Observation of Optical Polarization Möbius Strips

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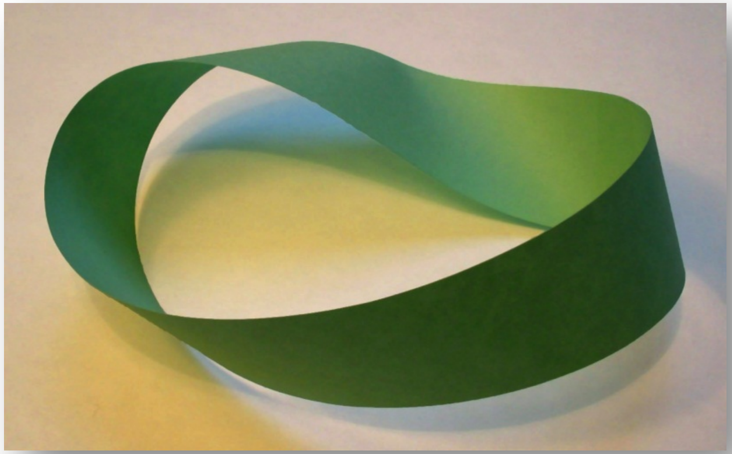
Optical Möbius Strips – When Light Turns One-Sided and Single-Edged

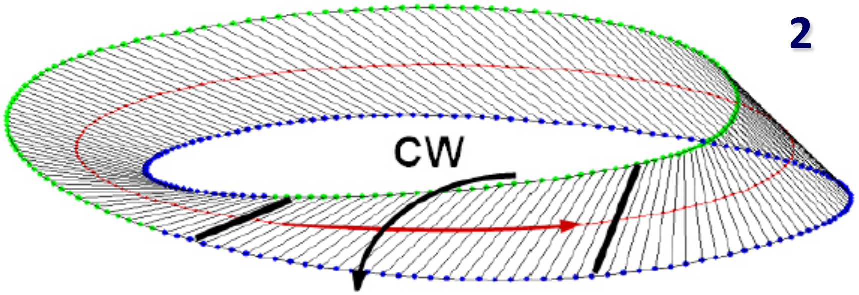
An ‘ordinary’ Möbius strip



1

A polarization Möbius strip

(introduced by Isaac Freund)



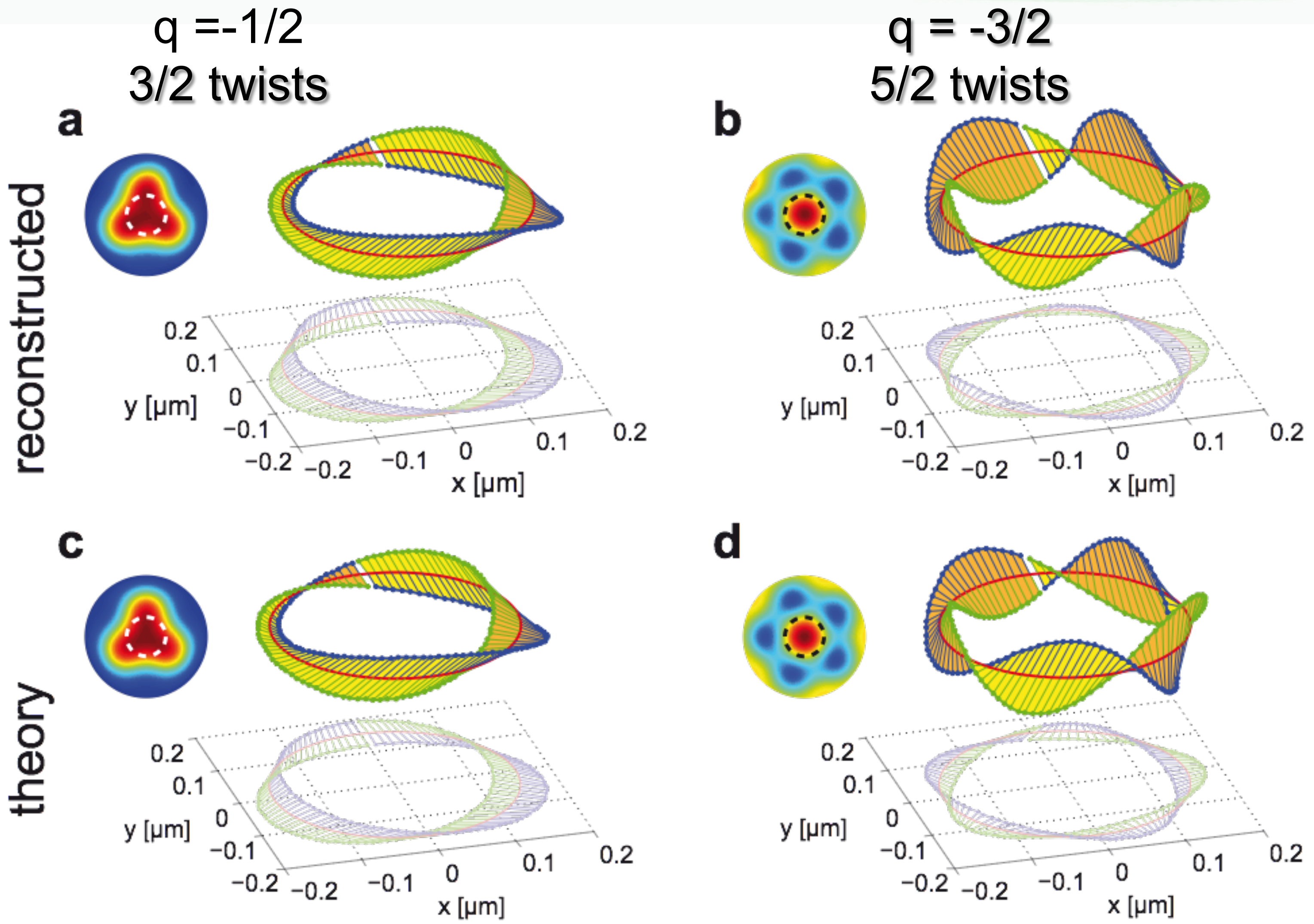
2

Isaac Freund discovered, described, and investiated these unusal objects

- **Optical Möbius strips can be found in light fields**
- **One has to look at a very special field distribution in a very special way**
- **By doing so, one can observe optical Möbius strips in the field structure**

