The Abdus Salam
International Centre for Theoretical Physics

United Nations
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WINTER COLLEGE

on

QUANTUM AND CLASSICAL ASPECTS

of

INFORMATION OPTICS

30 January - 10 February 2006

Optical Vortices: The Generic State of Light

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Trieste Feb 2006

Optical Vortices: The Generic State of Light

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Optical vortex =Helical phasefronts

- Description of light
  - Intensity (θ,r), $I \geq 0$
  - Phase (θ,r), $2\pi \geq \phi \geq 0$

    $\phi(\theta,r) = \omega t + kz + \ell\theta$

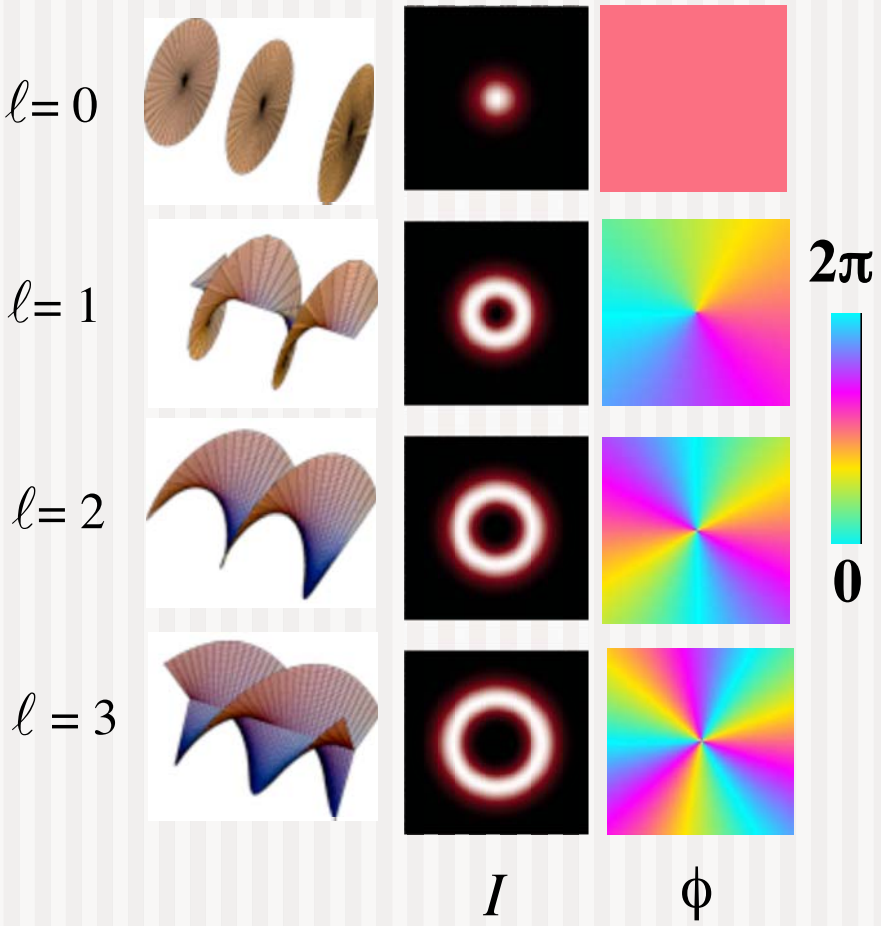
    ℓ = 0, plane wave

    ℓ = 1, helical wave

    ℓ = 2, (double) helical

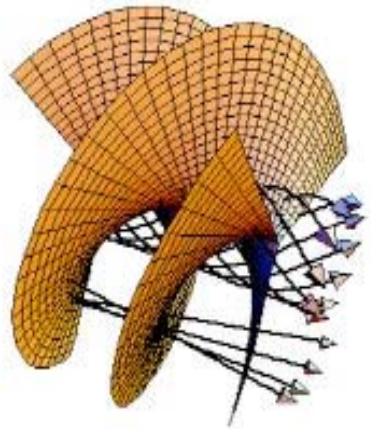
    etc.

ℓ= vortex charge



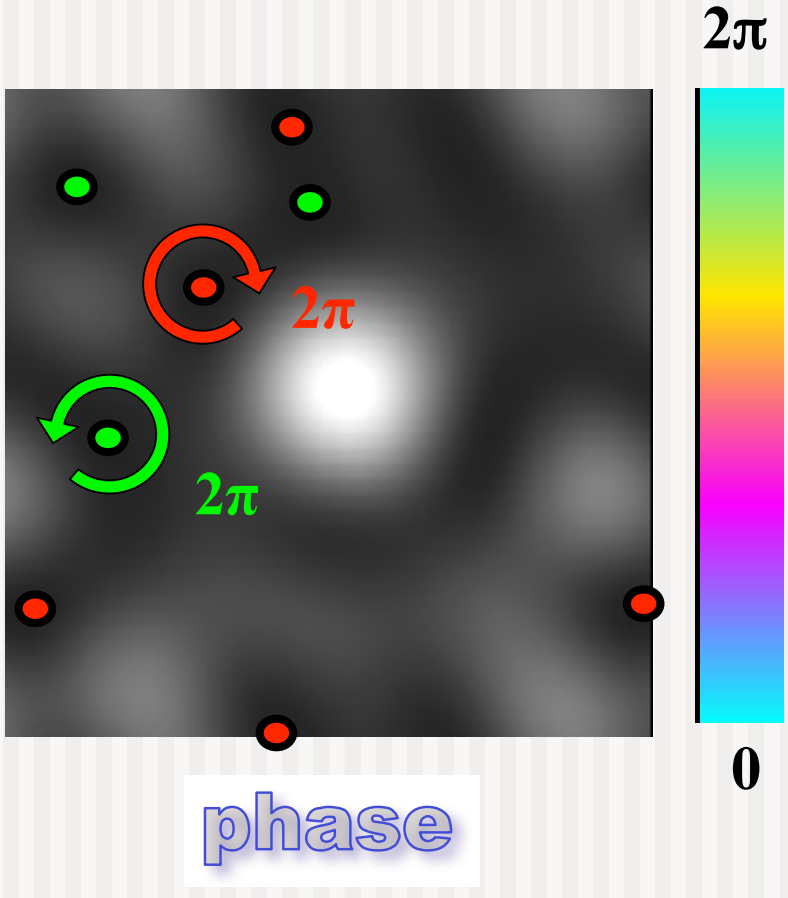
A vortex of what?

- Momentum flow perpendicular to phase-fronts
- Helical phasefronts
  - azimuthal momentum
    - orbital angular momentum
    - $\ell\hbar$ per photon (Allen *et al.*)
- A vortex of optical energy and momentum



Vortices are ubiquitous in nature

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



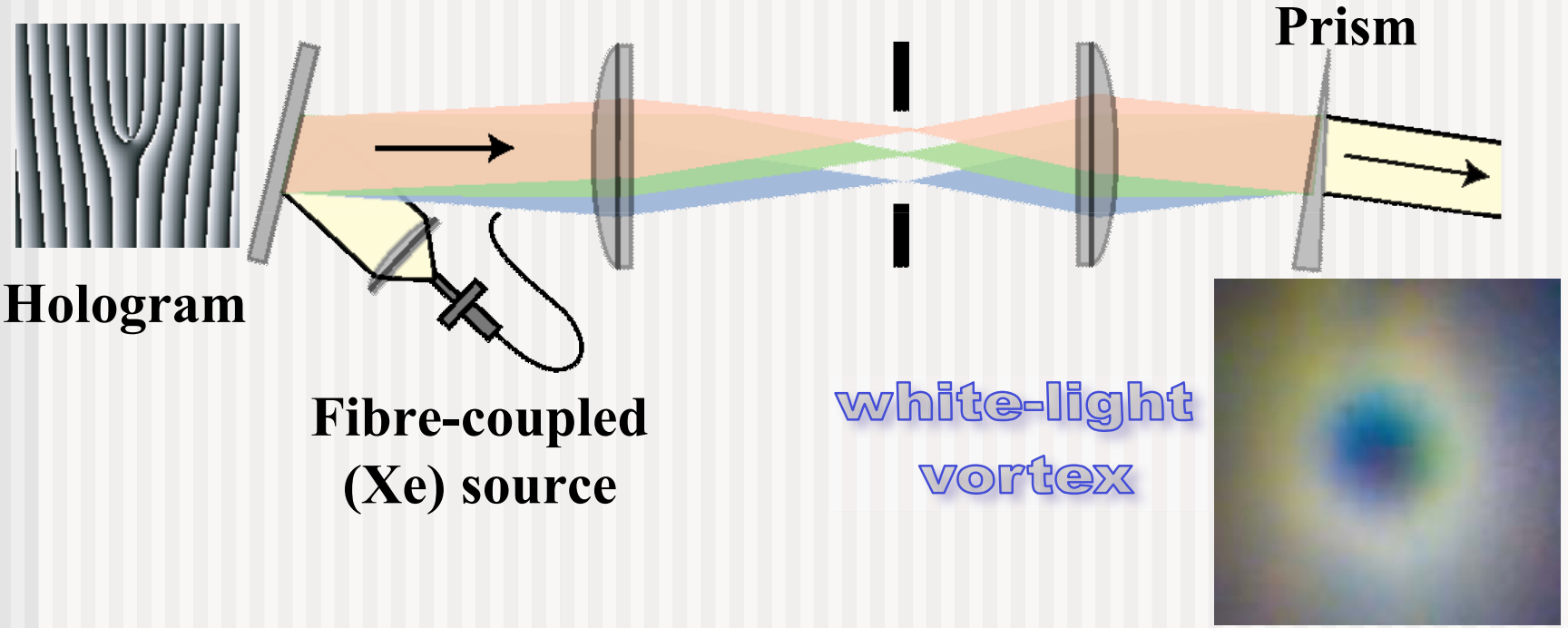
Colours in the vortex

Berry, New J Phys 2002

Leach and Padgett, New J Phys 2004

Making a white-light vortex

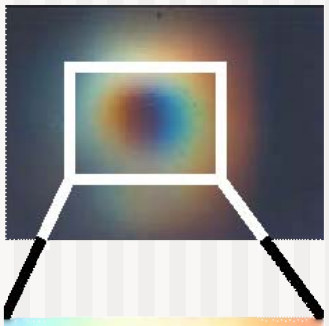
- Fibre-coupled (≈spatially coherent) white-light source
- Hologram to create vortex
- Prism to correct chromatic dispersion

