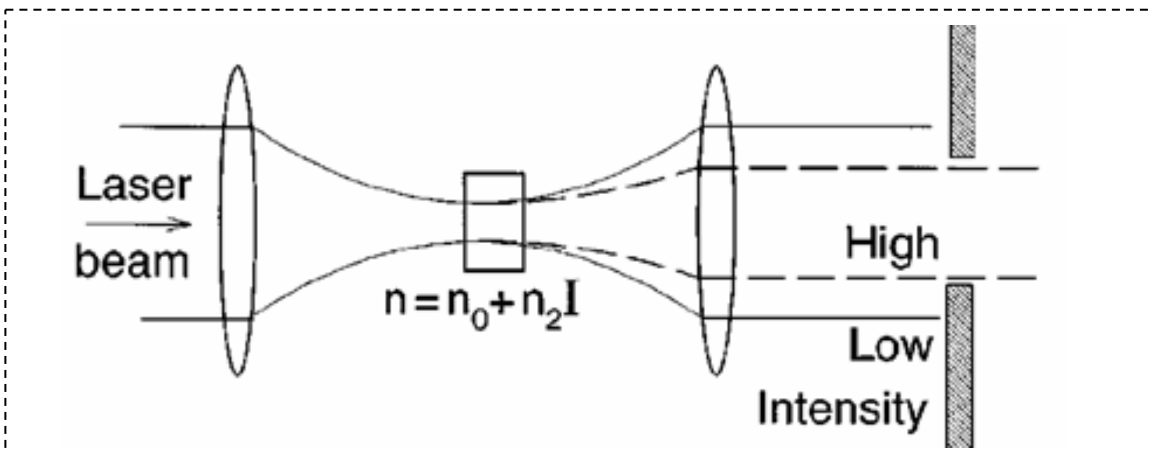
Solitons and self-focussing in Ti:Sapphire

42 OPTICS LETTERS / Vol. 16, No. 1 / January 1, 1991

60-fsec pulse generation from a self-mode-locked Ti:sapphire laser

D. E. Spence, P. N. Kean, and W. Sibbett

J. F. Allen Physics Research Laboratories, Department of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife, KY16 9SS, Scotland



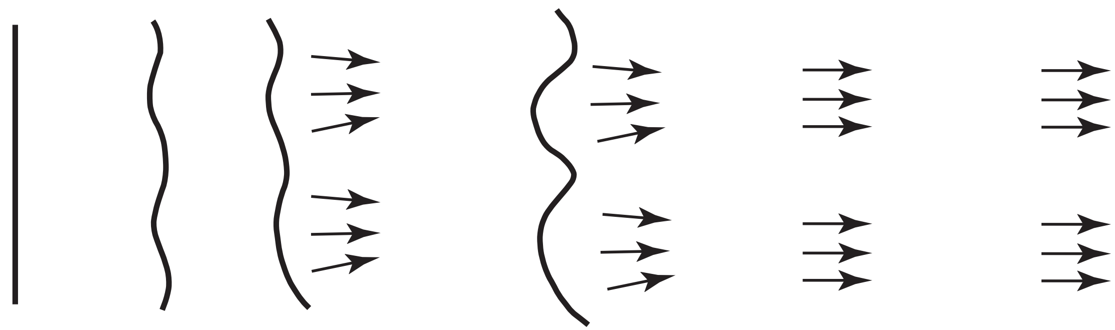
Diffraction-management controls the spatial self-focussing

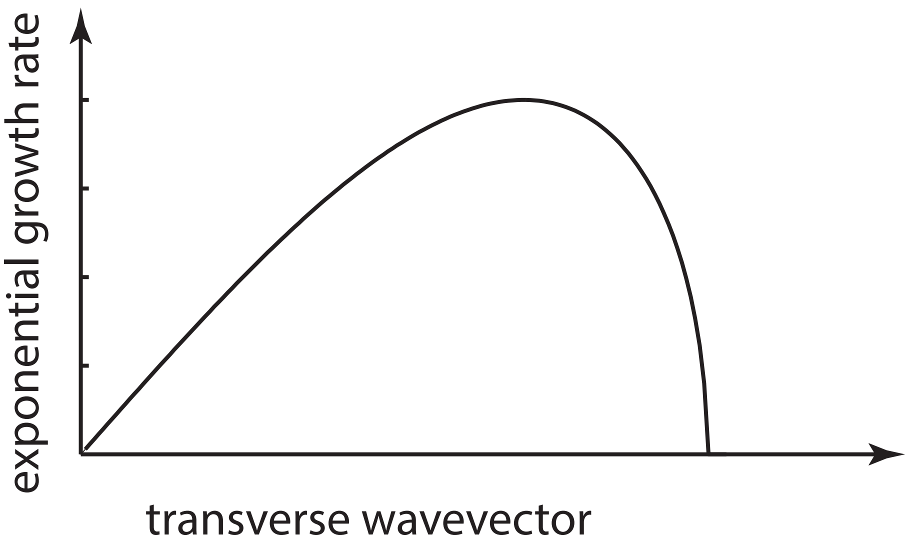
Dispersion-management controls the temporal self-focussing