[1] Wikipedia
[2] Isaac Freund, Bar-Ilan Univ., Talk: *Optical Moebius Strips and Twisted Ribbons*, Conf. on Singular Optics, ICTP Trieste, Part II, 30 May 2011
Isaac Freund, Opt. Commun. 242, 65-78 (2004)
Isaac Freund, Opt. Commun. 249, 7-22 (2005)
Isaac Freund, Opt. Commun. 256, 220-241 (2005)
Isaac Freund, Opt. Commun. 283, 1-15 (2010)
Isaac Freund, Opt. Commun. 283, 16-28 (2010)
Isaac Freund, Opt. Lett. 35, 148-150 (2010)
Isaac Freund, Opt. Commun. 284, 3816-3845 (2011)

Möbius strips with half-twists



We have |q|+1 twists

Bauer T, Banzer P, Karimi E, Orlovas S, Rubano A, Marrucci L, Santamato E, Boyd RW, and Leuchs G, *in review*.

Experimental Observation of Optical Polarization Möbius Strips

Introduction and Background

Singularities in Optics – Undefined Points in Scalar and Vectorial Light Fields

Optical Möbius Strips – When Light Turns One-Sided and Single-Edged

Theoretical and Experimental Techniques

How to Realize an Optical Möbius Strip with Tightly Focused Light

How to Measure (an Optical Möbius Strip in) a Tightly Focused Light Beam

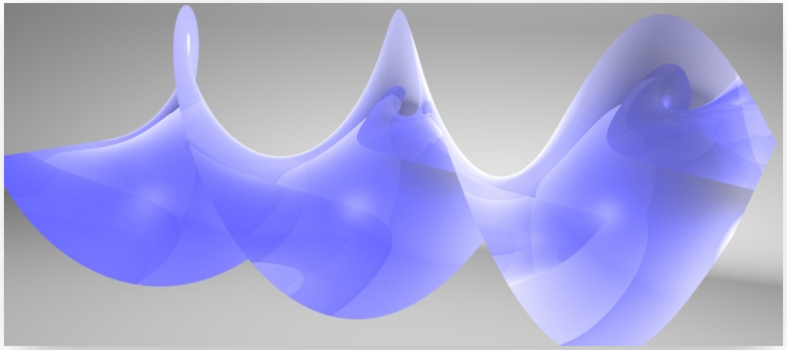
Experimental Results

A Polarization Möbius Strip in the Lab

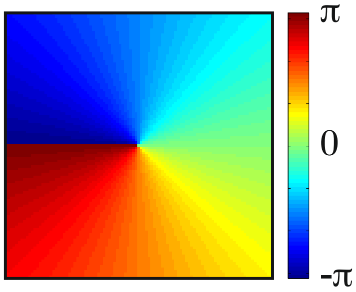
Singularities in Optics

Phase singularities in scalar light beams and scalar wave fields

Laguerre-Gaussian (LG) beams (solutions of the paraxial, scalar wave equation)



- **Phase vortex/singularity in an LG beam**
- **Spiraling (non-planar) phase front**
- **Screw dislocation[1]**



- **Helical phase term $e^{im\varphi}$**
- **m: charge; related to orbital angular momentum[2]**
- **Singularity is on-axis at a point of zero intensity**

[1] J.F. Nye, M.V. Berry, Proc. R. Soc. London A 336 (1974) 165

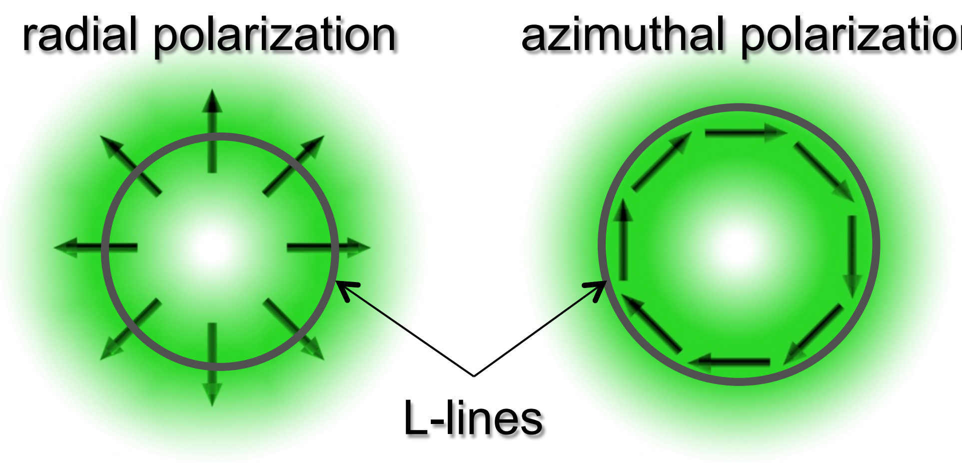
[2] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Phys. Rev. A 45, 8185–8189 (1992)

M. V. Berry, "Singularities in waves and rays," in Les Houches Session XXV - Physics of Defects, R. Balian, M. Kléman, and J.-P. Poirier, eds., (North-Holland, 1981)

Singularities in Optics

Polarization singularities – C (circular polarization) points or L (linear) lines

(Paraxially) propagating vectorial light beams – vortices and L-lines



Each has a polarization singularity associated with an intensity null on axis

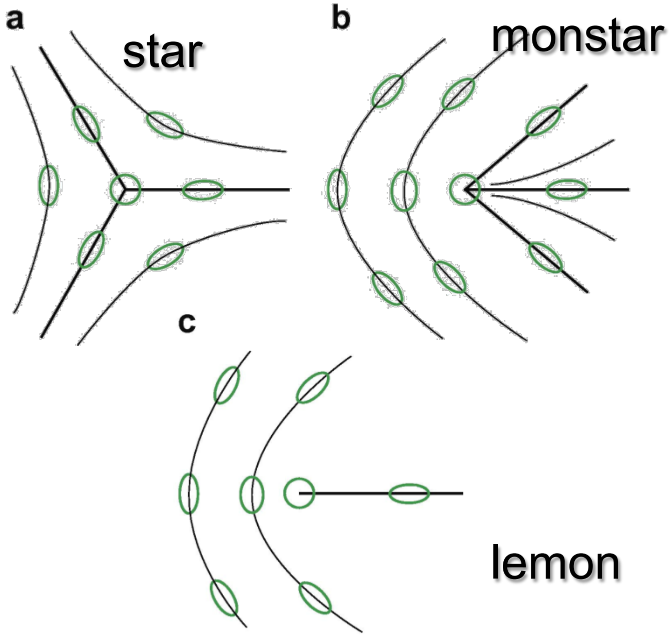
- **Cylindrical vector beams can exhibit polarization singularities on-axis**
- **Non-homogeneous polarization distribution**