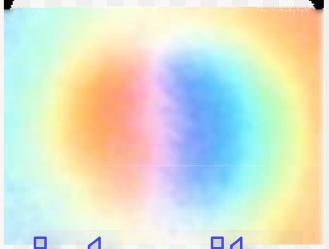


Dispersion in the vortex

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

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} \Rightarrow \begin{pmatrix} R \\ G \\ B \end{pmatrix} \Big/ \max(R, G, B).$$



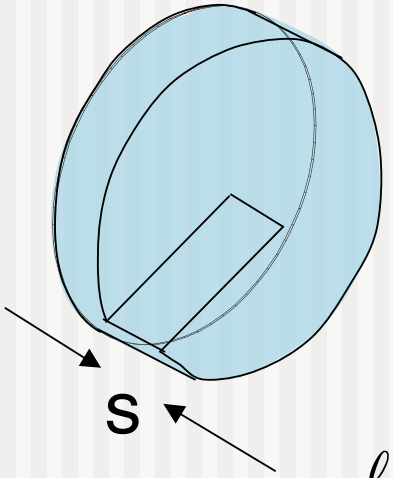


Structure in non integer vortex

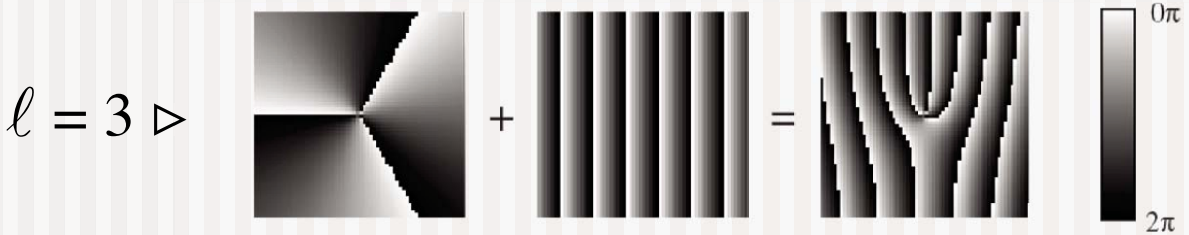
Berry J. Opt. A 2004

Leach *et al.* New J Phys 2004

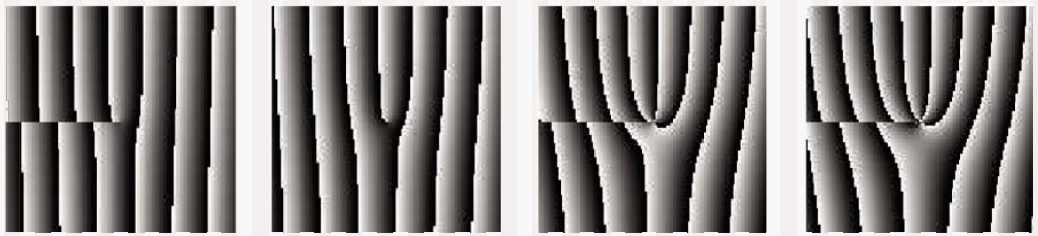
Making a fractional charge vortex



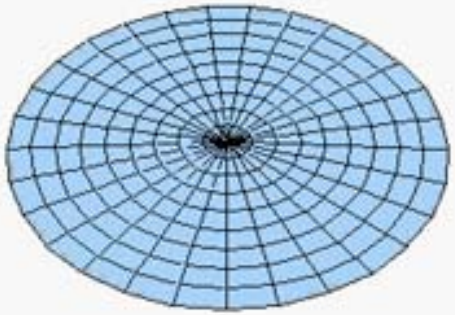
- Spiral Phase-plate
  s= $\ell\lambda/(n-1)$, ℓ need not be an integer

