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The Abdus Salam International Centre for Theoretical Physics

Light in a Twist

Prof Miles Padgett

School of Physics and Astronomy

Optics Group

Outline

- The orbital angular momentum (OAM) of Light
- Topology of speckle lines
- Quantum entanglement and EPR
- OAM and EPR/Bell
- Measuring OAM

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
  - Abraham/Minkowski (1909/08)
- Spin AM momentum
  - Maxwell
  - Poynting/Beth (1909/36)
- Orbital AM (not spin) momentum
  - Maxwell
  - Various ≈ 1930s
- Orbital AM (helical phase) momentum in a beam
  - Allen et al. (1992)

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Getting started on Orbital Angular Momentum of Light

- 1992, Les Allen et al.

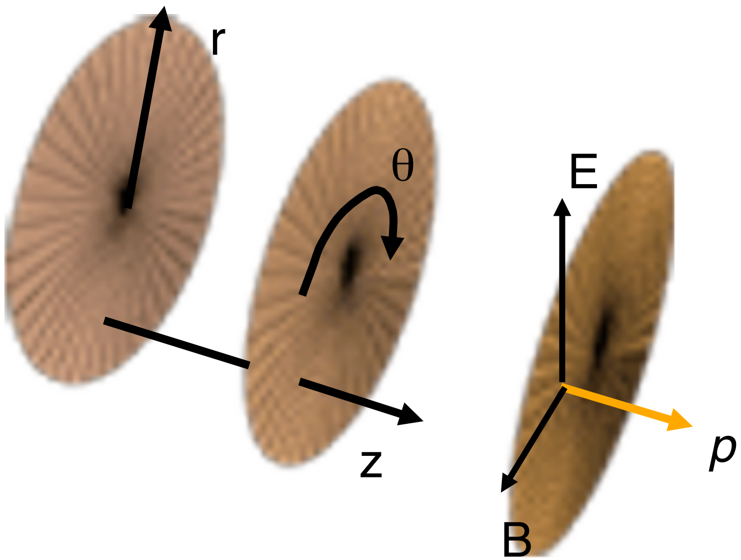
PHYSICAL REVIEW A VOLUME 45, NUMBER 11 1 JUNE 1992

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

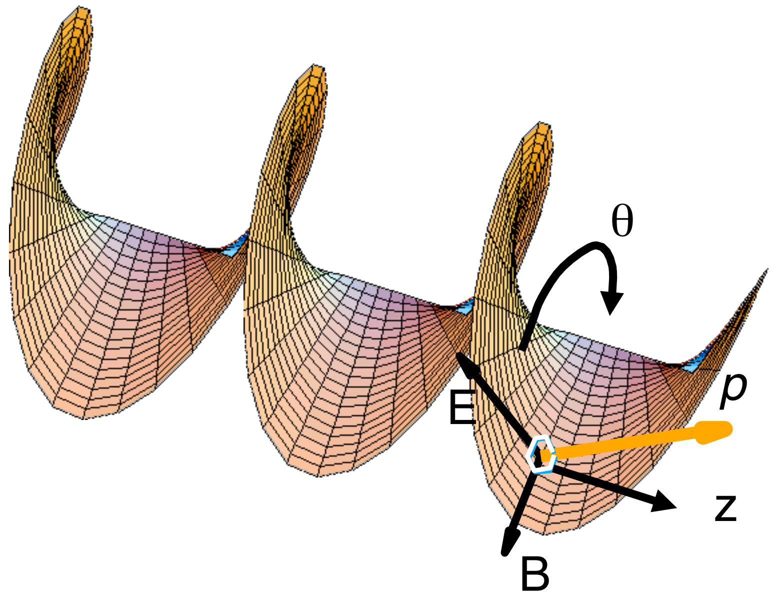
L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman
Huygens Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands
(Received 6 January 1992)

- 1994, Les and Miles have dinner……

Orbital Angular Momentum from helical phase fronts



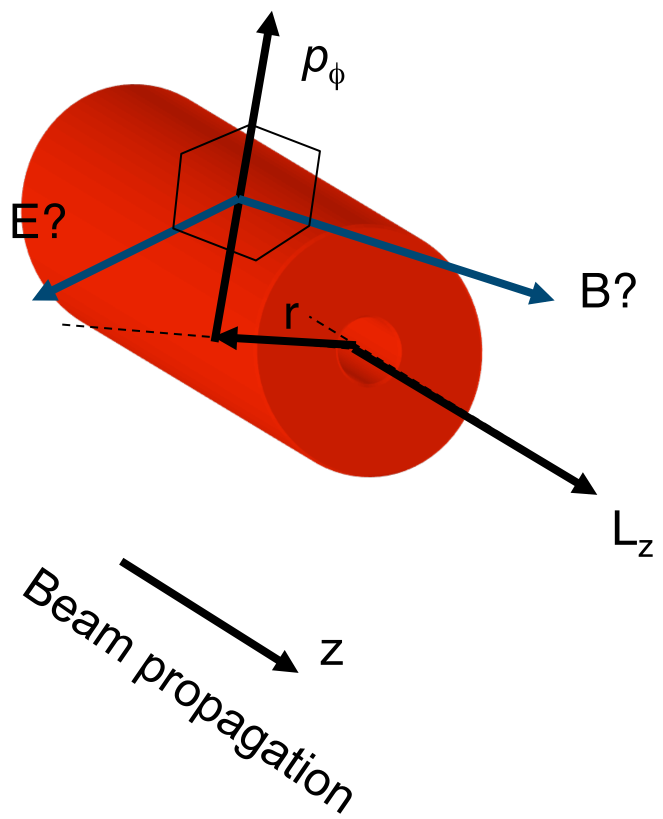
$p_\theta = 0$



$p_\theta \neq 0$

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



Calculate AM from EM field

Depends upon
phase structure of beam

Depends upon
polarisation state &
intensity gradient of
beam

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

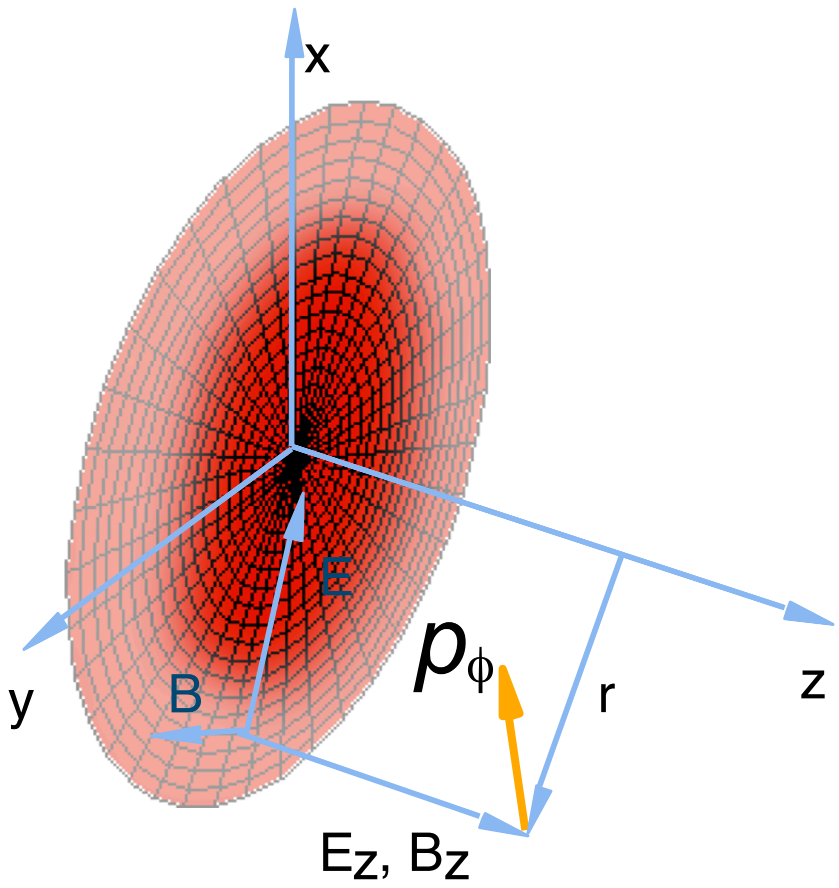
ϕ- component
gives OAM

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

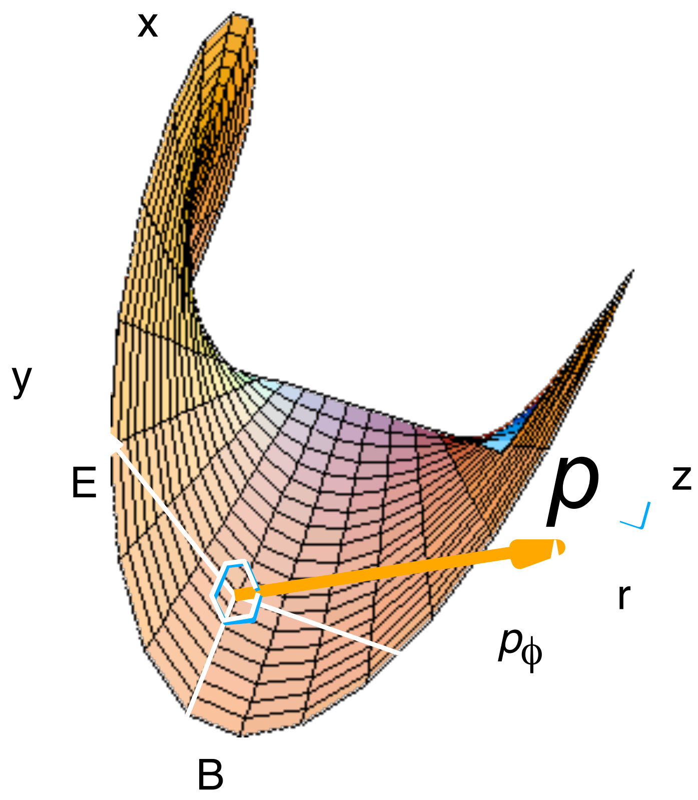
Spin AM (more complicated!)

- 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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Optical vortices, Helical phasefronts , Angular momentum

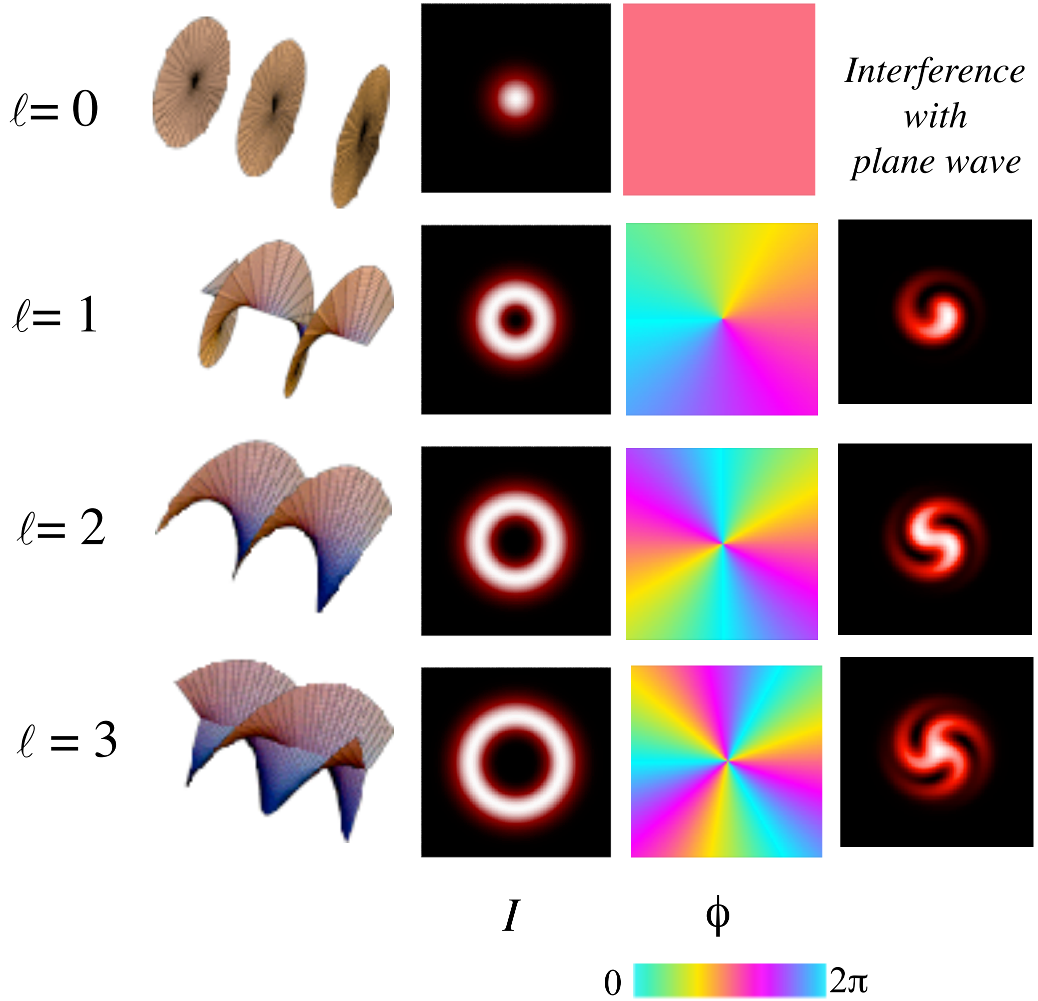
- Description of light
  - Intensity, $I \geq 0$
  - Phase, $2\pi \geq \phi \geq 0$

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

    - ℓ = 0, plane wave
    - ℓ = 1, helical wave
    - ℓ = 2, double helix
    - ℓ = 3, pasta fusilli

    etc.

ℓ= vortex charge



Angular momentum in terms of photons

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

$\sigma = +1$

$\sigma = -1$

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

A double-start helix (ℓ=2)

Optical Spanners

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
Department of Physics, The University of Queensland, Brisbane, Queensland, Australia Q4072
(Received 28 November 1994; revised manuscript received 4 April 1995)

OPTICS LETTERS / Vol. 22, No. 1 / January 1, 1997

Mechanical equivalence of spin and orbital angular momentum of light: an optical spanner

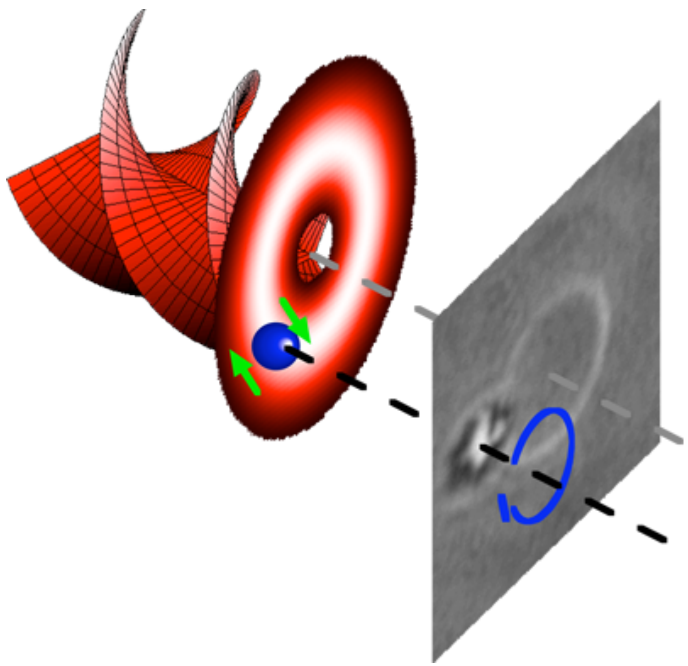
N. B. Simpson, K. Dholakia, L. Allen, and M. J. Padgett
J. F. Allen Physics Research Laboratories, Department of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife KY16 9SS, Scotland

VOLUME 88, NUMBER 5 PHYSICAL REVIEW LETTERS 4 FEBRUARY 2002

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

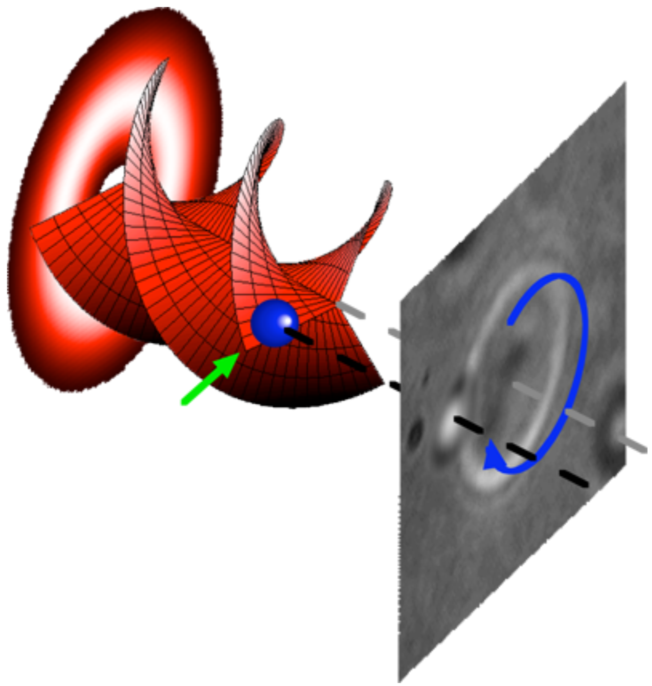
A. T. O'Neil, I. MacVicar, L. Allen, and M. J. Padgett
Department of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland
(Received 28 June 2001; published 16 January 2002)

Off-axis Spin and Orbital transfer



SAM

Particle spins on its own axis



OAM

Particle orbits the beam axis

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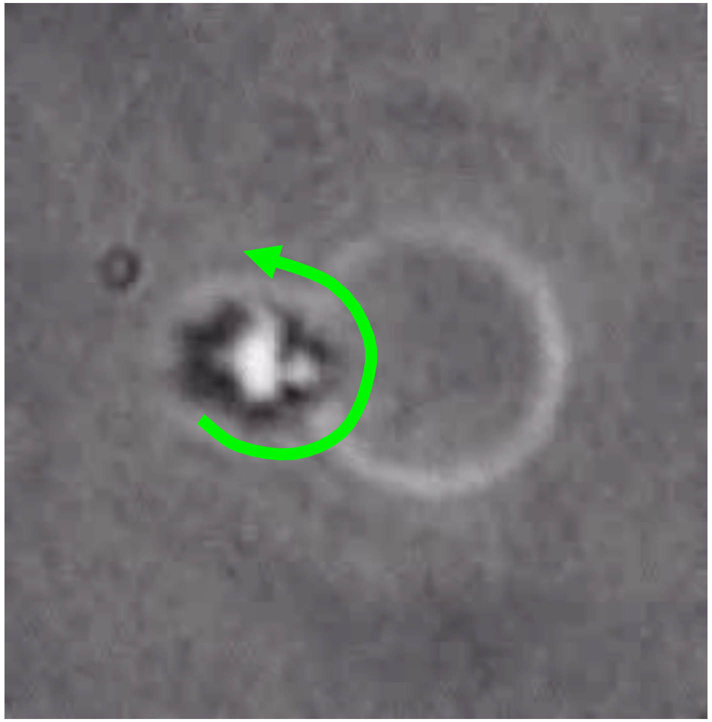
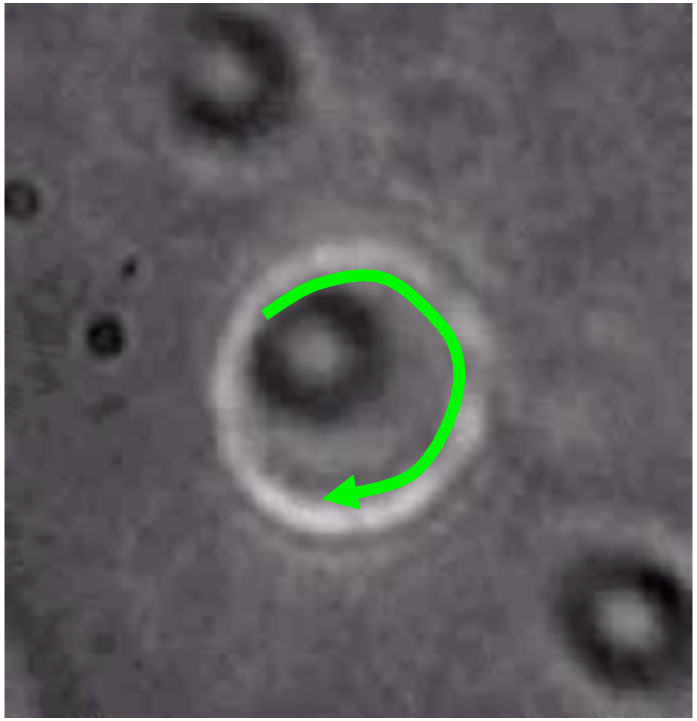
OAM / SAM transfer to particle held in optical tweezers



SAM

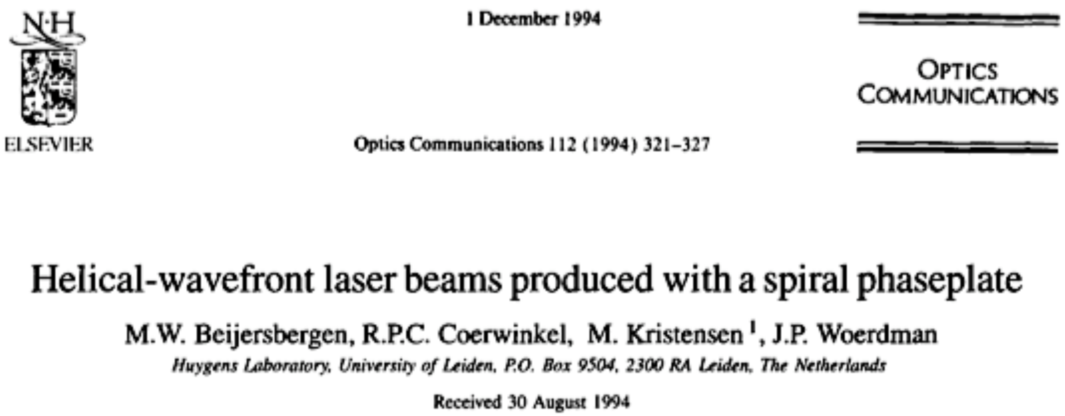
Particle spins on its own axis



OAM

Particle orbits the beam axis

Making helical phasefronts



ELSEVIER

1 December 1994

Optics Communications 112 (1994) 321–327

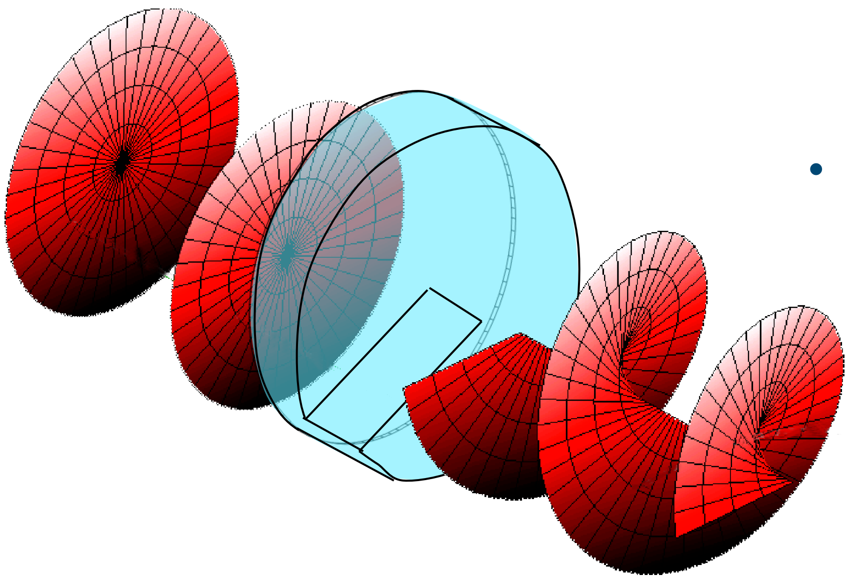
OPTICS COMMUNICATIONS

Helical-wavefront laser beams produced with a spiral phaseplate

M.W. Beijersbergen, R.P.C. Coerwinkel, M. Kristensen [1], J.P. Woerdman

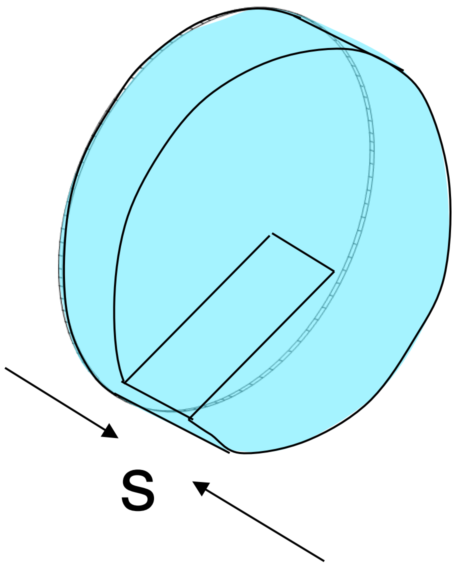
Huygens Laboratory, University of Leiden, P.O. Box 9504, 2300 RA Leiden, The Netherlands

Received 30 August 1994



- Pass plane-wave through a spiral-phase plate (thickness α ϕ)
  – step height= $\ell\lambda/(n-1)$

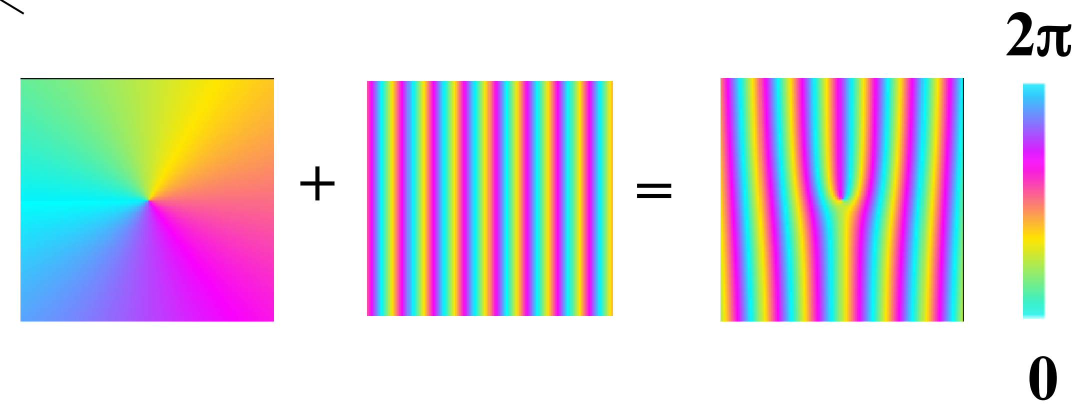
Designing helical phase hologram



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

- Holographically

e.g. $\ell = 1$ ▷



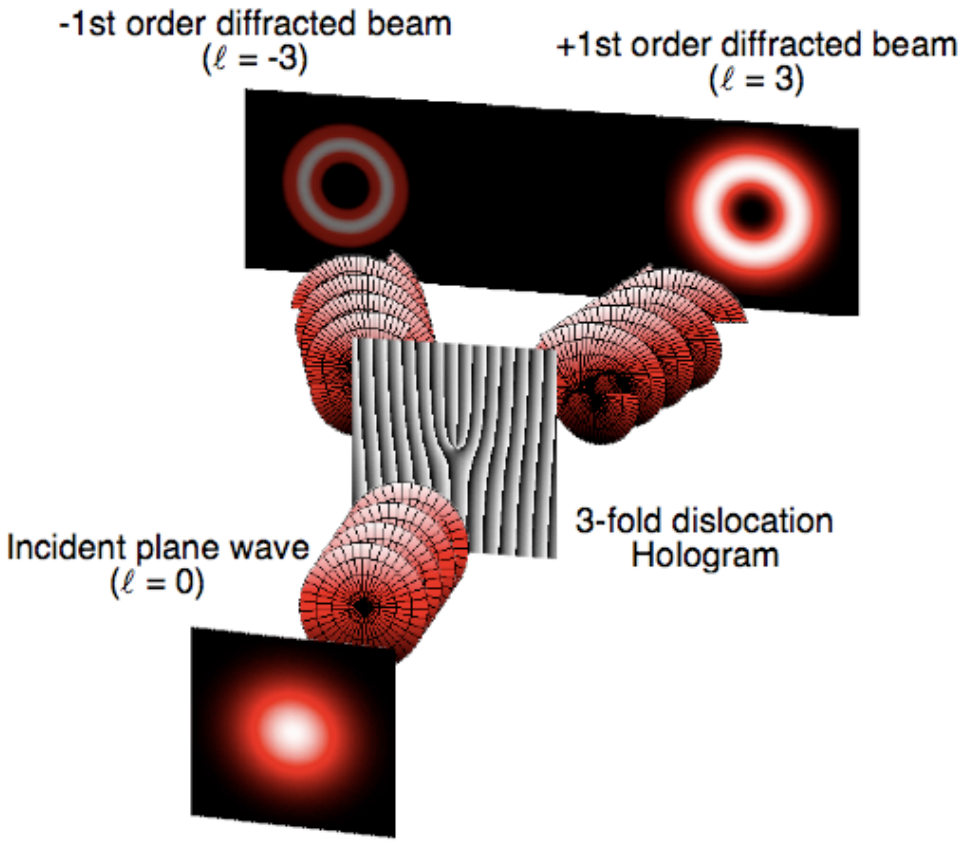
Making helical phasefronts with holograms

Screw dislocations in light wavefronts

V. YU. BAZHENOV, M. S. SOSKIN and M. V. VASNETSOV
Institute of Physics, Academy of Sciences of Ukraine,
252650 Kiev, Prospect Nauki 46, Ukraine

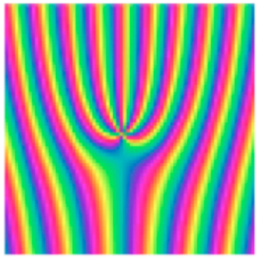
(*Received 14 June 1991; revision received 8 January 1992*)

JOURNAL OF MODERN OPTICS, 1992, VOL. 39, NO. 5, 985–990

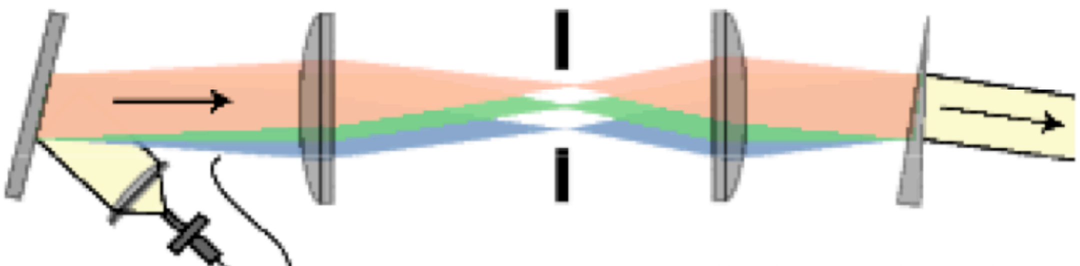


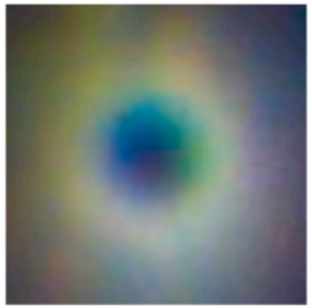
Making a white-light vortex

- Fibre-coupled (≈spatially coherent) white-light source
- Hologram to create vortex
- Prism to correct chromatic dispersion



Hologram





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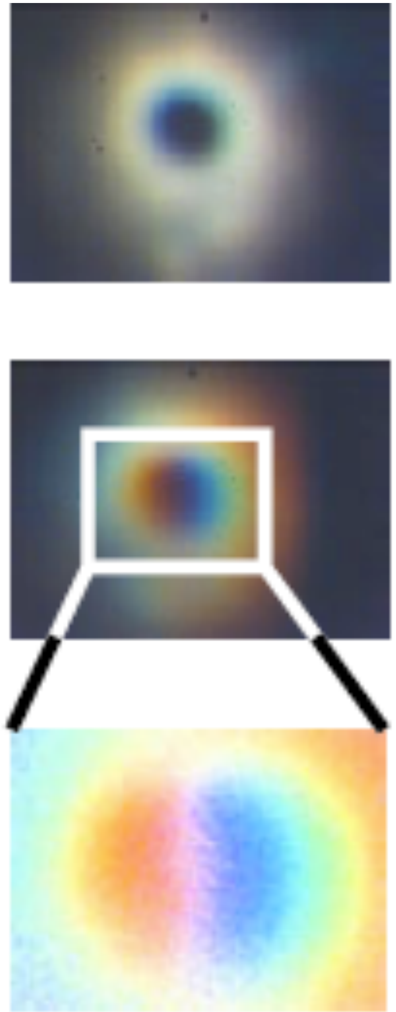
Dispersion in the vortex

- De-optimise dispersion correction
  - Non-colinear spectral components
- Need to ***boost colour*** in dark core
  - Chromascope (Berry)