M. R. Dennis, Optics Communications 213, 201-221 (2002)
M. R. Dennis, "Topological Singularities in Wave Fields," PhD thesis, University of Bristol, 2001

Singularities in Optics

Polarization singularities – C points or L lines – introduced by Nye[1-4]
Bright singular points/lines in wave fields or beams

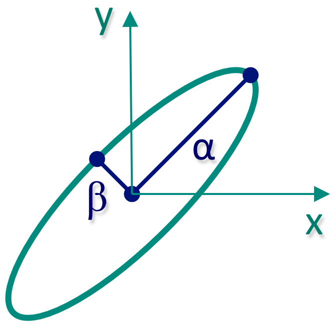
2D Ellipse-fields[5] Each shows a C point)



Definition of polarization ellipse

(Berry's equations[6])

$\alpha = \mathit{Re}(\mathbf{E}^*(\mathbf{E}\cdot\mathbf{E})^{1/2})$
$\beta = \mathit{Im}(\mathbf{E}^*(\mathbf{E}\cdot\mathbf{E})^{1/2})$
$\gamma = \mathit{Im}(\mathbf{E}^*\times\mathbf{E})$

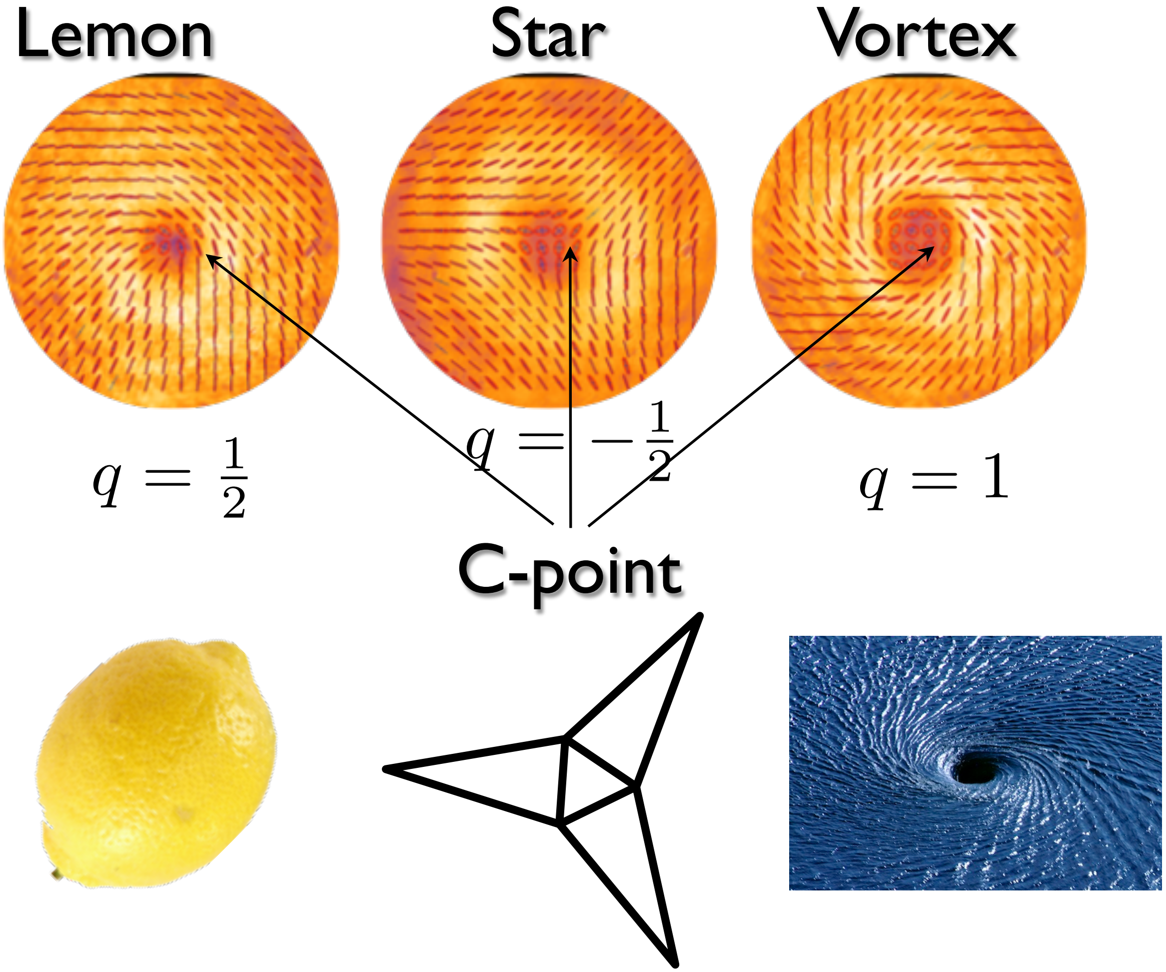


At a C (circular) point: $\alpha = \beta$
Hence, orientation of the polarization ellipse is undefined (singular)

On an L (linear) line: $\beta = \gamma = 0$
Hence, handedness of the polarization ellipse is undefined

[1] J.F. Nye, Proc. R. Soc. London A 389, 279 (1983)
[2] J.F. Nye, Proc. R. Soc. London A 387, 105 (1983)
[3] J.F. Nye, J.V. Hajnal, Proc. R. Soc. London A 409, 21 (1987)
[4] J.F. Nye, Natural focusing and fine structure of light: caustics and wave dislocations, Institute of Physics Publishing, Bristol, 1999
M.V. Berry, M.R. Dennis, Proc. R. Soc. London A 457, 141 (2001)
[5] I.O. Buinyi, V.G. Denisenko, M.S. Soskin, Optics Communications 282, 143–155 (2009)
[6] M.V. Berry, in: M.S. Soskin, M.V. Vasnetsov (Eds.), Second International Conference on Singular Optics, Proc. SPIE, 4403, 2001, p. 1. etc.