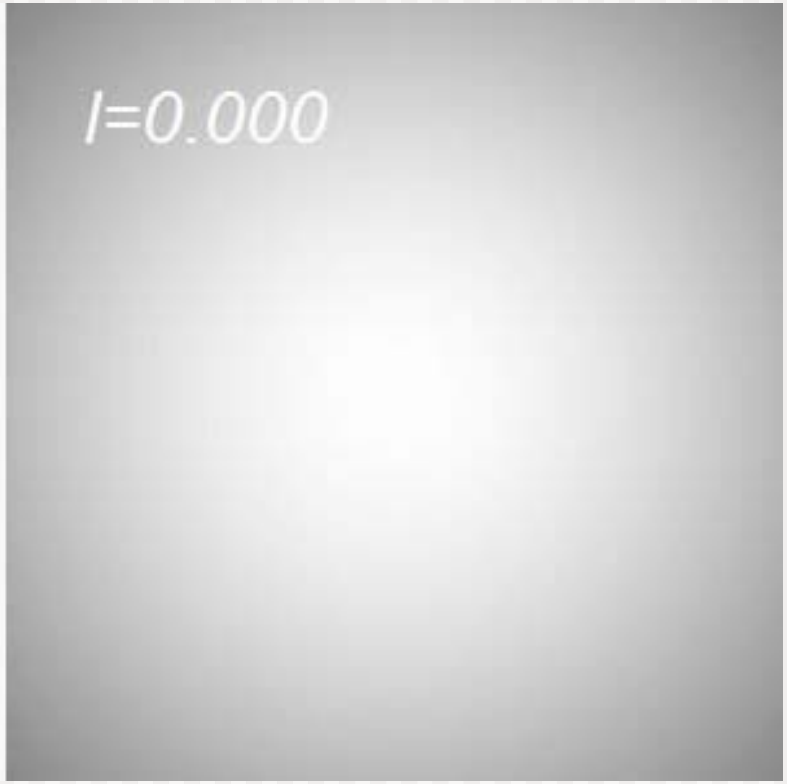


- Holographically



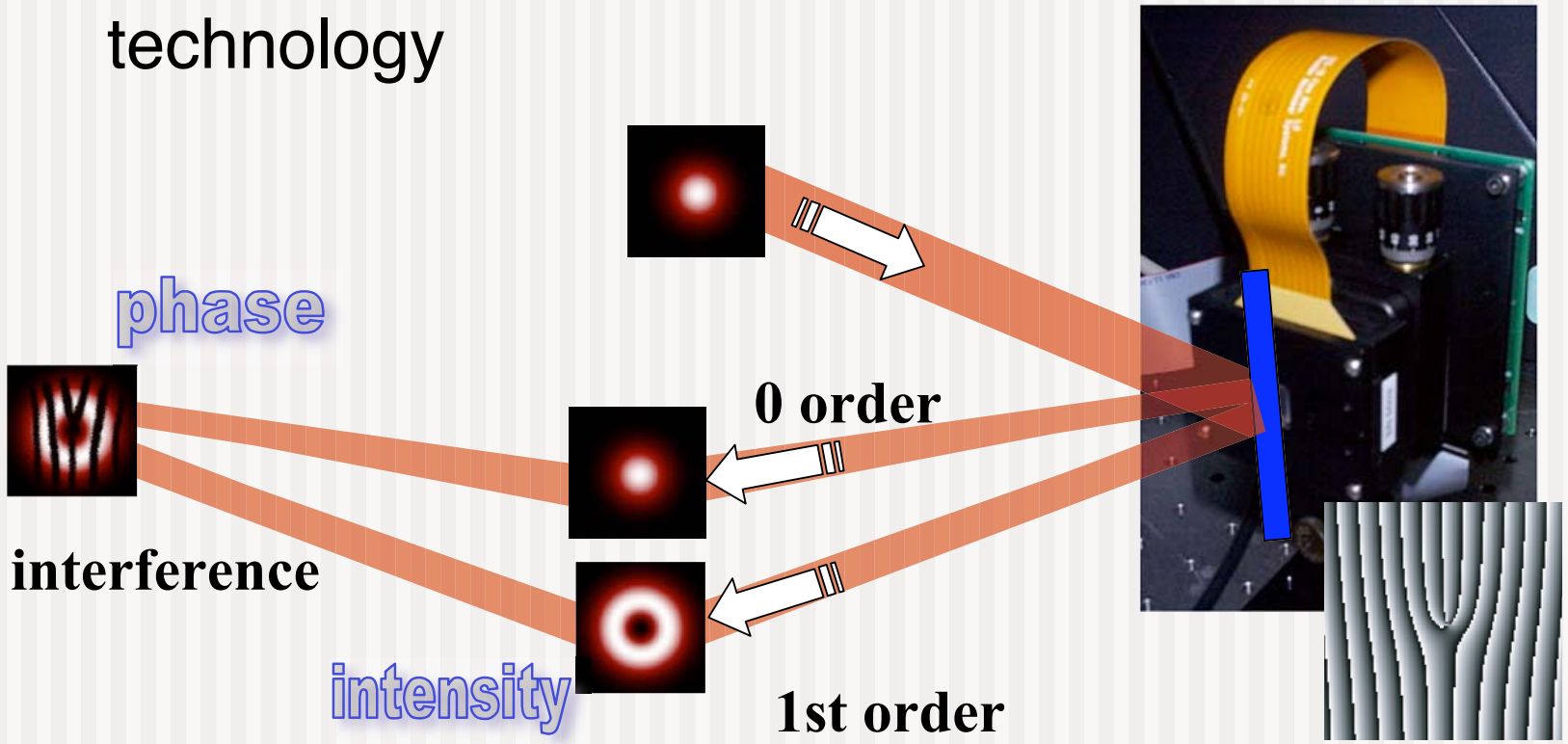
Increasing ℓ





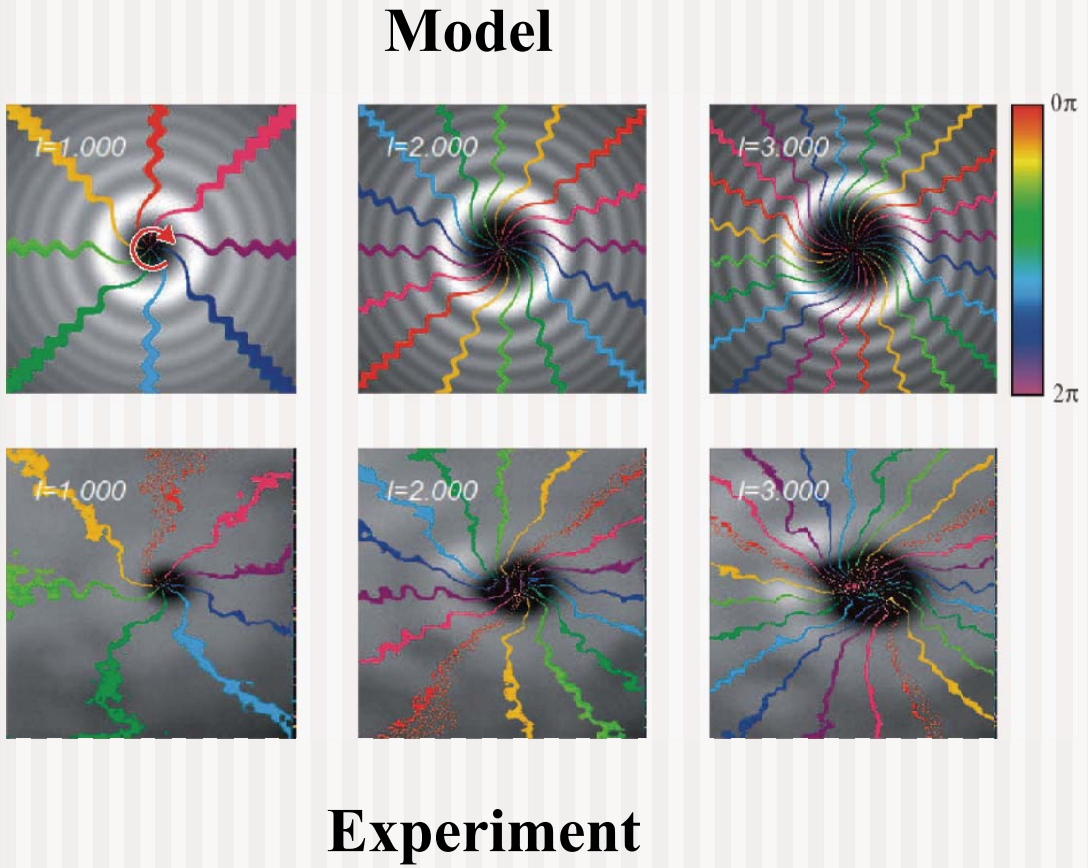
Spatial Light Modulators: Interactive holograms

- Make reconfigurable with data-projector technology

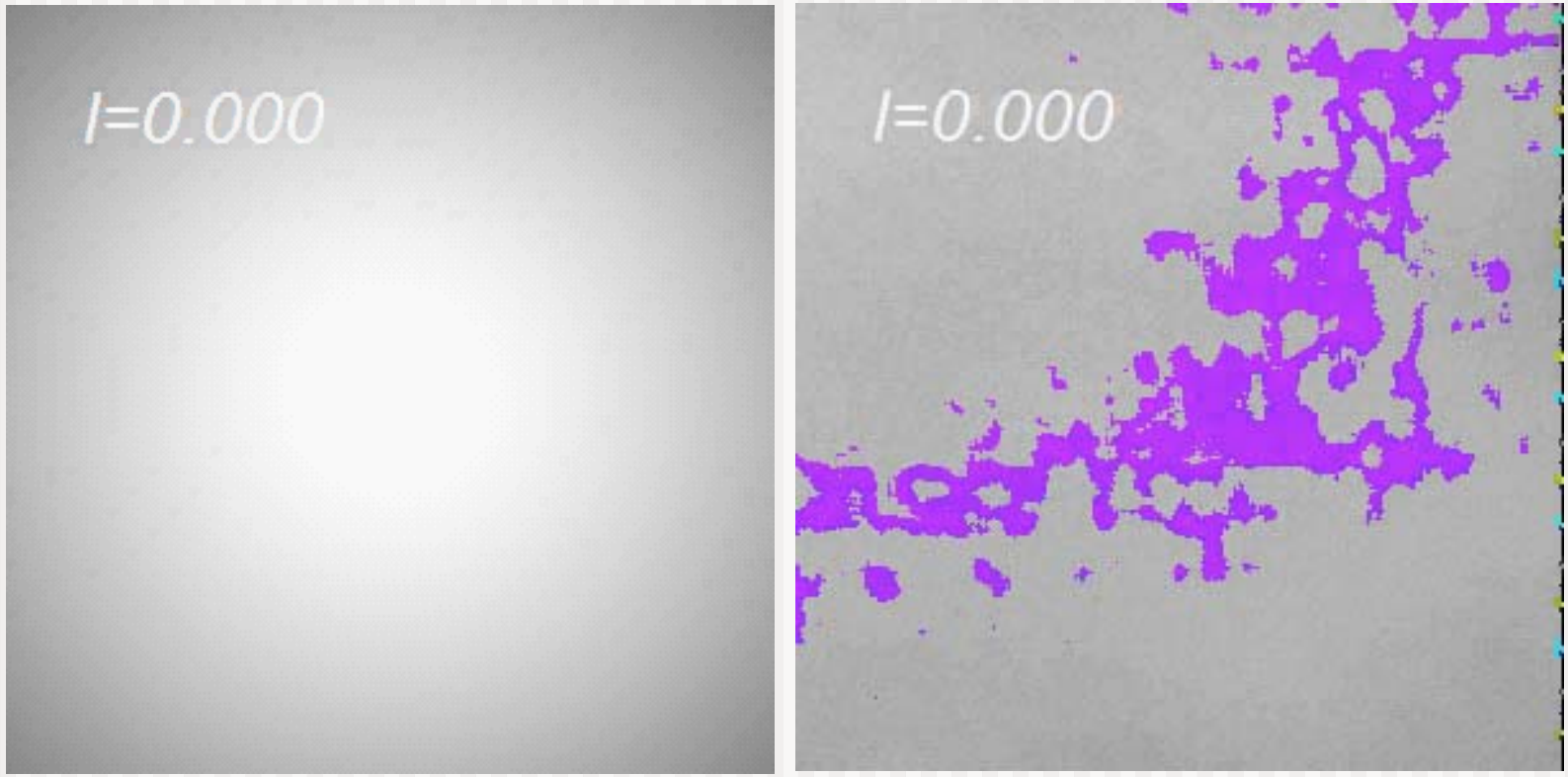


The (phase) vortex structure

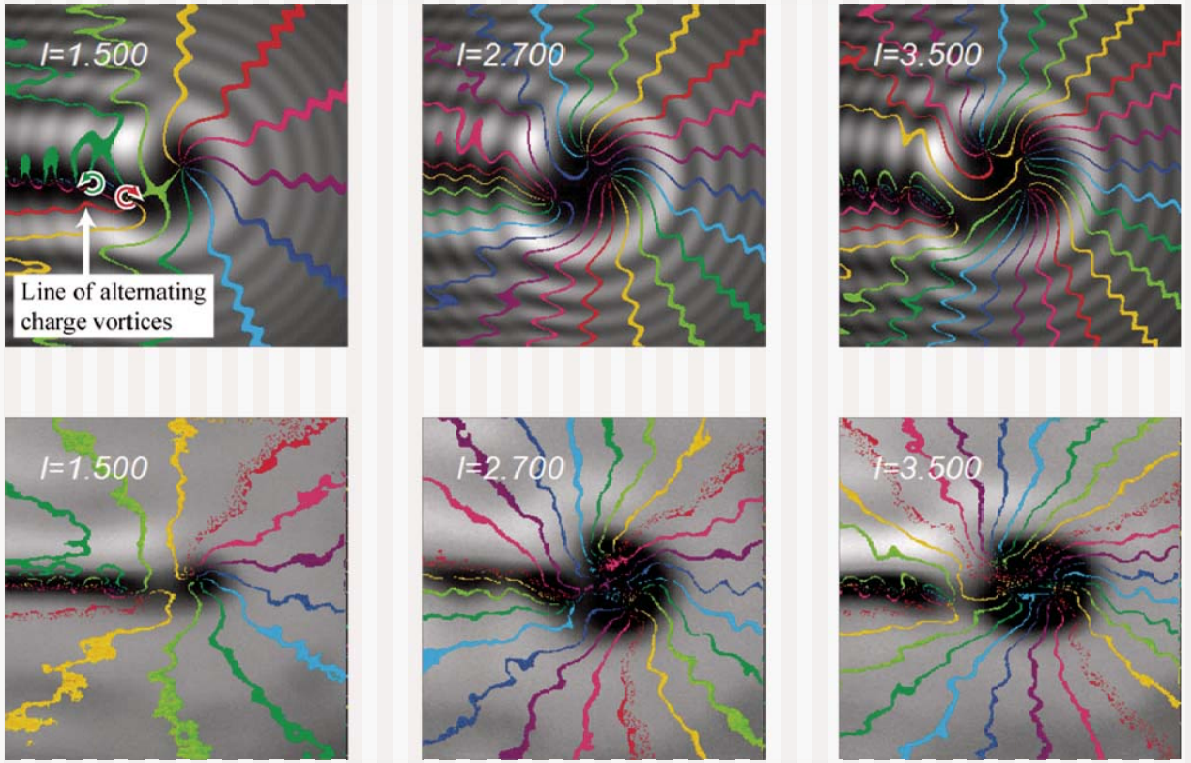
- Overlay intensity with phase structure