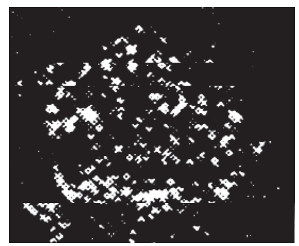
Beam Breakup by Small-Scale Filamentation

Predicted by Bespalov and Talanov (1966)

Exponential growth of wavefront imperfections by four-wave mixing processes

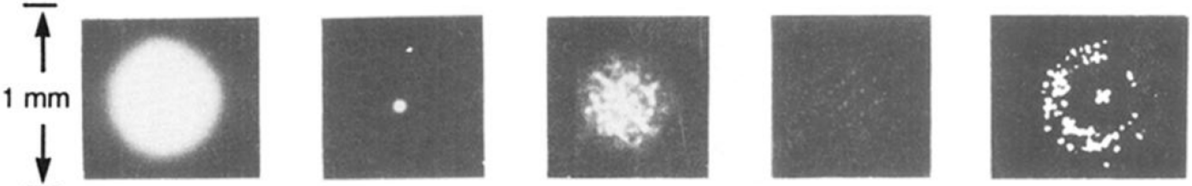






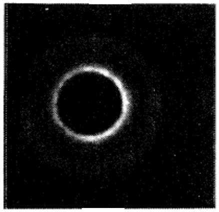
Rabi Sideband Generation in Sodium from Four-Wave Mixing in Filaments

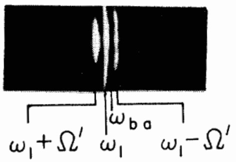
Beam at exit of cell:



Incident beam | Single filament | Multiple filaments | Patterns for structured input beams

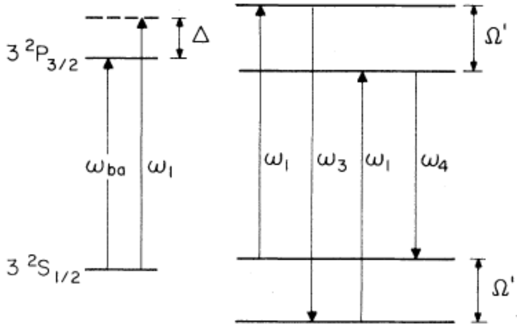
Beam in far field (conical emission)



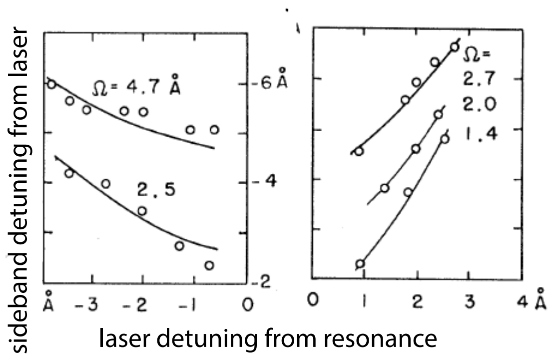


Spectrum of beam shows Rabi side-bands

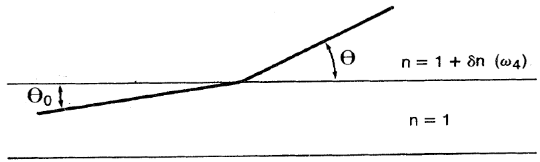
Rabi-sideband model



$$\Omega' = (\Delta^2 + \Omega^2)^{1/2}$$



Four-wave mixing in filament (wave-guide) explains spectrum and cone emission angle

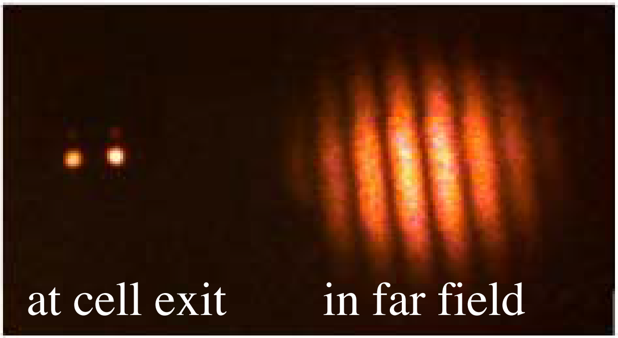


Harter et al., PRL 46, 1192 (1981); PRA 29, 739 (1984); Boyd et al., PRA 24, 411 (1981).