Poincaré Beams
(Vector Beams)

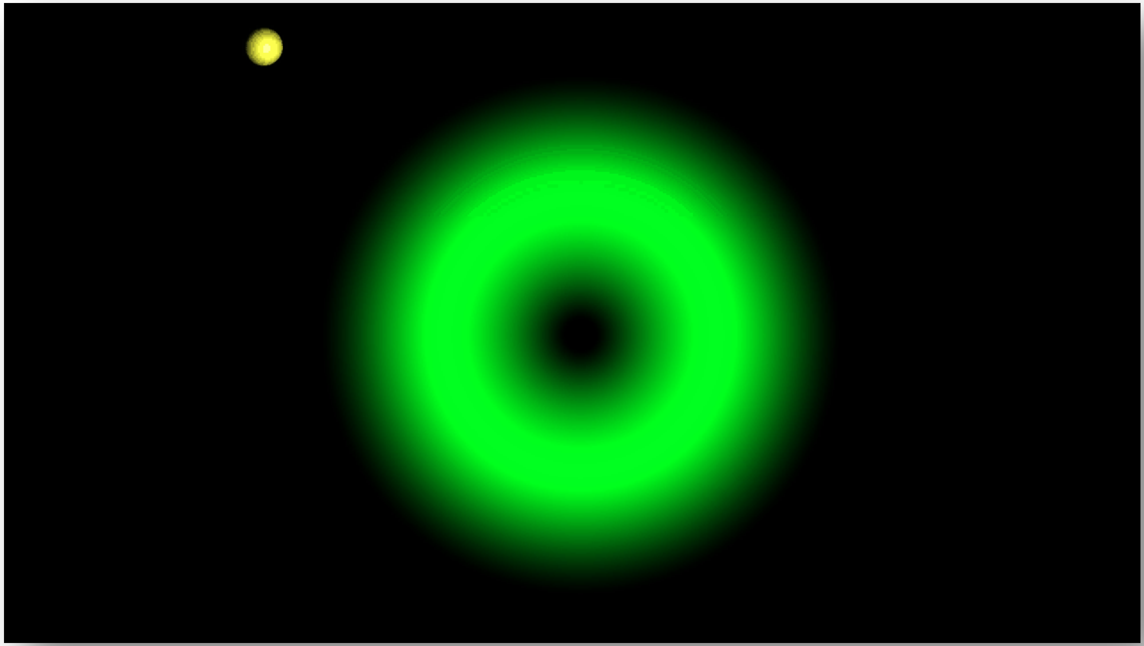


Cardano F, Karimi E, Slussarenko S, Marrucci L, de Lisio C, and Santamato E, *Applied Optics*, **51**, C1 (2012).

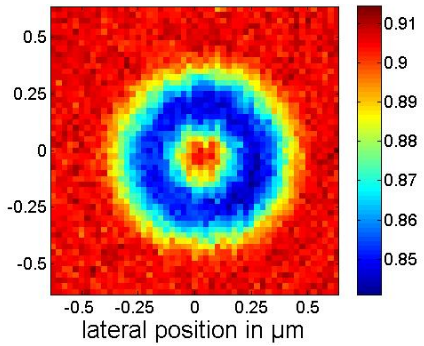
Full vectorial beam measurement on the nanoscale

Nanoparticle-based probing technique for vector beam reconstruction

1. A dipole-like spherical nanoparticle (90 nm diameter) is scanned through the beam
2. The forward- and backward-scattered light for each position of the nanoparticle relative to the beam in the focal plane is measured



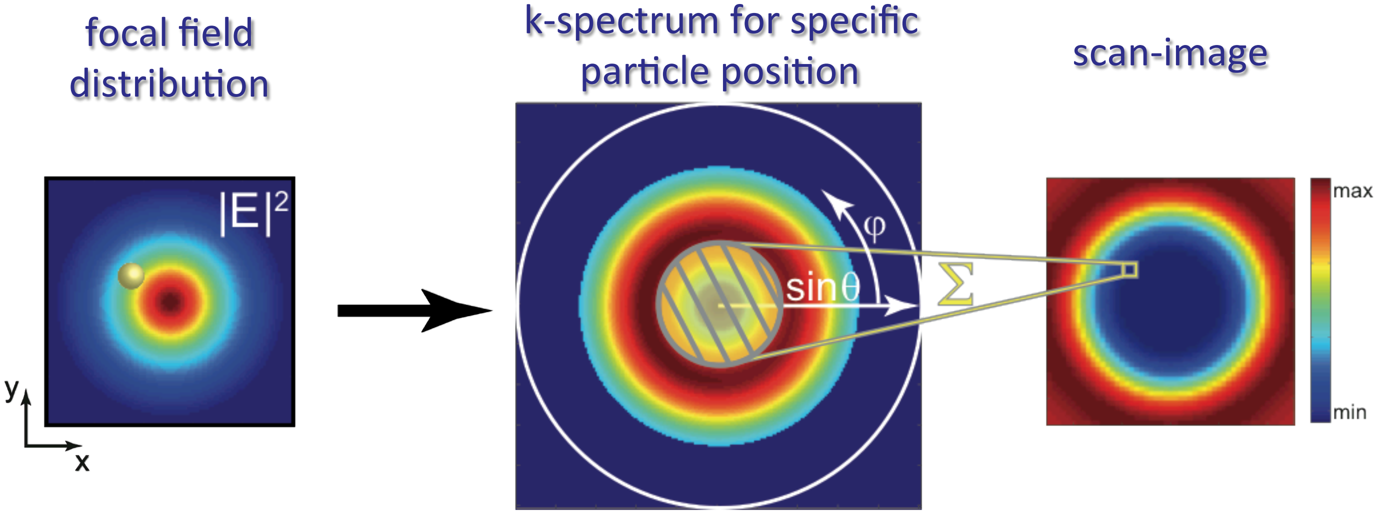
measured intensity
(can also measure
polarization and phase)



Full amplitude and phase reconstruction scheme:
T. Bauer, S. Orlov, U. Peschel, P. B. and G. Leuchs, “Nanointerferometric Amplitude and Phase Reconstruction of Tightly Focused Vector Beams”, Nat. Photon 8, 23 - 27 (2014).

