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SUSSP67: Quantum Information & Coherence

Scottish Universities Summer Schools in Physics

Entangled with a twist

Miles Padgett

School of Physics and Astronomy

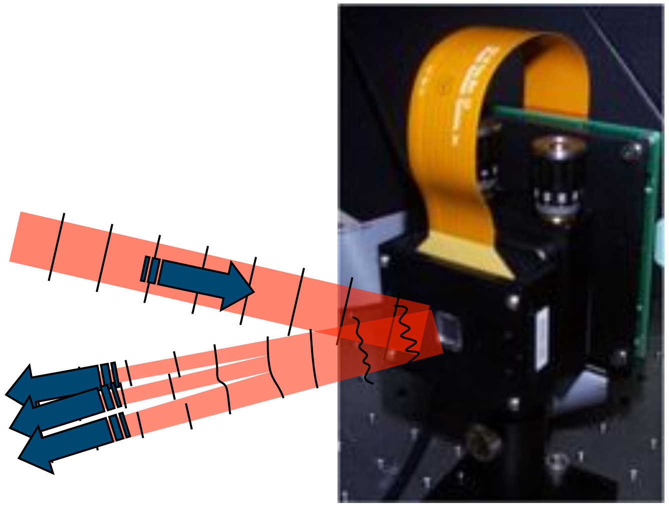
Optics Group

University of Glasgow

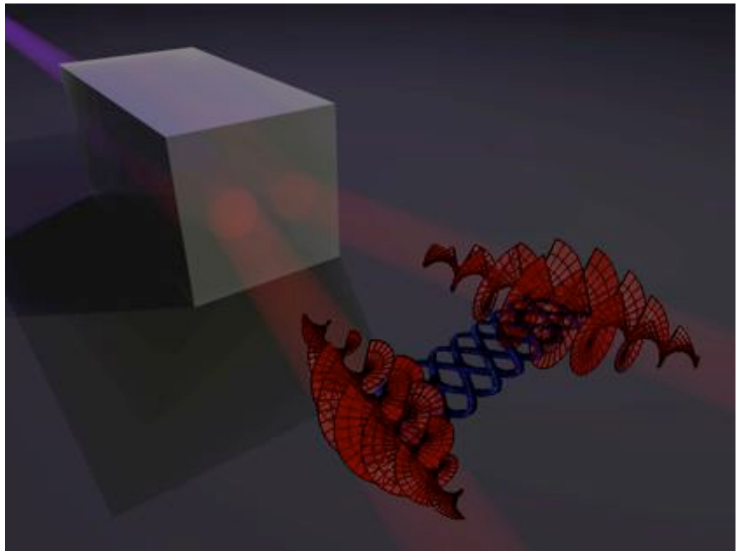
SLMs and Quantum optics

- Spatial light modulator
  - ≈Hologram
  - ≈Diffractive optic

(>50 Hz, >50%)



- Quantum Optics
  - Entanglement of spatial modes
  - Modes have BOTH intensity and phase



That light has a momentum (History)

- The momentum of light
  - Momentum/energy = $\hbar k_0 / \hbar\omega$
  - Spin AM/energy = $\hbar / \hbar\omega$

(True both for photons and classical fields)

- The push of light
  - Force = P/c (e.g. 3mW -> 10pN)
- The twist of light (circularly polarised)
  - Toque = P/ω (e.g. 3mW @633nm -> 1pN.μm)
- The twist of light (skew ray, @ f#, acting at r)
  - Toque ≈ Pr/(2c.f#)
- The twist of light (helical phase, @ f#, acting at r)
  - Toque ≈ $P\,\ell/\omega$ ($\ell_{max} \approx k_0 r/2f\#$)

P = optical power, f# = “f-number” of optics

- Linear momentum
  - Maxwell eqns.
  - Abraham/Minkowski (1909/08)
- Spin AM momentum
  - Maxwell eqns.
  - Poynting/Beth (1909/36)
- Orbital AM (not spin) momentum
  - Various, 1930s, inc. Majorana and Darwin
- Orbital AM (helical phase) momentum in a beam
  - Allen et al. (1992)

Getting started on Orbital Angular Momentum of Light

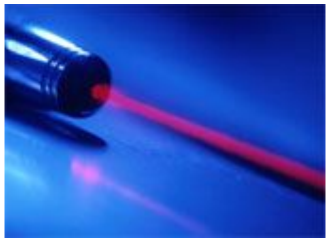
- 1992, Les Allen et al.

PHYSICAL REVIEW A VOLUME 45, NUMBER 11 1 JUNE 1992

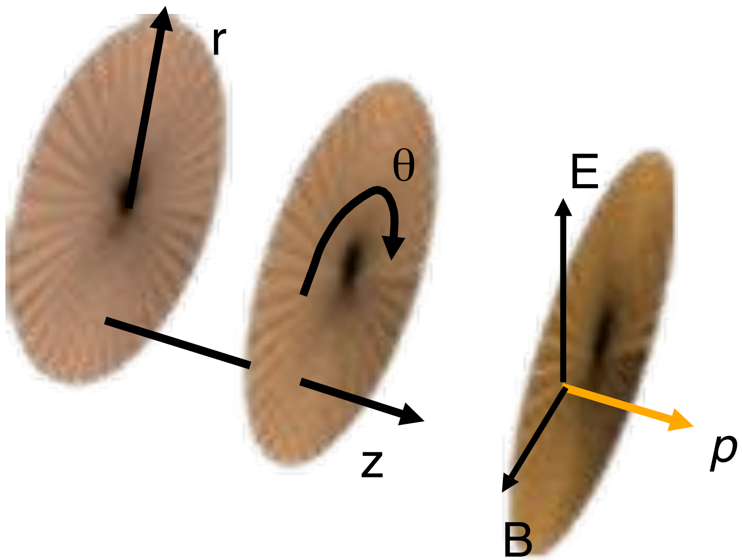
Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes

L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman
Huygens Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands
(Received 6 January 1992)

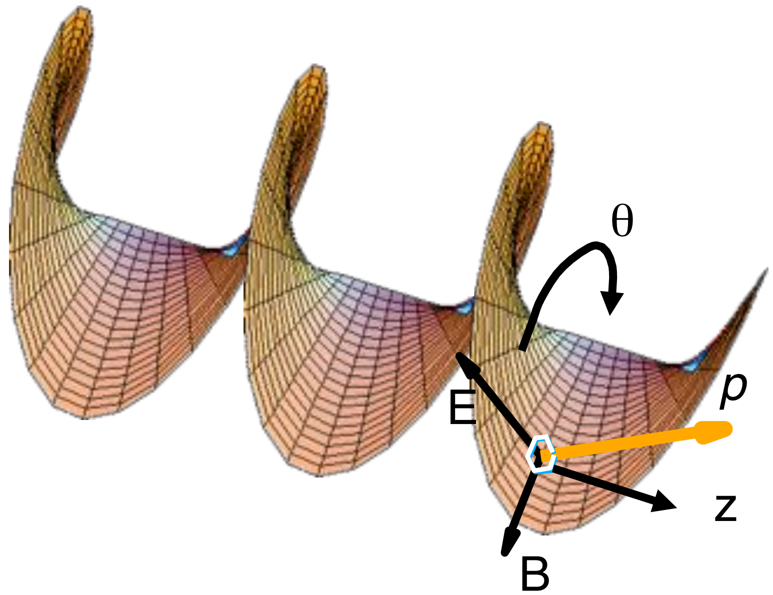
- 1994, Les and Miles have dinner…...



Orbital Angular Momentum from helical phase fronts



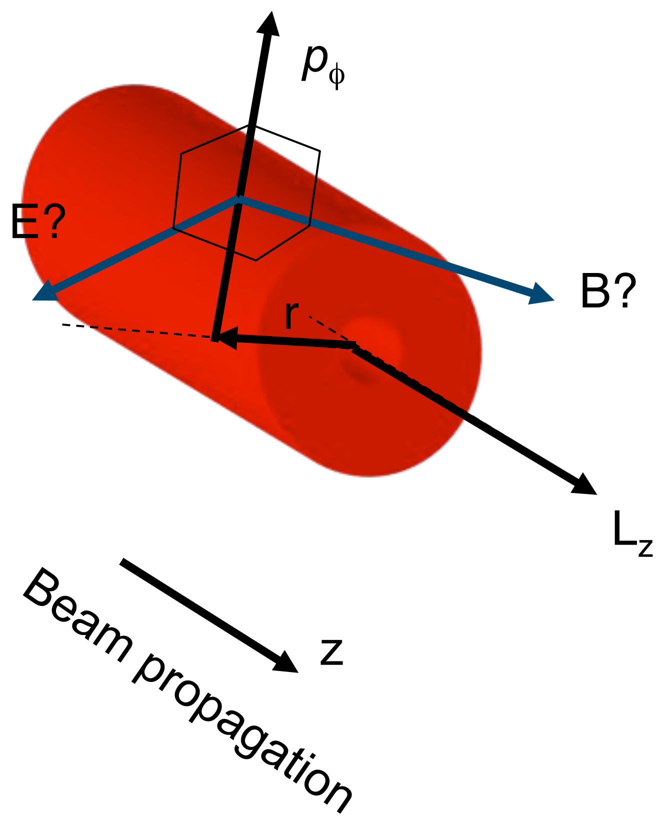
$p_\theta = 0$



$p_\theta \neq 0$

Angular-momentum of light

- In the "classical world" all effects can be explained by the electro-magnetic field
  - Angular momentum z-direction requires linear momentum in ϕ-direction
    - i.e. $L_z = r\, p_\phi$
  - Linear momentum in ϕ-direction needs component of E or B in z-direction
- Angular momentum requires field component in direction of propagation



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Calculate AM from EM field

Depends upon phase structure of beam

Depends upon polarisation state & intensity gradient of beam

$$p = \frac{\varepsilon_0}{2}\left(E^* \times B + E \times B^*\right) = i\omega\frac{\varepsilon_0}{2}\left(u^*\nabla u - u\nabla u^*\right) + \omega k\varepsilon_0 |u|^2 z + \omega\sigma\frac{\varepsilon_0}{2}\frac{\partial |u|^2}{\partial r}\Phi$$

ϕ- component gives OAM

ϕ- component gives SAM

u ≈ the local amplitude of the beam (proportional to E)
Orbital terms arises from phase gradient
Spin term arises from intensity gradient

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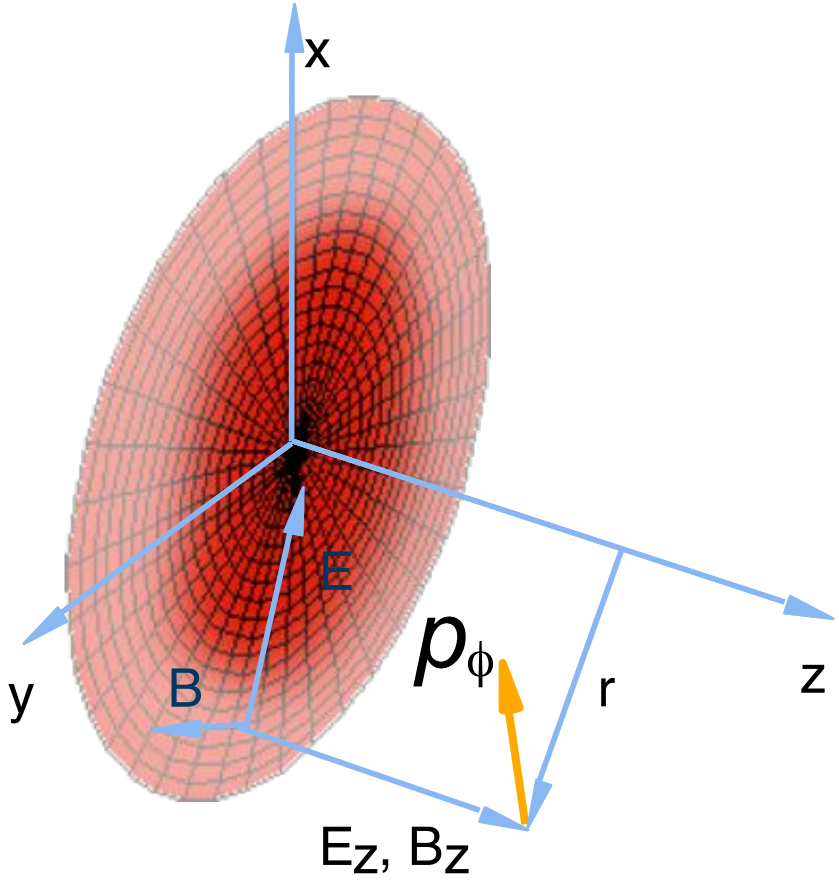
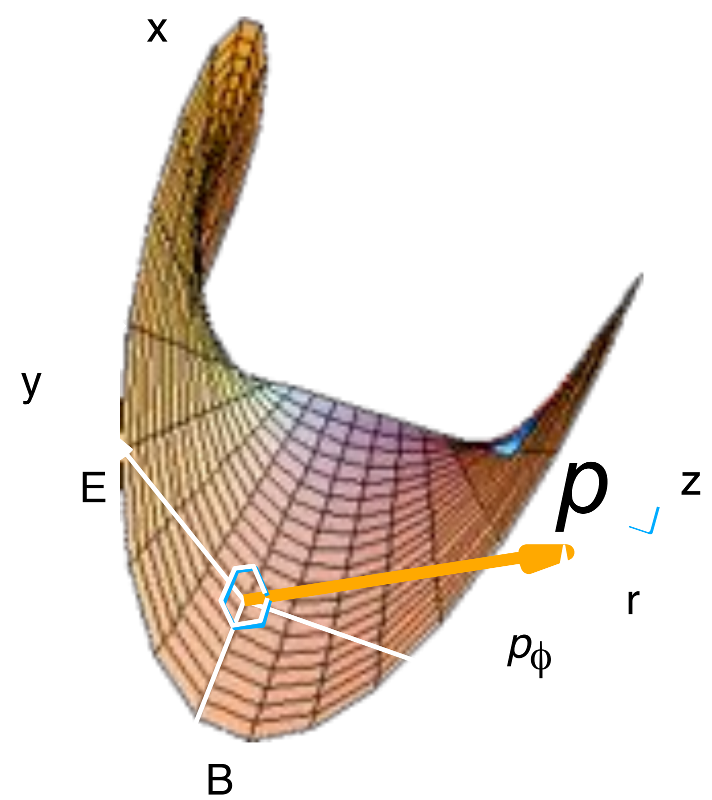
Spin AM (more complicated!)

- SAM requires both circular polarisation & an intensity gradient!
  - B α Curl E
  - e.g. if $\frac{dE_y}{dx} \neq 0$ & $\sigma \neq 0$
  - $B_z \neq 0$
- Intensity gradient approach gives right answer to
  - Transfer of SAM to particles



Orbital angular momentum

- OAM arises from helical phasefronts
  - E_z & $H_z \neq 0$
  - $p_\phi \neq 0$
  - $L_z \neq 0$
- OAM arises from "skew rays"
- Skew rays give the right answer to
  - Transfer of OAM to particles
  - Generation of OAM
  - Frequency shift



Simmons and Guttmann (1970)

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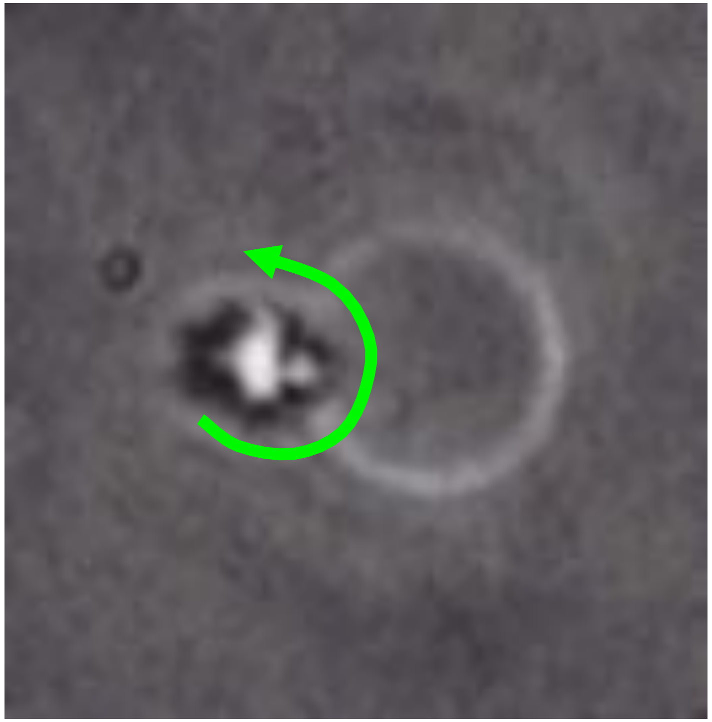
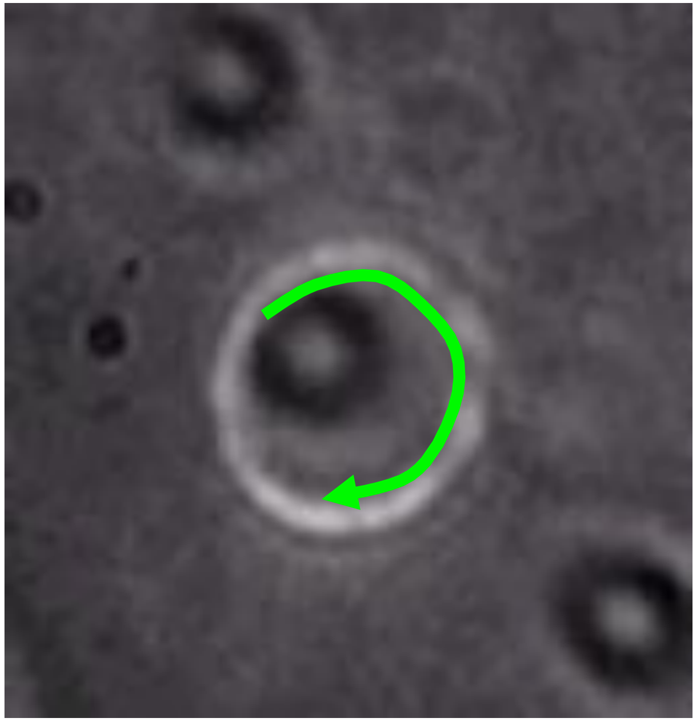
OAM / SAM transfer to particle held in optical tweezers



SAM

Particle spins on its own axis



OAM

Particle orbits the beam axis

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Optical vortices, Helical waves , Angular momentum

- Description of light
  - Intensity, $I \geq 0$
  - Phase, $2\pi \geq \phi \geq 0$

    $\phi = \omega t + kz + \ell\theta$

    ℓ = 0, plane wave

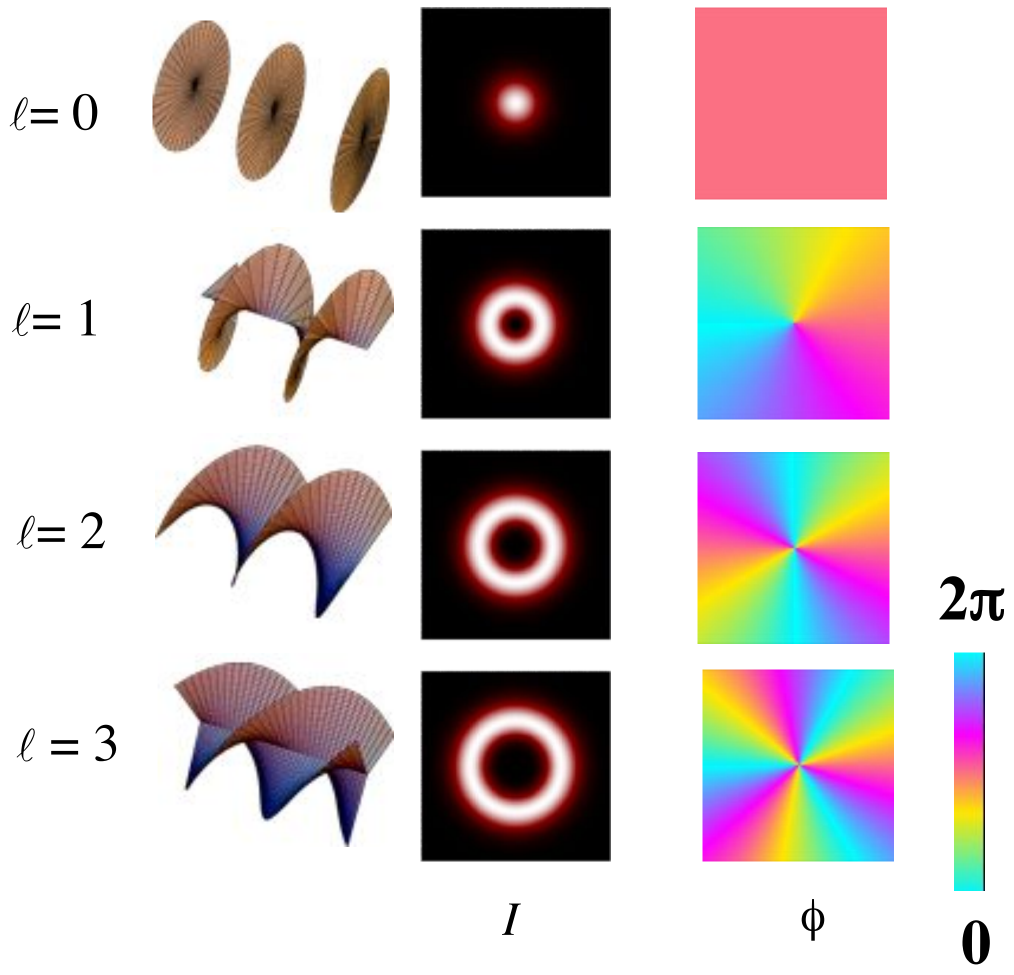
    ℓ = 1, helical wave

    ℓ = 2, double helix

    ℓ = 3, pasta fusilli

    etc.

  ℓ= vortex charge



A double-start helix (ℓ=2)

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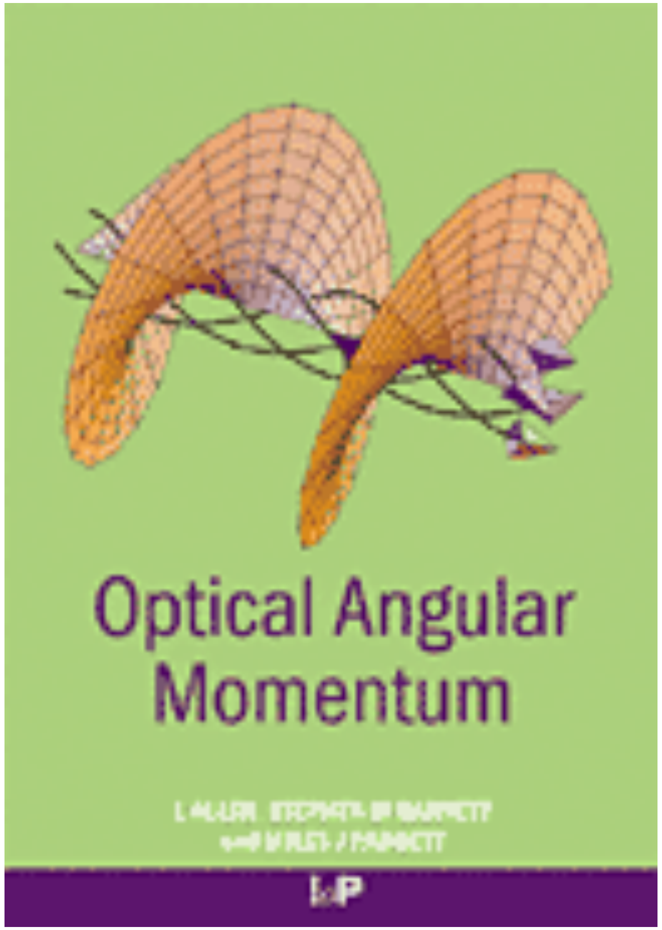
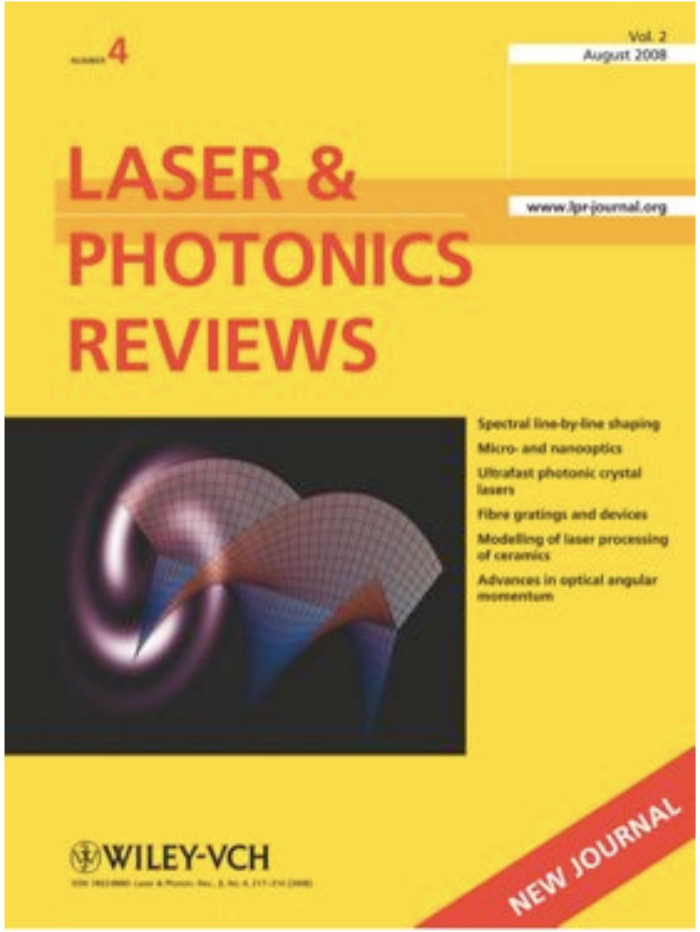
Further reading on OAM?

92-02



-08



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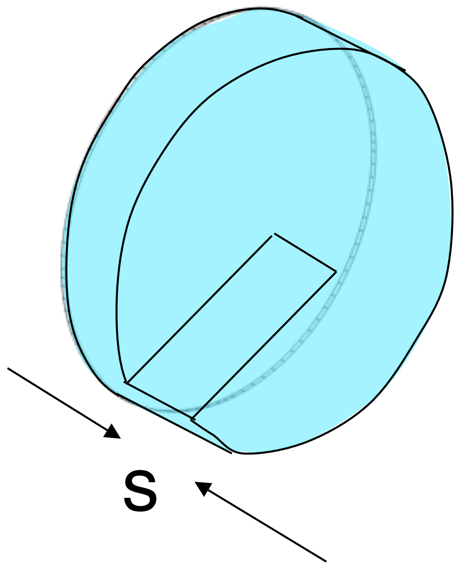
Designing helical phase hologram

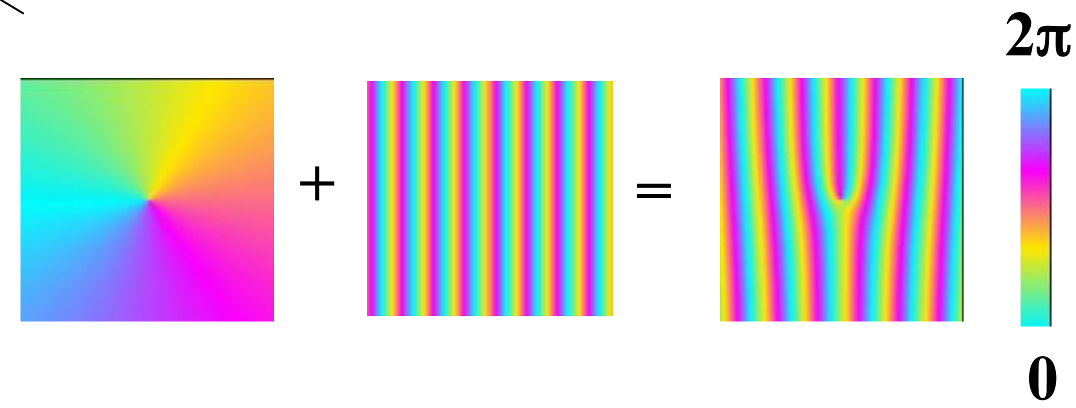


- Spiral Phase-plate
  $s = \ell\lambda/(n-1)$

- Phase accuracy of diffracted beam derives from SPATIAL stability of hologram.