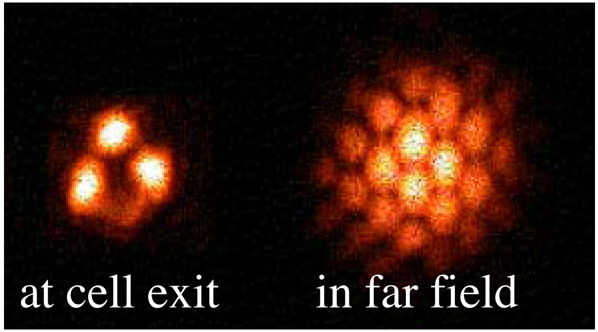
Honeycomb Pattern Formation

Output from cell with a single gaussian input beam

At medium input power



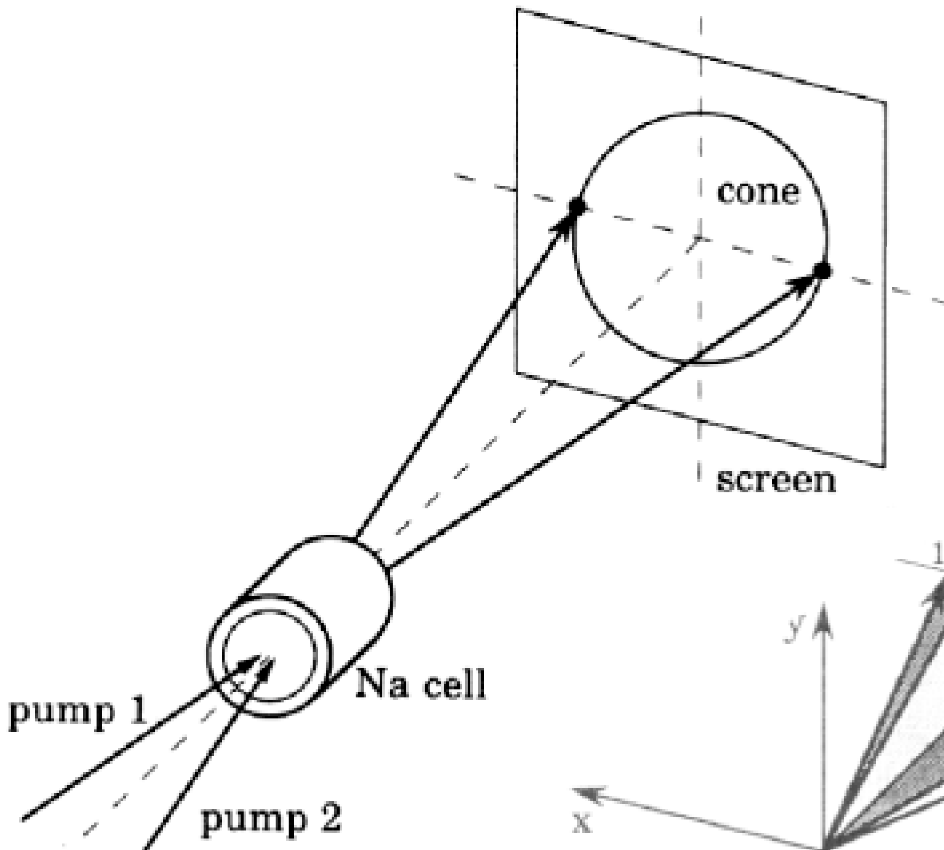
At high input power

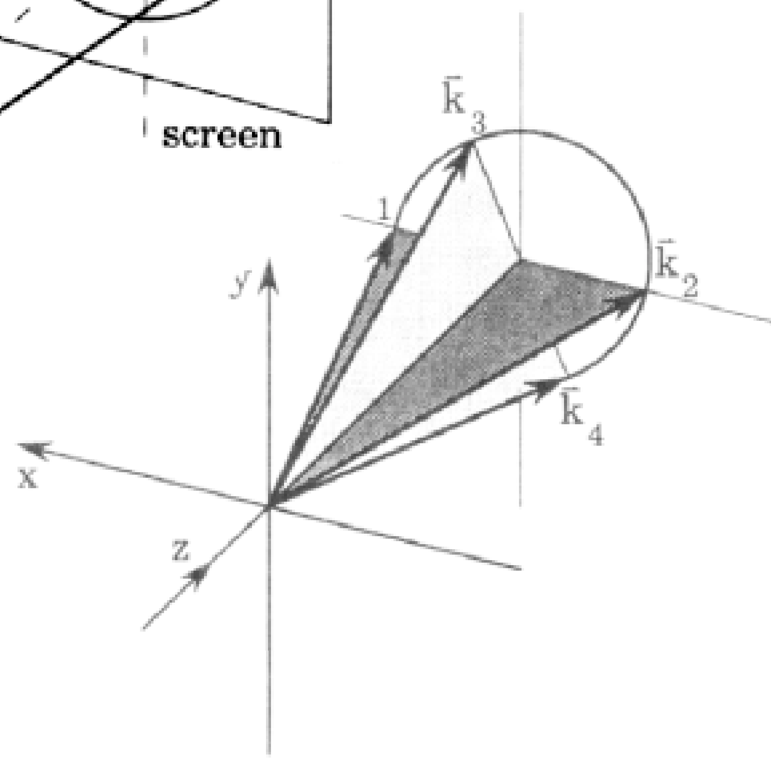


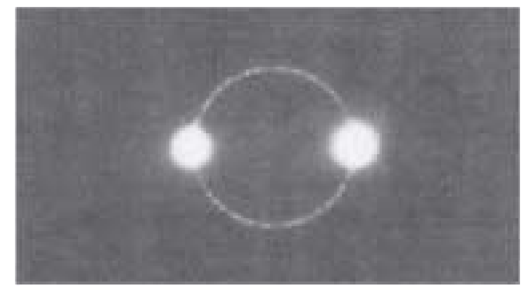
Input power 100 to150 mW
Input beam diameter 0.22 mm

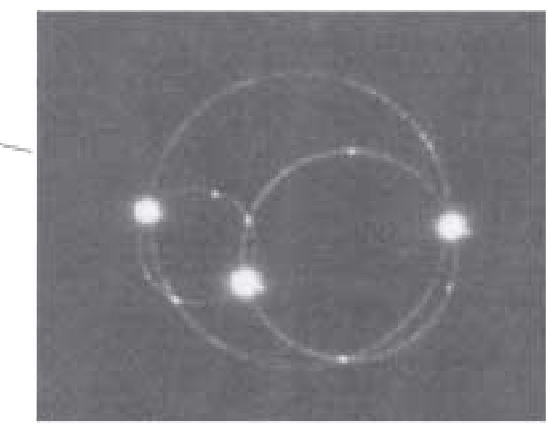