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Acoustic Spanners

PRL **100**, 024302 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

Transfer of Angular Momentum to Matter from Acoustical Vortices in Free Space

Karen Volke-Sepúlveda,[1] Arturo O. Santillán,[2,*] and Ricardo R. Boullosa[2]
[1]*Instituto de Física, Universidad Nacional Autónoma de México, Apartado Postal 20-364, 01000 Mexico D.F., Mexico*
[2]*Centro de Ciencias Aplicadas y Desarrollo Tecnológico, Universidad Nacional Autónoma de México, Apartado Postal 70-186, 04510 México D. F., México*
(Received 14 July 2007; revised manuscript received 10 October 2007; published 16 January 2008)

New Journal of Physics
The open-access journal for physics

An acoustic spanner and its associated rotational Doppler shift

K D Skeldon, C Wilson, M Edgar and M J Padgett[1]
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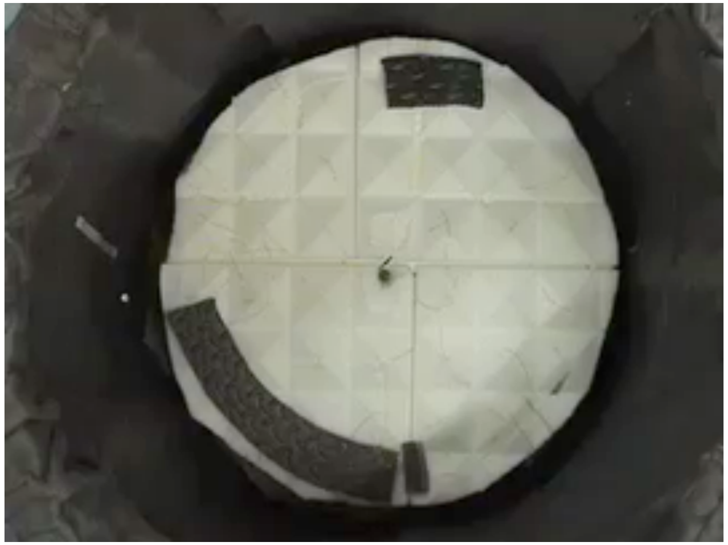
E-mail: m.padgett@physics.gla.ac.uk

New Journal of Physics **10** (2008) 013018 (9pp)
Received 17 September 2007
Published 21 January 2008



Watt for watt, sound (in air) has 10^6 times more push than light (in vacuum)

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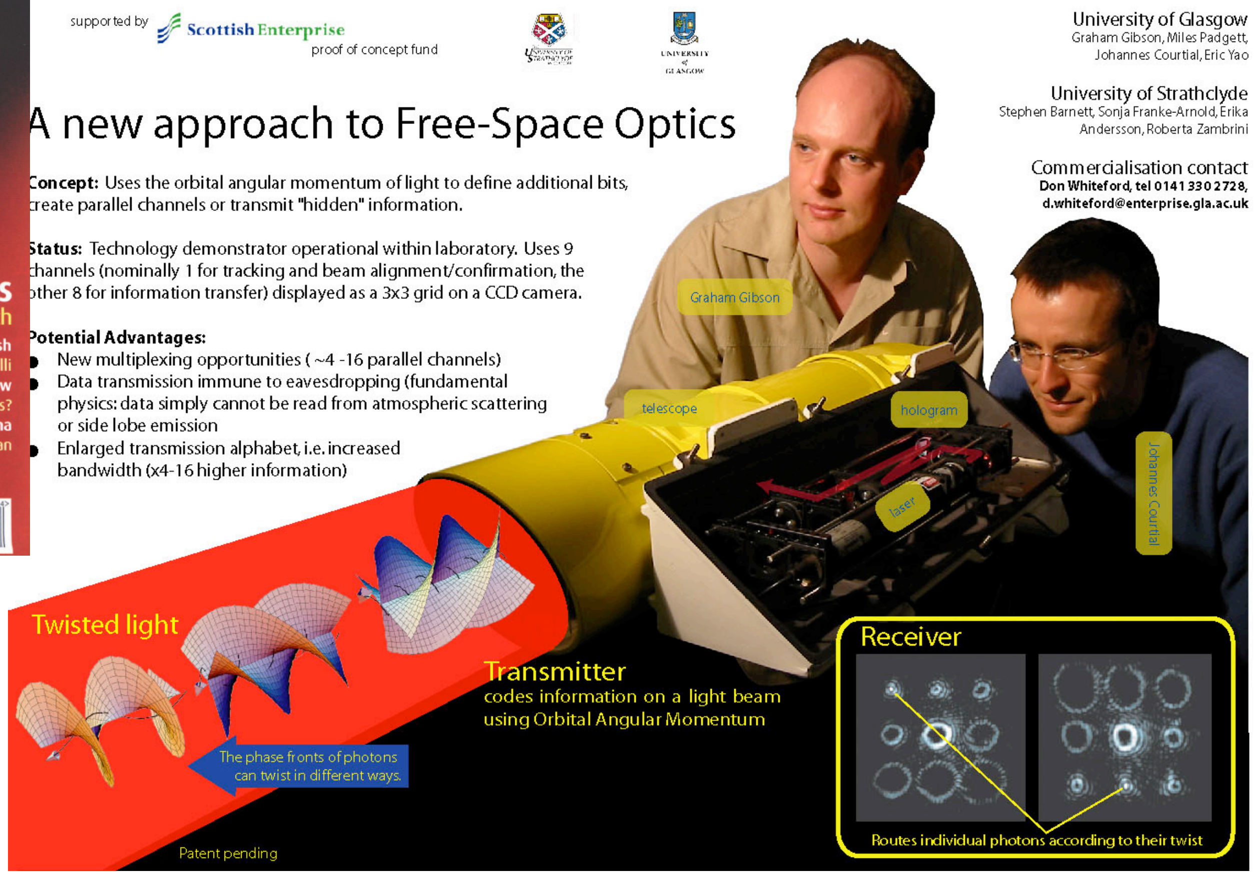
Free-space information transfer using light beams carrying orbital angular momentum

Graham Gibson, Johannes Courtial, Miles J. Padgett
Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, Scotland

1 November 2004 / Vol. 12, No. 22 / OPTICS EXPRESS 5448

Free-space comms



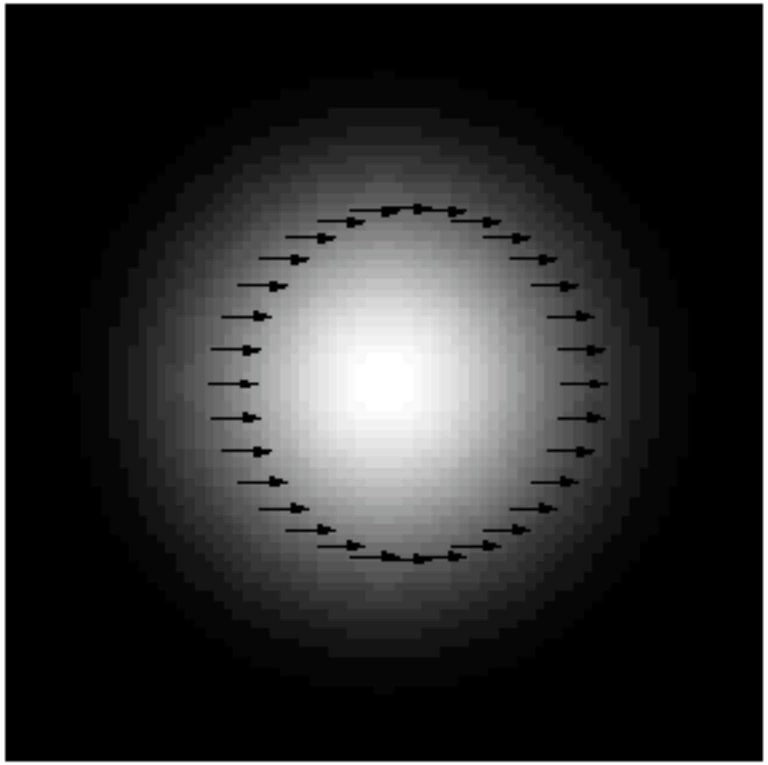
Annular Doppler shift for circularly polarised light

- Additional rotation of polarisation (at Ω) shifts frequency

  $\Delta\omega = \Omega$

  $= \sigma\Omega \quad (\sigma=\pm1)$

- c.f. time speeds up if you rotate a clock!



Annular Doppler for helically phased circ. polarised light -1

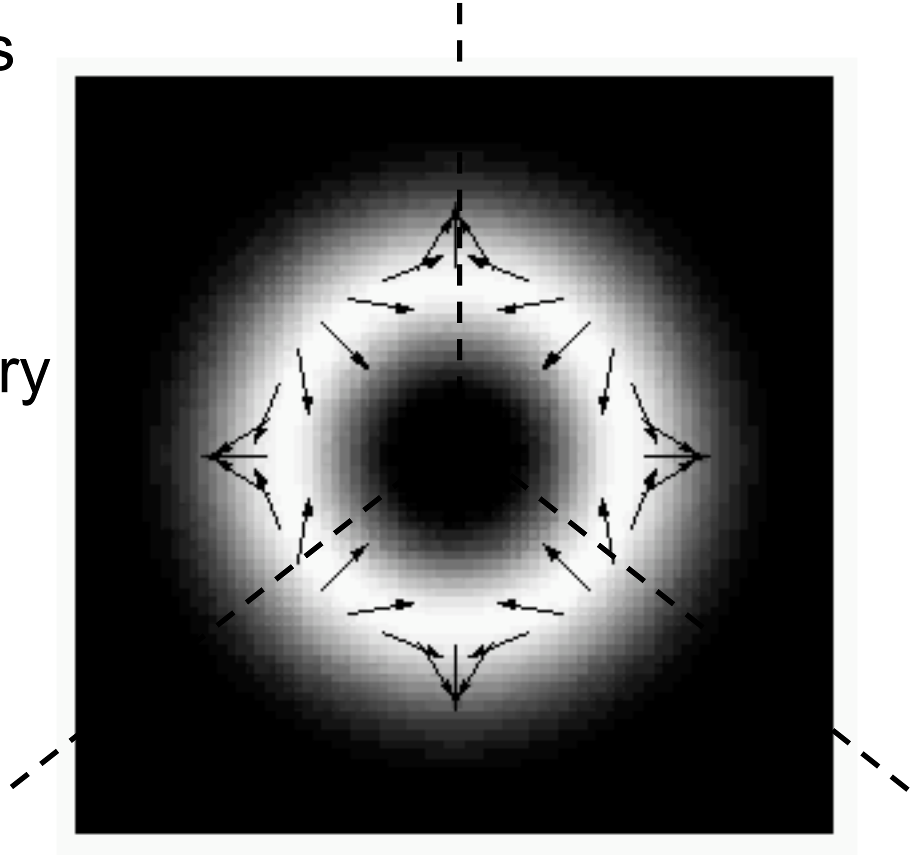
- Such a beam contains both SAM and OAM
- Example 1

  $\ell = 3$, $\sigma = +1$
- Four fold rot. Symmetry
- Rotate beam at Ω

  $\Delta\omega = (\ell+\sigma)\Omega$

  $= J\Omega$

  $= 4\Omega$



Rot. Doppler for helically phased, circ. polarised light -2

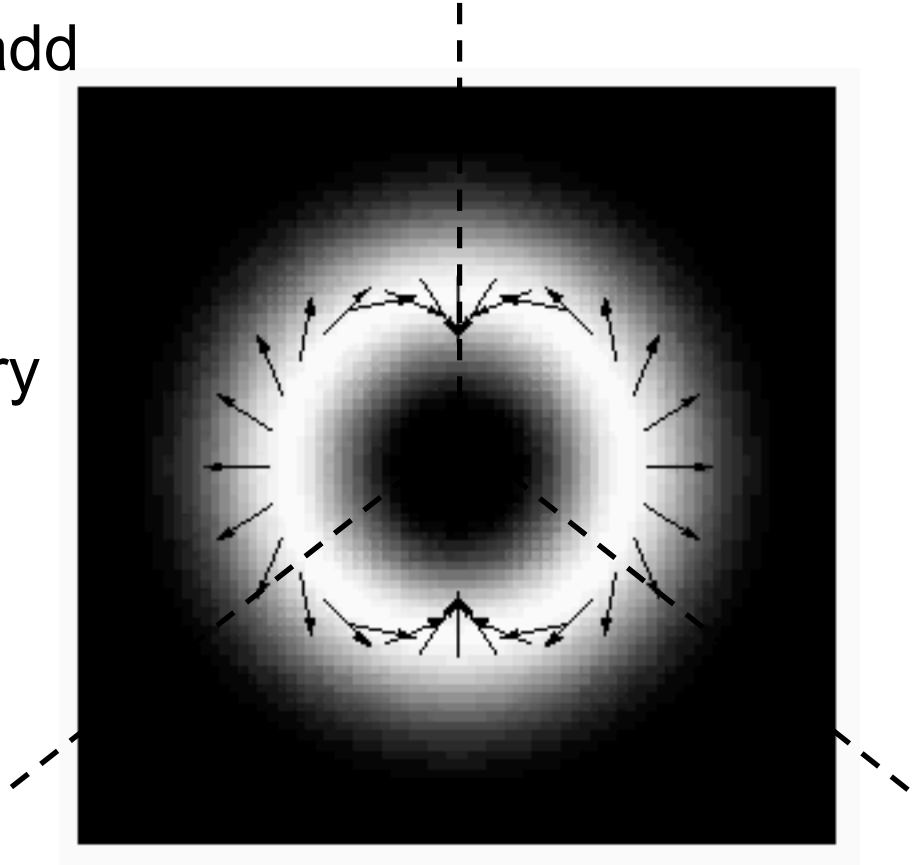
- The SAM and OAM add or subtract
- Example 2

  ℓ = -3, σ =+1
- Two fold rot. Symmetry
- Rotate beam at Ω

  $\Delta\omega = (\ell+\sigma)\Omega$

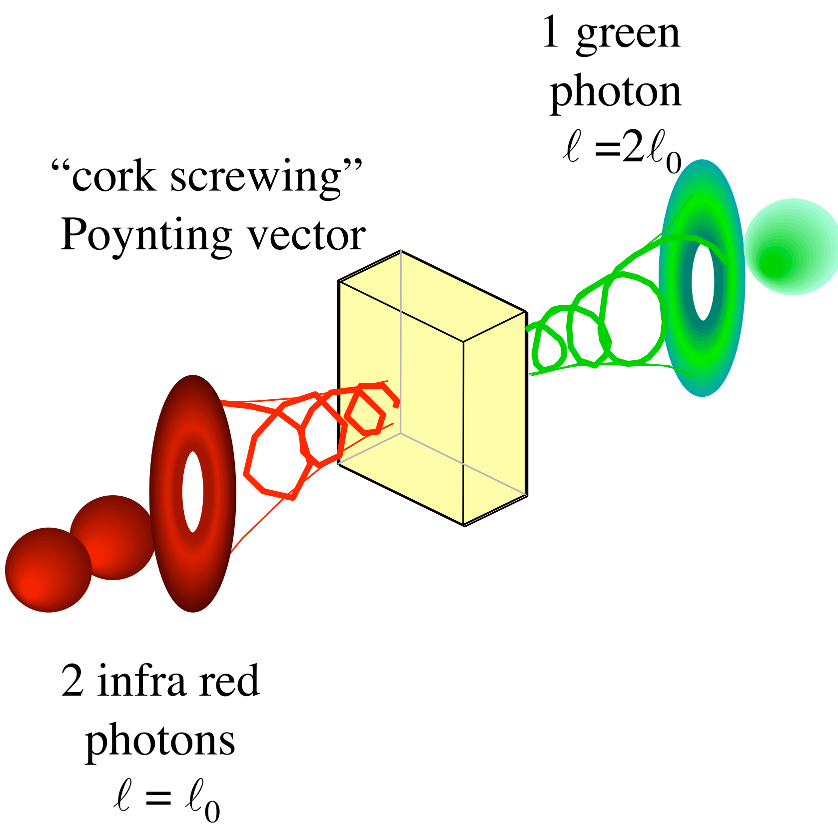
  $= J\Omega$

  $= 2\ \Omega$



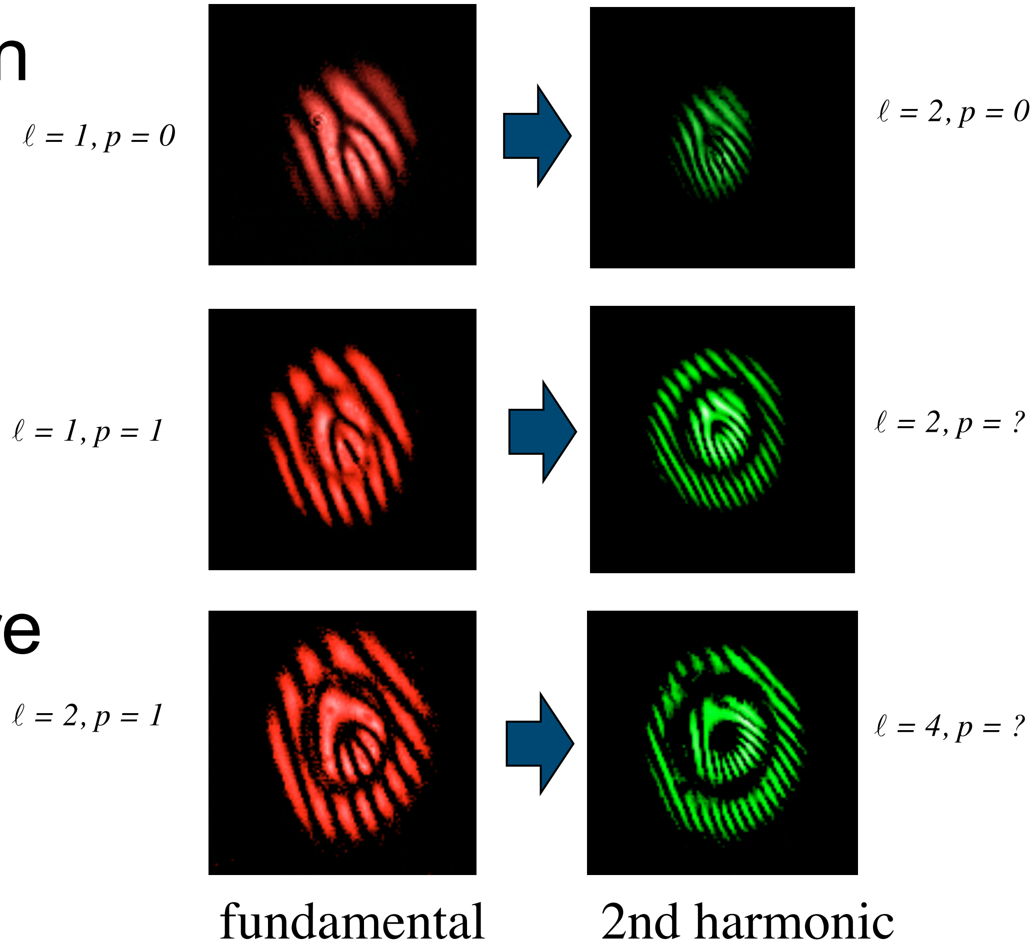
OAM in second harmonic generation

- Poynting vector "cork screws", azimuthal skew angle is
  - $\theta = \ell/kr$
- Does this upset a co-linear phase match? -No
- Frequency & ℓ-index both double
- "Path" of Poynting vector stays the same
  - phase matching maintained



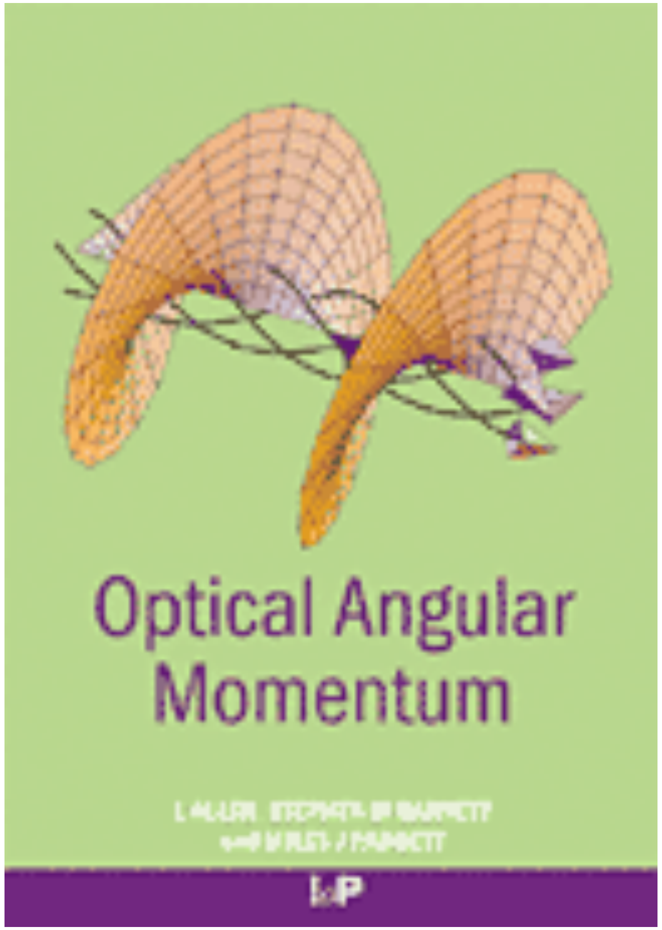
OAM conserved in SHG

- OAM conserved in the light beam
- c.f. SAM in which OAM is not conserved
- But, down conversion is more complicated!

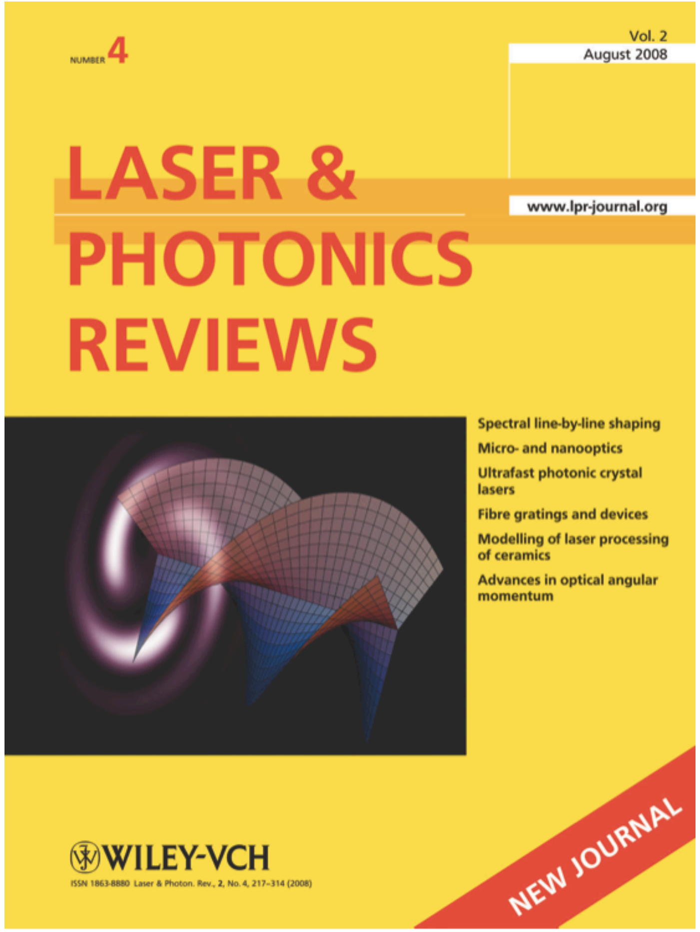


Further reading on OAM?

92-02



-08



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Electromagnetism and beyond!

PRL **100,** 124801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

Proposal for Generating Brilliant X-Ray Beams Carrying Orbital Angular Momentum

Shigemi Sasaki and Ian McNulty

PRL **99,** 087701 (2007) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2007

Utilization of Photon Orbital Angular Momentum in the Low-Frequency Radio Domain

B. Thidé,[1,*] H. Then,[2] J. Sjöholm,[3] K. Palmer,[3] J. Bergman,[1] T. D. Carozzi,[4] Ya. N. Istomin,[5] N. H. Ibragimov,[6] and R. Khamitova[6]

NH ELSEVIER 15 June 1996 Optics Communications 127 (1996) 183–188 OPTICS COMMUNICATIONS

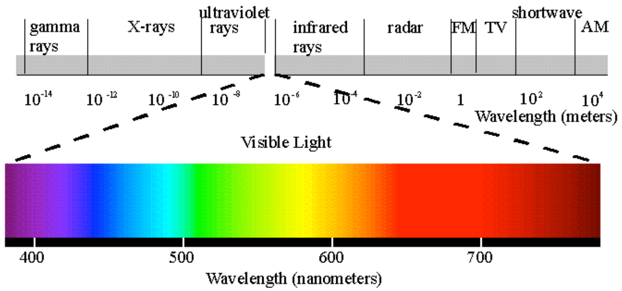
The generation of free-space Laguerre-Gaussian modes at millimetre-wave frequencies by use of a spiral phaseplate

G.A. Turnbull, D.A. Robertson, G.M. Smith, L. Allen, M.J. Padgett

Transfer of orbital angular momentum from a super-continuum, white-light beam

Amanda J Wright[1*], John M Girkin[1], Graham M Gibson[2], Jonathan Leach[2] and Miles J Padgett[2]

23 June 2008 / Vol. 16, No. 13 / OPTICS EXPRESS 9495



PRL **100,** 024302 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

Transfer of Angular Momentum to Matter from Acoustical Vortices in Free Space

Karen Volke-Sepúlveda,[1] Arturo O. Santillán,[2,*] and Ricardo R. Boullosa[2]

Vol 464 | 1 April 2010 | doi:10.1038/nature08904 nature

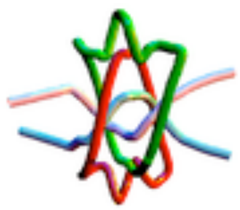
LETTERS

Generation of electron beams carrying orbital angular momentum

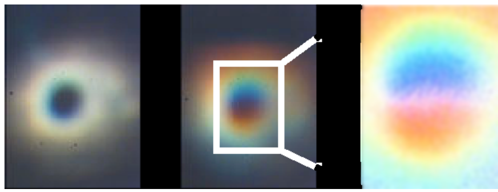
Masaya Uchida[1] & Akira Tonomura[1]

University of Glasgow

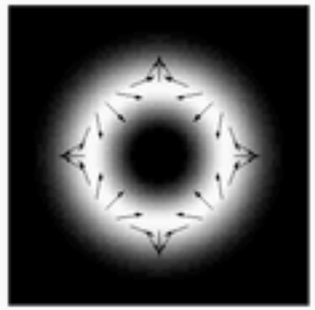
What else for OAM



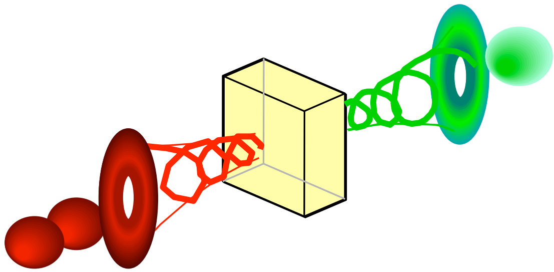
Vortex loops



White light vortices

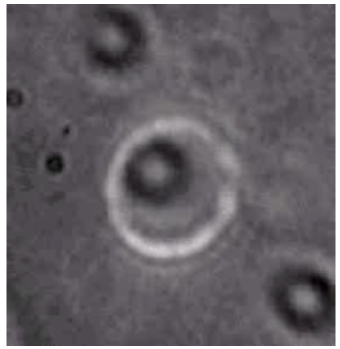


Rotational Frequency Shifts



Non-linear freq. conversion

OAM communication



Optical spanners

Optical Vortices before Angular Momentum

Proc. R. Soc. Lond. A. **336**, 165–190 (1974)
Printed in Great Britain

Dislocations in wave trains

BY J. F. NYE AND M. V. BERRY
H. H. Wills Physics Laboratory, University of Bristol

And vortex lines in electron wavefunctions

Quantised Singularities in the Electromagnetic Field

P. A. M. Dirac

Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 133, No. 821. (Sep. 1, 1931), pp. 60-72.

Fractality and Topology of Light's darkness

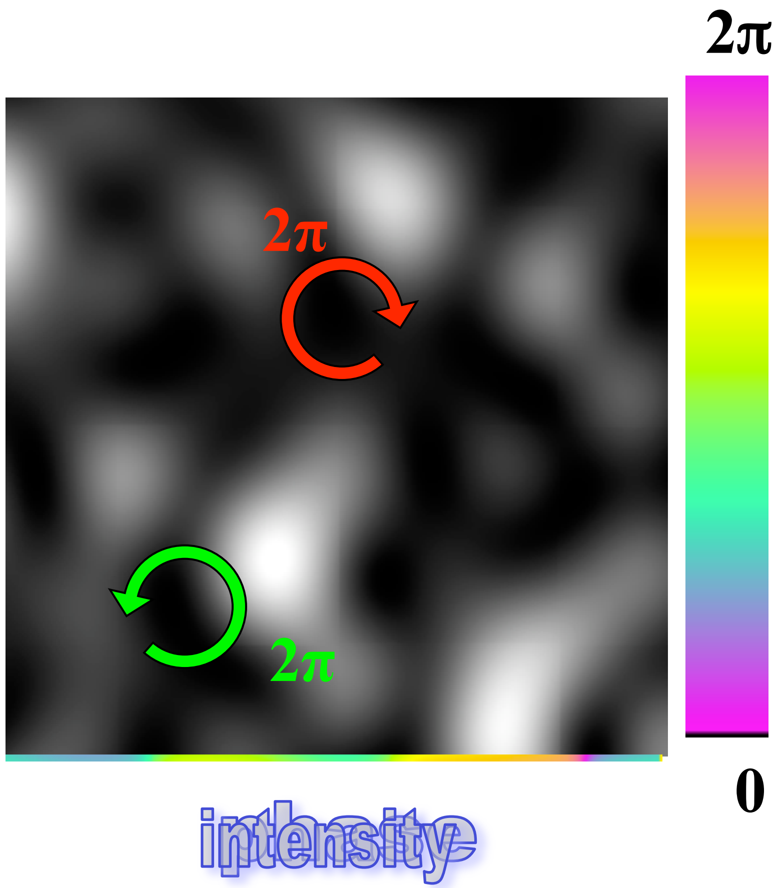
Kevin O'Holleran

Florian Flossmann

Mark Dennis (Bristol)

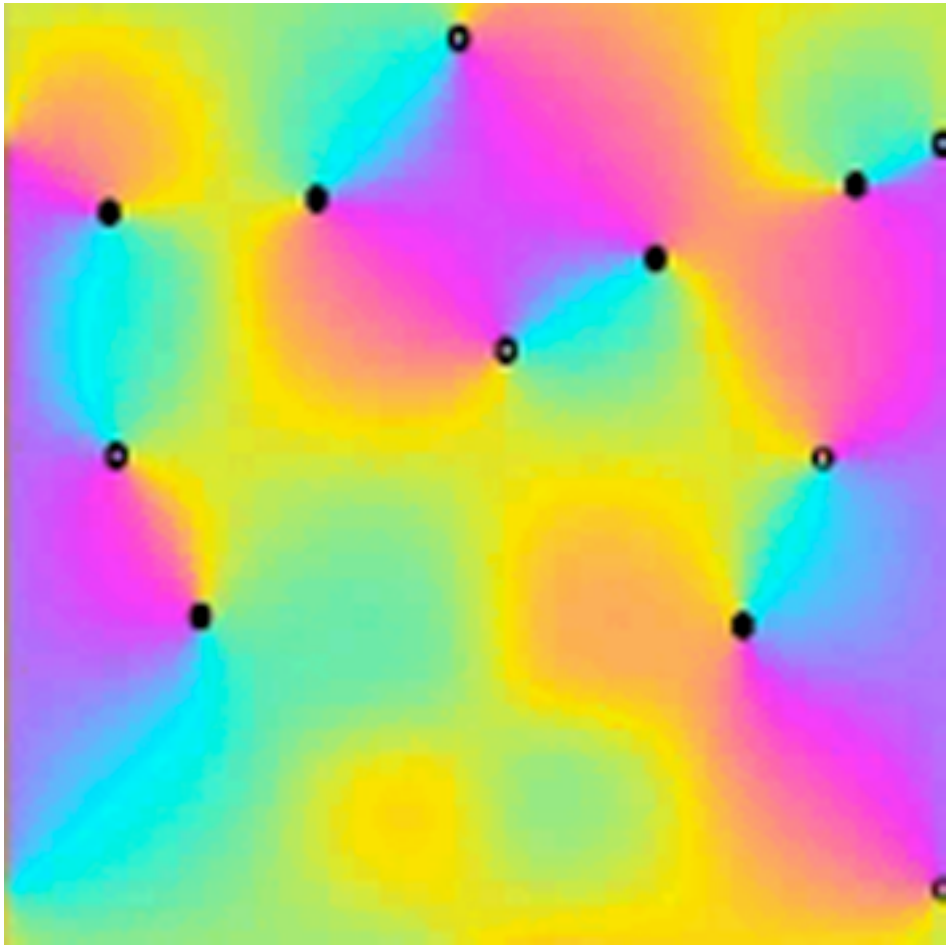
Vortices are ubiquitous in nature

- Whenever ***three*** (or more) plane waves interfere optical vortices are formed
  - Charge one vortices occur wherever there is diffraction or scattering