- Holographically

e.g. $\ell = 1 \triangleright$



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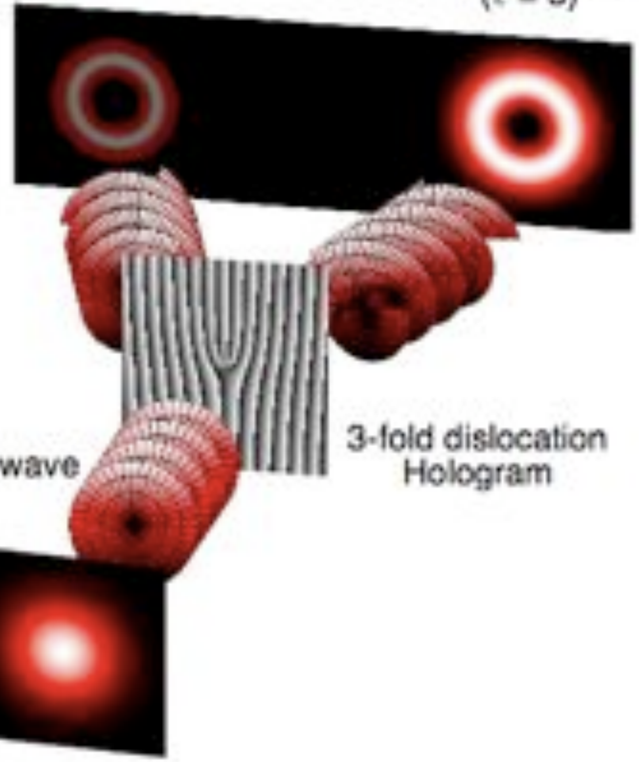
Making helical phasefronts with holograms

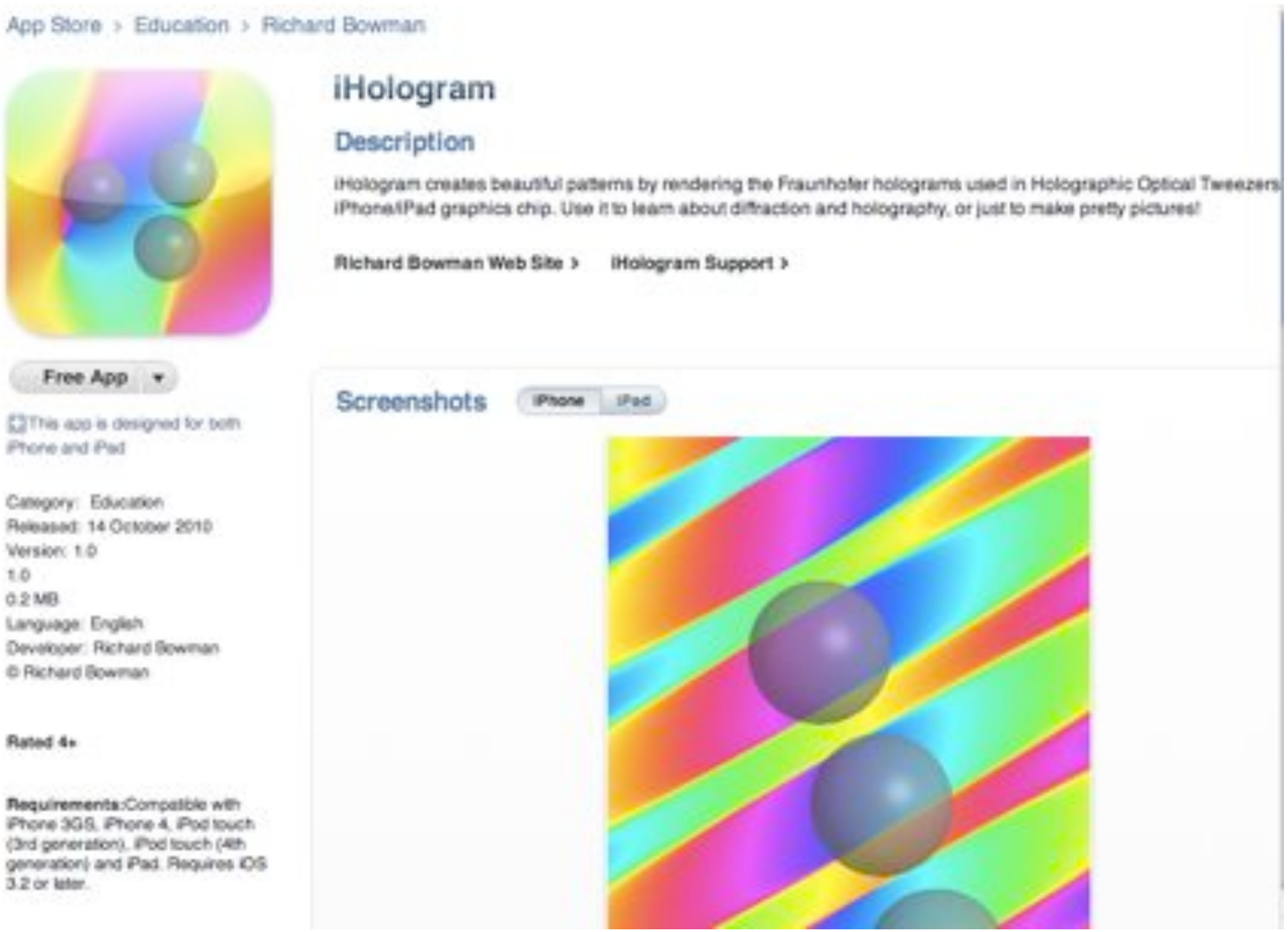
Laser beams with screw dislocations in their wavefronts

V. Yu. Bazhenov, M. V. Vasnetsov, and M. S. Soskin
Institute of Physics, Academy of Sciences of the Ukrainian SSR

(Submitted 28 August 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 8, 1037–1039 (25 October 1990)



A gift for all the family…..



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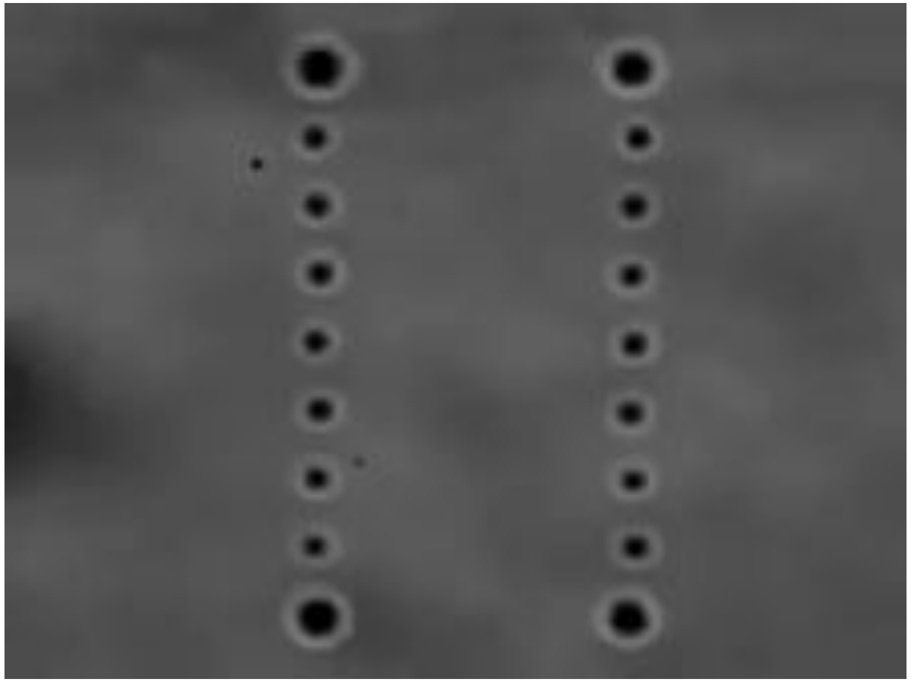
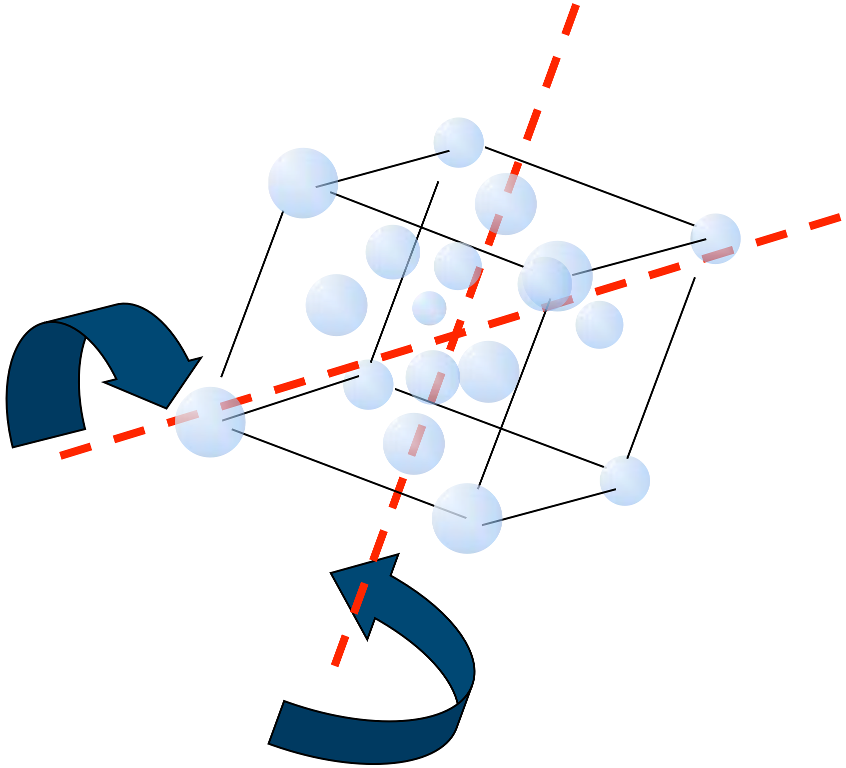
Gavin Sinclair
02-06

Diamond structure





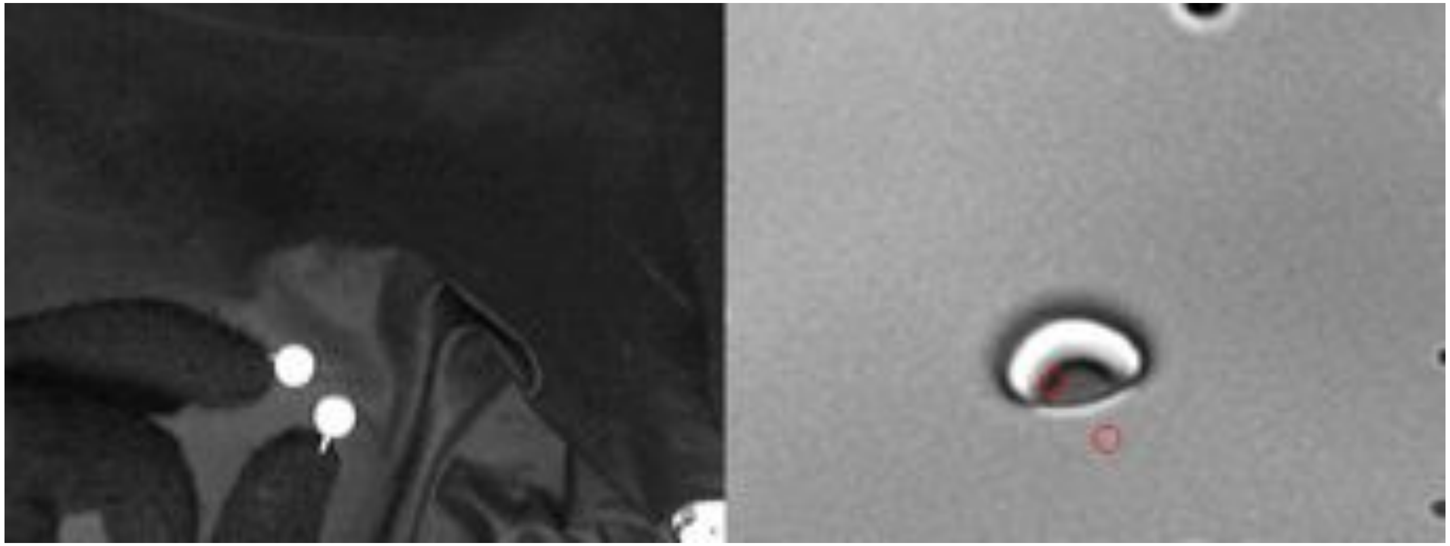
- 18 beads in 5 planes

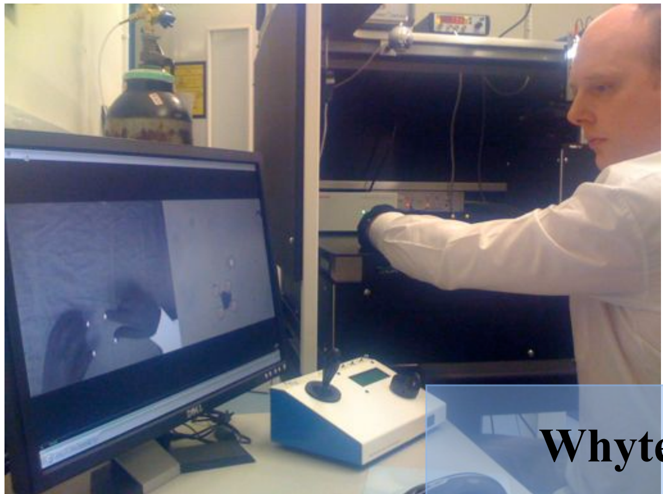
Sinclair *et al.* Opt. Express 12, 5475, 2004

Graham Gibson

Graeme Whyte
02-06

The nano hand



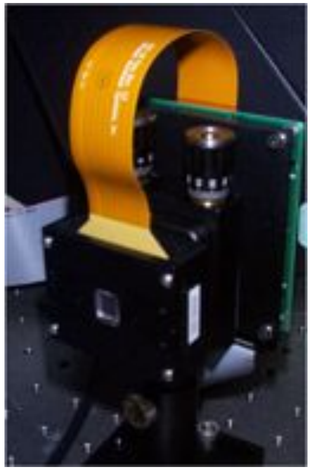


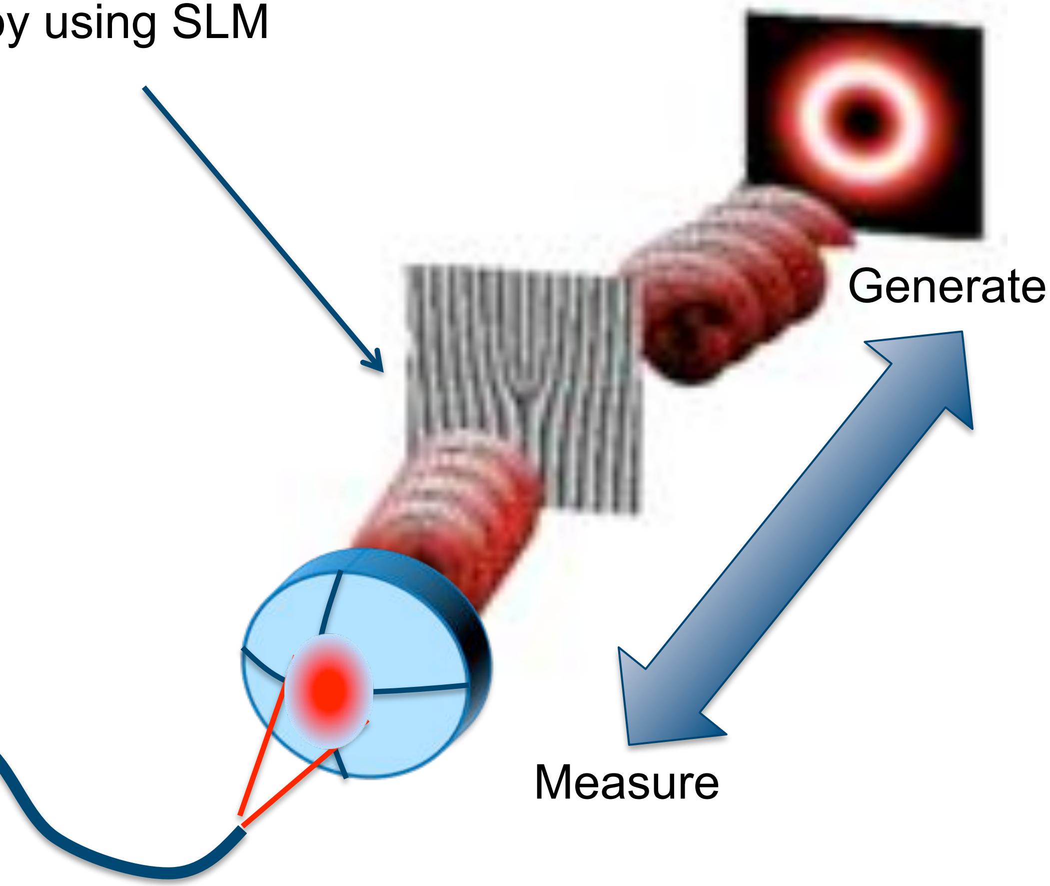
Whyte *et al.* Opt. Express 14, 12497, 2006

Making OR measuring phasefronts with holograms

Make interactive by using SLM

Switching time
≈5-20mSec
Efficiency ≈50%





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Quantum entanglement with spatial light modulators

Jacqui Romero
Barry Jack
Sonja Franke-Arnold
Daniele Giovannini
(Glasgow)



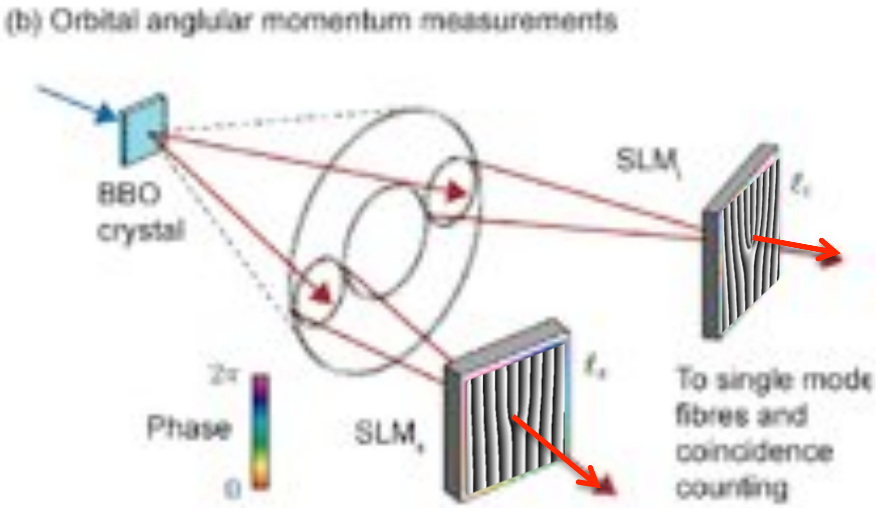

Steve Barnett
and Alison Yao (Strathclyde)

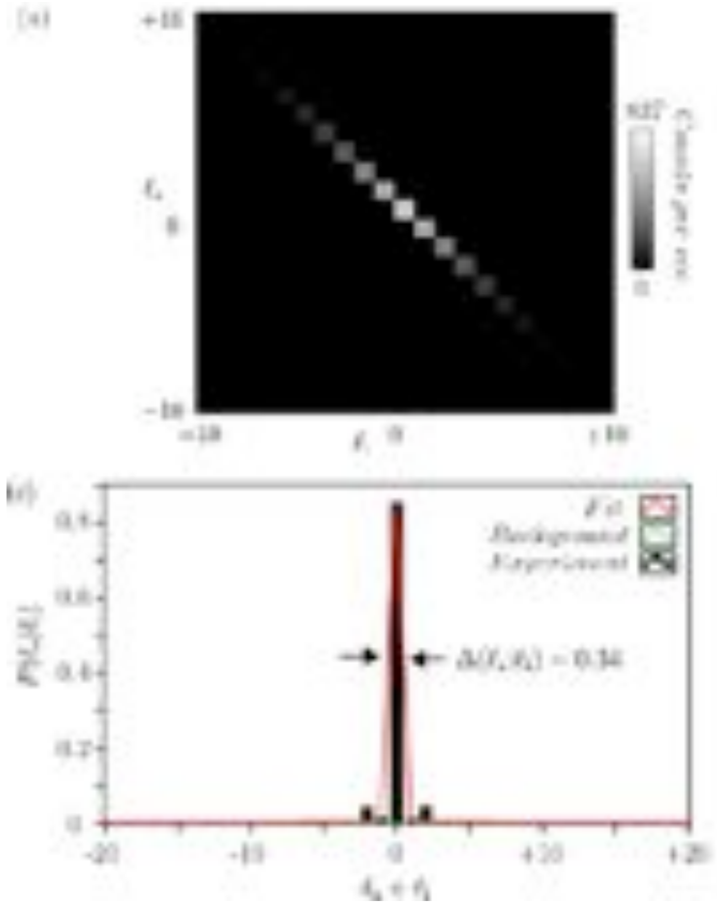

Jonathan Leach,
Bob Boyd
Anand Jha (Ottawa/Rochester)