Sodium vapor cell T = 220^{o} C
Wavelength = 588 nm
Bennink et al., PRL 88, 113901 2002.

Generation of Quantum States of Light by Two-Beam Excited Conical Emission







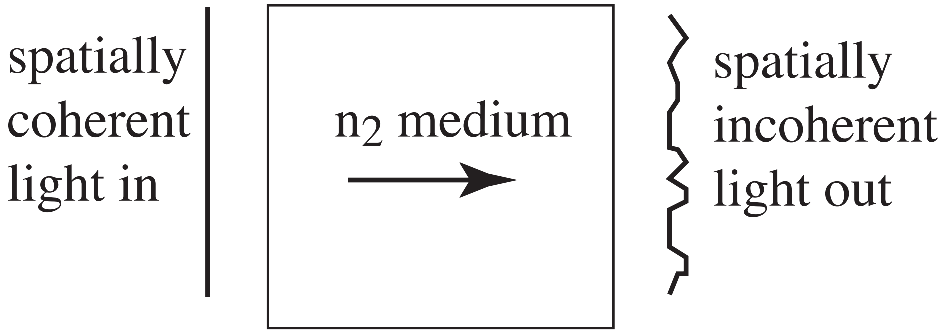


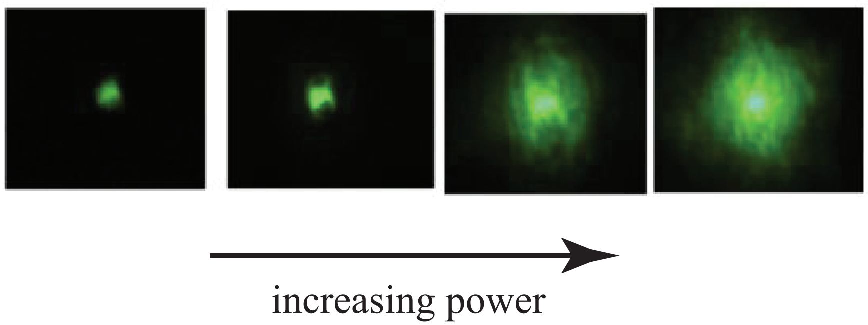
Kauranen et al, Opt. Lett. 16, 943, 1991; Kauranen and Boyd, Phys. Rev. A, 47, 4297, 1993.