Full vectorial beam reconstruction on the nanoscale

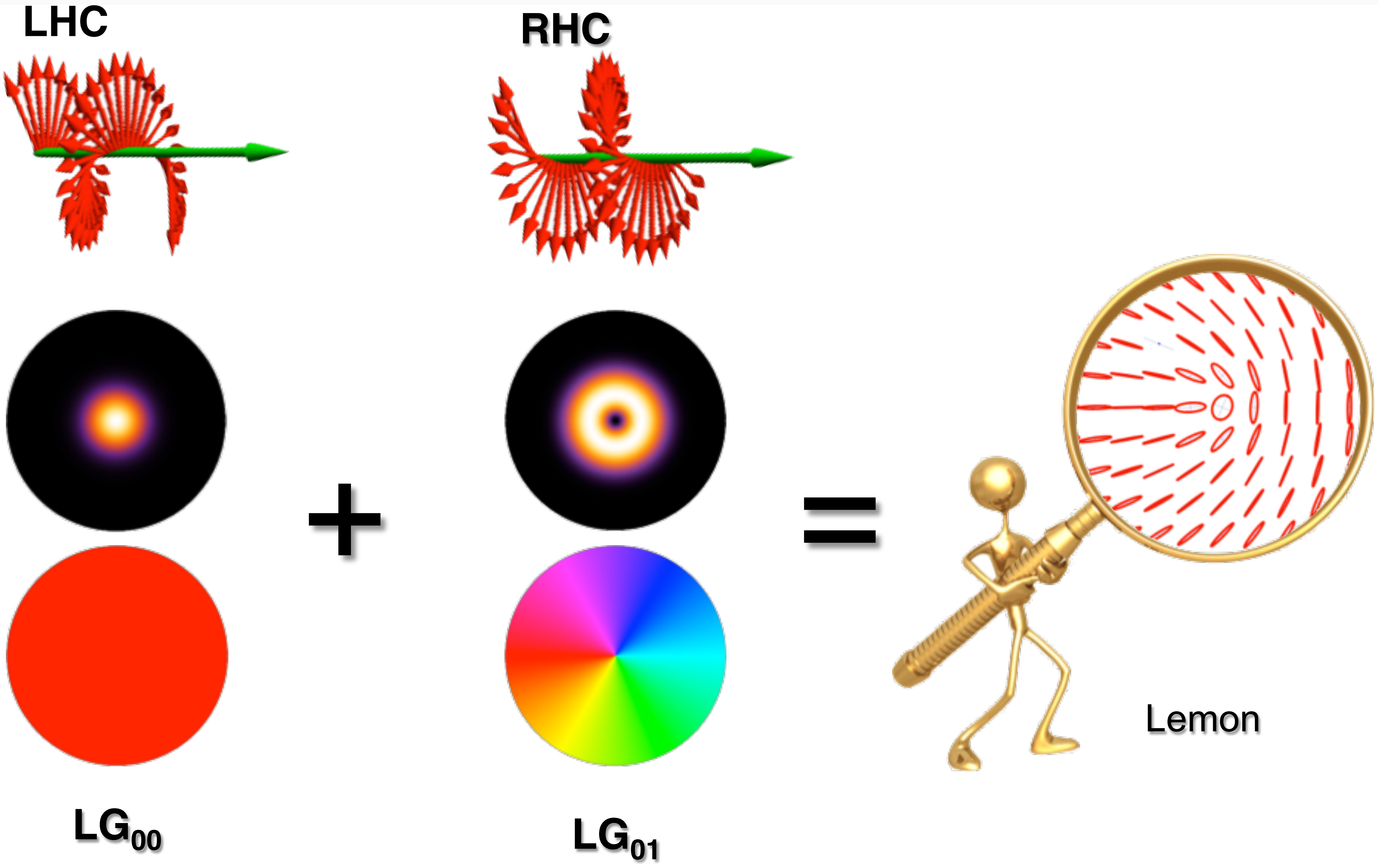
2D-scanning of particle through focal plane:



- Scan scattering particle through focal plane
- Collect k-spectrum of transmitted light (image back-focal plane of objective lens) for each position of the particle relative to the beam in the focal plane $\mathrm{P_T}(\theta,\varphi) = \mathrm{P_{in}}(\theta,\varphi) + \mathrm{P_s}(\theta,\varphi) + \mathrm{P_{int}}(\theta,\varphi)$
- Reduce complexity by integrating over specific sectors
- free parameters: λ, r_{sphere}, ε_m, ε_{gold}, number of multipoles

T. Bauer, S. Orlov, U. Peschel, P. B. and G. Leuchs, Nat. Photon 8, 23 - 27 (2014).

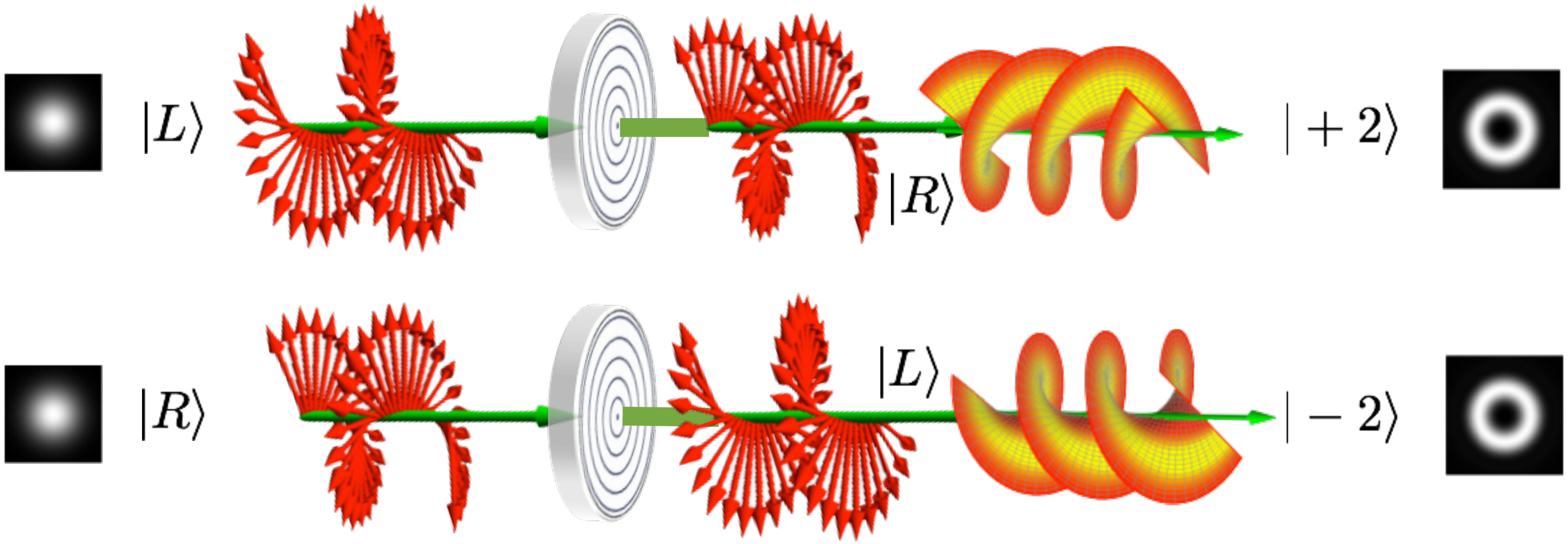
Our Experimental Procedure: Superposition of Two Beams