Funding from EPSRC,
Royal Society, EU
commission and DARPA

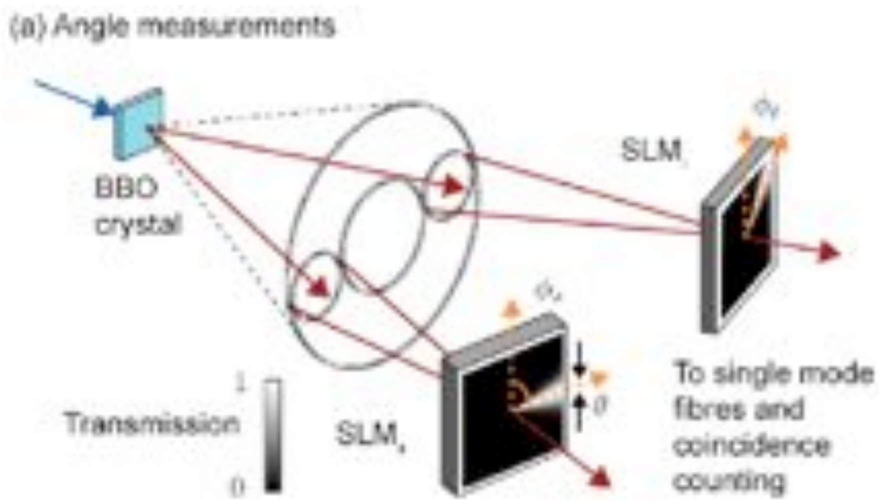
Correlations angular momentum

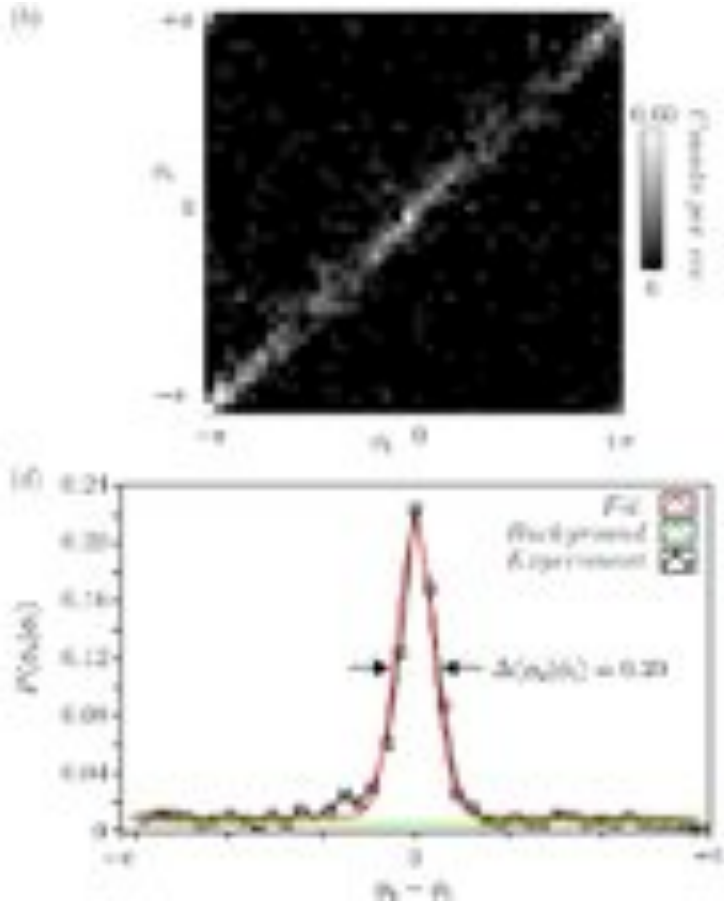




Near perfect (anti)
Correlations in Angular
momentum

Correlations angle





Near perfect
Correlations in angle

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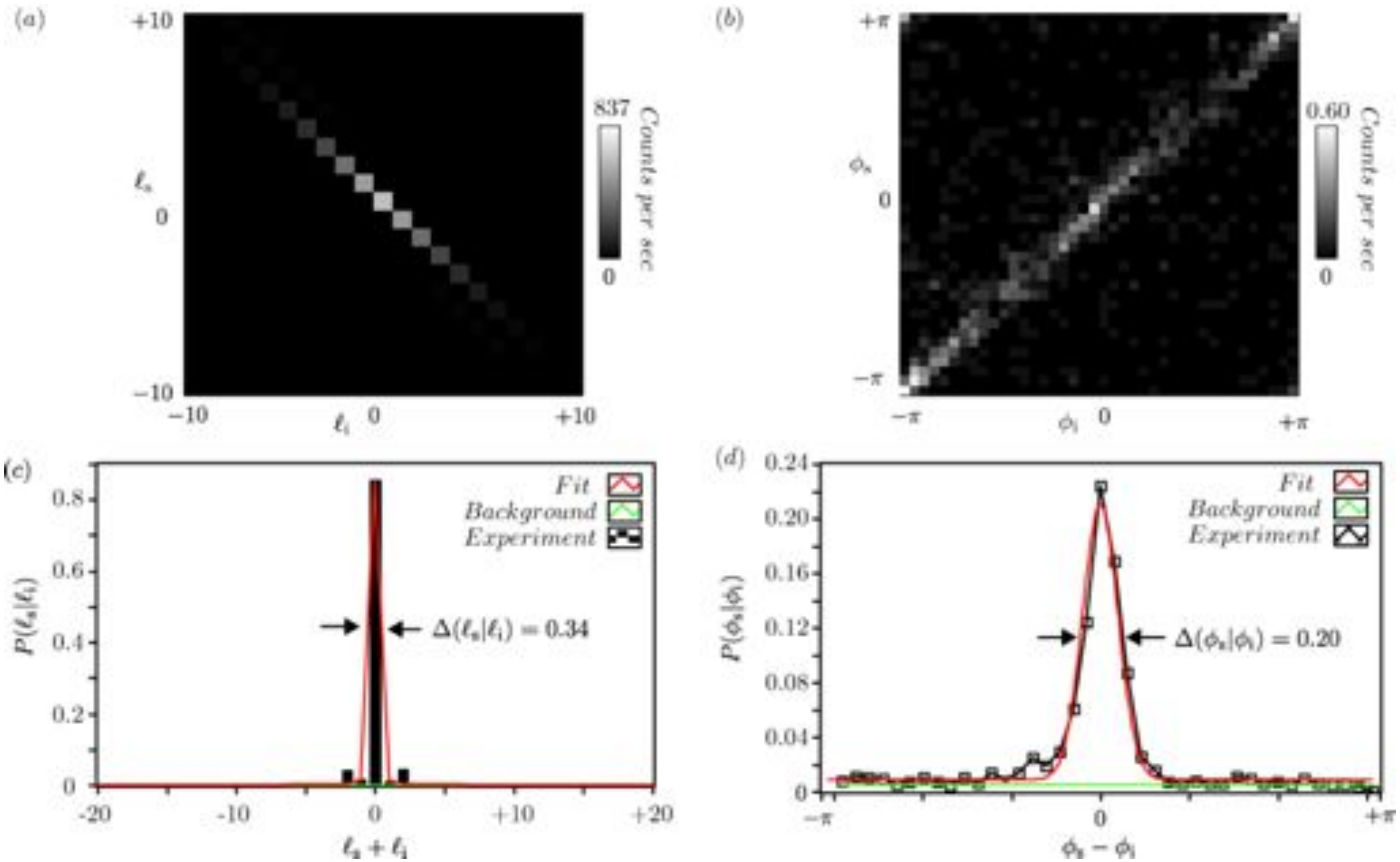
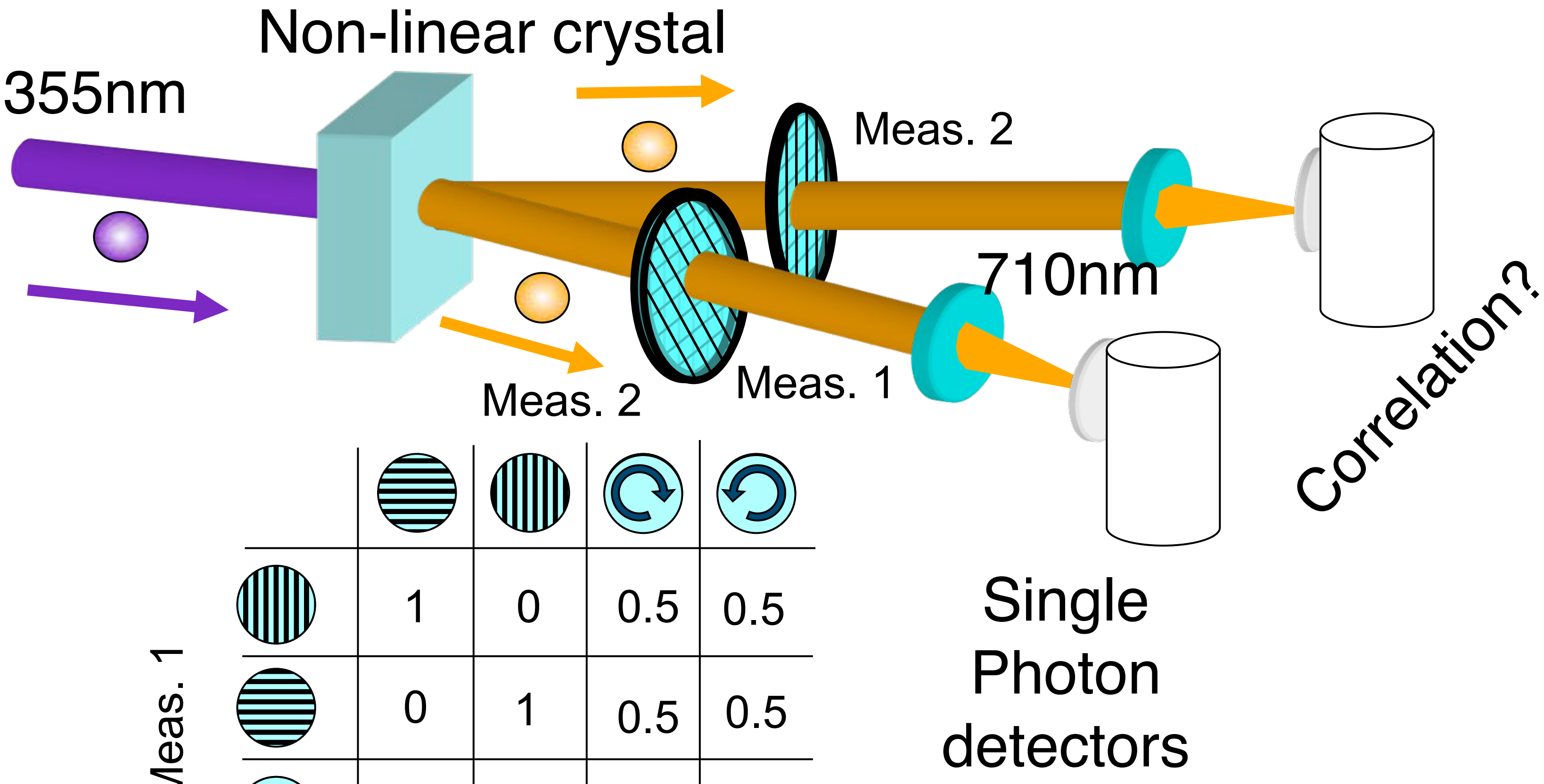
Quantum Correlations in Optical Angle Orbital Angular Momentum Variables
Jonathan Leach, *et al.*
Science **329**, 662 (2010);

Angular EPR



$$\left[\Delta\left(\ell_s|\ell_i\right)\hbar\right]^2\left[\Delta\left(\phi_s|\phi_i\right)\right]^2 = 0.024\hbar^2 << 0.25\hbar^2$$

Quantum Entanglement – with polarisers



Meas. 1

	1	0	0.5	0.5
	0	1	0.5	0.5
	0.5	0.5	1	0
	0.5	0.5	0	1

430 OPTICS LETTERS / Vol. 24, No. 7 / April 1, 1999

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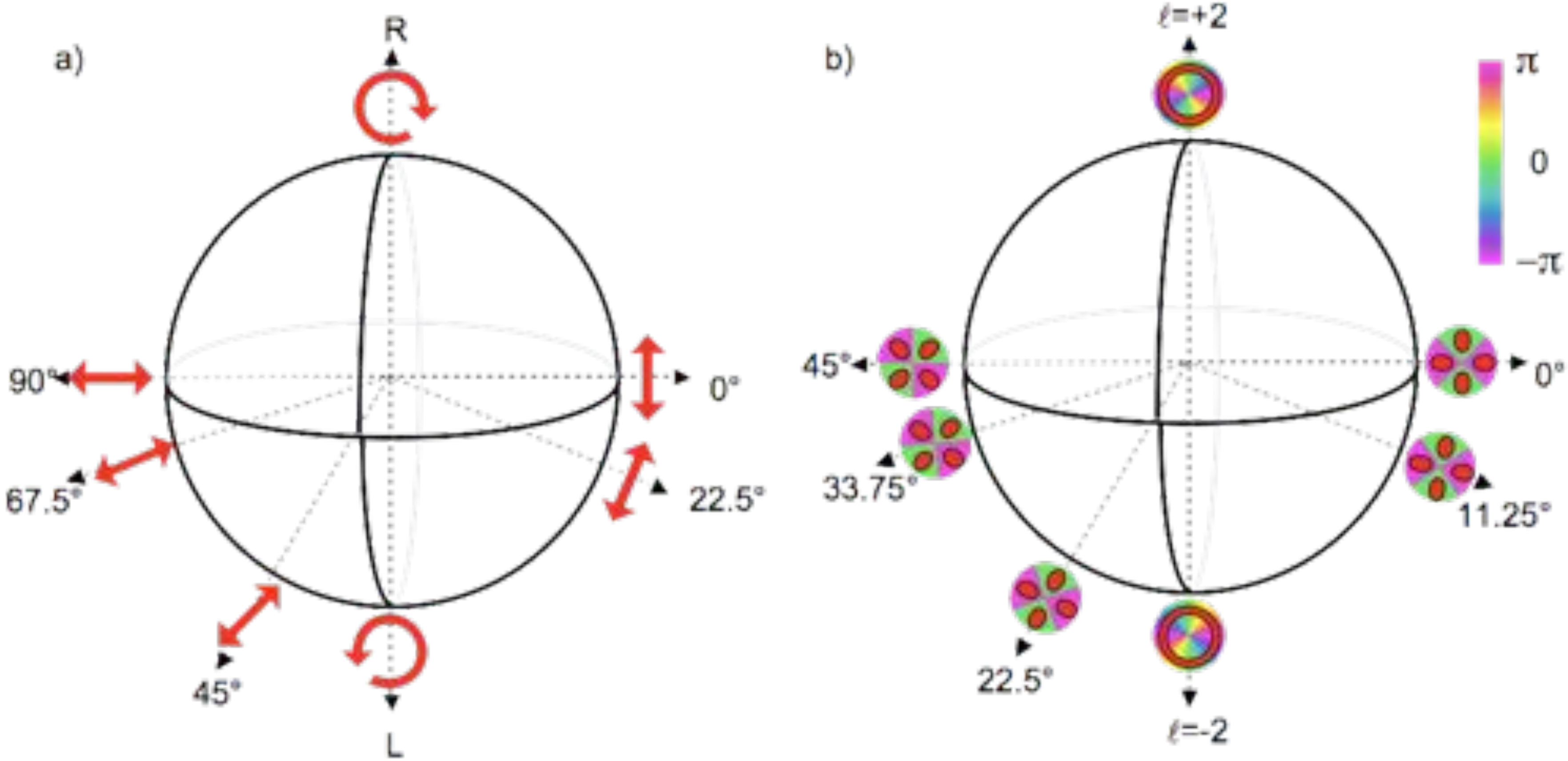
Poincaré-sphere equivalent for light beams containing orbital angular momentum

M. J. Padgett and J. Courtial

Poincaré sphere equivalent for OAM



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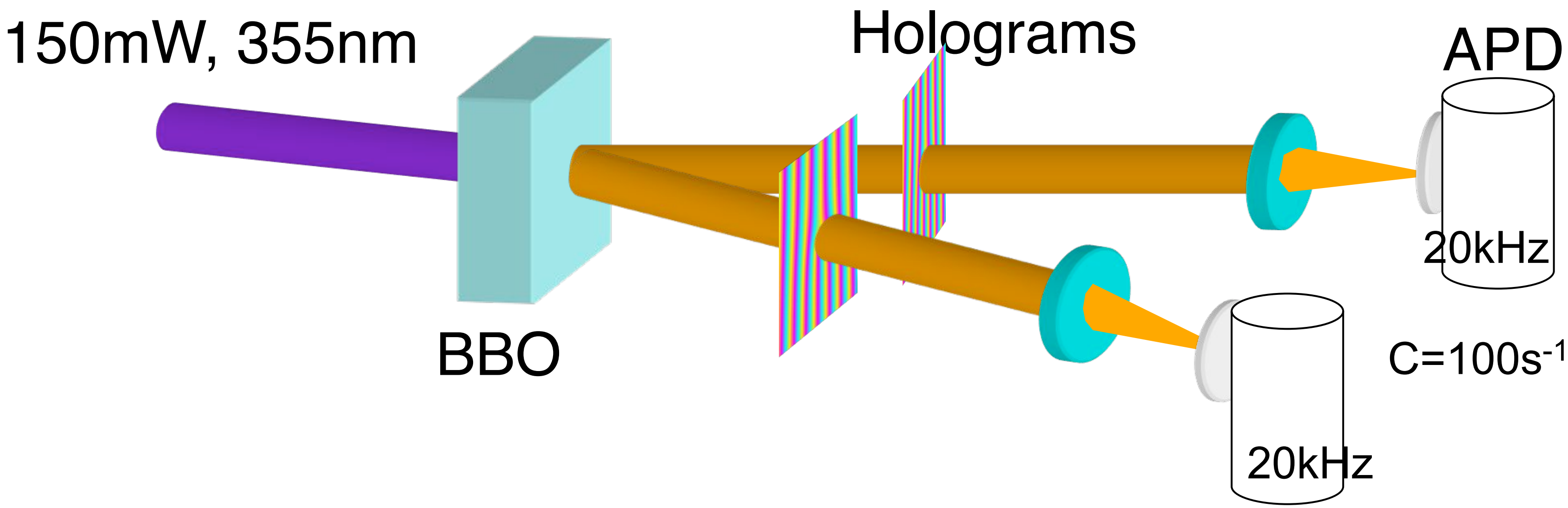
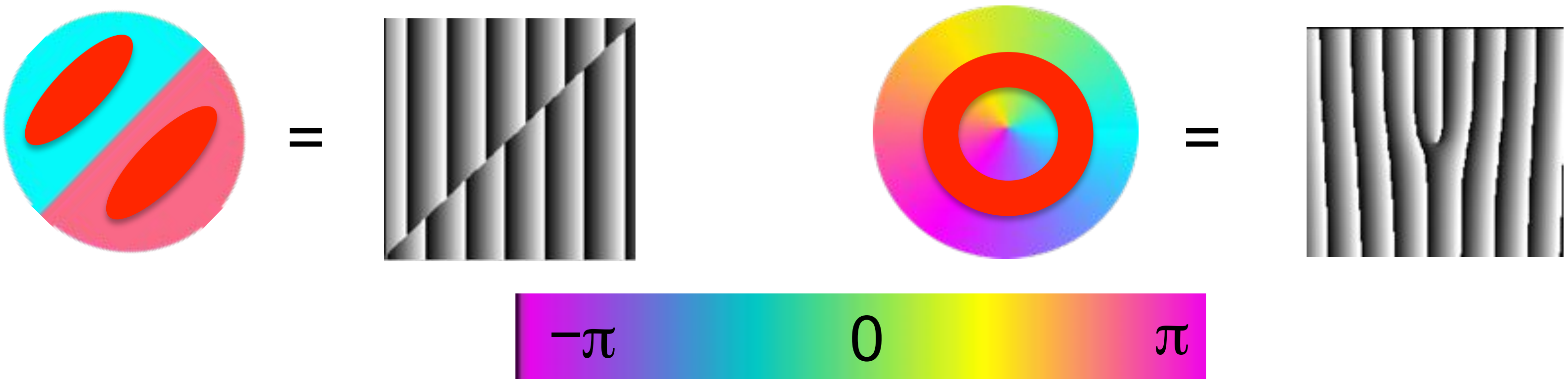
Measuring angle and angular momentum





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Violation of a Bell inequality in two-dimensional orbital angular momentum state-spaces

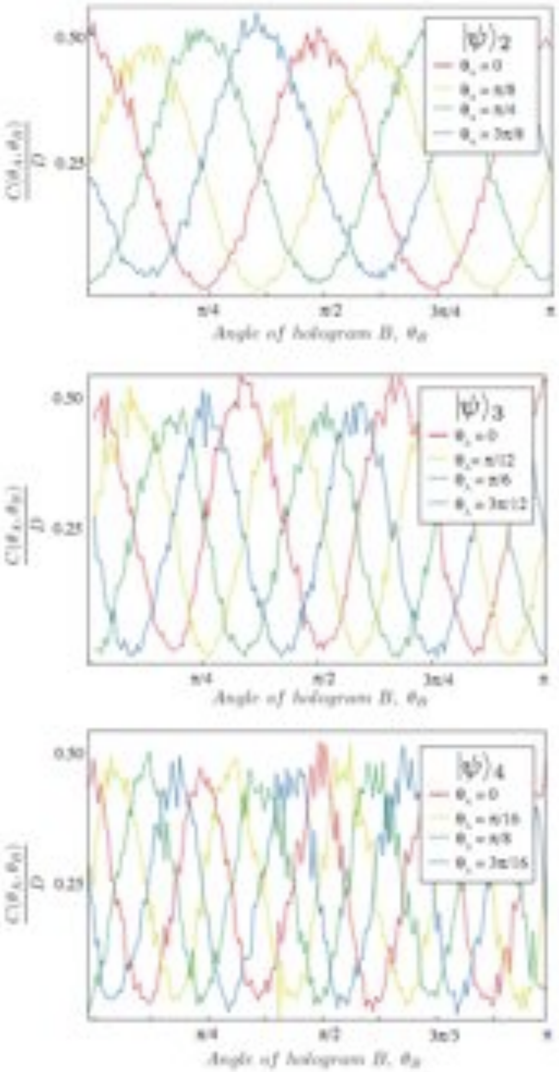
J. Leach[1], B. Jack[1], J. Romero[1], M. Ritsch-Marte[2], R. W. Boyd[3], A. K. Jha[3], S. M. Barnett[4], S. Franke-Arnold[1] and M. J. Padgett[1]

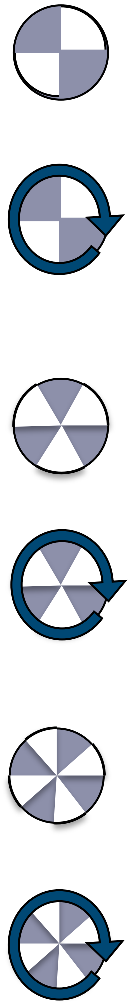
11 May 2009 / Vol. 17, No. 10 / OPTICS EXPRESS 8287

Around the "equator" of the Poincare sphere

- Bell violation for the angular variable
  - Violation for ℓ = 2,3,4, etc
  - We get a violation for ℓ<=24

Entangled state	S	Violation by σ
$\|\psi\rangle_2$	2.69 ± 0.02	35
$\|\psi\rangle_3$	2.55 ± 0.04	14
$\|\psi\rangle_4$	2.33 ± 0.07	5





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Entanglement of OAM states

Entanglement of the orbital angular momentum states of photons

NATURE | VOL 412 | 19 JULY 2001 |

Alois Mair*, Alipasha Vaziri, Gregor Weihs & Anton Zeilinger

VOLUME 93, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 30 JULY 2004

Measuring Entangled Qutrits and Their Use for Quantum Bit Commitment

N. K. Langford,* R. B. Dalton, M. D. Harvey, J. L. O'Brien, G. J. Pryde, A. Gilchrist, S. D. Bartlett, and A. G. White

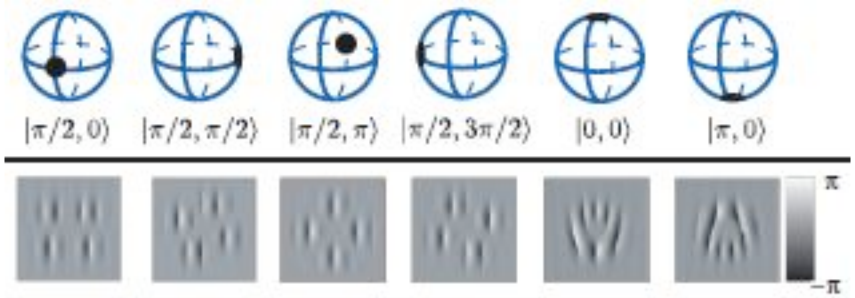
PHYSICAL REVIEW A **81**, 043844 (2010)

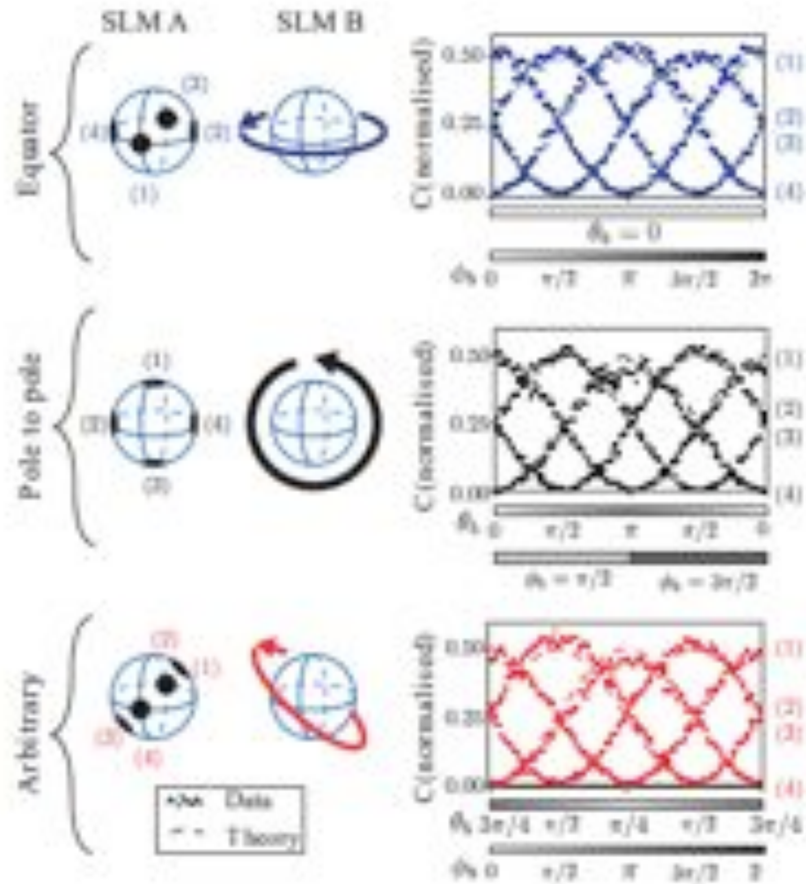
University of Glasgow

Entanglement of arbitrary superpositions of modes within two-dimensional orbital angular momentum state spaces

B. Jack,[1] A. M. Yao,[2] J. Leach,[1] J. Romero,[1,2] S. Franke-Arnold,[1] D. G. Ireland,[1] S. M. Barnett,[2] and M. J. Padgett[1]

Measuring anywhere on the sphere





New Journal of Physics
The open-access journal for physics

Violation of Leggett inequalities in orbital angular momentum subspaces

J Romero[1,2], J Leach[1], B Jack[1], S M Barnett[2], M J Padgett[1] and S Franke-Arnold[1,3]

New Journal of Physics **12** (2010) 123007

Demo

University of Glasgow

Optical Knots

Kevin O’Holleran

Florian Flossmann

Mark Dennis (Bristol)

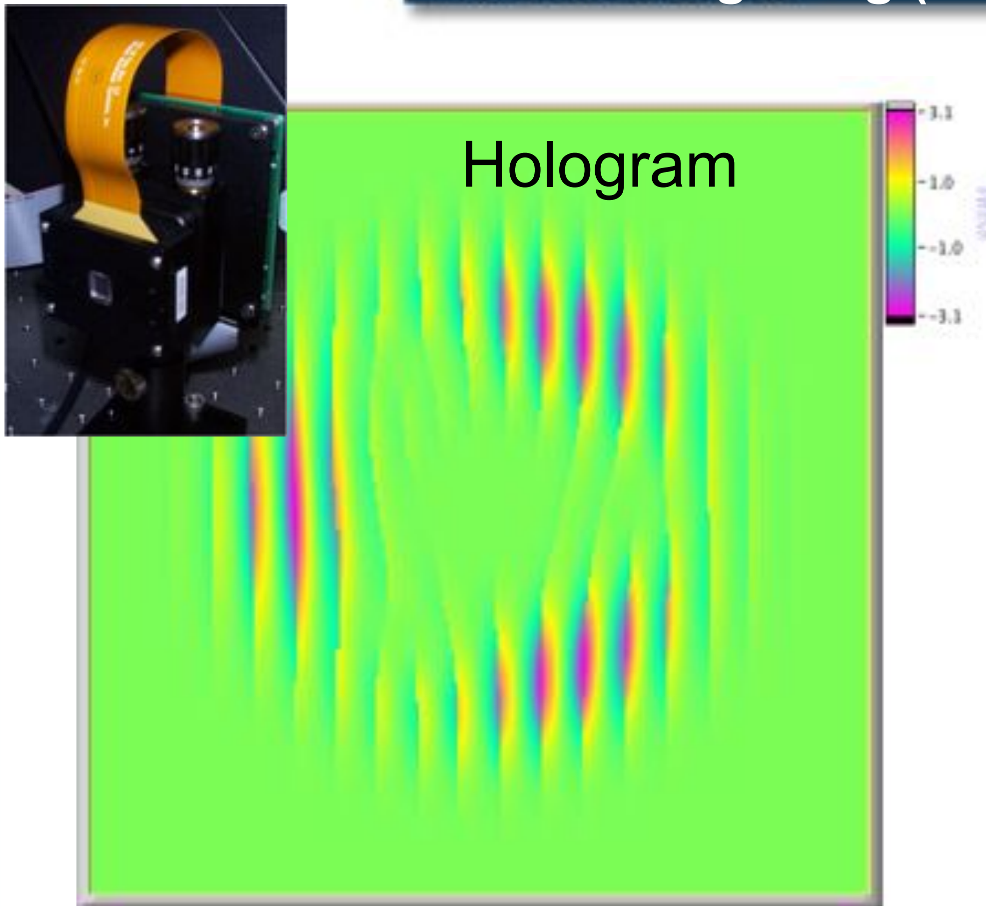
LETTERS
PUBLISHED ONLINE: 17 JANUARY 2010 | DOI: 10.1038/NPHYS1504
nature physics

University of Glasgow

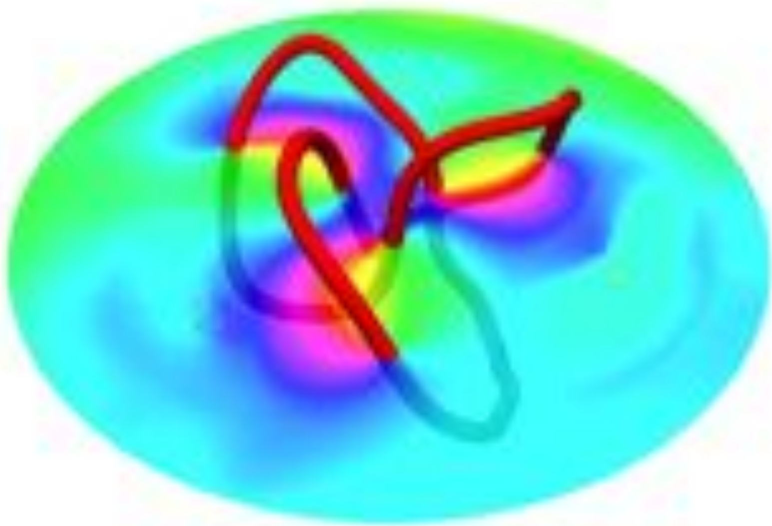
Isolated optical vortex knots

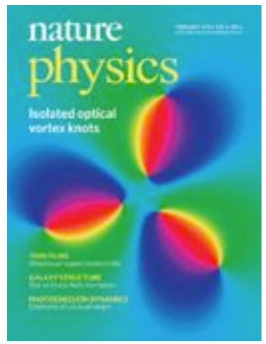
Mark R. Dennis[1]*, Robert P. King[1,2], Barry Jack[3], Kevin O'Holleran[3] and Miles J. Padgett[3]*