Increasing the vortex charge



Half integer vortex structure



- Half integer beams carry a string of alternating charge (+/-1) vortices

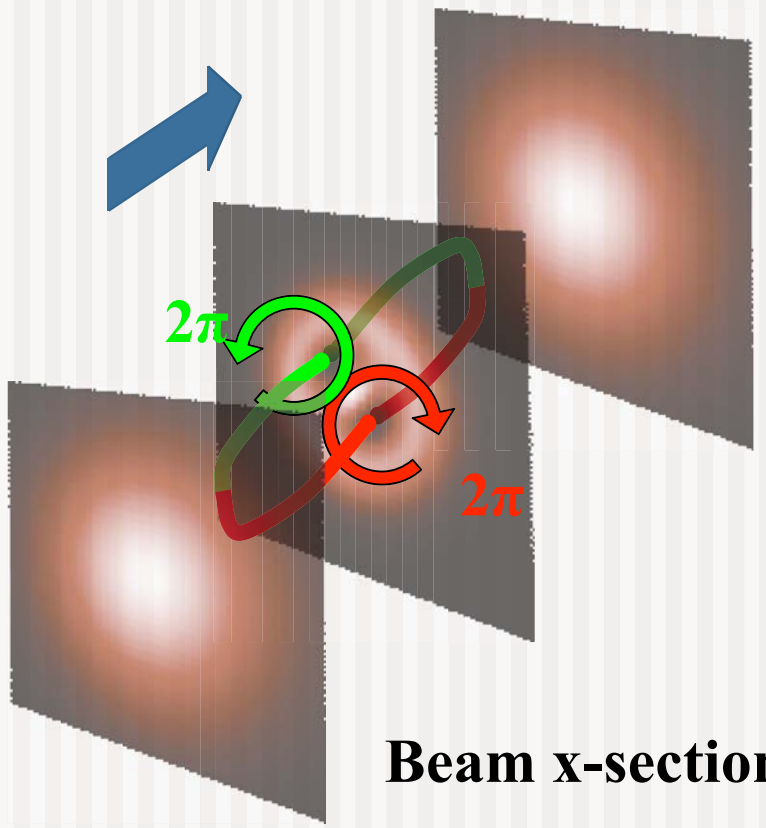
Knots of the vortex

Berry and Dennis, Proc Roy Soc A, 2001

Leach *et al.* Nature, 2004

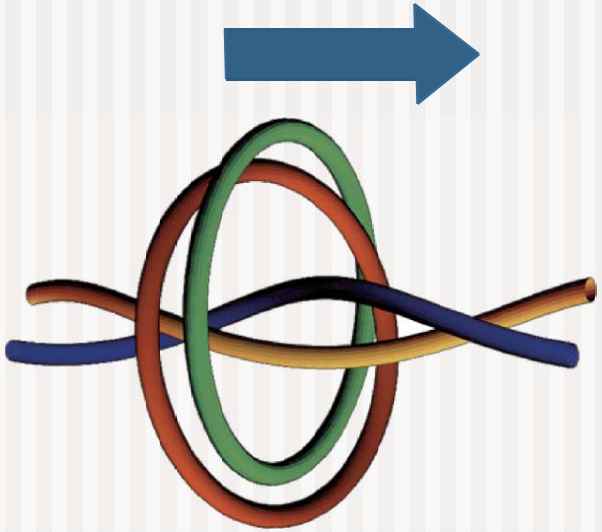
Simpler understanding
Vortices form loops in 3D

- The birth and annihilation of opposite sign vortices better explained by vortex loop in 3D

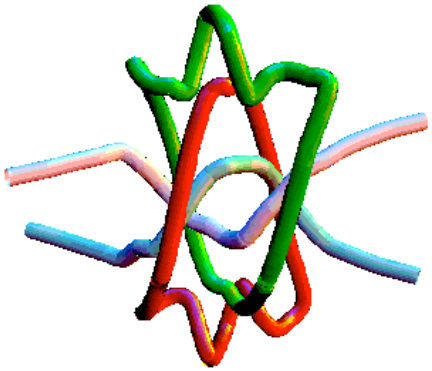


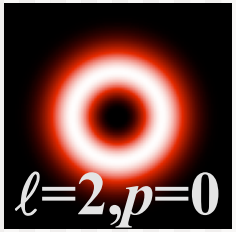
loops of darkness

Linking the loops

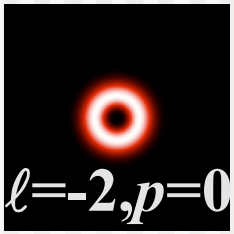


link of darkness

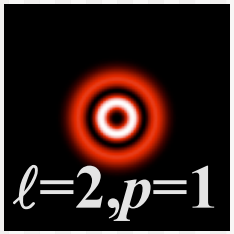




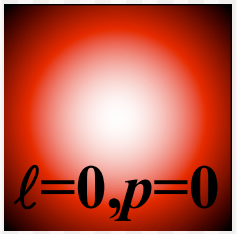
+0.35



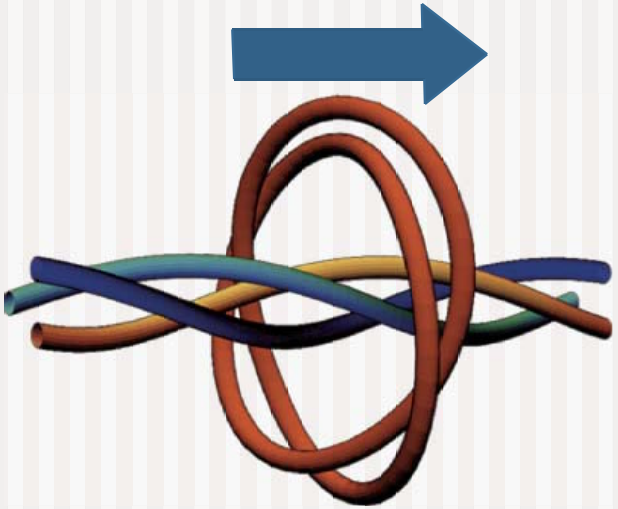
+0.36



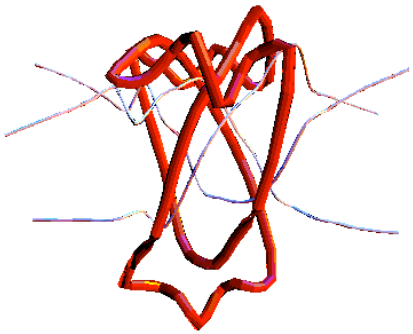
+0.25

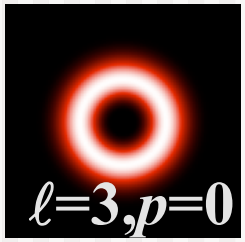


Knotting the thread

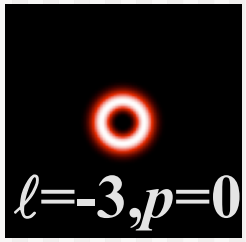


knots of darkness

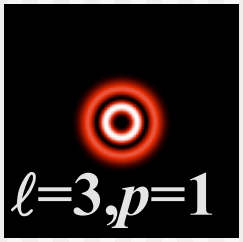




+0.26



+0.29



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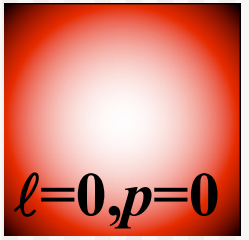


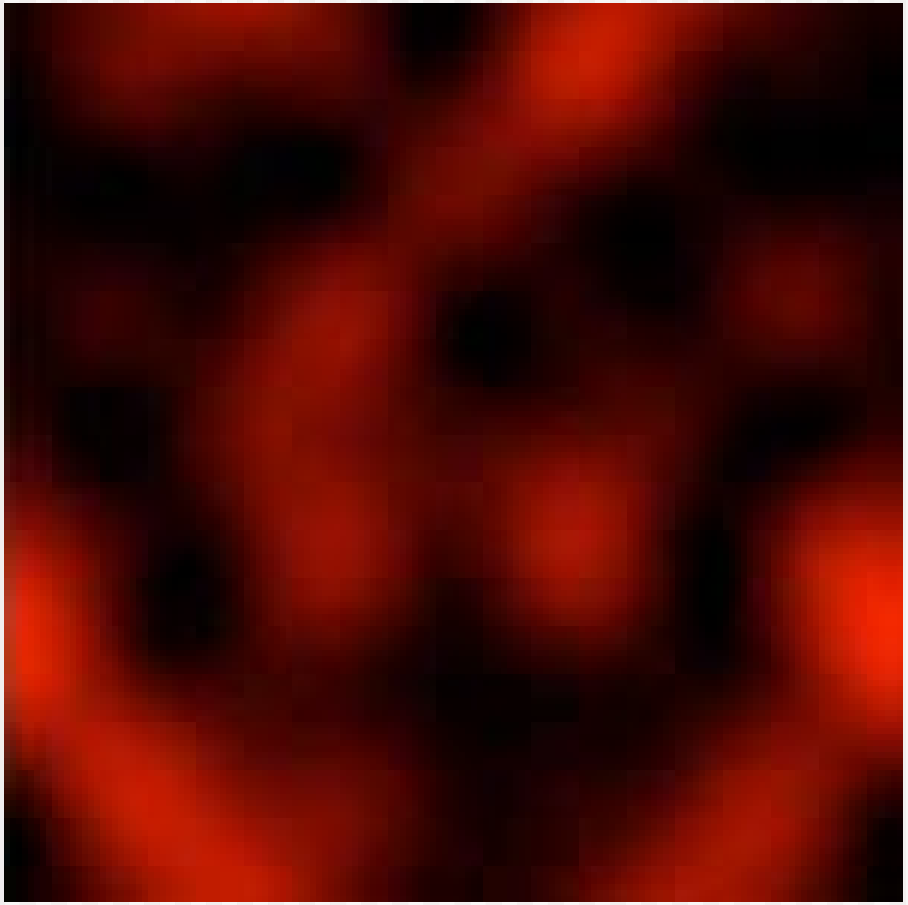
General vortex topology

Work in progress

Leverhulme Trust 2006-2008

Topologies of optical vortices

- Speckle patterns
- The dark specs map out lines in 3D
- What topologies are possible?