We use q-plates to form vector beams

q-plate: a non-uniform wave plate

Action of a q=1 q-plate

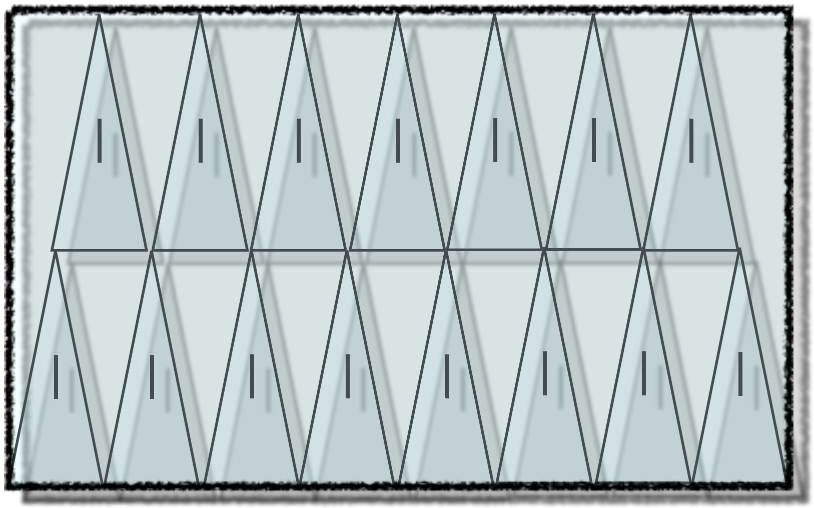


Marrucci L, et al., *PRL* **96**, 163905 (2006).
Karimi E et al., *APL* **98**, 231124 (2009).
Karimi E, et al., *OL* **34**, 1225 (2009).

$q=1$-plate

Here, in concept, is how to construct a $q=1$ q-plate

Consider a standard half-wave plate, and imagine cutting it into pie-shaped wedges

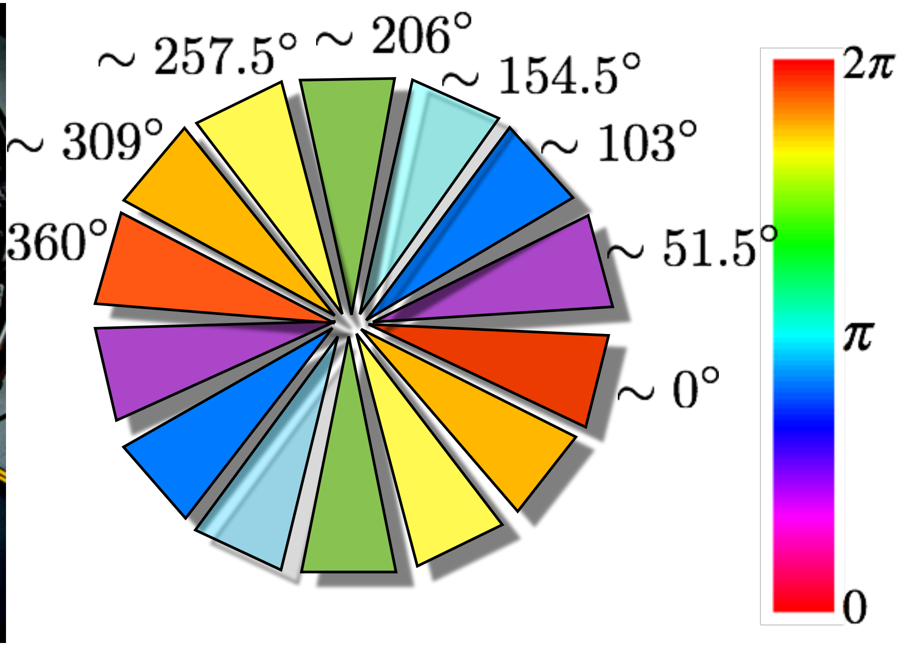


Short lines show the fast axis of the waveplate

q=1-plate

Now rearrange the wedges as shown

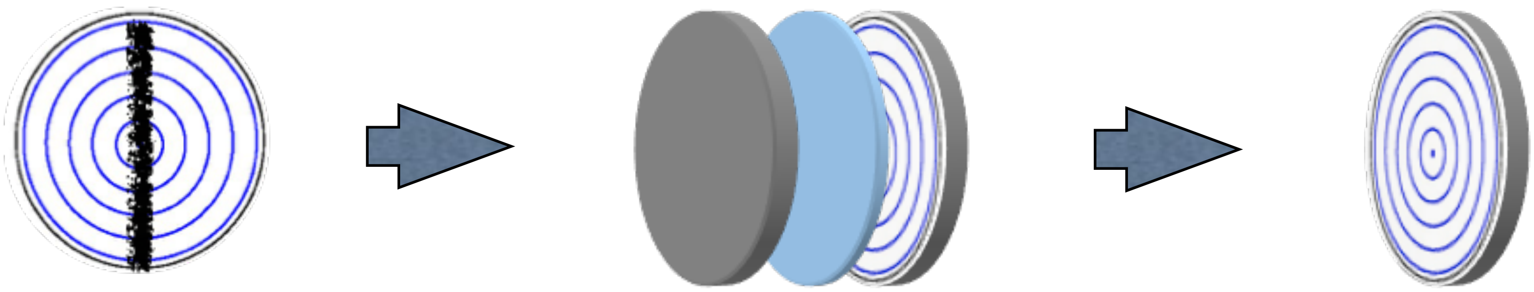
Phase structure of output beam



Marrucci L, et al., *PRL* **96**, 163905 (2006).
Karimi E et al., *APL* **98**, 231124 (2009).
Karimi E, et al., *OL* **34**, 1225 (2009).