Diffraction grating (hologram) to make Knots

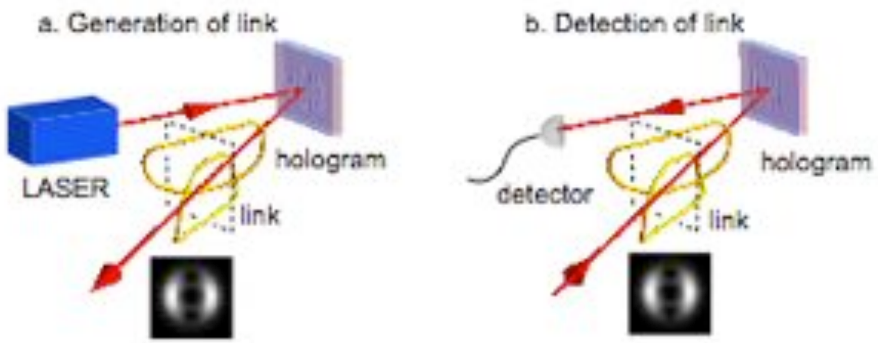


Hologram to shape phase *AND* intensity



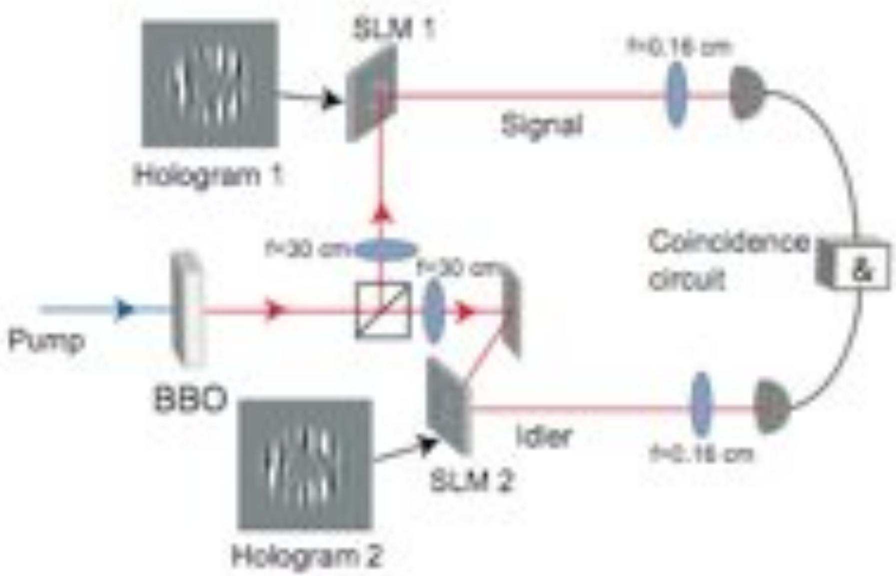


Entangled, tangles



Hologram to make OR measure beam

Non-local measurement of separated topological features in the EM field



PRL 106, 100407 (2011) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2011

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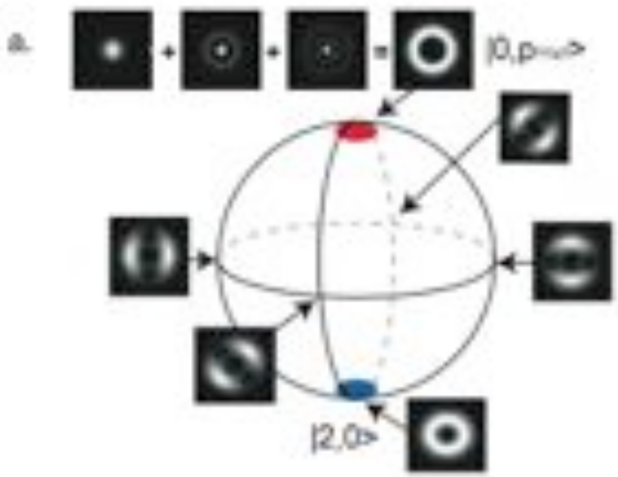
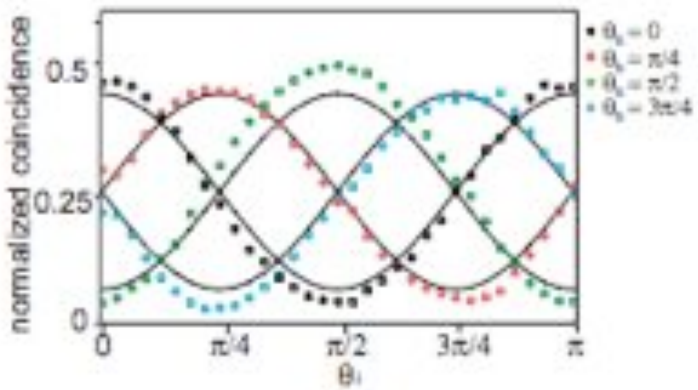
Entangled Optical Vortex Links

J. Romero,[1,2] J. Leach,[1] B. Jack,[1] M. R. Dennis,[3] S. Franke-Arnold,[1] S. M. Barnett,[2] and M. J. Padgett[1]

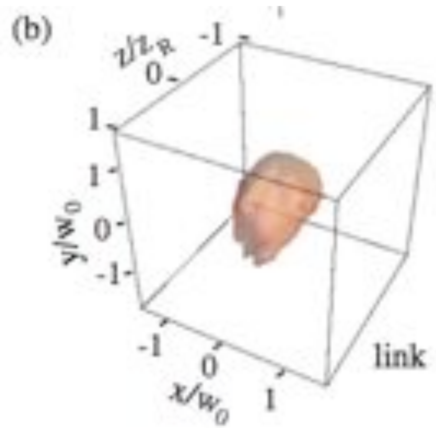
Correlations to show Quantum Entanglement



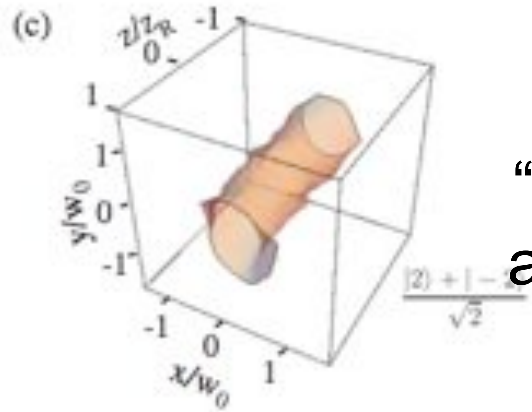
Two-state formation of links allows "Bell-test"



Volume over which S>2



Links are "entangled" *only* over finite volume



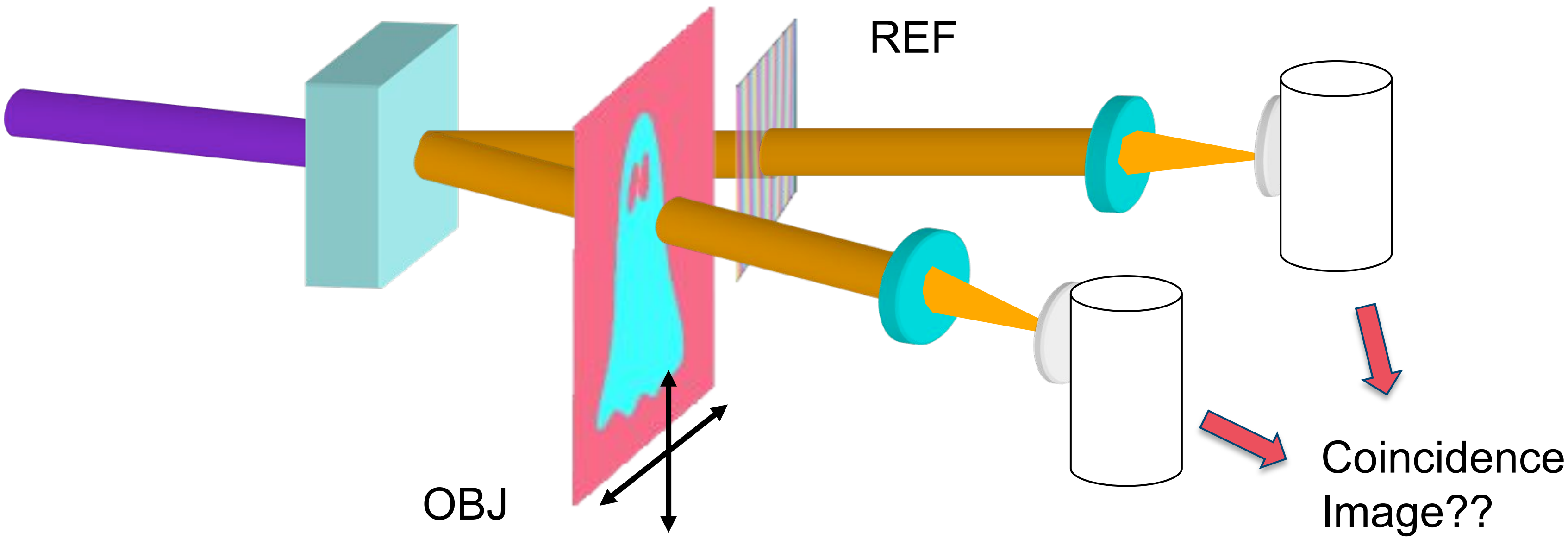
OAM "entangled" along entire beam axis

Holographic Ghost Imaging

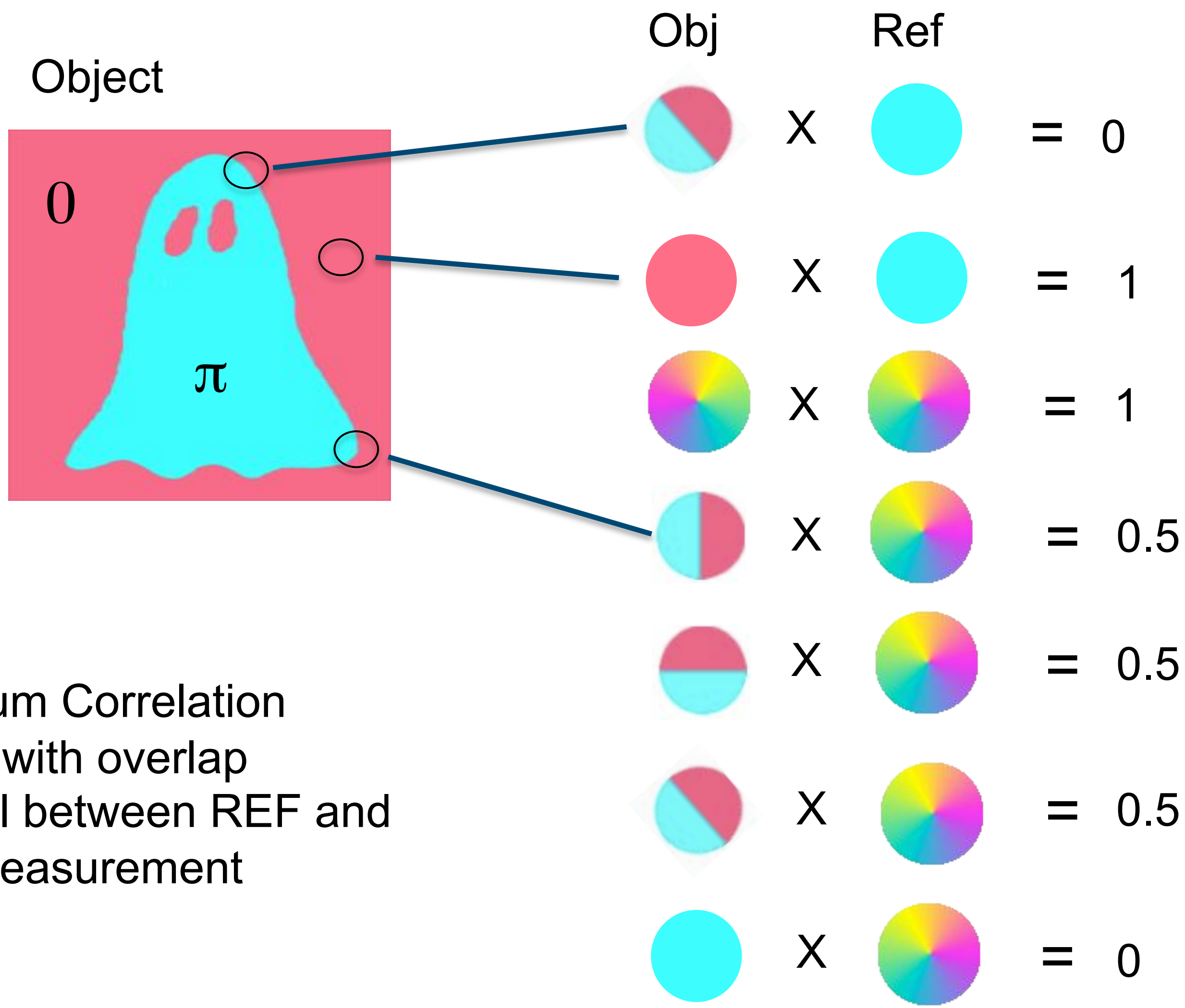
B. Jack, J. Leach, J. Romero, S. Franke-Arnold, M. Ritsch-Marte, S. M. Barnett, and M. J. Padgett

University of Glasgow

Holographic Ghost Imaging



Ghost Edge Detection



Quantum Correlation scales with overlap integral between REF and OBJ measurement

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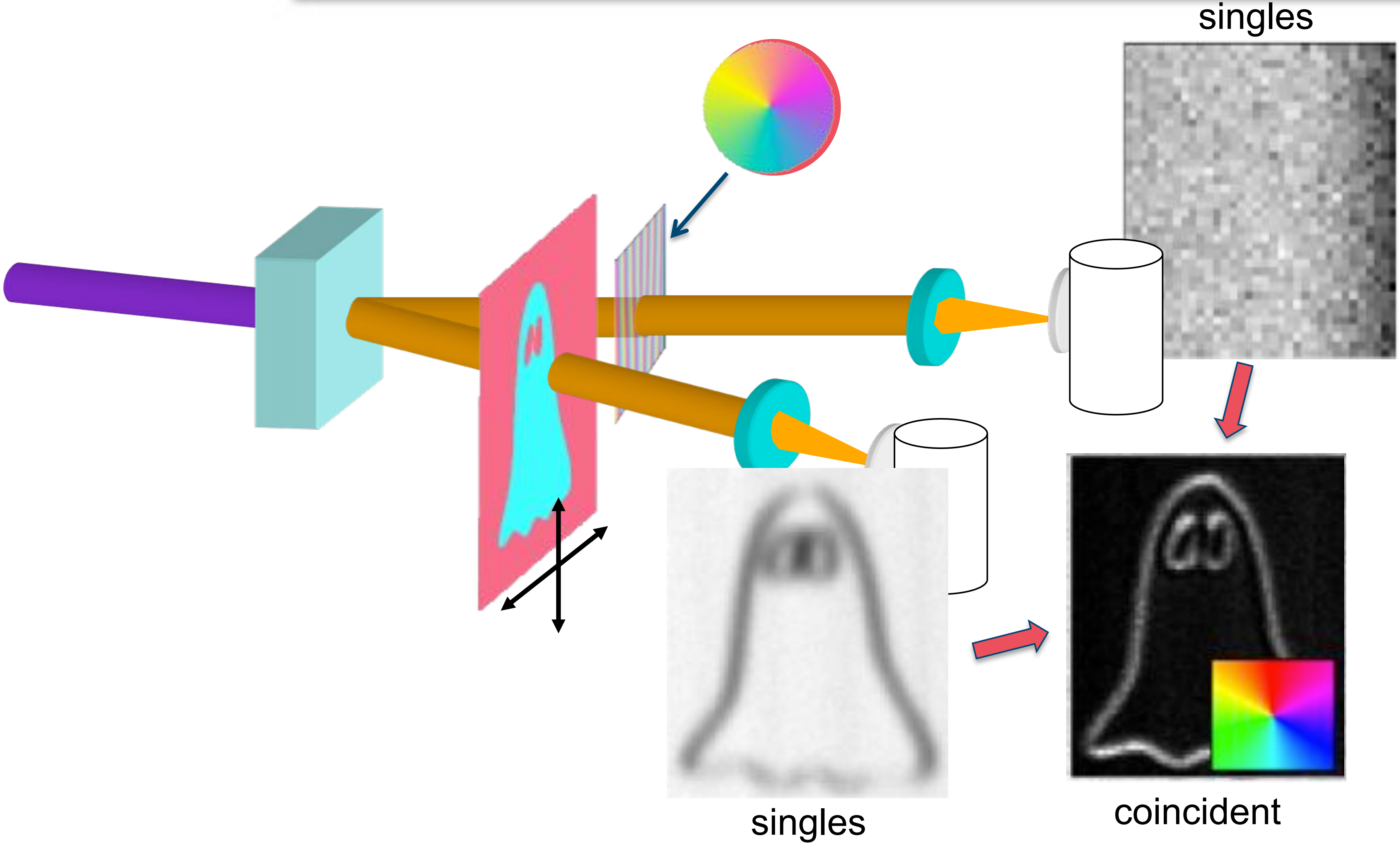
Holographic Ghost Imaging



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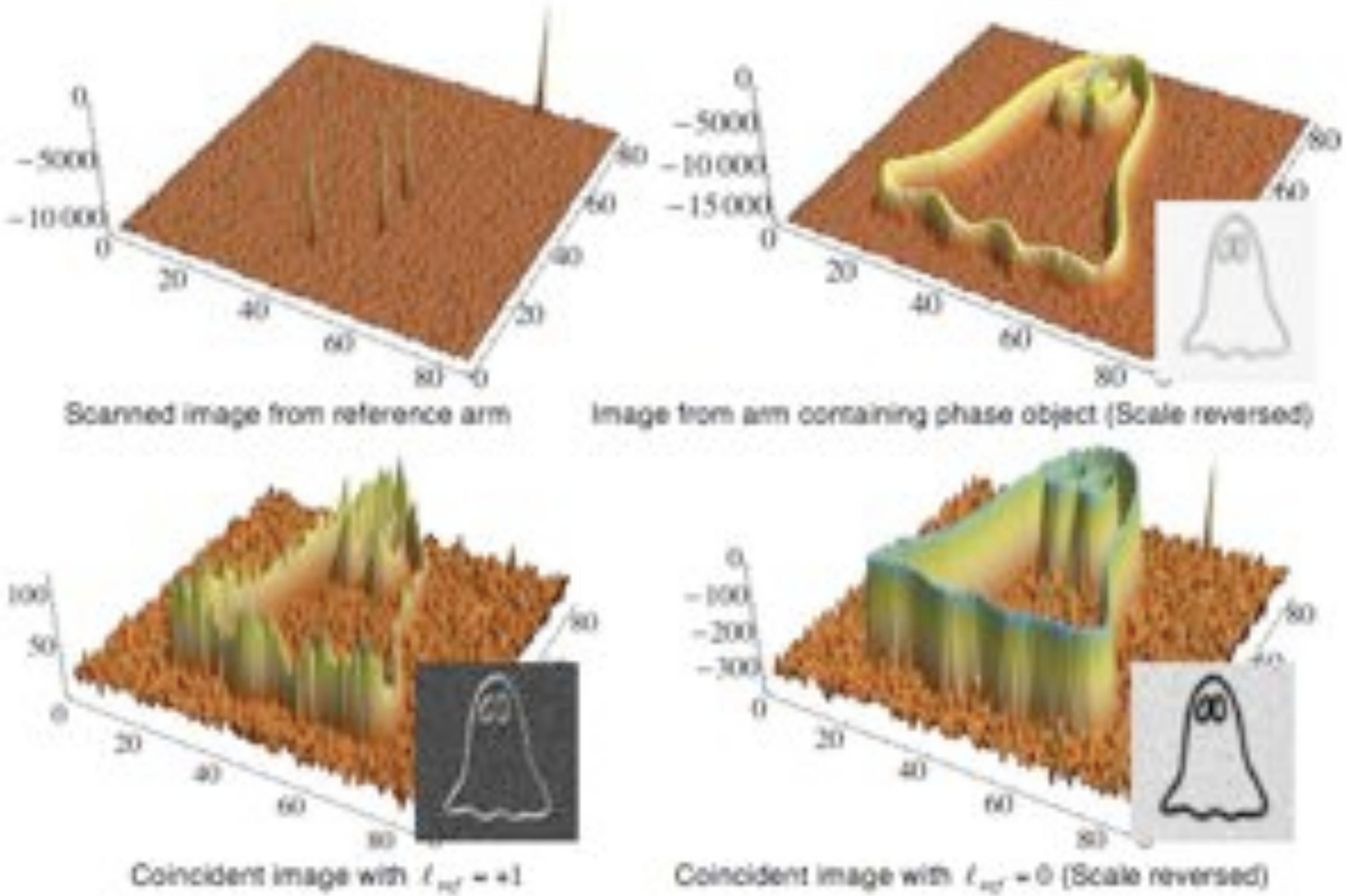
Edge Enhanced images



Preliminary single channel and coincidence images obtained from our demonstration ghost imaging system. Note both enhanced contrast and enhanced resolution of coincident image compared to single channel

430 OPTICS LETTERS / Vol. 24, No. 7 / April 1, 1999

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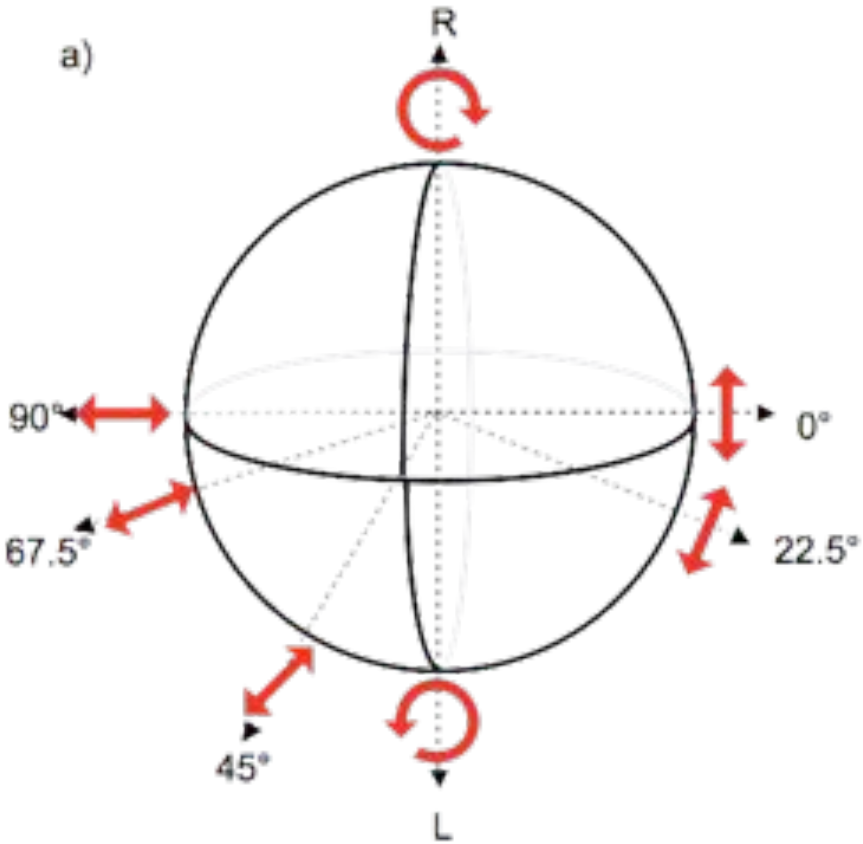
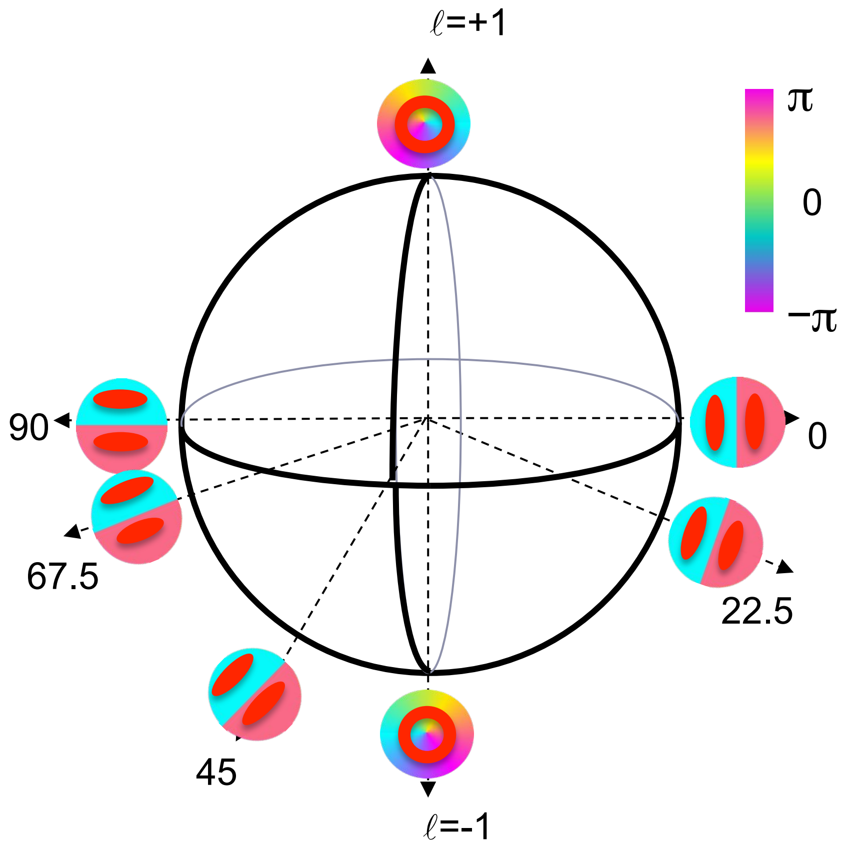
Poincaré-sphere equivalent for light beams containing orbital angular momentum