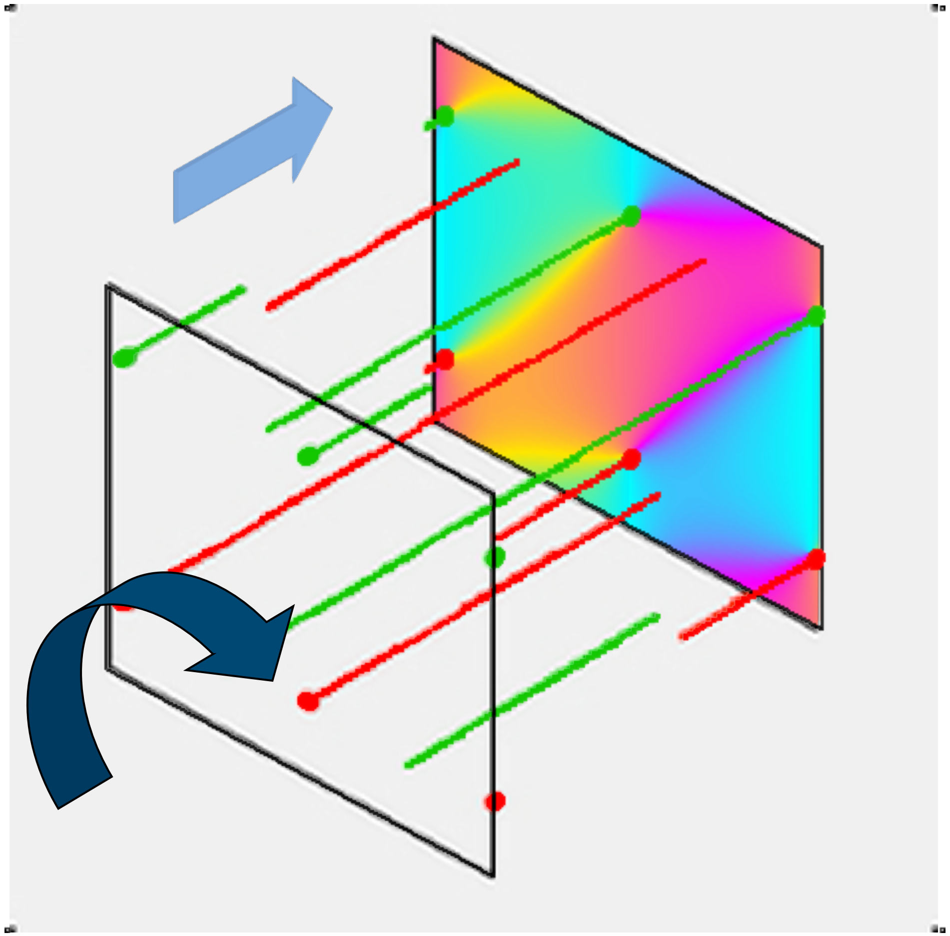


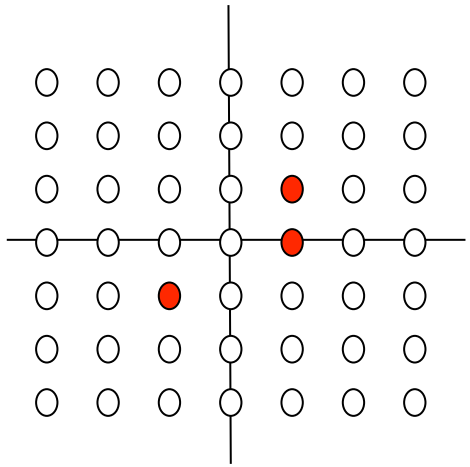
Map out the vortex position in different planes

- Either numerically or experimentally one can map the vortex positions in different planes



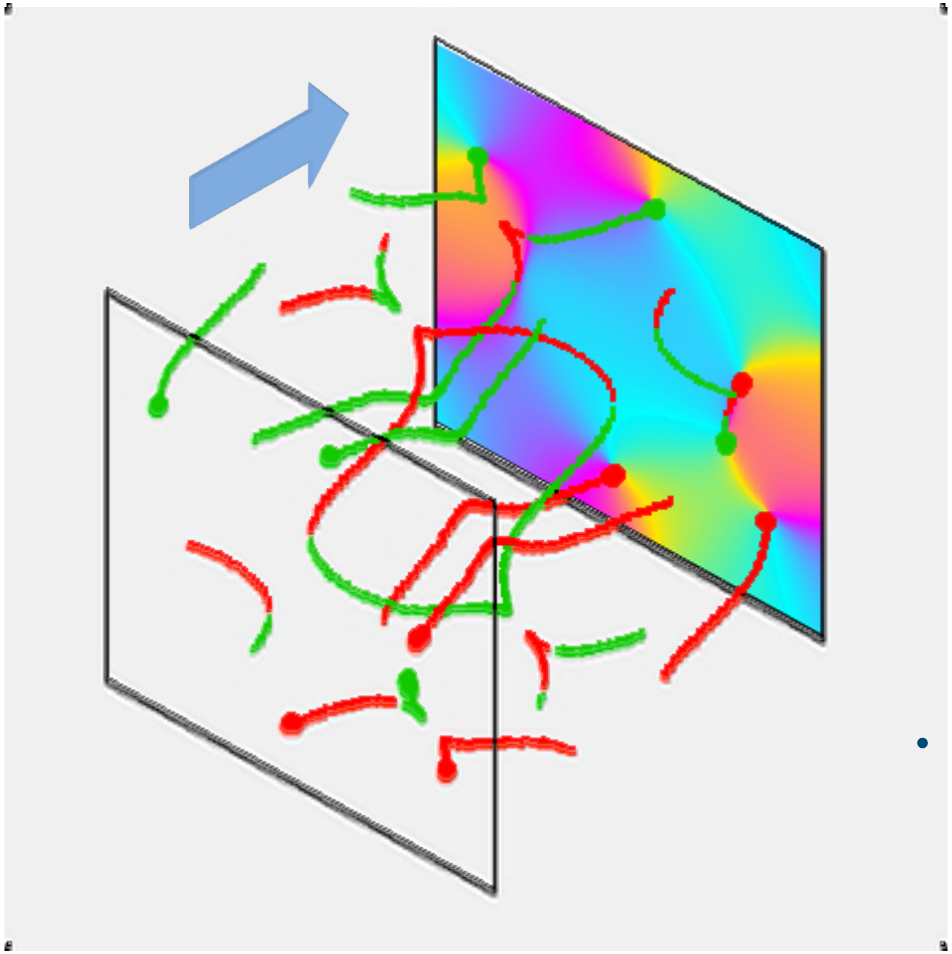
3-plane waves (= amplitude)

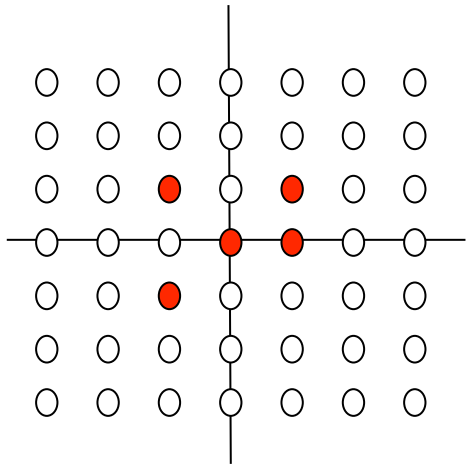




Vortex threads are straight and parallel

5-plane waves (= amplitude)

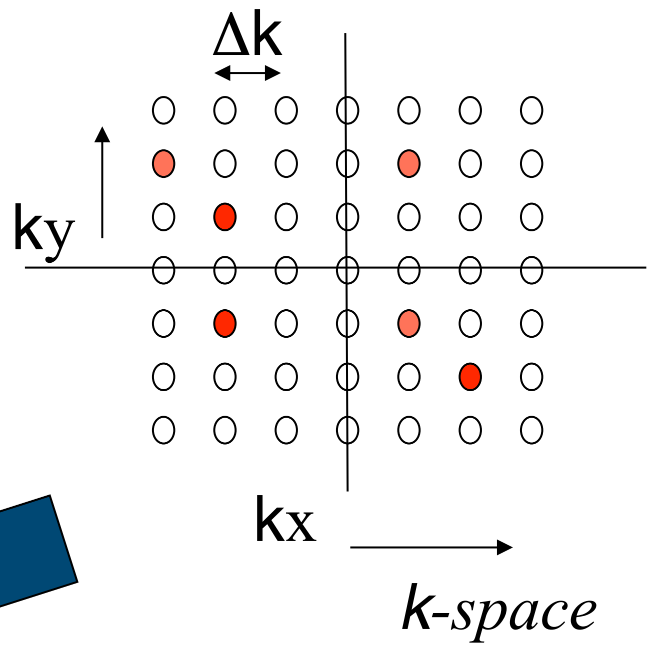


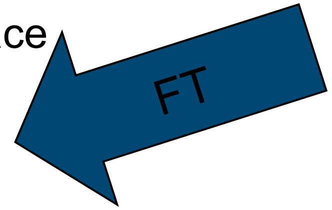


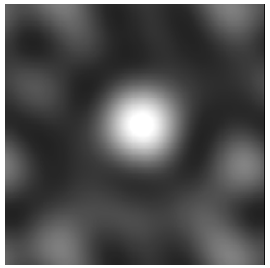
- Vortex threads form closed loops & open lines

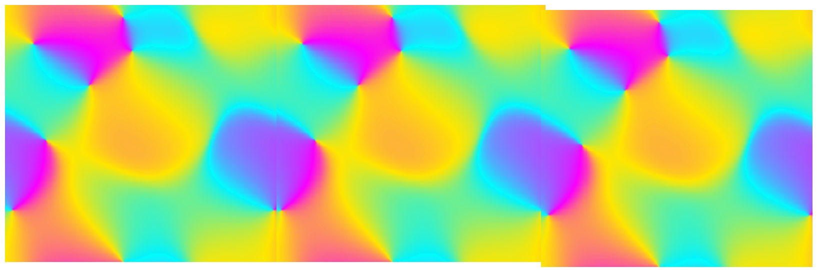
Modeling plane-wave interference 3D patterns

- Multiple plane-wave described in *k-space*
- Use a discrete spatial spectrum, gives an interference pattern with
  - lateral periodicity $2\pi/\Delta k$
  - axial periodicity $2\pi/(\Delta k^2/2k_0)$
- Can calculate interference pattern over a representative “Talbot cube”
- Tile cubes together to cover all space



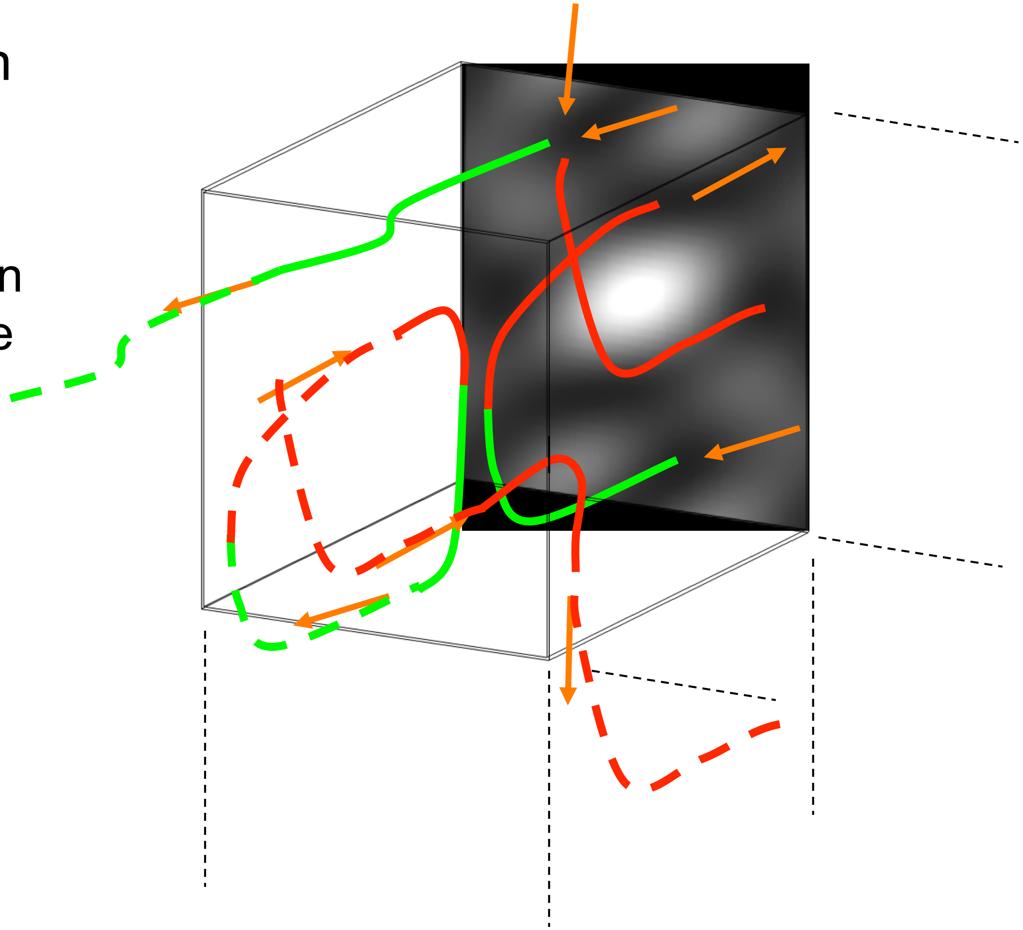






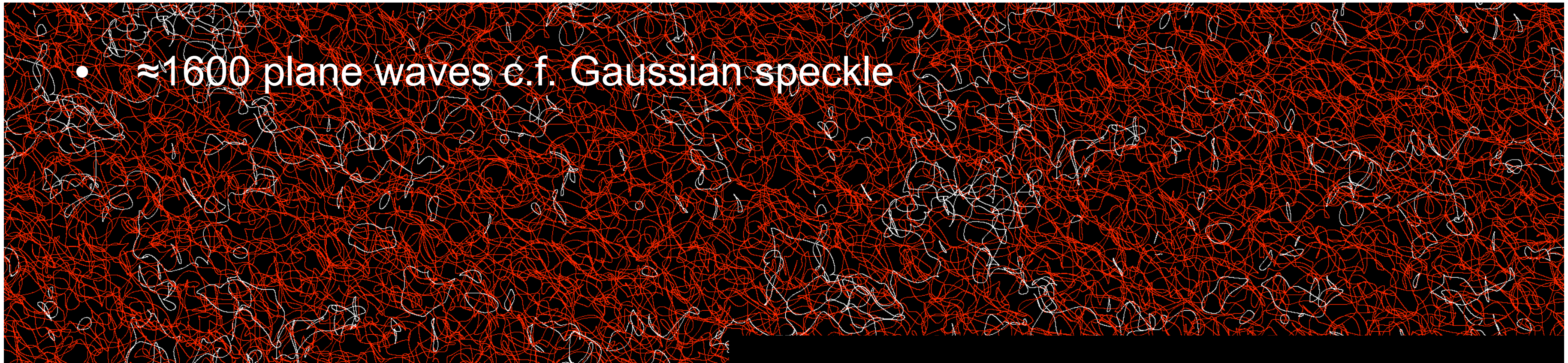
Within the "Talbot cube"

- Map out the vortex lines in 3D
- Vortex lines re-enter cube
  - Can "tile" the cube to gain knowledge over all space

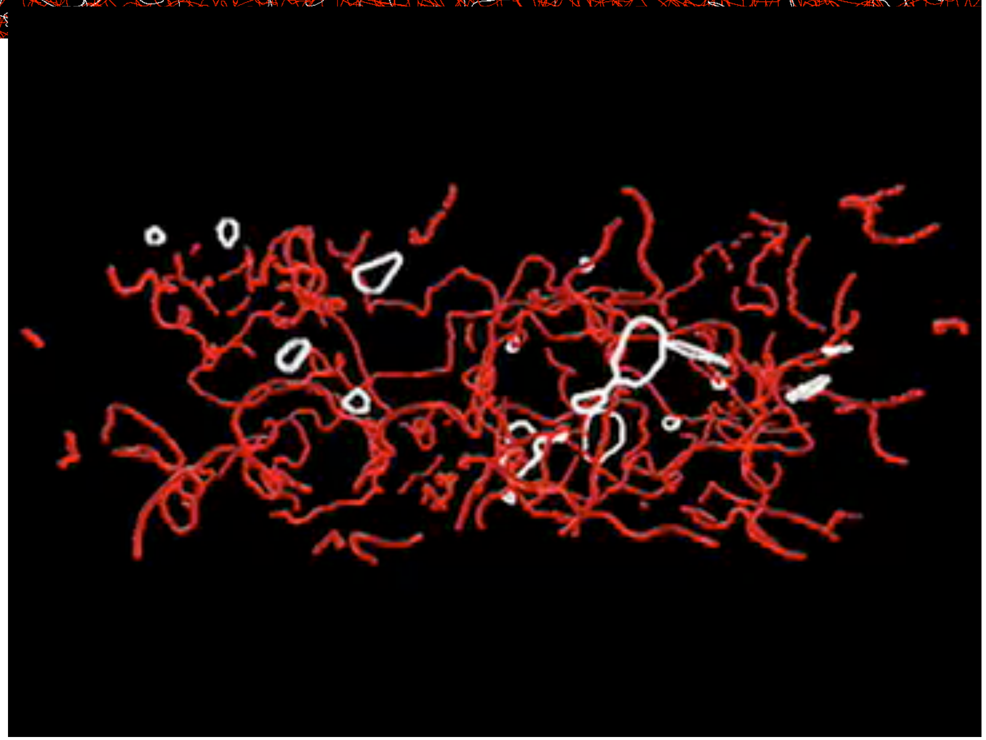


The tangled web of speckle

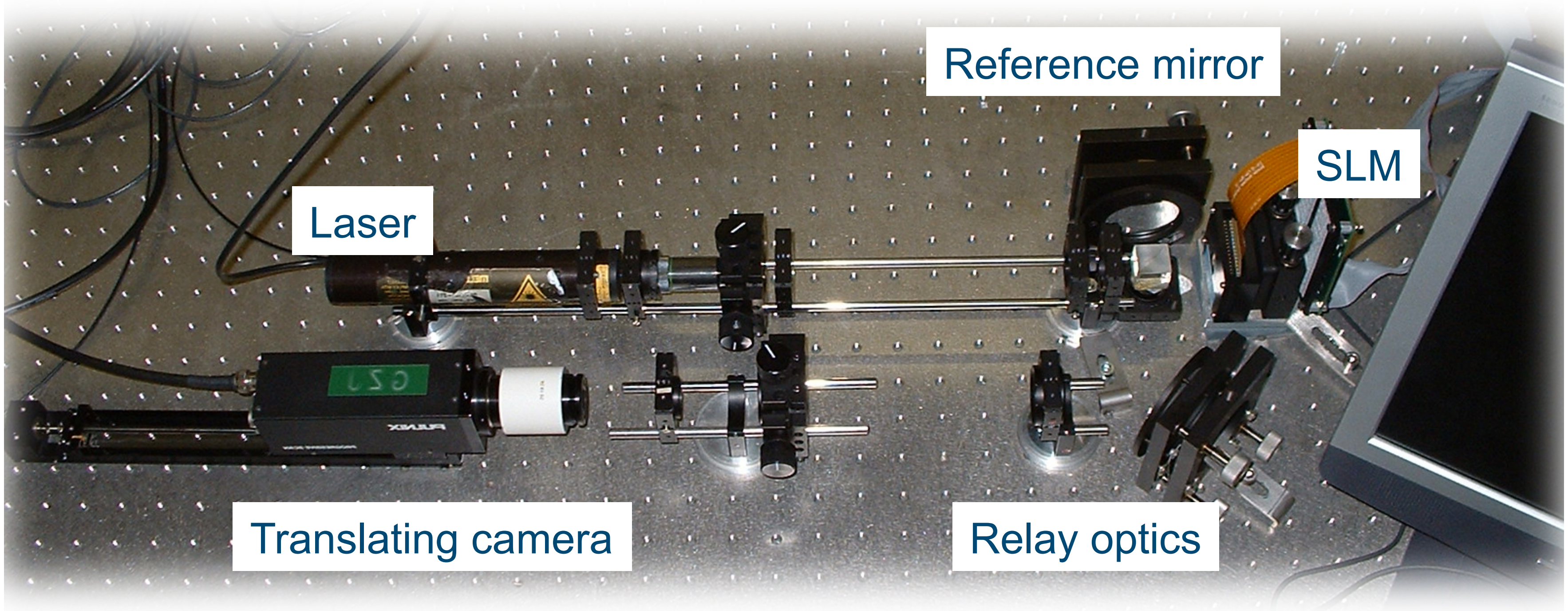
- ≈1600 plane waves c.f. Gaussian speckle



- Experiment



Experimental recording of 3D interferograms



University of Glasgow

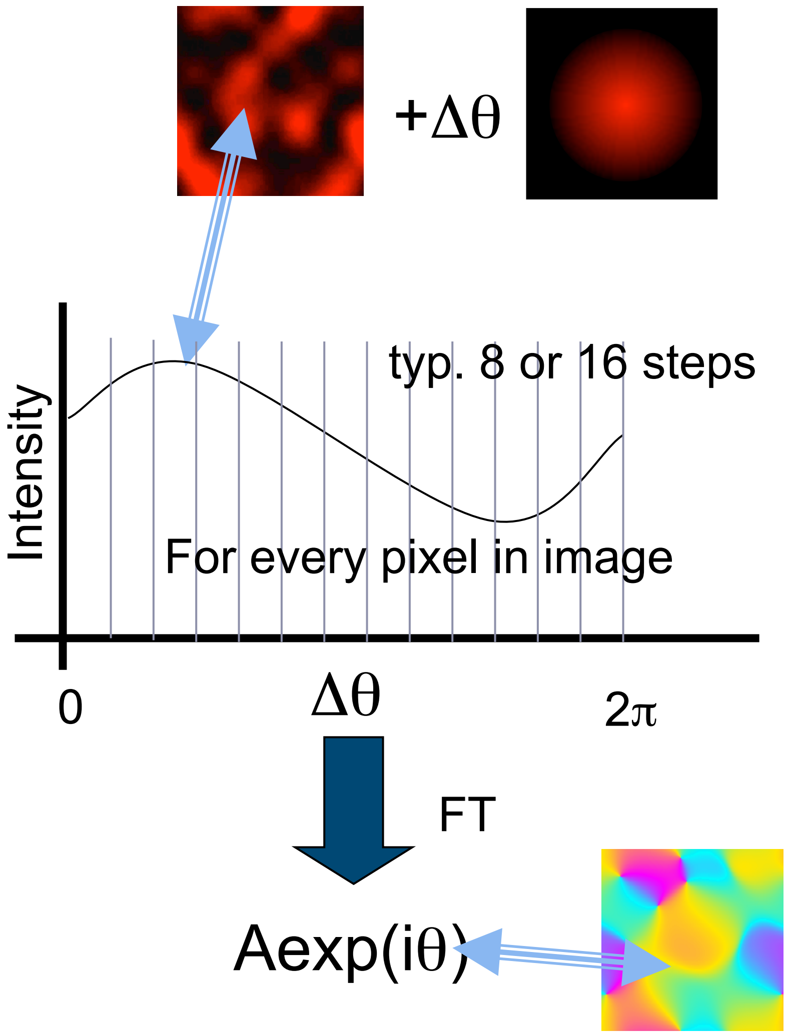
IOP PUBLISHING JOURNAL OF OPTICS A: PURE AND APPLIED OPTICS
J. Opt. A: Pure Appl. Opt. 11 (2009) 094020 (7pp) doi:10.1088/1464-4258/11/9/094020

Methodology for imaging the 3D structure of singularities in scalar and vector optical fields

K O'Holleran[1], F Flossmann[1], M R Dennis[2] and M J Padgett[1]

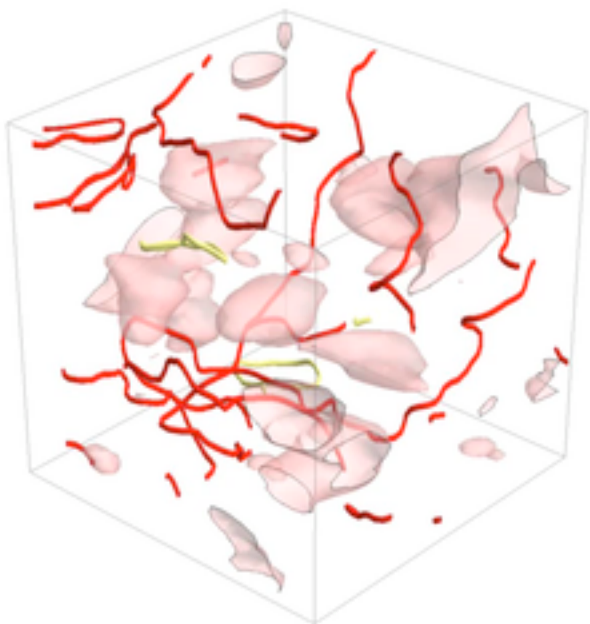
Fourier to recover phase

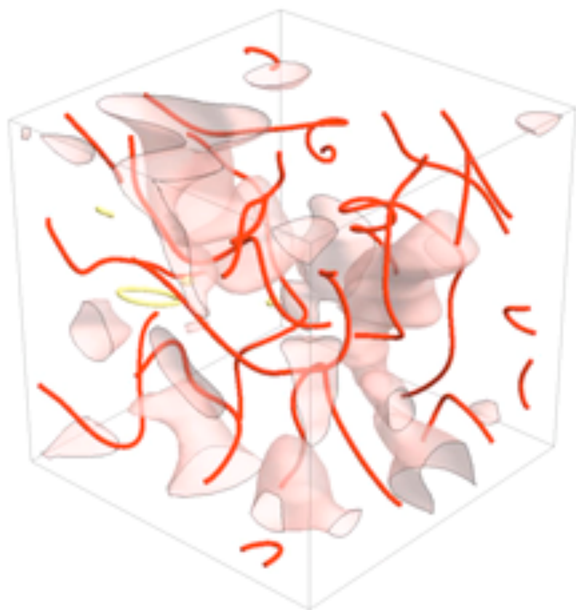
- Use SLM to phase step the reference,
- Record intensity (12-bit) of EVERY pixel as a function of phase
  - Over sample phase to give improved noise immunity
- FT of the pixel variation gives relative phase of random pattern with respect to reference



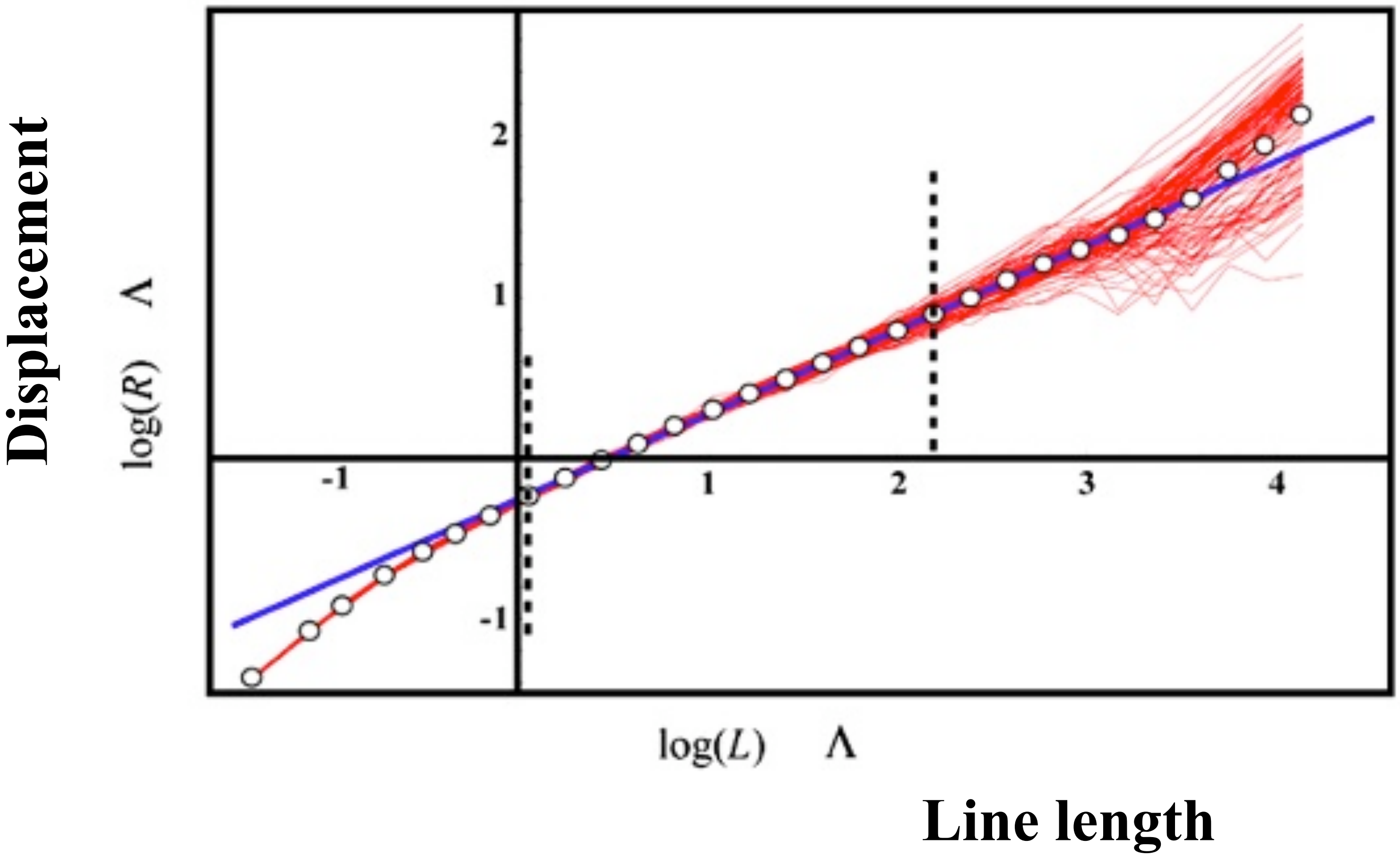
University of Glasgow

Vortex lines in Speckle





Fractality of Light's darkness

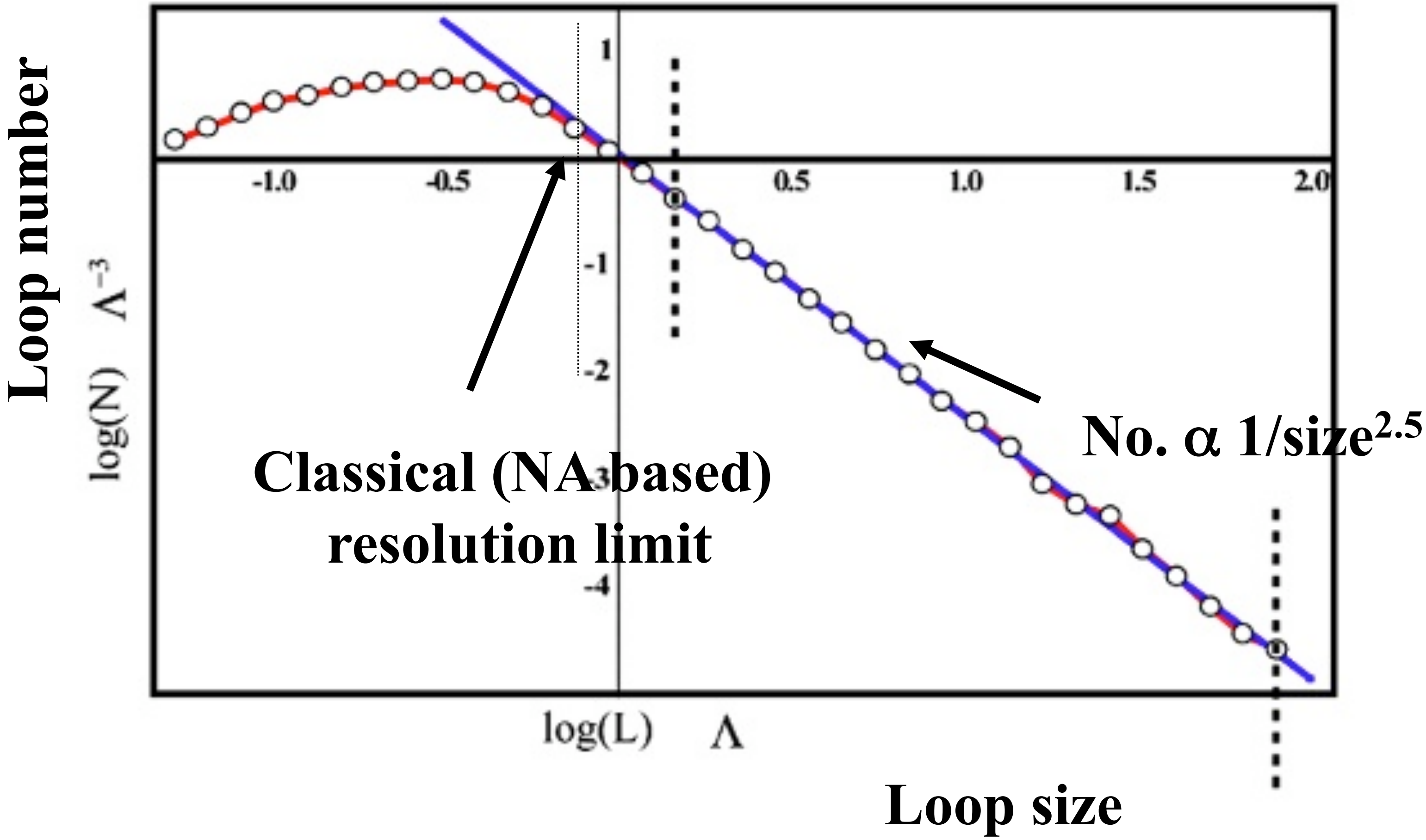


PRL 100, 053902 (2008) PHYSICAL REVIEW LETTERS week ending 8 FEBRUARY 2008

Fractality of Light's Darkness

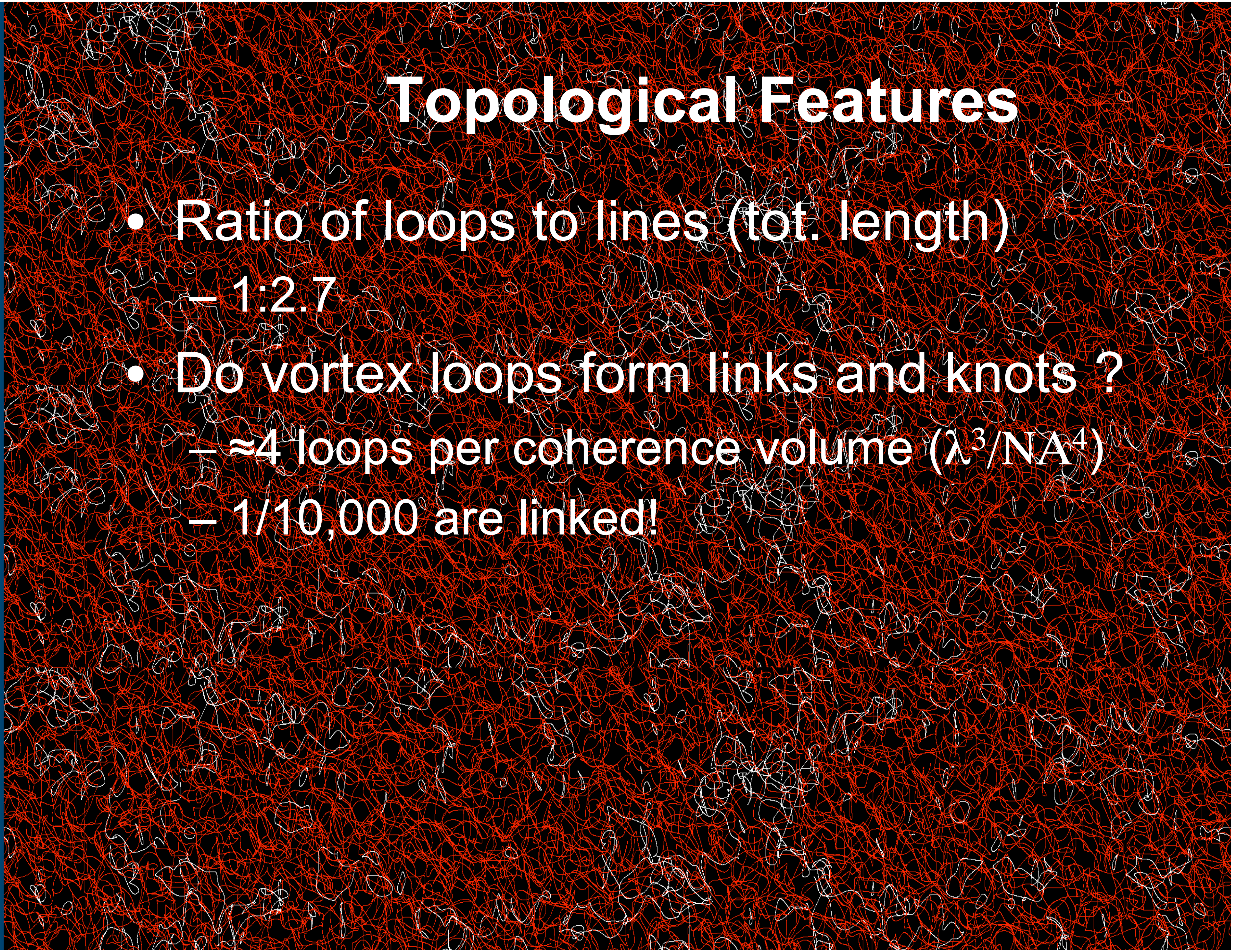
Kevin O'Holleran,[1,*] Mark R. Dennis,[2] Florian Flossmann,[1] and Miles J. Padgett[1]