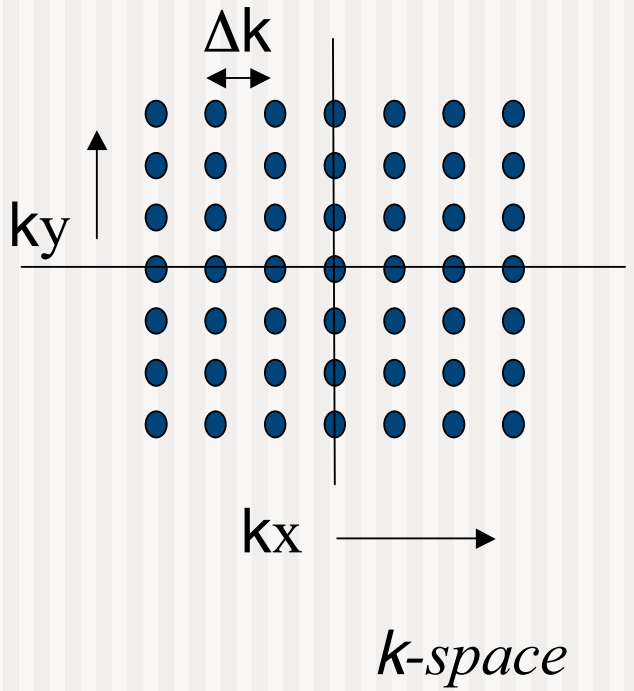


(Take a step back to) plane-wave interference 3D patterns

- Specific combinations of helically-phased beams can create exotic vortex topologies
- But how about the topologies found in random light fields, e.g. speckle patterns
- Can numerically model - but plane waves have infinite aperture….

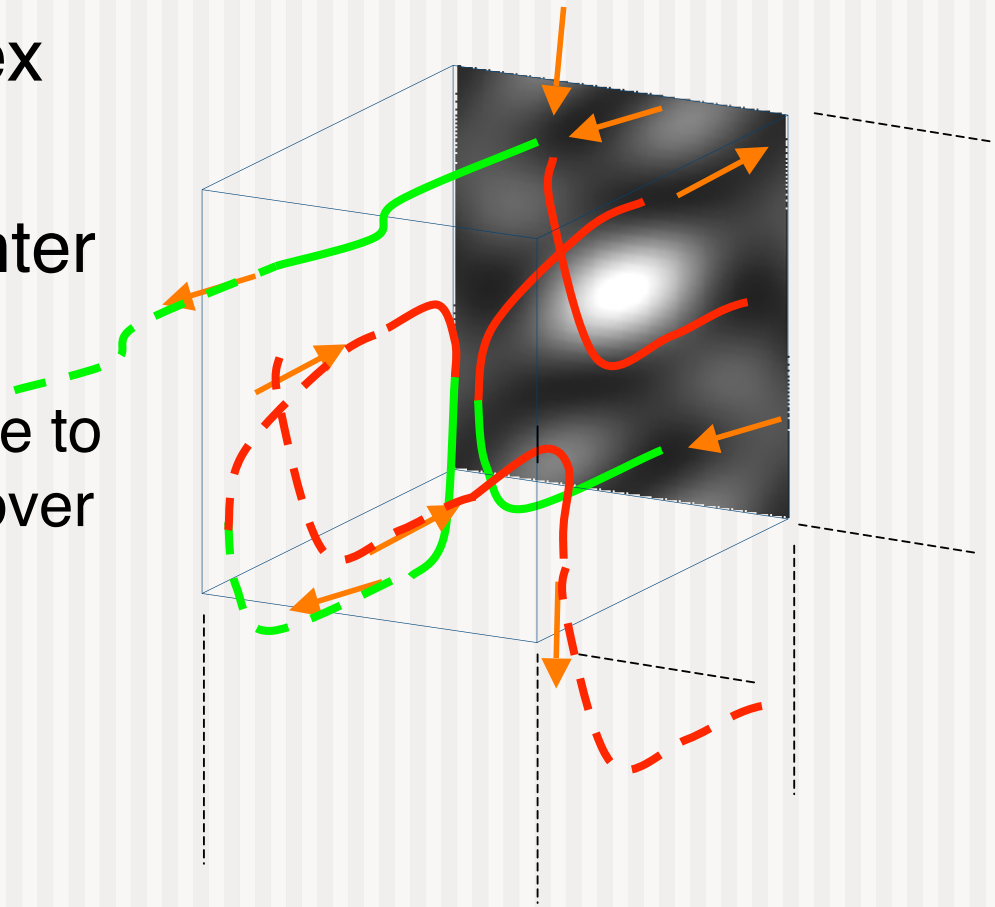
Modeling plane-wave interference 3D patterns

- 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



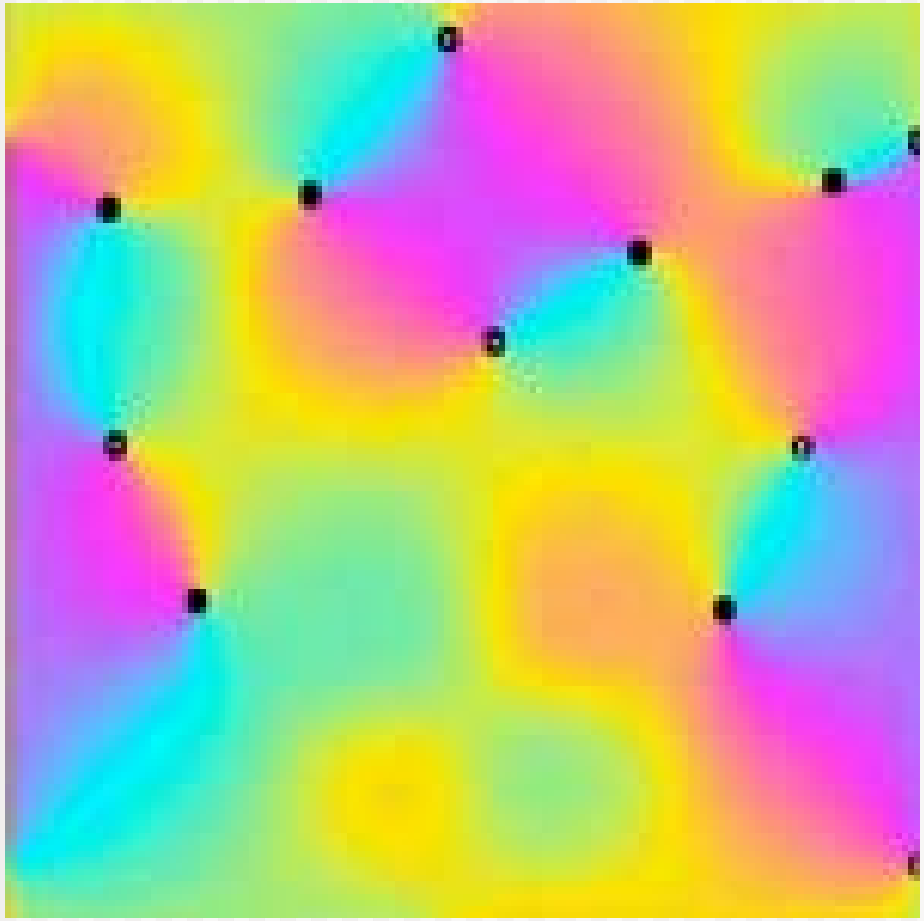
Within the “Talbot cube”