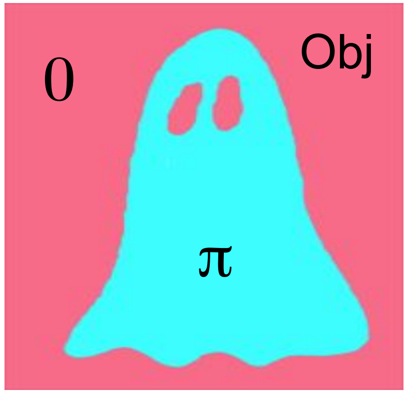
M. J. Padgett and J. Courtial

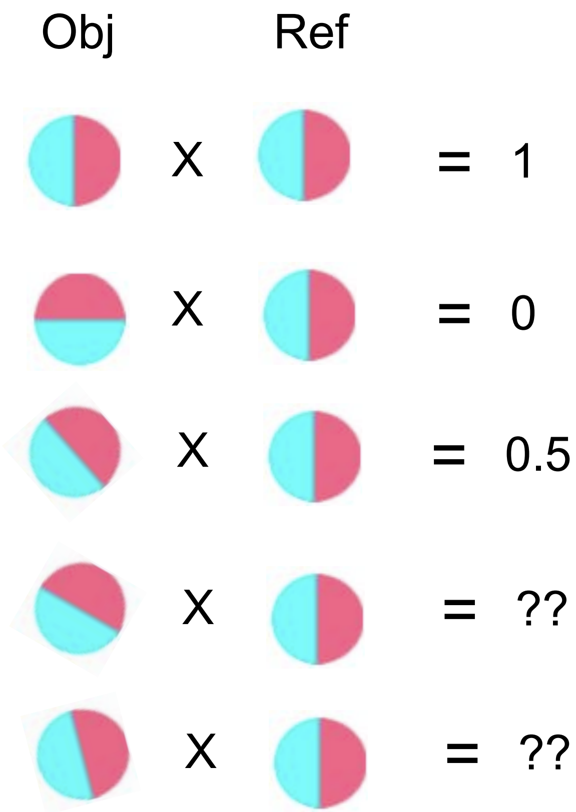
Poincaré sphere equivalent for OAM





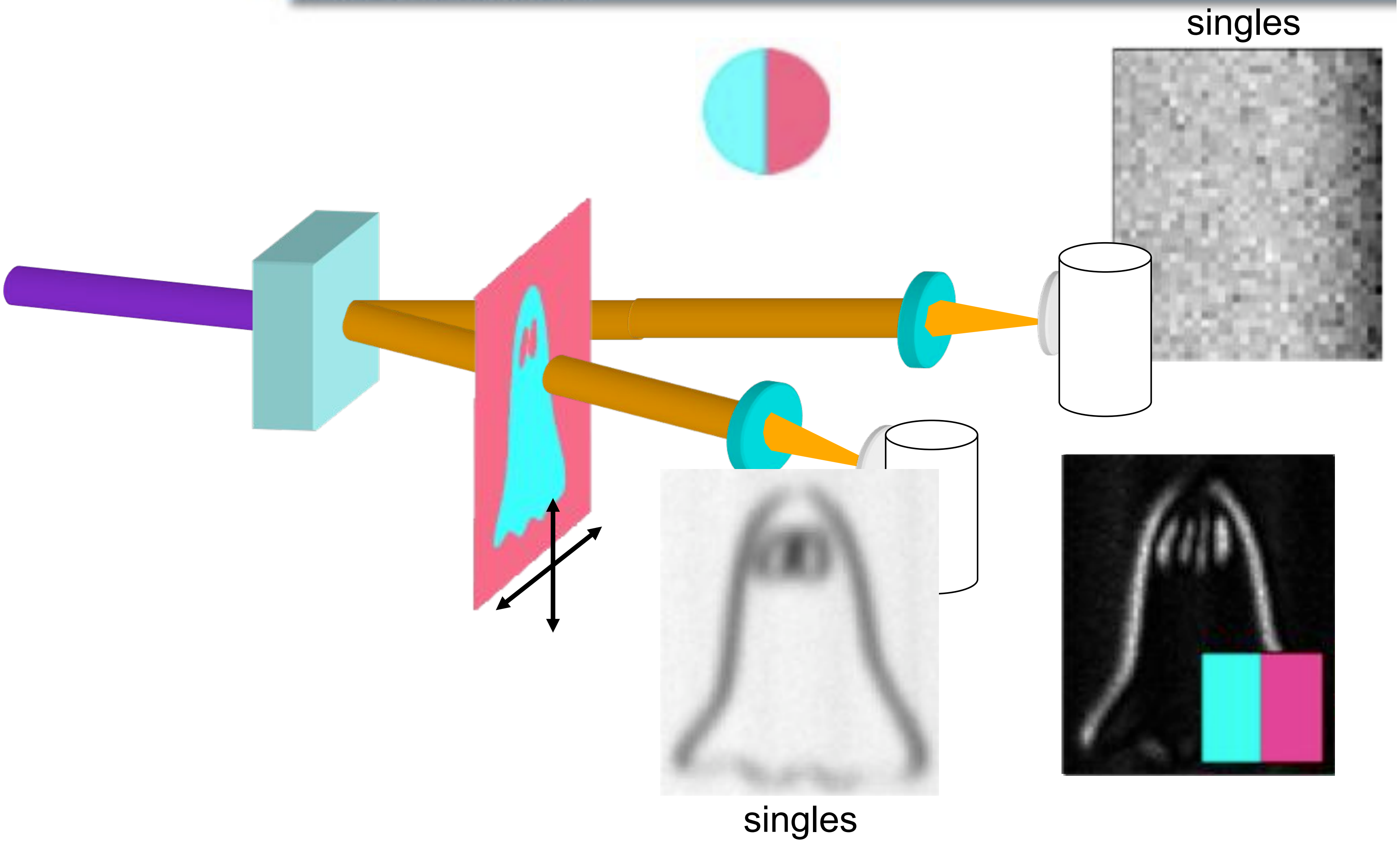
Ghost Edge Detection





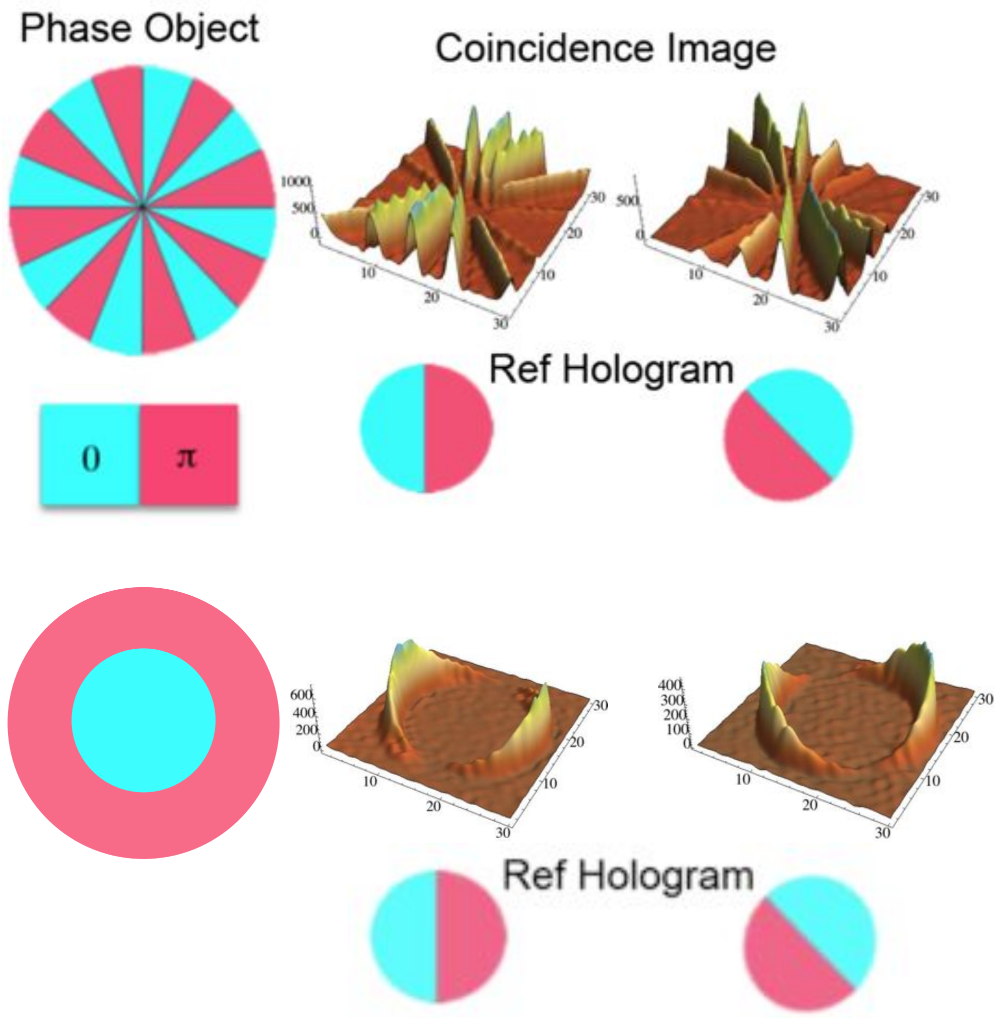
Correlation proportional to overlap integral between REF and OBJ measurement

Holographic Ghost Imaging



Edge enhancement of phase object

- Single mode coincident image
- Enhancement of edge depends upon its orientation
- Sinusoidal dependence ?



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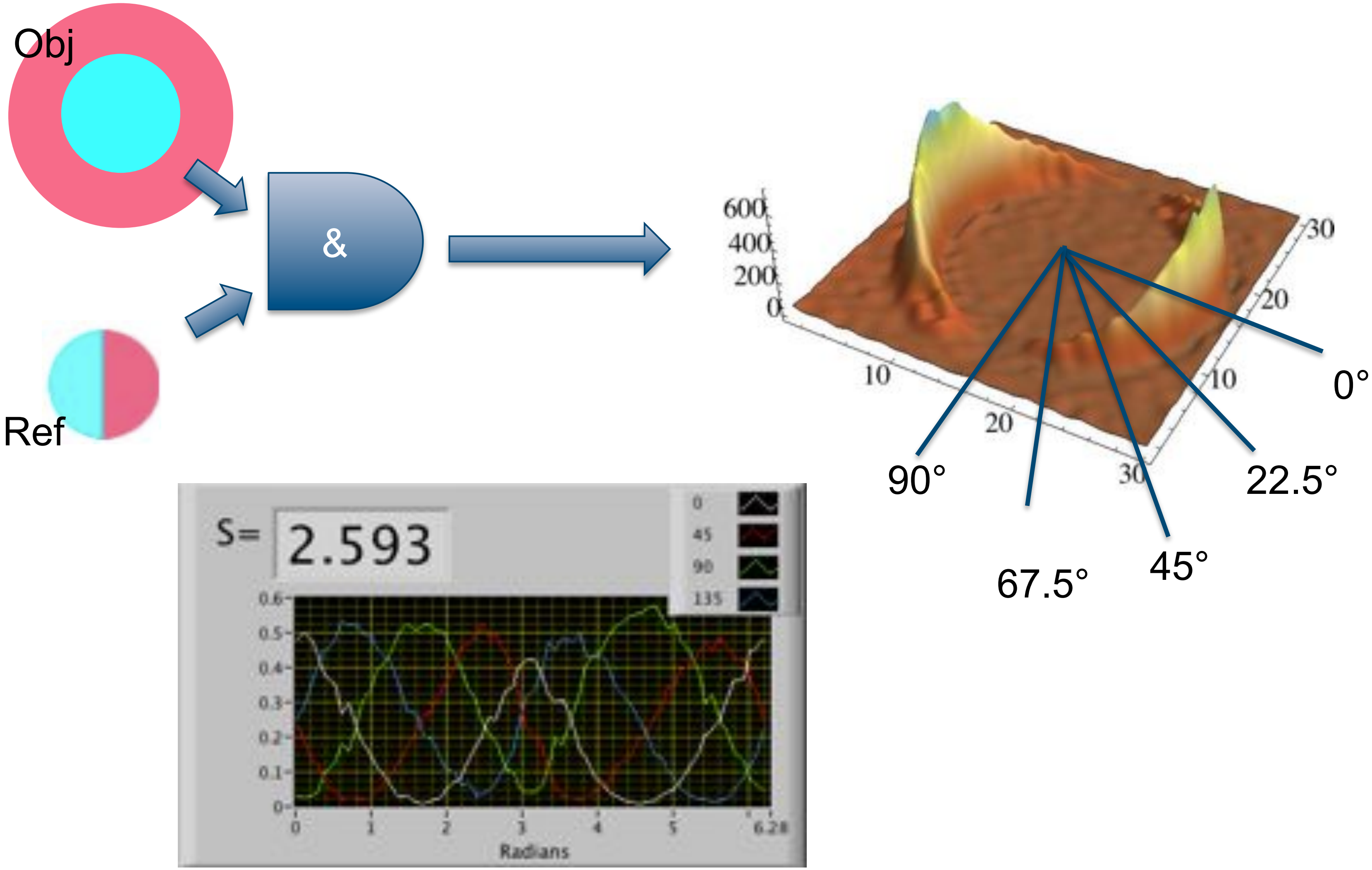
Does this image show the Quantum in the Ghost?



Full-field Quantum Correlations

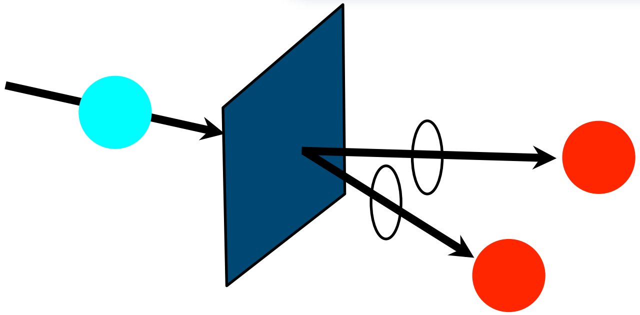
J. Leach, R. E. Warburton, D. G. Ireland, F. Izdebski, S. M. Barnett, A. M. Yao, G. S. Buller and M. J. Padgett

University of Glasgow

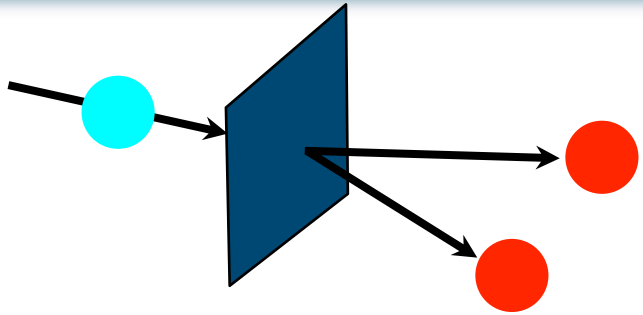
VOLUME 92, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 28 MAY 2004

Realization of the Einstein-Podolsky-Rosen Paradox Using Momentum- and Position-Entangled Photons from Spontaneous Parametric Down Conversion

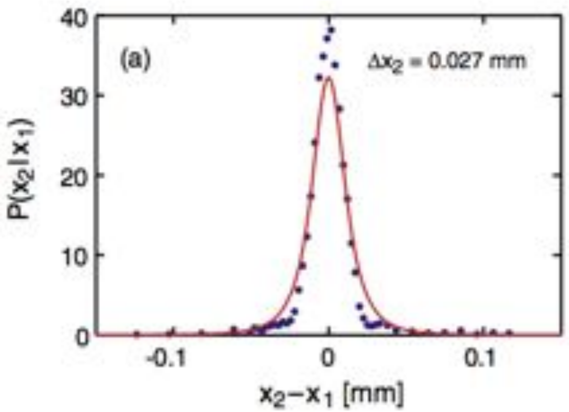
John C. Howell,[1] Ryan S. Bennink,[2] Sean J. Bentley,[2,*] and R.W. Boyd[2]
[1]*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA*
[2]*The Institute of Optics, University of Rochester, Rochester, New York 14627, USA*
(Received 15 September 2003; published 28 May 2004)

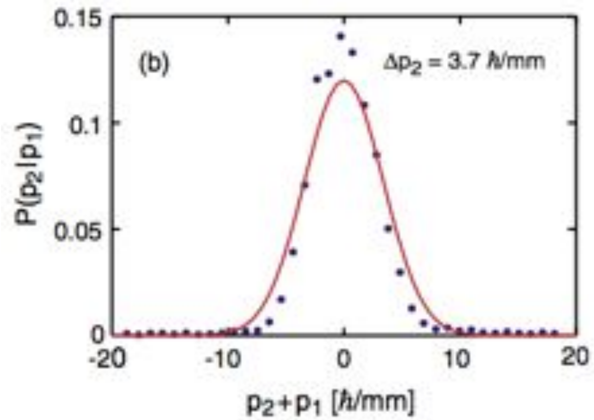


Position correlations



Momentum correlations





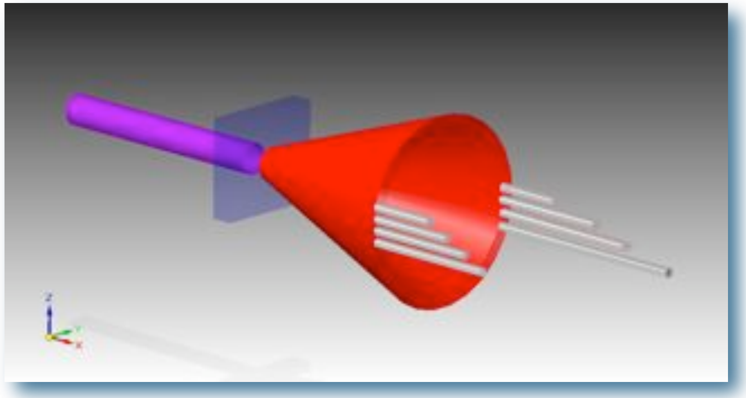
PRL 94, 220501 (2005) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2005

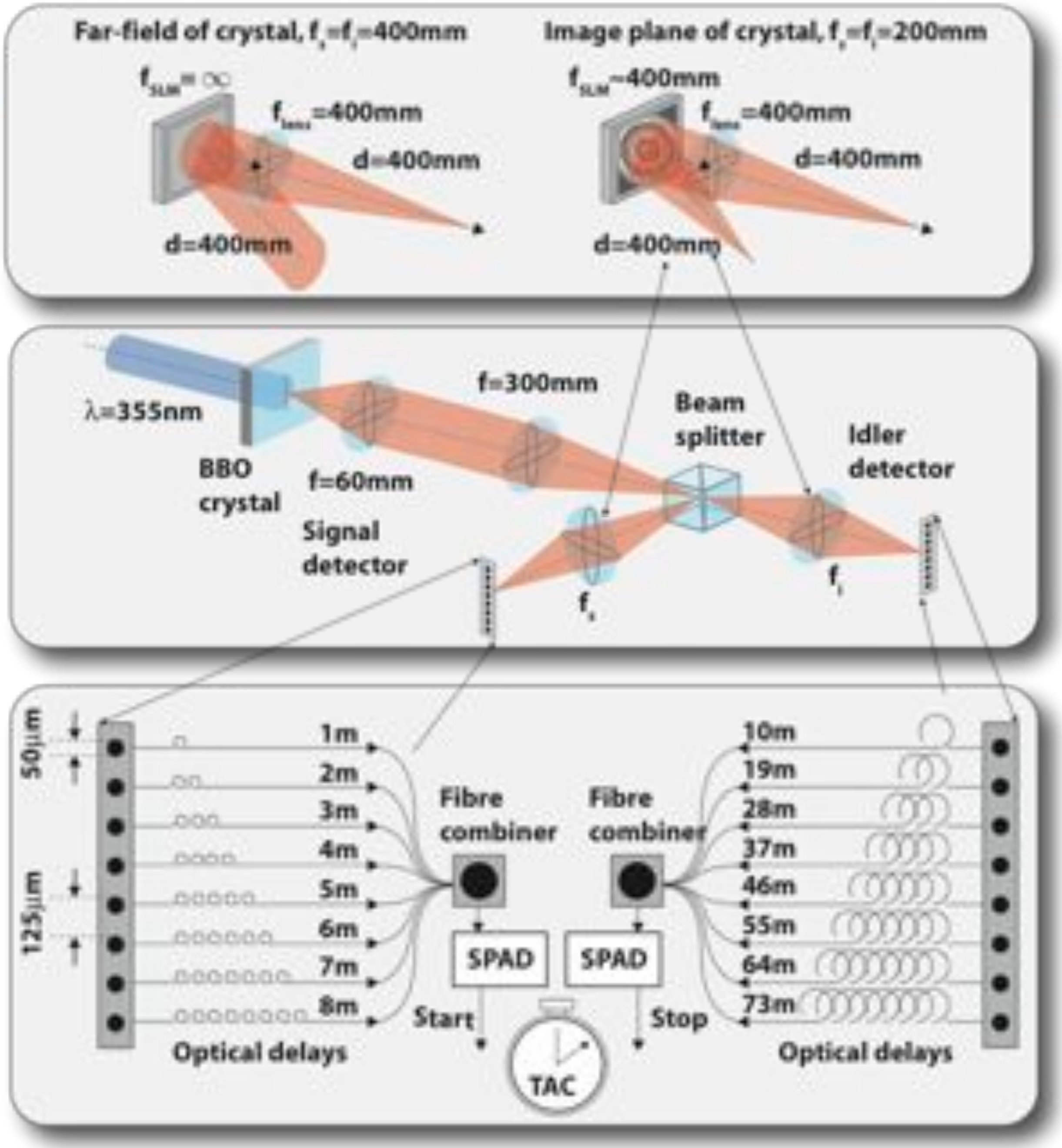
Pixel Entanglement: Experimental Realization of Optically Entangled $d = 3$ and $d = 6$ Qudits

Malcolm N. O'Sullivan-Hale,[1,*] Irfan Ali Khan,[2] Robert W. Boyd,[1,2] and John C. Howell[2]
[1]*The Institute of Optics, University of Rochester, Rochester, New York 14627, USA*
[2]*The Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA*
(Received 25 May 2004; published 7 June 2005)

The “idea”

- Use a fibre array to measure lateral position of single photons
- Join all fibres to the same detector
- Make fibres of different length to convert position to time
- Utilises that APDs have timing resolution far better than their reciprocal max. count rate





Far-field of crystal, f_s=f_i=400mm
Image plane of crystal, f_s=f_i=200mm
f_SLM= ∞
f_lens=400mm
d=400mm
d=400mm
f_SLM=400mm
f_lens=400mm
d=400mm
d=400mm
λ=355nm
BBO crystal
f=60mm
f=300mm
Beam splitter
Idler detector
Signal detector
f_s
f_i
50μm
125μm
1m
2m
3m
4m
5m
6m
7m
8m
Fibre combiner
Fibre combiner
10m
19m
28m
37m
46m
55m
64m
73m
SPAD
SPAD
Start
Stop
TAC
Optical delays
Optical delays

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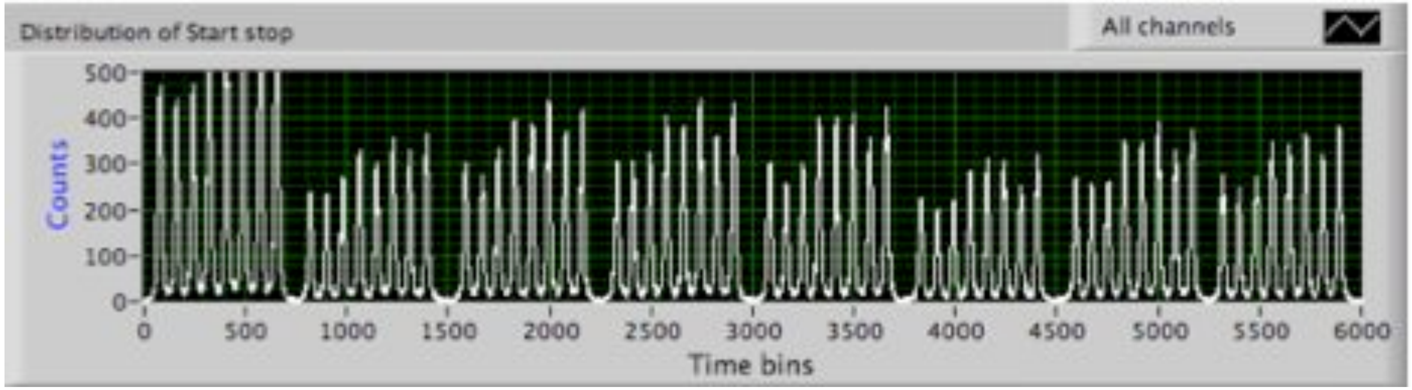
Time to position



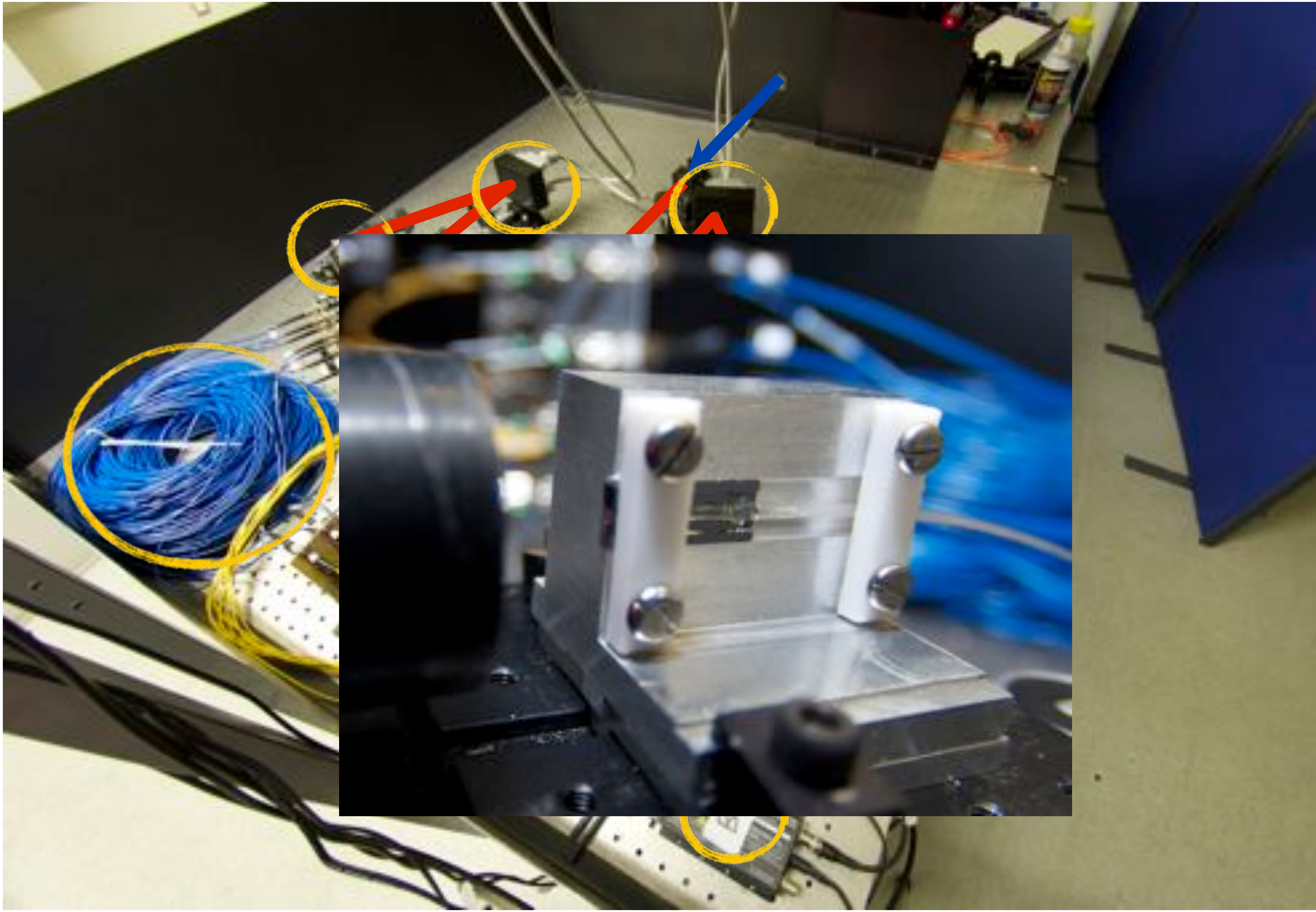
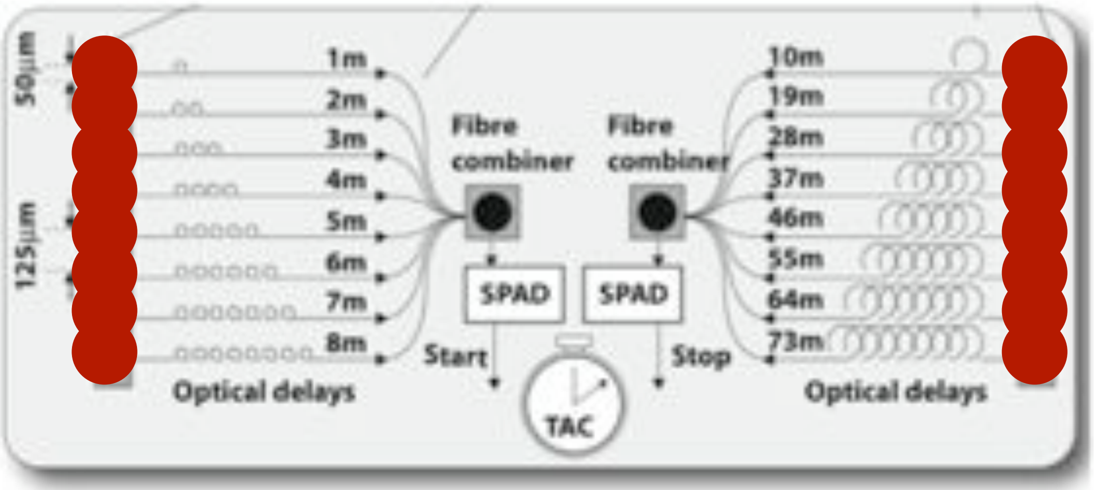
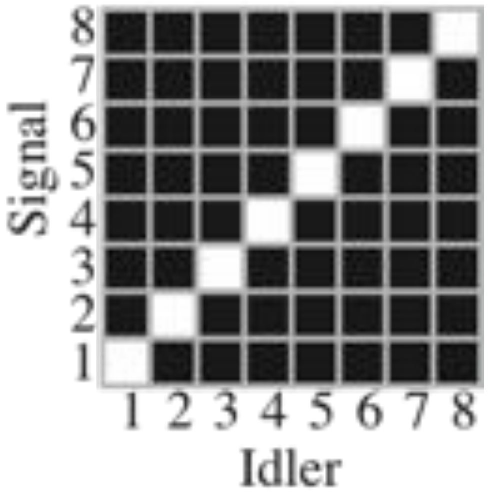
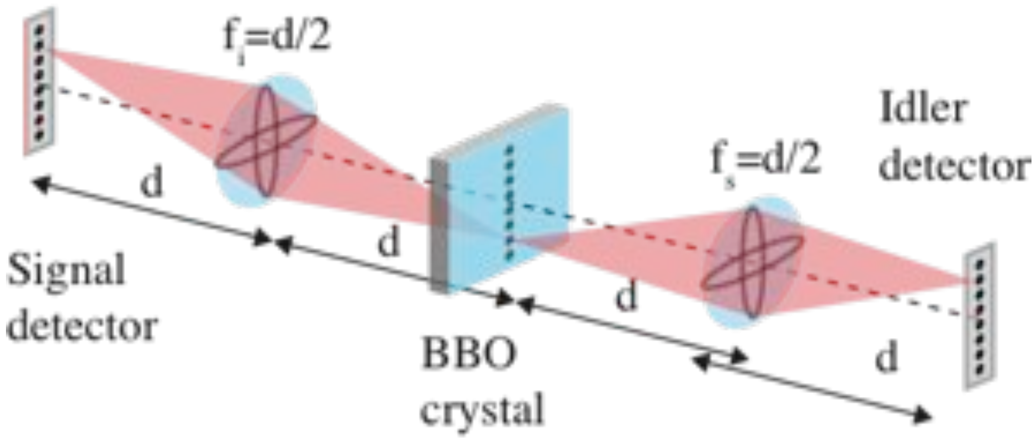