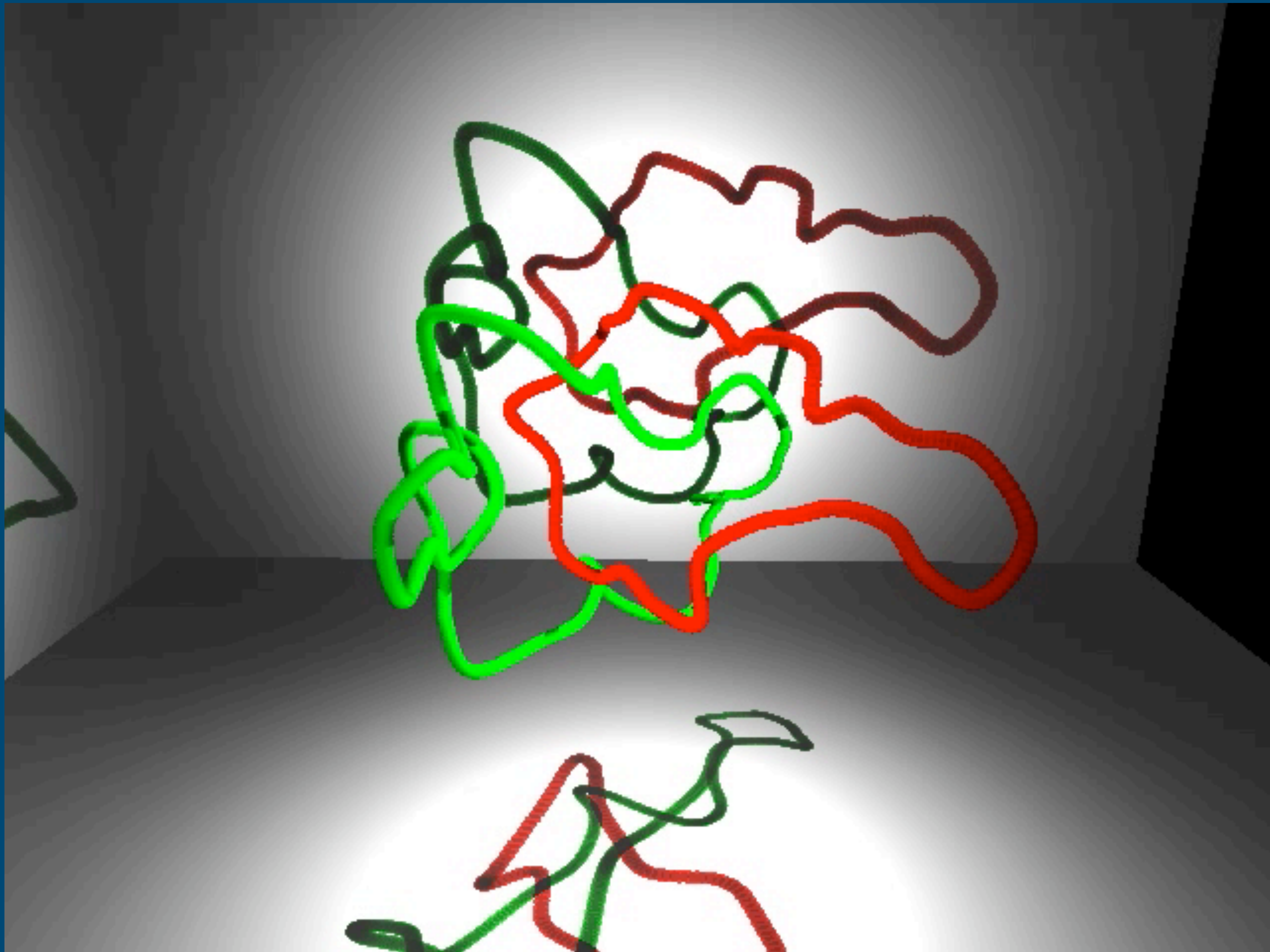
Closed vortex loops have a defined size distribution



Topological Features

- Ratio of loops to lines (tot. length)
  - 1:2.7
- Do vortex loops form links and knots ?
  - ≈4 loops per coherence volume (λ^3/NA^4)
  - 1/10,000 are linked!



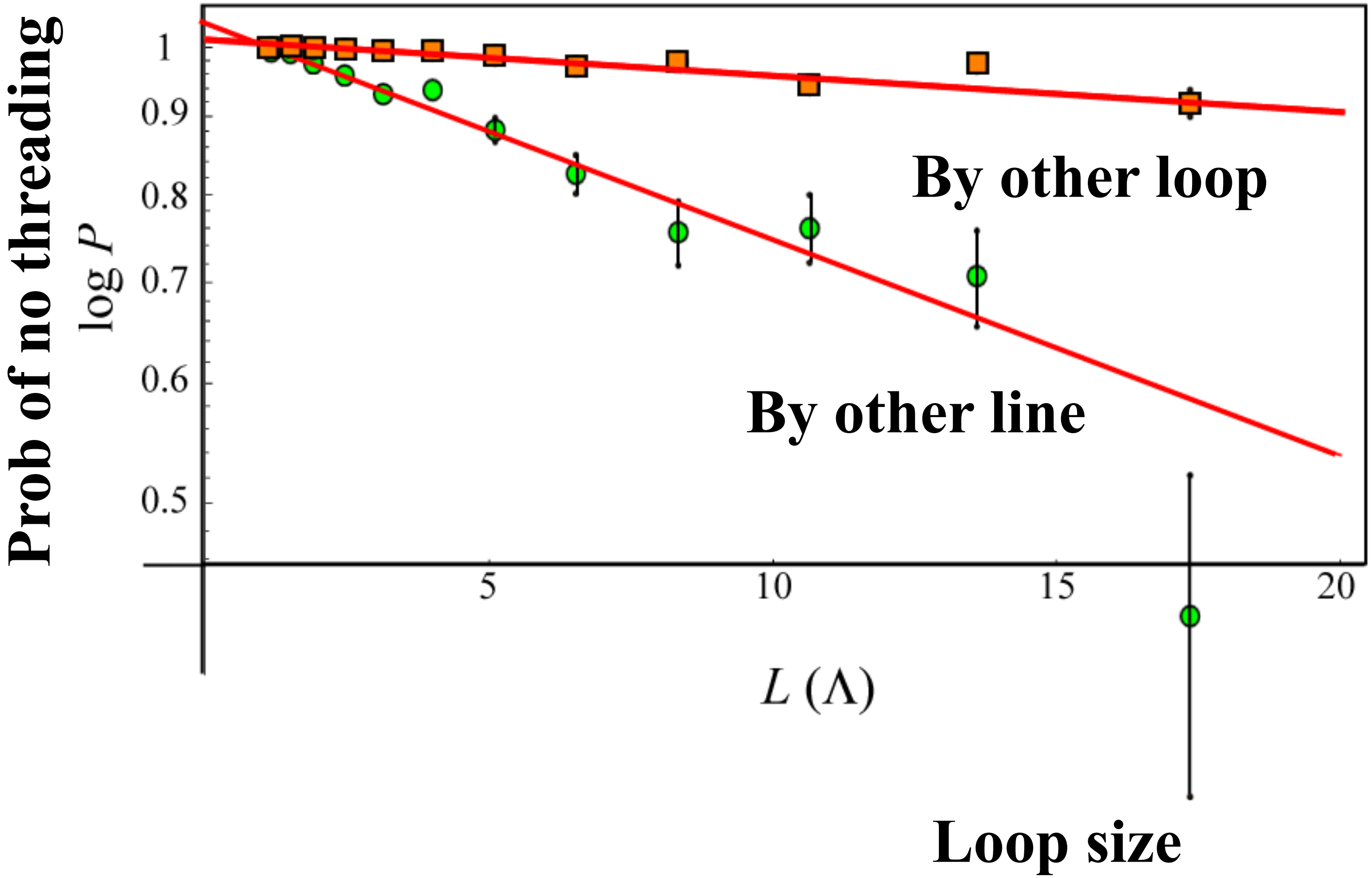


PRL 102, 143902 (2009) PHYSICAL REVIEW LETTERS week ending 10 APRIL 2009

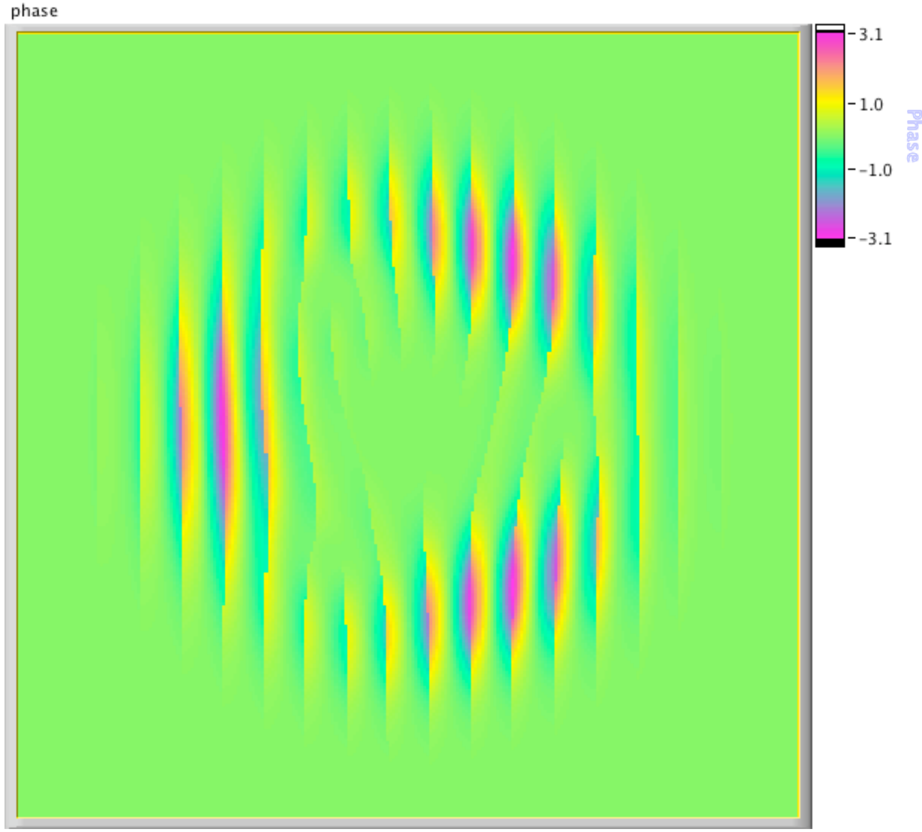
Topology of Light's Darkness

Kevin O'Holleran,[1] Mark R. Dennis,[2] and Miles J. Padgett[1,*]

Loops have exponential chance of NOT being threaded

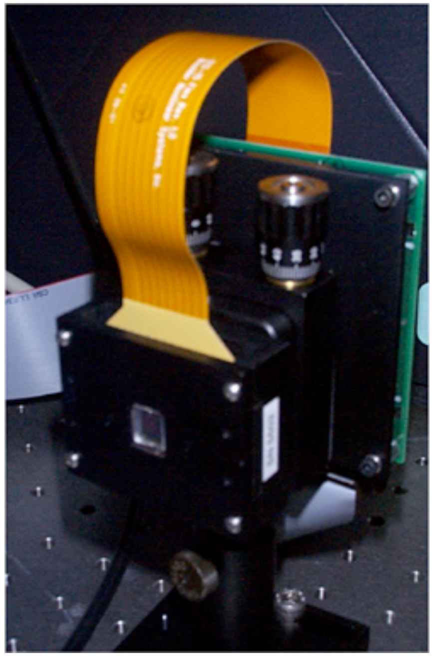


Diffraction grating (hologram) to make Knots



Hologram to shape phase *AND* intensity of beam

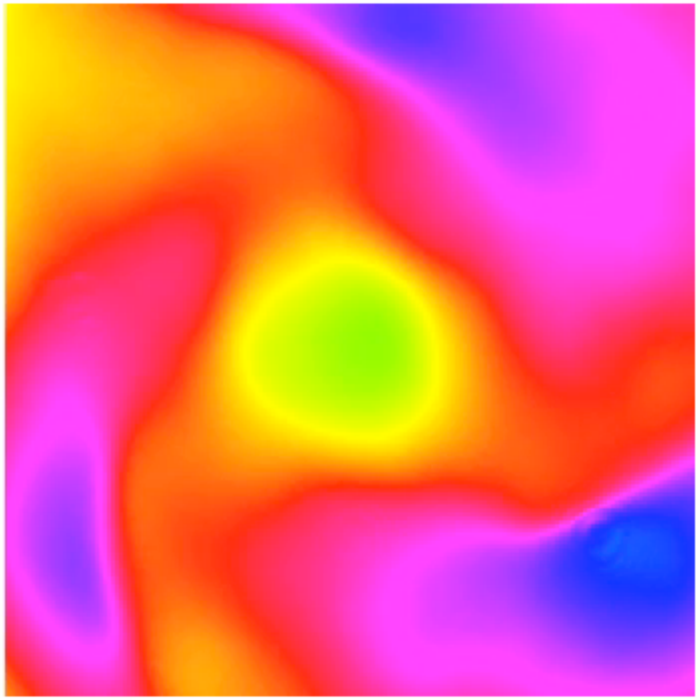
Display hologram



Demo

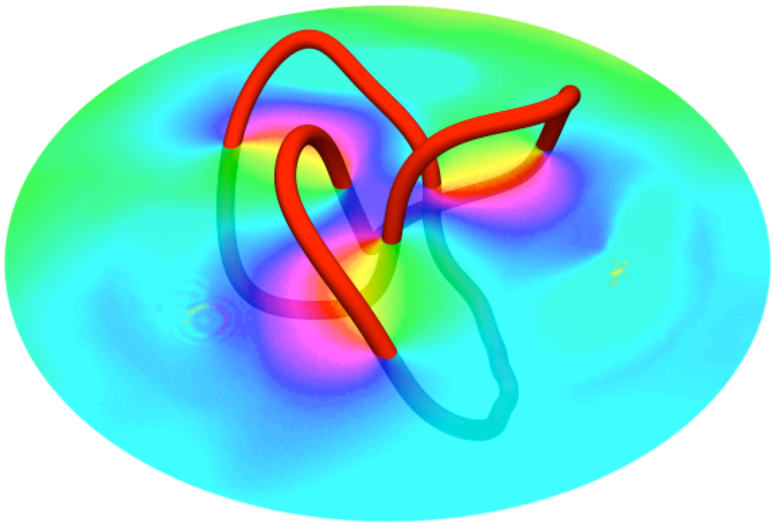
University of Glasgow

And the Knot

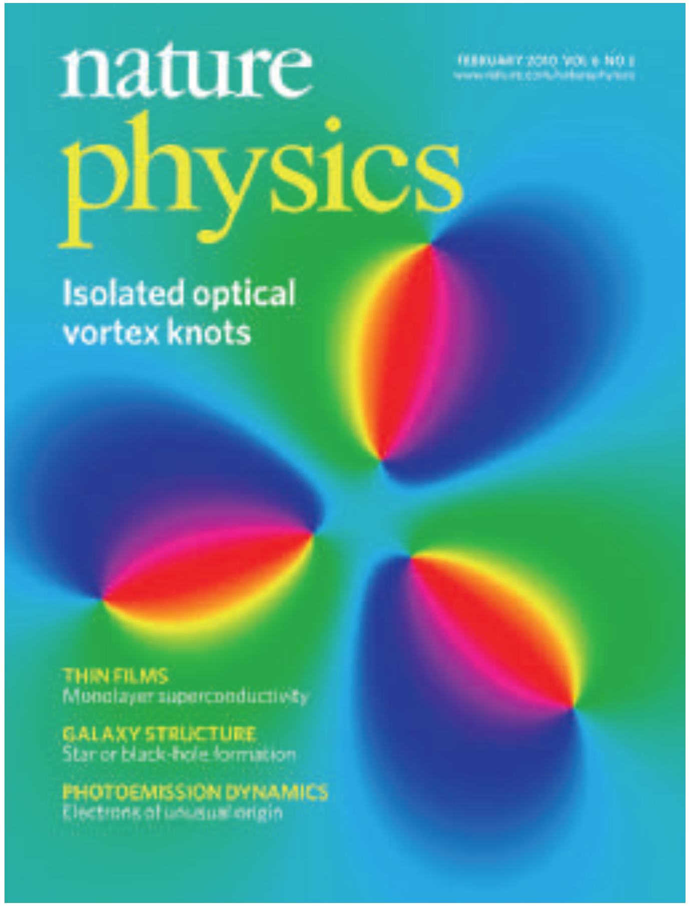


Cross-sections through holographically created knot

Tomographic reconstruction



The Nature of Science



Robert King, Kevin O’Holleran, Barry Jack

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

PRL 95, 240501 (2005) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2005

Experimental Demonstration of Fractional Orbital Angular Momentum Entanglement of Two Photons

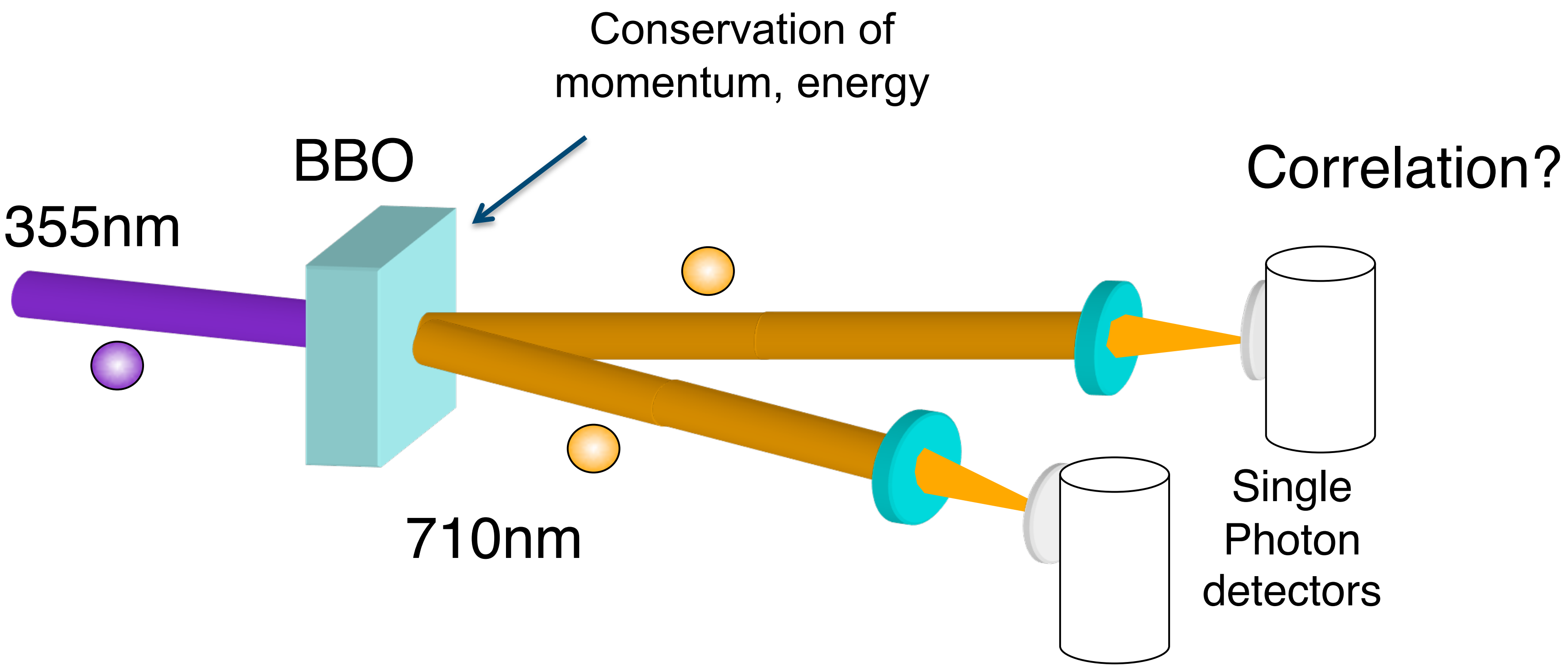
S. S. R. Oemrawsingh,* X. Ma, D. Voigt, A. Aiello, E. R. Eliel, G. W. 't Hooft,† and J. P. Woerdman

PRL 95, 260501 (2005) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2005

Generation of Hyperentangled Photon Pairs

Julio T. Barreiro,[1] Nathan K. Langford,[2] Nicholas A. Peters,[1] and Paul G. Kwiat[1]

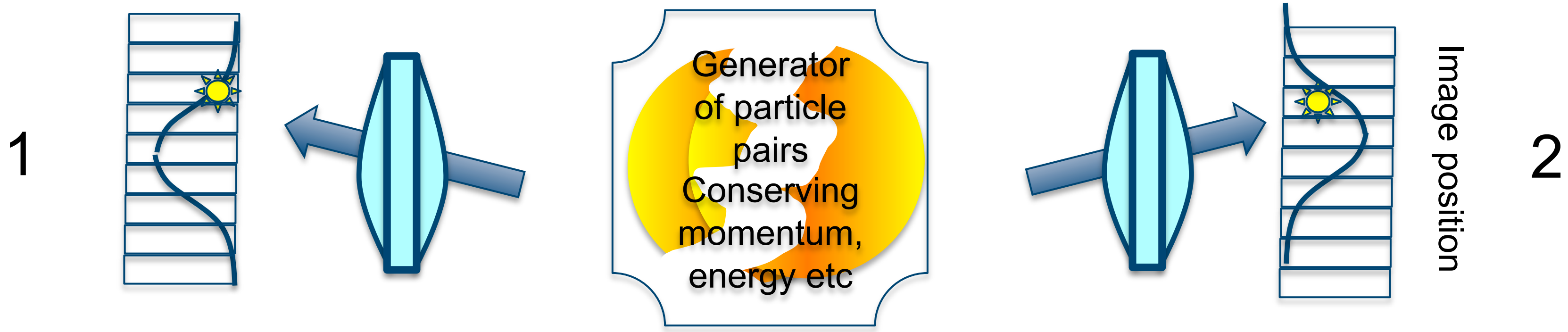
Quantum Entanglement and Down Conversion



Entanglement of →

Polarisation (Apin AM)
Energy (frequency) – time
Position – Momentum
Spatial modes

What is EPR?



Particles are distributed in position, but each individual particle has precisely defined x_1

$x_1 - x_2 = 0$

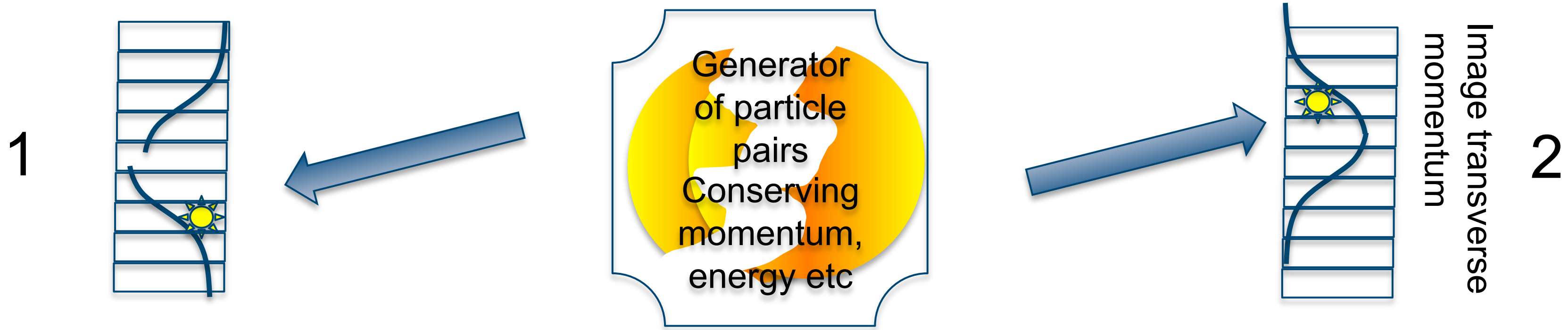
Particles are distributed in position, but each individual particle has precisely defined x_2

The particles “started” from the same position (i.e. conservation)

Measuring position of one particle gives instantaneous (non local) knowledge of the other particle

One concludes that particles carry position information from source to point of measurement.

What is EPR - continued



Particles are distributed in momentum, but each individual particle has precisely defined p_1

$p_1+p_2 = 0$

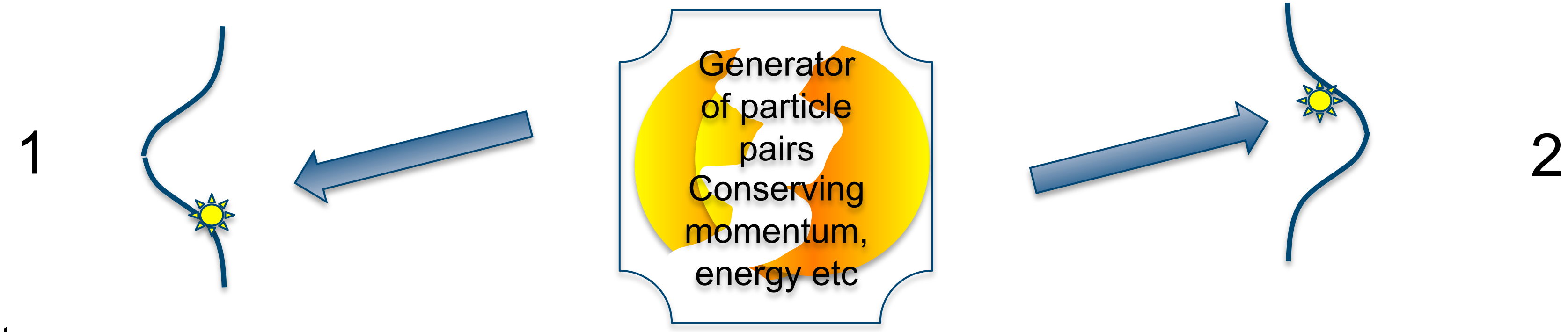
Particles are distributed in momentum, but each individual particle has precisely defined p_2

The particles “started” with the opposite momentum (i.e. conservation)

Measuring momentum of one particle gives instantaneous (non local) knowledge of momentum of the other particle

One concludes that particles carry the momentum information from source to point of measurement.

So what is the problem?



It seems we can measure momentum of 1 and know position from having measured the position of 2

$$p_1+p_2 = 0$$
$$x_1-x_2 = 0$$

It seems we can measure position of 1 and know momentum from having measured the momentum of 2

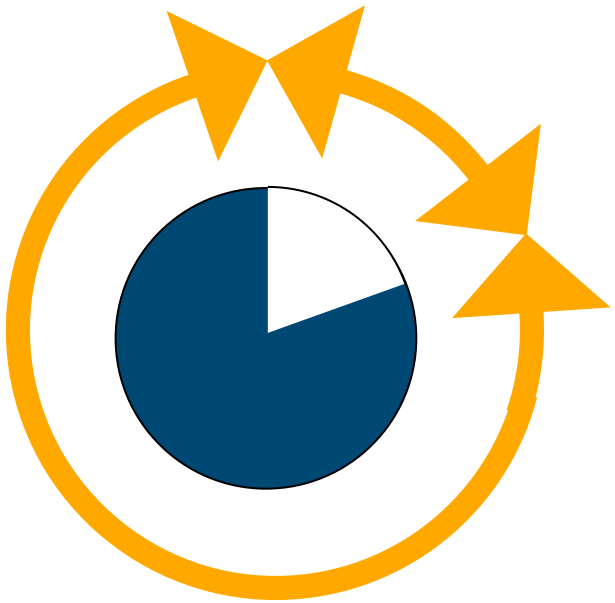
Quantum mechanics is either Incomplete, e.g. there are additional “hidden variables” (instructions)

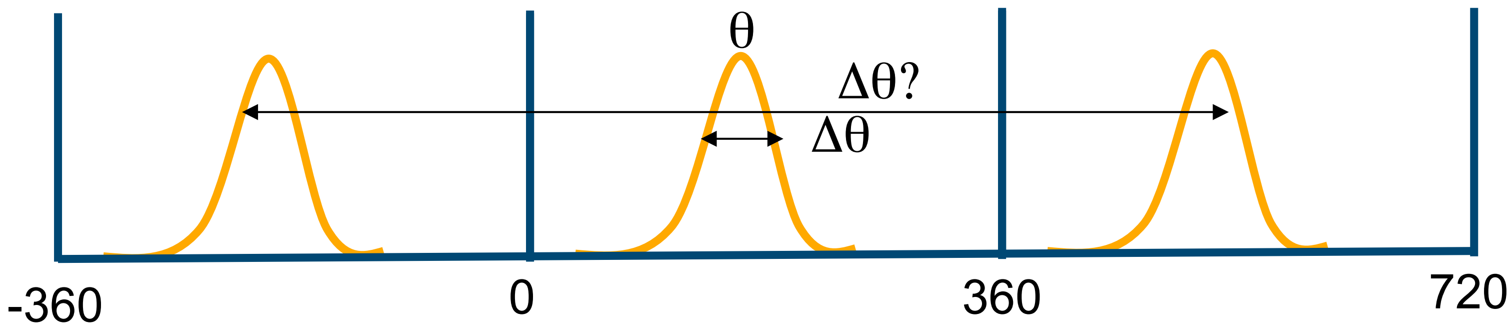
OR non local e.g. that measuring the position (momentum) of one particle instantaneously defines the position (momentum) of the other AND creates uncertainty in the momentum (position) of both.