Fabricating a *q=1*-plate

How do we fabricate the *q*-plate?

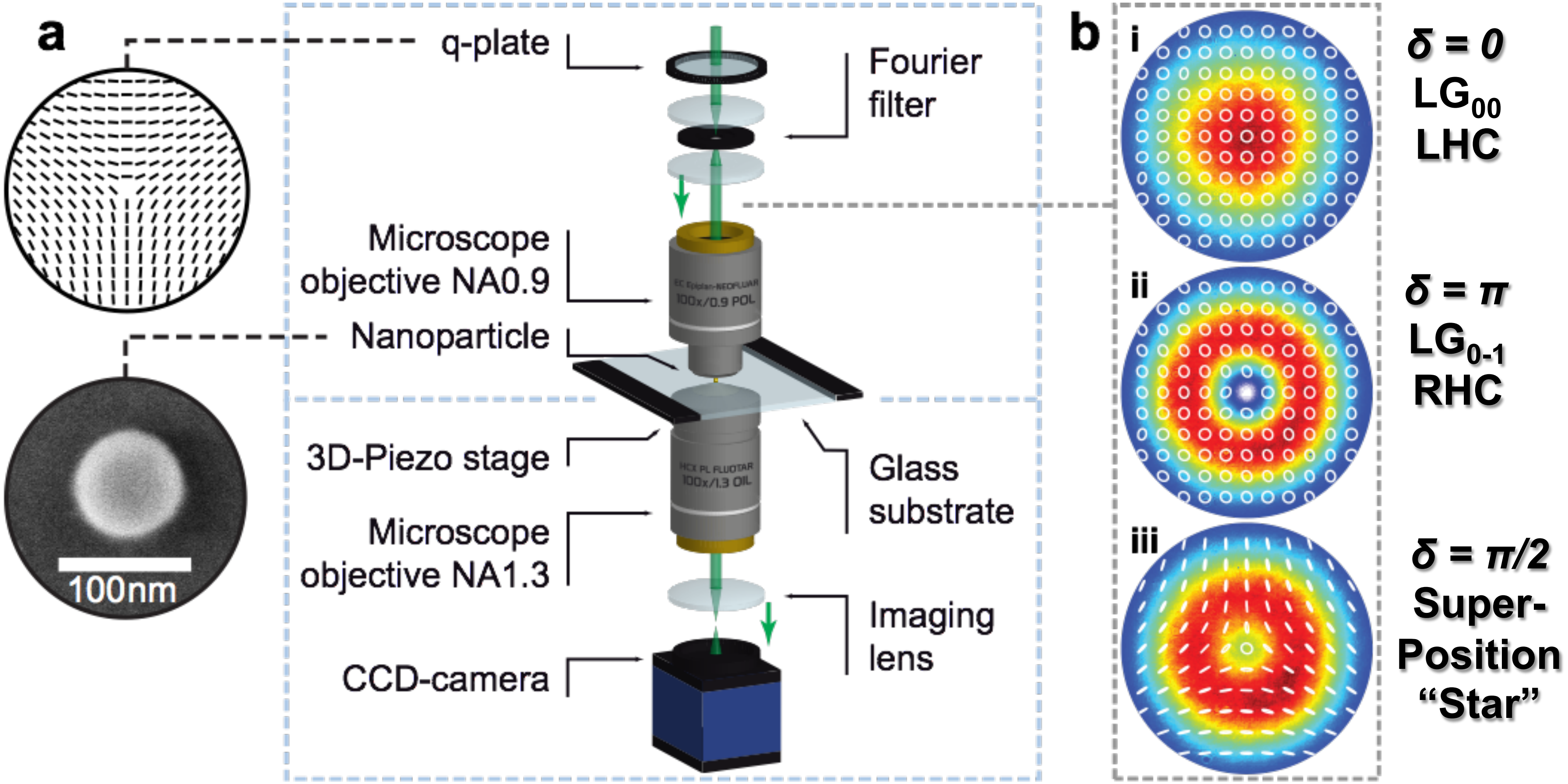


Rub circular nano-ridges onto a polymer-coated glass substrate

Sandwich liquid crystal between two glass plates

$q=1$ plate

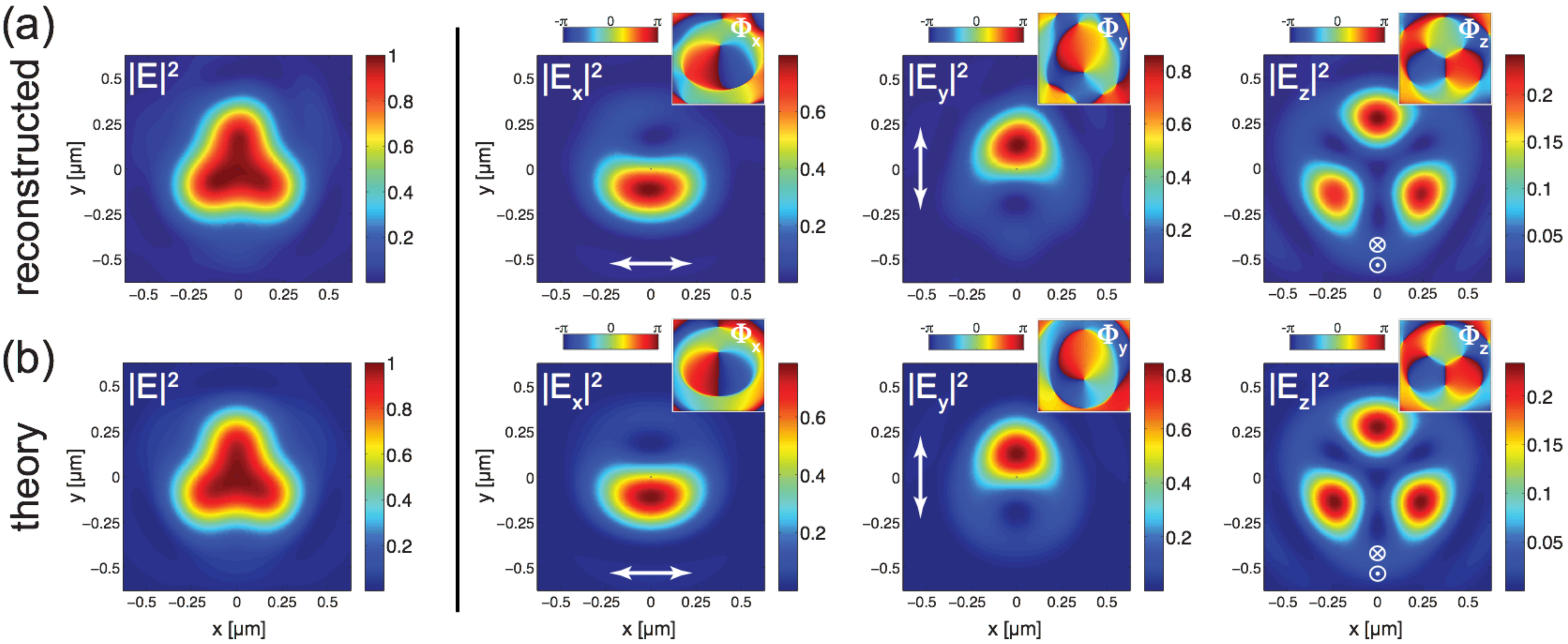
Observing a Polarization Möbius Strip



Crucial: tight focusing enhances the Möbius effect, which depends on the z component of the field

Bauer T, Banzer P, Karimi E, Orlovas S, Rubano A, Marrucci L, Santamato E, Boyd RW, and Leuchs G, *under review*.