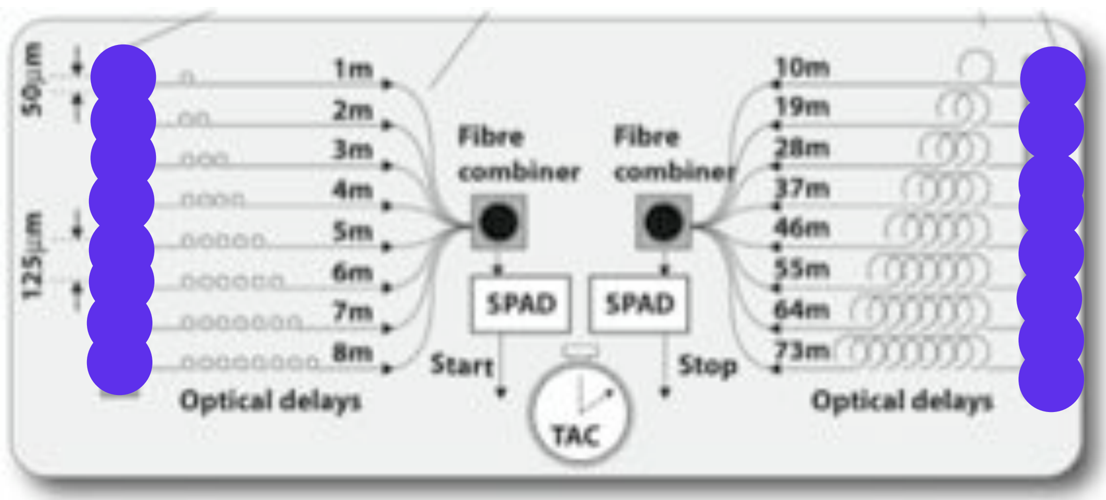
Image plane correlations

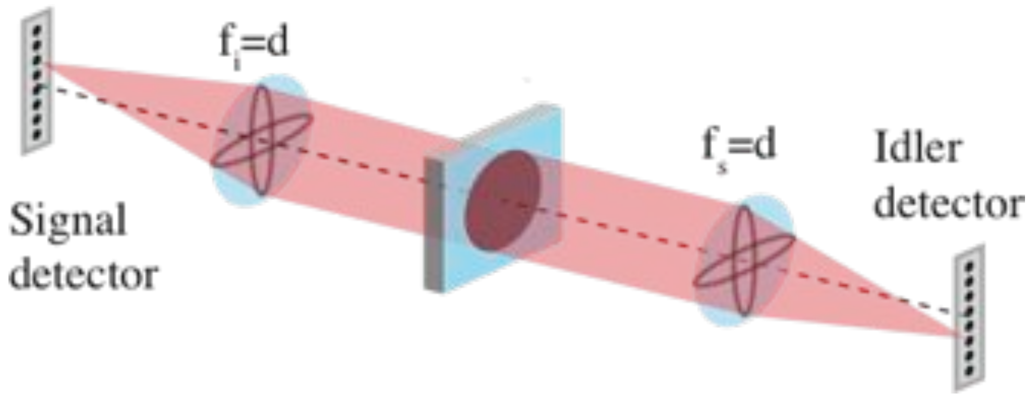






Far-field correlations





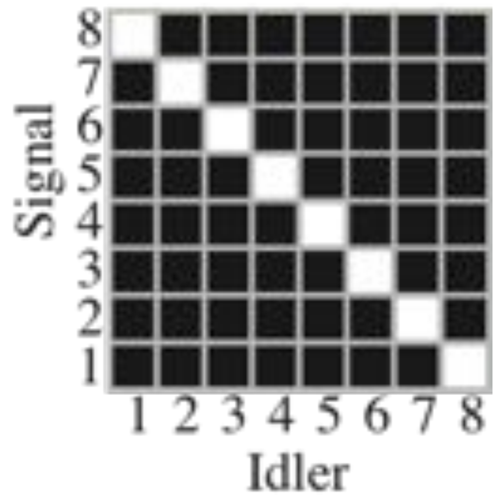
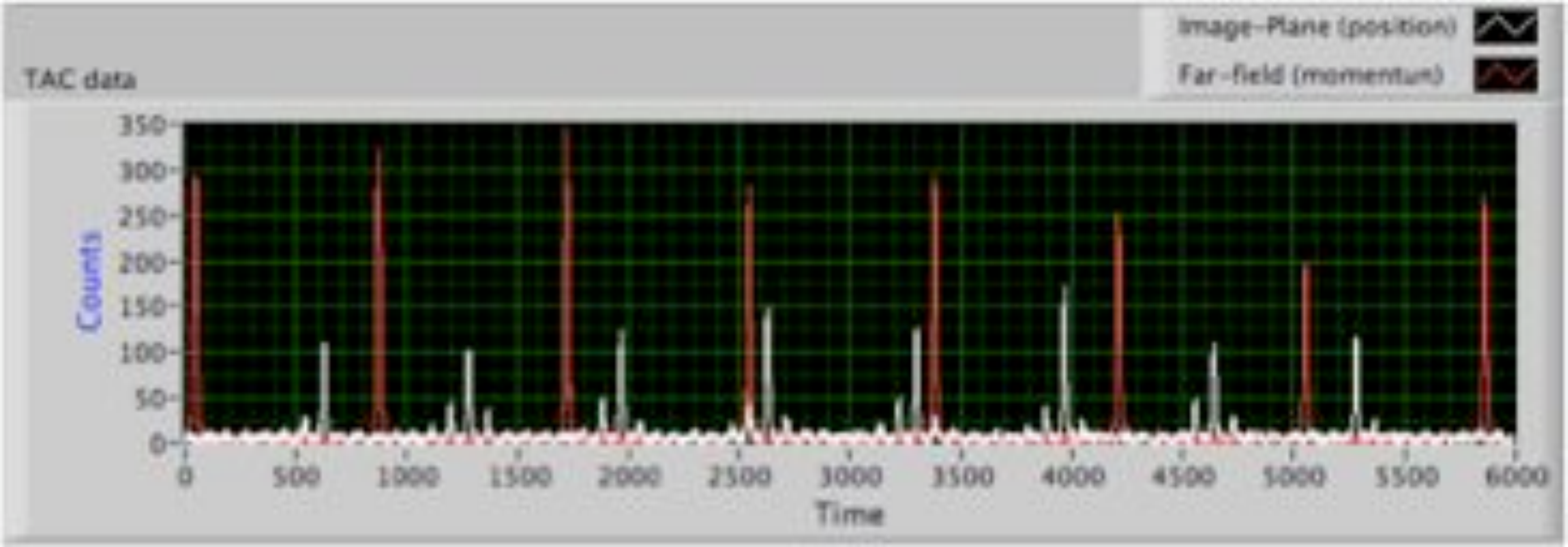
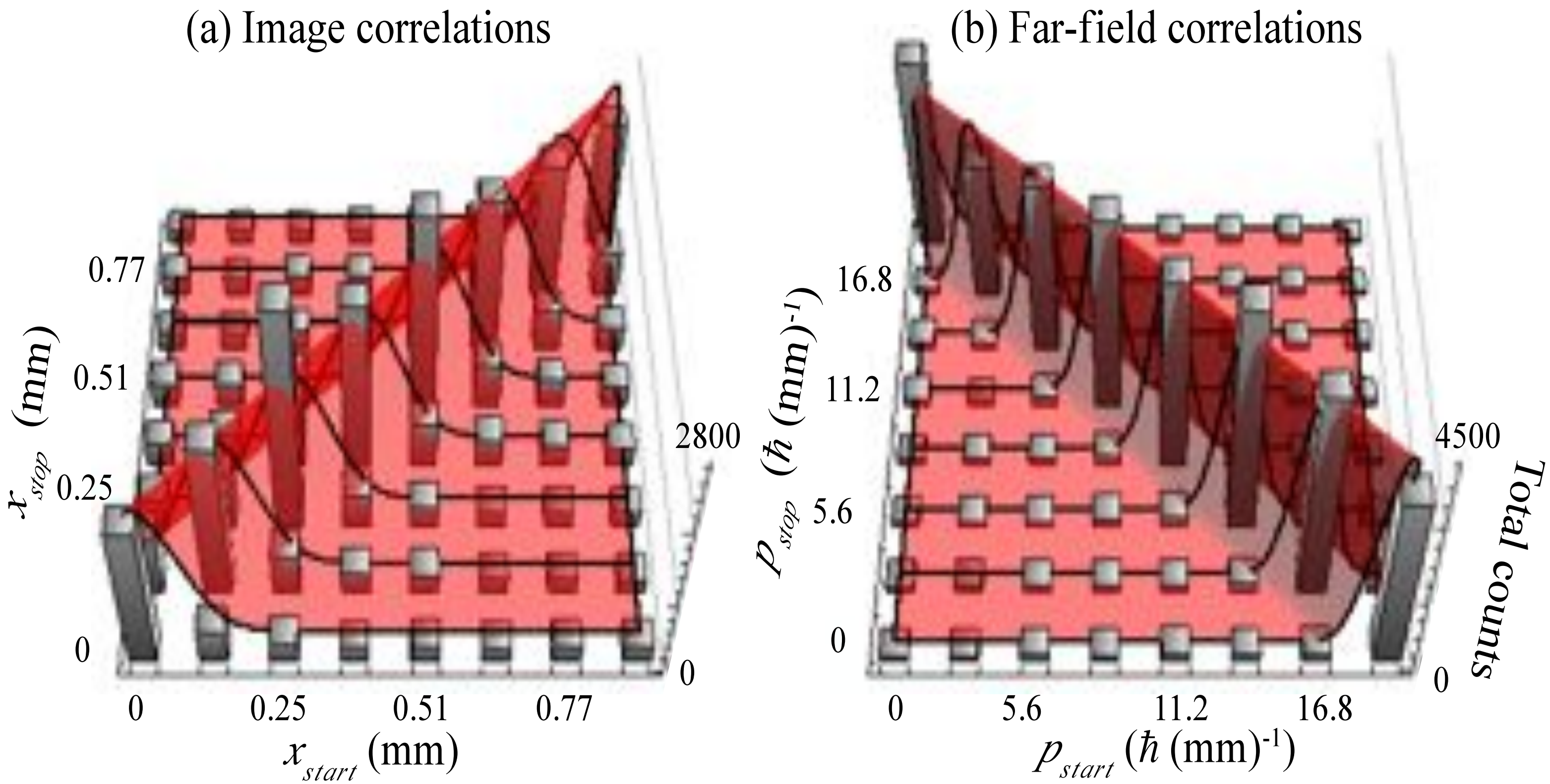


Image and Far-field stop-start timing data



Our results (again)



$$\Delta_{\inf} x^2 \Delta_{\inf} p_x^2 = 0.016\hbar^2$$

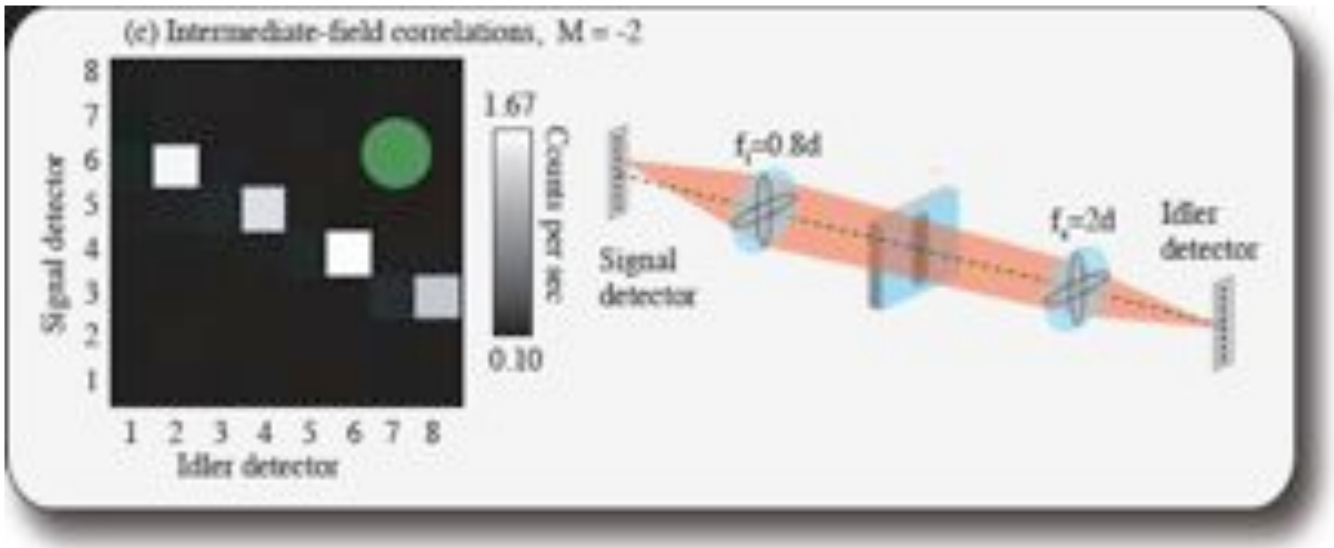
Between Image and Far-field to intermediate

PHYSICAL REVIEW A VOLUME 53, NUMBER 4 APRIL 1996

Two-photon geometric optics

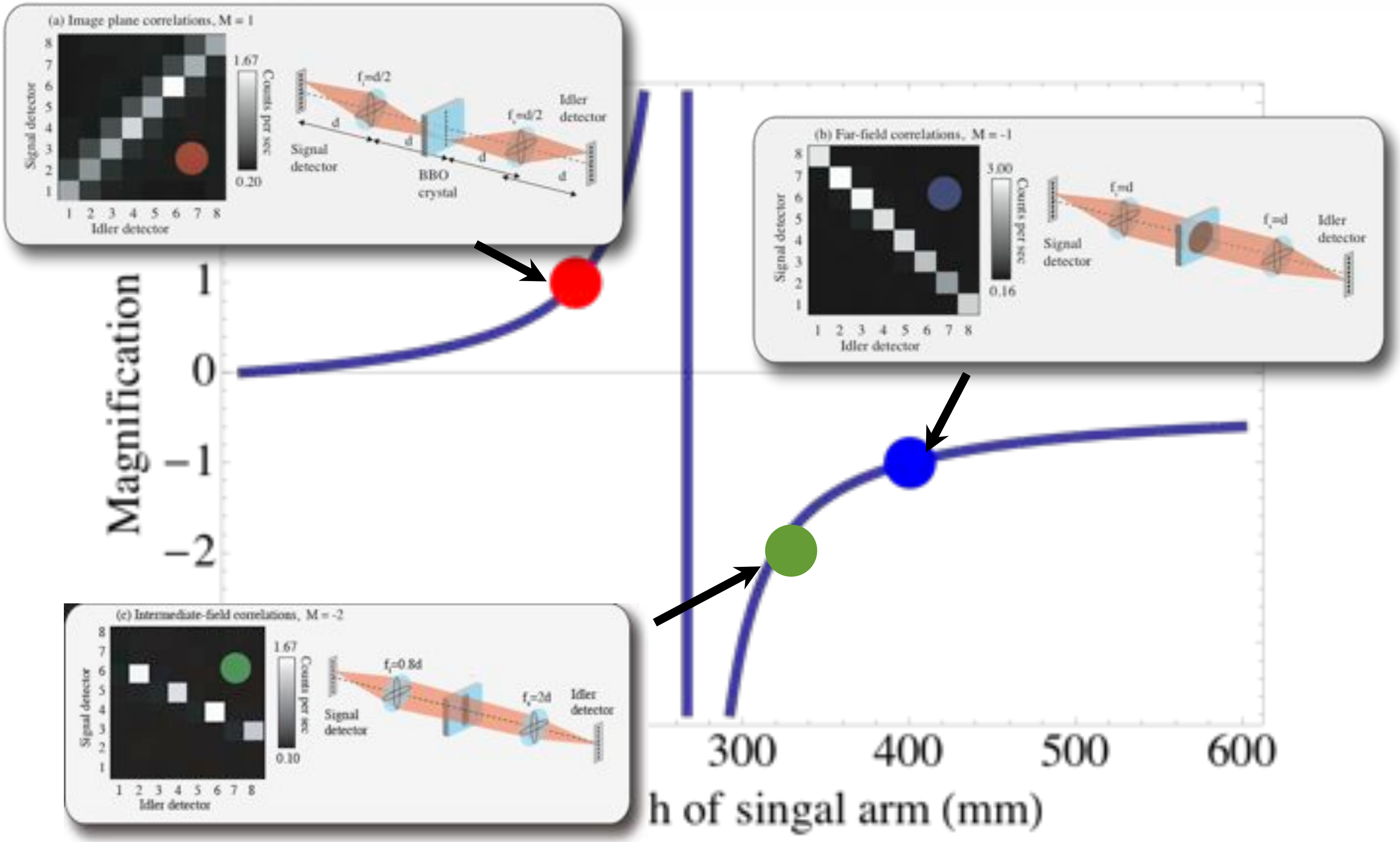
T. B. Pittman, D. V. Strekalov, D. N. Klyshko,* M. H. Rubin, A. V. Sergienko, and Y. H. Shih
Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228
(Received 10 October 1995)

Condition for coincidences is that the detectors are in image planes of each other



Magnification = -2

Correlations for image, far-field AND intermediate planes



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Summary

- Arrays of optical fibres can form the basis of single photon position measurements
- We use two x 8-fibre arrays to measure full-field correlations in image, far-field and intermediate planes
- Our results demonstrate a “no-scanning” EPR
- Possible Application to multi-bit QKD and single-photon ghost imaging.

Measuring the OAM of single Photons

Martin Lavery, Gregorius Berkhout, Marco Beijersbergen
David Robertson, Gordon Love, J Courtial and Miles J. Padgett,

University of Glasgow
Universiteit Leiden
Durham University

University of Glasgow

Universiteit Leiden

Durham University

Measuring the OAM of single Photons

Martin Lavery, Gregorius Berkhout, Marco Beijersbergen
David Robertson, Gordon Love, J Courtial and Miles J. Padgett,

University of Glasgow

Angular momentum in terms of photons

- Spin angular momentum
  - Circular polarisation
  - $\sigma\hbar$ per photon
- Orbital angular momentum
  - Helical phasefronts
  - $\ell\hbar$ per photon

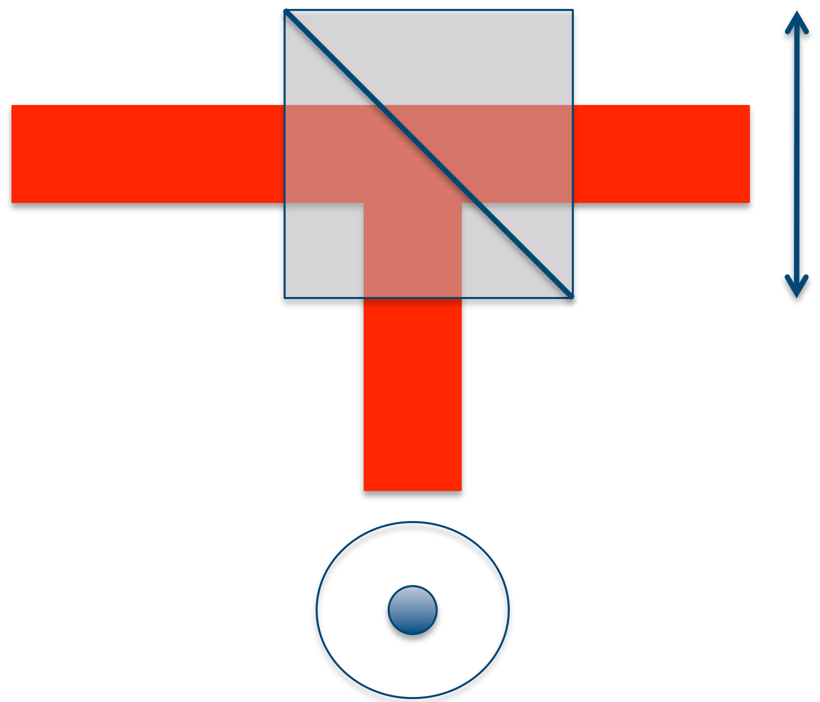
$\sigma = +1$

$\sigma = -1$

$\ell = 0$ $\quad \ell = 1$ $\quad \ell = 2$ $\quad \ell = 3$ $\quad$ etc

Measuring Polarisation (spin AM)

- Polarising beam splitter give the "perfect" separation of orthogonal (linear) states
  - Use quarter waveplate to separate circular states
  - Works for classical beams AND single photons



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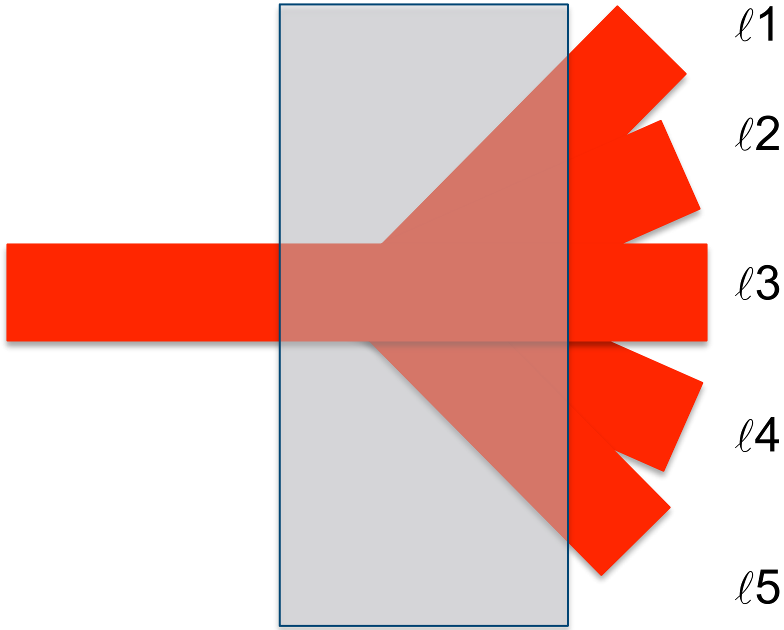
Measuring OAM

- OAM beam splitter give the “perfect” separation of orthogonal states
  - But how?



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Measuring OAM - 1

- Observe rotation of trapped particle in optical tweezers
  - But would be a challenge for a single photon!
  - Various clever schemes now shown for OAM measurement in tweezers, ideal for mW beams

VOLUME 75, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JULY 1995

Direct Observation of Transfer of Angular Momentum to Absorptive Particles from a Laser Beam with a Phase Singularity

H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop

VOLUME 88, NUMBER 5 PHYSICAL REVIEW LETTERS 4 FEBRUARY 2002

Intrinsic and Extrinsic Nature of the Orbital Angular Momentum of a Light Beam

A. T. O'Neil, I. MacVicar, L. Allen, and M. J. Padgett
Department of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland
(Received 28 June 2001; published 16 January 2002)

University of Glasgow

Measuring OAM - 2

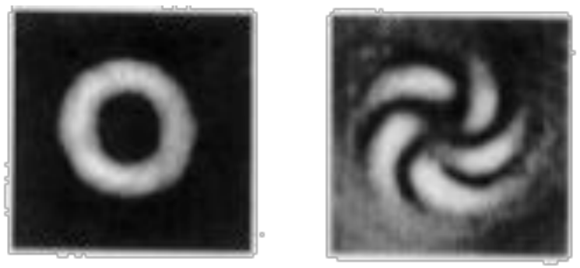
- Interference of helical beam with a plane wave gives ℓ spiral fringes
  - Requires many photons in the same mode

An experiment to observe the intensity and phase structure of Laguerre–Gaussian laser modes

M. Padgett, J. Arlt, and N. Simpson
J. F. Allen Research Laboratories, Department of Physics and Astronomy, The University of St. Andrews, North Haugh, St. Andrews, Fife, KY16 9SS, United Kingdom

L. Allen
Department of Physics, University of Essex, Colchester, Essex CO4 3SQ, United Kingdom

Am. J. Phys., Vol. 64, No. 1, January 1996



PHYSICAL REVIEW A VOLUME 56, NUMBER 5 NOVEMBER 1997

Topological charge and angular momentum of light beams carrying optical vortices

M. S. Soskin, V. N. Gorshkov, and M. V. Vasnetsov
Institute of Physics, National Academy of Sciences of the Ukraine, Kiev 252650, Ukraine

J. T. Malos and N. R. Heckenberg
Department of Physics, University of Queensland, Brisbane 4072, Australia

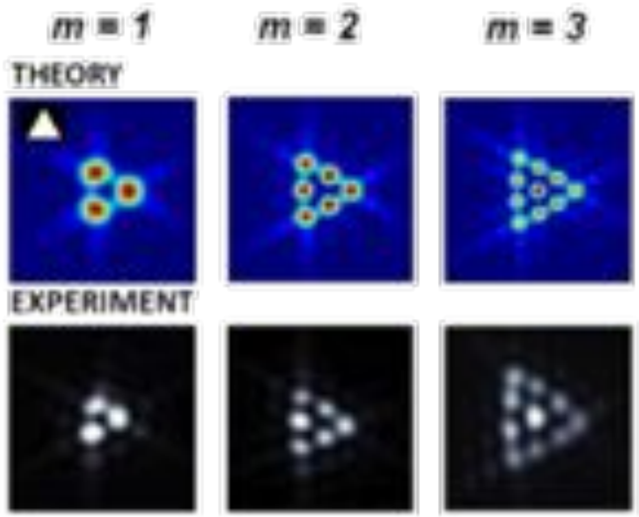
Measuring OAM - 3

- e.g. Diffraction pattern from a triangular aperture
  - Gives sign and magnitude of ℓ
  - Requires many photons in the same mode

PRL 105, 053904 (2010) PHYSICAL REVIEW LETTERS week ending 30 JULY 2010

Unveiling a Truncated Optical Lattice Associated with a Triangular Aperture Using Light's Orbital Angular Momentum

J. M. Hickmann,* E. J. S. Fonseca, W. C. Soares, and S. Chávez-Cerda†



Single-slit diffraction of an optical beam with phase singularity

Devinder Pal Ghai [a,b,*], P. Senthilkumaran [a], R.S. Sirohi [c]

Optics and Lasers in Engineering 47 (2009) 123–126

April 1, 2006 / Vol. 31, No. 7 / OPTICS LETTERS

Double-slit interference with Laguerre–Gaussian beams

H. I. Sztul and R. R. Alfano

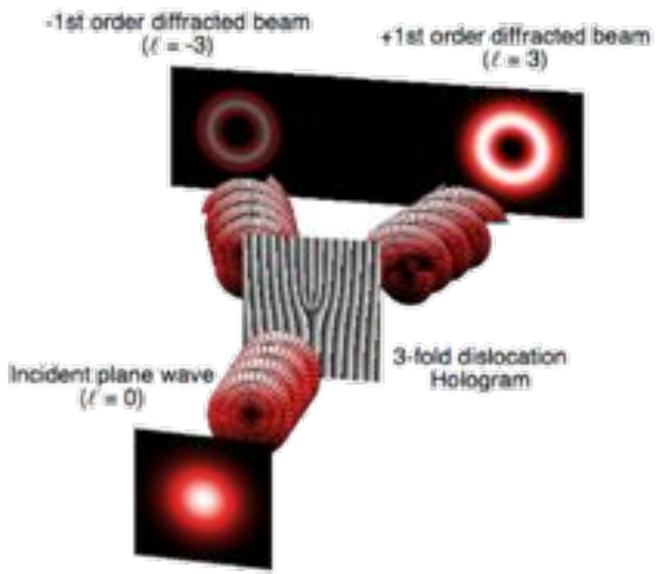
PRL 101, 100801 (2008) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2008

Method for Probing the Orbital Angular Momentum of Optical Vortices in Electromagnetic Waves from Astronomical Objects

Gregorius C. G. Berkhout[1,2,*] and Marco W. Beijersbergen[1,2]