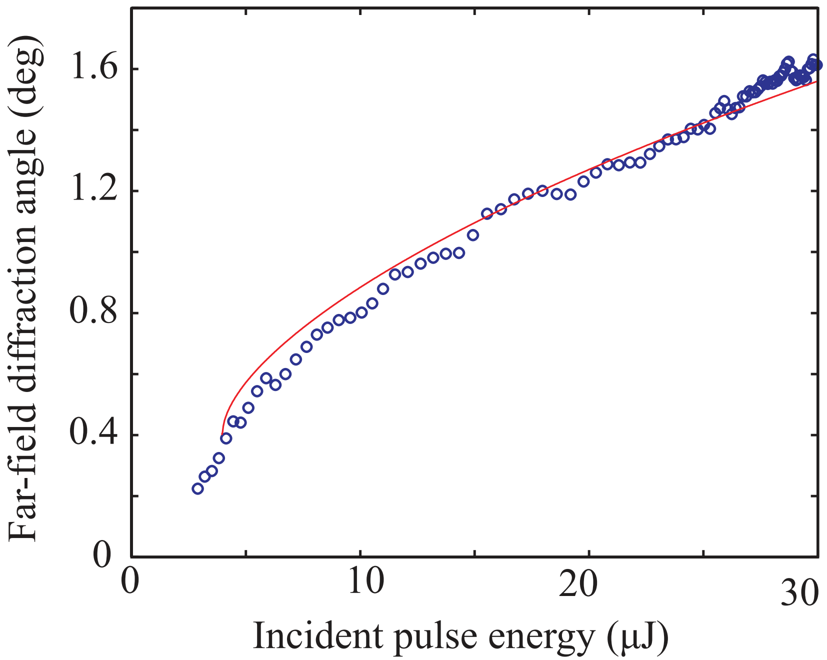
Optical Radiance Limiter Based on Spatial Coherence Control

Controlled small-scale filamentation used to modify spatial degree of coherence

Alternative to standard appropches to optical power limiting



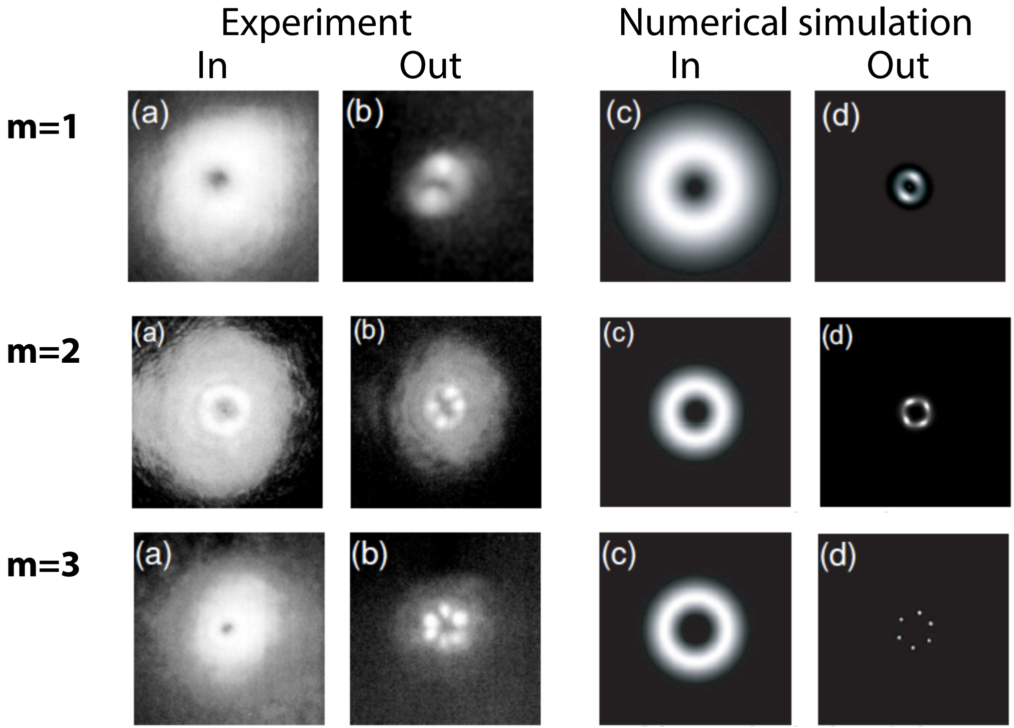




Schweinsberg et al., Phys. Rev. A 84, 053837 (2011).