A (much) more subtle test is “Bell” which shows that hidden variables cannot account for the observed correlations in a 2-state system

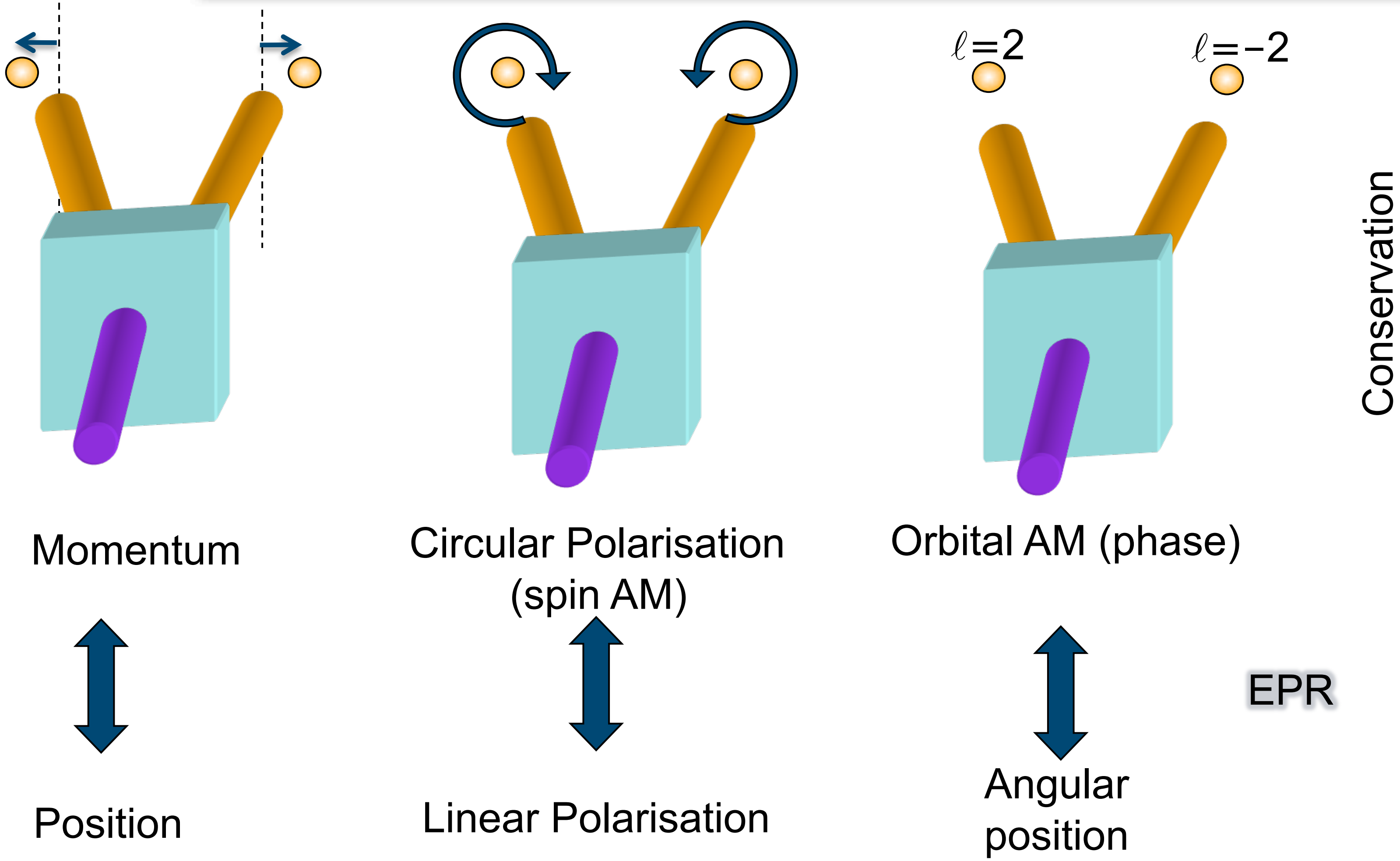
The problem with angle

- Angle is ambiguous
  - $\theta = \theta + N \times 360°$
  - $\Delta\theta = 360° - \Delta\theta$





Conservation c.f. Entanglement (EPR)



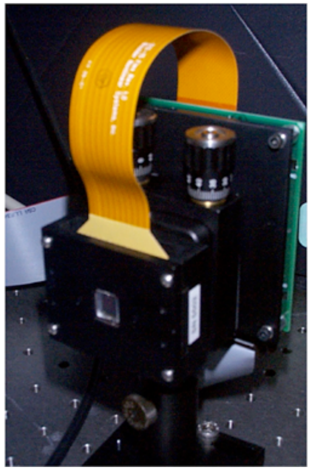
Entanglement requires correlation measured in complimentary variables

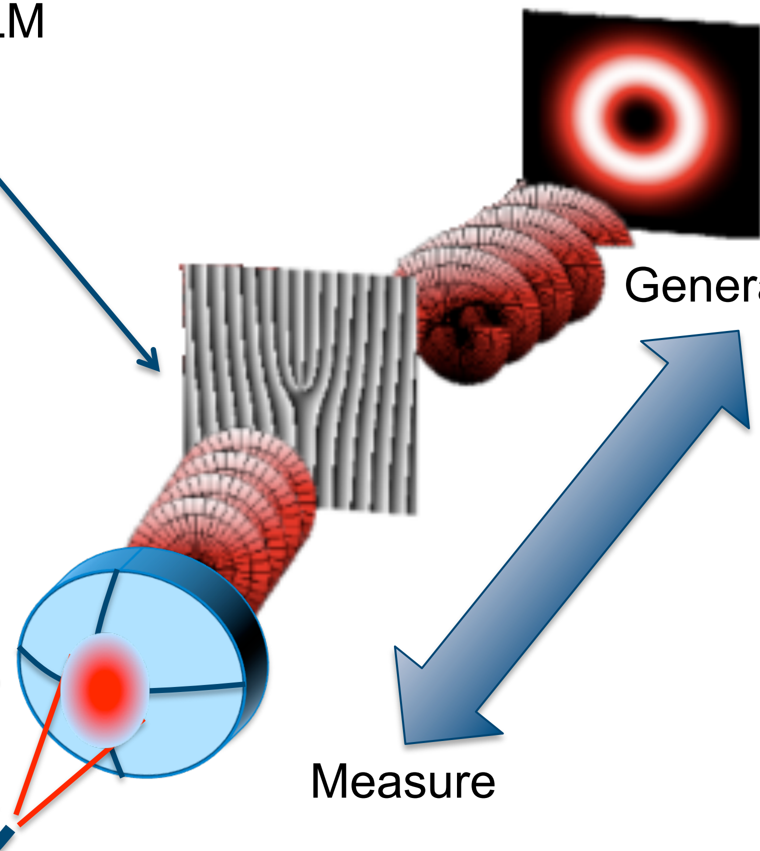
Entanglement of the orbital angular momentum states of photons
Alois Mair*, Alipasha Vaziri, Gregor Weihs & Anton Zeilinger
NATURE | VOL 412 | 19 JULY 2001 |

University of Glasgow

Making OR measuring phasefronts with holograms

Make interactive by using SLM





Generate

Measure

Light source
OR detector

Single-mode fibre

Entanglement of OAM states

Entanglement of the orbital angular momentum states of photons

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

NATURE | VOL 412 | 19 JULY 2001 |

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Huygens Laboratory, Leiden University, Post Office Box 9504, 2300 RA Leiden, The Netherlands

(Received 29 April 2005; published 8 December 2005)

PRL 95, 260501 (2005) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2005

Generation of Hyperentangled Photon Pairs

Julio T. Barreiro,[1] Nathan K. Langford,[2] Nicholas A. Peters,[1] and Paul G. Kwiat[1]

Entangled Twist

Jonathan Leach
Barry Jack
Sonja Franke Arnold
(Glasgow)

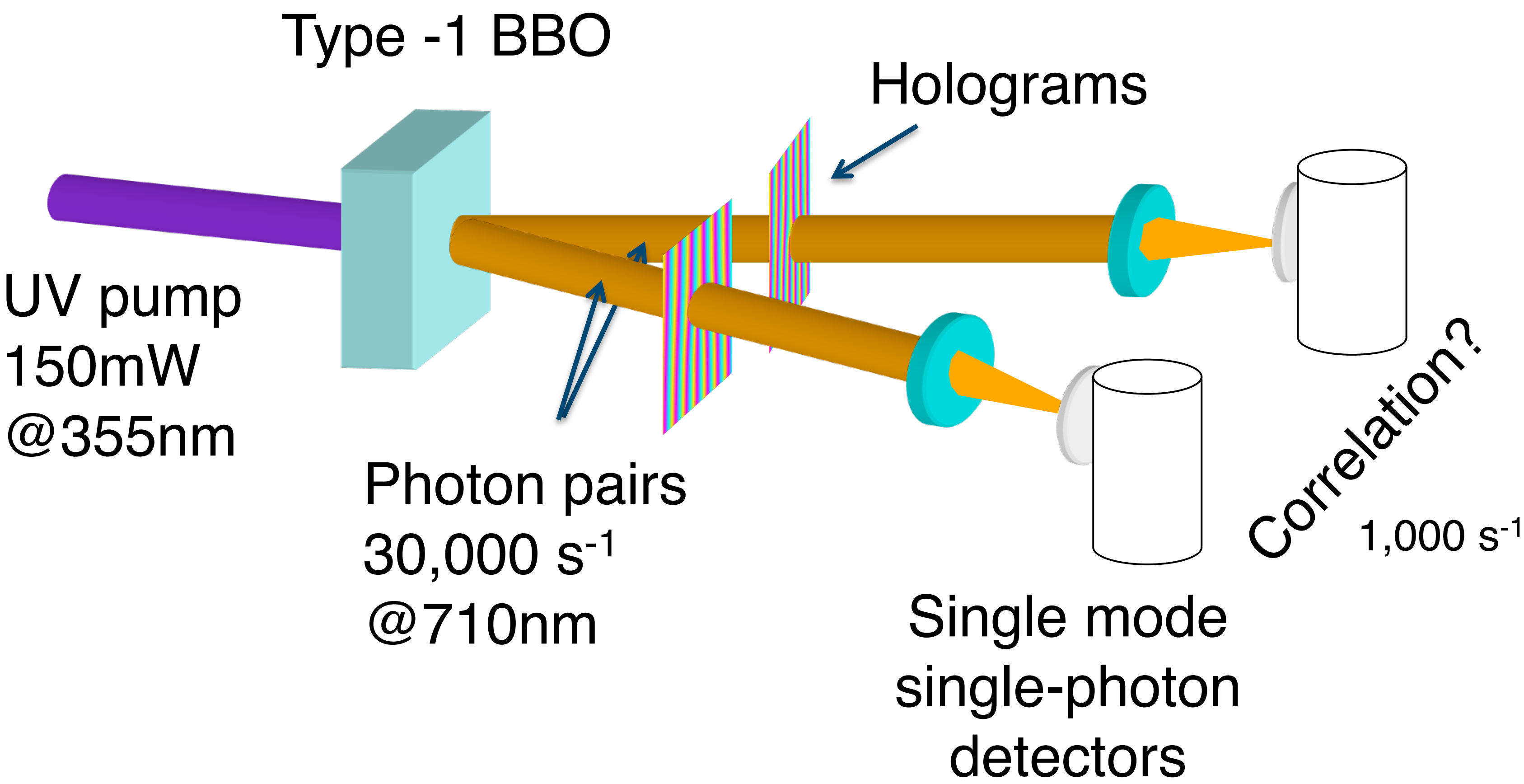



Steve Barnett (Strathclyde)
Monika Ritsch-Marte (Innsbruck)


Bob Boyd (Rochester)
Anand Jha (Rochester)


Gerald Buller (Heriot Watt)
Ryan Warburton (Heriot Watt)

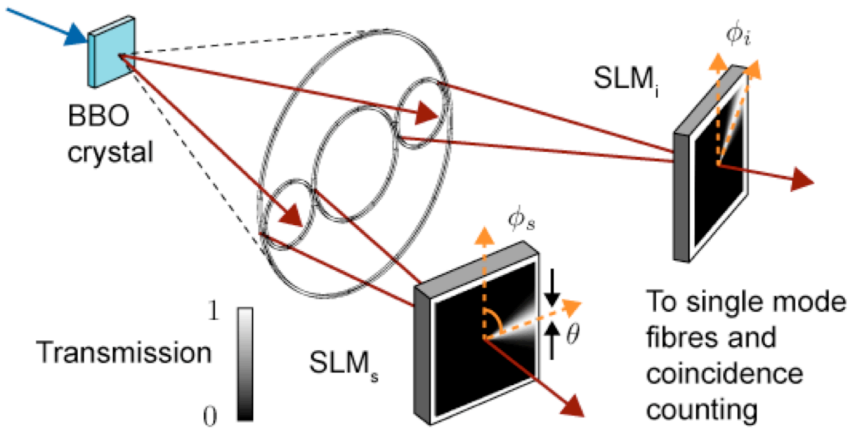

Our experiment



Quantum Correlations in Optical Angle Orbital Angular Momentum Variables
Jonathan Leach, *et al.*
Science **329**, 662 (2010);
DOI: 10.1126/science.1190523

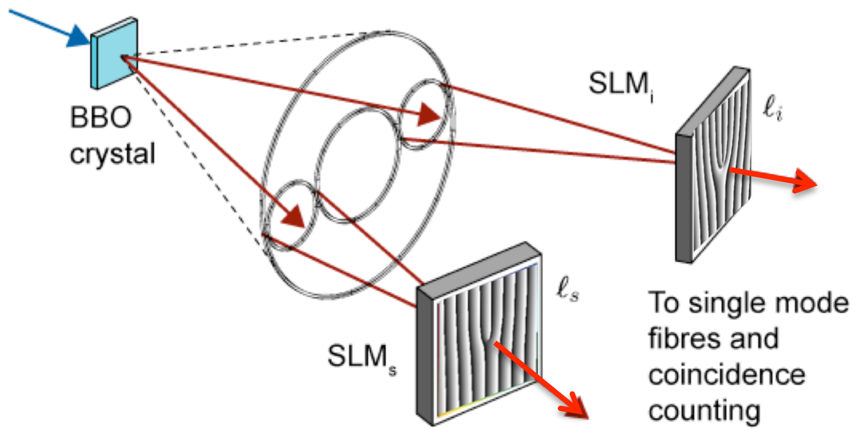
Angular Correlations

(a) Angle measurements



Measure Correlations in Angle

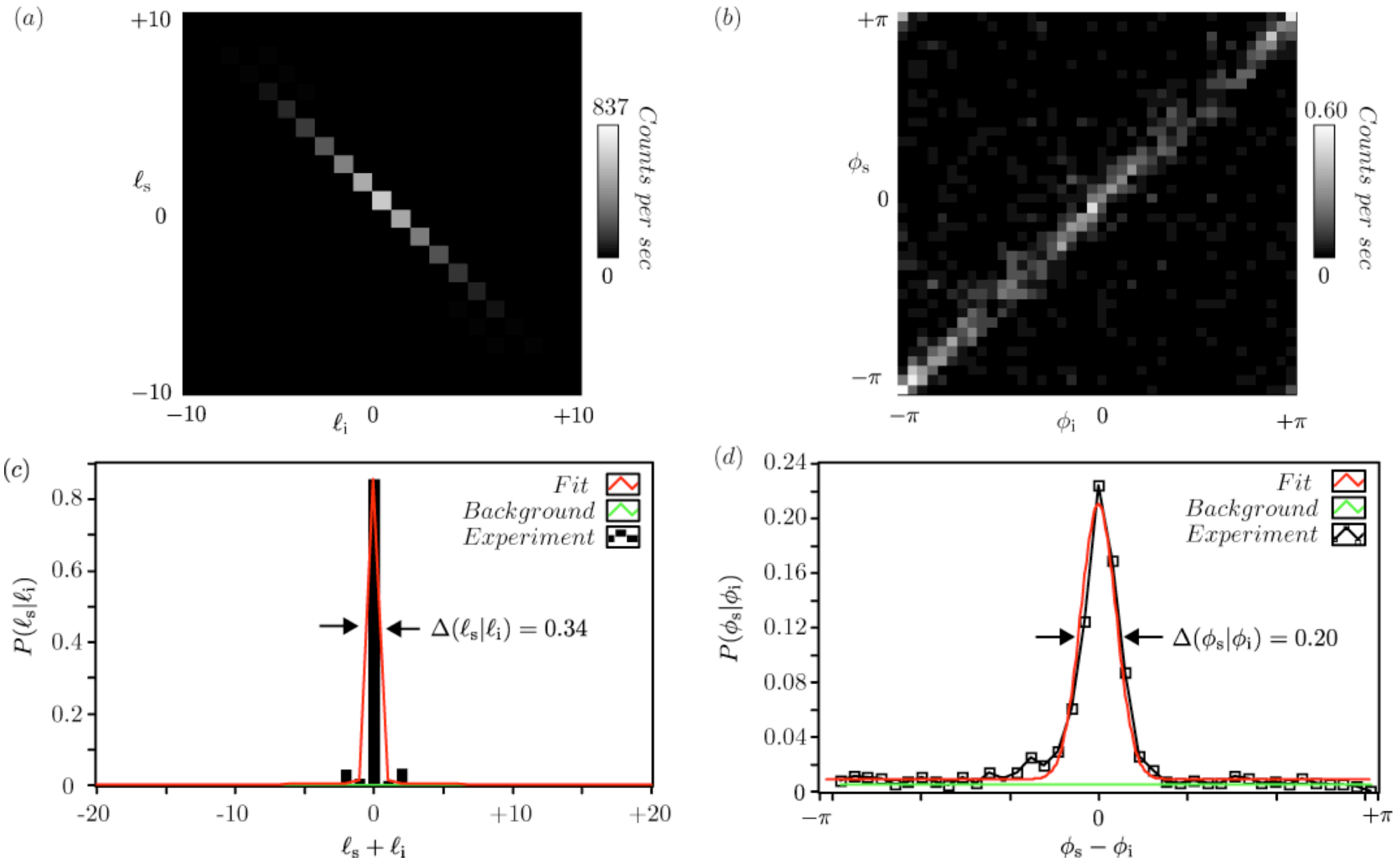
(b) Orbital anglular momentum measurements



Measure Correlations in Angular Momentum

Angles ARE Entangled

Angular EPR



$$\left[\Delta\left(\ell_s|\ell_i\right)\hbar\right]^2\left[\Delta\left(\phi_s|\phi_i\right)\right]^2 = 0.00475\hbar^2 << 0.25\hbar^2$$

University of Glasgow

From EPR to Bell….

EPR establishes

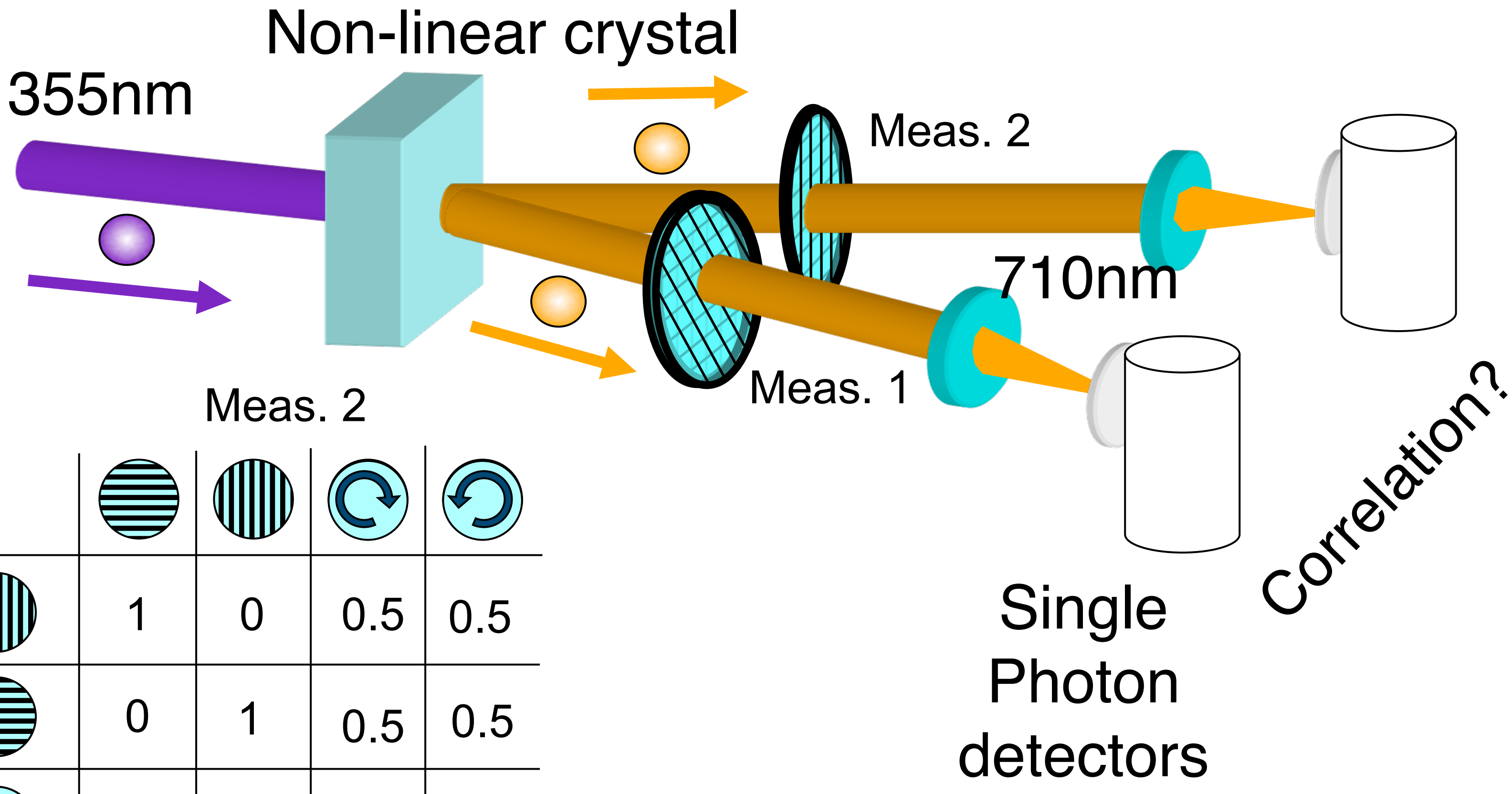
- Quantum mechanics is either Incomplete, e.g. there are additional "hidden variables" (instructions)

- OR non local e.g. that measuring the position (momentum) of one particle instantaneously defines the position (momentum) of the other AND creates uncertainty in the momentum (position) of both.

A Bell violation rules out hidden variables, leaving…

- Quantum mechanics is a non-local theory

Quantum Entanglement with polarisation



Meas. 2

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

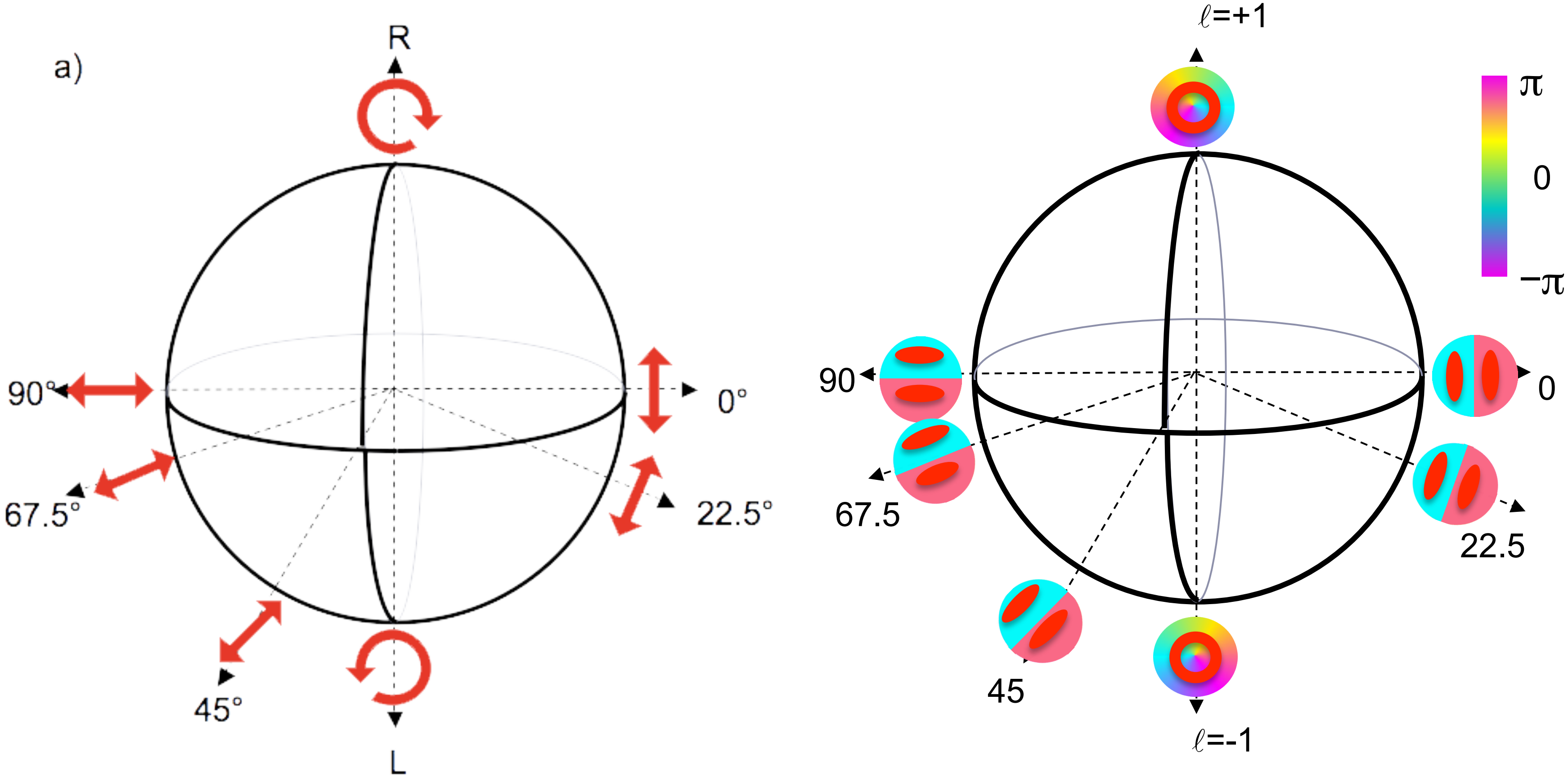
430 OPTICS LETTERS / Vol. 24, No. 7 / April 1, 1999