Making OAM

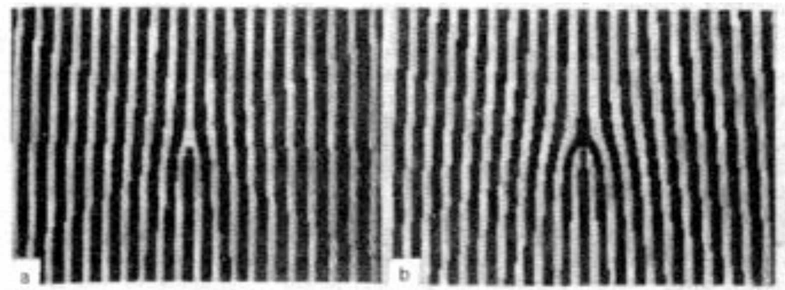
- Diffractive optical elements (hologram)
  - “forked” diffraction grating



Laser beams with screw dislocations in their wavefronts

V. Yu. Bazhenov, M. V. Vasnetsov, and M. S. Soskin
Institute of Physics, Academy of Sciences of the Ukrainian SSR

(Submitted 28 August 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 8, 1037–1039 (25 October 1990)



Generation of optical phase singularities by computer-generated holograms

N. R. Heckenberg, R. McDuff, C. P. Smith, and A. G. White

1992 / Vol. 17, No. 3 / OPTICS LETTERS 221

University of Glasgow

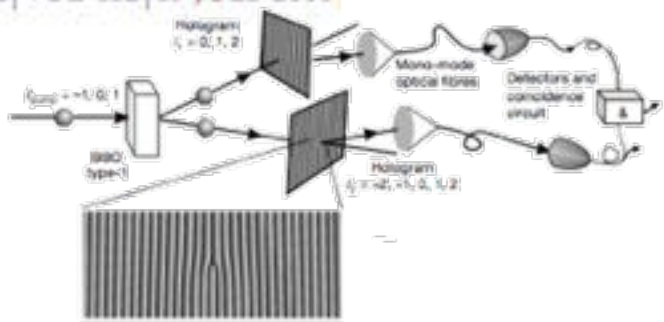
Measuring OAM - 4

- Use diffractive optic to couple helical beam to single mode fibre(s)
  - works for single photons
  - “test” for one ℓ at a time
  - or multiple orders to test for multiple ℓ

Entanglement of the orbital angular momentum states of photons

Alois Mair*, Alipasha Vaziri, Gregor Weihs & Anton Zeilinger

NATURE | VOL 412 | 19 JULY 2001

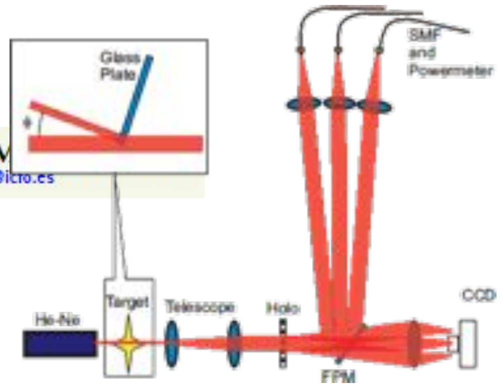


Journal of the European Optical Society - Rapid Publications 2, 07014 (2007)

Probing canonical geometrical objects by digital spiral imaging

Gabriel M

gabriel.molina@icfo.es



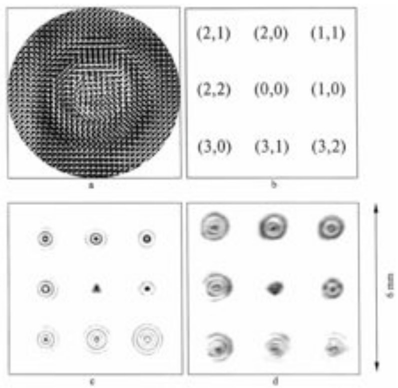
Measuring OAM - 5

- Use diffractive optic to separate N-OAM states
  - works for single photons
  - But efficiency only≈ 1/N

Gauss–Laguerre modes with different indices in prescribed diffraction orders of a diffractive phase element

S.N. Khonina [a], V.V. Kotlyar [a], R.V. Skidanov [a], V.A. Soifer [a], P. Laakkonen [b], J. Turunen [b,*]

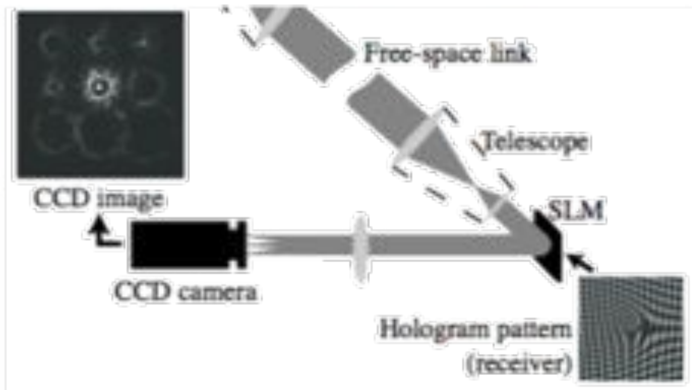
Optics Communications 175 (2000) 301–308



Free-space information transfer using light beams carrying orbital angular momentum

Graham Gibson, Johannes Courtial, Miles J. Padgett

Vol. 12, No. 22 / OPTICS EXPRESS 5448



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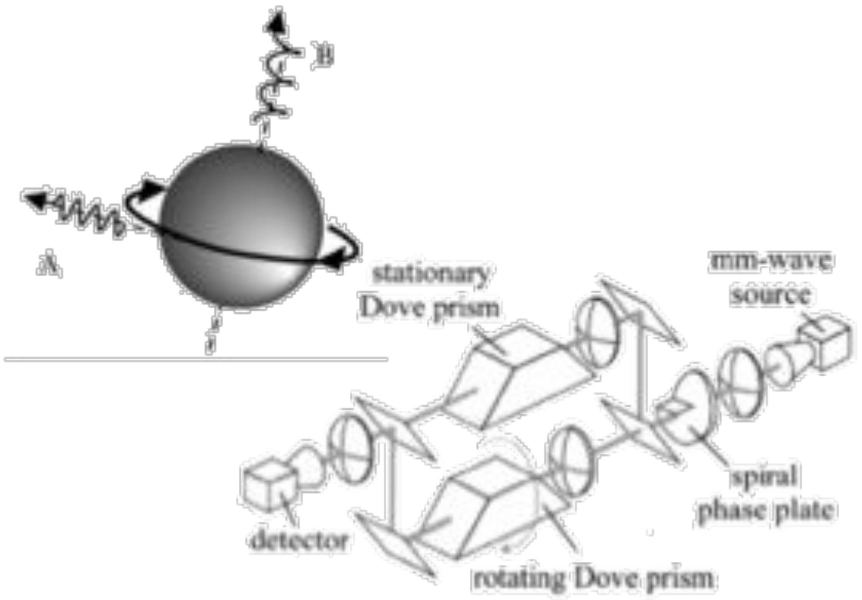
Measuring OAM – 6

- Rotating a beam with OAM shifts the frequency
  - Gives sign and magnitude of ℓ
  - In principle could work for single photons, but….
  - Try spinning a beam…. It's hard!

VOLUME 81, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1998

Rotational Frequency Shift of a Light Beam

J. Courtial, D. A. Robertson, K. Dholakia, L. Allen, and M. J. Padgett



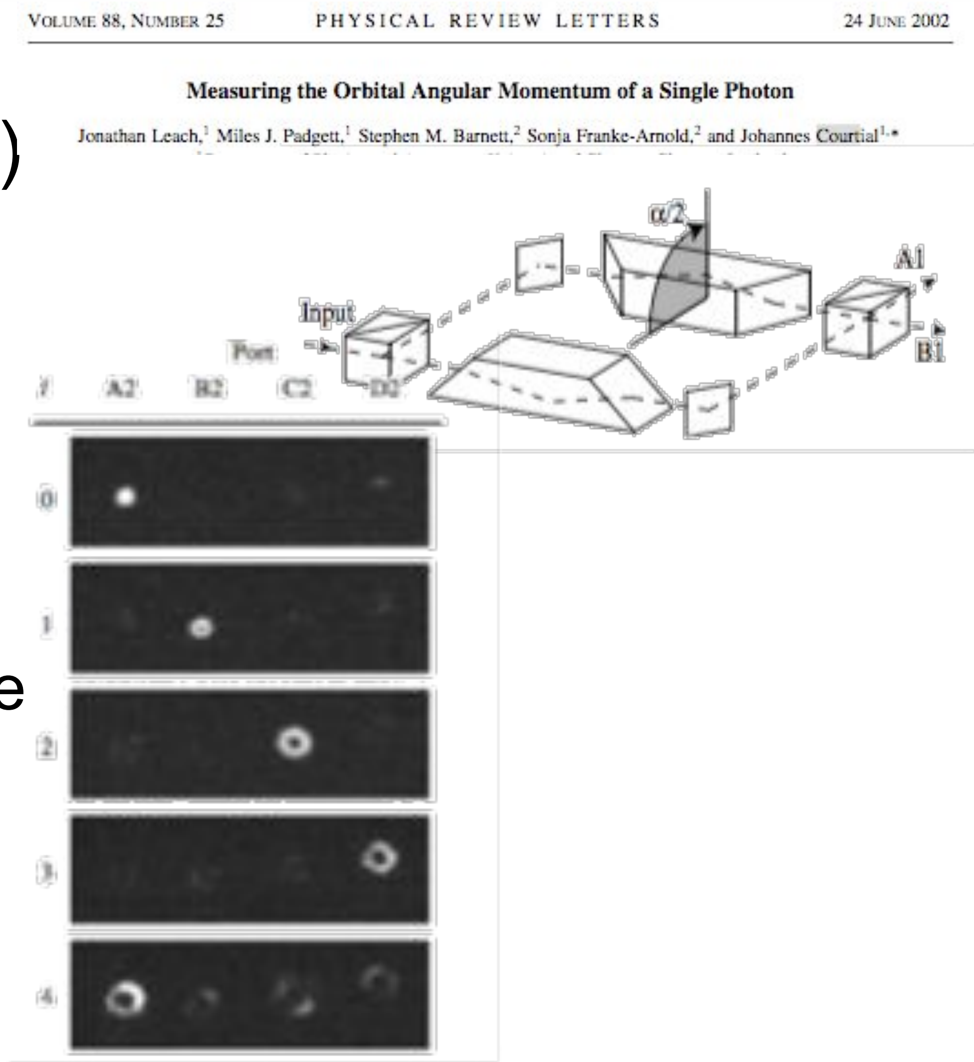
VOLUME 88, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 2002

Management of the Angular Momentum of Light: Preparation of Photons in Multidimensional Vector States of Angular Momentum

Gabriel Molina-Terriza, Juan P. Torres, and Lluis Torner

Measuring OAM - 7

- Use (image rotating) Mach Zehnder interferometer
  - works for single photons
  - Efficiency ≈ 100%
  - But 2^n states, require 2^n-1 interferometers (and 2^n students!)



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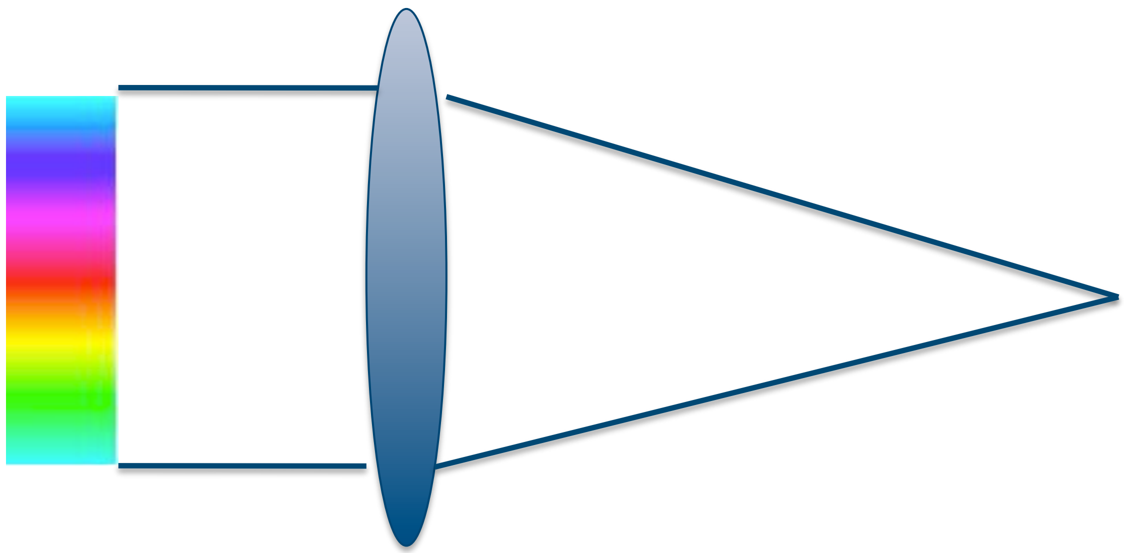
It MUST be possible

- OAM states are “orthogonal”
- The Dove prism interferometer shows it’s possible

It works for plane waves

- A “plane-wave” is focused by a lens
- A phase ramp of 2π displaces the spot



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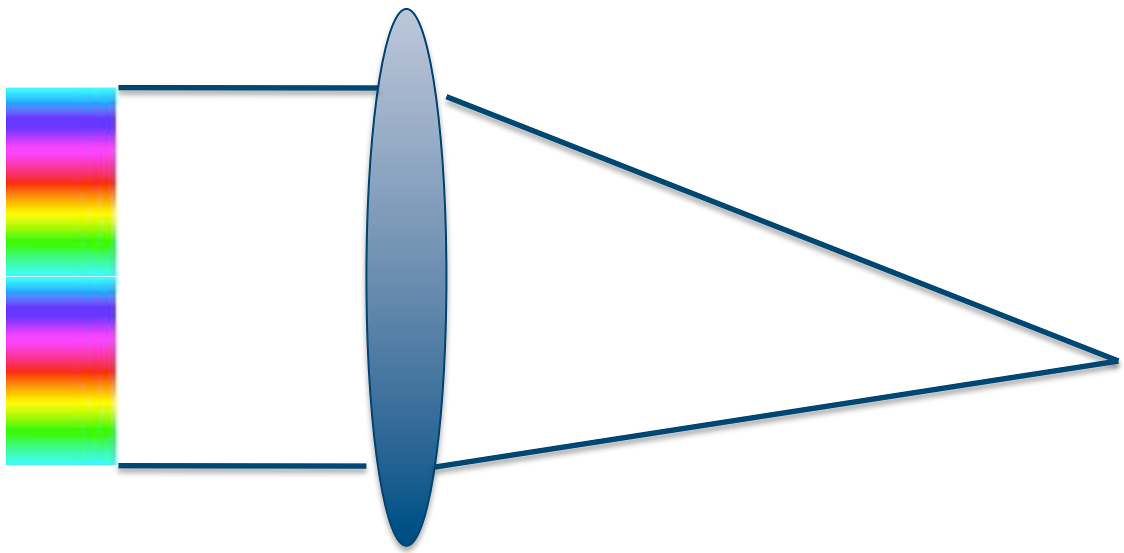

University of Glasgow

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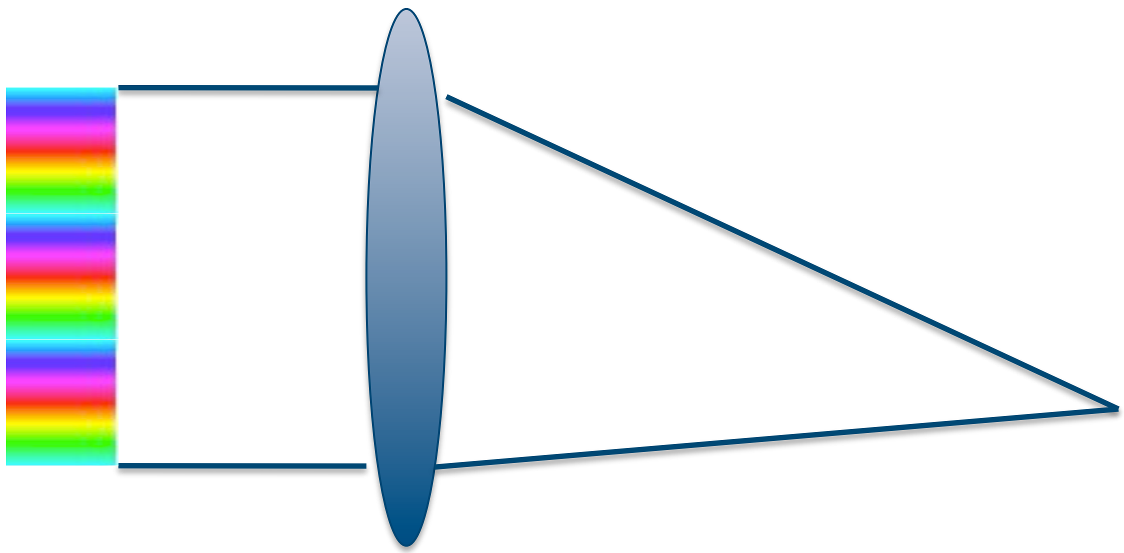

It works for plane waves

- A “plane-wave” is focused by a lens
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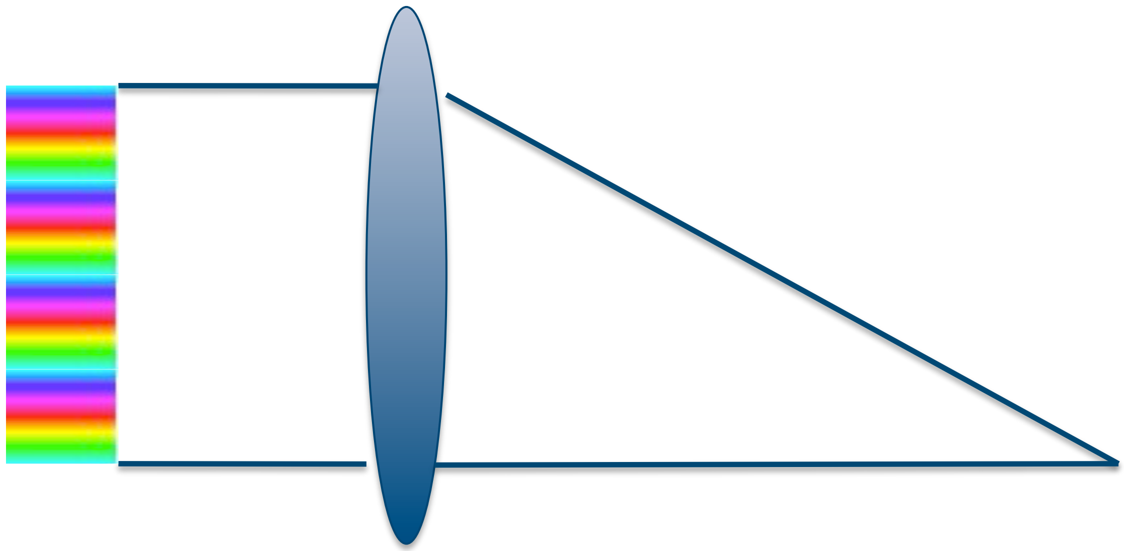
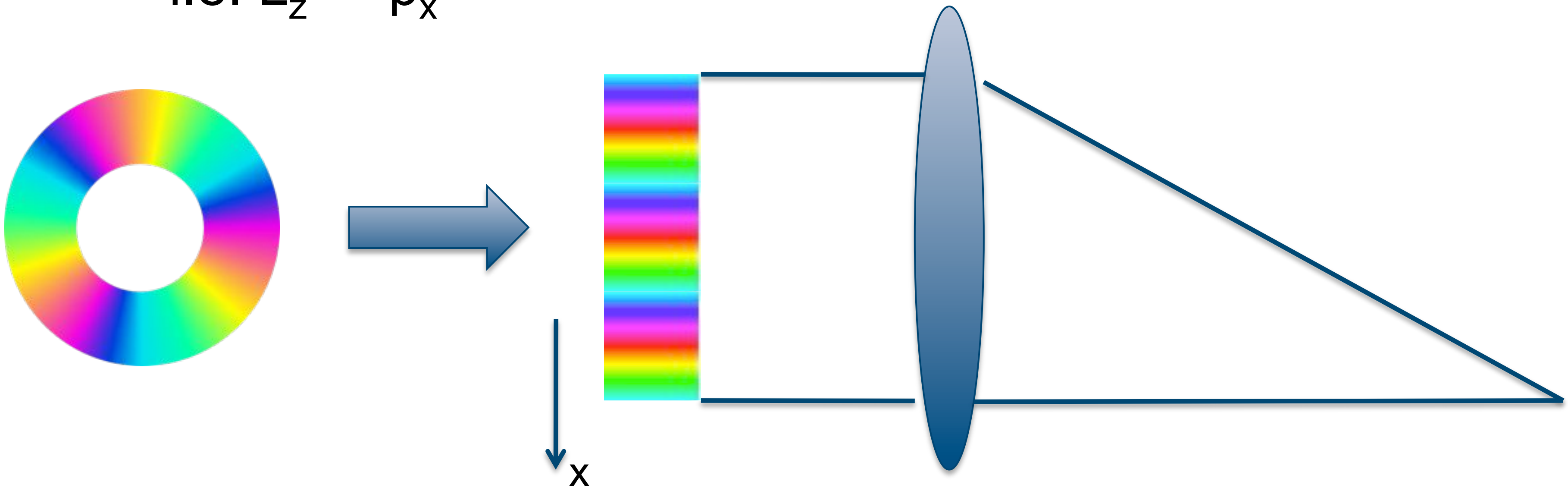


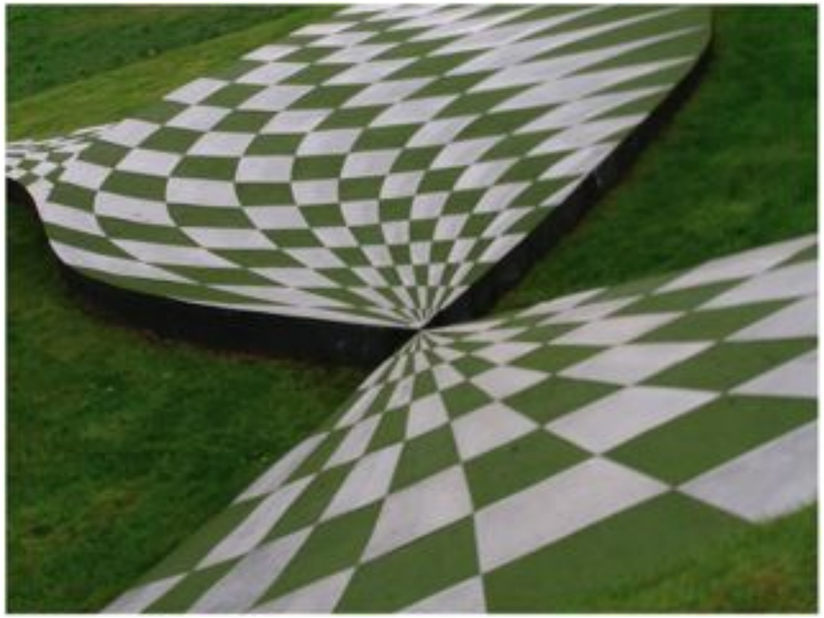
So we need to convert helical phase to linear phase

- Image transformation
  - ϕ -> x and r -> y
  - i.e. L_z -> p_x



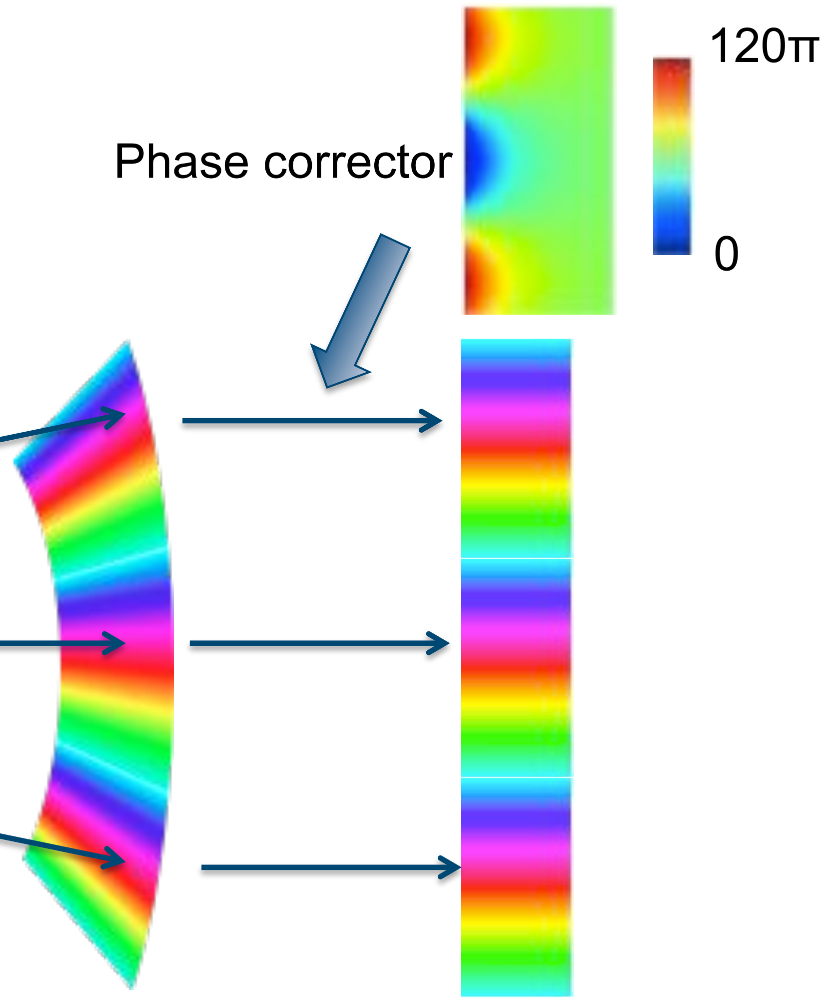
We NEED image distortion….