Breakup of Ring Beams Carrying Orbital Angular Momentum (OAM) in Sodium Vapor

- Firth and Skryabin predicted that ring shaped beams in a saturable Kerr medium are unstable to azimuthal instabilities.
- Beams with OAM of $m\hbar$ tend to break into $2m$ filaments.
  (But aberrated OAM beams tend to break into $2m + 1$ filaments.)



M.S. Bigelow, P. Zerom, and R.W. Boyd, Phys. Rev. Lett 92, 083902 (2004)

Nonlinear evolution of space-varying polarized light beams

Hugo Larocque, Frédéric Bouchard, Alison M. Yao, Christopher Travis, Israel De Leon, Lorenzo Marrucci, Ebrahim Karimi, Gian-Luca Oppo, and Robert W. Boyd

Max Planck - University of Ottawa Centre
for Extreme and Quantum Photonics

SQO Group

Department of Physics

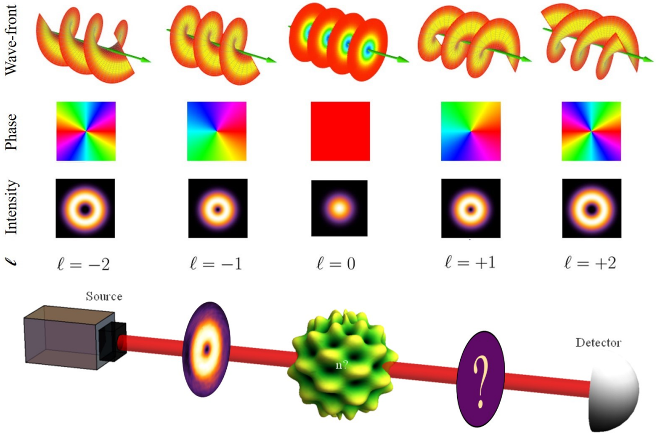
Max Planck Centre for Extreme
and Quantum Photonics

University of Ottawa

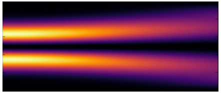
May 24, 2016

Orbital Angular Momentum (OAM)

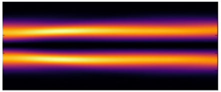
- Helical wavefronts
- Laguerre-Gauss modes ($LG_{p,\ell}$)
  - ℓ appears in $e^{i\ell\varphi}$ term
  - $LG_{p,\ell}$: $\ell\hbar$ OAM per photon
  - $LG_{p,\ell}$: wavefront consists of ℓ intertwined helices
  - Set of orthonormal solutions to the paraxial wave equation



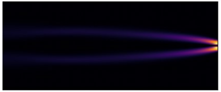
Modeling of Propagation through Nonlinear Media



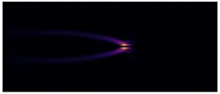
Linear Diffraction*



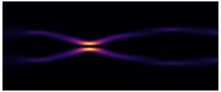
Kerr Nonlinearities: Self-Trapping



Kerr Nonlinearities: Self-Focusing



Kerr Nonlinearities: Filamentation



Saturable Kerr Nonlinearities**

- Paraxial wave equation (*)

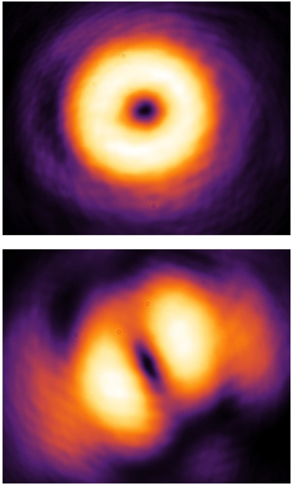
$$\frac{\partial E}{\partial \zeta} - \frac{i}{2}\nabla_{\perp}^{2} E = 0$$

- Nonlinear Schrödinger equation (**):
  - γ: nonlinear parameter
  - σ: saturation parameter

$$\frac{\partial E}{\partial \zeta} - \frac{i}{2}\nabla_{\perp}^{2} E = i\gamma \frac{|E|^2}{1+\sigma |E|^2} E$$