University of Glasgow

Poincaré-sphere equivalent for light beams containing orbital angular momentum

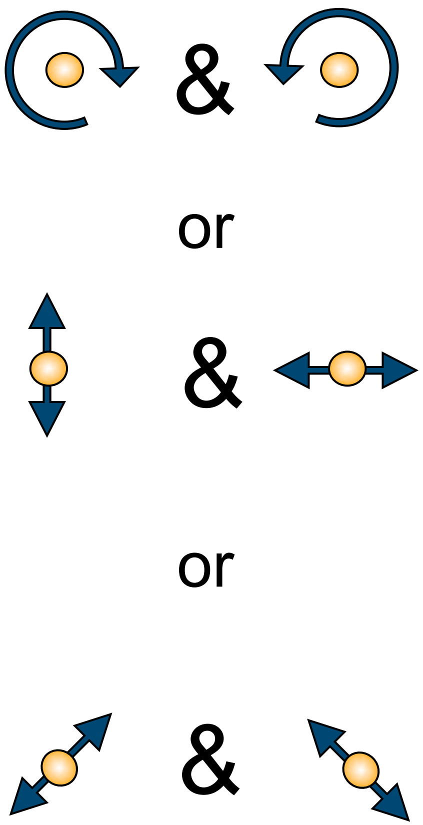
M. J. Padgett and J. Courtial

Poincaré sphere equivalent for OAM

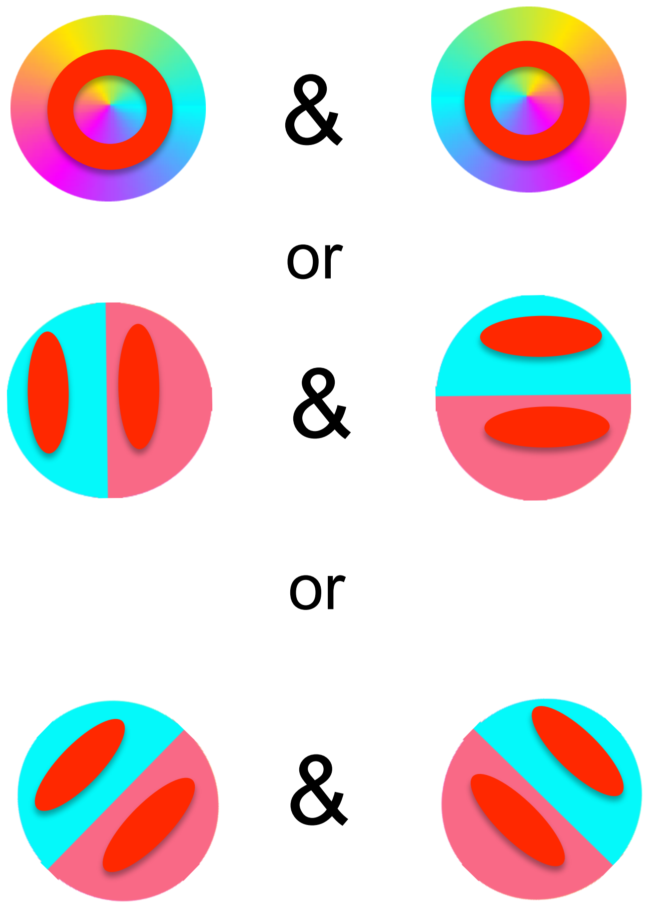


Complementary States

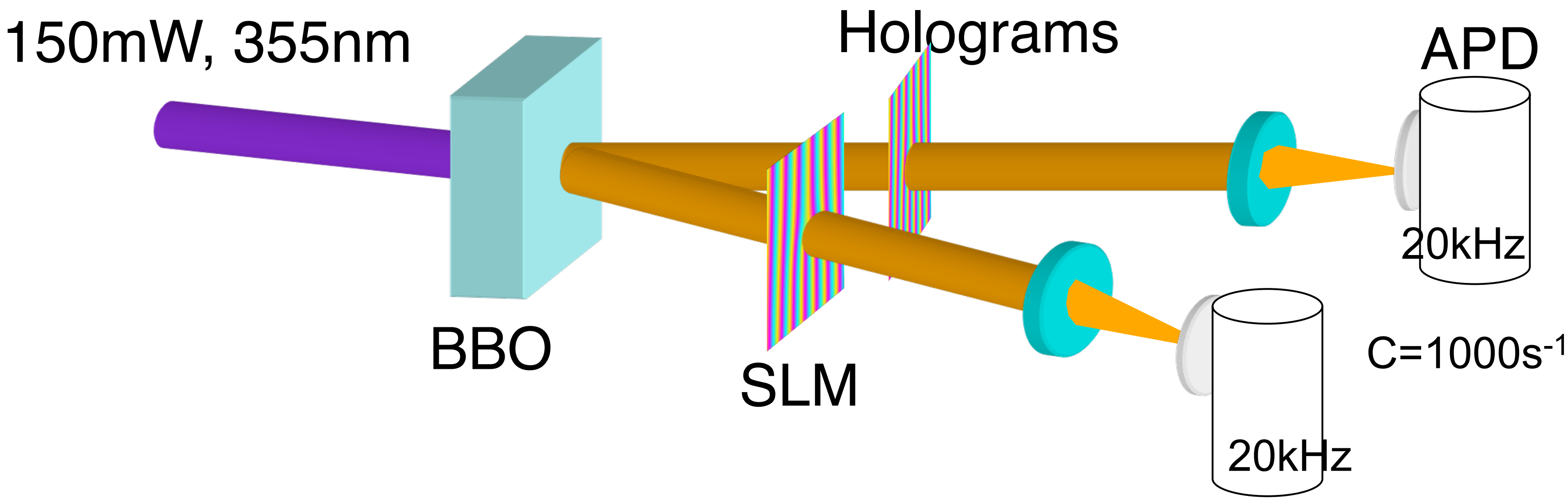
Any Polarisation, described by

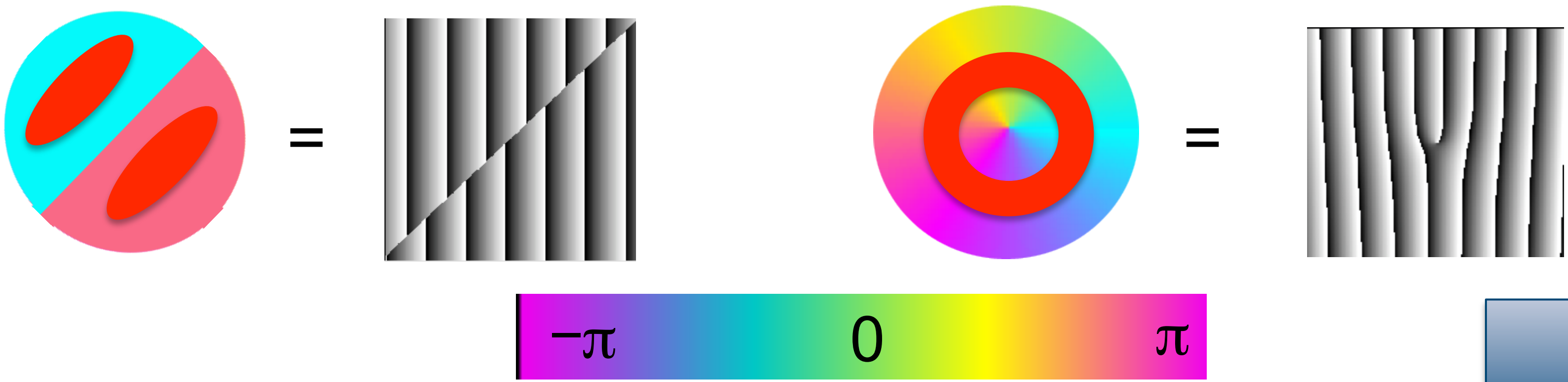


Any mode (on the sphere), described by



Measuring angle and angular momentum





Demo

EPR Orbital Angular Momentum and Angular Distribution

Meas. 2

Meas. 1

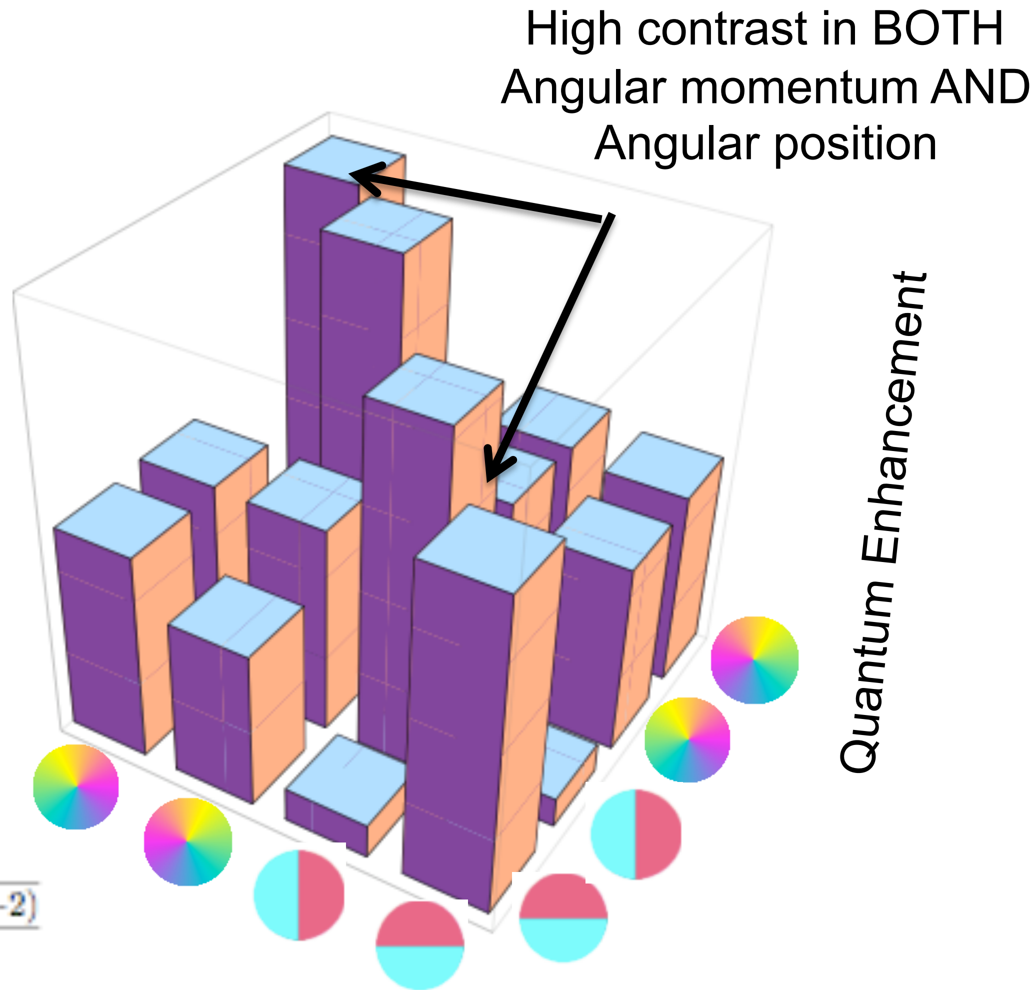
	1	0	0.5	0.5
	0	1	0.5	0.5
	0.5	0.5	1	0
	0.5	0.5	0	1

Conditional Probability for EPR

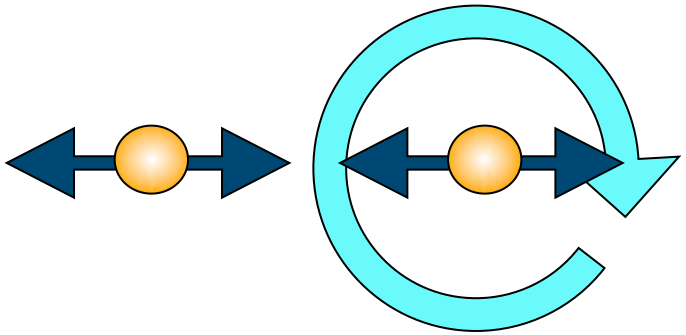
$$\sqrt{P_{min}(+2,-2)} > \frac{\sqrt{P_{min}(\otimes,\oplus)}+\sqrt{P_{max}(\otimes,\oplus)}}{\sqrt{2}}$$

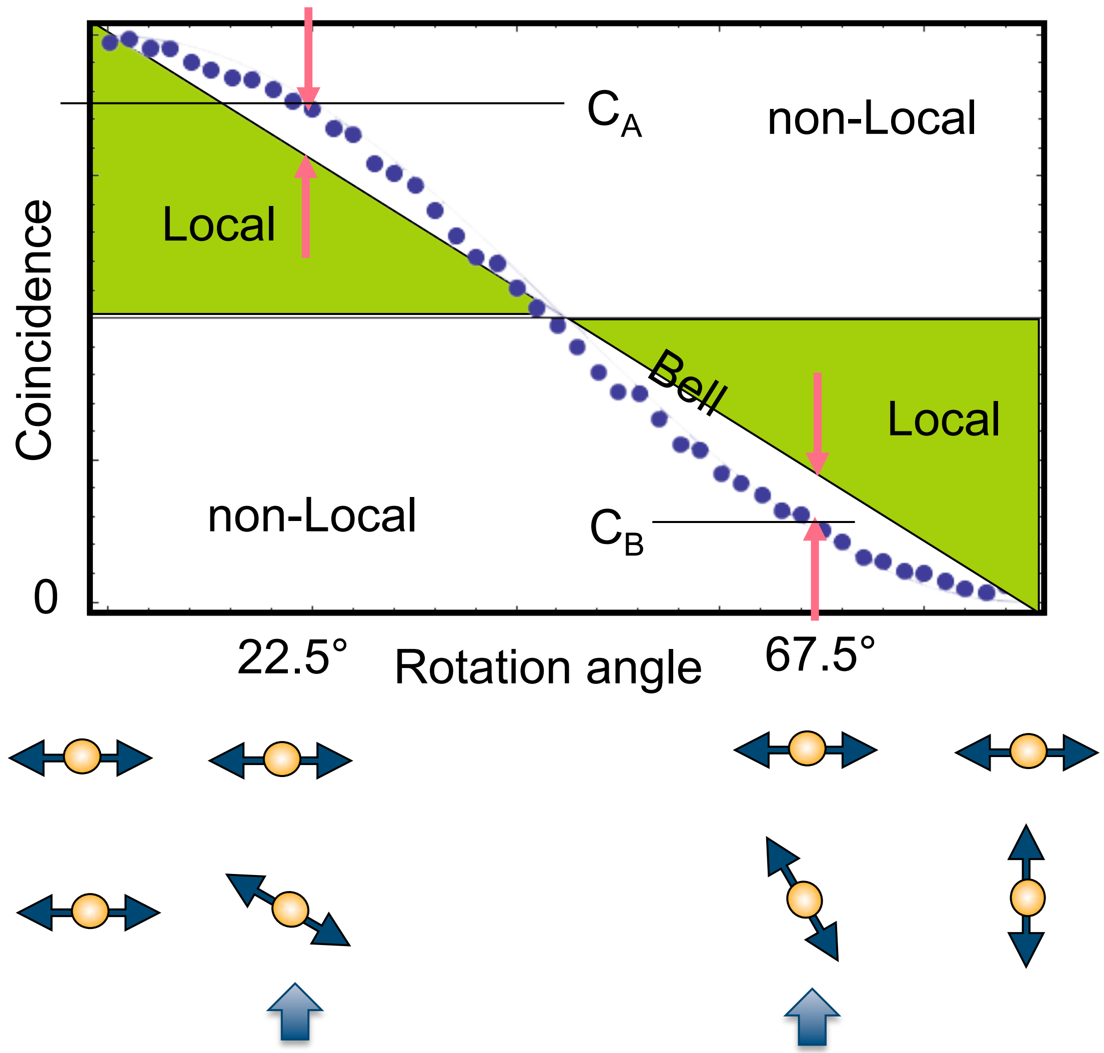
$$\sqrt{P_{min}(\otimes,\oplus)} > \frac{\sqrt{P_{min}(+2,-2)}+\sqrt{P_{max}(+2,-2)}}{\sqrt{2}}$$

0.961 > 0.888



Bell (Freedman inequality) c.f. Aspect *et al*. 1981



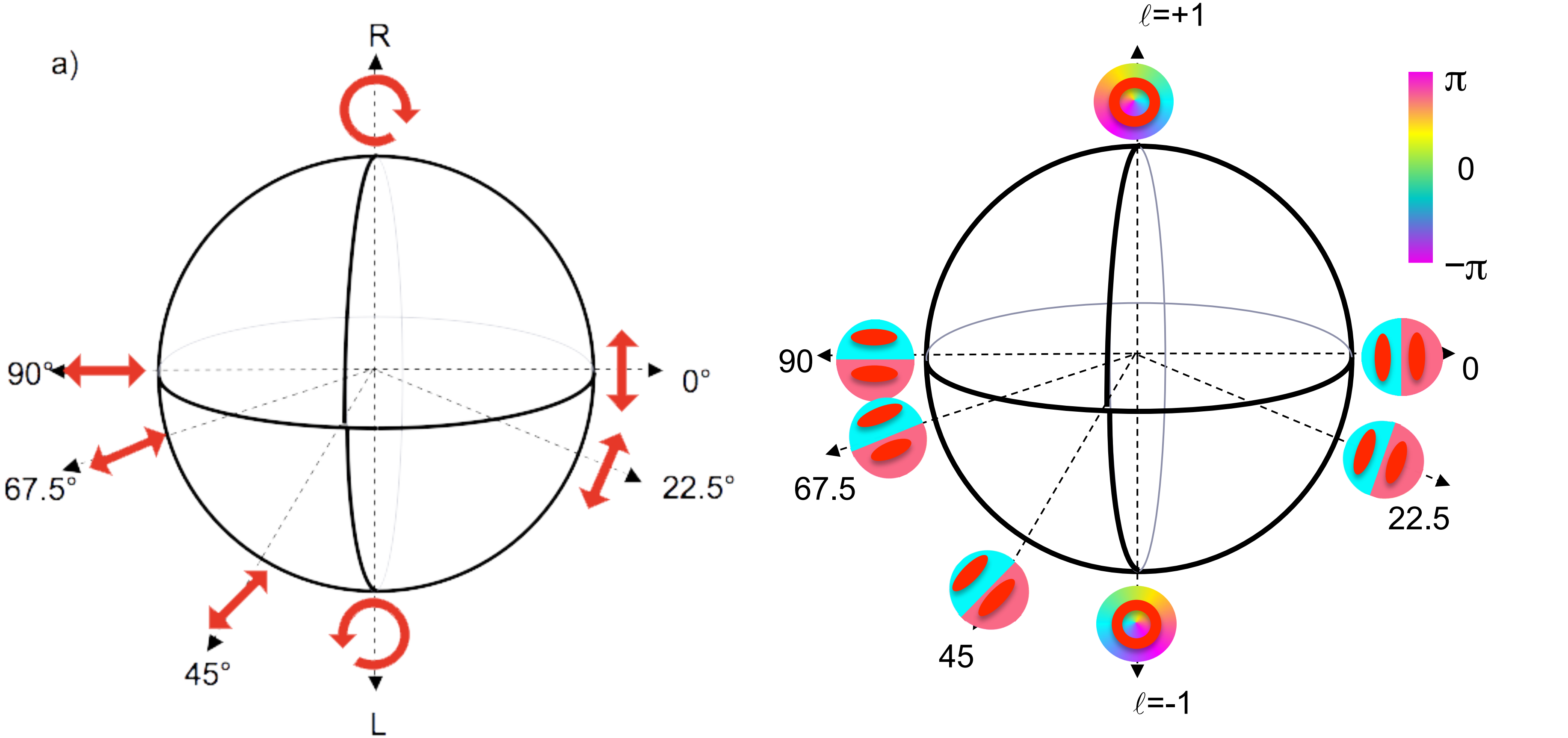


430 OPTICS LETTERS / Vol. 24, No. 7 / April 1, 1999

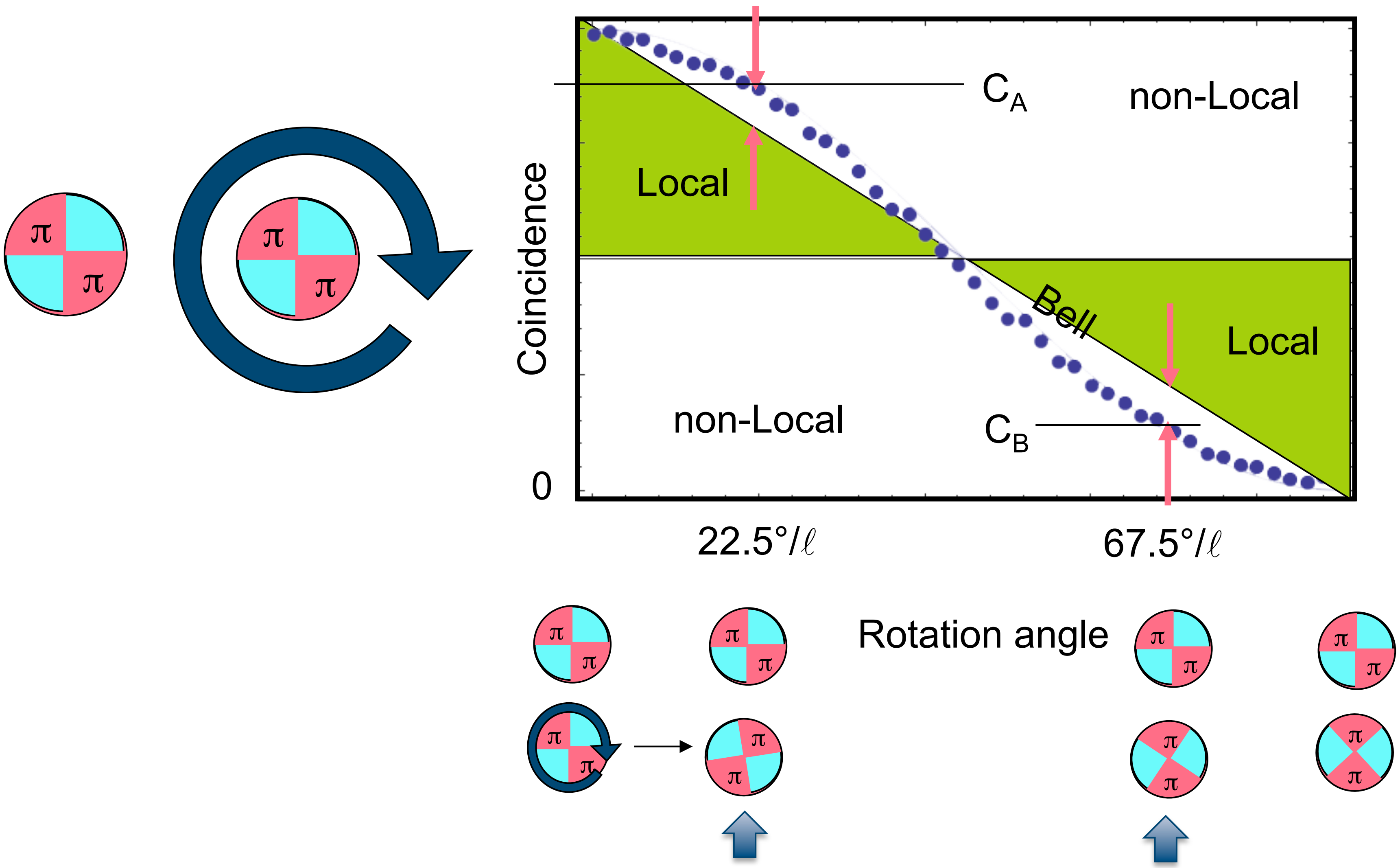
Poincaré-sphere equivalent for light beams containing orbital angular momentum

M. J. Padgett and J. Courtial

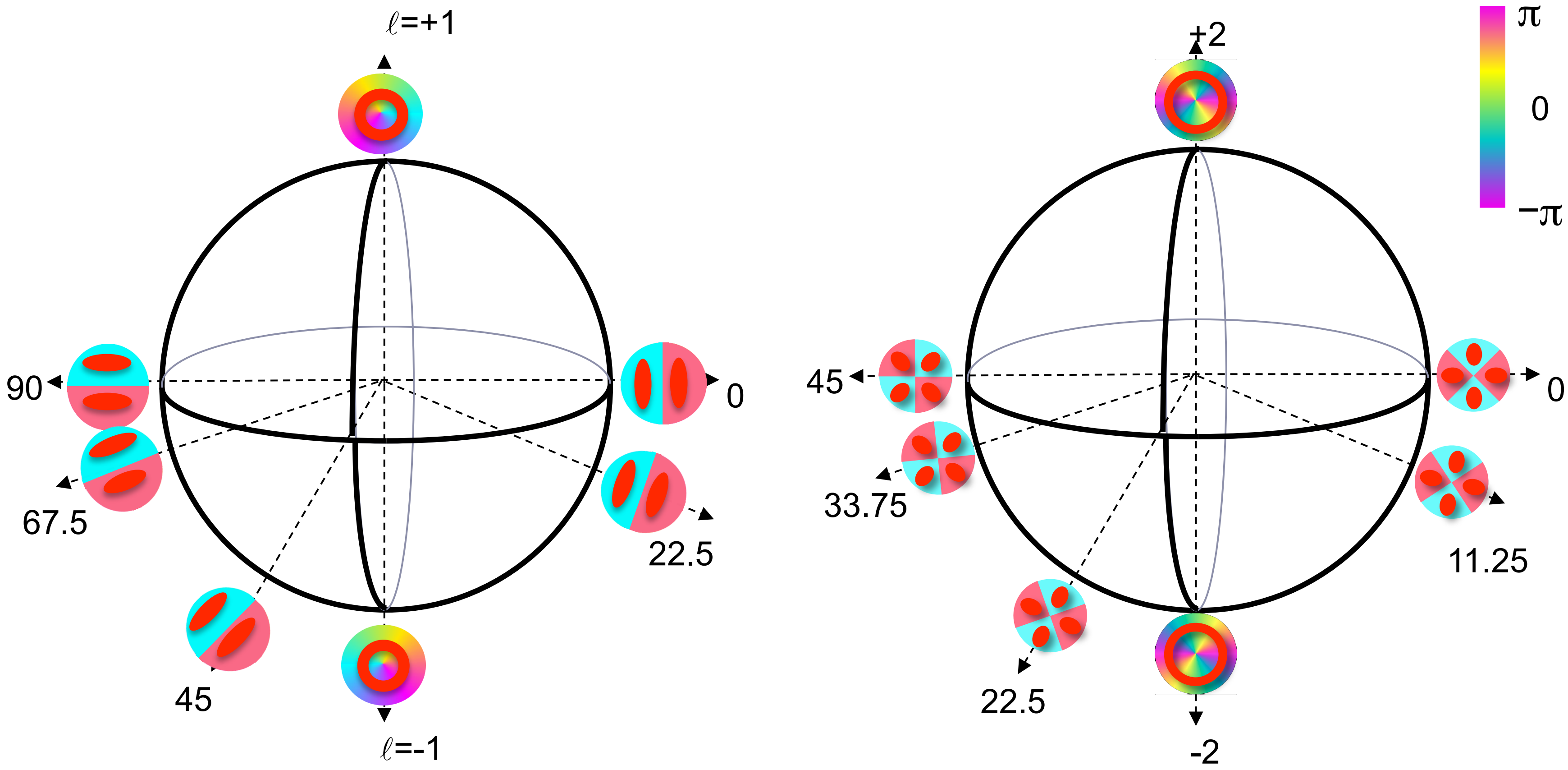
Poincaré sphere equivalent for OAM



Bell for OAM states



Higher order Poincaré sphere equivalent for OAM



University of Glasgow

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

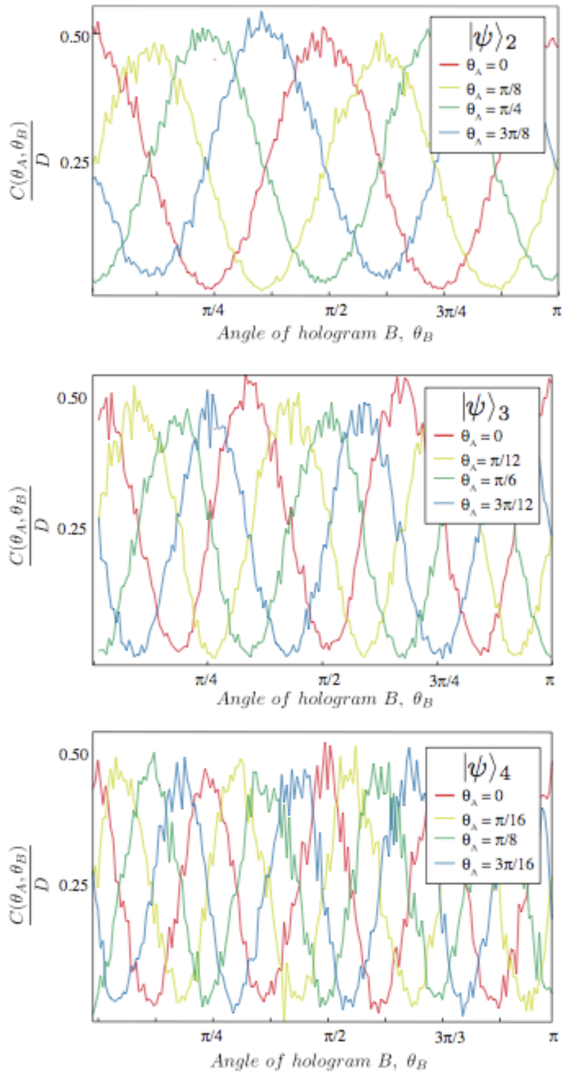
Violation of a Bell inequality in two-dimensional orbital angular momentum state-spaces

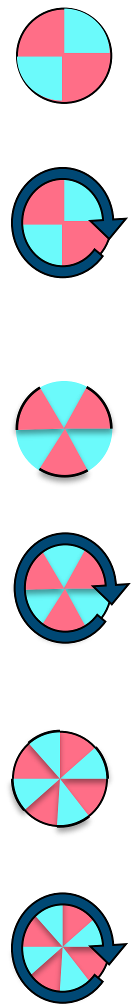
J. Leach[1], B. Jack[1], J. Romero[1], M. Ritsch-Marte[2], R. W. Boyd[3], A. K. Jha[3], S. M. Barnett[4], S. Franke-Arnold[1] and M. J. Padgett[1]

Bell (CHSH) for OAM

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

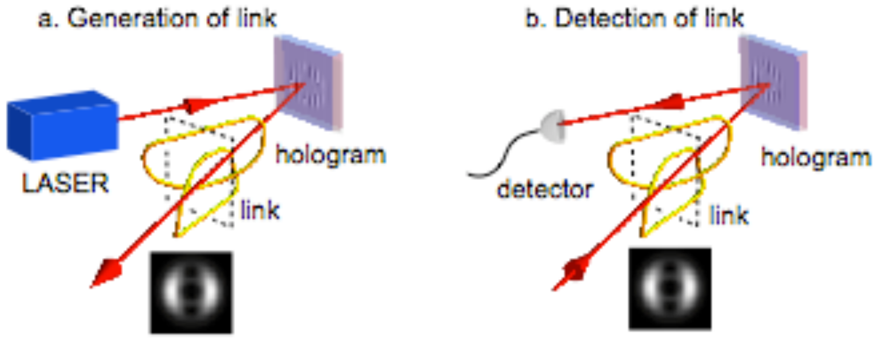
Entangled state	S	Violation by σ
$\|\psi\rangle_2$	2.69 ± 0.02	35
$\|\psi\rangle_3$	2.55 ± 0.04	14
$\|\psi\rangle_4$	2.33 ± 0.07	5





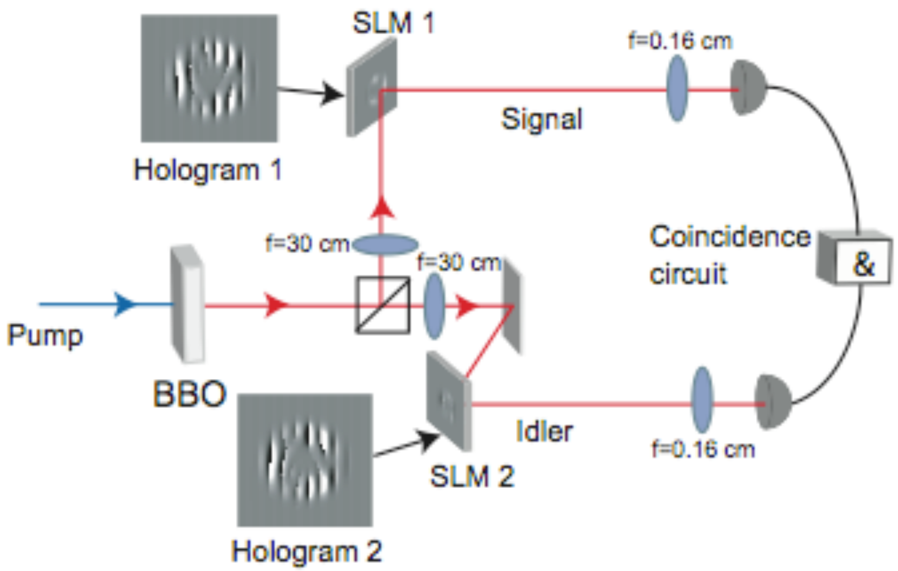
Angles have NO "Hidden variables"

Entangled, tangles



Hologram to make OR measure beam

Non-local measurement of separated topological features



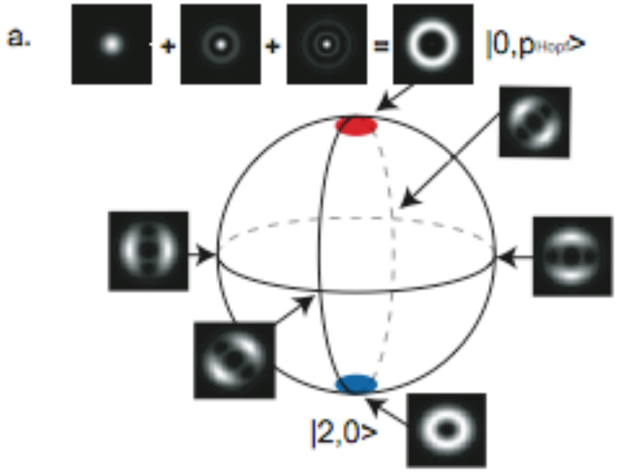
PRL **106,** 100407 (2011) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2011

University of Glasgow

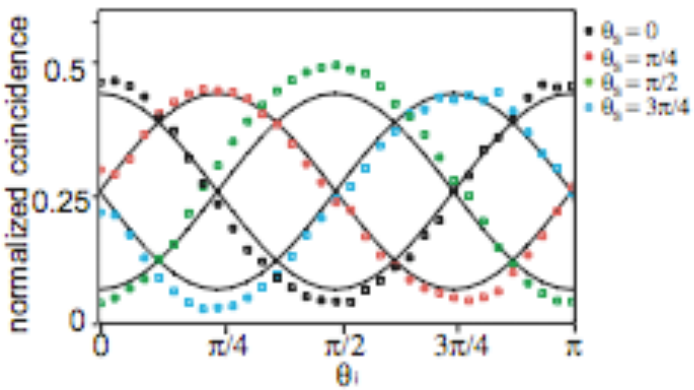
Entangled Optical Vortex Links

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]

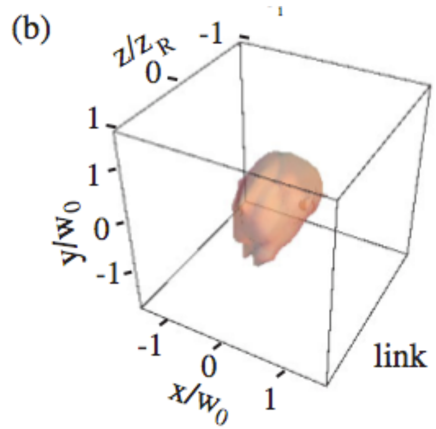
Correlations to show Quantum Entanglement



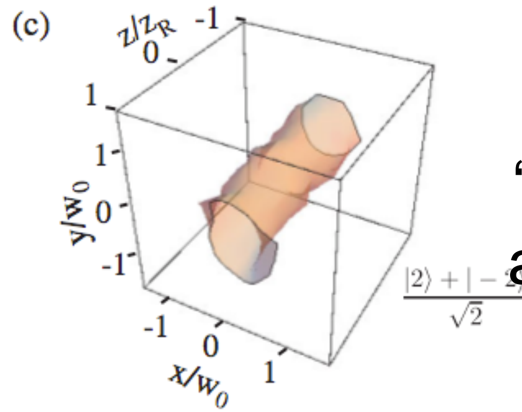
Two-state formation of links allows "Bell-test"



Volume over which S>2



Links are "entangled" *only* over finite volume



OAM "entangled" along entire beam axis

University of Glasgow

Measuring the orbital angular momentum of single photons

- Martin Lavery, Johannes Courtial and Miles J. Padgett,
- University of Glasgow, Scotland

- Gregorius Berkhout and Marco Beijersbergen
- Leiden University, Netherlands

Universiteit Leiden

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

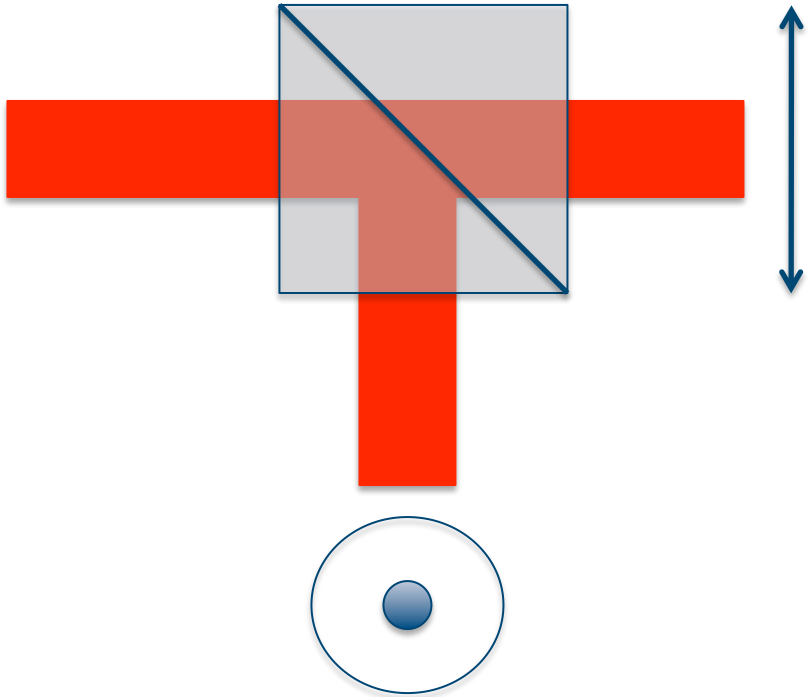
$\sigma = +1$

$\sigma = -1$

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



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

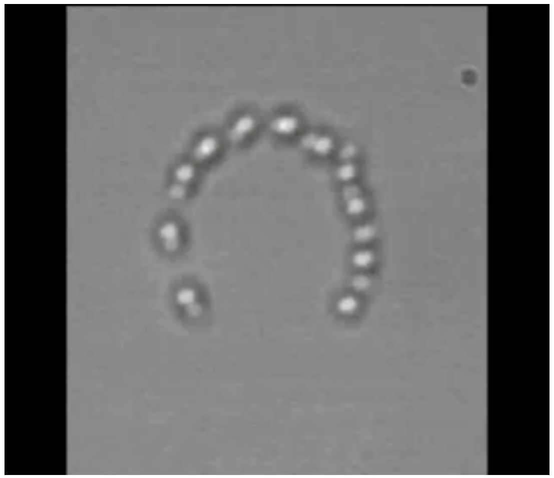
Direct Observation of Transfer of Angular Momentum to Absorptive Particles from a Laser Beam with a Phase Singularity