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

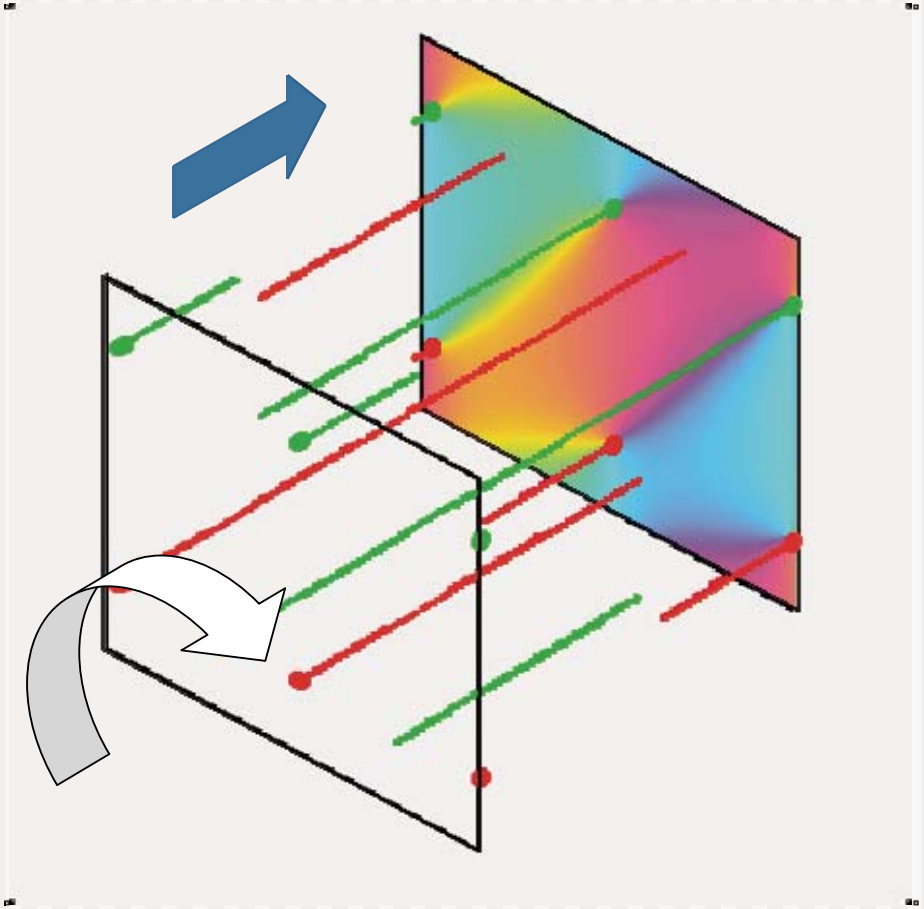


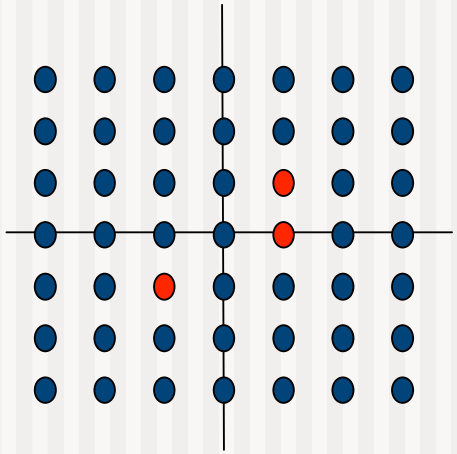
Map out the vortex position in different planes

- Both numerically and experimentally one can map the vortex positions in different planes



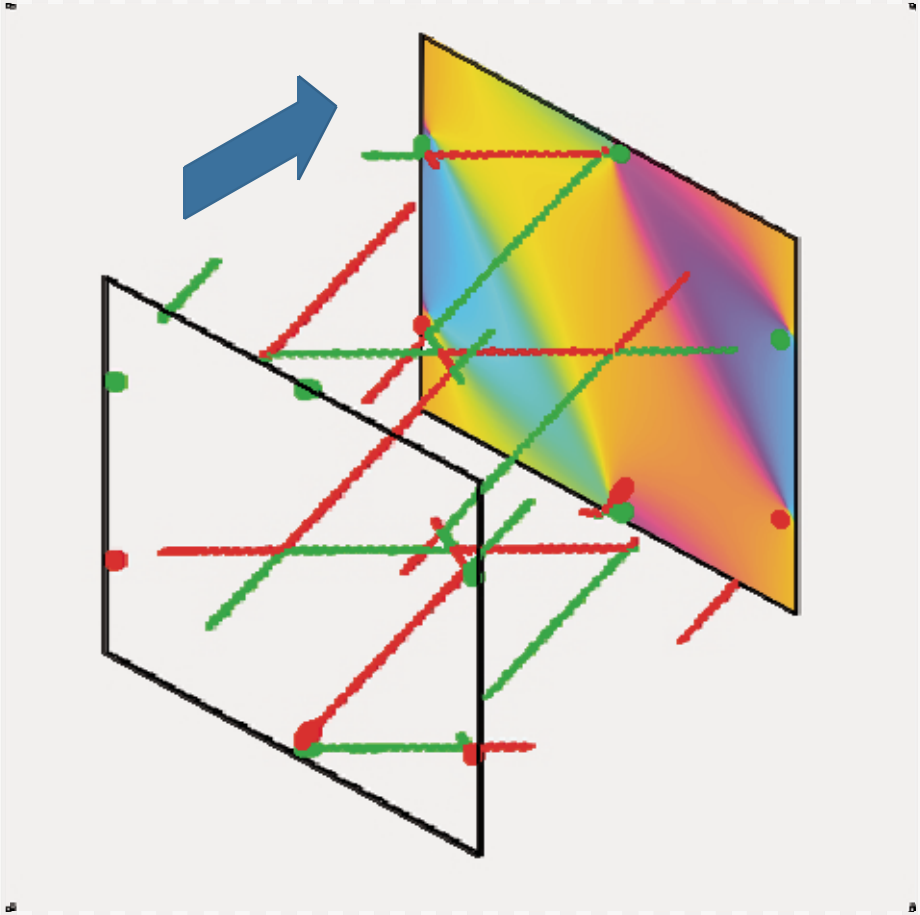
3-plane waves (= amplitude)

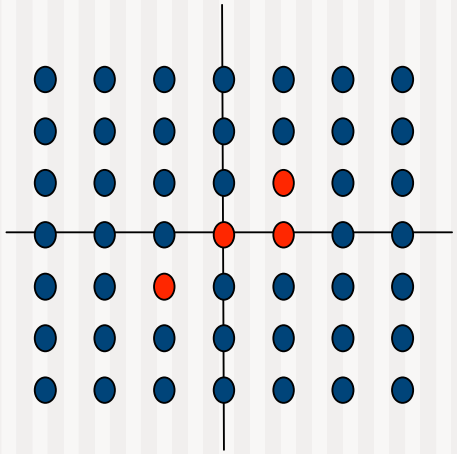




- Vortex threads are straight and parallel

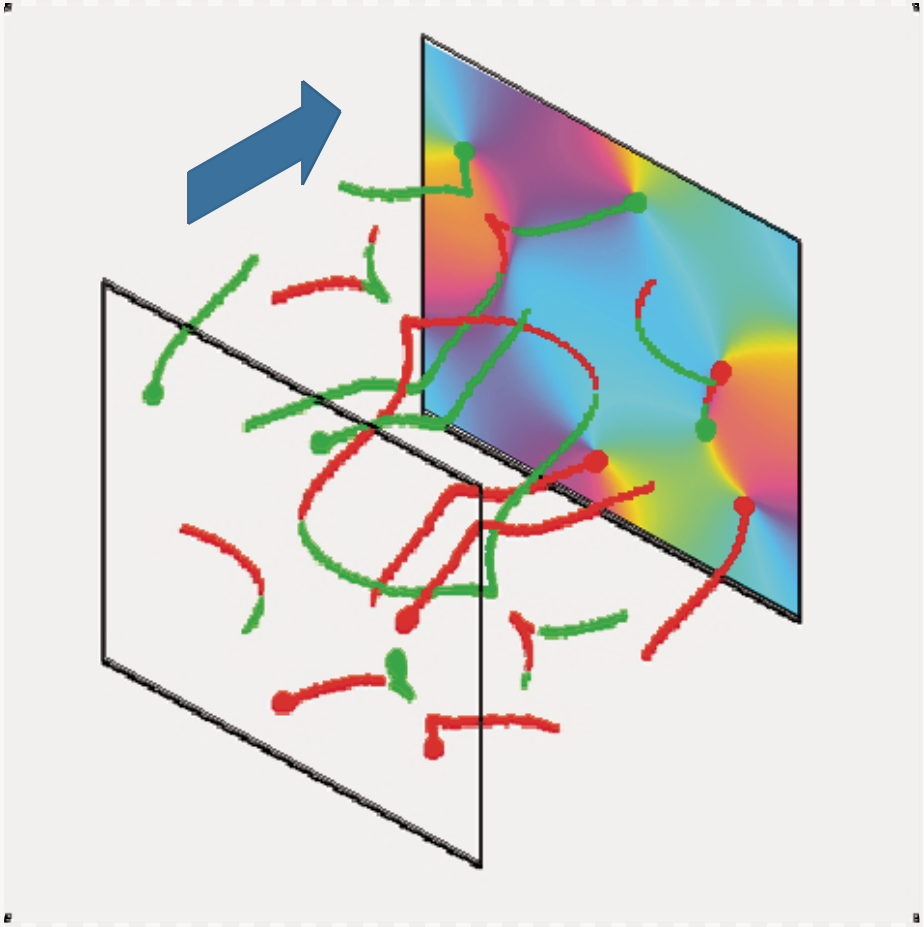
4-plane waves (= amplitude)

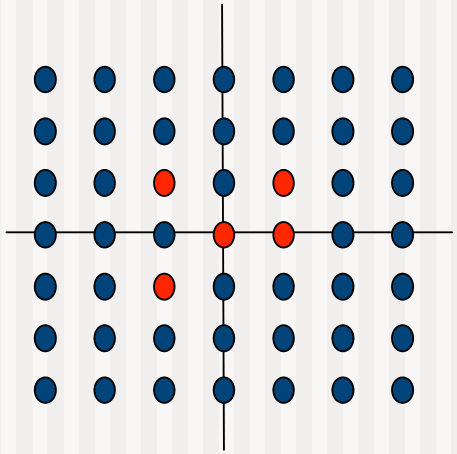




- Vortex threads form “wicker basket”

5-plane waves (= amplitude)