OAM Carrying Beams in Nonlinear Media

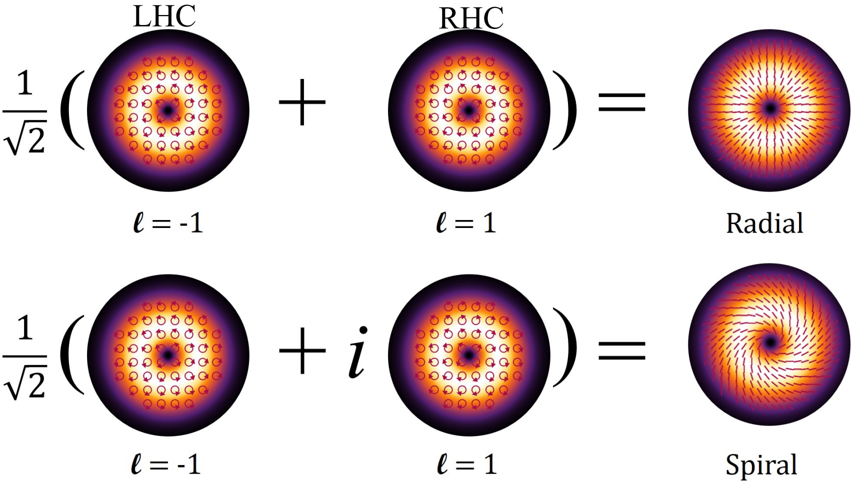
- Modulational instabilities in OAM carrying beams $\rightarrow$ Alterations to their intensity profile
    - Beam breakup
    - Filamentation
    - Soliton formation (specific ICs)
- Alternatives: *Structured*/space-varying polarized light beams in a nonlinear medium.



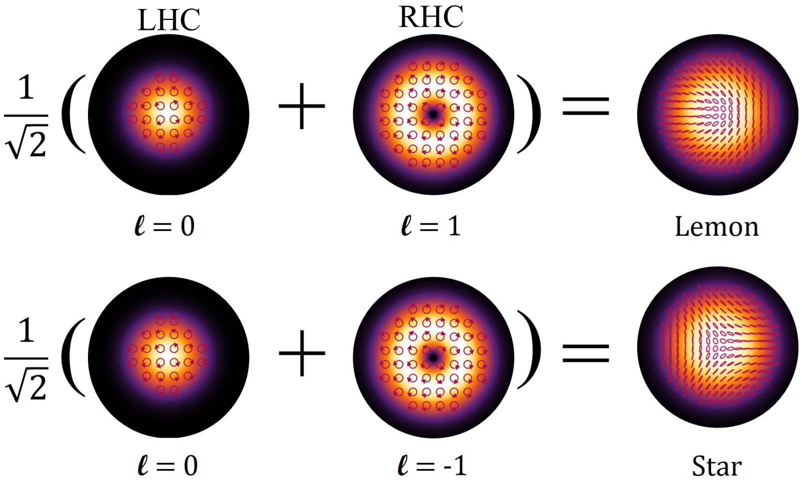
Before Propagation

After Propagation

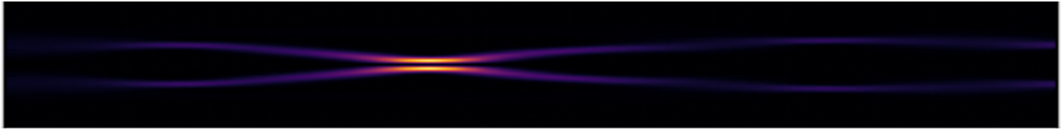
Space-varying Polarized light beams – Vector Vortex Beams



Space-varying Polarized light beams – Poincaré Beams



Space-varying Polarized light beams – Nonlinear Propagation

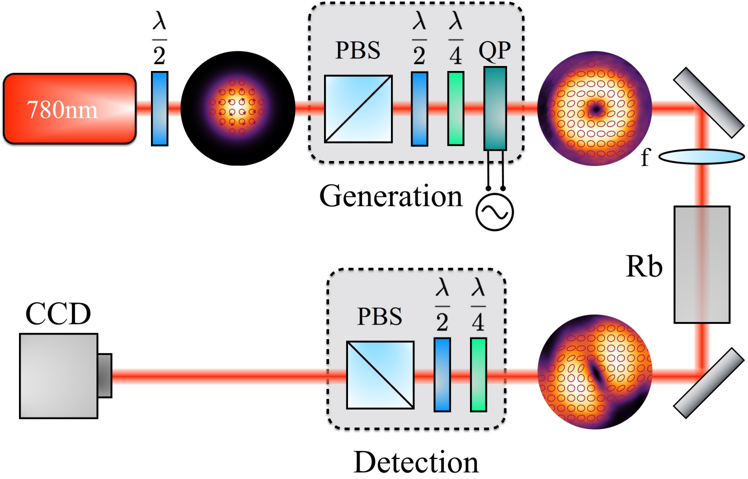


$$\frac{\partial E_L}{\partial \zeta} - \frac{i}{2}\nabla_\perp^2 E_L = i\gamma \frac{|E_L|^2 + \nu |E_R|^2}{1 + \sigma\left(|E_L|^2 + \nu |E_R|^2\right)} E_L$$