Field distribution for q = -1/2



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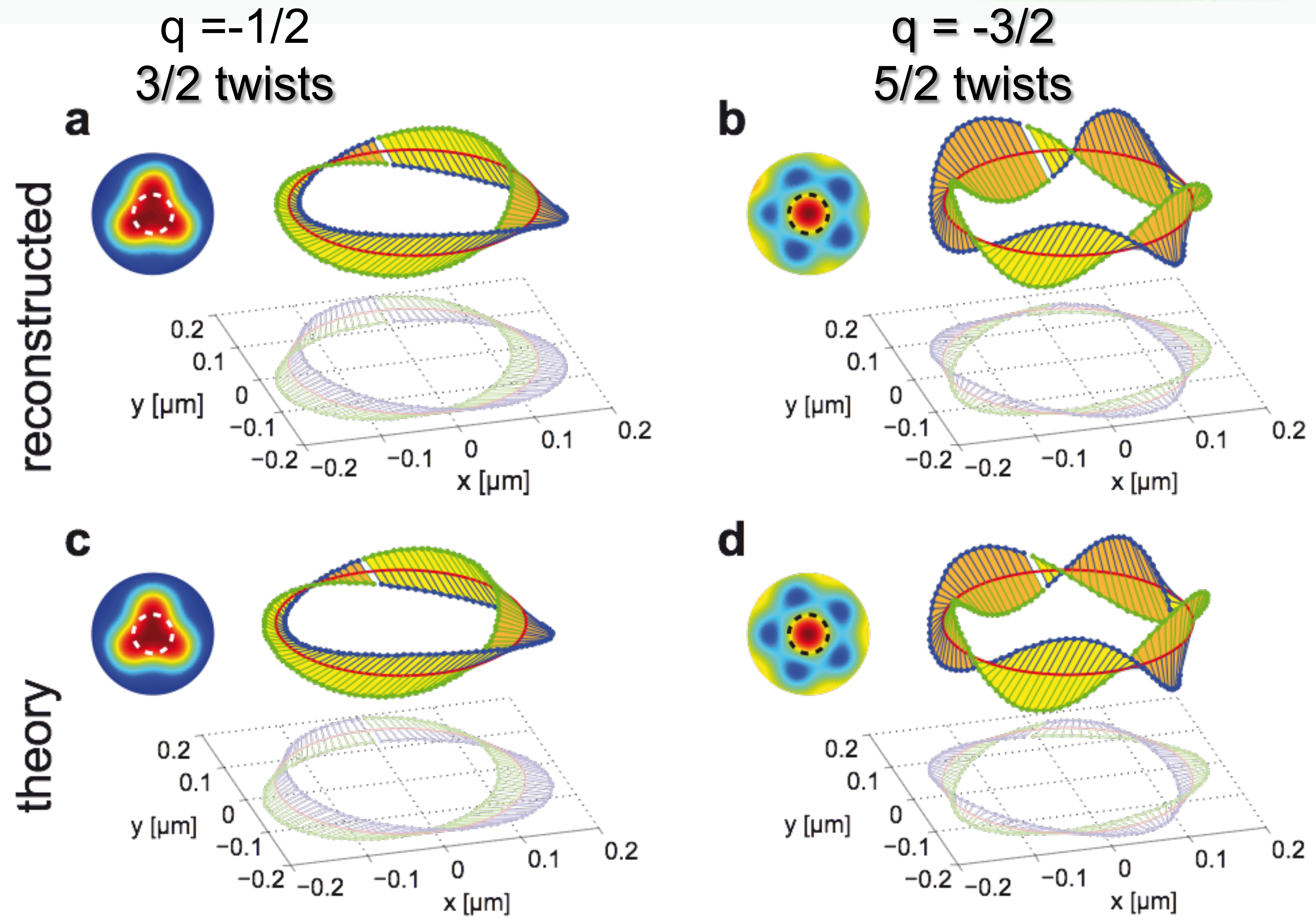
Möbius strips with half-twists

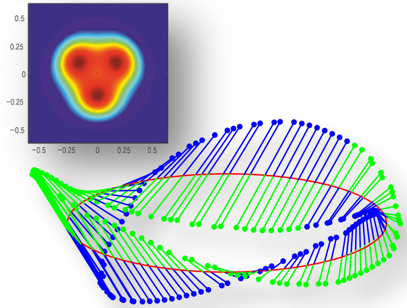


We have |q|+1 twists

Bauer T, Banzer P, Karimi E, Orlovas S, Rubano A, Marrucci L, Santamato E, Boyd RW, and Leuchs G, *in review*.

Conclusions

- Generation and investigation of an optical polarization Möbius strip in tightly focused light beams



- Experimental observation using a particle-based nanoprobing technique