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

PHYSICAL REVIEW A VOLUME 54, NUMBER 2 AUGUST 1996

Optical angular-momentum transfer to trapped absorbing particles

M. E. J. Friese,[1] J. Enger,[2] H. Rubinsztein-Dunlop,[1] and N. R. Heckenberg[1]



Measuring OAM - 2

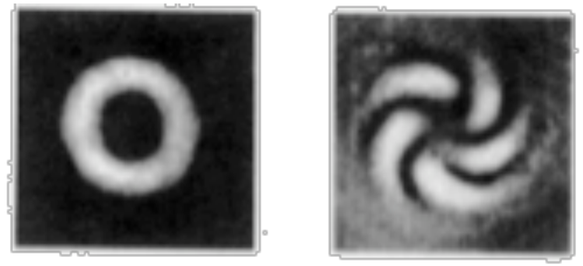
- Interference of helical beam with a plane wave gives ℓ spiral fringes
  - Requires many photons in the same mode

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

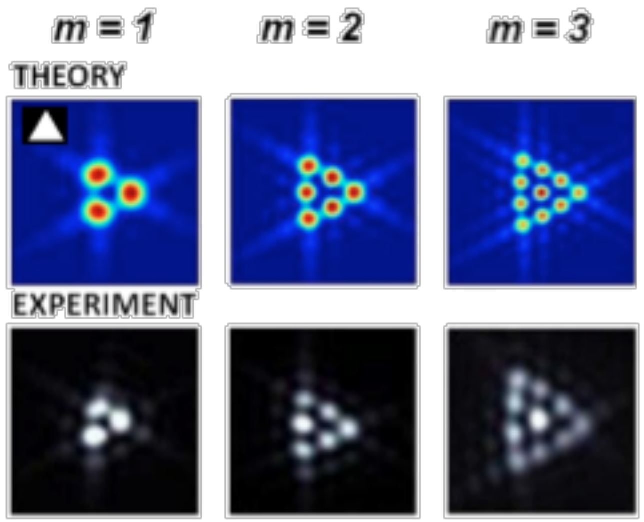
Measuring OAM - 3

- 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

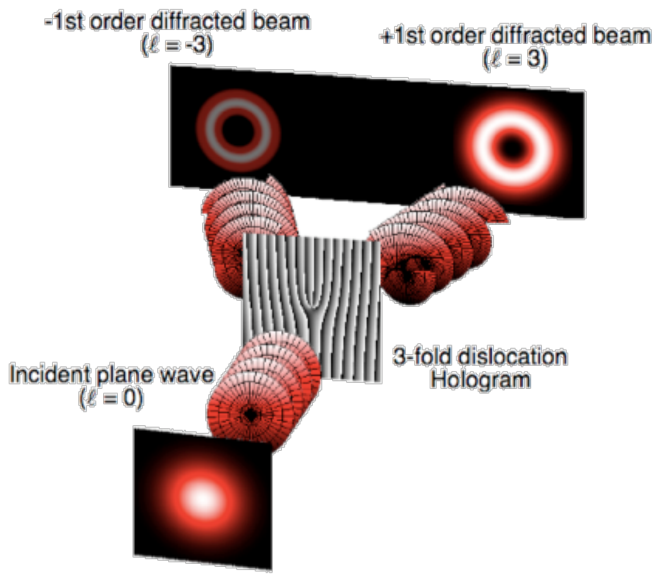
PRL 101, 100801 (2008) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2008

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

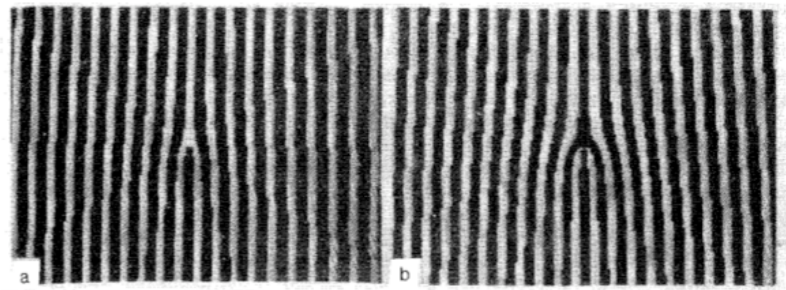
- Diffractive optical elements (hologram)
  - “forked” diffraction grating



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)



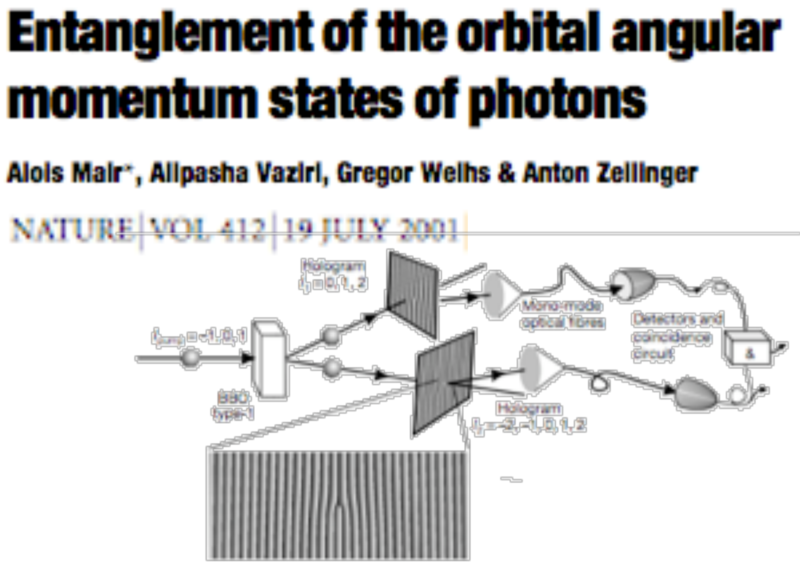
Generation of optical phase singularities by computer-generated holograms

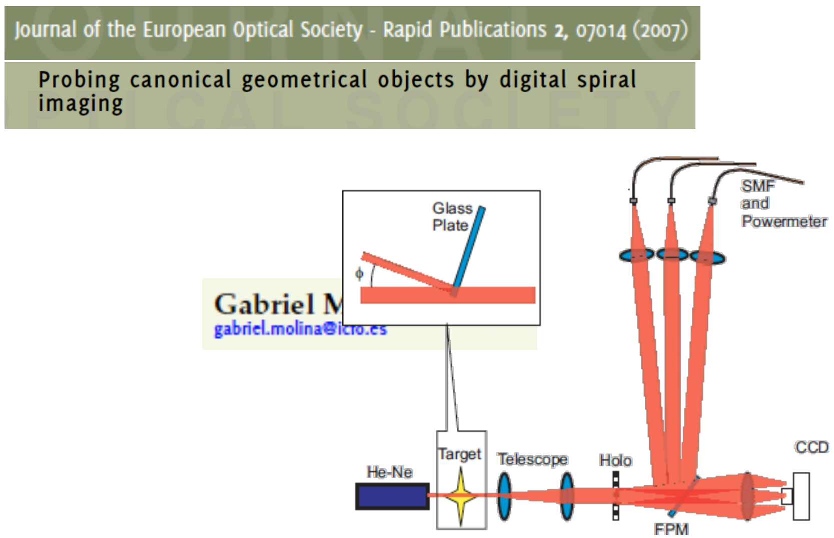
N. R. Heckenberg, R. McDuff, C. P. Smith, and A. G. White

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

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





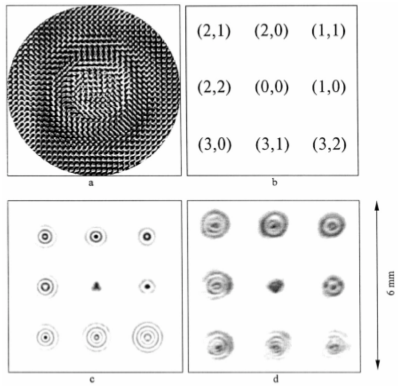
Measuring OAM - 5

- 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,*]

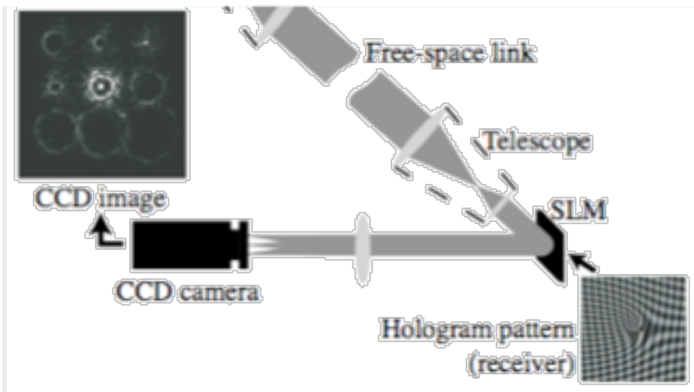
Optics Communications 175 (2000) 301–308



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



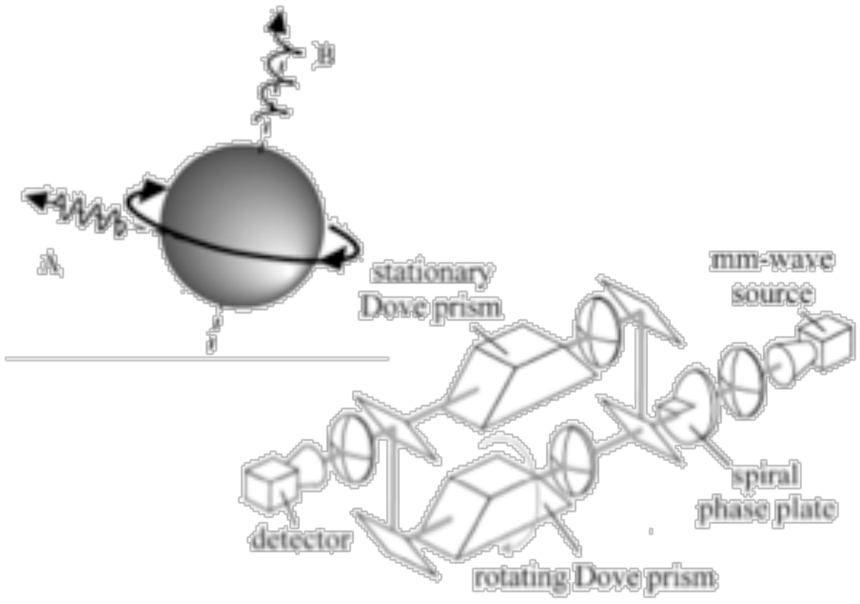
Measuring OAM – 6

- 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

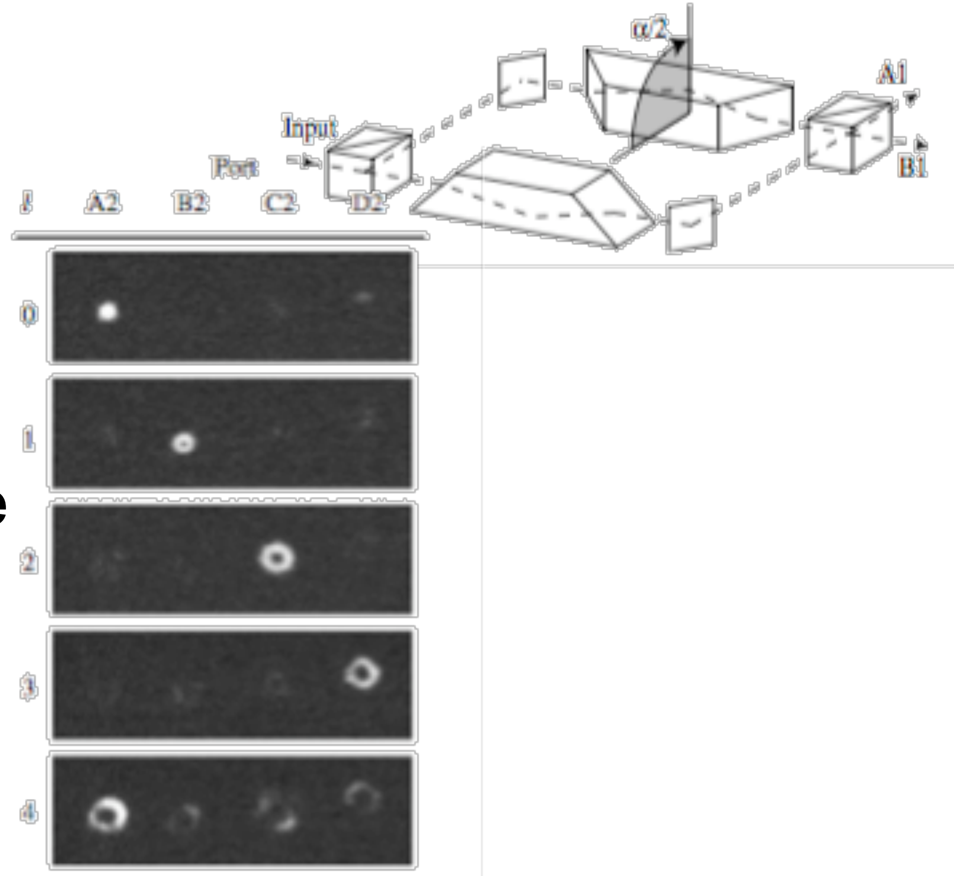
Measuring OAM - 7

- 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!)

VOLUME 88, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 2002

Measuring the Orbital Angular Momentum of a Single Photon

Jonathan Leach,[1] Miles J. Padgett,[1] Stephen M. Barnett,[2] Sonja Franke-Arnold,[2] and Johannes Courtial[1,*]



Our wish list

- Works for single photons
- Separates (sorts) many states with ≈100% efficiency
- Easy to align and operate

University of Glasgow

It MUST be possible

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

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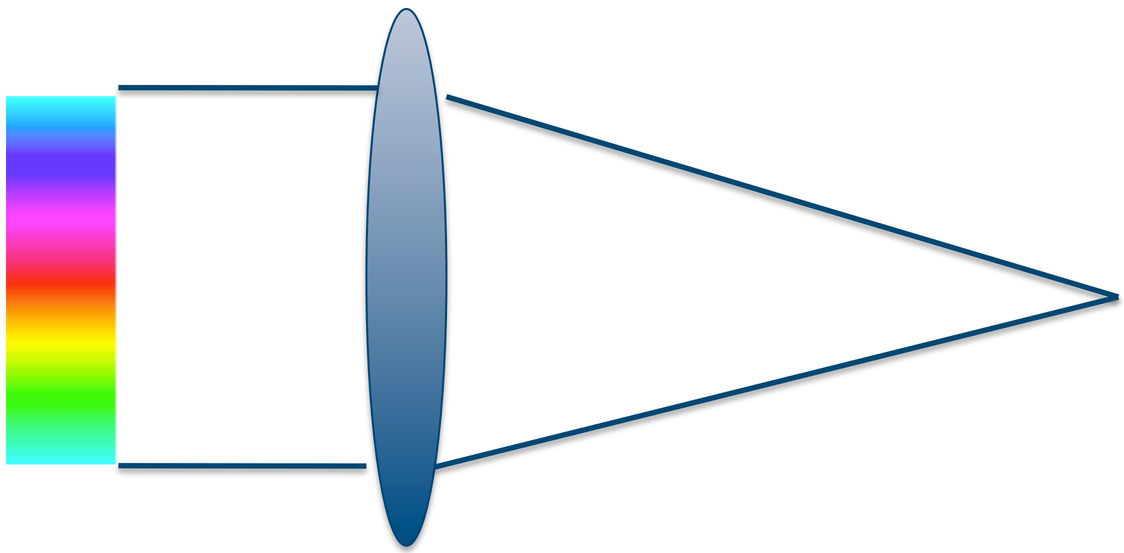
It works for plane waves

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



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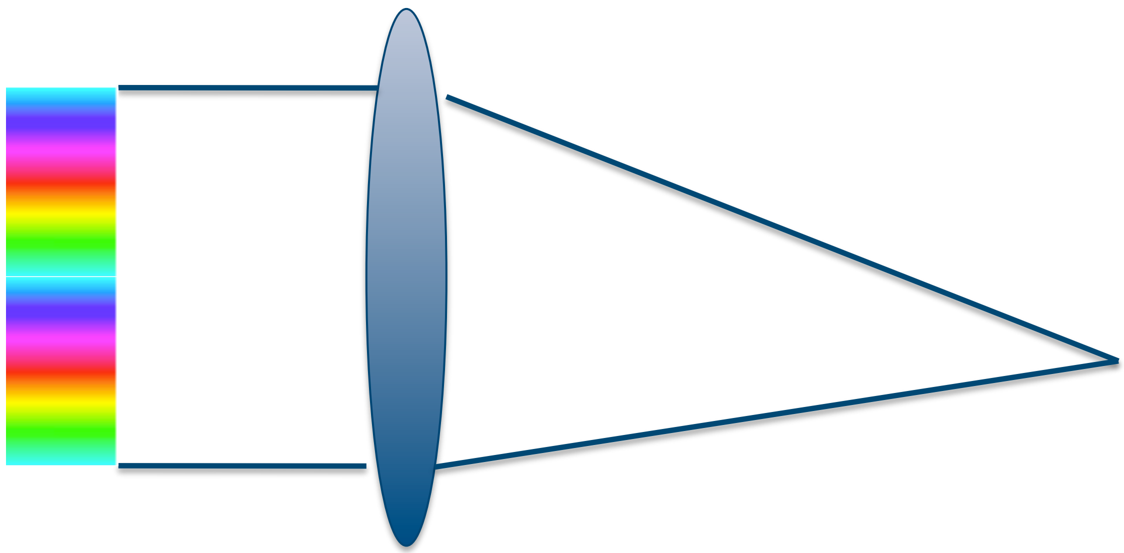

It works for plane waves

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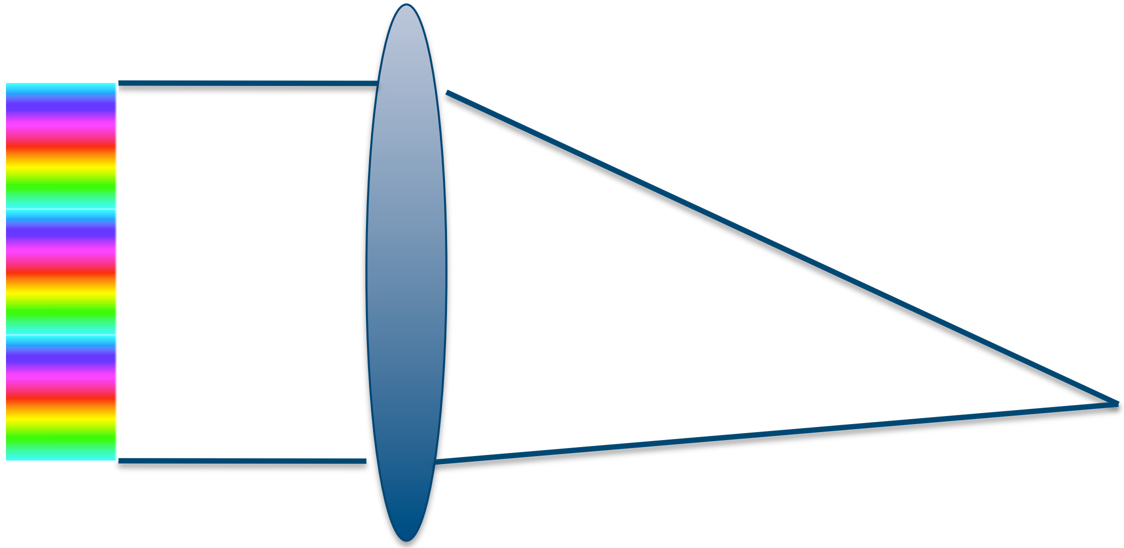
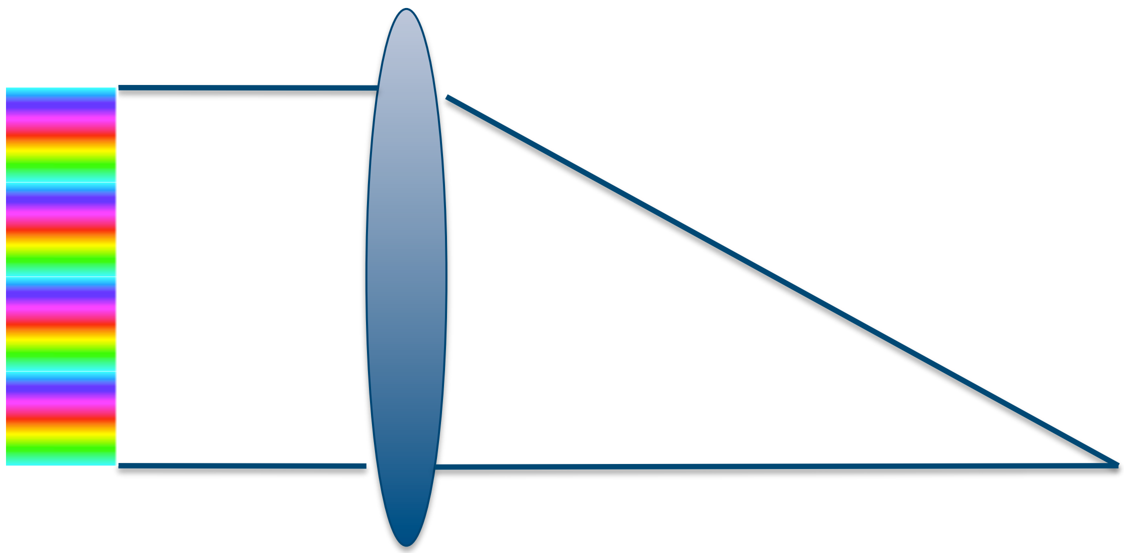


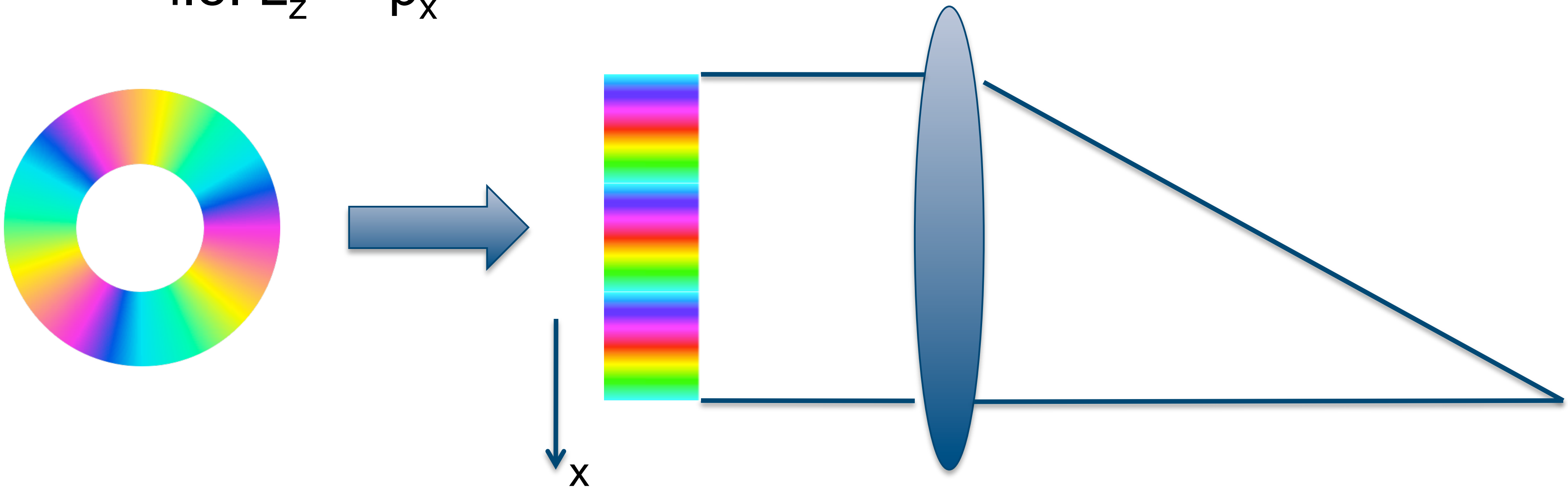
It works for plane waves

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



So we need to convert helical phase to linear phase

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



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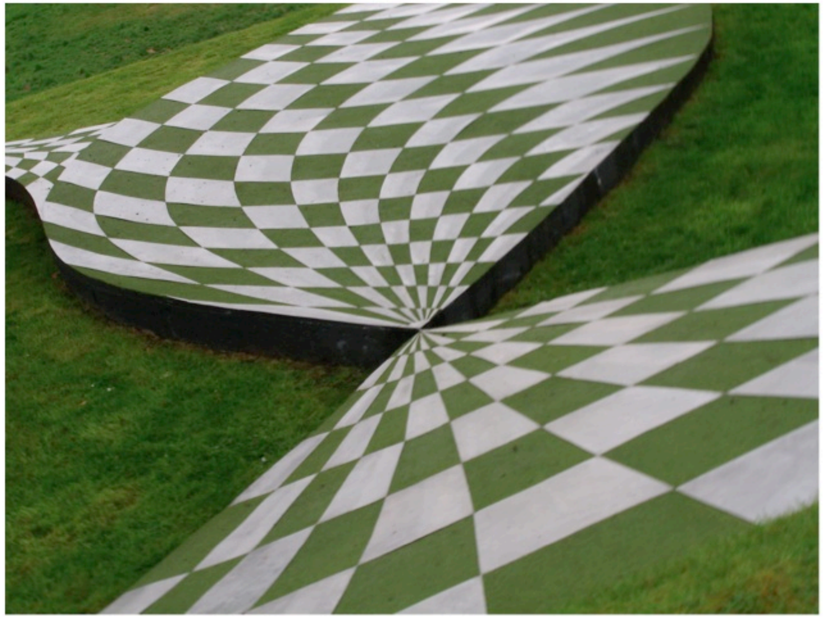
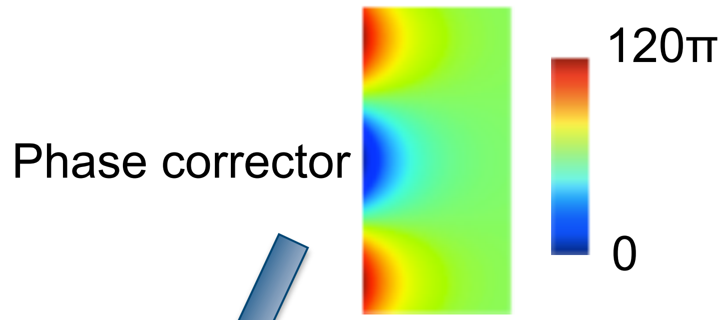
We NEED image distortion….

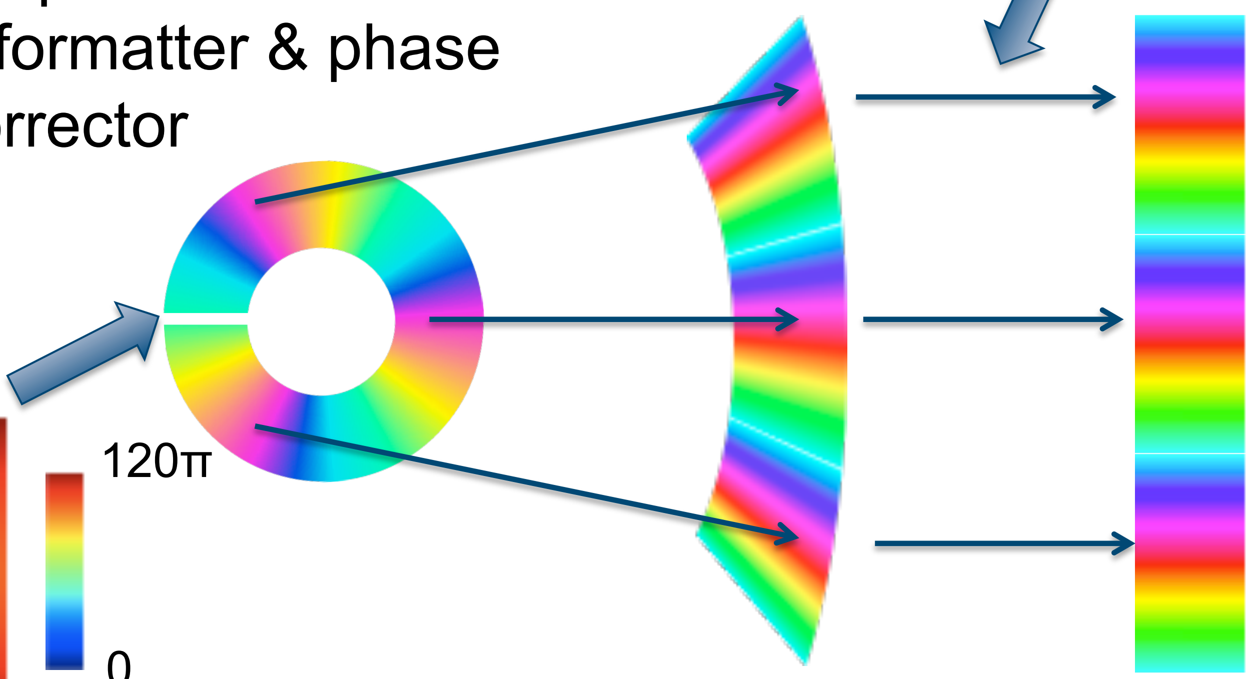
- Pin-Cushion and Barrel distortion make straight lines look curved…
  - But must also make curved lines look straight

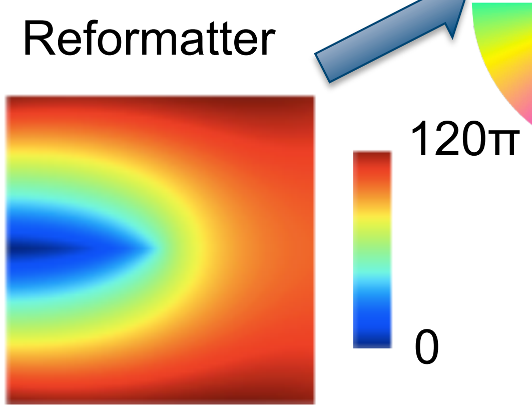


Azimuthal to linear mapping

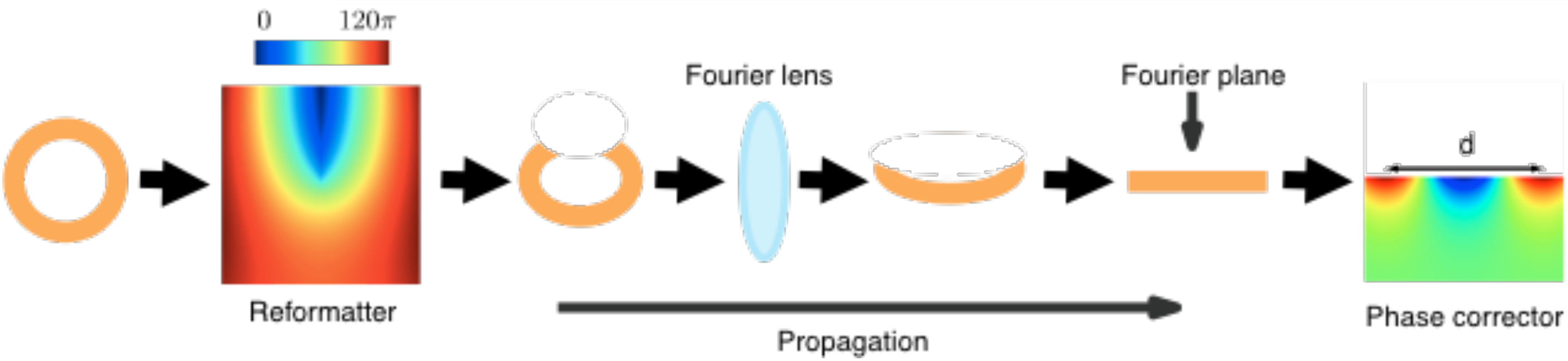
- Image transformation
  - ϕ -> x and r -> y
  - Requires reformatter & phase corrector