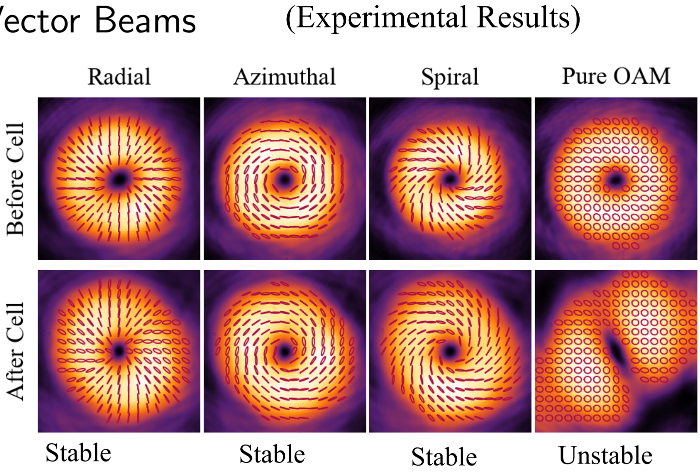
$$\frac{\partial E_R}{\partial \zeta} - \frac{i}{2}\nabla_\perp^2 E_R = i\gamma \frac{|E_R|^2 + \nu |E_L|^2}{1 + \sigma\left(|E_R|^2 + \nu |E_L|^2\right)} E_R$$

- Coupled nonlinear Schrödinger equations
- ν: coupling parameter
- L: left-handed circular polarization
- R: right-handed circular polarization

Experimental Setup



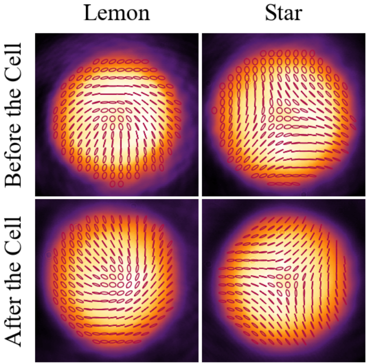
Results – Vector Beams



Intensity and polarization distributions of vector and LG beams before and after propagating through the Rb atomic vapour.

Results – Poincaré Beams

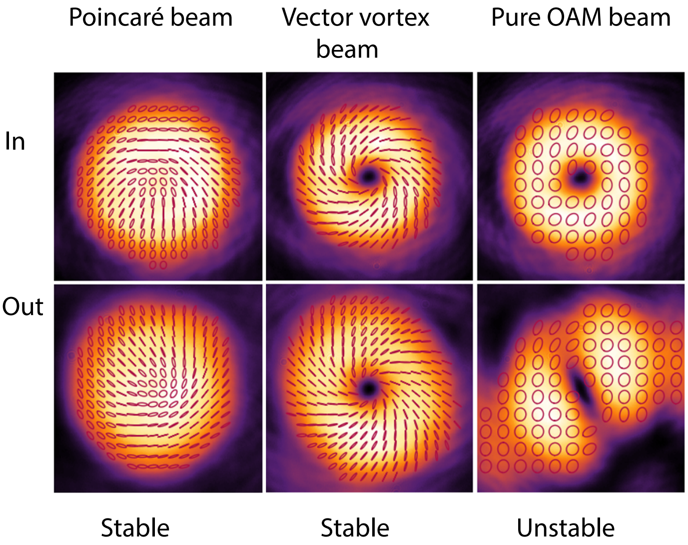
Note that both the lemon and star beams are extremely stable and only undergo an overall rotation.



Intensity and polarization distributions of fundamental topology Poincaré beams before and after propagating through the Rb atomic vapour.

Conclusions: propagation through a nonlinear medium

- Pure OAM beam:
  beam breakup
- Vector vortex beams:
  stable propagation
- Poincaré beams:
  stable propagation



Boyd Name Origin

(Road outside Glasgow)

uOttawa University of Glasgow UNIVERSITY of ROCHESTER