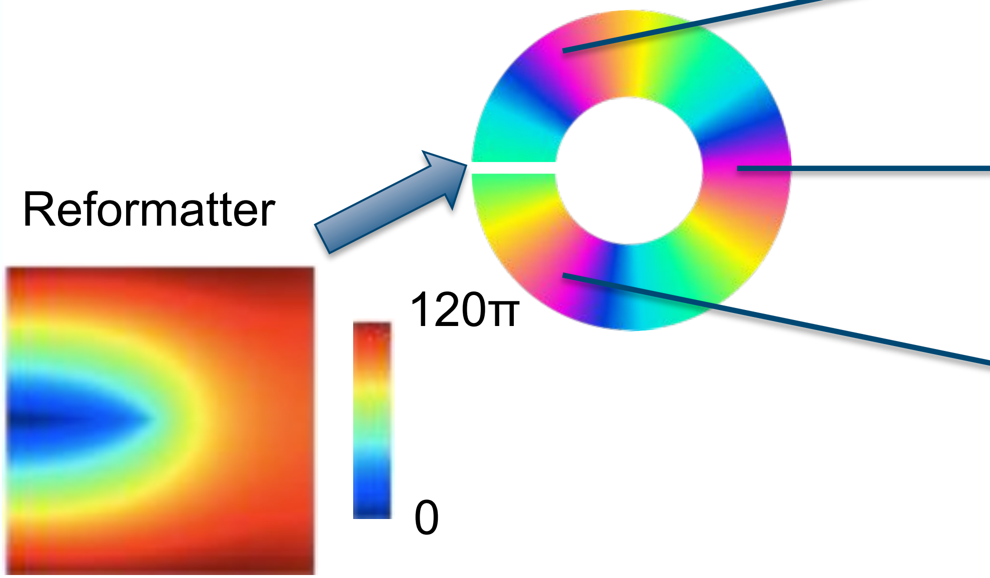
- Pin-Cushion and Barrel distortion make straight lines look curved…
  - But must also make curved lines look straight



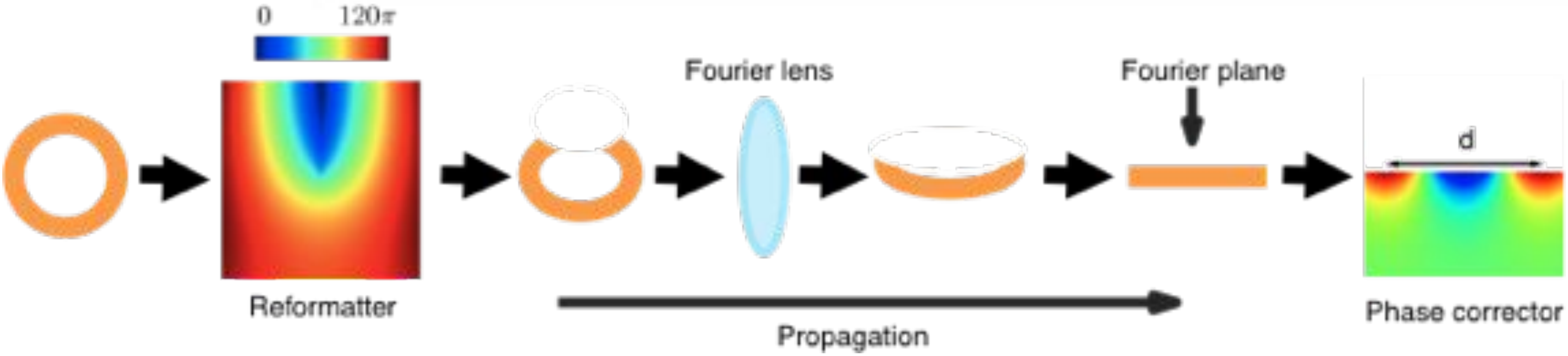
Azimuthal to linear mapping

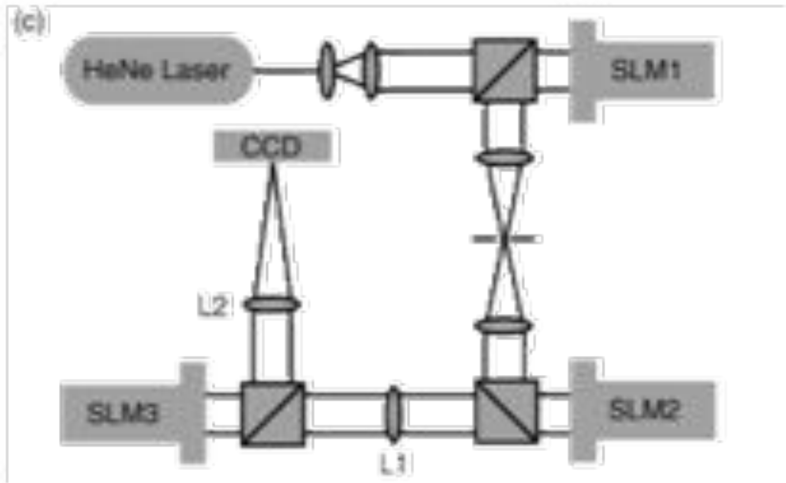
- Image transformation
  - ϕ -> x and r -> y
  - Requires reformatter & phase corrector

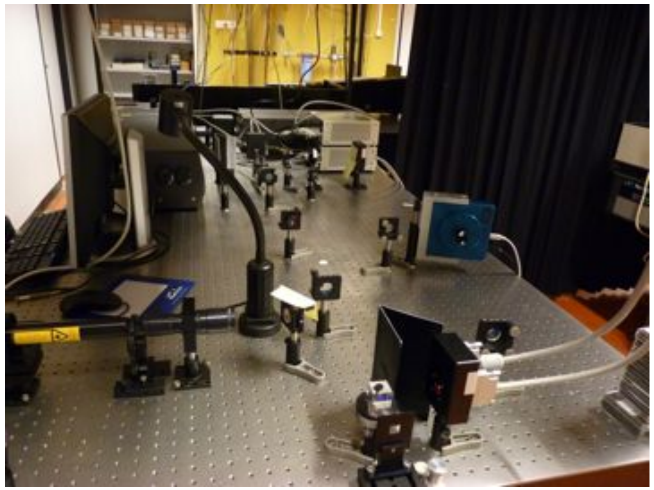




The Experimental implementation







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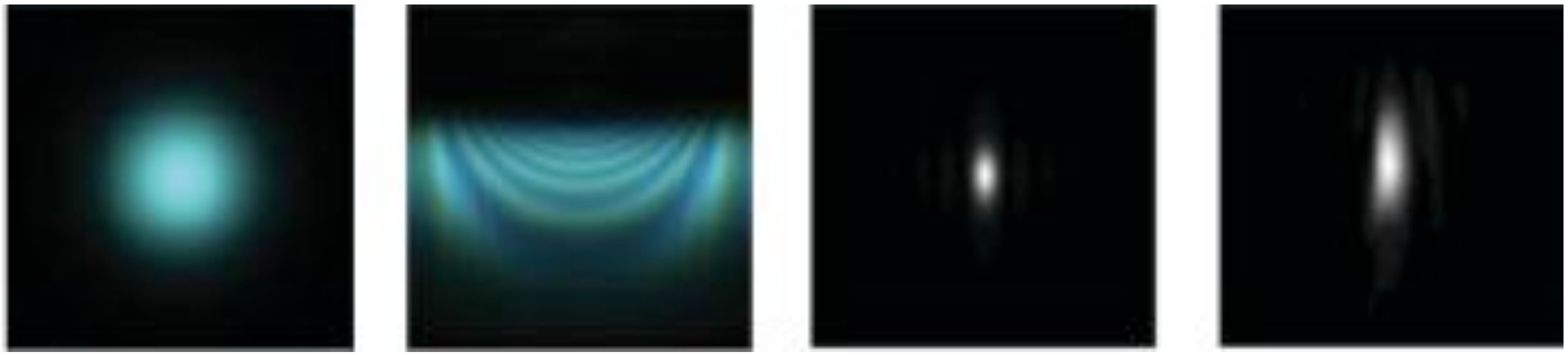
The results -1

Input mode | Transformed mode | Predicted output | Measured output

$\ell = 0$



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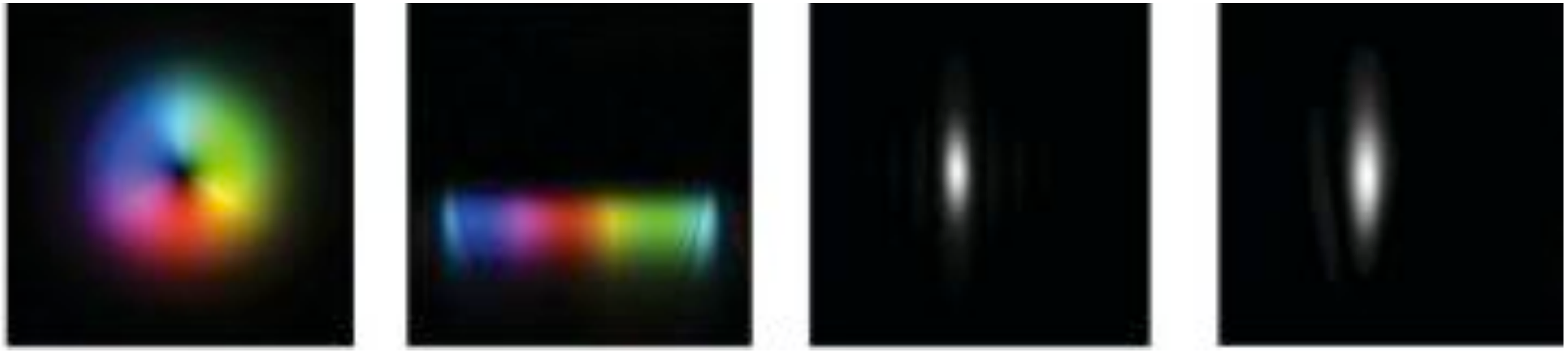
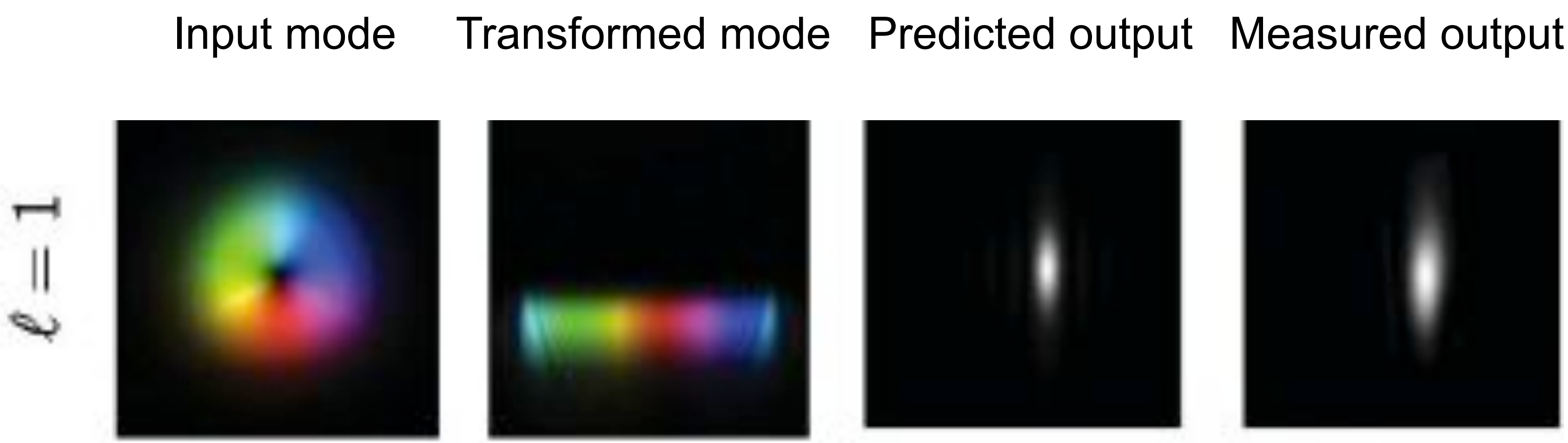
The results -1

Input mode | Transformed mode | Predicted output | Measured output

$\ell = -1$



The results -1



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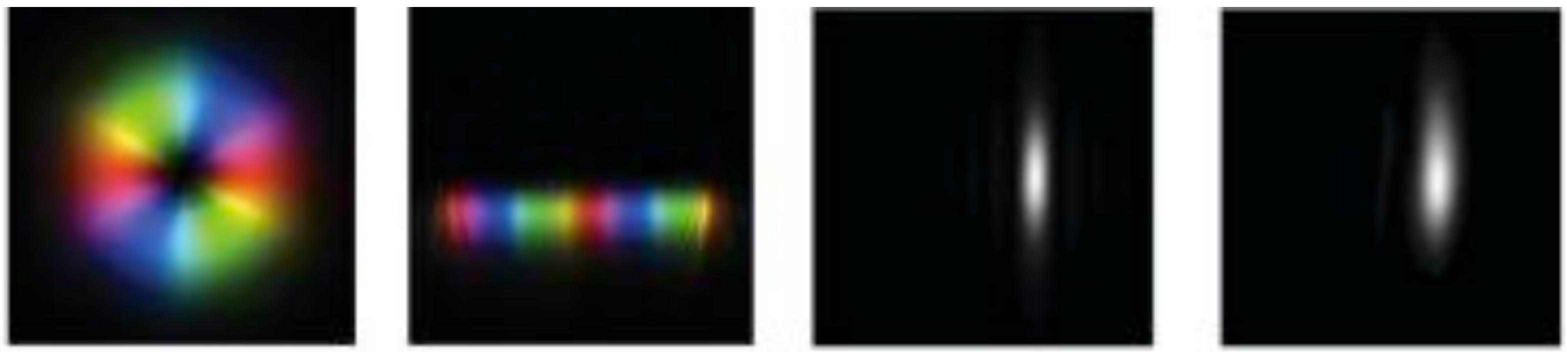
The results -1

Input mode | Transformed mode | Predicted output | Measured output

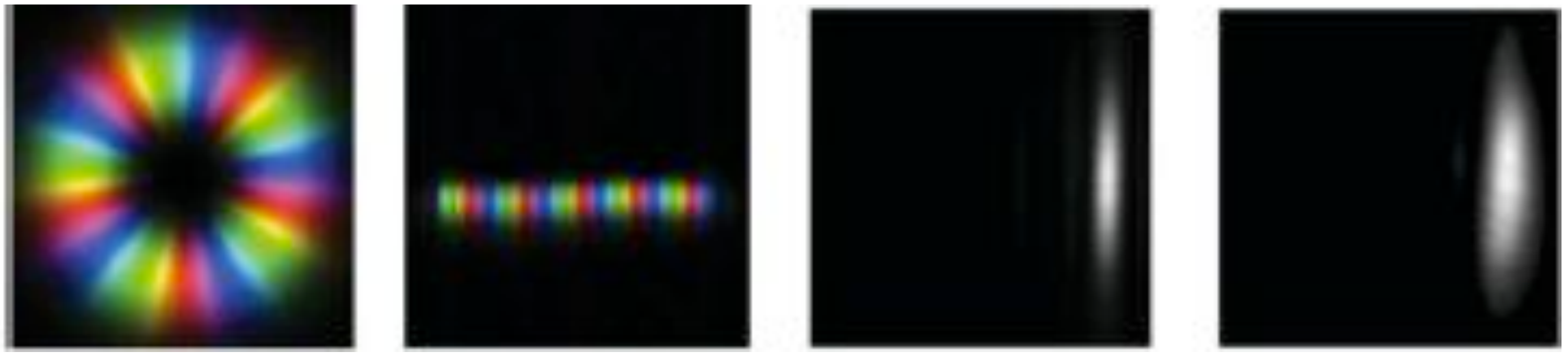
$\ell = 2$



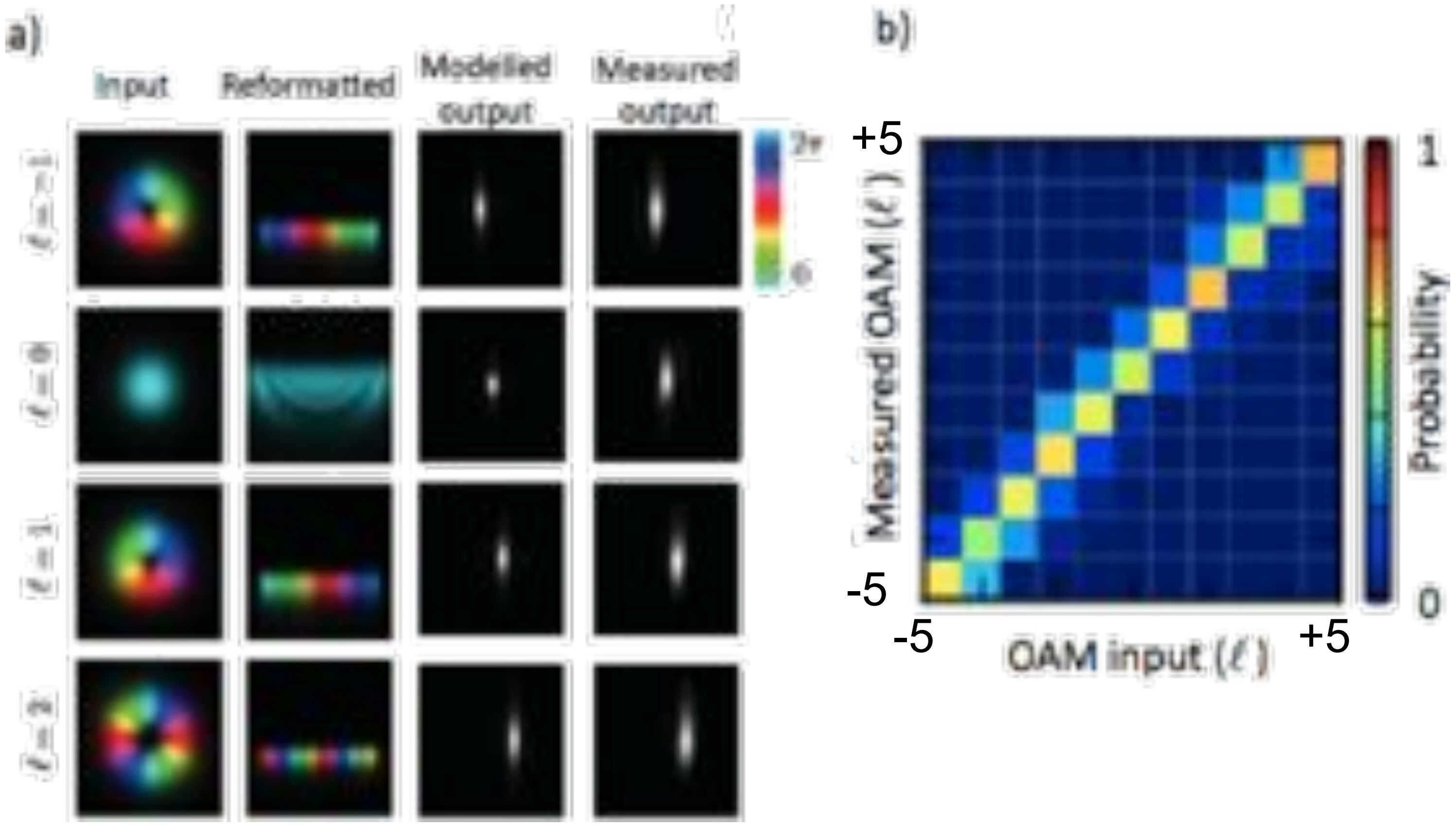
The results -1

Input mode | Transformed mode | Predicted output | Measured output

$\ell = 5$



The results -2

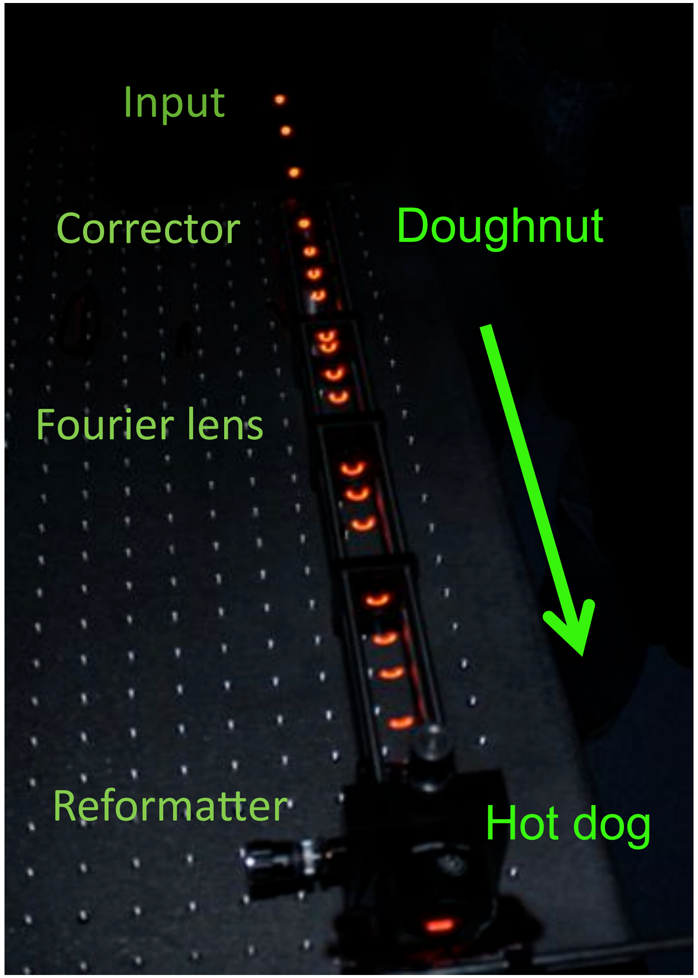


PRL **105,** 153601 (2010) PHYSICAL REVIEW LETTERS week ending 8 OCTOBER 2010

Efficient Sorting of Orbital Angular Momentum States of Light

Where next -1

- The principle works
- But the SLMs are inefficient (≈50% x 2)
- Use bespoke optical elements (glass/plastic)
  - Prof. David J Robertson
  - Prof. Gordon Love



Where next -1

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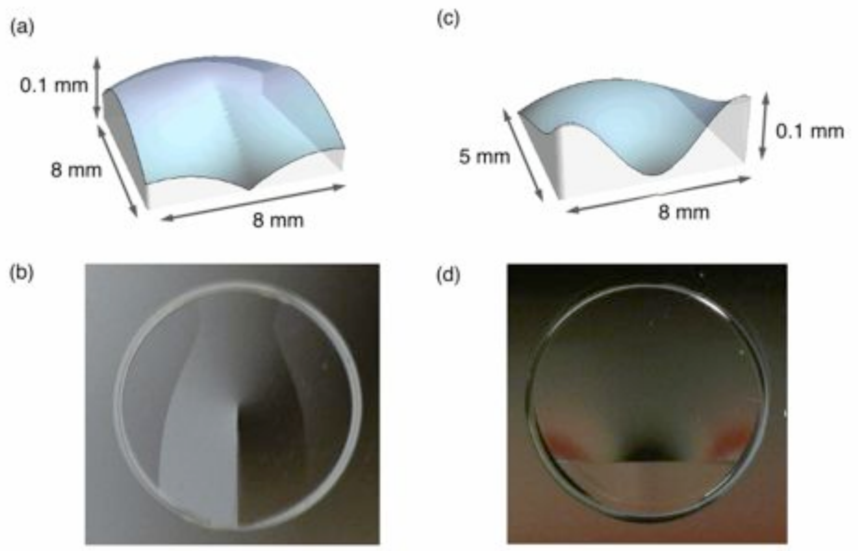
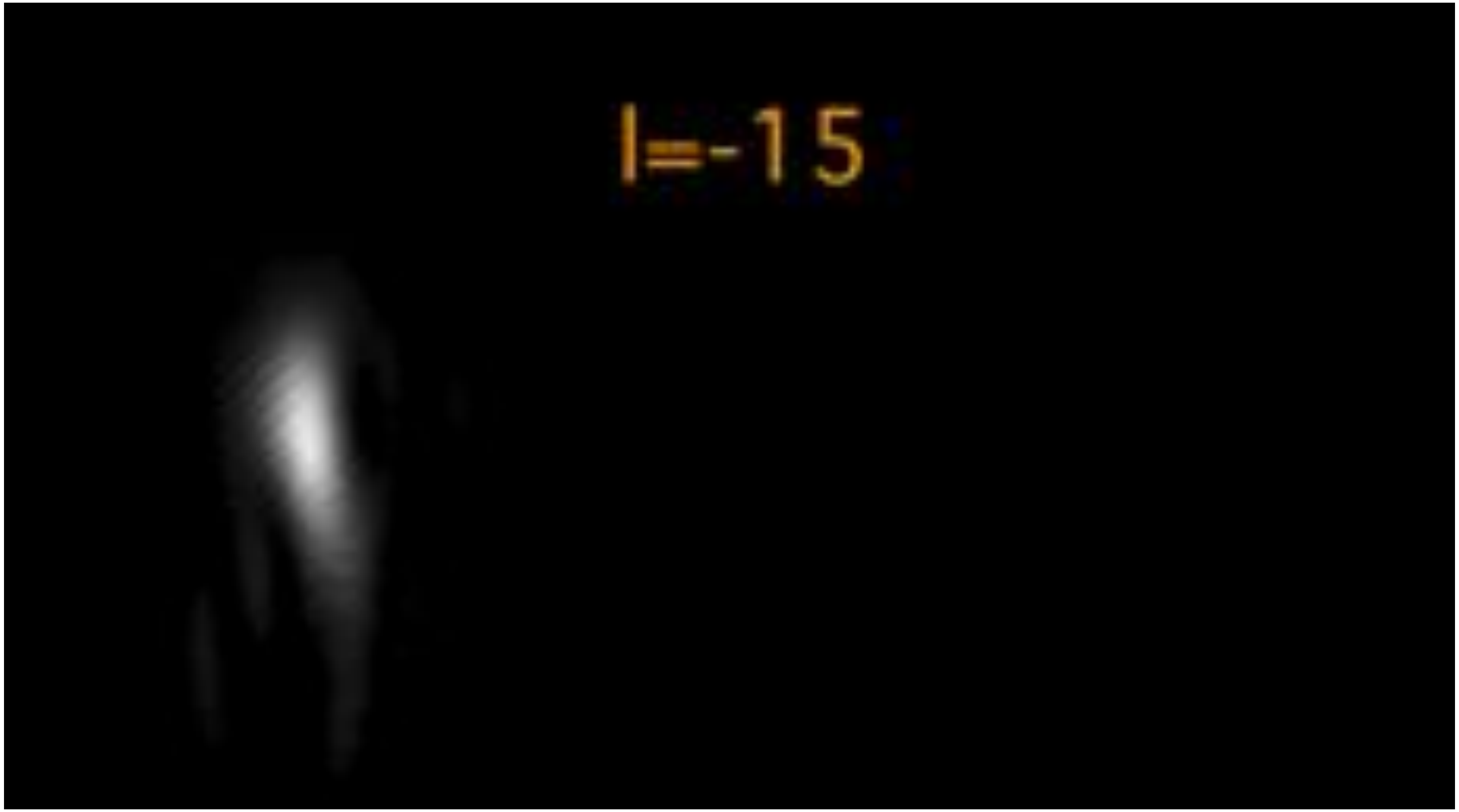


reformater

phase corrector

Where next -2



View at the camera whist we change the OAM

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Further Reading

- # SLMs for making exotic beams
  - M. R. Dennis et al., *Isolated optical vortex knots, Nature Phys. 6, 118-121 (2010)*
  - M. Padgett and R. Bowman, *Tweezers with a twist, Nature Photon. 5, 343-348 (2011)*
- # SLMs for ≈tests of QM
  - J. Leach, et al., *Violation of a Bell inequality in two-dimensional orbital angular momentum state-spaces, Opt. Express 17, 8287-8293 (2009)*
  - B. Jack, et al. *Holographic Ghost Imaging and the Violation of a Bell Inequality, Phys. Rev. Lett. 103, 083602 (2009)*
  - J. Leach, et al. *Quantum Correlations in Optical Angle-Orbital Angular Momentum Variables, Science 329, 662-665 (2010)*
  - J. Romero et al. *Violation of Leggett inequalities in orbital angular momentum subspaces, New J. Phys. 12, 123007 (2010),*
  - J. Romero, et al. *Entangled Optical Vortex Links, Phys. Rev. Lett. 105, 100407 (2011)*
  - A C. Dada et al. *Experimental high-dimensional two-photon entanglement and violations of generalized Bell inequalities, Nature Physics (2011)*
- # Sorting OAM states
  - G. C. G. Berkhout, et al. *Efficient Sorting of Orbital Angular Momentum States of Light, Phys. Rev. Lett.* ***105, 153601 (2010)***

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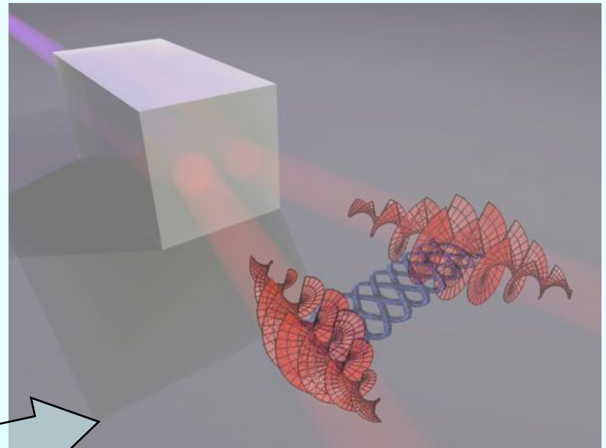
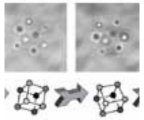
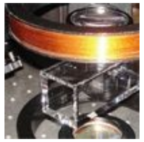


- Software
- Movies
- Publications

Areas of Research


OPTICAL TWEEZERS

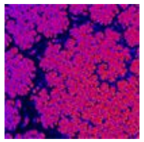

ATOM OPTICS

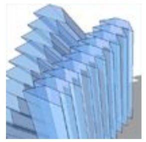

QUANTUM OPTICS & GHOST IMAGING


ANGULAR MOMENTUM OF LIGHT & OPTICAL VORTICES


OPTICS FOR ENVIRONMENTAL GAS MONITORING


MEDICAL OPTICS FOR DIAGNOSTICS AND TREATMENT


LASER MODES: FRACTALS & BOSE-EINSTEIN CONDENSATES


METATOYS


PUBLICATIONS