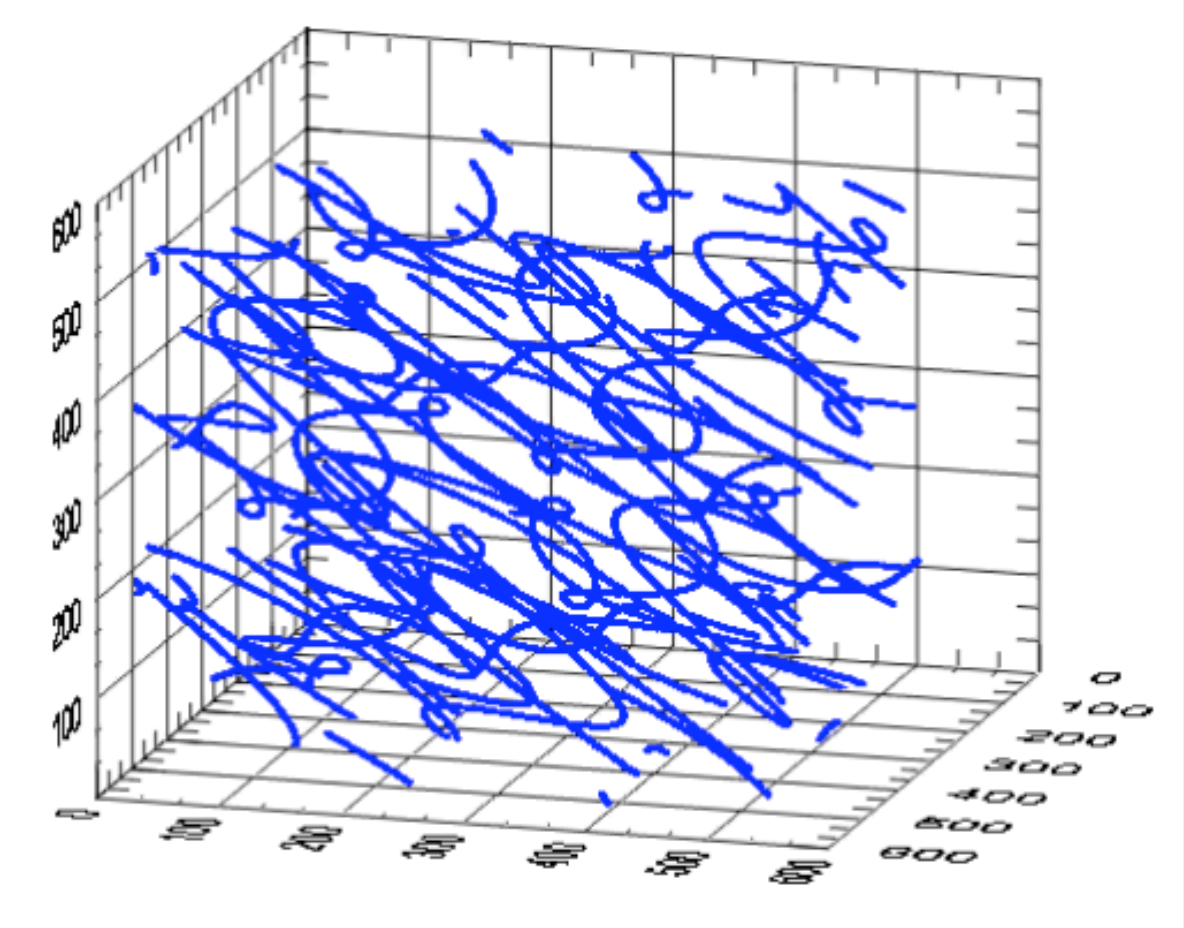




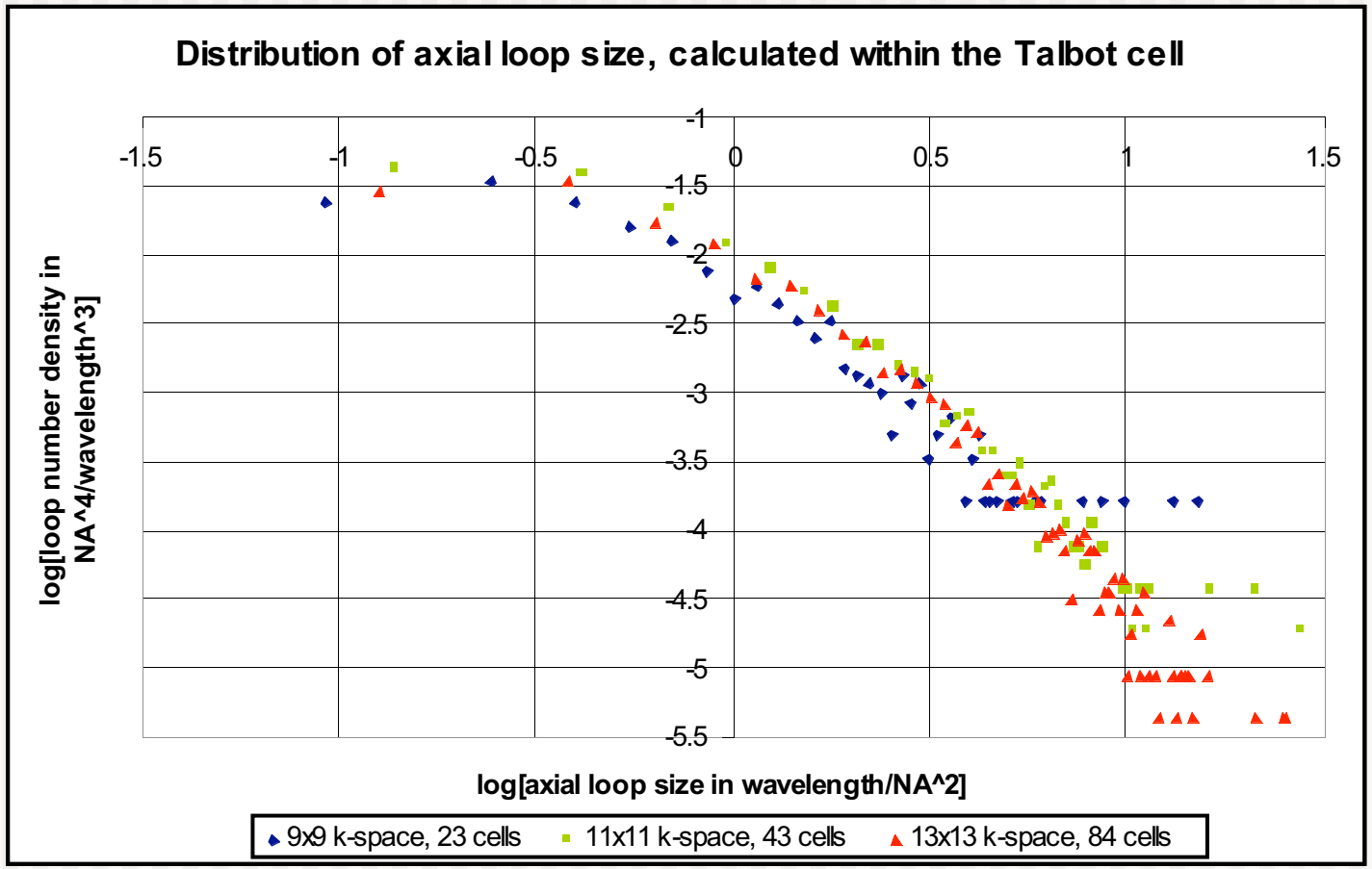
- Vortex threads form closed loops & open lines

Automatically unwrapping the cubes

- 5 waves on a 7x7 grid in a 512 x 512 x 512 Talbot cube
- 1-hour of a 3GHz P4
- 2 loops and 4 lines



Sample distribution of open (lines) vs closed loops



Questions to ask (answer)

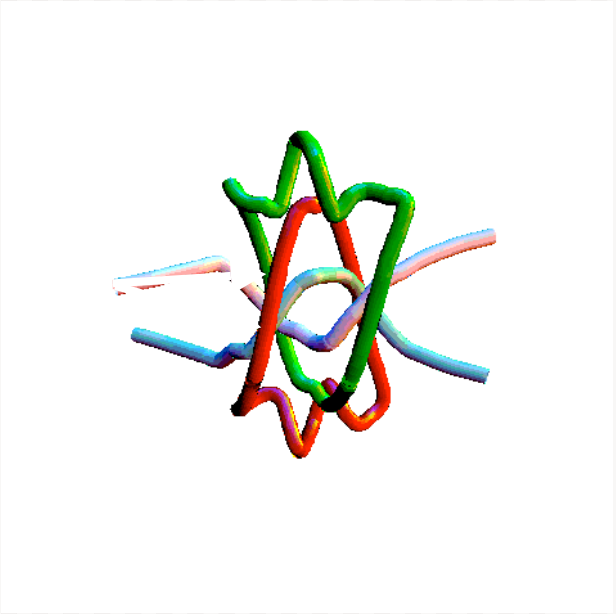
- By examining many random cubes
  - Ratio of loops to lines
  - Aspect ratio of loops/lines
  - Size of loops/lines
- Let size of grid tend to infinity, with a Gaussian weighting each plane wave
  - Loop:Line -> infinity
  - Probability of given loop size α 1/size^2
  - Small size cut off
    - Lateral $\approx \lambda/NA$
    - Axial $\approx \lambda/NA^2$

More Questions

- Can one form links and knots from discrete plane waves?
  - Haven't seen any yet
- Do vortex links and loops form in speckle fields?
  - Haven't found one yet!
- Just how special (rare) are these links and knots?

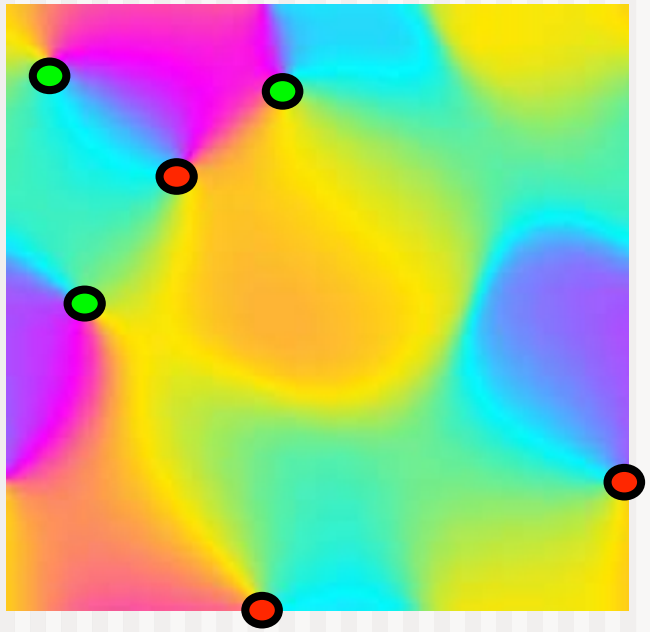
What's needed for a link?