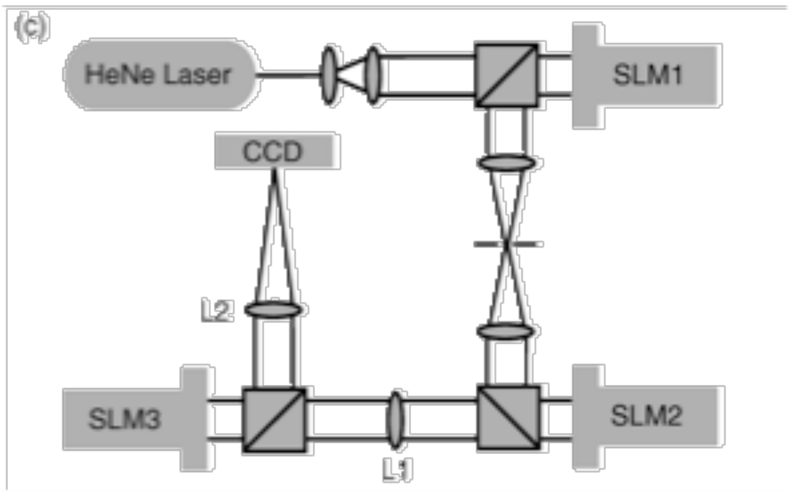


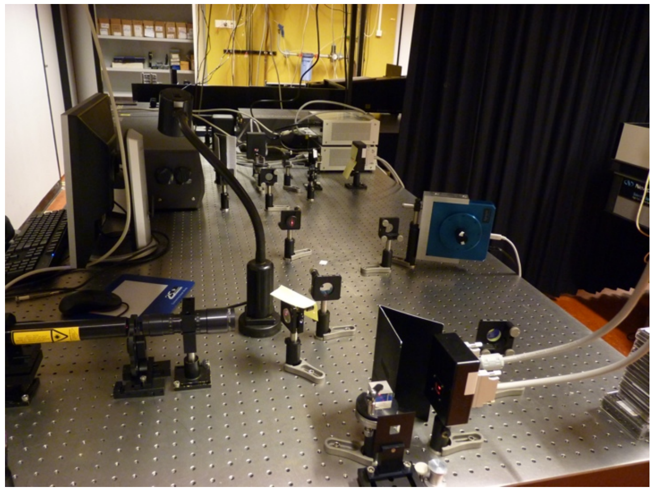




The Experimental implementation







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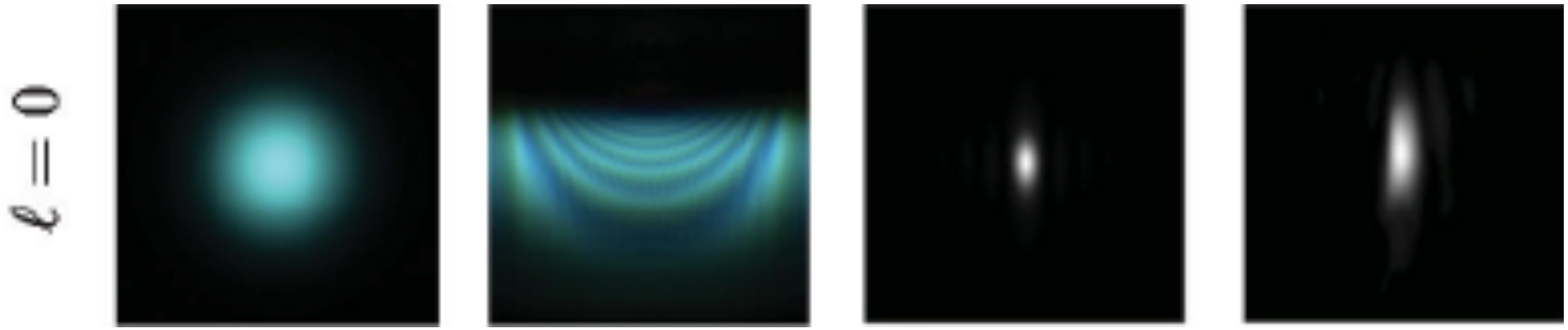
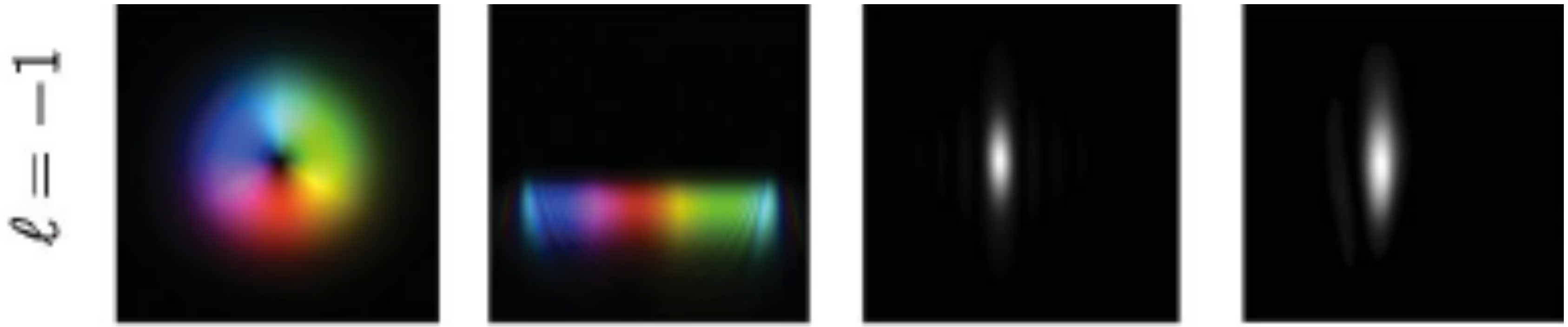
The results -1

Input mode | Transformed mode | Predicted output | Measured output



The results -1

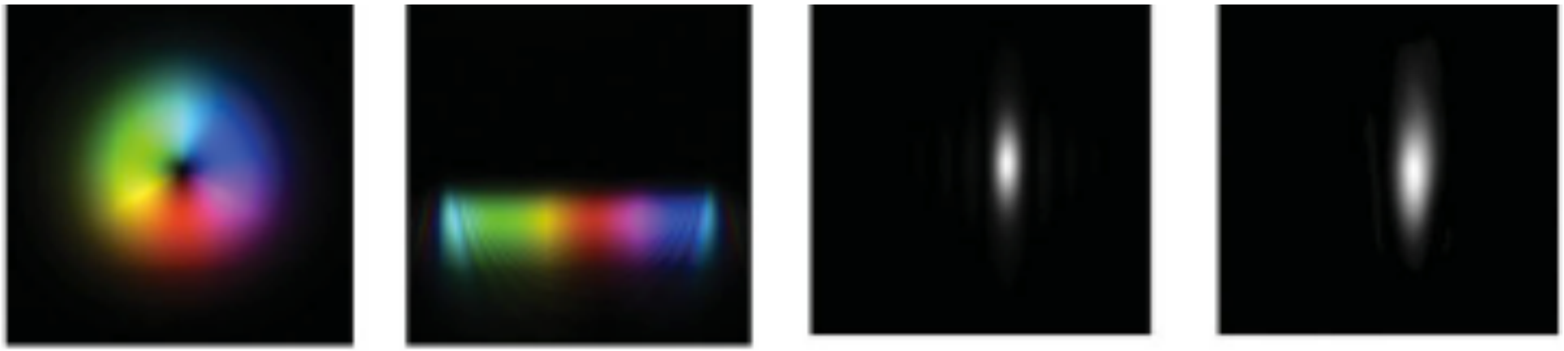
Input mode Transformed mode Predicted output Measured output



The results -1

Input mode | Transformed mode | Predicted output | Measured output

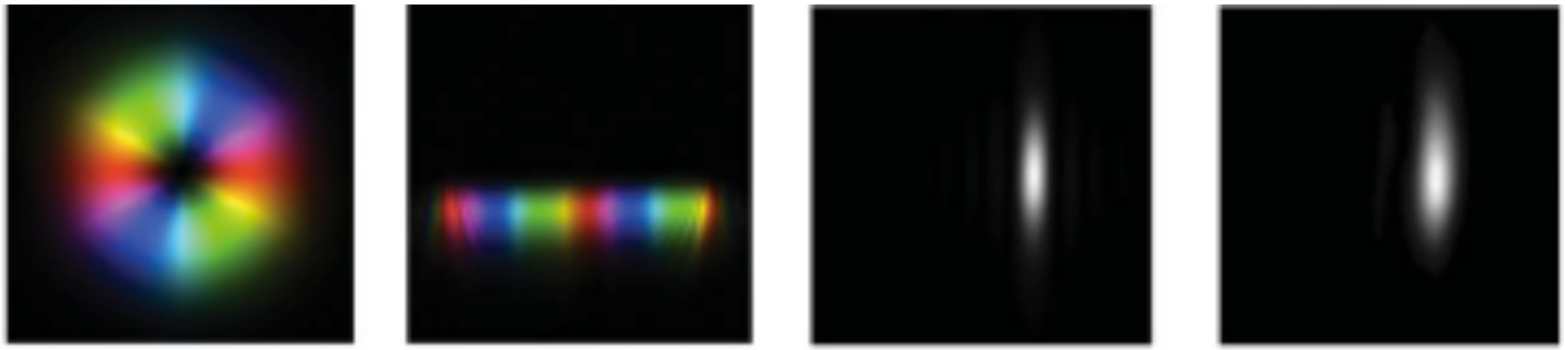
$\ell = 1$



The results -1

Input mode | Transformed mode | Predicted output | Measured output

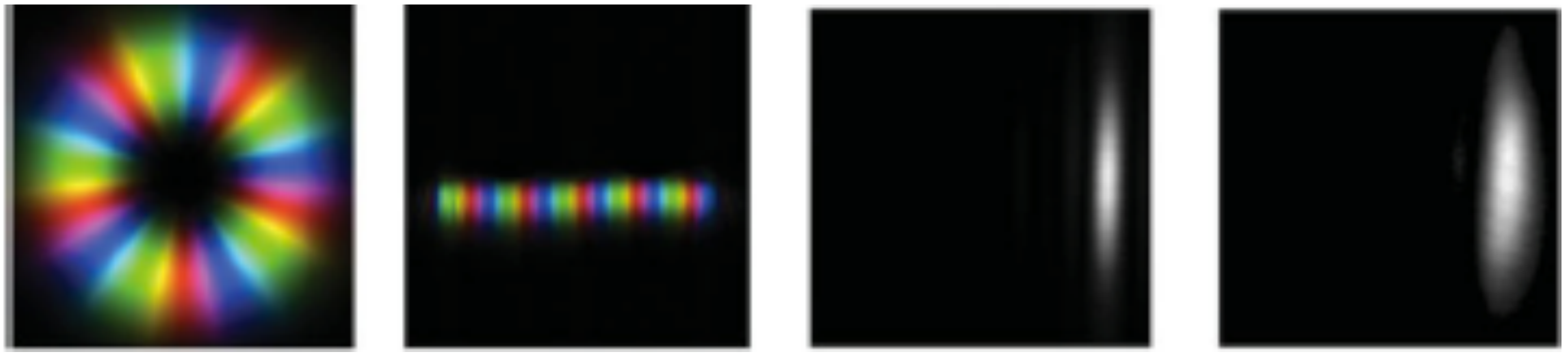
$\ell = 2$



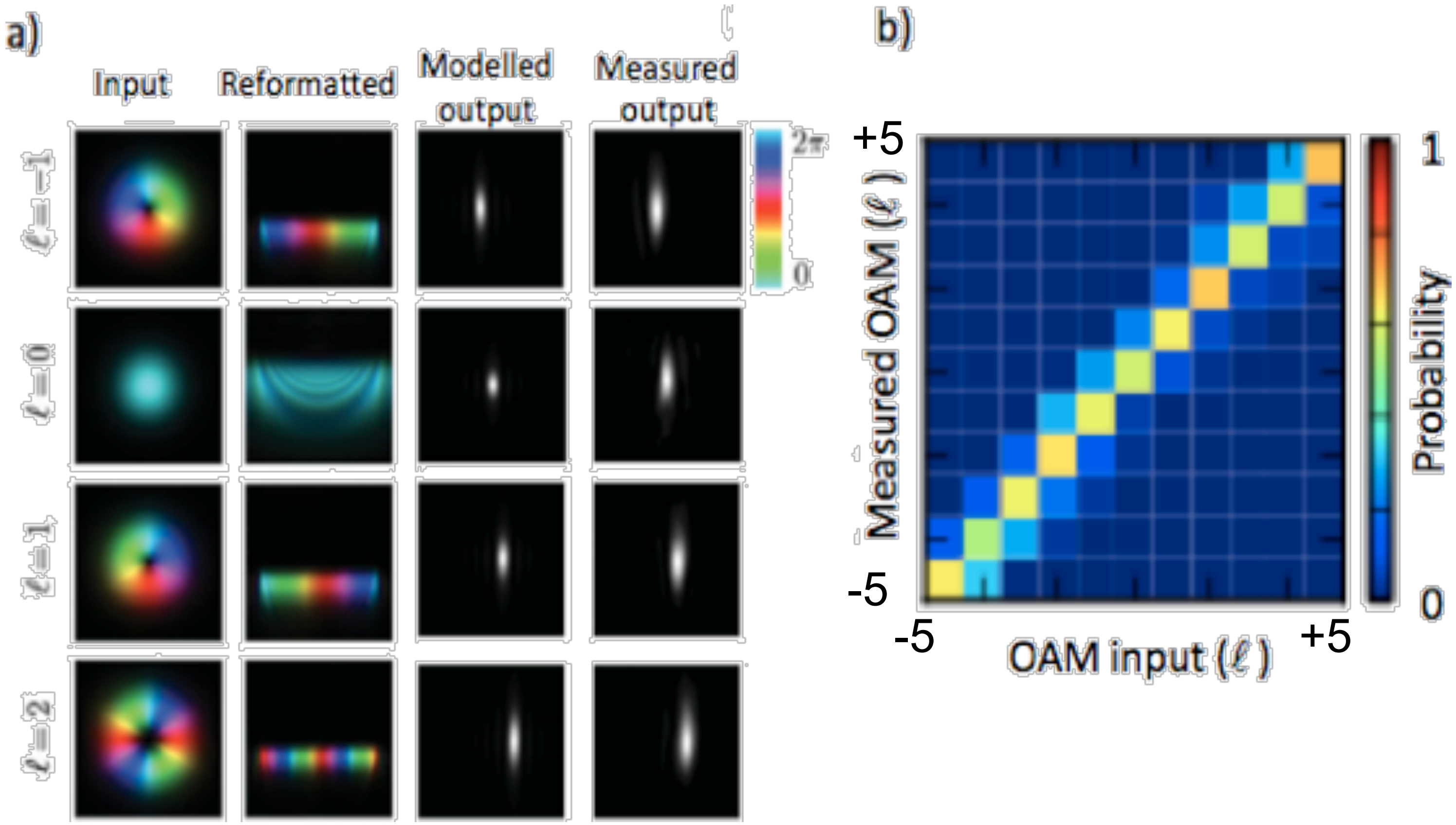
The results -1

Input mode | Transformed mode | Predicted output | Measured output

$\ell = 5$



The results -2

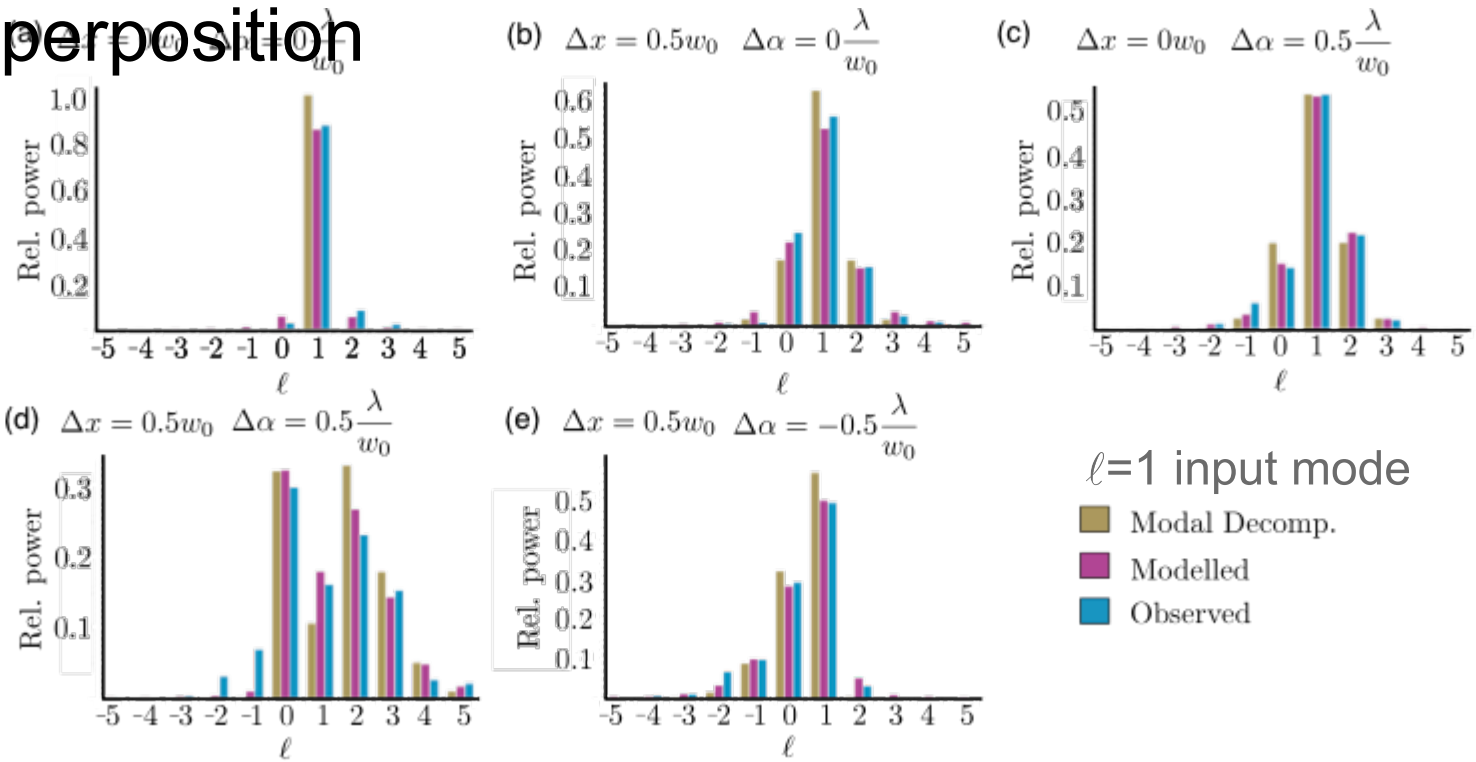


PRL 105, 153601 (2010) PHYSICAL REVIEW LETTERS week ending 8 OCTOBER 2010

Efficient Sorting of Orbital Angular Momentum States of Light

The results -3

- A misaligned LG beam is no longer a pure OAM state
- Mode sorter ≈ correctly measures the resulting superposition

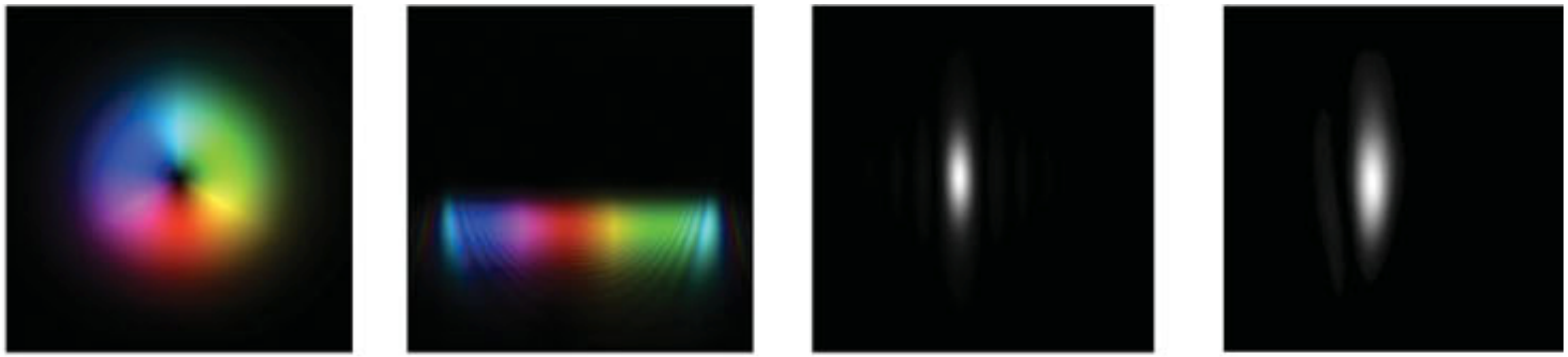


The results -4

- It works for superpositions of modes

Input mode | Transformed mode | Predicted output | Measured output

$\ell = -1$



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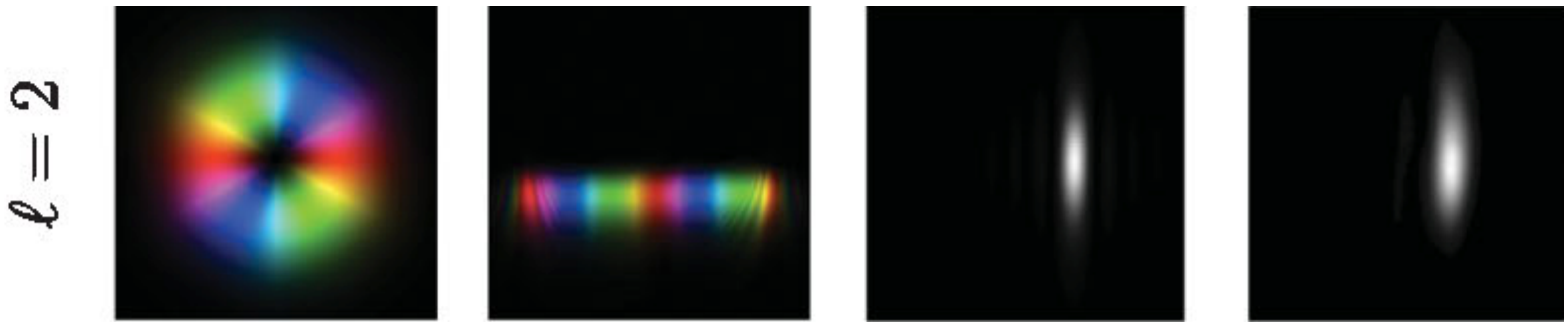
The results -4

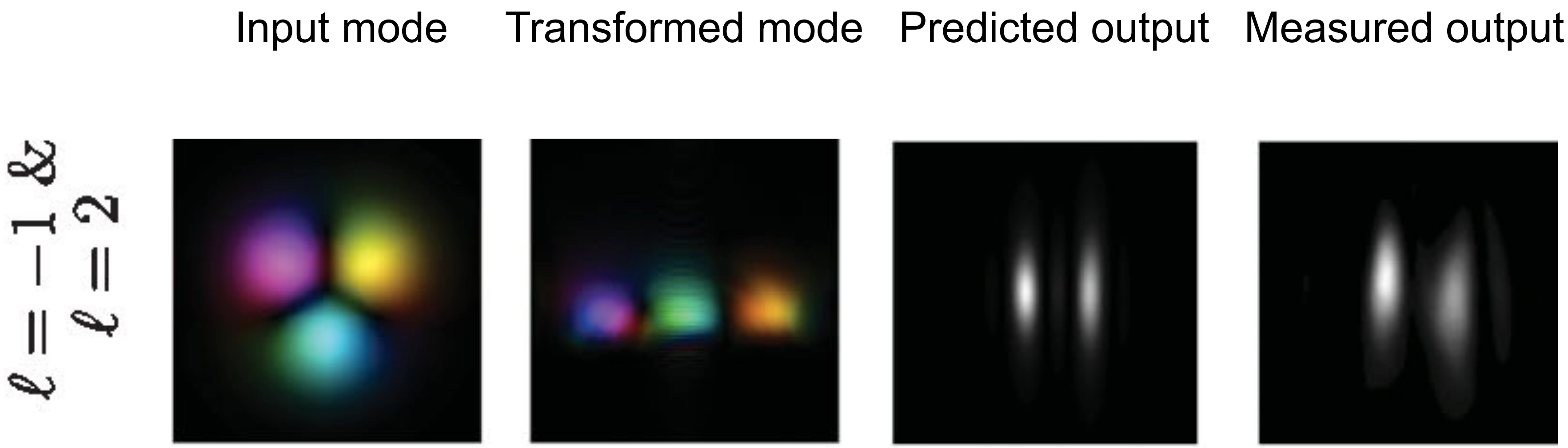
- It works for superpositions of modes

Input mode | Transformed mode | Predicted output | Measured output



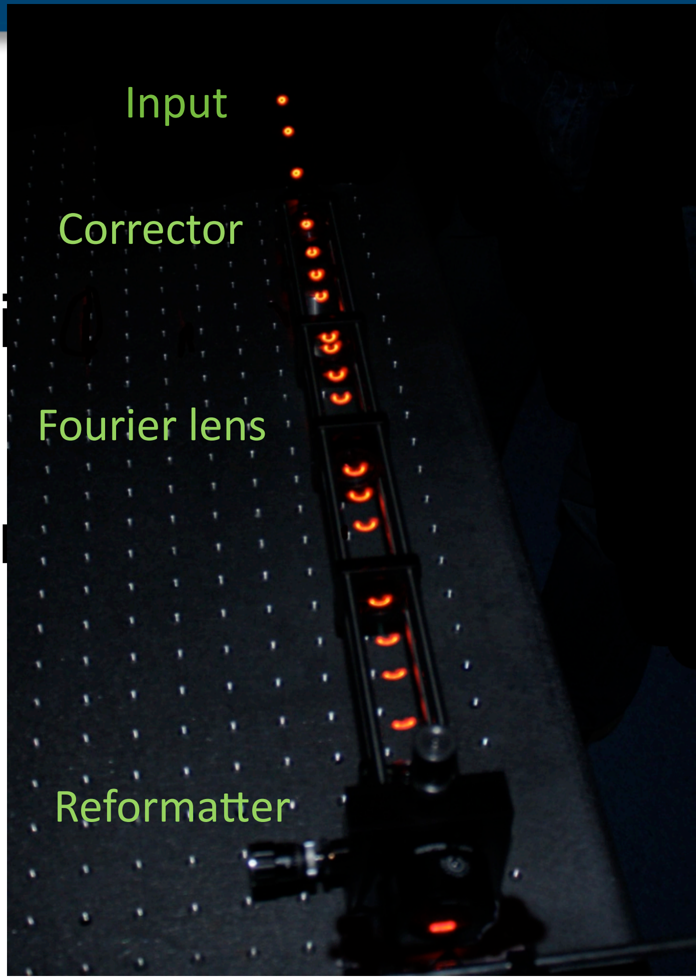
The results -4

- It works for superpositions of modes



Where next -1

- The principle works
- But the SLMs are ineffici
- Use bespoke optical ele
  - Prof. David J Robertson
  - Prof. Gordon Love



Durham University

Universiteit Leiden

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Where next -2

View at the camera whist we change the OAM

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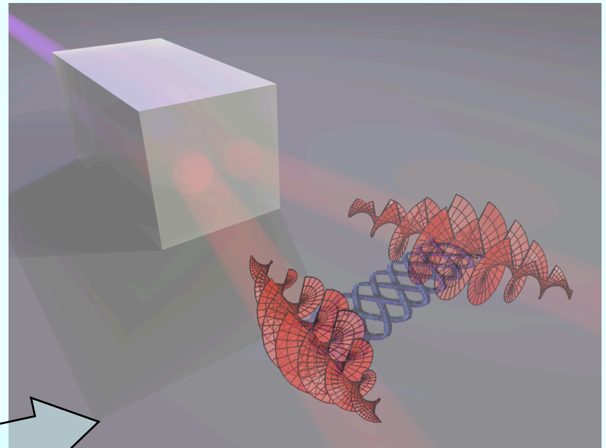
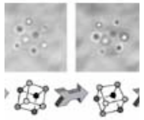
Optics

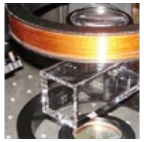
www.physics.gla.ac.uk/Optics



- Software
- Movies
- Publications

Areas of Research


OPTICAL TWEEZERS

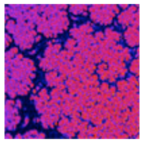

ATOM OPTICS

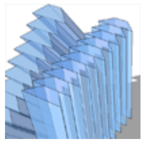

QUANTUM OPTICS & GHOST IMAGING


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

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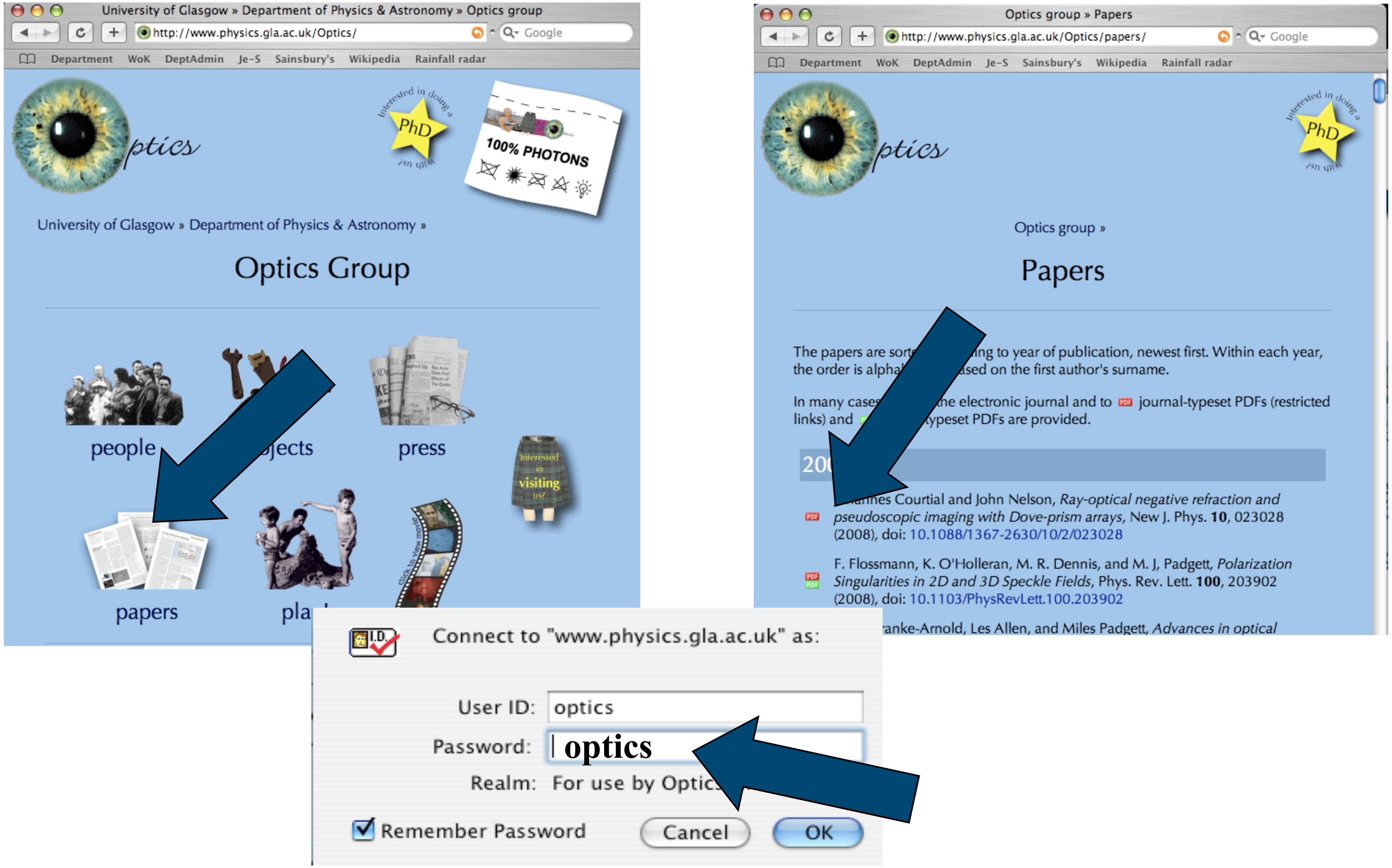

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SUPA

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- ❑ Glasgow Physics & Astronomy: www.physics.gla.ac.uk
- ❑ SUPA: www.supa.ac.uk/prize/prize.php
- ❑ Or email: physci.gla.ac.uk for advice and specific contact information

University of Glasgow

Questions

- Electron vortex beams can be made using e.g. spiral phase plates. What does the B-field do at the end of the singularity? (i.e. where's the monopole!)
- How many plane waves does it take to make a link of vortex loops?
- Why are the SAM and OAM both quantised in units of $\hbar$?
- How can one make (easily) the OAM equivalent of optical activity?