- Take another look at the known link
- The linked loops were threaded by two same-sign vortices
  - Was this a coincidence?
- (The knotted loop was threaded by three same-sign vortices)



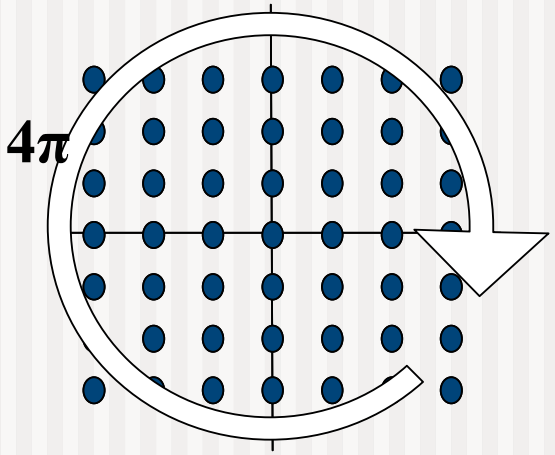
Nearest neighbour vortices tend to be opposite signs

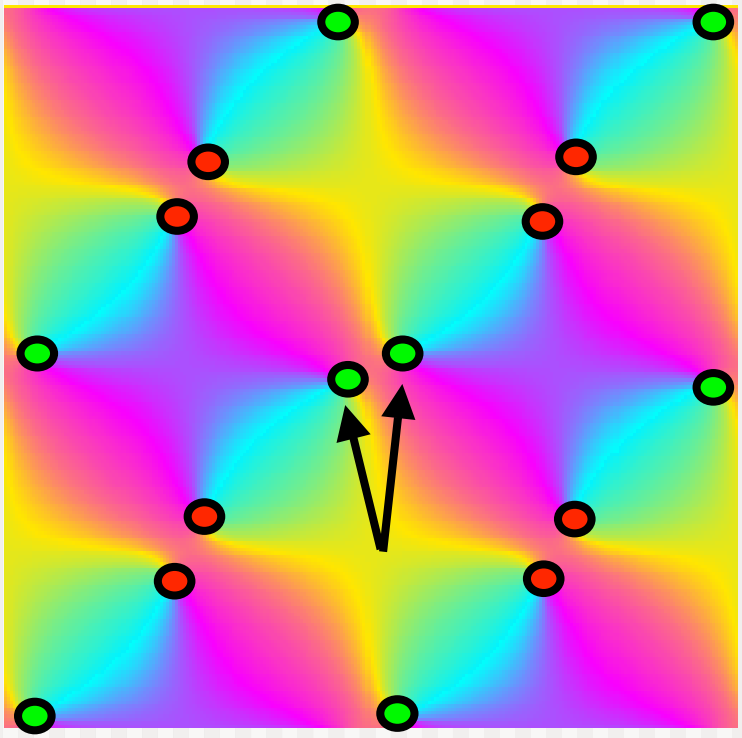
- In interference patterns arising from random combinations of plane-waves, nearest neighbour vortices (always?) have opposite signs



Encouraging vortices of the same sign together

- When using plane-waves
  - Need to set phase of perimeter waves



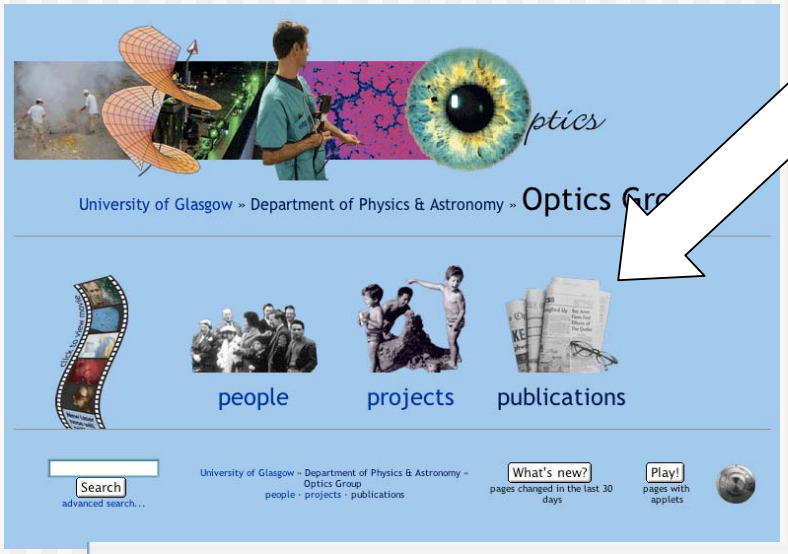


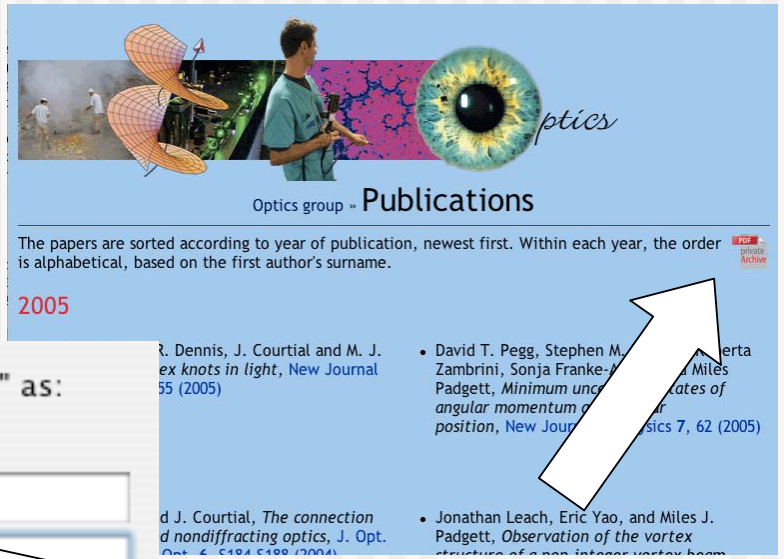
Talbot Cube (9 waves)

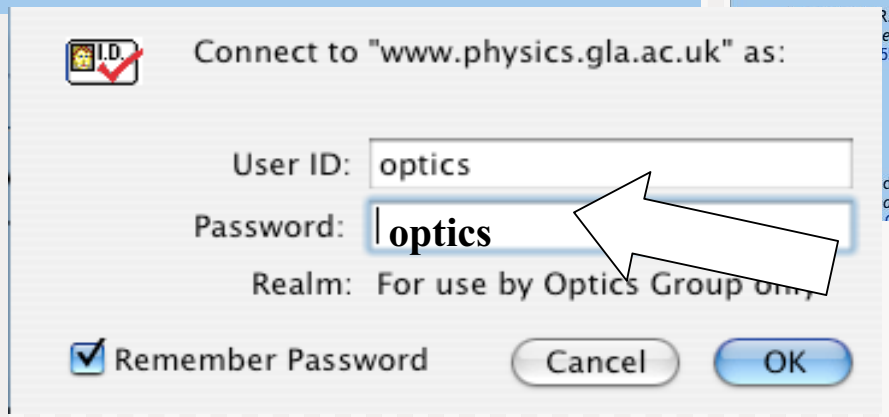
The (pre) conditions for links/knots

- Getting same signed vortices to neighbour each other requires non-zero azimuthal phase
- If links/knots are always threaded
  - Formation of links and knots requires orbital angular momentum
  - Perhaps not very likely in a random speckle field (possible with local variations?)
  - If links require ℓ=2 and knots ℓ=3 etc then these topologies need a minimum number of waves

www.physics.gla.ac.uk/Optics







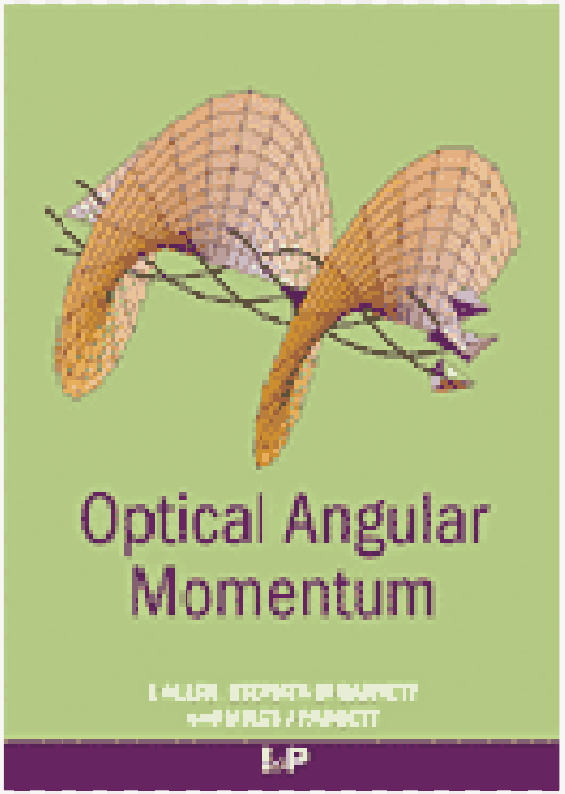
Further reading on OAM?

Allen, Padgett and Babiker
Prog. in Optics 1999

Padgett and Allen
Contemp. Physics 2000

Allen Barnett and Padgett
Optical Angular Momentum
IOP 2003 (collected papers)

Padgett, Courtial and Allen
Physics Today 2004



and special thanks to..

Les Allen - who introduced me to the field and has inspired me to keep twisting!

Johannes Courtial - who I've worked with along the way

Thank You

Scotland, a 40km cycle ride from my lab